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# Electroweak Symmetry Breaking
# University of Chicago, 2011

- Introduction to Electroweak Symmetry Breaking
  - Review of the SU(2) x U(1) Electroweak theory
  - Constraints from Precision Measurements
  - Experimental Searches for the Higgs
- Theoretical problems with the Standard Model
- Beyond the SM
  - Why are we sure there is physics BSM?
  - What do the LHC and Tevatron tell us?

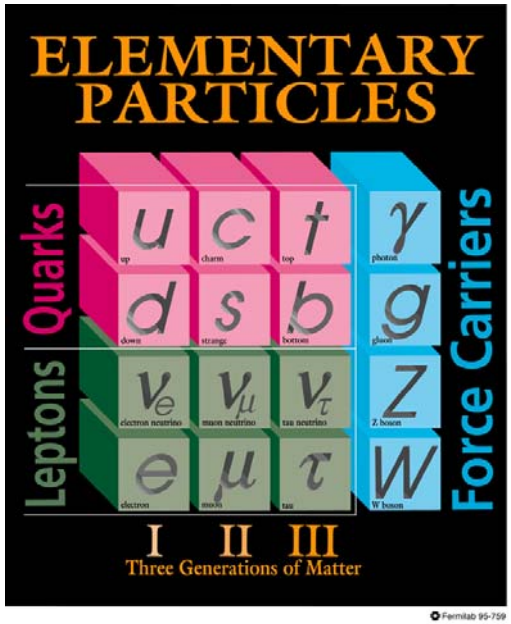
# Exciting times: Large Hadron Collider

- proton-proton collider at CERN running now!
- 7 TeV total energy
- Total integrated luminosity ~2.5 $fb^{-1}$
- Typical energy of quarks and gluons 1-2 TeV

If there is a SM Higgs boson, we expect it soon!

# What we know

- The photon and gluon appear to be massless
- The W and Z gauge bosons are heavy
  - $M_W$=80.399 ± 0.023 GeV
  - $M_Z$ =91.1875 ± 0.0021 GeV
- There are 6 quarks
  - $M_t$=172.9 ±0.9 GeV
  - $M_t$ >> all the other quark masses
- There appear to be 3 distinct neutrinos with small but non-zero masses
- The pattern of fermions appears to replicate itself 3 times
  - Why not more?



# Abelian Higgs Model

- Why are the W and Z boson masses non-zero?
- U(1) gauge theory with single spin-1 gauge field, $A_\mu$

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$F_{\mu\nu} = \partial_\nu A_\mu - \partial_\mu A_\nu$$

- U(1) local gauge invariance:

$$A_\mu(x) \to A_\mu(x) - \partial_\mu \eta(x)$$

- Mass term for A would look like:

$$L = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m^2 A_\mu A^\mu$$

- Mass term violates local gauge invariance
- We understand why $M_A = 0$

Gauge invariance is guiding principle

# Non-Abelian Higgs Mechanism

- Vector fields $A^a_\mu(x)$ and scalar fields $\varphi_i(x)$ of SU(N) group

$$\Phi = \begin{pmatrix} \phi_1 \\ \cdot \\ \cdot \\ \cdot \\ \phi_N \end{pmatrix} \qquad L_\Phi = (D_\mu \Phi)^+ (D^\mu \Phi) - V(\Phi), \qquad V(\Phi) = \mu^2 \Phi^+ \Phi + \lambda (\Phi^+ \Phi)^2$$

i=1…N

- L is invariant under the non-Abelian symmetry:

$$\phi_i \to (1 - i\eta^a \tau^a)_{ij} \phi_j$$

$$D_\mu \phi = \left(\partial_\mu - ig\tau^a A^a_\mu\right)\phi$$

- $\tau_a$ are group generators, a=1…$N^2$-1 for SU(N)

For SU(2): $\tau^a = \sigma^a/2$ $\qquad$ $\sigma$ are Pauli matrices

# Non-Abelian Higgs Mechanism, 2

$$D_\mu \phi = \left(\partial_\mu - ig\tau^a A_\mu^a\right)\phi$$

$$(D_\mu \Phi)^+ (D^\mu \Phi) \quad \rightarrow \quad \ldots + g^2 (\tau^a \phi^+)_i (\tau^b \phi)_i A_\mu^a A^{b\mu} + \ldots$$

$$\rightarrow^{\phi \to \phi_0} \ldots + g^2 (\tau^a \phi_0{}^+)_i (\tau^b \phi_0)_i A_\mu^a A^{b\mu} + \ldots$$

- $\tau^a \varphi_0 \neq 0$

  $\Rightarrow$ Massive vector boson + Goldstone boson

- $\tau^a \varphi_0 = 0$

  $\Rightarrow$ Massless vector boson + massive scalar field

***Simplest, but not the only way, to give gauge bosons mass***

# Standard Model Synopsis

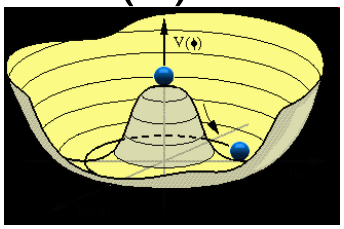
- Group: $\underbrace{SU(3)}_{\text{QCD}} \times \underbrace{SU(2) \times U(1)}_{\text{Electroweak}}$
- Gauge bosons:
  - SU(3): $G_\mu^i$, i=1…8
  - SU(2): $W_\mu^i$, i=1,2,3
  - U(1): $B_\mu$
- Gauge couplings: $g_s$, $g$, $g'$
- Complex SU(2) Higgs doublet: $\Phi$

***Minimal Model***

# SM Higgs Mechanism

- Standard Model includes complex Higgs SU(2) doublet

$$\Phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix} = \begin{pmatrix}\varphi^+ \\ \varphi^0\end{pmatrix}$$




- With SU(2) x U(1) invariant scalar potential

$$V = \mu^2 \Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

Invariant under $\Phi \rightarrow -\Phi$

- If $\mu^2 < 0$, then spontaneous symmetry breaking
- Minimum of potential at: $\langle\Phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix}0 \\ v\end{pmatrix}$ $\quad \Phi \rightarrow e^{i\varpi^a \cdot \sigma^a / v}\begin{pmatrix}0 \\ \frac{h+v}{\sqrt{2}}\end{pmatrix}$
  - Choice of minimum breaks gauge symmetry

# More on SM Higgs Mechanism

- Couple $\Phi$ to SU(2) x U(1) gauge bosons ($W_i^\mu$, i=1,2,3; $B^\mu$)

$$L_S = (D_\mu \Phi)^+ (D^\mu \Phi) - V(\Phi)$$

$$D_\mu = \partial_\mu - i\frac{g}{2}\sigma^i W^i{}_\mu - i\frac{g'}{2}B_\mu$$

- Gauge boson mass terms from:

$$(D_\mu \Phi)^+ D^\mu \Phi \to \ldots + \frac{1}{8}(0,v)(gW_\mu^a \sigma^a + g'B_\mu)(gW^{b\mu}\sigma^b + g'B^\mu)\begin{pmatrix}0\\ v\end{pmatrix} + \ldots$$

$$\to \ldots + \frac{v^2}{8}\left(g^2(W_\mu^1)^2 + g^2(W_\mu^2)^2 + (-gW_\mu^3 + g'B_\mu)^2\right) + \ldots$$

# More on SM Higgs Mechanism

- With massive gauge bosons:

$$W_\mu^\pm = \left( \frac{W_\mu^1 \mp W_\mu^2}{\sqrt{2}} \right)$$

$$Z_\mu^0 = \left( \frac{g W_\mu^3 - g' B_\mu}{\sqrt{g^2 + g'^2}} \right)$$

$$\boxed{\begin{aligned} M_W &= \frac{gv}{2} \\ M_Z &= \sqrt{g^2 + g'^2}\,\frac{v}{2} \end{aligned}}$$

- Orthogonal combination to Z is massless photon

$$A_\mu^0 = \frac{g' W_\mu^3 + g B_\mu}{\sqrt{g^2 + g'^2}}$$

# More on SM Higgs Mechanism

- Weak mixing angle defined :

$Z = -\sin\theta_W B + \cos\theta_W W^3$

$A = \cos\theta_W B + \sin\theta_W W^3$

$$\cos\theta_W = \frac{g}{\sqrt{g^2 + g'^2}} \qquad \sin\theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}$$

➡ Natural Relationship: $M_W = M_Z \cos\theta_W$

$$\rho = \frac{M_W}{M_Z \cos\theta_W} = 1$$

# W, Z, Higgs Couplings

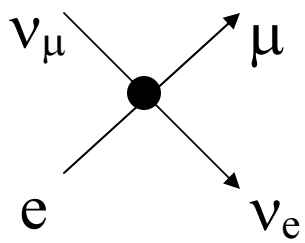
- Lagrangian in terms of massive gauge bosons and Higgs boson:

$$L = gM_W W^{+\mu} W_\mu^- h + \frac{gM_Z}{\cos\theta_W} Z^\mu Z_\mu h$$

- Higgs couples to gauge boson mass
- Spontaneous symmetry breaking gives W/Z mass $\Rightarrow$ longitudinal polarization

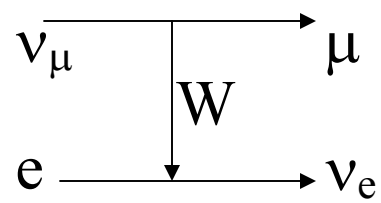
# Muon decay

- Consider $\nu_\mu e \rightarrow \mu \nu_e$
- Fermi Theory:




$$-i2\sqrt{2}G_F g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$

- EW Theory:




$$\frac{ig^2}{2}\frac{1}{k^2-M_W^2}g_{\mu\nu}\bar{u}_\mu\gamma^\mu\left(\frac{1-\gamma_5}{2}\right)u_{\nu_\mu}\bar{u}_{\nu_e}\gamma^\nu\left(\frac{1-\gamma_5}{2}\right)u_e$$

