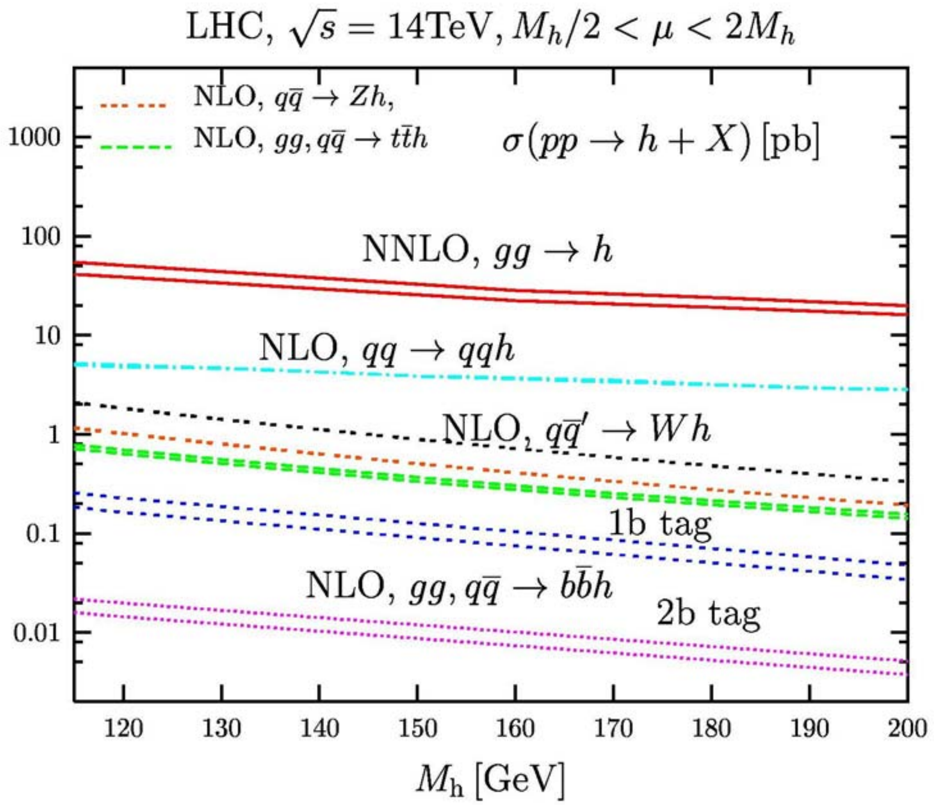
What Do We Know About EWSB?

Sally Dawson (BNL)

