

# New Heavy Bosons ( $W'$ , $Z'$ , leptoquarks, etc.), Searches for

We list here various limits on charged and neutral heavy vector bosons (other than  $W$ 's and  $Z$ 's), heavy scalar bosons (other than Higgs bosons), vector or scalar leptoquarks, and axigluons. The latest unpublished results are described in " $W'$  Searches" and " $Z'$  Searches" reviews. For recent searches on scalar bosons which could be identified as Higgs bosons, see the listings in the Higgs boson section.

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See the related review(s):

[\$W'\$ -Boson Searches](#)

## MASS LIMITS for $W'$ (Heavy Charged Vector Boson Other Than $W$ ) in Hadron Collider Experiments

Couplings of  $W'$  to quarks and leptons are taken to be identical with those of  $W$ . The following limits are obtained from  $p\bar{p}$  or  $p p \rightarrow W'X$  with  $W'$  decaying to the mode

indicated in the comments. New decay channels (e.g.,  $W' \rightarrow WZ$ ) are assumed to be suppressed. The most recent preliminary results can be found in the “ $W'$ -boson searches” review above.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;6000 (CL = 95%) OUR LIMIT</b>				
none 1000–3400	95	1 SIRUNYAN	21Y CMS	$W' \rightarrow tb$
>3200	95	2 AAD	20AJ ATLS	$W' \rightarrow WH$
>4300	95	3 AAD	20AT ATLS	$W' \rightarrow WZ$
none 1100–4000	95	4 AAD	20T ATLS	$W' \rightarrow q\bar{q}$
none 1800–3600	95	5 SIRUNYAN	20AI CMS	$W' \rightarrow q\bar{q}$
none 1200–3800	95	6 SIRUNYAN	20Q CMS	$W' \rightarrow WZ$
		7 AABOUD	19B ATLS	$W' \rightarrow Nl \rightarrow lljj$
none 500–3250	95	8 AABOUD	19E ATLS	$W' \rightarrow tb$
<b>&gt;6000</b>	95	9 AAD	19C ATLS	$W' \rightarrow e\nu, \mu\nu$
none 1300–3600	95	10 AAD	19D ATLS	$W' \rightarrow WZ$
none 400–4000	95	11 SIRUNYAN	19AY CMS	$W' \rightarrow \tau\nu$
>4300	95	12 SIRUNYAN	19CP CMS	$W' \rightarrow WZ, WH, l\nu$
>2600	95	13 SIRUNYAN	19I CMS	$W' \rightarrow WH$
none 1000–3000	95	14 AABOUD	18AF ATLS	$W' \rightarrow tb$
none 500–2820	95	15 AABOUD	18AI ATLS	$W' \rightarrow WH$
none 300–3000	95	16 AABOUD	18AK ATLS	$W' \rightarrow WZ$
none 800–3200	95	17 AABOUD	18AL ATLS	$W' \rightarrow WZ$
>5100	95	18 AABOUD	18BG ATLS	$W' \rightarrow e\nu, \mu\nu$
none 250–2460	95	19 AABOUD	18CH ATLS	$W' \rightarrow WZ$
none 1200–3300	95	20 AABOUD	18F ATLS	$W' \rightarrow WZ$
none 500–3700	95	21 AABOUD	18K ATLS	$W' \rightarrow \tau\nu$
none 1000–3600	95	22 SIRUNYAN	18 CMS	$W' \rightarrow tb$
none 1000–3050	95	23 SIRUNYAN	18AX CMS	$W' \rightarrow WZ$
none 400–5200	95	24 SIRUNYAN	18AZ CMS	$W' \rightarrow e\nu, \mu\nu$
none 1000–3400	95	25 SIRUNYAN	18BK CMS	$W' \rightarrow WZ$
none 600–3300	95	26 SIRUNYAN	18BO CMS	$W' \rightarrow q\bar{q}$
none 900–4400	95	27 SIRUNYAN	18CV CMS	$W' \rightarrow Nl \rightarrow lljj$
none 800–2330	95	28 SIRUNYAN	18DJ CMS	$W' \rightarrow WZ$
>2800	95	29 SIRUNYAN	18ED CMS	$W' \rightarrow WH$
none 1200–3200, 3300–3600	95	30 SIRUNYAN	18P CMS	$W' \rightarrow WZ$
>3600	95	31 AABOUD	17AK ATLS	$W' \rightarrow q\bar{q}$
none 1100–2500	95	32 AABOUD	17AO ATLS	$W' \rightarrow WH$
>2220	95	33 AABOUD	17B ATLS	$W' \rightarrow WH$
>2300	95	34 KHACHATRY...17J	CMS	$W' \rightarrow N_\tau \tau \rightarrow \tau\tau jj$
none 600–2700	95	35 KHACHATRY...17W	CMS	$W' \rightarrow q\bar{q}$
>4100	95	36 KHACHATRY...17Z	CMS	$W' \rightarrow e\nu, \mu\nu$
>2200	95	37 SIRUNYAN	17A CMS	$W' \rightarrow WZ$
>2300	95	38 SIRUNYAN	17AK CMS	$W' \rightarrow WZ, WH$
>2900	95	39 SIRUNYAN	17H CMS	$W' \rightarrow \tau N$
>2600	95	40 SIRUNYAN	17I CMS	$W' \rightarrow tb$
>2450	95	41 SIRUNYAN	17R CMS	$W' \rightarrow WH$
none 2780–3150	95	41 SIRUNYAN	17R CMS	$W' \rightarrow WH$
>2600	95	42 AABOUD	16AE ATLS	$W' \rightarrow WZ$

>4070	95	43	AABOUD	16V	ATLS	$W' \rightarrow e\nu, \mu\nu$
>1810	95	44	AAD	16R	ATLS	$W' \rightarrow WZ$
>2600	95	45	AAD	16S	ATLS	$W' \rightarrow q\bar{q}$
>2150	95	46	KHACHATRY...16AO	CMS		$W' \rightarrow tb$
none 1000–1600	95	47	KHACHATRY...16AP	CMS		$W' \rightarrow WH$
none 800–1500	95	48	KHACHATRY...16BD	CMS		$W' \rightarrow WH \rightarrow b\bar{b}l\nu$
none 1500–2600	95	49	KHACHATRY...16K	CMS		$W' \rightarrow q\bar{q}$
none 500–1600	95	50	KHACHATRY...16L	CMS		$W' \rightarrow q\bar{q}$
none 300–2700	95	51	KHACHATRY...16O	CMS		$W' \rightarrow \tau\nu$
none 400–1590	95	52	AAD	15AU	ATLS	$W' \rightarrow WZ$
none 1500–1760	95	53	AAD	15AV	ATLS	$W' \rightarrow tb$
none 300–1490	95	54	AAD	15AZ	ATLS	$W' \rightarrow WZ$
none 1300–1500	95	55	AAD	15CP	ATLS	$W' \rightarrow WZ$
none 500–1920	95	56	AAD	15R	ATLS	$W' \rightarrow tb$
none 800–2450	95	57	AAD	15V	ATLS	$W' \rightarrow q\bar{q}$
>1470	95	58	KHACHATRY...15C	CMS		$W' \rightarrow WZ$
>3710	95	59	KHACHATRY...15T	CMS		$W' \rightarrow e\nu, \mu\nu$
none 1000–3010	95	60	KHACHATRY...14O	CMS		$W' \rightarrow Nl \rightarrow lljj$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●						
		61	AAD	20AD	ATLS	$W' \rightarrow JJ$
		62	AAD	20W	ATLS	$W' \rightarrow WZ' \rightarrow l\nu q\bar{q}$
		63	AABOUD	19BB	ATLS	$W' \rightarrow Nl \rightarrow jll$
		64	SIRUNYAN	19V	CMS	$W' \rightarrow Bt, Tb$
		65	AABOUD	18AA	ATLS	$W' \rightarrow W\gamma$
		66	AABOUD	18AD	ATLS	$W' \rightarrow HX$
>4500	95	67	AABOUD	18CJ	ATLS	$W' \rightarrow WZ, WH, l\nu$
		68	KHACHATRY...17U	CMS		$W' \rightarrow WH$
		69	AAD	15BB	ATLS	$W' \rightarrow WH$
none 300–880	95	70	AALTONEN	15C	CDF	$W' \rightarrow tb$
none 1200–1900 and 2000–2200	95	71	KHACHATRY...15V	CMS		$W' \rightarrow q\bar{q}$
>3240	95		AAD	14AI	ATLS	$W' \rightarrow e\nu, \mu\nu$
		72	AAD	14AT	ATLS	$W' \rightarrow W\gamma$
none 200–1520	95	73	AAD	14S	ATLS	$W' \rightarrow WZ$
none 1000–1700	95	74	KHACHATRY...14	CMS		$W' \rightarrow WZ$
		75	KHACHATRY...14A	CMS		$W' \rightarrow WZ$
none 500–950	95	76	AAD	13AO	ATLS	$W' \rightarrow WZ$
none 1100–1680	95		AAD	13D	ATLS	$W' \rightarrow q\bar{q}$
none 1000–1920	95		CHATRCHYAN 13A	CMS		$W' \rightarrow q\bar{q}$
		77	CHATRCHYAN 13AJ	CMS		$W' \rightarrow WZ$
>2900	95	78	CHATRCHYAN 13AQ	CMS		$W' \rightarrow e\nu, \mu\nu$
none 800–1510	95	79	CHATRCHYAN 13E	CMS		$W' \rightarrow tb$
none 700–940	95	80	CHATRCHYAN 13U	CMS		$W' \rightarrow WZ$
none 700–1130	95	81	AAD	12AV	ATLS	$W' \rightarrow tb$
none 200–760	95	82	AAD	12BB	ATLS	$W' \rightarrow WZ$
		83	AAD	12CK	ATLS	$W' \rightarrow \bar{t}q$
>2550	95	84	AAD	12CR	ATLS	$W' \rightarrow e\nu, \mu\nu$
		85	AAD	12M	ATLS	$W' \rightarrow Nl \rightarrow lljj$

		86	AALTONEN	12N	CDF	$W' \rightarrow \bar{\tau}q$
none 200–1143	95	82	CHATRCHYAN	12AF	CMS	$W' \rightarrow WZ$
		87	CHATRCHYAN	12AR	CMS	$W' \rightarrow \bar{\tau}q$
		88	CHATRCHYAN	12BG	CMS	$W' \rightarrow N\ell \rightarrow \ell\ell jj$
>1120	95		AALTONEN	11C	CDF	$W' \rightarrow e\nu$
none 180–690	95	89	ABAZOV	11H	D0	$W' \rightarrow WZ$
none 600–863	95	90	ABAZOV	11L	D0	$W' \rightarrow tb$
none 285–516	95	91	AALTONEN	10N	CDF	$W' \rightarrow WZ$
none 280–840	95	92	AALTONEN	09AC	CDF	$W' \rightarrow q\bar{q}$
>1000	95		ABAZOV	08C	D0	$W' \rightarrow e\nu$
none 300–800	95		ABAZOV	04C	D0	$W' \rightarrow q\bar{q}$
none 225–536	95	93	ACOSTA	03B	CDF	$W' \rightarrow tb$
none 200–480	95	94	AFFOLDER	02C	CDF	$W' \rightarrow WZ$
> 786	95	95	AFFOLDER	01I	CDF	$W' \rightarrow e\nu, \mu\nu$
none 300–420	95	96	ABE	97G	CDF	$W' \rightarrow q\bar{q}$
> 720	95	97	ABACHI	96C	D0	$W' \rightarrow e\nu$
> 610	95	98	ABACHI	95E	D0	$W' \rightarrow e\nu, \tau\nu$
none 260–600	95	99	RIZZO	93	RVUE	$W' \rightarrow q\bar{q}$

<sup>1</sup> SIRUNYAN 21Y search for resonances decaying to  $tb$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 2 for limits on  $\sigma \cdot B(W' \rightarrow tb)$ .

<sup>2</sup> AAD 20AJ search for resonances decaying to  $HW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 2900$  GeV for  $g_V = 1$ . See their Fig. 6 for limits on  $\sigma \cdot B$ .

<sup>3</sup> AAD 20AT search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 3900$  GeV for  $g_V = 1$ . See their Fig. 13 for limits on  $\sigma \cdot B$ .

<sup>4</sup> AAD 20T search for  $W'$  with SM-like couplings in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 4(c) for limits on the product of the cross section, acceptance, and branching fraction.

<sup>5</sup> SIRUNYAN 20AI limit is for  $W'$  with SM-like coupling using  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>6</sup> SIRUNYAN 20Q search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ .

<sup>7</sup> AABOUD 19B search for right-handed  $W_R$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $W_R$  is assumed to decay into  $\ell$  and hypothetical heavy neutrino  $N$ , with  $N$  decaying to  $\ell jj$ . See their Figs. 7 and 8 for excluded regions in  $M_{W_R} - M_N$  plane.

<sup>8</sup> AABOUD 19E search for right-handed  $W'$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 8 for limit on  $\sigma \cdot B$ .

<sup>9</sup> AAD 19C search for  $W'$  with SM-like couplings in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Bosonic decays and  $W - W'$  interference are neglected. The limits on  $e$  and  $\mu$  separately are 6.0 and 5.1 TeV respectively. See their Fig. 2 for limits on  $\sigma \cdot B$ .

<sup>10</sup> AAD 19D search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 3400$  GeV for  $g_V = 1$ . If we assume  $M_{W'} = M_{Z'}$ , the limit increases  $M_{W'} > 3800$  GeV and  $M_{W'} > 3500$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig. 9 for limits on  $\sigma \cdot B$ .

<sup>11</sup> SIRUNYAN 19AY limits shown for  $W'$  with SM-like coupling using  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $W - W'$  interference and bosonic decays of  $W'$  are not included. See their Fig. 5 for limits on  $\sigma \cdot B$ . Limits in the context of a nonuniversal gauge interaction are shown in Fig. 7. Model independent limits on  $\sigma B A \epsilon$  can be seen in Fig. 8.

- <sup>12</sup> SIRUNYAN 19CP present a statistical combinations of searches for  $W'$  decaying to pairs of bosons or leptons in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . If we assume  $M_{W'} = M_{Z'}$ , the limit becomes  $M_{W'} > 4500$  GeV for  $g_V = 3$  and  $M_{W'} > 5000$  GeV for  $g_V = 1$ . See their Figs. 2 and 3 for limits on  $\sigma \cdot B$ .
- <sup>13</sup> SIRUNYAN 19I search for resonances decaying to  $HW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 2800$  GeV if we assume  $M_{W'} = M_{Z'}$ .
- <sup>14</sup> AABOUD 18AF give the limit above for right-handed  $W'$  using  $pp$  collisions at  $\sqrt{s} = 13$  TeV. These limits also exclude  $W$  bosons with left-handed couplings with masses below 2.9 TeV, at the 95% confidence level.  $W' \rightarrow \ell\nu_R$  is assumed to be forbidden. See their Fig.5 for limits on  $\sigma \cdot B$  for both cases of left- and right-handed  $W'$ .
- <sup>15</sup> AABOUD 18AI search for resonances decaying to  $HW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 2670$  GeV for  $g_V = 1$ . If we assume  $M_{W'} = M_{Z'}$ , the limit increases  $M_{W'} > 2930$  GeV and  $M_{W'} > 2800$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig. 5 for limits on  $\sigma \cdot B$ .
- <sup>16</sup> AABOUD 18AK search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 2800$  GeV for  $g_V = 1$ .
- <sup>17</sup> AABOUD 18AL search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 2900$  GeV for  $g_V = 1$ .
- <sup>18</sup> AABOUD 18BG limit is for  $W'$  with SM-like couplings using  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Bosonic decays of  $W'$  and  $W - W'$  interference are neglected. See Fig. 2 for limits on  $\sigma \cdot B$ .
- <sup>19</sup> AABOUD 18CH search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 2260$  GeV for  $g_V = 1$ .
- <sup>20</sup> AABOUD 18F search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 3000$  GeV for  $g_V = 1$ . If we assume  $M_{Z'} = M_{W'}$ , the limit increases  $M_{W'} > 3500$  GeV and  $M_{W'} > 3100$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig.5 for limits on  $\sigma \cdot B$ .
- <sup>21</sup> AABOUD 18K limit is for  $W'$  with SM-like coupling using  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $W - W'$  interference and bosonic decays of  $W'$  are not included. See their Fig. 4 for limit on  $\sigma \cdot B$ .
- <sup>22</sup> SIRUNYAN 18 limit is for right-handed  $W'$  using  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $W' \rightarrow \ell\nu_R$  decay is assumed to be forbidden. The limit becomes  $M_{W'} > 3.4$  TeV if  $M_{\nu_R} \ll M_{W'}$ . See their Fig. 5 for exclusion limits on  $W'$  models having both left- and right-handed couplings.
- <sup>23</sup> SIRUNYAN 18AX search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . See their Fig.6 for limits on  $\sigma \cdot B$ .
- <sup>24</sup> SIRUNYAN 18AZ limit is derived for  $W'$  with SM-like coupling using  $pp$  collisions at  $\sqrt{s} = 13$  TeV. No interference with SM  $W$  process is considered. The bosonic decays are assumed to be negligible. See their Fig.6 for limits on  $\sigma \cdot B$ .
- <sup>25</sup> SIRUNYAN 18BK search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 3100$  GeV for  $g_V = 1$ .

- <sup>26</sup> SIRUNYAN 18B0 limit is for  $W'$  with SM-like coupling using  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>27</sup> SIRUNYAN 18CV search for right-handed  $W_R$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $W_R$  is assumed to decay into  $\ell$  and hypothetical heavy neutrino  $N$ , with  $N$  decaying to  $\ell jj$ . The quoted limit is for  $M_N = M_{W_R}/2$ . See their Fig. 6 for excluded regions in the  $M_{W_R} - M_N$  plane.
- <sup>28</sup> SIRUNYAN 18DJ search for resonances decaying to  $WZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 2270$  GeV for  $g_V = 1$ .
- <sup>29</sup> SIRUNYAN 18ED search for resonances decaying to  $HW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . If we assume  $M_{W'} = M_{Z'}$ , the limit increases  $M_{W'} > 2900$  GeV and  $M_{W'} > 2800$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively.
- <sup>30</sup> SIRUNYAN 18P give this limit for a heavy-vector-triplet  $W'$  with  $g_V = 3$ . If they assume  $M_{Z'} = M_{W'}$ , the limit increases to  $M_{W'} > 3800$  GeV.
- <sup>31</sup> AABOUD 17AK search for a new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above is for a  $W'$  boson having axial-vector SM couplings and decaying to quarks with 75% branching fraction.
- <sup>32</sup> AABOUD 17AO search for resonances decaying to  $HW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for a  $W'$  in the heavy-vector-triplet model with  $g_V = 3$ . See their Fig.4 for limits on  $\sigma \cdot B$ .
- <sup>33</sup> AABOUD 17B search for resonances decaying to  $HW$  ( $H \rightarrow b\bar{b}, c\bar{c}$ ;  $W \rightarrow \ell\nu$ ) in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 1750$  GeV for  $g_V = 1$ . If we assume  $M_{W'} = M_{Z'}$ , the limit increases  $M_{W'} > 2310$  GeV and  $M_{W'} > 1730$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig.3 for limits on  $\sigma \cdot B$ .
- <sup>34</sup> KHACHATRYAN 17J search for right-handed  $W_R$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $W_R$  is assumed to decay into  $\tau$  and hypothetical heavy neutrino  $N_\tau$ , with  $N_\tau$  decaying into  $\tau jj$ . The quoted limit is for  $M_{N_\tau} = M_{W_R}/2$ . The limit becomes  $M_{W_R} > 2350$  GeV (1630 GeV) for  $M_{W_R}/M_{N_\tau} = 0.8$  (0.2). See their Fig. 4 for excluded regions in the  $M_{W_R} - M_{N_\tau}$  plane.
- <sup>35</sup> KHACHATRYAN 17W search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>36</sup> KHACHATRYAN 17Z limit is for  $W'$  with SM-like coupling using  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The bosonic decays of  $W'$  and the interference with SM  $W$  process are neglected.
- <sup>37</sup> SIRUNYAN 17A search for resonances decaying to  $WZ$  with  $WZ \rightarrow \ell\nu q\bar{q}, q\bar{q}q\bar{q}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 2000$  GeV for  $g_V = 1$ . If we assume  $M_{Z'} = M_{W'}$ , the limit increases  $M_{W'} > 2400$  GeV and  $M_{W'} > 2300$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig.6 for limits on  $\sigma \cdot B$ .
- <sup>38</sup> SIRUNYAN 17AK search for resonances decaying to  $WZ$  or  $HW$  in  $pp$  collisions at  $\sqrt{s} = 8$  and 13 TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . The limit becomes  $M_{W'} > 2300$  GeV for  $g_V = 1$ . If we assume  $M_{W'} = M_{Z'}$ , the limit increases  $M_{W'} > 2400$  GeV for both  $g_V = 3$  and  $g_V = 1$ . See their Fig.1 and 2 for limits on  $\sigma \cdot B$ .
- <sup>39</sup> SIRUNYAN 17H search for right-handed  $W'$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $W'$  is assumed to decay into  $\tau$  and a heavy neutrino  $N$ , with  $N$  decaying to  $\tau q\bar{q}$ . The limit above assumes  $M_N = M_{W'}/2$ .
- <sup>40</sup> SIRUNYAN 17I limit is for a right-handed  $W'$  using  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit becomes  $M_{W'} > 2400$  GeV for  $M_{\nu_R} \ll M_{W'}$ .

- 41 SIRUNYAN 17R search for resonances decaying to  $HW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ . Mass regions  $M_{W'} < 2370$  GeV and  $2870 < M_{W'} < 2970$  GeV are excluded for  $g_V = 1$ . If we assume  $M_{Z'} = M_{W'}$ , the excluded mass regions are  $1000 < M_{W'} < 2500$  GeV and  $2760 < M_{W'} < 3300$  GeV for  $g_V = 3$ ;  $1000 < M_{W'} < 2430$  GeV and  $2810 < M_{W'} < 3130$  GeV for  $g_V = 1$ . See their Fig.5 for limits on  $\sigma \cdot B$ .
- 42 AABOUD 16AE search for resonances decaying to  $VV$  ( $V = W$  or  $Z$ ) in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Results from  $\nu\nu qq$ ,  $\nu lqq$ ,  $llqq$  and  $qqqq$  final states are combined. The quoted limit is for a heavy-vector-triplet  $W'$  with  $g_V = 3$  and  $M_{W'} = M_{Z'}$ .
- 43 AABOUD 16V limit is for  $W'$  with SM-like coupling using  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The bosonic decays of  $W'$  and the interference with SM  $W$  process are neglected.
- 44 AAD 16R search for  $W' \rightarrow WZ$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.  $l\nu l' l'$ ,  $llq\bar{q}$ ,  $l\nu q\bar{q}$ , and all hadronic channels are combined. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ .
- 45 AAD 16S search for a new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for a  $W'$  having SM-like couplings to quarks.
- 46 KHACHATRYAN 16AO limit is for a SM-like right-handed  $W'$  using  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The quoted limit combines  $t \rightarrow qq\bar{b}$  and  $t \rightarrow l\nu b$  events.
- 47 KHACHATRYAN 16AP search for a resonance decaying to  $HW$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. Both  $H$  and  $W$  are assumed to decay to fat jets. The quoted limit is for heavy-vector-triplet  $W'$  with  $g_V = 3$ .
- 48 KHACHATRYAN 16BD search for resonance decaying to  $HW$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The quoted limit is for heavy-vector-triplet (HVT)  $W'$  with  $g_V = 3$ . The HVT model  $m_{W'} = m_{Z'} > 1.8$  TeV is also obtained by combining  $W'/Z' \rightarrow WH/ZH \rightarrow l\nu bb$ ,  $qq\tau\tau$ ,  $qq\bar{b}b$ , and  $qqqqqq$  channels.
- 49 KHACHATRYAN 16K search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- 50 KHACHATRYAN 16L search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the data scouting technique, increasing the sensitivity to the low mass resonances.
- 51 KHACHATRYAN 16O limit is for  $W'$  having universal couplings. Interferences with the SM amplitudes are assumed to be absent.
- 52 AAD 15AU search for  $W'$  decaying into the  $WZ$  final state with  $W \rightarrow q\bar{q}'$ ,  $Z \rightarrow \ell^+ \ell^-$  using  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ .
- 53 AAD 15AV limit is for a SM like right-handed  $W'$  using  $pp$  collisions at  $\sqrt{s} = 8$  TeV.  $W' \rightarrow l\nu$  decay is assumed to be forbidden.
- 54 AAD 15AZ search for  $W'$  decaying into the  $WZ$  final state with  $W \rightarrow l\nu$ ,  $Z \rightarrow q\bar{q}$  using  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ .
- 55 AAD 15CP search for  $W'$  decaying into the  $WZ$  final state with  $W \rightarrow q\bar{q}$ ,  $Z \rightarrow q\bar{q}$  using  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ .
- 56 AAD 15R limit is for a SM like right-handed  $W'$  using  $pp$  collisions at  $\sqrt{s} = 8$  TeV.  $W' \rightarrow l\nu$  decay is assumed to be forbidden.
- 57 AAD 15V search for new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.
- 58 KHACHATRYAN 15C search for  $W'$  decaying via  $WZ$  to fully leptonic final states using  $pp$  collisions at  $\sqrt{s}=8$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = M_W M_{Z'}/M_{W'}^2$ .

- 59 KHACHATRYAN 15T limit is for  $W'$  with SM-like coupling which interferes the SM  $W$  boson constructively using  $pp$  collisions at  $\sqrt{s} = 8$  TeV. For  $W'$  without interference, the limit becomes  $> 3280$  GeV.
- 60 KHACHATRYAN 14O search for right-handed  $W_R$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.  $W_R$  is assumed to decay into  $\ell$  and hypothetical heavy neutrino  $N$ , with  $N$  decaying into  $\ell jj$ . The quoted limit is for  $M_{\nu_{eR}} = M_{\nu_{\mu R}} = M_{W_R}/2$ . See their Fig. 3 and Fig. 5 for excluded regions in the  $M_{W_R} - M_\nu$  plane.
- 61 AAD 20AD search for a narrow resonance decaying to a pair of large-radius-jets  $J_1$  and  $J_2$  employing a machine-learning procedure. See their Fig. 3 for limits on  $\sigma \cdot B$  depending on assumptions about invariant masses for  $J_1$ ,  $J_2$ , and  $J_1 J_2$ .
- 62 AAD 20W search for  $W'$  decaying to  $WZ'$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 5(b) for limits on  $\sigma \cdot B$  as a function of  $m_{Z'}$ . The  $W' \rightarrow WZ'$  branching fraction was chosen to be 0.5 and the mass difference between the  $W'$  and  $Z'$  was set to 250 GeV.
- 63 AABOUD 19BB search for right handed  $W_R$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $W_R$  is assumed to decay into  $\ell$  and a boosted hypothetical heavy neutrino  $N$ , with  $N$  decaying to  $\ell$  and a large radius jet  $j = q\bar{q}$ . See their Fig. 7 for excluded regions in  $M_{W_R} - M_N$  plane.
- 64 SIRUNYAN 19V search for a new resonance decaying to a top quark and a heavy vector-like bottom partner  $B$  decaying to  $Hb$  (or a bottom quark and a heavy vector-like top partner  $T$  decaying to  $Ht$ ) in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 8 for limits on  $\sigma \cdot B$ .
- 65 AABOUD 18AA search for a narrow charged vector boson decaying to  $W\gamma$ . See their Fig. 9 for the exclusion limit in  $M_{W'} - \sigma B$  plane.
- 66 AABOUD 18AD search for resonances decaying to  $HX$  ( $H \rightarrow b\bar{b}$ ,  $X \rightarrow q\bar{q}'$ ) in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Figs. 3–5 for limits on  $\sigma \cdot B$ .
- 67 AABOUD 18CJ search for heavy-vector-triplet  $W'$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for model with  $g_V = 3$  assuming  $M_{W'} = M_{Z'}$ . The limit becomes  $M_{W'} > 5500$  GeV for model with  $g_V = 1$ .
- 68 KHACHATRYAN 17U search for resonances decaying to  $HW$  ( $H \rightarrow b\bar{b}$ ;  $W \rightarrow \ell\nu$ ) in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit on the heavy-vector-triplet model is  $M_{Z'} = M_{W'} > 2$  TeV for  $g_V = 3$ , in which constraints from the  $Z' \rightarrow HZ$  ( $H \rightarrow b\bar{b}$ ;  $Z \rightarrow \ell^+\ell^-, \nu\bar{\nu}$ ) are combined. See their Fig.3 and Fig.4 for limits on  $\sigma \cdot B$ .
- 69 AAD 15BB search for  $W'$  decaying into  $WH$  with  $W \rightarrow \ell\nu$ ,  $H \rightarrow b\bar{b}$ . See their Fig. 4 for the exclusion limits in the heavy vector triplet benchmark model parameter space.
- 70 AALTONEN 15C limit is for a SM-like right-handed  $W'$  assuming  $W' \rightarrow \ell\nu$  decays are forbidden, using  $p\bar{p}$  collisions at  $\sqrt{s}=1.96$  TeV. See their Fig. 3 for limit on  $g_{W'}/g_W$ .
- 71 KHACHATRYAN 15V search new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.
- 72 AAD 14AT search for a narrow charged vector boson decaying to  $W\gamma$ . See their Fig. 3a for the exclusion limit in  $m_{W'} - \sigma B$  plane.
- 73 AAD 14S search for  $W'$  decaying into the  $WZ$  final state with  $W \rightarrow \ell\nu$ ,  $Z \rightarrow \ell\ell$  using  $pp$  collisions at  $\sqrt{s}=8$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ .
- 74 KHACHATRYAN 14 search for  $W'$  decaying into  $WZ$  final state with  $W \rightarrow q\bar{q}$ ,  $Z \rightarrow q\bar{q}$  using  $pp$  collisions at  $\sqrt{s}=8$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ .
- 75 KHACHATRYAN 14A search for  $W'$  decaying into the  $WZ$  final state with  $W \rightarrow \ell\nu$ ,  $Z \rightarrow q\bar{q}$ , or  $W \rightarrow q\bar{q}$ ,  $Z \rightarrow \ell\ell$ .  $pp$  collisions data at  $\sqrt{s}=8$  TeV are used for the search. See their Fig. 13 for the exclusion limit on the number of events in the mass–width plane.