For $|k| << M_W$, $2\sqrt{2}G_F = g^2/2M_W^2$

# Higgs Parameters

- $G_F$ measured precisely

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W{}^2} = \frac{1}{2v^2}$$

$$v^2 = (\sqrt{2}G_F)^{-1} = (246GeV)^2$$

- Higgs potential has 2 free parameters, $\mu^2$, $\lambda$

$$V = \mu^2\Phi^+\Phi + \lambda(\Phi^+\Phi)^2$$

- Trade $\mu^2$, $\lambda$ for $v^2$, $M_h^2$

$$V = \frac{M_h{}^2}{2}h^2 + \frac{M_h{}^2}{2v}h^3 + \frac{M_h{}^2}{8v^2}h^4$$

$$v^2 = -\frac{\mu^2}{2\lambda}$$

$$M_h{}^2 = 2v^2\lambda$$

  - Large $M_h$ $\rightarrow$strong Higgs self-coupling
  - A priori, Higgs mass can be anything

# What about fermion masses?

- Fermion mass term:

$$L = m\overline{\Psi}\Psi = m\left(\overline{\Psi}_L \Psi_R + \overline{\Psi}_R \Psi_L\right)$$

← Forbidden by SU(2)xU(1) gauge invariance

- Left-handed fermions are SU(2) doublets

$$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L$$

- Scalar couplings to fermions:

$$L_d = -\lambda_d \overline{Q}_L \Phi d_R + h.c.$$

- Effective Higgs-fermion coupling

$$L_d = -\lambda_d \frac{1}{\sqrt{2}} (\overline{u}_L, \overline{d}_L) \begin{pmatrix} 0 \\ v+h \end{pmatrix} d_R + h.c.$$

- Mass term for down quark:

$$\boxed{\lambda_d = \frac{M_d \sqrt{2}}{v}}$$

# Fermion Masses, 2

- $M_u$ from $\Phi_c = i\sigma_2\Phi^*$ (not allowed in SUSY)

$$\Phi_c = \begin{pmatrix} \bar{\phi}^0 \\ -\phi^- \end{pmatrix}$$

$$L = -\lambda_u \overline{Q}_L \Phi_c u_R + hc$$

$$\boxed{\lambda_u = \frac{M_u\sqrt{2}}{v}}$$

- For 3 generations, $\alpha$, $\beta$=1,2,3 (flavor indices)

$$\boxed{L_Y = -\frac{(v+h)}{\sqrt{2}} \sum_{\alpha,\beta} \left( \lambda_u^{\alpha\beta} \bar{u}_L^{\alpha} u_R^{\beta} + \lambda_d^{\alpha\beta} \bar{d}_L^{\alpha} d_R^{\beta} \right) + h.c.}$$

** SUSY always has at least 2 Higgs doublets*

# Fermion masses, 3

- Unitary matrices diagonalize mass matrices

$$\boxed{\begin{array}{ll} u_L^\alpha = U_u^{\alpha\beta} u_L^{m\beta} & d_L^\alpha = U_d^{\alpha\beta} d_L^{m\beta} \\ u_R^\alpha = V_u^{\alpha\beta} u_R^{m\beta} & d_R^\alpha = V_d^{\alpha\beta} d_R^{m\beta} \end{array}}$$

  - Yukawa couplings are ***diagonal*** in mass basis
  - No flavor changing effects in Higgs sector
  - Not necessarily true in models with extended Higgs sectors

# Review of Higgs Couplings

- Higgs couples to fermion mass
  - Largest coupling is to heaviest fermion

$$L = -\frac{m_f}{v}\bar{f}fh = -\frac{m_f}{v}\left(\bar{f}_L f_R + \bar{f}_R f_L\right)h$$

  - Top-Higgs coupling plays special role?
  - No Higgs coupling to neutrinos
- Higgs couples to gauge boson masses

$$L = gM_W W^{+\mu} W_\mu^{-} h + \frac{gM_Z}{\cos\theta_W} Z^\mu Z_\mu h + \ldots.$$

- Only free parameter is Higgs mass!

# Basics of Radiative Corrections

- Four free parameters in gauge-Higgs sector (g, g', $\mu$, $\lambda$)
  - Conventionally chosen to be
    - $\alpha$=1/137.0359895(61)
    - $G_F$ =1.16637(1) x $10^{-5}$ GeV $^{-2}$
    - $M_Z$=91.1875 $\pm$ 0.0021 GeV
    - $M_h$
  - Express everything else in terms of these parameters

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2} = \frac{\pi\alpha}{2\left(1-\frac{M_W^2}{M_Z^2}\right)M_W^2}$$

$\Rightarrow$ Predicts $M_W$

# Inadequacy of Tree Level Calculations

- Mixing angle is predicted quantity
  - On-shell definition $\cos^2\theta_W = M_W^2/M_Z^2$
  - Predict $M_W$

$$M_W^2 = \pi\sqrt{2}\,\frac{\alpha}{G_F}\left(1-\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F M_Z^2}}\right)^{-1}$$

$$s_W{}^2 c_W{}^2 = \frac{\pi\alpha}{G_F M_Z^2}$$

  - Plug in numbers:
    - $M_W$ predicted =80.939 GeV
    - $M_W$ experimental =80.399 $\pm$ 0.023 GeV
  - Need to calculate beyond tree level

# Modification of tree level relations

$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2\theta_W}\frac{1}{(1-\Delta r)}$$

- $\Delta r$ is a physical quantity which incorporates 1-loop corrections

- Contributions to $\Delta r$ from top quark and Higgs loops

$$\Delta r^t = -\frac{3G_F m_t^2}{8\sqrt{2}\pi^2}\left(\frac{\cos^2\theta_W}{\sin^2\theta_W}\right)$$

$$\Delta r^h = \frac{11G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{M_h^2}{M_W^2}\right)$$

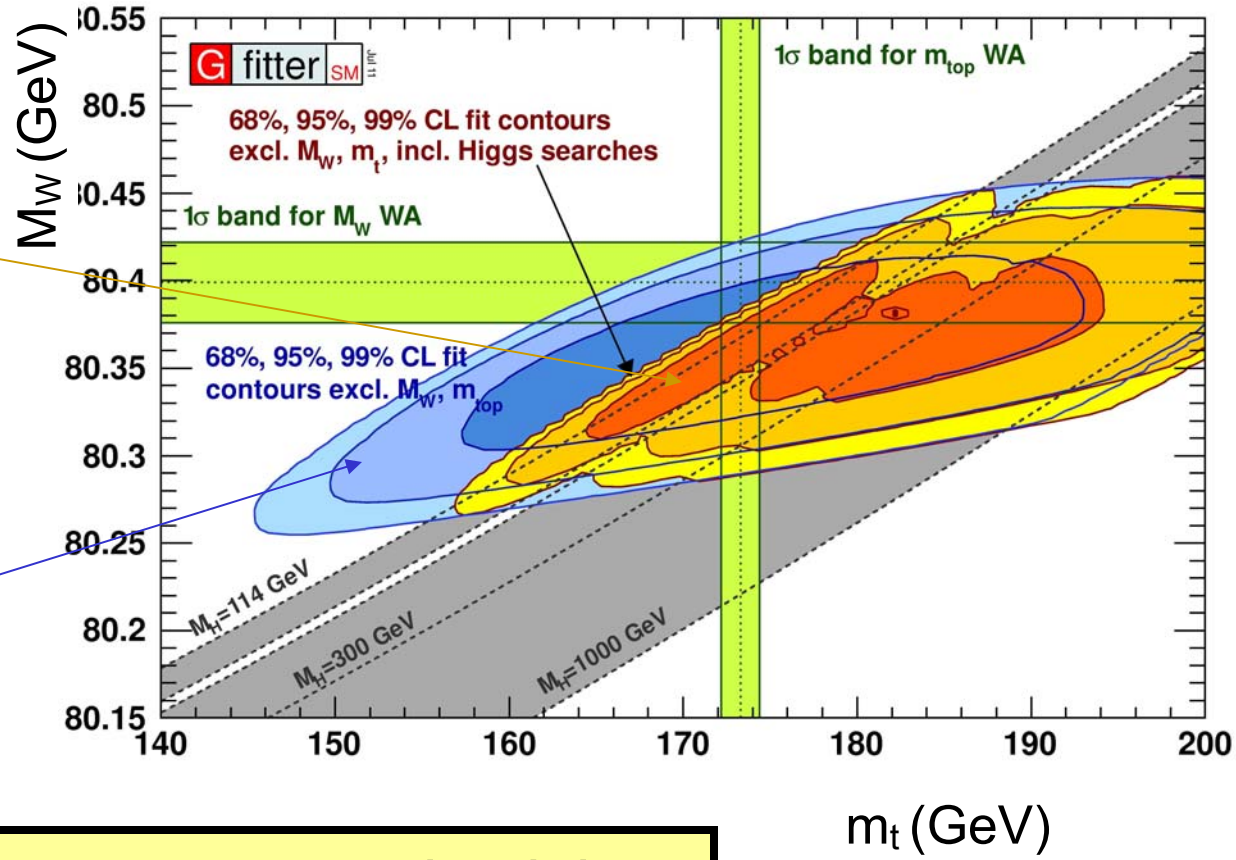
Extreme sensitivity of precision measurements to $m_t$

