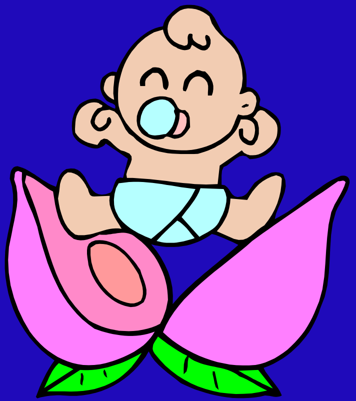
2. The Higgs Boson

- Goldstone Theorem
- Higgs Mechanism
- Higgs Properties
- Higgs Searches



SCALAR POTENCIAL

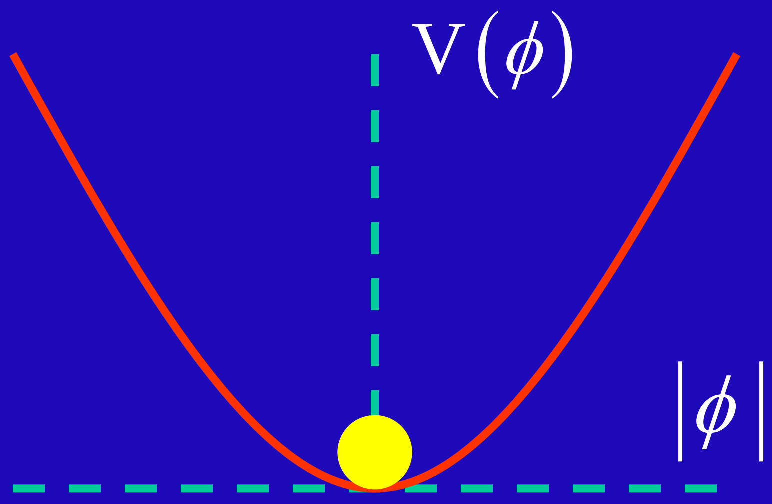
$$\mathcal{L}(\phi) = \partial_\mu \phi^\dagger \partial^\mu \phi - V(\phi)$$

$$V(\phi) = \mu^2 \, \phi^\dagger \phi + h \, (\phi^\dagger \phi)^2$$

Phase Symmetry: $\phi(x) \to e^{i\theta} \phi(x)$

$h > 0 \quad ; \quad \mu^2 > 0$

$M_\phi = \mu$



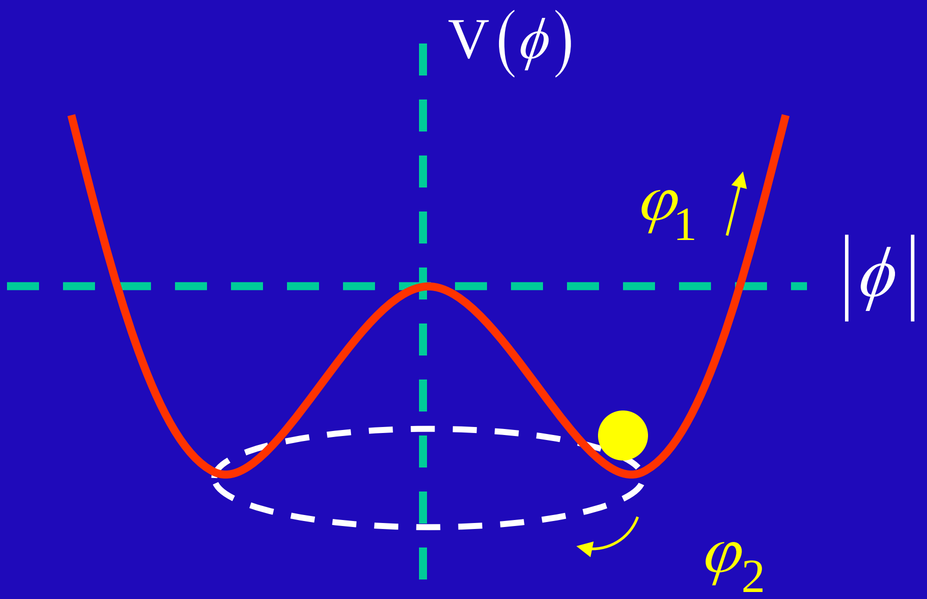
Trivial Minimum (Ground State / Vacuum): $\phi = \phi_0 = 0$

$$\mathrm{V}(\phi) = \mu^2\, \phi^\dagger \phi + h\, (\phi^\dagger \phi)^2$$

Phase Symmetry:

$$\phi(x) \to \mathrm{e}^{i\theta}\, \phi(x)$$

$$\mu^2 < 0$$



Degenerate Minima

(Ground State / Vacuum)

$$|\phi_0| = \sqrt{\frac{-\mu^2}{2h}} \equiv \frac{\mathrm{v}}{\sqrt{2}} > 0 \quad ; \quad V(\phi_0) = -\frac{1}{4} h\, \mathrm{v}^4$$

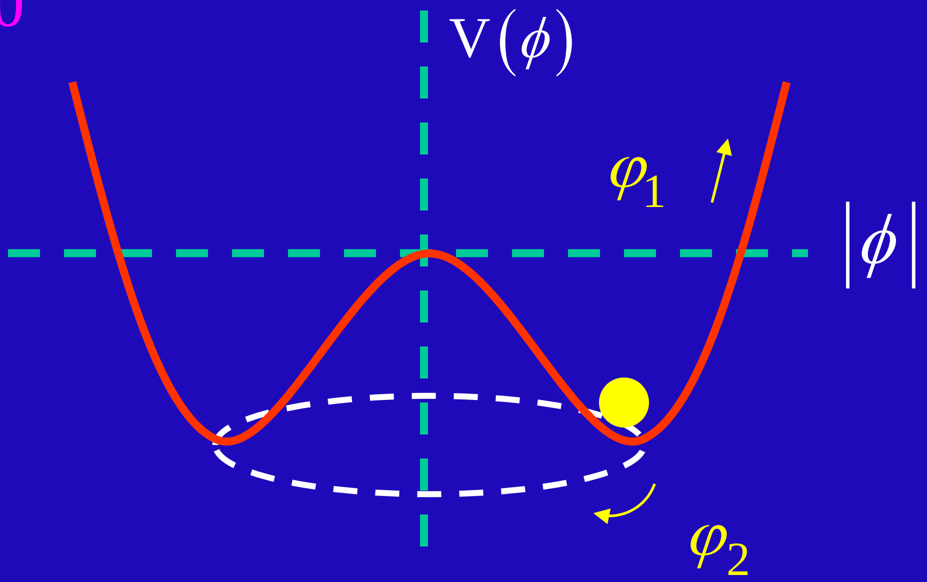
Spontaneous Symmetry Breaking:

$$\phi \equiv \frac{1}{\sqrt{2}} \left[\mathrm{v} + \varphi_1(x)\right] \mathrm{e}^{i\,\varphi_2(x)/\mathrm{v}}$$

Vacuum Choice

Spontaneous Symmetry Breaking

$\mu^2 < 0$



$$\phi \equiv \frac{1}{\sqrt{2}}\left[\mathrm{v} + \varphi_1(x)\right]\, e^{i\varphi_2(x)/\mathrm{v}}$$

$$\mathcal{L}(\phi) = \frac{1}{2}\partial_\mu\varphi_1\,\partial^\mu\varphi_1 + \frac{1}{2}\left(1+\frac{\varphi_1}{\mathrm{v}}\right)^2 \partial_\mu\varphi_2\,\partial^\mu\varphi_2 - V(\phi)$$

$$V(\phi) = V(\phi_0) + \frac{1}{2}M^2_{\varphi_1}\,\varphi_1^2 + h\,\mathrm{v}\,\varphi_1^3 + \frac{1}{4}h\,\varphi_1^4$$

$$M^2_{\varphi_1} = -2\mu^2 > 0 \quad ; \quad M^2_{\varphi_2} = 0$$

1 Massless Goldstone Boson

ELECTROWEAK SSB

New Scalar Doublet
$$\phi(x) \equiv \begin{pmatrix} \phi^{(+)}(x) \\ \phi^{(0)}(x) \end{pmatrix} \quad ; \quad y_\phi = Q_\phi - T_3 = \frac{1}{2}$$

$$\mathcal{L}(\phi) = (\mathbf{D}_\mu \phi)^\dagger \, \mathbf{D}^\mu \phi - \mu^2 \, \phi^\dagger \phi - h \, (\phi^\dagger \phi)^2$$

$$\mathbf{D}^\mu \phi = \left[\partial^\mu + i\, g\, \mathbf{W}^\mu + i\, g'\, y_\phi\, B^\mu\right] \phi \quad ; \quad \mathbf{W}^\mu = \frac{\vec{\tau}}{2} \cdot \vec{W}^\mu$$

$SU(2)_L \otimes U(1)_Y$ Symmetry

Degenerate Vacuum States:
$(\mu^2 < 0 \;,\; h > 0)$

$$\left|\langle 0 | \phi^{(0)} | 0 \rangle\right| = \sqrt{\frac{-\mu^2}{2h}} \equiv \frac{v}{\sqrt{2}}$$

Spontaneous Symmetry Breaking:
$$\phi(x) = \exp\left\{ i \frac{\vec{\tau}}{2} \cdot \vec{\theta}(x) \right\} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

HIGGS MECHANISM

$$\phi(x) = \exp\left\{ i \frac{\vec{\tau}}{2} \cdot \vec{\theta}(x) \right\} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \mathrm{v} + H(x) \end{pmatrix}$$

$\mathrm{SU(2)_L}$ Invariance ➡ $\vec{\theta}(x)$ can be gauged away

Unitary Gauge: $\vec{\theta}(x) = 0$

$$(\mathrm{D}_\mu \phi)^\dagger \mathrm{D}^\mu \phi \quad \to \quad \frac{1}{2} \partial_\mu H \, \partial^\mu H + \frac{g^2}{4} (\mathrm{v} + H)^2 \left\{ W_\mu^\dagger W^\mu + \frac{1}{2 \cos^2 \theta_W} Z_\mu Z^\mu \right\}$$