- 76 AAD 13AO search for  $W'$  decaying into the  $WZ$  final state with  $W \rightarrow \ell\nu$ ,  $Z \rightarrow 2j$  using  $pp$  collisions at  $\sqrt{s}=7$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ .
- 77 CHATRCHYAN 13AJ search for resonances decaying to  $WZ$  pair, using the hadronic decay modes of  $W$  and  $Z$ , in  $pp$  collisions at  $\sqrt{s}=7$  TeV. See their Fig. 7 for the limit on the cross section.
- 78 CHATRCHYAN 13AQ limit is for  $W'$  with SM-like coupling which interferes with the SM  $W$  boson using  $pp$  collisions at  $\sqrt{s}=7$  TeV.
- 79 CHATRCHYAN 13E limit is for  $W'$  with SM-like coupling which interferes with the SM  $W$  boson using  $pp$  collisions at  $\sqrt{s}=7$  TeV. For  $W'$  with right-handed coupling, the bound becomes  $>1850$  GeV ( $>1910$  GeV) if  $W'$  decays to both leptons and quarks (only to quarks). If both left- and right-handed couplings are present, the limit becomes  $>1640$  GeV.
- 80 CHATRCHYAN 13U search for  $W'$  decaying to the  $WZ$  final state, with  $W$  decaying into jets, in  $pp$  collisions at  $\sqrt{s}=7$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ .
- 81 The AAD 12AV quoted limit is for a SM-like right-handed  $W'$  using  $pp$  collisions at  $\sqrt{s}=7$  TeV.  $W' \rightarrow \ell\nu$  decay is assumed to be forbidden.
- 82 AAD 12BB use  $pp$  collisions data at  $\sqrt{s}=7$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ .
- 83 AAD 12CK search for  $pp \rightarrow tW'$ ,  $W' \rightarrow \bar{t}q$  events in  $pp$  collisions. See their Fig. 5 for the limit on  $\sigma \cdot B$ .
- 84 AAD 12CR use  $pp$  collisions at  $\sqrt{s}=7$  TeV.
- 85 AAD 12M search for right-handed  $W_R$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.  $W_R$  is assumed to decay into  $\ell$  and hypothetical heavy neutrino  $N$ , with  $N$  decaying into  $\ell jj$ . See their Fig. 4 for the limit in the  $m_N - m_{W'}$  plane.
- 86 AALTONEN 12N search for  $p\bar{p} \rightarrow tW'$ ,  $W' \rightarrow \bar{t}d$  events in  $p\bar{p}$  collisions. See their Fig. 3 for the limit on  $\sigma \cdot B$ .
- 87 CHATRCHYAN 12AR search for  $pp \rightarrow tW'$ ,  $W' \rightarrow \bar{t}d$  events in  $pp$  collisions. See their Fig. 2 for the limit on  $\sigma \cdot B$ .
- 88 CHATRCHYAN 12BG search for right-handed  $W_R$  in  $pp$  collisions  $\sqrt{s} = 7$  TeV.  $W_R$  is assumed to decay into  $\ell$  and hypothetical heavy neutrino  $N$ , with  $N$  decaying into  $\ell jj$ . See their Fig. 3 for the limit in the  $m_N - m_{W'}$  plane.
- 89 ABAZOV 11H use data from  $p\bar{p}$  collisions at  $\sqrt{s}=1.96$  TeV. The quoted limit is obtained assuming  $W'WZ$  coupling strength is the same as the ordinary  $WWZ$  coupling strength in the Standard Model.
- 90 ABAZOV 11L limit is for  $W'$  with SM-like coupling which interferes with the SM  $W$  boson, using  $p\bar{p}$  collisions at  $\sqrt{s}=1.96$  TeV. For  $W'$  with right-handed coupling, the bound becomes  $>885$  GeV ( $>890$  GeV) if  $W'$  decays to both leptons and quarks (only to quarks). If both left- and right-handed couplings present, the limit becomes  $>916$  GeV.
- 91 AALTONEN 10N use  $p\bar{p}$  collision data at  $\sqrt{s}=1.96$  TeV. The quoted limit assumes  $g_{W'WZ}/g_{WWZ} = (M_W/M_{W'})^2$ . See their Fig. 4 for limits in mass-coupling plane.
- 92 AALTONEN 09AC search for new particle decaying to dijets using  $p\bar{p}$  collisions at  $\sqrt{s}=1.96$  TeV.
- 93 The ACOSTA 03B quoted limit is for  $M_{W'} \gg M_{\nu_R}$ , using  $p\bar{p}$  collisions at  $\sqrt{s}=1.8$  TeV. For  $M_{W'} < M_{\nu_R}$ ,  $M_{W'}$  between 225 and 566 GeV is excluded.
- 94 The quoted limit is obtained assuming  $W'WZ$  coupling strength is the same as the ordinary  $WWZ$  coupling strength in the Standard Model, using  $p\bar{p}$  collisions at  $\sqrt{s}=1.8$  TeV. See their Fig. 2 for the limits on the production cross sections as a function of the  $W'$  width.

- 95 AFFOLDER 01I combine a new bound on  $W' \rightarrow e\nu$  of 754 GeV, using  $p\bar{p}$  collisions at  $\sqrt{s}=1.8$  TeV, with the bound of ABE 00 on  $W' \rightarrow \mu\nu$  to obtain quoted bound.
- 96 ABE 97G search for new particle decaying to dijets using  $p\bar{p}$  collisions at  $\sqrt{s}=1.8$  TeV.
- 97 For bounds on  $W_R$  with nonzero right-handed mass, see Fig. 5 from ABACHI 96C.
- 98 ABACHI 95E assume that the decay  $W' \rightarrow WZ$  is suppressed and that the neutrino from  $W'$  decay is stable and has a mass significantly less  $m_{W'}$ .
- 99 RIZZO 93 analyses CDF limit on possible two-jet resonances. The limit is sensitive to the inclusion of the assumed  $K$  factor.

## $W_R$ (Right-Handed $W$ Boson) MASS LIMITS

Assuming a light right-handed neutrino, except for BEALL 82, LANGACKER 89B, and COLANGELO 91.  $g_R = g_L$  assumed. [Limits in the section MASS LIMITS for  $W'$  below are also valid for  $W_R$  if  $m_{\nu_R} \ll m_{W_R}$ .] Some limits assume manifest left-right symmetry, *i.e.*, the equality of left- and right Cabibbo-Kobayashi-Maskawa matrices. For a comprehensive review, see LANGACKER 89B. Limits on the  $W_L$ - $W_R$  mixing angle  $\zeta$  are found in the next section. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 592	90	<sup>1</sup> BUENO 11	TWST	$\mu$ decay
> <b>715</b>	90	<sup>2</sup> CZAKON 99	RVUE	Electroweak
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 235	90	<sup>3</sup> PRIEELS 14	PIE3	$\mu$ decay
> 245	90	<sup>4</sup> WAUTERS 10	CNTR	$^{60}\text{Co}$ $\beta$ decay
>2500		<sup>5</sup> ZHANG 08	THEO	$m_{K_L^0} - m_{K_S^0}$
> 180	90	<sup>6</sup> MELCONIAN 07	CNTR	$^{37}\text{K}$ $\beta^+$ decay
> 290.7	90	<sup>7</sup> SCHUMANN 07	CNTR	Polarized neutron decay
[> 3300]	95	<sup>8</sup> CYBURT 05	COSM	Nucleosynthesis; light $\nu_R$
> 310	90	<sup>9</sup> THOMAS 01	CNTR	$\beta^+$ decay
> 137	95	<sup>10</sup> ACKERSTAFF 99D	OPAL	$\tau$ decay
>1400	68	<sup>11</sup> BARENBOIM 98	RVUE	Electroweak, $Z$ - $Z'$ mixing
> 549	68	<sup>12</sup> BARENBOIM 97	RVUE	$\mu$ decay
> 220	95	<sup>13</sup> STAHL 97	RVUE	$\tau$ decay
> 220	90	<sup>14</sup> ALLET 96	CNTR	$\beta^+$ decay
> 281	90	<sup>15</sup> KUZNETSOV 95	CNTR	Polarized neutron decay
> 282	90	<sup>16</sup> KUZNETSOV 94B	CNTR	Polarized neutron decay
> 439	90	<sup>17</sup> BHATTACH... 93	RVUE	$Z$ - $Z'$ mixing
> 250	90	<sup>18</sup> SEVERIJNS 93	CNTR	$\beta^+$ decay
		<sup>19</sup> IMAZATO 92	CNTR	$K^+$ decay
> 475	90	<sup>20</sup> POLAK 92B	RVUE	$\mu$ decay
> 240	90	<sup>21</sup> AQUINO 91	RVUE	Neutron decay
> 496	90	<sup>21</sup> AQUINO 91	RVUE	Neutron and muon decay
> 700		<sup>22</sup> COLANGELO 91	THEO	$m_{K_L^0} - m_{K_S^0}$
> 477	90	<sup>23</sup> POLAK 91	RVUE	$\mu$ decay
[none 540–23000]		<sup>24</sup> BARBIERI 89B	ASTR	SN 1987A; light $\nu_R$
> 300	90	<sup>25</sup> LANGACKER 89B	RVUE	General
> 160	90	<sup>26</sup> BALKE 88	CNTR	$\mu \rightarrow e\nu\bar{\nu}$
> 406	90	<sup>27</sup> JODIDIO 86	ELEC	Any $\zeta$
> 482	90	<sup>27</sup> JODIDIO 86	ELEC	$\zeta = 0$

> 800		MOHAPATRA 86	RVUE	$SU(2)_L \times SU(2)_R \times U(1)$
> 400	95	28 STOKER	85	ELEC Any $\zeta$
> 475	95	28 STOKER	85	ELEC $\zeta < 0.041$
		29 BERGSMA	83	CHRM $\nu_\mu e \rightarrow \mu \nu_e$
> 380	90	30 CARR	83	ELEC $\mu^+$ decay
>1600		31 BEALL	82	THEO $m_{K_L^0} - m_{K_S^0}$

<sup>1</sup> The quoted limit is for manifest left-right symmetric model.

<sup>2</sup> CZAKON 99 perform a simultaneous fit to charged and neutral sectors.

<sup>3</sup> PRIEELS 14 limit is from  $\mu^+ \rightarrow e^+ \nu \bar{\nu}$  decay parameter  $\xi''$ , which is determined by the positron polarization measurement.

<sup>4</sup> WAUTERS 10 limit is from a measurement of the asymmetry parameter of polarized  $^{60}\text{Co}$   $\beta$  decays. The listed limit assumes no mixing.

<sup>5</sup> ZHANG 08 limit uses a lattice QCD calculation of the relevant hadronic matrix elements, while BEALL 82 limit used the vacuum saturation approximation.

<sup>6</sup> MELCONIAN 07 measure the neutrino angular asymmetry in  $\beta^+$ -decays of polarized  $^{37}\text{K}$ , stored in a magneto-optical trap. Result is consistent with SM prediction and does not constrain the  $W_L - W_R$  mixing angle appreciably.

<sup>7</sup> SCHUMANN 07 limit is from measurements of the asymmetry  $\langle \vec{p}_\nu \cdot \sigma_n \rangle$  in the  $\beta$  decay of polarized neutrons. Zero mixing is assumed.

<sup>8</sup> CYBURT 05 limit follows by requiring that three light  $\nu_R$ 's decouple when  $T_{dec} > 140$  MeV. For different  $T_{dec}$ , the bound becomes  $M_{W_R} > 3.3 \text{ TeV} (T_{dec} / 140 \text{ MeV})^{3/4}$ .

<sup>9</sup> THOMAS 01 limit is from measurement of  $\beta^+$  polarization in decay of polarized  $^{12}\text{N}$ . The listed limit assumes no mixing.

<sup>10</sup> ACKERSTAFF 99D limit is from  $\tau$  decay parameters. Limit increase to 145 GeV for zero mixing.

<sup>11</sup> BARENBOIM 98 assumes minimal left-right model with Higgs of  $SU(2)_R$  in  $SU(2)_L$  doublet. For Higgs in  $SU(2)_L$  triplet,  $m_{W_R} > 1100$  GeV. Bound calculated from effect of corresponding  $Z_{LR}$  on electroweak data through  $Z-Z_{LR}$  mixing.

<sup>12</sup> The quoted limit is from  $\mu$  decay parameters. BARENBOIM 97 also evaluate limit from  $K_L - K_S$  mass difference.

<sup>13</sup> STAHL 97 limit is from fit to  $\tau$ -decay parameters.

<sup>14</sup> ALLET 96 measured polarization-asymmetry correlation in  $^{12}\text{N} \beta^+$  decay. The listed limit assumes zero  $L-R$  mixing.

<sup>15</sup> KUZNETSOV 95 limit is from measurements of the asymmetry  $\langle \vec{p}_\nu \cdot \sigma_n \rangle$  in the  $\beta$  decay of polarized neutrons. Zero mixing assumed. See also KUZNETSOV 94B.

<sup>16</sup> KUZNETSOV 94B limit is from measurements of the asymmetry  $\langle \vec{p}_\nu \cdot \sigma_n \rangle$  in the  $\beta$  decay of polarized neutrons. Zero mixing assumed.

<sup>17</sup> BHATTACHARYYA 93 uses  $Z-Z'$  mixing limit from LEP '90 data, assuming a specific Higgs sector of  $SU(2)_L \times SU(2)_R \times U(1)$  gauge model. The limit is for  $m_t = 200$  GeV and slightly improves for smaller  $m_t$ .

<sup>18</sup> SEVERIJNS 93 measured polarization-asymmetry correlation in  $^{107}\text{In} \beta^+$  decay. The listed limit assumes zero  $L-R$  mixing. Value quoted here is from SEVERIJNS 94 erratum.

<sup>19</sup> IMAZATO 92 measure positron asymmetry in  $K^+ \rightarrow \mu^+ \nu_\mu$  decay and obtain  $\xi_{P_\mu} > 0.990$  (90% CL). If  $W_R$  couples to  $u\bar{s}$  with full weak strength ( $V_{us}^R = 1$ ), the result corresponds to  $m_{W_R} > 653$  GeV. See their Fig. 4 for  $m_{W_R}$  limits for general  $|V_{us}^R|^2 = 1 - |V_{ud}^R|^2$ .

<sup>20</sup> POLAK 92B limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming  $\zeta = 0$ . Supersedes POLAK 91.

<sup>21</sup> AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right symmetry assumed. Stronger of the two limits also includes muon decay results.

- 22 COLANGELO 91 limit uses hadronic matrix elements evaluated by QCD sum rule and is less restrictive than BEALL 82 limit which uses vacuum saturation approximation. Manifest left-right symmetry assumed.
- 23 POLAK 91 limit is from fit to muon decay parameters and is essentially determined by JODIDIO 86 data assuming  $\zeta=0$ . Superseded by POLAK 92B.
- 24 BARBIERI 89B limit holds for  $m_{\nu_R} \leq 10$  MeV.
- 25 LANGACKER 89B limit is for any  $\nu_R$  mass (either Dirac or Majorana) and for a general class of right-handed quark mixing matrices.
- 26 BALKE 88 limit is for  $m_{\nu_{eR}} = 0$  and  $m_{\nu_{\mu R}} \leq 50$  MeV. Limits come from precise measurements of the muon decay asymmetry as a function of the positron energy.
- 27 JODIDIO 86 is the same TRIUMF experiment as STOKER 85 (and CARR 83); however, it uses a different technique. The results given here are combined results of the two techniques. The technique here involves precise measurement of the end-point  $e^+$  spectrum in the decay of the highly polarized  $\mu^+$ .
- 28 STOKER 85 is same TRIUMF experiment as CARR 83. Here they measure the decay  $e^+$  spectrum asymmetry above 46 MeV/c using a muon-spin-rotation technique. Assumed a light right-handed neutrino. Quoted limits are from combining with CARR 83.
- 29 BERGSMA 83 set limit  $m_{W_2}/m_{W_1} > 1.9$  at CL = 90%.
- 30 CARR 83 is TRIUMF experiment with a highly polarized  $\mu^+$  beam. Looked for deviation from  $V-A$  at the high momentum end of the decay  $e^+$  energy spectrum. Limit from previous world-average muon polarization parameter is  $m_{W_R} > 240$  GeV. Assumes a light right-handed neutrino.
- 31 BEALL 82 limit is obtained assuming that  $W_R$  contribution to  $K_L^0-K_S^0$  mass difference is smaller than the standard one, neglecting the top quark contributions. Manifest left-right symmetry assumed.

### Limit on $W_L$ - $W_R$ Mixing Angle $\zeta$

Lighter mass eigenstate  $W_1 = W_L \cos \zeta - W_R \sin \zeta$ . Light  $\nu_R$  assumed unless noted. Values in brackets are from cosmological and astrophysical considerations.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
-0.020 to 0.017	90	BUENO 11	TWST	$\mu \rightarrow e \nu \bar{\nu}$
< 0.022	90	MACDONALD 08	TWST	$\mu \rightarrow e \nu \bar{\nu}$
< 0.12	95	<sup>1</sup> ACKERSTAFF 99D	OPAL	$\tau$ decay
< 0.013	90	<sup>2</sup> CZAKON 99	RVUE	Electroweak
< 0.0333		<sup>3</sup> BARENBOIM 97	RVUE	$\mu$ decay
< 0.04	90	<sup>4</sup> MISHRA 92	CCFR	$\nu N$ scattering
-0.0006 to 0.0028	90	<sup>5</sup> AQUINO 91	RVUE	
[none 0.00001-0.02]		<sup>6</sup> BARBIERI 89B	ASTR	SN 1987A
< 0.040	90	<sup>7</sup> JODIDIO 86	ELEC	$\mu$ decay
-0.056 to 0.040	90	<sup>7</sup> JODIDIO 86	ELEC	$\mu$ decay

<sup>1</sup> ACKERSTAFF 99D limit is from  $\tau$  decay parameters.

<sup>2</sup> CZAKON 99 perform a simultaneous fit to charged and neutral sectors.

<sup>3</sup> The quoted limit is from  $\mu$  decay parameters. BARENBOIM 97 also evaluate limit from  $K_L-K_S$  mass difference.

<sup>4</sup> MISHRA 92 limit is from the absence of extra large- $x$ , large- $y$   $\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X$  events at Tevatron, assuming left-handed  $\nu$  and right-handed  $\bar{\nu}$  in the neutrino beam. The result gives  $\zeta^2(1-2m_{W_1}^2/m_{W_2}^2) < 0.0015$ . The limit is independent of  $\nu_R$  mass.

<sup>5</sup> AQUINO 91 limits obtained from neutron lifetime and asymmetries together with unitarity of the CKM matrix. Manifest left-right asymmetry is assumed.

<sup>6</sup> BARBIERI 89B limit holds for  $m_{\nu_R} \leq 10$  MeV.

<sup>7</sup> First JODIDIO 86 result assumes  $m_{W_R} = \infty$ , second is for unconstrained  $m_{W_R}$ .

See the related review(s):

[Z'-Boson Searches](#)

## MASS LIMITS for Z' (Heavy Neutral Vector Boson Other Than Z)

### Limits for Z'<sub>SM</sub>

Z'<sub>SM</sub> is assumed to have couplings with quarks and leptons which are identical to those of Z, and decays only to known fermions. The most recent preliminary results can be found in the “Z'-boson searches” review above.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;5150 (CL = 95%) OUR LIMIT</b>				
<b>&gt;5150</b>	95	<sup>1</sup> SIRUNYAN	21N CMS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
none 1133–2700	95	<sup>2</sup> AAD	20T ATLS	$pp; Z'_{SM} \rightarrow b\bar{b}$
none 1800–2900, 3100–3300	95	<sup>3</sup> SIRUNYAN	20AI CMS	$pp; Z'_{SM} \rightarrow q\bar{q}$
none 250–5100	95	<sup>4</sup> AAD	19L ATLS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
none 600–2000	95	<sup>5</sup> AABOUD	18AB ATLS	$pp; Z'_{SM} \rightarrow b\bar{b}$
>2420	95	<sup>6</sup> AABOUD	18G ATLS	$pp; Z'_{SM} \rightarrow \tau^+ \tau^-$
none 200–4500	95	<sup>7</sup> SIRUNYAN	18BB CMS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
none 600–2700	95	<sup>8</sup> SIRUNYAN	18BO CMS	$pp; Z'_{SM} \rightarrow q\bar{q}$
>4500	95	<sup>9</sup> AABOUD	17AT ATLS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
>2100	95	<sup>10</sup> KHACHATRY...17H	CMS	$pp; Z'_{SM} \rightarrow \tau^+ \tau^-$
>3370	95	<sup>11</sup> KHACHATRY...17T	CMS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
none 600–2100, 2300–2600	95	<sup>12</sup> KHACHATRY...17W	CMS	$pp; Z'_{SM} \rightarrow q\bar{q}$
>3360	95	<sup>13</sup> AABOUD	16U ATLS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
>2900	95	<sup>14</sup> KHACHATRY...15AE	CMS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
none 1200–1700	95	<sup>15</sup> KHACHATRY...15V	CMS	$pp; Z'_{SM} \rightarrow q\bar{q}$
>2900	95	<sup>16</sup> AAD	14V ATLS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>1900	95	<sup>17</sup> BOBOVNIKOV	18 RVUE	$pp; Z'_{SM} \rightarrow W^+ W^-$
>2020	95	<sup>18</sup> AABOUD	16AA ATLS	$pp; Z'_{SM} \rightarrow \tau^+ \tau^-$
>1400	95	<sup>19</sup> AAD	15AM ATLS	$pp; Z'_{SM} \rightarrow \tau^+ \tau^-$
>1470	95	<sup>20</sup> AAD	13S ATLS	$pp; Z'_{SM} \rightarrow \tau^+ \tau^-$
>2590	95	<sup>21</sup> CHATRCHYAN	13A CMS	$pp; Z'_{SM} \rightarrow q\bar{q}$
>2220	95	<sup>22</sup> CHATRCHYAN	13AF CMS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
>1400	95	<sup>23</sup> AAD	12CC ATLS	$pp; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
>1071	95	<sup>24</sup> CHATRCHYAN	12O CMS	$pp; Z'_{SM} \rightarrow \tau^+ \tau^-$
>1023	95	<sup>25</sup> AALTONEN	11I CDF	$p\bar{p}; Z'_{SM} \rightarrow \mu^+ \mu^-$
none 247–544	95	<sup>26</sup> ABAZOV	11A D0	$p\bar{p}; Z'_{SM} \rightarrow e^+ e^-$
none 320–740	95	<sup>27</sup> AALTONEN	10N CDF	$Z' \rightarrow WW$
		<sup>28</sup> AALTONEN	09AC CDF	$Z' \rightarrow q\bar{q}$

> 963	95	26 AALTONEN	09T	CDF	$p\bar{p}, Z'_{SM} \rightarrow e^+ e^-$
>1403	95	29 ERLER	09	RVUE	Electroweak
>1305	95	30 ABDALLAH	06C	DLPH	$e^+ e^-$
> 399	95	31 ACOSTA	05R	CDF	$\bar{p}p: Z'_{SM} \rightarrow \tau^+ \tau^-$
none 400–640	95	ABAZOV	04C	D0	$p\bar{p}: Z'_{SM} \rightarrow q\bar{q}$
>1018	95	32 ABBIENDI	04G	OPAL	$e^+ e^-$
> 670	95	33 ABAZOV	01B	D0	$p\bar{p}, Z'_{SM} \rightarrow e^+ e^-$
>1500	95	34 CHEUNG	01B	RVUE	Electroweak
> 710	95	35 ABREU	00S	DLPH	$e^+ e^-$
> 898	95	36 BARATE	00I	ALEP	$e^+ e^-$
> 809	95	37 ERLER	99	RVUE	Electroweak
> 690	95	38 ABE	97S	CDF	$p\bar{p}; Z'_{SM} \rightarrow e^+ e^-, \mu^+ \mu^-$
> 398	95	39 VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
> 237	90	40 ALITTI	93	UA2	$p\bar{p}; Z'_{SM} \rightarrow q\bar{q}$
none 260–600	95	41 RIZZO	93	RVUE	$p\bar{p}; Z'_{SM} \rightarrow q\bar{q}$
> 426	90	42 ABE	90F	VNS	$e^+ e^-$

<sup>1</sup> SIRUNYAN 21N search for resonance decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>2</sup> AAD 20T search for resonances decaying to  $b\bar{b}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 7(b) for limits on the product of the cross section, acceptance,  $b$ -tagging efficiency, and branching fraction.

<sup>3</sup> SIRUNYAN 20AI search for resonances decaying into dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>4</sup> AAD 19L search for resonances decaying to  $\ell^+ \ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>5</sup> AABOUD 18AB search for resonances decaying to  $b\bar{b}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>6</sup> AABOUD 18G search for resonances decaying to  $\tau^+ \tau^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>7</sup> SIRUNYAN 18BB search for resonances decaying to  $\ell^+ \ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig.5 for limits on the  $Z'$  coupling strengths with light quarks.

<sup>8</sup> SIRUNYAN 18B0 search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>9</sup> AABOUD 17AT search for resonances decaying to  $\ell^+ \ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>10</sup> KHACHATRYAN 17H search for resonances decaying to  $\tau^+ \tau^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>11</sup> KHACHATRYAN 17T search for resonances decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 8, 13$  TeV.

<sup>12</sup> KHACHATRYAN 17W search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>13</sup> AABOUD 16U search for resonances decaying to  $\ell^+ \ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>14</sup> KHACHATRYAN 15AE search for resonances decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.

<sup>15</sup> KHACHATRYAN 15V search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.

<sup>16</sup> AAD 14V search for resonances decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.

<sup>17</sup> BOBOVNIKOV 18 use the ATLAS limits on  $\sigma(pp \rightarrow Z') \cdot \mathcal{B}(Z' \rightarrow W^+ W^-)$  to constrain the  $Z$ - $Z'$  mixing parameter  $\xi$ . See their Fig. 11 for limits in  $M_{Z'} - \xi$  plane.

<sup>18</sup> AABOUD 16AA search for resonances decaying to  $\tau^+ \tau^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>19</sup> AAD 15AM search for resonances decaying to  $\tau^+ \tau^-$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.

<sup>20</sup> AAD 13S search for resonances decaying to  $\tau^+ \tau^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.

- 21 CHATRCHYAN 13A use  $pp$  collisions at  $\sqrt{s}=7$  TeV.
- 22 CHATRCHYAN 13AF search for resonances decaying to  $e^+e^-$ ,  $\mu^+\mu^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV and 8 TeV.
- 23 AAD 12CC search for resonances decaying to  $e^+e^-$ ,  $\mu^+\mu^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.
- 24 CHATRCHYAN 120 search for resonances decaying to  $\tau^+\tau^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.
- 25 AALTONEN 11I search for resonances decaying to  $\mu^+\mu^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- 26 ABAZOV 11A, AALTONEN 09T, AALTONEN 07H, and ABULENCIA 06L search for resonances decaying to  $e^+e^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- 27 The quoted limit assumes  $g_{WWZ'}/g_{WWZ} = (M_W/M_{Z'})^2$ . See their Fig. 4 for limits in mass-coupling plane.
- 28 AALTONEN 09AC search for new particle decaying to dijets.
- 29 ERLER 09 give 95% CL limit on the  $Z$ - $Z'$  mixing  $-0.0026 < \theta < 0.0006$ .
- 30 ABDALLAH 06C use data  $\sqrt{s} = 130$ – $207$  GeV.
- 31 ACOSTA 05R search for resonances decaying to tau lepton pairs in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- 32 ABBIENDI 04G give 95% CL limit on  $Z$ - $Z'$  mixing  $-0.00422 < \theta < 0.00091$ .  $\sqrt{s} = 91$  to  $207$  GeV.
- 33 ABAZOV 01B search for resonances in  $p\bar{p} \rightarrow e^+e^-$  at  $\sqrt{s}=1.8$  TeV. They find  $\sigma \cdot B(Z' \rightarrow ee) < 0.06$  pb for  $M_{Z'} > 500$  GeV.
- 34 CHEUNG 01B limit is derived from bounds on contact interactions in a global electroweak analysis.
- 35 ABREU 00S uses LEP data at  $\sqrt{s}=90$  to  $189$  GeV.
- 36 BARATE 00I search for deviations in cross section and asymmetries in  $e^+e^- \rightarrow$  fermions at  $\sqrt{s}=90$  to  $183$  GeV. Assume  $\theta=0$ . Bounds in the mass-mixing plane are shown in their Figure 18.
- 37 ERLER 99 give 90%CL limit on the  $Z$ - $Z'$  mixing  $-0.0041 < \theta < 0.0003$ .  $\rho_0=1$  is assumed.
- 38 ABE 97S find  $\sigma(Z') \times B(e^+e^-, \mu^+\mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s}=1.8$  TeV.
- 39 VILAIN 94B assume  $m_t = 150$  GeV.
- 40 ALITTI 93 search for resonances in the two-jet invariant mass. The limit assumes  $B(Z' \rightarrow q\bar{q})=0.7$ . See their Fig. 5 for limits in the  $m_{Z'}-B(q\bar{q})$  plane.
- 41 RIZZO 93 analyses CDF limit on possible two-jet resonances.
- 42 ABE 90F use data for  $R$ ,  $R_{\ell\ell}$ , and  $A_{\ell\ell}$ . They fix  $m_W = 80.49 \pm 0.43 \pm 0.24$  GeV and  $m_Z = 91.13 \pm 0.03$  GeV.

### Limits for $Z_{LR}$

$Z_{LR}$  is the extra neutral boson in left-right symmetric models.  $g_L = g_R$  is assumed unless noted. Values in parentheses assume stronger constraint on the Higgs sector, usually motivated by specific left-right symmetric models (see the Note on the  $W'$ ). Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino. Direct search bounds assume decays to Standard Model fermions only, unless noted.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>1162	95	<sup>1</sup> DEL-AGUILA	10 RVUE	Electroweak
> 630	95	<sup>2</sup> ABE	97S CDF	$p\bar{p}; Z'_{LR} \rightarrow e^+e^-, \mu^+\mu^-$

• • • We do not use the following data for averages, fits, limits, etc. • • •

		<sup>3</sup> BOBOVNIKOV 18	RVUE	$pp, Z'_{LR} \rightarrow W^+ W^-$
> 998	95	<sup>4</sup> ERLER 09	RVUE	Electroweak
> 600	95	SCHAEL 07A	ALEP	$e^+ e^-$
> 455	95	<sup>5</sup> ABDALLAH 06C	DLPH	$e^+ e^-$
> 518	95	<sup>6</sup> ABBIENDI 04G	OPAL	$e^+ e^-$
> 860	95	<sup>7</sup> CHEUNG 01B	RVUE	Electroweak
> 380	95	<sup>8</sup> ABREU 00S	DLPH	$e^+ e^-$
> 436	95	<sup>9</sup> BARATE 00I	ALEP	Repl. by SCHAEL 07A
> 550	95	<sup>10</sup> CHAY 00	RVUE	Electroweak
		<sup>11</sup> ERLER 00	RVUE	Cs
		<sup>12</sup> CASALBUONI 99	RVUE	Cs
(> 1205)	90	<sup>13</sup> CZAKON 99	RVUE	Electroweak
> 564	95	<sup>14</sup> ERLER 99	RVUE	Electroweak
(> 1673)	95	<sup>15</sup> ERLER 99	RVUE	Electroweak
(> 1700)	68	<sup>16</sup> BARENBOIM 98	RVUE	Electroweak
> 244	95	<sup>17</sup> CONRAD 98	RVUE	$\nu_\mu N$ scattering
> 253	95	<sup>18</sup> VILAIN 94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e$ and $\bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
none 200–600	95	<sup>19</sup> RIZZO 93	RVUE	$p\bar{p}; Z_{LR} \rightarrow q\bar{q}$
[> 2000]		WALKER 91	COSM	Nucleosynthesis; light $\nu_R$
none 200–500		<sup>20</sup> GRIFOLS 90	ASTR	SN 1987A; light $\nu_R$
none 350–2400		<sup>21</sup> BARBIERI 89B	ASTR	SN 1987A; light $\nu_R$

<sup>1</sup> DEL-AGUILA 10 give 95% CL limit on the  $Z$ - $Z'$  mixing  $-0.0012 < \theta < 0.0004$ .

<sup>2</sup> ABE 97S find  $\sigma(Z') \times B(e^+ e^-, \mu^+ \mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s} = 1.8$  TeV.

<sup>3</sup> BOBOVNIKOV 18 use the ATLAS limits on  $\sigma(pp \rightarrow Z') \cdot B(Z' \rightarrow W^+ W^-)$  to constrain the  $Z$ - $Z'$  mixing parameter  $\xi$ . See their Fig. 10 for limits in  $M_{Z'} - \xi$  plane.

<sup>4</sup> ERLER 09 give 95% CL limit on the  $Z$ - $Z'$  mixing  $-0.0013 < \theta < 0.0006$ .

<sup>5</sup> ABDALLAH 06C give 95% CL limit  $|\theta| < 0.0028$ . See their Fig. 14 for limit contours in the mass-mixing plane.

<sup>6</sup> ABBIENDI 04G give 95% CL limit on  $Z$ - $Z'$  mixing  $-0.00098 < \theta < 0.00190$ . See their Fig. 20 for the limit contour in the mass-mixing plane.  $\sqrt{s} = 91$  to 207 GeV.

