

# GAUGE AND HIGGS BOSONS

**$\gamma$  (photon)**

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

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

Charge  $q < 1 \times 10^{-46}$  e (mixed charge)

Charge  $q < 1 \times 10^{-35}$  e (single charge)

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

**$g$   
or gluon**

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

Mass  $m = 0$  [a]

SU(3) color octet

**graviton**

$$J = 2$$

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

**$W$**

$$J = 1$$

Charge =  $\pm 1$  e

Mass  $m = 80.379 \pm 0.012$  GeV

$W/Z$  mass ratio =  $0.88147 \pm 0.00013$

$m_Z - m_W = 10.809 \pm 0.012$  GeV

$m_{W^+} - m_{W^-} = -0.029 \pm 0.028$  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.

<b><math>W^+</math> DECAY MODES</b>	Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$P$ (MeV/c)
$\ell^+ \nu$	[b] $(10.86 \pm 0.09) \%$		–
$e^+ \nu$	$(10.71 \pm 0.16) \%$		40189
$\mu^+ \nu$	$(10.63 \pm 0.15) \%$		40189
$\tau^+ \nu$	$(11.38 \pm 0.21) \%$		40170
hadrons	$(67.41 \pm 0.27) \%$		–
$\pi^+ \gamma$	$< 7$	$\times 10^{-6}$	95% 40189
$D_s^+ \gamma$	$< 1.3$	$\times 10^{-3}$	95% 40165
$cX$	$(33.3 \pm 2.6) \%$		–
$c\bar{s}$	$(31^{+13}_{-11}) \%$		–
invisible	[c] $(1.4 \pm 2.9) \%$		–
$\pi^+ \pi^+ \pi^-$	$< 1.01$	$\times 10^{-6}$	95% 40189



$$J = 1$$

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

$\Gamma(\mu^+ \mu^-)/\Gamma(e^+ e^-) = 1.0001 \pm 0.0024$

$\Gamma(\tau^+ \tau^-)/\Gamma(e^+ e^-) = 1.0020 \pm 0.0032$  [f]

#### Average charged multiplicity

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

#### Couplings to quarks and leptons

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

$$g_V^u = 0.266 \pm 0.034$$

$$g_V^d = -0.38^{+0.04}_{-0.05}$$

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

$$g_A^u = 0.519^{+0.028}_{-0.033}$$

$$g_A^d = -0.527^{+0.040}_{-0.028}$$

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

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

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

**Asymmetry parameters [g]**

$$\begin{aligned}
 A_e &= 0.1515 \pm 0.0019 \\
 A_\mu &= 0.142 \pm 0.015 \\
 A_\tau &= 0.143 \pm 0.004 \\
 A_s &= 0.90 \pm 0.09 \\
 A_c &= 0.670 \pm 0.027 \\
 A_b &= 0.923 \pm 0.020
 \end{aligned}$$

