

# Particle Physics

# The Standard Model

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# 7. Electroweak Phenomenology



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



# Quarks



up



down



charm



strange



top



beauty

# Leptons



electron



neutrino e



muon



neutrino μ



tau



neutrino τ

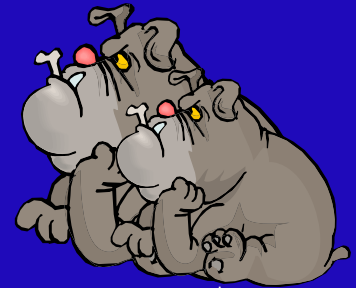
# Bosons



photon



gluon



Z<sup>0</sup> W<sup>±</sup>



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

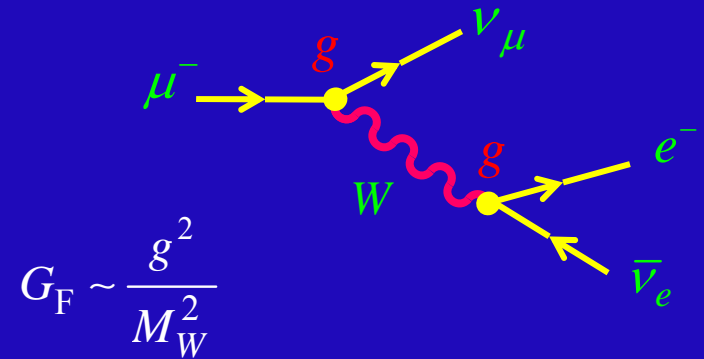
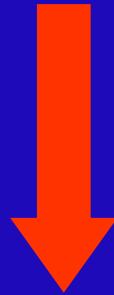
$$G_F = (1.166\,371 \pm 0.000\,006) \times 10^{-5} \text{ GeV}^{-2}$$

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

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

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

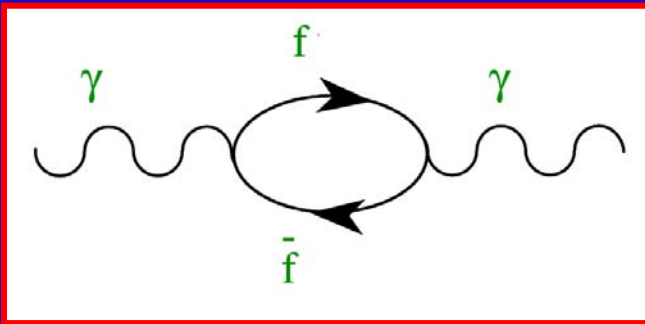
$$M_W^2 \sin^2 \theta_W = \frac{\pi \alpha}{\sqrt{2} G_F}$$
$$\sin^2 \theta_W = 1 - \frac{M_W^2}{M_Z^2}$$



$$M_W = 80.94 \text{ GeV} \quad (79.96)$$

$$[\text{Exp: } 80.398 \pm 0.025]$$

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

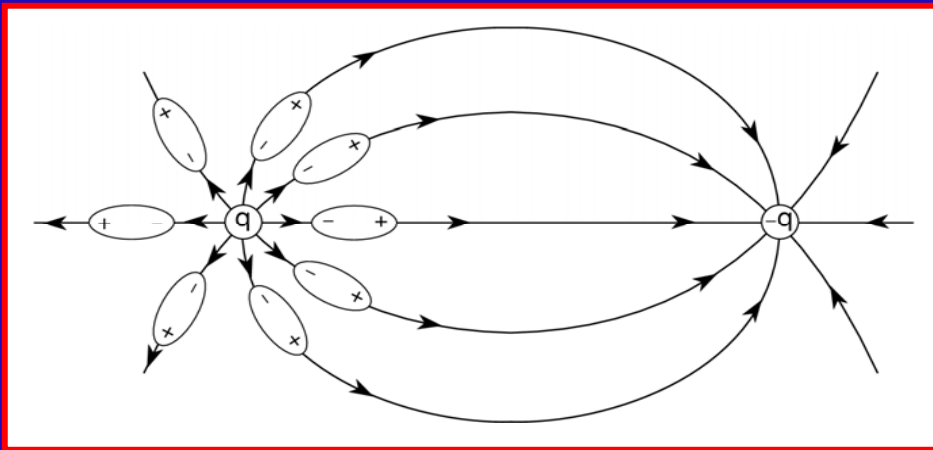


# VACUUM

ZORN-HAN-RAFOP

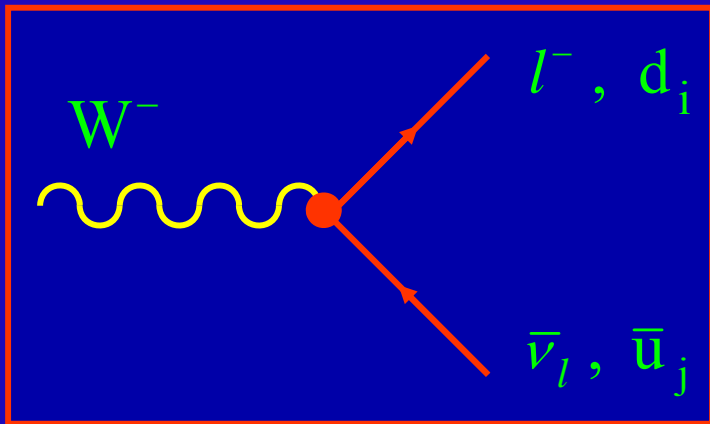
The Photon Couples to *Virtual  $f \bar{f}$  Pairs*

**Vacuum**  $\longleftrightarrow$  **Polarized Dielectric Medium**



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

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



$$W^- \rightarrow e^- \bar{\nu}_e, \mu^- \bar{\nu}_\mu, \tau^- \bar{\nu}_\tau, d' \bar{u}, s' \bar{c}$$

$$\bar{u}_j = \bar{u}, \bar{c} \quad ; \quad \begin{pmatrix} d' \\ s' \end{pmatrix} \approx \begin{pmatrix} \cos \theta_C & \sin \theta_C \\ -\sin \theta_C & \cos \theta_C \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

$$\text{Br}(W^- \rightarrow l^- \bar{\nu}_l) \equiv \frac{\Gamma(W^- \rightarrow l^- \bar{\nu}_l)}{\Gamma(W^- \rightarrow \text{all})} = \frac{1}{3 + 2 N_C} = 11.1\%$$

**QCD:**  $N_C \left\{ 1 + \frac{\alpha_s(M_Z)}{\pi} \right\} \approx 3.115 \quad \longrightarrow \quad \text{Br}(W^- \rightarrow l^- \bar{\nu}_l) \approx 10.8\%$

**Experiment:**

$$\text{Br}(W^- \rightarrow e^- \bar{\nu}_e) = (10.65 \pm 0.17)\%$$

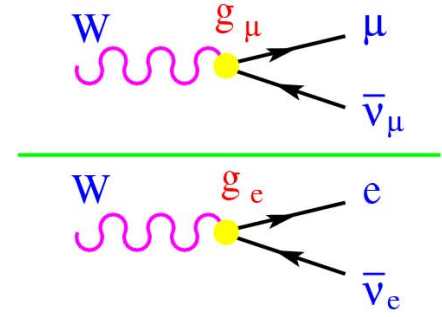
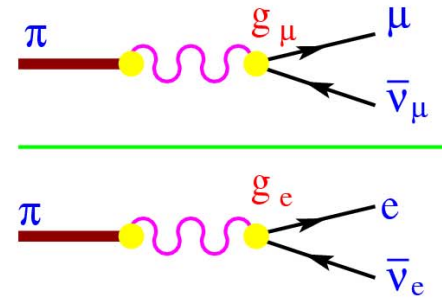
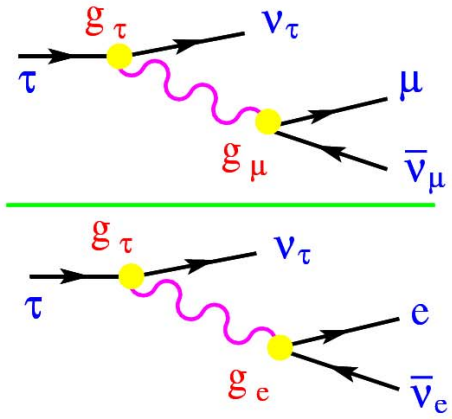
$$\text{Br}(W^- \rightarrow \mu^- \bar{\nu}_\mu) = (10.59 \pm 0.15)\%$$

$$\text{Br}(W^- \rightarrow \tau^- \bar{\nu}_\tau) = (11.44 \pm 0.22)\%$$

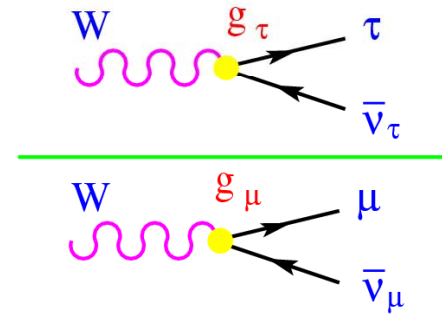
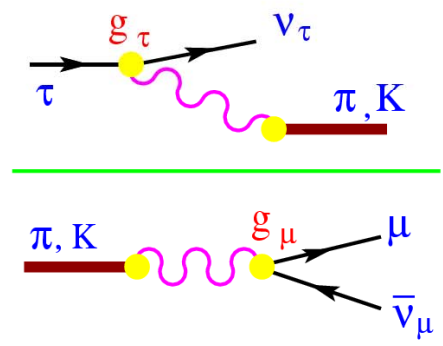
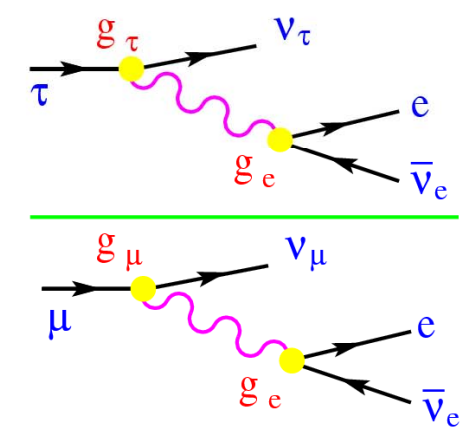
**Universal  $W l \bar{\nu}_l$  Couplings**

# LEPTON UNIVERSALITY

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



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





# CHARGED CURRENT UNIVERSALITY

$$|g_\mu / g_e|$$

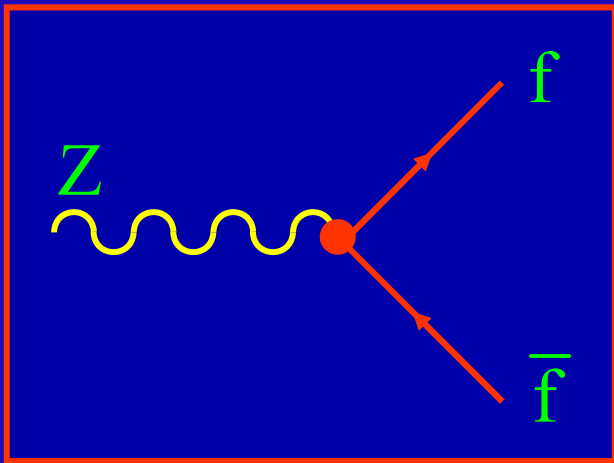
$B_{\tau \rightarrow \mu} / B_{\tau \rightarrow e}$	$1.0000 \pm 0.0020$
$B_{\pi \rightarrow \mu} / B_{\pi \rightarrow e}$	$1.0021 \pm 0.0016$
$B_{K \rightarrow \mu} / B_{K \rightarrow e}$	$1.004 \pm 0.007$
$B_{K \rightarrow \pi\mu} / B_{K \rightarrow \pi e}$	$1.002 \pm 0.002$
$B_{W \rightarrow \mu} / B_{W \rightarrow e}$	$0.997 \pm 0.010$

$$|g_\tau / g_\mu|$$

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

$$|g_\tau / g_e|$$

$B_{\tau \rightarrow \mu} \tau_\mu / \tau_\tau$	$1.0005 \pm 0.0023$
$B_{W \rightarrow \tau} / B_{W \rightarrow e}$	$1.036 \pm 0.014$