➡ $$M_Z \cos\theta_W = M_W = \frac{1}{2} \mathrm{v} \, g$$

Massive Gauge Bosons

Bosonic Degrees of Freedom

Massless $W^{\pm}\,,\ Z$

3 x 2 polarizations **= 6**

+

3 Goldstones $\vec{\theta}$

SSB ↓

Massive $W^{\pm}\,,\ Z$

3 x 3 polarizations **= 9**

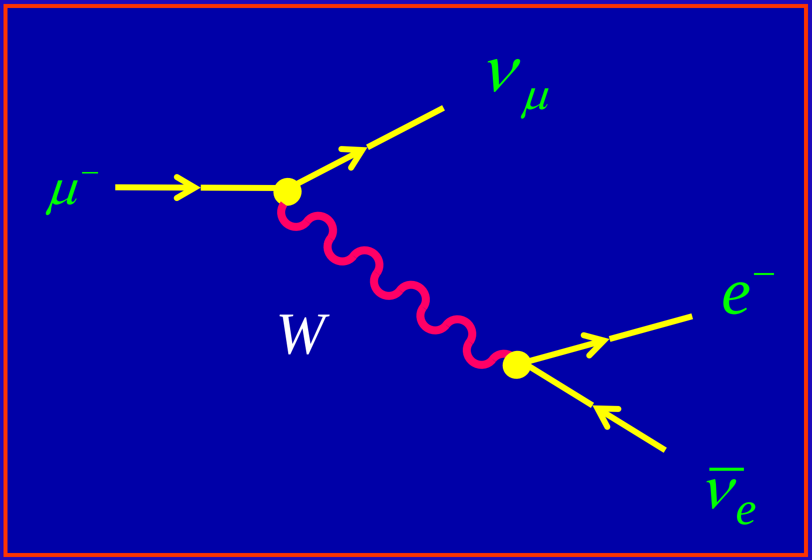
SAME PHYSICS

$$M_Z \cos\theta_W = M_W = \frac{1}{2}\, \mathrm{v}\, g$$

$$M_Z = 91.1875 \ \text{GeV} \ > \ M_W = 80.399 \ \text{GeV} \ \Rightarrow \ \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} = 0.223$$

$$\frac{g^2}{M_W^2 - q^2} \approx \frac{g^2}{M_W^2} \equiv 4\sqrt{2}\, G_F$$

$$\frac{1}{\tau_\mu} \equiv \Gamma = \frac{G_F^2\, m_\mu^5}{192\,\pi^3}$$



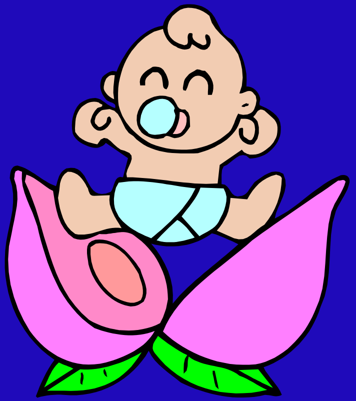
$$G_F = 1.16637 \times 10^{-5} \ \text{GeV}^{-2}$$

$$g = \frac{e}{\sin\theta_W} \quad , \quad M_W$$

$$\Rightarrow \quad \sin^2\theta_W = 0.215$$

$$\mathrm{v} = \left(\sqrt{2}\, G_F\right)^{-1/2} = 246 \ \text{GeV}$$

THE HIGGS BOSON



$$\mathcal{L}_S = \frac{h\,\mathrm{v}^4}{4} + \mathcal{L}_H + \mathcal{L}_{HG^2}$$

$$\mathcal{L}_H = \frac{1}{2}\partial_\mu H\,\partial^\mu H - \frac{1}{2} M_H^2\, H^2 - \frac{M_H^2}{2\mathrm{v}}\, H^3 - \frac{M_H^2}{8\mathrm{v}^2}\, H^4$$

$$\mathcal{L}_{HG^2} = \left[M_W^2\, W_\mu^\dagger W^\mu + \frac{1}{2} M_Z^2\, Z_\mu Z^\mu \right] \left\{ 1 + \frac{2}{\mathrm{v}} H + \frac{H^2}{\mathrm{v}^2} \right\}$$

1 Scalar Particle H^0 to be Discovered

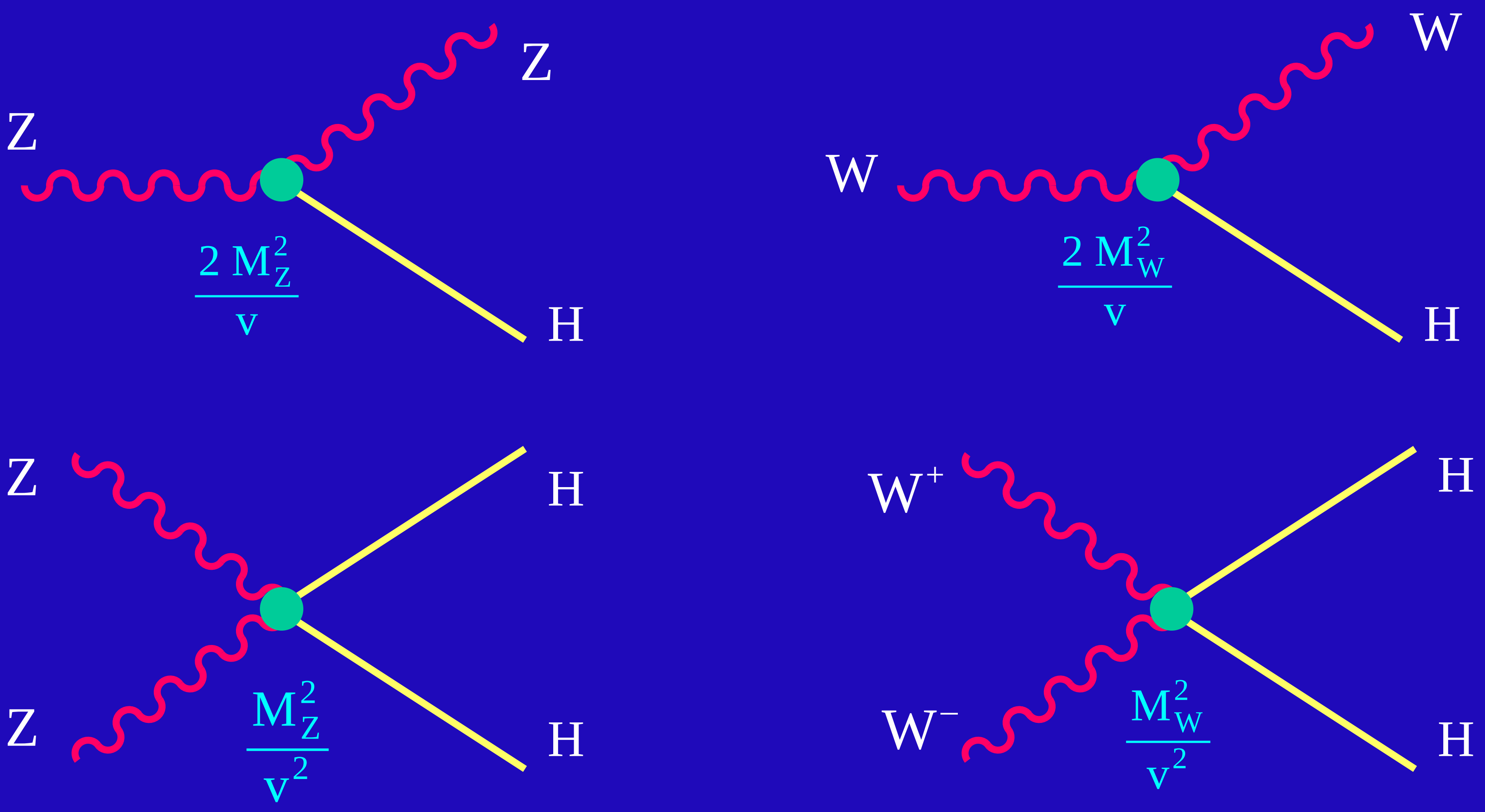
$$M_H = \sqrt{-2\mu^2} = \sqrt{2h}\,\mathrm{v}$$

Free Parameter

LEP: $114.4\ \mathrm{GeV} < M_H < 158\ \mathrm{GeV}$ (95% CL)

(Direct) (Indirect)

Higgs Couplings ∝ Masses



$$v = \left(\sqrt{2}\, G_F\right)^{-1/2} = 246 \quad \text{GeV}$$

FERMION MASSES

Scalar – Fermion Couplings allowed by Gauge Symmetry

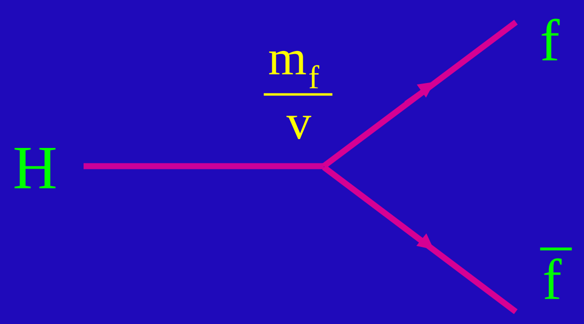
$$\mathcal{L}_Y = (\bar{q}_u\,,\bar{q}_d)_L \left[c^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} (q_d)_R + c^{(u)} \begin{pmatrix} \phi^{(0)\dagger} \\ -\phi^{(+)\dagger} \end{pmatrix} (q_u)_R \right] + (\bar{\nu}_l, \bar{l}\,)_L \; c^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} l_R + \text{h.c.}$$

