# GAUGE AND HIGGS BOSONS

## $\gamma$

$I(J^{PC}) = 0,1(1^{--})$

Mass $m < 1 \times 10^{-18}$ eV
Charge $q < 1 \times 10^{-35}$ $e$
Mean life $\tau =$ Stable

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## $g$ or gluon

$I(J^{P}) = 0(1^{-})$

Mass $m = 0$ [a]
SU(3) color octet

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## graviton

$J = 2$

Mass $m < 6 \times 10^{-32}$ eV

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## $W$

$J = 1$

Charge $= \pm 1$ $e$
Mass $m = 80.385 \pm 0.015$ GeV
$m_Z - m_W = 10.4 \pm 1.6$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.085 \pm 0.042$ GeV
$\langle N_{\pi^\pm} \rangle = 15.70 \pm 0.35$
$\langle N_{K^\pm} \rangle = 2.20 \pm 0.19$
$\langle N_p \rangle = 0.92 \pm 0.14$
$\langle N_{\text{charged}} \rangle = 19.39 \pm 0.08$

$W^-$ modes are charge conjugates of the modes below.

| $W^+$ DECAY MODES | | Fraction ($\Gamma_i/\Gamma$) | Confidence level | $p$ (MeV/$c$) |
|---|---|---|---|---|
| $\ell^+ \nu$ | [b] | (10.86 ± 0.09) % | | – |
| $e^+ \nu$ | | (10.71 ± 0.16) % | | 40192 |
| $\mu^+ \nu$ | | (10.63 ± 0.15) % | | 40192 |
| $\tau^+ \nu$ | | (11.38 ± 0.21) % | | 40173 |
| hadrons | | (67.41 ± 0.27) % | | – |

| | | | | | |
|---|---|---|---|---|---|
| $\pi^+\gamma$ | $<$ | 7 | $\times 10^{-5}$ | 95% | 40192 |
| $D_s^+\gamma$ | $<$ | 1.3 | $\times 10^{-3}$ | 95% | 40168 |
| $c$X | | (33.3 $\pm$ 2.6 ) % | | | – |
| $c\overline{s}$ | | (31 $^{+13}_{-11}$ ) % | | | – |
| invisible | [c] | ( 1.4 $\pm$ 2.9 ) % | | | – |

## Z

$J = 1$

Charge = 0
Mass $m = 91.1876 \pm 0.0021$ GeV [d]
Full width $\Gamma = 2.4952 \pm 0.0023$ GeV
$\Gamma(\ell^+\ell^-) = 83.984 \pm 0.086$ MeV [b]
$\Gamma(\text{invisible}) = 499.0 \pm 1.5$ MeV [e]
$\Gamma(\text{hadrons}) = 1744.4 \pm 2.0$ MeV
$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.0009 \pm 0.0028$
$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) = 1.0019 \pm 0.0032$ [f]

### Average charged multiplicity

$\langle N_{charged} \rangle = 20.76 \pm 0.16$ (S = 2.1)

### Couplings to quarks and leptons

$g_V^\ell = -0.03783 \pm 0.00041$
$g_V^u = 0.25^{+0.07}_{-0.06}$
$g_V^d = -0.33^{+0.05}_{-0.06}$
$g_A^\ell = -0.50123 \pm 0.00026$
$g_A^u = 0.50^{+0.04}_{-0.06}$
$g_A^d = -0.523^{+0.050}_{-0.029}$
$g^{\nu\ell} = 0.5008 \pm 0.0008$
$g^{\nu_e} = 0.53 \pm 0.09$
$g^{\nu_\mu} = 0.502 \pm 0.017$

### Asymmetry parameters [g]

$A_e = 0.1515 \pm 0.0019$
$A_\mu = 0.142 \pm 0.015$
$A_\tau = 0.143 \pm 0.004$
$A_s = 0.90 \pm 0.09$
$A_c = 0.670 \pm 0.027$
$A_b = 0.923 \pm 0.020$

