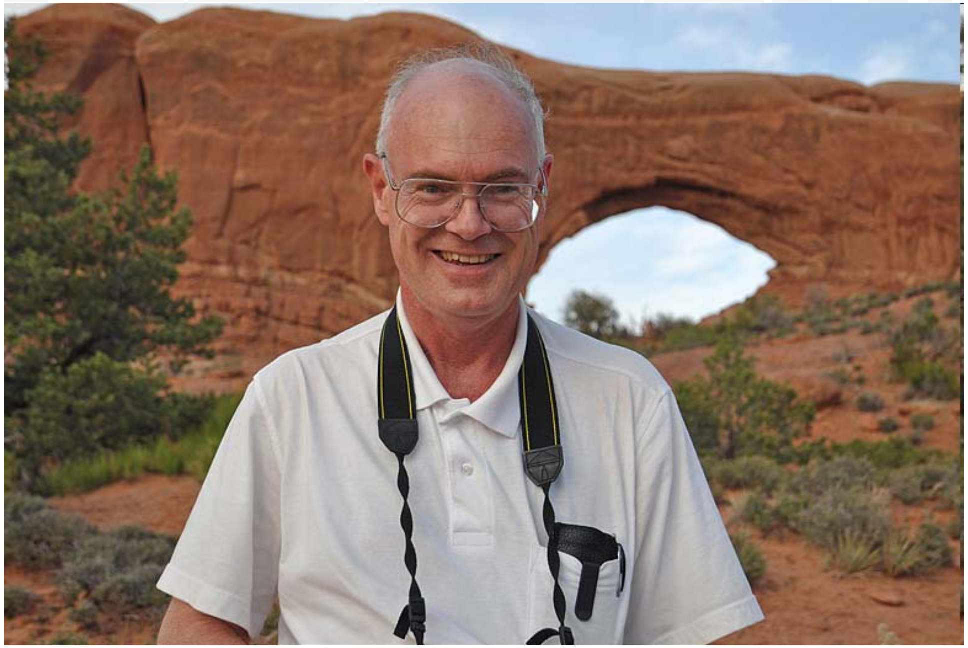
Exploring Electroweak Symmetry Breaking



S. Dawson, BNL

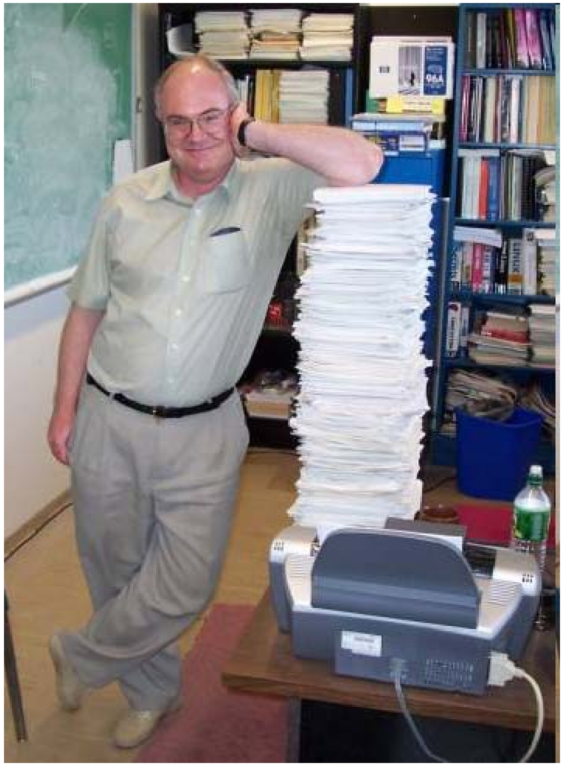
U. Baur Memorial Symposium

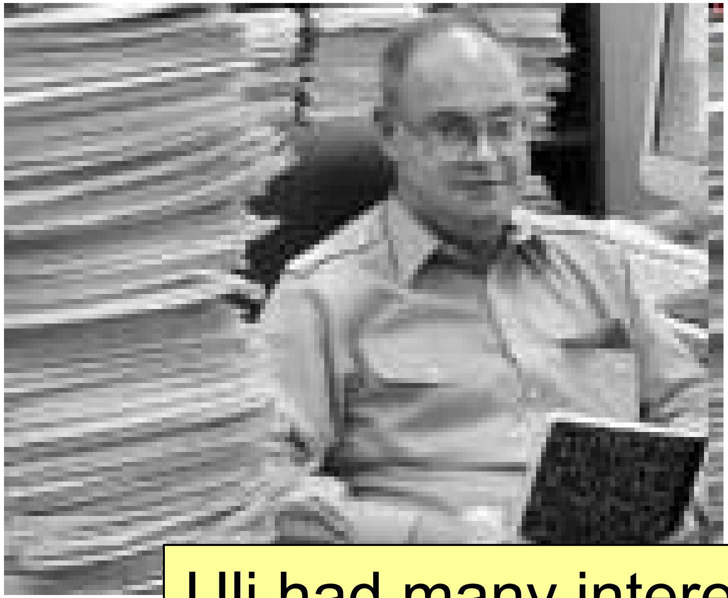
September 24, 2011

Buffalo, NY

Uli was a leader in the physics of EWSB

- I will speak about Uli's seminal work on electroweak symmetry breaking and how it fits into the big picture of particle physics

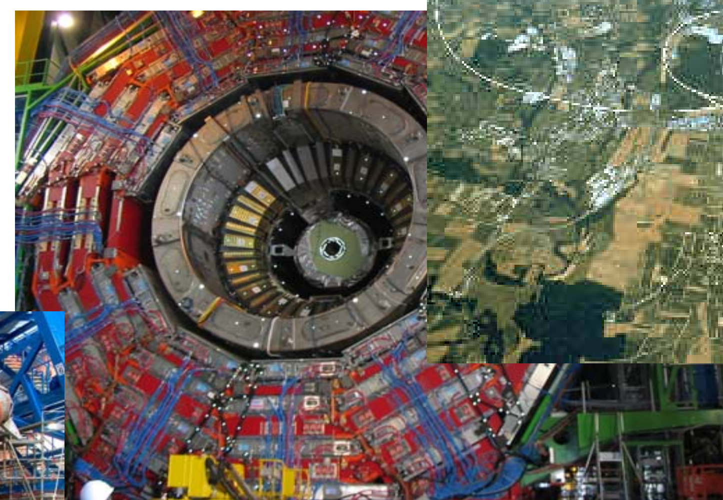


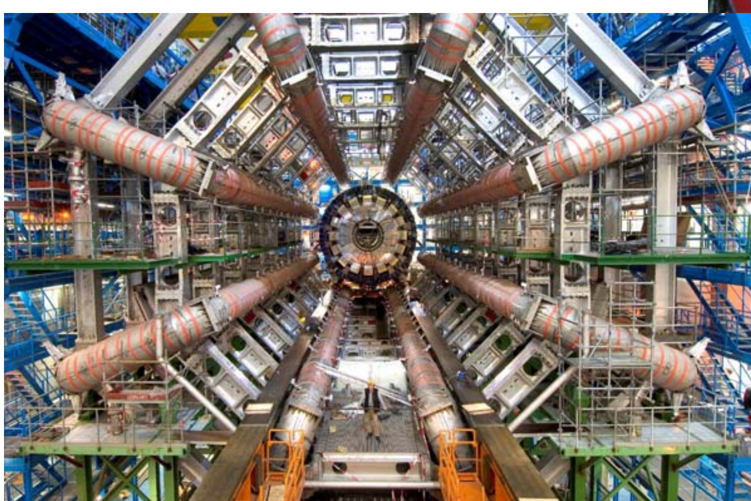


Uli had many interests!

Exciting times: Large Hadron Collider

- proton-proton collider at CERN running now!
- 7 TeV total energy
- Total integrated luminosity ~3 fb^{-1}
- Typical energy of quarks and gluons 1-2 TeV

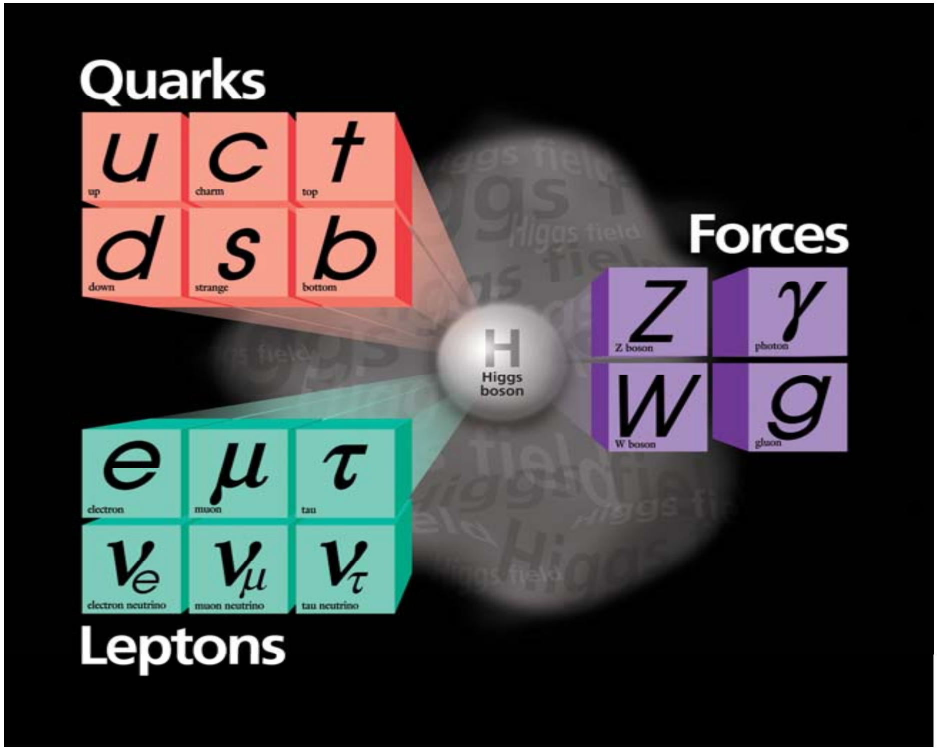




If there is a SM Higgs boson, we expect it soon!