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

$$\Gamma(Z \rightarrow l\bar{l}) \propto (|v_l|^2 + |a_l|^2)$$

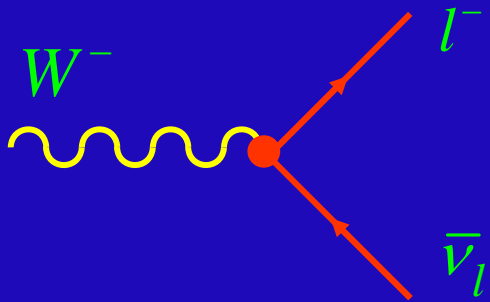
$$\frac{\Gamma_{\text{inv}}}{\Gamma_{ll}} \equiv \frac{\Gamma(Z \rightarrow \text{invisible})}{\Gamma(Z \rightarrow l^+ l^-)} = N_\nu \frac{\Gamma(Z \rightarrow \nu_l \bar{\nu}_l)}{\Gamma(Z \rightarrow l^+ l^-)} = N_\nu \frac{2}{(1 - 4 \sin^2 \theta_W)^2 + 1} = 1.955 N_\nu \quad (1.989)$$

**Experiment:**



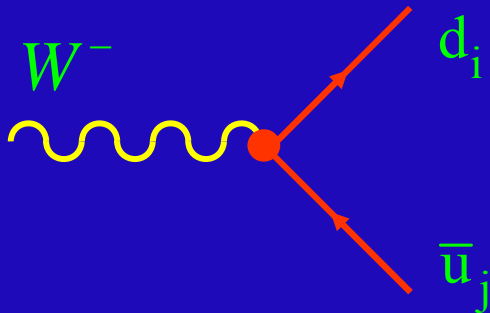
$$\frac{\Gamma_{\text{inv}}}{\Gamma_{ll}} = 5.942 \pm 0.016 \quad \longrightarrow \quad N_\nu = 3.04 \quad (2.99)$$

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



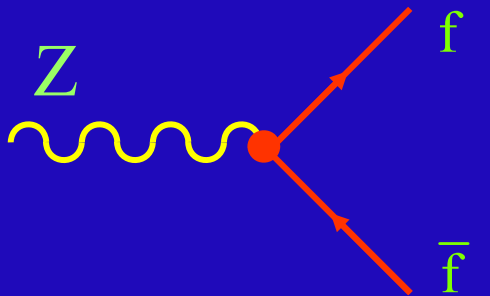
$$W^- \rightarrow e^- \bar{\nu}_e, \mu^- \bar{\nu}_\mu, \tau^- \bar{\nu}_\tau$$

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



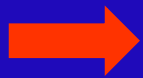
$$W^- \rightarrow d' \bar{u}, s' \bar{c}$$

$$\Gamma = \frac{G_F M_W^3}{6\pi\sqrt{2}} |V_{ij}|^2 N_C$$



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

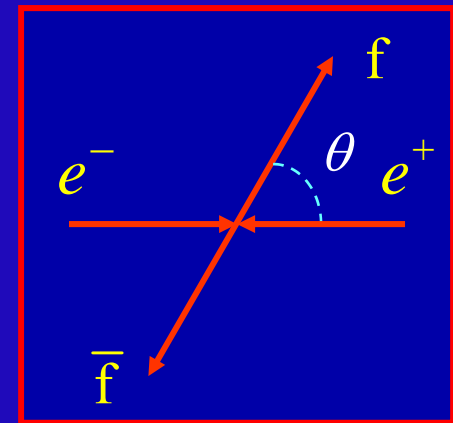
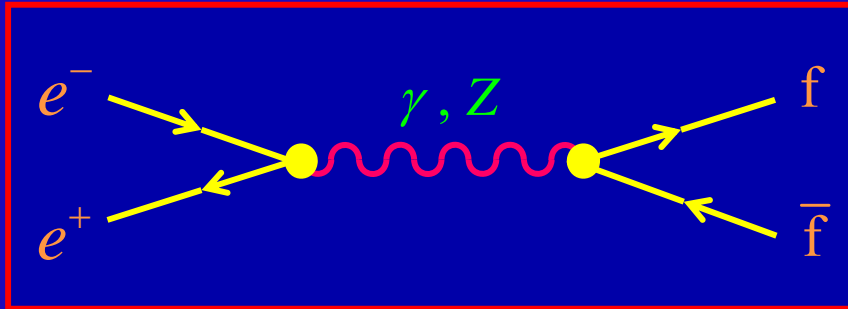
$$\Gamma = \frac{G_F M_Z^3}{6\pi\sqrt{2}} \left( |v_f|^2 + |a_f|^2 \right) N_f \quad ; \quad N_l = 1, \quad N_q = N_C$$



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

$$\text{Exp:} \quad 2.140 \pm 0.060 \quad \quad 2.4952 \pm 0.0023$$

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



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

$$N_l = 1 \quad ; \quad N_q = N_C \left\{ 1 + \frac{\alpha_s(M_Z^2)}{\pi} + \dots \right\} \quad ; \quad h_f = \pm 1$$

$$A = 1 + 2 v_e v_f \operatorname{Re}(\chi) + (v_e^2 + a_e^2)(v_f^2 + a_f^2) |\chi|^2$$

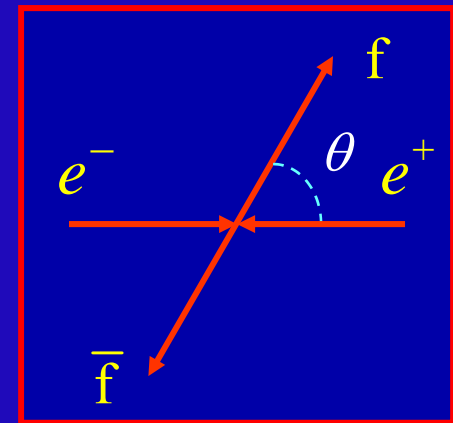
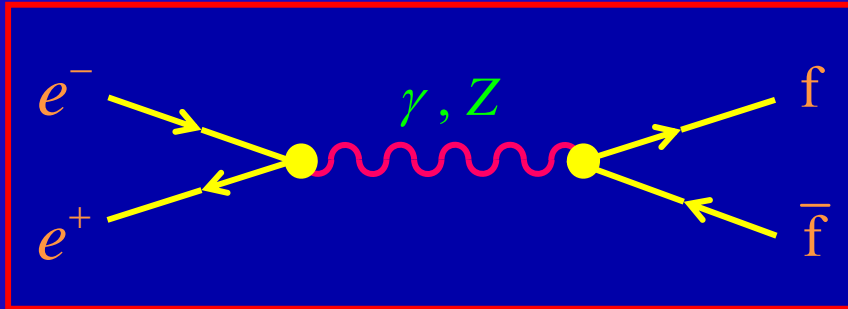
$$B = 4 a_e a_f \operatorname{Re}(\chi) + 8 v_e a_e v_f a_f |\chi|^2$$

$$C = 2 v_e a_f \operatorname{Re}(\chi) + 2 (v_e^2 + a_e^2) v_f a_f |\chi|^2$$

$$D = 4 a_e v_f \operatorname{Re}(\chi) + 4 v_e a_e (v_f^2 + a_f^2) |\chi|^2$$

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

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



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

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

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

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

# Z Peak ( $s = M_Z^2$ )

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

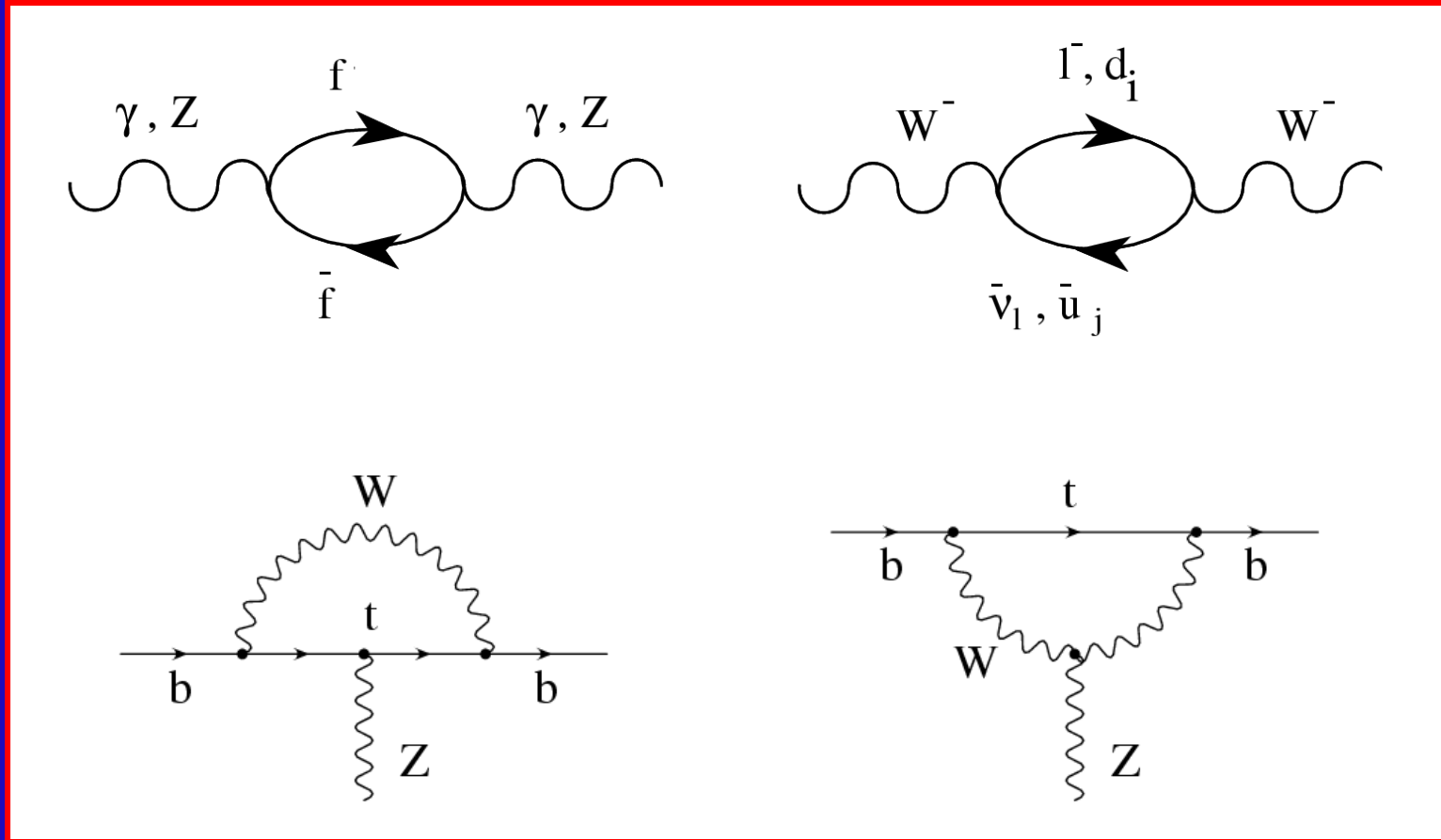
$$\mathcal{A}_{\text{FB}}(s) = \frac{3}{4} \mathcal{P}_e \mathcal{P}_f \quad ; \quad \mathcal{A}_{\text{Pol}}(s) = \mathcal{P}_f \quad ; \quad \mathcal{A}_{\text{FB}}^{\text{Pol}}(s) = \frac{3}{4} \mathcal{P}_e$$

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

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

$|v_l| = \frac{1}{2} |-1 + 4 \sin^2 \theta| \ll 1 \quad \Rightarrow \quad \mathcal{P}_l$  **Sensitive to Higher Order Corrections**

