Particle Physics
The Standard Model

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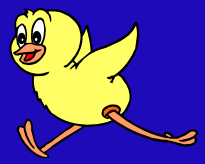
7. Electroweak Phenomenology

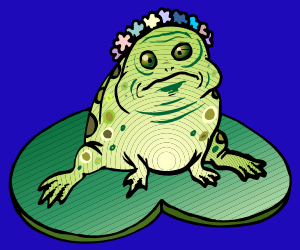
- **Inputs**
- $Z \to f\ \bar{f}\ ,\ \ W \to f_1\ \bar{f}_2$
- **Z Peak Asymmetries**
- **Sensitivity to Higher Scales**
- **Standard Model Fits:** M_H
- $e^+ e^- \to W^+ W^-\ ,\ \ e^+ e^- \to Z\, Z$
- **Higgs Search**

Quarks



up

down



charm

strange

top

beauty

Leptons

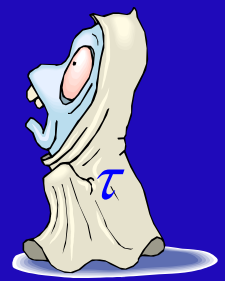
electron

neutrino e

muon

neutrino μ

tau

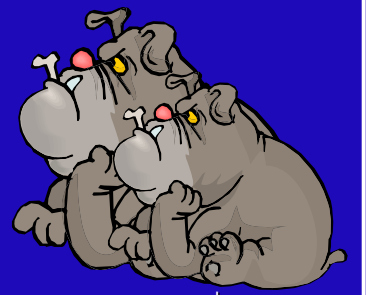


neutrino τ

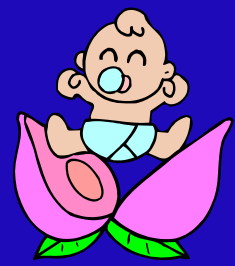
Bosons

photon

gluon



Z^0 $W^{\pm}$



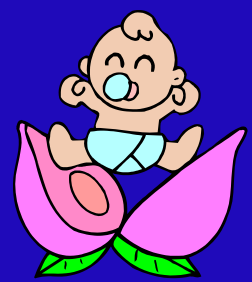
Higgs

Standard Model Parameters

QCD: $\alpha_S(M_Z)$ **1**

EW Gauge / Scalar Sector: **4**

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



INPUTS

$$G_F = (1.166\,37 \pm 0.000\,01) \times 10^{-5}\ \text{GeV}^{-2}$$

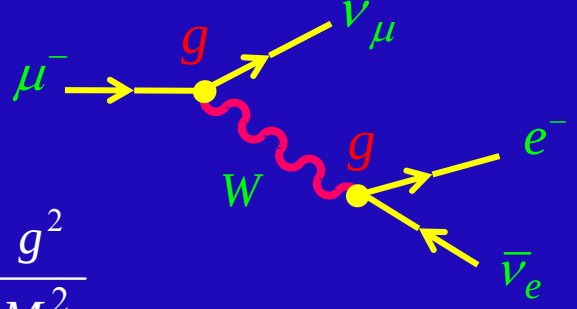
$$\alpha^{-1} = 137.035\,999\,11 \pm 0.000\,000\,46$$

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

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

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

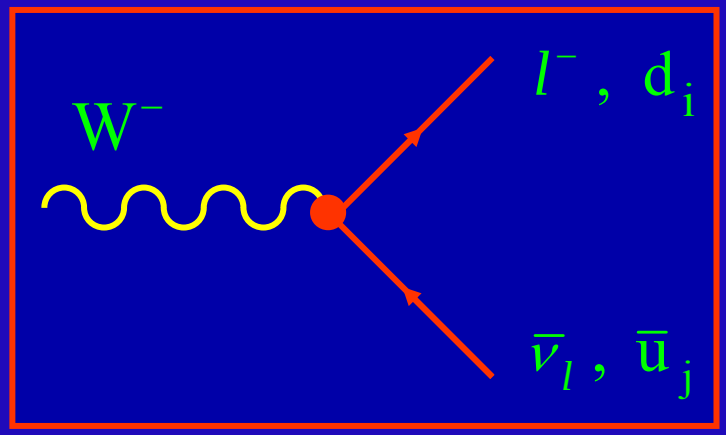
$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$



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

$M_W = 80.94\ \text{GeV}$ (79.96) [Exp: 80.425 ± 0.034]

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



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

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

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

QCD: $N_C \left\{ 1 + \dfrac{\alpha_s(M_Z)}{\pi} \right\} \approx 3.115$ ➡ $\mathrm{Br}\left(W^- \to l^- \bar{\nu}_l\right) \approx 10.8\%$

Experiment:

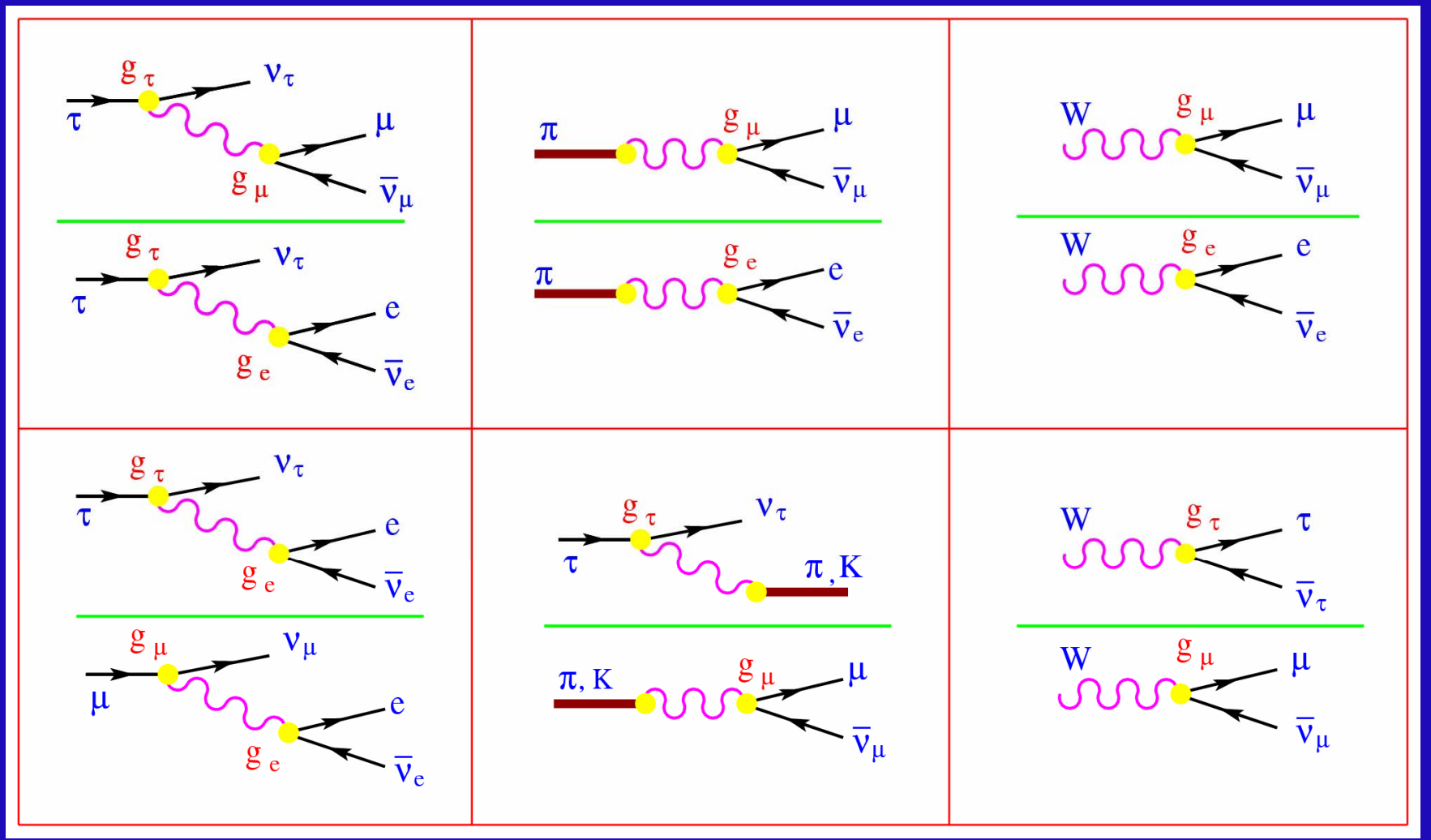
$$\mathrm{Br}\left(W^- \to e^- \bar{\nu}_e\right) = (10.65 \pm 0.17)\%$$
$$\mathrm{Br}\left(W^- \to \mu^- \bar{\nu}_\mu\right) = (10.59 \pm 0.15)\%$$
$$\mathrm{Br}\left(W^- \to \tau^- \bar{\nu}_\tau\right) = (11.44 \pm 0.22)\%$$

