3. Electroweak Phenomenology

- **Inputs**
- $Z \to f\,\bar{f}\ ,\ \ W \to f_1\,\bar{f}_2$
- **Z Peak Asymmetries**
- **Sensitivity to Higher Scales**
- **Standard Model Fits:** M_H
- $e^+e^- \to W^+W^-\ ,\ \ e^+e^- \to Z\,Z$
- **Higgs Search**


Quarks
Leptons
Bosons
up
down
electron
neutrino e
photon
gluon
charm
strange
muon
neutrino μ
Z0 W±
top
beauty
tau
neutrino τ
Higgs

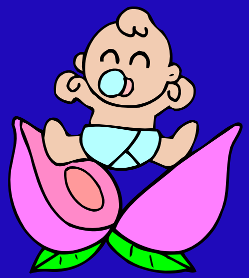
Standard Model Parameters

QCD: $\alpha_S(M_Z)$

1

EW Gauge / Scalar Sector: **4**

$$g\,,\,g'\,,\,\mu^2\,,\,\lambda \quad \Longleftrightarrow \quad \alpha\,,\,\theta_W\,,\,M_W\,,\,M_H \quad \Longleftrightarrow \quad \alpha\,,\,G_F\,,\,M_Z\,,\,M_H$$



INPUTS

$$G_F = (1.166\,371 \pm 0.000\,006) \times 10^{-5}\ \mathrm{GeV}^{-2}$$

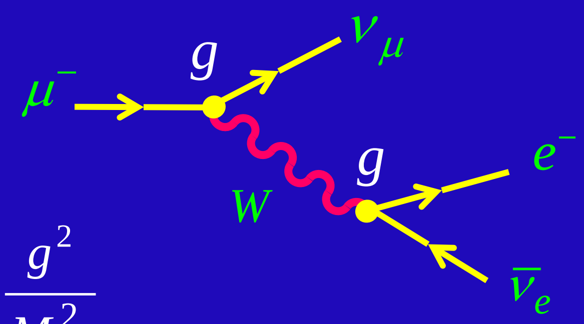
$$\alpha^{-1} = 137.035\,999\,710 \pm 0.000\,000\,096$$

$$M_Z = (91.1875 \pm 0.0021)\ \mathrm{GeV}$$

$$\alpha^{-1}(M_Z^2) = 128.93 \pm 0.05$$

$$M_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\,G_F}$$

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

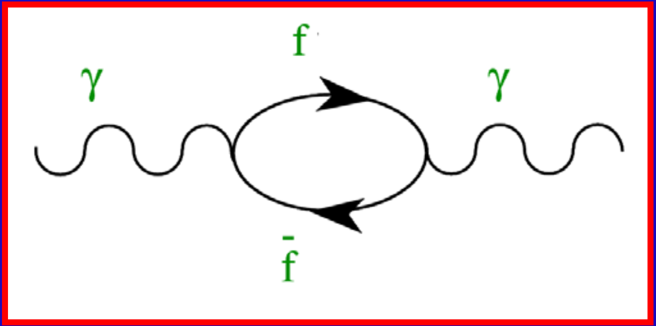


$$G_F \sim \frac{g^2}{M_W^2}$$

$$M_W = 80.94\ \mathrm{GeV} \qquad (79.96) \qquad [\,\mathrm{Exp:}\ 80.399 \pm 0.023\,]$$

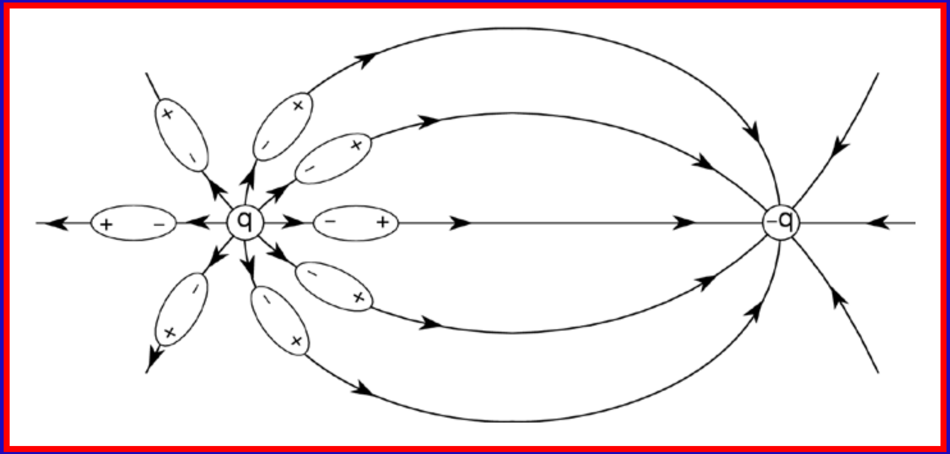
$$\sin^2\theta_W = 0.212 \qquad (0.231)$$

VACUUM POLARIZATION



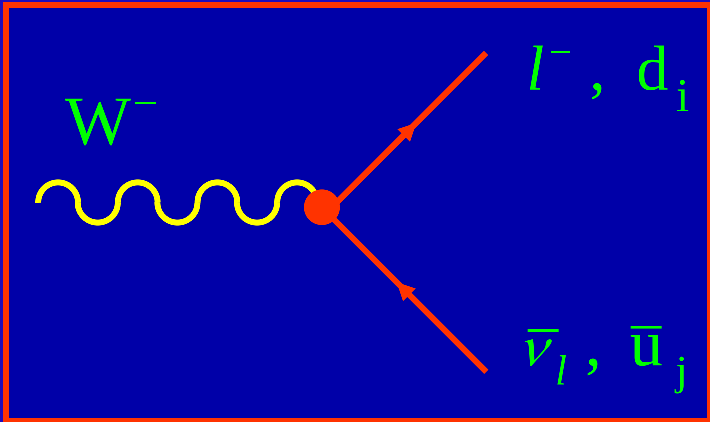
The Photon Couples to *Virtual* $f\,\bar{f}$ *Pairs*

Vacuum ⟷ **Polarized Dielectric Medium**



$$\alpha^{-1} = \alpha(m_e^2)^{-1} = 137.035999710\;\;(96) \qquad ; \qquad \alpha\,(M_Z^2)^{-1} = 128.93 \pm 0.05$$

($l^-\,l^+$ and $q\,\bar{q}$ contributions included)



$$W^- \to e^- \overline{\nu}_e \,,\; \mu^- \overline{\nu}_\mu \,,\; \tau^- \overline{\nu}_\tau \,,\; d' \,\overline{u} \,,\; s' \,\overline{c}$$

$$\overline{u}_{\mathrm{j}} = \overline{u}\,, \overline{c} \qquad ; \qquad \begin{pmatrix} d' \\ s' \end{pmatrix} \approx \begin{pmatrix} \cos\theta_C & \sin\theta_C \\ -\sin\theta_C & \cos\theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\mathrm{Br}\left(W^- \to l^- \overline{\nu}_l\right) \equiv \frac{\Gamma\left(W^- \to l^- \overline{\nu}_l\right)}{\Gamma\left(W^- \to \mathrm{all}\right)} = \frac{1}{3 + 2\, N_C} = 11.1\%$$

QCD: $$N_C \left\{1 + \frac{\alpha_s(M_Z)}{\pi}\right\} \approx 3.115 \quad \Rightarrow \quad \mathrm{Br}\left(W^- \to l^- \overline{\nu}_l\right) \approx 10.8\,\%$$

Experiment:

$$\mathrm{Br}\left(W^- \to e^- \overline{\nu}_e\right) = \left(10.65 \pm 0.17\right)\%$$

$$\mathrm{Br}\left(W^- \to \mu^- \overline{\nu}_\mu\right) = \left(10.59 \pm 0.15\right)\%$$

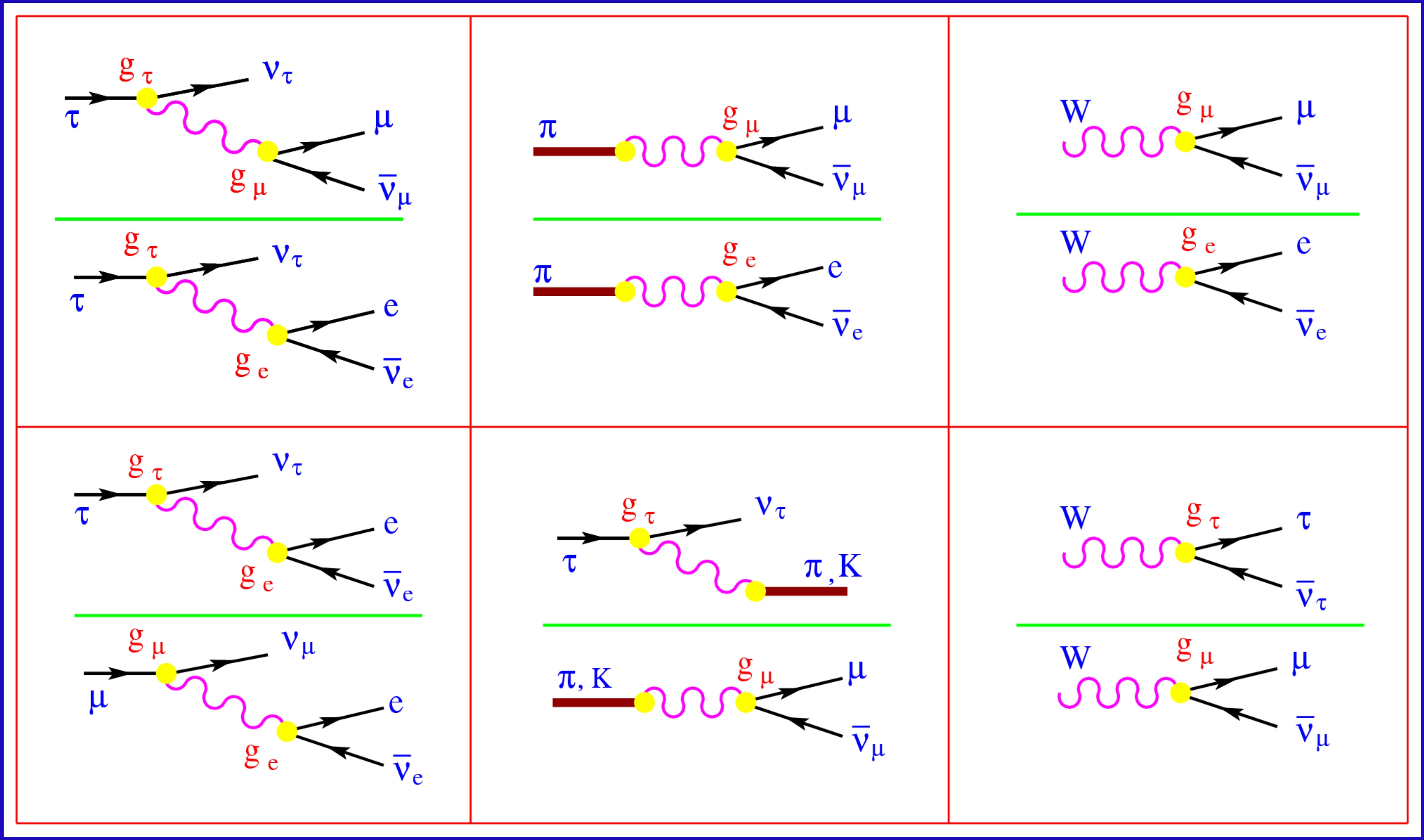
$$\mathrm{Br}\left(W^- \to \tau^- \overline{\nu}_\tau\right) = \left(11.44 \pm 0.22\right)\%$$