Standard Model

- Particle physics has a “Standard Model” of particles and their interactions



Quarks come in pairs with charge 2/3 e and -1/3 e

Each lepton has its own neutrino

Force carriers communicate between quarks and leptons

Standard Model is Predictive

- Standard model provides excellent interpretation of experimental data starting with LEP/SLD
- Where is electroweak symmetry breaking?

Experimental data consistent with Standard Model with single scalar boson, H

Standard Model Synopsis

- Group: SU(3) x SU(2) x U(1)

  QCD (SU(3)) Electroweak (SU(2) x U(1))

- Gauge bosons:
  - SU(3): G_μ^i, i=1…8
  - SU(2): W_μ^i, i=1,2,3
  - U(1): B_μ
- Gauge couplings: g_s, g, g'
- Complex SU(2) Higgs doublet: Φ

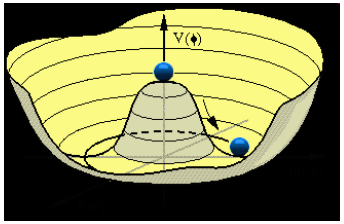
Higgs boson is missing link in our understanding

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:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\Phi \rightarrow e^{i\varpi^a \cdot \sigma^a / v} \begin{pmatrix} 0 \\ \frac{h+v}{\sqrt{2}} \end{pmatrix}$$

  – Choice of minimum breaks symmetry

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, μ^2, λ

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

- Trade μ^2, λ 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

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

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

- Only free parameter is Higgs mass!

Predictions

- Four free parameters in gauge-Higgs sector (g, g', μ, λ)
  - Conventionally chosen to be
    - α=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

Beyond Tree Level

- Predict M_W

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

  – Plug in numbers:
    - M_W predicted =80.939 GeV
    - M_W experimental =80.399 $\pm$ 0.023 GeV

  – Need to calculate beyond tree level

Precision measurements require precision calculations

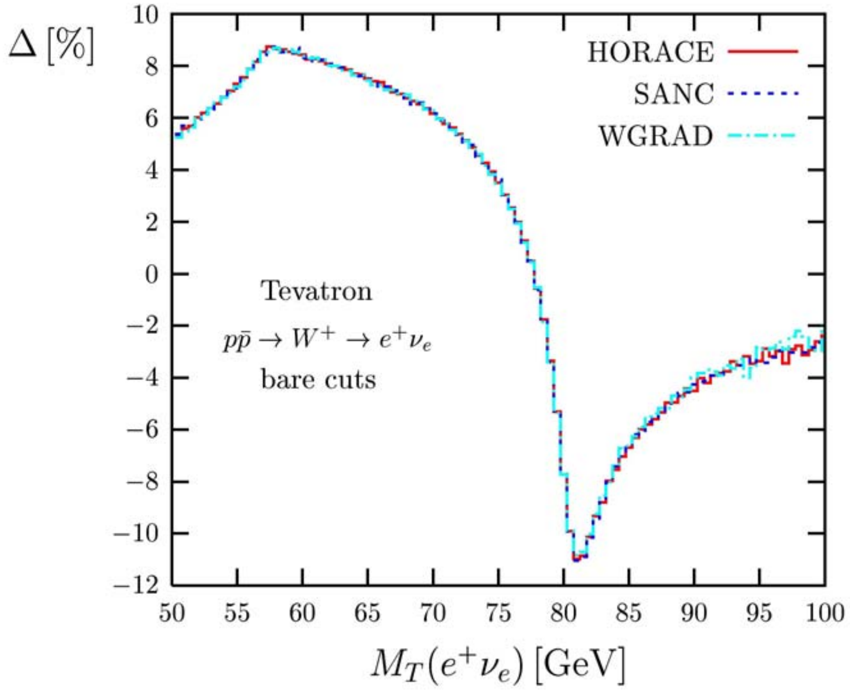
Match theory/experiment precision on M_W

- Goal: $\delta M_W < 10$ MeV at LHC
- QCD corrections smear Jacobian peak
  - NNLO differential cross section (FEWZ)
  - NLL (RESBOS)
  - NLO matched to Herwig with MC@NLO and POWHEG
- Electroweak corrections shift mass ~ 100 MeV (WGRAD, ZGRAD)

Years of work to get to current understanding

Electroweak Corrections to M_W

- Electroweak corrections change kinematic distributions

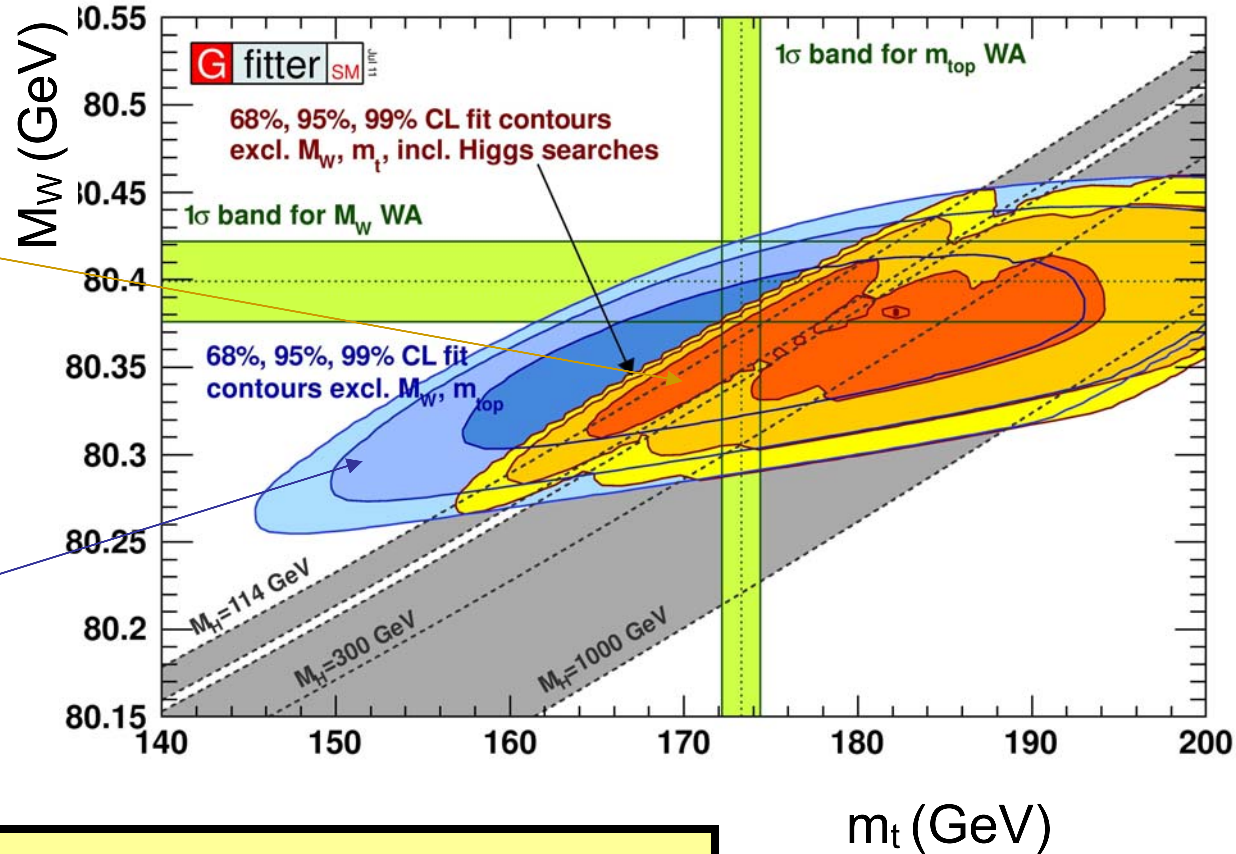


[Baur, Wackeroth]