* Lots of other corrections from gauge boson loops, etc

# $M_W$ vs $m_t$

Masses inferred from precision measurements and Higgs searches*

Masses inferred from precision measurements

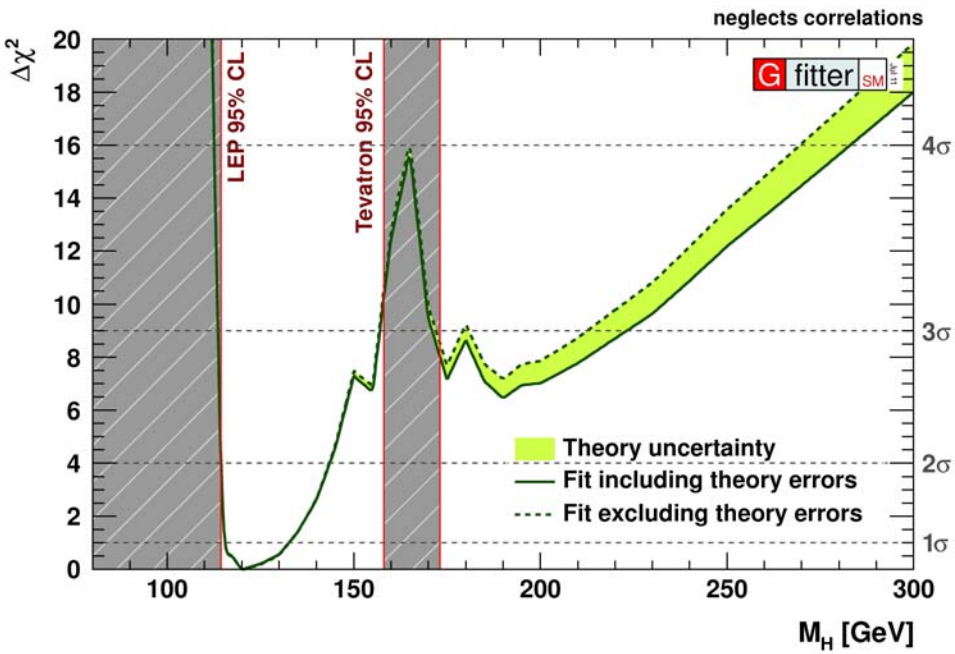



Higgs boson wants to be light

* Includes LHC searches

# Higgs Boson

- Standard Model Higgs expected to be light




Includes LHC limits

- This assumes the Standard Model!

$\Delta\chi^2=4$ gives 95% confidence level limit

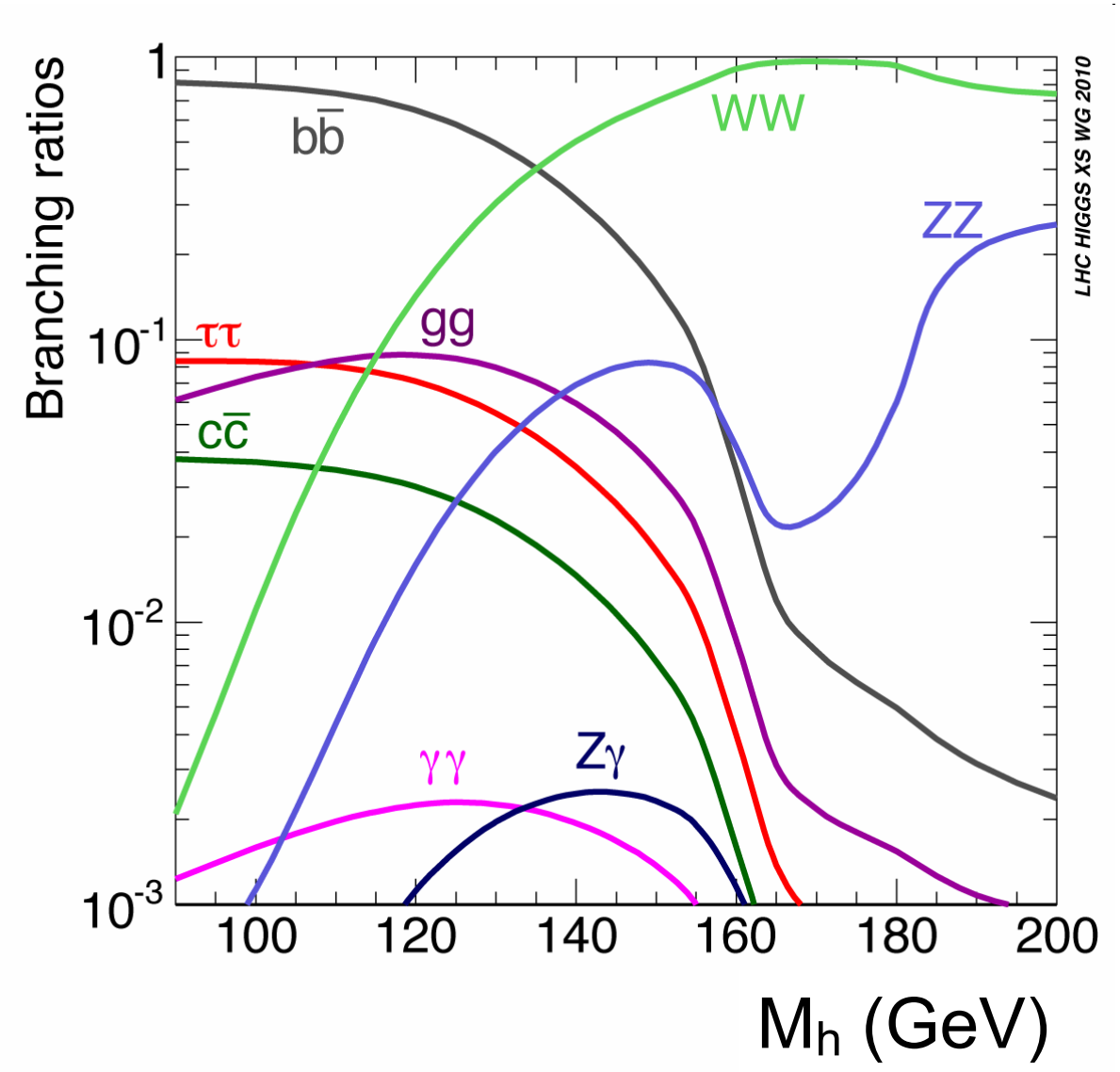
# Higgs Limits

- From Gfitter (2011)
  - If you don't include direct search limits for Higgs, 95% CL upper bound: $M_h < 169$ GeV
  - If you include LEP, Tevatron, LHC limits, 95% CL upper bound: $M_h < 143$ GeV
  - ***Test of consistency of Standard Model***

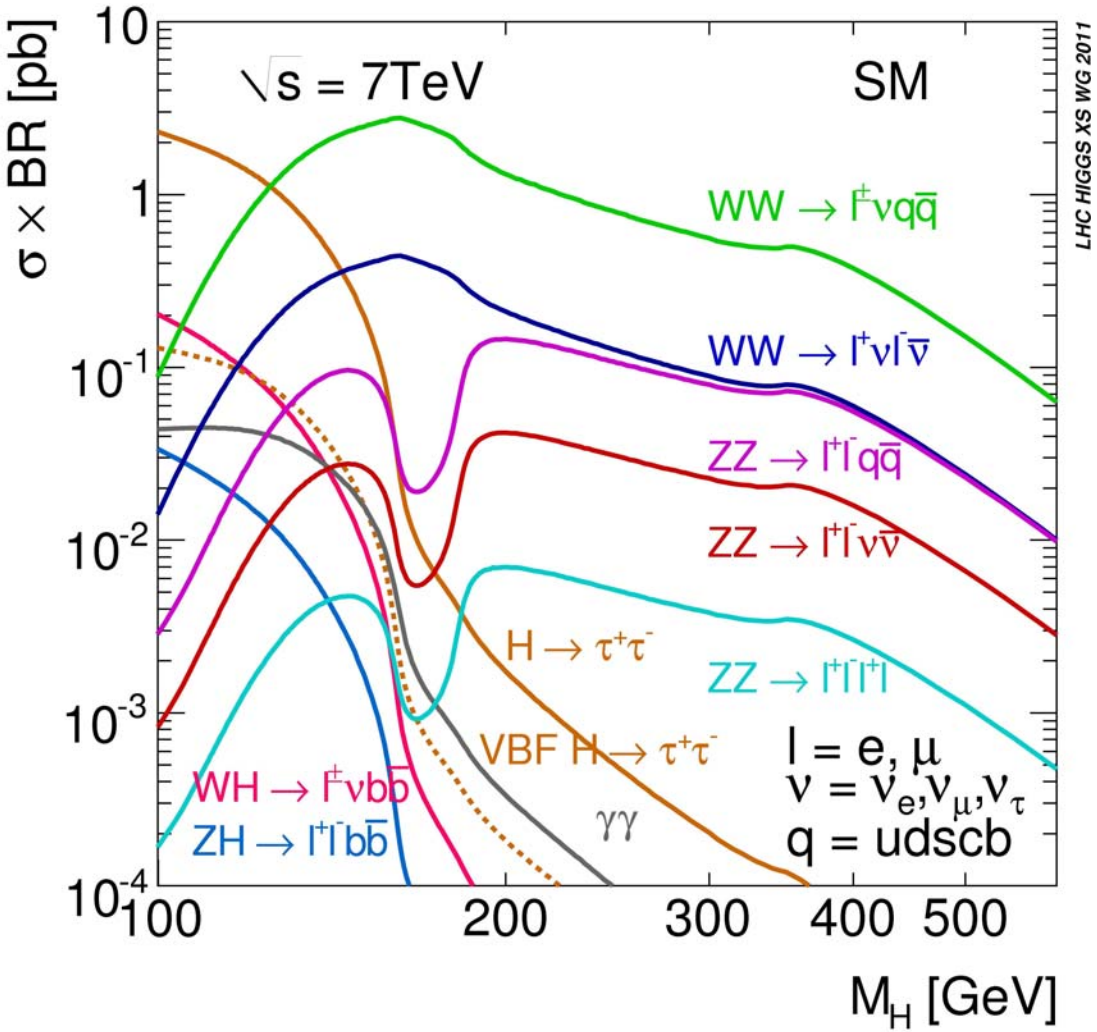
**Not hard to fit bounds with new physics**