Universal $W\, l\, \overline{\nu}_l$ **Couplings**

LEPTON UNIVERSALITY

$$\frac{g_\mu}{g_e}$$

$$\frac{g_\tau}{g_\mu}$$



CHARGED CURRENT UNIVERSALITY

$|g_\mu / g_e|$

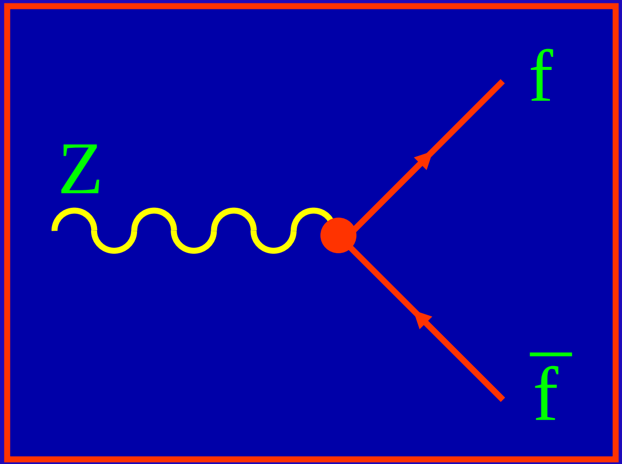
$B_{\tau\to\mu}/B_{\tau\to e}$	1.0018 ± 0.0015
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0021 ± 0.0016
$B_{K\to\mu}/B_{K\to e}$	1.004 ± 0.007
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.002 ± 0.002
$B_{W\to\mu}/B_{W\to e}$	0.997 ± 0.010

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0006 ± 0.0022
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.996 ± 0.005
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.979 ± 0.017
$B_{W\to\tau}/B_{W\to\mu}$	1.039 ± 0.013

$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0005 ± 0.0023
$B_{W\to\tau}/B_{W\to e}$	1.036 ± 0.014



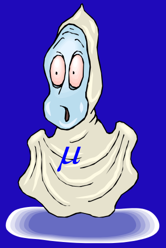
$$Z \to l^- \, l^+ \, , \; \nu_l \, \bar{\nu}_l$$

$$\Gamma\left(Z \to l \,\bar{l}\right) \propto \left(|v_l|^2 + |a_l|^2 \right)$$

$$\frac{\Gamma_{\text{inv}}}{\Gamma_{ll}} \equiv \frac{\Gamma\left(Z \to \text{invisible}\right)}{Z \to l^+ \, l^-} = N_\nu \, \frac{\Gamma\left(Z \to \nu_l \, \bar{\nu}_l\right)}{\Gamma\left(Z \to l^+ \, l^-\right)} = N_\nu \, \frac{2}{\left(1 - 4\sin^2\theta_W\right)^2 + 1} = 1.955 \; N_\nu$$

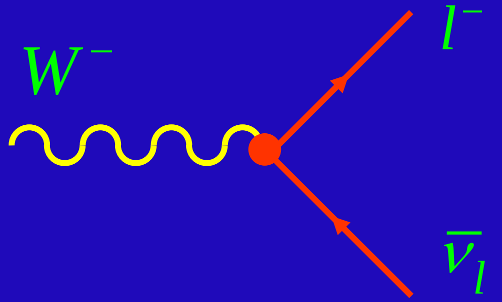
$$(1.989)$$

Experiment:



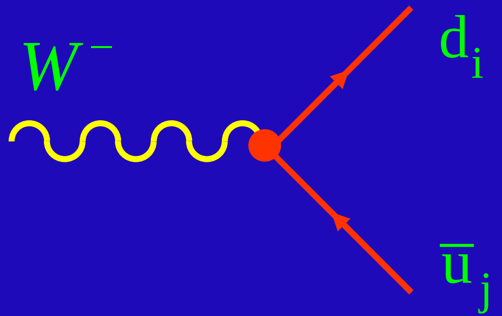
$$\frac{\Gamma_{\text{inv}}}{\Gamma_{ll}} = 5.942 \pm 0.016 \quad \Longrightarrow \quad N_\nu = 3.04 \qquad (2.99)$$

$$N_\nu = 2.9840 \pm 0.0082$$



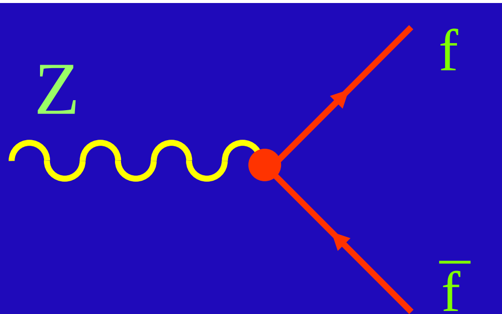
$$W^- \to e^- \bar{\nu}_e \ , \ \mu^- \bar{\nu}_\mu \ , \ \tau^- \bar{\nu}_\tau$$

$$\Gamma = \frac{G_F M_W^3}{6\pi\sqrt{2}}$$



$$W^- \to d'\bar{u} \ , \ s'\bar{c}$$

$$\Gamma = \frac{G_F M_W^3}{6\pi\sqrt{2}} \left|\mathrm{V}_{ij}\right|^2 \ N_C$$



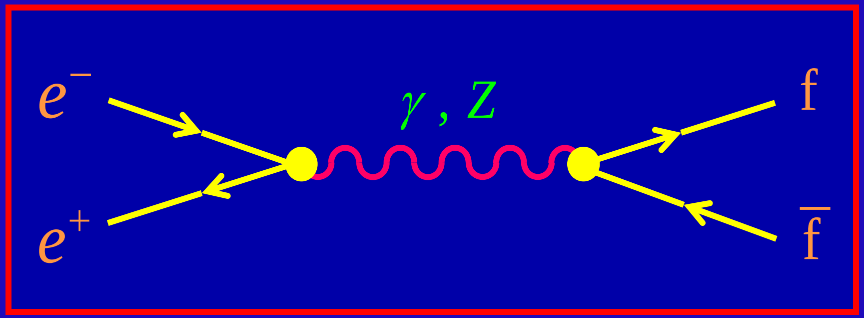
$$Z \to l^- l^+ \ , \ \nu_i \bar{\nu}_i \ , \ \mathrm{q}\,\bar{\mathrm{q}} \qquad (\mathrm{q} = \mathrm{u, d, s, c, b})$$

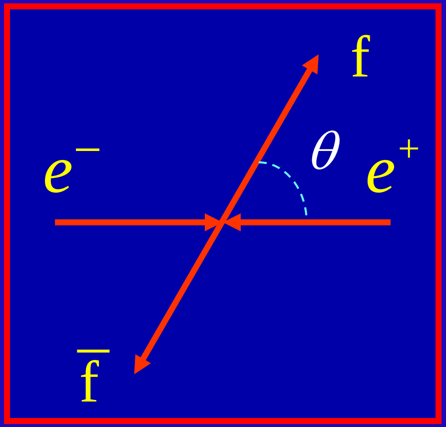
$$\Gamma = \frac{G_F M_Z^3}{6\pi\sqrt{2}} \left(\left|\mathrm{v}_f\right|^2 + \left|a_f\right|^2 \right) N_f \quad ; \quad N_l = 1 \ , \ N_\mathrm{q} = N_C$$

$$\Gamma_W = 2.09 \ \text{GeV} \quad , \quad \Gamma_Z = 2.48 \ \text{GeV}$$

Exp: 2.098 ± 0.048 $\qquad$ 2.4952 ± 0.0023

$$e^+ e^- \to \gamma\,,\, Z \to f\,\bar{f}$$





$$\boxed{\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s}\, N_{\mathrm{f}} \left\{ A\ (1+\cos^2\theta) + B\cos\theta - h_{\mathrm{f}} \left[C\ (1+\cos^2\theta) + D\cos\theta \right] \right\}}$$

$$N_l = 1 \quad ; \quad N_q = N_C \left\{ 1 + \frac{\alpha_s(M_Z^2)}{\pi} + \cdots \right\} \quad ; \quad h_{\mathrm{f}} = \pm 1$$

$$A = 1 + 2\, \mathrm{v}_e\, \mathrm{v}_{\mathrm{f}}\ \mathrm{Re}(\chi) + (\mathrm{v}_e^2 + a_e^2)(\mathrm{v}_{\mathrm{f}}^2 + a_{\mathrm{f}}^2)\ |\chi|^2$$

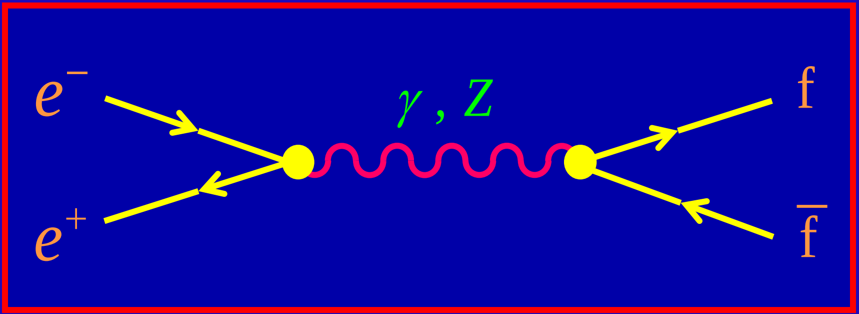
$$B = 4\ a_e\, a_{\mathrm{f}}\ \mathrm{Re}(\chi) + 8\, \mathrm{v}_e\, a_e\, \mathrm{v}_{\mathrm{f}}\, a_{\mathrm{f}}\ |\chi|^2$$