M_W versus m_t

Masses inferred from precision measurements and Higgs searches*

Masses inferred from precision measurements

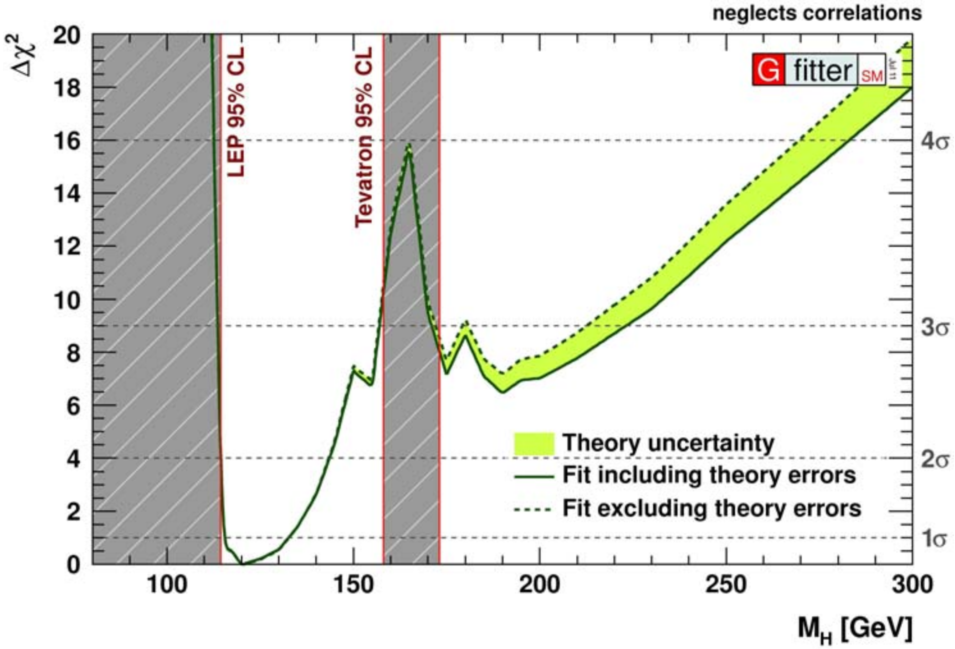


Higgs boson wants to be light

* 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/

Uli founded the Loopfest workshops in 2002

The Spirit of Loopfest

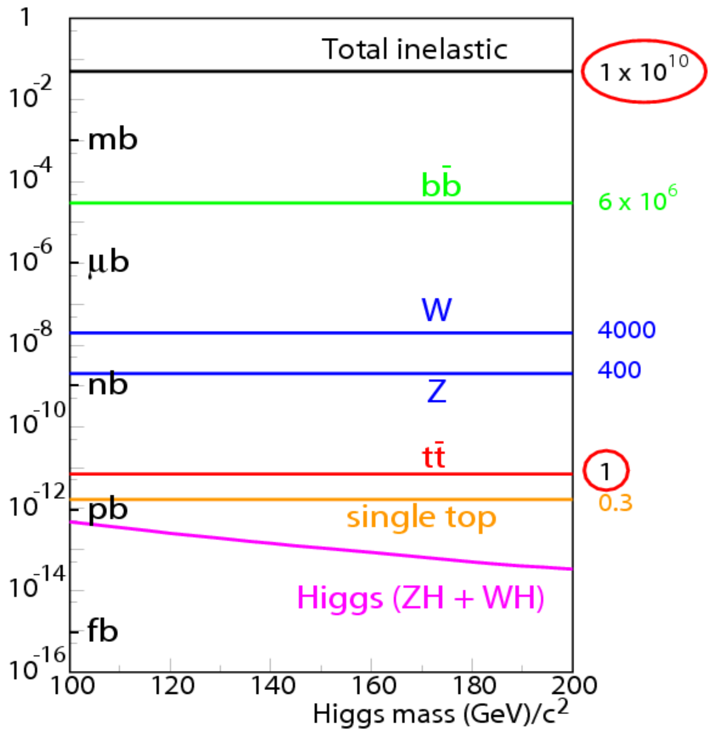
- A very democratic meeting
- The youngest post-doc gets the same time (and billing as the most senior physicist)

