3. EW Phenomenology

- Precision Electroweak Tests
- Sensitivity to M_H
- Higgs Searches

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

$$G_F = (1.166\,3788 \pm 0.000\,000\,7) \times 10^{-5}\ \text{GeV}^{-2}$$

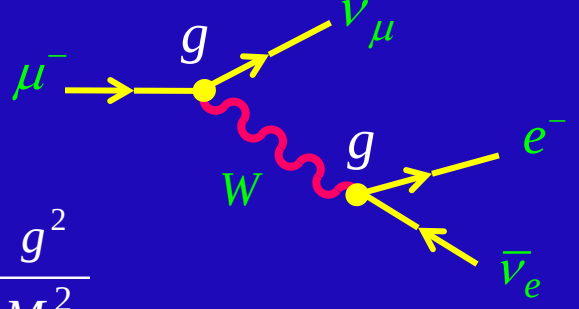
$$\alpha^{-1} = 137.035\,999\,084 \pm 0.000\,000\,051$$

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

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

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

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

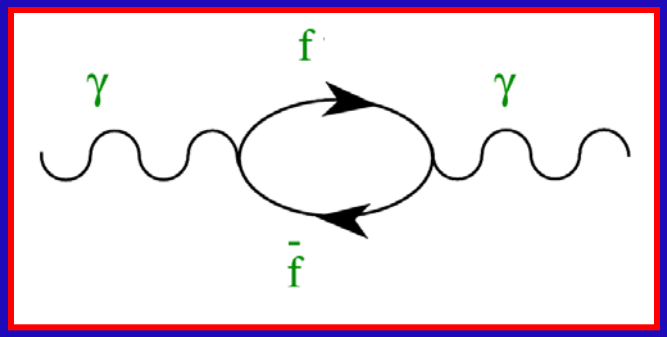


$$G_F \sim \frac{g^2}{M_W^2}$$

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

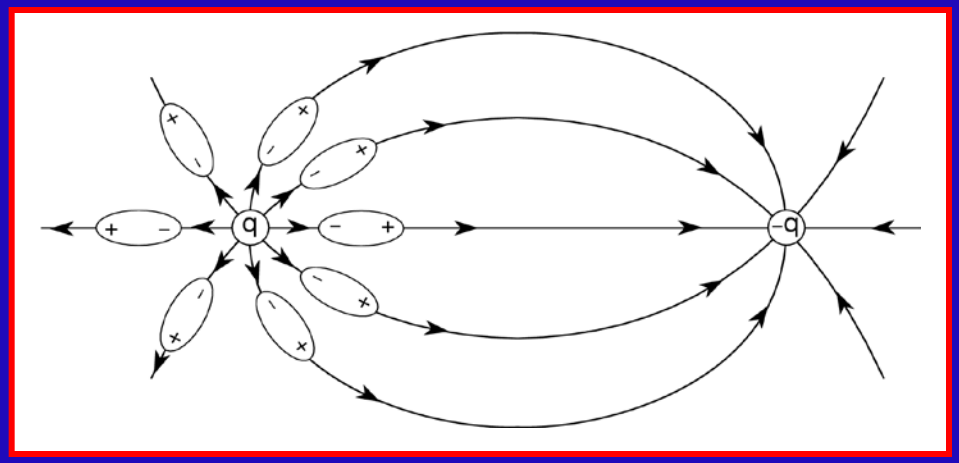
$$\sin^2\theta_W = 0.212 \qquad (0.231)$$

VACUUM POLARIZATION



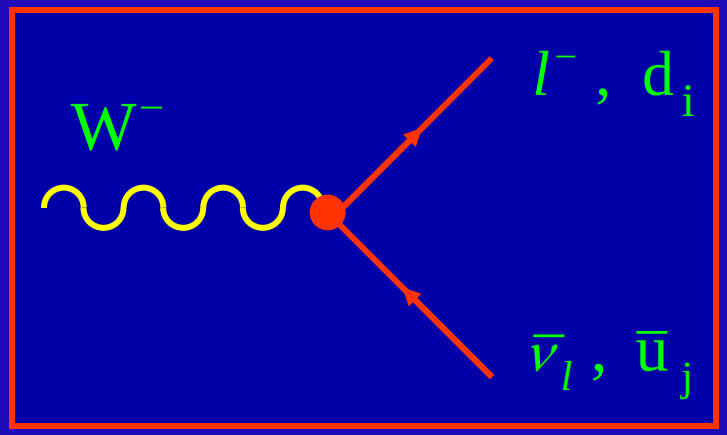
The Photon Couples to *Virtual* $f\,\bar{f}$ *Pairs*

Vacuum ⟷ Polarized Dielectric Medium



$$\alpha^{-1} = \alpha(m_e^2)^{-1} = 137.035999084\ (51) \quad ; \quad \alpha\,(M_Z^2)^{-1} = 128.95 \pm 0.05$$

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



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

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

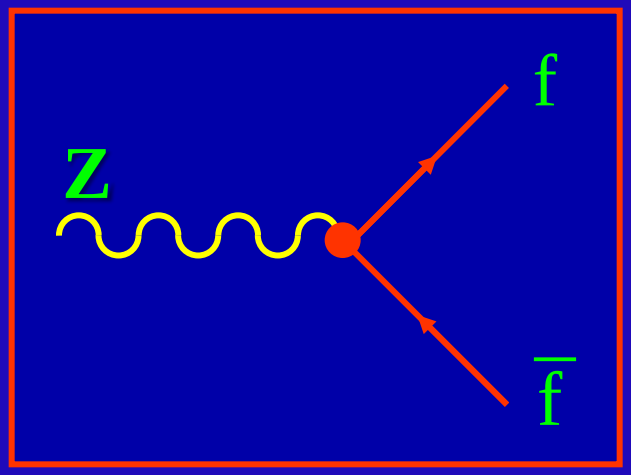
$$\mathrm{Br}\left(W^- \to l^- \bar{\nu}_l\right) \equiv \frac{\Gamma\left(W^- \to l^- \bar{\nu}_l\right)}{\Gamma\left(W^- \to \mathrm{all}\right)} = \frac{1}{3 + 2\,N_C} = 11.1\%$$

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**



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

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

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

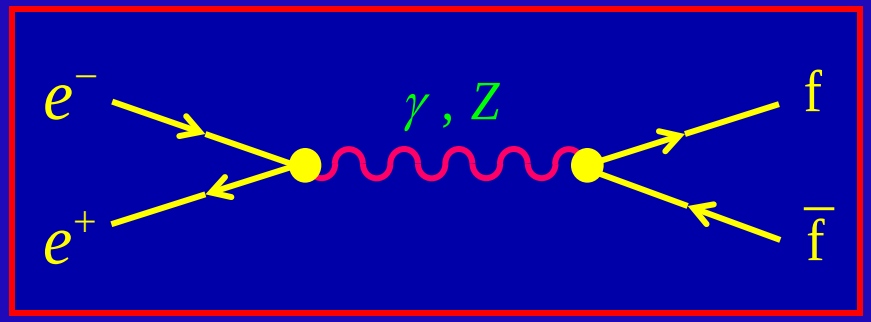
$$(1.989)$$

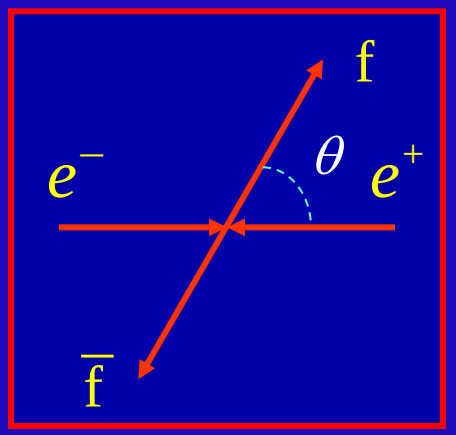
Experiment:

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

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

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





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

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

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

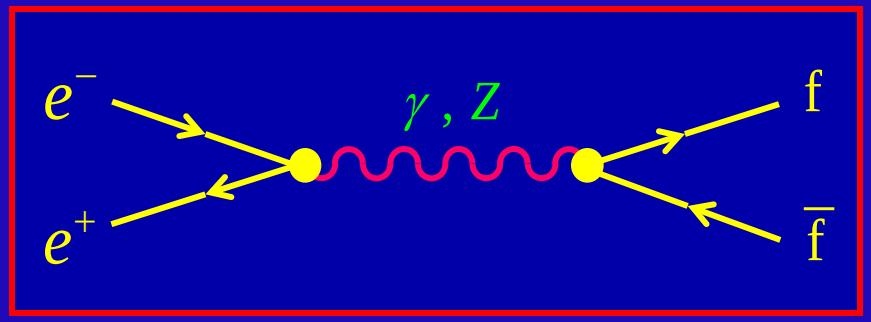
$$B = 4\, a_e a_f\, \mathrm{Re}(\chi) + 8\, v_e a_e v_f a_f\, |\chi|^2$$

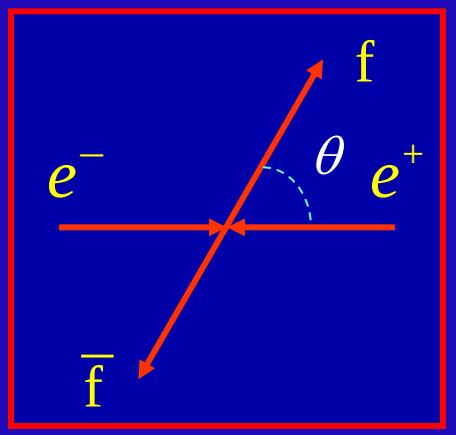
$$C = 2\, v_e a_f\, \mathrm{Re}(\chi) + 2\,(v_e^2 + a_e^2)\, v_f a_f\, |\chi|^2$$

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

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

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





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

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

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

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

Z Peak $(s = M_Z^2)$

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

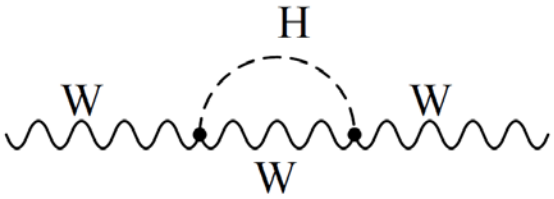
$$\mathcal{A}_{FB}(s) = \frac{3}{4} \mathcal{P}_e \mathcal{P}_f \quad ; \quad \mathcal{A}_{Pol}(s) = \mathcal{P}_f \quad ; \quad \mathcal{A}_{FB}^{Pol}(s) = \frac{3}{4} \mathcal{P}_e$$

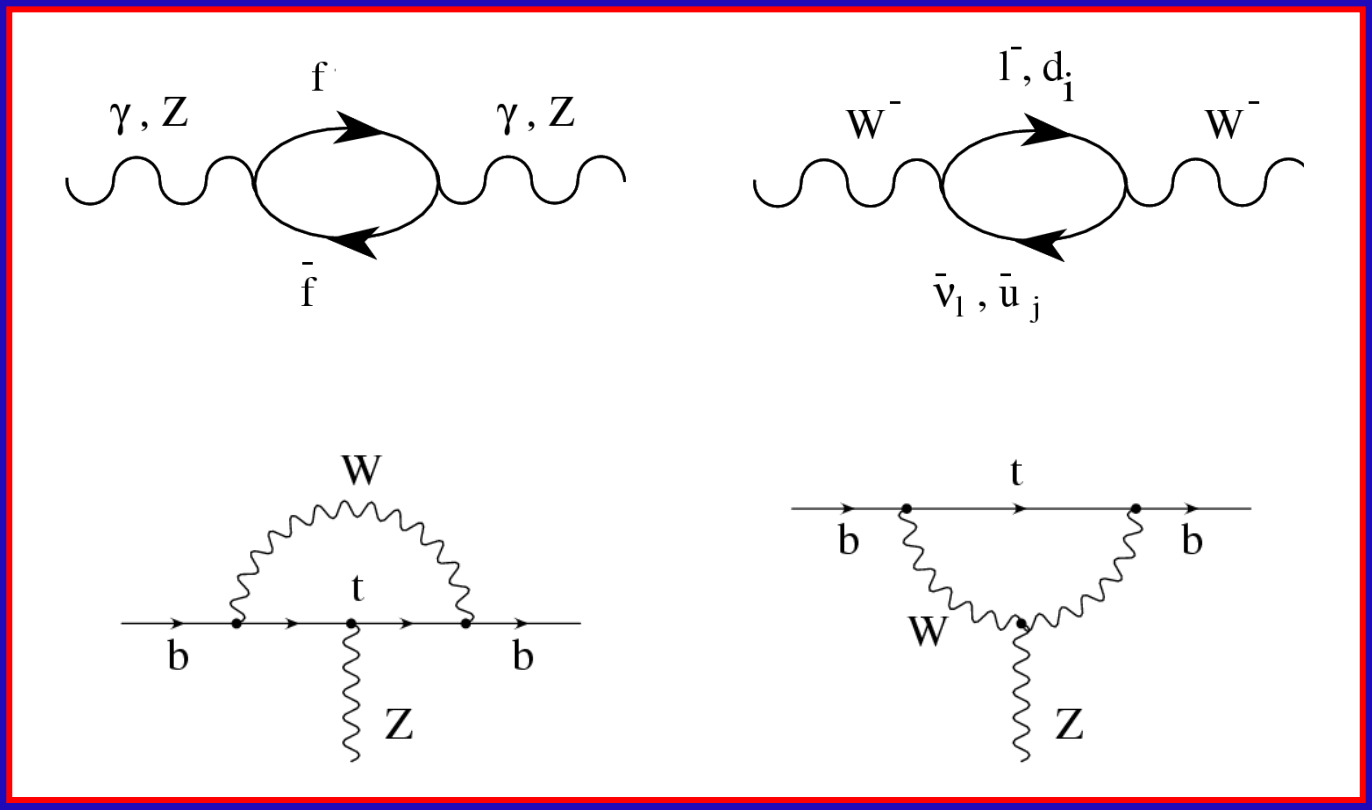
$$\mathcal{A}_{LR}(s) \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\mathcal{P}_e \quad ; \quad \mathcal{A}_{FB}^{LR}(s) = -\frac{3}{4} \mathcal{P}_f$$