# Higher Order Corrections



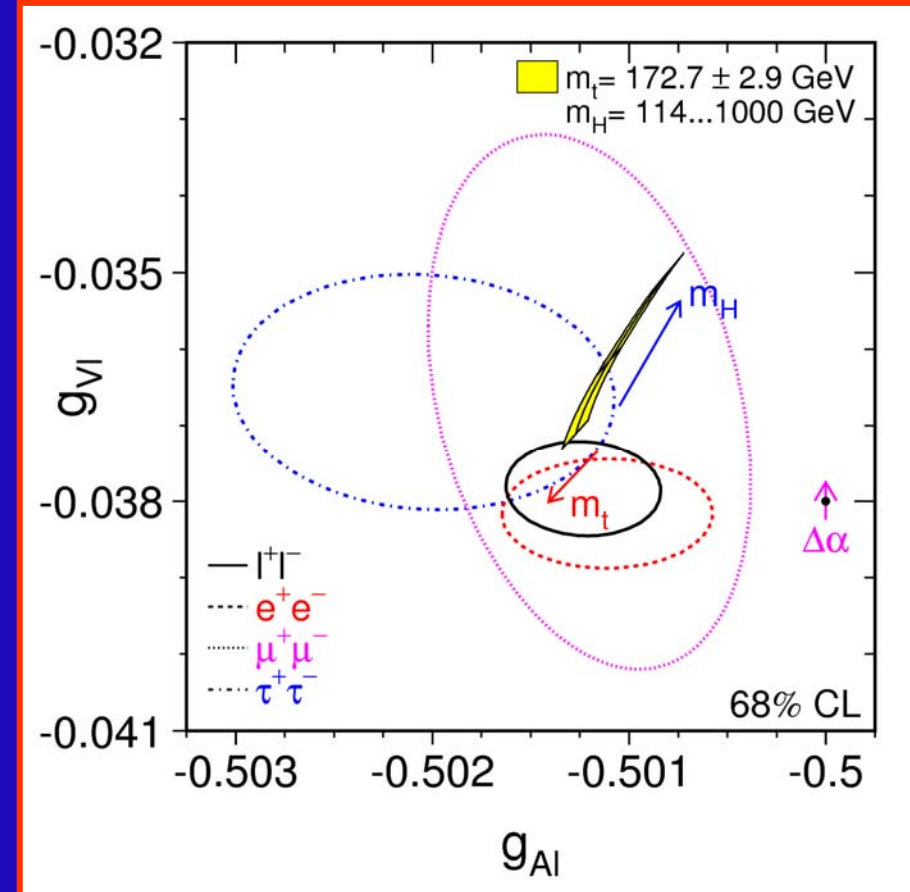
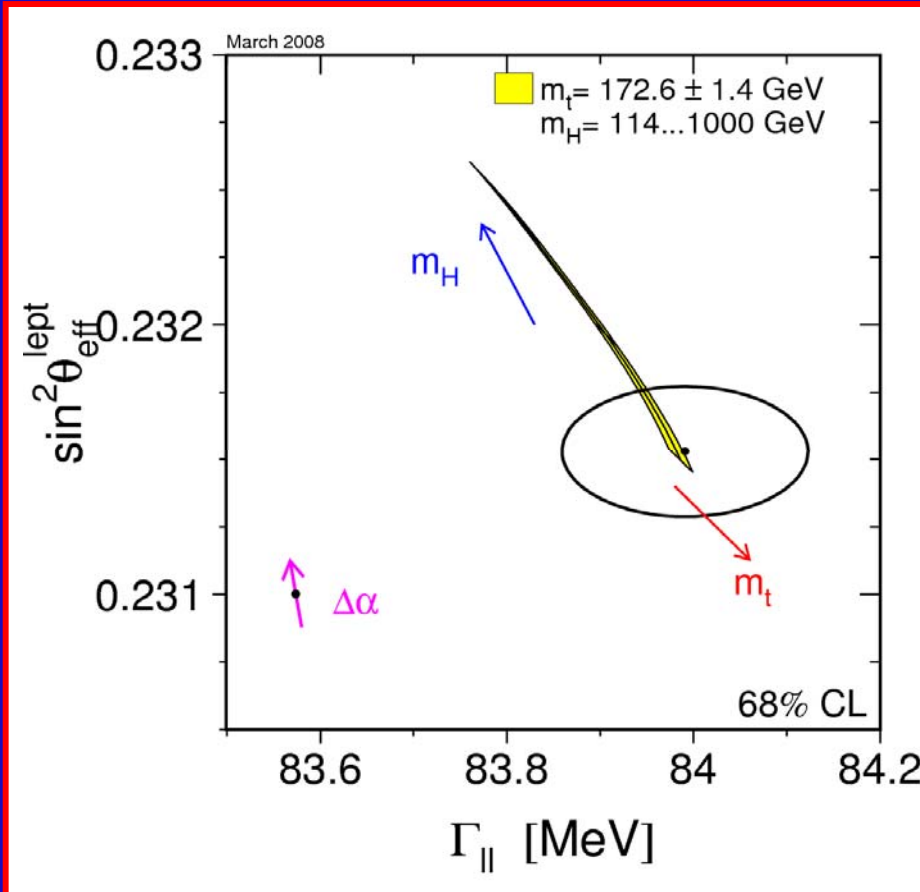
**Sensitive to Heavier Particles: TOP , HIGGS**

# Evidence of Electroweak Corrections

March 2008

LEPEWWG

September 2005



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

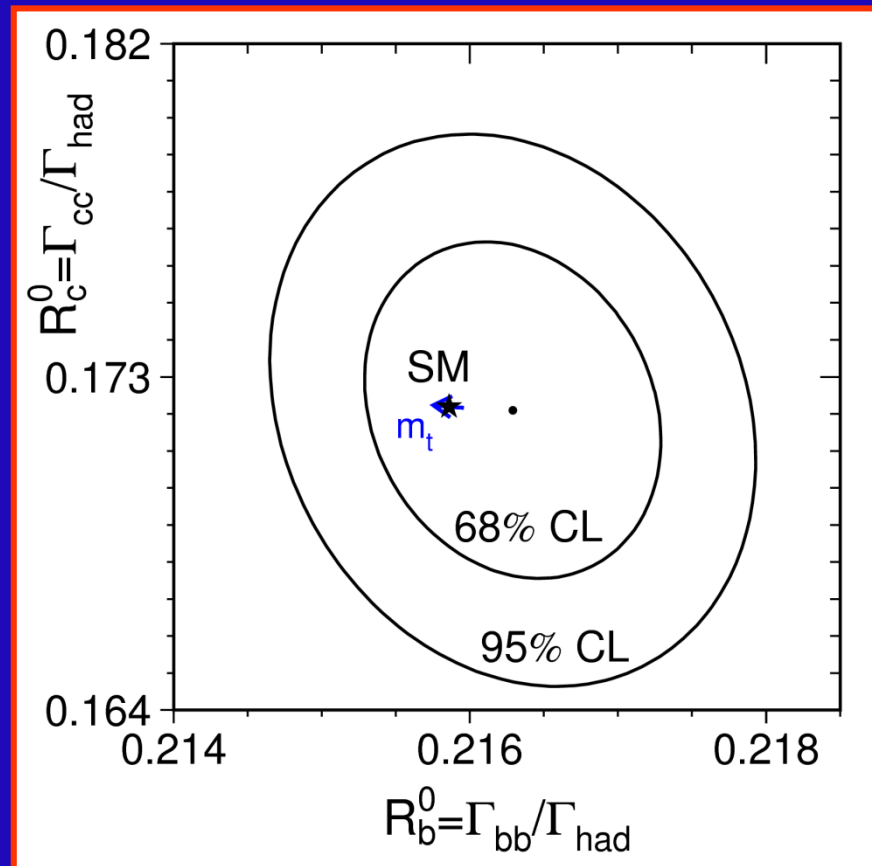
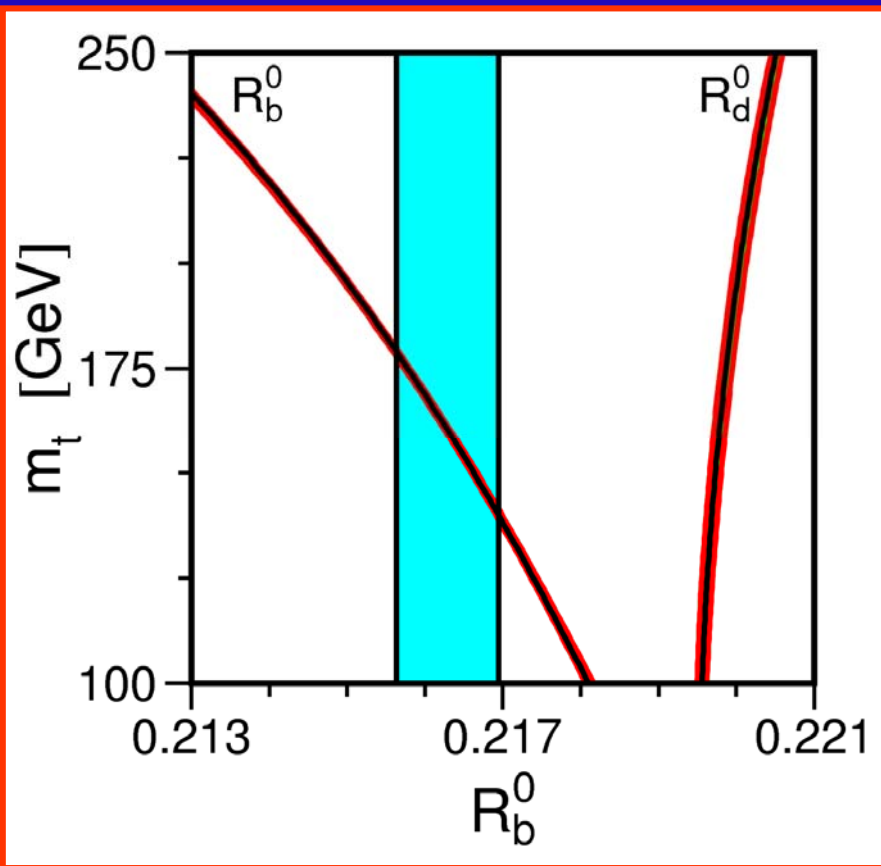
**Low Values of  $M_H$  Preferred**



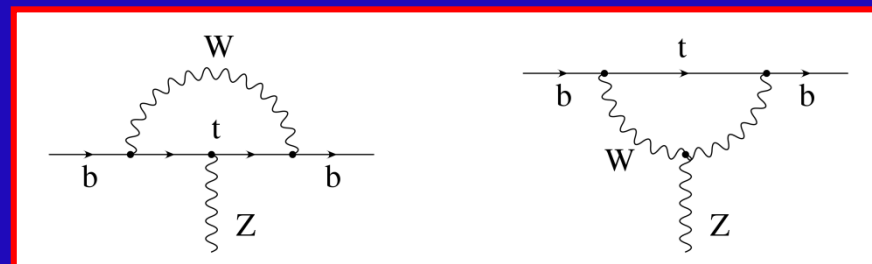
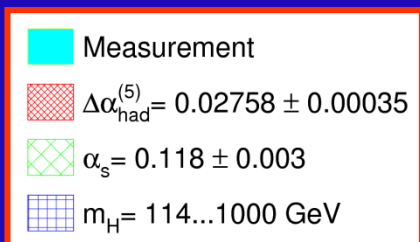
$$R_b \equiv \Gamma(Z \rightarrow b\bar{b}) / \Gamma(Z \rightarrow \text{hadrons})$$