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

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

Z DECAY MODES	Fraction ( $\Gamma_i/\Gamma$ )	Scale factor/ Confidence level	$p$ (MeV/c)
$e^+ e^-$	[h] ( 3.3632±0.0042 ) %		45594
$\mu^+ \mu^-$	[h] ( 3.3662±0.0066 ) %		45594
$\tau^+ \tau^-$	[h] ( 3.3696±0.0083 ) %		45559
$\ell^+ \ell^-$	[b,h] ( 3.3658±0.0023 ) %		—
$\ell^+ \ell^- \ell^+ \ell^-$	[i] ( 4.63 ±0.21 ) × 10 <sup>-6</sup>		45594
invisible	[h] (20.000 ±0.055 ) %		—
hadrons	[h] (69.911 ±0.056 ) %		—
( $u\bar{u} + c\bar{c}$ )/2	(11.6 ±0.6 ) %		—
( $d\bar{d} + s\bar{s} + b\bar{b}$ )/3	(15.6 ±0.4 ) %		—
$c\bar{c}$	(12.03 ±0.21 ) %		—
$b\bar{b}$	(15.12 ±0.05 ) %		—
$b\bar{b}b\bar{b}$	( 3.6 ±1.3 ) × 10 <sup>-4</sup>		—
$ggg$	< 1.1	% CL=95%	—
$\pi^0 \gamma$	< 2.01	× 10 <sup>-5</sup> CL=95%	45594
$\eta \gamma$	< 5.1	× 10 <sup>-5</sup> CL=95%	45592
$\rho^0 \gamma$	< 2.5	× 10 <sup>-5</sup> CL=95%	45591
$\omega \gamma$	< 6.5	× 10 <sup>-4</sup> CL=95%	45590
$\eta'(958) \gamma$	< 4.2	× 10 <sup>-5</sup> CL=95%	45589
$\phi \gamma$	< 9	× 10 <sup>-7</sup> CL=95%	45588
$\gamma \gamma$	< 1.46	× 10 <sup>-5</sup> CL=95%	45594
$\pi^0 \pi^0$	< 1.52	× 10 <sup>-5</sup> CL=95%	45594
$\gamma \gamma \gamma$	< 2.2	× 10 <sup>-6</sup> CL=95%	45594
$\pi^\pm W^\mp$	[j] < 7	× 10 <sup>-5</sup> CL=95%	10167
$\rho^\pm W^\mp$	[j] < 8.3	× 10 <sup>-5</sup> CL=95%	10142

$J/\psi(1S)X$		$( 3.51 \begin{smallmatrix} +0.23 \\ -0.25 \end{smallmatrix} ) \times 10^{-3}$	$S=1.1$	—
$J/\psi(1S)\gamma$		$< 1.4$	$\times 10^{-6}$	CL=95% 45541
$\psi(2S)X$		$( 1.60 \pm 0.29 ) \times 10^{-3}$		—
$\psi(2S)\gamma$		$< 4.5$	$\times 10^{-6}$	CL=95% 45519
$J/\psi(1S)J/\psi(1S)$		$< 2.2$	$\times 10^{-6}$	CL=95% 45489
$\chi_{c1}(1P)X$		$( 2.9 \pm 0.7 ) \times 10^{-3}$		—
$\chi_{c2}(1P)X$		$< 3.2$	$\times 10^{-3}$	CL=90% —
$\Upsilon(1S) X + \Upsilon(2S) X$ $+ \Upsilon(3S) X$		$( 1.0 \pm 0.5 ) \times 10^{-4}$		—
$\Upsilon(1S)X$		$< 3.4$	$\times 10^{-6}$	CL=95% —
$\Upsilon(1S)\gamma$		$< 2.8$	$\times 10^{-6}$	CL=95% 45103
$\Upsilon(2S)X$		$< 6.5$	$\times 10^{-6}$	CL=95% —
$\Upsilon(2S)\gamma$		$< 1.7$	$\times 10^{-6}$	CL=95% 45043
$\Upsilon(3S)X$		$< 5.4$	$\times 10^{-6}$	CL=95% —
$\Upsilon(3S)\gamma$		$< 4.8$	$\times 10^{-6}$	CL=95% 45006
$\Upsilon(1, 2, 3S) \Upsilon(1, 2, 3S)$		$< 1.5$	$\times 10^{-6}$	CL=95% —
$(D^0/\bar{D}^0) X$		$(20.7 \pm 2.0) \%$		—
$D^\pm X$		$(12.2 \pm 1.7) \%$		—
$D^*(2010)^\pm X$	[j]	$(11.4 \pm 1.3) \%$		—
$D_{s1}(2536)^\pm X$		$( 3.6 \pm 0.8 ) \times 10^{-3}$		—
$D_{sJ}(2573)^\pm X$		$( 5.8 \pm 2.2 ) \times 10^{-3}$		—
$D^{*'}(2629)^\pm X$		searched for		—
$B^+ X$	[k]	$( 6.08 \pm 0.13 ) \%$		—
$B_s^0 X$	[k]	$( 1.59 \pm 0.13 ) \%$		—
$B_c^+ X$		searched for		—
$\Lambda_c^+ X$		$( 1.54 \pm 0.33 ) \%$		—
$\Xi_c^0 X$		seen		—
$\Xi_b X$		seen		—
$b$ -baryon X	[k]	$( 1.38 \pm 0.22 ) \%$		—
anomalous $\gamma$ + hadrons	[l]	$< 3.2$	$\times 10^{-3}$	CL=95% —
$e^+ e^- \gamma$	[l]	$< 5.2$	$\times 10^{-4}$	CL=95% 45594
$\mu^+ \mu^- \gamma$	[l]	$< 5.6$	$\times 10^{-4}$	CL=95% 45594
$\tau^+ \tau^- \gamma$	[l]	$< 7.3$	$\times 10^{-4}$	CL=95% 45559
$\ell^+ \ell^- \gamma \gamma$	[n]	$< 6.8$	$\times 10^{-6}$	CL=95% —
$q\bar{q}\gamma\gamma$	[n]	$< 5.5$	$\times 10^{-6}$	CL=95% —
$\nu\bar{\nu}\gamma\gamma$	[n]	$< 3.1$	$\times 10^{-6}$	CL=95% 45594
$e^\pm \mu^\mp$	LF	[j]	$< 7.5$	$\times 10^{-7}$ CL=95% 45594
$e^\pm \tau^\mp$	LF	[j]	$< 9.8$	$\times 10^{-6}$ CL=95% 45576
$\mu^\pm \tau^\mp$	LF	[j]	$< 1.2$	$\times 10^{-5}$ 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