SSB

$$\mathcal{L}_Y = -\left(1 + \frac{H}{\mathrm{v}}\right) \left\{ m_{q_d}\; \bar{q}_d\, q_d + m_{q_u}\; \bar{q}_u\, q_u + m_l\; \bar{l}\, l \right\}$$

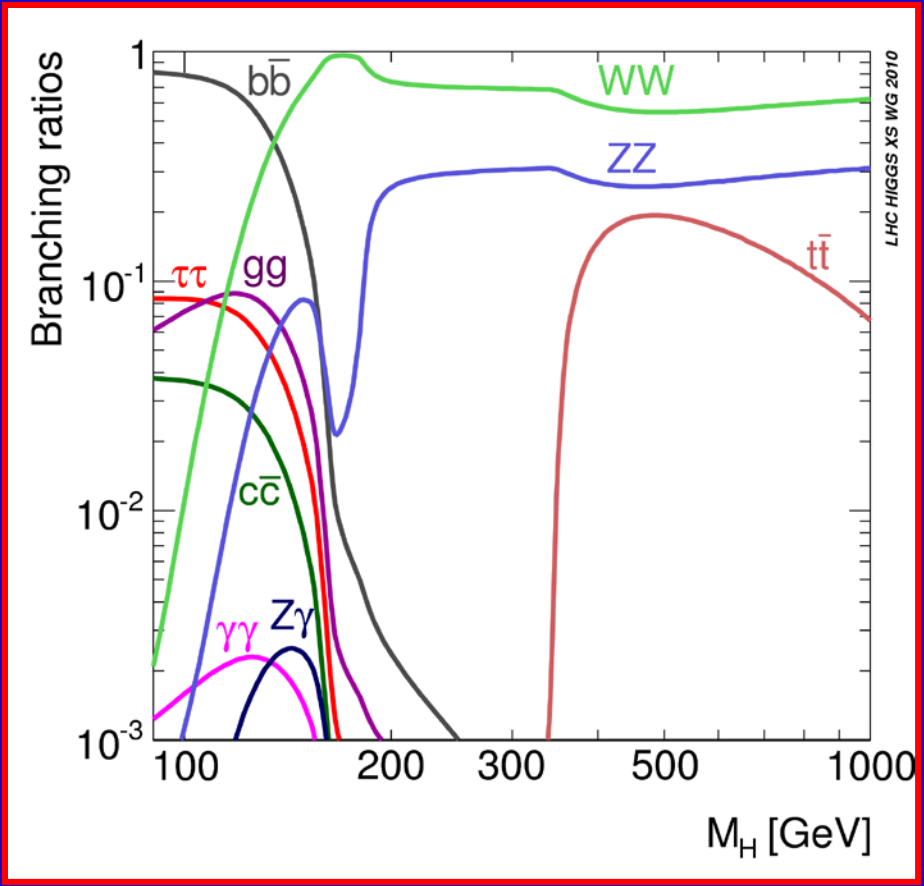
Fermion Masses are New Free Parameters

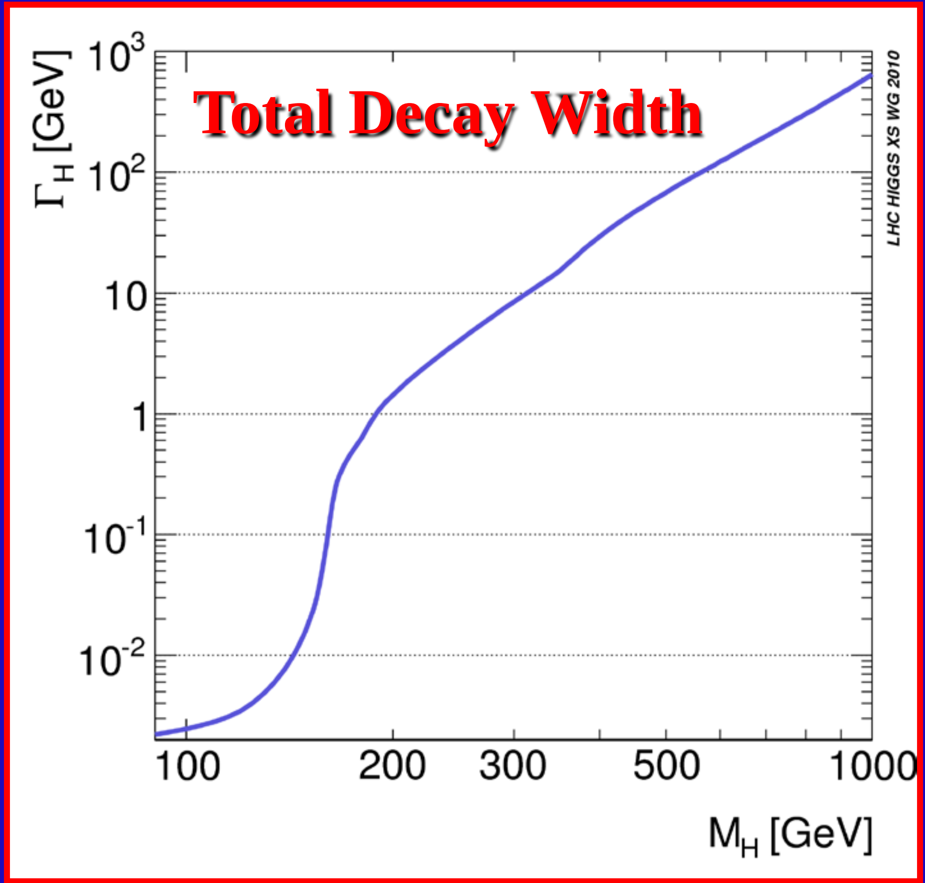
$$\left[m_{q_d}\,,\; m_{q_u}\,,\; m_l \right] = -\left[c^{(d)}\,,\; c^{(u)}\,,\; c^{(l)} \right] \frac{\mathrm{v}}{\sqrt{2}}$$