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

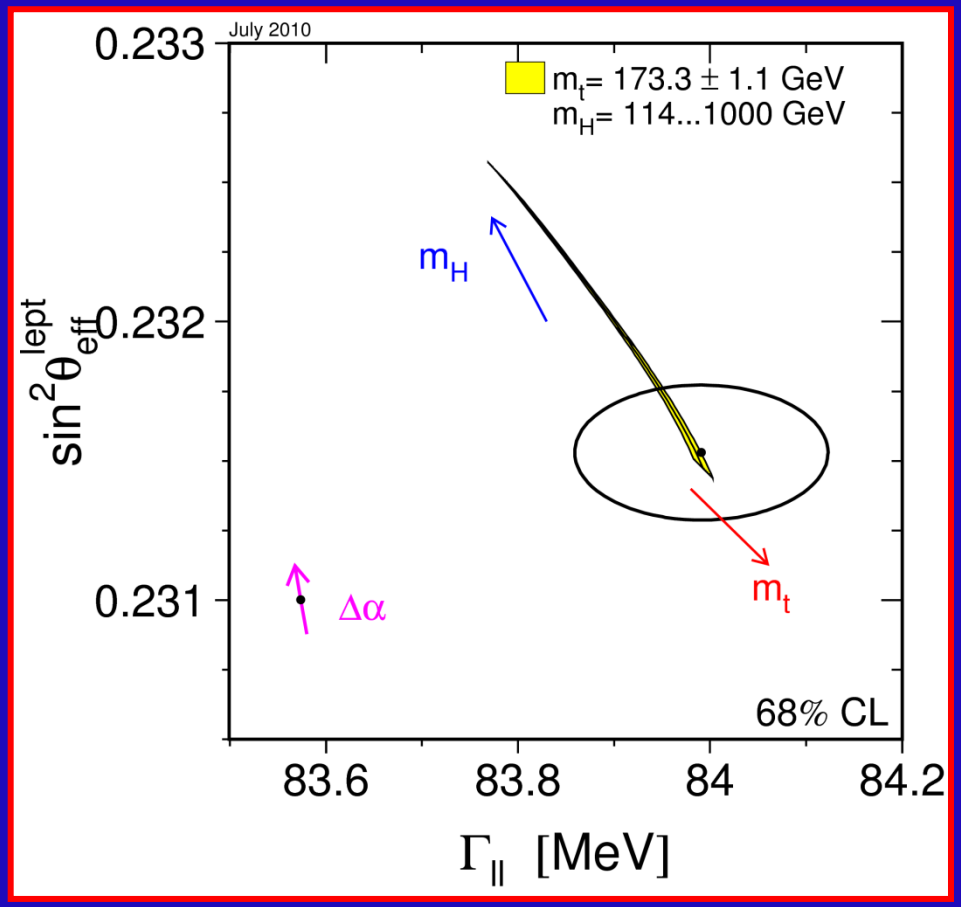


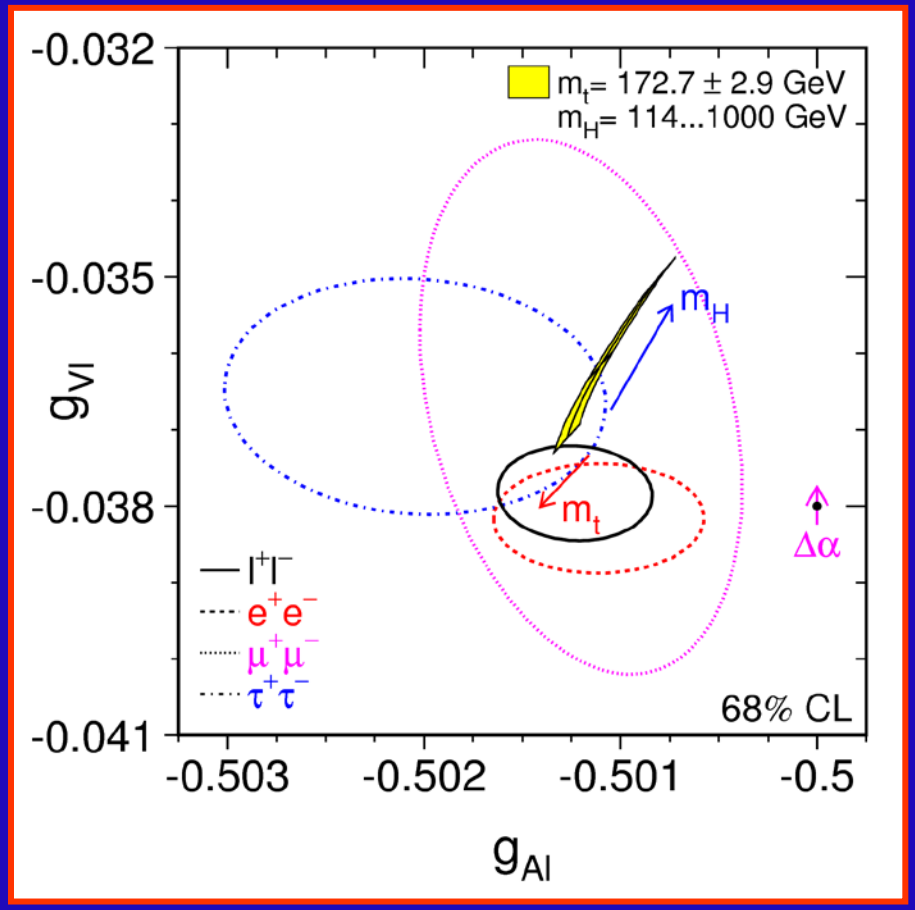


Sensitive to Heavier Particles: TOP , HIGGS

Evidence of Electroweak Corrections

July 2010 LEPEWWG September 2005



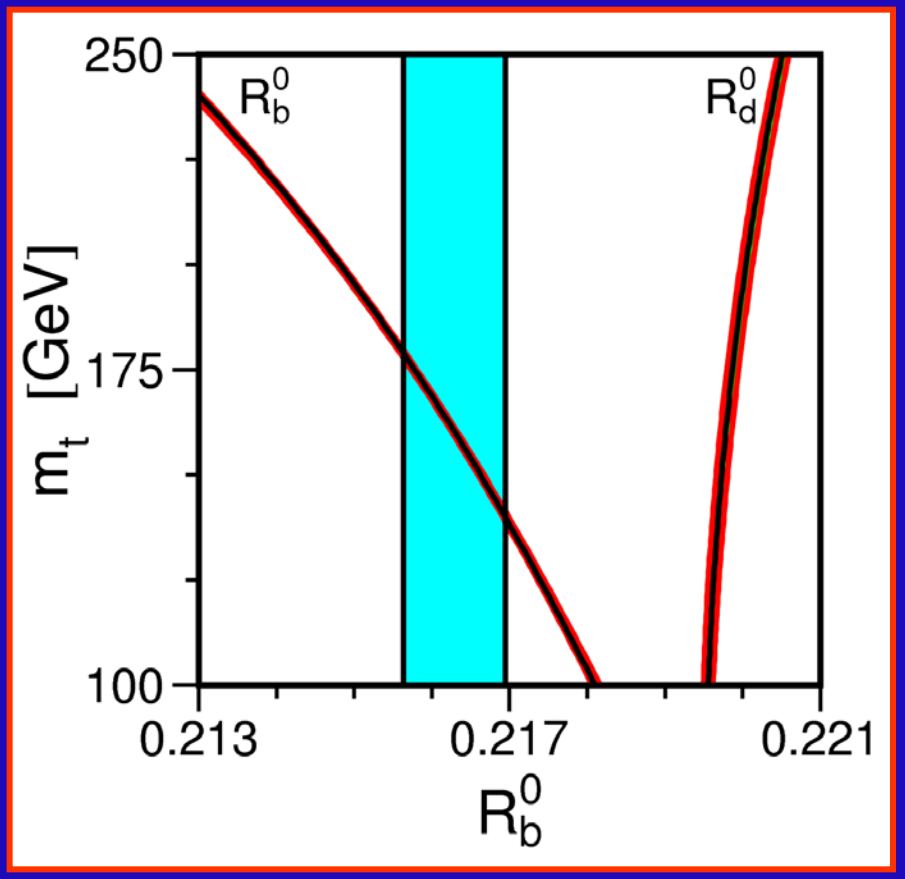


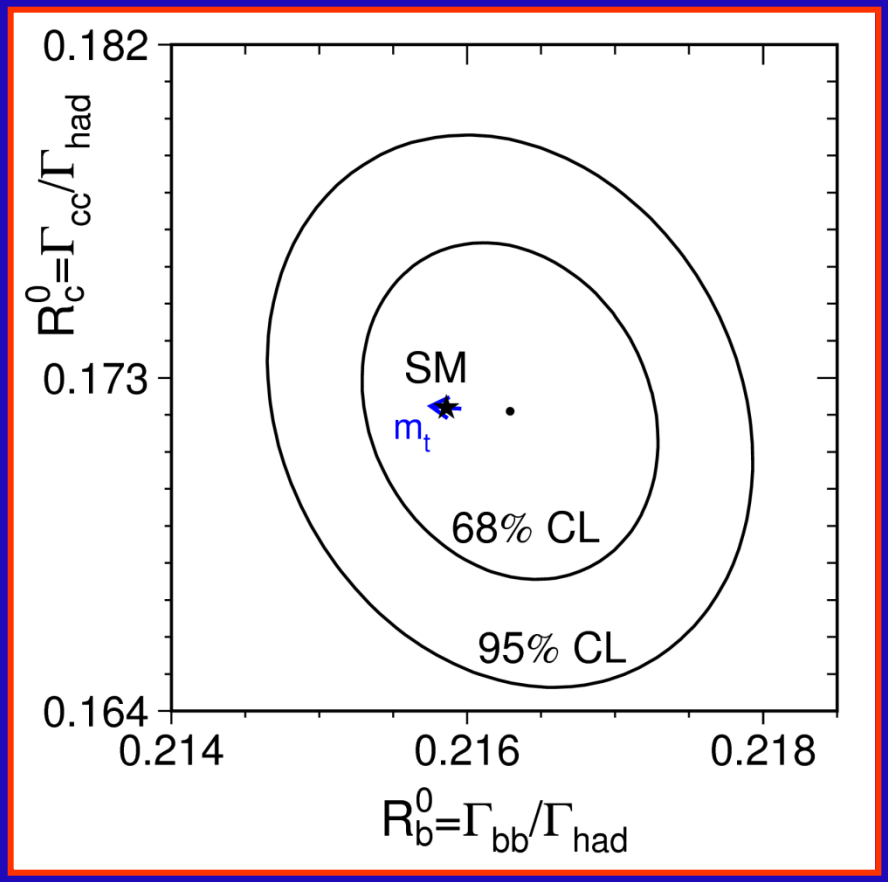
$\alpha(M_Z^2)^{-1} = 128.95 \pm 0.05$

Low Values of M_H Preferred

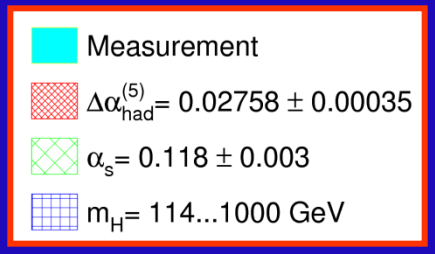
$$R_b \equiv \Gamma(Z \to b\bar{b})/\Gamma(Z \to \text{hadrons})$$