$$J = 0$$

Mass  $m = 125.10 \pm 0.14$  GeV

Full width  $\Gamma < 0.013$  GeV, CL = 95% (assumes equal on-shell and off-shell effective couplings)

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

Combined Final States =  $1.13 \pm 0.06$

$W W^* = 1.19 \pm 0.12$

$Z Z^* = 1.20^{+0.12}_{-0.11}$

$\gamma\gamma = 1.11^{+0.10}_{-0.09}$

$c\bar{c}$  Final State < 110, CL = 95%

$b\bar{b} = 1.04 \pm 0.13$

$\mu^+ \mu^- = 0.6 \pm 0.8$

$\tau^+ \tau^- = 1.15^{+0.16}_{-0.15}$

$Z\gamma < 6.6$ , CL = 95%

top Yukawa coupling < 1.7, CL = 95%

$t\bar{t}H^0$  Production =  $1.28 \pm 0.20$

$H^0$  Production Cross Section in  $pp$  Collisions at  $\sqrt{s} = 13$  TeV =  $59 \pm 5$  pb

$H^0$ DECAY MODES		Fraction ( $\Gamma_i/\Gamma$ )	Confidence level	$P$ (MeV/c)
$e^+ e^-$		$< 3.6 \times 10^{-4}$	95%	62550
$J/\psi \gamma$		$< 3.5 \times 10^{-4}$	95%	62511
$J/\psi J/\psi$		$< 1.8 \times 10^{-3}$	95%	62473
$\psi(2S) \gamma$		$< 2.0 \times 10^{-3}$	95%	62495
$\Upsilon(1S) \gamma$		$< 4.9 \times 10^{-4}$	95%	62192
$\Upsilon(2S) \gamma$		$< 5.9 \times 10^{-4}$	95%	62148
$\Upsilon(3S) \gamma$		$< 5.7 \times 10^{-4}$	95%	62121
$\Upsilon(nS) \Upsilon(mS)$		$< 1.4 \times 10^{-3}$	95%	—
$\rho(770) \gamma$		$< 8.8 \times 10^{-4}$	95%	62547
$\phi(1020) \gamma$		$< 4.8 \times 10^{-4}$	95%	62546
$e\mu$	LF	$< 6.1 \times 10^{-5}$	95%	62550
$e\tau$	LF	$< 4.7 \times 10^{-3}$	95%	62537
$\mu\tau$	LF	$< 2.5 \times 10^{-3}$	95%	62537
$\gamma$ invisible		$< 4.6 \%$	95%	—