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

LEPTON UNIVERSALITY

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

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



CHARGED CURRENT UNIVERSALITY

$|g_\mu / g_e|$

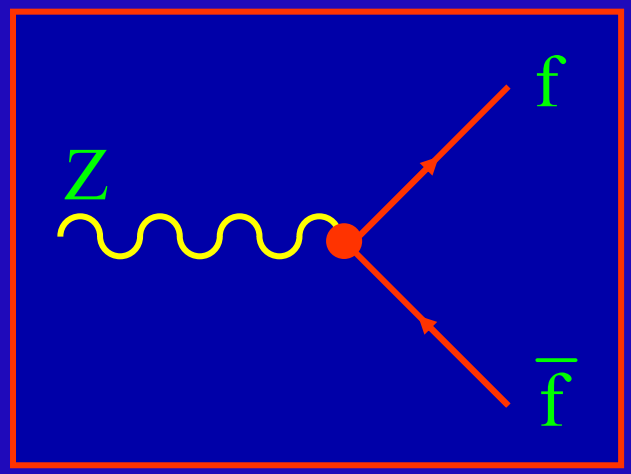
$B_{\tau\to\mu}/B_{\tau\to e}$	0.9999 ± 0.0020
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0017 ± 0.0015
$B_{W\to\mu}/B_{W\to e}$	0.997 ± 0.011

$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0002 ± 0.0022
$B_{W\to\tau}/B_{W\to e}$	1.036 ± 0.013

$|g_\tau / g_\mu|$

$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0004 ± 0.0023
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.9999 ± 0.0036
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.979 ± 0.017
$B_{W\to\tau}/B_{W\to\mu}$	1.039 ± 0.012



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

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

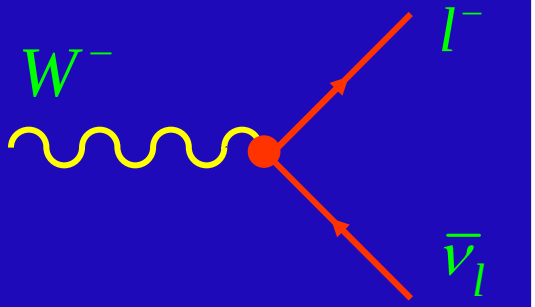
$$\frac{\Gamma_{\text{inv}}}{\Gamma_{ll}} \equiv \frac{\Gamma\left(Z \to \text{invisible}\right)}{Z \to l^+ l^-} = N_\nu \frac{\Gamma\left(Z \to \nu_l \bar{\nu}_l\right)}{\Gamma\left(Z \to l^+ l^-\right)} = N_\nu \frac{2}{\left(1 - 4\sin^2\theta_W\right)^2 + 1} = 1.955 \; N_\nu$$

$$(1.989)$$

Experiment:

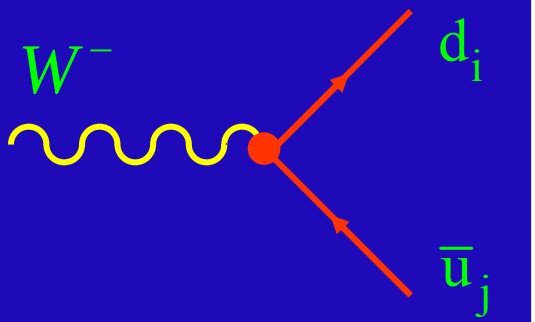
$$\frac{\Gamma_{\text{inv}}}{\Gamma_{ll}} = 5.942 \pm 0.016 \quad \Rightarrow \quad N_\nu = 3.04 \qquad (2.99)$$

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



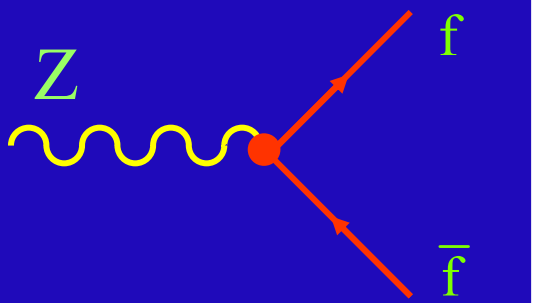
$$W^- \to e^- \bar{\nu}_e \;,\; \mu^- \bar{\nu}_\mu \;,\; \tau^- \bar{\nu}_\tau$$

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



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

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



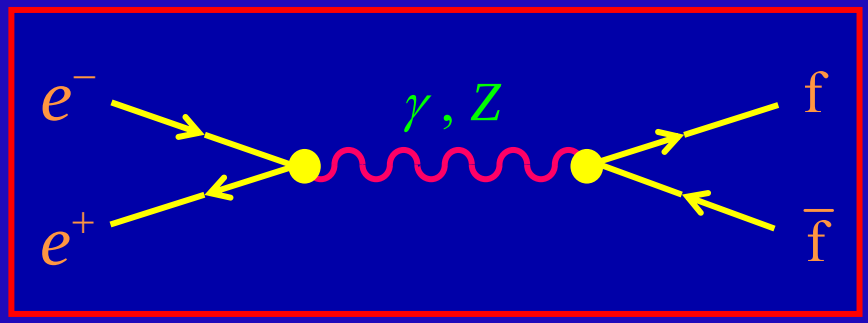
$$Z \to l^- l^+ \;,\; \nu_i \bar{\nu}_i \;,\; q\,\bar{q} \qquad (q = u, d, s, c, b)$$

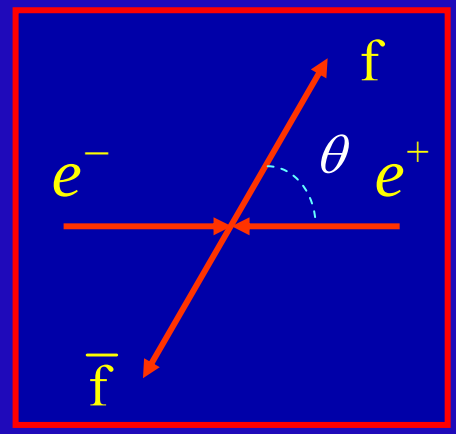
$$\Gamma = \frac{G_F M_Z^3}{6\pi\sqrt{2}} \left(\left|v_f\right|^2 + \left|a_f\right|^2 \right) N_f \quad ; \quad N_l = 1 \;,\; N_q = N_C$$

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

Exp:	2.123 ± 0.067	2.4952 ± 0.0023

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





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

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

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

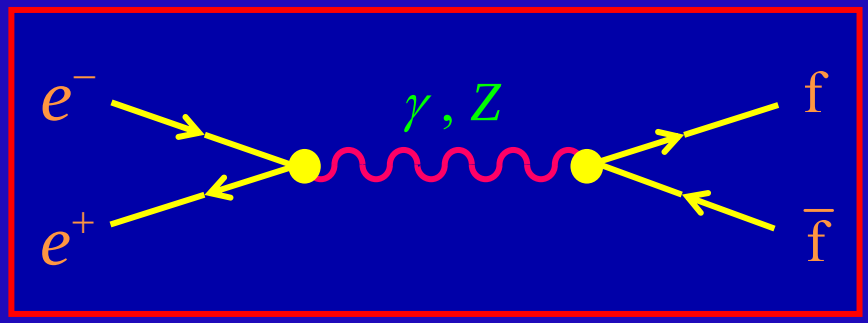
$$B = 4\, a_e\, a_f\, \mathrm{Re}(\chi) + 8\, v_e\, a_e\, v_f\, a_f\, |\chi|^2$$

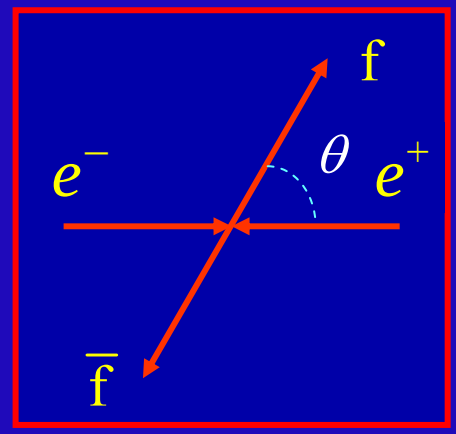
$$C = 2\, v_e\, a_f\, \mathrm{Re}(\chi) + 2\,(v_e^2 + a_e^2)\, v_f\, a_f\, |\chi|^2$$