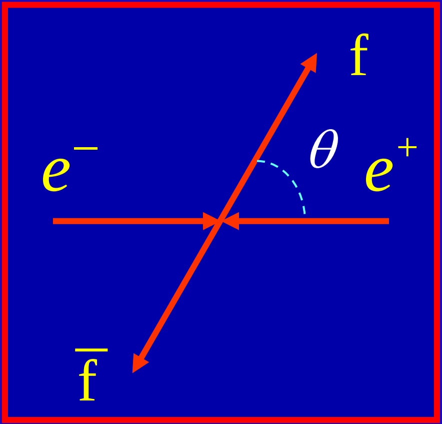
$$C = 2\ \mathrm{v}_e\, a_{\mathrm{f}}\ \mathrm{Re}(\chi) + 2\,(\mathrm{v}_e^2 + a_e^2)\, \mathrm{v}_{\mathrm{f}}\, a_{\mathrm{f}}\ |\chi|^2$$

$$D = 4\ a_e\, \mathrm{v}_{\mathrm{f}}\ \mathrm{Re}(\chi) + 4\, \mathrm{v}_e\, a_e\, (\mathrm{v}_{\mathrm{f}}^2 + a_{\mathrm{f}}^2)\ |\chi|^2$$

$$\chi = \frac{G_F M_Z^2}{2\sqrt{2}\,\pi\alpha}\ \frac{s}{s - M_Z^2 + i\,s\,\Gamma_Z / M_Z}$$

$$e^+ e^- \to \gamma\,,\, Z \to f\,\bar{f}$$





$$\boxed{\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{8s}\, N_f \left\{ A\;(1+\cos^2\theta) + B\cos\theta - h_f \left[C\;(1+\cos^2\theta) + D\cos\theta \right] \right\}}$$

$$\mathcal{A}_{\mathrm{FB}}(s) \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{3}{8}\,\frac{B}{A}$$

$$\mathcal{A}_{\mathrm{Pol}}(s) \equiv \frac{\sigma^{(h_f=+1)} - \sigma^{(h_f=-1)}}{\sigma^{(h_f=+1)} + \sigma^{(h_f=-1)}} = -\frac{C}{A} \qquad ; \qquad \sigma = \frac{4\pi\alpha^2}{3s}\, N_f\, A$$

$$\mathcal{A}_{\mathrm{FB}}^{\mathrm{Pol}}(s) \equiv \frac{N_F^{(+1)} - N_F^{(-1)} - N_B^{(+1)} + N_B^{(-1)}}{N_F^{(+1)} + N_F^{(-1)} + N_B^{(+1)} + N_B^{(-1)}} = -\frac{3}{8}\,\frac{D}{A}$$

Z Peak $\quad (s = M_Z^2)$

$$\sigma = \frac{12\pi}{M_Z^2}\,\frac{\Gamma_e\,\Gamma_f}{\Gamma_Z^2} \qquad ; \qquad \Gamma_f \equiv \Gamma(Z \to f\,\bar{f})$$

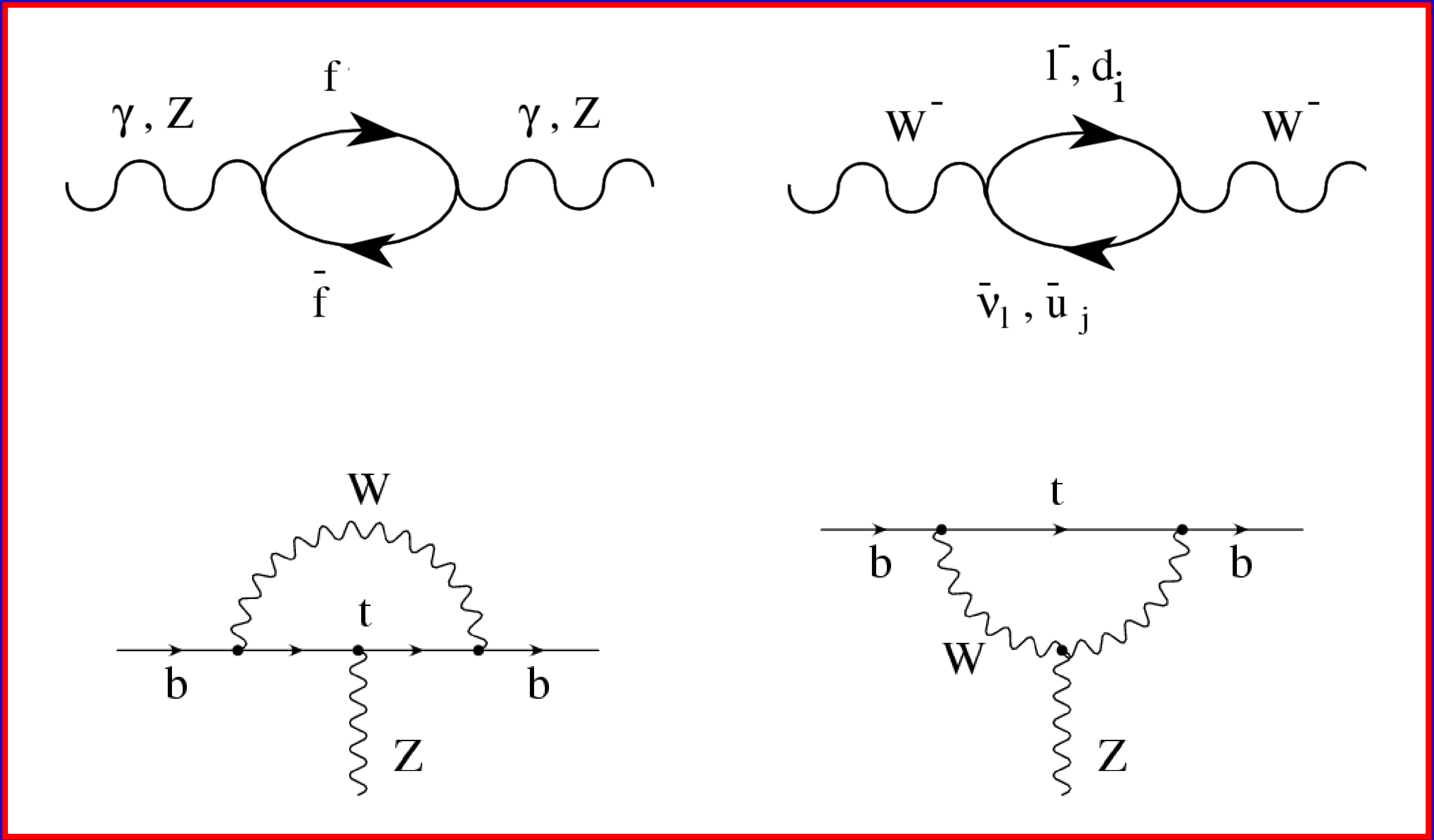
$$\mathcal{A}_{\text{FB}}(s) = \frac{3}{4}\,\mathcal{P}_e\,\mathcal{P}_f \qquad ; \qquad \mathcal{A}_{\text{Pol}}(s) = \mathcal{P}_f \qquad ; \qquad \mathcal{A}_{\text{FB}}^{\text{Pol}}(s) = \frac{3}{4}\,\mathcal{P}_e$$

$$\mathcal{A}_{\text{LR}}(s) \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\mathcal{P}_e \qquad ; \qquad \mathcal{A}_{\text{FB}}^{\text{LR}}(s) = -\frac{3}{4}\,\mathcal{P}_f$$

Final Polarization $\quad \mathcal{P}_f \equiv -A_f = \dfrac{-2\,v_f\,a_f}{|v_f|^2 + |a_f|^2}$ **Only Available for** $\; f = \tau$

$|v_l| = \dfrac{1}{2}\,\left|-1 + 4\sin^2\theta\right| \ll 1$ ➡ $\mathcal{P}_l$ **Sensitive to Higher Order Corrections**