**http://gfitter.desy.de/**

# Higgs Branching Ratios



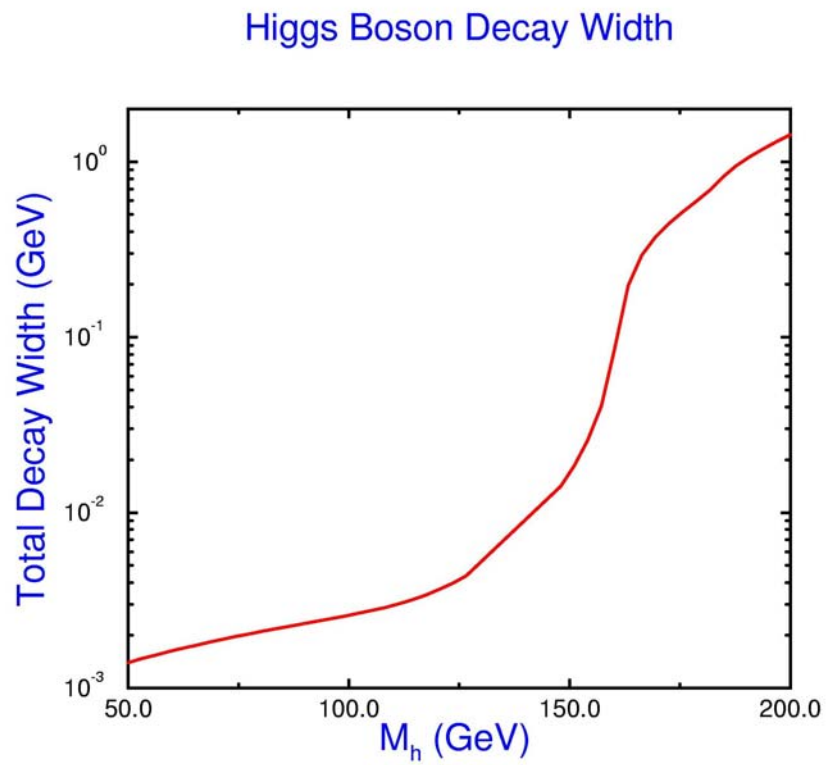
# More Branching Ratios



# Total Higgs Width

- Small $M_h$, Higgs is narrower than detector resolution
- As $M_h$ becomes large, width also increases
  - No clear resonance
  - For $M_h$ ~1.4 TeV, $\Gamma_{tot}$ ~$M_h$

$$\Gamma(h \to W^+W^-) \approx \frac{\alpha}{16\sin^2\theta_W}\frac{M_h^{\ 3}}{M_W^{\ 2}}$$
$$\approx 330GeV\left(\frac{M_h}{1TeV}\right)^3$$

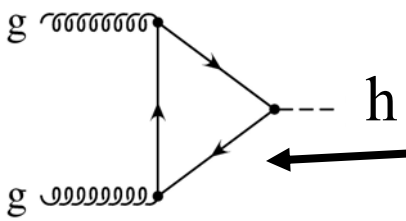


# Higgs production at Hadron Colliders

- Many possible production mechanisms; Importance depends on:
  - Size of production cross section
  - Size of branching ratios to observable channels
  - Size of background
- Importance varies with Higgs mass
- Need to see more than one channel to establish Higgs properties and verify that it is a Higgs boson

# Production Mechanisms in Hadron Colliders

- Gluon fusion
  - Largest rate for all $M_h$ at LHC and Tevatron
  - Gluon-gluon initial state
  - Sensitive to top quark Yukawa $\lambda_t$




Largest contribution is top loop

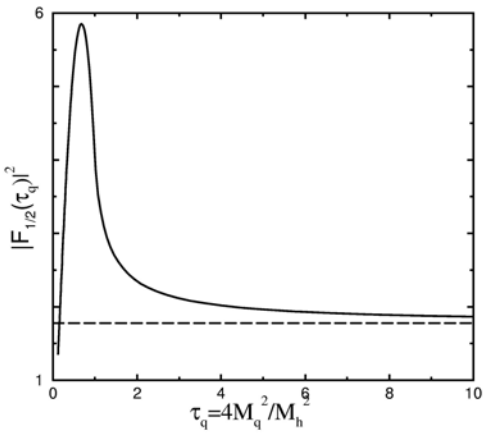
In Standard Model, b-quark loop contribution small

Counts number of heavy fermions

# Gluon Fusion

- Lowest order cross section:
  - $\tau_q = 4m_q^2/M_h^2$
  - Light Quarks: $F_{1/2} \rightarrow (m_b/M_h)^2 \log^2(m_b/M_h)$
  - Heavy Quarks: $F_{1/2} \rightarrow -4/3$

$$\hat{\sigma}_{gg\rightarrow h}(\hat{s}) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2}\left|\sum_q F_{1/2}(\tau_q)\right|^2 \delta(1-\frac{M_h^2}{\hat{s}})$$




- Rapid approach to heavy quark limit: Counts number of heavy fermions
- NNLO corrections calculated in heavy top limit

# Gluon Fusion

- Integrate parton level cross section with gluon parton distribution functions: $\hat{\sigma}_{gg\to h} = C_0 \delta(1 - \frac{M_h^2}{\hat{s}})$ $\hat{s} = x_1 x_2 S$

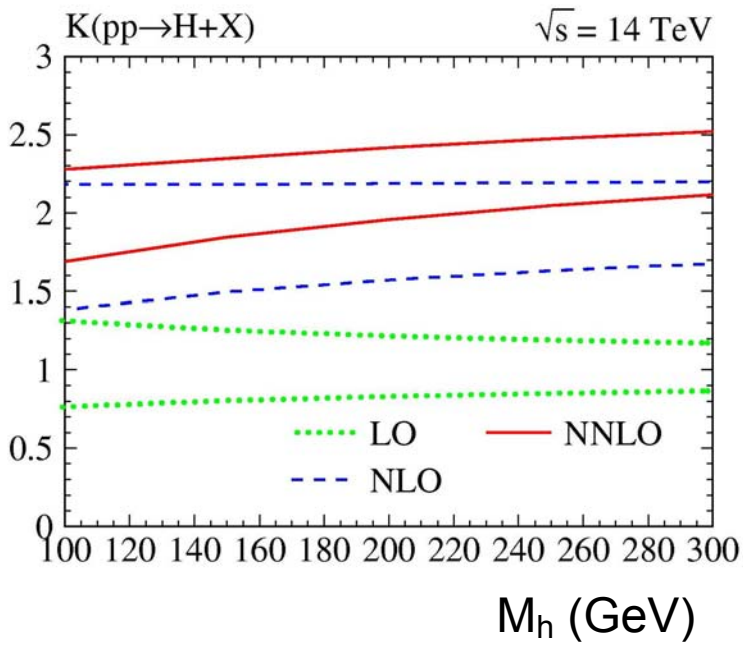
$$\sigma(pp \to h) = \int dx_1 dx_2 g(x_1, \mu_F) g(x_2, \mu_F) \hat{\sigma}_{gg\to h}(x_1 x_2 S)$$

$$\boxed{\sigma(pp \to h) = C_0 \int_{M_h^2/S}^{1} \frac{dx_1}{x_1} g(x_1, \mu_F) g\left(\frac{M_h^2}{S x_1}, \mu_F\right)}$$

$$\boxed{C_0 \to \frac{\alpha_s(\mu_R)^2}{576\pi v^2}}$$

  - S is hadronic center of mass energy
- Rate depends on $\mu_R$, $\mu_F$ at $O(\alpha_s^3)$
  - $\mu_R$, $\mu_F$ arbitrary renormalization/factorization scales
  - Numerically significant
- Uncertainty from gluon parton distribution functions

# Higher order corrections to gg→h




Rates depend on renormalization scale, $\alpha_s(\mu_R)$, and factorization scale, $g(\mu_F)$

Bands show $.5M_h < \mu < 2\ M_h$

LO and NLO $\mu$ dependence bands don't overlap

$\mu$ dependence used as estimate of theoretical uncertainty

$$K \equiv \frac{\sigma_{NLO}}{\sigma_{LO}}$$

These corrections are large!

# Vector Boson Fusion

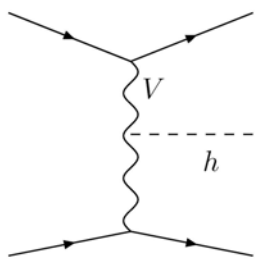
- $W^+W^- \rightarrow X$ is a real process: $\sigma_{pp\rightarrow WW\rightarrow X}(s) = \int dz \left.\frac{dL}{dz}\right|_{pp/WW} \sigma_{WW\rightarrow X}(zs)$

- Rate increases at large s: $\sigma \approx (1/M_W^2)\log(s/M_W^2)$
- Integral of cross section over final state phase space has contribution from W boson propagator:

$$\int \frac{d\theta}{(k^2 - M_W{}^2)^2} \approx \int \frac{d\theta}{(2EE'(1-\cos\theta) + M_W{}^2)^2}$$