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

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

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





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

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

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

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

Z Peak $(s = M_Z^2)$

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

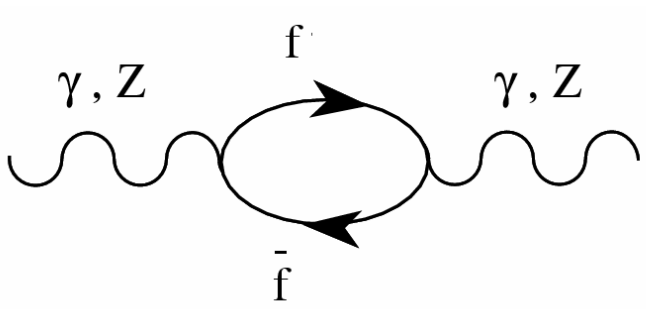
$$\mathcal{A}_{FB}(s) = \frac{3}{4} \mathcal{P}_e \mathcal{P}_f \quad ; \quad \mathcal{A}_{Pol}(s) = \mathcal{P}_f \quad ; \quad \mathcal{A}_{FB}^{Pol}(s) = \frac{3}{4} \mathcal{P}_e$$

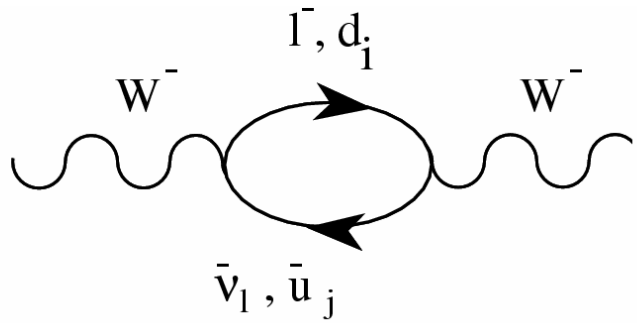
$$\mathcal{A}_{LR}(s) \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\mathcal{P}_e \quad ; \quad \mathcal{A}_{FB}^{LR}(s) = -\frac{3}{4} \mathcal{P}_f$$

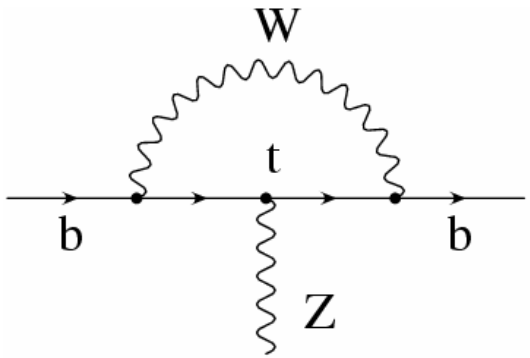
Final Polarization $\mathcal{P}_f \equiv -A_f = \dfrac{-2\, v_f\, a_f}{|v_f|^2 + |a_f|^2}$ **Only Available for** $f = \tau$

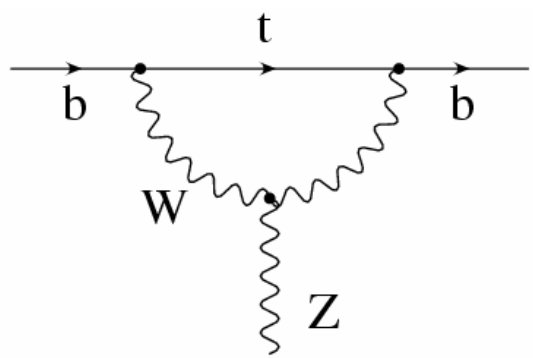
$|v_l| = \frac{1}{2} |-1 + 4\sin^2\theta| \ll 1$ ➡ $\mathcal{P}_l$ **Sensitive to Higher Order Corrections**

Higher Order Corrections







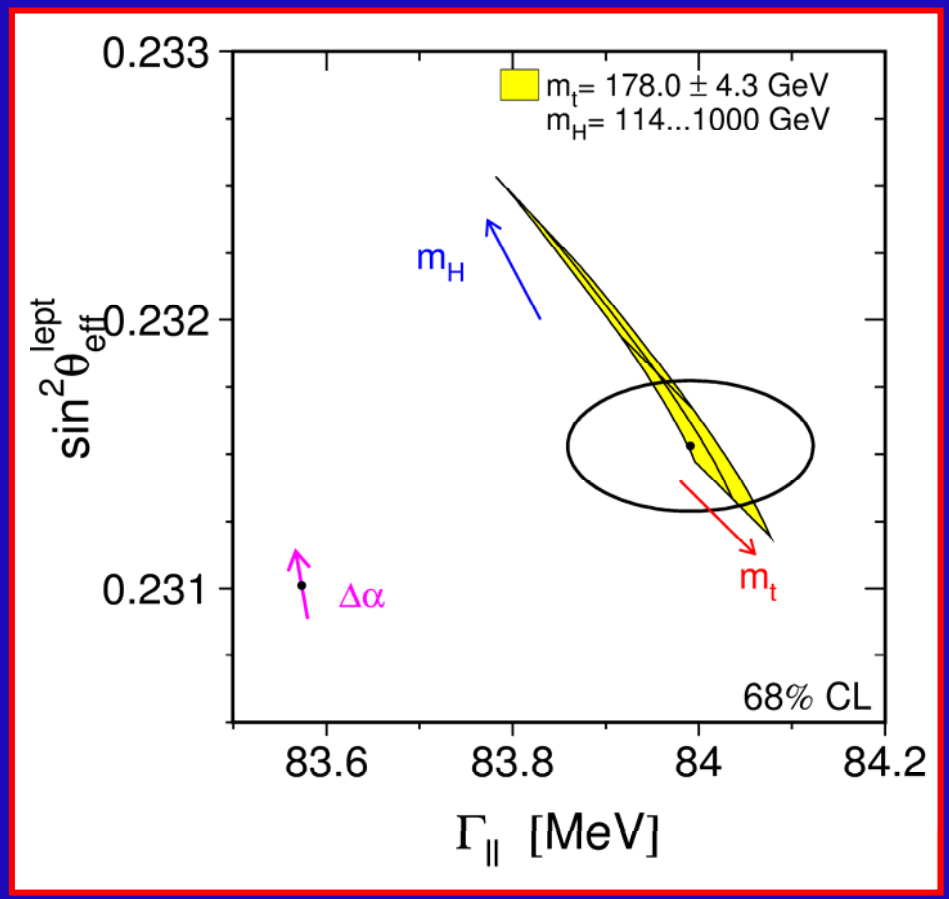


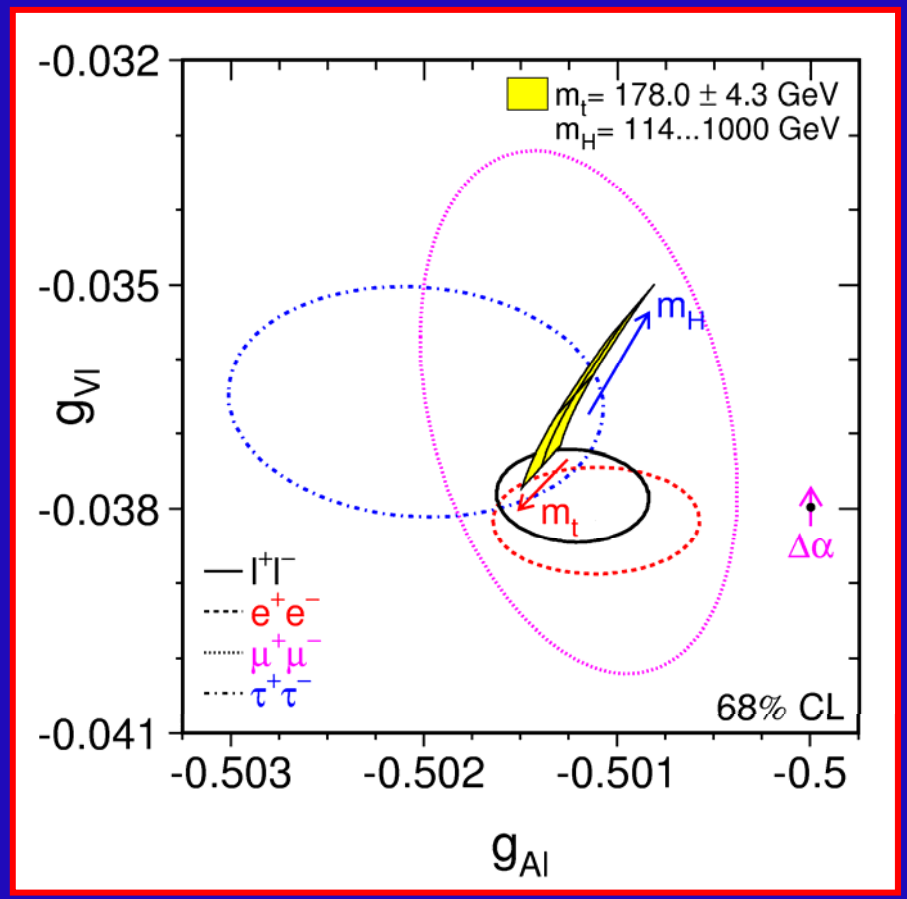
Sensitive to Heavier Particles: TOP , HIGGS