Couplings Fixed: $$g_{Hf\bar{f}} = \frac{m_f}{\mathrm{v}}$$

Searching for the HIGGS

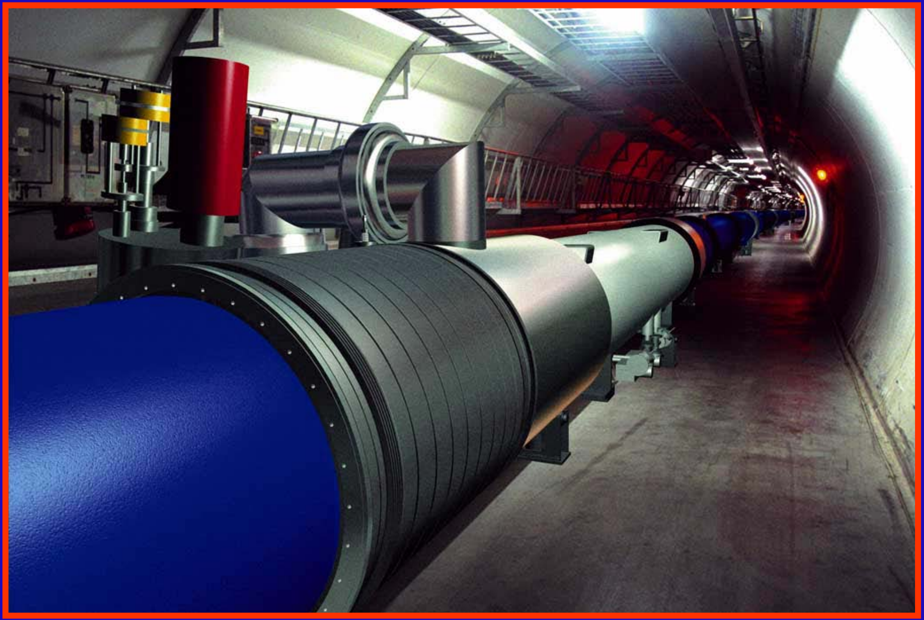


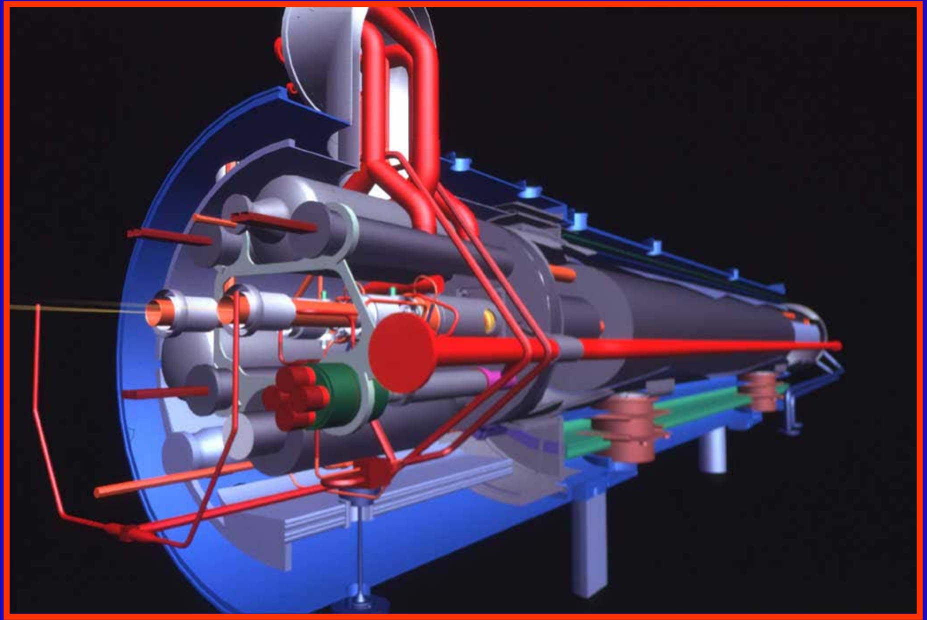


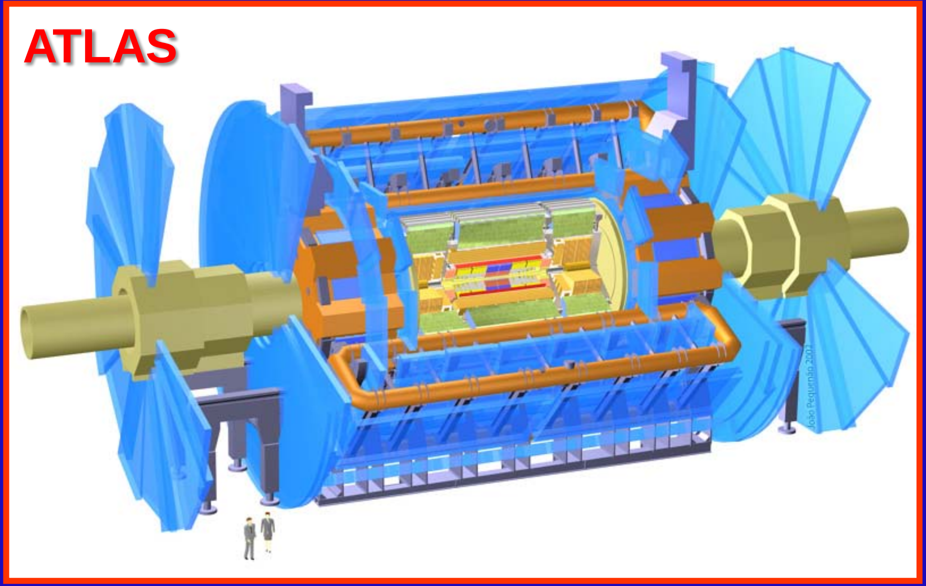
Interaction proportional to mass $(M_W^2\,,M_Z^2\,,m_f)$

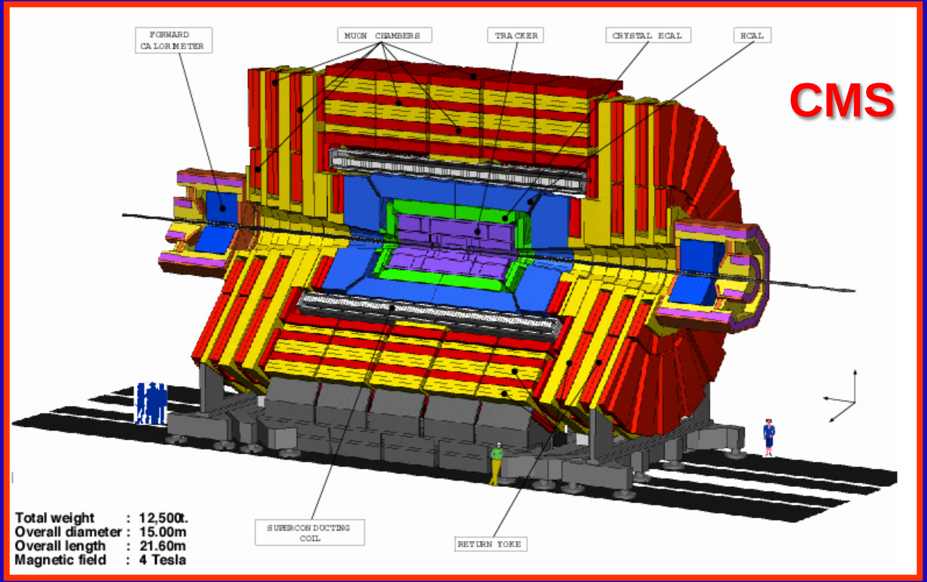
The Higgs decays into the heaviest possible particles

The Large Hadron Collider

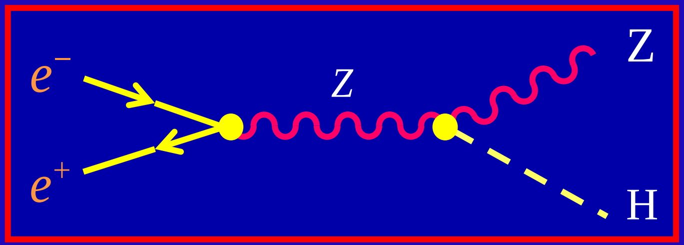




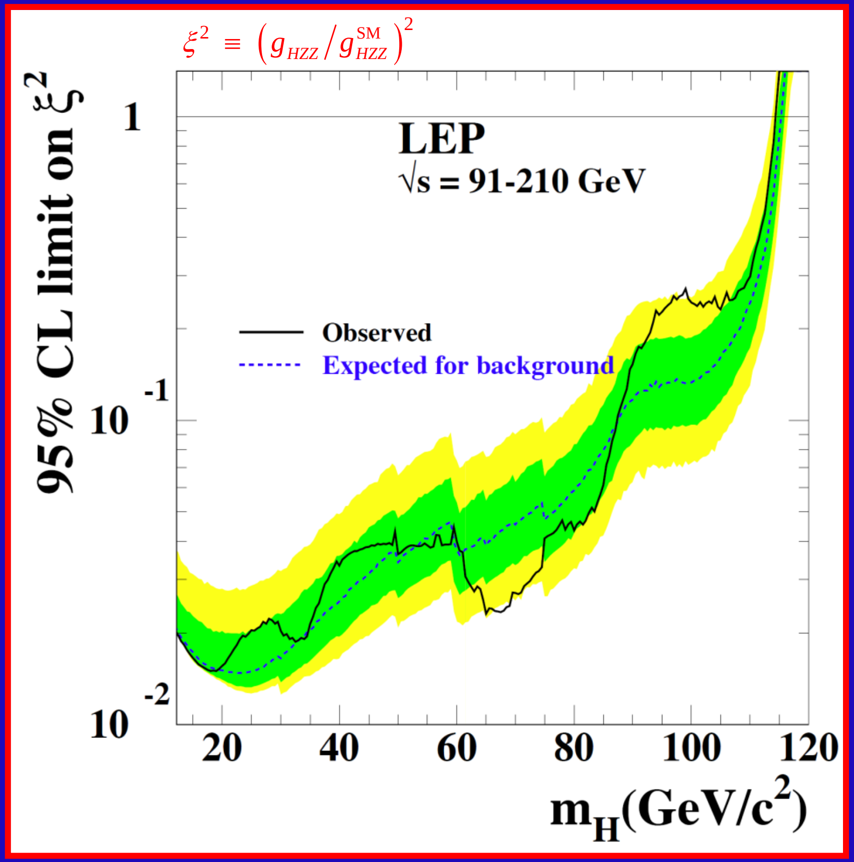




LEP Searches



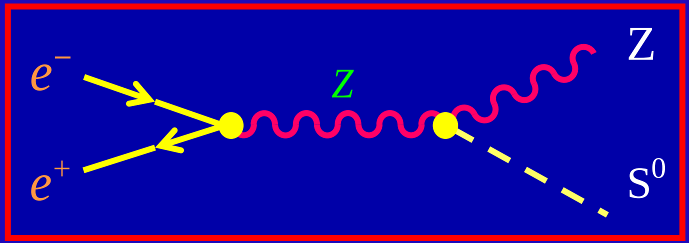
1) $H \to b\bar{b}\ ,\ Z \to q\bar{q}$
2) $H \to \tau^+\tau^-\ ,\ Z \to q\bar{q}$
   $H \to b\bar{b}\ ,\ H \to \tau^+\tau^-$
3) $H \to b\bar{b}\ ,\ Z \to \nu\bar{\nu}$
4) $H \to b\bar{b}\ ,\ Z \to e^+e^-, \mu^+\mu^-$



M_H > 114.4 GeV (95% CL)

3σ excess @ 115 GeV (ALEPH)

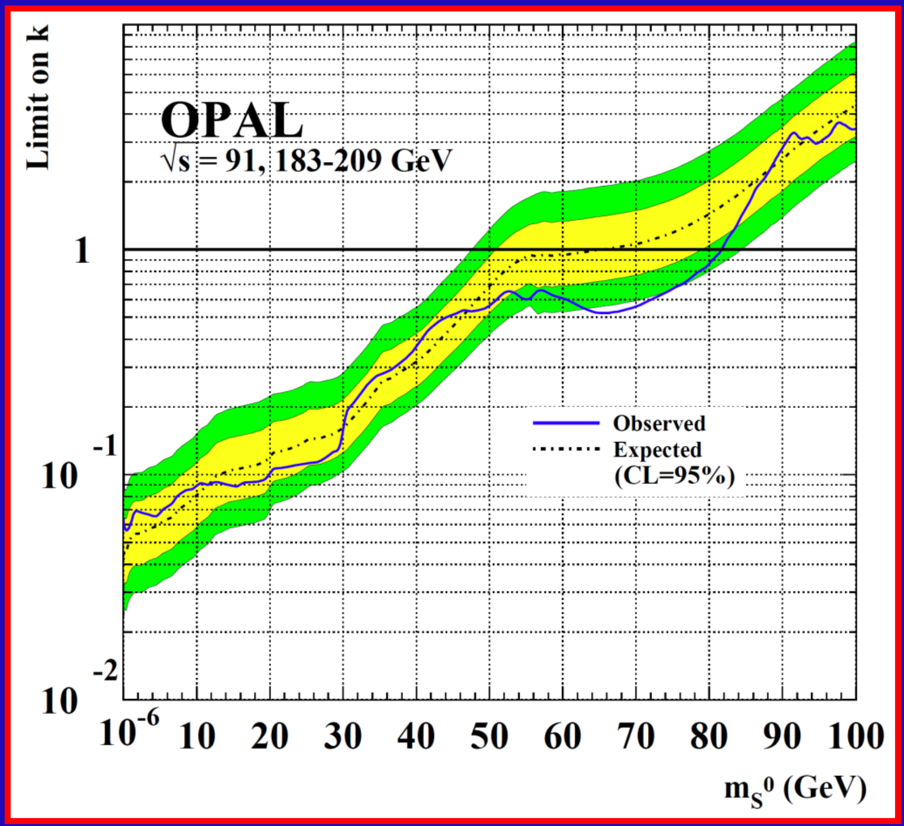
Not seen at DELPHI, L3 and OPAL



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

2) $S^0 \to e^+e^-\,,\; Z \to \nu\bar{\nu}$

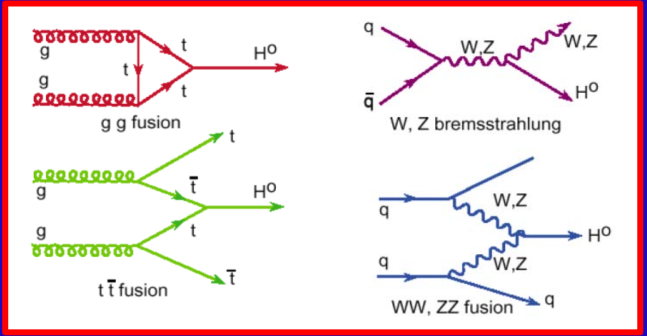
$$k \equiv \sigma(e^+e^- \to Z\,S^0)\big/\sigma(e^+e^- \to Z\,H)_{SM}$$