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

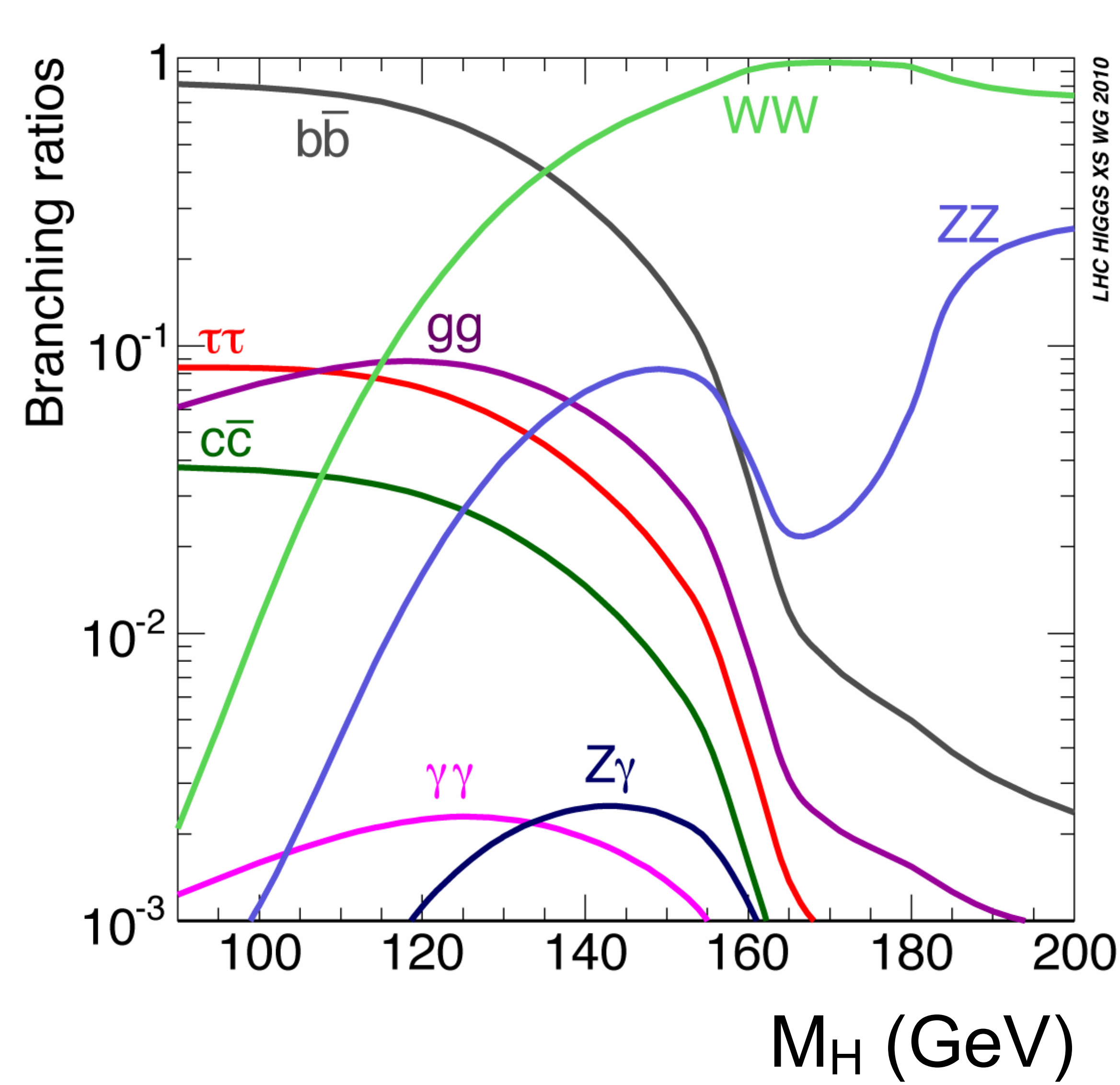
Higgs at the Tevatron

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

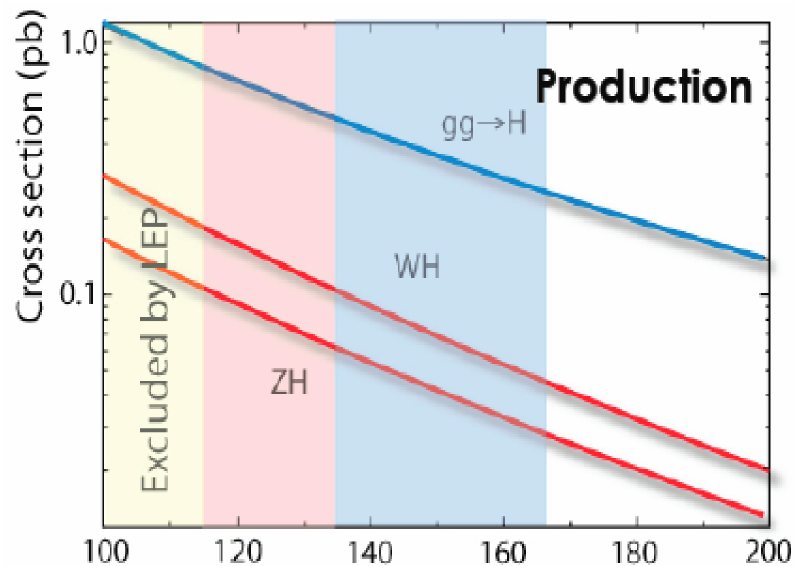


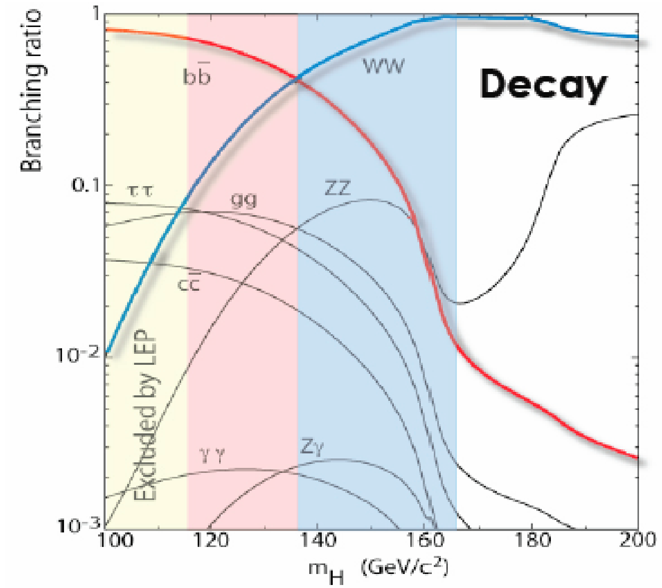
$\sigma(gg \to H) \sim 1$ pb $<< \sigma(b\bar{b})$

Higgs Branching Ratios



Looking for the Higgs at the Tevatron

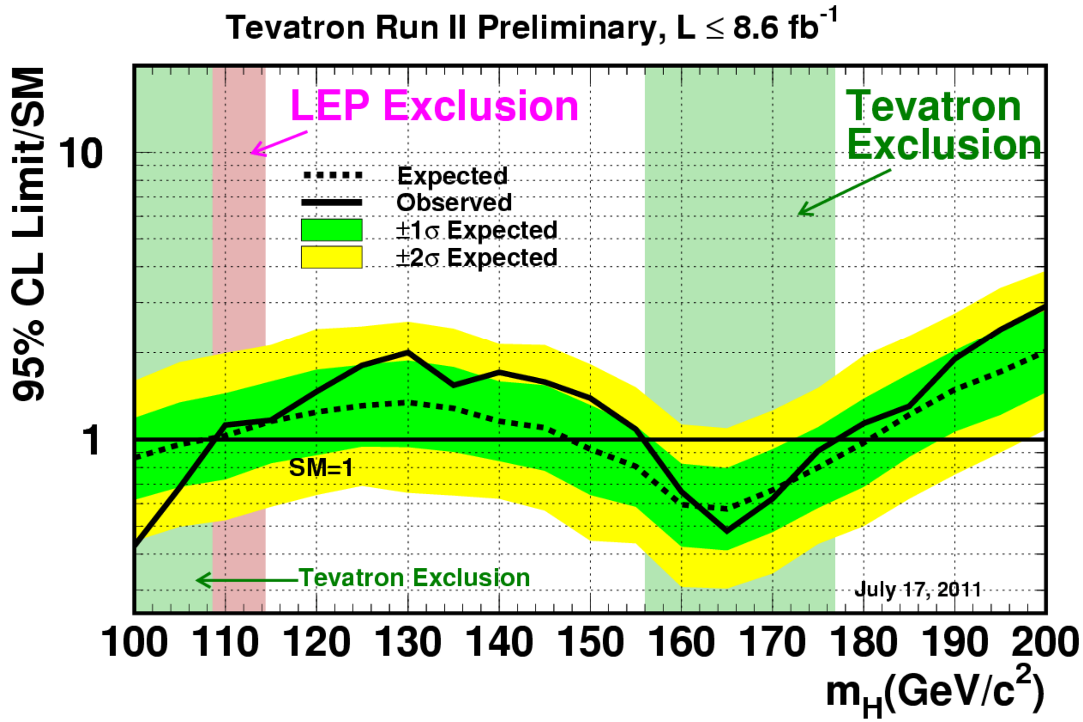




- High mass: Look for H→WW*
  Large gg→H production rate

- Low Mass: H→bb̄, Huge QCD bb̄ background
  Use associated production with W or Z

Tevatron Higgs Exclusion



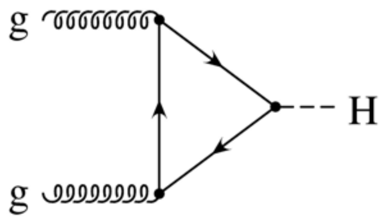
Limits normalized to Standard Model predictions

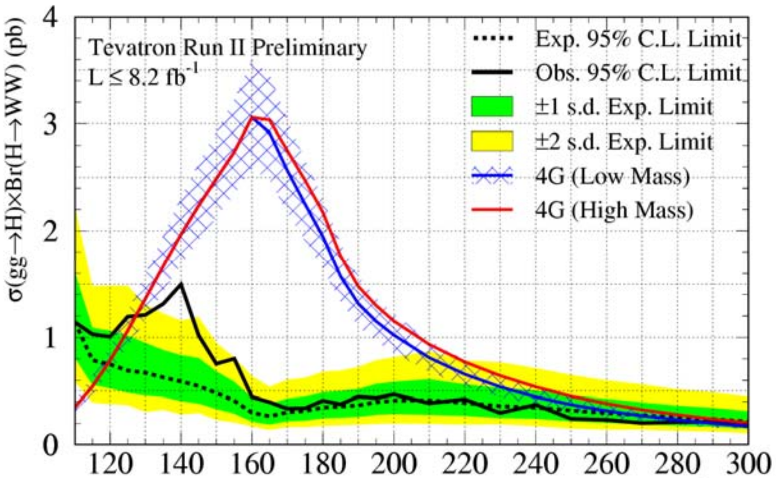
Tevatron Exclusion: [100 GeV < M_H < 109 GeV],

[156 GeV < M_H < 177 GeV]

Gluon fusion counts generations

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



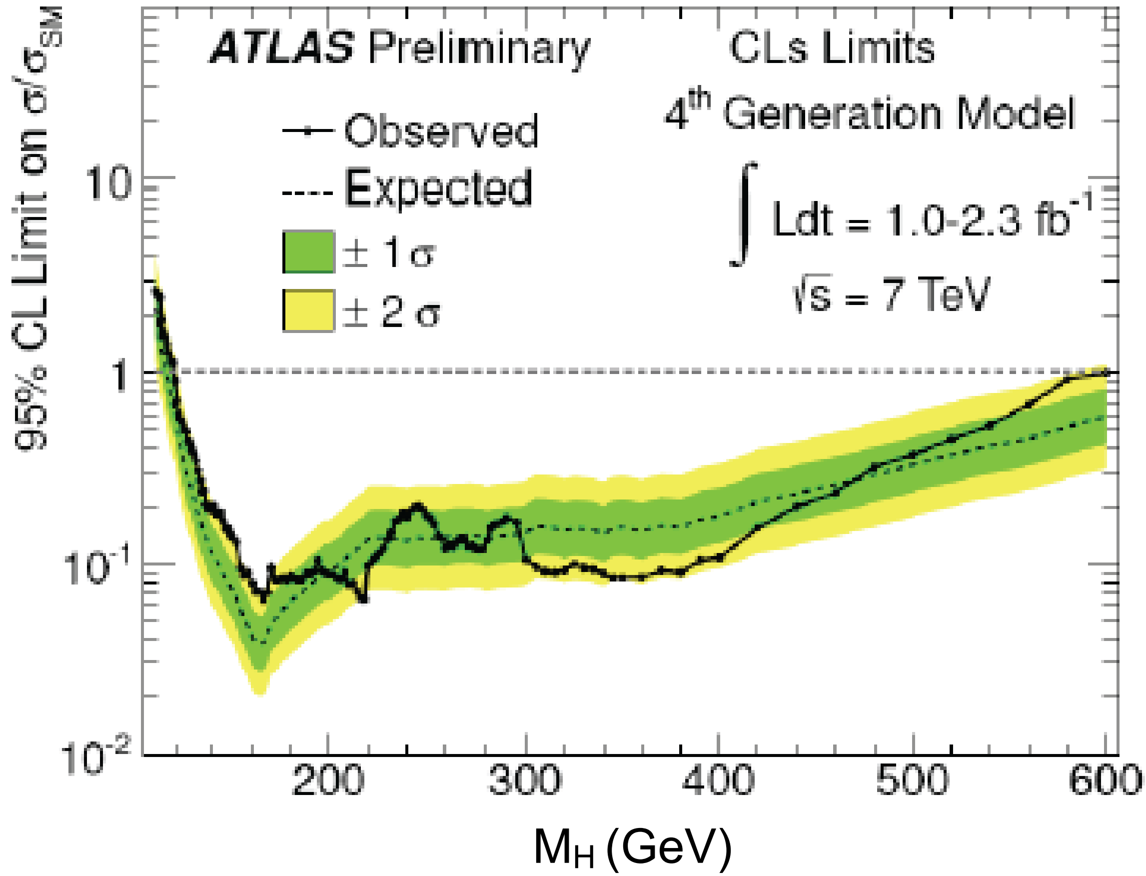


M_H (GeV)