Lecture 2

XIII Mexican School of Particles and Fields, 2008

Production Mechanisms at LHC



Bands show scale dependence

All important channels calculated to NLO or NNLO

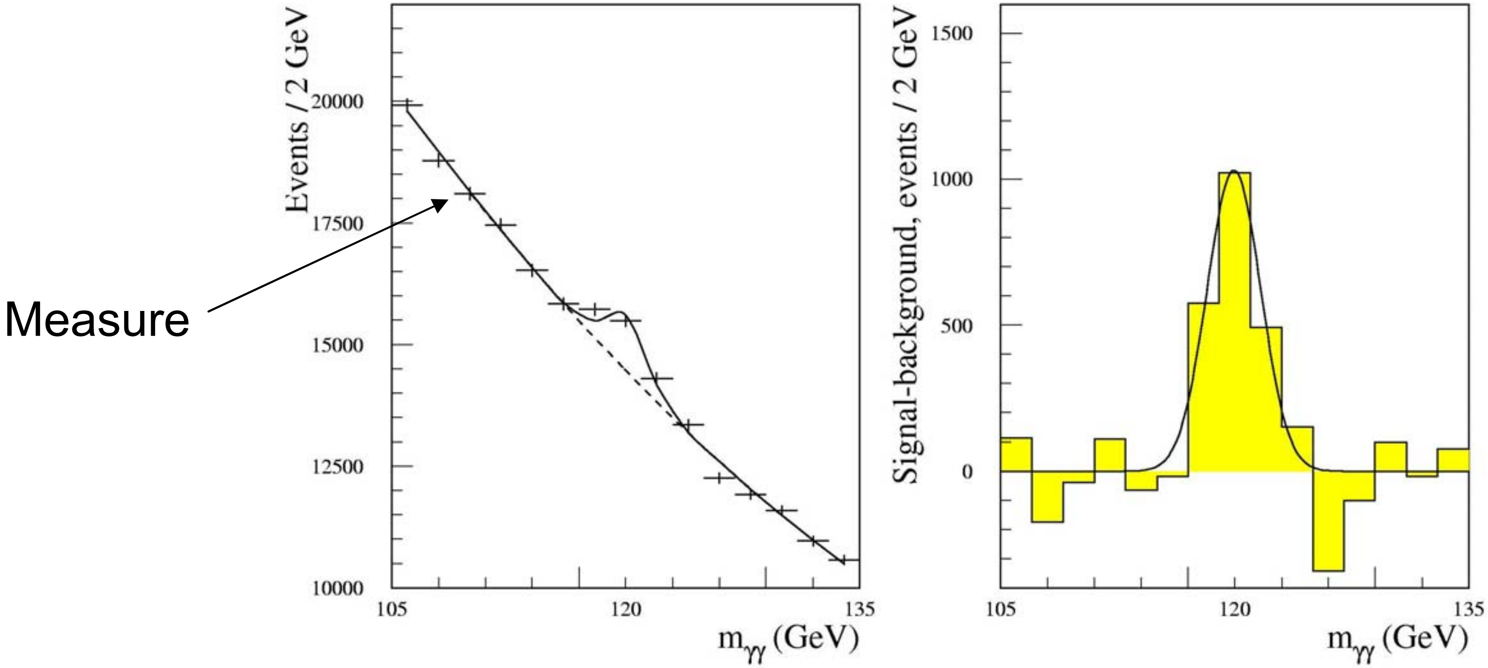
Search Channels at the LHC

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

- $gg \to H \to \gamma\gamma$
  - 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

