

GAUGE AND HIGGS BOSONS

γ

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

Mass $m < 1 \times 10^{-18}$ eV

Charge $q < 5 \times 10^{-30}$ e

Mean life $\tau = \text{Stable}$

g

or gluon

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

Mass $m = 0$ [a]

SU(3) color octet

W

$$J = 1$$

Charge = ± 1 e

Mass $m = 80.398 \pm 0.025$ GeV

$m_Z - m_W = 10.4 \pm 1.6$ GeV

$m_{W^+} - m_{W^-} = -0.2 \pm 0.6$ GeV

Full width $\Gamma = 2.141 \pm 0.041$ 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 (Γ_i/Γ) | Confidence level | P (MeV/c) |
|-------------------------------------|--------------------------------|------------------|----------------|
| $\ell^+ \nu$ | [b] $(10.80 \pm 0.09) \%$ | | — |
| $e^+ \nu$ | $(10.75 \pm 0.13) \%$ | | 40199 |
| $\mu^+ \nu$ | $(10.57 \pm 0.15) \%$ | | 40199 |
| $\tau^+ \nu$ | $(11.25 \pm 0.20) \%$ | | 40179 |
| hadrons | $(67.60 \pm 0.27) \%$ | | — |
| $\pi^+ \gamma$ | < 8 | $\times 10^{-5}$ | 95% 40199 |
| $D_s^+ \gamma$ | < 1.3 | $\times 10^{-3}$ | 95% 40175 |
| cX | $(33.4 \pm 2.6) \%$ | | — |
| $c\bar{s}$ | $(31^{+13}_{-11}) \%$ | | — |
| invisible | [c] $(1.4 \pm 2.8) \%$ | | — |



$$J = 1$$

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

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

Couplings to leptons

$$g_V^\ell = -0.03783 \pm 0.00041$$

$$g_A^\ell = -0.50123 \pm 0.00026$$

$$g^{\nu\ell} = 0.5008 \pm 0.0008$$

$$g^{\nu e} = 0.53 \pm 0.09$$

$$g^{\nu\mu} = 0.502 \pm 0.017$$

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 (Γ_i/Γ) | 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) % | | — |
| invisible | (20.00 \pm 0.06) % | | — |
| hadrons | (69.91 \pm 0.06) % | | — |
| ($u\bar{u} + c\bar{c}$)/2 | (11.6 \pm 0.6) % | | — |
| ($d\bar{d} + s\bar{s} + b\bar{b}$)/3 | (15.6 \pm 0.4) % | | — |
| $c\bar{c}$ | (12.03 \pm 0.21) % | | — |
| $b\bar{b}$ | (15.12 \pm 0.05) % | | — |
| $b\bar{b}b\bar{b}$ | (3.6 \pm 1.3) $\times 10^{-4}$ | | — |
| ggg | < 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 |
| $\pi^\pm W^\mp$ | [h] < 7 | $\times 10^{-5}$ CL=95% | 10150 |
| $\rho^\pm W^\mp$ | [h] < 8.3 | $\times 10^{-5}$ CL=95% | 10125 |
| $J/\psi(1S) X$ | (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% | — |
| $(D^0/\bar{D}^0) X$ | (20.7 \pm 2.0) % | | — |
| $D^\pm X$ | (12.2 \pm 1.7) % | | — |