**Peaks at small $\theta$**

- Outgoing jets are mostly forward and can be tagged

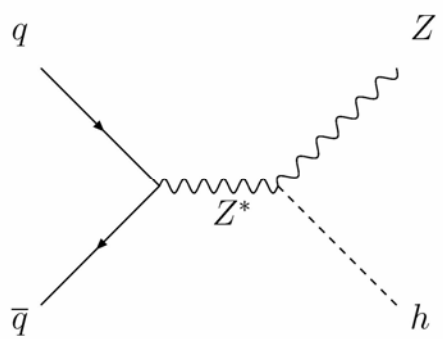



h

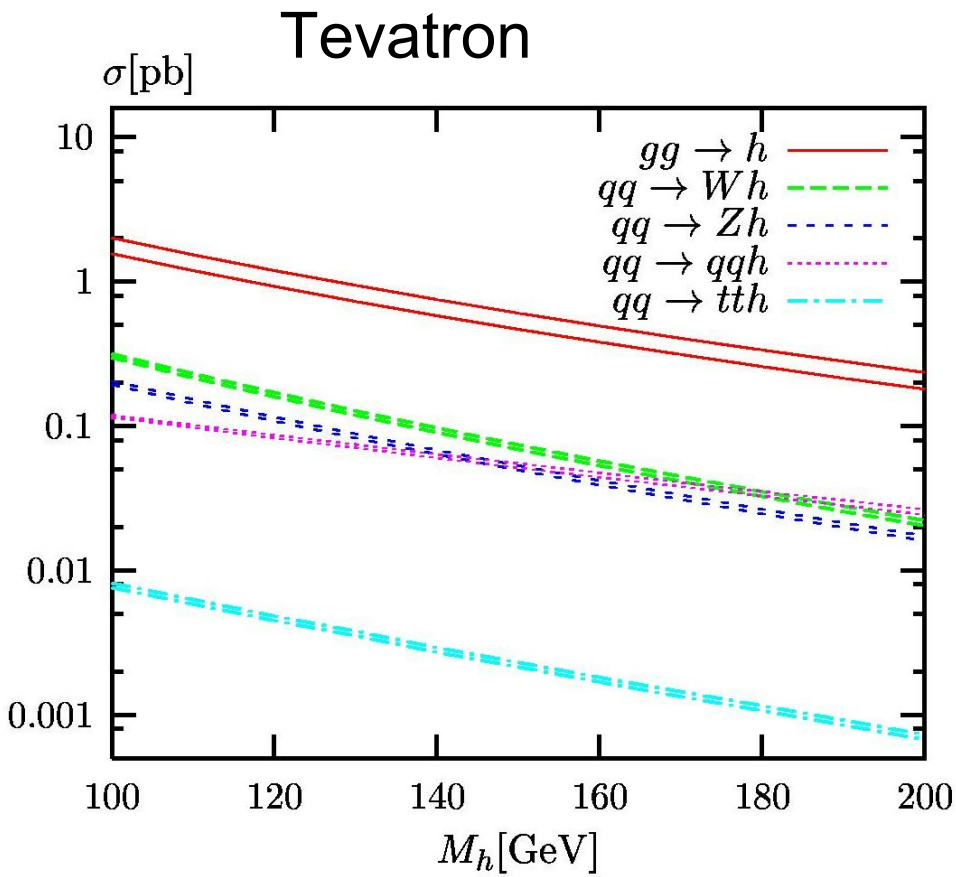
k=W,Z momentum

# W(Z)-strahlung

- W(Z)-strahlung ($q\bar{q} \rightarrow Wh$, $Zh$) important at Tevatron
  - Same couplings as vector boson fusion
  - Rate proportional to ***weak*** coupling
- Theoretically very clean channel



# Producing the Higgs at the Tevatron

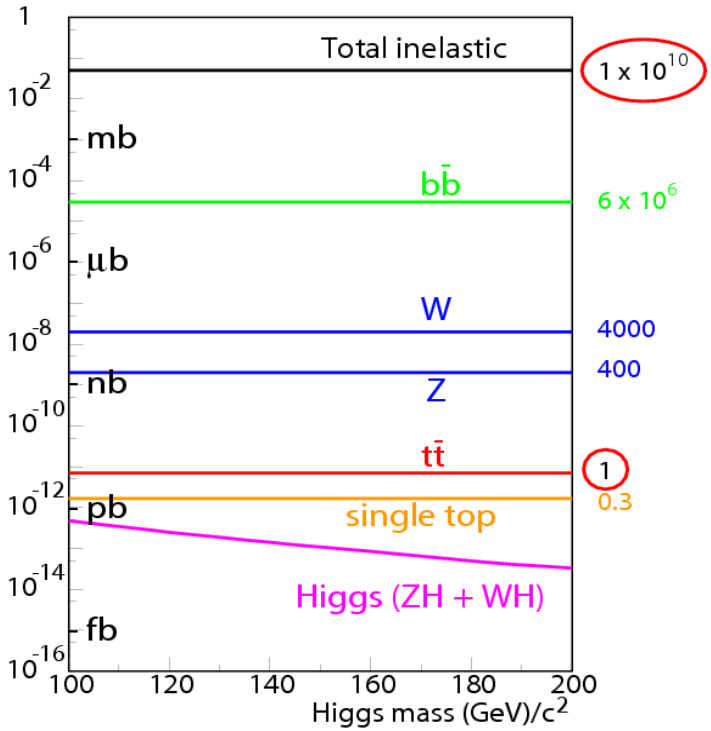



NNLO or NLO rates

$M_h/2 < \mu < M_h/4$

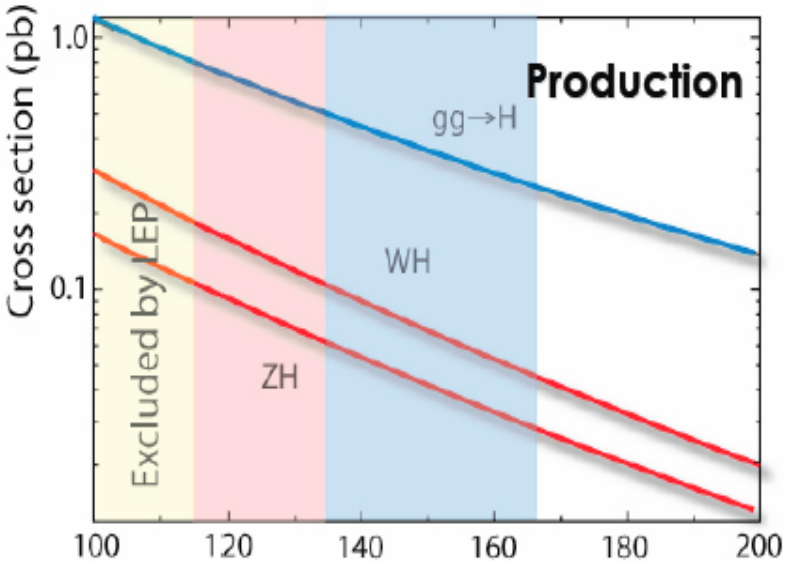
# Higgs at the Tevatron

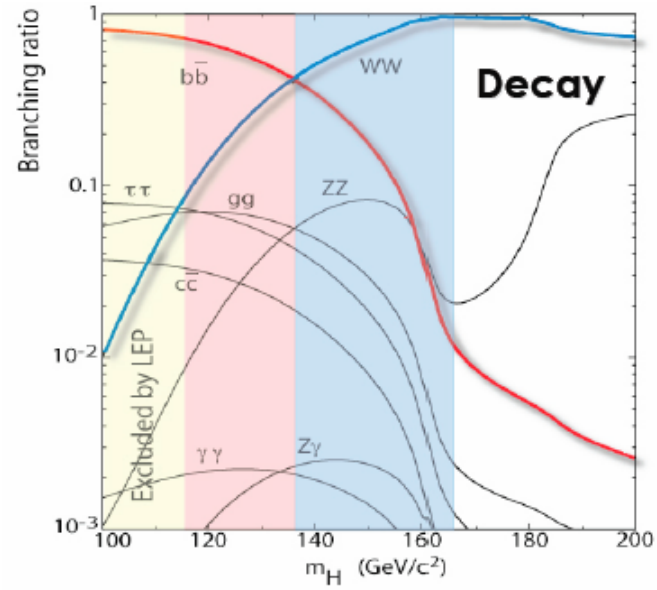
- Largest rate, $gg \to h$, $h \to b\bar{b}$, is overwhelmed by background




$\sigma(gg \to h) \sim 1$ pb $<< \sigma(b\bar{b})$

# Looking for the Higgs at the Tevatron

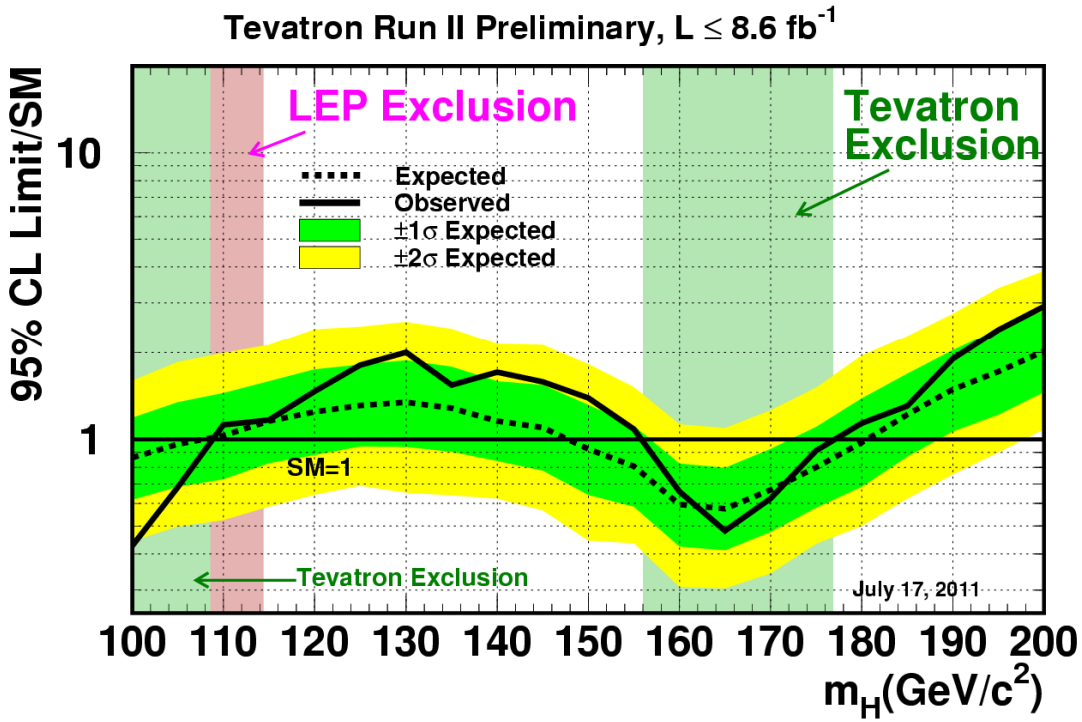



- High mass: Look for $h \to WW^*$
  Large $gg \to h$ production rate

- Low Mass: $h \to b\bar{b}$, Huge QCD $b\bar{b}$ background
  Use associated production with W or Z

