Extra Dimensions

For explanation of terms used and discussion of significant model dependence of following limits, see the "Extra Dimensions" review. Footnotes describe originally quoted limit. δ indicates the number of extra dimensions.

Limits not encoded here are summarized in the "Extra Dimensions" review, where the latest unpublished results are also described.

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CONTENTS:

Limits on *R* from Deviations in Gravitational Force Law

This section includes limits on the size of extra dimensions from deviations in the Newtonian ($1/r^2$) gravitational force law at short distances. Deviations are parametrized by a gravitational potential of the form $V = -(G\ m\ m'/r)\ [1 + \alpha\ \exp(-r/R)]$. For δ toroidal extra dimensions of equal size, $\alpha = 8\delta/3$. Quoted bounds are for $\delta = 2$ unless otherwise noted.

VALUE (μm)	CL%	DOCUMENT ID		COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
		[1] BEZERRA	11	Torsion oscillator
		[2] SUSHKOV	11	Torsion pendulum
		[3] BEZERRA	10	Microcantilever
		[4] MASUDA	09	Torsion pendulum
		[5] GERACI	08	Microcantilever
		[6] TRENKEL	08	Newton's constant
		[7] DECCA	07A	Torsion oscillator
$<$ 30	95	[8] KAPNER	07	Torsion pendulum
$<$ 47	95	[9] TU	07	Torsion pendulum
		[10] SMULLIN	05	Microcantilever
$<$130	95	[11] HOYLE	04	Torsion pendulum
		[12] CHIAVERINI	03	Microcantilever
$\lesssim$ 200	95	[13] LONG	03	Microcantilever
$<$190	95	[14] HOYLE	01	Torsion pendulum
		[15] HOSKINS	85	Torsion pendulum

[1] BEZERRA 11 obtain constraints on non-Newtonian forces with strengths $10^{11} \lesssim |\alpha| \lesssim 10^{18}$ and length scales R = 30–1260 nm. See their Fig. 2 for more details. These constraints do not place limits on the size of extra flat dimensions.

[2] SUSHKOV 11 obtain improved limits on non-Newtonian forces with strengths $10^7 \lesssim |\alpha| \lesssim 10^{11}$ and length scales 0.4 μm $< R <$ 4 μm (95% CL). See their Fig. 2. These bounds do not place limits on the size of extra flat dimensions. However, a model dependent bound of $M_* > 70$ TeV is obtained assuming gauge bosons that couple to baryon number also propagate in $(4 + \delta)$ dimensions.

[3] BEZERRA 10 obtain improved constraints on non-Newtonian forces with strengths $10^{19} \lesssim |\alpha| \lesssim 10^{29}$ and length scales R = 1.6–14 nm (95% CL). See their Fig. 1. This bound does not place limits on the size of extra flat dimensions.

[4] MASUDA 09 obtain improved constraints on non-Newtonian forces with strengths $10^9 \lesssim |\alpha| \lesssim 10^{11}$ and length scales R = 1.0–2.9 μm (95% CL). See their Fig. 3. This bound does not place limits on the size of extra flat dimensions.

[5] GERACI 08 obtain improved constraints on non-Newtonian forces with strengths $|\alpha| >$ 14,000 and length scales R = 5–15 μm. See their Fig. 9. This bound does not place limits on the size of extra flat dimensions.

[6] TRENKEL 08 uses two independent measurements of Newton's constant G to constrain new forces with strength $|\alpha| \simeq 10^{-4}$ and length scales R = 0.02–1 m. See their Fig. 1. This bound does not place limits on the size of extra flat dimensions.

[7] DECCA 07A search for new forces and obtain bounds in the region with strengths $|\alpha| \simeq 10^{13}$–10^{18} and length scales R = 20–86 nm. See their Fig. 6. This bound does not place limits on the size of extra flat dimensions.

[8] KAPNER 07 search for new forces, probing a range of $\alpha \simeq 10^{-3}$–10^5 and length scales $R \simeq$ 10–1000 μm. For $\delta = 1$ the bound on R is 44 μm. For $\delta = 2$, the bound is expressed in terms of M_*, here translated to a bound on the radius. See their Fig. 6 for details on the bound.

[9] TU 07 search for new forces probing a range of $|\alpha| \simeq 10^{-1}$–10^5 and length scales $R \simeq$ 20–1000 μm. For $\delta = 1$ the bound on R is 53 μm. See their Fig. 3 for details on the bound.

[10] SMULLIN 05 search for new forces, and obtain bounds in the region with strengths $\alpha \simeq 10^3$–10^8 and length scales R = 6–20 μm. See their Figs. 1 and 16 for details on the bound. This work does not place limits on the size of extra flat dimensions.

[11] HOYLE 04 search for new forces, probing α down to 10^{-2} and distances down to 10μm. Quoted bound on R is for $\delta = 2$. For $\delta = 1$, bound goes to 160 μm. See their Fig. 34 for details on the bound.

[12] CHIAVERINI 03 search for new forces, probing α above 10^4 and λ down to 3μm, finding no signal. See their Fig. 4 for details on the bound. This bound does not place limits on the size of extra flat dimensions.

[13] LONG 03 search for new forces, probing α down to 3, and distances down to about 10μm. See their Fig. 4 for details on the bound.

[14] HOYLE 01 search for new forces, probing α down to 10^{-2} and distances down to 20μm. See their Fig. 4 for details on the bound. The quoted bound is for $\alpha \geq 3$.

[15] HOSKINS 85 search for new forces, probing distances down to 4 mm. See their Fig. 13 for details on the bound. This bound does not place limits on the size of extra flat dimensions.