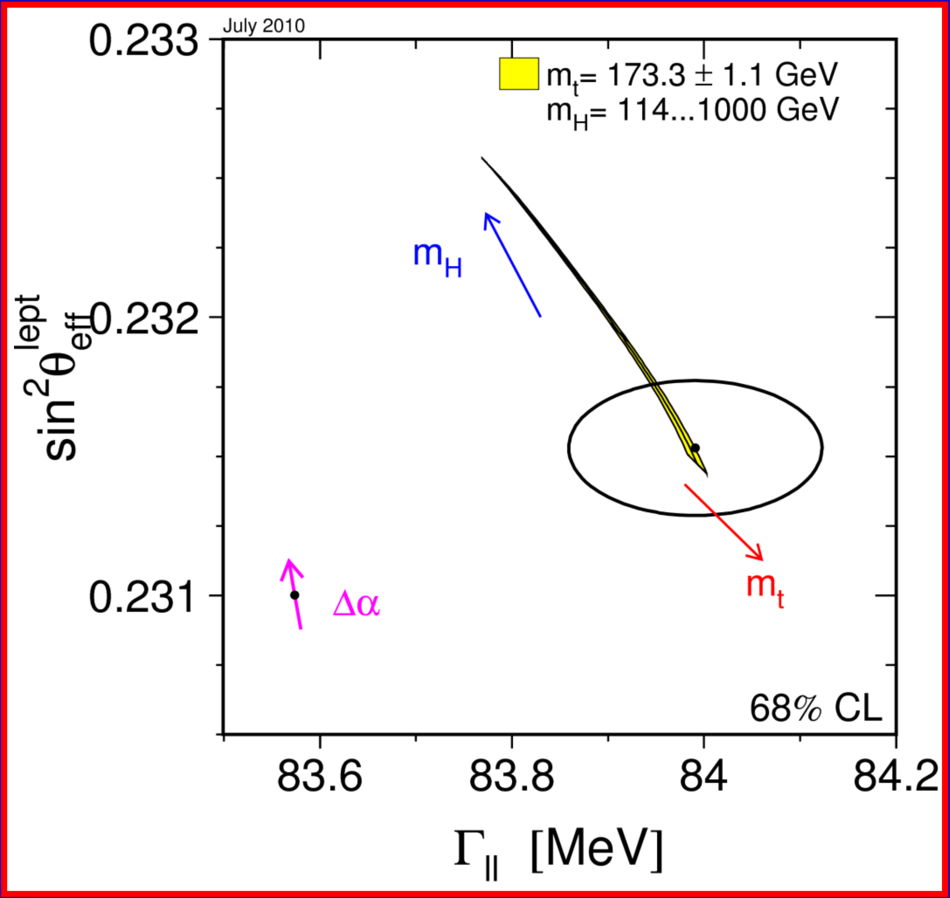
Higher Order Corrections

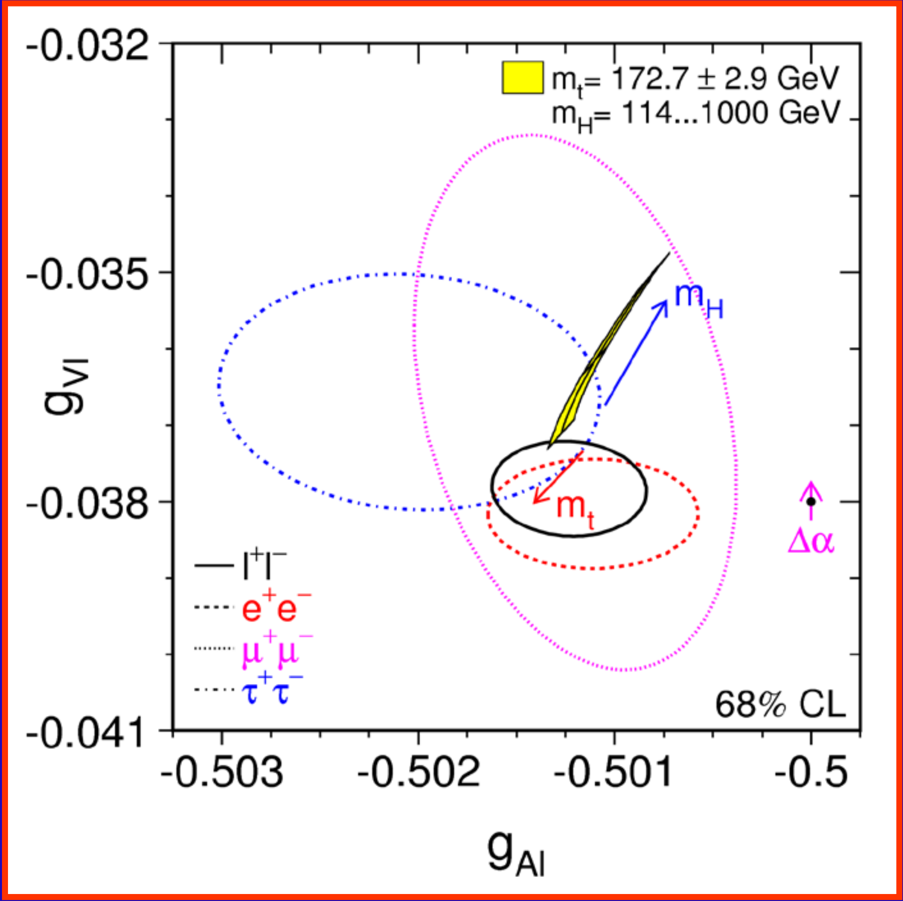


Sensitive to Heavier Particles: TOP , HIGGS

Evidence of Electroweak Corrections

July 2010 LEPEWWG September 2005



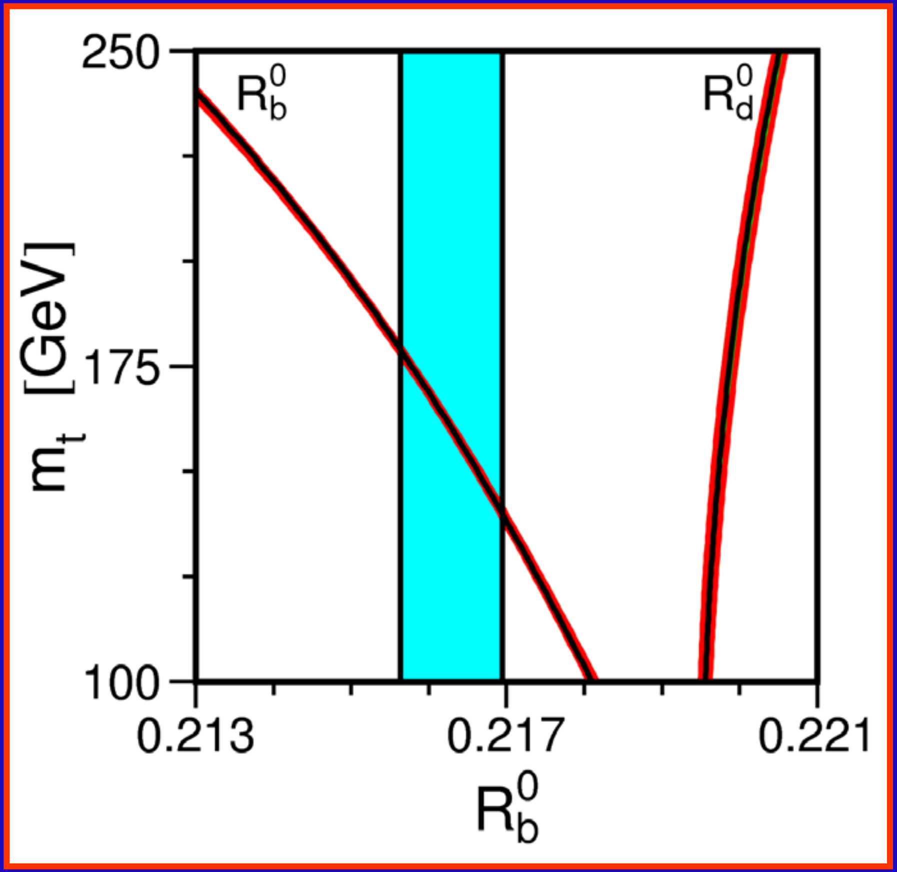


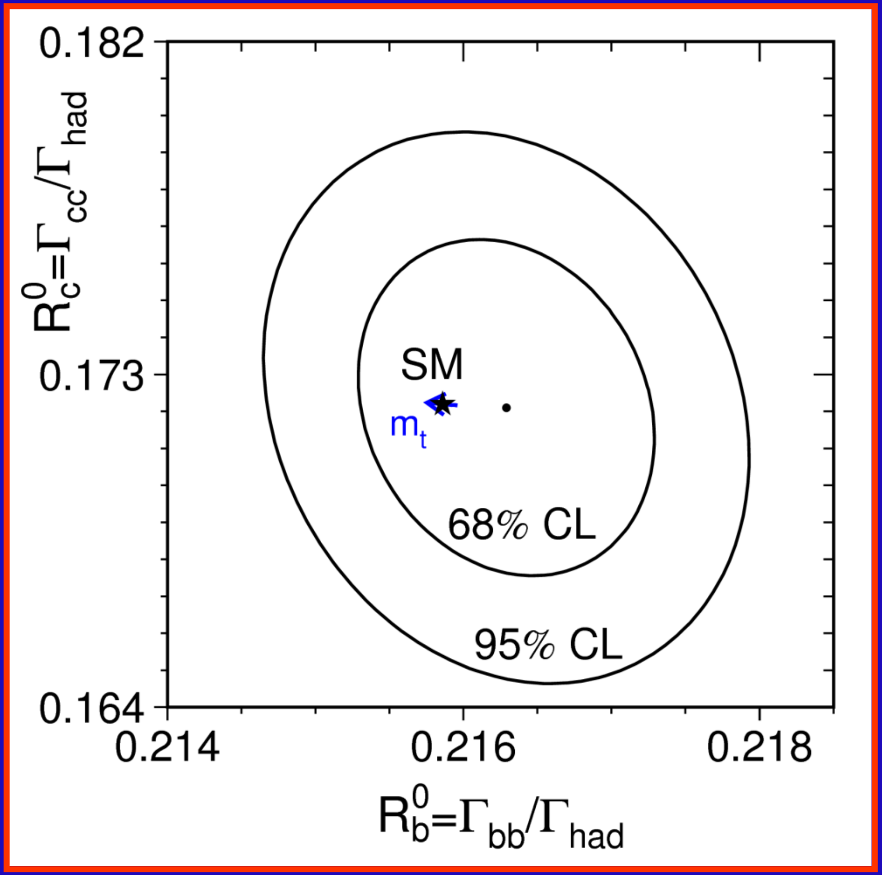
$$\alpha(M_Z^2)^{-1} = 128.93 \pm 0.05$$

Low Values of M_H Preferred

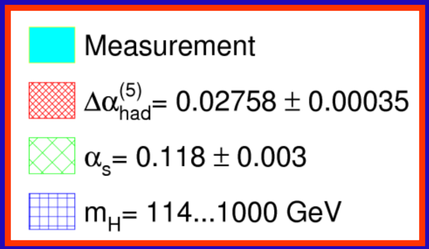
$$R_b \equiv \Gamma(Z \to b\bar{b}) / \Gamma(Z \to \text{hadrons})$$