### Charge asymmetry (%) at $Z$ pole

$A_{FB}^{(0\ell)} = 1.71 \pm 0.10$
$A_{FB}^{(0u)} = 4 \pm 7$
$A_{FB}^{(0s)} = 9.8 \pm 1.1$
$A_{FB}^{(0c)} = 7.07 \pm 0.35$
$A_{FB}^{(0b)} = 9.92 \pm 0.16$

| **$Z$ DECAY MODES** | | Fraction ($\Gamma_i/\Gamma$) | | Scale factor/ Confidence level | | $p$ (MeV/$c$) |
|---|---|---|---|---|---|---|
| $e^+ e^-$ | | ( 3.363 | $\pm 0.004$ ) % | | | 45594 |
| $\mu^+ \mu^-$ | | ( 3.366 | $\pm 0.007$ ) % | | | 45594 |
| $\tau^+ \tau^-$ | | ( 3.370 | $\pm 0.008$ ) % | | | 45559 |
| $\ell^+ \ell^-$ | [b] | ( 3.3658 | $\pm 0.0023$) % | | | – |
| $\ell^+ \ell^- \ell^+ \ell^-$ | [h] | ( 4.2 | $^{+0.9}_{-0.8}$ ) $\times 10^{-6}$ | | | 45594 |
| invisible | | (20.00 | $\pm 0.06$ ) % | | | – |
| hadrons | | (69.91 | $\pm 0.06$ ) % | | | – |
| $(u\overline{u}+c\overline{c})/2$ | | (11.6 | $\pm 0.6$ ) % | | | – |
| $(d\overline{d}+s\overline{s}+b\overline{b})/3$ | | (15.6 | $\pm 0.4$ ) % | | | – |
| $c\overline{c}$ | | (12.03 | $\pm 0.21$ ) % | | | – |
| $b\overline{b}$ | | (15.12 | $\pm 0.05$ ) % | | | – |
| $b\overline{b}\,b\overline{b}$ | | ( 3.6 | $\pm 1.3$ ) $\times 10^{-4}$ | | | – |
| $g\,g\,g$ | | $<$ 1.1 | | % | CL=95% | – |
| $\pi^0\gamma$ | | $<$ 5.2 | | $\times 10^{-5}$ | CL=95% | 45594 |
| $\eta\gamma$ | | $<$ 5.1 | | $\times 10^{-5}$ | CL=95% | 45592 |
| $\omega\gamma$ | | $<$ 6.5 | | $\times 10^{-4}$ | CL=95% | 45590 |
| $\eta'(958)\gamma$ | | $<$ 4.2 | | $\times 10^{-5}$ | CL=95% | 45589 |
| $\gamma\gamma$ | | $<$ 5.2 | | $\times 10^{-5}$ | CL=95% | 45594 |
| $\gamma\gamma\gamma$ | | $<$ 1.0 | | $\times 10^{-5}$ | CL=95% | 45594 |
| $\pi^\pm W^\mp$ | [i] | $<$ 7 | | $\times 10^{-5}$ | CL=95% | 10162 |
| $\rho^\pm W^\mp$ | [i] | $<$ 8.3 | | $\times 10^{-5}$ | CL=95% | 10136 |
| $J/\psi(1S)$X | | ( 3.51 | $^{+0.23}_{-0.25}$ ) $\times 10^{-3}$ | | S=1.1 | – |
| $\psi(2S)$X | | ( 1.60 | $\pm 0.29$ ) $\times 10^{-3}$ | | | – |
| $\chi_{c1}(1P)$X | | ( 2.9 | $\pm 0.7$ ) $\times 10^{-3}$ | | | – |
| $\chi_{c2}(1P)$X | | $<$ 3.2 | | $\times 10^{-3}$ | CL=90% | – |
| $\Upsilon(1S)$ X + $\Upsilon(2S)$ X + $\Upsilon(3S)$ X | | ( 1.0 | $\pm 0.5$ ) $\times 10^{-4}$ | | | – |
| $\Upsilon(1S)$X | | $<$ 4.4 | | $\times 10^{-5}$ | CL=95% | – |
| $\Upsilon(2S)$X | | $<$ 1.39 | | $\times 10^{-4}$ | CL=95% | – |
| $\Upsilon(3S)$X | | $<$ 9.4 | | $\times 10^{-5}$ | CL=95% | – |
| $(D^0/\overline{D}^0)$ X | | (20.7 | $\pm 2.0$ ) % | | | – |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $D^{\pm}$X | | | (12.2 | $\pm$1.7 | ) % | | – |
| $D^*(2010)^{\pm}$X | | [i] | (11.4 | $\pm$1.3 | ) % | | – |
| $D_{s1}(2536)^{\pm}$X | | | ( 3.6 | $\pm$0.8 | ) $\times 10^{-3}$ | | – |
| $D_{sJ}(2573)^{\pm}$X | | | ( 5.8 | $\pm$2.2 | ) $\times 10^{-3}$ | | – |
| $D^{*\prime}(2629)^{\pm}$X | | | searched for | | | | – |
| $B^+$X | | [j] | ( 6.08 | $\pm$0.13 | ) % | | – |
| $B^0_s$X | | [j] | ( 1.59 | $\pm$0.13 | ) % | | – |
| $B^+_c$X | | | searched for | | | | – |
| $\Lambda^+_c$X | | | ( 1.54 | $\pm$0.33 | ) % | | – |
| $\Xi^0_c$X | | | seen | | | | – |
| $\Xi_b$X | | | seen | | | | – |
| $b$-baryon X | | [j] | ( 1.38 | $\pm$0.22 | ) % | | – |
| anomalous $\gamma+$ hadrons | | [k] | $<$ 3.2 | | $\times 10^{-3}$ | CL=95% | – |
| $e^+e^-\gamma$ | | [k] | $<$ 5.2 | | $\times 10^{-4}$ | CL=95% | 45594 |
| $\mu^+\mu^-\gamma$ | | [k] | $<$ 5.6 | | $\times 10^{-4}$ | CL=95% | 45594 |
| $\tau^+\tau^-\gamma$ | | [k] | $<$ 7.3 | | $\times 10^{-4}$ | CL=95% | 45559 |
| $\ell^+\ell^-\gamma\gamma$ | | [l] | $<$ 6.8 | | $\times 10^{-6}$ | CL=95% | – |
| $q\overline{q}\gamma\gamma$ | | [l] | $<$ 5.5 | | $\times 10^{-6}$ | CL=95% | – |
| $\nu\overline{\nu}\gamma\gamma$ | | [l] | $<$ 3.1 | | $\times 10^{-6}$ | CL=95% | 45594 |
| $e^{\pm}\mu^{\mp}$ | LF | [i] | $<$ 1.7 | | $\times 10^{-6}$ | CL=95% | 45594 |
| $e^{\pm}\tau^{\mp}$ | LF | [i] | $<$ 9.8 | | $\times 10^{-6}$ | CL=95% | 45576 |
| $\mu^{\pm}\tau^{\mp}$ | LF | [i] | $<$ 1.2 | | $\times 10^{-5}$ | CL=95% | 45576 |
| $pe$ | L,B | | $<$ 1.8 | | $\times 10^{-6}$ | CL=95% | 45589 |
| $p\mu$ | L,B | | $<$ 1.8 | | $\times 10^{-6}$ | CL=95% | 45589 |