Limits on R from On-Shell Production of Gravitons: $\delta = 2$

This section includes limits on on-shell production of gravitons in collider and astrophysical processes. Bounds quoted are on R, the assumed common radius of the flat extra dimensions, for $\delta = 2$ extra dimensions. Studies often quote bounds in terms of derived parameter; experiments are actually sensitive to the masses of the KK gravitons: $m_{\vec{n}} = |\vec{n}|/R$. See the Review on "Extra Dimensions" for details. Bounds are given in μm for δ=2.

VALUE (μm)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 92	95	[16] AAD	11S	ATLS	$p p \to j G$
$<$ 72	95	[17] CHATRCHYAN	11U	CMS	$p p \to j G$
$<$ 245	95	[18] AALTONEN	08AC	CDF	$p \overline{p} \to \gamma G, j G$
$<$ 615	95	[19] ABAZOV	08S	D0	$p \overline{p} \to \gamma G$
$<$ 0.916	95	[20] DAS	08		Supernova cooling
$<$ 350	95	[21] ABULENCIA,A	06	CDF	$p \overline{p} \to j G$
$<$ 270	95	[22] ABDALLAH	05B	DLPH	$e^+ e^- \to \gamma G$
$<$ 210	95	[23] ACHARD	04E	L3	$e^+ e^- \to \gamma G$
$<$ 480	95	[24] ACOSTA	04C	CDF	$\overline{p} p \to j G$
$<$ 0.00038	95	[25] CASSE	04		Neutron star γ sources
$<$ 610	95	[26] ABAZOV	03	D0	$\overline{p} p \to j G$
$<$ 0.96	95	[27] HANNESTAD	03		Supernova cooling
$<$ 0.096	95	[28] HANNESTAD	03		Diffuse γ background
$<$ 0.051	95	[29] HANNESTAD	03		Neutron star γ sources
$<$ 0.00016	95	[30] HANNESTAD	03		Neutron star heating
$<$ 300	95	[31] HEISTER	03C	ALEP	$e^+ e^- \to \gamma G$
		[32] FAIRBAIRN	01		Cosmology
$<$ 0.66	95	[33] HANHART	01		Supernova cooling
		[34] CASSISI	00		Red giants
$<$1300	95	[35] ACCIARRI	99S	L3	$e^+ e^- \to Z G$

Limits on *R* from On-Shell Production of Gravitons: $\delta \geq 3$

This section includes limits similar to those in the previous section, but for $\delta = 3$ extra dimensions. Bounds are given in nm for $\delta = 3$. Entries are also shown for papers examining models with $\delta > 3$.

VALUE (nm)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<$ 1.1	95	[16] AAD	11S	ATLS	$p p \to j G$
$<$ 1.05	95	[17] CHATRCHYAN	11U	CMS	$p p \to j G$
$<$ 2.8	95	[18] AALTONEN	08AC	CDF	$p \overline{p} \to \gamma G, j G$
$<$ 4.56	95	[19] ABAZOV	08S	D0	$p \overline{p} \to \gamma G$
$<$ 2.09	95	[20] DAS	08		Supernova cooling
$<$ 3.6	95	[21] ABULENCIA,A	06	CDF	$p \overline{p} \to j G$
$<$ 3.5	95	[22] ABDALLAH	05B	DLPH	$e^+ e^- \to \gamma G$
$<$ 2.9	95	[23] ACHARD	04E	L3	$e^+ e^- \to \gamma G$
	95	[24] ACOSTA	04C	CDF	$\overline{p} p \to j G$
$<$ 0.0042	95	[25] CASSE	04		Neutron star γ sources
$<$ 6.1	95	[26] ABAZOV	03	D0	$\overline{p} p \to j G$
$<$ 1.14	95	[27] HANNESTAD	03		Supernova cooling
$<$ 0.025	95	[28] HANNESTAD	03		Diffuse γ background
$<$ 0.11	95	[29] HANNESTAD	03		Neutron star γ sources
$<$ 0.0026	95	[30] HANNESTAD	03		Neutron star heating
$<$ 3.9	95	[31] HEISTER	03C	ALEP	$e^+ e^- \to \gamma G$
		[32] FAIRBAIRN	01		Cosmology
$<$ 0.8	95	[33] HANHART	01		Supernova cooling
		[34] CASSISI	00		Red giants
$<$18	95	[35] ACCIARRI	99S	L3	$e^+ e^- \to Z G$

[16] AAD 11S search for $pp \rightarrow jG$, using 33 pb^{-1} of data at $\sqrt{s} = 7$ TeV, to place bounds on M_D for two to four extra dimensions, from which these bounds on R are derived. See their Table 3 for bounds on all $\delta \leq 4$.

[17] CHATRCHYAN 11U search for $pp \rightarrow jG$, using 36 pb^{-1} of data at $\sqrt{s} = 7$ TeV, to place bounds on M_D for two to six extra dimensions, from which these bounds on R are derived. See their Table 3 for bounds on all $\delta \leq 6$.

[18] AALTONEN 08AC search for $p\overline{p} \rightarrow \gamma G$ and $p\overline{p} \rightarrow jG$ at $\sqrt{s} = 1.96$ TeV with 2.0 fb^{-1} and 1.1 fb^{-1} respectively, in order to place bounds on the fundamental scale and size of the extra dimensions. See their Table III for limits on all $\delta \leq 6$.

[19] ABAZOV 08S search for $p\overline{p} \rightarrow \gamma G$, using 1 fb^{-1} of data at $\sqrt{s} = 1.96$ TeV to place bounds on M_D for two to eight extra dimensions, from which these bounds on R are derived. See their paper for intermediate values of δ.

[20] DAS 08 obtain a limit on R from Kaluza-Klein graviton cooling of SN1987A due to plasmon-plasmon annihilation.

[21] ABULENCIA,A 06 search for $p\overline{p} \rightarrow jG$ using 368 pb^{-1} of data at $\sqrt{s} = 1.96$ TeV. See their Table II for bounds for all $\delta \leq 6$.

