Lagrangian

$$\mathcal{L} = \mathcal{L}_{Jauge} + \mathcal{L}_{lepton} + \mathcal{L}_{quark} + \mathcal{L}_{scalaire} + \mathcal{L}_{scal-lepton} + \mathcal{L}_{scal-q}$$

$$\mathcal{L}_{Jauge} = -\frac{1}{4}F_{\mu\nu l}F^{\mu\nu l} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

$$\mathcal{L}_{lepton} = i\left[\overline{e_R}\gamma^\mu D^R_\mu e_R + \overline{L}\gamma^\mu D^L_\mu L\right]$$

$$\mathcal{L}_{quark} = i\left[\sum_{u,d}\overline{q_R}\gamma^\mu D^R_\mu q_R + \overline{Q}\gamma^\mu D^L_\mu Q\right]$$

$$\mathcal{L}_{scalaire} = D^\mu\Phi^\dagger D_\mu\Phi - \mu^2\Phi^\dagger\Phi - \lambda(\Phi^\dagger\Phi)^2$$

$$\mathcal{L}_{scal-lepton} = -\lambda_e\left[\overline{e_R}\Phi^\dagger L + \overline{L}\Phi e_R\right]$$

$$\mathcal{L}_{scal-q} = -\lambda_u\left[\overline{Q\Phi}u_R + \overline{u}_R\overline{\Phi}^\dagger Q\right] - \lambda_d\left[\overline{Q}\Phi d_R + \overline{d}_R\Phi^\dagger Q\right]$$

$$L = \begin{pmatrix} \nu \\ e \end{pmatrix} \quad Q = \begin{pmatrix} u \\ d \end{pmatrix}$$

$$D^R_\mu = \partial_\mu + i\frac{g'}{2}B_\mu Y$$

$$D^L_\mu = \partial_\mu + i\frac{g}{2}\sigma\cdot\mathbf{A}_\mu Y + i\frac{g'}{2}B_\mu Y$$

$$F^l_{\mu\nu} = \partial_\mu b^l_\nu - \partial_\nu b^l_\mu + g\epsilon_{jkl}b^j_\mu b^k_\nu$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

After symmetry breaking

$$Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu \quad f_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\begin{aligned}\mathcal{L}_{jauge} + \mathcal{L}_{scalaire} = & -\frac{1}{4} f_{\mu\nu} f^{\mu\nu} - \frac{1}{2} F^{\dagger}_{W\mu\nu} F^{\mu\nu}_{W} + m_W^2 W^{\dagger}_{\mu} W^{\mu} \\ & -\frac{1}{4} Z_{\mu\nu} Z^{\mu\nu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu + \frac{1}{2} \partial_\mu h \partial^\mu h - \frac{1}{2} m_H^2 h^2 \\ & + \mathcal{L}^{BB} + \mathcal{L}^{SS} + \mathcal{L}^{SB}\end{aligned}$$

Les interactions à trois et quatre bosons de jauge

$$\begin{aligned}\mathcal{L}^{BB} = & \; ig\cos\theta_W \left[(W^{\dagger}_{\alpha} W_\beta - W^{\dagger}_{\beta} W_\alpha)\partial^\alpha Z^\beta + (\partial_\alpha W_\beta - \partial_\beta W_\alpha) W^{\dagger\beta} Z^\alpha - (\partial_\alpha W^{\dagger}_{\beta} - \partial_\beta W^{\dagger}_{\alpha}) W^\beta Z^\alpha \right] \\ & + ie \left[(W^{\dagger}_{\alpha} W_\beta - W^{\dagger}_{\beta} W_\alpha)\partial^\alpha A^\beta + (\partial_\alpha W_\beta - \partial_\beta W_\alpha) W^{\dagger\beta} A^\alpha - (\partial_\alpha W^{\dagger}_{\beta} - \partial_\beta W^{\dagger}_{\alpha}) W^\beta A^\alpha \right] \\ & + g^2\cos^2\theta_W (W_\alpha W^{+}_{\beta} Z^\alpha Z^\beta - W_\beta W^{+\beta} Z_\alpha Z^\alpha) + e^2 (W_\alpha W^{+}_{\beta} A^\alpha A^\beta - W_\beta W^{+\beta} A_\alpha A^\alpha) \\ & + eg\cos^2\theta_W (W_\alpha W^{+}_{\beta} (Z^\alpha A^\beta - A_\alpha Z^\beta) - 2 W_\beta W^{+\beta} A_\alpha Z^\alpha) \\ & + \frac{g^2}{2} W^{+}_{\alpha} W_\beta \left[W^{+\alpha} W^\beta - W^\alpha W^{+\beta} \right] \qquad (1.20)\end{aligned}$$