LEPEWWG

September 2005

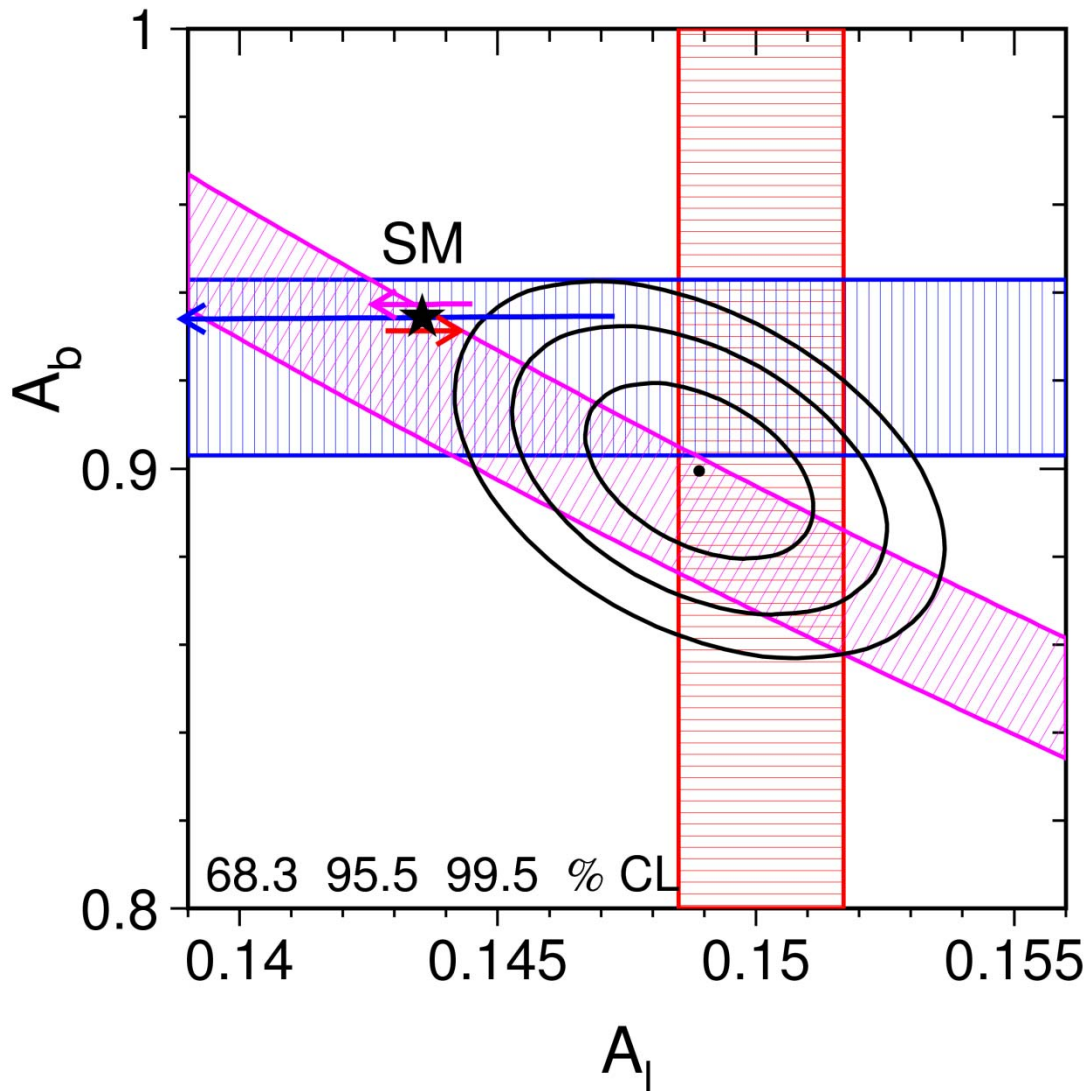


Bernabéu-Pich-Santamaría 1988



# LEPEWWG

September 2005

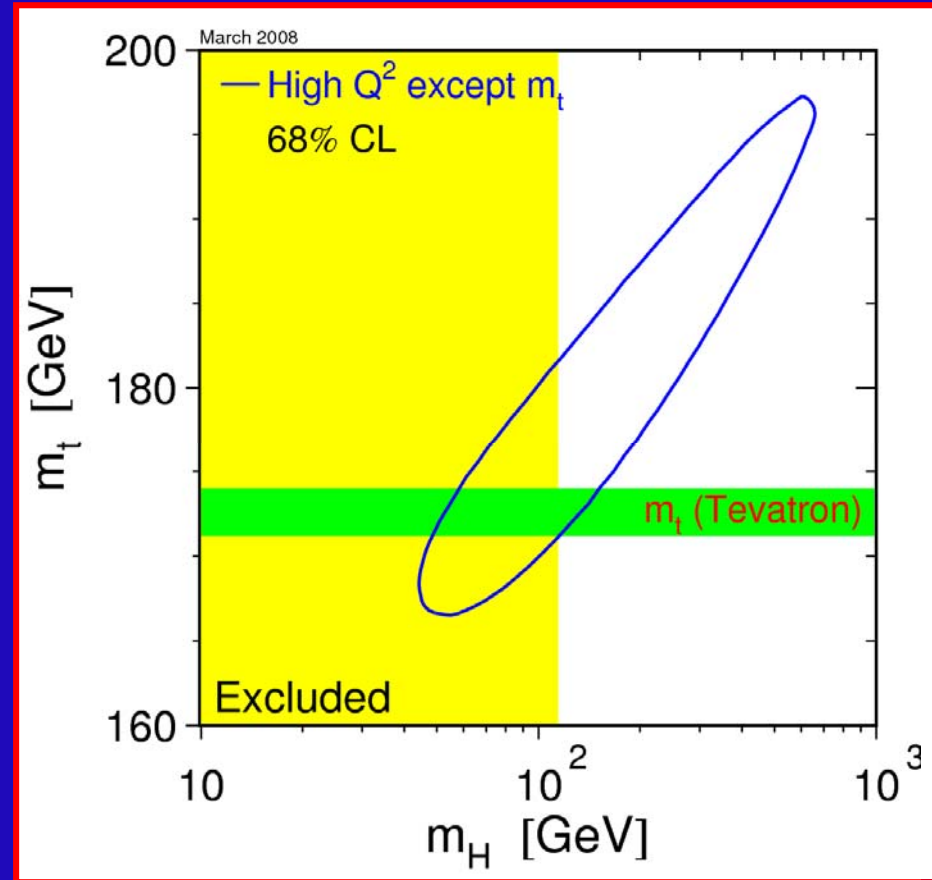
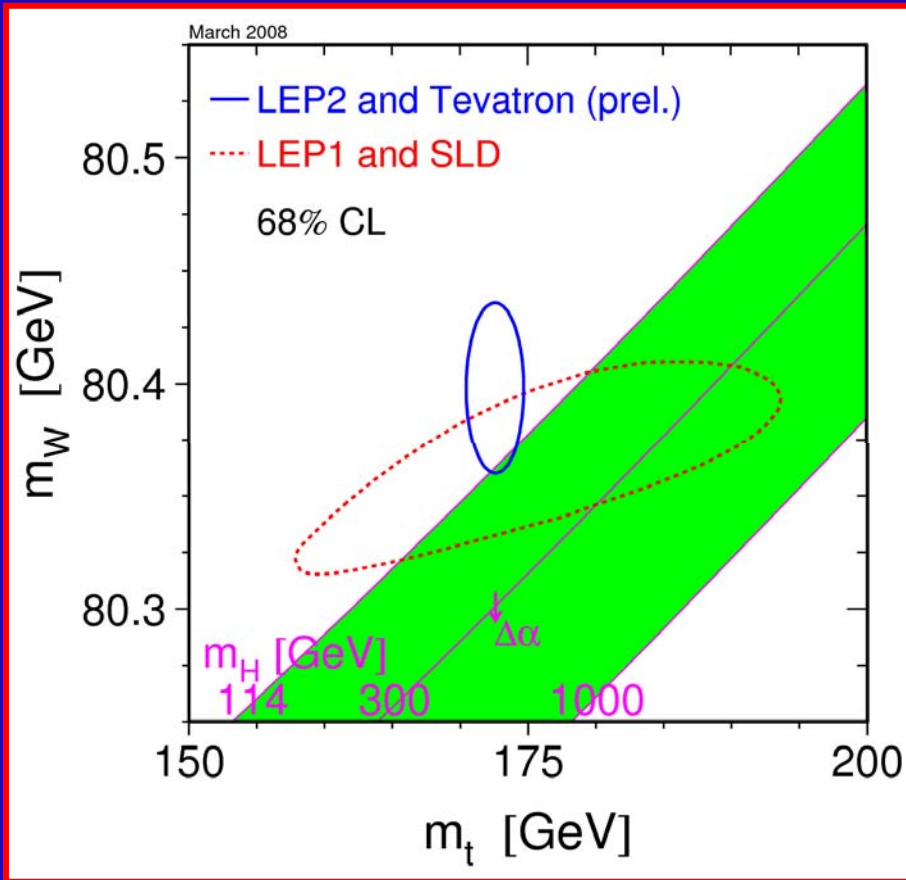


$$m_t = (172.7 \pm 2.9) \text{ GeV}$$

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

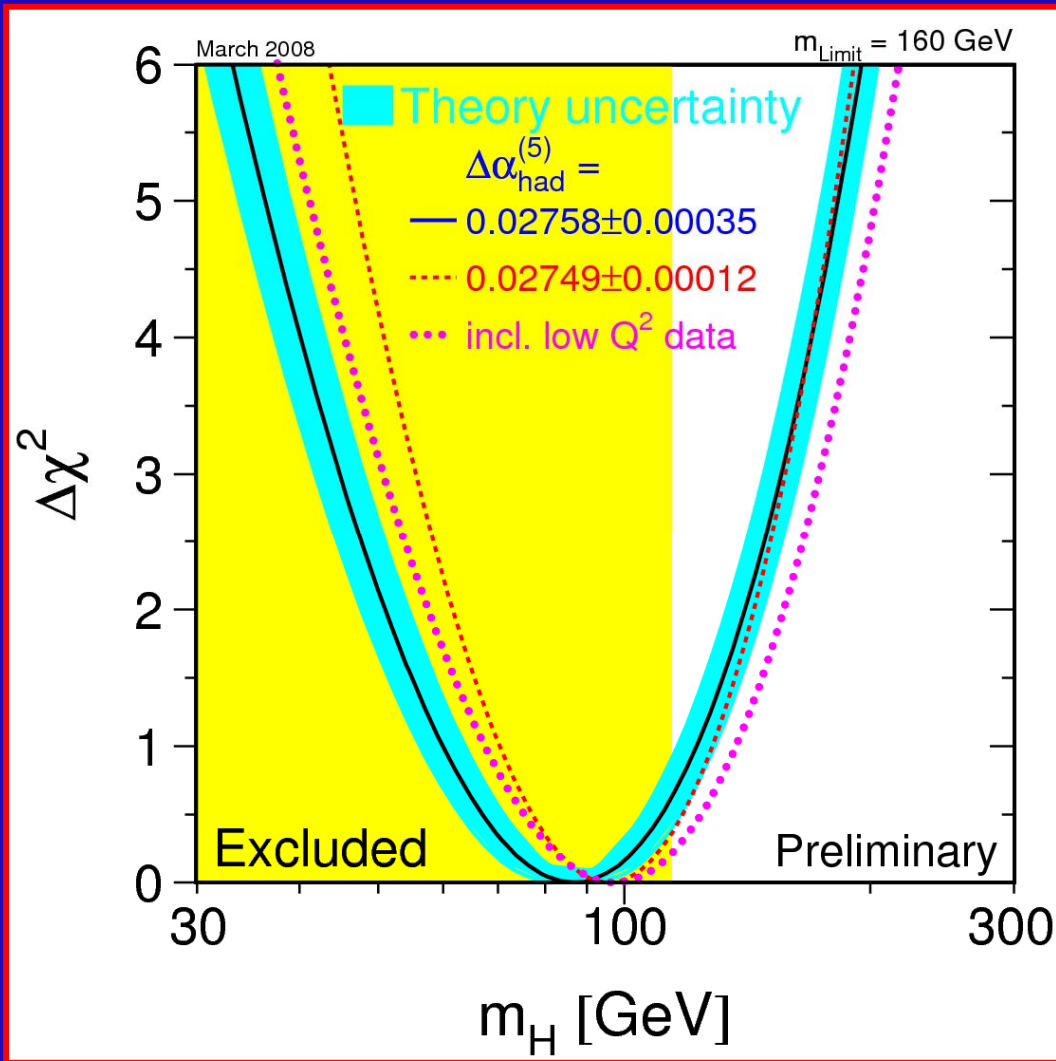
$$\alpha(M_Z^2)^{-1} = 128.93 \pm 0.05$$