[22] ABDALLAH 05B search for $e^+e^- \rightarrow \gamma G$ at $\sqrt{s} =$ 180–209 GeV to place bounds on the size of extra dimensions and the fundamental scale. Limits for all $\delta \leq 6$ are given in their Table 6. These limits supersede those in ABREU 00Z.

[23] ACHARD 04E search for $e^+e^- \rightarrow \gamma G$ at $\sqrt{s} =$ 189–209 GeV to place bounds on the size of extra dimensions and the fundamental scale. See their Table 8 for limits with $\delta \leq 8$. These limits supersede those in ACCIARRI 99R.

[24] ACOSTA 04C search for $\overline{p}p \rightarrow jG$ at $\sqrt{s} = 1.8$ TeV to place bounds on the size of extra dimensions and the fundamental scale. See their paper for bounds on $\delta = 4, 6$.

[25] CASSE 04 obtain a limit on R from the gamma-ray emission of point γ sources that arises from the photon decay of gravitons around newly born neutron stars, applying the technique of HANNESTAD 03 to neutron stars in the galactic bulge. Limits for all $\delta \leq 7$ are given in their Table I.

[26] ABAZOV 03 search for $p\overline{p} \rightarrow jG$ at $\sqrt{s}$=1.8 TeV to place bounds on M_D for 2 to 7 extra dimensions, from which these bounds on R are derived. See their paper for bounds on intermediate values of δ. We quote results without the approximate NLO scaling introduced in the paper.

[27] HANNESTAD 03 obtain a limit on R from graviton cooling of supernova SN1987a. Limits for all $\delta \leq 7$ are given in their Tables V and VI.

[28] HANNESTAD 03 obtain a limit on R from gravitons emitted in supernovae and which subsequently decay, contaminating the diffuse cosmic γ background. Limits for all $\delta \leq 7$ are given in their Tables V and VI. These limits supersede those in HANNESTAD 02.

[29] HANNESTAD 03 obtain a limit on R from gravitons emitted in two recent supernovae and which subsequently decay, creating point γ sources. Limits for all $\delta \leq 7$ are given in their Tables V and VI. These limits are corrected in the published erratum.

[30] HANNESTAD 03 obtain a limit on R from the heating of old neutron stars by the surrounding cloud of trapped KK gravitons. Limits for all $\delta \leq 7$ are given in their Tables V and VI. These limits supersede those in HANNESTAD 02.

[31] HEISTER 03C use the process $e^+e^- \rightarrow \gamma G$ at $\sqrt{s} =$ 189–209 GeV to place bounds on the size of extra dimensions and the scale of gravity. See their Table 4 for limits with $\delta \leq 6$ for derived limits on M_D.

[32] FAIRBAIRN 01 obtains bounds on R from over production of KK gravitons in the early universe. Bounds are quoted in paper in terms of fundamental scale of gravity. Bounds depend strongly on temperature of QCD phase transition and range from $R< 0.13\,\mu$m to 0.001 μm for δ=2; bounds for δ=3,4 can be derived from Table 1 in the paper.

[33] HANHART 01 obtain bounds on R from limits on graviton cooling of supernova SN 1987a using numerical simulations of proto-neutron star neutrino emission.

[34] CASSISI 00 obtain rough bounds on M_D (and thus R) from red giant cooling for δ=2,3. See their paper for details.

[35] ACCIARRI 99S search for $e^+e^- \rightarrow ZG$ at $\sqrt{s}$=189 GeV. Limits on the gravity scale are found in their Table 2, for $\delta \leq 4$.

Mass Limits on M_{TT}

This section includes limits on the cut-off mass scale, M_{TT}, of dimension-8 operators from KK graviton exchange in models of large extra dimensions. Ambiguities in the UV-divergent summation are absorbed into the parameter λ, which is taken to be $\lambda = \pm1$ in the following analyses. Bounds for $\lambda = -1$ are shown in parenthesis after the bound for $\lambda = +1$, if appropriate. Different papers use slightly different definitions of the mass scale. The definition used here is related to another popular convention by $M^4_{TT} = (2/\pi)\ \Lambda^4_T$, as discussed in the above Review on "Extra Dimensions."

