# GAUGE AND HIGGS BOSONS

## $\gamma$

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

Mass $m < 2 \times 10^{-16}$ eV
Charge $q < 5 \times 10^{-30}$ $e$
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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## $W$

$J = 1$

Charge $= \pm 1$ $e$
Mass $m = 80.41 \pm 0.10$ GeV
$m_Z - m_W = 10.78 \pm 0.10$ GeV
$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV
Full width $\Gamma = 2.06 \pm 0.06$ GeV

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

| $W^+$ DECAY MODES | | Fraction ($\Gamma_i/\Gamma$) | Confidence level | $p$ (MeV/$c$) |
|---|---|---|---|---|
| $\ell^+ \nu$ | [b] | (10.74±0.33) % | | – |
| $e^+ \nu$ | | (10.9 ±0.4 ) % | | 40205 |
| $\mu^+ \nu$ | | (10.2 ±0.5 ) % | | 40205 |
| $\tau^+ \nu$ | | (11.3 ±0.8 ) % | | 40185 |
| hadrons | | (67.8 ±1.0 ) % | | – |
| $\pi^+ \gamma$ | | $< 2.2 \times 10^{-4}$ | 95% | 40205 |

# Z

$J = 1$

Charge = 0
Mass $m = 91.187 \pm 0.007$ GeV [c]
Full width $\Gamma = 2.490 \pm 0.007$ GeV
$\Gamma(\ell^+ \ell^-) = 83.83 \pm 0.27$ MeV [b]
$\Gamma(\text{invisible}) = 498.3 \pm 4.2$ MeV [d]
$\Gamma(\text{hadrons}) = 1740.7 \pm 5.9$ MeV
$\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-) = 1.000 \pm 0.005$
$\Gamma(\tau^+ \tau^-)/\Gamma(e^+ e^-) = 0.998 \pm 0.005$ [e]

**Average charged multiplicity**

$\langle N_{charged} \rangle = 21.00 \pm 0.13$

**Couplings to leptons**

$g_V^\ell = -0.0377 \pm 0.0007$
$g_A^\ell = -0.5008 \pm 0.0008$
$g^{\nu_e} = 0.53 \pm 0.09$
$g^{\nu_\mu} = 0.502 \pm 0.017$

**Asymmetry parameters** [f]

$A_e = 0.1519 \pm 0.0034$
$A_\mu = 0.102 \pm 0.034$
$A_\tau = 0.143 \pm 0.008$
$A_c = 0.59 \pm 0.19$
$A_b = 0.89 \pm 0.11$

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

$A_{FB}^{(0\ell)} = 1.59 \pm 0.18$
$A_{FB}^{(0u)} = 4.0 \pm 7.3$
$A_{FB}^{(0s)} = 9.9 \pm 3.1 \quad (S = 1.2)$
$A_{FB}^{(0c)} = 7.32 \pm 0.58$
$A_{FB}^{(0b)} = 10.02 \pm 0.28$