Scalars:

$$\mathcal{L}^{SS} = -\frac{1}{4}\lambda h^4 - \lambda v h^3$$

$$\mathcal{L}^{SB} = \frac{1}{2} v g^2 W^{\dagger}_{\alpha} W^\alpha h + \frac{1}{4} g^2 W^{\dagger}_{\alpha} W^\alpha h^2 + \frac{g v^2}{4\cos^2\theta_W} Z_\alpha Z^\alpha h + \frac{g^2}{8\cos^2\theta_W} g^2 Z_\alpha Z^\alpha h^2$$

$$\mathcal{L}_{lepton} + \mathcal{L}_{scalaire-lepton} = \mathcal{L}_0 + \mathcal{L}_{CC} + \mathcal{L}_{NC} + \mathcal{L}_{lepton-h}$$

$$\mathcal{L}_0 = \sum_i \left[\overline{e_i}(i\partial\!\!\!/ - m)e_i + i\overline{\nu_{iL}}\partial\!\!\!/\nu_{iL}\right]$$

$$\mathcal{L}_{CC} = \sum_i \frac{-g}{2\sqrt{2}}\left[\overline{\nu_i}\gamma_\mu(1-\gamma_5)e_i W^\mu + \overline{e_i}\gamma_\mu(1-\gamma_5)\nu_i W^{\mu\dagger}\right]$$

$$\mathcal{L}_{NC} = e\overline{e_i}\gamma_\mu e_i A^\mu - \frac{g}{2\cos^2\theta_W}\sum_{f=\nu_i,e_i}\left[\overline{f}\gamma_\mu(1-\gamma_5)f c_L^f + \overline{f}\gamma_\mu(1+\gamma_5)f c_R^f\right] Z^\mu$$

$$\mathcal{L}_{lepton-h} = -\frac{\lambda_{ei}}{\sqrt{2}}\left(\overline{e}_{iR}e_{iL} + \overline{e}_{iL}e_{iR}\right) h \qquad (1.23)$$

$$\mathcal{L}_{quark} + \mathcal{L}_{scalaire-quark} = \mathcal{L}_{q0} + \mathcal{L}_{qCC} + \mathcal{L}_{qNC} + \mathcal{L}_{quark-h}$$

$$\mathcal{L}_{CC} = \frac{-g}{2\sqrt{2}}\sum_{ij}\left[\overline{u_i}\gamma_\mu(1-\gamma_5)K_{ij}d_j W^\mu + \overline{d_j}\gamma_\mu(1-\gamma_5)K_{ij}^* u_i W^{\mu\dagger}\right]$$

$$\mathcal{L}_{NC} = -\sum_i Q_i(\overline{u_i}\gamma_\mu u_i + \overline{d_i}\gamma_\mu d_i)A^\mu$$

$$-\frac{g}{2\cos^2\theta_W}\sum_{q=u_i,d_i}\left[\overline{q}\gamma_\mu(1-\gamma_5)q c_L^q + \overline{q}\gamma_\mu(1+\gamma_5)q c_R^q\right] Z^\mu$$

$$\mathcal{L}_{quark-h} = -\sum_{q=u_i,d_i}\frac{\lambda_q}{\sqrt{2}}\left(\overline{q}_{iR}q_{iL} + \overline{q}_{iL}q_{iR}\right) h$$

Feynman rules

- W e- neutrino
- W u d
- Z f f
- ZWW
- γ γ WW
- ZZWW

$$-i\frac{g}{2\sqrt{2}}\gamma_\mu(1-\gamma_5)$$

$$-i\frac{g}{2\sqrt{2}}K_{ud}\gamma_\mu(1-\gamma_5)$$

$$-i\frac{g}{2\cos^2\theta_W}\gamma_\mu(c_L^f(1-\gamma_5)+c_R^f(1+\gamma_5))$$

$$ig\cos^2\theta_W\left[g^{\alpha\beta}(k^+-k^-)^\mu - g^{\alpha\mu}(p+k^+)^\beta - g^{\beta\mu}(p+k^-)^\alpha\right]$$

$$-ie^2\left[2g_{\alpha\beta}g_{\mu\nu} - g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\nu}g_{\beta\mu}\right]$$

$$ig^2\left[2g_{\alpha\mu}g_{\beta\nu} - g_{\alpha\beta}g_{\mu\nu} - g_{\alpha\nu}g_{\beta\mu}\right]$$

Free parameters

- SU(2) XU(1) only (17 parameters)

Constante de couplage	g, g'	$e, \sin\theta_W$
Scalaire	μ, λ	v, m_h
Couplages de Yukawa	$\lambda_e, \lambda_\mu, \lambda_\tau$	m_e, m_μ, m_τ
	$\lambda_u, \lambda_c, \lambda_t$	m_u, m_c, m_t
	$\lambda_d, \lambda_s, \lambda_b$	m_d, m_s, m_b
Mélange des quarks	A, ρ, η, δ	s_1, s_2, s_3, δ
SU(3)	g_3	