VALUE (TeV)		CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •						
$>$ 0.90	(>0.92)	95	[36] AARON	11C	H1	$e^\pm p \rightarrow e^\pm X$
$>$ 1.74	(>1.71)	95	[37] CHATRCHYAN	11A	CMS	$pp \rightarrow \gamma\gamma$
$>$ 1.48		95	[38] ABAZOV	09AE	D0	$p\overline{p} \rightarrow$ dijet, angular distrib.
$>$ 1.45		95	[39] ABAZOV	09D	D0	$p\overline{p} \rightarrow e^+e^-, \gamma\gamma$
$>$ 1.1	($>$ 1.0)	95	[40] SCHAEL	07A	ALEP	$e^+e^- \rightarrow e^+e^-$
$>$ 0.898	($>$ 0.998)	95	[41] ABDALLAH	06C	DLPH	$e^+e^- \rightarrow \ell^+\ell^-$
$>$ 0.853	($>$ 0.939)	95	[42] GERDES	06		$p\overline{p} \rightarrow e^+e^-, \gamma\gamma$
$>$ 0.96	($>$ 0.93)	95	[43] ABAZOV	05V	D0	$p\overline{p} \rightarrow \mu^+\mu^-$
$>$ 0.78	($>$ 0.79)	95	[44] CHEKANOV	04B	ZEUS	$e^\pm p \rightarrow e^\pm X$
$>$ 0.805	($>$ 0.956)	95	[45] ABBIENDI	03D	OPAL	$e^+e^- \rightarrow \gamma\gamma$
$>$ 0.7	($>$ 0.7)	95	[46] ACHARD	03D	L3	$e^+e^- \rightarrow ZZ$
$>$ 0.82	($>$ 0.78)	95	[47] ADLOFF	03	H1	$e^\pm p \rightarrow e^\pm X$
$>$ 1.28	($>$ 1.25)	95	[48] GIUDICE	03	RVUE	
$>$20.6	($>$ 15.7)	95	[49] GIUDICE	03	RVUE	Dim-6 operators
$>$ 0.80	($>$ 0.85)	95	[50] HEISTER	03C	ALEP	$e^+e^- \rightarrow \gamma\gamma$
$>$ 0.84	($>$ 0.99)	95	[51] ACHARD	02D	L3	$e^+e^- \rightarrow \gamma\gamma$
$>$ 1.2	($>$ 1.1)	95	[52] ABBOTT	01	D0	$p\overline{p} \rightarrow e^+e^-, \gamma\gamma$
$>$ 0.60	($>$ 0.63)	95	[53] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \mu^+\mu^-$
$>$ 0.63	($>$ 0.50)	95	[53] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \tau^+\tau^-$
$>$ 0.68	($>$ 0.61)	95	[53] ABBIENDI	00R	OPAL	$e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-$
			[54] ABREU	00A	DLPH	$e^+e^- \rightarrow \gamma\gamma$
$>$ 0.680	($>$ 0.542)	95	[55] ABREU	00S	DLPH	$e^+e^- \rightarrow \mu^+\mu^-, \tau^+\tau^-$
$>$ 15–28		99.7	[56] CHANG	00B	RVUE	Electroweak
$>$ 0.98		95	[57] CHEUNG	00	RVUE	$e^+e^- \rightarrow \gamma\gamma$
$>$ 0.29–0.38		95	[58] GRAESSER	00	RVUE	$(g-2)_\mu$
$>$ 0.50–1.1		95	[59] HAN	00	RVUE	Electroweak
$>$ 2.0	($>$ 2.0)	95	[60] MATHEWS	00	RVUE	$\overline{p}p \rightarrow jj$
$>$ 1.0	($>$ 1.1)	95	[61] MELE	00	RVUE	$e^+e^- \rightarrow VV$
			[62] ABBIENDI	99P	OPAL	
			[63] ACCIARRI	99M	L3	
			[64] ACCIARRI	99S	L3	
$>$ 1.412	($>$ 1.077)	95	[65] BOURILKOV	99		$e^+e^- \rightarrow e^+e^-$

[36] AARON 11C search for deviations in the differential cross section of $e^{\pm} p \rightarrow e^{\pm} X$ in 446 pb^{-1} of data taken at $\sqrt{s} = 301$ and 319 GeV to place a bound on M_{TT}.

[37] CHATRCHYAN 11A use 36 pb^{-1} of data from pp collisions at $\sqrt{s} = 7$ TeV to place lower limits on Λ_T, here converted to M_{TT}.

[38] ABAZOV 09AE use dijet angular distributions in 0.7 fb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV to place lower bounds on Λ_T (equivalent to their M_S), here converted to M_{TT}.

[39] ABAZOV 09D use 1.05 fb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV to place lower bounds on Λ_T (equivalent to their M_s), here converted to M_{TT}.

[40] SCHAEL 07A use e^+e^- collisions at $\sqrt{s} = 189$–209 GeV to place lower limits on Λ_T, here converted to limits on M_{TT}.

[41] ABDALLAH 06C use e^+e^- collisions at $\sqrt{s} \sim 130$–207 GeV to place lower limits on M_{TT}, which is equivalent to their definition of M_s. Bound shown includes all possible final state leptons, $\ell = e$, μ, τ. Bounds on individual leptonic final states can be found in their Table 31.

[42] GERDES 06 use 100 to 110 pb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV, as recorded by the CDF Collaboration during Run I of the Tevatron. Bound shown includes a K-factor of 1.3. Bounds on individual e^+e^- and $\gamma\gamma$ final states are found in their Table I.

[43] ABAZOV 05V use 246 pb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV to search for deviations in the differential cross section to $\mu^+\mu^-$ from graviton exchange.

[44] CHEKANOV 04B search for deviations in the differential cross section of $e^{\pm} p \rightarrow e^{\pm} X$ with 130 pb^{-1} of combined data and Q^2 values up to 40,000 GeV^2 to place a bound on M_{TT}.

[45] ABBIENDI 03D use e^+e^- collisions at $\sqrt{s}$=181–209 GeV to place bounds on the ultraviolet scale M_{TT}, which is equivalent to their definition of M_s.

[46] ACHARD 03D look for deviations in the cross section for $e^+e^- \rightarrow ZZ$ from $\sqrt{s}$ = 200–209 GeV to place a bound on M_{TT}.

[47] ADLOFF 03 search for deviations in the differential cross section of $e^{\pm} p \rightarrow e^{\pm} X$ at $\sqrt{s}$=301 and 319 GeV to place bounds on M_{TT}.

[48] GIUDICE 03 review existing experimental bounds on M_{TT} and derive a combined limit.

[49] GIUDICE 03 place bounds on Λ_6, the coefficient of the gravitationally-induced dimension-6 operator $(2\pi\lambda/\Lambda_6^2)(\sum \overline{f}\gamma_\mu\gamma^5 f)(\sum \overline{f}\gamma^\mu\gamma^5 f)$, using data from a variety of experiments. Results are quoted for $\lambda = \pm 1$ and are independent of δ.

[50] HEISTER 03C use e^+e^- collisions at $\sqrt{s}$= 189–209 GeV to place bounds on the scale of dim-8 gravitational interactions. Their $M_s^{\pm}$ is equivalent to our M_{TT} with $\lambda = \pm 1$.

[51] ACHARD 02 search for s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at E_{cm} = 192–209 GeV.

[52] ABBOTT 01 search for variations in differential cross sections to e^+e^- and $\gamma\gamma$ final states at the Tevatron.