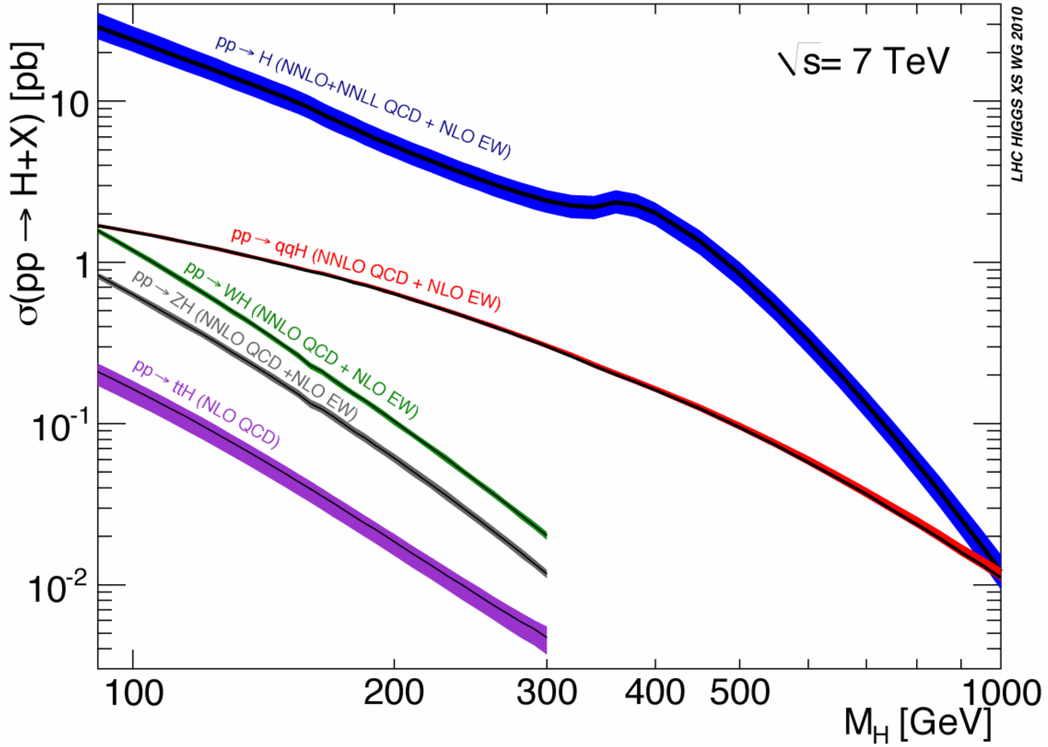
Look for $gg \rightarrow H \rightarrow W^+W^-$

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

LHC excludes Higgs + 4th Generation



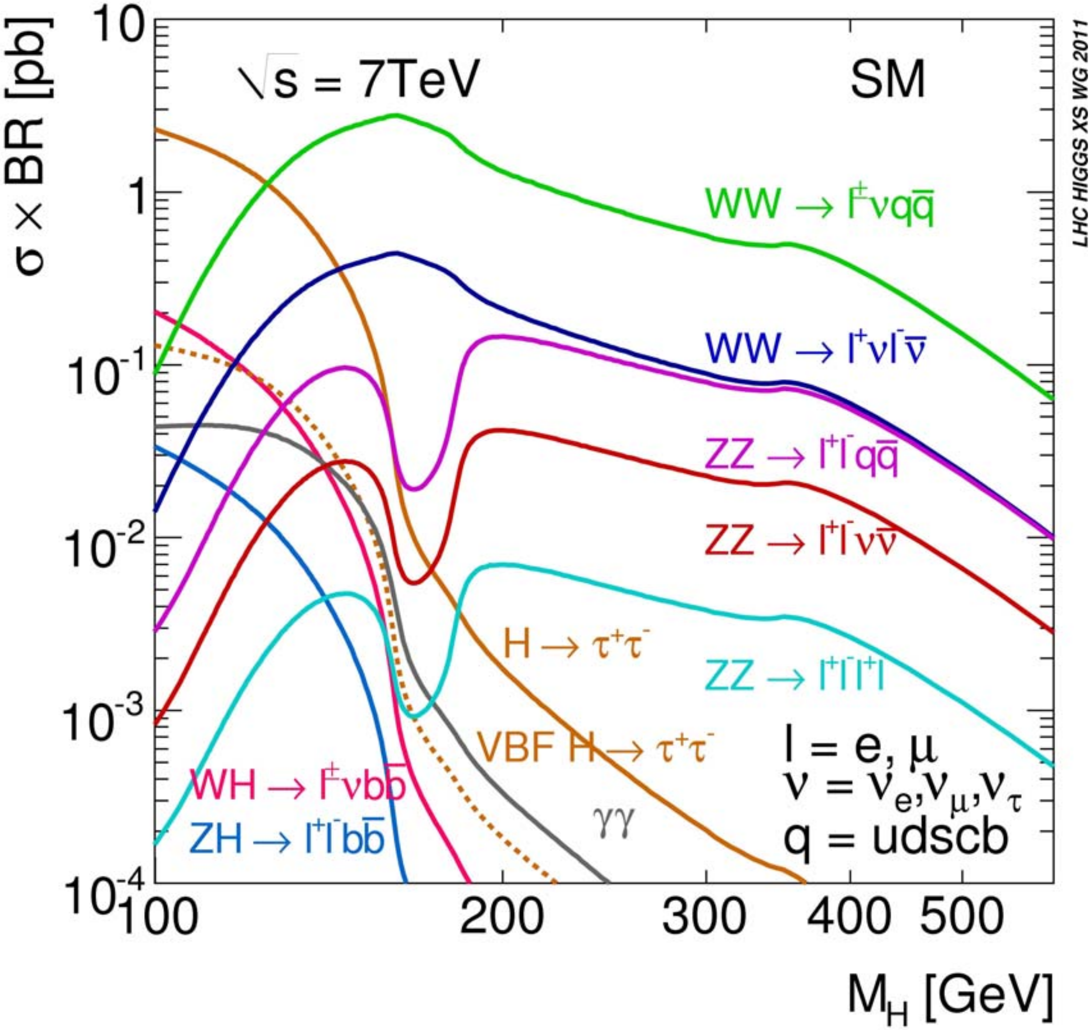
Production Mechanisms at the LHC



Bands show scale dependence

All important channels calculated to NLO or NNLO

More Branching Ratios



Do some numbers…

- ATLAS and CMS have ~ 2.5 fb $^{-1}$ of data

Now 3.5!

- For M_H=120 GeV:
  - σ(gluon fusion)=17 pb
  - 42,500 Higgs events
  - But we have to see them:
    - Branching ratio $H \to \gamma\gamma$ = 2 x 10^{-3} $\Rightarrow$ 85 events
    - Branching ratio $H \to 4$ leptons = 8 x 10^{-5} ($l=e,\mu$) $\Rightarrow$ 3.4 events
- For M_H=180 GeV:
  - σ(gluon fusion)=7 pb
  - 17,500 Higgs events
    - Branching ratio $H \to \gamma\gamma$ = 1 x 10^{-4} $\Rightarrow$ 1.75 events
    - Branching ratio $H \to 4$ leptons = 3 x 10^{-4} ($l=e,\mu$) $\Rightarrow$ 5.2 events

Event numbers further reduced by detector efficiency….