## $H^0$

$J = 0$

Mass $m = 125.7 \pm 0.4$ GeV

### $H^0$ Signal Strengths in Different Channels

Combined Final States $= 1.17 \pm 0.17$ (S = 1.2)

$WW^* = 0.87^{+0.24}_{-0.22}$

$ZZ^* = 1.11^{+0.34}_{-0.28}$ (S = 1.3)

$\gamma\gamma = 1.58^{+0.27}_{-0.23}$

$b\overline{b} = 1.1 \pm 0.5$

$\tau^+\tau^- = 0.4 \pm 0.6$

$Z\gamma < 9.5$, CL = 95%

## Neutral Higgs Bosons, Searches for

### Searches for a Higgs Boson with Standard Model Couplings

Mass $m > 122$ and none 128–710 GeV, CL = 95%

The limits for $H_1^0$ and $A^0$ in supersymmetric models refer to the $m_h^{\max}$ benchmark scenario for the supersymmetric parameters.

### $H_1^0$ in Supersymmetric Models ($m_{H_1^0} < m_{H_2^0}$)

Mass $m >$ 92.8 GeV, CL = 95%

### $A^0$ Pseudoscalar Higgs Boson in Supersymmetric Models [n]

Mass $m >$ 93.4 GeV, CL = 95% $\tan\beta > 0.4$

## Charged Higgs Bosons ($H^\pm$ and $H^{\pm\pm}$), Searches for

$H^\pm$ Mass $m >$ 80 GeV, CL = 95%

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

### Additional $W$ Bosons

$W'$ with standard couplings
Mass $m > 2.900 \times 10^3$ GeV, CL = 95% ($pp$ direct search)

$W_R$ (Right-handed $W$ Boson)
Mass $m >$ 715 GeV, CL = 90% (electroweak fit)