Evidence of Electroweak Corrections

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

LEPEWWG July 2005





Low Values of M_H Preferred

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

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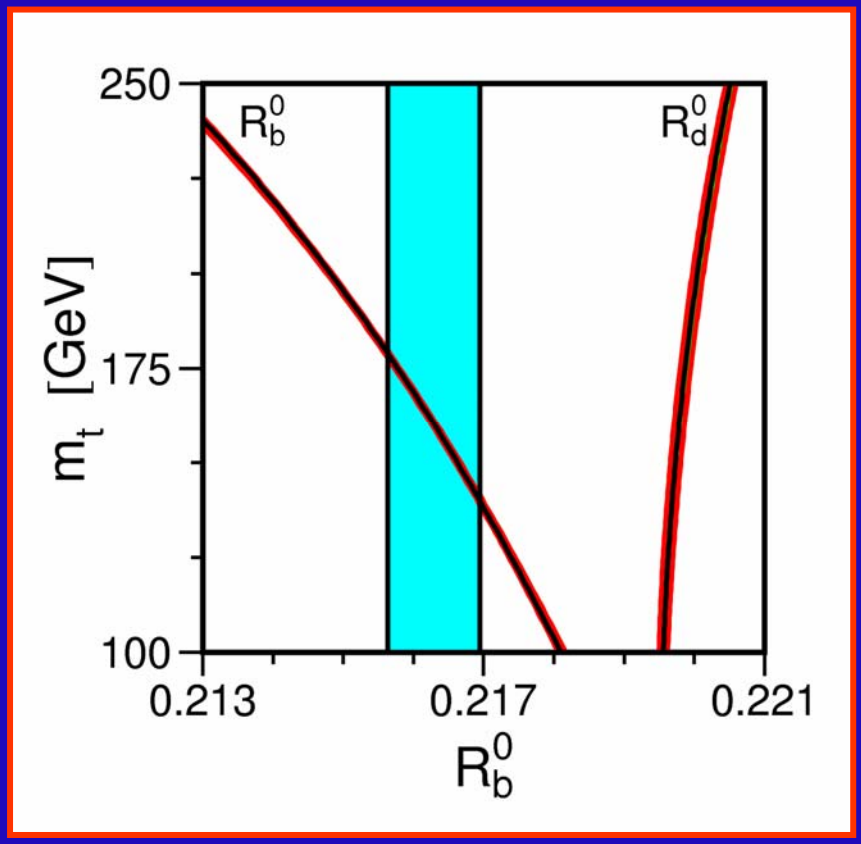
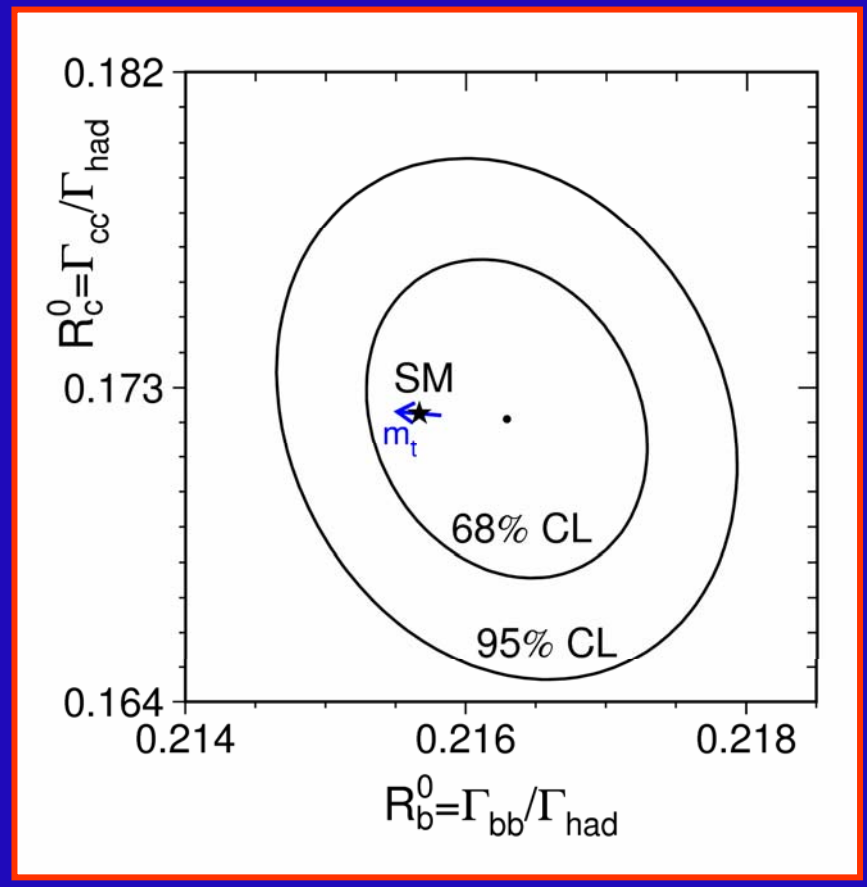
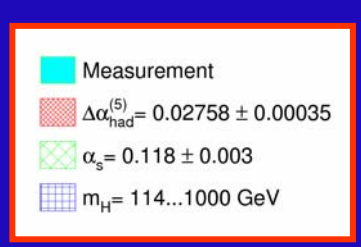
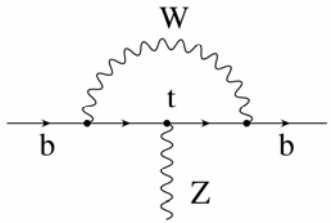
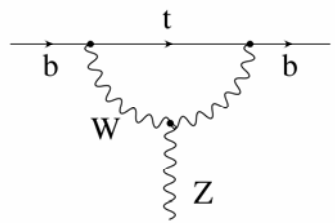