# Tevatron Higgs Exclusion



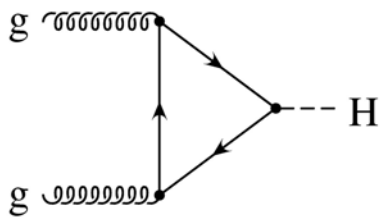

Limits normalized to Standard Model predictions

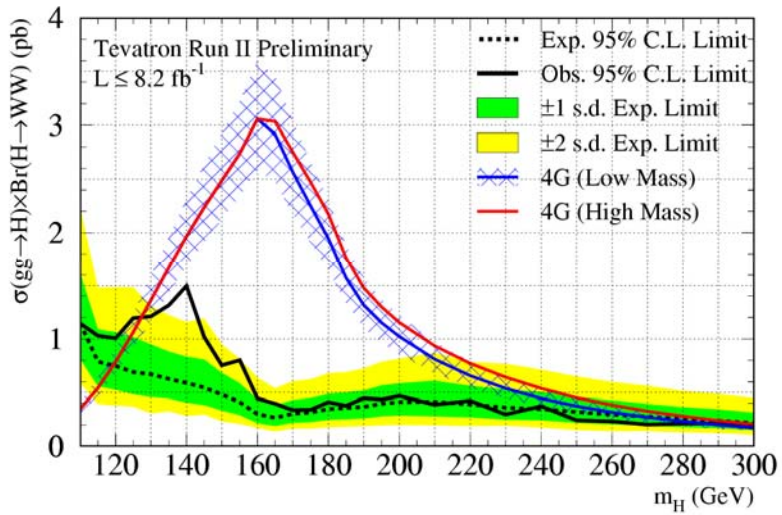
Tevatron Exclusion: [100 GeV < $M_h$ < 109 GeV],

[156 GeV < $M_h$ < 177 GeV]

# Gluon fusion counts generations

- $4^{th}$ generation (b',t') increases rate by factor of 9

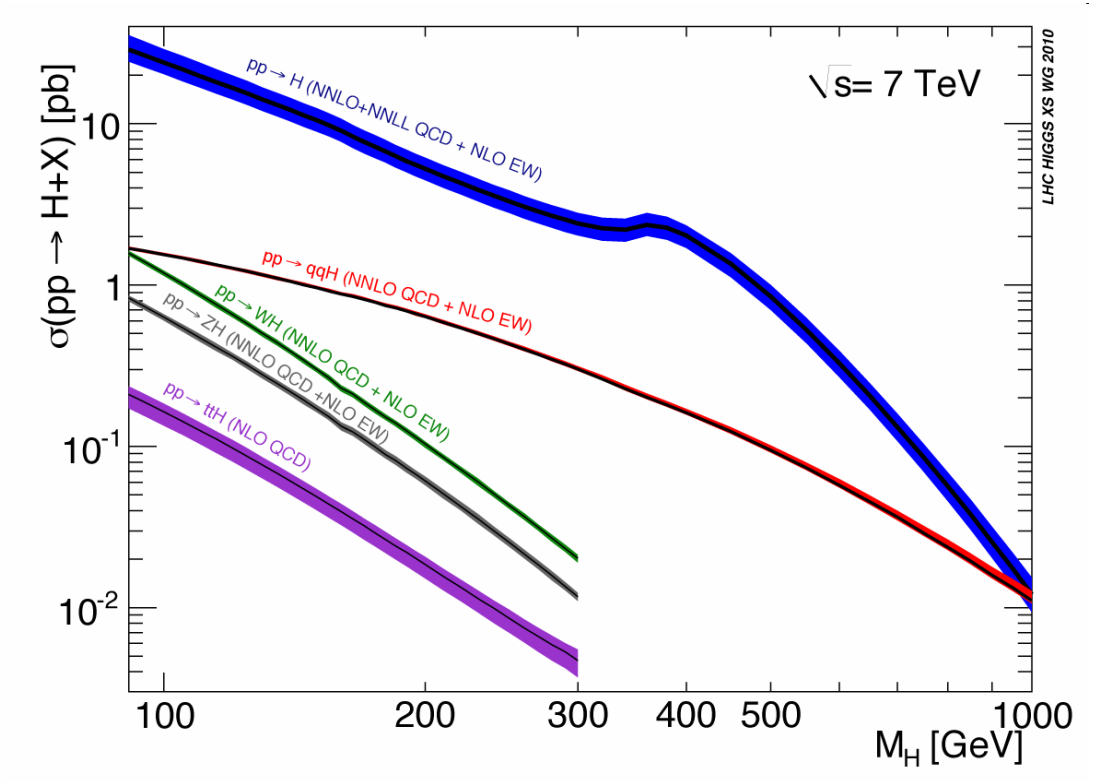



Look for $gg \rightarrow h \rightarrow W^+W^-$

Excludes 124 GeV < $M_h$ < 286 GeV if heavy $4^{th}$ generation

# Production Mechanisms at the LHC




Bands show scale dependence

All important channels calculated to NLO or NNLO

# Do some numbers…

- ATLAS and CMS have ~ 2.5 $fb^{-1}$ of data
- For $M_h$=120 GeV:
  - $\sigma$(gluon fusion)=17 pb
  - 42,500 Higgs events
  - But we have to see them:
    - Branching ratio $h \rightarrow \gamma\gamma$ = 2 x $10^{-3}$ $\Rightarrow$ 85 events
    - Branching ratio $h \rightarrow$4 leptons = 8 x $10^{-5}$ (l=e,$\mu$) $\Rightarrow$ 3.4 events
- For $M_h$=180 GeV:
  - $\sigma$(gluon fusion)=7 pb
  - 17,500 Higgs events
    - Branching ratio $h \rightarrow \gamma\gamma$ = 1 x $10^{-4}$ $\Rightarrow$ 1.75 events
    - Branching ratio $h \rightarrow$4 leptons = 3 x $10^{-4}$ (l=e,$\mu$) $\Rightarrow$ 5.2 events

Event numbers further reduced by detector efficiency…

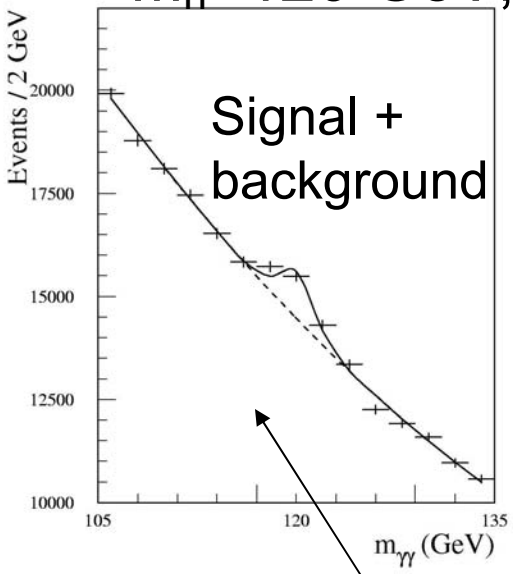
# Search Channels at the LHC

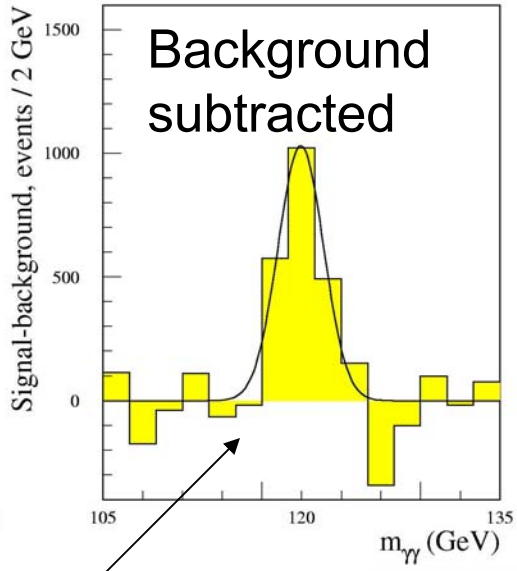
$gg \rightarrow h \rightarrow b\bar{b}$ has huge QCD background: Must use rare decay modes of h

- $gg \rightarrow h \rightarrow \gamma\gamma$
  - Small BR ($10^{-3}$ – $10^{-4}$)
  - Only measurable for $M_h < 140$ GeV
- Largest Background: QCD continuum production of $\gamma\gamma$
- Also from $\gamma$-jet production, with jet faking $\gamma$, or fragmenting to $\pi^0$
- Fit background from data