### Additional $Z$ Bosons

$Z'_{\rm SM}$ with standard couplings
Mass $m > 2.590 \times 10^3$ GeV, CL = 95% ($pp$ direct search)
Mass $m > 1.500 \times 10^3$ GeV, CL = 95% (electroweak fit)

$Z_{LR}$ of $\mathrm{SU(2)}_L \times \mathrm{SU(2)}_R \times \mathrm{U(1)}$ (with $g_L = g_R$)
Mass $m >$ 630 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 1162 GeV, CL = 95% (electroweak fit)

$Z_\chi$ of $\mathrm{SO(10)} \rightarrow \mathrm{SU(5)} \times \mathrm{U(1)}_\chi$ (with $g_\chi = e/\cos\theta_W$)
Mass $m > 1.970 \times 10^3$ GeV, CL = 95% ($pp$ direct search)
Mass $m > 1.141 \times 10^3$ GeV, CL = 95% (electroweak fit)

$Z_\psi$ of $E_6 \rightarrow \mathrm{SO(10)} \times \mathrm{U(1)}_\psi$ (with $g_\psi = e/\cos\theta_W$)
Mass $m > 2.260 \times 10^3$ GeV, CL = 95% ($pp$ direct search)

Mass $m >$ 476 GeV, CL = 95% (electroweak fit)

$Z_\eta$ of $E_6 \rightarrow$ SU(3)×SU(2)×U(1)×U(1)$_\eta$ (with $g_\eta = e/\cos\theta_W$)

Mass $m > 1.870 \times 10^3$ GeV, CL = 95% ($pp$ direct search)

Mass $m >$ 619 GeV, CL = 95% (electroweak fit)

**Scalar Leptoquarks**

Mass $m >$ 830 GeV, CL = 95% (1st generation, pair prod.)

Mass $m >$ 304 GeV, CL = 95% (1st gener., single prod.)

Mass $m >$ 840 GeV, CL = 95% (2nd gener., pair prod.)

Mass $m >$ 73 GeV, CL = 95% (2nd gener., single prod.)

Mass $m >$ 525 GeV, CL = 95% (3rd gener., pair prod.)

(See the Particle Listings for assumptions on leptoquark quantum numbers and branching fractions.)

**Diquarks**

Mass $m > 3.750 \times 10^3$ GeV, CL = 95%

**Axigluon**

Mass $m > 3.360 \times 10^3$ GeV, CL = 95%

## Axions ($A^0$) and Other Very Light Bosons, Searches for

The standard Peccei-Quinn axion is ruled out. Variants with reduced couplings or much smaller masses are constrained by various data. The Particle Listings in the full *Review* contain a Note discussing axion searches.

The best limit for the half-life of neutrinoless double beta decay with Majoron emission is $> 7.2 \times 10^{24}$ years (CL = 90%).

# NOTES

[*a*] Theoretical value. A mass as large as a few MeV may not be precluded.

[*b*] $\ell$ indicates each type of lepton ($e$, $\mu$, and $\tau$), not sum over them.

[*c*] This represents the width for the decay of the $W$ boson into a charged particle with momentum below detectability, p$<$ 200 MeV.

[*d*] The $Z$-boson mass listed here corresponds to a Breit-Wigner resonance parameter. It lies approximately 34 MeV above the real part of the position of the pole (in the energy-squared plane) in the $Z$-boson propagator.

[*e*] This partial width takes into account $Z$ decays into $\nu\overline{\nu}$ and any other possible undetected modes.

[*f*] This ratio has not been corrected for the $\tau$ mass.

[*g*] Here $A \equiv 2g_V g_A/(g_V^2+g_A^2)$.

[*h*] Here $\ell$ indicates $e$ or $\mu$.

[*i*] The value is for the sum of the charge states or particle/antiparticle states indicated.

[*j*] This value is updated using the product of (i) the $Z \to b\overline{b}$ fraction from this listing and (ii) the $b$-hadron fraction in an unbiased sample of weakly decaying $b$-hadrons produced in $Z$-decays provided by the Heavy Flavor Averaging Group (HFAG, http://www.slac.stanford.edu/xorg/hfag/osc/PDG_2009/#FRACZ).

[*k*] See the $Z$ Particle Listings for the $\gamma$ energy range used in this measurement.

[*l*] For $m_{\gamma\gamma} = (60 \pm 5)$ GeV.

[*n*] The limits assume no invisible decays.