[53] ABBIENDI 00R uses e^+e^- collisions at $\sqrt{s}$= 189 GeV.

[54] ABREU 00A search for s-channel graviton exchange effects in $e^+e^- \rightarrow \gamma\gamma$ at E_{cm}= 189–202 GeV.

[55] ABREU 00S uses e^+e^- collisions at $\sqrt{s}$=183 and 189 GeV. Bounds on μ and τ individual final states given in paper.

[56] CHANG 00B derive 3σ limit on M_{TT} of (28,19,15) TeV for δ=(2,4,6) respectively assuming the presence of a torsional coupling in the gravitational action. Highly model dependent.

[57] CHEUNG 00 obtains limits from anomalous diphoton production at OPAL due to graviton exchange. Original limit for δ=4. However, unknown UV theory renders δ dependence unreliable. Original paper works in HLZ convention.

[58] GRAESSER 00 obtains a bound from graviton contributions to $g-2$ of the muon through loops of 0.29 TeV for δ=2 and 0.38 TeV for δ=4,6. Limits scale as $\lambda^{1/2}$. However

calculational scheme not well-defined without specification of high-scale theory. See the "Extra Dimensions Review."

[59] HAN 00 calculates corrections to gauge boson self-energies from KK graviton loops and constrain them using S and T. Bounds on M_{TT} range from 0.5 TeV (δ=6) to 1.1 TeV (δ=2); see text. Limits have strong dependence, $\lambda^{\delta+2}$, on unknown λ coefficient.

[60] MATHEWS 00 search for evidence of graviton exchange in CDF and DØ dijet production data. See their Table 2 for slightly stronger δ-dependent bounds. Limits expressed in terms of $\widetilde{M}_S^4 = M_{TT}^4/8$.

[61] MELE 00 obtains bound from KK graviton contributions to $e^+ e^- \rightarrow VV$ (V=γ,W,Z) at LEP. Authors use Hewett conventions.

[62] ABBIENDI 99P search for s-channel graviton exchange effects in $e^+ e^- \rightarrow \gamma\gamma$ at E_{cm}=189 GeV. The limits $G_+ > 660$ GeV and $G_- > 634$ GeV are obtained from combined E_{cm}=183 and 189 GeV data, where $G_\pm$ is a scale related to the fundamental gravity scale.

[63] ACCIARRI 99M search for the reaction $e^+ e^- \rightarrow \gamma G$ and s-channel graviton exchange effects in $e^+ e^- \rightarrow \gamma\gamma$, $W^+ W^-$, ZZ, $e^+ e^-$, $\mu^+ \mu^-$, $\tau^+ \tau^-$, $q\overline{q}$ at E_{cm}=183 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.

[64] ACCIARRI 99S search for the reaction $e^+ e^- \rightarrow ZG$ and s-channel graviton exchange effects in $e^+ e^- \rightarrow \gamma\gamma$, $W^+ W^-$, ZZ, $e^+ e^-$, $\mu^+ \mu^-$, $\tau^+ \tau^-$, $q\overline{q}$ at E_{cm}=189 GeV. Limits on the gravity scale are listed in their Tables 1 and 2.

[65] BOURILKOV 99 performs global analysis of LEP data on $e^+ e^-$ collisions at $\sqrt{s}$=183 and 189 GeV. Bound is on Λ_T.

Direct Limits on Gravitational or String Mass Scale

This section includes limits on the fundamental gravitational scale and/or the string scale from processes which depend directly on one or the other of these scales.

VALUE (TeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$\gtrsim$ 1–2	[66] ANCHORDOQ...	02B	RVUE	Cosmic Rays
>0.49	[67] ACCIARRI	00P	L3	$e^+ e^- \rightarrow e^+ e^-$

[66] ANCHORDOQUI 02B derive bound on M_D from non-observation of black hole production in high-energy cosmic rays. Bound is stronger for larger δ, but depends sensitively on threshold for black hole production.

[67] ACCIARRI 00P uses $e^+ e^-$ collisions at $\sqrt{s}$= 183 and 189 GeV. Bound on string scale M_s from massive string modes. M_s is defined in hep-ph/0001166 by $M_s(1/\pi)^{1/8}\alpha^{-1/4} = M$ where $(4\pi G)^{-1} = M^{n+2}R^n$.

Limits on $1/R = M_c$

This section includes limits on $1/R = M_c$, the compactification scale in models with TeV extra dimensions, due to exchange of Standard Model KK excitations. Bounds assume fermions are not in the bulk, unless stated otherwise. See the "Extra Dimensions" review for discussion of model dependence.

VALUE (TeV)	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
>0.729	95	[68] AAD	11F	ATLS	$pp \rightarrow \gamma\gamma$, δ=6, M_D=5 TeV
>0.961	95	[69] AAD	11X	ATLS	$pp \rightarrow \gamma\gamma$, δ=6, M_D=5 TeV

>0.477	95	[70] ABAZOV	10P	D0	$p\overline{p} \to \gamma\gamma$, δ=6, M_D=5 TeV
>1.59	95	[71] ABAZOV	09AE	D0	$p\overline{p} \to$ dijet, angular dist.
>0.6	95	[72] HAISCH	07	RVUE	$\overline{B} \to X_s\gamma$
>0.6	90	[73] GOGOLADZE	06	RVUE	Electroweak
>3.3	95	[74] CORNET	00	RVUE	Electroweak
> 3.3–3.8	95	[75] RIZZO	00	RVUE	Electroweak

[68] AAD 11F use diphoton events with large missing transverse energy in 3.1 pb^{-1} of data produced from pp collisions at $\sqrt{s}$ = 7 TeV to place a lower bound on the compactification scale in a universal extra dimension model with gravitational decays. The bound assumes that the cutoff scale Λ, for the radiative corrections to the Kaluza-Klein masses, satisfies Λ/M_c = 20. The model parameters are chosen such that the decay $\gamma^* \to G\gamma$ occurs with an appreciable branching fraction.