Heavy Quarks (Leptons) Favour High (Low)  $M_H$



**$m_t = (172.6 \pm 1.4) \text{ GeV}$**

**(CDF + D0)**



LEPEWWG

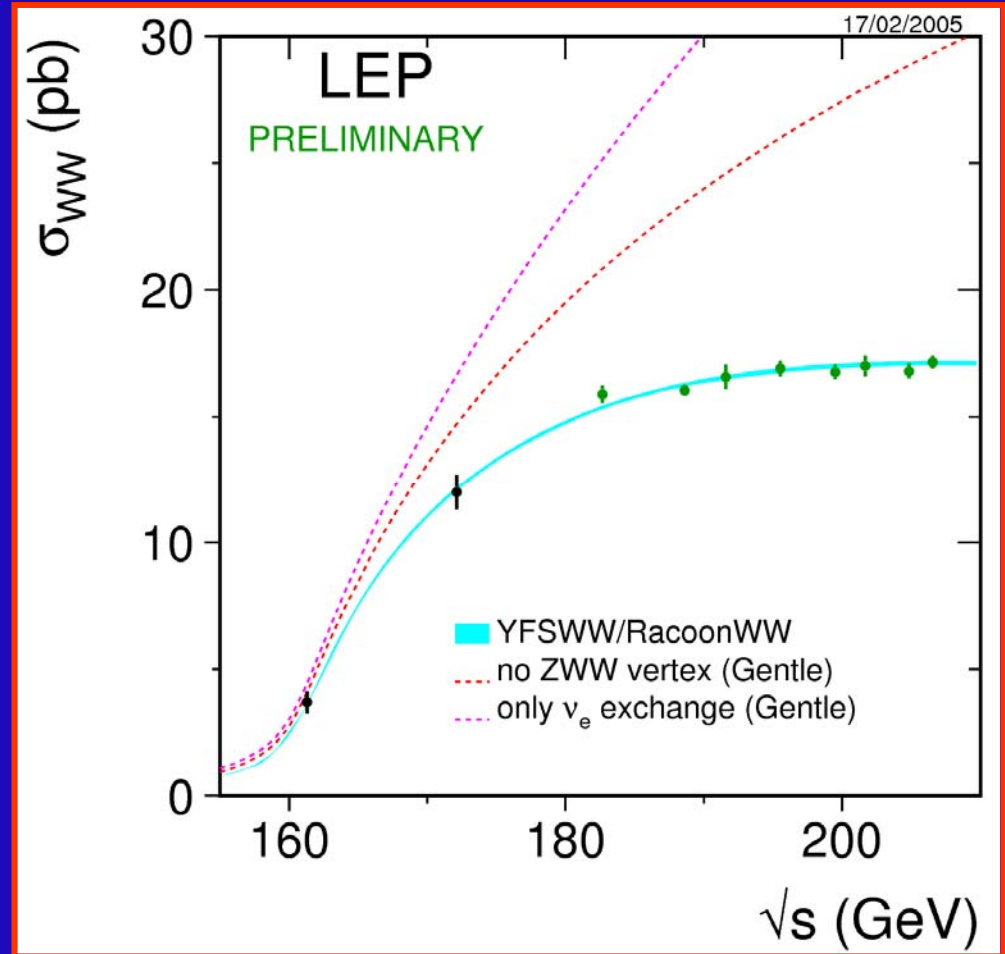
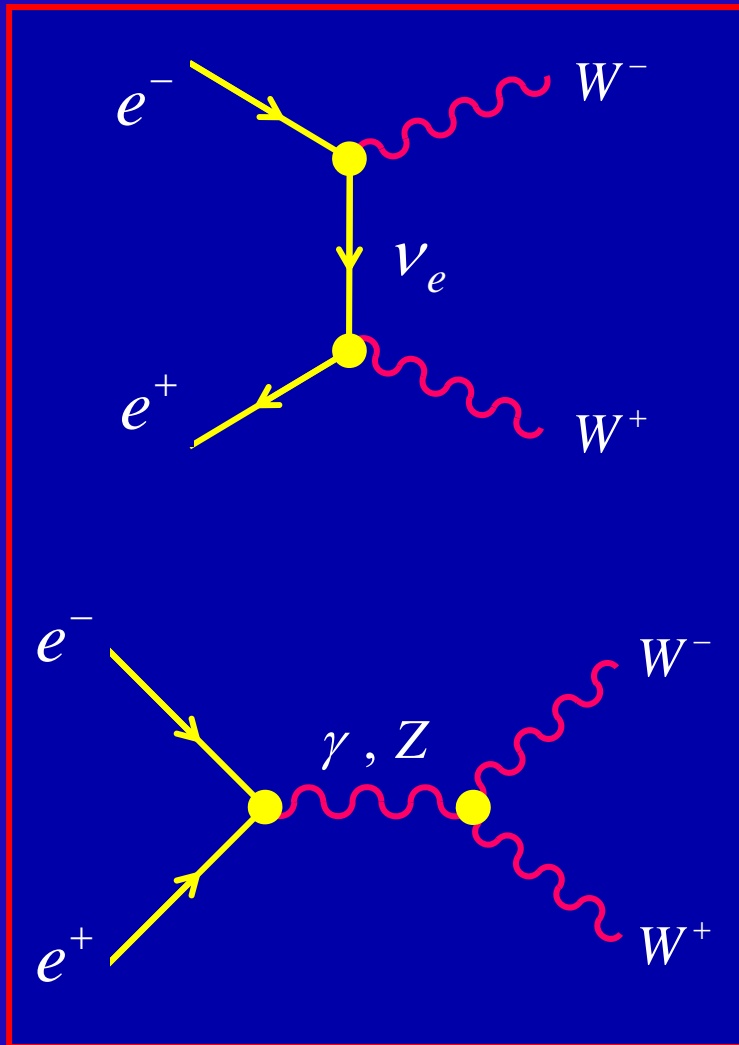
March 2008



$114.4 \text{ GeV} < M_H < 160 \text{ GeV}$

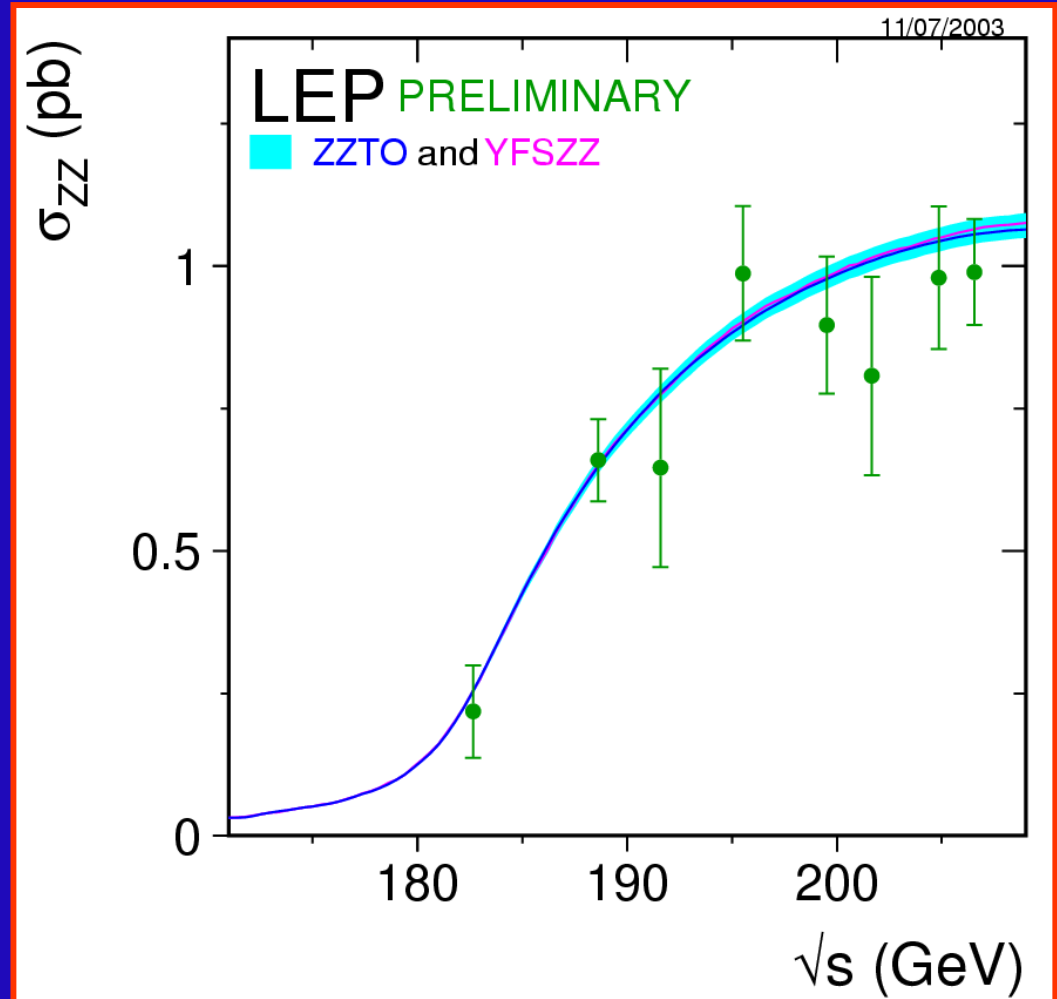
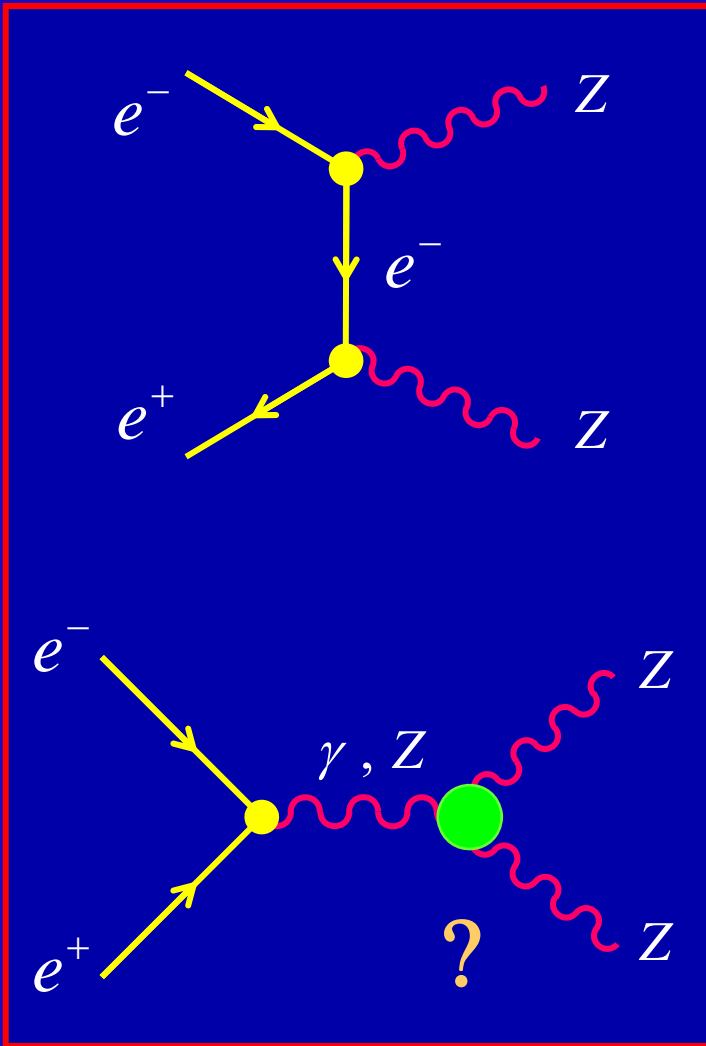
(95% CL)