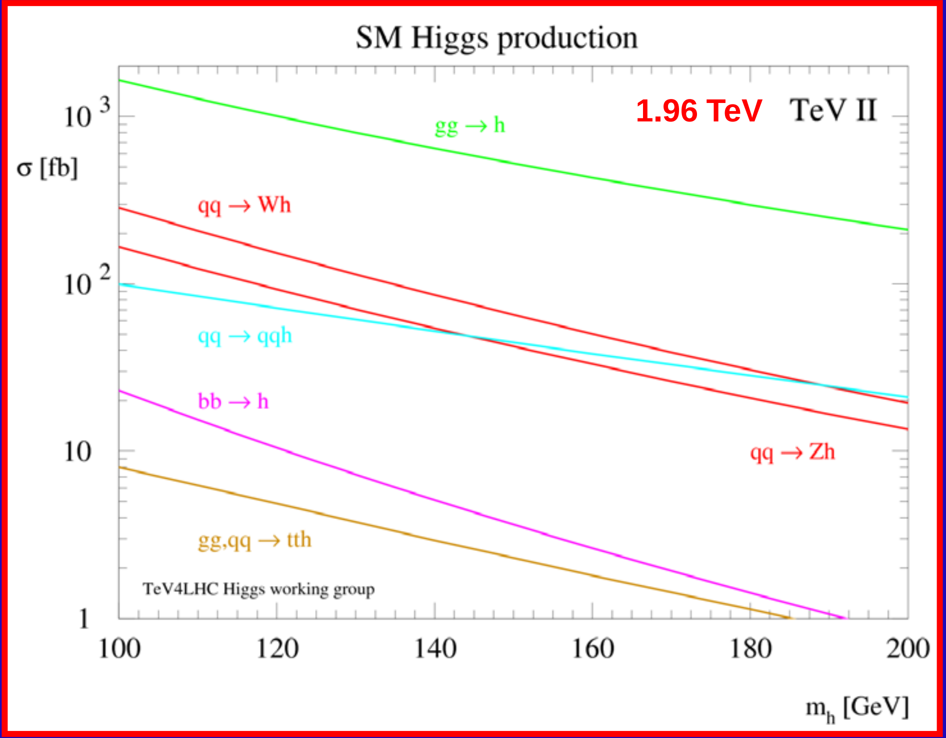
Low-mass Higgs excluded

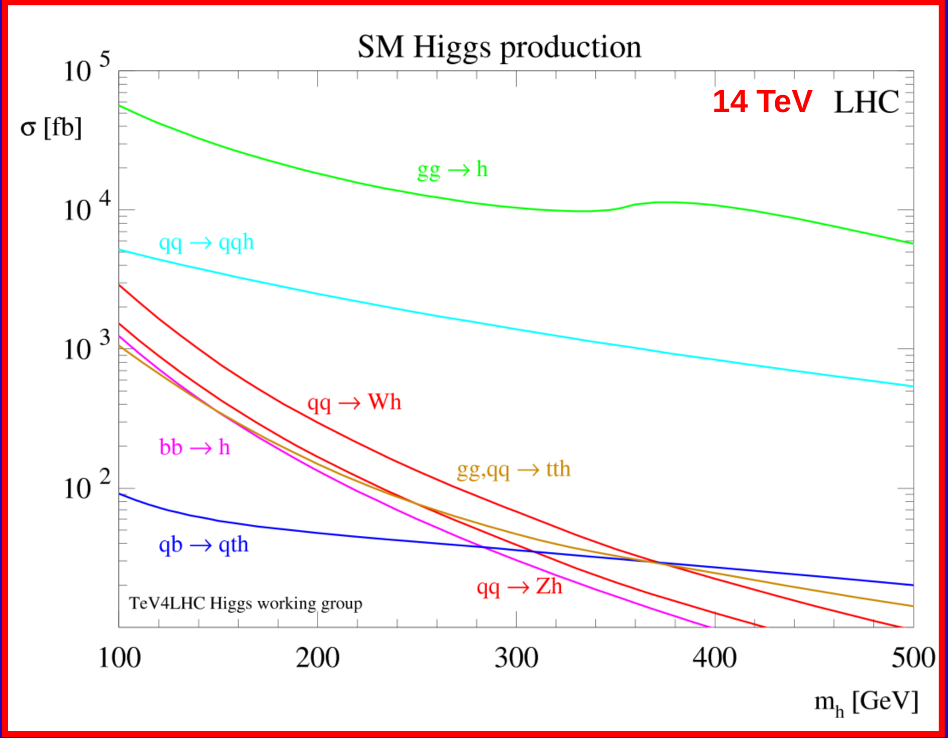
Decay-mode-independent limits

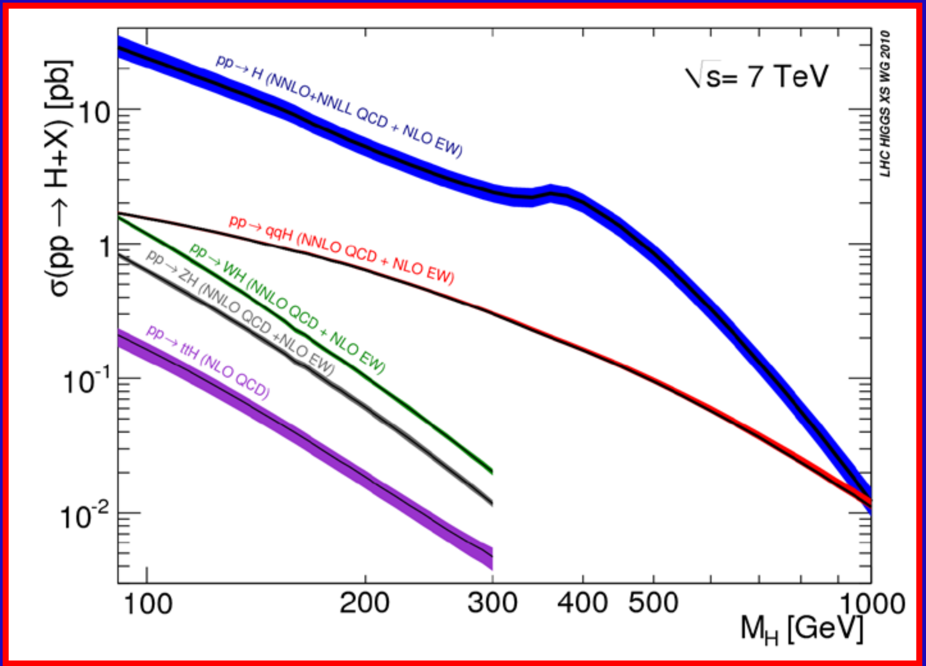
Higgs Production @ Colliders



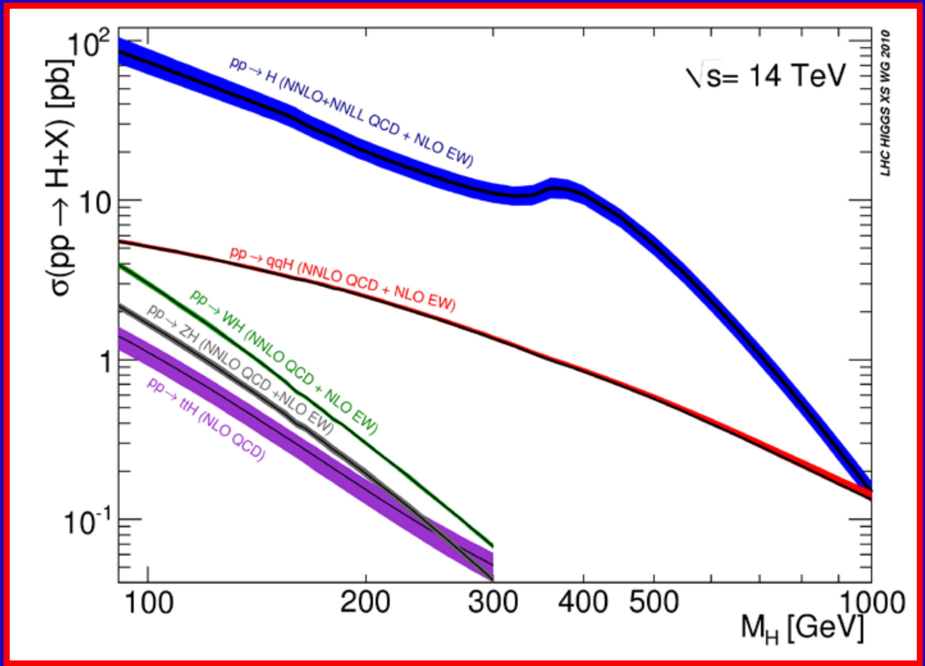
F. Maltoni



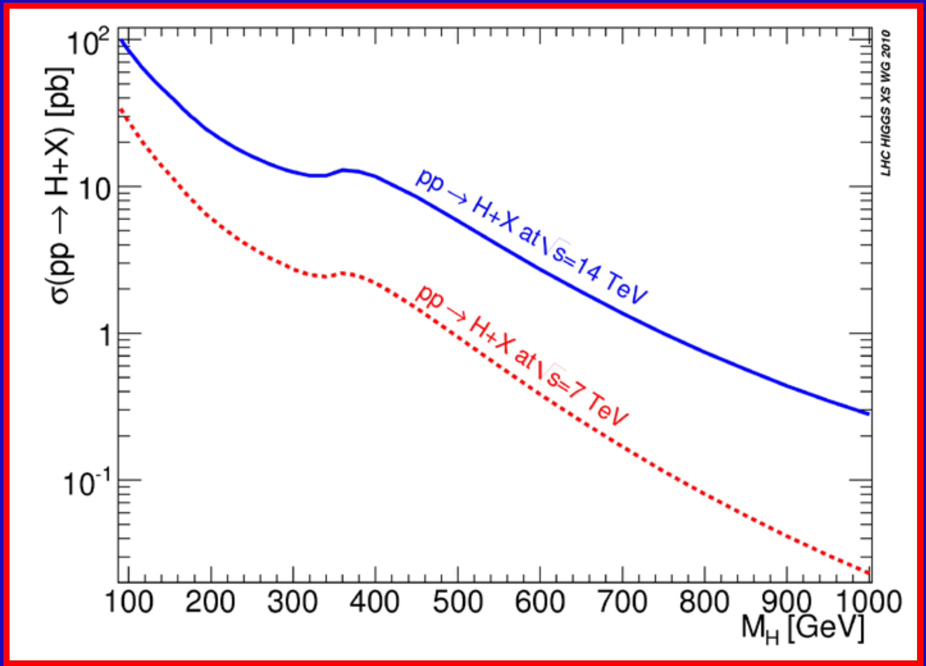




σ(pp → H+X) [pb]
√s= 7 TeV
pp → H (NNLO+NNLL QCD + NLO EW)
pp → qqH (NNLO QCD + NLO EW)
pp → WH (NNLO QCD + NLO EW)
pp → ZH (NNLO QCD +NLO EW)