$H \to \gamma\gamma$

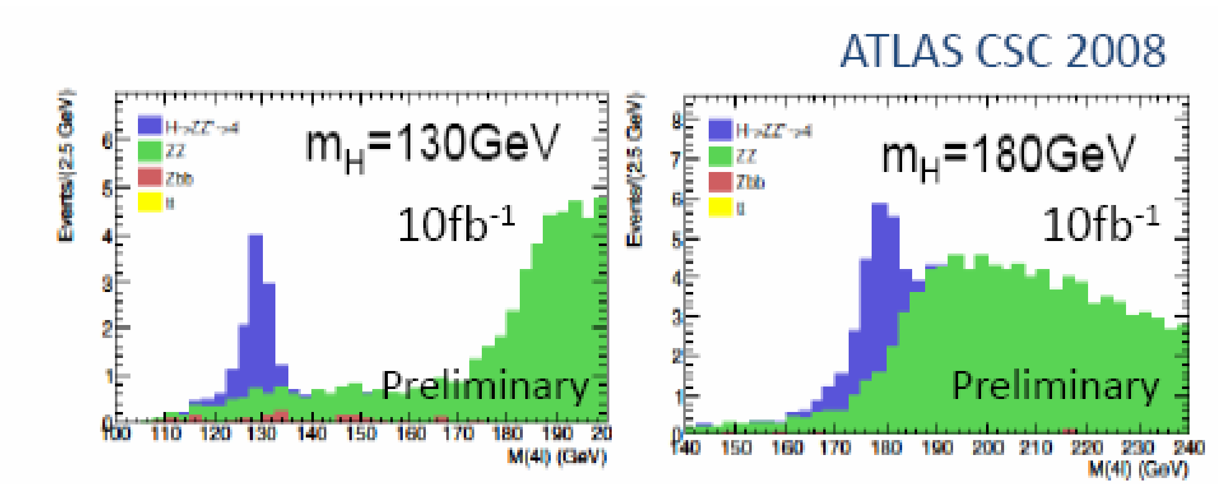
M_H=120 GeV; L=100 fb^{-1}

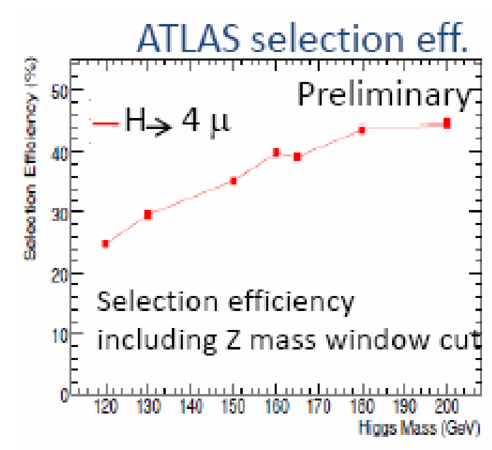


$S/\sqrt{B}$ = 2.8 to 4.3 σ

Golden Channel: H→ZZ→4 leptons

- Need excellent lepton ID

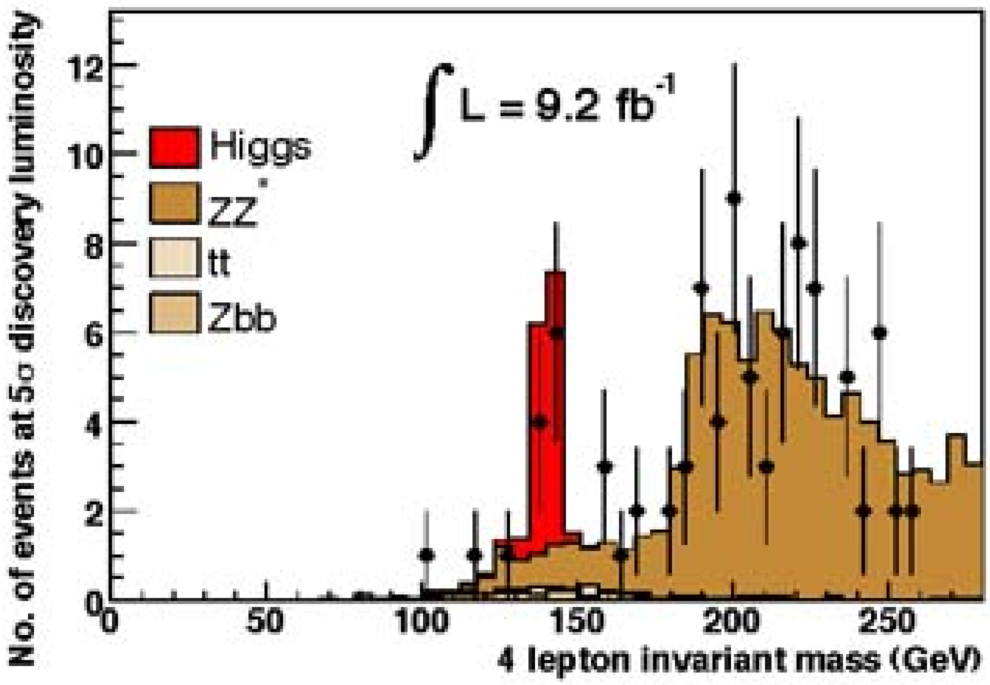




- Below M_H ~130 GeV, rate is too small for discovery

H→ZZ→(4 leptons)

CMS:

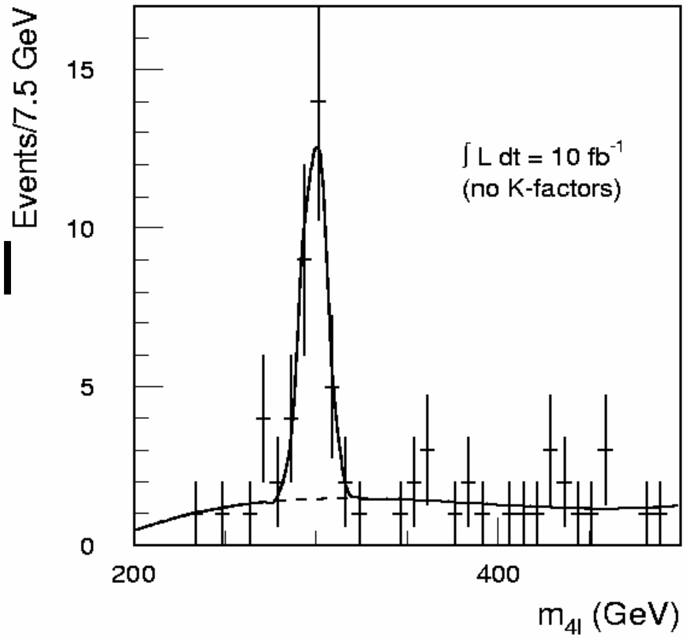


Possible discovery with < 10 fb^{-1}

Heavy Higgs in 4-lepton Mode

200 GeV < M_H < 600 GeV:

$H \rightarrow ZZ \rightarrow l^+l^- l^+l^-$



- Discovery in $H \rightarrow ZZ \rightarrow l^+l^- l^+l^-$

•Background smaller than signal

•Higgs width larger than experimental resolution (M_H > 300 GeV)

Confirmation in $H \rightarrow ZZ \rightarrow l^+l^- jj$

Heavy Higgs

$M_H > 600$ GeV:

4 lepton channel statistically limited

Look for:

$H \rightarrow ZZ \rightarrow l^+l^- \nu\nu$

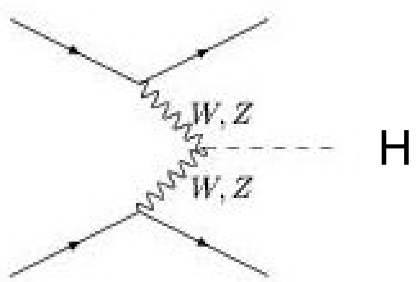
$H \rightarrow ZZ \rightarrow l^+l^- jj$