[69] AAD 11X use diphoton events with large missing transverse energy in 36 pb^{-1} of data produced from pp collisions at $\sqrt{s}$ = 7 TeV to place a lower bound on the compactification scale in a universal extra dimension model with gravitational decays. The bound assumes that the cutoff scale Λ, for the radiative corrections to the Kaluza-Klein masses, satisfies Λ/M_c = 20. The model parameters are chosen such that the decay $\gamma^* \to G\gamma$ occurs with an appreciable branching fraction.

[70] ABAZOV 10P use diphoton events with large missing transverse energy in 6.3 fb^{-1} of data produced from $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to place a lower bound on the compactification scale in a universal extra dimension model with gravitational decays. The bound assumes that the cutoff scale Λ, for the radiative corrections to the Kaluza-Klein masses, satisfies Λ/M_c=20. The model parameters are chosen such that the decay $\gamma^* \to G\gamma$ occurs with an appreciable branching fraction.

[71] ABAZOV 09AE use dijet angular distributions in 0.7 fb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to place a lower bound on the compactification scale.

[72] HAISCH 07 use inclusive $\overline{B}$-meson decays to place a Higgs mass independent bound on the compactification scale $1/R$ in the minimal universal extra dimension model.

[73] GOGOLADZE 06 use electroweak precision observables to place a lower bound on the compactification scale in models with universal extra dimensions. Bound assumes a 115 GeV Higgs mass. See their Fig. 3 for the bound as a function of the Higgs mass.

[74] CORNET 00 translates a bound on the coefficient of the 4-fermion operator $(\overline{\ell}\gamma_\mu\tau^a\ell)(\overline{\ell}\gamma^\mu\tau^a\ell)$ derived by Hagiwara and Matsumoto into a limit on the mass scale of KK W bosons.

[75] RIZZO 00 obtains limits from global electroweak fits in models with a Higgs in the bulk (3.8 TeV) or on the standard brane (3.3 TeV).

Limits on Kaluza-Klein Gravitons in Warped Extra Dimensions

This sections places limits on the mass of the first Kaluza-Klein (KK) excitation of the graviton in the warped extra dimension model of Randall and Sundrum. Experimental bounds depend strongly on the warp parameter, k. See the "Extra Dimensions" review for a full discussion.

Here we list limits for the value of the warp parameter $k/\overline{M}_P$ = 0.1.

VALUE (GeV)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>1630	95	[76] AAD	11AD	ATLS	$pp \to G \to \ell\overline{\ell}$

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

		[77] AALTONEN	11G	CDF	$p\overline{p} \to G \to ZZ$
>1058	95	[78] AALTONEN	11R	CDF	$p\overline{p} \to G \to e^+e^-, \gamma\gamma$
> 754	95	[79] ABAZOV	11H	D0	$p\overline{p} \to G \to WW$
>1079	95	[80] CHATRCHYAN	11	CMS	$pp \to G \to \ell\overline{\ell}$
> 607		[81] AALTONEN	10N	CDF	$p\overline{p} \to G \to WW$
>1050		[82] ABAZOV	10F	D0	$p\overline{p} \to G \to e^+e^-, \gamma\gamma$
		[83] AALTONEN	08S	CDF	$p\overline{p} \to G \to ZZ$
> 900		[84] ABAZOV	08J	D0	$p\overline{p} \to G \to e^+e^-, \gamma\gamma$
		[85] AALTONEN	07G	CDF	$p\overline{p} \to G \to \gamma\gamma$
> 889		[86] AALTONEN	07H	CDF	$p\overline{p} \to G \to e\overline{e}$
> 785		[87] ABAZOV	05N	D0	$p\overline{p} \to G \to \ell\ell, \gamma\gamma$
> 710		[88] ABULENCIA	05A	CDF	$p\overline{p} \to G \to \ell\overline{\ell}$

[76] AAD 11AD use 1.08 and 1.21 fb^{-1} of data from pp collisions at $\sqrt{s}$ = 7 TeV in the dielectron and dimuon channels, respectively, to place a lower bound on the mass of the lightest graviton. For warp parameter values $k/\overline{M}_P$ between 0.01 to 0.1 the lower limit on the mass of the lightest graviton is between 0.71 and 1.63 TeV. See their Table IV for more details.

[77] AALTONEN 11G use 2.5–2.9 fb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to search for KK gravitons in a warped extra dimension decaying to ZZ dibosons via the $eeee$, $ee\mu\mu$, $\mu\mu\mu\mu$, $eejj$, and $\mu\mu jj$ channels. See their Fig. 20 for limits on the cross section $\sigma(G \to ZZ)$ as a function of the graviton mass.

[78] AALTONEN 11R uses 5.7 fb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV in the dielectron channel to place a lower bound on the mass of the lightest graviton. It provides combined limits with the diphoton channel analysis of AALTONEN 11U. For warp parameter values $k/\overline{M}_P$ between 0.01 to 0.1 the lower limit on the mass of the lightest graviton is between 612 and 1058 GeV. See their Table I for more details.

[79] ABAZOV 11H use 5.4 fb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to place a lower bound on the mass of the lightest graviton. Their 95% C.L. exclusion limit does not include masses less than 300 GeV.

[80] CHATRCHYAN 11 use 35 and 40 pb^{-1} of data from pp collisions at $\sqrt{s}$ = 7 TeV in the dielectron and dimuon channels, respectively, to place a lower bound on the mass of the lightest graviton. For a warp parameter value $k/\overline{M}_P$ = 0.05, the lower limit on the mass of the lightest graviton is 0.855 TeV.

[81] AALTONEN 10N use 2.9 fb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to place a lower bound on the mass of the lightest graviton.