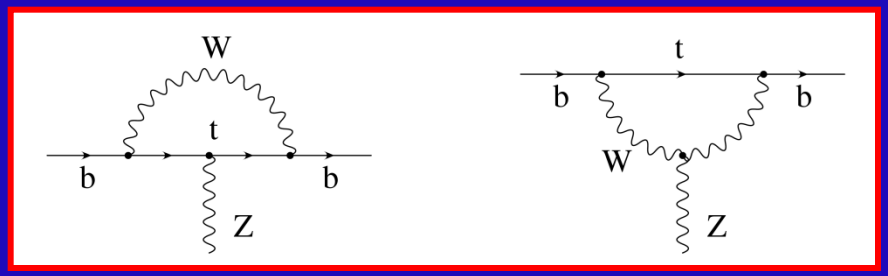
LEPEWWG **September 2005**

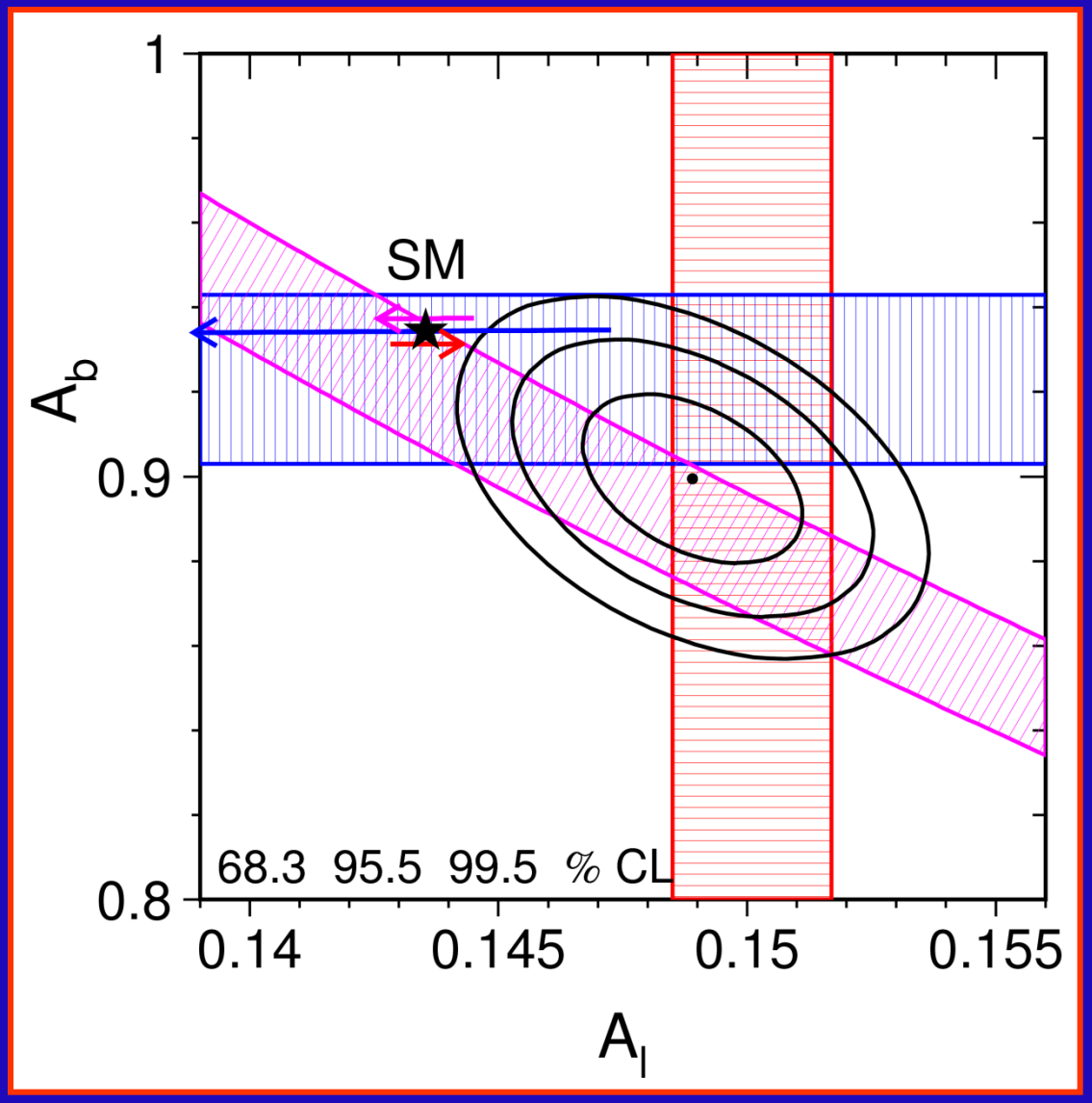




Bernabéu-Pich-Santamaría 1988







LEPEWWG

September 2005

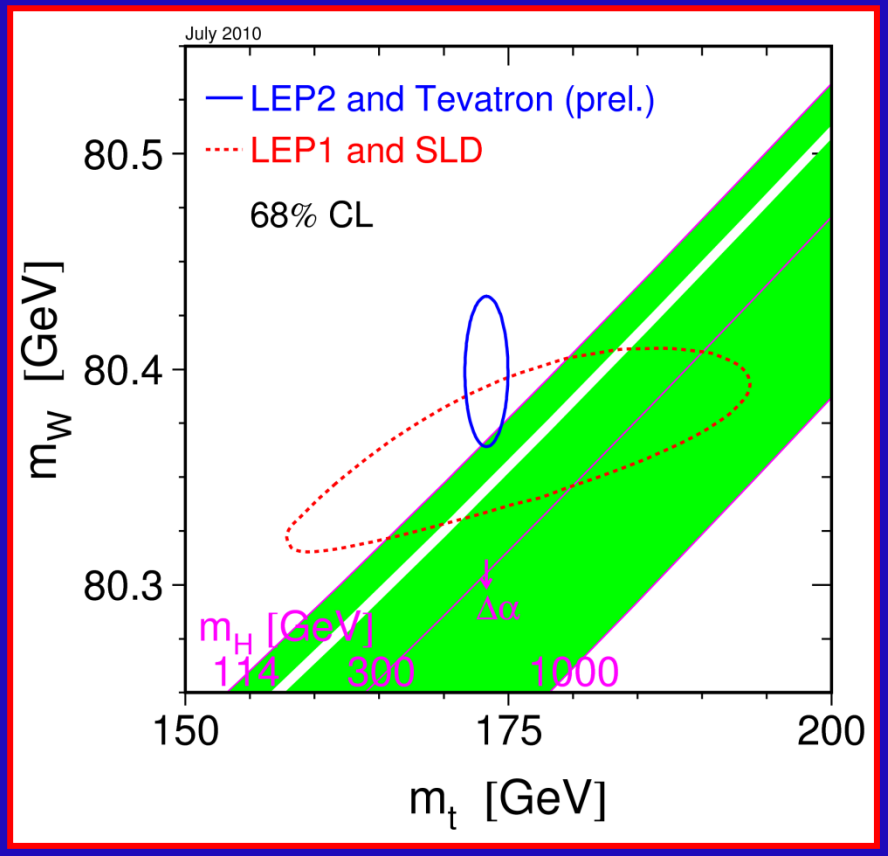
$m_t = (172.7 \pm 2.9)$ GeV

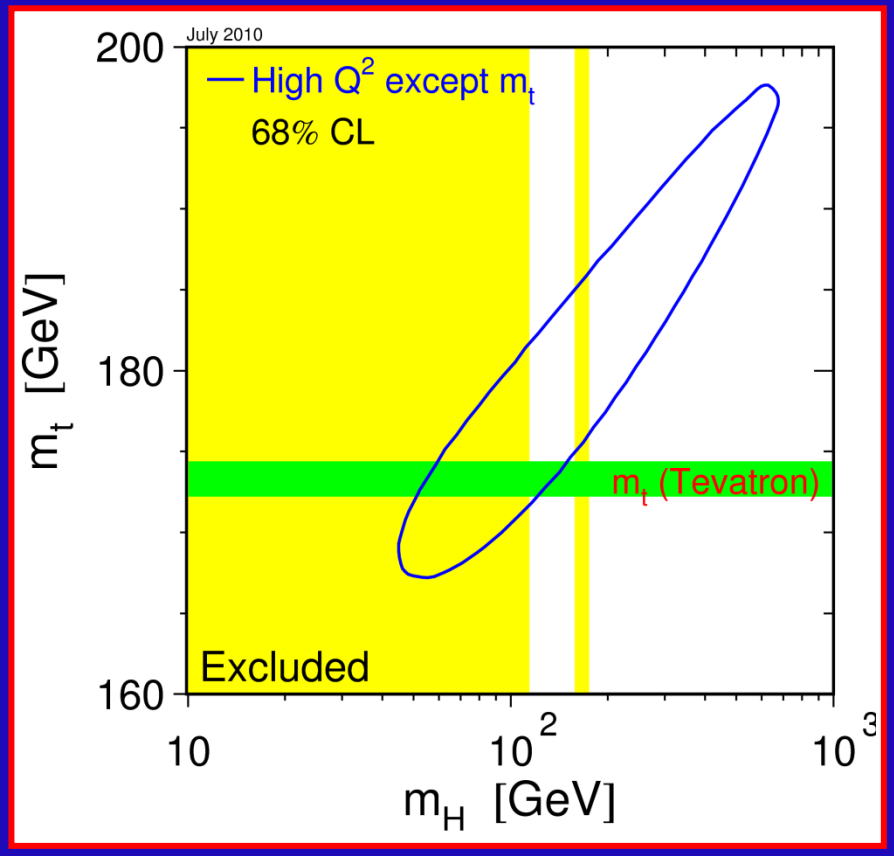
$M_H = (300\,^{+700}_{-186})$ GeV

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

Heavy Quarks (Leptons) Favour High (Low) M_H

LEPEWWG July 2010



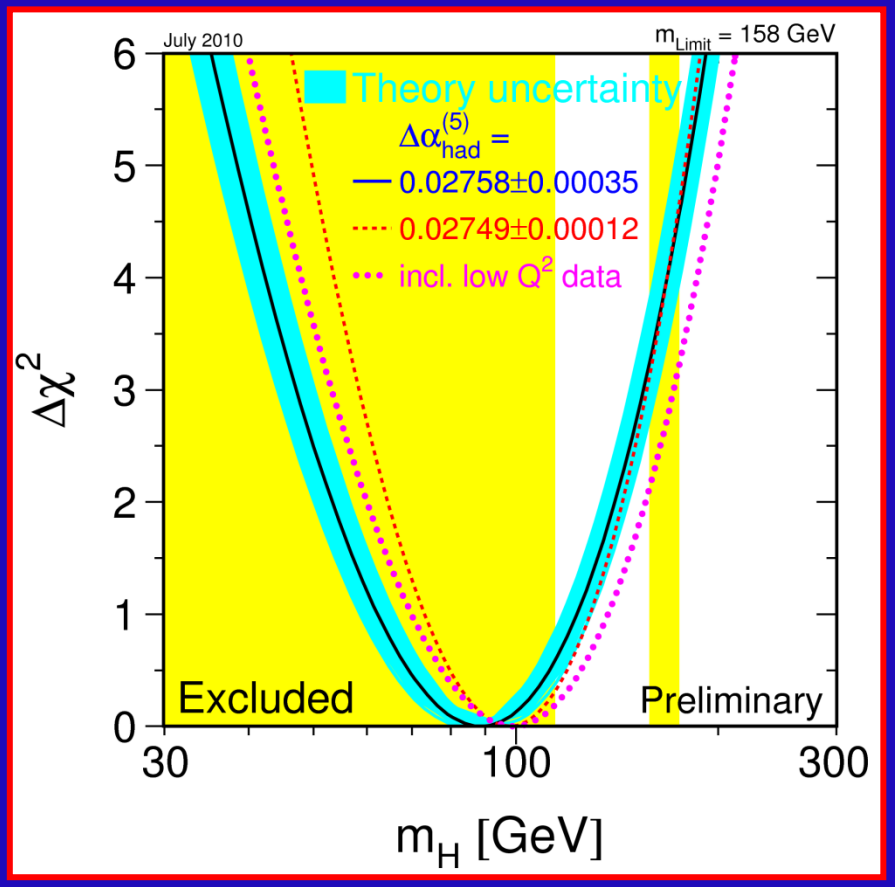


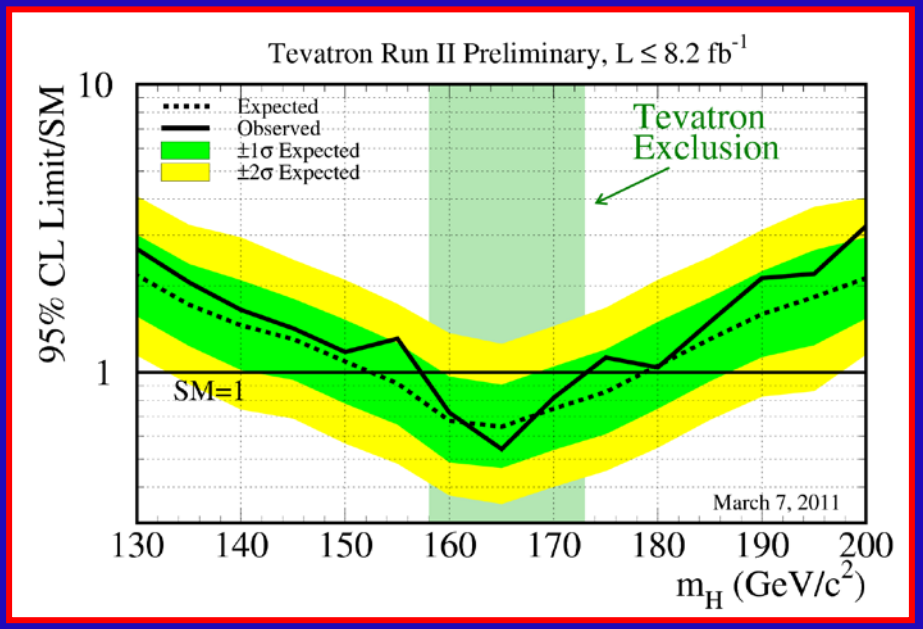
m_t = (173.3 ± 1.1) GeV (CDF + D0)

LEPEWWG (July 2010)