-
-
-
- Gauge bosons masses and couplings only depe on g,g',v

$$M_W = \frac{gv}{2}$$
$$M_Z = \frac{\sqrt{g^2+g'^2}v}{2} = \frac{gv}{2\cos^2\theta_W}$$
$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

- Most precisely measured input parameters

$$G_\mu = (1.16637 \pm .00001) \times 10^{-5} GeV \quad \frac{\Delta G_\mu}{G_\mu} = 8.6 \times 10^{-6}$$
$$M_Z = 91.1876 \pm .0021 GeV \quad \frac{\Delta M_Z}{M_Z} = 2 \times 10^{-5}$$
$$\alpha^{-1} = 137.03599235(73) \quad \frac{\Delta\alpha^{-1}}{\alpha^{-1}} = 5 \times 10^{-9}$$

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{e^2}{8M_W^2\sin^2\theta_W}$$
$$e^2 = 4\pi\alpha$$
$$M_Z^2 = \frac{M_W^2}{\cos^2\theta_W}$$

- These relations are modified by higher order corrections

Seulement trois paramètres dans le secteur de jauge

$$g, g', v$$

Les bosons de jauge et leurs interactions ne dépendent que de ces paramètres

$$\begin{aligned} M_W &= \frac{gv}{2} \\ M_Z &= \frac{\sqrt{g^2 + g'^2}v}{2} = \frac{gv}{2\cos^2\theta_W} \\ \sin^2\theta_W &= 1 - \frac{M_W^2}{M_Z^2} \end{aligned}$$

Paramètres mesures
Avec precision

$$\begin{aligned} G_\mu &= (1.16637 \pm .00001) \times 10^{-5} GeV \quad \frac{\Delta G_\mu}{G_\mu} = 8.6 \times 10^{-6} \\ M_Z &= 91.1876 \pm .0021 GeV \quad \frac{\Delta M_Z}{M_Z} = 2 \times 10^{-5} \\ \alpha^{-1} &= 137.03599235(73) \quad \frac{\Delta \alpha^{-1}}{\alpha^{-1}} = 5 \times 10^{-9} \end{aligned}$$

Experimental tests of standard model

- Neutral currents
- Z couplings
- Production of W and Z at CERN
- Top quark discovery at Fermilab
- Gauge structure in three vector boson interactions
- Higgs discovery

Collisionneur électron-positron

LEP

Location:

CERN, Geneva Switzerland

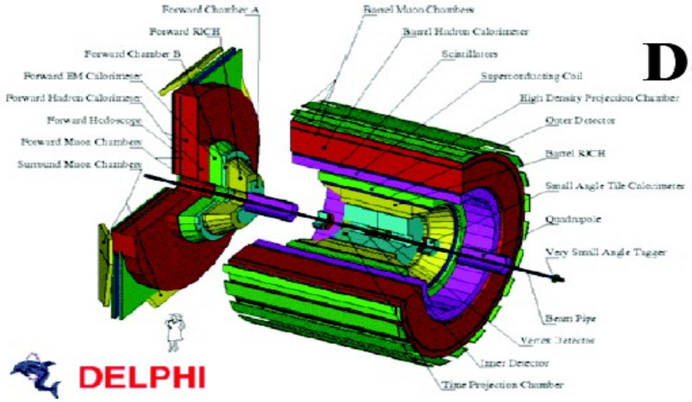
e^+e^- machine

$P_{e+} = P_{e-}$

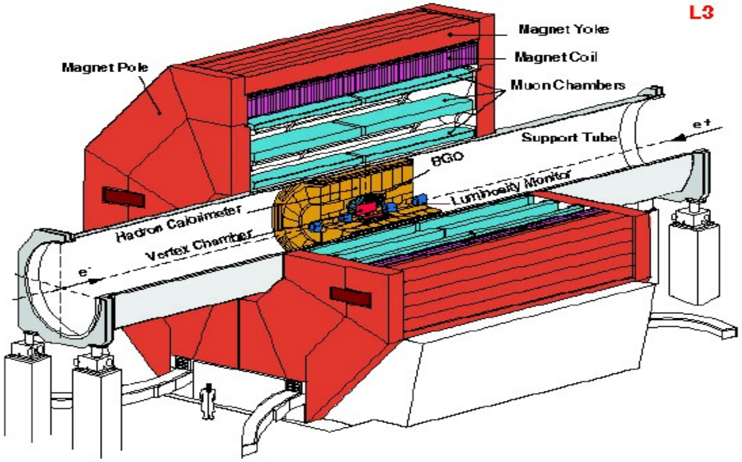
Maximum
C.O.M. Energy = 209 GeV

Circumference of machine = 26.7km

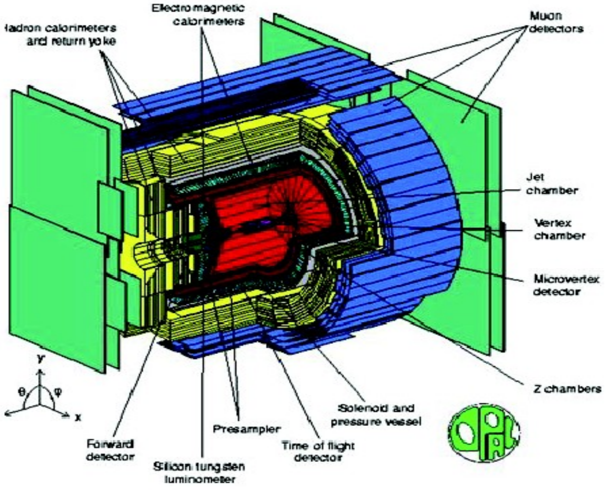
Experiments at LEP1,LEP2



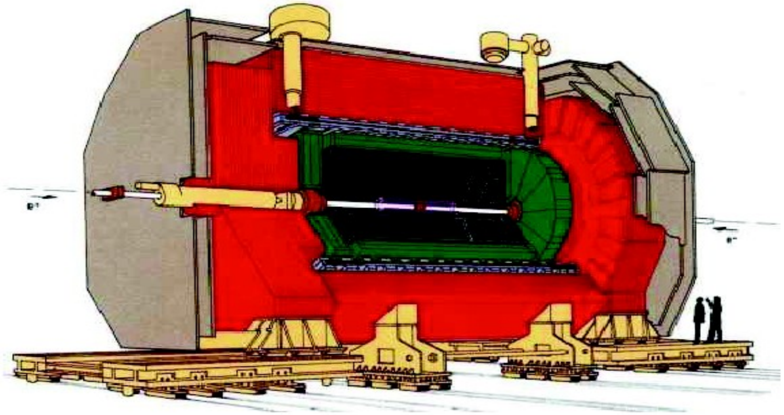
Delphi



L3

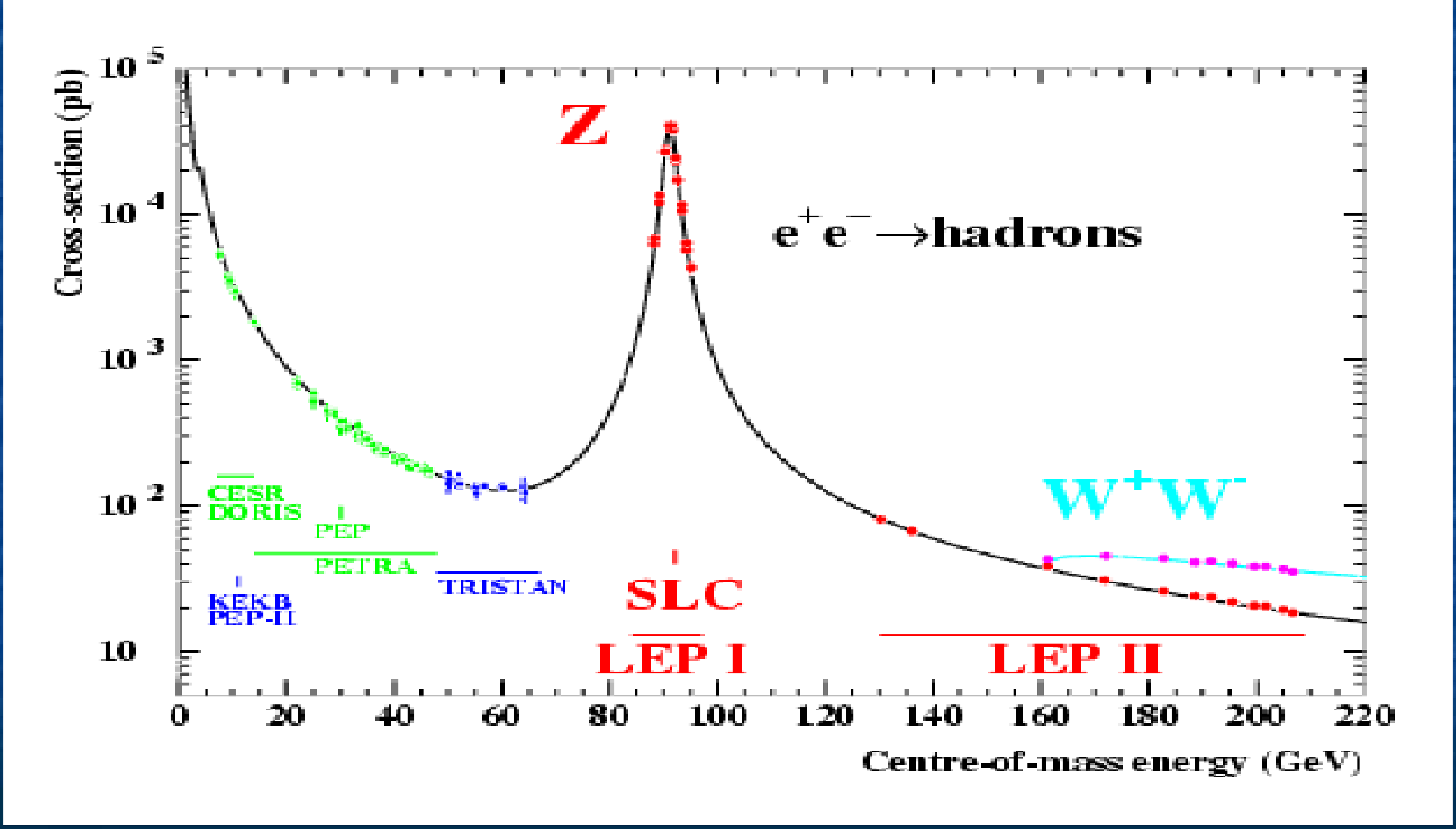


Opal

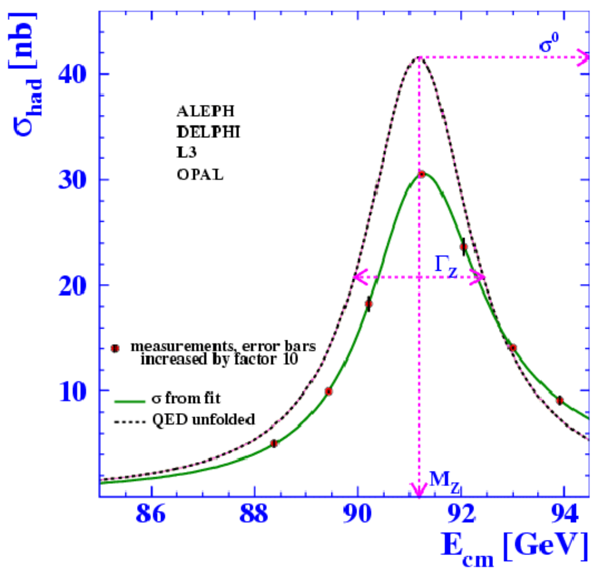


Aleph

Production fermion pair



$$e^+e^- \to Z^0 \to f\bar{f} \quad \text{à} \sqrt{s} = M_{z_0}$$



$$\sigma^0_{had} = \frac{12\pi\Gamma_{ee}\Gamma_{had}}{M_Z^2\Gamma_Z^2}$$

$$R_f = \Gamma_{had} / \Gamma_{ll}$$

Measurement of Z mass and width

The final LEP1 results

M_Z = 91.1875 ± 0.0021 GeV

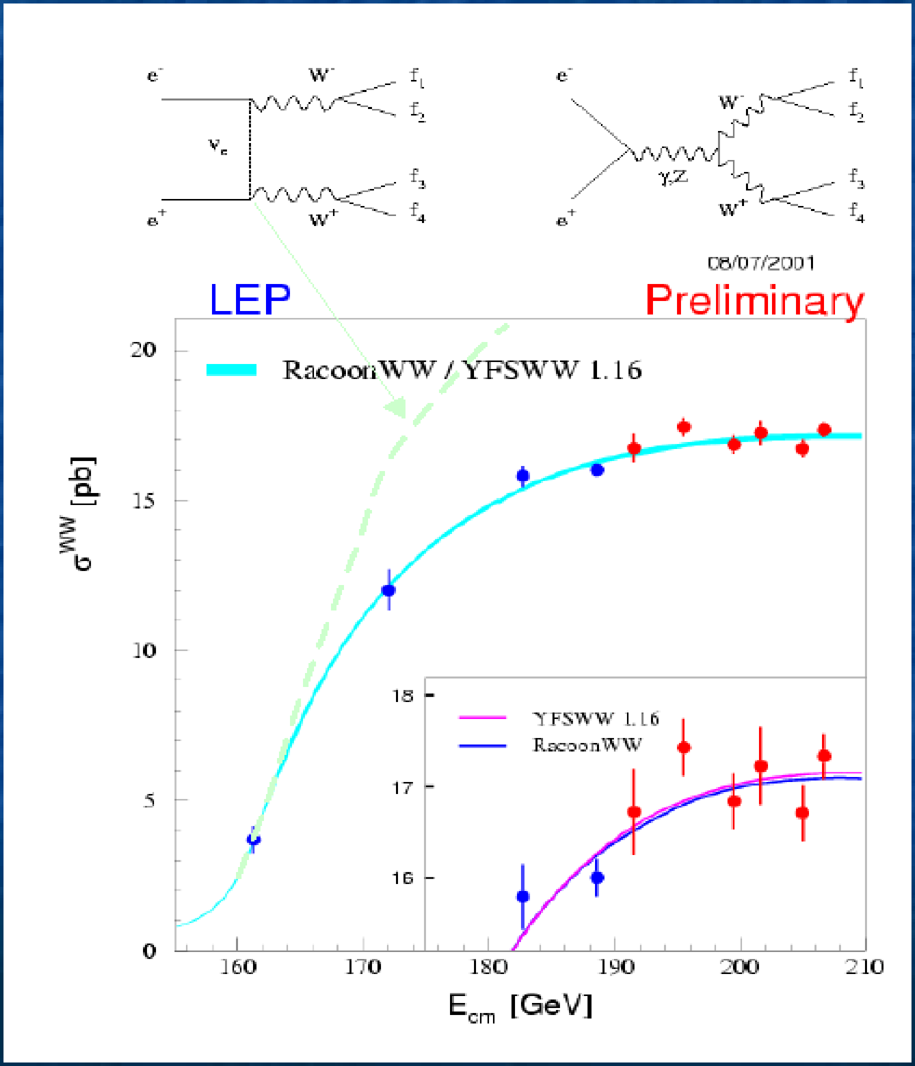
Γ_Z = 2.4952 ± 0.0023 GeV

Observables at Z peak

Quantity	Group(s)	Value
M_Z [GeV]	LEP	91.1876 ± 0.0021
Γ_Z [GeV]	LEP	2.4952 ± 0.0023