[82] ABAZOV 10F use 5.4 fb^{-1} of data from $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to place a lower bound on the mass of the lightest graviton. For warp parameter values of $k/\overline{M}_P$ between 0.01 and 0.1 the lower limit on the mass of the lightest graviton is between 560 and 1050 GeV. See their Fig. 3 for more details.

[83] AALTONEN 08S use $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to four electrons via two Z bosons using 1.1 fb^{-1} of data. See their Fig. 8 for limits on $\sigma \cdot$ B($G \to ZZ$) versus the graviton mass.

[84] ABAZOV 08J use $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to electrons and photons using 1 fb^{-1} of data. For warp parameter values of $k/\overline{M}_P$ between 0.01 and 0.1 the lower limit on the mass of the lightest excitation is between 300 and 900 GeV. See their Fig. 4 for more details.

[85] AALTONEN 07G use $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to photons using 1.2 fb^{-1} of data. For warp parameter values of $k/\overline{M}_P$ = 0.1, 0.05, and 0.01 the bounds on the graviton mass are 850, 694, and 230 GeV, respectively. See their Fig. 3 for more details. See also AALTONEN 07H.

[86] AALTONEN 07H use $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to electrons using 1.3 fb^{-1} of data. For a warp parameter value of $k/\overline{M}_P$ = 0.1 the bound on the graviton mass is 807 GeV. See their Fig. 4 for more details. A combined analysis with the diphoton data of AALTONEN 07G yields for $k/\overline{M}_P$ = 0.1 a graviton mass lower bound of 889 GeV.

[87] ABAZOV 05N use $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to muons, electrons or photons, using 260 pb^{-1} of data. For warp parameter values of $k/\overline{M}_P$ = 0.1, 0.05, and 0.01, the bounds on the graviton mass are 785, 650 and 250 GeV respectively. See their Fig. 3 for more details.

[88] ABULENCIA 05A use $p\overline{p}$ collisions at $\sqrt{s}$ = 1.96 TeV to search for KK gravitons in warped extra dimensions. They search for graviton resonances decaying to muons or electrons, using 200 pb^{-1} of data. For warp parameter values of $k/\overline{M}_P$ = 0.1, 0.05, and 0.01, the bounds on the graviton mass are 710, 510 and 170 GeV respectively.

Limits on Mass of Radion

This section includes limits on mass of radion, usually in context of Randall-Sundrum models. See the "Extra Dimension Review" for discussion of model dependence.

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •				
	[89] ABBIENDI	05	OPAL	$e^+e^- \rightarrow Z$ radion
$\gtrsim$ 35	[90] MAHANTA	00		$Z \rightarrow$ radion $\ell\overline{\ell}$
>120	[91] MAHANTA	00B		$p\overline{p} \rightarrow$ radion $\rightarrow \gamma\gamma$

[89] ABBIENDI 05 use e^+e^- collisions at $\sqrt{s}$ = 91 GeV and $\sqrt{s}$ = 189–209 GeV to place bounds on the radion mass in the RS model. See their Fig. 5 for bounds that depend on the radion-Higgs mixing parameter ξ and on $\Lambda_W = \Lambda_\phi/\sqrt{6}$. No parameter-independent bound is obtained.

[90] MAHANTA 00 obtain bound on radion mass in the RS model. Bound is from Higgs boson search at LEP I.

[91] MAHANTA 00B uses $p\overline{p}$ collisions at $\sqrt{s}$= 1.8 TeV; production via gluon-gluon fusion. Authors assume a radion vacuum expectation value of 1 TeV.

REFERENCES FOR Extra Dimensions

AAD	11AD	PRL 107 272002	G. Aad et al.	(ATLAS Collab.)
AAD	11F	PRL 106 121803	G. Aad et al.	(ATLAS Collab.)
AAD	11S	PL B705 294	G. Aad et al.	(ATLAS Collab.)
AAD	11X	EPJ C71 1744	G. Aad et al.	(ATLAS Collab.)
AALTONEN	11G	PR D83 112008	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	11R	PRL 107 051801	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	11U	PR D83 011102	T. Aaltonen et al.	(CDF Collab.)
AARON	11C	PL B705 52	F. D. Aaron et al.	(H1 Collab.)
ABAZOV	11H	PRL 107 011801	V. M. Abazov et al.	(D0 Collab.)
BEZERRA	11	PR D83 075004	V.B. Bezerra et al.	
CHATRCHYAN	11	JHEP 1105 093	S. Chatrchyan et al.	(CMS Collab.)
CHATRCHYAN	11A	JHEP 1105 085	S. Chatrchyan et al.	(CMS Collab.)
CHATRCHYAN	11U	PRL 107 201804	S. Chatychyan et al.	(CMS Collab.)
SUSHKOV	11	PRL 107 171101	A.O. Sushkov et al.	
AALTONEN	10N	PRL 104 241801	T. Aaltonen et al.	(CDF Collab.)
ABAZOV	10F	PRL 104 241802	V.M. Abazov et al.	(D0 Collab.)
ABAZOV	10P	PRL 105 221802	V.M. Abazov et al.	(D0 Collab.)
BEZERRA	10	PR D81 055003	V.B. Bezerra et al.	
ABAZOV	09AE	PRL 103 191803	V.M. Abazov et al.	(D0 Collab.)
ABAZOV	09D	PRL 102 051601	V.M. Abazov et al.	(D0 Collab.)
MASUDA	09	PRL 102 171101	M. Masuda, M. Sasaki	(ICRR)
AALTONEN	08AC	PRL 101 181602	T. Aaltonen et al.	(CDF Collab.)
AALTONEN	08S	PR D78 012008	T. Aaltonen et al.	(CDF Collab.)