$H \to W^+W^-$

CDF / D0

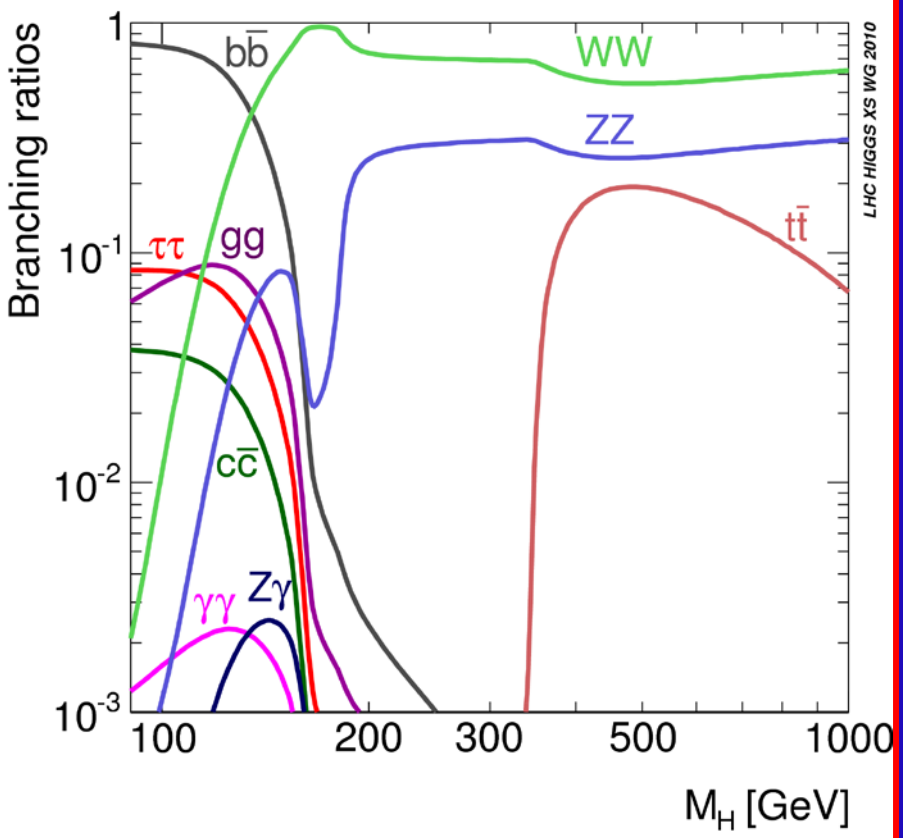


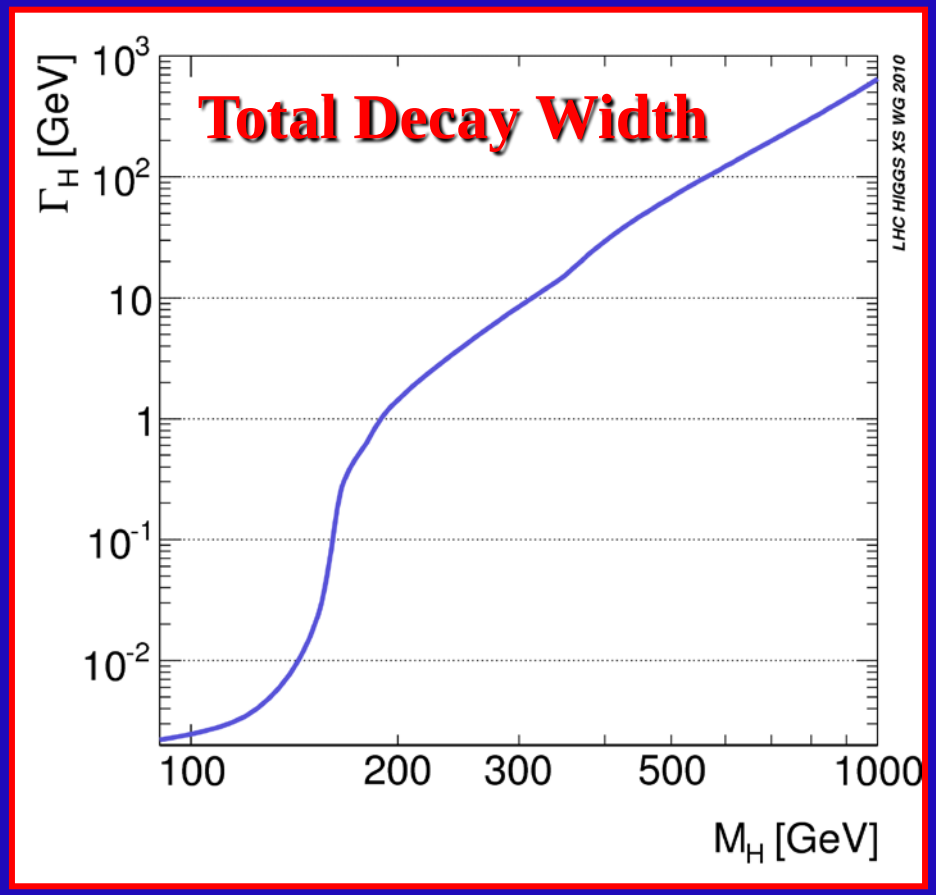


$M_H \in [158,173]$ excluded (95% CL)

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

Searching for the HIGGS

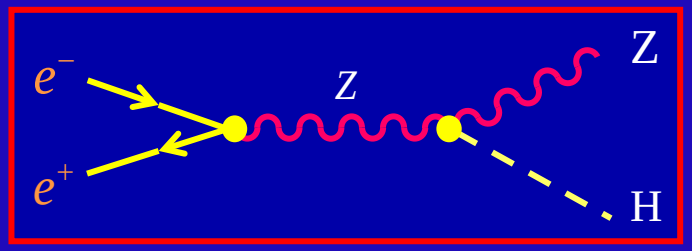




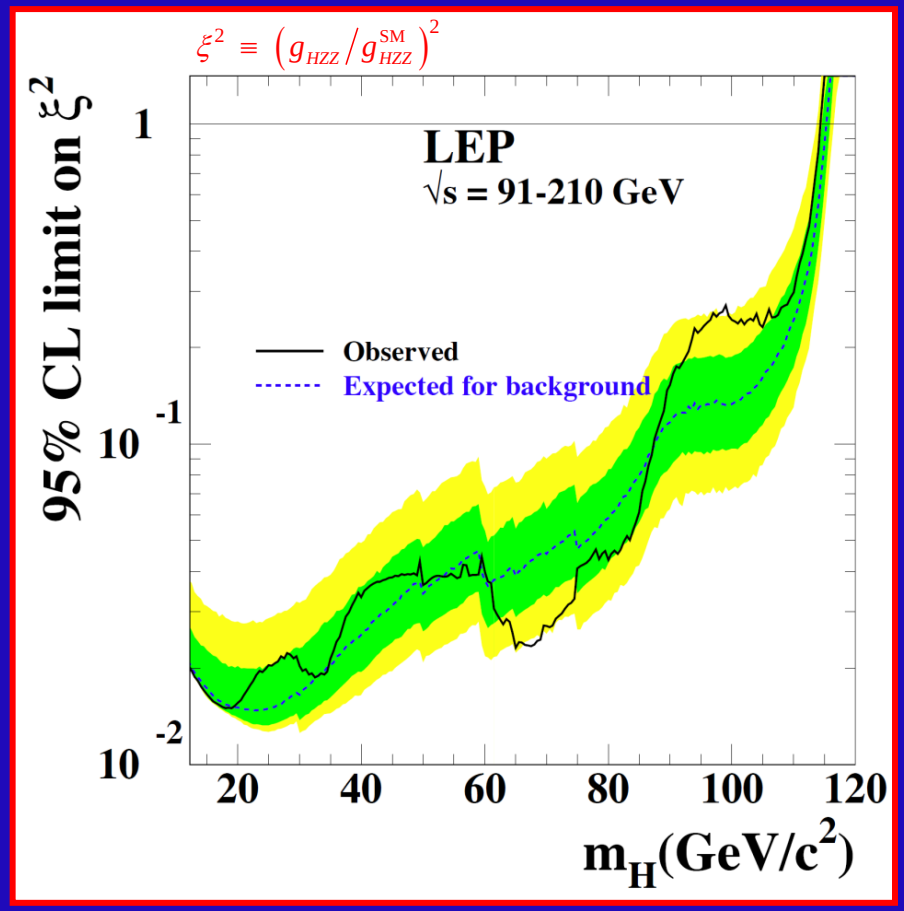
Interaction proportional to mass (M_W^2 , M_Z^2 , m_f)

The Higgs decays into the heaviest possible particles

LEP Searches



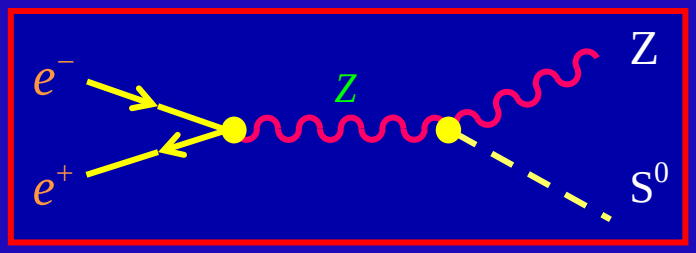
1) $H \to b\bar{b}\ ,\ Z \to q\bar{q}$
2) $H \to \tau^+\tau^-\ ,\ Z \to q\bar{q}$
   $H \to b\bar{b}\ ,\ H \to \tau^+\tau^-$
3) $H \to b\bar{b}\ ,\ Z \to \nu\bar{\nu}$
4) $H \to b\bar{b}\ ,\ Z \to e^+e^-, \mu^+\mu^-$



$M_H > 114.4$ GeV (95% CL)

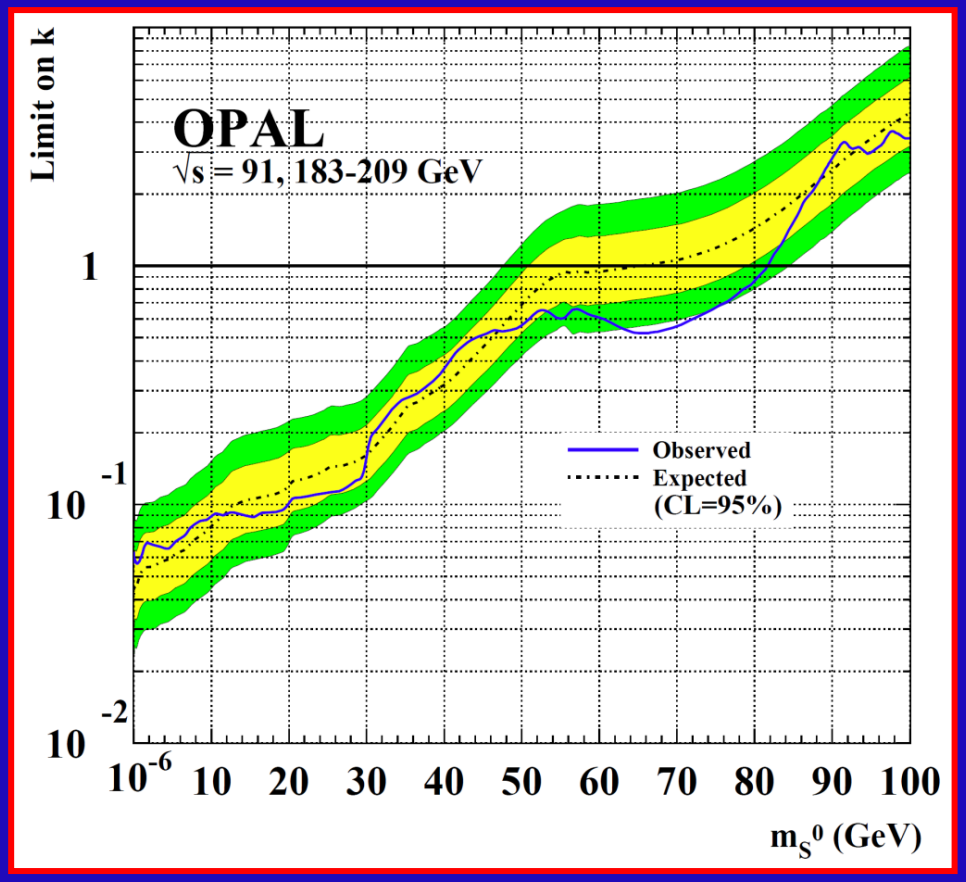
3σ excess @ 115 GeV (ALEPH)

Not seen at DELPHI, L3 and OPAL



1) $S^0 \to \text{all}\,,\ Z \to e^+e^-, \mu^+\mu^-$
2) $S^0 \to e^+e^-\,,\ Z \to \nu\bar{\nu}$

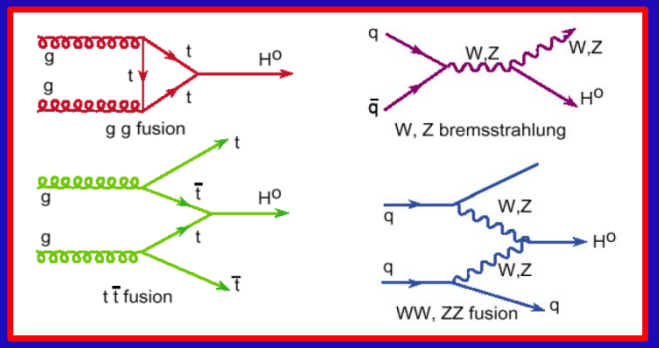
$k \equiv \sigma(e^+e^- \to Z\,S^0)/\sigma(e^+e^- \to Z\,H)_{\rm SM}$