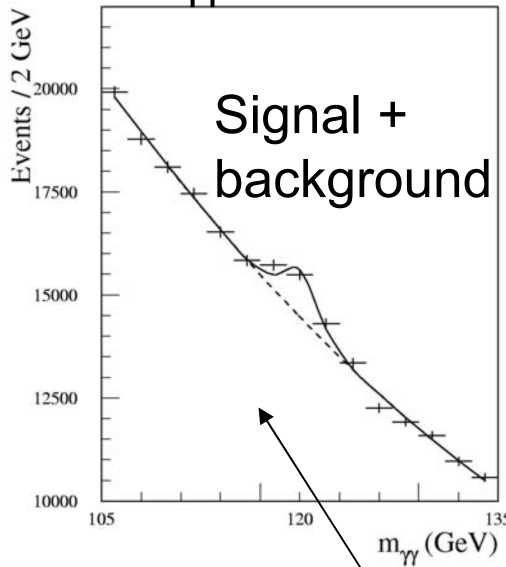
Search Channels at the LHC

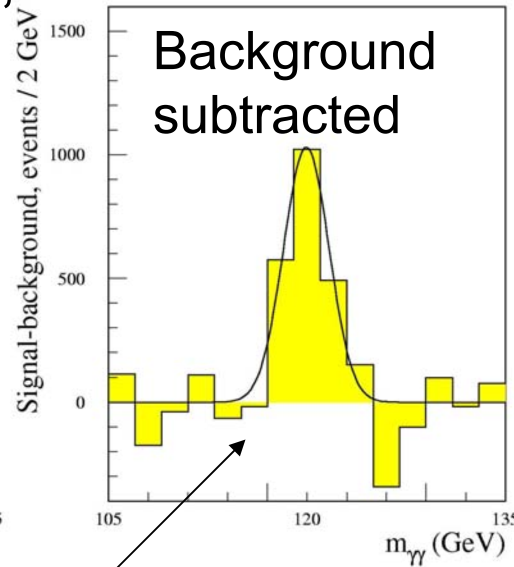
$gg \rightarrow H \rightarrow b\bar{b}$ has huge QCD background: Must use rare decay modes of h