ABAZOV	08J	PRL 100 091802	V.M. Abazov *et al.*	(D0 Collab.)
ABAZOV	08S	PRL 101 011601	V.M. Abazov *et al.*	(D0 Collab.)
DAS	08	PR D78 063011	P.K. Das, V.H.S. Kumar, P.K. Suresh	
GERACI	08	PR D78 022002	A.A. Geraci *et al.*	(STAN)
TRENKEL	08	PR D77 122001	C. Trenkel	
AALTONEN	07G	PRL 99 171801	T. Aaltonen *et al.*	(CDF Collab.)
AALTONEN	07H	PRL 99 171802	T. Aaltonen *et al.*	(CDF Collab.)
DECCA	07A	EPJ C51 963	R.S. Decca *et al.*	
HAISCH	07	PR D76 034014	U. Haisch, A. Weiler	
KAPNER	07	PRL 98 021101	D.J. Kapner *et al.*	
SCHAEL	07A	EPJ C49 411	S. Schael *et al.*	(ALEPH Collab.)
TU	07	PRL 98 201101	L.-C. Tu *et al.*	
ABDALLAH	06C	EPJ C45 589	J. Abdallah *et al.*	(DELPHI Collab.)
ABULENCIA,A	06	PRL 97 171802	A. Abulencia *et al.*	(CDF Collab.)
GERDES	06	PR D73 112008	D. Gerdes *et al.*	
GOGOLADZE	06	PR D74 093012	I. Gogoladze, C. Macesanu	
ABAZOV	05N	PRL 95 091801	V.M. Abazov *et al.*	(D0 Collab.)
ABAZOV	05V	PRL 95 161602	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	05	PL B609 20	G. Abbiendi *et al.*	(OPAL Collab.)
ABDALLAH	05B	EPJ C38 395	J. Abdallah *et al.*	(DELPHI Collab.)
ABULENCIA	05A	PRL 95 252001	A. Abulencia *et al.*	(CDF Collab.)
SMULLIN	05	PR D72 122001	S.J. Smullin *et al.*	
ACHARD	04E	PL B587 16	P. Achard *et al.*	(L3 Collab.)
ACOSTA	04C	PRL 92 121802	D. Acosta *et al.*	(CDF Collab.)
CASSE	04	PRL 92 111102	M. Casse *et al.*	
CHEKANOV	04B	PL B591 23	S. Chekanov *et al.*	(ZEUS Collab.)
HOYLE	04	PR D70 042004	C.D. Hoyle *et al.*	(WASH)
ABAZOV	03	PRL 90 251802	V.M. Abazov *et al.*	(D0 Collab.)
ABBIENDI	03D	EPJ C26 331	G. Abbiendi *et al.*	(OPAL Collab.)
ACHARD	03D	PL B572 133	P. Achard *et al.*	(L3 Collab.)
ADLOFF	03	PL B568 35	C. Adloff *et al.*	(H1 Collab.)
CHIAVERINI	03	PRL 90 151101	J. Chiaverini *et al.*	
GIUDICE	03	NP B663 377	G.F. Giudice, A. Strumia	
HANNESTAD	03	PR D67 125008	S. Hannestad, G.G. Raffelt	
Also		PR D69 029901(erratum)	S. Hannestad, G.G. Raffelt	
HEISTER	03C	EPJ C28 1	A. Heister *et al.*	(ALEPH Collab.)
LONG	03	Nature 421 922	J.C. Long *et al.*	
ACHARD	02	PL B524 65	P. Achard *et al.*	(L3 Collab.)
ACHARD	02D	PL B531 28	P. Achard *et al.*	(L3 Collab.)
ANCHORDOQ...	02B	PR D66 103002	L. Anchordoqui *et al.*	
HANNESTAD	02	PRL 88 071301	S. Hannestad, G. Raffelt	
ABBOTT	01	PRL 86 1156	B. Abbott *et al.*	(D0 Collab.)
FAIRBAIRN	01	PL B508 335	M. Fairbairn	
HANHART	01	PL B509 1	C. Hanhart *et al.*	
HOYLE	01	PRL 86 1418	C.D. Hoyle *et al.*	
ABBIENDI	00R	EPJ C13 553	G. Abbiendi *et al.*	(OPAL Collab.)
ABREU	00A	PL B491 67	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00S	PL B485 45	P. Abreu *et al.*	(DELPHI Collab.)
ABREU	00Z	EPJ C17 53	P. Abreu *et al.*	(DELPHI Collab.)
ACCIARRI	00P	PL B489 81	M. Acciarri *et al.*	(L3 Collab.)
CASSISI	00	PL B481 323	S. Cassisi *et al.*	
CHANG	00B	PRL 85 3765	L.N. Chang *et al.*	
CHEUNG	00	PR D61 015005	K. Cheung	
CORNET	00	PR D61 037701	F. Cornet, M. Relano, J. Rico	
GRAESSER	00	PR D61 074019	M.L. Graesser	
HAN	00	PR D62 125018	T. Han, D. Marfatia, R.-J. Zhang	
MAHANTA	00	PL B480 176	U. Mahanta, S. Rakshit	
MAHANTA	00B	PL B483 196	U. Mahanta, A. Datta	
MATHEWS	00	JHEP 0007 008	P. Mathews, S. Raychaudhuri, K. Sridhar	
MELE	00	PR D61 117901	S. Mele, E. Sanchez	
RIZZO	00	PR D61 016007	T.G. Rizzo, J.D. Wells	
ABBIENDI	99P	PL B465 303	G. Abbiendi *et al.*	(OPAL Collab.)
ACCIARRI	99M	PL B464 135	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99R	PL B470 268	M. Acciarri *et al.*	(L3 Collab.)
ACCIARRI	99S	PL B470 281	M. Acciarri *et al.*	(L3 Collab.)
BOURILKOV	99	JHEP 9908 006	D. Bourilkov	
HOSKINS	85	PR D32 3084	J.K. Hoskins *et al.*	