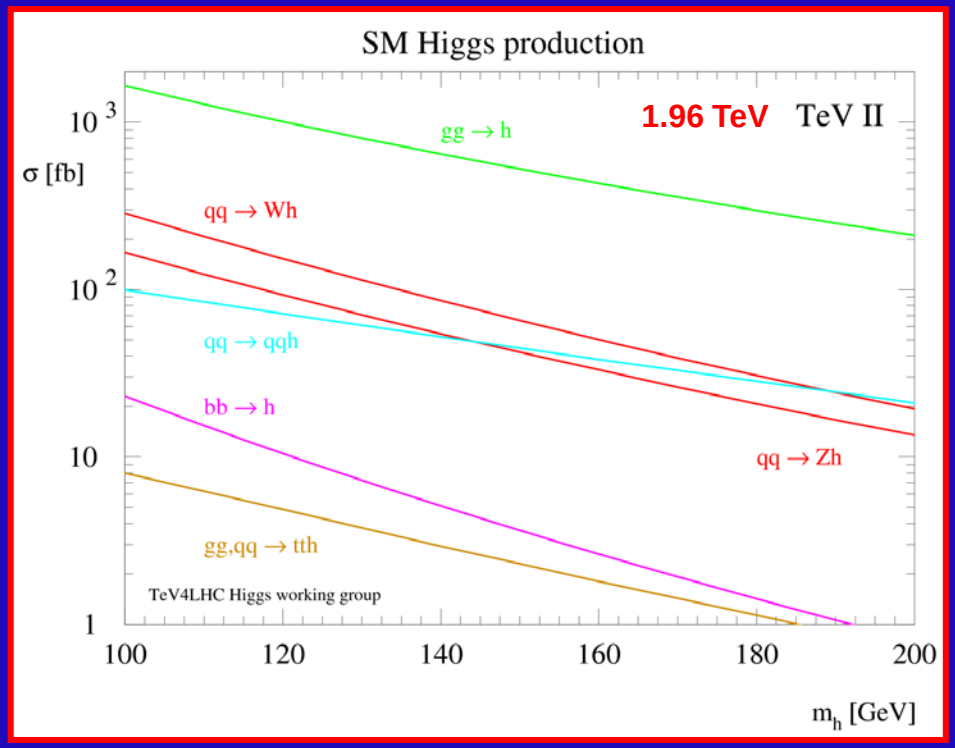
Low-mass Higgs excluded

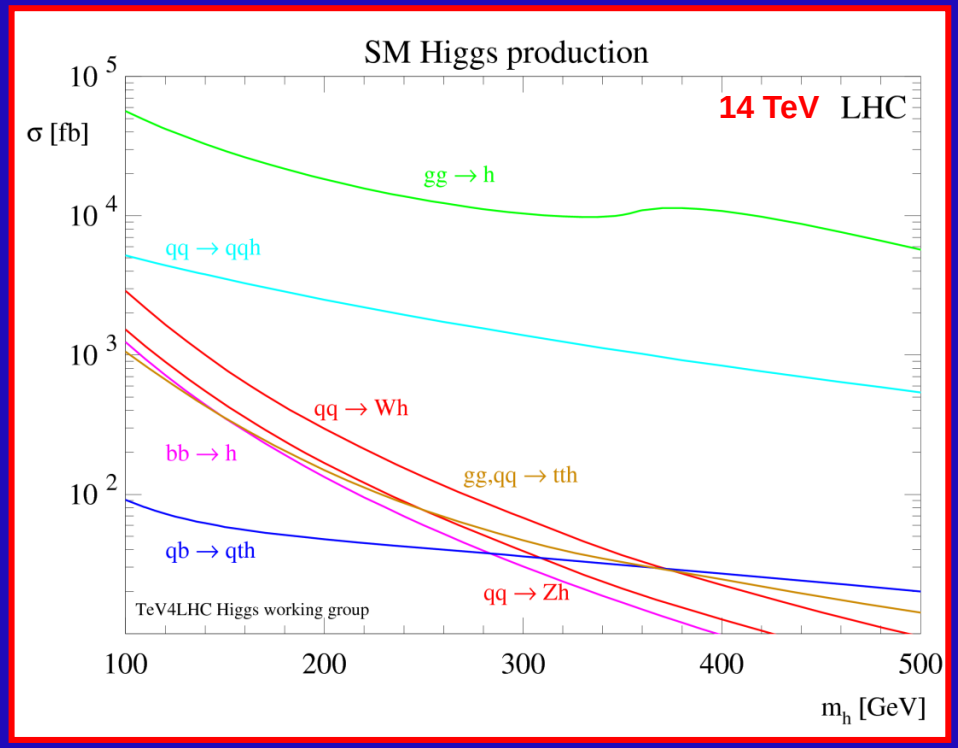
Decay-mode-independent limits

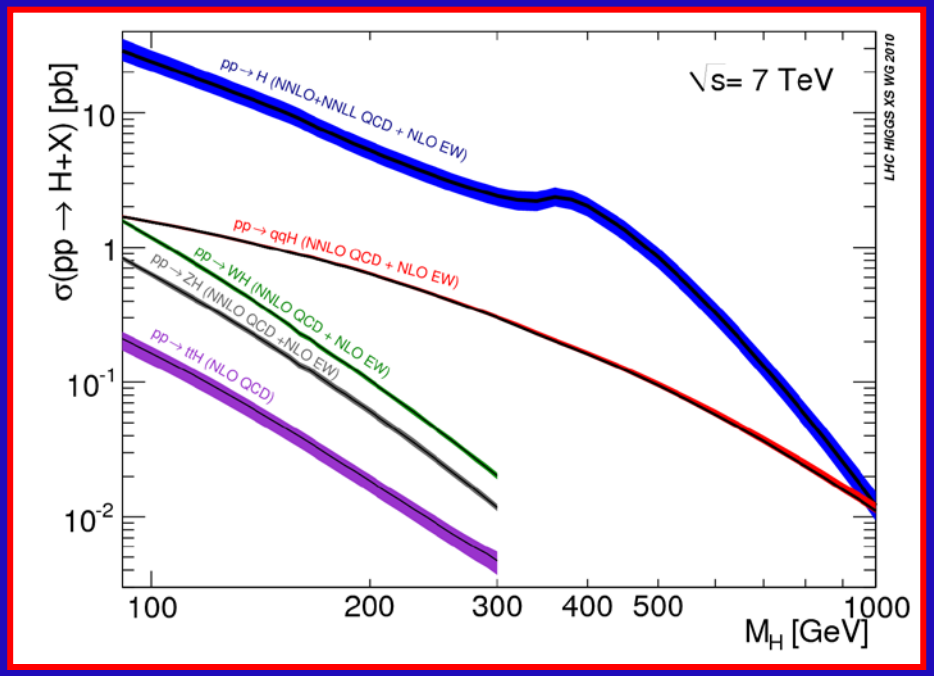
Higgs Production @ Colliders

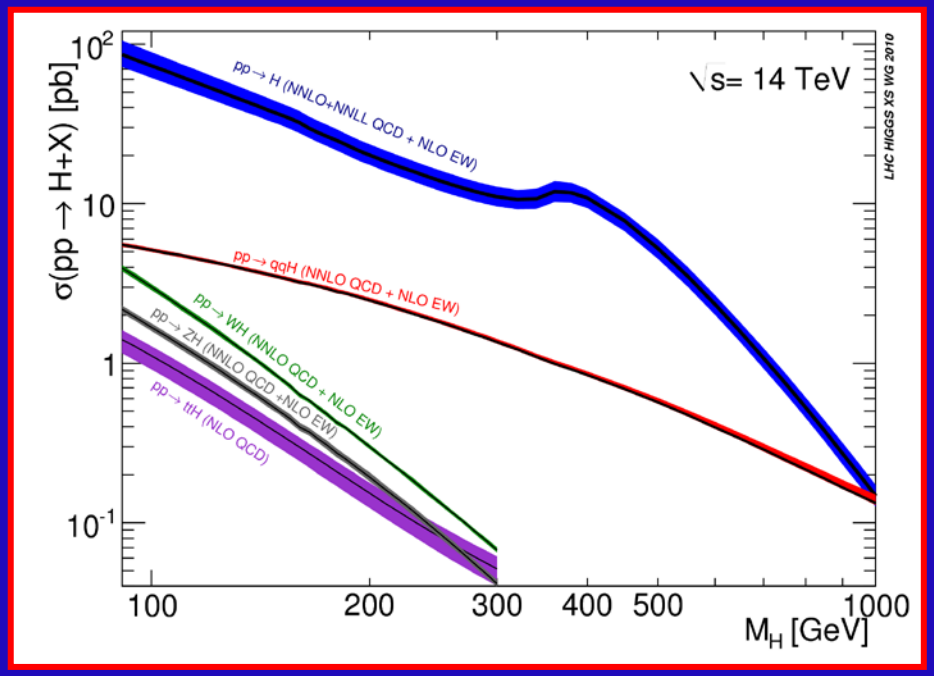


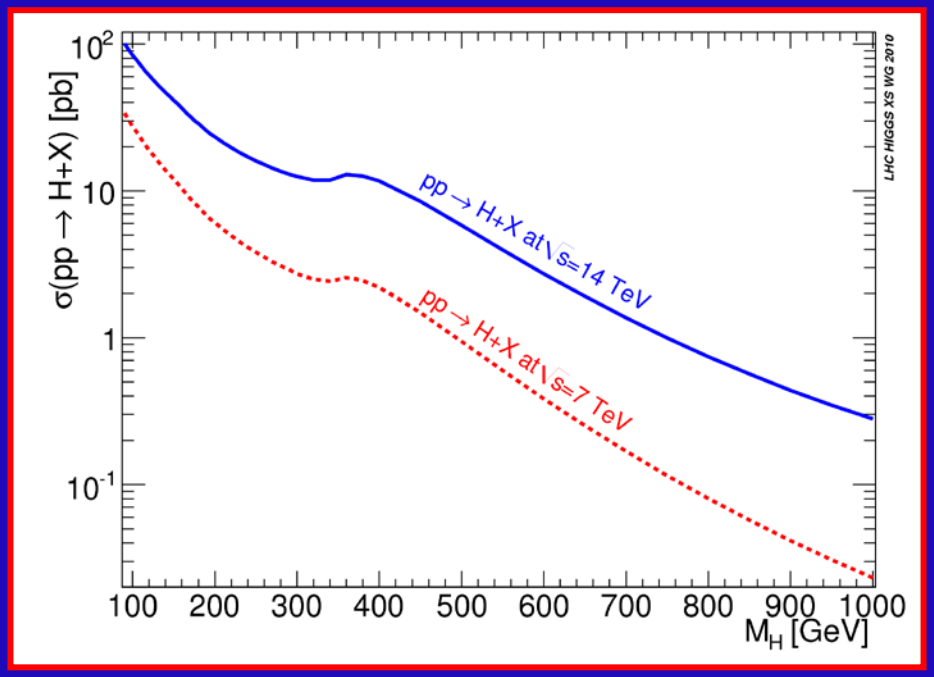
F. Maltoni






√s= 7 TeV
pp→ H (NNLO+NNLL QCD + NLO EW)
pp→ qqH (NNLO QCD + NLO EW)
pp→ WH (NNLO QCD + NLO EW)
pp→ ZH (NNLO QCD +NLO EW)
pp→ ttH (NLO QCD)
σ(pp → H+X) [pb]
M_H [GeV]
LHC HIGGS XS WG 2010


√s= 14 TeV
pp→ H (NNLO+NNLL QCD + NLO EW)
pp→ qqH (NNLO QCD + NLO EW)
pp→ WH (NNLO QCD + NLO EW)
pp→ ZH (NNLO QCD +NLO EW)
pp→ ttH (NLO QCD)
σ(pp → H+X) [pb]
M_H [GeV]
LHC HIGGS XS WG 2010

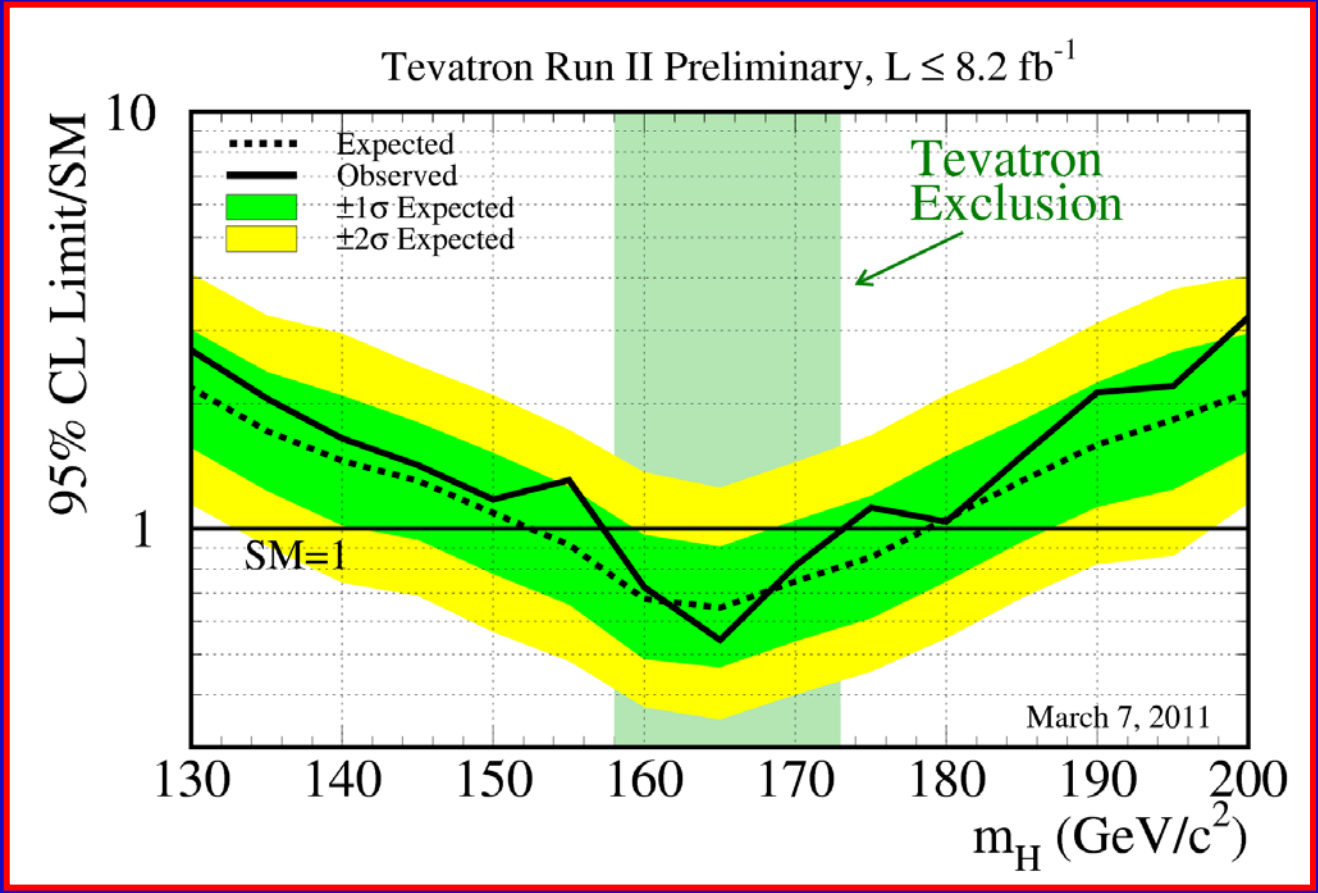

pp → H+X at √s=14 TeV
pp → H+X at √s=7 TeV
σ(pp → H+X) [pb]
M_H [GeV]
LHC HIGGS XS WG 2010