pp → ttH (NLO QCD)
LHC HIGGS XS WG 2010
M_H [GeV]



σ(pp → H+X) [pb]
√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)
LHC HIGGS XS WG 2010
M_H [GeV]



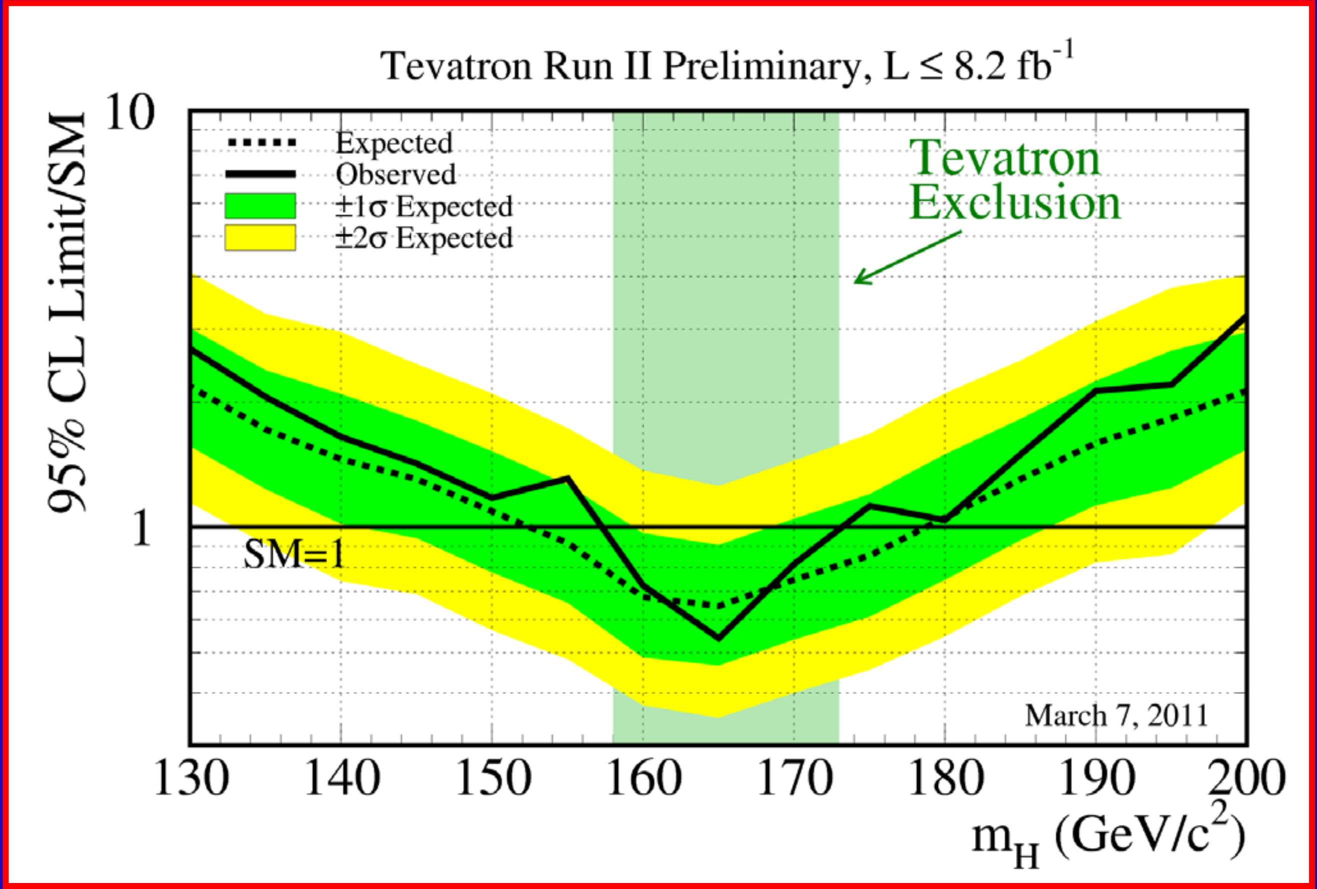
σ(pp → H+X) [pb]
pp → H+X at √s=14 TeV
pp → H+X at √s=7 TeV
LHC HIGGS XS WG 2010
M_H [GeV]

Tevatron Limits

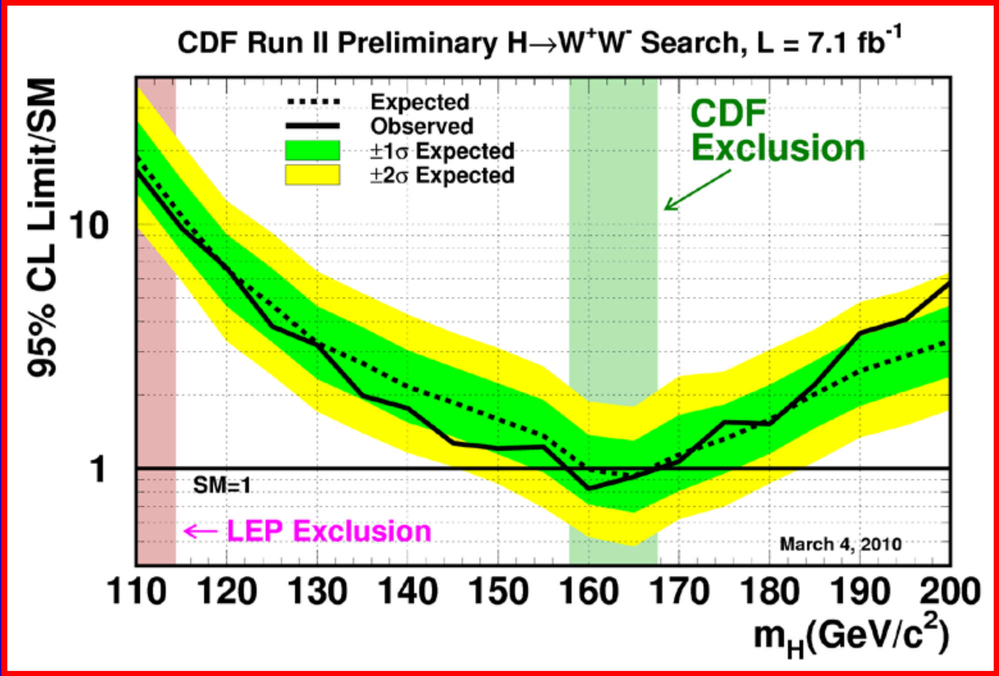
arXiv:1103.3233

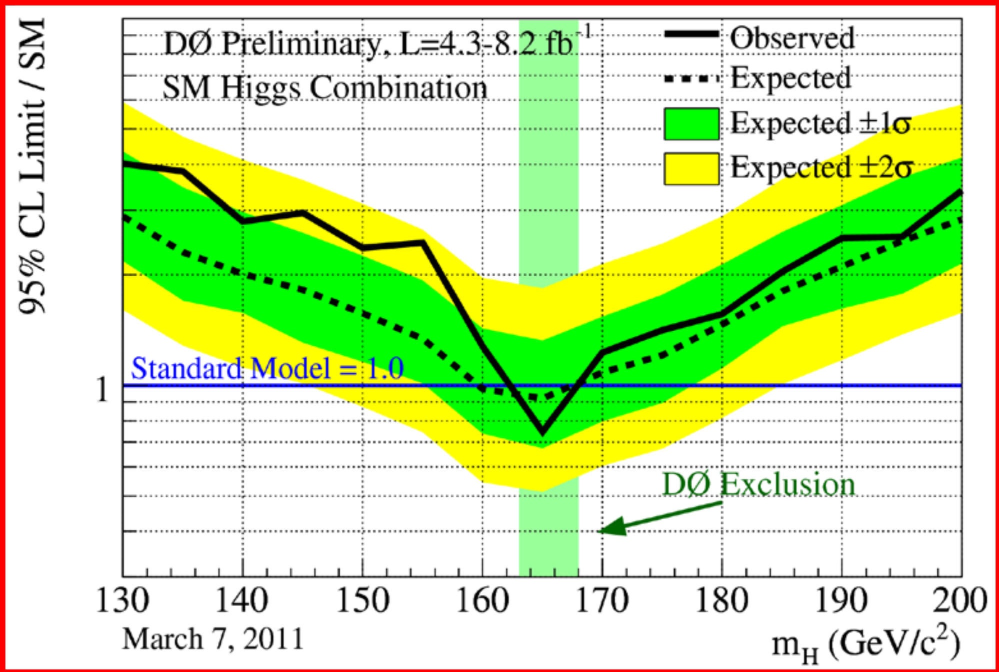
$L \leq 7.1\ fb^{-1}$ (CDF), $8.2\ fb^{-1}$ (D0)