$$e^+ e^- \rightarrow W^+ W^-$$



# Evidence of Gauge Self-Interactions

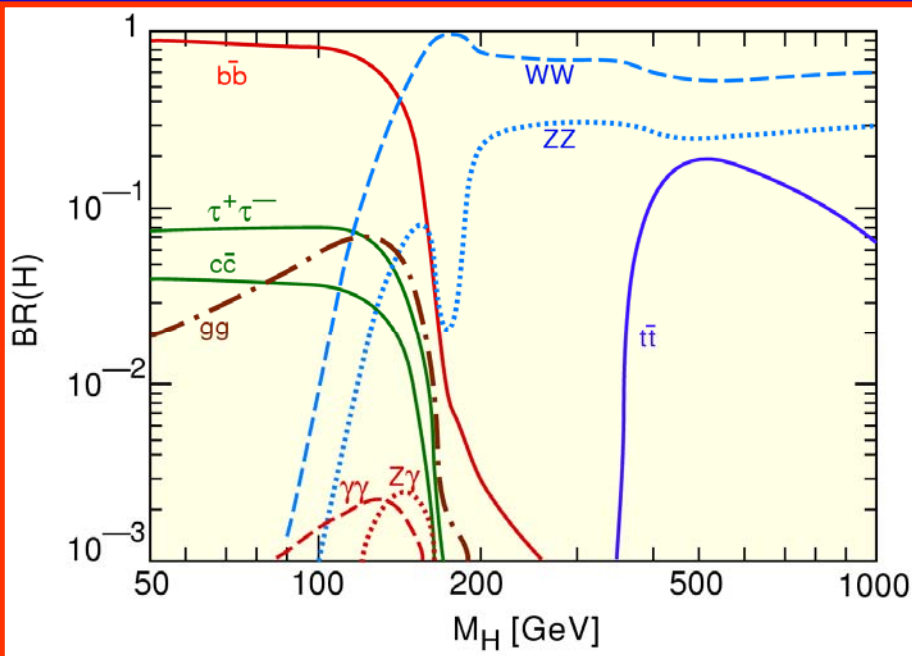
$$e^+ e^- \rightarrow ZZ$$



**No Evidence of  $\gamma ZZ$  or  $ZZZ$  couplings**

# Searching for the HIGGS

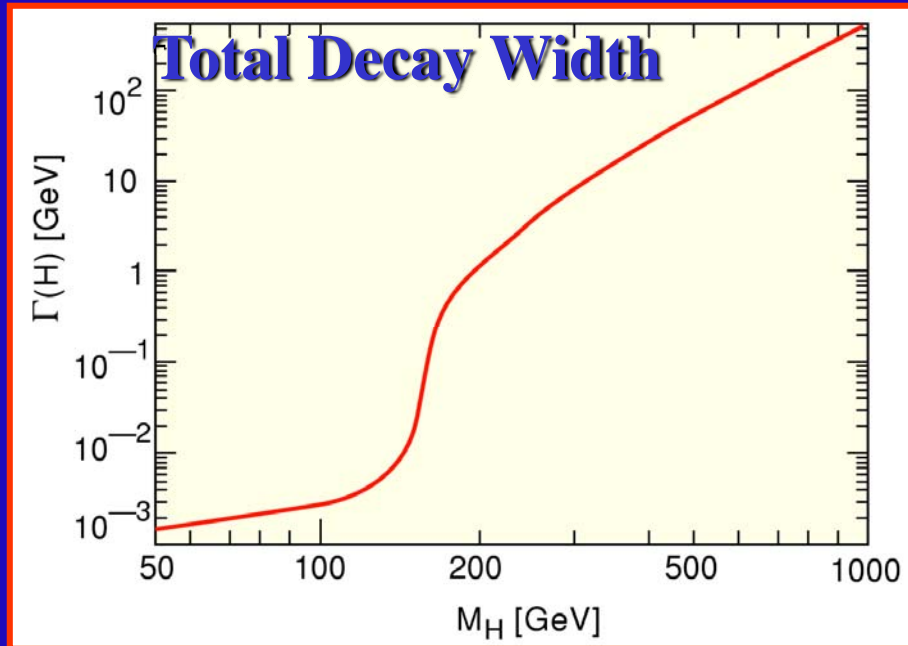
D. Denegri



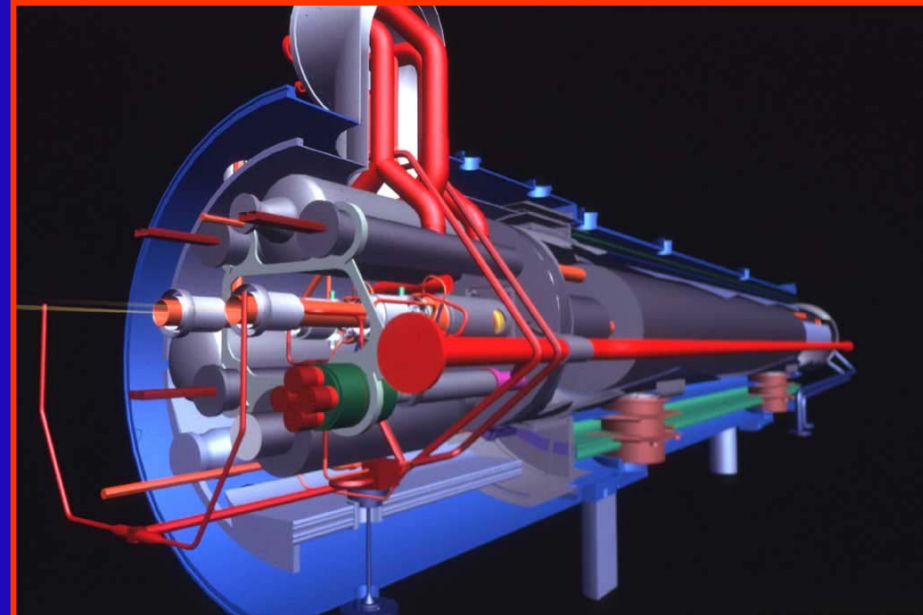
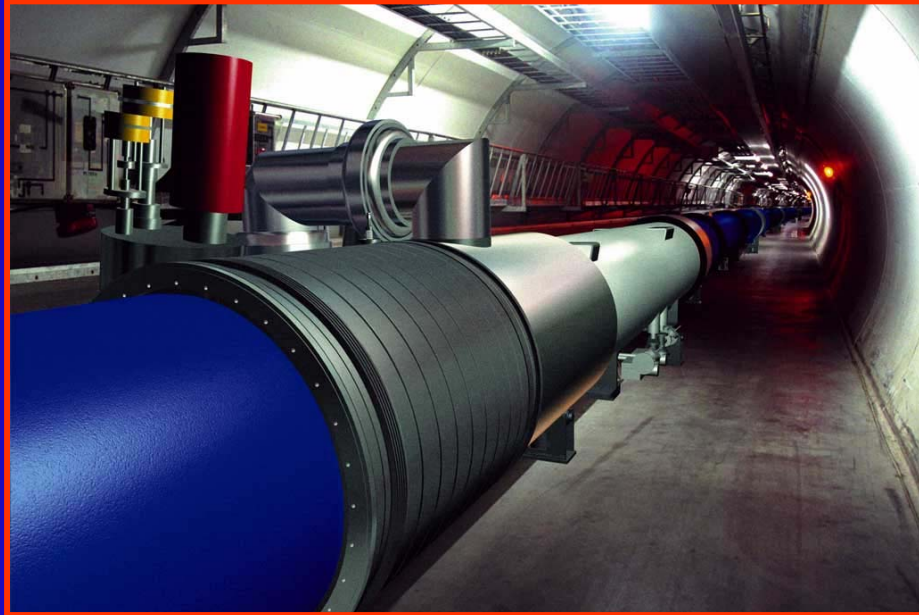
## Branching Ratios

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

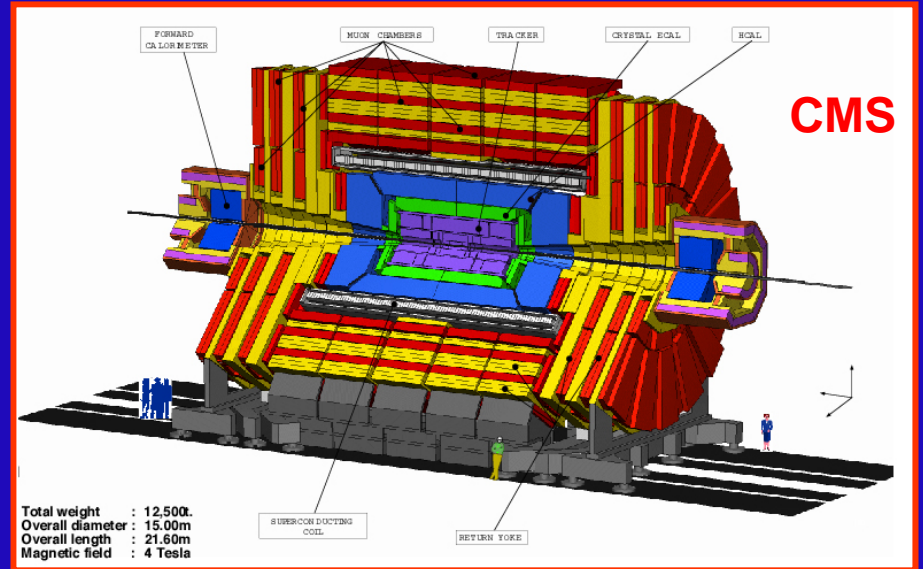
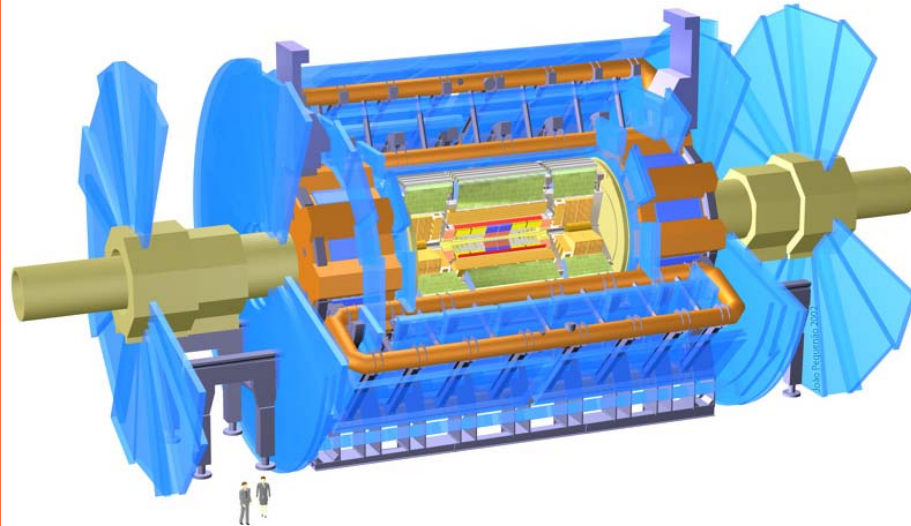
The Higgs decays into the heaviest possible particles