Tevatron Limits

arXiv:1103.3233

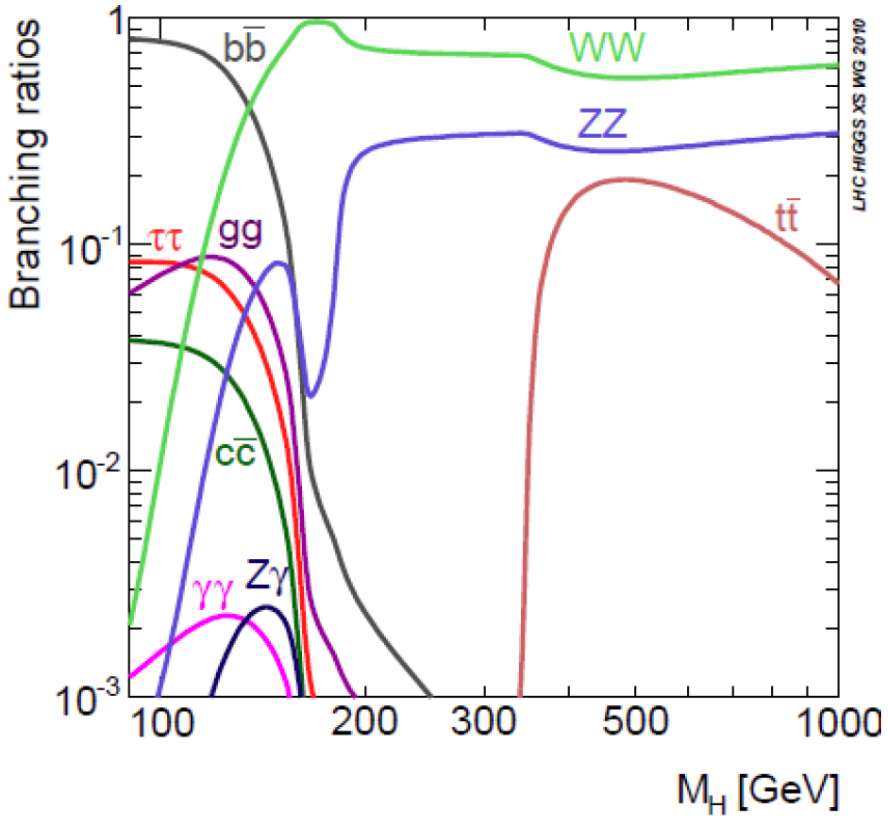
$L \leq 7.1\ fb^{-1}$ (CDF), $8.2\ fb^{-1}$ (D0)

$H \to W^+W^-$



$M_H \notin [158,173]$ GeV (95% CL)

SM Higgs Search Channels



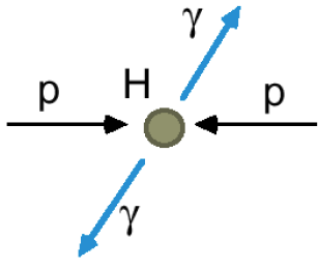
Channels included	Higgs mass range used in analyses (GeV)
H→γγ	115-150
VBF H→ττ	115-145
VH, H→bb (highly boosted)	115-125
VH, H→WW→lνjj	130-200
H→WW→2l2ν + 0/1 jets	120-600
VBF H→WW→2l2ν	130-500
H→ZZ→4l	120-600
H→ZZ→2l2ν	200-600
H→ZZ→2l2b	300-600

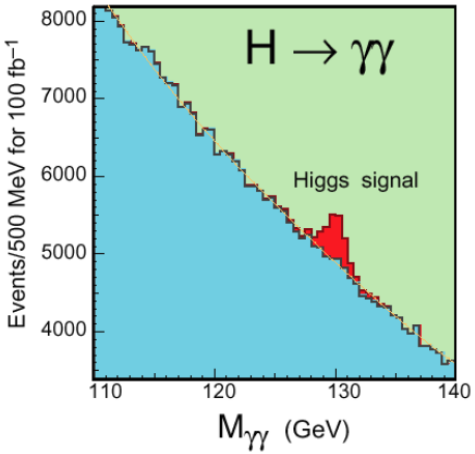
Channels with H → γγ, H → ττ, H → WW*, H → ZZ* are all used for the search

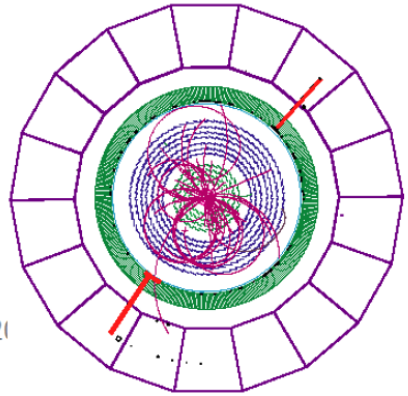
H → γγ and H → ZZ* → 4ℓ are the channels where mass can be measured with ~1% res.