<sup>7</sup> CHEUNG 01B limit is derived from bounds on contact interactions in a global electroweak analysis.

<sup>8</sup> ABREU 00S give 95% CL limit on  $Z$ - $Z'$  mixing  $|\theta| < 0.0018$ . See their Fig. 6 for the limit contour in the mass-mixing plane.  $\sqrt{s} = 90$  to 189 GeV.

<sup>9</sup> BARATE 00I search for deviations in cross section and asymmetries in  $e^+ e^- \rightarrow$  fermions at  $\sqrt{s} = 90$  to 183 GeV. Assume  $\theta = 0$ . Bounds in the mass-mixing plane are shown in their Figure 18.

<sup>10</sup> CHAY 00 also find  $-0.0003 < \theta < 0.0019$ . For  $g_R$  free,  $m_{Z'} > 430$  GeV.

<sup>11</sup> ERLER 00 discuss the possibility that a discrepancy between the observed and predicted values of  $Q_W(\text{Cs})$  is due to the exchange of  $Z'$ . The data are better described in a certain class of the  $Z'$  models including  $Z_{LR}$  and  $Z_\chi$ .

<sup>12</sup> CASALBUONI 99 discuss the discrepancy between the observed and predicted values of  $Q_W(\text{Cs})$ . It is shown that the data are better described in a class of models including the  $Z_{LR}$  model.

<sup>13</sup> CZAKON 99 perform a simultaneous fit to charged and neutral sectors. Assumes manifest left-right symmetric model. Finds  $|\theta| < 0.0042$ .

<sup>14</sup> ERLER 99 give 90% CL limit on the  $Z$ - $Z'$  mixing  $-0.0009 < \theta < 0.0017$ .

<sup>15</sup> ERLER 99 assumes 2 Higgs doublets, transforming as 10 of  $SO(10)$ , embedded in  $E_6$ .



- <sup>16</sup> BARENBOIM 98 also gives 68% CL limits on the  $Z$ - $Z'$  mixing  $-0.0005 < \theta < 0.0033$ . Assumes Higgs sector of minimal left-right model.
- <sup>17</sup> CONRAD 98 limit is from measurements at CCFR, assuming no  $Z$ - $Z'$  mixing.
- <sup>18</sup> VILAIN 94B assume  $m_t = 150$  GeV and  $\theta=0$ . See Fig. 2 for limit contours in the mass-mixing plane.
- <sup>19</sup> RIZZO 93 analyses CDF limit on possible two-jet resonances.
- <sup>20</sup> GRIFOLS 90 limit holds for  $m_{\nu_R} \lesssim 1$  MeV. A specific Higgs sector is assumed. See also GRIFOLS 90D, RIZZO 91.
- <sup>21</sup> BARBIERI 89B limit holds for  $m_{\nu_R} \leq 10$  MeV. Bounds depend on assumed supernova core temperature.

### Limits for $Z_\chi$

$Z_\chi$  is the extra neutral boson in  $SO(10) \rightarrow SU(5) \times U(1)_\chi$ .  $g_\chi = e/\cos\theta_W$  is assumed unless otherwise stated. We list limits with the assumption  $\rho=1$  but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;4800 (CL = 95%) OUR LIMIT</b>				
<b>none 250–4800</b>	95	<sup>1</sup> AAD	19L ATLS	$pp; Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
>4100	95	<sup>2</sup> AABOUD	17AT ATLS	$pp; Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>3050	95	<sup>3</sup> BOBOVNIKOV 18	RVUE	$pp, Z'_\chi \rightarrow W^+W^-$
>2620	95	<sup>4</sup> AABOUD	16U ATLS	$pp; Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
>1970	95	<sup>5</sup> AAD	14V ATLS	$pp, Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
> 930	95	<sup>6</sup> AAD	12CC ATLS	$pp, Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
> 903	95	<sup>7</sup> AALTONEN	11I CDF	$p\bar{p}; Z'_\chi \rightarrow \mu^+\mu^-$
>1022	95	<sup>8</sup> ABAZOV	11A D0	$p\bar{p}, Z'_\chi \rightarrow e^+e^-$
> 862	95	<sup>9</sup> DEL-AGUILA	10 RVUE	Electroweak
> 892	95	<sup>8</sup> AALTONEN	09T CDF	$p\bar{p}, Z'_\chi \rightarrow e^+e^-$
>1141	95	<sup>10</sup> AALTONEN	09V CDF	Repl. by AALTONEN 11I
> 822	95	<sup>11</sup> ERLER	09 RVUE	Electroweak
> 680	95	<sup>8</sup> AALTONEN	07H CDF	Repl. by AALTONEN 09T
> 545	95	SCHAEL	07A ALEP	$e^+e^-$
> 740	95	<sup>12</sup> ABDALLAH	06C DLPH	$e^+e^-$
> 690	95	<sup>8</sup> ABULENCIA	06L CDF	Repl. by AALTONEN 07H
> 781	95	<sup>13</sup> ABULENCIA	05A CDF	$p\bar{p}; Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
>2100	95	<sup>14</sup> ABBIENDI	04G OPAL	$e^+e^-$
> 680	95	<sup>15</sup> BARGER	03B COSM	Nucleosynthesis; light $\nu_R$
> 440	95	<sup>16</sup> CHEUNG	01B RVUE	Electroweak
> 533	95	<sup>17</sup> ABREU	00S DLPH	$e^+e^-$
> 554	95	<sup>18</sup> BARATE	00I ALEP	Repl. by SCHAEL 07A
> 545	95	<sup>19</sup> CHO	00 RVUE	Electroweak
		<sup>20</sup> ERLER	00 RVUE	Cs
		<sup>21</sup> ROSNER	00 RVUE	Cs
> 545	95	<sup>22</sup> ERLER	99 RVUE	Electroweak

(> 1368)	95	23 ERLER	99	RVUE	Electroweak
> 215	95	24 CONRAD	98	RVUE	$\nu_\mu N$ scattering
> 595	95	25 ABE	97S	CDF	$p\bar{p}; Z'_\chi \rightarrow e^+e^-, \mu^+\mu^-$
> 190	95	26 ARIMA	97	VNS	Bhabha scattering
> 262	95	27 VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e; \bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
[>1470]		28 FARAGGI	91	COSM	Nucleosynthesis; light $\nu_R$
> 231	90	29 ABE	90F	VNS	$e^+e^-$
[> 1140]		30 GONZALEZ...	90D	COSM	Nucleosynthesis; light $\nu_R$
[> 2100]		31 GRIFOLS	90	ASTR	SN 1987A; light $\nu_R$

- <sup>1</sup> AAD 19L search for resonances decaying to  $\ell^+\ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>2</sup> AABOUD 17AT search for resonances decaying to  $\ell^+\ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>3</sup> BOBOVNIKOV 18 use the ATLAS limits on  $\sigma(pp \rightarrow Z') \cdot \mathcal{B}(Z' \rightarrow W^+W^-)$  to constrain the  $Z$ - $Z'$  mixing parameter  $\xi$ . See their Fig. 9 for limits in  $M_{Z'} - \xi$  plane.
- <sup>4</sup> AABOUD 16U search for resonances decaying to  $\ell^+\ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>5</sup> AAD 14V search for resonances decaying to  $e^+e^-, \mu^+\mu^-$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.
- <sup>6</sup> AAD 12CC search for resonances decaying to  $e^+e^-, \mu^+\mu^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.
- <sup>7</sup> AALTONEN 11I search for resonances decaying to  $\mu^+\mu^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- <sup>8</sup> ABAZOV 11A, AALTONEN 09T, AALTONEN 07H, and ABULENCIA 06L search for resonances decaying to  $e^+e^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- <sup>9</sup> DEL-AGUILA 10 give 95% CL limit on the  $Z$ - $Z'$  mixing  $-0.0011 < \theta < 0.0007$ .
- <sup>10</sup> AALTONEN 09V search for resonances decaying to  $\mu^+\mu^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- <sup>11</sup> ERLER 09 give 95% CL limit on the  $Z$ - $Z'$  mixing  $-0.0016 < \theta < 0.0006$ .
- <sup>12</sup> ABDALLAH 06C give 95% CL limit  $|\theta| < 0.0031$ . See their Fig. 14 for limit contours in the mass-mixing plane.
- <sup>13</sup> ABULENCIA 05A search for resonances decaying to electron or muon pairs in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- <sup>14</sup> ABBIENDI 04G give 95% CL limit on  $Z$ - $Z'$  mixing  $-0.00099 < \theta < 0.00194$ . See their Fig. 20 for the limit contour in the mass-mixing plane.  $\sqrt{s} = 91$  to 207 GeV.
- <sup>15</sup> BARGER 03B limit is from the nucleosynthesis bound on the effective number of light neutrino  $\delta N_\nu < 1$ . The quark-hadron transition temperature  $T_c = 150$  MeV is assumed. The limit with  $T_c = 400$  MeV is  $> 4300$  GeV.
- <sup>16</sup> CHEUNG 01B limit is derived from bounds on contact interactions in a global electroweak analysis.
- <sup>17</sup> ABREU 00S give 95% CL limit on  $Z$ - $Z'$  mixing  $|\theta| < 0.0017$ . See their Fig. 6 for the limit contour in the mass-mixing plane.  $\sqrt{s} = 90$  to 189 GeV.
- <sup>18</sup> BARATE 00I search for deviations in cross section and asymmetries in  $e^+e^- \rightarrow$  fermions at  $\sqrt{s} = 90$  to 183 GeV. Assume  $\theta = 0$ . Bounds in the mass-mixing plane are shown in their Figure 18.
- <sup>19</sup> CHO 00 use various electroweak data to constrain  $Z'$  models assuming  $m_H = 100$  GeV. See Fig. 3 for limits in the mass-mixing plane.
- <sup>20</sup> ERLER 00 discuss the possibility that a discrepancy between the observed and predicted values of  $Q_W(C_s)$  is due to the exchange of  $Z'$ . The data are better described in a certain class of the  $Z'$  models including  $Z_{LR}$  and  $Z_\chi$ .
- <sup>21</sup> ROSNER 00 discusses the possibility that a discrepancy between the observed and predicted values of  $Q_W(C_s)$  is due to the exchange of  $Z'$ . The data are better described in a certain class of the  $Z'$  models including  $Z_\chi$ .

- 22 ERLER 99 give 90% CL limit on the  $Z$ - $Z'$  mixing  $-0.0020 < \theta < 0.0015$ .
- 23 ERLER 99 assumes 2 Higgs doublets, transforming as 10 of  $SO(10)$ , embedded in  $E_6$ .
- 24 CONRAD 98 limit is from measurements at CCFR, assuming no  $Z$ - $Z'$  mixing.
- 25 ABE 97S find  $\sigma(Z') \times B(e^+ e^-, \mu^+ \mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s} = 1.8$  TeV.
- 26  $Z$ - $Z'$  mixing is assumed to be zero.  $\sqrt{s} = 57.77$  GeV.
- 27 VILAIN 94B assume  $m_t = 150$  GeV and  $\theta = 0$ . See Fig. 2 for limit contours in the mass-mixing plane.
- 28 FARAGGI 91 limit assumes the nucleosynthesis bound on the effective number of neutrinos  $\Delta N_\nu < 0.5$  and is valid for  $m_{\nu_R} < 1$  MeV.
- 29 ABE 90F use data for  $R$ ,  $R_{\ell\ell}$ , and  $A_{\ell\ell}$ . ABE 90F fix  $m_W = 80.49 \pm 0.43 \pm 0.24$  GeV and  $m_Z = 91.13 \pm 0.03$  GeV.
- 30 Assumes the nucleosynthesis bound on the effective number of light neutrinos ( $\delta N_\nu < 1$ ) and that  $\nu_R$  is light ( $\lesssim 1$  MeV).
- 31 GRIFOLS 90 limit holds for  $m_{\nu_R} \lesssim 1$  MeV. See also GRIFOLS 90D, RIZZO 91.

### Limits for $Z_\psi$

$Z_\psi$  is the extra neutral boson in  $E_6 \rightarrow SO(10) \times U(1)_\psi$ .  $g_\psi = e/\cos\theta_W$  is assumed unless otherwise stated. We list limits with the assumption  $\rho = 1$  but with no further constraints on the Higgs sector. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;4560 (CL = 95%) OUR LIMIT</b>				
<b>&gt;4560</b>	95	<sup>1</sup> SIRUNYAN	21N CMS	$pp; Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
none 250–4500	95	<sup>2</sup> AAD	19L ATLS	$pp; Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
none 200–3900	95	<sup>3</sup> SIRUNYAN	18BB CMS	$pp; Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
>3800	95	<sup>4</sup> AABOUD	17AT ATLS	$pp; Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
>2820	95	<sup>5</sup> KHACHATRY...17T	CMS	$pp; Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
>1100	95	<sup>6</sup> CHATRCHYAN 120	CMS	$pp, Z'_\psi \rightarrow \tau^+ \tau^-$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		<sup>7</sup> BOBOVNIKOV 18	RVUE	$pp, Z'_\psi \rightarrow W^+ W^-$
>2740	95	<sup>8</sup> AABOUD	16U ATLS	$pp; Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
>2570	95	<sup>9</sup> KHACHATRY...15AE	CMS	$pp; Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
>2510	95	<sup>10</sup> AAD	14V ATLS	$pp, Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
>2260	95	<sup>11</sup> CHATRCHYAN 13AF	CMS	$pp, Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
>1790	95	<sup>12</sup> AAD	12CC ATLS	$pp, Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
>2000	95	<sup>13</sup> CHATRCHYAN 12M	CMS	Repl. by CHATRCHYAN 13AF
> 917	95	<sup>14</sup> AALTONEN	11I CDF	$p\bar{p}; Z'_\psi \rightarrow \mu^+ \mu^-$
> 891	95	<sup>15</sup> ABAZOV	11A D0	$p\bar{p}, Z'_\psi \rightarrow e^+ e^-$
> 476	95	<sup>16</sup> DEL-AGUILA	10 RVUE	Electroweak
> 851	95	<sup>15</sup> AALTONEN	09T CDF	$p\bar{p}, Z'_\psi \rightarrow e^+ e^-$
> 878	95	<sup>17</sup> AALTONEN	09V CDF	Repl. by AALTONEN 11I
> 147	95	<sup>18</sup> ERLER	09 RVUE	Electroweak
> 822	95	<sup>15</sup> AALTONEN	07H CDF	Repl. by AALTONEN 09T
> 410	95	SCHAEL	07A ALEP	$e^+ e^-$

> 475	95	19 ABDALLAH	06C DLPH	$e^+ e^-$
> 725		15 ABULENCIA	06L CDF	Repl. by AALTONEN 07H
> 675	95	20 ABULENCIA	05A CDF	Repl. by AALTONEN 11I and AALTONEN 09T
> 366	95	21 ABBIENDI	04G OPAL	$e^+ e^-$
> 600		22 BARGER	03B COSM	Nucleosynthesis; light $\nu_R$
> 350	95	23 ABREU	00S DLPH	$e^+ e^-$
> 294	95	24 BARATE	00I ALEP	Repl. by SCHAEEL 07A
> 137	95	25 CHO	00 RVUE	Electroweak
> 146	95	26 ERLER	99 RVUE	Electroweak
> 54	95	27 CONRAD	98 RVUE	$\nu_\mu N$ scattering
> 590	95	28 ABE	97S CDF	$p\bar{p}; Z'_\psi \rightarrow e^+ e^-, \mu^+ \mu^-$
> 135	95	29 VILAIN	94B CHM2	$\nu_\mu e \rightarrow \nu_\mu e; \bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
> 105	90	30 ABE	90F VNS	$e^+ e^-$
[> 160]		31 GONZALEZ...	90D COSM	Nucleosynthesis; light $\nu_R$
[> 2000]		32 GRIFOLS	90D ASTR	SN 1987A; light $\nu_R$

- <sup>1</sup> SIRUNYAN 21N search for resonance decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>2</sup> AAD 19L search for resonances decaying to  $\ell^+ \ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>3</sup> SIRUNYAN 18BB search for resonances decaying to  $\ell^+ \ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>4</sup> AABOUD 17AT search for resonances decaying to  $\ell^+ \ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>5</sup> KHACHATRYAN 17T search for resonances decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 8, 13$  TeV.
- <sup>6</sup> CHATRCHYAN 120 search for resonances decaying to  $\tau^+ \tau^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.
- <sup>7</sup> BOBOVNIKOV 18 use the ATLAS limits on  $\sigma(pp \rightarrow Z') \cdot B(Z' \rightarrow W^+ W^-)$  to constrain the  $Z$ - $Z'$  mixing parameter  $\xi$ . See their Fig. 10 for limits in  $M_{Z'} - \xi$  plane.
- <sup>8</sup> AABOUD 16U search for resonances decaying to  $\ell^+ \ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>9</sup> KHACHATRYAN 15AE search for resonances decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.
- <sup>10</sup> AAD 14V search for resonances decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.
- <sup>11</sup> CHATRCHYAN 13AF search for resonances decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV and 8 TeV.
- <sup>12</sup> AAD 12CC search for resonances decaying to  $e^+ e^-, \mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.
- <sup>13</sup> CHATRCHYAN 12M search for resonances decaying to  $e^+ e^-$  or  $\mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.
- <sup>14</sup> AALTONEN 11I search for resonances decaying to  $\mu^+ \mu^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- <sup>15</sup> ABAZOV 11A, AALTONEN 09T, AALTONEN 07H, and ABULENCIA 06L search for resonances decaying to  $e^+ e^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- <sup>16</sup> DEL-AGUILA 10 give 95% CL limit on the  $Z$ - $Z'$  mixing  $-0.0019 < \theta < 0.0007$ .
- <sup>17</sup> AALTONEN 09V search for resonances decaying to  $\mu^+ \mu^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.
- <sup>18</sup> ERLER 09 give 95% CL limit on the  $Z$ - $Z'$  mixing  $-0.0018 < \theta < 0.0009$ .
- <sup>19</sup> ABDALLAH 06C give 95% CL limit  $|\theta| < 0.0027$ . See their Fig. 14 for limit contours in the mass-mixing plane.
- <sup>20</sup> ABULENCIA 05A search for resonances decaying to electron or muon pairs in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.

- <sup>21</sup> ABBIENDI 04G give 95% CL limit on  $Z$ - $Z'$  mixing  $-0.00129 < \theta < 0.00258$ . See their Fig. 20 for the limit contour in the mass-mixing plane.  $\sqrt{s} = 91$  to 207 GeV.
- <sup>22</sup> BARGER 03B limit is from the nucleosynthesis bound on the effective number of light neutrino  $\delta N_\nu < 1$ . The quark-hadron transition temperature  $T_c=150$  MeV is assumed. The limit with  $T_c=400$  MeV is  $>1100$  GeV.
- <sup>23</sup> ABREU 00S give 95% CL limit on  $Z$ - $Z'$  mixing  $|\theta| < 0.0018$ . See their Fig. 6 for the limit contour in the mass-mixing plane.  $\sqrt{s}=90$  to 189 GeV.
- <sup>24</sup> BARATE 00I search for deviations in cross section and asymmetries in  $e^+ e^- \rightarrow$  fermions at  $\sqrt{s}=90$  to 183 GeV. Assume  $\theta=0$ . Bounds in the mass-mixing plane are shown in their Figure 18.
- <sup>25</sup> CHO 00 use various electroweak data to constrain  $Z'$  models assuming  $m_H=100$  GeV. See Fig. 3 for limits in the mass-mixing plane.
- <sup>26</sup> ERLER 99 give 90% CL limit on the  $Z$ - $Z'$  mixing  $-0.0013 < \theta < 0.0024$ .
- <sup>27</sup> CONRAD 98 limit is from measurements at CCFR, assuming no  $Z$ - $Z'$  mixing.
- <sup>28</sup> ABE 97S find  $\sigma(Z') \times B(e^+ e^-, \mu^+ \mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s}=1.8$  TeV.
- <sup>29</sup> VILAIN 94B assume  $m_t = 150$  GeV and  $\theta=0$ . See Fig.2 for limit contours in the mass-mixing plane.
- <sup>30</sup> ABE 90F use data for  $R$ ,  $R_{\ell\ell}$ , and  $A_{\ell\ell}$ . ABE 90F fix  $m_W = 80.49 \pm 0.43 \pm 0.24$  GeV and  $m_Z = 91.13 \pm 0.03$  GeV.
- <sup>31</sup> Assumes the nucleosynthesis bound on the effective number of light neutrinos ( $\delta N_\nu < 1$ ) and that  $\nu_R$  is light ( $\lesssim 1$  MeV).
- <sup>32</sup> GRIFOLS 90D limit holds for  $m_{\nu_R} \lesssim 1$  MeV. See also RIZZO 91.

### Limits for $Z_\eta$

$Z_\eta$  is the extra neutral boson in  $E_6$  models, corresponding to  $Q_\eta = \sqrt{3/8} Q_\chi - \sqrt{5/8} Q_\psi$ .  $g_\eta = e/\cos\theta_W$  is assumed unless otherwise stated. We list limits with the assumption  $\rho=1$  but with no further constraints on the Higgs sector. Values in parentheses assume stronger constraint on the Higgs sector motivated by superstring models. Values in brackets are from cosmological and astrophysical considerations and assume a light right-handed neutrino.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;3900</b>	95	<sup>1</sup> AABOUD	17AT ATLS	$p\bar{p}; Z'_\eta \rightarrow e^+ e^-, \mu^+ \mu^-$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		<sup>2</sup> BOBOVNIKOV 18	RVUE	$p\bar{p}, Z'_\eta \rightarrow W^+ W^-$
>2810	95	<sup>3</sup> AABOUD	16U ATLS	$p\bar{p}; Z'_\eta \rightarrow e^+ e^-, \mu^+ \mu^-$
>1870	95	<sup>4</sup> AAD	12CC ATLS	$p\bar{p}, Z'_\eta \rightarrow e^+ e^-, \mu^+ \mu^-$
> 938	95	<sup>5</sup> AALTONEN	11I CDF	$p\bar{p}; Z'_\eta \rightarrow \mu^+ \mu^-$
> 923	95	<sup>6</sup> ABAZOV	11A D0	$p\bar{p}, Z'_\eta \rightarrow e^+ e^-$
> 488	95	<sup>7</sup> DEL-AGUILA	10 RVUE	Electroweak
> 877	95	<sup>6</sup> AALTONEN	09T CDF	$p\bar{p}, Z'_\eta \rightarrow e^+ e^-$
> 904	95	<sup>8</sup> AALTONEN	09V CDF	Repl. by AALTONEN 11I
> 427	95	<sup>9</sup> ERLER	09 RVUE	Electroweak
> 891	95	<sup>6</sup> AALTONEN	07H CDF	Repl. by AALTONEN 09T
> 350	95	SCHAEEL	07A ALEP	$e^+ e^-$
> 360	95	<sup>10</sup> ABDALLAH	06C DLPH	$e^+ e^-$
> 745		<sup>6</sup> ABULENCIA	06L CDF	Repl. by AALTONEN 07H
> 720	95	<sup>11</sup> ABULENCIA	05A CDF	Repl. by AALTONEN 11I and AALTONEN 09T

> 515	95	12	ABBIENDI	04G	OPAL	$e^+e^-$
>1600		13	BARGER	03B	COSM	Nucleosynthesis; light $\nu_R$
> 310	95	14	ABREU	00S	DLPH	$e^+e^-$
> 329	95	15	BARATE	00I	ALEP	Repl. by SCHAEEL 07A
> 619	95	16	CHO	00	RVUE	Electroweak
> 365	95	17	ERLER	99	RVUE	Electroweak
> 87	95	18	CONRAD	98	RVUE	$\nu_\mu N$ scattering
> 620	95	19	ABE	97S	CDF	$p\bar{p}; Z'_\eta \rightarrow e^+e^-, \mu^+\mu^-$
> 100	95	20	VILAIN	94B	CHM2	$\nu_\mu e \rightarrow \nu_\mu e; \bar{\nu}_\mu e \rightarrow \bar{\nu}_\mu e$
> 125	90	21	ABE	90F	VNS	$e^+e^-$
[> 820]		22	GONZALEZ...	90D	COSM	Nucleosynthesis; light $\nu_R$
[> 3300]		23	GRIFOLS	90	ASTR	SN 1987A; light $\nu_R$
[> 1040]		22	LOPEZ	90	COSM	Nucleosynthesis; light $\nu_R$

<sup>1</sup> AABOUD 17AT search for resonances decaying to  $\ell^+\ell^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>2</sup> BOBOVNIKOV 18 use the ATLAS limits on  $\sigma(p\bar{p} \rightarrow Z')$ · $B(Z' \rightarrow W^+W^-)$  to constrain the  $Z$ - $Z'$  mixing parameter  $\xi$ . See their Fig. 9 for limits in  $M_{Z'} - \xi$  plane.

<sup>3</sup> AABOUD 16U search for resonances decaying to  $\ell^+\ell^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>4</sup> AAD 12CC search for resonances decaying to  $e^+e^-, \mu^+\mu^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 7$  TeV.

<sup>5</sup> AALTONEN 11I search for resonances decaying to  $\mu^+\mu^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.

<sup>6</sup> ABAZOV 11A, AALTONEN 09T, AALTONEN 07H, and ABULENCIA 06L search for resonances decaying to  $e^+e^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.

<sup>7</sup> DEL-AGUILA 10 give 95% CL limit on the  $Z$ - $Z'$  mixing  $-0.0023 < \theta < 0.0027$ .

<sup>8</sup> AALTONEN 09V search for resonances decaying to  $\mu^+\mu^-$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.

<sup>9</sup> ERLER 09 give 95% CL limit on the  $Z$ - $Z'$  mixing  $-0.0047 < \theta < 0.0021$ .

<sup>10</sup> ABDALLAH 06C give 95% CL limit  $|\theta| < 0.0092$ . See their Fig. 14 for limit contours in the mass-mixing plane.

<sup>11</sup> ABULENCIA 05A search for resonances decaying to electron or muon pairs in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV.

<sup>12</sup> ABBIENDI 04G give 95% CL limit on  $Z$ - $Z'$  mixing  $-0.00447 < \theta < 0.00331$ . See their Fig. 20 for the limit contour in the mass-mixing plane.  $\sqrt{s} = 91$  to 207 GeV.

<sup>13</sup> BARGER 03B limit is from the nucleosynthesis bound on the effective number of light neutrino  $\delta N_\nu < 1$ . The quark-hadron transition temperature  $T_c=150$  MeV is assumed. The limit with  $T_c=400$  MeV is  $>3300$  GeV.

<sup>14</sup> ABREU 00S give 95% CL limit on  $Z$ - $Z'$  mixing  $|\theta| < 0.0024$ . See their Fig. 6 for the limit contour in the mass-mixing plane.  $\sqrt{s}=90$  to 189 GeV.

<sup>15</sup> BARATE 00I search for deviations in cross section and asymmetries in  $e^+e^- \rightarrow$  fermions at  $\sqrt{s}=90$  to 183 GeV. Assume  $\theta=0$ . Bounds in the mass-mixing plane are shown in their Figure 18.

<sup>16</sup> CHO 00 use various electroweak data to constrain  $Z'$  models assuming  $m_H=100$  GeV. See Fig. 3 for limits in the mass-mixing plane.

<sup>17</sup> ERLER 99 give 90% CL limit on the  $Z$ - $Z'$  mixing  $-0.0062 < \theta < 0.0011$ .

<sup>18</sup> CONRAD 98 limit is from measurements at CCFR, assuming no  $Z$ - $Z'$  mixing.

<sup>19</sup> ABE 97S find  $\sigma(Z') \times B(e^+e^-, \mu^+\mu^-) < 40$  fb for  $m_{Z'} > 600$  GeV at  $\sqrt{s}=1.8$  TeV.

<sup>20</sup> VILAIN 94B assume  $m_t = 150$  GeV and  $\theta=0$ . See Fig.2 for limit contours in the mass-mixing plane.

<sup>21</sup> ABE 90F use data for  $R, R_{\ell\ell}$ , and  $A_{\ell\ell}$ . ABE 90F fix  $m_W = 80.49 \pm 0.43 \pm 0.24$  GeV and  $m_Z = 91.13 \pm 0.03$  GeV.

<sup>22</sup> These authors claim that the nucleosynthesis bound on the effective number of light neutrinos ( $\delta N_\nu < 1$ ) constrains  $Z'$  masses if  $\nu_R$  is light ( $\lesssim 1$  MeV).

<sup>23</sup> GRIFOLS 90 limit holds for  $m_{\nu_R} \lesssim 1$  MeV. See also GRIFOLS 90D, RIZZO 91.