# The Large Hadron Collider



## ATLAS



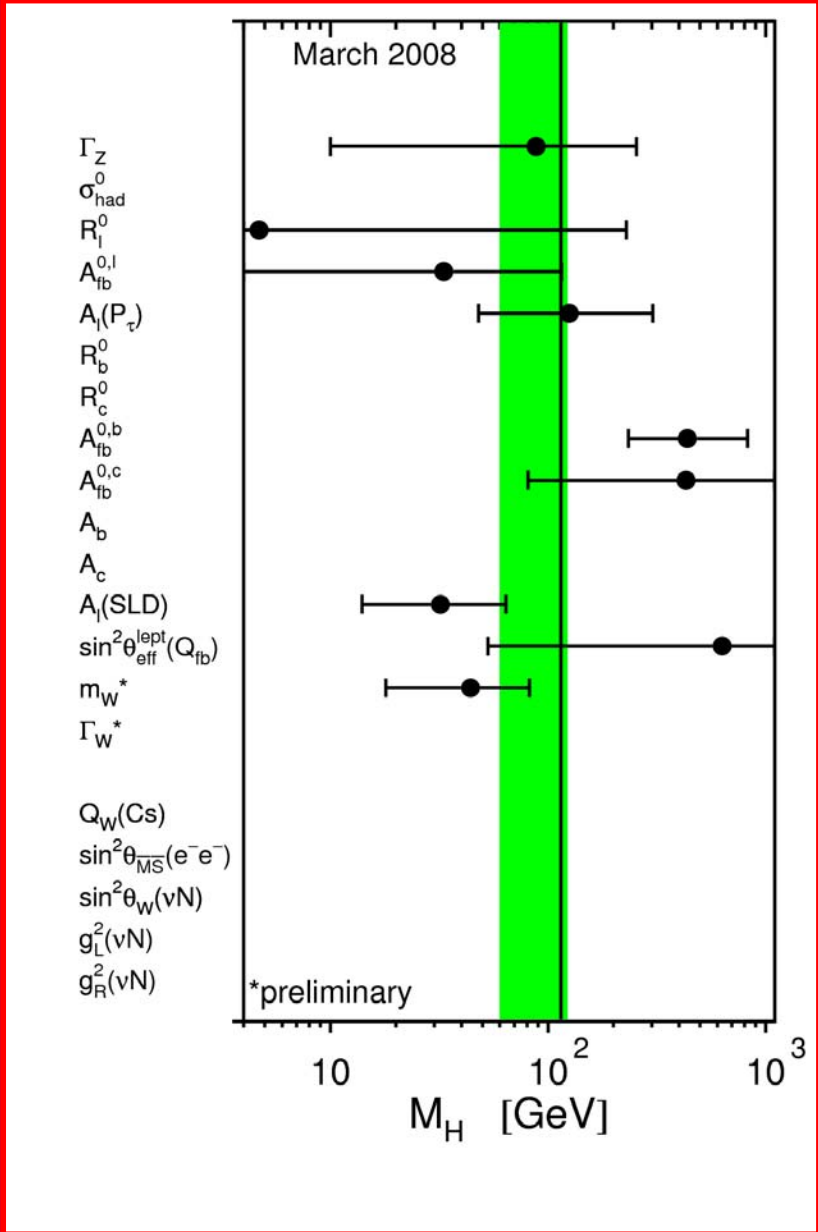
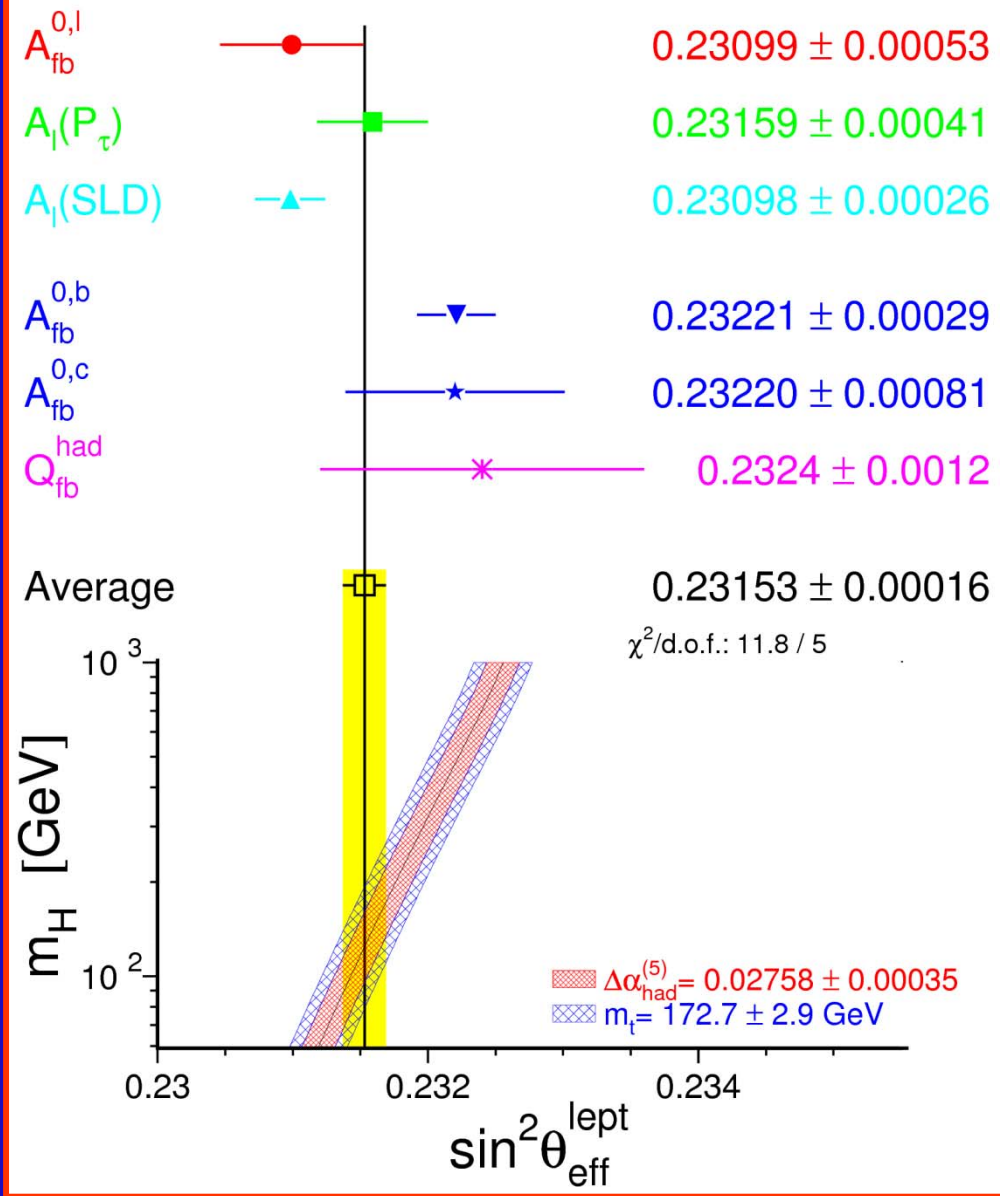
Total weight : 12.500.  
Overall diameter : 15.00m  
Overall length : 21.60m  
Magnetic field : 4 Tesla