$H \to W^+W^-$

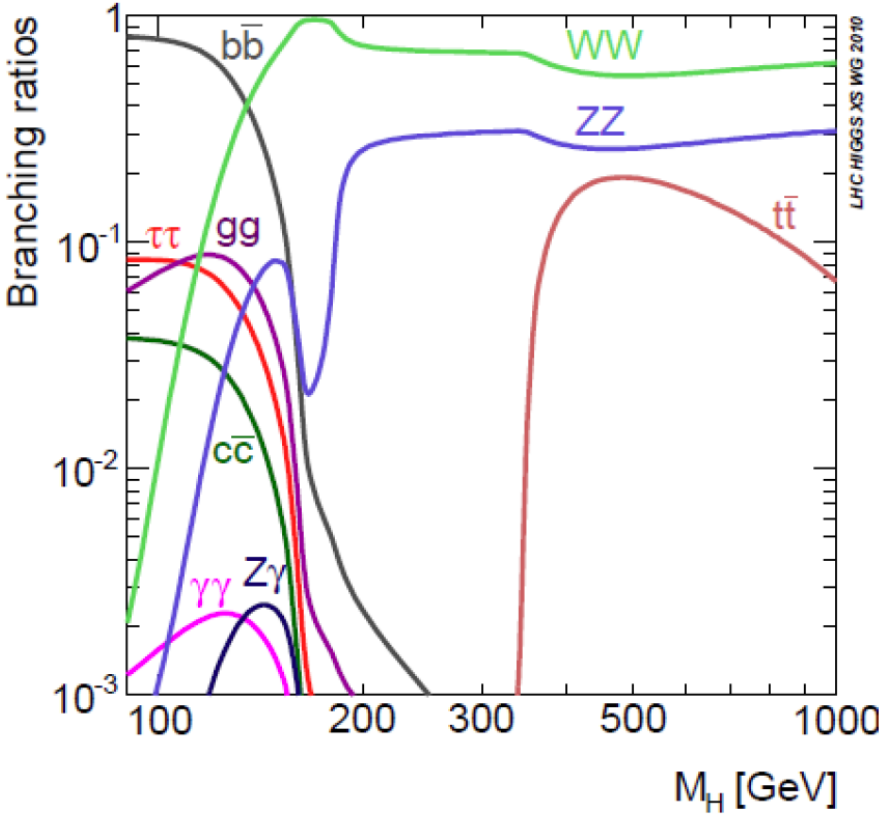


$$M_H \notin [158, 173]\ \text{GeV} \qquad (95\%\ \text{CL})$$


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

SM Higgs Search Channels

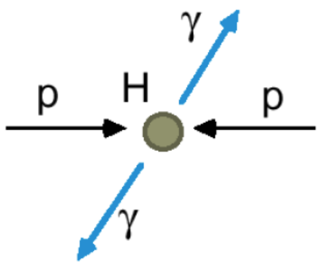


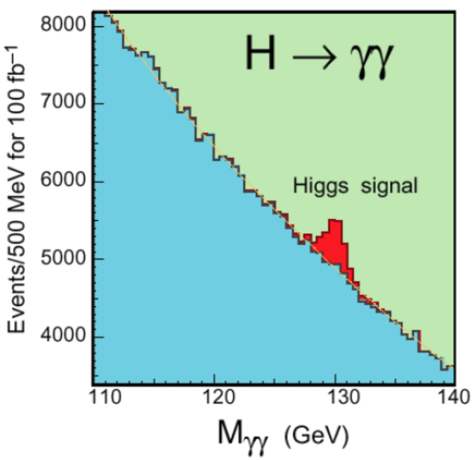
Channels included	**Higgs mass range used in analyses (GeV)**
H→γγ	115-150
VBF H→ττ	115-145
VH, H→bb (highly boosted)	115-125
VH, H→WW→lνjj	130-200
H→WW→2l2ν + 0/1 jets	120-600
VBF H→WW→2l2ν	130-500
H→ZZ→4l	120-600
H→ZZ→2l2ν	200-600
H→ZZ→2l2b	300-600

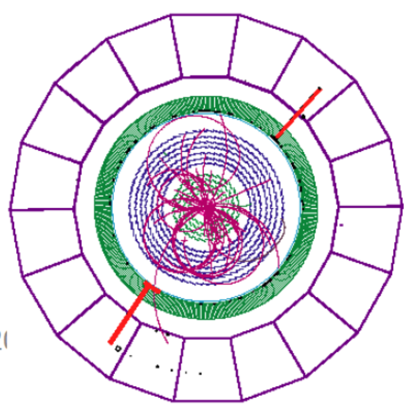
Channels with H → γγ, H → ττ, H → WW*, H → ZZ* are all used for the search
H → γγ and H → ZZ* → 4ℓ are the channels where mass can be measured with ~1% res.