### Limits for other $Z'$

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
none 800–3700	95	1 SIRUNYAN	21X CMS	$Z' \rightarrow HZ$
>2650	95	2 AAD	20AJ ATLS	$Z' \rightarrow HZ$
>3900	95	3 AAD	20AMATLS	$Z' \rightarrow t\bar{t}$
>3900	95	4 AAD	20AT ATLS	$Z' \rightarrow WW$
none 1200–3500	95	5 SIRUNYAN	20Q CMS	$Z' \rightarrow WW$
none 580–3100	95	6 AABOUD	19AS ATLS	$Z' \rightarrow t\bar{t}$
none 1300–3100	95	7 AAD	19D ATLS	$Z' \rightarrow WW$
>3800	95	8 SIRUNYAN	19AA CMS	$Z' \rightarrow t\bar{t}$
>3700	95	9 SIRUNYAN	19CP CMS	$Z' \rightarrow WW, HZ, \ell^+ \ell^-$
>1800	95	10 SIRUNYAN	19I CMS	$Z' \rightarrow HZ$
none 600–2100	95	11 AABOUD	18AB ATLS	$Z' \rightarrow b\bar{b}$
none 500–2830	95	12 AABOUD	18AI ATLS	$Z' \rightarrow HZ$
none 300–3000	95	13 AABOUD	18AK ATLS	$Z' \rightarrow WW$
>1300	95	14 AABOUD	18B ATLS	$Z' \rightarrow WW$
none 400–3000	95	15 AABOUD	18BI ATLS	$Z' \rightarrow t\bar{t}$
none 1200–2800	95	16 AABOUD	18F ATLS	$Z' \rightarrow WW$
>2300	95	17 SIRUNYAN	18ED CMS	$Z' \rightarrow HZ$
none 1200–2700	95	18 SIRUNYAN	18P CMS	$Z' \rightarrow WW$
>2900	95	19 AABOUD	17AK ATLS	$Z' \rightarrow q\bar{q}$
none 1100–2600	95	20 AABOUD	17AO ATLS	$Z' \rightarrow HZ$
>2300	95	21 SIRUNYAN	17AK CMS	$Z' \rightarrow WW, HZ$
>2500	95	22 SIRUNYAN	17Q CMS	$Z' \rightarrow t\bar{t}$
>1190	95	23 SIRUNYAN	17R CMS	$Z' \rightarrow HZ$
none 1210–2260	95	23 SIRUNYAN	17R CMS	$Z' \rightarrow HZ$

• • • We do not use the following data for averages, fits, limits, etc. • • •

24 AAD	22 ATLS	$pp \rightarrow b\bar{b}Z' \rightarrow b\bar{b}b\bar{b}$
25 AAD	21AQ ATLS	$pp, \ell^+ \ell^- \ell^+ \ell^-$
26 AAD	21AZ ATLS	DM mediator $Z'$
27 AAD	21BB ATLS	$Z' \rightarrow AH$
28 AAD	21D ATLS	dark Higgs $Z'$
29 AAD	21K ATLS	$Z' \rightarrow \chi\chi$
30 BURAS	21 RVUE	leptophilic $Z'$
31 CAEDDU	21 RVUE	$\nu$ -nucleus scattering
32 COLARESI	21 HPGE	$\nu$ -nucleus scattering
33 KRIBS	21 RVUE	$e p$ scattering
34 TUMASYAN	21D CMS	$Z' \rightarrow \chi\chi$
35 AAD	20AF ATLS	$Z' \rightarrow H\gamma$
36 AAD	20T ATLS	DM simplified $Z'$
37 AAD	20W ATLS	DM simplified $Z'$
38 AAIJ	20AL LHCb	$Z' \rightarrow \mu^+ \mu^-$
39 ADACHI	20 BEL2	$e^+ e^- \rightarrow \mu^+ \mu^- Z',$ $e^\pm \mu^\mp Z'$
40 SIRUNYAN	20AI CMS	$Z' \rightarrow q\bar{q}$
41 SIRUNYAN	20AQ CMS	$Z' \rightarrow \mu^+ \mu^-$

		42	SIRUNYAN	20M	CMS	$Z' \rightarrow q\bar{q}$
		43	AABOUD	19AJ	ATLS	$Z' \rightarrow q\bar{q}$
		44	AABOUD	19D	ATLS	$Z' \rightarrow q\bar{q}$
		45	AABOUD	19V	ATLS	DM simplified $Z'$
		46	AAD	19L	ATLS	$Z' \rightarrow e^+e^-, \mu^+\mu^-$
		47	LONG	19	RVUE	Electroweak
		48	PANDEY	19	RVUE	neutrino NSI
		49	SIRUNYAN	19AL	CMS	$Z' \rightarrow tT, T \rightarrow Ht,$ $Zt, Wb$
		50	SIRUNYAN	19AN	CMS	DM simplified $Z'$
		51	SIRUNYAN	19CB	CMS	$Z' \rightarrow q\bar{q}$
		52	SIRUNYAN	19CD	CMS	$Z' \rightarrow q\bar{q}$
		53	SIRUNYAN	19D	CMS	$Z' \rightarrow H\gamma$
		54	AABOUD	18AA	ATLS	$Z' \rightarrow H\gamma$
>4500	95	55	AABOUD	18CJ	ATLS	$Z' \rightarrow WW, HZ, \ell^+\ell^-$
		56	AABOUD	18N	ATLS	$Z' \rightarrow q\bar{q}$
		57	AAIJ	18AQ	LHCB	$Z' \rightarrow \mu^+\mu^-$
		58	SIRUNYAN	18DR	CMS	$Z' \rightarrow \mu^+\mu^-$
		59	SIRUNYAN	18G	CMS	$Z' \rightarrow q\bar{q}$
		60	SIRUNYAN	18I	CMS	$Z' \rightarrow b\bar{b}$
>1580	95	61	AABOUD	17B	ATLS	$Z' \rightarrow HZ$
		62	KHACHATRY...17AX	CMS		$Z' \rightarrow \ell\ell\ell\ell$
		63	KHACHATRY...17U	CMS		$Z' \rightarrow HZ$
>1700	95	64	SIRUNYAN	17A	CMS	$Z' \rightarrow WW$
		65	SIRUNYAN	17AP	CMS	$Z' \rightarrow HA$
		66	SIRUNYAN	17T	CMS	$Z' \rightarrow q\bar{q}$
		67	SIRUNYAN	17V	CMS	$Z' \rightarrow Tt$
none 1100–1500	95	68	AABOUD	16	ATLS	$Z' \rightarrow b\bar{b}$
none 1500–2600	95	69	AAD	16L	ATLS	$Z' \rightarrow a\gamma, a \rightarrow \gamma\gamma$
none 1000–1100, none 1300–1500	95	70	AAD	16S	ATLS	$Z' \rightarrow q\bar{q}$
>2400	95	71	KHACHATRY...16AP	CMS		$Z' \rightarrow HZ$
		72	KHACHATRY...16E	CMS		$Z' \rightarrow t\bar{t}$
		73	AAD	15AO	ATLS	$Z' \rightarrow t\bar{t}$
		74	AAD	15AT	ATLS	monotop
		75	AAD	15CD	ATLS	$H \rightarrow ZZ', Z'Z';$ $Z' \rightarrow \ell^+\ell^-$
		76	KHACHATRY...15F	CMS		monotop
		77	KHACHATRY...15O	CMS		$Z' \rightarrow HZ$
		78	AAD	14AT	ATLS	$Z' \rightarrow Z\gamma$
		79	KHACHATRY...14A	CMS		$Z' \rightarrow VV$
		80	MARTINEZ	14	RVUE	Electroweak
none 500–1740	95	81	AAD	13AQ	ATLS	$Z' \rightarrow t\bar{t}$
>1320 or 1000–1280	95	82	AAD	13G	ATLS	$Z' \rightarrow t\bar{t}$
> 915	95	82	AALTONEN	13A	CDF	$Z' \rightarrow t\bar{t}$
>1300	95	83	CHATRCHYAN	13AP	CMS	$Z' \rightarrow t\bar{t}$
>2100	95	82	CHATRCHYAN	13BM	CMS	$Z' \rightarrow t\bar{t}$
		84	AAD	12BV	ATLS	$Z' \rightarrow t\bar{t}$
		85	AAD	12K	ATLS	$Z' \rightarrow t\bar{t}$



		86	AALTONEN	12AR	CDF	Chromophilic
		87	AALTONEN	12N	CDF	$Z' \rightarrow \bar{\tau} u$
> 835	95	88	ABAZOV	12R	D0	$Z' \rightarrow t \bar{\tau}$
		89	CHATRCHYAN	12AI	CMS	$Z' \rightarrow t \bar{u}$
		90	CHATRCHYAN	12AQ	CMS	$Z' \rightarrow t \bar{\tau}$
>1490	95	82	CHATRCHYAN	12BL	CMS	$Z' \rightarrow t \bar{\tau}$
		91	AALTONEN	11AD	CDF	$Z' \rightarrow t \bar{\tau}$
		92	AALTONEN	11AE	CDF	$Z' \rightarrow t \bar{\tau}$
		93	CHATRCHYAN	11O	CMS	$pp \rightarrow tt$
		94	AALTONEN	08D	CDF	$Z' \rightarrow t \bar{\tau}$
		94	AALTONEN	08Y	CDF	$Z' \rightarrow t \bar{\tau}$
		94	ABAZOV	08AA	D0	$Z' \rightarrow t \bar{\tau}$
		95	ABAZOV	04A	D0	Repl. by ABAZOV 08AA
		96	BARGER	03B	COSM	Nucleosynthesis; light $\nu_R$
		97	CHO	00	RVUE	$E_6$ -motivated
		98	CHO	98	RVUE	$E_6$ -motivated
		99	ABE	97G	CDF	$Z' \rightarrow \bar{q} q$

<sup>1</sup> SIRUNYAN 21X search for resonances decaying to  $HZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 3500$  GeV for  $g_V = 1$ .

<sup>2</sup> AAD 20AJ search for resonances decaying to  $HZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 2200$  GeV for  $g_V = 1$ . See their Fig. 6 for limits on  $\sigma \cdot B$ .

<sup>3</sup> AAD 20AM search for a resonance decaying to  $t\bar{t}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for a leptophobic top-color  $Z'$  with  $\Gamma_{Z'}/M_{Z'} = 0.01$ . The limit becomes  $M_{Z'} > 4700$  GeV for  $\Gamma_{Z'}/M_{Z'} = 0.03$ .

<sup>4</sup> AAD 20AT search for resonances decaying to  $WW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 3500$  GeV for  $g_V = 1$ . See their Fig. 14 for limits on  $\sigma \cdot B$ .

<sup>5</sup> SIRUNYAN 20Q search for resonances decaying to  $WW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ .

<sup>6</sup> AABOUD 19AS search for a resonance decaying to  $t\bar{t}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for a top-color  $Z'$  with  $\Gamma_{Z'}/M_{Z'} = 0.01$ . Limits are also set on  $Z'$  masses in simplified Dark Matter models.

<sup>7</sup> AAD 19D search for resonances decaying to  $WW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 2900$  GeV for  $g_V = 1$ . If we assume  $M_{Z'} = M_{W'}$ , the limit increases  $M_{Z'} > 3800$  GeV and  $M_{Z'} > 3500$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig. 9 for limits on  $\sigma \cdot B$ .

<sup>8</sup> SIRUNYAN 19AA search for a resonance decaying to  $t\bar{t}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for a leptophobic top-color  $Z'$  with  $\Gamma_{Z'}/M_{Z'} = 0.01$ .

<sup>9</sup> SIRUNYAN 19CP present a statistical combinations of searches for  $Z'$  decaying to pairs of bosons or leptons in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . If we assume  $M_{Z'} = M_{W'}$ , the limit becomes  $M_{Z'} > 4500$  GeV for  $g_V = 3$  and  $M_{Z'} > 5000$  GeV for  $g_V = 1$ . See their Figs. 2 and 3 for limits on  $\sigma \cdot B$ .

<sup>10</sup> SIRUNYAN 19I search for resonances decaying to  $ZW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 2800$  GeV if we assume  $M_{Z'} = M_{W'}$ .

- 11 AABOUD 18AB search for resonances decaying to  $b\bar{b}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for a leptophobic  $Z'$  with SM-like couplings to quarks. See their Fig. 6 for limits on  $\sigma \cdot B$ . Additional limits on a  $Z'$  axial-vector mediator in a simplified dark-matter model are shown in Fig. 7.
- 12 AABOUD 18AI search for resonances decaying to  $HZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 2650$  GeV for  $g_V = 1$ . If we assume  $M_{W'} = M_{Z'}$ , the limit increases  $M_{Z'} > 2930$  GeV and  $M_{Z'} > 2800$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig. 5 for limits on  $\sigma \cdot B$ .
- 13 AABOUD 18AK search for resonances decaying to  $WW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 2750$  GeV for  $g_V = 1$ .
- 14 AABOUD 18B search for resonances decaying to  $WW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 1$ . See their Fig.11 for limits on  $\sigma \cdot B$ .
- 15 AABOUD 18BI search for a resonance decaying to  $t\bar{t}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for a top-color assisted TC  $Z'$  with  $\Gamma_{Z'}/M_{Z'} = 0.01$ . The limits for wider resonances are available. See their Fig. 14 for limits on  $\sigma \cdot B$ .
- 16 AABOUD 18F search for resonances decaying to  $WW$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 2200$  GeV for  $g_V = 1$ . If we assume  $M_{Z'} = M_{W'}$ , the limit increases  $M_{Z'} > 3500$  GeV and  $M_{Z'} > 3100$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig.5 for limits on  $\sigma \cdot B$ .
- 17 SIRUNYAN 18ED search for resonances decaying to  $HZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . If we assume  $M_{Z'} = M_{W'}$ , the limit increases  $M_{Z'} > 2900$  GeV and  $M_{Z'} > 2800$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively.
- 18 SIRUNYAN 18P give this limit for a heavy-vector-triplet  $Z'$  with  $g_V = 3$ . If they assume  $M_{Z'} = M_{W'}$ , the limit increases to  $M_{Z'} > 3800$  GeV.
- 19 AABOUD 17AK search for a new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for a leptophobic  $Z'$  boson having axial-vector coupling strength with quarks  $g_q = 0.2$ . The limit is 2100 GeV if  $g_q = 0.1$ .
- 20 AABOUD 17AO search for resonances decaying to  $HZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for a  $Z'$  in the heavy-vector-triplet model with  $g_V = 3$ . See their Fig.4 for limits on  $\sigma \cdot B$ .
- 21 SIRUNYAN 17AK search for resonances decaying to  $WW$  or  $HZ$  in  $pp$  collisions at  $\sqrt{s} = 8$  and 13 TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 2200$  GeV for  $g_V = 1$ . If we assume  $M_{Z'} = M_{W'}$ , the limit increases  $M_{Z'} > 2400$  GeV for both  $g_V = 3$  and  $g_V = 1$ . See their Fig.1 and 2 for limits on  $\sigma \cdot B$ .
- 22 SIRUNYAN 17Q search for a resonance decaying to  $t\bar{t}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for a resonance with relative width  $\Gamma_{Z'}/M_{Z'} = 0.01$ . Limits for wider resonances are available. See their Fig.6 for limits on  $\sigma \cdot B$ .
- 23 SIRUNYAN 17R search for resonances decaying to  $HZ$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . Mass regions  $M_{Z'} < 1150$  GeV and  $1250$  GeV  $< M_{Z'} < 1670$  GeV are excluded for  $g_V = 1$ . If we assume  $M_{Z'} = M_{W'}$ , the excluded mass regions are  $1000 < M_{Z'} < 2500$  GeV and  $2760 < M_{Z'} < 3300$  GeV for  $g_V = 3$ ;  $1000 < M_{Z'} < 2430$  GeV and  $2810 < M_{Z'} < 3130$  GeV for  $g_V = 1$ . See their Fig.5 for limits on  $\sigma \cdot B$ .
- 24 AAD 22 search for  $b\bar{b}Z'$  productions in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $Z'$  is assumed to decay into  $b\bar{b}$ . See their Fig.4 for limits on  $\sigma \cdot B$ .

- 25 AAD 21AQ limits are for a  $B - L$  gauge boson model derived from their measurements on four-lepton differential cross sections. See their Fig. 13 for exclusion limits on the  $B - L$  breaking Higgs boson mass.
- 26 AAD 21AZ search for DM mediator  $Z'$  produced in association with a SM Higgs boson in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $Z'$  is assumed to decay invisibly  $Z' \rightarrow \chi\chi$ . See their Fig.7 for limits in  $M_{Z'} - M_\chi$  plane.
- 27 AAD 21BB search for  $Z'$  productions in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $Z'$  is assumed to decay into a SM Higgs boson  $H$  and an invisible particle  $A$ . See their Fig.7 for limits in  $M_{Z'} - M_A$  plane.
- 28 AAD 21D set limits on a dark Higgs model with a spin-1 mediator  $Z'$  and a scalar dark Higgs boson  $s$ . Dark Higgs  $s$  is assumed to decay into  $WW$  or  $ZZ$ . See their Fig.4 for limits in  $M_{Z'} - M_s$  plane.
- 29 AAD 21K search for  $\gamma + \cancel{E}_T$  events in  $pp$  collision at  $\sqrt{s} = 13$  TeV. See their Fig. 5 for limits on  $Z'$  particle invisibly decaying to  $\chi\chi$ .
- 30 BURAS 21 performed global fit to leptophilic  $Z'$  models using a large number of observables.
- 31 CADEDU 21 obtain limits on  $Z'$  coupling  $g_{Z'}$  from coherent  $\nu$ -nucleus scattering data collected by COHERENT experiment. For limits in the  $M_{Z'} - g_{Z'}$  plane, see their Figures 3 and 4 for the universal  $Z'$  model and Figures 5 and 6 for the  $B - L$  model.
- 32 COLARESI 21 obtain limits on  $Z'$  coupling from coherent  $\nu$ -nucleus scattering data collected by a Ge detector at the Dresden-II power reactor. See their Fig.7 for limits in mass-coupling plane.
- 33 KRIBS 21 set decay-agnostic limits on kinetic mixing parameter between  $U(1)_Y$  field and new heavy abelian vector boson (dark photon) field using the HERA  $ep$  collision data. See their Fig. 3 for limits in mass-mixing plane.
- 34 TUMASYAN 21D search for energetic jets +  $\cancel{E}_T$  events in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.  $Z'$  is assumed to decay into a pair of invisible particles  $\chi\chi$ . See their Fig. 7 for limits on signal strength in  $M_{Z'} - M_\chi$  plane, and Fig. 8 for limits on signal strength in quark and dark matter coupling vs mediator mass.
- 35 AAD 20AF search for resonances decaying to  $H\gamma$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 1c for limits on  $\sigma \cdot B$  for the mass range  $0.7 < m_{Z'} < 4$  TeV.
- 36 AAD 20T search for Dark Matter mediator  $Z'$  decaying invisibly or decaying to  $q\bar{q}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 5 for limits in  $M_{Z'} - g_q$  plane from the inclusive category. See their Fig. 7(a) for limits on the product of the cross section, acceptance,  $b$ -tagging efficiency, and branching fraction from the 2  $b$ -tag category.
- 37 AAD 20W search for a Dark Matter (DM) simplified model  $Z'$  produced in association with  $W$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 5 for limits on  $Z'$  production cross section.
- 38 AAIJ 20AL search for spin-0 and spin-1 resonances decaying to  $\mu^+\mu^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV in the mass regions  $M_{Z'} < 60$  GeV, with non-negligible widths considered above 20 GeV. See their Figs. 7, 8, and 9 for limits on  $\sigma \cdot B$ .
- 39 ADACHI 20 search for production of  $Z'$  in  $e^+e^-$  collisions. The  $Z'$  is assume to decay invisibly. See their Fig. 3 and Fig. 5 for limits on  $Z'$  coupling and  $\sigma(e^+e^- \rightarrow e^\pm\mu^\mp Z')$ .
- 40 SIRUNYAN 20AI search for broad resonances decaying into dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 11 for exclusion limits in mass-coupling plane.
- 41 SIRUNYAN 20AQ search for a narrow resonance lighter than 200 GeV decaying to  $\mu^+\mu^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 3 for limits on  $Z'$  kinetic mixing coefficient.
- 42 SIRUNYAN 20M search for a narrow resonance with a mass between 350 and 700 GeV in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig.3 for exclusion limits in mass-coupling plane.

- 43 AABOUD 19AJ search in  $pp$  collisions at  $\sqrt{s} = 13$  TeV for a new resonance decaying to  $q\bar{q}$  and produced in association with a high  $p_T$  photon. For a leptophobic axial-vector  $Z'$  in the mass region  $250 \text{ GeV} < M_{Z'} < 950 \text{ GeV}$ , the  $Z'$  coupling with quarks  $g_q$  is constrained below 0.18. See their Fig.2 for limits in  $M_{Z'} - g_q$  plane.
- 44 AABOUD 19D search in  $pp$  collisions at  $\sqrt{s} = 13$  TeV for a new resonance decaying to  $q\bar{q}$  and produced in association with a high- $p_T$  photon or jet. For a leptophobic axial-vector  $Z'$  in the mass region  $100 \text{ GeV} < M_{Z'} < 220 \text{ GeV}$ , the  $Z'$  coupling with quarks  $g_q$  is constrained below 0.23. See their Fig. 6 for limits in  $M_{Z'} - g_q$  plane.
- 45 AABOUD 19V search for Dark Matter simplified  $Z'$  decaying invisibly or decaying to fermion pair in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- 46 AAD 19L search for resonances decaying to  $\ell^+ \ell^-$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 4 for limits in the heavy vector triplet model couplings.
- 47 LONG 19 uses the weak charge data of Cesium and proton to constrain mass of  $Z'$  in the 3-3-1 models.
- 48 PANDEY 19 obtain limits on  $Z'$  induced neutrino non-standard interaction (NSI) parameter  $\epsilon$  from LHC and IceCube data. See their Fig.2 for limits in  $M_{Z'} - \epsilon$  plane, where  $\epsilon = g_q g_\nu v^2 / (2 M_{Z'}^2)$ .
- 49 SIRUNYAN 19AL search for a new resonance decaying to a top quark and a heavy vector-like top partner in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 8 for limits on  $Z'$  production cross section.
- 50 SIRUNYAN 19AN search for a Dark Matter (DM) simplified model  $Z'$  decaying to  $H$  DM in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 7 for limits on the signal strength modifiers.
- 51 SIRUNYAN 19CB search in  $pp$  collisions at  $\sqrt{s} = 13$  TeV for a new resonance decaying to  $q\bar{q}$ . For a leptophobic  $Z'$  in the mass region 50–300 GeV, the  $Z'$  coupling with quarks  $g'_q$  is constrained below 0.2. See their Figs. 4 and 5 for limits on  $g'_q$  in the mass range  $50 < M_{Z'} < 450 \text{ GeV}$ .
- 52 SIRUNYAN 19CD search in  $pp$  collisions at  $\sqrt{s}=13$  TeV for a leptophobic  $Z'$  produced in association of high  $p_T$  ISR photon and decaying to  $q\bar{q}$ . See their Fig. 2 for limits on the  $Z'$  coupling strength  $g'_q$  to  $q\bar{q}$  in the mass range between 10 and 125 GeV.
- 53 SIRUNYAN 19D search for a narrow neutral vector resonance decaying to  $H\gamma$ . See their Fig. 3 for exclusion limit in  $M_{Z'} - \sigma \cdot B$  plane. Upper limits on the production of  $H\gamma$  resonances are set as a function of the resonance mass in the range of 720–3250 GeV.
- 54 AABOUD 18AA search for a narrow neutral vector boson decaying to  $H\gamma$ . See their Fig. 10 for the exclusion limit in  $M_{Z'} - \sigma B$  plane.
- 55 AABOUD 18CJ search for heavy-vector-triplet  $Z'$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for model with  $g_V = 3$  assuming  $M_{Z'} = M_{W'}$ . The limit becomes  $M_{Z'} > 5500 \text{ GeV}$  for model with  $g_V = 1$ .
- 56 AABOUD 18N search for a narrow resonance decaying to  $q\bar{q}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV using trigger level analysis to improve the low mass region sensitivity. See their Fig. 5 for limits in the mass-coupling plane in the  $Z'$  mass range 450–1800 GeV.
- 57 AAIJ 18AQ search for spin-0 and spin-1 resonances decaying to  $\mu^+ \mu^-$  in  $pp$  collisions at  $\sqrt{s} = 7$  and 8 TeV in the mass region near 10 GeV. See their Figs. 4 and 5 for limits on  $\sigma \cdot B$ .
- 58 SIRUNYAN 18DR searches for  $\mu^+ \mu^-$  resonances produced in association with  $b$ -jets in the  $pp$  collision data with  $\sqrt{s} = 8$  TeV and 13 TeV. An excess of events near  $m_{\mu\mu} = 28 \text{ GeV}$  is observed in the 8 TeV data. See their Fig. 3 for the measured fiducial signal cross sections at  $\sqrt{s} = 8$  TeV and the 95% CL upper limits at  $\sqrt{s} = 13$  TeV.
- 59 SIRUNYAN 18G search for a new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV in the mass range 50–300 GeV. See their Fig.7 for limits in the mass-coupling plane.

- <sup>60</sup> SIRUNYAN 18I search for a narrow resonance decaying to  $b\bar{b}$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV using dedicated b-tagged dijet triggers to improve the sensitivity in the low mass region. See their Fig. 3 for limits on  $\sigma \cdot B$  in the  $Z'$  mass range 325–1200 GeV.
- <sup>61</sup> AABOUD 17B search for resonances decaying to  $HZ$  ( $H \rightarrow b\bar{b}, c\bar{c}; Z \rightarrow \ell^+\ell^-, \nu\bar{\nu}$ ) in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 1490$  GeV for  $g_V = 1$ . If we assume  $M_{Z'} = M_{W'}$ , the limit increases  $M_{Z'} > 2310$  GeV and  $M_{Z'} > 1730$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig.3 for limits on  $\sigma \cdot B$ .
- <sup>62</sup> KHACHATRYAN 17AX search for lepto-phobic resonances decaying to four leptons in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.
- <sup>63</sup> KHACHATRYAN 17U search for resonances decaying to  $HZ$  ( $H \rightarrow b\bar{b}; Z \rightarrow \ell^+\ell^-, \nu\bar{\nu}$ ) in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit on the heavy-vector-triplet model is  $M_{Z'} = M_{W'} > 2$  TeV for  $g_V = 3$ , in which constraints from the  $W' \rightarrow HW$  ( $H \rightarrow b\bar{b}; W \rightarrow \ell\nu$ ) are combined. See their Fig.3 and Fig.4 for limits on  $\sigma \cdot B$ .
- <sup>64</sup> SIRUNYAN 17A search for resonances decaying to  $WW$  with  $WW \rightarrow \ell\nu q\bar{q}, q\bar{q}q\bar{q}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ . The limit becomes  $M_{Z'} > 1600$  GeV for  $g_V = 1$ . If we assume  $M_{Z'} = M_{W'}$ , the limit increases  $M_{Z'} > 2400$  GeV and  $M_{Z'} > 2300$  GeV for  $g_V = 3$  and  $g_V = 1$ , respectively. See their Fig.6 for limits on  $\sigma \cdot B$ .
- <sup>65</sup> SIRUNYAN 17AP search for resonances decaying into a SM-like Higgs scalar  $H$  and a light pseudo scalar  $A$ .  $A$  is assumed to decay invisibly. See their Fig.9 for limits on  $\sigma \cdot B$ .
- <sup>66</sup> SIRUNYAN 17T search for a new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV in the mass range 100–300 GeV. See their Fig.3 for limits in the mass-coupling plane.
- <sup>67</sup> SIRUNYAN 17V search for a new resonance decaying to a top quark and a heavy vector-like top partner  $T$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their table 5 for limits on the  $Z'$  production cross section for various values of  $M_{Z'}$  and  $M_T$  in the range of  $M_{Z'} = 1500$ –2500 GeV and  $M_T = 700$ –1500 GeV.
- <sup>68</sup> AABOUD 16 search for a narrow resonance decaying into  $b\bar{b}$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for a leptophobic  $Z'$  with SM-like couplings to quarks. See their Fig.6 for limits on  $\sigma \cdot B$ .
- <sup>69</sup> AAD 16L search for  $Z' \rightarrow a\gamma, a \rightarrow \gamma\gamma$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. See their Table 6 for limits on  $\sigma \cdot B$ .
- <sup>70</sup> AAD 16S search for a new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above is for a leptophobic  $Z'$  having coupling strength with quark  $g_q = 0.3$  and is taken from their Figure 3.
- <sup>71</sup> KHACHATRYAN 16AP search for a resonance decaying to  $HZ$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. Both  $H$  and  $Z$  are assumed to decay to fat jets. The quoted limit is for heavy-vector-triplet  $Z'$  with  $g_V = 3$ .
- <sup>72</sup> KHACHATRYAN 16E search for a leptophobic top-color  $Z'$  decaying to  $t\bar{t}$  using  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The quoted limit assumes that  $\Gamma_{Z'}/m_{Z'} = 0.012$ . Also  $m_{Z'} < 2.9$  TeV is excluded for wider topcolor  $Z'$  with  $\Gamma_{Z'}/m_{Z'} = 0.1$ .
- <sup>73</sup> AAD 15AO search for narrow resonance decaying to  $t\bar{t}$  using  $pp$  collisions at  $\sqrt{s} = 8$  TeV. See Fig. 11 for limit on  $\sigma B$ .
- <sup>74</sup> AAD 15AT search for monotop production plus large missing  $E_T$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV and give constraints on a  $Z'$  model having  $Z' u\bar{t}$  coupling.  $Z'$  is assumed to decay invisibly. See their Fig. 6 for limits on  $\sigma \cdot B$ .
- <sup>75</sup> AAD 15CD search for decays of Higgs bosons to 4  $\ell$  states via  $Z'$  bosons,  $H \rightarrow ZZ' \rightarrow 4\ell$  or  $H \rightarrow Z'Z' \rightarrow 4\ell$ . See Fig. 5 for the limit on the signal strength of the  $H \rightarrow ZZ' \rightarrow 4\ell$  process and Fig. 16 for the limit on  $H \rightarrow Z'Z' \rightarrow 4\ell$ .

- 76 KHACHATRYAN 15F search for monotop production plus large missing  $E_T$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV and give constraints on a  $Z'$  model having  $Z' u \bar{t}$  coupling.  $Z'$  is assumed to decay invisibly. See Fig. 3 for limits on  $\sigma B$ .
- 77 KHACHATRYAN 15O search for narrow  $Z'$  resonance decaying to  $ZH$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. See their Fig. 6 for limit on  $\sigma B$ .
- 78 AAD 14AT search for a narrow neutral vector boson decaying to  $Z\gamma$ . See their Fig. 3b for the exclusion limit in  $m_{Z'} - \sigma B$  plane.
- 79 KHACHATRYAN 14A search for new resonance in the  $WW (\ell\nu q\bar{q})$  and the  $ZZ (\ell\ell q\bar{q})$  channels using  $pp$  collisions at  $\sqrt{s}=8$  TeV. See their Fig.13 for the exclusion limit on the number of events in the mass-width plane.
- 80 MARTINEZ 14 use various electroweak data to constrain the  $Z'$  boson in the 3-3-1 models.
- 81 AAD 13AQ search for a leptophobic top-color  $Z'$  decaying to  $t\bar{t}$ . The quoted limit assumes that  $\Gamma_{Z'}/m_{Z'} = 0.012$ .
- 82 CHATRCHYAN 13BM search for top-color  $Z'$  decaying to  $t\bar{t}$  using  $pp$  collisions at  $\sqrt{s}=8$  TeV. The quoted limit is for  $\Gamma_{Z'}/m_{Z'} = 0.012$ .
- 83 CHATRCHYAN 13AP search for top-color leptophobic  $Z'$  decaying to  $t\bar{t}$  using  $pp$  collisions at  $\sqrt{s}=7$  TeV. The quoted limit is for  $\Gamma_{Z'}/m_{Z'} = 0.012$ .
- 84 AAD 12BV search for narrow resonance decaying to  $t\bar{t}$  using  $pp$  collisions at  $\sqrt{s}=7$  TeV. See their Fig. 7 for limit on  $\sigma \cdot B$ .
- 85 AAD 12K search for narrow resonance decaying to  $t\bar{t}$  using  $pp$  collisions at  $\sqrt{s}=7$  TeV. See their Fig. 5 for limit on  $\sigma \cdot B$ .
- 86 AALTONEN 12AR search for chromophilic  $Z'$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV. See their Fig. 5 for limit on  $\sigma \cdot B$ .
- 87 AALTONEN 12N search for  $p\bar{p} \rightarrow tZ', Z' \rightarrow \bar{t}u$  events in  $p\bar{p}$  collisions. See their Fig. 3 for the limit on  $\sigma \cdot B$ .
- 88 ABAZOV 12R search for top-color  $Z'$  boson decaying exclusively to  $t\bar{t}$ . The quoted limit is for  $\Gamma_{Z'}/m_{Z'} = 0.012$ .
- 89 CHATRCHYAN 12AI search for  $pp \rightarrow tt$  events and give constraints on a  $Z'$  model having  $Z' \bar{u}t$  coupling. See their Fig. 4 for the limit in mass-coupling plane.
- 90 Search for resonance decaying to  $t\bar{t}$ . See their Fig. 6 for limit on  $\sigma \cdot B$ .
- 91 Search for narrow resonance decaying to  $t\bar{t}$ . See their Fig. 4 for limit on  $\sigma \cdot B$ .
- 92 Search for narrow resonance decaying to  $t\bar{t}$ . See their Fig. 3 for limit on  $\sigma \cdot B$ .
- 93 CHATRCHYAN 11O search for same-sign top production in  $pp$  collisions induced by a hypothetical FCNC  $Z'$  at  $\sqrt{s} = 7$  TeV. See their Fig. 3 for limit in mass-coupling plane.
- 94 Search for narrow resonance decaying to  $t\bar{t}$ . See their Fig. 3 for limit on  $\sigma \cdot B$ .
- 95 Search for narrow resonance decaying to  $t\bar{t}$ . See their Fig. 2 for limit on  $\sigma \cdot B$ .
- 96 BARGER 03B use the nucleosynthesis bound on the effective number of light neutrino  $\delta N_\nu$ . See their Figs. 4–5 for limits in general  $E_6$  motivated models.
- 97 CHO 00 use various electroweak data to constrain  $Z'$  models assuming  $m_H=100$  GeV. See Fig. 2 for limits in general  $E_6$ -motivated models.
- 98 CHO 98 study constraints on four-Fermi contact interactions obtained from low-energy electroweak experiments, assuming no  $Z$ - $Z'$  mixing.
- 99 Search for  $Z'$  decaying to dijets at  $\sqrt{s}=1.8$  TeV. For  $Z'$  with electromagnetic strength coupling, no bound is obtained.