March 2006

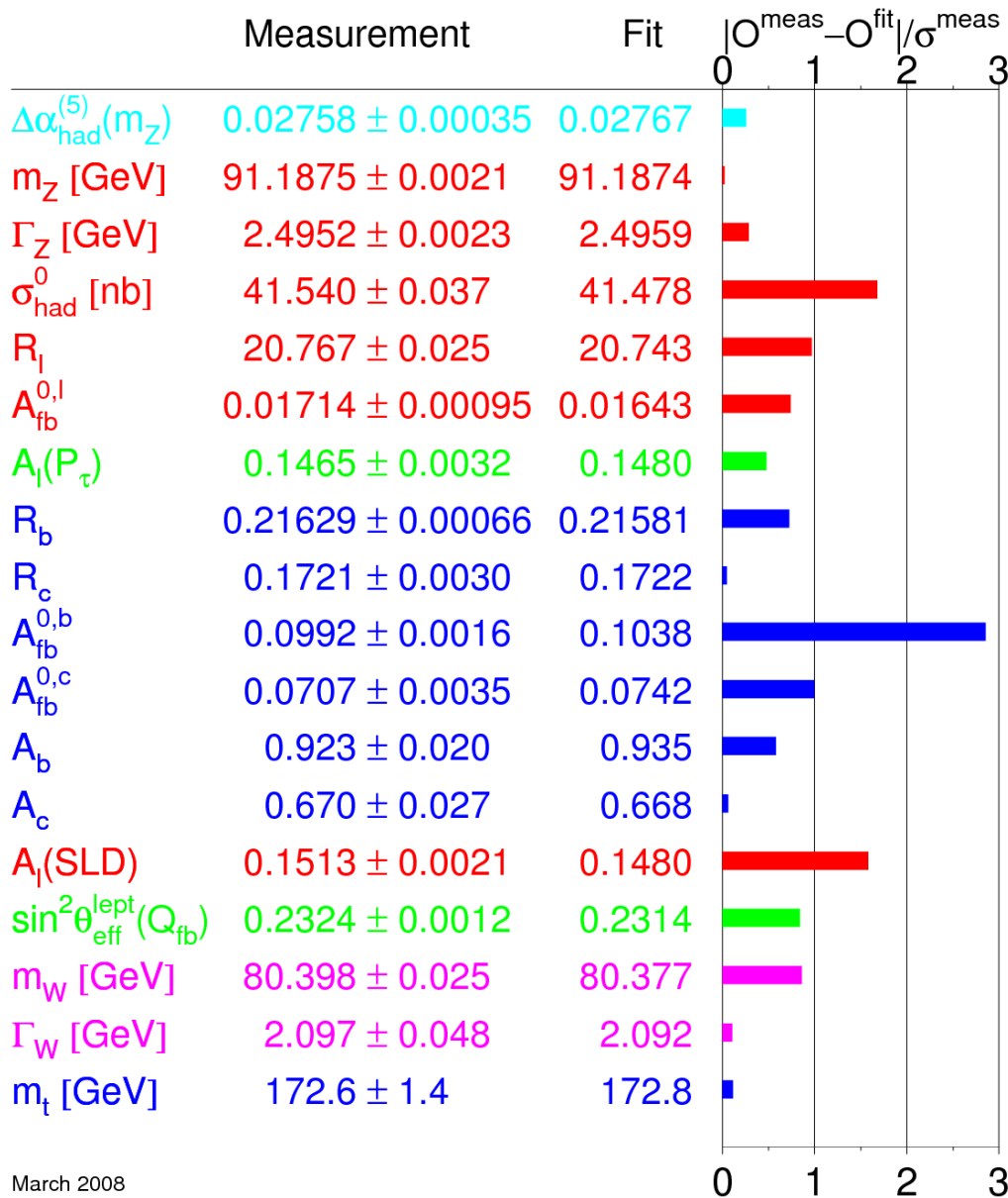
LEPEWWG

March 2008

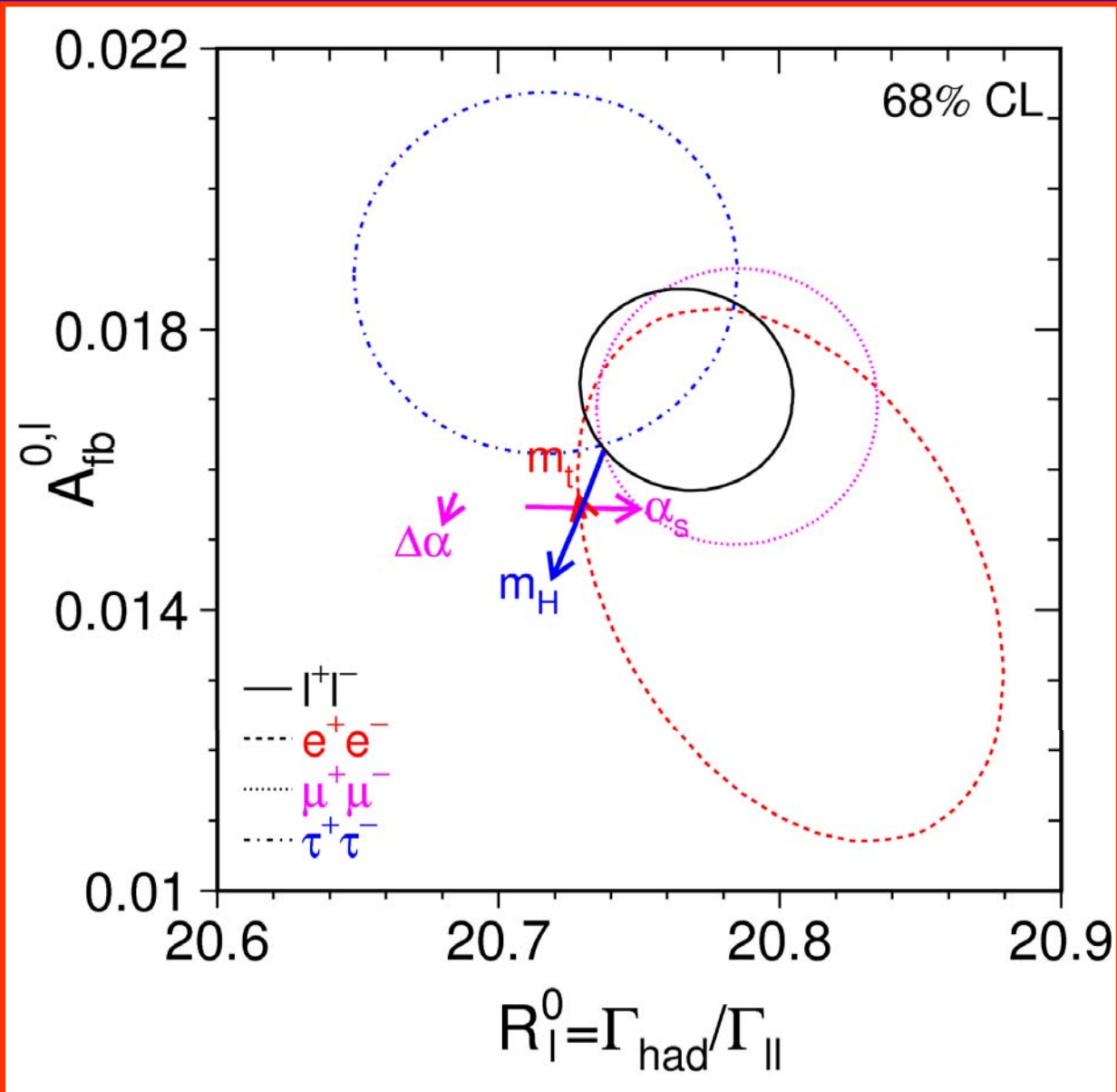


# LEPEWWG

March 2008



March 2008

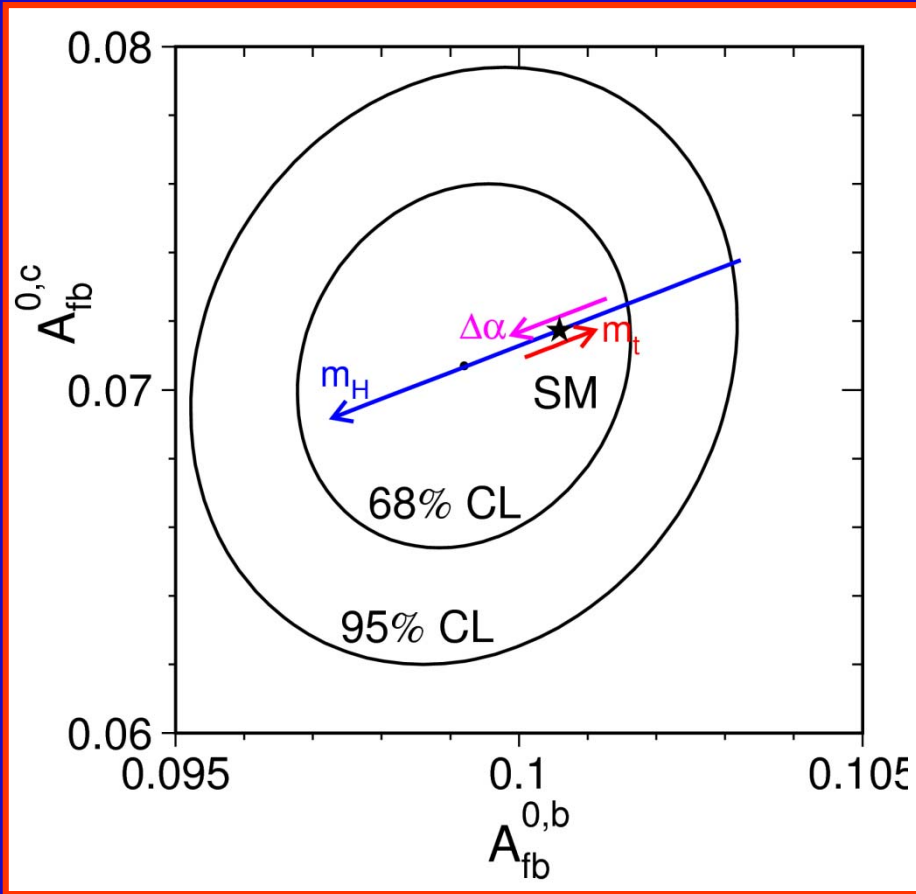


$$m_t = (172.7 \pm 2.9) \text{ GeV}$$

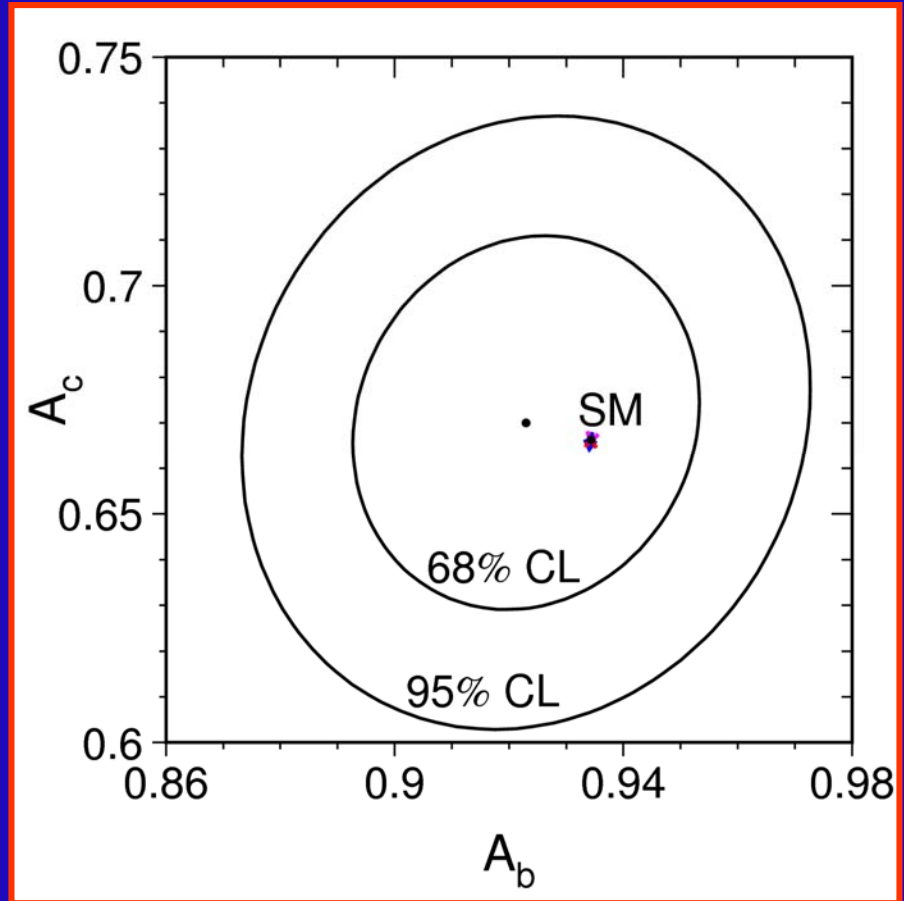
$$M_H = (300_{-186}^{+700}) \text{ GeV}$$

$$\alpha(M_Z^2)^{-1} = 128.95 \pm 0.05$$

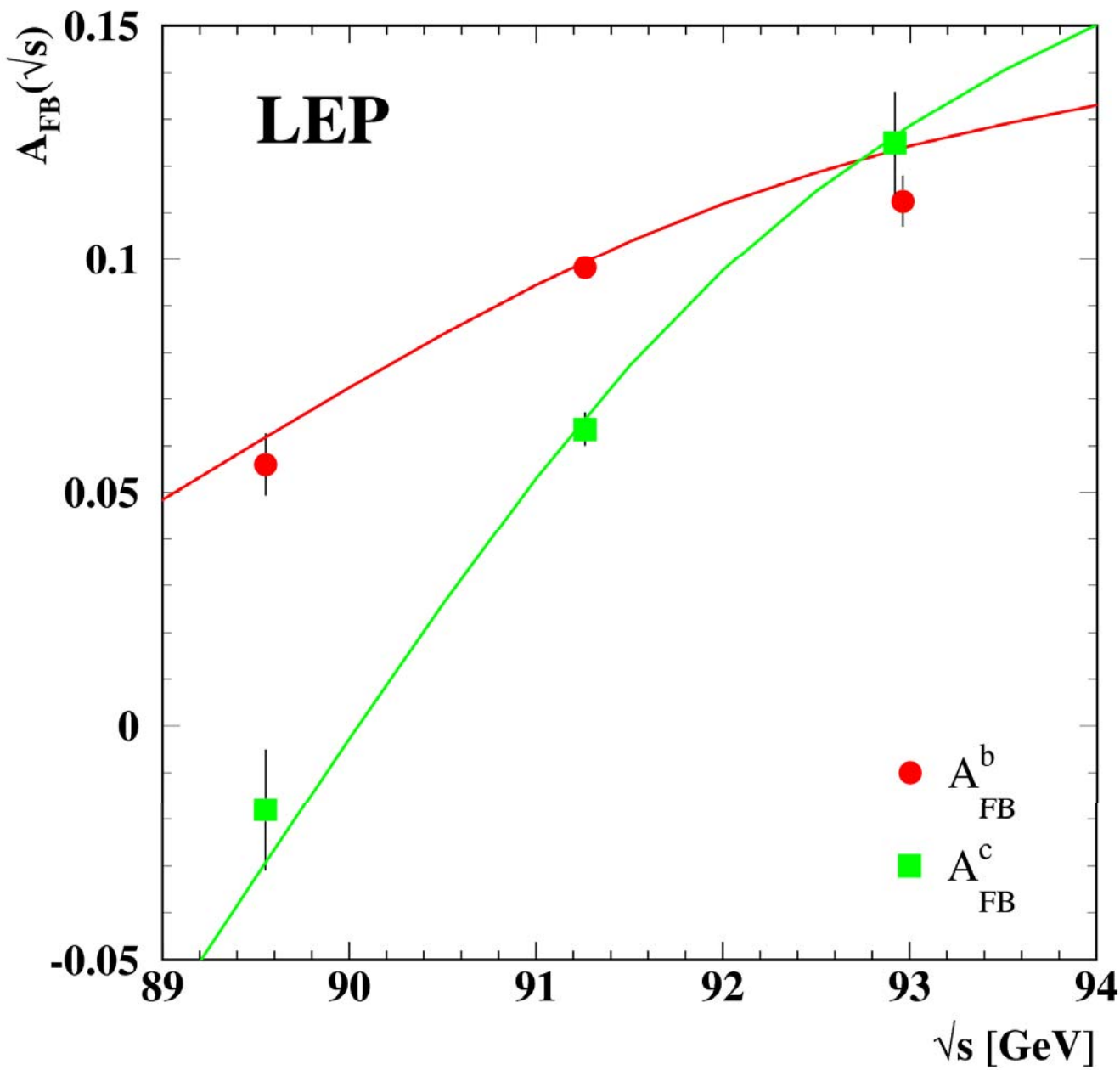
$$\alpha_s(M_Z^2) = 0.118 \pm 0.003$$



$$m_t = (172.7 \pm 2.9) \text{ GeV}$$



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



$$m_t = 172.7 \text{ GeV}$$

$$M_H = 300 \text{ GeV}$$