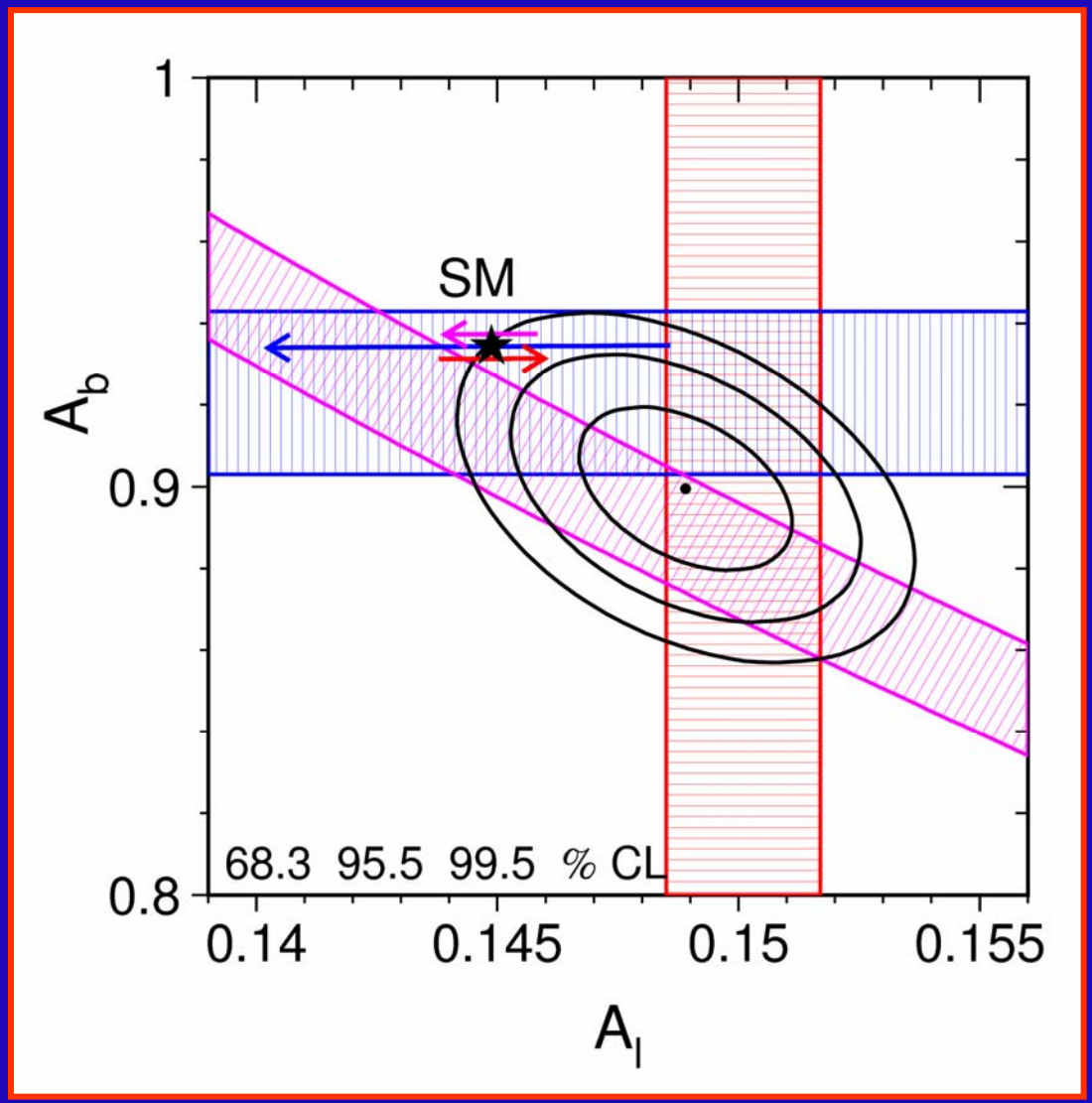
Bernabéu-Pich-Santamaría 1988











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$m_t = (178.0 \pm 4.3)\ \text{GeV}$

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

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

Heavy Quarks (Leptons) Favour High (Low) M_H

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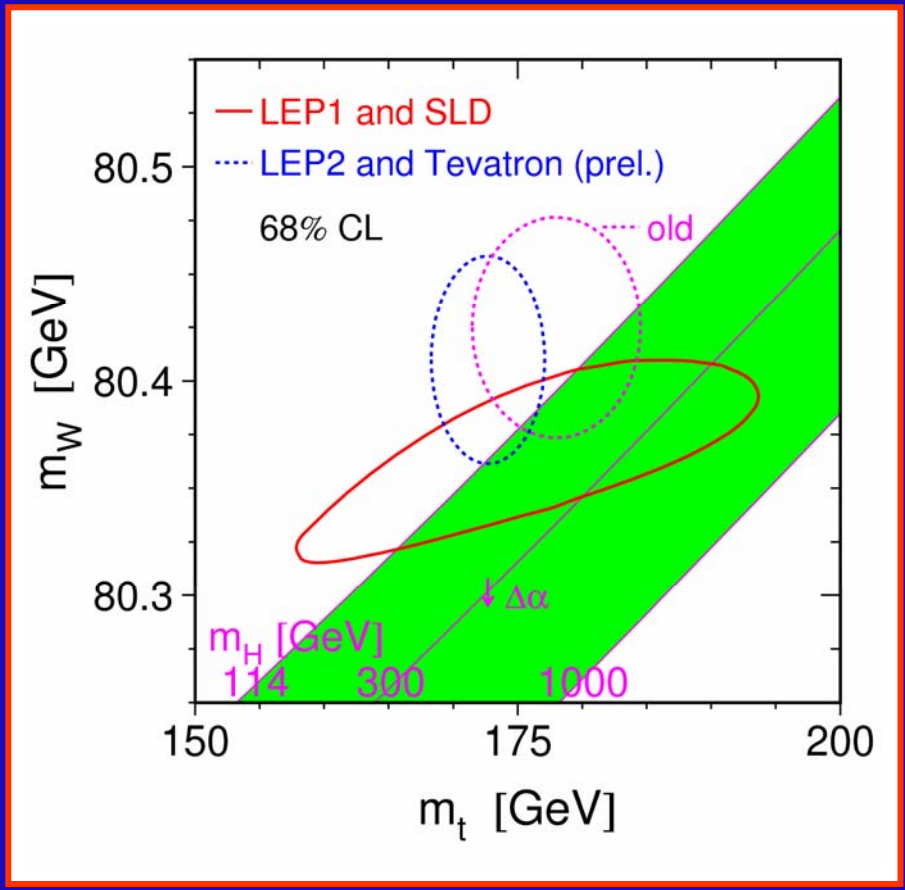
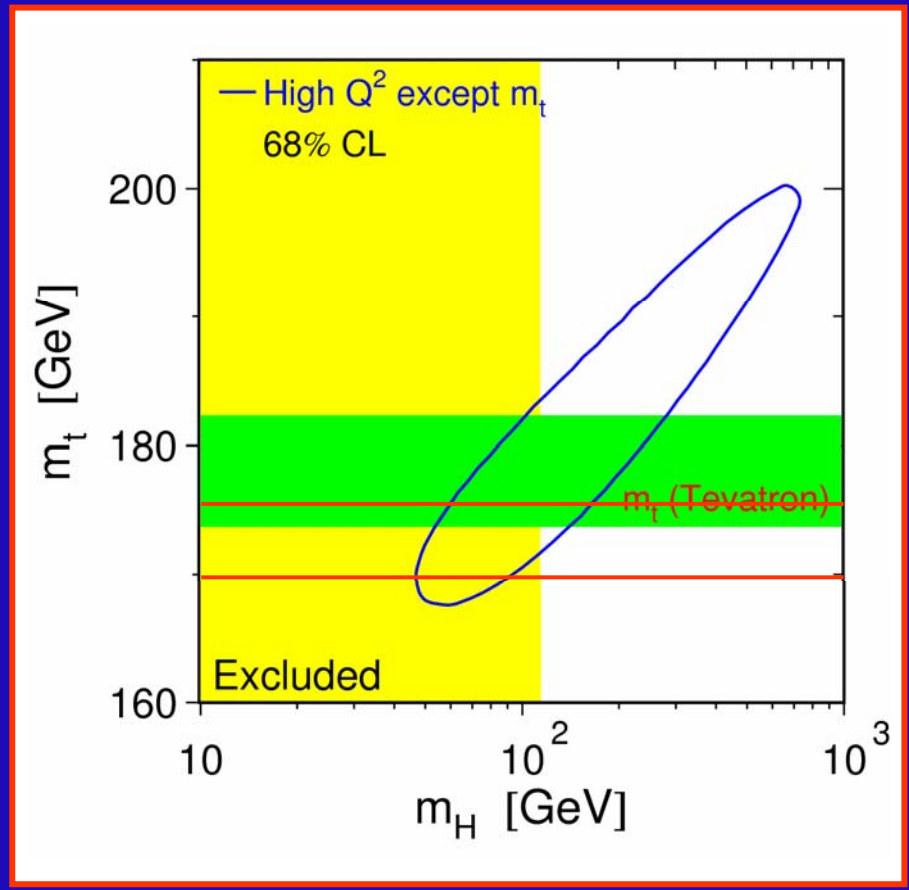
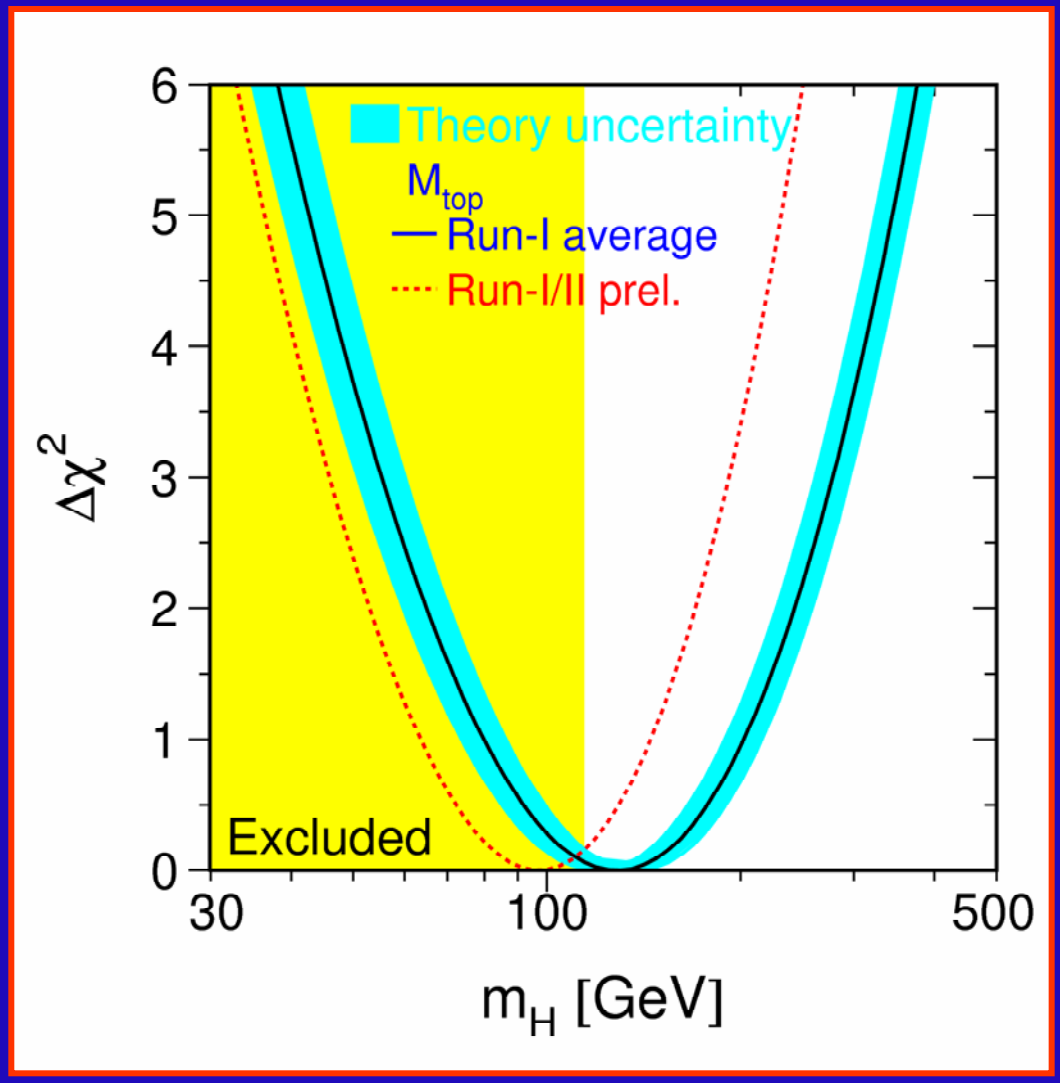
July 2005