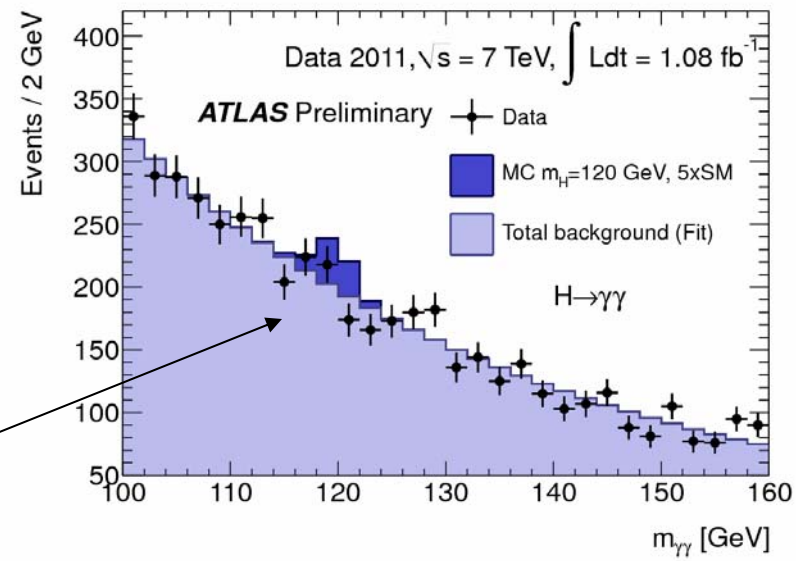
# $h \rightarrow \gamma\gamma$

$M_h$=120 GeV; L=100 $fb^{-1}$




Monte Carlo predictions



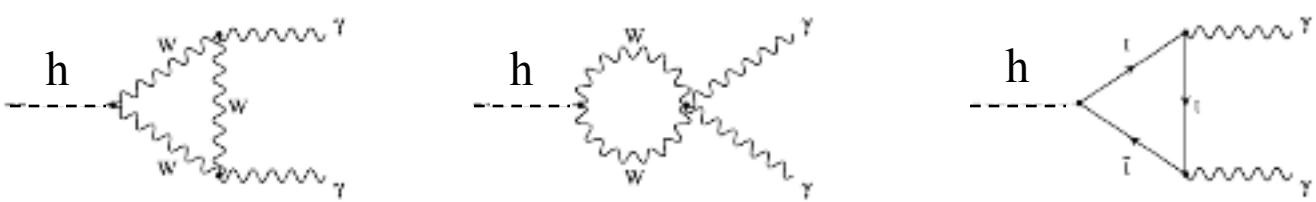

Data

# Higgs Decays to Photons

- Dominant contribution is W loops
- Contribution from top is small

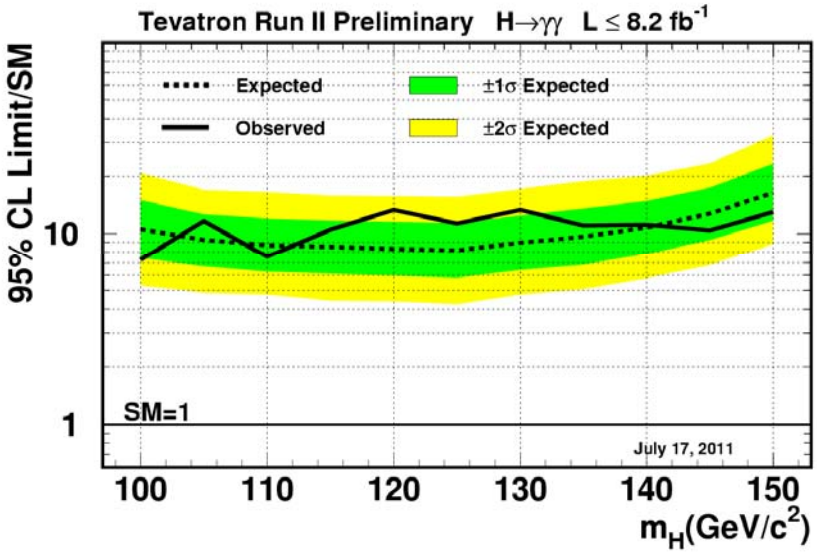
$$\Gamma(h \to \gamma\gamma) \approx \frac{\alpha^3}{256\pi^2 s_W^2} \frac{M_h^3}{M_W^2} \left| 7 - \frac{16}{9} + \ldots \right|^2$$