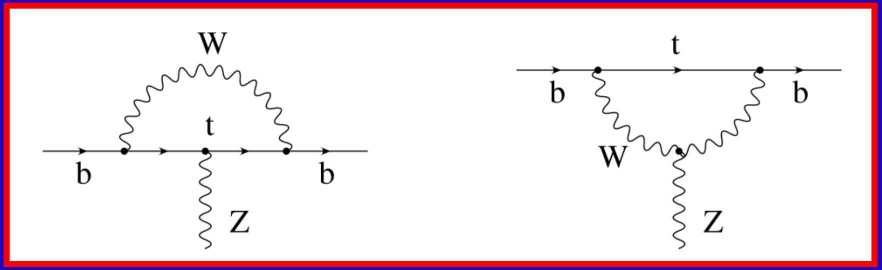
LEPEWWG September 2005

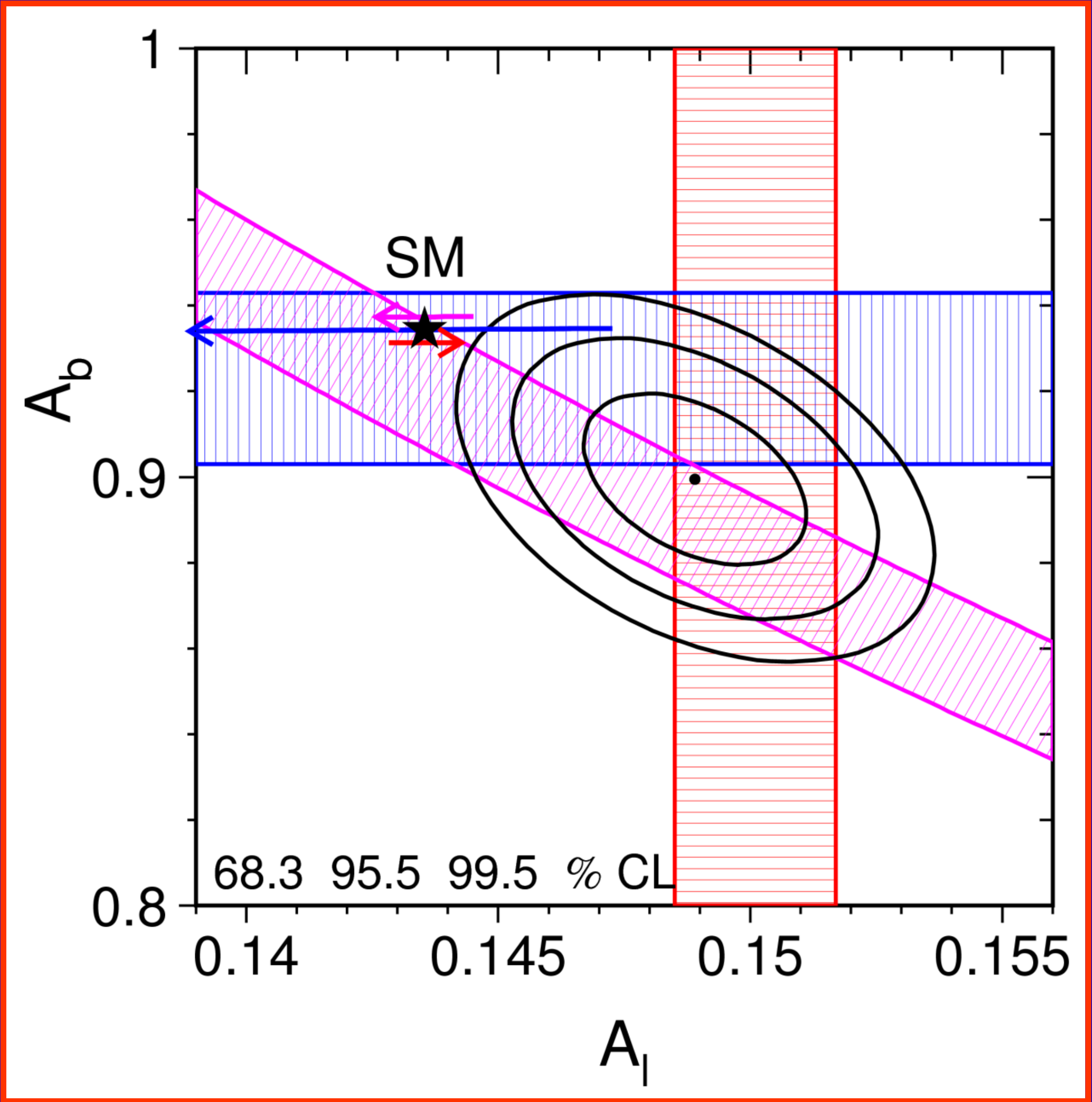




Bernabéu-Pich-Santamaría 1988







LEPEWWG

September 2005

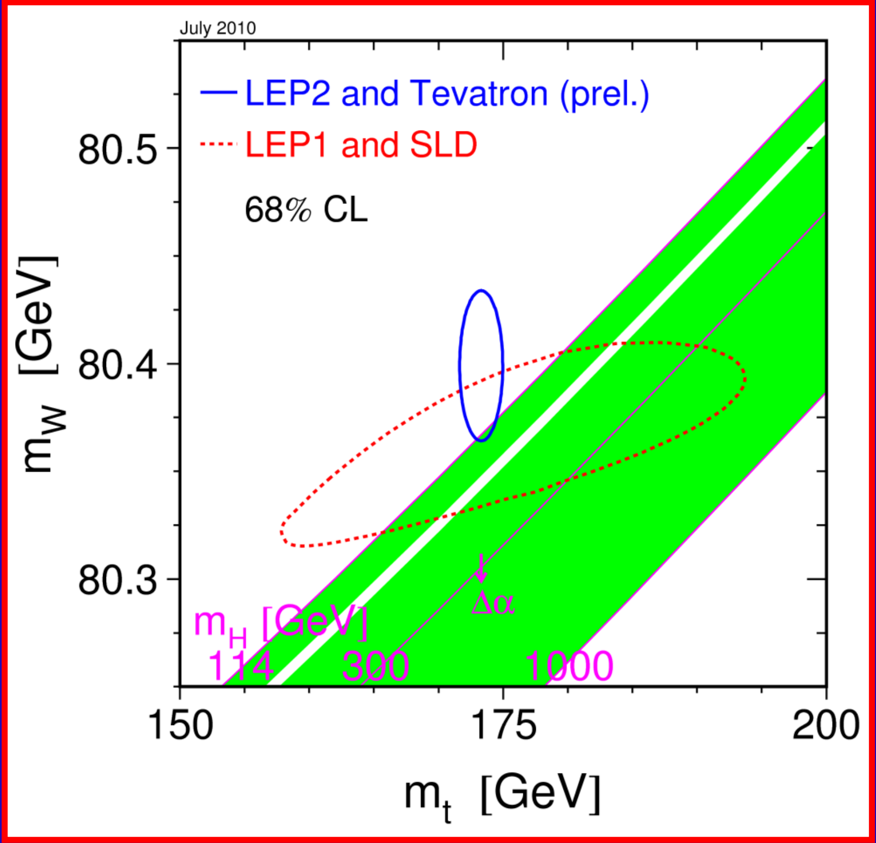
$m_t = (172.7 \pm 2.9)$ GeV

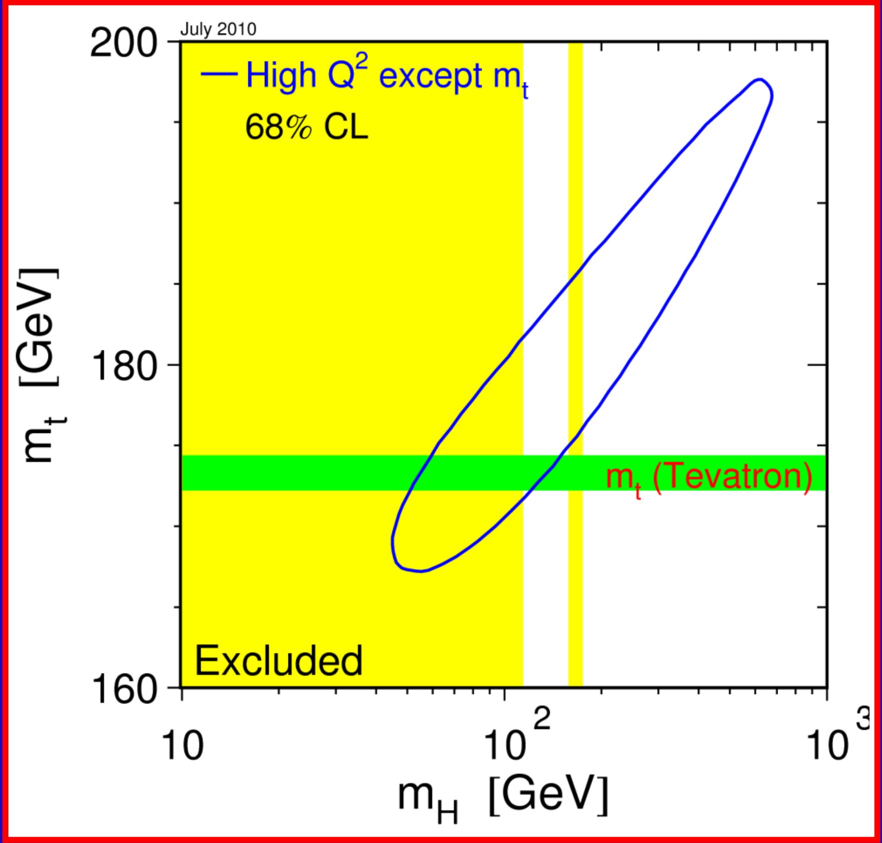
$M_H = (300\,^{+700}_{-186})$ GeV

$\alpha(M_Z^2)^{-1} = 128.93 \pm 0.05$

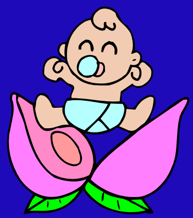
Heavy Quarks (Leptons) Favour High (Low) M_H

LEPEWWG July 2010

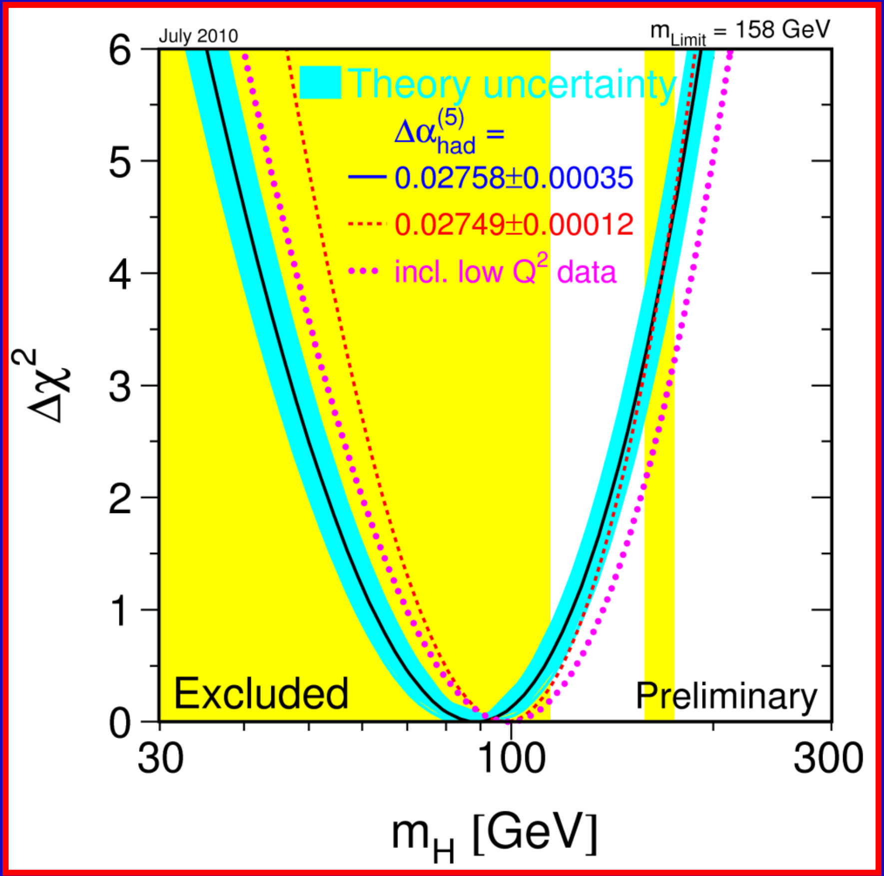




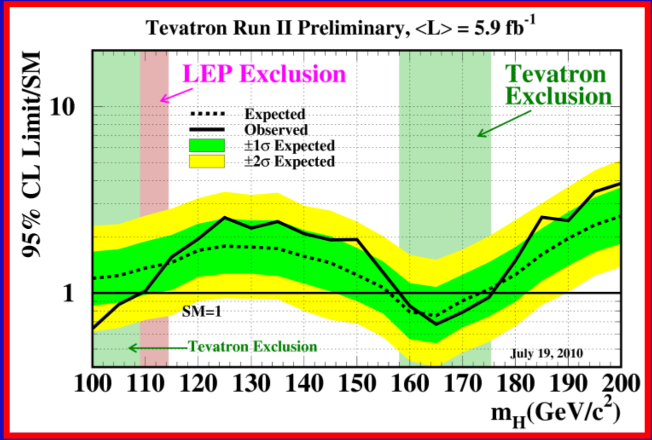
$m_t = (173.3 \pm 1.1)$ GeV **(CDF + D0)**