$m_t = (172.7 \pm 2.9)$ GeV (CDF + D0)



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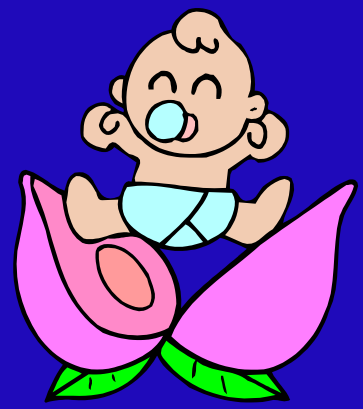
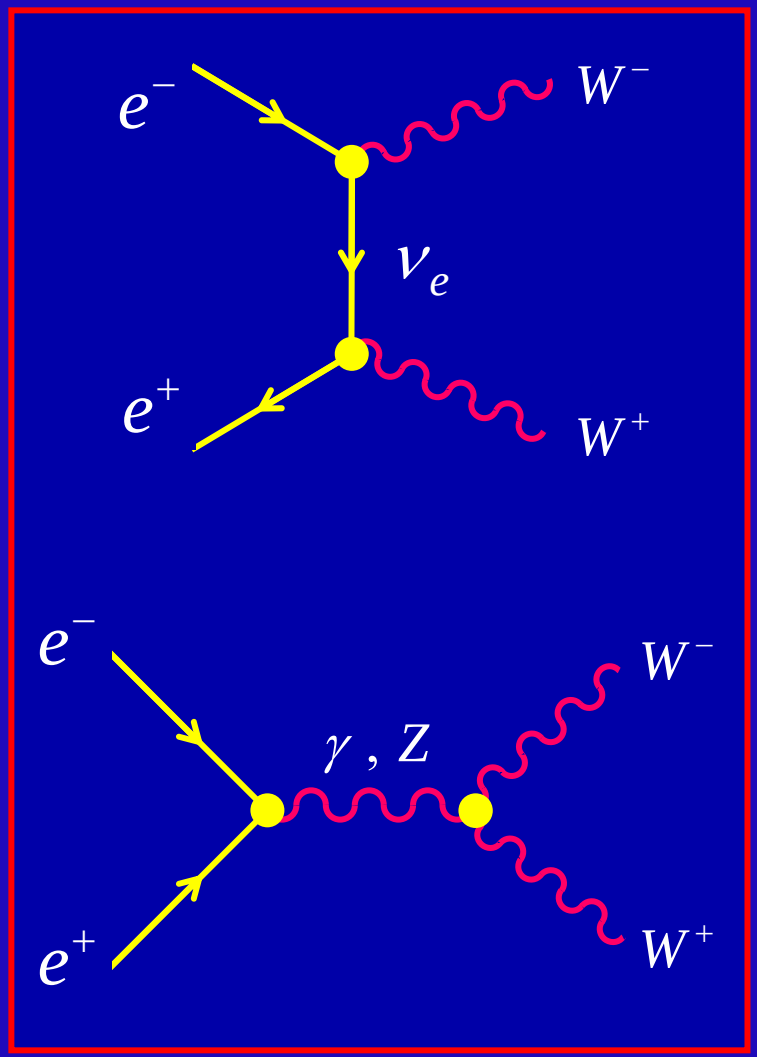
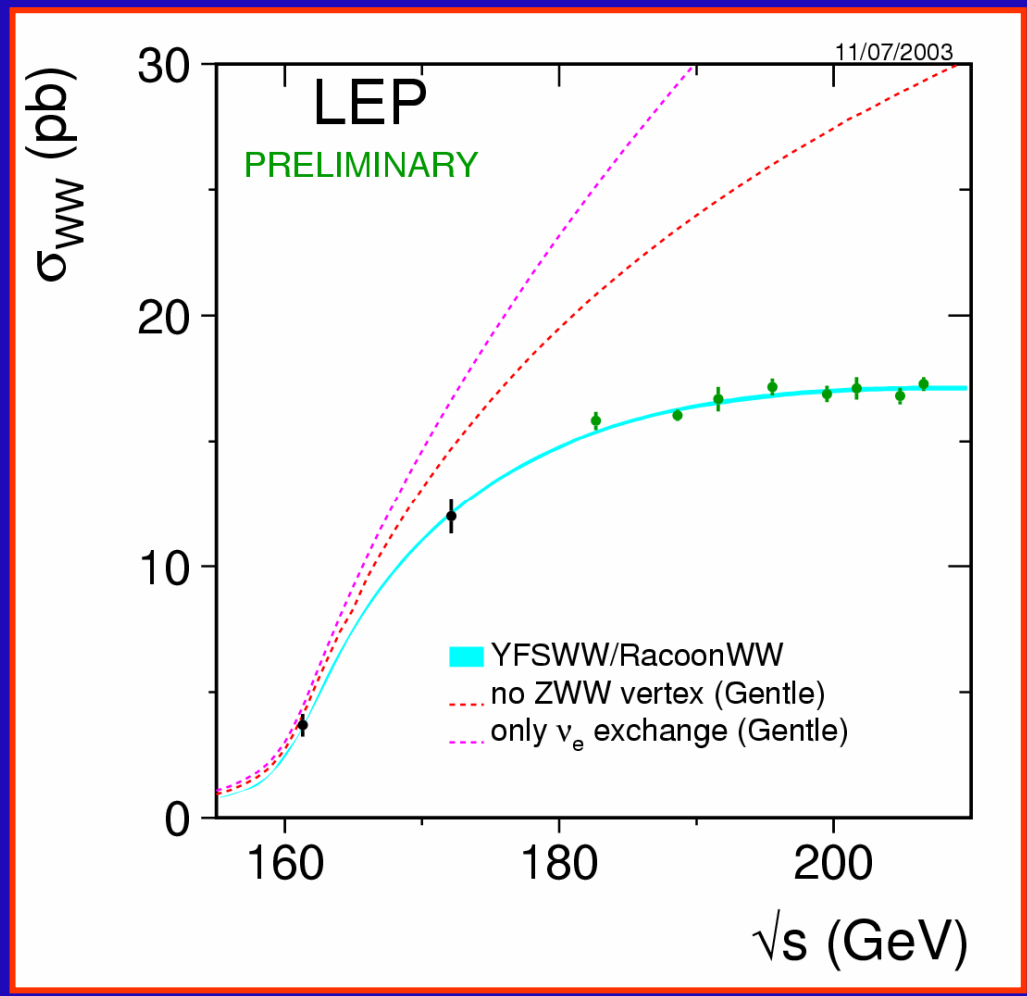