## Searches for $Z'$ with Lepton-Flavor-Violating decays

The following limits are obtained from  $p\bar{p}$  or  $pp \rightarrow Z' X$  with  $Z'$  decaying to the mode indicated in the comments.

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
1	AABOUD	18CM ATLS	$Z' \rightarrow e\mu, e\tau, \mu\tau$
2	SIRUNYAN	18AT CMS	$Z' \rightarrow e\mu$
3	AABOUD	16P ATLS	$Z' \rightarrow e\mu, e\tau, \mu\tau$
4	KHACHATRYAN	16BE CMS	$Z' \rightarrow e\mu$
5	AAD	15O ATLS	$Z' \rightarrow e\mu, e\tau, \mu\tau$
6	AAD	11H ATLS	$Z' \rightarrow e\mu$
7	AAD	11Z ATLS	$Z' \rightarrow e\mu$
8	ABULENCIA	06M CDF	$Z' \rightarrow e\mu$

<sup>1</sup> AABOUD 18CM search for a new particle with lepton-flavor violating decay in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Figs. 4, 5, and 6 for limits on  $\sigma \cdot B$ .

<sup>2</sup> SIRUNYAN 18AT search for a narrow resonance  $Z'$  decaying into  $e\mu$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig.5 for limit on  $\sigma \cdot B$  in the range of  $600 \text{ GeV} < M_{Z'} < 5000$  GeV.

<sup>3</sup> AABOUD 16P search for new particle with lepton flavor violating decay in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Figs.2, 3, and 4 for limits on  $\sigma \cdot B$ .

<sup>4</sup> KHACHATRYAN 16BE search for new particle  $Z'$  with lepton flavor violating decay in  $pp$  collisions at  $\sqrt{s} = 8$  TeV in the range of  $200 \text{ GeV} < M_{Z'} < 2000$  GeV. See their Fig.4 for limits on  $\sigma \cdot B$  and their Table 5 for bounds on various masses.

<sup>5</sup> AAD 15O search for new particle  $Z'$  with lepton flavor violating decay in  $pp$  collisions at  $\sqrt{s} = 8$  TeV in the range of  $500 \text{ GeV} < M_{Z'} < 3000$  GeV. See their Fig. 2 for limits on  $\sigma B$ .

<sup>6</sup> AAD 11H search for new particle  $Z'$  with lepton flavor violating decay in  $pp$  collisions at  $\sqrt{s} = 7$  TeV in the range of  $700 \text{ GeV} < M_{Z'} < 1000$  GeV. See their Fig. 3 for limits on  $\sigma \cdot B$ .

<sup>7</sup> AAD 11Z search for new particle  $Z'$  with lepton flavor violating decay in  $pp$  collisions at  $\sqrt{s} = 7$  TeV in the range  $700 \text{ GeV} < M_{Z'} < 2000$  GeV. See their Fig. 3 for limits on  $\sigma \cdot B$ .

<sup>8</sup> ABULENCIA 06M search for new particle  $Z'$  with lepton flavor violating decay in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV in the range of  $100 \text{ GeV} < M_{Z'} < 800$  GeV. See their Fig. 4 for limits in the mass-coupling plane.

## Indirect Constraints on Kaluza-Klein Gauge Bosons

Bounds on a Kaluza-Klein excitation of the  $Z$  boson or photon in  $d=1$  extra dimension. These bounds can also be interpreted as a lower bound on  $1/R$ , the size of the extra dimension. Unless otherwise stated, bounds assume all fermions live on a single brane and all gauge fields occupy the  $4+d$ -dimensional bulk. See also the section on "Extra Dimensions" in the "Searches" Listings in this Review.

<u>VALUE (TeV)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 4.7		1 MUECK	02 RVUE	Electroweak
> 3.3	95	2 CORNET	00 RVUE	$e\nu q q'$
>5000		3 DELGADO	00 RVUE	$\epsilon_K$
> 2.6	95	4 DELGADO	00 RVUE	Electroweak
> 3.3	95	5 RIZZO	00 RVUE	Electroweak

> 2.9	95	<sup>6</sup> MARCIANO	99	RVUE	Electroweak
> 2.5	95	<sup>7</sup> MASIP	99	RVUE	Electroweak
> 1.6	90	<sup>8</sup> NATH	99	RVUE	Electroweak
> 3.4	95	<sup>9</sup> STRUMIA	99	RVUE	Electroweak

<sup>1</sup> MUECK 02 limit is  $2\sigma$  and is from global electroweak fit ignoring correlations among observables. Higgs is assumed to be confined on the brane and its mass is fixed. For scenarios of bulk Higgs, of brane-SU(2)<sub>L</sub>, bulk-U(1)<sub>Y</sub>, and of bulk-SU(2)<sub>L</sub>, brane-U(1)<sub>Y</sub>, the corresponding limits are  $> 4.6$  TeV,  $> 4.3$  TeV and  $> 3.0$  TeV, respectively.

<sup>2</sup> Bound is derived from limits on  $e\nu qq'$  contact interaction, using data from HERA and the Tevatron.

<sup>3</sup> Bound holds only if first two generations of quarks lives on separate branes. If quark mixing is not complex, then bound lowers to 400 TeV from  $\Delta m_K$ .

<sup>4</sup> See Figs. 1 and 2 of DELGADO 00 for several model variations. Special boundary conditions can be found which permit KK states down to 950 GeV and that agree with the measurement of  $Q_W(Cs)$ . Quoted bound assumes all Higgs bosons confined to brane; placing one Higgs doublet in the bulk lowers bound to 2.3 TeV.

<sup>5</sup> Bound is derived from global electroweak analysis assuming the Higgs field is trapped on the matter brane. If the Higgs propagates in the bulk, the bound increases to 3.8 TeV.

<sup>6</sup> Bound is derived from global electroweak analysis but considering only presence of the KK  $W$  bosons.

<sup>7</sup> Global electroweak analysis used to obtain bound independent of position of Higgs on brane or in bulk.

<sup>8</sup> Bounds from effect of KK states on  $G_F$ ,  $\alpha$ ,  $M_W$ , and  $M_Z$ . Hard cutoff at string scale determined using gauge coupling unification. Limits for  $d=2,3,4$  rise to 3.5, 5.7, and 7.8 TeV.

<sup>9</sup> Bound obtained for Higgs confined to the matter brane with  $m_H=500$  GeV. For Higgs in the bulk, the bound increases to 3.5 TeV.

## See the related review(s): Leptoquarks

### MASS LIMITS for Leptoquarks from Pair Production

These limits rely only on the color or electroweak charge of the leptoquark.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
>1480	95	<sup>1</sup> AAD	21AG ATLS	Scalar LQ. $B(te) = 1$
>1470	95	<sup>2</sup> AAD	21AG ATLS	Scalar LQ. $B(t\mu) = 1$
>1190	95	<sup>3</sup> AAD	21AW ATLS	Scalar LQ. $B(b\tau) = 1$
>1030	95	<sup>4</sup> AAD	21AW ATLS	Scalar LQ. $B(t\tau) = 1$
>1760	95	<sup>5</sup> AAD	21AW ATLS	Vector LQ. $\kappa = 1$ . $B(b\tau) = 1$
>1260	95	<sup>6</sup> AAD	21S ATLS	Scalar LQ. $B(b\nu) = 1$
<b>&gt;1430</b>	95	<sup>7</sup> AAD	21T ATLS	Scalar LQ. $B(t\tau) = 1$
> 950	95	<sup>8</sup> SIRUNYAN	21J CMS	Scalar LQ. $B(t\tau)=B(b\nu)=0.5$
>1650	95	<sup>9</sup> SIRUNYAN	21J CMS	Vector LQ. $\kappa=1$ , $B(t\nu) = B(b\tau) = 0.5$
<b>&gt;1800</b>	95	<sup>10</sup> AAD	20AK ATLS	Scalar LQ. $B(eq) = 1$
<b>&gt;1700</b>	95	<sup>11</sup> AAD	20AK ATLS	Scalar LQ. $B(\mu q) = 1$
>1240	95	<sup>12</sup> AAD	20S ATLS	Scalar LQ. $B(t\nu) = 1$
>1185	95	<sup>13</sup> SIRUNYAN	20A CMS	Scalar LQ. $B(\nu b) = 1$
>1140	95	<sup>14</sup> SIRUNYAN	20A CMS	Scalar LQ. $B(\nu t) = 1$
>1140	95	<sup>15</sup> SIRUNYAN	20A CMS	Scalar LQ. $B(\nu q) = 1$ with $q = u, d, s, c$
>1925	95	<sup>16</sup> SIRUNYAN	20A CMS	Vector LQ. $\kappa = 1$ . $B(\nu b) = 1$
>1825	95	<sup>17</sup> SIRUNYAN	20A CMS	Vector LQ. $\kappa = 1$ . $B(\nu t) = 1$



>1980	95	18	SIRUNYAN	20A	CMS	Vector LQ. $\kappa = 1$ . $B(\nu q) = 1$ with $q = u, d, s, c$
>1400	95	19	AABOUD	19AX	ATLS	Scalar LQ. $B(e q) = 1$
>1560	95	20	AABOUD	19AX	ATLS	Scalar LQ. $B(\mu q) = 1$
>1000	95	21	AABOUD	19X	ATLS	Scalar LQ. $B(t\nu) = 1$
>1030	95	22	AABOUD	19X	ATLS	Scalar LQ. $B(b\tau) = 1$
> 970	95	23	AABOUD	19X	ATLS	Scalar LQ. $B(b\nu) = 1$
> 920	95	24	AABOUD	19X	ATLS	Scalar LQ. $B(t\tau) = 1$
>1530	95	25	SIRUNYAN	19BI	CMS	Scalar LQ. $B(\mu q)+B(\nu q) = 1$
>1435	95	26	SIRUNYAN	19BJ	CMS	Scalar LQ. $B(e q)+B(\nu q) = 1$
>1020	95	27	SIRUNYAN	19Y	CMS	Scalar LQ. $B(\tau b) = 1$
none 300–900	95	28	SIRUNYAN	18CZ	CMS	Scalar LQ. $B(\tau t) = 1$
>1420	95	29	SIRUNYAN	18EC	CMS	Scalar LQ. $B(\mu t) = 1$
>1190	95	30	SIRUNYAN	18EC	CMS	Vector LQ. $\mu t, \tau t, \nu b$
>1100	95	31	SIRUNYAN	18U	CMS	Scalar LQ. $B(\nu b) = 1$
> 980	95	32	SIRUNYAN	18U	CMS	Scalar LQ. $B(\nu q) = 1$ with $q = u, d, s, c$
>1020	95	33	SIRUNYAN	18U	CMS	Scalar LQ. $B(\nu t) = 1$
>1810	95	34	SIRUNYAN	18U	CMS	Vector LQ. $\kappa=1$ . $LQ \rightarrow b\nu$
>1790	95	35	SIRUNYAN	18U	CMS	Vector LQ. $\kappa=1$ . $LQ \rightarrow q\nu$ with $q = u, d, s, c$
>1780	95	36	SIRUNYAN	18U	CMS	Vector LQ. $\kappa=1$ . $LQ \rightarrow t\nu$
> 740	95	37	KHACHATRY...17J		CMS	Scalar LQ. $B(\tau b) = 1$
> 850	95	38	SIRUNYAN	17H	CMS	Scalar LQ. $B(\tau b) = 1$
>1050	95	39	AAD	16G	ATLS	Scalar LQ. $B(e q) = 1$
>1000	95	40	AAD	16G	ATLS	Scalar LQ. $B(\mu q) = 1$
> 625	95	41	AAD	16G	ATLS	Scalar LQ. $B(\nu b) = 1$
none 200–640	95	42	AAD	16G	ATLS	Scalar LQ. $B(\nu t) = 1$
>1010	95	43	KHACHATRY...16AF		CMS	Scalar LQ. $B(e q) = 1$
>1080	95	44	KHACHATRY...16AF		CMS	Scalar LQ. $B(\mu q) = 1$
> 685	95	45	KHACHATRY...15AJ		CMS	Scalar LQ. $B(\tau t) = 1$
> 740	95	46	KHACHATRY...14T		CMS	Scalar LQ. $B(\tau b) = 1$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●						
		47	SIRUNYAN	19BC	CMS	Scalar LQ ( $\rightarrow \mu q$ ) LQ ( $\rightarrow X + DM$ )
> 534	95	48	AAD	13AE	ATLS	Third generation
> 525	95	49	CHATRCHYAN	13M	CMS	Third generation
> 660	95	50	AAD	12H	ATLS	First generation
> 685	95	51	AAD	12O	ATLS	Second generation
> 830	95	52	CHATRCHYAN	12AG	CMS	First generation
> 840	95	53	CHATRCHYAN	12AG	CMS	Second generation
> 450	95	54	CHATRCHYAN	12BO	CMS	Third generation
> 376	95	55	AAD	11D	ATLS	Superseded by AAD 12H
> 422	95	56	AAD	11D	ATLS	Superseded by AAD 12O
> 326	95	57	ABAZOV	11V	D0	First generation
> 339	95	58	CHATRCHYAN	11N	CMS	Superseded by CHA-TRCHYAN 12AG
> 384	95	59	KHACHATRY...11D		CMS	Superseded by CHA-TRCHYAN 12AG
> 394	95	60	KHACHATRY...11E		CMS	Superseded by CHA-TRCHYAN 12AG
> 247	95	61	ABAZOV	10L	D0	Third generation
> 316	95	62	ABAZOV	09	D0	Second generation
> 299	95	63	ABAZOV	09AF	D0	Superseded by ABAZOV 11V

		64	AALTONEN	08P	CDF	Third generation
> 153	95	65	AALTONEN	08Z	CDF	Third generation
> 205	95	66	ABAZOV	08AD	D0	All generations
> 210	95	65	ABAZOV	08AN	D0	Third generation
> 229	95	67	ABAZOV	07J	D0	Superseded by ABAZOV 10L
> 251	95	68	ABAZOV	06A	D0	Superseded by ABAZOV 09
> 136	95	69	ABAZOV	06L	D0	Superseded by ABAZOV 08AD
> 226	95	70	ABULENCIA	06T	CDF	Second generation
> 256	95	71	ABAZOV	05H	D0	First generation
> 117	95	66	ACOSTA	05I	CDF	First generation
> 236	95	72	ACOSTA	05P	CDF	First generation
> 99	95	73	ABBIENDI	03R	OPAL	First generation
> 100	95	73	ABBIENDI	03R	OPAL	Second generation
> 98	95	73	ABBIENDI	03R	OPAL	Third generation
> 98	95	74	ABAZOV	02	D0	All generations
> 225	95	75	ABAZOV	01D	D0	First generation
> 85.8	95	76	ABBIENDI	00M	OPAL	Superseded by ABBIENDI 03R
> 85.5	95	76	ABBIENDI	00M	OPAL	Superseded by ABBIENDI 03R
> 82.7	95	76	ABBIENDI	00M	OPAL	Superseded by ABBIENDI 03R
> 200	95	77	ABBOTT	00C	D0	Second generation
> 123	95	78	AFFOLDER	00K	CDF	Second generation
> 148	95	79	AFFOLDER	00K	CDF	Third generation
> 160	95	80	ABBOTT	99J	D0	Second generation
> 225	95	81	ABBOTT	98E	D0	First generation
> 94	95	82	ABBOTT	98J	D0	Third generation
> 202	95	83	ABE	98S	CDF	Second generation
> 242	95	84	GROSS-PILCH.98			First generation
> 99	95	85	ABE	97F	CDF	Third generation
> 213	95	86	ABE	97X	CDF	First generation
> 45.5	95	87,88	ABREU	93J	DLPH	First + second generation
> 44.4	95	89	ADRIANI	93M	L3	First generation
> 44.5	95	89	ADRIANI	93M	L3	Second generation
> 45	95	89	DECAMP	92	ALEP	Third generation
none 8.9–22.6	95	90	KIM	90	AMY	First generation
none 10.2–23.2	95	90	KIM	90	AMY	Second generation
none 5–20.8	95	91	BARTEL	87B	JADE	
none 7–20.5	95	92	BEHREND	86B	CELL	

<sup>1</sup> AAD 21AG search for scalar leptoquarks decaying to  $t e$ . See their Fig. 6 for exclusion limit on  $B(te)$  as function of  $M_{LQ}$ .

<sup>2</sup> AAD 21AG search for scalar leptoquarks decaying to  $t \mu$ . See their Fig. 6 for exclusion limit on  $B(t\mu)$  as function of  $M_{LQ}$ .

<sup>3</sup> AAD 21AW search for scalar leptoquarks decaying to  $b \tau$ . See their Fig. 9 for exclusion contour in  $B(b\tau) - M_{LQ}$  plane.

<sup>4</sup> AAD 21AW search for scalar leptoquarks decaying to  $t \tau$ . See their Fig. 9 for exclusion contour in  $B(t\tau) - M_{LQ}$  plane.

<sup>5</sup> AAD 21AW search for  $\kappa = 1$  vector leptoquarks decaying to  $b \tau$ . See their Fig. 10 for exclusion contour in  $B(b\tau) - M_{LQ}$  plane and for limit on  $\kappa = 0$  vector leptoquarks.

<sup>6</sup> AAD 21S search for scalar leptoquarks decaying to  $b \nu$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above assumes  $B(b\nu) = 1$ . For  $B(b\nu) = 0.05$ , the limit becomes 400 GeV.

- <sup>7</sup> AAD 21T search for scalar leptoquarks decaying to  $t\tau$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above assumes  $B(t\tau) = 1$ . For  $B(t\tau) = 0.5$ , the limit becomes 1220 GeV. See their Fig. 15b for limits on  $B(t\tau)$  as a function of leptoquark mass.
- <sup>8</sup> SIRUNYAN 21J search for scalar leptoquarks decaying to  $t\tau$  and  $b\nu$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>9</sup> SIRUNYAN 21J search for vector leptoquarks decaying to  $t\nu$  and  $b\tau$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above assumes  $\kappa = 1$ . If we assume  $\kappa = 0$ , the limit becomes  $M_{LQ} > 1290$  GeV.
- <sup>10</sup> AAD 20AK search for scalar leptoquarks decaying to  $eq$ ,  $eb$ ,  $ec$ ,  $\mu q$ ,  $\mu b$ ,  $\mu c$ . The quoted limit assumes  $B(eq) = 1$ . See their Fig. 9 for limits on  $B(eq)$ ,  $B(eb)$ ,  $B(ec)$ ,  $B(\mu q)$ ,  $B(\mu b)$ ,  $B(\mu c)$  as a function of leptoquark mass.
- <sup>11</sup> AAD 20AK search for scalar leptoquarks decaying to  $eq$ ,  $eb$ ,  $ec$ ,  $\mu q$ ,  $\mu b$ ,  $\mu c$ . The quoted limit assumes  $B(\mu q) = 1$ . See their Fig. 9 for limits on  $B(eq)$ ,  $B(eb)$ ,  $B(ec)$ ,  $B(\mu q)$ ,  $B(\mu b)$ ,  $B(\mu c)$  as a function of leptoquark mass.
- <sup>12</sup> AAD 20S search for scalar leptoquarks decaying to  $t\nu$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>13</sup> SIRUNYAN 20A search for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$  ( $q = u, d, s, c$ ). The limit quoted above assumes scalar leptoquark with  $B(\nu b) = 1$ .
- <sup>14</sup> SIRUNYAN 20A search for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$  ( $q = u, d, s, c$ ). The limit quoted above assumes scalar leptoquark with  $B(\nu t) = 1$ .
- <sup>15</sup> SIRUNYAN 20A search for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$  ( $q = u, d, s, c$ ). The limit quoted above assumes scalar leptoquark with  $B(\nu q) = 1$ .
- <sup>16</sup> SIRUNYAN 20A search for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$  ( $q = u, d, s, c$ ). The limit quoted above assumes vector leptoquark with  $B(\nu b) = 1$  and  $\kappa = 1$ . If we assume  $\kappa = 0$ , the limit becomes  $M_{LQ} > 1560$  GeV.
- <sup>17</sup> SIRUNYAN 20A search for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$  ( $q = u, d, s, c$ ). The limit quoted above assumes vector leptoquark with  $B(\nu t) = 1$  and  $\kappa = 1$ . If we assume  $\kappa = 0$ , the limit becomes  $M_{LQ} > 1475$  GeV.
- <sup>18</sup> SIRUNYAN 20A search for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$  ( $q = u, d, s, c$ ). The limit quoted above assumes vector leptoquark with  $B(\nu q) = 1$  and  $\kappa = 1$ . If we assume  $\kappa = 0$ , the limit becomes  $M_{LQ} > 1560$  GeV.
- <sup>19</sup> AABOUD 19AX search for leptoquarks using  $eejj$  events in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above assumes  $B(eq) = 1$ .
- <sup>20</sup> AABOUD 19AX search for leptoquarks using  $\mu\mu jj$  events in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above assumes  $B(\mu q) = 1$ .
- <sup>21</sup> AABOUD 19X search for scalar leptoquarks decaying to  $t\nu$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>22</sup> AABOUD 19X search for scalar leptoquarks decaying to  $b\tau$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>23</sup> AABOUD 19X search for scalar leptoquarks decaying to  $b\nu$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>24</sup> AABOUD 19X search for scalar leptoquarks decaying to  $t\tau$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.
- <sup>25</sup> SIRUNYAN 19BI search for a pair of scalar leptoquarks decaying to  $\mu\mu jj$  and to  $\mu\nu jj$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Limits are shown as a function of  $\beta$  where  $\beta$  is the branching fraction to a muon and a quark. For  $\beta = 1.0$  (0.5) LQ masses up to 1530 (1285) GeV are excluded. See Fig. 9 for exclusion limits in the plane of  $\beta$  and LQ mass.
- <sup>26</sup> SIRUNYAN 19BJ search for a pair of scalar leptoquarks decaying to  $eejj$  and  $e\nu jj$  final states in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. Limits are shown as a function of the branching fraction  $\beta$  to an electron and a quark. For  $\beta = 1.0$  (0.5) LQ masses up to 1435 (1270) GeV are excluded. See Fig. 9 for exclusion limits in the plane of  $\beta$  and LQ mass.
- <sup>27</sup> SIRUNYAN 19Y search for a pair of third generation scalar leptoquarks, each decaying to  $\tau$  and a jet. Assuming  $B(\tau b) = 1$ , leptoquark masses below 1.02 TeV are excluded.
- <sup>28</sup> SIRUNYAN 18CZ search for scalar leptoquarks decaying to  $\tau t$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above assumes  $B(\tau t) = 1$ .

- 29 SIRUNYAN 18EC set limits for scalar and vector leptoquarks decaying to  $\mu t$ ,  $\tau t$ , and  $\nu b$ . The limit quoted above assumes scalar leptoquark with  $B(\mu t) = 1$ .
- 30 SIRUNYAN 18EC set limits for scalar and vector leptoquarks decaying to  $\mu t$ ,  $\tau t$ , and  $\nu b$ . The limit quoted above assumes vector leptoquark with all possible combinations of branching fractions to  $\mu t$ ,  $\tau t$ , and  $\nu b$ .
- 31 SIRUNYAN 18U set limits for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$ . The limit quoted above assumes scalar leptoquark with  $B(b\nu) = 1$ . Vector leptoquarks with  $\kappa = 1$  are excluded below masses of 1810 GeV.
- 32 SIRUNYAN 18U set limits for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$ . The limit quoted above assumes scalar leptoquark with  $B(q\nu) = 1$ . Vector leptoquarks with  $\kappa = 1$  are excluded below masses of 1790 GeV.
- 33 SIRUNYAN 18U set limits for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$ . The limit quoted above assumes scalar leptoquark with  $B(\nu t) = 1$ . Vector leptoquarks with  $\kappa = 1$  are excluded below masses of 1780 GeV.
- 34 SIRUNYAN 18U set limits for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$ .  $\kappa = 1$  and  $LQ \rightarrow b\nu$  are assumed.
- 35 SIRUNYAN 18U set limits for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$ .  $\kappa = 1$  and  $LQ \rightarrow q\nu$  with  $q = u, d, s, c$  are assumed.
- 36 SIRUNYAN 18U set limits for scalar and vector leptoquarks decaying to  $t\nu$ ,  $b\nu$ , and  $q\nu$ .  $\kappa = 1$  and  $LQ \rightarrow t\nu$  are assumed.
- 37 KHACHATRYAN 17J search for scalar leptoquarks decaying to  $\tau b$  using  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above assumes  $B(\tau b) = 1$ .
- 38 SIRUNYAN 17H search for scalar leptoquarks using  $\tau\tau bb$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The limit above assumes  $B(\tau b) = 1$ .
- 39 AAD 16G search for scalar leptoquarks using  $eejj$  events in collisions at  $\sqrt{s} = 8$  TeV. The limit above assumes  $B(eq) = 1$ .
- 40 AAD 16G search for scalar leptoquarks using  $\mu\mu jj$  events in collisions at  $\sqrt{s} = 8$  TeV. The limit above assumes  $B(\mu q) = 1$ .
- 41 AAD 16G search for scalar leptoquarks decaying to  $b\nu$ . The limit above assumes  $B(b\nu) = 1$ .
- 42 AAD 16G search for scalar leptoquarks decaying to  $t\nu$ . The limit above assumes  $B(t\nu) = 1$ .
- 43 KHACHATRYAN 16AF search for scalar leptoquarks using  $eejj$  and  $e\nu jj$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The limit above assumes  $B(eq) = 1$ . For  $B(eq) = 0.5$ , the limit becomes 850 GeV.
- 44 KHACHATRYAN 16AF search for scalar leptoquarks using  $\mu\mu jj$  and  $\mu\nu jj$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The limit above assumes  $B(\mu q) = 1$ . For  $B(\mu q) = 0.5$ , the limit becomes 760 GeV.
- 45 KHACHATRYAN 15AJ search for scalar leptoquarks using  $\tau\tau tt$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The limit above assumes  $B(\tau t) = 1$ .
- 46 KHACHATRYAN 14T search for scalar leptoquarks decaying to  $\tau b$  using  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The limit above assumes  $B(\tau b) = 1$ . See their Fig. 5 for the exclusion limit as function of  $B(\tau b)$ .
- 47 SIRUNYAN 19BC search for scalar leptoquark (LQ) pair production in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. One LQ is assumed to decay to  $\mu q$ , while the other decays to dark matter pair and SM particles. See their Fig. 4 for limits in  $M_{LQ} - M_{DM}$  plane.
- 48 AAD 13AE search for scalar leptoquarks using  $\tau\tau bb$  events in  $pp$  collisions at  $E_{cm} = 7$  TeV. The limit above assumes  $B(\tau b) = 1$ .
- 49 CHATRCHYAN 13M search for scalar and vector leptoquarks decaying to  $\tau b$  in  $pp$  collisions at  $E_{cm} = 7$  TeV. The limit above is for scalar leptoquarks with  $B(\tau b) = 1$ .
- 50 AAD 12H search for scalar leptoquarks using  $eejj$  and  $e\nu jj$  events in  $pp$  collisions at  $E_{cm} = 7$  TeV. The limit above assumes  $B(eq) = 1$ . For  $B(eq) = 0.5$ , the limit becomes 607 GeV.
- 51 AAD 12O search for scalar leptoquarks using  $\mu\mu jj$  and  $\mu\nu jj$  events in  $pp$  collisions at  $E_{cm} = 7$  TeV. The limit above assumes  $B(\mu q) = 1$ . For  $B(\mu q) = 0.5$ , the limit becomes 594 GeV.

- 52 CHATRCHYAN 12AG search for scalar leptoquarks using  $eejj$  and  $e\nu jj$  events in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV. The limit above assumes  $B(eq) = 1$ . For  $B(eq) = 0.5$ , the limit becomes 640 GeV.
- 53 CHATRCHYAN 12AG search for scalar leptoquarks using  $\mu\mu jj$  and  $\mu\nu jj$  events in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV. The limit above assumes  $B(\mu q) = 1$ . For  $B(\mu q) = 0.5$ , the limit becomes 650 GeV.
- 54 CHATRCHYAN 12B0 search for scalar leptoquarks decaying to  $\nu b$  in  $pp$  collisions at  $\sqrt{s} = 7$  TeV. The limit above assumes  $B(\nu b) = 1$ .
- 55 AAD 11D search for scalar leptoquarks using  $eejj$  and  $e\nu jj$  events in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV. The limit above assumes  $B(eq) = 1$ . For  $B(eq) = 0.5$ , the limit becomes 319 GeV.
- 56 AAD 11D search for scalar leptoquarks using  $\mu\mu jj$  and  $\mu\nu jj$  events in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV. The limit above assumes  $B(\mu q) = 1$ . For  $B(\mu q) = 0.5$ , the limit becomes 362 GeV.
- 57 ABAZOV 11V search for scalar leptoquarks using  $e\nu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The limit above assumes  $B(eq) = 0.5$ .
- 58 CHATRCHYAN 11N search for scalar leptoquarks using  $e\nu jj$  events in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV. The limit above assumes  $B(eq) = 0.5$ .
- 59 KHACHATRYAN 11D search for scalar leptoquarks using  $eejj$  events in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV. The limit above assumes  $B(eq) = 1$ .
- 60 KHACHATRYAN 11E search for scalar leptoquarks using  $\mu\mu jj$  events in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV. The limit above assumes  $B(\mu q) = 1$ .
- 61 ABAZOV 10L search for pair productions of scalar leptoquark state decaying to  $\nu b$  in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The limit above assumes  $B(\nu b) = 1$ .
- 62 ABAZOV 09 search for scalar leptoquarks using  $\mu\mu jj$  and  $\mu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The limit above assumes  $B(\mu q) = 1$ . For  $B(\mu q) = 0.5$ , the limit becomes 270 GeV.
- 63 ABAZOV 09AF search for scalar leptoquarks using  $eejj$  and  $e\nu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The limit above assumes  $B(eq) = 1$ . For  $B(eq) = 0.5$  the bound becomes 284 GeV.
- 64 AALTONEN 08P search for vector leptoquarks using  $\tau^+\tau^-b\bar{b}$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. Assuming Yang-Mills (minimal) couplings, the mass limit is  $>317$  GeV (251 GeV) at 95% CL for  $B(\tau b) = 1$ .
- 65 Search for pair production of scalar leptoquark state decaying to  $\tau b$  in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The limit above assumes  $B(\tau b) = 1$ .
- 66 Search for scalar leptoquarks using  $\nu\nu jj$  events in  $\bar{p}p$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The limit above assumes  $B(\nu q) = 1$ .
- 67 ABAZOV 07J search for pair productions of scalar leptoquark state decaying to  $\nu b$  in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The limit above assumes  $B(\nu b) = 1$ .
- 68 ABAZOV 06A search for scalar leptoquarks using  $\mu\mu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.8$  TeV and 1.96 TeV. The limit above assumes  $B(\mu q) = 1$ . For  $B(\mu q) = 0.5$ , the limit becomes 204 GeV.
- 69 ABAZOV 06L search for scalar leptoquarks using  $\nu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.8$  TeV and at 1.96 TeV. The limit above assumes  $B(\nu q) = 1$ .
- 70 ABULENCIA 06T search for scalar leptoquarks using  $\mu\mu jj$ ,  $\mu\nu jj$ , and  $\nu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The quoted limit assumes  $B(\mu q) = 1$ . For  $B(\mu q) = 0.5$  or 0.1, the bound becomes 208 GeV or 143 GeV, respectively. See their Fig. 4 for the exclusion limit as a function of  $B(\mu q)$ .
- 71 ABAZOV 05H search for scalar leptoquarks using  $eejj$  and  $e\nu jj$  events in  $\bar{p}p$  collisions at  $E_{\text{cm}} = 1.8$  TeV and 1.96 TeV. The limit above assumes  $B(eq) = 1$ . For  $B(eq) = 0.5$  the bound becomes 234 GeV.
- 72 ACOSTA 05P search for scalar leptoquarks using  $eejj$ ,  $e\nu jj$  events in  $\bar{p}p$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The limit above assumes  $B(eq) = 1$ . For  $B(eq) = 0.5$  and 0.1, the bound becomes 205 GeV and 145 GeV, respectively.
- 73 ABBIENDI 03R search for scalar/vector leptoquarks in  $e^+e^-$  collisions at  $\sqrt{s} = 189\text{--}209$  GeV. The quoted limits are for charge  $-4/3$  isospin 0 scalar-leptoquark with  $B(\ell q) = 1$ . See their table 12 for other cases.