$H \rightarrow WW \rightarrow l \nu jj$

-150 times larger BR than 4 lepton channel

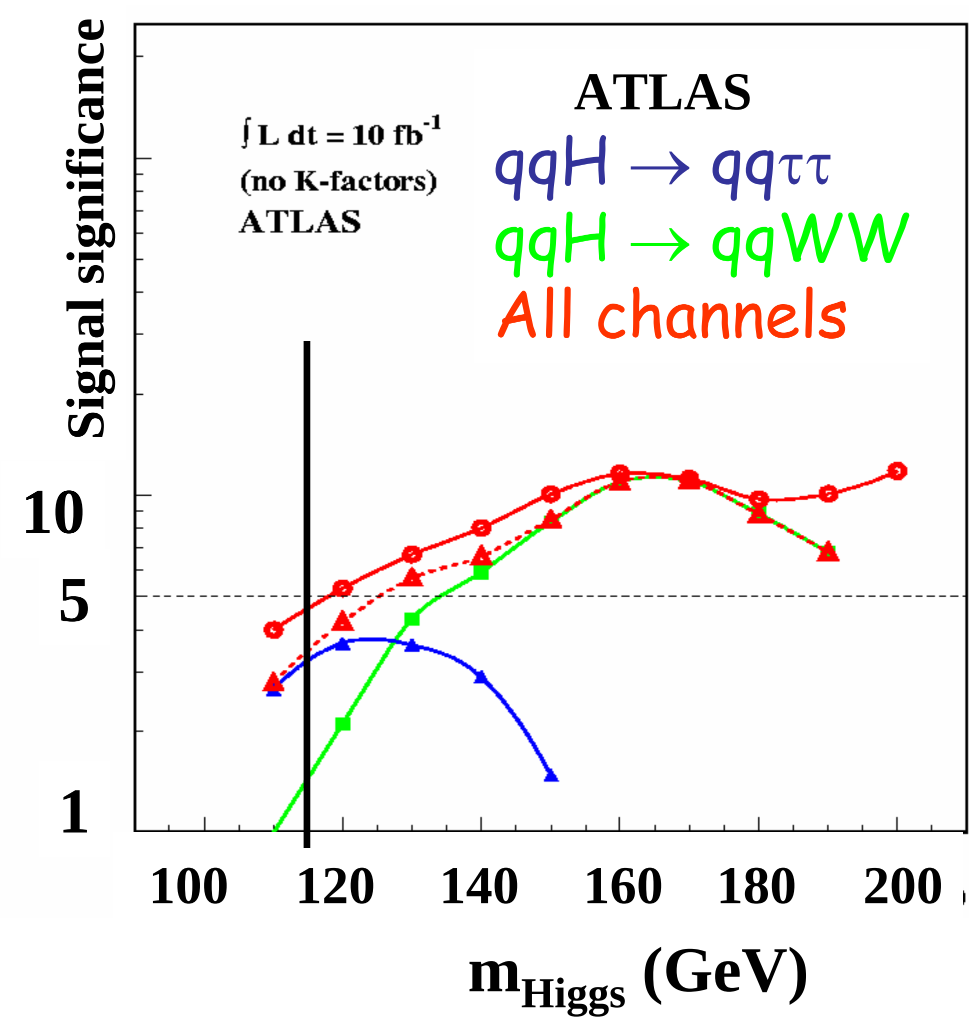
Vector Boson Fusion

- Outgoing jets are mostly forward and can be tagged
  - Little jet activity in central rapidity region
- Idea: Look for different H decay channels in Vector boson fusion
  - Ratio will have smaller errors than total rate