SM Higgs Search Strategies - Examples

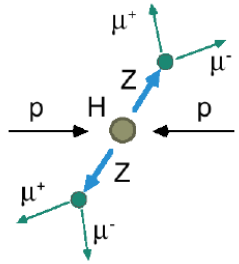
Low M_H < 140 GeV

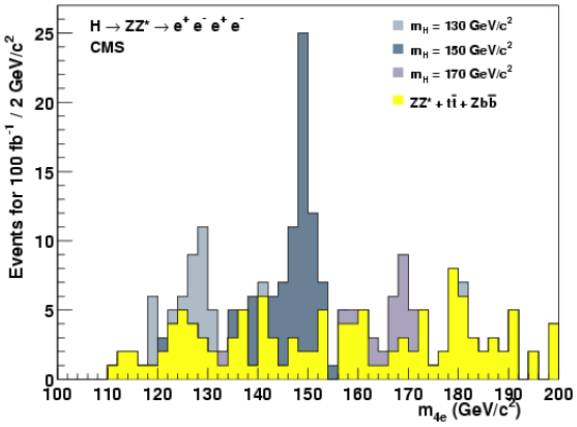


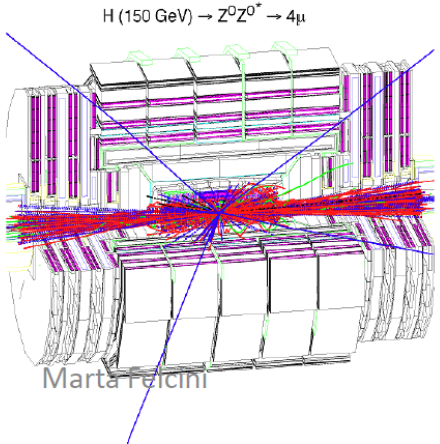




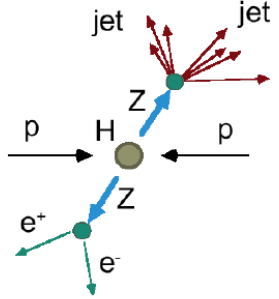
Medium 130<M_H<500 GeV/

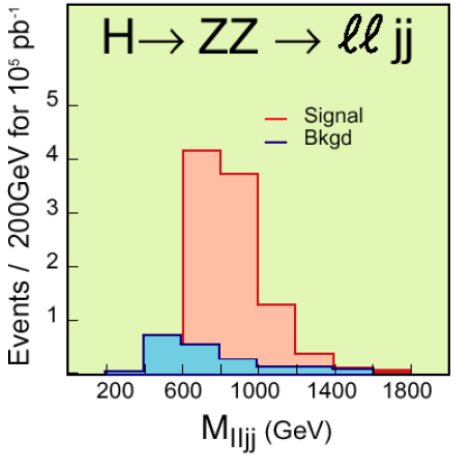


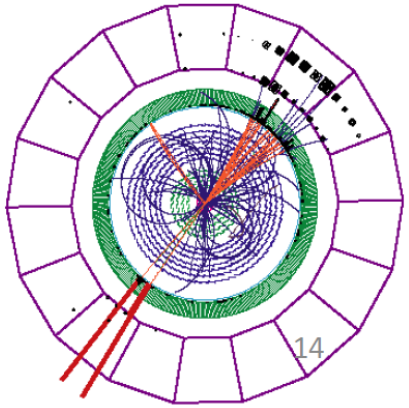




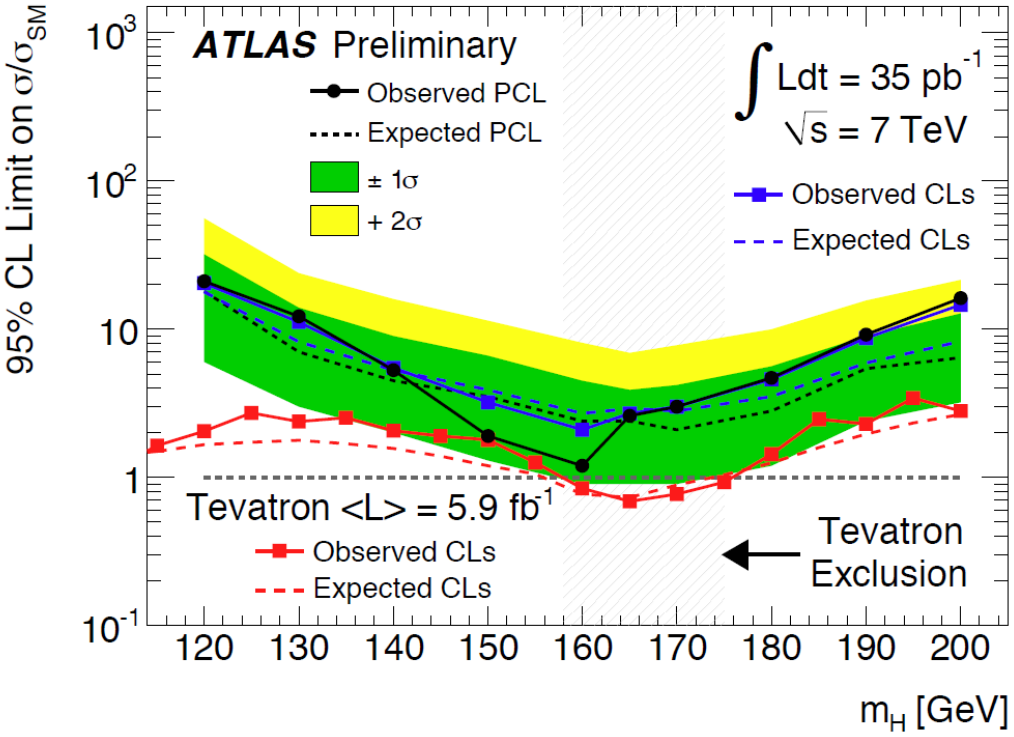
High M_H > ~500 GeV/c^2

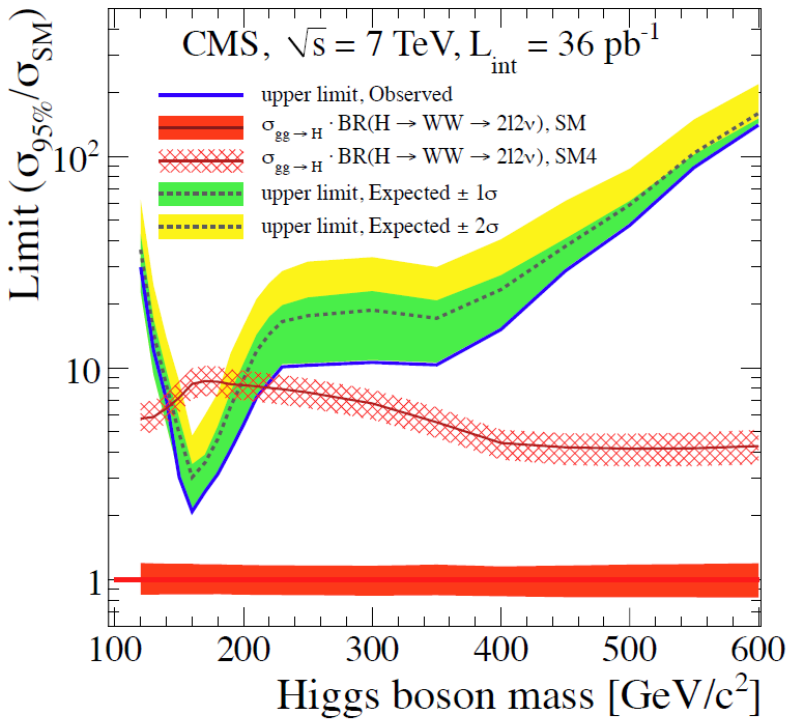






H→WW→lνlν : Exclusion Limits





⇒ At M_H=160 GeV

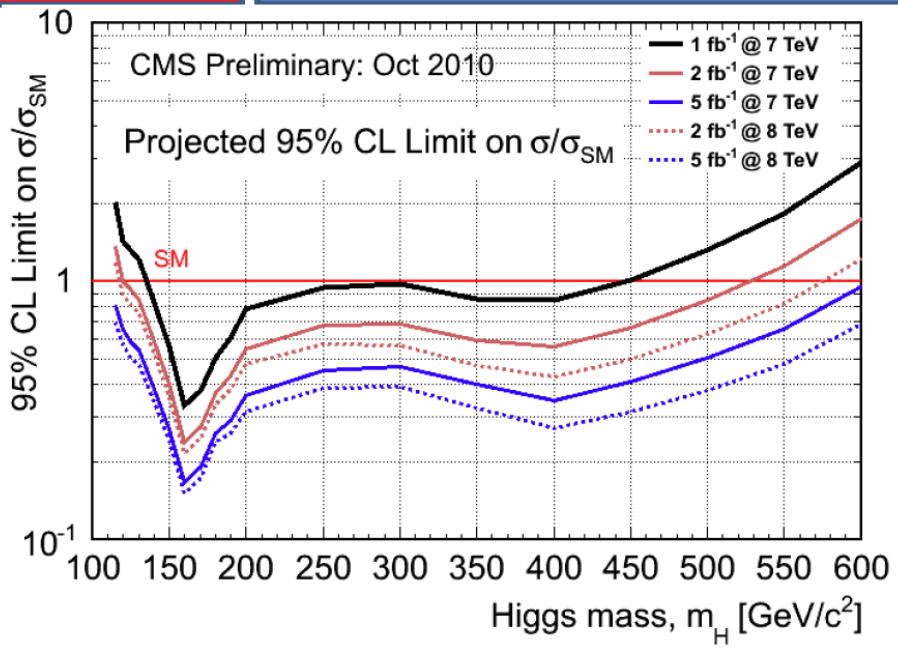
→ ATLAS excludes 2.1×σ_{SM} (obs) and 2.7×σ_{SM}(exp) CL_S

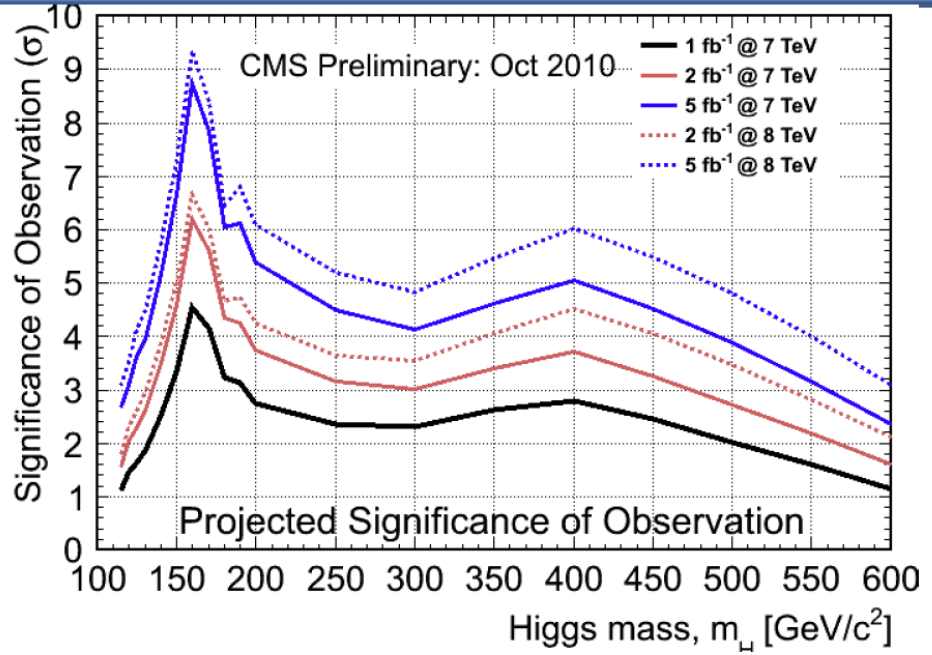
→ CMS excludes 2.1×σ_{SM} (obs) and 3.0×σ_{SM}(exp) bayesian

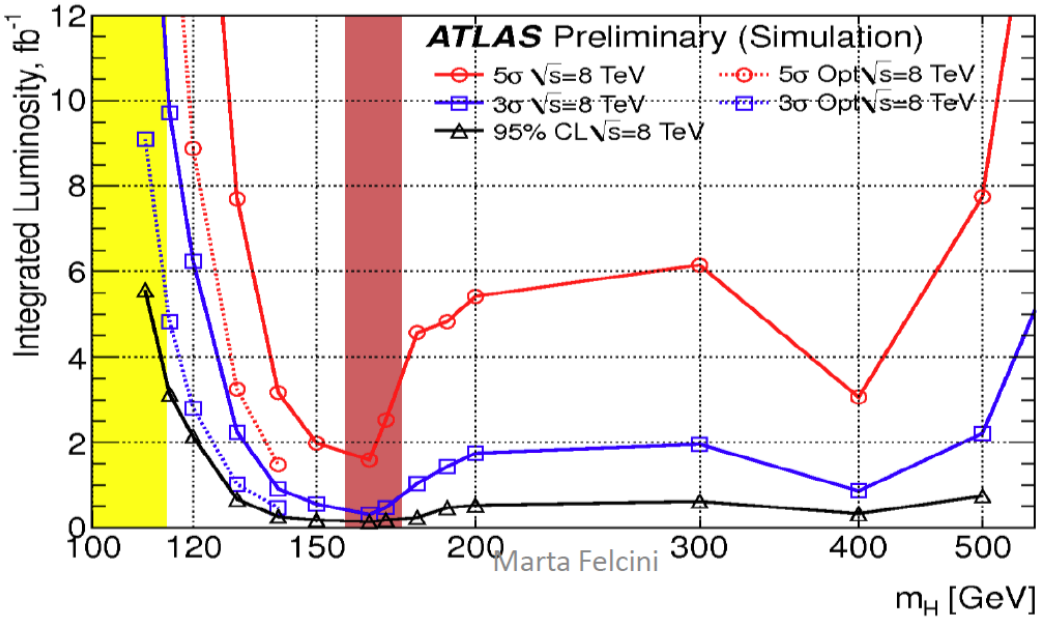
⇒ Neither experiment excludes any M_H in the Standard Model