$\Gamma(\text{had})$ [GeV]	LEP	1.7444 ± 0.0020
$\Gamma(\text{inv})$ [MeV]	LEP	499.0 ± 1.5
$\Gamma(\ell^+\ell^-)$ [MeV]	LEP	83.984 ± 0.086
σ_{had} [nb]	LEP	41.541 ± 0.037
R_e	LEP	20.804 ± 0.050
R_μ	LEP	20.785 ± 0.033
R_τ	LEP	20.764 ± 0.045
$A_{FB}(e)$	LEP	0.0145 ± 0.0025
$A_{FB}(\mu)$	LEP	0.0169 ± 0.0013
$A_{FB}(\tau)$	LEP	0.0188 ± 0.0017
R_b	LEP + SLD	0.21664 ± 0.00065
R_c	LEP + SLD	0.1718 ± 0.0031
$R_{s,d}/R_{(d+u+s)}$	OPAL	0.371 ± 0.023
$A_{FB}(b)$	LEP	0.0995 ± 0.0017
$A_{FB}(c)$	LEP	0.0713 ± 0.0036
$A_{FB}(s)$	DELPHI,OPAL	0.0976 ± 0.0114
A_b	SLD	0.922 ± 0.020
A_c	SLD	0.670 ± 0.026
A_s	SLD	0.895 ± 0.091
A_{LR} (hadrons)	SLD	0.15138 ± 0.00216
A_{LR} (leptons)	SLD	0.1544 ± 0.0060
A_μ	SLD	0.142 ± 0.015
A_τ	SLD	0.136 ± 0.015

Table 2: Measurements of key quantities at the Z peak

Gauge structure



- Evidence for ZWW coupling at LEP2 e+e- collisions @200GeV
- Trilinear coupling essential for high energy behaviour