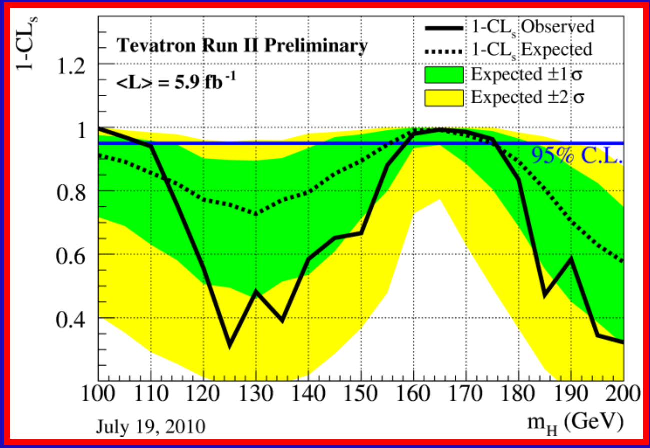


LEPEWWG (July 2010)



$H \to W^+W^-$ CDF / D0 (July 2010)

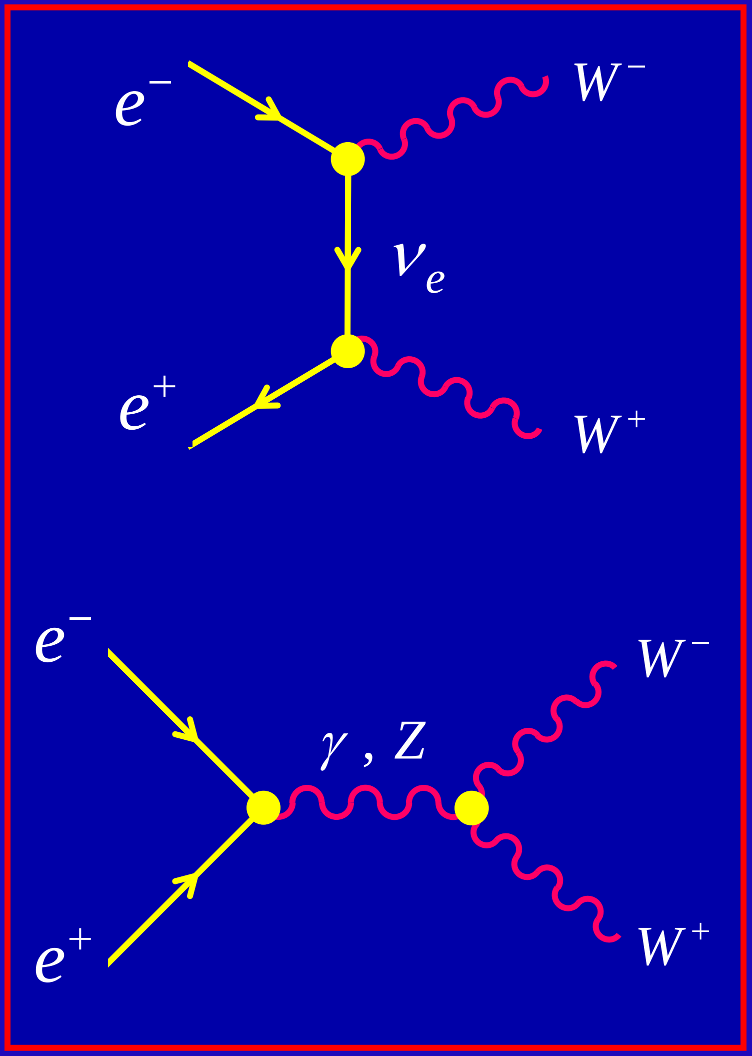


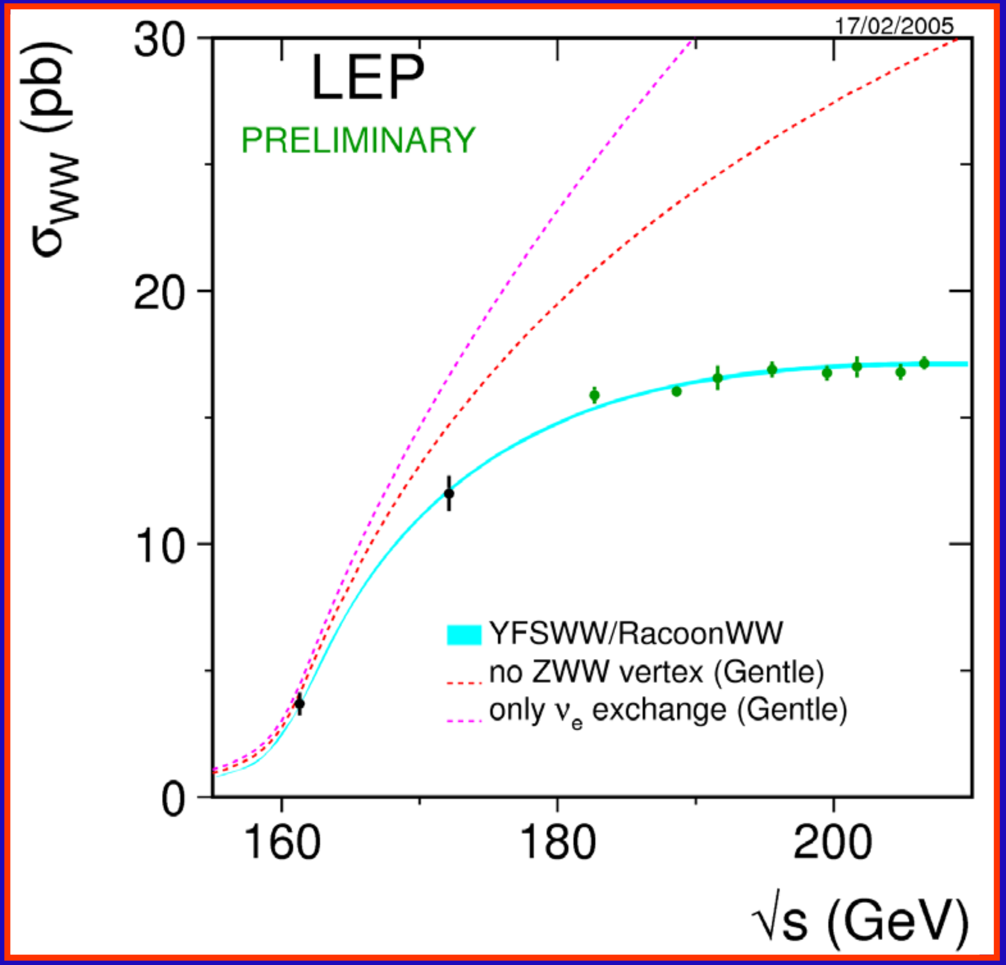


$M_H \in [158,175]$ excluded (95% CL)