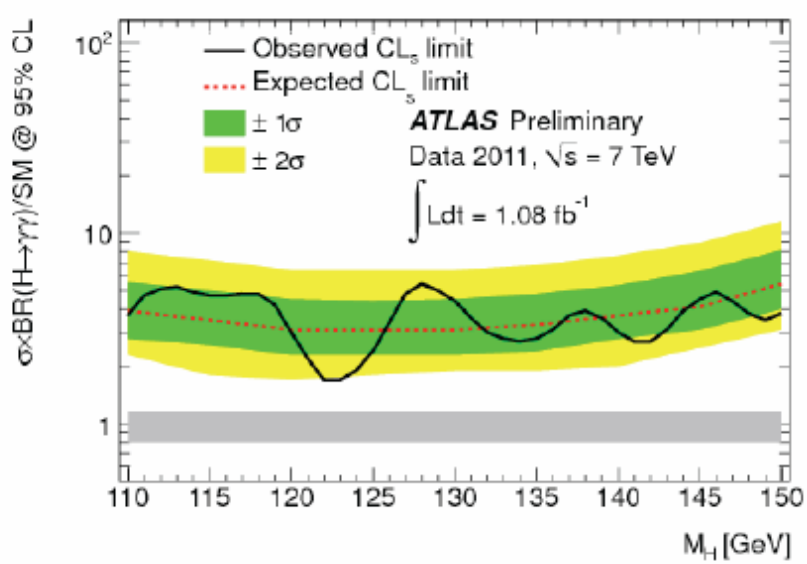
W top



# $h \rightarrow \gamma\gamma$

- Sensitive to new physics in loops

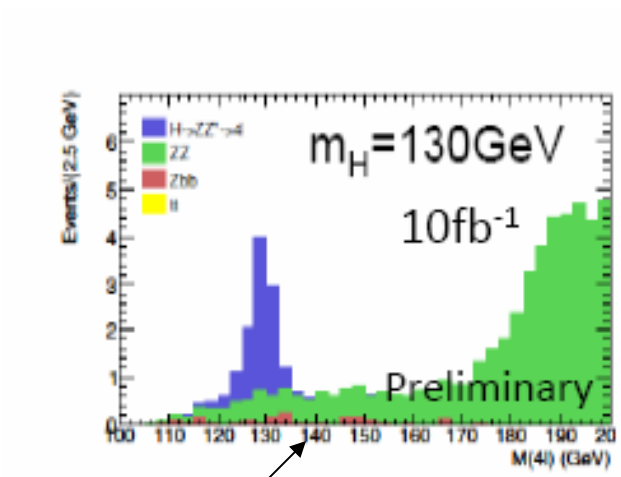


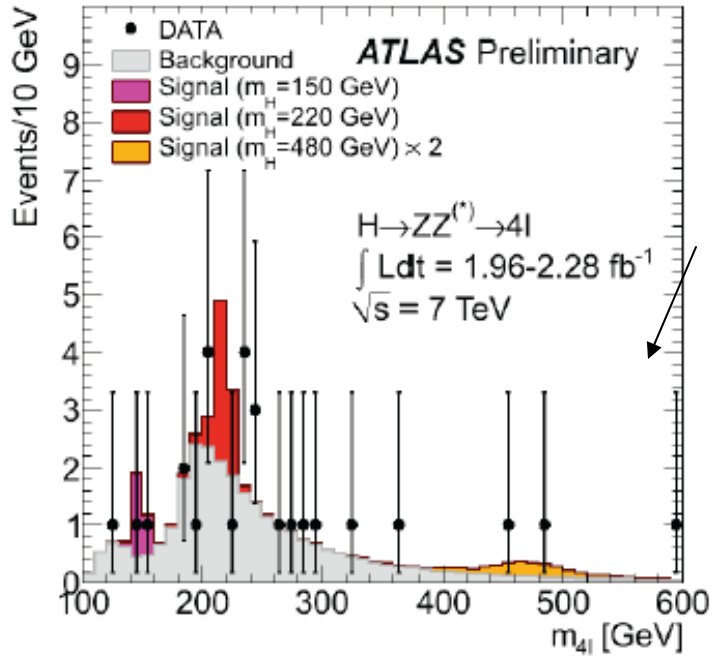




***Factor of 5-10 from SM sensitivity***

# Golden Channel: h→ZZ→4 leptons

- Reconstruct Higgs mass



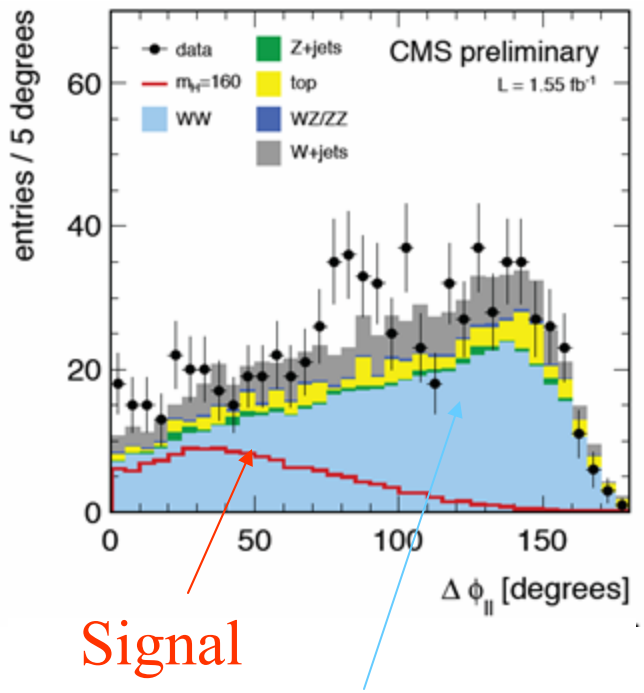

Data

Monte Carlo predictions

- Below $M_h$ ~130 GeV, rate is too small for discovery

# What about $h \rightarrow W^+W^-$ ?

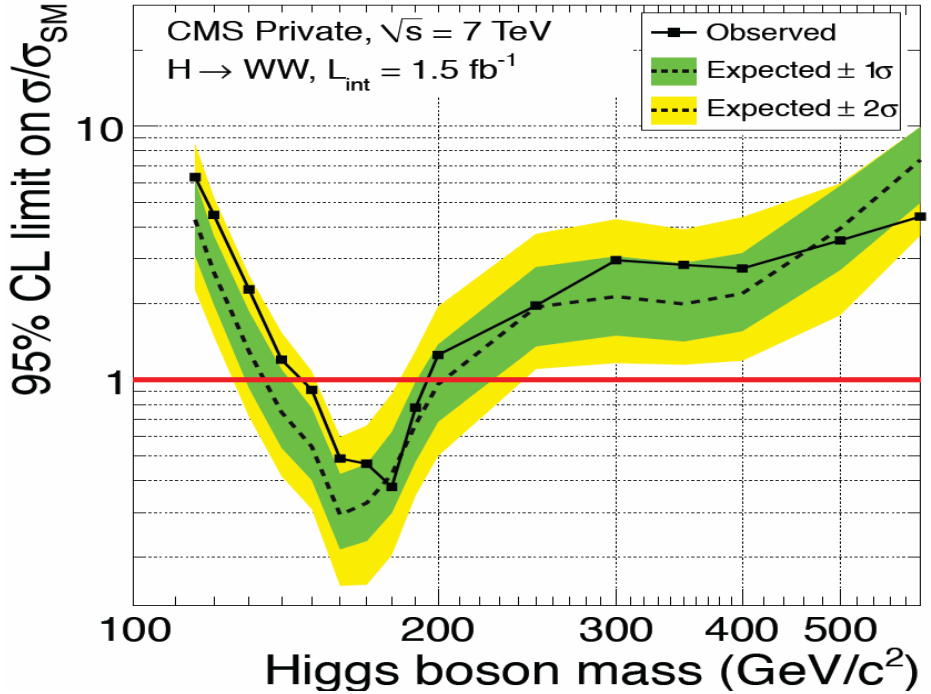
- Large rate (good)
- Look for $W \rightarrow l\nu$
  - Can't reconstruct mass peak (bad)
- Background from $q\bar{q} \rightarrow Z^* \rightarrow W^+W^-$ (vector decay)
- Signal from $gg \rightarrow h \rightarrow W^+W^-$ (scalar decay)
  - Angular distributions help



# Limit from $h \rightarrow W^+W^-$

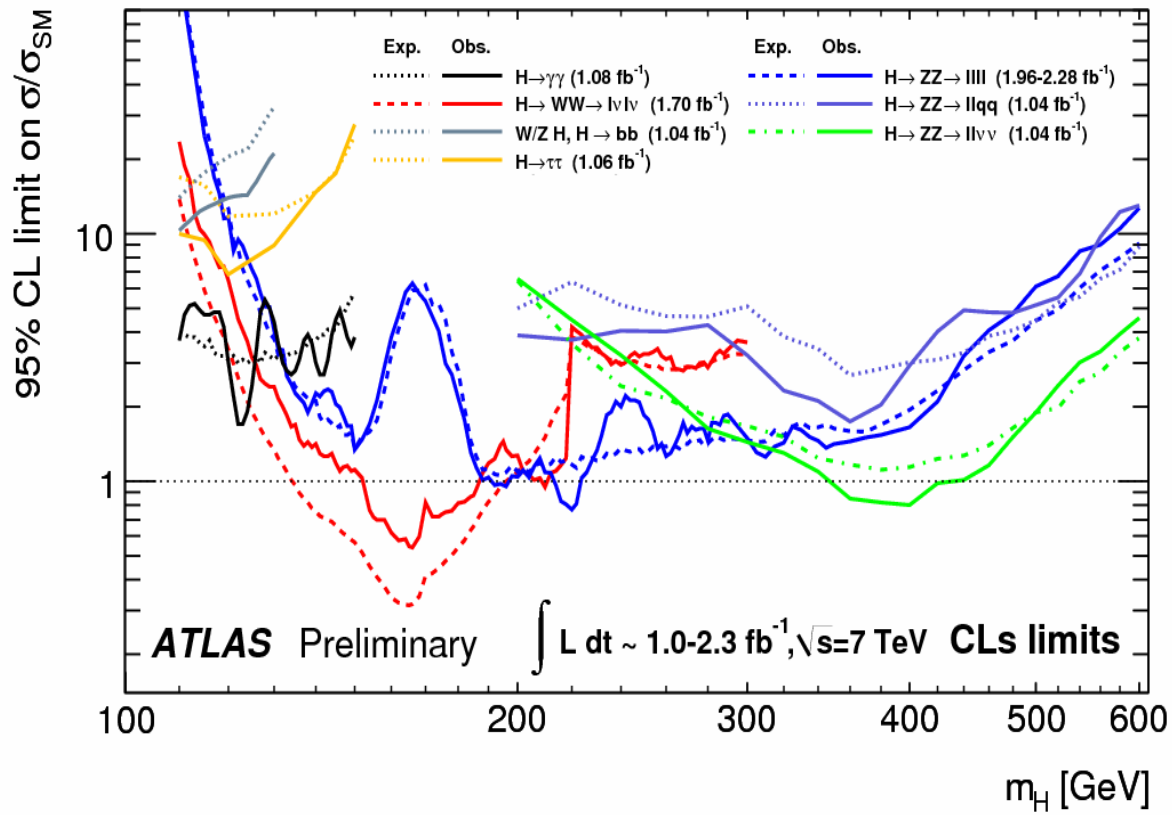
- CMS: **$147 < M_h < 194$ GeV** ruled out at 95% cl

- SM Higgs boson <u>expected</u> sensitivity $136 < M_h < 200$ GeV



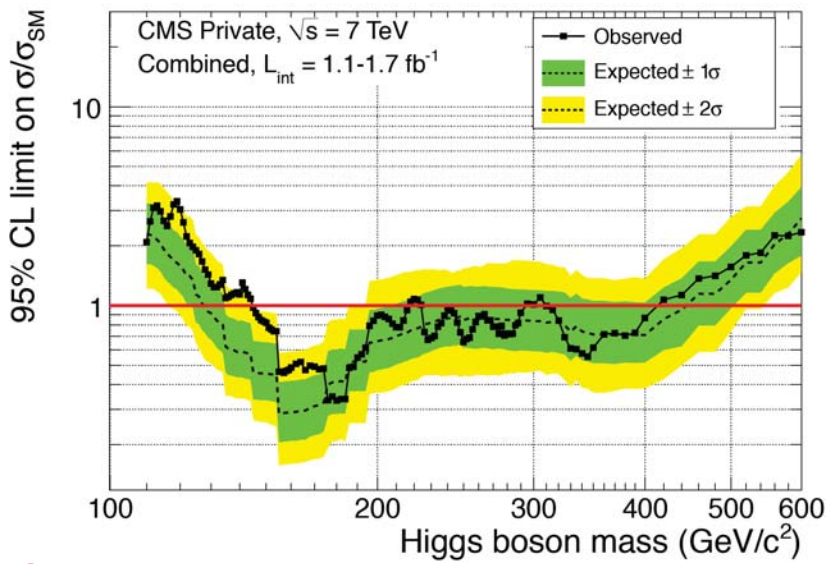

Source of rumors, blog posts, etc….

# Many Channels contribute to Limits




[146<$M_h$<232 GeV, 256<$M_h$<282, 296 < $M_h$ <466 GeV] ATLAS

# Higgs Limits from the LHC




95% CL exclusion:

[$145<M_h<216$ Gev, $226<M_h<288$, $310<M_h<440$ GeV] CMS

# Higgs Discovery

$\sqrt{s}$=7 TeV

| ATLAS + CMS ≈ 2 x CMS | 95% CL exclusion | 3σ sensitivity | 5σ sensitivity |
|---|---|---|---|
| 1 $fb^{-1}$ | 120 - 530 | 135 - 475 | 152 - 175 |
| 2 $fb^{-1}$ | 114 - 585 | 120 - 545 | 140 - 200 |
| 5 $fb^{-1}$ | 114 - 600 | 114 - 600 | 128 - 482 |
| 10 $fb^{-1}$ | 114 - 600 | 114 - 600 | 117 - 535 |

If the SM Higgs exists, we'll know soon

# Is it a Higgs?

- How do we know what we've found?
- Measure couplings to fermions & gauge bosons

$$\frac{\Gamma(h \to b\bar{b})}{\Gamma(h \to \tau^+\tau^-)} \approx 3\frac{m_b{}^2}{m_\tau{}^2}$$

- Measure spin/parity

$$J^{PC} = 0^{++}$$

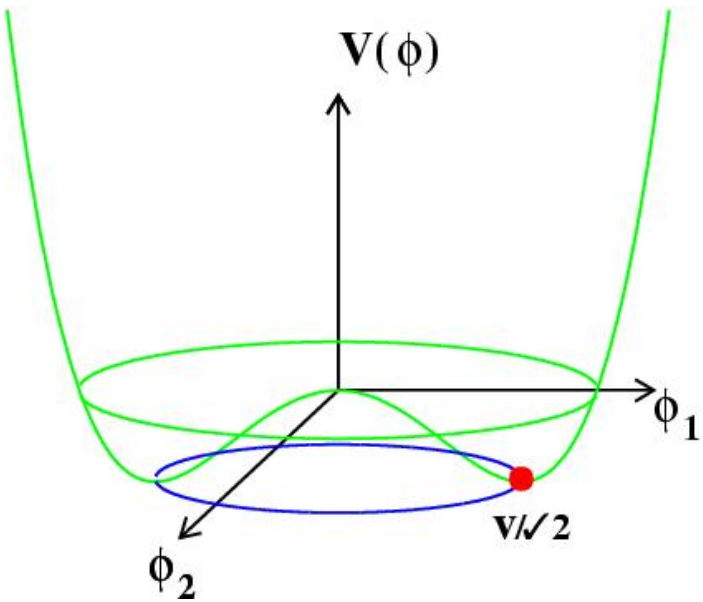
- Measure self interactions

$$V = \frac{M_h{}^2}{2}h^2 + \frac{M_h{}^2}{2v}h^3 + \frac{M_h{}^2}{8v^2}h^4$$

# Can we reconstruct the Higgs potential?

$$V = \frac{M_h^{\ 2}}{2} h^2 + \lambda_3 v h^3 + \frac{\lambda_4}{4} h^4$$

$$\boxed{SM: \ \lambda_3 = \lambda_4 = \frac{M_h^{\ 2}}{2v^2}}$$




- Fundamental test of model!

- We have no idea how to measure $\lambda_4$

# ??????????????

- Within the next 1-2 years, we should know whether or not a SM-like Higgs exists
- We can already put meaningful limits on many models
- The fun is just beginning