- Effect can be seen just a few GeV above threshold

Z and number of neutrinos

Starting from Feunman rules

$$
\begin{aligned}
-\mathrm{i}\mathcal{M} &= \frac{g}{\cos\theta_W}\bar{u}(p_1)\left[\gamma_\mu\frac{(1-\gamma_5)}{2}c_L^f+\gamma_\mu\frac{(1+\gamma_5)}{2}c_R^f\right]u(p_2)\epsilon^\mu(k) \\
|\mathcal{M}|^2 &= \frac{g^2}{\cos^2\theta_W}\mathrm{Tr}\left[\not{\epsilon}\left[c_L^f P_L + c_R^f P_R\right]\ \not{p}_2\left[c_L^f P_R + c_R^f P_L\right]\ \not{\epsilon}^*\ \not{p}_1\right] \\
&= \frac{g^2}{\cos^2\theta_W}\mathrm{Tr}\left[\not{\epsilon}\ \not{p}_2\ \not{\epsilon}^*\ \not{p}_1\left[c_L^{f^2}P_R + c_R^{f^2}P_L\right]\right] \\
&= \frac{g^2}{2\cos^2\theta_W}\left\{\left(c_L^{f^2}+c_R^{f^2}\right)\mathrm{Tr}\left[\gamma^\alpha\ \not{p}_2\gamma^\beta\ \not{p}_1\right]\right. \\
&\qquad\left.+\left(c_R^{f^2}-c_L^{f^2}\right)\mathrm{Tr}\left[\gamma_\alpha\ \not{p}_2\gamma_\beta\ \not{p}_1\gamma_5\right]\right\}
\end{aligned}
$$