$$114 \text{ GeV} < M_H < 219 \text{ GeV} \qquad (95\% \text{ CL})$$

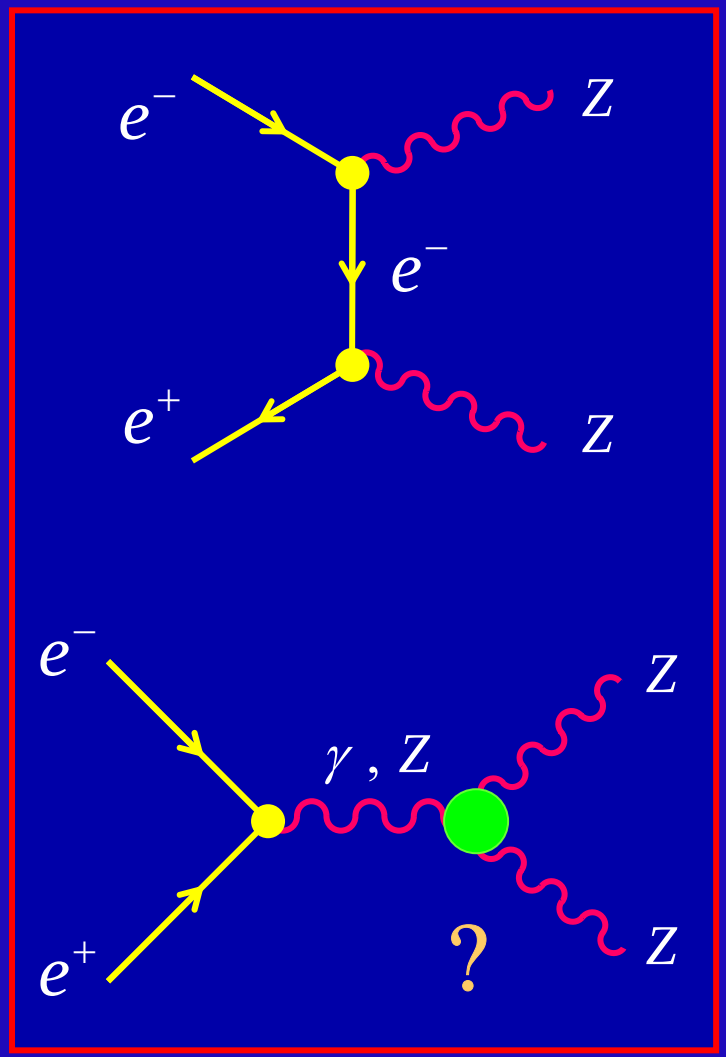
$e^+ e^- \to W^+ W^-$

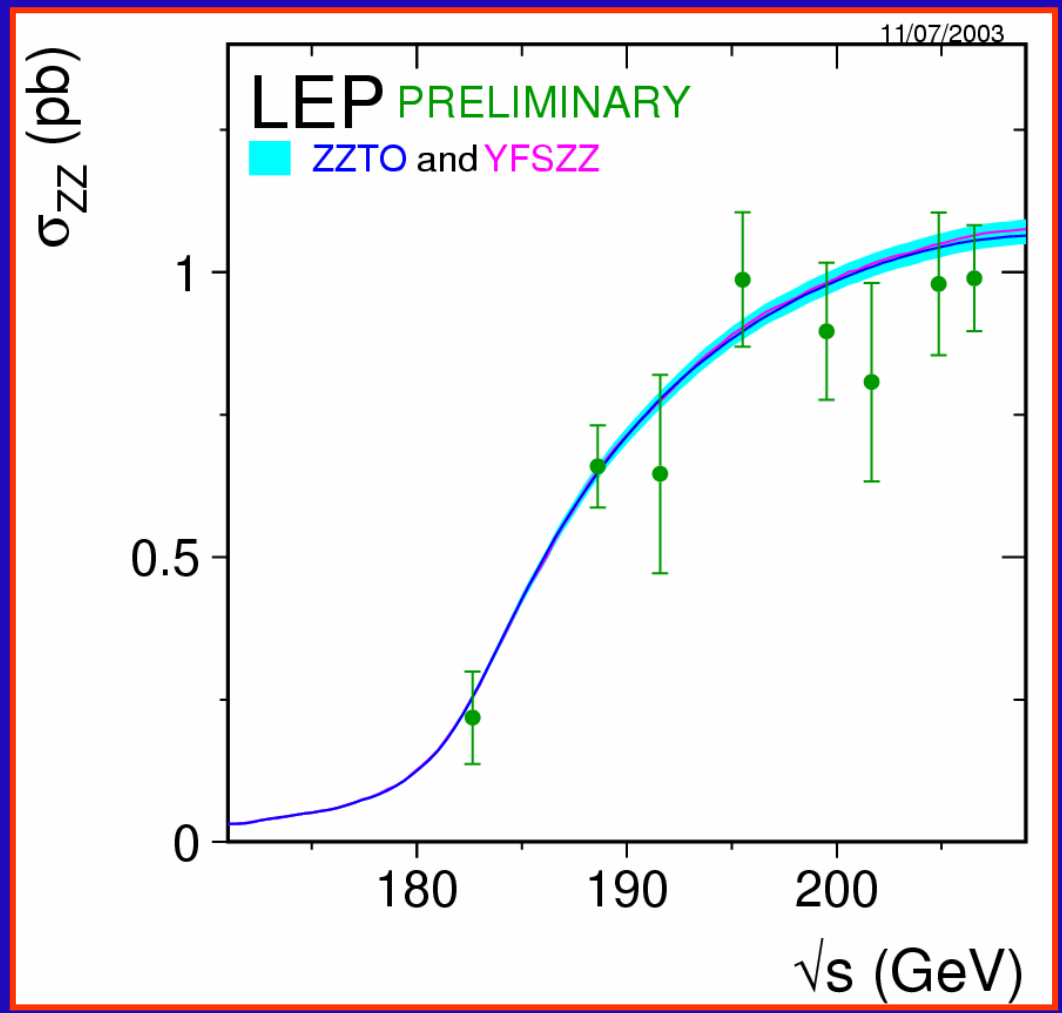




Evidence of Gauge Self-Interactions

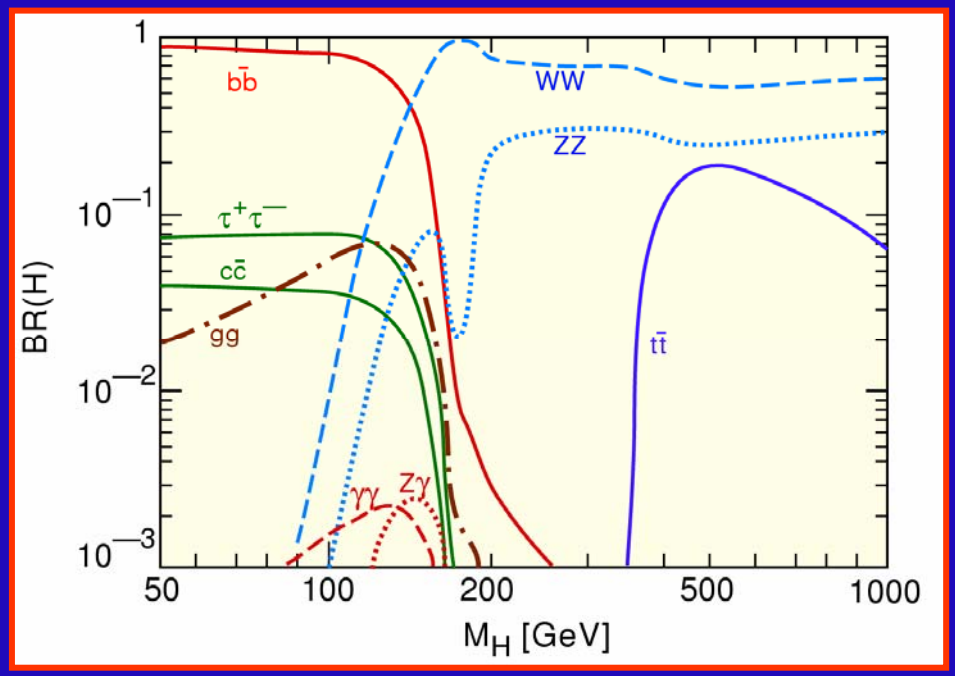
$e^+ e^- \to Z Z$





No Evidence of γZZ or ZZZ couplings

Searching for the HIGGS

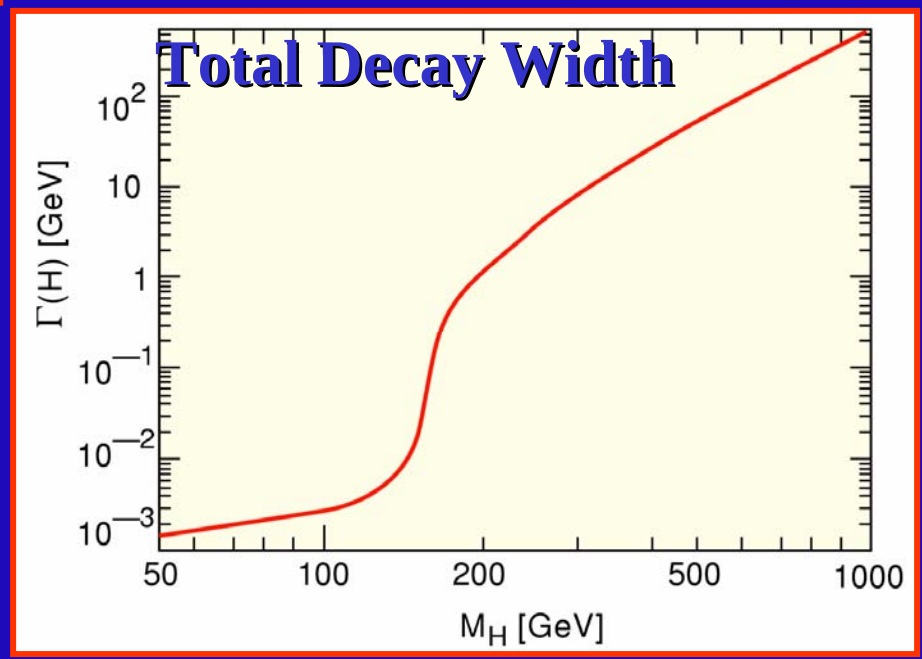


D. Denegri