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

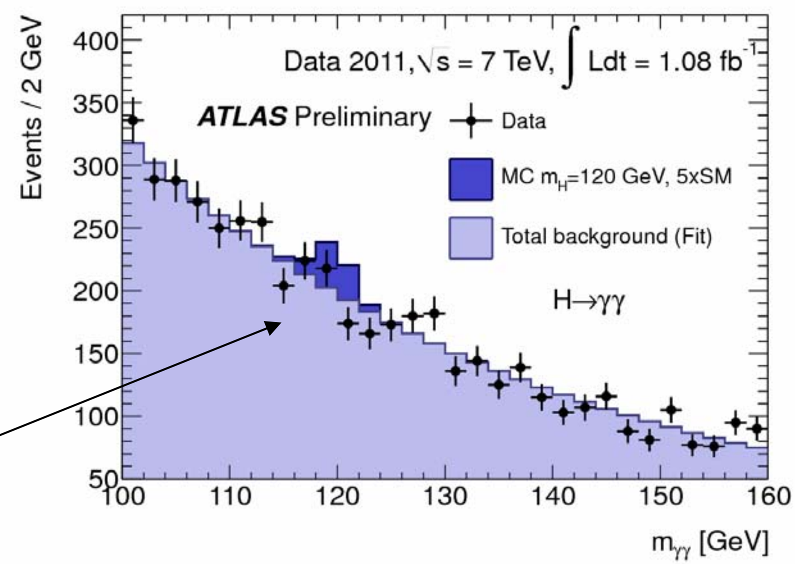
$H \rightarrow \gamma\gamma$

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





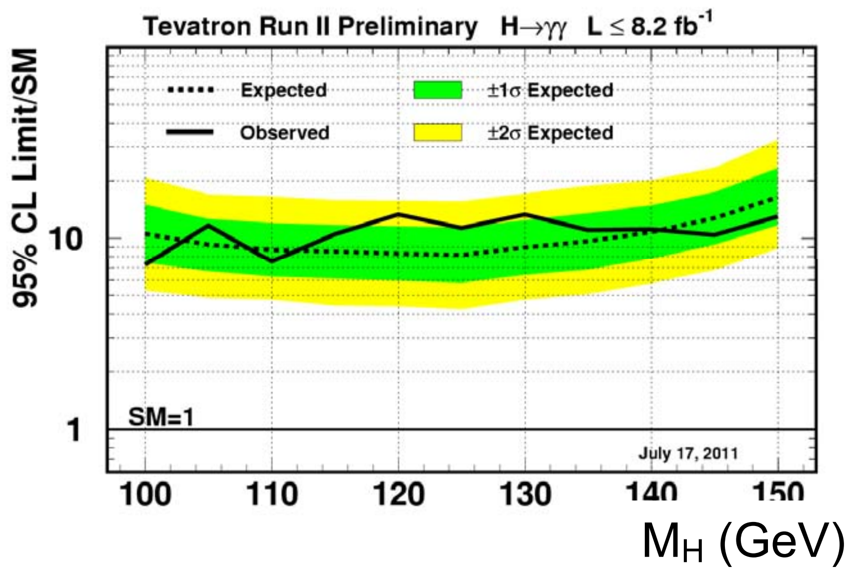
Monte Carlo predictions

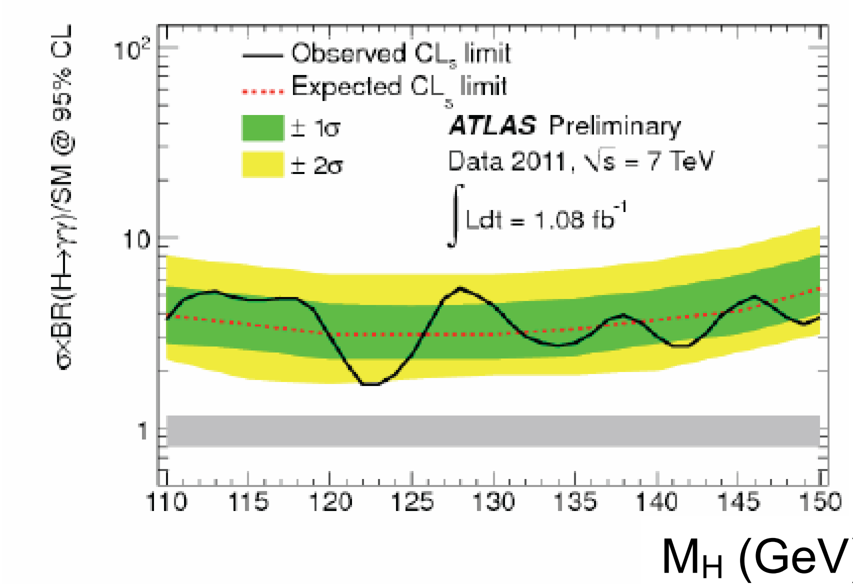


Data

H→γγ

- Sensitive to new physics in loops

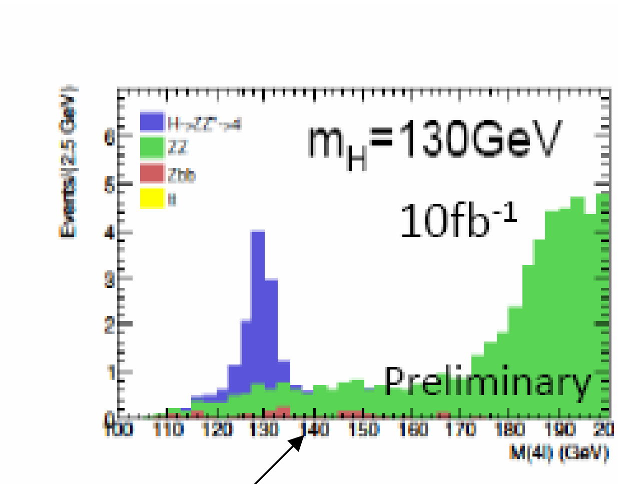


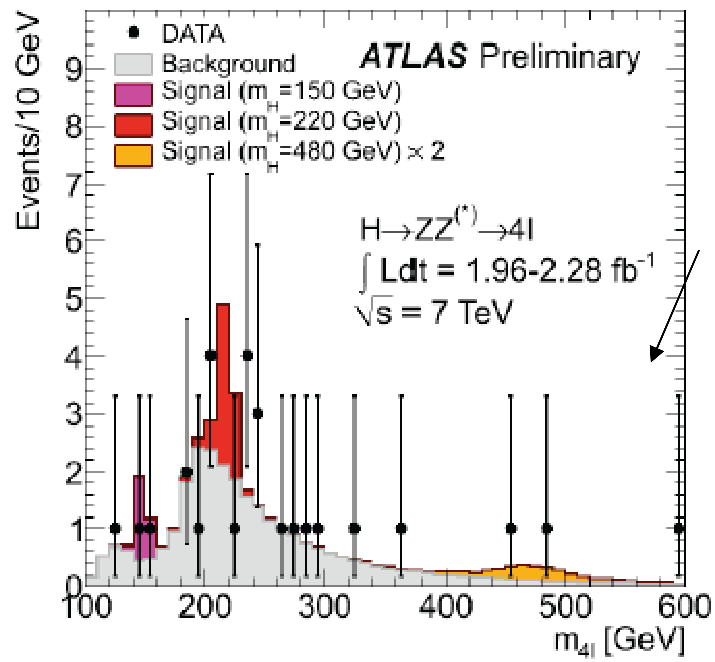


Factor of 5-10 from Standard Model sensitivity

Golden Channel: H→ZZ→4 leptons

- Reconstruct Higgs mass





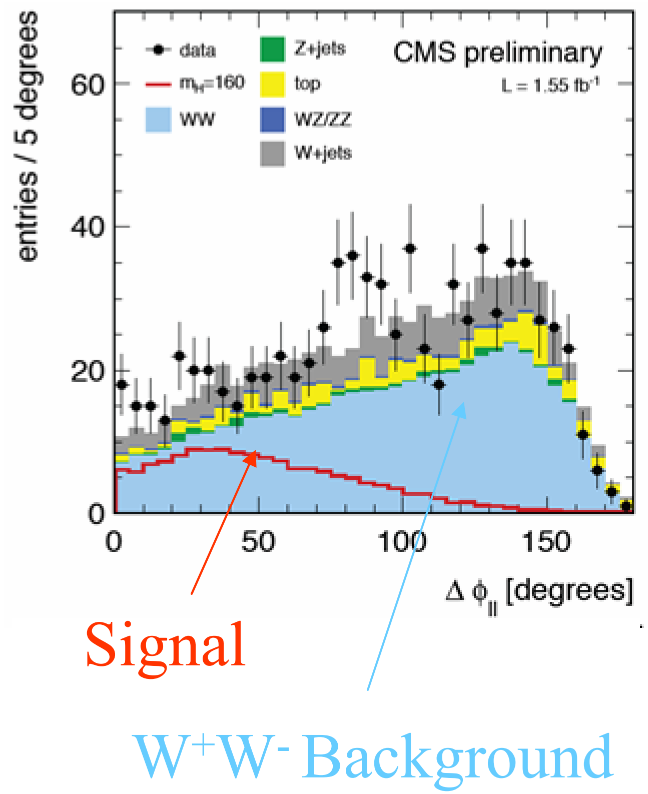
Monte Carlo predictions

Data

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

What about $H \rightarrow W^+W^-$?

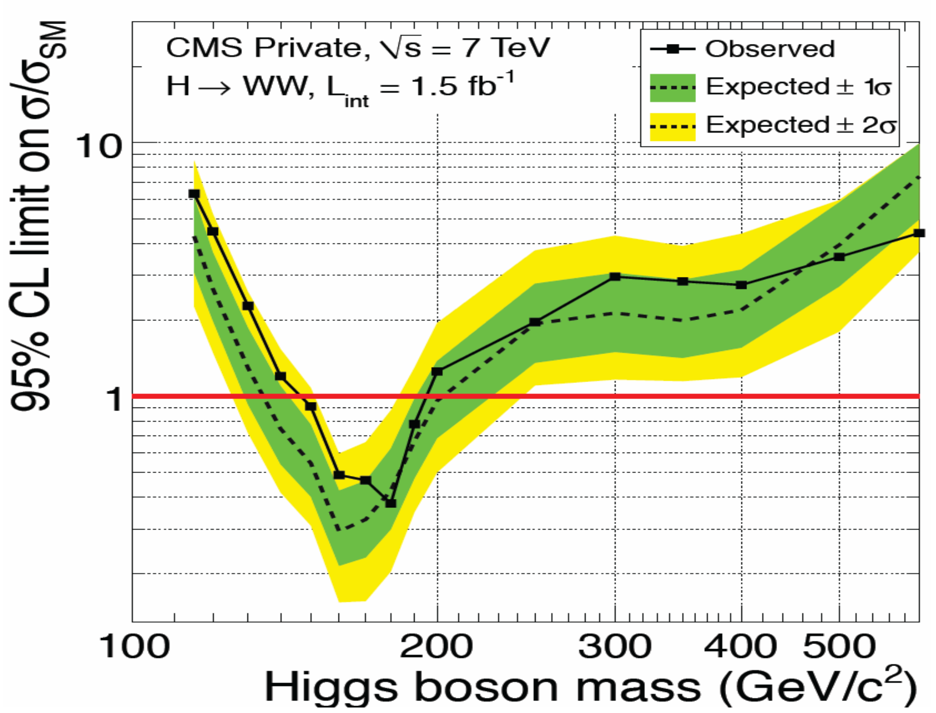
- Large rate (good)
- Look for $W \rightarrow l\nu$
  - Can't reconstruct mass peak (bad)
- Background from $q\bar{q} \rightarrow Z^* \rightarrow W^+W^-$ (vector decay)
- Signal from $gg \rightarrow H \rightarrow W^+W^-$ (scalar decay)
  - Angular distributions help



Limit from $H \rightarrow W^+W^-$

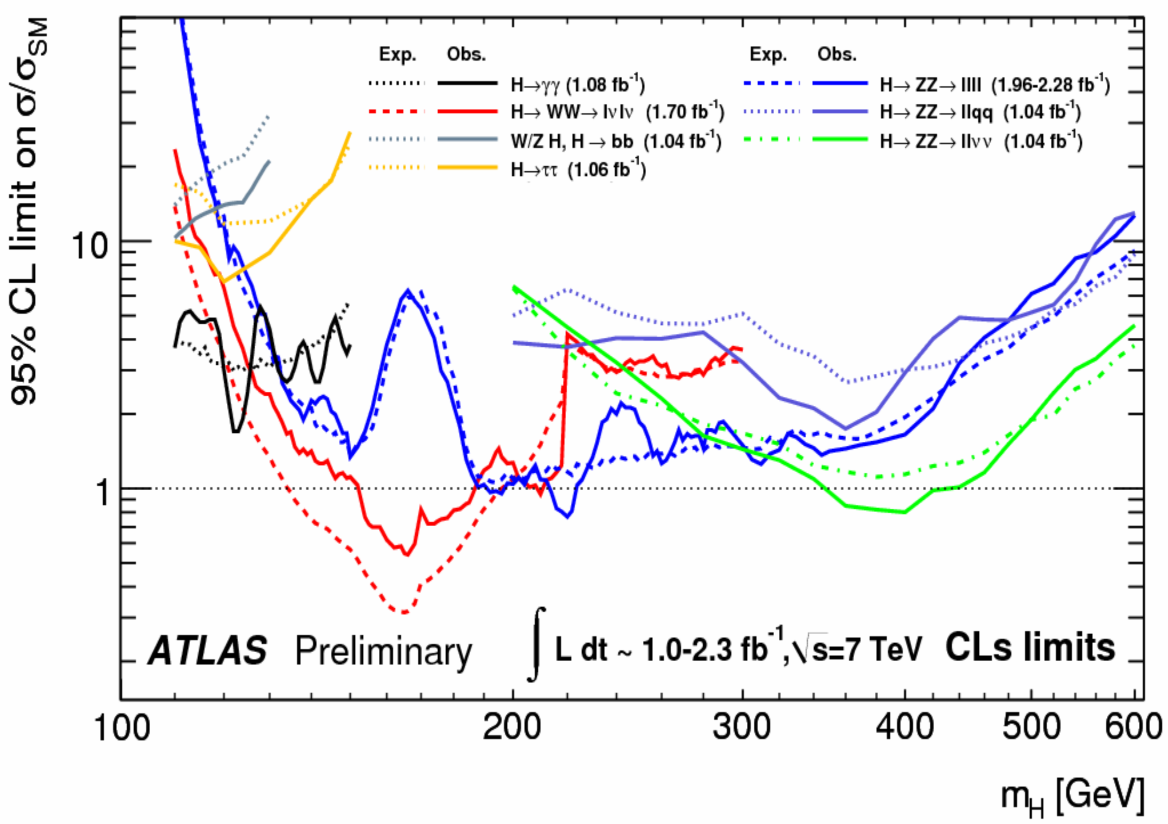
• CMS: **147 < M_H < 194 GeV** ruled out at 95% cl

• SM Higgs boson expected sensitivity 136 < M_H< 200 GeV



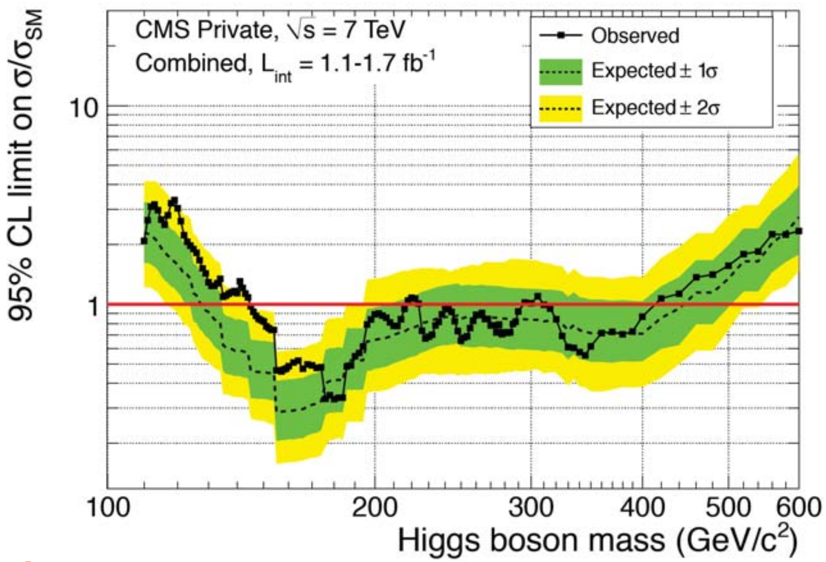
Source of rumors, blog posts, etc….