- Sum over final polarisations and average over initial polarisations (1/3)

$$\sum_{\rm pol} \epsilon^{\alpha}\epsilon^{*\beta} = (-)\left(g^{\alpha\beta} - \frac{k^{\alpha}k^{\beta}}{M_Z^2}\right)$$

$$|\bar{\mathcal{M}}|^2 = \frac{1}{6}\frac{g^2}{\cos^2\theta_W}(-)\left(g^{\alpha\beta} - \frac{k^{\alpha}k^{\beta}}{M_Z^2}\right)\left[\left(c_L^{f\,2} + c_R^{f\,2}\right)\right.$$

$$\left. 4\left(p_2^{\alpha}p_1^{\beta} - g^{\alpha\beta}p_1\cdot p_2 + p_2^{\beta}p_1^{\alpha}\right) + 4\left(c_R^{f\,2} - c_L^{f\,2}\right)\epsilon_{\alpha\beta\mu\nu}p_2^{\mu}p_1^{\nu}\right]$$

$$= -\frac{2}{3}\frac{g^2}{\cos^2\theta_W}\left(c_L^{f\,2} + c_R^{f\,2}\right)\left(2p_2\cdot p_1 - 4p_2\cdot p_1 - 2\frac{p_1\cdot k p_2\cdot k}{M^2 z} + \frac{k^2 p_1\cdot p_2}{M^2 z}\right]$$

$$p_1\cdot p_2 = \frac{M_Z^2}{2}, \qquad k^2 = M_Z^2, \qquad p_1\cdot k = p_2\cdot k = \frac{M_Z^2}{2}$$

$$|\bar{\mathcal{M}}|^2 = \frac{2}{3}\frac{g^2}{\cos^2\theta_W}M_Z^2\left(c_L^{f\,2} + c_R^{f\,2}\right)$$

$$\Gamma_{Z\to\bar{f}f} = \underbrace{\frac{1}{3\pi}\frac{G_F}{\sqrt{2}}M_Z^3}_{\Gamma_{Z_0}}\left(c_L^{f\,2} + c_R^{f\,2}\right)$$

$$\Gamma_{Z\to\bar{f}f} = N_c\frac{G_F}{\sqrt{2}\pi}M_Z^3\left[c_L^{f\,2} + c_R^{f\,2}\right] = N_c\left(c_L^{f\,2} + c_R^{f\,2}\right)\Gamma_{Z^0}$$