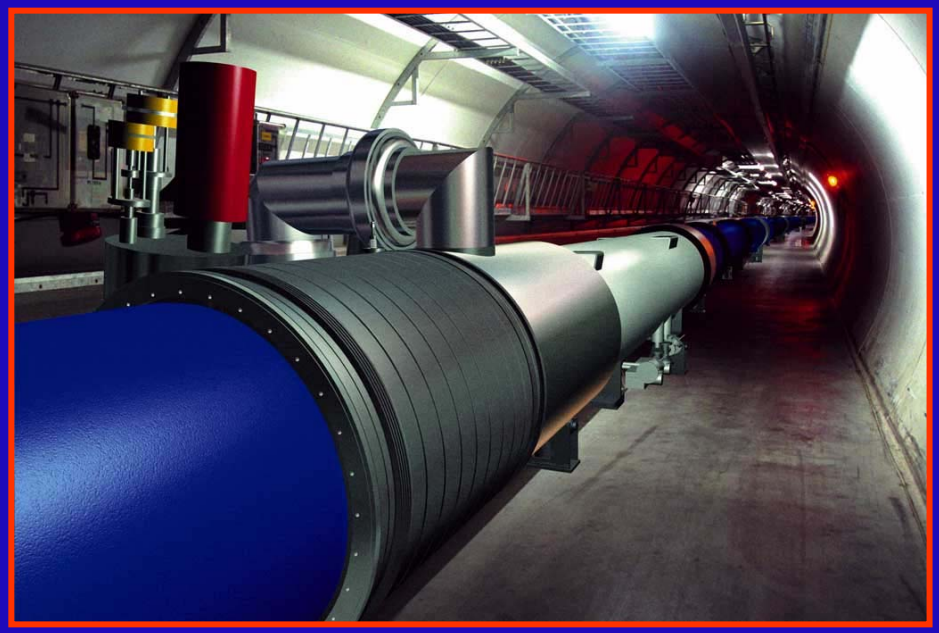
Branching Ratios

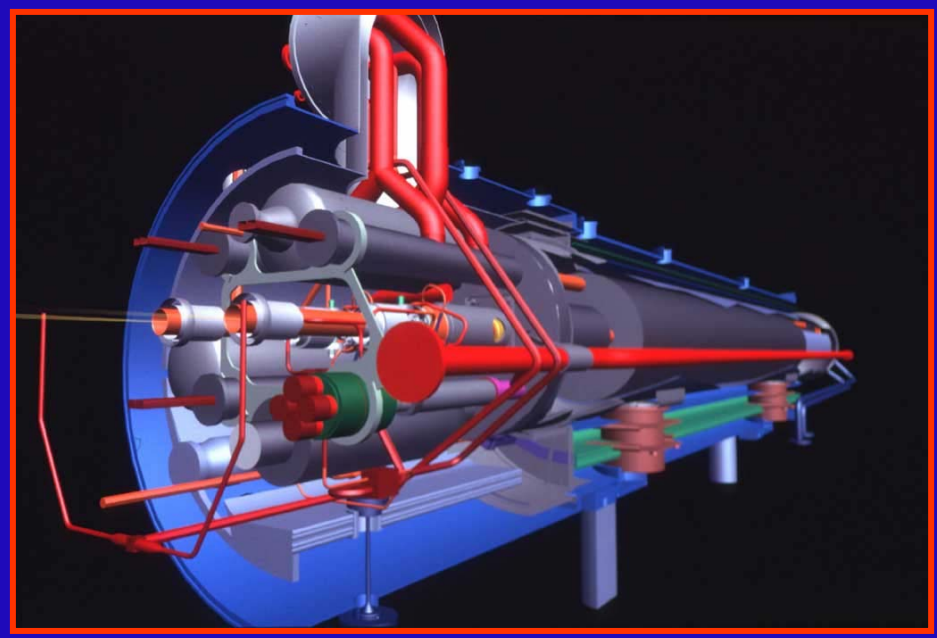
Interaction proportional to mass (M_W^2 , M_Z^2 , m_f)

The Higgs decays into the heaviest possible particles

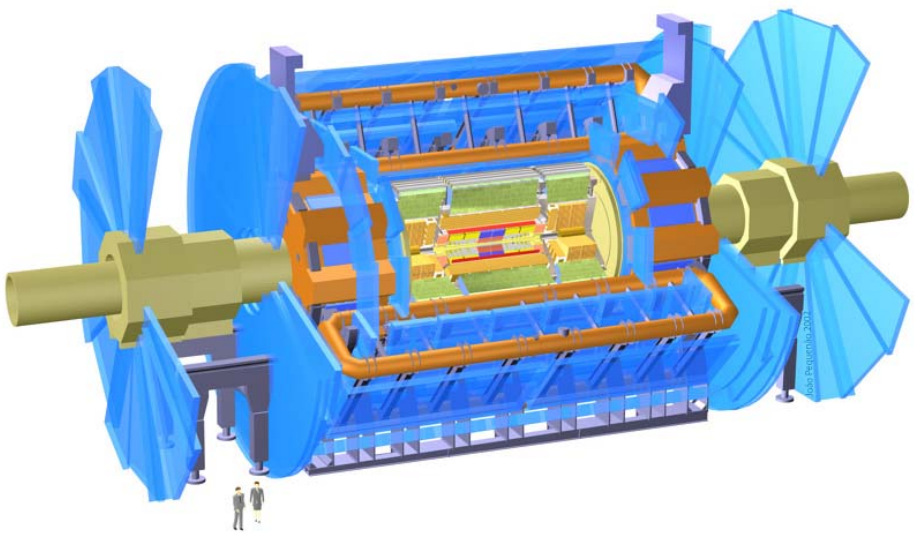


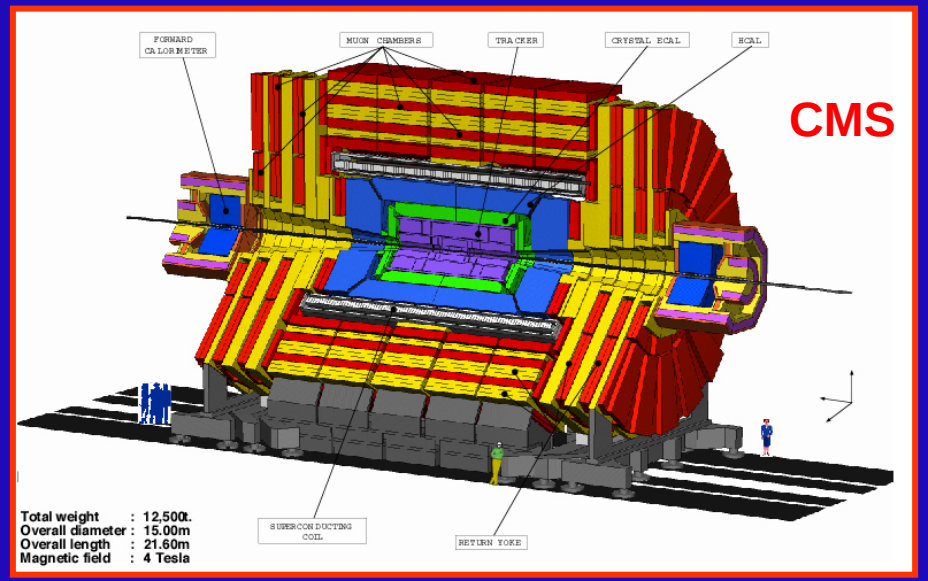
The Large Hadron Collider





ATLAS





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