| **Z DECAY MODES** | | | Fraction ($\Gamma_i/\Gamma$) | Confidence level | ($p$ MeV/$c$) |
|---|---|---|---|---|---|
| $e^+ e^-$ | | | ( 3.366 ± 0.008) % | | 45594 |
| $\mu^+ \mu^-$ | | | ( 3.367 ± 0.013) % | | 45593 |
| $\tau^+ \tau^-$ | | | ( 3.360 ± 0.015) % | | 45559 |
| $\ell^+ \ell^-$ | | [b] | ( 3.366 ± 0.006) % | | – |
| invisible | | | (20.01 ± 0.16 ) % | | – |
| hadrons | | | (69.90 ± 0.15 ) % | | – |
| $(u\overline{u}+c\overline{c})/2$ | | | (10.1 ± 1.1 ) % | | – |
| $(d\overline{d}+s\overline{s}+b\overline{b})/3$ | | | (16.6 ± 0.6 ) % | | – |
| $c\overline{c}$ | | | (12.4 ± 0.6 ) % | | – |
| $b\overline{b}$ | | | (15.16 ± 0.09 ) % | | – |
| $g\,g\,g$ | | | < 1.1 % | 95% | – |
| $\pi^0 \gamma$ | | | < 5.2 $\times 10^{-5}$ | 95% | 45593 |
| $\eta \gamma$ | | | < 5.1 $\times 10^{-5}$ | 95% | 45592 |
| $\omega \gamma$ | | | < 6.5 $\times 10^{-4}$ | 95% | 45590 |
| $\eta'(958) \gamma$ | | | < 4.2 $\times 10^{-5}$ | 95% | 45588 |
| $\gamma \gamma$ | | | < 5.2 $\times 10^{-5}$ | 95% | 45594 |
| $\gamma \gamma \gamma$ | | | < 1.0 $\times 10^{-5}$ | 95% | 45594 |
| $\pi^\pm W^\mp$ | | [g] | < 7 $\times 10^{-5}$ | 95% | 10139 |
| $\rho^\pm W^\mp$ | | [g] | < 8.3 $\times 10^{-5}$ | 95% | 10114 |
| $J/\psi(1S)$X | | | ( 3.66 ± 0.23 ) $\times 10^{-3}$ | | – |
| $\psi(2S)$X | | | ( 1.60 ± 0.29 ) $\times 10^{-3}$ | | – |
| $\chi_{c1}(1P)$X | | | ( 2.9 ± 0.7 ) $\times 10^{-3}$ | | – |
| $\chi_{c2}(1P)$X | | | < 3.2 $\times 10^{-3}$ | 90% | – |
| $\Upsilon(1S)$ X + $\Upsilon(2S)$ X + $\Upsilon(3S)$ X | | | ( 1.0 ± 0.5 ) $\times 10^{-4}$ | | – |
| $\Upsilon(1S)$X | | | < 5.5 $\times 10^{-5}$ | 95% | – |
| $\Upsilon(2S)$X | | | < 1.39 $\times 10^{-4}$ | 95% | – |
| $\Upsilon(3S)$X | | | < 9.4 $\times 10^{-5}$ | 95% | – |
| $(D^0/\overline{D}^0)$ X | | | (20.7 ± 2.0 ) % | | – |
| $D^\pm$X | | | (12.2 ± 1.7 ) % | | – |
| $D^*(2010)^\pm$X | | [g] | (11.4 ± 1.3 ) % | | – |
| $B_s^0$X | | | seen | | – |
| anomalous $\gamma$ + hadrons | | [h] | < 3.2 $\times 10^{-3}$ | 95% | – |
| $e^+ e^- \gamma$ | | [h] | < 5.2 $\times 10^{-4}$ | 95% | 45594 |
| $\mu^+ \mu^- \gamma$ | | [h] | < 5.6 $\times 10^{-4}$ | 95% | 45593 |
| $\tau^+ \tau^- \gamma$ | | [h] | < 7.3 $\times 10^{-4}$ | 95% | 45559 |
| $\ell^+ \ell^- \gamma \gamma$ | | [i] | < 6.8 $\times 10^{-6}$ | 95% | – |
| $q\overline{q}\gamma\gamma$ | | [i] | < 5.5 $\times 10^{-6}$ | 95% | – |
| $\nu\overline{\nu}\gamma\gamma$ | | [i] | < 3.1 $\times 10^{-6}$ | 95% | 45594 |
| $e^\pm \mu^\mp$ | *LF* | [g] | < 1.7 $\times 10^{-6}$ | 95% | 45593 |
| $e^\pm \tau^\mp$ | *LF* | [g] | < 9.8 $\times 10^{-6}$ | 95% | 45576 |
| $\mu^\pm \tau^\mp$ | *LF* | [g] | < 1.2 $\times 10^{-5}$ | 95% | 45576 |

## Higgs Bosons — $H^0$ and $H^\pm$, Searches for

$H^0$ Mass $m >$ 77.5 GeV, CL = 95%

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

Mass $m >$ 62.5 GeV, CL = 95%

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

Mass $m >$ 62.5 GeV, CL = 95% $\quad \tan\beta > 1$

$H^\pm$ Mass $m >$ 54.5 GeV, CL = 95%

See the Particle Listings for a Note giving details of Higgs Bosons.

# Heavy Bosons Other Than Higgs Bosons, Searches for

### Additional *W* Bosons

$W_R$ — right-handed $W$
Mass $m >$ 549 GeV
(assuming light right-handed neutrino)

$W'$ with standard couplings decaying to $e\nu$, $\mu\nu$
Mass $m >$ 720 GeV, CL = 95%

### Additional *Z* Bosons

$Z'_{\rm SM}$ with standard couplings
Mass $m >$ 690 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 779 GeV, CL = 95% (electroweak fit)

$Z_{LR}$ of $SU(2)_L \times SU(2)_R \times U(1)$
(with $g_L = g_R$)
Mass $m >$ 630 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 389 GeV, CL = 95% (electroweak fit)

$Z_\chi$ of $SO(10) \rightarrow SU(5) \times U(1)_\chi$
(coupling constant derived from G.U.T.)
Mass $m >$ 595 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 321 GeV, CL = 95% (electroweak fit)

$Z_\psi$ of $E_6 \rightarrow SO(10) \times U(1)_\psi$
(coupling constant derived from G.U.T.)
Mass $m >$ 590 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 160 GeV, CL = 95% (electroweak fit)

$Z_\eta$ of $E_6 \rightarrow SU(3) \times SU(2) \times U(1) \times U(1)_\eta$
(coupling constant derived from G.U.T.);
charges are $Q_\eta = \sqrt{3/8}\,Q_\chi - \sqrt{5/8}\,Q_\psi$)
Mass $m >$ 620 GeV, CL = 95% ($p\overline{p}$ direct search)
Mass $m >$ 182 GeV, CL = 95% (electroweak fit)

### Scalar Leptoquarks

Mass $m >$ 225 GeV, CL = 95% (1st generation, pair prod.)
Mass $m >$ 237 GeV, CL = 95% (1st gener., single prod.)
Mass $m >$ 119 GeV, CL = 95% (2nd gener., pair prod.)
Mass $m >$ 73 GeV, CL = 95% (2nd gener., single prod.)
Mass $m >$ 99 GeV, CL = 95% (3rd gener., pair prod.)
(See the Particle Listings for assumptions on leptoquark quantum numbers and branching fractions.)

## 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%).

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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*] 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.

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

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

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

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

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

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

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