- 74 ABAZOV 02 search for scalar leptoquarks using  $\nu\nu jj$  events in  $\bar{p}p$  collisions at  $E_{\text{cm}}=1.8$  TeV. The bound holds for all leptoquark generations. Vector leptoquarks are likewise constrained to lie above 200 GeV.
- 75 ABAZOV 01D search for scalar leptoquarks using  $e\nu jj$ ,  $eejj$ , and  $\nu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The limit above assumes  $B(eq)=1$ . For  $B(eq)=0.5$  and 0, the bound becomes 204 and 79 GeV, respectively. Bounds for vector leptoquarks are also given. Supersedes ABBOTT 98E.
- 76 ABBIENDI 00M search for scalar/vector leptoquarks in  $e^+e^-$  collisions at  $\sqrt{s}=183$  GeV. The quoted limits are for charge  $-4/3$  isospin 0 scalar-leptoquarks with  $B(\ell q)=1$ . See their Table 8 and Figs. 6–9 for other cases.
- 77 ABBOTT 00C search for scalar leptoquarks using  $\mu\mu jj$ ,  $\mu\nu jj$ , and  $\nu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The limit above assumes  $B(\mu q)=1$ . For  $B(\mu q)=0.5$  and 0, the bound becomes 180 and 79 GeV respectively. Bounds for vector leptoquarks are also given.
- 78 AFFOLDER 00K search for scalar leptoquark using  $\nu\nu cc$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The quoted limit assumes  $B(\nu c)=1$ . Bounds for vector leptoquarks are also given.
- 79 AFFOLDER 00K search for scalar leptoquark using  $\nu\nu bb$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The quoted limit assumes  $B(\nu b)=1$ . Bounds for vector leptoquarks are also given.
- 80 ABBOTT 99J search for leptoquarks using  $\mu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The quoted limit is for a scalar leptoquark with  $B(\mu q) = B(\nu q) = 0.5$ . Limits on vector leptoquarks range from 240 to 290 GeV.
- 81 ABBOTT 98E search for scalar leptoquarks using  $e\nu jj$ ,  $eejj$ , and  $\nu\nu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The limit above assumes  $B(eq)=1$ . For  $B(eq)=0.5$  and 0, the bound becomes 204 and 79 GeV, respectively.
- 82 ABBOTT 98J search for charge  $-1/3$  third generation scalar and vector leptoquarks in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The quoted limit is for scalar leptoquark with  $B(\nu b)=1$ .
- 83 ABE 98S search for scalar leptoquarks using  $\mu\mu jj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The limit is for  $B(\mu q)=1$ . For  $B(\mu q)=B(\nu q)=0.5$ , the limit is  $> 160$  GeV.
- 84 GROSS-PILCHER 98 is the combined limit of the CDF and DØ Collaborations as determined by a joint CDF/DØ working group and reported in this FNAL Technical Memo. Original data published in ABE 97X and ABBOTT 98E.
- 85 ABE 97F search for third generation scalar and vector leptoquarks in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The quoted limit is for scalar leptoquark with  $B(\tau b) = 1$ .
- 86 ABE 97X search for scalar leptoquarks using  $eejj$  events in  $p\bar{p}$  collisions at  $E_{\text{cm}}=1.8$  TeV. The limit is for  $B(eq)=1$ .
- 87 Limit is for charge  $-1/3$  isospin-0 leptoquark with  $B(\ell q) = 2/3$ .
- 88 First and second generation leptoquarks are assumed to be degenerate. The limit is slightly lower for each generation.
- 89 Limits are for charge  $-1/3$ , isospin-0 scalar leptoquarks decaying to  $\ell^- q$  or  $\nu q$  with any branching ratio. See paper for limits for other charge-isospin assignments of leptoquarks.
- 90 KIM 90 assume pair production of charge  $2/3$  scalar-leptoquark via photon exchange. The decay of the first (second) generation leptoquark is assumed to be any mixture of  $d e^+$  and  $u \bar{\nu}$  ( $s \mu^+$  and  $c \bar{\nu}$ ). See paper for limits for specific branching ratios.
- 91 BARTEL 87B limit is valid when a pair of charge  $2/3$  spinless leptoquarks  $X$  is produced with point coupling, and when they decay under the constraint  $B(X \rightarrow c \bar{\nu}_\mu) + B(X \rightarrow s \mu^+) = 1$ .
- 92 BEHREND 86B assumed that a charge  $2/3$  spinless leptoquark,  $\chi$ , decays either into  $s \mu^+$  or  $c \bar{\nu}$ :  $B(\chi \rightarrow s \mu^+) + B(\chi \rightarrow c \bar{\nu}) = 1$ .
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## MASS LIMITS for Leptoquarks from Single Production

These limits depend on the  $q$ - $\ell$ -leptoquark coupling  $g_{LQ}$ . It is often assumed that  $g_{LQ}^2/4\pi=1/137$ . Limits shown are for a scalar, weak isoscalar, charge  $-1/3$  leptoquark.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
> 550	95	<sup>1</sup> SIRUNYAN 21J	CMS	Third generation
<b>none 150–740</b>	95	<sup>2</sup> SIRUNYAN 18BJ	CMS	Third generation
<b>&gt;1755</b>	95	<sup>3</sup> KHACHATRYAN 16AG	CMS	First generation
<b>&gt; 660</b>	95	<sup>4</sup> KHACHATRYAN 16AG	CMS	Second generation
> 304	95	<sup>5</sup> ABRAMOWICZ 12A	ZEUS	First generation
> 73	95	<sup>6</sup> ABREU 93J	DLPH	Second generation
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		<sup>7</sup> TUMASYAN 21D	CMS	First generation
		<sup>8</sup> DEY 16	ICCB	$\nu q \rightarrow LQ \rightarrow \nu q$
		<sup>9</sup> AARON 11A	H1	Lepton-flavor violation
> 300	95	<sup>10</sup> AARON 11B	H1	First generation
		<sup>11</sup> ABAZOV 07E	D0	Second generation
> 295	95	<sup>12</sup> AKTAS 05B	H1	First generation
		<sup>13</sup> CHEKANOV 05A	ZEUS	Lepton-flavor violation
> 298	95	<sup>14</sup> CHEKANOV 03B	ZEUS	First generation
> 197	95	<sup>15</sup> ABBIENDI 02B	OPAL	First generation
		<sup>16</sup> CHEKANOV 02	ZEUS	Repl. by CHEKANOV 05A
> 290	95	<sup>17</sup> ADLOFF 01C	H1	First generation
> 204	95	<sup>18</sup> BREITWEG 01	ZEUS	First generation
		<sup>19</sup> BREITWEG 00E	ZEUS	First generation
> 161	95	<sup>20</sup> ABREU 99G	DLPH	First generation
> 200	95	<sup>21</sup> ADLOFF 99	H1	First generation
		<sup>22</sup> DERRICK 97	ZEUS	Lepton-flavor violation
> 168	95	<sup>23</sup> DERRICK 93	ZEUS	First generation

<sup>1</sup> SIRUNYAN 21J search for single production of charge  $-1/3$  scalar leptoquarks decaying to  $t\tau^-$  and  $b\nu$ , and charge  $2/3$  vector leptoquarks decaying to  $t\nu$  and  $b\tau^+$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit quoted above assumes a scalar leptoquark with  $B(t\tau) = B(b\nu) = 0.5$  and the leptoquark coupling strength  $\lambda = 1.5$ . The limit becomes  $M_{LQ} > 750$  GeV for  $\lambda = 2.5$ .

<sup>2</sup> SIRUNYAN 18BJ search for single production of charge  $2/3$  scalar leptoquarks decaying to  $\tau b$  in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above assumes  $B(\tau b) = 1$  and the leptoquark coupling strength  $\lambda = 1$ .

<sup>3</sup> KHACHATRYAN 16AG search for single production of charge  $\pm 1/3$  scalar leptoquarks using  $eej$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The limit above assumes  $B(eq) = 1$  and the leptoquark coupling strength  $\lambda = 1$ .

<sup>4</sup> KHACHATRYAN 16AG search for single production of charge  $\pm 1/3$  scalar leptoquarks using  $\mu\mu j$  events in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The limit above assumes  $B(\mu q) = 1$  and the leptoquark coupling strength  $\lambda = 1$ .

<sup>5</sup> ABRAMOWICZ 12A limit is for a scalar, weak isoscalar, charge  $-1/3$  leptoquark coupled with  $eP$ . See their Figs. 12–17 and Table 4 for states with different quantum numbers.

<sup>6</sup> Limit from single production in  $Z$  decay. The limit is for a leptoquark coupling of electromagnetic strength and assumes  $B(\ell q) = 2/3$ . The limit is 77 GeV if first and second leptoquarks are degenerate.

<sup>7</sup> TUMASYAN 21D search for energetic jets +  $\cancel{E}_T$  events in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The branching fraction for the decay of the leptoquark into an electron neutrino and up quark is assumed to be 100% ( $\beta = 0$ ). See their Fig. 12 for exclusion limits in mass-coupling plane.

- <sup>8</sup> DEY 16 use the 2010-2012 IceCube PeV energy data set to constrain the leptoquark production cross section through the  $\nu q \rightarrow LQ \rightarrow \nu q$  process. See their Figure 4 for the exclusion limit in the mass-coupling plane.
- <sup>9</sup> AARON 11A search for various leptoquarks with lepton-flavor violating couplings. See their Figs. 2–3 and Tables 1–4 for detailed limits.
- <sup>10</sup> The quoted limit is for a scalar, weak isoscalar, charge  $-1/3$  leptoquark coupled with  $e_R$ . See their Figs. 3–5 for limits on states with different quantum numbers.
- <sup>11</sup> ABAZOV 07E search for leptoquark single production through  $qg$  fusion process in  $p\bar{p}$  collisions. See their Fig. 4 for exclusion plot in mass-coupling plane.
- <sup>12</sup> AKTAS 05B limit is for a scalar, weak isoscalar, charge  $-1/3$  leptoquark coupled with  $e_R$ . See their Fig. 3 for limits on states with different quantum numbers.
- <sup>13</sup> CHEKANOV 05 search for various leptoquarks with lepton-flavor violating couplings. See their Figs. 6–10 and Tables 1–8 for detailed limits.
- <sup>14</sup> CHEKANOV 03B limit is for a scalar, weak isoscalar, charge  $-1/3$  leptoquark coupled with  $e_R$ . See their Figs. 11–12 and Table 5 for limits on states with different quantum numbers.
- <sup>15</sup> For limits on states with different quantum numbers and the limits in the mass-coupling plane, see their Fig. 4 and Fig. 5.
- <sup>16</sup> CHEKANOV 02 search for various leptoquarks with lepton-flavor violating couplings. See their Figs. 6–7 and Tables 5–6 for detailed limits.
- <sup>17</sup> For limits on states with different quantum numbers and the limits in the mass-coupling plane, see their Fig. 3.
- <sup>18</sup> See their Fig. 14 for limits in the mass-coupling plane.
- <sup>19</sup> BREITWEG 00E search for  $F=0$  leptoquarks in  $e^+p$  collisions. For limits in mass-coupling plane, see their Fig. 11.
- <sup>20</sup> ABREU 99G limit obtained from process  $e\gamma \rightarrow LQ+q$ . For limits on vector and scalar states with different quantum numbers and the limits in the coupling-mass plane, see their Fig. 4 and Table 2.
- <sup>21</sup> For limits on states with different quantum numbers and the limits in the mass-coupling plane, see their Fig. 13 and Fig. 14. ADLOFF 99 also search for leptoquarks with lepton-flavor violating couplings. ADLOFF 99 supersedes AID 96B.
- <sup>22</sup> DERRICK 97 search for various leptoquarks with lepton-flavor violating couplings. See their Figs. 5–8 and Table 1 for detailed limits.
- <sup>23</sup> DERRICK 93 search for single leptoquark production in  $ep$  collisions with the decay  $eq$  and  $\nu q$ . The limit is for leptoquark coupling of electromagnetic strength and assumes  $B(eq) = B(\nu q) = 1/2$ . The limit for  $B(eq) = 1$  is 176 GeV. For limits on states with different quantum numbers, see their Table 3.

### Indirect Limits for Leptoquarks

<u>VALUE (TeV)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
> 3.1	95	<sup>1</sup> CRIVELLIN 21A	RVUE	First generation
		<sup>2</sup> AEBISCHER 20	RVUE	$B$ decays
		<sup>3</sup> DEPPISCH 20	RVUE	$K \rightarrow \pi\nu\nu$
		<sup>4</sup> ABRAMOWICZ19	ZEUS	First generation
		<sup>5</sup> MANDAL 19	RVUE	$\tau, \mu, e, K$
		<sup>6</sup> ZHANG 18A	RVUE	$D$ decays
		<sup>7</sup> BARRANCO 16	RVUE	$D$ decays
> 14	95	<sup>8</sup> KUMAR 16	RVUE	neutral $K$ mixing, rare $K$ decays
		<sup>9</sup> BESSAA 15	RVUE	$q\bar{q} \rightarrow e^+e^-$
		<sup>10</sup> SAHOO 15A	RVUE	$B_{s,d} \rightarrow \mu^+\mu^-$
		<sup>11</sup> SAKAKI 13	RVUE	$B \rightarrow D^{(*)}\tau\bar{\nu}, B \rightarrow X_S\nu\bar{\nu}$
		<sup>12</sup> KOSNIK 12	RVUE	$b \rightarrow s\ell^+\ell^-$



>	2.5	95	13 AARON	11C	H1	First generation
			14 DORSNER	11	RVUE	scalar, weak singlet, charge 4/3
			15 AKTAS	07A	H1	Lepton-flavor violation
>	0.49	95	16 SCHAEEL	07A	ALEP	$e^+e^- \rightarrow q\bar{q}$
			17 SMIRNOV	07	RVUE	$K \rightarrow e\mu, B \rightarrow e\tau$
			18 CHEKANOV	05A	ZEUS	Lepton-flavor violation
>	1.7	96	19 ADLOFF	03	H1	First generation
>	46	90	20 CHANG	03	BELL	Pati-Salam type
			21 CHEKANOV	02	ZEUS	Repl. by CHEKANOV 05A
>	1.7	95	22 CHEUNG	01B	RVUE	First generation
>	0.39	95	23 ACCIARRI	00P	L3	$e^+e^- \rightarrow q\bar{q}$
>	1.5	95	24 ADLOFF	00	H1	First generation
>	0.2	95	25 BARATE	00i	ALEP	Repl. by SCHAEEL 07A
			26 BARGER	00	RVUE	Cs
			27 GABRIELLI	00	RVUE	Lepton flavor violation
>	0.74	95	28 ZARNECKI	00	RVUE	$S_1$ leptoquark
			29 ABBIENDI	99	OPAL	
>	19.3	95	30 ABE	98V	CDF	$B_s \rightarrow e^\pm \mu^\mp$ , Pati-Salam type
			31 ACCIARRI	98J	L3	$e^+e^- \rightarrow q\bar{q}$
			32 ACKERSTAFF	98V	OPAL	$e^+e^- \rightarrow q\bar{q}, e^+e^- \rightarrow b\bar{b}$
>	0.76	95	33 DEANDREA	97	RVUE	$\tilde{R}_2$ leptoquark
			34 DERRICK	97	ZEUS	Lepton-flavor violation
			35 GROSSMAN	97	RVUE	$B \rightarrow \tau^+\tau^- (X)$
			36 JADACH	97	RVUE	$e^+e^- \rightarrow q\bar{q}$
>1200			37 KUZNETSOV	95B	RVUE	Pati-Salam type
			38 MIZUKOSHI	95	RVUE	Third generation scalar leptoquark
>	0.3	95	39 BHATTACH...	94	RVUE	Spin-0 leptoquark coupled to $\bar{e}_R t_L$
			40 DAVIDSON	94	RVUE	
>	18		41 KUZNETSOV	94	RVUE	Pati-Salam type
>	0.43	95	42 LEURER	94	RVUE	First generation spin-1 leptoquark
>	0.44	95	42 LEURER	94B	RVUE	First generation spin-0 leptoquark
			43 MAHANTA	94	RVUE	$P$ and $T$ violation
>	1		44 SHANKER	82	RVUE	Nonchiral spin-0 leptoquark
>	125		44 SHANKER	82	RVUE	Nonchiral spin-1 leptoquark

<sup>1</sup> CRIVELLIN 21A set limits on coupling strengths of scalar and vector leptoquarks using  $K \rightarrow \pi\nu\nu, K \rightarrow \pi e^+e^-, K^0 - \bar{K}^0$  and  $D^0 - \bar{D}^0$  mixings, and weak neutral current measurements. See their Fig. 2 and Fig. 3 for the limits in mass-coupling plane.

<sup>2</sup> AEBISCHER 20 explain the  $B$  decay anomalies using four-fermion operator Wilson coefficients. See their Table 1. These Wilson coefficients may be generated by a  $U_1$  vector leptoquark with  $U_1$  transforming as  $(3,1)_{2/3}$  under the SM gauge group. See their Figures 6, 7, 8 for the regions of the LQ parameter space which explains the  $B$  anomalies and avoids the indirect low energy constraints.

<sup>3</sup> DEPPISCH 20 limits on the lepton-number-violating higher-dimensional-operators are derived from  $K \rightarrow \pi\nu\nu$  in the standard model effective field theory. These higher-dimensional-operators may be induced from leptoquark-exchange diagrams.

<sup>4</sup> ABRAMOWICZ 19 obtain a limit on  $\lambda/M_{LQ} > 1.16 \text{ TeV}^{-1}$  for weak isotriplet spin-0 leptoquark  $S_1^L$ . We obtain the limit quoted above by converting the limit on  $\lambda/M_{LQ}$  for  $S_1^L$  assuming  $\lambda = \sqrt{4\pi}$ . See their Table 5 for the limits of leptoquarks with different quantum numbers. These limits are derived from bounds of  $e q$  contact interactions.

<sup>5</sup> MANDAL 19 give bounds on leptoquarks from  $\tau$ -decays, leptonic dipole moments, lepton-flavor-violating processes, and  $K$  decays.

- <sup>6</sup> ZHANG 18A give bounds on leptoquark induced four-fermion interactions from  $D \rightarrow K\ell\nu$ . The authors inform us that the shape parameter of the vector form factor in both the abstract and the conclusions of ZHANG 18A should be  $r_{+1} = 2.16 \pm 0.07$  rather than  $\pm 0.007$ . The numbers listed in their Table 7 are correct.
- <sup>7</sup> BARRANCO 16 give bounds on leptoquark induced four-fermion interactions from  $D \rightarrow K\ell\nu$  and  $D_S \rightarrow \ell\nu$ .
- <sup>8</sup> KUMAR 16 gives bound on SU(2) singlet scalar leptoquark with charge  $-1/3$  from  $K^0 - \bar{K}^0$  mixing,  $K \rightarrow \pi\nu\bar{\nu}$ ,  $K_L^0 \rightarrow \mu^+\mu^-$ , and  $K_L^0 \rightarrow \mu^\pm e^\mp$  decays.
- <sup>9</sup> BESSAA 15 obtain limit on leptoquark induced four-fermion interactions from the ATLAS and CMS limit on the  $\bar{q}q\bar{e}e$  contact interactions.
- <sup>10</sup> SAHOO 15A obtain limit on leptoquark induced four-fermion interactions from  $B_{s,d} \rightarrow \mu^+\mu^-$  for  $\lambda \simeq O(1)$ .
- <sup>11</sup> SAKAKI 13 explain the  $B \rightarrow D^{(*)}\tau\bar{\nu}$  anomaly using Wilson coefficients of leptoquark-induced four-fermion operators.
- <sup>12</sup> KOSNIK 12 obtains limits on leptoquark induced four-fermion interactions from  $b \rightarrow s\ell^+\ell^-$  decays.
- <sup>13</sup> AARON 11C limit is for weak isotriplet spin-0 leptoquark at strong coupling  $\lambda = \sqrt{4\pi}$ . For the limits of leptoquarks with different quantum numbers, see their Table 3. Limits are derived from bounds of  $eq$  contact interactions.
- <sup>14</sup> DORSNER 11 give bounds on scalar, weak singlet, charge  $4/3$  leptoquark from  $K$ ,  $B$ ,  $\tau$  decays, meson mixings,  $LFV$ ,  $g-2$  and  $Z \rightarrow b\bar{b}$ .
- <sup>15</sup> AKTAS 07A search for lepton-flavor violation in  $ep$  collision. See their Tables 4–7 for limits on lepton-flavor violating four-fermion interactions induced by various leptoquarks.
- <sup>16</sup> SCHAEEL 07A limit is for the weak-isoscalar spin-0 left-handed leptoquark with the coupling of electromagnetic strength. For the limits of leptoquarks with different quantum numbers, see their Table 35.
- <sup>17</sup> SMIRNOV 07 obtains mass limits for the vector and scalar chiral leptoquark states from  $K \rightarrow e\mu$ ,  $B \rightarrow e\tau$  decays.
- <sup>18</sup> CHEKANOV 05 search for various leptoquarks with lepton-flavor violating couplings. See their Figs.6–10 and Tables 1–8 for detailed limits.
- <sup>19</sup> ADLOFF 03 limit is for the weak isotriplet spin-0 leptoquark at strong coupling  $\lambda = \sqrt{4\pi}$ . For the limits of leptoquarks with different quantum numbers, see their Table 3. Limits are derived from bounds on  $e^\pm q$  contact interactions.
- <sup>20</sup> The bound is derived from  $B(B^0 \rightarrow e^\pm\mu^\mp) < 1.7 \times 10^{-7}$ .
- <sup>21</sup> CHEKANOV 02 search for lepton-flavor violation in  $ep$  collisions. See their Tables 1–4 for limits on lepton-flavor violating and four-fermion interactions induced by various leptoquarks.
- <sup>22</sup> CHEUNG 01B quoted limit is for a scalar, weak isoscalar, charge  $-1/3$  leptoquark with a coupling of electromagnetic strength. The limit is derived from bounds on contact interactions in a global electroweak analysis. For the limits of leptoquarks with different quantum numbers, see Table 5.
- <sup>23</sup> ACCIARRI 00P limit is for the weak isoscalar spin-0 leptoquark with the coupling of electromagnetic strength. For the limits of leptoquarks with different quantum numbers, see their Table 4.
- <sup>24</sup> ADLOFF 00 limit is for the weak isotriplet spin-0 leptoquark at strong coupling,  $\lambda = \sqrt{4\pi}$ . For the limits of leptoquarks with different quantum numbers, see their Table 2. ADLOFF 00 limits are from the  $Q^2$  spectrum measurement of  $e^+p \rightarrow e^+X$ .
- <sup>25</sup> BARATE 00I search for deviations in cross section and jet-charge asymmetry in  $e^+e^- \rightarrow \bar{q}q$  due to  $t$ -channel exchange of a leptoquark at  $\sqrt{s} = 130$  to  $183$  GeV. Limits for other scalar and vector leptoquarks are also given in their Table 22.
- <sup>26</sup> BARGER 00 explain the deviation of atomic parity violation in cesium atoms from prediction is explained by scalar leptoquark exchange.
- <sup>27</sup> GABRIELLI 00 calculate various process with lepton flavor violation in leptoquark models.

- <sup>28</sup> ZARNECKI 00 limit is derived from data of HERA, LEP, and Tevatron and from various low-energy data including atomic parity violation. Leptoquark coupling with electromagnetic strength is assumed.
- <sup>29</sup> ABBIENDI 99 limits are from  $e^+e^- \rightarrow q\bar{q}$  cross section at 130–136, 161–172, 183 GeV. See their Fig. 8 and Fig. 9 for limits in mass-coupling plane.
- <sup>30</sup> ABE 98V quoted limit is from  $B(B_s \rightarrow e^\pm\mu^\mp) < 8.2 \times 10^{-6}$ . ABE 98V also obtain a similar limit on  $M_{LQ} > 20.4$  TeV from  $B(B_d \rightarrow e^\pm\mu^\mp) < 4.5 \times 10^{-6}$ . Both bounds assume the non-canonical association of the  $b$  quark with electrons or muons under SU(4).
- <sup>31</sup> ACCIARRI 98J limit is from  $e^+e^- \rightarrow q\bar{q}$  cross section at  $\sqrt{s}=130$ –172 GeV which can be affected by the  $t$ - and  $u$ -channel exchanges of leptoquarks. See their Fig. 4 and Fig. 5 for limits in the mass-coupling plane.
- <sup>32</sup> ACKERSTAFF 98V limits are from  $e^+e^- \rightarrow q\bar{q}$  and  $e^+e^- \rightarrow b\bar{b}$  cross sections at  $\sqrt{s}=130$ –172 GeV, which can be affected by the  $t$ - and  $u$ -channel exchanges of leptoquarks. See their Fig. 21 and Fig. 22 for limits of leptoquarks in mass-coupling plane.
- <sup>33</sup> DEANDREA 97 limit is for  $\tilde{R}_2$  leptoquark obtained from atomic parity violation (APV). The coupling of leptoquark is assumed to be electromagnetic strength. See Table 2 for limits of the four-fermion interactions induced by various scalar leptoquark exchange. DEANDREA 97 combines APV limit and limits from Tevatron and HERA. See Fig. 1–4 for combined limits of leptoquark in mass-coupling plane.
- <sup>34</sup> DERRICK 97 search for lepton-flavor violation in  $e p$  collision. See their Tables 2–5 for limits on lepton-flavor violating four-fermion interactions induced by various leptoquarks.
- <sup>35</sup> GROSSMAN 97 estimate the upper bounds on the branching fraction  $B \rightarrow \tau^+\tau^- (X)$  from the absence of the  $B$  decay with large missing energy. These bounds can be used to constrain leptoquark induced four-fermion interactions.
- <sup>36</sup> JADACH 97 limit is from  $e^+e^- \rightarrow q\bar{q}$  cross section at  $\sqrt{s}=172.3$  GeV which can be affected by the  $t$ - and  $u$ -channel exchanges of leptoquarks. See their Fig. 1 for limits on vector leptoquarks in mass-coupling plane.
- <sup>37</sup> KUZNETSOV 95B use  $\pi$ ,  $K$ ,  $B$ ,  $\tau$  decays and  $\mu e$  conversion and give a list of bounds on the leptoquark mass and the fermion mixing matrix in the Pati-Salam model. The quoted limit is from  $K_L \rightarrow \mu e$  decay assuming zero mixing.
- <sup>38</sup> MIZUKOSHI 95 calculate the one-loop radiative correction to the  $Z$ -physics parameters in various scalar leptoquark models. See their Fig. 4 for the exclusion plot of third generation leptoquark models in mass-coupling plane.
- <sup>39</sup> BHATTACHARYYA 94 limit is from one-loop radiative correction to the leptonic decay width of the  $Z$ .  $m_H=250$  GeV,  $\alpha_s(m_Z)=0.12$ ,  $m_t=180$  GeV, and the electroweak strength of leptoquark coupling are assumed. For leptoquark coupled to  $\bar{e}_L t_R$ ,  $\bar{\mu} t$ , and  $\bar{\tau} t$ , see Fig. 2 in BHATTACHARYYA 94B erratum and Fig. 3.
- <sup>40</sup> DAVIDSON 94 gives an extensive list of the bounds on leptoquark-induced four-fermion interactions from  $\pi$ ,  $K$ ,  $D$ ,  $B$ ,  $\mu$ ,  $\tau$  decays and meson mixings, *etc.* See Table 15 of DAVIDSON 94 for detail.
- <sup>41</sup> KUZNETSOV 94 gives mixing independent bound of the Pati-Salam leptoquark from the cosmological limit on  $\pi^0 \rightarrow \bar{\nu}\nu$ .
- <sup>42</sup> LEURER 94, LEURER 94B limits are obtained from atomic parity violation and apply to any chiral leptoquark which couples to the first generation with electromagnetic strength. For a nonchiral leptoquark, universality in  $\pi_{\ell 2}$  decay provides a much more stringent bound.
- <sup>43</sup> MAHANTA 94 gives bounds of  $P$ - and  $T$ -violating scalar-leptoquark couplings from atomic and molecular experiments.
- <sup>44</sup> From  $(\pi \rightarrow e\nu)/(\pi \rightarrow \mu\nu)$  ratio. SHANKER 82 assumes the leptoquark induced four-fermion coupling  $4g^2/M^2 (\bar{\nu}_{eL} u_R) (\bar{d}_L e_R)$  with  $g=0.004$  for spin-0 leptoquark and  $g^2/M^2 (\bar{\nu}_{eL} \gamma_\mu u_L) (\bar{d}_R \gamma^\mu e_R)$  with  $g \simeq 0.6$  for spin-1 leptoquark.

**MASS LIMITS for Diquarks**

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;7200 (CL = 95%) OUR LIMIT</b>				
<b>none 600–7200</b>	95	<sup>1</sup> SIRUNYAN 18BO	CMS	$E_6$ diquark
none 600–6900	95	<sup>2</sup> KHACHATRYAN 17W	CMS	$E_6$ diquark
none 1500–6000	95	<sup>3</sup> KHACHATRYAN 16K	CMS	$E_6$ diquark
none 500–1600	95	<sup>4</sup> KHACHATRYAN 16L	CMS	$E_6$ diquark
none 1200–4700	95	<sup>5</sup> KHACHATRYAN 15V	CMS	$E_6$ diquark
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
>3750	95	<sup>6</sup> CHATRCHYAN 13A	CMS	$E_6$ diquark
none 1000–4280	95	<sup>7</sup> CHATRCHYAN 13AS	CMS	Superseded by KHACHATRYAN 15V
>3520	95	<sup>8</sup> CHATRCHYAN 11Y	CMS	Superseded by CHATRCHYAN 13A
none 970–1080, 1450–1600	95	<sup>9</sup> KHACHATRYAN 10	CMS	Superseded by CHATRCHYAN 13A
none 290–630	95	<sup>10</sup> AALTONEN 09AC	CDF	$E_6$ diquark
none 290–420	95	<sup>11</sup> ABE 97G	CDF	$E_6$ diquark
none 15–31.7	95	<sup>12</sup> ABREU 940	DLPH	SUSY $E_6$ diquark

<sup>1</sup> SIRUNYAN 18BO search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>2</sup> KHACHATRYAN 17W search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>3</sup> KHACHATRYAN 16K search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>4</sup> KHACHATRYAN 16L search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the data scouting technique, increasing the sensitivity to the low mass resonances.

<sup>5</sup> KHACHATRYAN 15V search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.

<sup>6</sup> CHATRCHYAN 13A search for new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.

<sup>7</sup> CHATRCHYAN 13AS search for new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.

<sup>8</sup> CHATRCHYAN 11Y search for new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.

<sup>9</sup> KHACHATRYAN 10 search for new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.

<sup>10</sup> AALTONEN 09AC search for new narrow resonance decaying to dijets.

<sup>11</sup> ABE 97G search for new particle decaying to dijets.

<sup>12</sup> ABREU 940 limit is from  $e^+ e^- \rightarrow \bar{c} \bar{s} c s$ . Range extends up to 43 GeV if diquarks are degenerate in mass.

**MASS LIMITS for  $g_A$  (axigluon) and Other Color-Octet Gauge Bosons**

Axigluons are massive color-octet gauge bosons in chiral color models and have axial-vector coupling to quarks with the same coupling strength as gluons.

