

# 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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$W$

$$J = 1$$

Charge =  $\pm 1$  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.

<b><math>W^+</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	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] $(1.4 \pm 2.8) \%$		—

**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

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

#### Couplings to leptons

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

$$g_V^u = 0.29^{+0.10}_{-0.08}$$

$$g_V^d = -0.33^{+0.05}_{-0.07}$$

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

$$g_A^u = 0.50^{+0.04}_{-0.07}$$

$$g_A^d = -0.524^{+0.050}_{-0.030}$$

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

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

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

### 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 ) %		—
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 ) $\times 10^{-4}$		—
$g g g$	< 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
$\pi^\pm W^\mp$	[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]	$(11.4 \pm 1.3)$	%	—
$D_{s1}(2536)^\pm X$		$( 3.6 \pm 0.8 ) \times 10^{-3}$		—
$D_{sJ}(2573)^\pm X$		$( 5.8 \pm 2.2 ) \times 10^{-3}$		—
$D^{*J}(2629)^\pm X$		searched for		—
$B^+ X$	[i]	$( 6.08 \pm 0.13 )$	%	—
$B_s^0 X$	[i]	$( 1.59 \pm 0.13 )$	%	—
$B_c^+ X$		searched for		—
$\Lambda_c^+ X$		$( 1.54 \pm 0.33 )$	%	—
$\Xi_c^0 X$		seen		—
$\Xi_b X$		seen		—
$b$ -baryon $X$	[i]	$( 1.38 \pm 0.22 )$	%	—
anomalous $\gamma$ + hadrons	[j]	$< 3.2$	$\times 10^{-3}$ CL=95%	—
$e^+ e^- \gamma$	[j]	$< 5.2$	$\times 10^{-4}$ CL=95%	45594
$\mu^+ \mu^- \gamma$	[j]	$< 5.6$	$\times 10^{-4}$ CL=95%	45594
$\tau^+ \tau^- \gamma$	[j]	$< 7.3$	$\times 10^{-4}$ CL=95%	45559
$l^+ l^- \gamma \gamma$	[k]	$< 6.8$	$\times 10^{-6}$ CL=95%	—
$q\bar{q}\gamma\gamma$	[k]	$< 5.5$	$\times 10^{-6}$ CL=95%	—
$\nu\bar{\nu}\gamma\gamma$	[k]	$< 3.1$	$\times 10^{-6}$ 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
$pe$	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 [1]**

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%

### **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)

$Z_\chi$  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)

$Z_\psi$  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)

$Z_\eta$  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  $m > 316$  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.)

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### 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] 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  $\tau$  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] This value is updated using the product of (i) the  $Z \rightarrow b\bar{b}$  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](http://www.slac.stanford.edu/xorg/hfag/osc/PDG_2009/#FRACZ)).
- [j] See the  $Z$  Particle Listings for the  $\gamma$  energy range used in this measurement.
- [k] For  $m_{\gamma\gamma} = (60 \pm 5)$  GeV.
- [l] The limits assume no invisible decays.