⇒ Assuming a heavy 4th generation CMS excludes a Higgs with 144 GeV<M_H<207 GeV

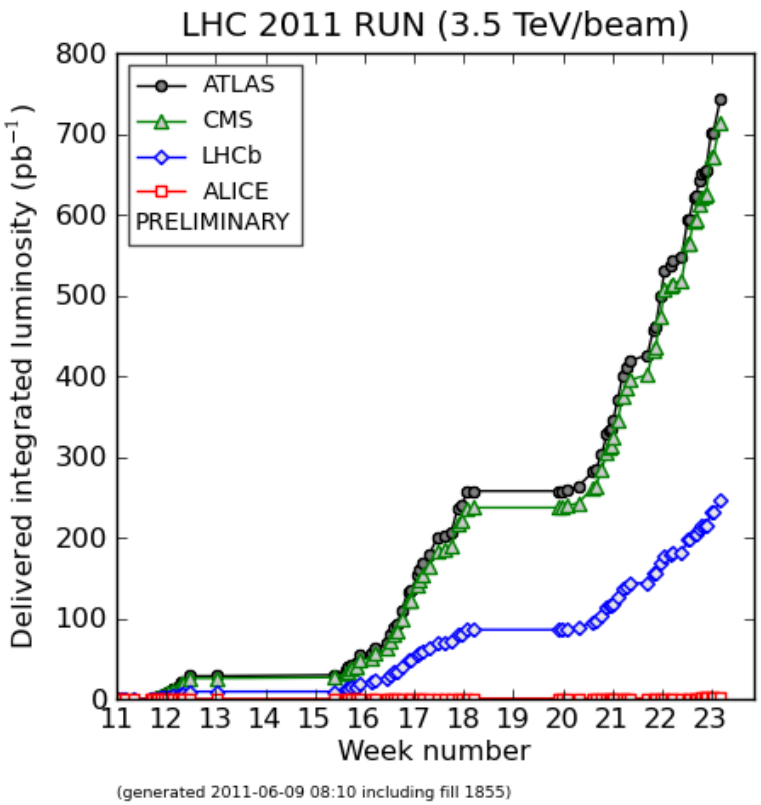
SM Higgs Search Performance at 7 TeV

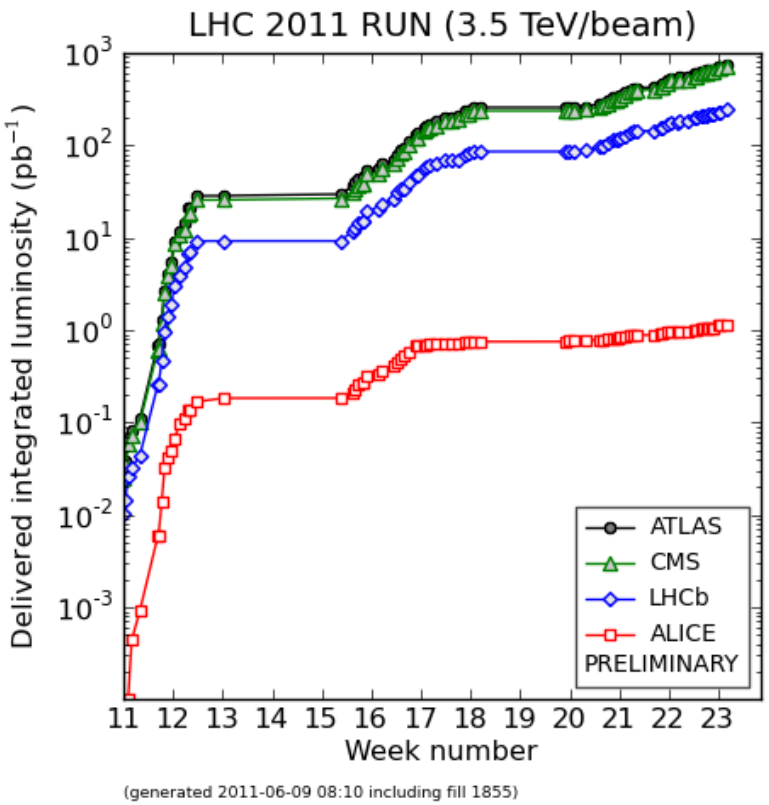






LHC Luminosity Chart



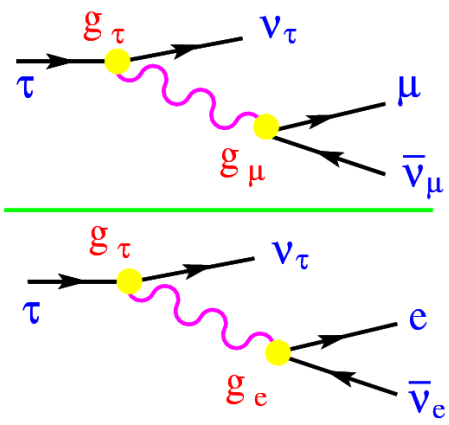


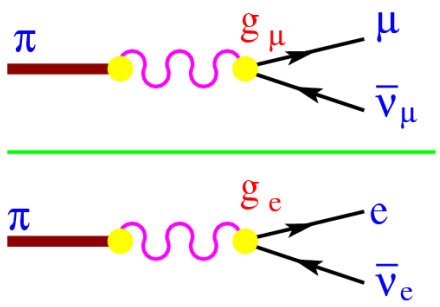
Reaching 1 fb^{-1}

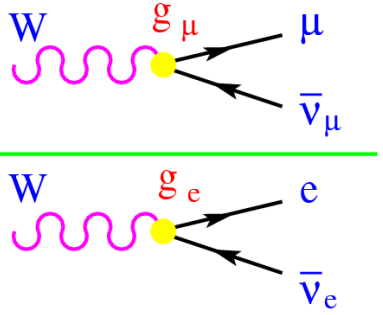
Backup Slides

LEPTON UNIVERSALITY

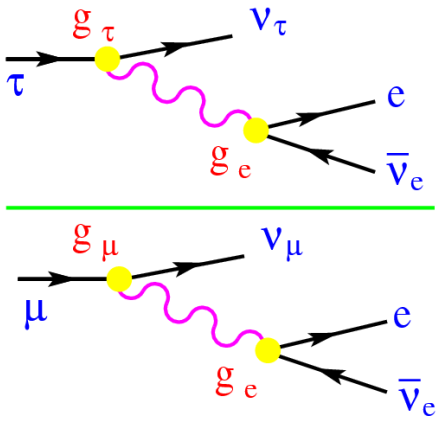
$\frac{g_\mu}{g_e}$

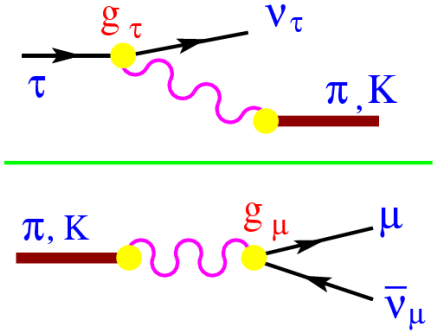


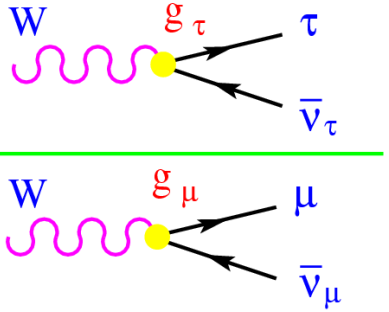




$\frac{g_\tau}{g_\mu}$







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$|g_\mu / g_e|$

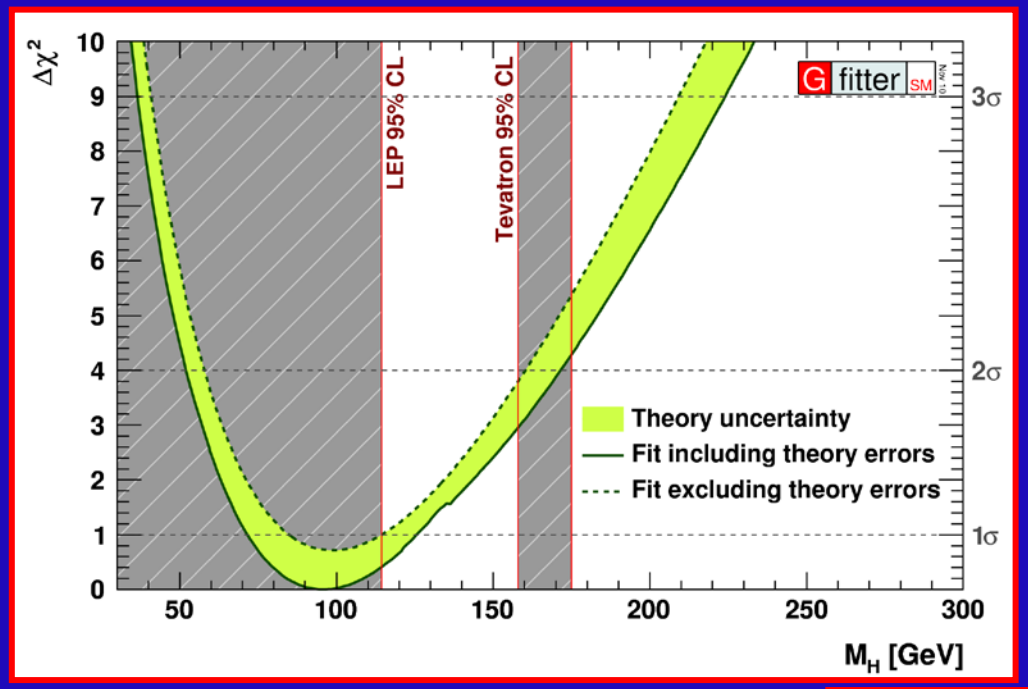
$B_{\tau\to\mu}/B_{\tau\to e}$	1.0018 ± 0.0014
$B_{\pi\to\mu}/B_{\pi\to e}$	1.0021 ± 0.0016
$B_{K\to\mu}/B_{K\to e}$	0.9978 ± 0.0024
$B_{K\to\pi\mu}/B_{K\to\pi e}$	1.0009 ± 0.0022
$B_{W\to\mu}/B_{W\to e}$	0.991 ± 0.009

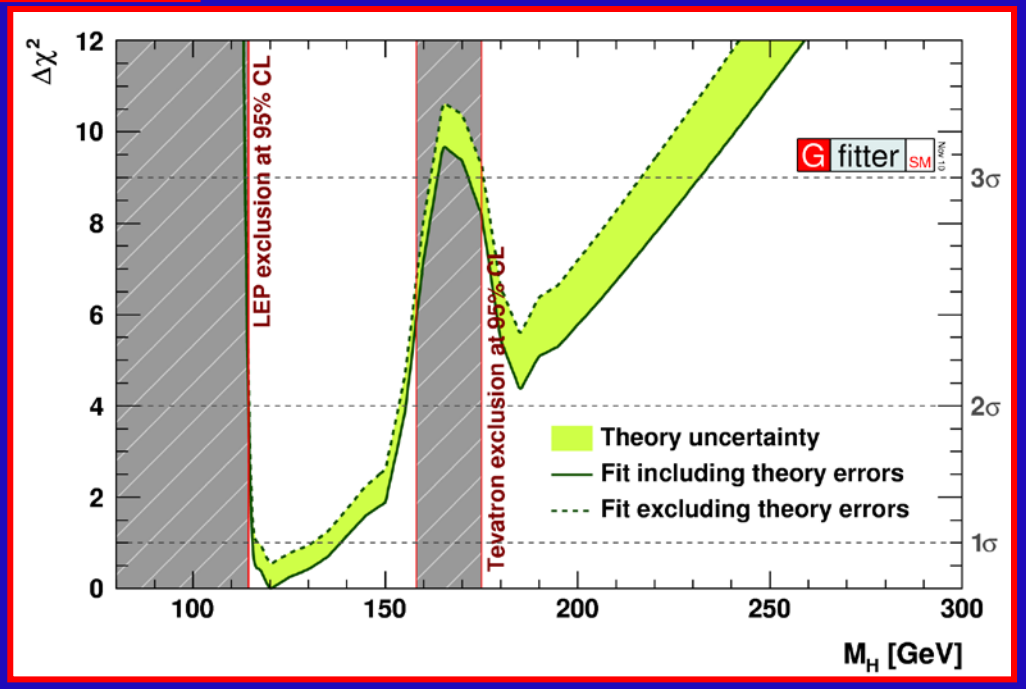
$|g_\tau / g_\mu|$

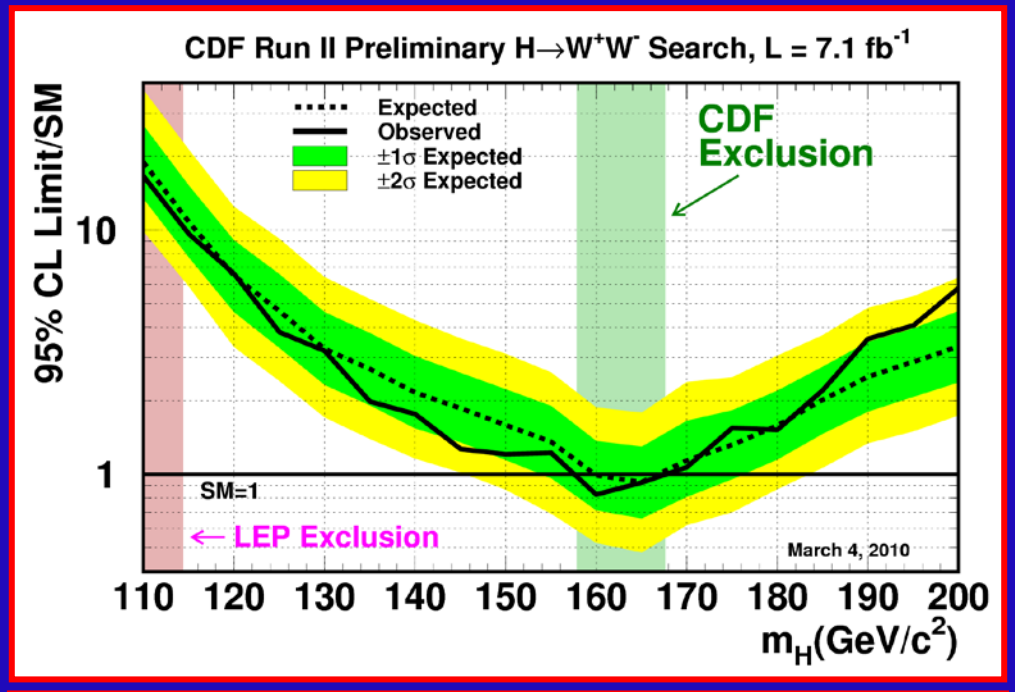
$B_{\tau\to e}\ \tau_\mu/\tau_\tau$	1.0007 ± 0.0022
$\Gamma_{\tau\to\pi}/\Gamma_{\pi\to\mu}$	0.992 ± 0.004
$\Gamma_{\tau\to K}/\Gamma_{K\to\mu}$	0.982 ± 0.008
$B_{W\to\tau}/B_{W\to\mu}$	1.032 ± 0.012

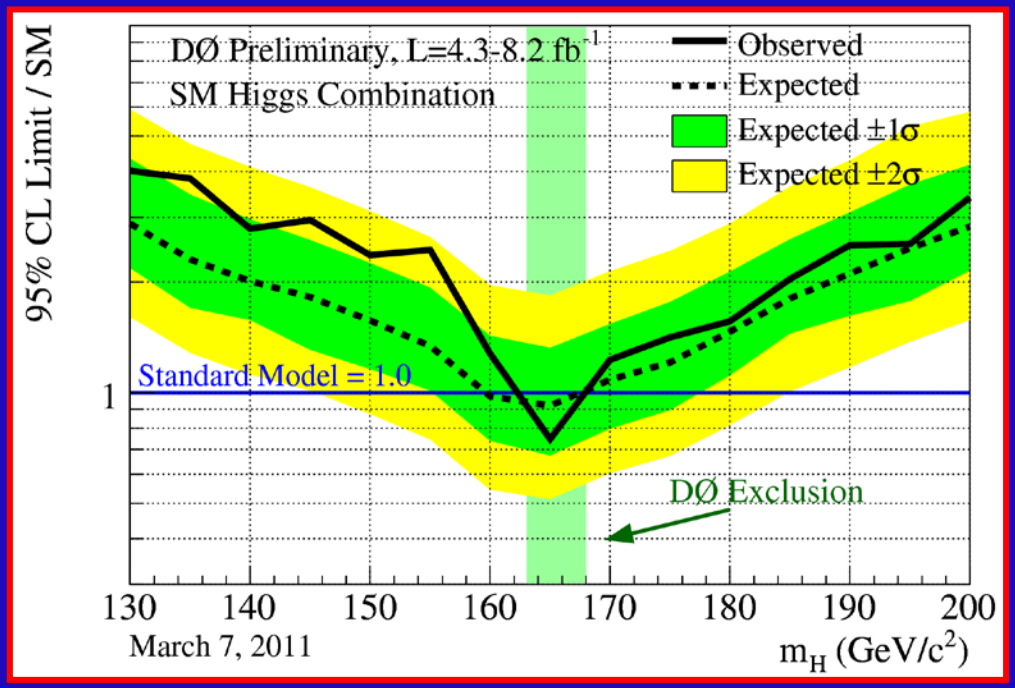
$|g_\tau / g_e|$

$B_{\tau\to\mu}\ \tau_\mu/\tau_\tau$	1.0006 ± 0.0023
$B_{W\to\tau}/B_{W\to e}$	1.023 ± 0.011

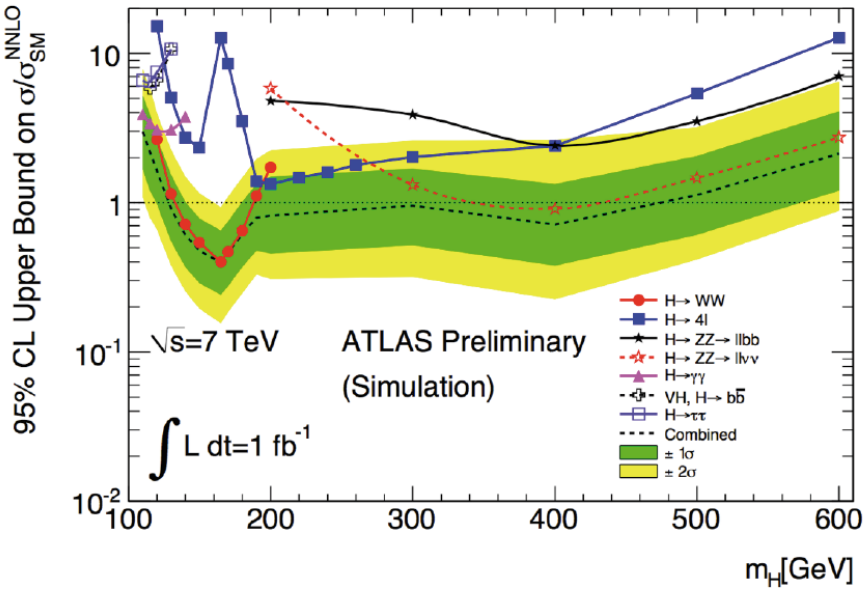

$\Delta\chi^2$
LEP 95% CL
Tevatron 95% CL
G fitter SM
Nov-10
3σ
2σ
1σ
Theory uncertainty
Fit including theory errors
Fit excluding theory errors
M_H [GeV]


$\Delta\chi^2$
LEP exclusion at 95% CL
Tevatron exclusion at 95% CL
G fitter SM
Nov-10
3σ
2σ
1σ
Theory uncertainty
Fit including theory errors
Fit excluding theory errors
M_H [GeV]


CDF Run II Preliminary H→W+W- Search, L = 7.1 fb-1
95% CL Limit/SM
Expected
Observed
±1σ Expected
±2σ Expected
CDF Exclusion
10
1
SM=1
← LEP Exclusion
March 4, 2010
110 120 130 140 150 160 170 180 190 200
mH(GeV/c2)


DØ Preliminary, L=4.3-8.2 fb-1
SM Higgs Combination
95% CL Limit / SM
Observed
Expected
Expected ±1σ
Expected ±2σ
Standard Model = 1.0
1
DØ Exclusion
130 140 150 160 170 180 190 200
March 7, 2011
mH (GeV/c2)

Higgs boson prospects for the (near) future



With ~1 fb^{-1} for EPS and 2 fb^{-1} by end of summer
for each experiment

⇒Sensitive to SM Higgs boson cross sections this summer!

If SM Higgs is not Nature's choice
we'll know by the end of this summer

Discovery more difficult →
BUT upward fluctuations may be observed!