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
<b>&gt;6600 (CL = 95%) OUR LIMIT</b>				
<b>none 1800–6600</b>	95	<sup>1</sup> SIRUNYAN 20AI	CMS	$pp \rightarrow g_A X, g_A \rightarrow 2j$
none 600–6100	95	<sup>2</sup> SIRUNYAN 18BO	CMS	$pp \rightarrow g_A X, g_A \rightarrow 2j$
none 600–5500	95	<sup>3</sup> KHACHATRYAN 17W	CMS	$pp \rightarrow g_A X, g_A \rightarrow 2j$
none 1500–5100	95	<sup>4</sup> KHACHATRYAN 16K	CMS	$pp \rightarrow g_A X, g_A \rightarrow 2j$
none 500–1600	95	<sup>5</sup> KHACHATRYAN 16L	CMS	$pp \rightarrow g_A X, g_A \rightarrow 2j$
none 1300–3600	95	<sup>6</sup> KHACHATRYAN 15V	CMS	$pp \rightarrow g_A X, g_A \rightarrow 2j$

• • • We do not use the following data for averages, fits, limits, etc. • • •

		7	KHACHATRYAN...17Y	CMS	$pp \rightarrow g_A g_A \rightarrow 8j$
		8	AAD	16W ATLS	$pp \rightarrow g_A X, g_A \rightarrow b\bar{b}b\bar{b}$
>2800	95	9	KHACHATRYAN...16E	CMS	$pp \rightarrow g_{KK} X, g_{KK} \rightarrow t\bar{t}$
		10	KHACHATRYAN...15AV	CMS	$pp \rightarrow \Theta^0 \Theta^0 \rightarrow b\bar{b}Zg$
		11	AALTONEN	13R CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow \sigma\sigma, \sigma \rightarrow 2j$
>3360	95	12	CHATRCHYAN 13A	CMS	$pp \rightarrow g_A X, g_A \rightarrow 2j$
none 1000–3270	95	13	CHATRCHYAN 13AS	CMS	Superseded by KHACHATRYAN 15V
none 250–740	95	14	CHATRCHYAN 13AU	CMS	$pp \rightarrow 2g_A X, g_A \rightarrow 2j$
> 775	95	15	ABAZOV	12R D0	$p\bar{p} \rightarrow g_A X, g_A \rightarrow t\bar{t}$
>2470	95	16	CHATRCHYAN 11Y	CMS	Superseded by CHATRCHYAN 13A
		17	AALTONEN	10L CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow t\bar{t}$
none 1470–1520	95	18	KHACHATRYAN...10	CMS	Superseded by CHATRCHYAN 13A
none 260–1250	95	19	AALTONEN	09AC CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow 2j$
> 910	95	20	CHOUDHURY 07	RVUE	$p\bar{p} \rightarrow t\bar{t}X$
> 365	95	21	DONCHESKI	98 RVUE	$\Gamma(Z \rightarrow \text{hadron})$
none 200–980	95	22	ABE	97G CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow 2j$
none 200–870	95	23	ABE	95N CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow q\bar{q}$
none 240–640	95	24	ABE	93G CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow 2j$
> 50	95	25	CUYPERS	91 RVUE	$\sigma(e^+e^- \rightarrow \text{hadrons})$
none 120–210	95	26	ABE	90H CDF	$p\bar{p} \rightarrow g_A X, g_A \rightarrow 2j$
> 29		27	ROBINETT	89 THEO	Partial-wave unitarity
none 150–310	95	28	ALBAJAR	88B UA1	$p\bar{p} \rightarrow g_A X, g_A \rightarrow 2j$
> 20			BERGSTROM	88 RVUE	$p\bar{p} \rightarrow \gamma X$ via $g_A g$
> 9		29	CUYPERS	88 RVUE	$\gamma$ decay
> 25		30	DONCHESKI	88B RVUE	$\gamma$ decay

<sup>1</sup> SIRUNYAN 20AI search for resonances decaying into dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>2</sup> SIRUNYAN 18B0 search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>3</sup> KHACHATRYAN 17W search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>4</sup> KHACHATRYAN 16K search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV.

<sup>5</sup> KHACHATRYAN 16L search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the data scouting technique, increasing the sensitivity to the low mass resonances.

<sup>6</sup> KHACHATRYAN 15V search for resonances decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.

<sup>7</sup> KHACHATRYAN 17Y search for pair production of color-octet gauge boson  $g_A$  each decaying to  $4j$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.

<sup>8</sup> AAD 16W search for a new resonance decaying to a pair of  $b$  and  $B_H$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The vector-like quark  $B_H$  is assumed to decay to  $bH$ . See their Fig. 3 and Fig. 4 for limits on  $\sigma \cdot B$ .

<sup>9</sup> KHACHATRYAN 16E search for KK gluon decaying to  $t\bar{t}$  in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.

<sup>10</sup> KHACHATRYAN 15AV search for pair productions of neutral color-octet weak-triplet scalar particles ( $\Theta^0$ ), decaying to  $b\bar{b}$ ,  $Zg$  or  $\gamma g$ , in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The  $\Theta^0$  particle is often predicted in coloron ( $G^I$ , color-octet gauge boson) models and appear

- in the  $pp$  collisions through  $G' \rightarrow \Theta^0 \Theta^0$  decays. Assuming  $B(\Theta^0 \rightarrow b\bar{b}) = 0.5$ , they give limits  $m_{\Theta^0} > 623$  GeV (426 GeV) for  $m_{G'} = 2.3 m_{\Theta^0}$  ( $m_{G'} = 5 m_{\Theta^0}$ ).
- 11 AALTONEN 13R search for new resonance decaying to  $\sigma\sigma$ , with hypothetical strongly interacting  $\sigma$  particle subsequently decaying to 2 jets, in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV, using data corresponding to an integrated luminosity of  $6.6 \text{ fb}^{-1}$ . For  $50 \text{ GeV} < m_\sigma < m_{g_A}/2$ , axigluons in mass range 150–400 GeV are excluded.
  - 12 CHATRCHYAN 13A search for new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.
  - 13 CHATRCHYAN 13AS search for new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 8$  TeV.
  - 14 CHATRCHYAN 13AU search for the pair produced color-octet vector bosons decaying to  $q\bar{q}$  pairs in  $pp$  collisions. The quoted limit is for  $B(g_A \rightarrow q\bar{q}) = 1$ .
  - 15 ABAZOV 12R search for massive color octet vector particle decaying to  $t\bar{t}$ . The quoted limit assumes  $g_A$  couplings with light quarks are suppressed by 0.2.
  - 16 CHATRCHYAN 11Y search for new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.
  - 17 AALTONEN 10L search for massive color octet non-chiral vector particle decaying into  $t\bar{t}$  pair with mass in the range  $400 \text{ GeV} < M < 800 \text{ GeV}$ . See their Fig. 6 for limit in the mass-coupling plane.
  - 18 KHACHATRYAN 10 search for new resonance decaying to dijets in  $pp$  collisions at  $\sqrt{s} = 7$  TeV.
  - 19 AALTONEN 09AC search for new narrow resonance decaying to dijets.
  - 20 CHOUDHURY 07 limit is from the  $t\bar{t}$  production cross section measured at CDF.
  - 21 DONCHESKI 98 compare  $\alpha_s$  derived from low-energy data and that from  $\Gamma(Z \rightarrow \text{hadrons})/\Gamma(Z \rightarrow \text{leptons})$ .
  - 22 ABE 97G search for new particle decaying to dijets.
  - 23 ABE 95N assume axigluons decaying to quarks in the Standard Model only.
  - 24 ABE 93G assume  $\Gamma(g_A) = N\alpha_s m_{g_A}/6$  with  $N = 10$ .
  - 25 CUYPERS 91 compare  $\alpha_s$  measured in  $\Upsilon$  decay and that from  $R$  at PEP/PETRA energies.
  - 26 ABE 90H assumes  $\Gamma(g_A) = N\alpha_s m_{g_A}/6$  with  $N = 5$  ( $\Gamma(g_A) = 0.09 m_{g_A}$ ). For  $N = 10$ , the excluded region is reduced to 120–150 GeV.
  - 27 ROBINETT 89 result demands partial-wave unitarity of  $J = 0$   $t\bar{t} \rightarrow t\bar{t}$  scattering amplitude and derives a limit  $m_{g_A} > 0.5 m_t$ . Assumes  $m_t > 56$  GeV.
  - 28 ALBAJAR 88B result is from the nonobservation of a peak in two-jet invariant mass distribution.  $\Gamma(g_A) < 0.4 m_{g_A}$  assumed. See also BAGGER 88.
  - 29 CUYPERS 88 requires  $\Gamma(\Upsilon \rightarrow g g_A) < \Gamma(\Upsilon \rightarrow g g g)$ . A similar result is obtained by DONCHESKI 88.
  - 30 DONCHESKI 88B requires  $\Gamma(\Upsilon \rightarrow g q\bar{q})/\Gamma(\Upsilon \rightarrow g g g) < 0.25$ , where the former decay proceeds via axigluon exchange. A more conservative estimate of  $< 0.5$  leads to  $m_{g_A} > 21$  GeV.

## MASS LIMITS for Color-Octet Scalar Bosons

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
none 1800–3700	95	<sup>1</sup> SIRUNYAN 20AI CMS		$pp \rightarrow S_8 X, S_8 \rightarrow gg$
none 600–3400	95	<sup>2</sup> SIRUNYAN 18BO CMS		$pp \rightarrow S_8 X, S_8 \rightarrow gg$
		<sup>3</sup> KHACHATRY...15AV CMS		$pp \rightarrow \Theta^0 \Theta^0 \rightarrow b\bar{b} Z g$
none 150–287	95	<sup>4</sup> AAD 13K ATLS		$pp \rightarrow S_8 S_8 X, S_8 \rightarrow 2 \text{ jets}$

<sup>1</sup> SIRUNYAN 20AI search for resonances decaying into dijets in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above assumes  $S_{8gg}$  coupling  $k_s^2 = 1/2$ .

- <sup>2</sup> SIRUNYAN 18B0 search for color octet scalar boson produced through gluon fusion process in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. The limit above assumes  $S_{8gg}$  coupling  $k_s^2 = 1/2$ .
- <sup>3</sup> KHACHATRYAN 15AV search for pair productions of neutral color-octet weak-triplet scalar particles ( $\Theta^0$ ), decaying to  $b\bar{b}$ ,  $Zg$  or  $\gamma g$ , in  $pp$  collisions at  $\sqrt{s} = 8$  TeV. The  $\Theta^0$  particle is often predicted in coloron ( $G'$ , color-octet gauge boson) models and appear in the  $pp$  collisions through  $G' \rightarrow \Theta^0 \Theta^0$  decays. Assuming  $B(\Theta^0 \rightarrow b\bar{b}) = 0.5$ , they give limits  $m_{\Theta^0} > 623$  GeV (426 GeV) for  $m_{G'} = 2.3 m_{\Theta^0}$  ( $m_{G'} = 5 m_{\Theta^0}$ ).
- <sup>4</sup> AAD 13K search for pair production of color-octet scalar particles in  $pp$  collisions at  $\sqrt{s} = 7$  TeV. Cross section limits are interpreted as mass limits on scalar partners of a Dirac gluino.

## $X^0$ (Heavy Boson) Searches in Z Decays

Searches for radiative transition of  $Z$  to a lighter spin-0 state  $X^0$  decaying to hadrons, a lepton pair, a photon pair, or invisible particles as shown in the comments. The limits are for the product of branching ratios.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
		1 RAINBOLT	19 RVUE	$X^0 \rightarrow \ell^+ \ell^-$
		2 SIRUNYAN	19AZ CMS	$X^0 \rightarrow \mu^+ \mu^-$
		3 BARATE	98U ALEP	$X^0 \rightarrow \ell\bar{\ell}, q\bar{q}, gg, \gamma\gamma, \nu\bar{\nu}$
		4 ACCIARRI	97Q L3	$X^0 \rightarrow$ invisible particle(s)
		5 ACTON	93E OPAL	$X^0 \rightarrow \gamma\gamma$
		6 ABREU	92D DLPH	$X^0 \rightarrow$ hadrons
		7 ADRIANI	92F L3	$X^0 \rightarrow$ hadrons
		8 ACTON	91 OPAL	$X^0 \rightarrow$ anything
$<1.1 \times 10^{-4}$	95	9 ACTON	91B OPAL	$X^0 \rightarrow e^+ e^-$
$<9 \times 10^{-5}$	95	9 ACTON	91B OPAL	$X^0 \rightarrow \mu^+ \mu^-$
$<1.1 \times 10^{-4}$	95	9 ACTON	91B OPAL	$X^0 \rightarrow \tau^+ \tau^-$
$<2.8 \times 10^{-4}$	95	10 ADEVA	91D L3	$X^0 \rightarrow e^+ e^-$
$<2.3 \times 10^{-4}$	95	10 ADEVA	91D L3	$X^0 \rightarrow \mu^+ \mu^-$
$<4.7 \times 10^{-4}$	95	11 ADEVA	91D L3	$X^0 \rightarrow$ hadrons
$<8 \times 10^{-4}$	95	12 AKRAWY	90J OPAL	$X^0 \rightarrow$ hadrons

- <sup>1</sup> RAINBOLT 19 limits are from  $B(Z \rightarrow \ell^+ \ell^- \ell^+ \ell^-)$ . See their Figs. 5 and 6 for limits in mass-coupling plane.
- <sup>2</sup> SIRUNYAN 19AZ search for  $pp \rightarrow Z \rightarrow X^0 \mu^+ \mu^- \rightarrow \mu^+ \mu^- \mu^+ \mu^-$  events in  $pp$  collisions at  $\sqrt{s} = 13$  TeV. See their Fig. 5 for limits on  $\sigma(pp \rightarrow X^0 \mu^+ \mu^-) \cdot B(X^0 \rightarrow \mu^+ \mu^-)$ .
- <sup>3</sup> BARATE 98U obtain limits on  $B(Z \rightarrow \gamma X^0) B(X^0 \rightarrow \ell\bar{\ell}, q\bar{q}, gg, \gamma\gamma, \nu\bar{\nu})$ . See their Fig. 17.
- <sup>4</sup> See Fig. 4 of ACCIARRI 97Q for the upper limit on  $B(Z \rightarrow \gamma X^0; E_\gamma > E_{\min})$  as a function of  $E_{\min}$ .
- <sup>5</sup> ACTON 93E give  $\sigma(e^+ e^- \rightarrow X^0 \gamma) \cdot B(X^0 \rightarrow \gamma\gamma) < 0.4$  pb (95%CL) for  $m_{X^0} = 60 \pm 2.5$  GeV. If the process occurs via  $s$ -channel  $\gamma$  exchange, the limit translates to  $\Gamma(X^0) \cdot B(X^0 \rightarrow \gamma\gamma)^2 < 20$  MeV for  $m_{X^0} = 60 \pm 1$  GeV.
- <sup>6</sup> ABREU 92D give  $\sigma_Z \cdot B(Z \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow \text{hadrons}) < (3-10)$  pb for  $m_{X^0} = 10-78$  GeV. A very similar limit is obtained for spin-1  $X^0$ .

- <sup>7</sup> ADRIANI 92F search for isolated  $\gamma$  in hadronic  $Z$  decays. The limit  $\sigma_Z \cdot B(Z \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow \text{hadrons}) < (2-10)$  pb (95%CL) is given for  $m_{X^0} = 25-85$  GeV.
- <sup>8</sup> ACTON 91 searches for  $Z \rightarrow Z^* X^0$ ,  $Z^* \rightarrow e^+ e^-$ ,  $\mu^+ \mu^-$ , or  $\nu \bar{\nu}$ . Excludes any new scalar  $X^0$  with  $m_{X^0} < 9.5$  GeV/ $c$  if it has the same coupling to  $Z Z^*$  as the MSM Higgs boson.
- <sup>9</sup> ACTON 91B limits are for  $m_{X^0} = 60-85$  GeV.
- <sup>10</sup> ADEVA 91D limits are for  $m_{X^0} = 30-89$  GeV.
- <sup>11</sup> ADEVA 91D limits are for  $m_{X^0} = 30-86$  GeV.
- <sup>12</sup> AKRAWY 90J give  $\Gamma(Z \rightarrow \gamma X^0) \cdot B(X^0 \rightarrow \text{hadrons}) < 1.9$  MeV (95%CL) for  $m_{X^0} = 32-80$  GeV. We divide by  $\Gamma(Z) = 2.5$  GeV to get product of branching ratios. For nonresonant transitions, the limit is  $B(Z \rightarrow \gamma q \bar{q}) < 8.2$  MeV assuming three-body phase space distribution.

### MASS LIMITS for a Heavy Neutral Boson Coupling to $e^+ e^-$

VALUE (GeV)	CL%	DOCUMENT ID	TECN	COMMENT
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
none 55–61		<sup>1</sup> ODAKA	89 VNS	$\Gamma(X^0 \rightarrow e^+ e^-) \cdot B(X^0 \rightarrow \text{had.}) \gtrsim 0.2$ MeV
>45	95	<sup>2</sup> DERRICK	86 HRS	$\Gamma(X^0 \rightarrow e^+ e^-) = 6$ MeV
>46.6	95	<sup>3</sup> ADEVA	85 MRKJ	$\Gamma(X^0 \rightarrow e^+ e^-) = 10$ keV
>48	95	<sup>3</sup> ADEVA	85 MRKJ	$\Gamma(X^0 \rightarrow e^+ e^-) = 4$ MeV
		<sup>4</sup> BERGER	85B PLUT	
none 39.8–45.5		<sup>5</sup> ADEVA	84 MRKJ	$\Gamma(X^0 \rightarrow e^+ e^-) = 10$ keV
>47.8	95	<sup>5</sup> ADEVA	84 MRKJ	$\Gamma(X^0 \rightarrow e^+ e^-) = 4$ MeV
none 39.8–45.2		<sup>5</sup> BEHREND	84C CELL	
>47	95	<sup>5</sup> BEHREND	84C CELL	$\Gamma(X^0 \rightarrow e^+ e^-) = 4$ MeV

<sup>1</sup> ODAKA 89 looked for a narrow or wide scalar resonance in  $e^+ e^- \rightarrow \text{hadrons}$  at  $E_{\text{cm}} = 55.0-60.8$  GeV.

<sup>2</sup> DERRICK 86 found no deviation from the Standard Model Bhabha scattering at  $E_{\text{cm}} = 29$  GeV and set limits on the possible scalar boson  $e^+ e^-$  coupling. See their figure 4 for excluded region in the  $\Gamma(X^0 \rightarrow e^+ e^-) - m_{X^0}$  plane. Electronic chiral invariance requires a parity doublet of  $X^0$ , in which case the limit applies for  $\Gamma(X^0 \rightarrow e^+ e^-) = 3$  MeV.

<sup>3</sup> ADEVA 85 first limit is from  $2\gamma$ ,  $\mu^+ \mu^-$ , hadrons assuming  $X^0$  is a scalar. Second limit is from  $e^+ e^-$  channel.  $E_{\text{cm}} = 40-47$  GeV. Supersedes ADEVA 84.

<sup>4</sup> BERGER 85B looked for effect of spin-0 boson exchange in  $e^+ e^- \rightarrow e^+ e^-$  and  $\mu^+ \mu^-$  at  $E_{\text{cm}} = 34.7$  GeV. See Fig. 5 for excluded region in the  $m_{X^0} - \Gamma(X^0)$  plane.

<sup>5</sup> ADEVA 84 and BEHREND 84C have  $E_{\text{cm}} = 39.8-45.5$  GeV. MARK-J searched  $X^0$  in  $e^+ e^- \rightarrow \text{hadrons}$ ,  $2\gamma$ ,  $\mu^+ \mu^-$ ,  $e^+ e^-$  and CELLO in the same channels plus  $\tau$  pair. No narrow or broad  $X^0$  is found in the energy range. They also searched for the effect of  $X^0$  with  $m_X > E_{\text{cm}}$ . The second limits are from Bhabha data and for spin-0 singlet. The same limits apply for  $\Gamma(X^0 \rightarrow e^+ e^-) = 2$  MeV if  $X^0$  is a spin-0 doublet. The second limit of BEHREND 84C was read off from their figure 2. The original papers also list limits in other channels.



**Search for  $X^0$  Resonance in  $e^+e^-$  Collisions**

The limit is for  $\Gamma(X^0 \rightarrow e^+e^-) \cdot B(X^0 \rightarrow f)$ , where  $f$  is the specified final state.

Spin 0 is assumed for  $X^0$ .

<u>VALUE (keV)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<10^3$	95	<sup>1</sup> ABE	93C VNS	$\Gamma(ee)$
$<(0.4-10)$	95	<sup>2</sup> ABE	93C VNS	$f = \gamma\gamma$
$<(0.3-5)$	95	<sup>3,4</sup> ABE	93D TOPZ	$f = \gamma\gamma$
$<(2-12)$	95	<sup>3,4</sup> ABE	93D TOPZ	$f = \text{hadrons}$
$<(4-200)$	95	<sup>4,5</sup> ABE	93D TOPZ	$f = ee$
$<(0.1-6)$	95	<sup>4,5</sup> ABE	93D TOPZ	$f = \mu\mu$
$<(0.5-8)$	90	<sup>6</sup> STERNER	93 AMY	$f = \gamma\gamma$

<sup>1</sup> Limit is for  $\Gamma(X^0 \rightarrow e^+e^-) m_{X^0} = 56-63.5$  GeV for  $\Gamma(X^0) = 0.5$  GeV.

<sup>2</sup> Limit is for  $m_{X^0} = 56-61.5$  GeV and is valid for  $\Gamma(X^0) \ll 100$  MeV. See their Fig. 5 for limits for  $\Gamma = 1, 2$  GeV.

<sup>3</sup> Limit is for  $m_{X^0} = 57.2-60$  GeV.

<sup>4</sup> Limit is valid for  $\Gamma(X^0) \ll 100$  MeV. See paper for limits for  $\Gamma = 1$  GeV and those for  $J = 2$  resonances.

<sup>5</sup> Limit is for  $m_{X^0} = 56.6-60$  GeV.

<sup>6</sup> STERNER 93 limit is for  $m_{X^0} = 57-59.6$  GeV and is valid for  $\Gamma(X^0) < 100$  MeV. See their Fig. 2 for limits for  $\Gamma = 1, 3$  GeV.

**Search for  $X^0$  Resonance in  $e p$  Collisions**

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	<sup>1</sup> CHEKANOV	02B ZEUS	$X \rightarrow jj$

<sup>1</sup> CHEKANOV 02B search for photoproduction of  $X$  decaying into dijets in  $e p$  collisions. See their Fig. 5 for the limit on the photoproduction cross section.

**Search for  $X^0$  Resonance in  $e^+e^- \rightarrow X^0\gamma$** 

<u>VALUE (GeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
• • • We do not use the following data for averages, fits, limits, etc. • • •			
	<sup>1</sup> ABBIENDI	03D OPAL	$X^0 \rightarrow \gamma\gamma$
	<sup>2</sup> ABREU	00Z DLPH	$X^0$ decaying invisibly
	<sup>3</sup> ADAM	96C DLPH	$X^0$ decaying invisibly

<sup>1</sup> ABBIENDI 03D measure the  $e^+e^- \rightarrow \gamma\gamma\gamma$  cross section at  $\sqrt{s}=181-209$  GeV. The upper bound on the production cross section,  $\sigma(e^+e^- \rightarrow X^0\gamma)$  times the branching ratio for  $X^0 \rightarrow \gamma\gamma$ , is less than 0.03 pb at 95%CL for  $X^0$  masses between 20 and 180 GeV. See their Fig. 9b for the limits in the mass-cross section plane.

<sup>2</sup> ABREU 00Z is from the single photon cross section at  $\sqrt{s}=183, 189$  GeV. The production cross section upper limit is less than 0.3 pb for  $X^0$  mass between 40 and 160 GeV. See their Fig. 4 for the limit in mass-cross section plane.

<sup>3</sup> ADAM 96C is from the single photon production cross at  $\sqrt{s}=130, 136$  GeV. The upper bound is less than 3 pb for  $X^0$  masses between 60 and 130 GeV. See their Fig. 5 for the exact bound on the cross section  $\sigma(e^+e^- \rightarrow \gamma X^0)$ .

**Search for  $X^0$  Resonance in  $Z \rightarrow f\bar{f}X^0$** 

The limit is for  $B(Z \rightarrow f\bar{f}X^0) \cdot B(X^0 \rightarrow F)$  where  $f$  is a fermion and  $F$  is the specified final state. Spin 0 is assumed for  $X^0$ .

<u>VALUE</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
$<3.7 \times 10^{-6}$	95	<sup>1</sup> ABREU	96T DLPH	$f=e,\mu,\tau; F=\gamma\gamma$
		<sup>2</sup> ABREU	96T DLPH	$f=\nu; F=\gamma\gamma$
		<sup>3</sup> ABREU	96T DLPH	$f=q; F=\gamma\gamma$
$<6.8 \times 10^{-6}$	95	<sup>2</sup> ACTON	93E OPAL	$f=e,\mu,\tau; F=\gamma\gamma$
$<5.5 \times 10^{-6}$	95	<sup>2</sup> ACTON	93E OPAL	$f=q; F=\gamma\gamma$
$<3.1 \times 10^{-6}$	95	<sup>2</sup> ACTON	93E OPAL	$f=\nu; F=\gamma\gamma$
$<6.5 \times 10^{-6}$	95	<sup>2</sup> ACTON	93E OPAL	$f=e,\mu; F=\ell\bar{\ell}, q\bar{q}, \nu\bar{\nu}$
$<7.1 \times 10^{-6}$	95	<sup>2</sup> BUSKULIC	93F ALEP	$f=e,\mu; F=\ell\bar{\ell}, q\bar{q}, \nu\bar{\nu}$
		<sup>4</sup> ADRIANI	92F L3	$f=q; F=\gamma\gamma$

<sup>1</sup> ABREU 96T obtain limit as a function of  $m_{X^0}$ . See their Fig. 6.

<sup>2</sup> Limit is for  $m_{X^0}$  around 60 GeV.

<sup>3</sup> ABREU 96T obtain limit as a function of  $m_{X^0}$ . See their Fig. 15.

<sup>4</sup> ADRIANI 92F give  $\sigma_Z \cdot B(Z \rightarrow q\bar{q}X^0) \cdot B(X^0 \rightarrow \gamma\gamma) < (0.75-1.5)$  pb (95%CL) for  $m_{X^0} = 10-70$  GeV. The limit is 1 pb at 60 GeV.

**Search for  $X^0$  Resonance in  $WX^0$  final state**

<u>VALUE (MeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
	<sup>1</sup> AALTONEN	13AA CDF	$X^0 \rightarrow jj$
	<sup>2</sup> CHATRCHYAN	12BR CMS	$X^0 \rightarrow jj$
	<sup>3</sup> ABAZOV	11I D0	$X^0 \rightarrow jj$
	<sup>4</sup> ABE	97W CDF	$X^0 \rightarrow b\bar{b}$

<sup>1</sup> AALTONEN 13AA search for  $X^0$  production associated with  $W$  (or  $Z$ ) in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The upper limit on the cross section  $\sigma(p\bar{p} \rightarrow WX^0)$  is 2.2 pb for  $M_{X^0} = 145$  GeV.

<sup>2</sup> CHATRCHYAN 12BR search for  $X^0$  production associated with  $W$  in  $pp$  collisions at  $E_{\text{cm}} = 7$  TeV. The upper limit on the cross section is 5.0 pb at 95% CL for  $m_{X^0} = 150$  GeV.

<sup>3</sup> ABAZOV 11I search for  $X^0$  production associated with  $W$  in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.96$  TeV. The 95% CL upper limit on the cross section ranges from 2.57 to 1.28 pb for  $X^0$  mass between 110 and 170 GeV.

<sup>4</sup> ABE 97W search for  $X^0$  production associated with  $W$  in  $p\bar{p}$  collisions at  $E_{\text{cm}} = 1.8$  TeV. The 95%CL upper limit on the production cross section times the branching ratio for  $X^0 \rightarrow b\bar{b}$  ranges from 14 to 19 pb for  $X^0$  mass between 70 and 120 GeV. See their Fig. 3 for upper limits of the production cross section as a function of  $m_{X^0}$ .

**Search for  $X^0$  Resonance in Quarkonium Decays**

Limits are for branching ratios to modes shown. Spin 1 is assumed for  $X^0$ .

<u>VALUE</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
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• • • We do not use the following data for averages, fits, limits, etc. • • •

$$< 3 \times 10^{-5} - 6 \times 10^{-3} \quad 90 \quad {}^1 \text{BALEST} \quad 95 \quad \text{CLE2} \quad \gamma(1S) \rightarrow X^0 \bar{X}^0 \gamma, \\ m_{X^0} < 3.9 \text{ GeV}$$

<sup>1</sup>BALEST 95 three-body limit is for phase-space photon energy distribution and angular distribution same as for  $\Upsilon \rightarrow gg\gamma$ .

### Search for $X^0$ Resonance in $H(125)$ Decays

Spin 1 is assumed for  $X^0$ . See neutral Higgs search listing for pseudoscalar  $X^0$ .

VALUE	DOCUMENT ID	TECN	COMMENT
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• • • We do not use the following data for averages, fits, limits, etc. • • •

<sup>1</sup> AABOUD	18AP ATLS	$H(125) \rightarrow ZX^0$
<sup>2</sup> AABOUD	18AP ATLS	$H(125) \rightarrow X^0 X^0$

<sup>1</sup>AABOUD 18AP use  $pp$  collision data at  $\sqrt{s} = 13$  TeV.  $X^0 \rightarrow \ell^+ \ell^-$  decay is assumed. See their Fig. 9 for limits on  $\sigma_{H(125)} \cdot \text{B}(ZX^0)$ .

<sup>2</sup>AABOUD 18AP use  $pp$  collision data at  $\sqrt{s} = 13$  TeV.  $X^0 \rightarrow \ell^+ \ell^-$  decay is assumed. See their Fig. 10 for limits on  $\sigma_{H(125)} \cdot \text{B}(X^0 X^0)$ .

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AAD	21AG	EPJ C81 313	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	21AQ	JHEP 2107 005	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	21AW	PR D104 112005	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	21AZ	JHEP 2110 013	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	21BB	JHEP 2111 209	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	21D	PRL 126 121802	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	21K	JHEP 2102 226	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	21S	JHEP 2105 093	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	21T	JHEP 2106 179	G. Aad <i>et al.</i>	(ATLAS Collab.)
BURAS	21	JHEP 2106 068	A.J. Buras <i>et al.</i>	(TUM, CERN, ZURI+)
CADEDU	21	JHEP 2101 116	M. Cadeddu <i>et al.</i>	(CAGLI, CAGL, INFN+)
COLARESI	21	PR D104 072003	J. Colaresi <i>et al.</i>	(MRION, FNAL, PNL+)
CRIVELLIN	21A	PR D103 115023	A. Crivellin, D. Mueller, L. Schnell	(CERN, ZURI+)
KRIBS	21	PRL 126 011801	G.D. Kribs, D. McKeen, N. Raj	(OREG, TRIU)
SIRUNYAN	21J	PL B819 136446	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	21N	JHEP 2107 208	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	21X	EPJ C81 688	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	21Y	PL B820 136535	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
TUMASYAN	21D	JHEP 2111 153	A. Tumasyan <i>et al.</i>	(CMS Collab.)
AAD	20AD	PRL 125 131801	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	20AF	PRL 125 251802	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	20AJ	PR D102 112008	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	20AK	JHEP 2010 112	G. Aad <i>et al.</i>	(ATLAS Collab.)
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AAD	20AT	EPJ C80 1165	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	20S	EPJ C80 737	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	20T	JHEP 2003 145	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	20W	JHEP 2006 151	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	20AL	JHEP 2010 156	R. Aaij <i>et al.</i>	(LHCb Collab.)
ADACHI	20	PRL 124 141801	I. Adachi <i>et al.</i>	(BELLE II Collab.)
AEBISCHER	20	EPJ C80 252	J. Aebischer <i>et al.</i>	(TUM, LAPTH, UCSC)
DEPPISCH	20	JHEP 2012 186	F.F. Deppisch, K. Fridell, J. Harz	(LOUC, TUM)
SIRUNYAN	20A	EPJ C80 3	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	20AI	JHEP 2005 033	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	20AQ	PRL 124 131802	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	20M	PL B805 135448	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	20Q	EPJ C80 237	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
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AABOUD	19AS	PR D99 092004	M. Aaboud <i>et al.</i>	(ATLAS Collab.)