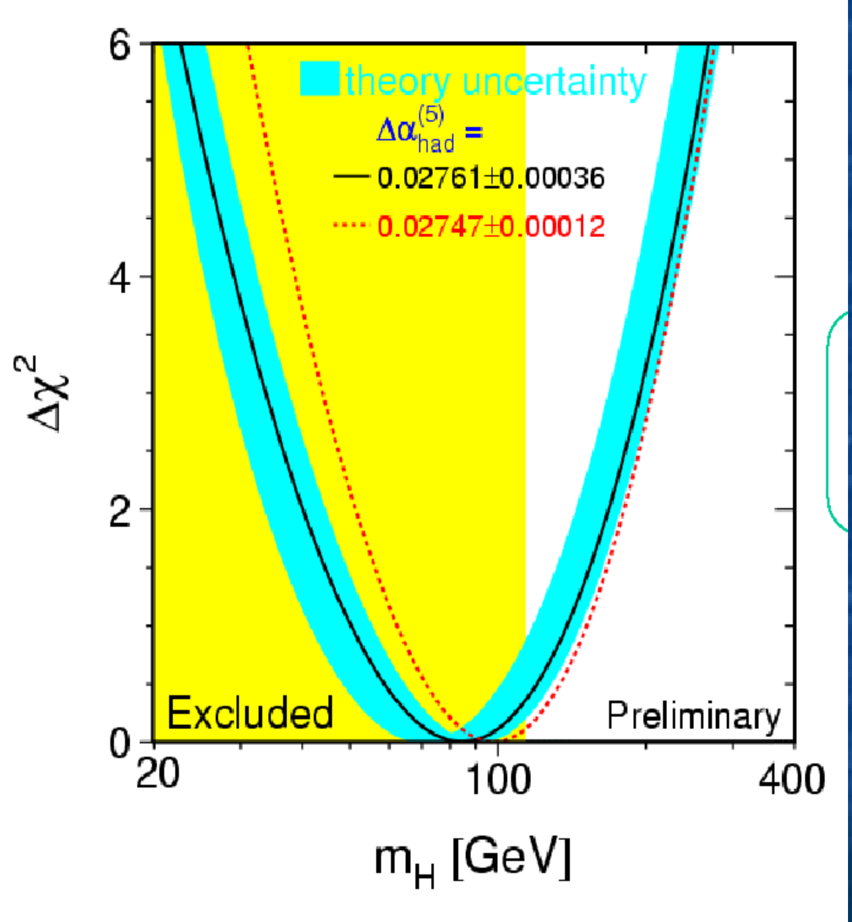
Partial widths

$Z \longrightarrow \nu\bar{\nu}$	$\Gamma_{z_0} \times \frac{1}{4} \times 3$	497 MeV	$\sim 20\%$	
$Z \longrightarrow e\bar{e}$	$\Gamma_{z_0}\left[\left(-\frac{1}{2}+s_W^2\right)^2+s_W^2\right]$	83.9 MeV	$\sim 3.4\%$	
			$\sim 3.4\%$	$\times 2 \left(\begin{smallmatrix}\mu\mu \\ \tau\tau\end{smallmatrix}\right)$
$Z \longrightarrow u\bar{u}$	$3\Gamma_{z_0}\left[\left(\frac{1}{2}-\frac{2}{3}s_W^2\right)^2+\left(\frac{2}{3}s_W^2\right)^2\right]$	290 MeV	$\sim 11.8\%$	
$Z \longrightarrow c\bar{c}$	$3\Gamma_{z_0}\left[\left(+\frac{1}{2}-\frac{2}{3}s_W^2\right)^2+\left(\frac{2}{3}s_W^2\right)^2\right]$	290 MeV	$\sim 11.8\%$	
$Z \longrightarrow d\bar{d}$	$3\Gamma_{z_0}\left[\left(-\frac{1}{2}+\frac{1}{3}s_W^2\right)^2+\left(\frac{1}{3}s_W^2\right)^2\right]$	371 MeV	$\sim 15.2\%$	
$s\bar{s}$			$\sim 15.2\%$	
$b\bar{b}$			$\sim 15.2\%$	
	Γ_{TOT}	2.44 GeV		

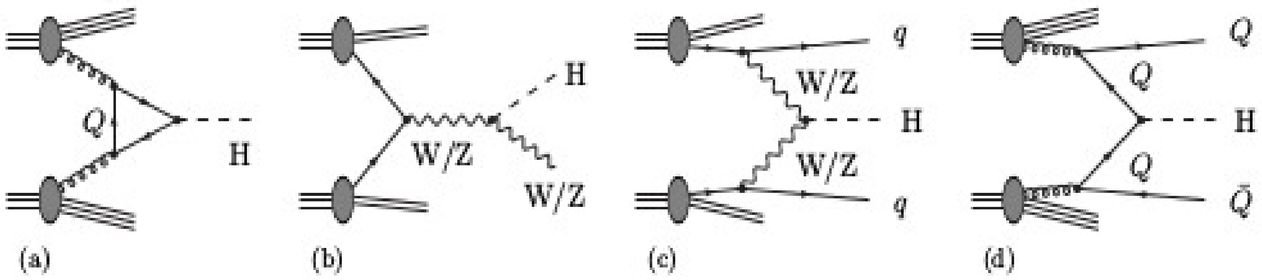
- The measured total width is 2.4952+/- .0023 GeV
- One neutrino contributes ~166MeV
- The measuremetn of Z width is incompatible with a fourth neutrino generation.

Higgs

- Mass not predicted
- LEP result favoured a light Higgs (from higher order effect)
- Discovery in 2012 at CERN mh=125GeV

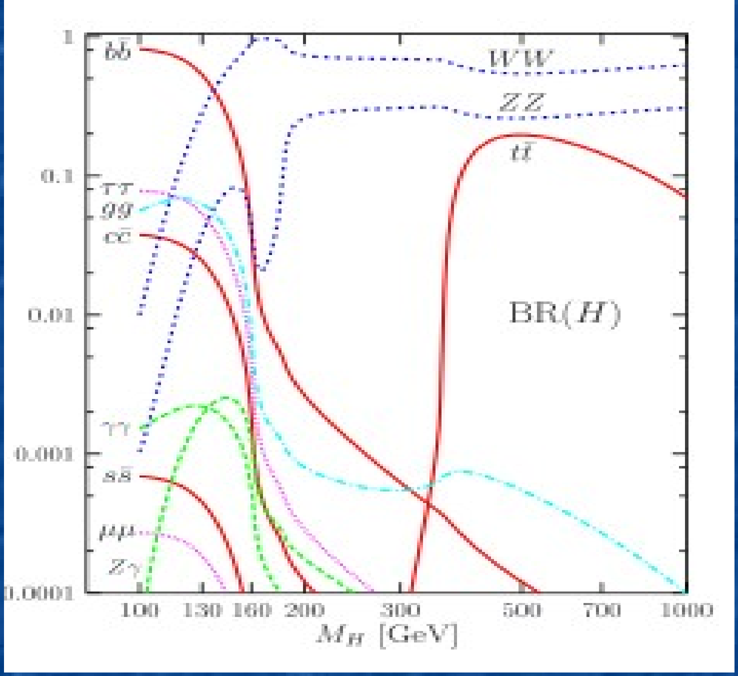


Higgs at LHC



Production in pp

- two independent production modes VBF+VH, ggF+ttH
- At 125 GeV: four independent final states: $\gamma\gamma$,VV, bb,$\tau\tau$
- Can determine Higgs couplings



- Severak decay modes accessible at 125GeV

Higgs couplings