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 Predictions

$\sqrt{s}$=7 TeV

ATLAS + CMS	95% CL exclusion	5σ discovery
1 fb^{-1}	120-530	152-175
2 fb^{-1}	114-585	140-200
5 fb^{-1}	114-600	128-482
10 fb^{-1}	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

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

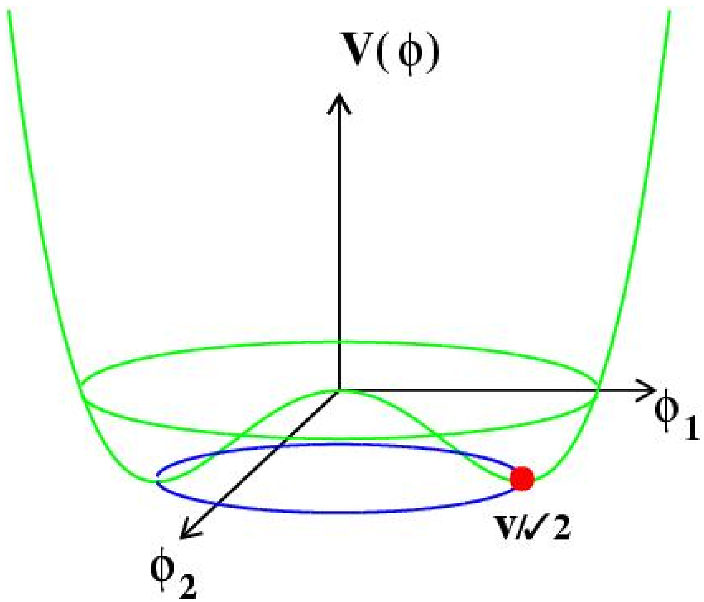
- Measure self interactions

$$V = \frac{M_H^{\ 2}}{2}H^2 + \frac{M_H^2}{2v}H^3 + \frac{M_H^{\ 2}}{8v^2}H^4$$

Can we reconstruct the Higgs potential?

$$V = \frac{M_H{}^2}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4$$

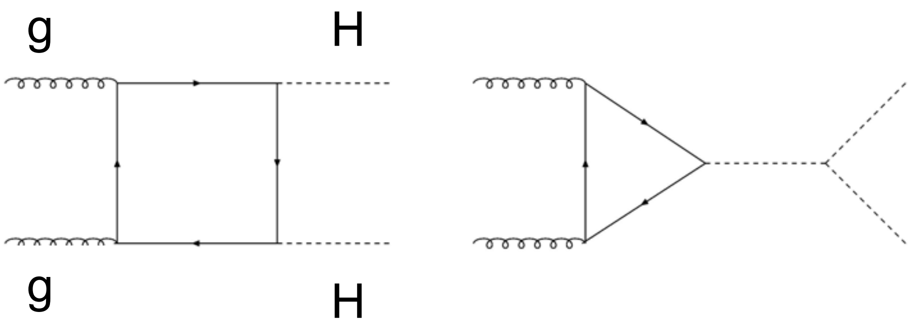
$$\boxed{SM:\ \lambda_3 = \lambda_4 = \frac{M_H{}^2}{2v^2}}$$



- Fundamental test of model!

Double Higgs Production from Gluons

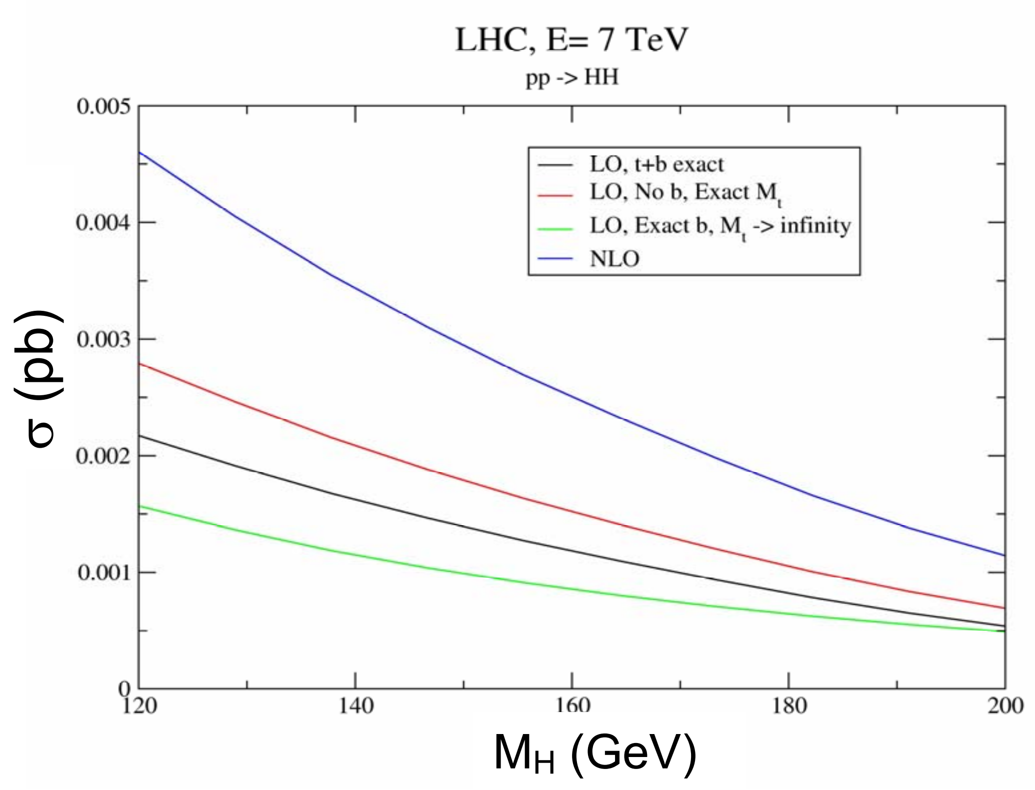
- Sensitive to heavy fermions (top quark)
- Contribution is dominantly triangle
- Destructive interference



$\sim\lambda_t^2$ $\sim\lambda_t\,\lambda_3$

Early work by Baur and collaborators demonstrated difficulties

Small rate for HH production



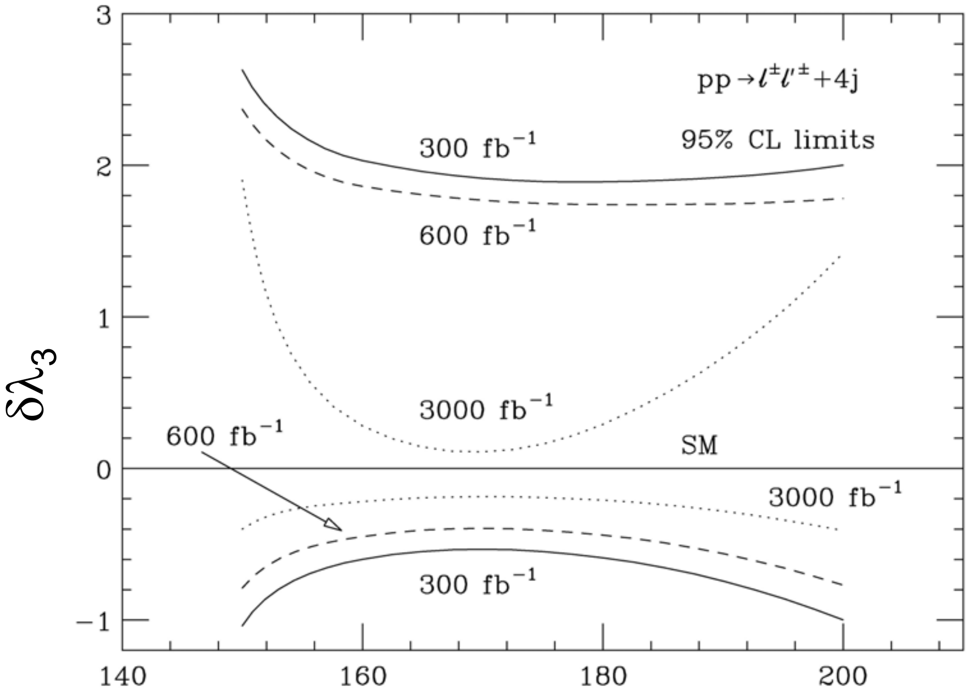
For M_H=160 GeV, 10 events in all channels with 3 fb^{-1}

HH Production can be enhanced in models with new physics

Small sensitivity to HHH coupling

- Contributions interfere destructively

$pp \rightarrow H\,H \rightarrow W^+W^-W^+W^- \rightarrow$ 2 leptons + 4 jets



M_H (GeV)

[Baur, 2002]

Summary

- 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

Uli's contributions are of fundamental importance to our understanding of EWSB