$$114.4 \text{ GeV} < M_H < 158 \; (185) \text{ GeV} \qquad (95\% \text{ CL})$$

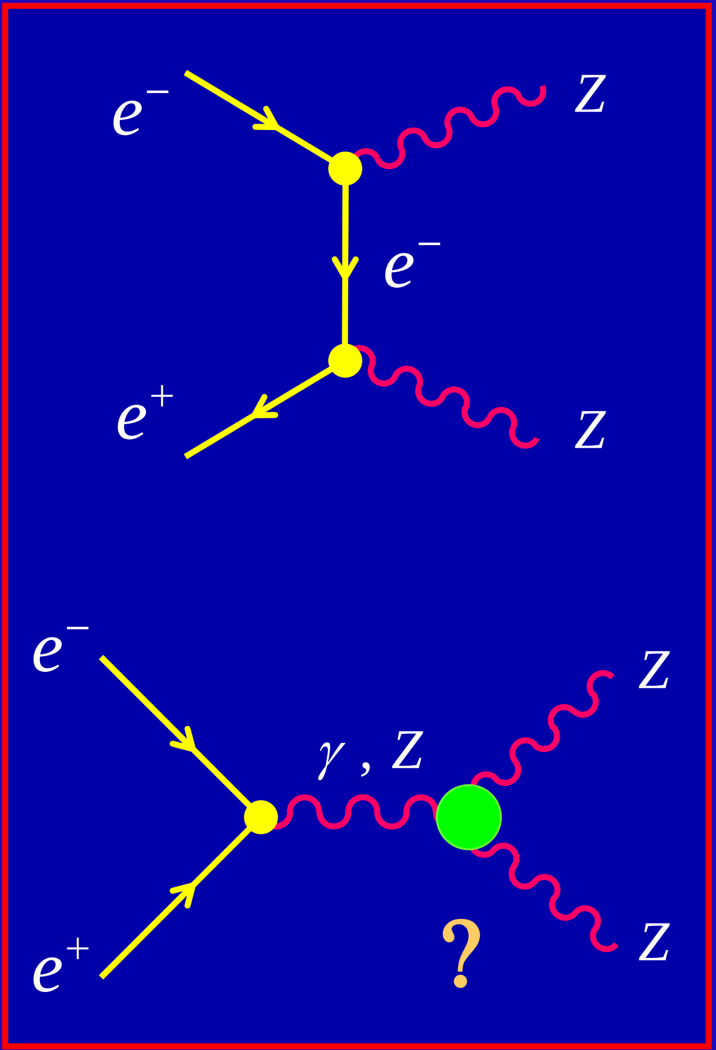
$$e^+ e^- \to W^+ W^-$$

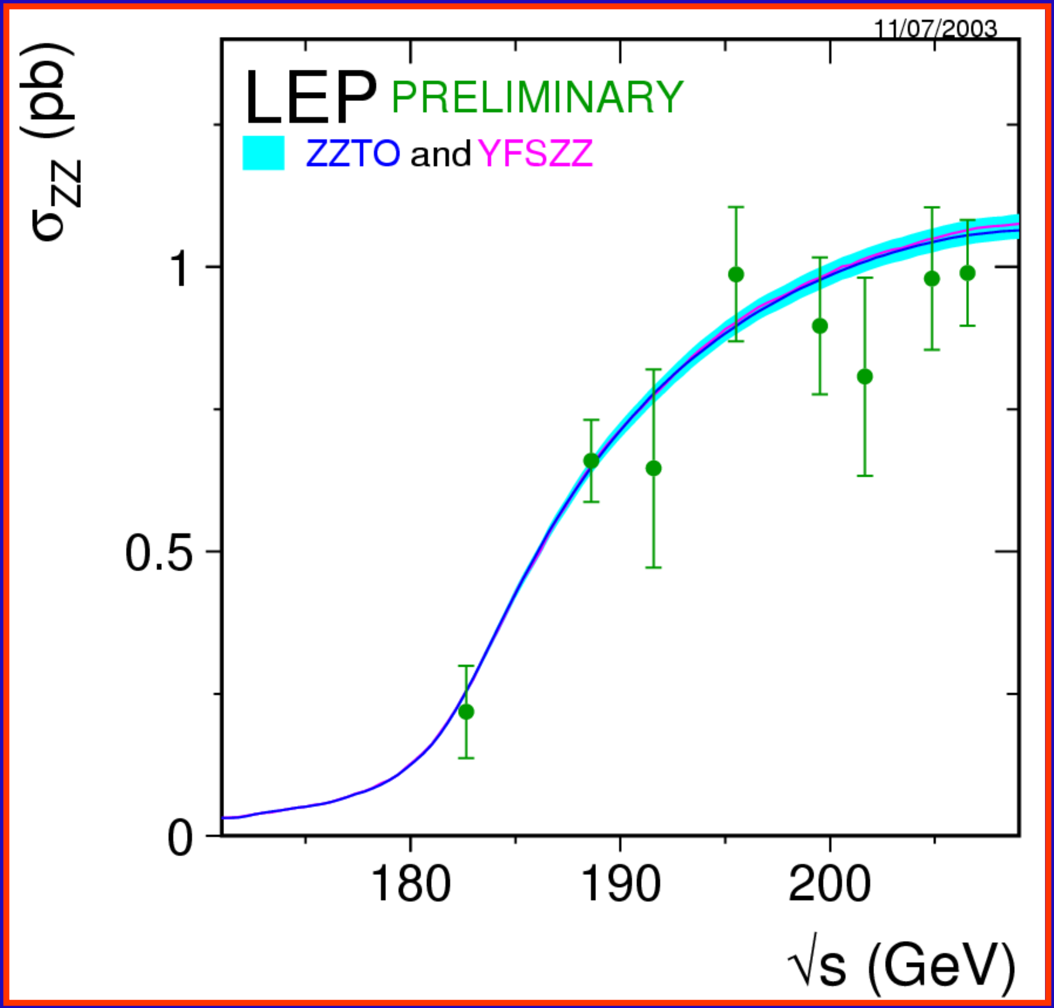




Evidence of Gauge Self-Interactions

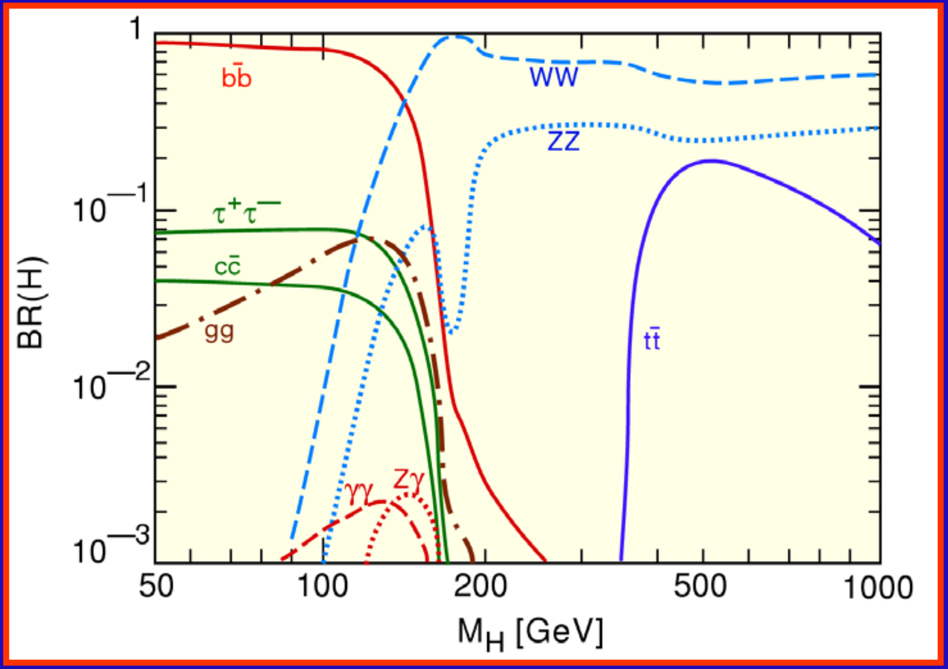
$$e^+ e^- \to Z\, Z$$





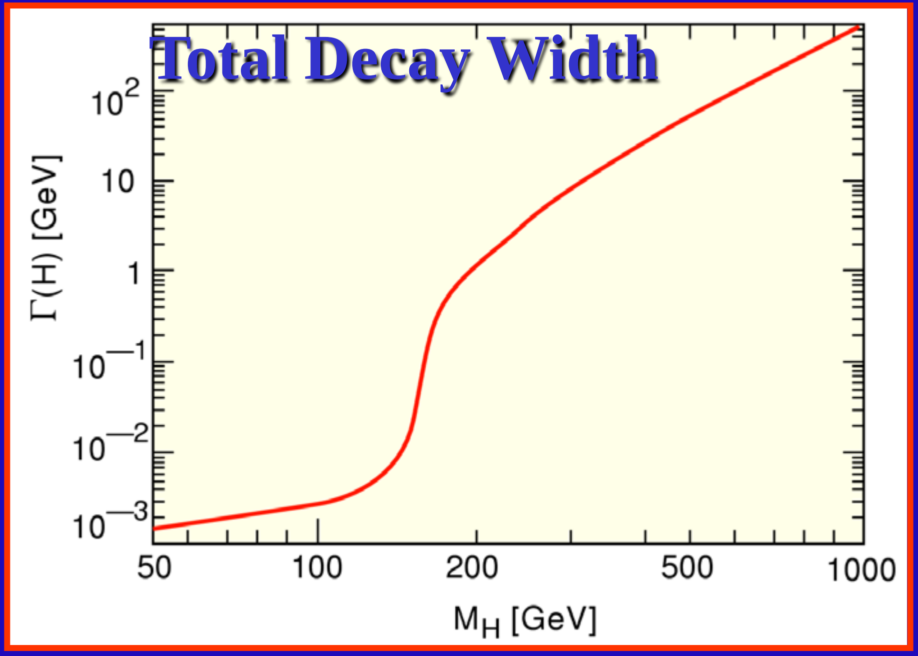
No Evidence of γZZ or ZZZ couplings

Searching for the HIGGS



D. Denegri

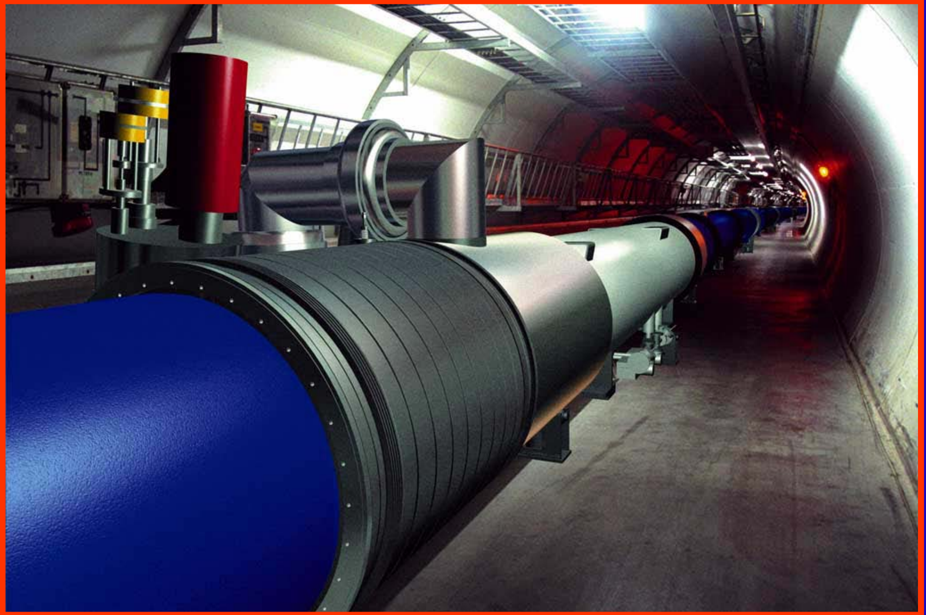
Branching Ratios

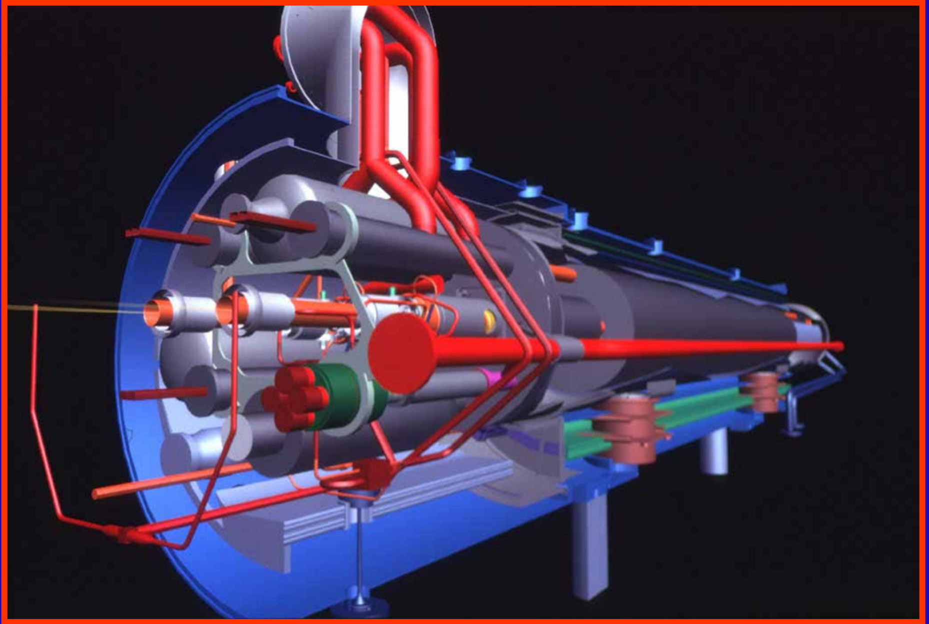


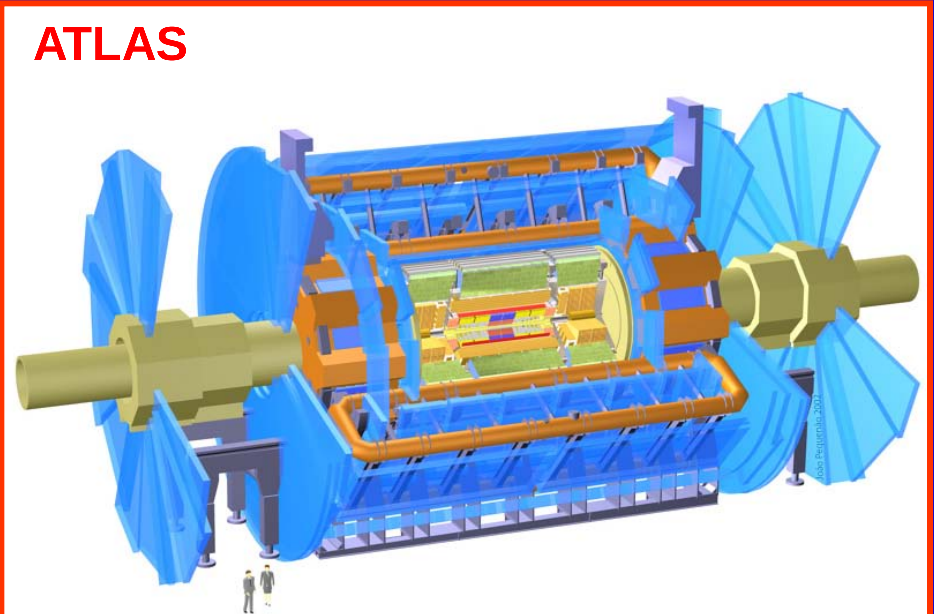
Interaction proportional to mass $(M_W^2\,, M_Z^2\,, m_f\,)$