SM Higgs Search Strategies - Examples

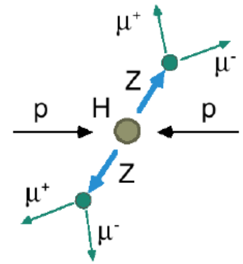
Low M_H < 140 GeV

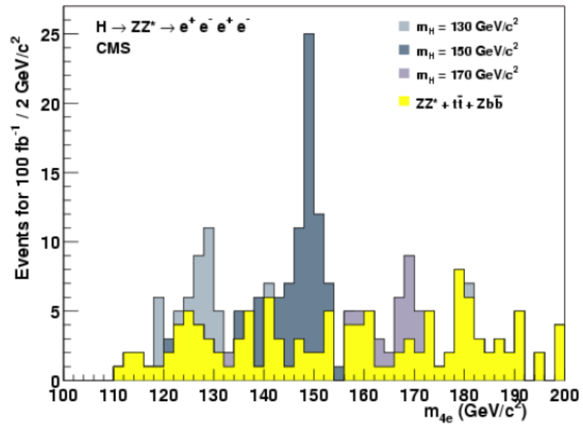


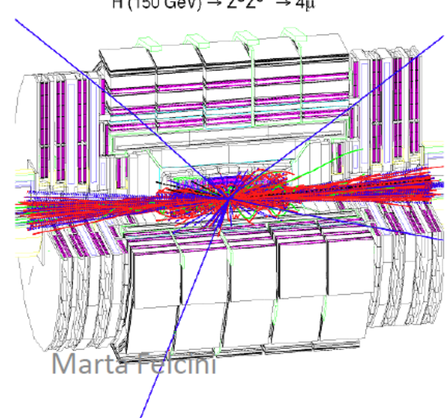




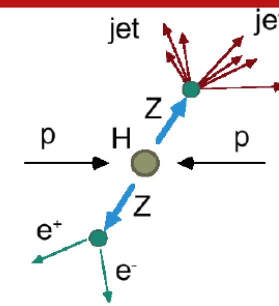
Medium 130<M_H<500 GeV/

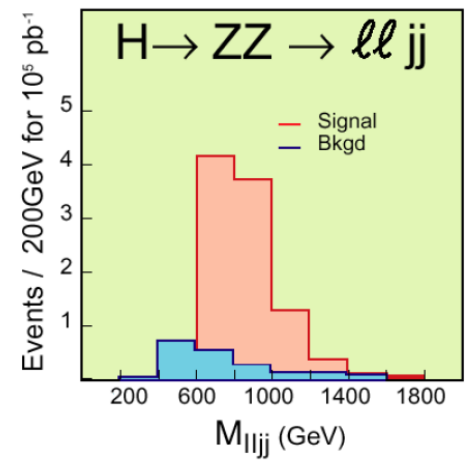


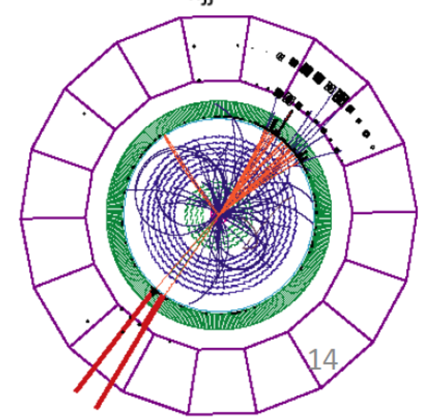




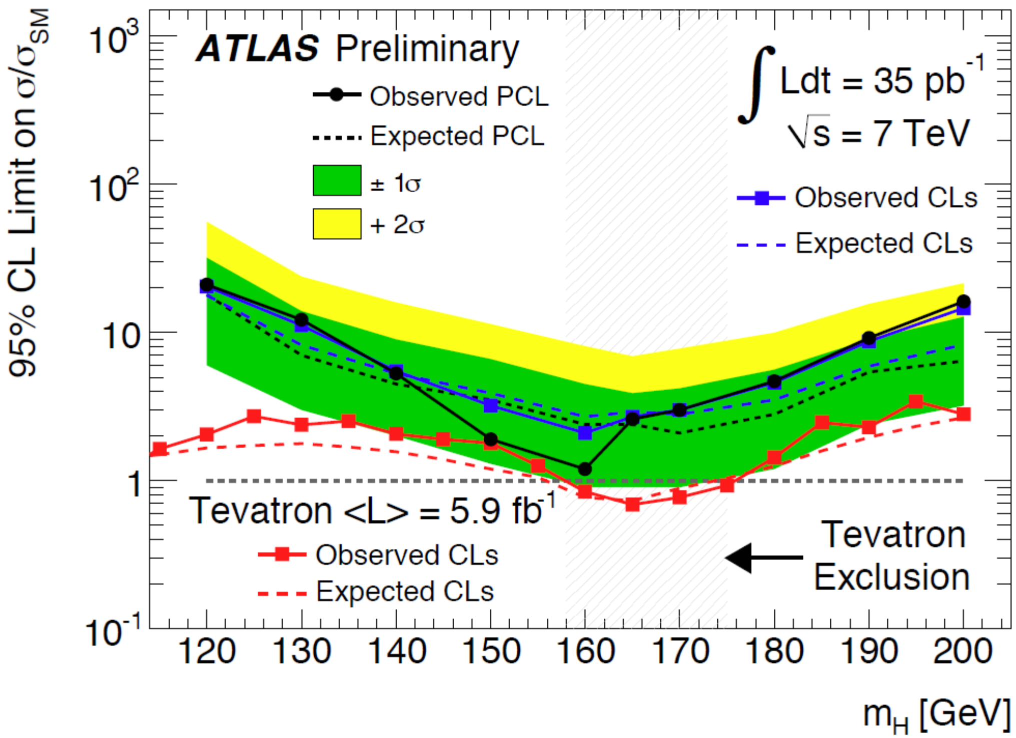
High M_H > ~500 GeV/c²

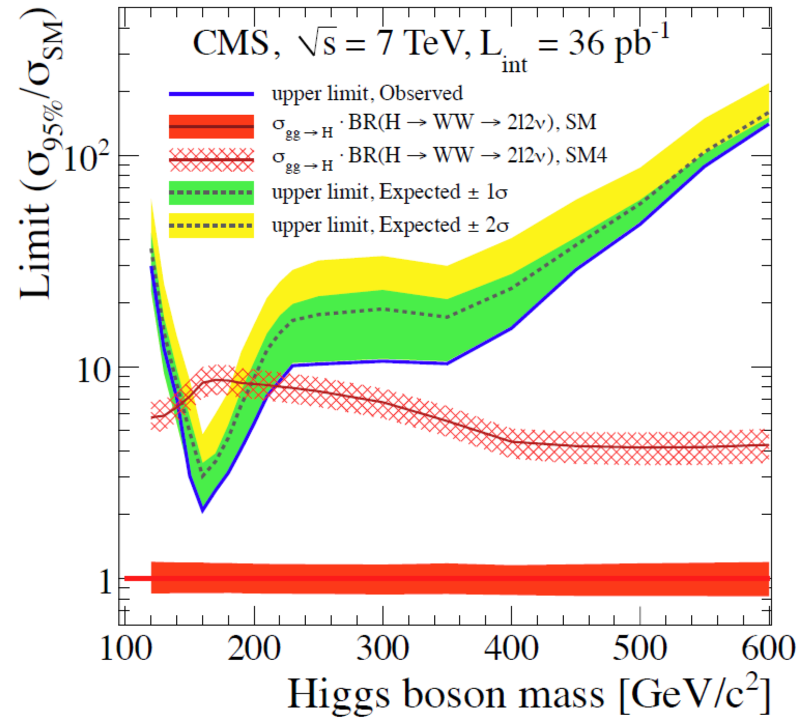






H→WW→lνlν : Exclusion Limits





⇒ At M_H=160 GeV

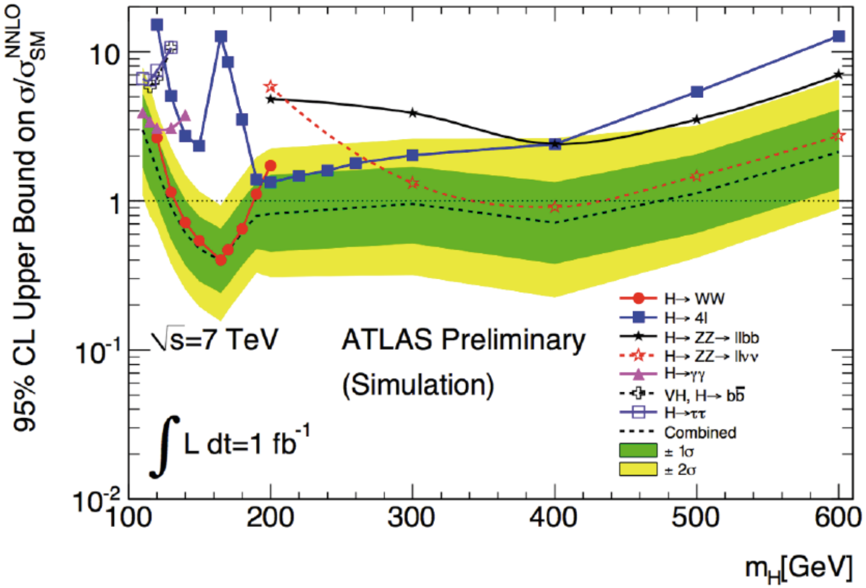
→ ATLAS excludes 2.1×σ_{SM} (obs) and 2.7×σ_{SM}(exp) CLs

→ 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

Higgs boson prospects for the (near) future

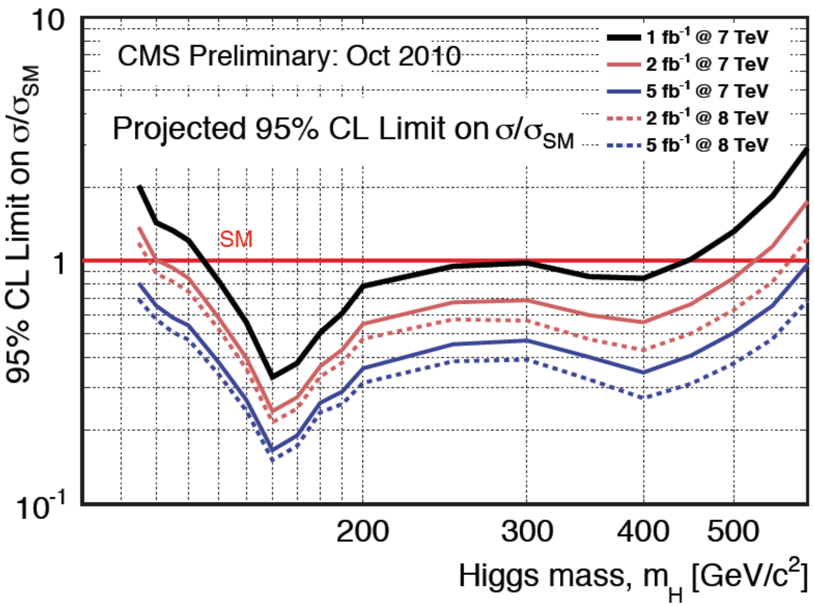


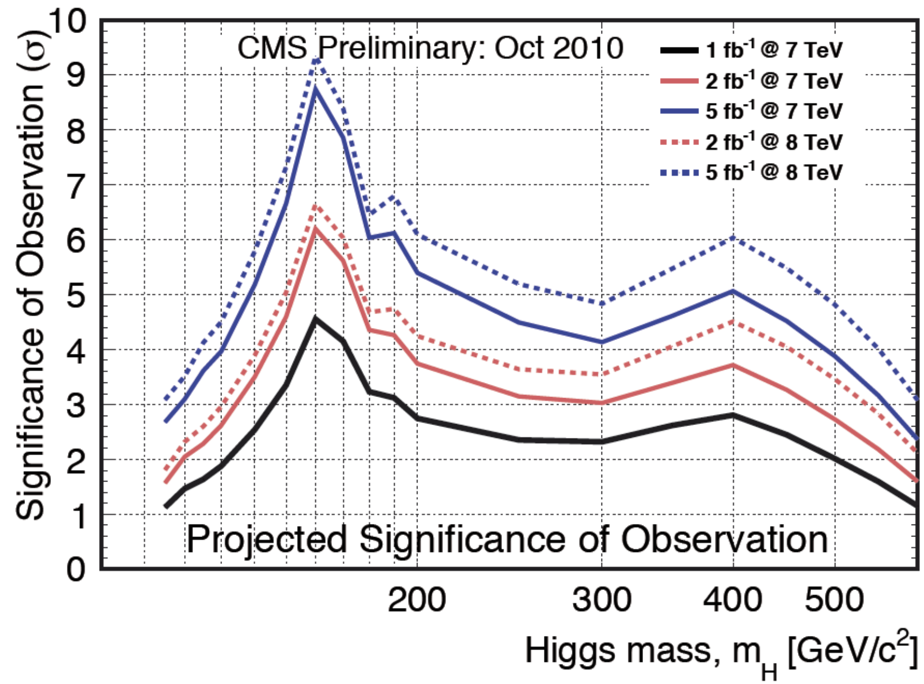
With ~1 fb^{-1} for EPS and 2 fb^{-1} by end of summer for each experiment

⇒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!





SM Higgs Search Performance at 7 TeV