| | | | | |
|------------------------------|-----|------------------------------------|--------|-------|
| $D^*(2010)^\pm X$ | | [h] (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) $\times 10^{-3}$ | | — |
| $D^{*'}(2629)^\pm X$ | | searched for | | — |
| $B^+ X$ | | (6.10 \pm 0.14) % | | — |
| $B_s^0 X$ | | (1.56 \pm 0.13) % | | — |
| $B_c^+ X$ | | searched for | | — |
| $\Lambda_c^+ X$ | | (1.54 \pm 0.33) % | | — |
| $\Xi_c^0 X$ | | seen | | — |
| $\Xi_b X$ | | seen | | — |
| b -baryon X | | (1.38 \pm 0.22) % | | — |
| anomalous γ + hadrons | | [i] < 3.2 $\times 10^{-3}$ | CL=95% | — |
| $e^+ e^- \gamma$ | | [i] < 5.2 $\times 10^{-4}$ | CL=95% | 45594 |
| $\mu^+ \mu^- \gamma$ | | [i] < 5.6 $\times 10^{-4}$ | CL=95% | 45594 |
| $\tau^+ \tau^- \gamma$ | | [i] < 7.3 $\times 10^{-4}$ | CL=95% | 45559 |
| $l^+ l^- \gamma \gamma$ | | [i] < 6.8 $\times 10^{-6}$ | CL=95% | — |
| $q\bar{q}\gamma\gamma$ | | [i] < 5.5 $\times 10^{-6}$ | CL=95% | — |
| $\nu\bar{\nu}\gamma\gamma$ | | [i] < 3.1 $\times 10^{-6}$ | CL=95% | 45594 |
| $e^\pm \mu^\mp$ | LF | [h] < 1.7 $\times 10^{-6}$ | CL=95% | 45594 |
| $e^\pm \tau^\mp$ | LF | [h] < 9.8 $\times 10^{-6}$ | CL=95% | 45576 |
| $\mu^\pm \tau^\mp$ | LF | [h] < 1.2 $\times 10^{-5}$ | CL=95% | 45576 |
| $p e$ | L,B | < 1.8 $\times 10^{-6}$ | CL=95% | 45589 |
| $p \mu$ | L,B | < 1.8 $\times 10^{-6}$ | CL=95% | 45589 |

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

The limits for H_1^0 and A_0 refer to the m_h^{\max} benchmark scenario for the supersymmetric parameters.

H^0 Mass $m > 114.4$ GeV, CL = 95%

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 ^[k]

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

H^\pm Mass $m > 79.3$ 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' with standard couplings decaying to $e\nu$

Mass $m > 1.000 \times 10^3$ GeV, CL = 95%

W_R — right-handed W

Mass $m > 715$ GeV, CL = 90% (electroweak fit)

Additional Z Bosons

Z'_{SM} with standard couplings

Mass $m > 923$ GeV, CL = 95% ($p\bar{p}$ direct search)

Mass $m > 1500$ 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% ($p\bar{p}$ direct search)

Mass $m > 860$ GeV, CL = 95% (electroweak fit)

Z_χ of $SO(10) \rightarrow SU(5) \times U(1)_\chi$ (with $g_\chi = e/\cos\theta_W$)

Mass $m > 822$ GeV, CL = 95% ($p\bar{p}$ direct search)

Mass $m > 781$ GeV, CL = 95% (electroweak fit)

Z_ψ of $E_6 \rightarrow SO(10) \times U(1)_\psi$ (with $g_\psi = e/\cos\theta_W$)

Mass $m > 822$ GeV, CL = 95% ($p\bar{p}$ direct search)

Mass $m > 475$ GeV, CL = 95% (electroweak fit)

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

Mass $m > 891$ GeV, CL = 95% ($p\bar{p}$ direct search)

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

Scalar Leptoquarks

Mass $m > 256$ GeV, CL = 95% (1st generation, pair prod.)

Mass $m > 298$ GeV, CL = 95% (1st gener., single prod.)

Mass $m > 251$ GeV, CL = 95% (2nd gener., pair prod.)

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

Mass $m > 229$ 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%).

NOTES

- [a] Theoretical value. A mass as large as a few MeV may not be precluded.
- [b] ℓ indicates each type of lepton (e , μ , and τ), 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 $\nu\bar{\nu}$ and any other possible undetected modes.
- [f] This ratio has not been corrected for the τ mass.
- [g] Here $A \equiv 2g_V g_A / (g_V^2 + g_A^2)$.
- [h] The value is for the sum of the charge states or particle/antiparticle states indicated.
- [i] See the Z Particle Listings for the γ energy range used in this measurement.
- [j] For $m_{\gamma\gamma} = (60 \pm 5)$ GeV.
- [k] The limits assume no invisible decays.