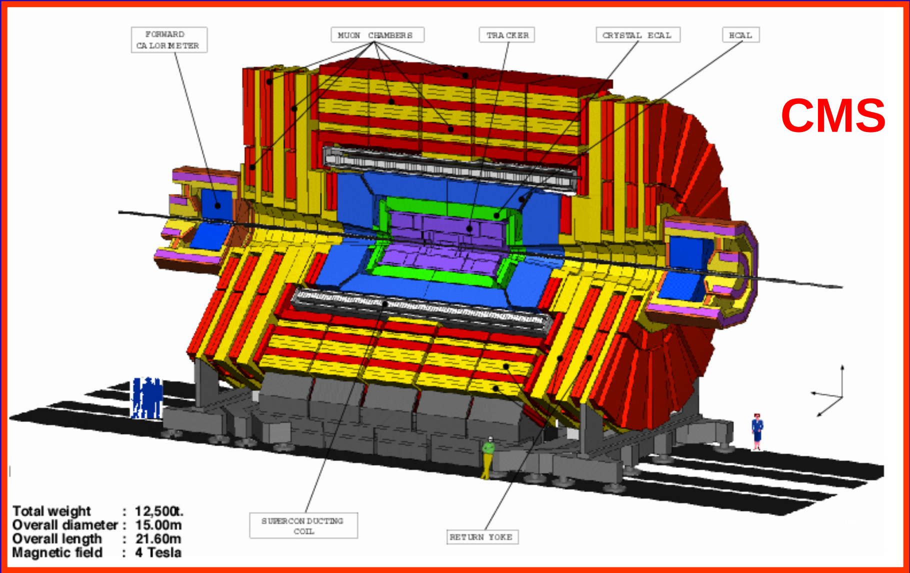
The Higgs decays into the heaviest possible particles

The Large Hadron Collider

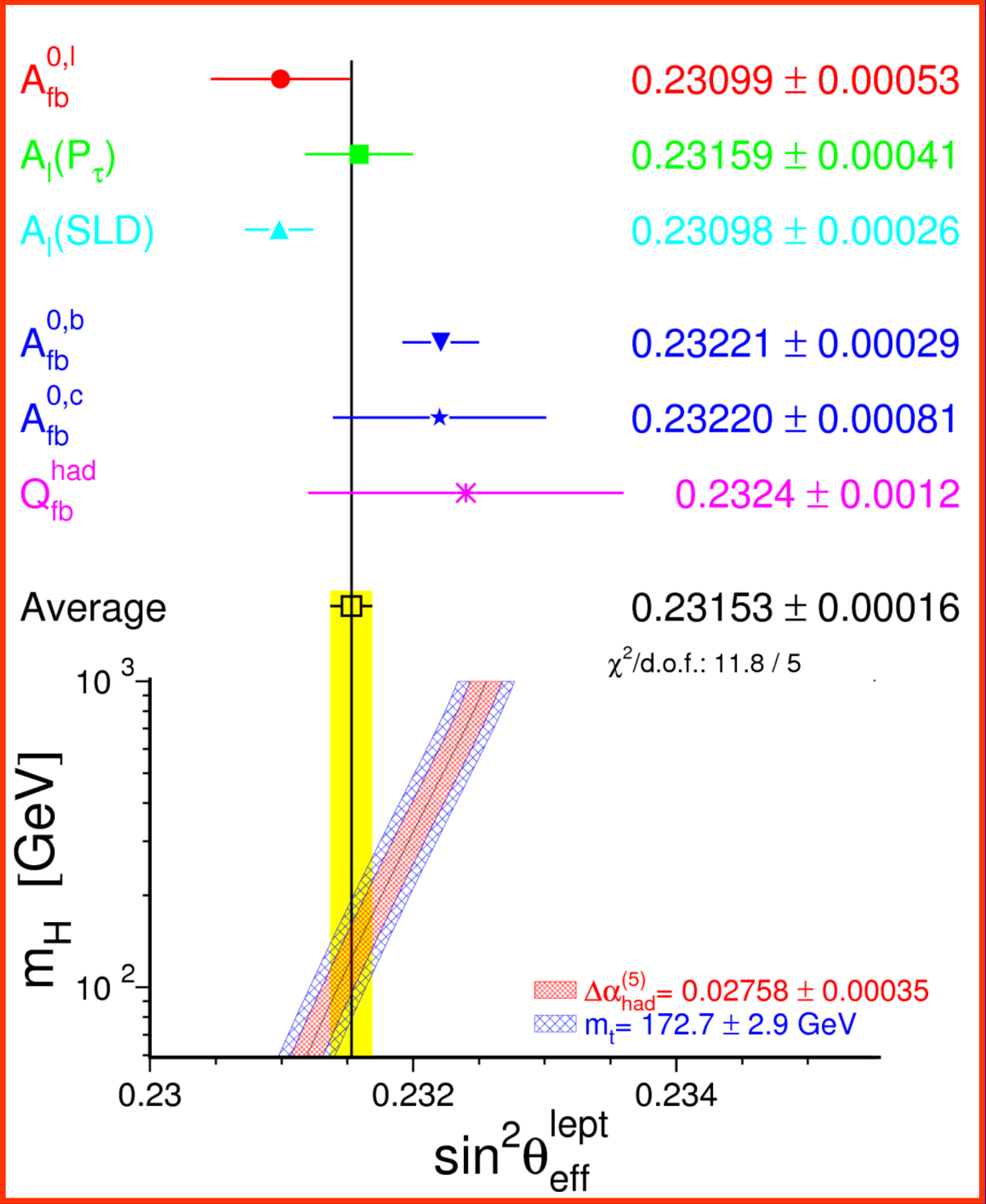


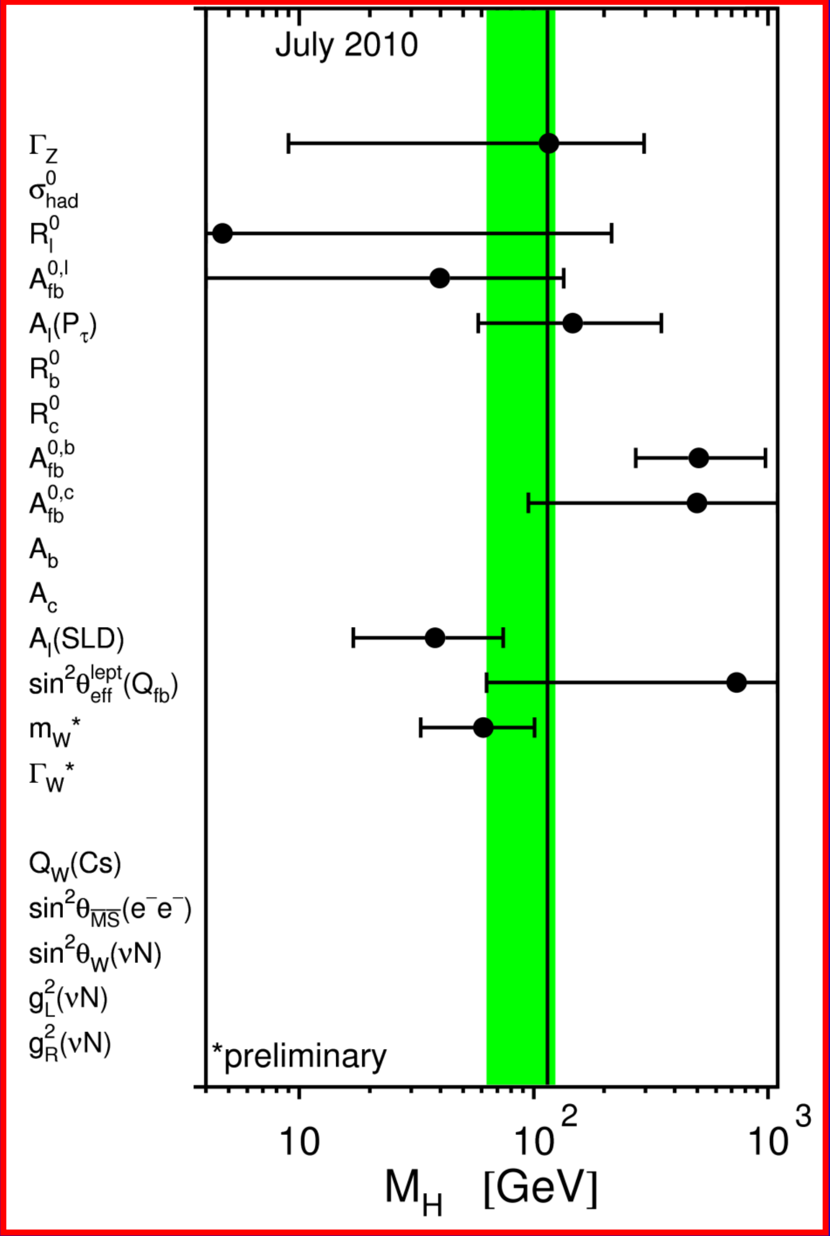




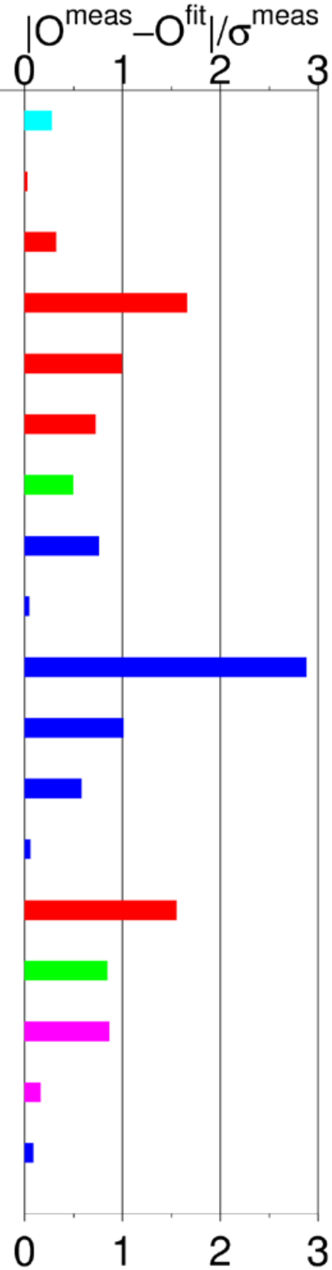


March 2006 **LEPEWWG** July 2010





	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4



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