## Neutral Higgs Bosons, Searches for

### Mass limits for heavy neutral Higgs bosons ( $H_2^0, A^0$ ) in the MSSM

$m > 389$ GeV, CL = 95%	( $\tan\beta = 10$ )
$m > 863$ GeV, CL = 95%	( $\tan\beta = 20$ )
$m > 1157$ GeV, CL = 95%	( $\tan\beta = 30$ )
$m > 1341$ GeV, CL = 95%	( $\tan\beta = 40$ )
$m > 1496$ GeV, CL = 95%	( $\tan\beta = 50$ )
$m > 1613$ GeV, CL = 95%	( $\tan\beta = 60$ )

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

### Mass limits for $m_{H^\pm} < m(\text{top})$

$m > 155$ GeV, CL = 95%
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### Mass limits for $m_{H^\pm} > m(\text{top})$

$m > 181$ GeV, CL = 95%	( $\tan\beta = 10$ )
$m > 249$ GeV, CL = 95%	( $\tan\beta = 20$ )
$m > 390$ GeV, CL = 95%	( $\tan\beta = 30$ )
$m > 894$ GeV, CL = 95%	( $\tan\beta = 40$ )
$m > 1017$ GeV, CL = 95%	( $\tan\beta = 50$ )
$m > 1103$ GeV, CL = 95%	( $\tan\beta = 60$ )

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

### Additional $W$ Bosons

$W'$  with standard couplings

Mass  $m > 5200$  GeV, CL = 95% ( $pp$  direct search)

$W_R$  (Right-handed  $W$  Boson)

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

### Additional $Z$ Bosons

$Z'_{SM}$  with standard couplings

Mass  $m > 4.500 \times 10^3$  GeV, CL = 95% ( $pp$  direct search)

$Z_{LR}$  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  $m > 1162$  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  $m > 4.100 \times 10^3$  GeV, CL = 95% ( $pp$  direct search)
- $Z_\psi$  of  $E_6 \rightarrow SO(10) \times U(1)_\psi$  (with  $g_\psi = e/\cos\theta_W$ )  
Mass  $m > 3900$  GeV, CL = 95% ( $pp$  direct search)
- $Z_\eta$  of  $E_6 \rightarrow SU(3) \times SU(2) \times U(1) \times U(1)_\eta$  (with  $g_\eta = e/\cos\theta_W$ )  
Mass  $m > 3.900 \times 10^3$  GeV, CL = 95% ( $pp$  direct search)

### Scalar Leptoquarks

- $m > 1050$  GeV, CL = 95% (1st gen., pair prod.,  $B(\tau t)=1$ )  
 $m > 1755$  GeV, CL = 95% (1st gen., single prod.,  $B(\tau b)=1$ )  
 $m > 1420$  GeV, CL = 95% (2nd gen., pair prod.,  $B(\mu t)=1$ )  
 $m > 660$  GeV, CL = 95% (2nd gen., single prod.,  $B(\mu q)=1$ )  
 $m > 900$  GeV, CL = 95% (3rd gen., pair prod.,  $B(e q)=1$ )  
 $m > 740$  GeV, CL = 95% (3rd gen., single prod.,  $B(e q)=1$ )  
(See the Particle Listings for assumptions on leptoquark quantum numbers and branching fractions.)

### Diquarks

- Mass  $m > 6000$  GeV, CL = 95% ( $E_6$  diquark)

### Axigluon

- Mass  $m > 6100$  GeV, CL = 95%

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

See the review on "Axions and other similar particles."

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] This parameter is not directly used in the overall fit but is derived using the fit results; see the note “The  $Z$  boson” and ref. LEP-SLC 06 (Physics Reports (Physics Letters C) **427** 257 (2006)).
- [i] Here  $\ell$  indicates  $e$  or  $\mu$ .
- [j] The value is for the sum of the charge states or particle/antiparticle states indicated.
- [k] 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 (HFLAV, [http://www.slac.stanford.edu/xorg/hflav/osc/PDG\\_2009/#FRACZ](http://www.slac.stanford.edu/xorg/hflav/osc/PDG_2009/#FRACZ)).
- [l] See the  $Z$  Particle Listings for the  $\gamma$  energy range used in this measurement.
- [n] For  $m_{\gamma\gamma} = (60 \pm 5)$  GeV.