AABOUD	19AX	EPJ C79 733	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	19B	JHEP 1901 016	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	19BB	PL B798 134942	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	19D	PL B788 316	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	19E	PL B788 347	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	19V	JHEP 1905 142	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	19X	JHEP 1906 144	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AAD	19C	PR D100 052013	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	19D	JHEP 1909 091	G. Aad <i>et al.</i>	(ATLAS Collab.)
Also		JHEP 2006 042 (errat.)	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	19L	PL B796 68	G. Aad <i>et al.</i>	(ATLAS Collab.)
ABRAMOWICZ	19	PR D99 092006	H. Abramowicz <i>et al.</i>	(ZEUS Collab.)
LONG	19	NP B943 114629	H.N. Long <i>et al.</i>	
MANDAL	19	JHEP 1912 089	R. Mandal, A. Pich	(VALE, SIEG)
PANDEY	19	JHEP 1911 046	S. Pandey, S. Karmakar, S. Rakshit	(IITI)
RAINBOLT	19	PR D99 013004	J.L. Rainbolt, M. Schmitt	(NWES)
SIRUNYAN	19AA	JHEP 1904 031	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19AL	EPJ C79 208	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19AN	EPJ C79 280	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19AY	PL B792 107	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19AZ	PL B792 345	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19BC	PL B795 76	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19BI	PR D99 032014	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
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SIRUNYAN	19CB	PR D100 112007	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	19CD	PRL 123 231803	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
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SIRUNYAN	19I	JHEP 1901 051	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
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SIRUNYAN	19Y	JHEP 1903 170	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
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AABOUD	18AD	PL B779 24	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18AF	PL B781 327	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18AI	JHEP 1803 174	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
Also		JHEP 1811 051 (errat.)	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18AK	JHEP 1803 042	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18AL	JHEP 1803 009	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18AP	JHEP 1806 166	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18B	EPJ C78 24	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18BG	EPJ C78 401	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18BI	EPJ C78 565	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18CH	PL B787 68	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18CJ	PR D98 052008	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18CM	PR D98 092008	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18F	PL B777 91	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18G	JHEP 1801 055	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18K	PRL 120 161802	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	18N	PRL 121 081801	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
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SIRUNYAN	18	PL B777 39	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18AT	JHEP 1804 073	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18AX	JHEP 1805 088	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18AZ	JHEP 1806 128	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18BB	JHEP 1806 120	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18BJ	JHEP 1807 115	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18BK	JHEP 1807 075	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18BO	JHEP 1808 130	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18CV	JHEP 1805 148	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18CZ	EPJ C78 707	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18DJ	JHEP 1809 101	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18DR	JHEP 1811 161	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18EC	PRL 121 241802	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18ED	JHEP 1811 172	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18G	JHEP 1801 097	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	18I	PRL 120 201801	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
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AABOUD	17AO	PL B774 494	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	17AT	JHEP 1710 182	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	17B	PL B765 32	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
KHACHATRY...	17AX	PL B773 563	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	17H	JHEP 1702 048	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	17J	JHEP 1703 077	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	17T	PL B768 57	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	17U	PL B768 137	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	17W	PL B769 520	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	17Y	PL B770 257	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	17Z	PL B770 278	V. Khachatryan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17A	JHEP 1703 162	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17AK	PL B774 533	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17AP	JHEP 1710 180	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17H	JHEP 1707 121	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17I	JHEP 1708 029	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17Q	JHEP 1707 001	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17R	EPJ C77 636	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17T	PRL 119 111802	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
SIRUNYAN	17V	JHEP 1709 053	A.M. Sirunyan <i>et al.</i>	(CMS Collab.)
AABOUD	16	PL B759 229	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	16AA	EPJ C76 585	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	16AE	JHEP 1609 173	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	16P	EPJ C76 541	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	16U	PL B761 372	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AABOUD	16V	PL B762 334	M. Aaboud <i>et al.</i>	(ATLAS Collab.)
AAD	16G	EPJ C76 5	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	16L	EPJ C76 210	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	16R	PL B755 285	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	16S	PL B754 302	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	16W	PL B758 249	G. Aad <i>et al.</i>	(ATLAS Collab.)
BARRANCO	16	JP G43 115004	J. Barranco <i>et al.</i>	
DEY	16	JHEP 1604 187	U.K. Dey, S. Mohanty	
KHACHATRY...	16AF	PR D93 032004	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16AG	PR D93 032005	V. Khachatryan <i>et al.</i>	(CMS Collab.)
Also		PR D95 039906 (errat.)	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16AO	JHEP 1602 122	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16AP	JHEP 1602 145	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16BD	EPJ C76 237	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16BE	EPJ C76 317	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16E	PR D93 012001	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16K	PRL 116 071801	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16L	PRL 117 031802	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	16O	PL B755 196	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KUMAR	16	PR D94 014022	G. Kumar	
AAD	15AM	JHEP 1507 157	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15AO	JHEP 1508 148	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15AT	EPJ C75 79	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15AU	EPJ C75 69	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15AV	EPJ C75 165	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15AZ	EPJ C75 209	G. Aad <i>et al.</i>	(ATLAS Collab.)
Also		EPJ C75 370 (errat.)	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15BB	EPJ C75 263	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15CD	PR D92 092001	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15CP	JHEP 1512 055	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15O	PRL 115 031801	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15R	PL B743 235	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	15V	PR D91 052007	G. Aad <i>et al.</i>	(ATLAS Collab.)
AALTONEN	15C	PRL 115 061801	T. Aaltonen <i>et al.</i>	(CDF Collab.)
BESSAA	15	EPJ C75 97	A. Bessaa, S. Davidson	
KHACHATRY...	15AE	JHEP 1504 025	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	15AJ	JHEP 1507 042	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	15AV	JHEP 1509 201	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	15C	PL B740 83	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	15F	PRL 114 101801	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	15O	PL B748 255	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	15T	PR D91 092005	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	15V	PR D91 052009	V. Khachatryan <i>et al.</i>	(CMS Collab.)
SAHOO	15A	PR D91 094019	S. Sahoo, R. Mohanta	
AAD	14AI	JHEP 1409 037	G. Aad <i>et al.</i>	(ATLAS Collab.)

AAD	14AT	PL B738 428	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	14S	PL B737 223	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	14V	PR D90 052005	G. Aad <i>et al.</i>	(ATLAS Collab.)
KHACHATRY...	14A	JHEP 1408 173	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	14A	JHEP 1408 173	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	14O	EPJ C74 3149	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRY...	14T	PL B739 229	V. Khachatryan <i>et al.</i>	(CMS Collab.)
MARTINEZ	14	PR D90 015028	R. Martinez, F. Ochoa	
PRIEELS	14	PR D90 112003	R. Priiels <i>et al.</i>	(LOUV, ETH, PSI+)
AAD	13AE	JHEP 1306 033	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	13AO	PR D87 112006	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	13AQ	PR D88 012004	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	13D	JHEP 1301 029	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	13G	JHEP 1301 116	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	13K	EPJ C73 2263	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	13S	PL B719 242	G. Aad <i>et al.</i>	(ATLAS Collab.)
AALTONEN	13A	PRL 110 121802	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	13AA	PR D88 092004	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	13R	PRL 111 031802	T. Aaltonen <i>et al.</i>	(CDF Collab.)
CHATRCHYAN	13A	JHEP 1301 013	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13AF	PL B720 63	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13AJ	PL B723 280	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13AP	PR D87 072002	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13AQ	PR D87 072005	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13AS	PR D87 114015	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13AU	PRL 110 141802	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13BM	PRL 111 211804	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
Also		PRL 112 119903 (errat.)	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13E	PL B718 1229	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13M	PRL 110 081801	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	13U	JHEP 1302 036	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
SAKAKI	13	PR D88 094012	Y. Sakaki <i>et al.</i>	
AAD	12AV	PRL 109 081801	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12BB	PR D85 112012	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12BV	JHEP 1209 041	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12CC	JHEP 1211 138	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12CK	PR D86 091103	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12CR	EPJ C72 2241	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12H	PL B709 158	G. Aad <i>et al.</i>	(ATLAS Collab.)
Also		PL B711 442 (errat.)	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12K	EPJ C72 2083	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12M	EPJ C72 2056	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	12O	EPJ C72 2151	G. Aad <i>et al.</i>	(ATLAS Collab.)
AALTONEN	12AR	PR D86 112002	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	12N	PRL 108 211805	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABAZOV	12R	PR D85 051101	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABRAMOWICZ	12A	PR D86 012005	H. Abramowicz <i>et al.</i>	(ZEUS Collab.)
CHATRCHYAN	12AF	PRL 109 141801	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12AG	PR D86 052013	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12AI	JHEP 1208 110	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12AQ	JHEP 1209 029	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
Also		JHEP 1403 132 (errat.)	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12AR	PL B717 351	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12BG	PRL 109 261802	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12BL	JHEP 1212 015	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12BO	JHEP 1212 055	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12BR	PRL 109 251801	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12M	PL B714 158	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	12O	PL B716 82	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
KOSNIK	12	PR D86 055004	N. Kosnik	(LALO, STFN)
AAD	11D	PR D83 112006	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	11H	PRL 106 251801	G. Aad <i>et al.</i>	(ATLAS Collab.)
AAD	11Z	EPJ C71 1809	G. Aad <i>et al.</i>	(ATLAS Collab.)
AALTONEN	11AD	PR D84 072003	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	11AE	PR D84 072004	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	11C	PR D83 031102	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	11I	PRL 106 121801	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AARON	11A	PL B701 20	F. D. Aaron <i>et al.</i>	(H1 Collab.)
AARON	11B	PL B704 388	F. D. Aaron <i>et al.</i>	(H1 Collab.)
AARON	11C	PL B705 52	F. D. Aaron <i>et al.</i>	(H1 Collab.)
ABAZOV	11A	PL B695 88	V.M. Abazov <i>et al.</i>	(D0 Collab.)

ABAZOV	11H	PRL 107 011801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	11I	PRL 107 011804	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	11L	PL B699 145	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	11V	PR D84 071104	V.M. Abazov <i>et al.</i>	(D0 Collab.)
BUENO	11	PR D84 032005	J.F. Bueno <i>et al.</i>	(TWIST Collab.)
Also		PR D85 039908 (errata.)	J.F. Bueno <i>et al.</i>	(TWIST Collab.)
CHATRCHYAN	11N	PL B703 246	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	11O	JHEP 1108 005	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
CHATRCHYAN	11Y	PL B704 123	S. Chatrchyan <i>et al.</i>	(CMS Collab.)
DORSNER	11	JHEP 1111 002	I. Dorsner <i>et al.</i>	
KHACHATRYAN	11D	PRL 106 201802	V. Khachatryan <i>et al.</i>	(CMS Collab.)
KHACHATRYAN	11E	PRL 106 201803	V. Khachatryan <i>et al.</i>	(CMS Collab.)
AALTONEN	10L	PL B691 183	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	10N	PRL 104 241801	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABAZOV	10L	PL B693 95	V.M. Abazov <i>et al.</i>	(D0 Collab.)
DEL-AGUILA	10	JHEP 1009 033	F. del Aguila, J. de Blas, M. Perez-Victoria	(GRAN)
KHACHATRYAN	10	PRL 105 211801	V. Khachatryan <i>et al.</i>	(CMS Collab.)
Also		PRL 106 029902	V. Khachatryan <i>et al.</i>	(CMS Collab.)
WAUTERS	10	PR C82 055502	F. Wauters <i>et al.</i>	(REZ, TAMU)
AALTONEN	09AC	PR D79 112002	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	09T	PRL 102 031801	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	09V	PRL 102 091805	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABAZOV	09	PL B671 224	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	09AF	PL B681 224	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ERLER	09	JHEP 0908 017	J. Erler <i>et al.</i>	
AALTONEN	08D	PR D77 051102	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	08P	PR D77 091105	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	08Y	PRL 100 231801	T. Aaltonen <i>et al.</i>	(CDF Collab.)
AALTONEN	08Z	PRL 101 071802	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABAZOV	08AA	PL B668 98	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	08AD	PL B668 357	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	08AN	PRL 101 241802	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	08C	PRL 100 031804	V.M. Abazov <i>et al.</i>	(D0 Collab.)
MACDONALD	08	PR D78 032010	R.P. MacDonald <i>et al.</i>	(TWIST Collab.)
ZHANG	08	NP B802 247	Y. Zhang <i>et al.</i>	(PKGU, UMD)
AALTONEN	07H	PRL 99 171802	T. Aaltonen <i>et al.</i>	(CDF Collab.)
ABAZOV	07E	PL B647 74	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	07J	PRL 99 061801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
AKTAS	07A	EPJ C52 833	A. Aktas <i>et al.</i>	(H1 Collab.)
CHOUDHURY	07	PL B657 69	D. Choudhury <i>et al.</i>	
MELCONIAN	07	PL B649 370	D. Melconian <i>et al.</i>	(TRIUMF)
SCHAEEL	07A	EPJ C49 411	S. Schaeel <i>et al.</i>	(ALEPH Collab.)
SCHUMANN	07	PRL 99 191803	M. Schumann <i>et al.</i>	(HEID, ILLG, KARL+)
SMIRNOV	07	MPL A22 2353	A.D. Smirnov	
ABAZOV	06A	PL B636 183	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	06L	PL B640 230	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABDALLAH	06C	EPJ C45 589	J. Abdallah <i>et al.</i>	(DELPHI Collab.)
ABULENCIA	06L	PRL 96 211801	A. Abulencia <i>et al.</i>	(CDF Collab.)
ABULENCIA	06M	PRL 96 211802	A. Abulencia <i>et al.</i>	(CDF Collab.)
ABULENCIA	06T	PR D73 051102	A. Abulencia <i>et al.</i>	(CDF Collab.)
ABAZOV	05H	PR D71 071104	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABULENCIA	05A	PRL 95 252001	A. Abulencia <i>et al.</i>	(CDF Collab.)
ACOSTA	05I	PR D71 112001	D. Acosta <i>et al.</i>	(CDF Collab.)
ACOSTA	05P	PR D72 051107	D. Acosta <i>et al.</i>	(CDF Collab.)
ACOSTA	05R	PRL 95 131801	D. Acosta <i>et al.</i>	(CDF Collab.)
AKTAS	05B	PL B629 9	A. Aktas <i>et al.</i>	(H1 Collab.)
CHEKANOV	05	PL B610 212	S. Chekanov <i>et al.</i>	(HERA ZEUS Collab.)
CHEKANOV	05A	EPJ C44 463	S. Chekanov <i>et al.</i>	(ZEUS Collab.)
CYBURT	05	ASP 23 313	R.H. Cyburt <i>et al.</i>	
ABAZOV	04A	PRL 92 221801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	04C	PR D69 111101	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABBIENDI	04G	EPJ C33 173	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	03D	EPJ C26 331	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBIENDI	03R	EPJ C31 281	G. Abbiendi <i>et al.</i>	(OPAL)
ACOSTA	03B	PRL 90 081802	D. Acosta <i>et al.</i>	(CDF Collab.)
ADLOFF	03	PL B568 35	C. Adloff <i>et al.</i>	(H1 Collab.)
BARGER	03B	PR D67 075009	V. Barger, P. Langacker, H. Lee	
CHANG	03	PR D68 111101	M.-C. Chang <i>et al.</i>	(BELLE Collab.)
CHEKANOV	03B	PR D68 052004	S. Chekanov <i>et al.</i>	(ZEUS Collab.)
ABAZOV	02	PRL 88 191801	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABBIENDI	02B	PL B526 233	G. Abbiendi <i>et al.</i>	(OPAL Collab.)

AFFOLDER	02C	PRL 88 071806	T. Affolder <i>et al.</i>	(CDF Collab.)
CHEKANOV	02	PR D65 092004	S. Chekanov <i>et al.</i>	(ZEUS Collab.)
CHEKANOV	02B	PL B531 9	S. Chekanov <i>et al.</i>	(ZEUS Collab.)
MUECK	02	PR D65 085037	A. Mueck, A. Pilaftsis, R. Rueckl	
ABAZOV	01B	PRL 87 061802	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ABAZOV	01D	PR D64 092004	V.M. Abazov <i>et al.</i>	(D0 Collab.)
ADLOFF	01C	PL B523 234	C. Adloff <i>et al.</i>	(H1 Collab.)
AFFOLDER	01I	PRL 87 231803	T. Affolder <i>et al.</i>	(CDF Collab.)
BREITWEG	01	PR D63 052002	J. Breitweg <i>et al.</i>	(ZEUS Collab.)
CHEUNG	01B	PL B517 167	K. Cheung	
THOMAS	01	NP A694 559	E. Thomas <i>et al.</i>	
ABBIENDI	00M	EPJ C13 15	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBOTT	00C	PRL 84 2088	B. Abbott <i>et al.</i>	(D0 Collab.)
ABE	00	PRL 84 5716	F. Abe <i>et al.</i>	(CDF Collab.)
ABREU	00S	PL B485 45	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ABREU	00Z	EPJ C17 53	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACCIARRI	00P	PL B489 81	M. Acciarri <i>et al.</i>	(L3 Collab.)
ADLOFF	00	PL B479 358	C. Adloff <i>et al.</i>	(H1 Collab.)
AFFOLDER	00K	PRL 85 2056	T. Affolder <i>et al.</i>	(CDF Collab.)
BARATE	00I	EPJ C12 183	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARGER	00	PL B480 149	V. Barger, K. Cheung	
BREITWEG	00E	EPJ C16 253	J. Breitweg <i>et al.</i>	(ZEUS Collab.)
CHAY	00	PR D61 035002	J. Chay, K.Y. Lee, S. Nam	
CHO	00	MPL A15 311	G. Cho	
CORNET	00	PR D61 037701	F. Cornet, M. Relano, J. Rico	
DELGADO	00	JHEP 0001 030	A. Delgado, A. Pomarol, M. Quiros	
ERLER	00	PRL 84 212	J. Erler, P. Langacker	
GABRIELLI	00	PR D62 055009	E. Gabrielli	
RIZZO	00	PR D61 016007	T.G. Rizzo, J.D. Wells	
ROSNER	00	PR D61 016006	J.L. Rosner	
ZARNECKI	00	EPJ C17 695	A. Zarnecki	
ABBIENDI	99	EPJ C6 1	G. Abbiendi <i>et al.</i>	(OPAL Collab.)
ABBOTT	99J	PRL 83 2896	B. Abbott <i>et al.</i>	(D0 Collab.)
ABREU	99G	PL B446 62	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACKERSTAFF	99D	EPJ C8 3	K. Ackerstaff <i>et al.</i>	(OPAL Collab.)
ADLOFF	99	EPJ C11 447	C. Adloff <i>et al.</i>	(H1 Collab.)
	Also	EPJ C14 553 (errat.)	C. Adloff <i>et al.</i>	(H1 Collab.)
CASALBUONI	99	PL B460 135	R. Casalbuoni <i>et al.</i>	
CZAKON	99	PL B458 355	M. Czakon, J. Gluza, M. Zralek	
ERLER	99	PL B456 68	J. Erler, P. Langacker	
MARCIANO	99	PR D60 093006	W. Marciano	
MASIP	99	PR D60 096005	M. Masip, A. Pomarol	
NATH	99	PR D60 116004	P. Nath, M. Yamaguchi	
STRUMIA	99	PL B466 107	A. Strumia	
ABBOTT	98E	PRL 80 2051	B. Abbott <i>et al.</i>	(D0 Collab.)
ABBOTT	98J	PRL 81 38	B. Abbott <i>et al.</i>	(D0 Collab.)
ABE	98S	PRL 81 4806	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	98V	PRL 81 5742	F. Abe <i>et al.</i>	(CDF Collab.)
ACCIARRI	98J	PL B433 163	M. Acciarri <i>et al.</i>	(L3 Collab.)
ACKERSTAFF	98V	EPJ C2 441	K. Ackerstaff <i>et al.</i>	(OPAL Collab.)
BARATE	98U	EPJ C4 571	R. Barate <i>et al.</i>	(ALEPH Collab.)
BARENBOIM	98	EPJ C1 369	G. Barenboim	
CHO	98	EPJ C5 155	G. Cho, K. Hagiwara, S. Matsumoto	
CONRAD	98	RMP 70 1341	J.M. Conrad, M.H. Shaevitz, T. Bolton	
DONCHESKI	98	PR D58 097702	M.A. Doncheski, R.W. Robinett	
GROSS-PILCHER	98	hep-ex/9810015	C. Grosso-Pilcher, G. Landsberg, M. Paterno	
ABE	97F	PRL 78 2906	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	97G	PR D55 5263	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	97S	PRL 79 2192	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	97W	PRL 79 3819	F. Abe <i>et al.</i>	(CDF Collab.)
ABE	97X	PRL 79 4327	F. Abe <i>et al.</i>	(CDF Collab.)
ACCIARRI	97Q	PL B412 201	M. Acciarri <i>et al.</i>	(L3 Collab.)
ARIMA	97	PR D55 19	T. Arima <i>et al.</i>	(VENUS Collab.)
BARENBOIM	97	PR D55 4213	G. Barenboim <i>et al.</i>	(VALE, IFIC)
DEANDREA	97	PL B409 277	A. Deandrea	(MARS)
DERRICK	97	ZPHY C73 613	M. Derrick <i>et al.</i>	(ZEUS Collab.)
GROSSMAN	97	PR D55 2768	Y. Grossman, Z. Ligeti, E. Nardi	(REHO, CIT)
JADACH	97	PL B408 281	S. Jadach, B.F.L. Ward, Z. Was	(CERN, INPK+)
STAHL	97	ZPHY C74 73	A. Stahl, H. Voss	(BONN)
ABACHI	96C	PRL 76 3271	S. Abachi <i>et al.</i>	(D0 Collab.)
ABREU	96T	ZPHY C72 179	P. Abreu <i>et al.</i>	(DELPHI Collab.)



ADAM	96C	PL B380 471	W. Adam <i>et al.</i>	(DELPHI Collab.)
AID	96B	PL B369 173	S. Aid <i>et al.</i>	(H1 Collab.)
ALLET	96	PL B383 139	M. Allet <i>et al.</i>	(VILL, LEUV, LOUV, WISC)
ABACHI	95E	PL B358 405	S. Abachi <i>et al.</i>	(D0 Collab.)
ABE	95N	PRL 74 3538	F. Abe <i>et al.</i>	(CDF Collab.)
BALEST	95	PR D51 2053	R. Balest <i>et al.</i>	(CLEO Collab.)
KUZNETSOV	95	PRL 75 794	I.A. Kuznetsov <i>et al.</i>	(PNPI, KIAE, HARV+)
KUZNETSOV	95B	PAN 58 2113	A.V. Kuznetsov, N.V. Mikheev	(YARO)
		Translated from YAF 58 2228.		
MIZUKOSHI	95	NP B443 20	J.K. Mizukoshi, O.J.P. Eboli, M.C. Gonzalez-Garcia	
ABREU	94O	ZPHY C64 183	P. Abreu <i>et al.</i>	(DELPHI Collab.)
BHATTACH...	94	PL B336 100	G. Bhattacharyya, J. Ellis, K. Sridhar	(CERN)
Also		PL B338 522 (erratum)	G. Bhattacharyya, J. Ellis, K. Sridhar	(CERN)
BHATTACH...	94B	PL B338 522 (erratum)	G. Bhattacharyya, J. Ellis, K. Sridhar	(CERN)
DAVIDSON	94	ZPHY C61 613	S. Davidson, D. Bailey, B.A. Campbell	(CFPA+)
KUZNETSOV	94	PL B329 295	A.V. Kuznetsov, N.V. Mikheev	(YARO)
KUZNETSOV	94B	JETPL 60 315	I.A. Kuznetsov <i>et al.</i>	(PNPI, KIAE, HARV+)
		Translated from ZETFP 60 311.		
LEURER	94	PR D50 536	M. Leurer	(REHO)
LEURER	94B	PR D49 333	M. Leurer	(REHO)
Also		PRL 71 1324	M. Leurer	(REHO)
MAHANTA	94	PL B337 128	U. Mahanta	(MEHTA)
SEVERIJNS	94	PRL 73 611 (erratum)	N. Severijns <i>et al.</i>	(LOUV, WISC, LEUV+)
VILAIN	94B	PL B332 465	P. Vilain <i>et al.</i>	(CHARM II Collab.)
ABE	93C	PL B302 119	K. Abe <i>et al.</i>	(VENUS Collab.)
ABE	93D	PL B304 373	T. Abe <i>et al.</i>	(TOPAZ Collab.)
ABE	93G	PRL 71 2542	F. Abe <i>et al.</i>	(CDF Collab.)
ABREU	93J	PL B316 620	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ACTON	93E	PL B311 391	P.D. Acton <i>et al.</i>	(OPAL Collab.)
ADRIANI	93M	PRPL 236 1	O. Adriani <i>et al.</i>	(L3 Collab.)
ALITTI	93	NP B400 3	J. Alitti <i>et al.</i>	(UA2 Collab.)
BHATTACH...	93	PR D47 3693	G. Bhattacharyya <i>et al.</i>	(CALC, JADA, ICTP+)
BUSKULIC	93F	PL B308 425	D. Buskulic <i>et al.</i>	(ALEPH Collab.)
DERRICK	93	PL B306 173	M. Derrick <i>et al.</i>	(ZEUS Collab.)
RIZZO	93	PR D48 4470	T.G. Rizzo	(ANL)
SEVERIJNS	93	PRL 70 4047	N. Severijns <i>et al.</i>	(LOUV, WISC, LEUV+)
Also		PRL 73 611 (erratum)	N. Severijns <i>et al.</i>	(LOUV, WISC, LEUV+)
STERNER	93	PL B303 385	K.L. Sterner <i>et al.</i>	(AMY Collab.)
ABREU	92D	ZPHY C53 555	P. Abreu <i>et al.</i>	(DELPHI Collab.)
ADRIANI	92F	PL B292 472	O. Adriani <i>et al.</i>	(L3 Collab.)
DECAMP	92	PRPL 216 253	D. Decamp <i>et al.</i>	(ALEPH Collab.)
IMAZATO	92	PRL 69 877	J. Imazato <i>et al.</i>	(KEK, INUS, TOKY+)
MISHRA	92	PRL 68 3499	S.R. Mishra <i>et al.</i>	(COLU, CHIC, FNAL+)
POLAK	92B	PR D46 3871	J. Polak, M. Zralek	(SILES)
ACTON	91	PL B268 122	D.P. Acton <i>et al.</i>	(OPAL Collab.)
ACTON	91B	PL B273 338	D.P. Acton <i>et al.</i>	(OPAL Collab.)
ADEVA	91D	PL B262 155	B. Adeva <i>et al.</i>	(L3 Collab.)
AQUINO	91	PL B261 280	M. Aquino, A. Fernandez, A. Garcia	(CINV, PUEB)
COLANGELO	91	PL B253 154	P. Colangelo, G. Nardulli	(BARI)
CUYPERS	91	PL B259 173	F. Cuyper, A.F. Falk, P.H. Frampton	(DURH, HARV+)
FARAGGI	91	MPL A6 61	A.E. Faraggi, D.V. Nanopoulos	(TAMU)
POLAK	91	NP B363 385	J. Polak, M. Zralek	(SILES)
RIZZO	91	PR D44 202	T.G. Rizzo	(WISC, ISU)
WALKER	91	APJ 376 51	T.P. Walker <i>et al.</i>	(HSCA, OSU, CHIC+)
ABE	90F	PL B246 297	K. Abe <i>et al.</i>	(VENUS Collab.)
ABE	90H	PR D41 1722	F. Abe <i>et al.</i>	(CDF Collab.)
AKRAWY	90J	PL B246 285	M.Z. Akrawy <i>et al.</i>	(OPAL Collab.)
GONZALEZ...	90D	PL B240 163	M.C. Gonzalez-Garcia, J.W.F. Valle	(VALE)
GRIFOLS	90	NP B331 244	J.A. Grifols, E. Masso	(BARC)
GRIFOLS	90D	PR D42 3293	J.A. Grifols, E. Masso, T.G. Rizzo	(BARC, CERN+)
KIM	90	PL B240 243	G.N. Kim <i>et al.</i>	(AMY Collab.)
LOPEZ	90	PL B241 392	J.L. Lopez, D.V. Nanopoulos	(TAMU)
BARBIERI	89B	PR D39 1229	R. Barbieri, R.N. Mohapatra	(PISA, UMD)
LANGACKER	89B	PR D40 1569	P. Langacker, S. Uma Sankar	(PENN)
ODAKA	89	JPSJ 58 3037	S. Odaka <i>et al.</i>	(VENUS Collab.)
ROBINETT	89	PR D39 834	R.W. Robinett	(PSU)
ALBAJAR	88B	PL B209 127	C. Albajar <i>et al.</i>	(UA1 Collab.)
BAGGER	88	PR D37 1188	J. Bagger, C. Schmidt, S. King	(HARV, BOST)
BALKE	88	PR D37 587	B. Balke <i>et al.</i>	(LBL, UCB, COLO, NWES+)
BERGSTROM	88	PL B212 386	L. Bergstrom	(STOH)
CUYPERS	88	PRL 60 1237	F. Cuyper, P.H. Frampton	(UNCCH)

DONCHESKI	88	PL B206 137	M.A. Doncheski, H. Grotch, R. Robinett	(PSU)
DONCHESKI	88B	PR D38 412	M.A. Doncheski, H. Grotch, R.W. Robinett	(PSU)
BARTEL	87B	ZPHY C36 15	W. Bartel <i>et al.</i>	(JADE Collab.)
BEHREND	86B	PL B178 452	H.J. Behrend <i>et al.</i>	(CELLO Collab.)
DERRICK	86	PL 166B 463	M. Derrick <i>et al.</i>	(HRS Collab.)
Also		PR D34 3286	M. Derrick <i>et al.</i>	(HRS Collab.)
JODIDIO	86	PR D34 1967	A. Jodidio <i>et al.</i>	(LBL, NWES, TRIU)
Also		PR D37 237 (erratum)	A. Jodidio <i>et al.</i>	(LBL, NWES, TRIU)
MOHAPATRA	86	PR D34 909	R.N. Mohapatra	(UMD)
ADEVA	85	PL 152B 439	B. Adeva <i>et al.</i>	(Mark-J Collab.)
BERGER	85B	ZPHY C27 341	C. Berger <i>et al.</i>	(PLUTO Collab.)
STOKER	85	PRL 54 1887	D.P. Stoker <i>et al.</i>	(LBL, NWES, TRIU)
ADEVA	84	PRL 53 134	B. Adeva <i>et al.</i>	(Mark-J Collab.)
BEHREND	84C	PL 140B 130	H.J. Behrend <i>et al.</i>	(CELLO Collab.)
BERGSMA	83	PL 122B 465	F. Bergsma <i>et al.</i>	(CHARM Collab.)
CARR	83	PRL 51 627	J. Carr <i>et al.</i>	(LBL, NWES, TRIU)
BEALL	82	PRL 48 848	G. Beall, M. Bander, A. Soni	(UCI, UCLA)
SHANKER	82	NP B204 375	O. Shanker	(TRIU)

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