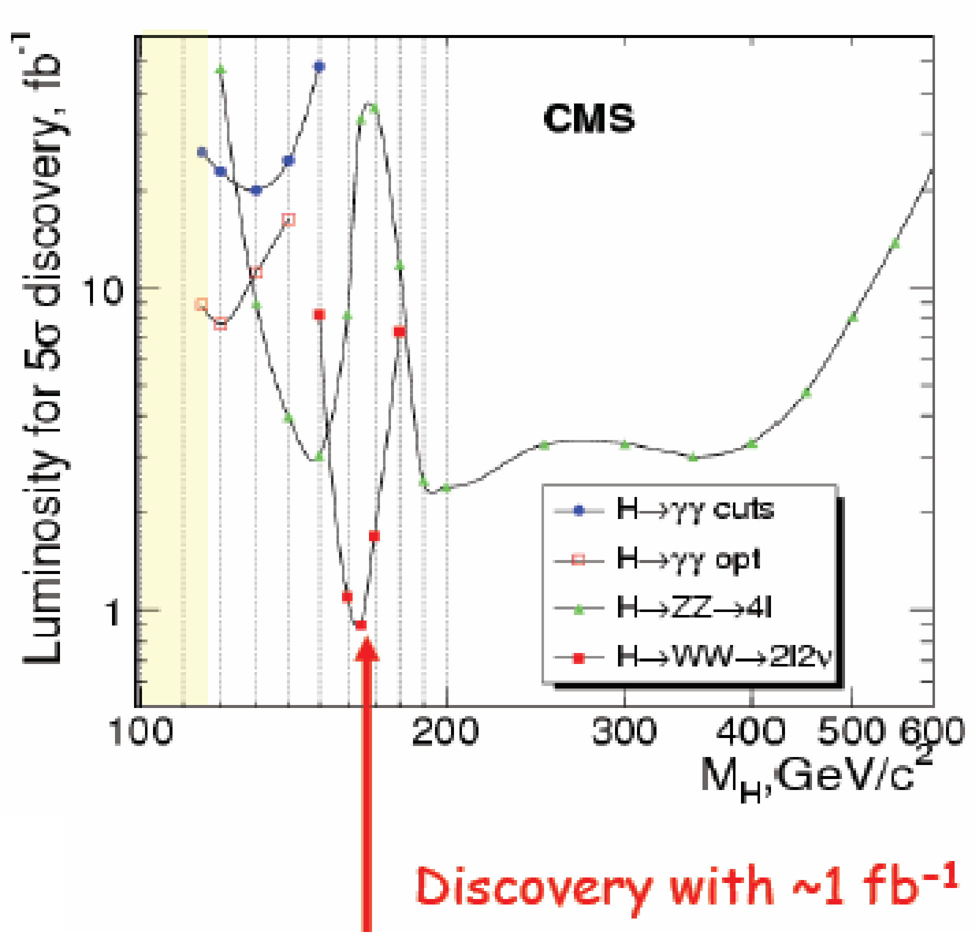


Vector Boson Fusion for light Higgs

Vector boson fusion effective for measuring Higgs couplings

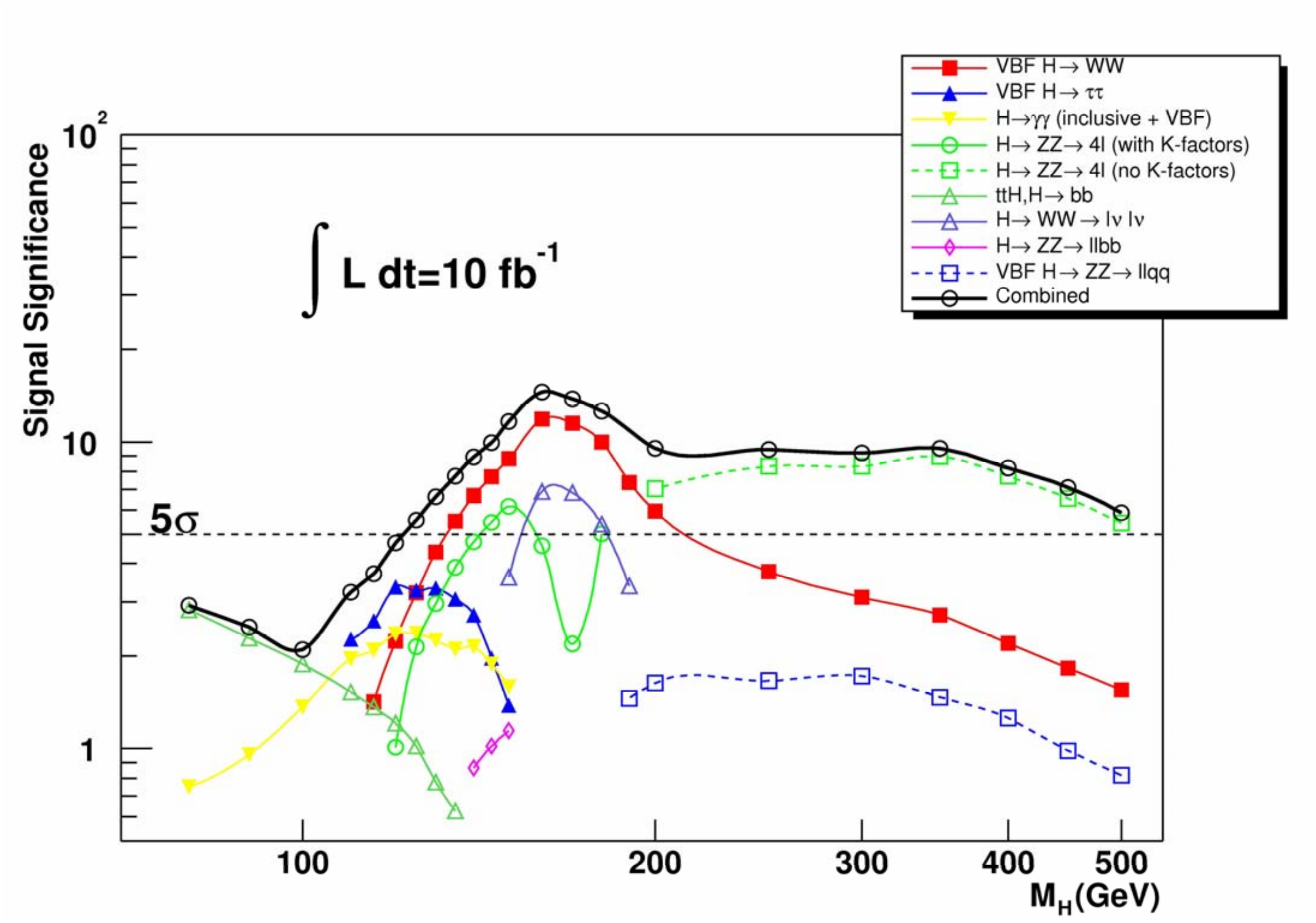


Higgs Discovery Reach at LHC



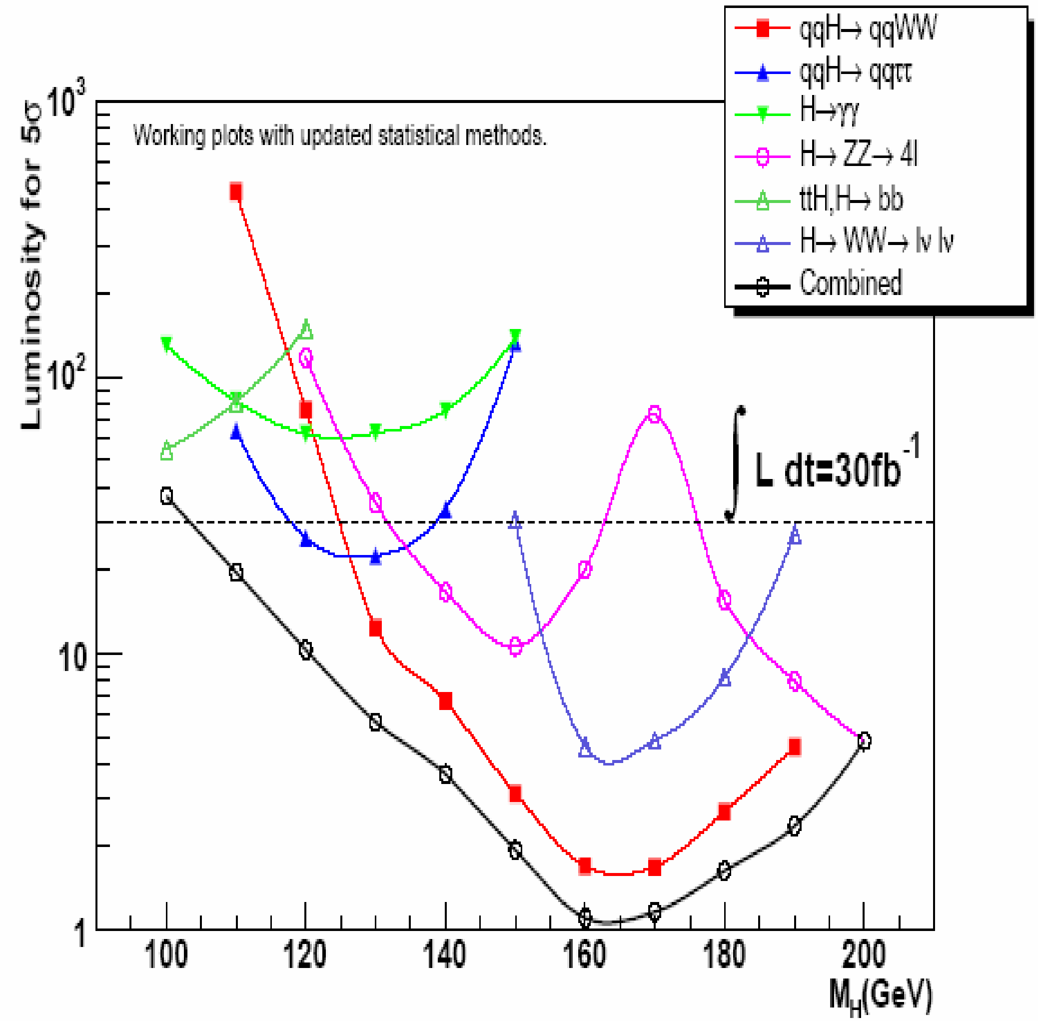
- Improvement in $\gamma\gamma$ channel from earlier studies

Early Higgs Physics



ATLAS

Higgs Discovery at ATLAS



ATLAS

If we find a “Higgs-like” object, what then?

- We need to:
  - Measure Higgs couplings to fermions & gauge bosons
  - Measure Higgs spin/parity
  - Reconstruct Higgs potential
  - Is it the SM Higgs?
- Reminder: Many models have other signatures:
  - New gauge bosons (little Higgs)
  - Other new resonances (Extra D)
  - Scalar triplets (little Higgs, NMSSM)
  - Colored scalars (MSSM)

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

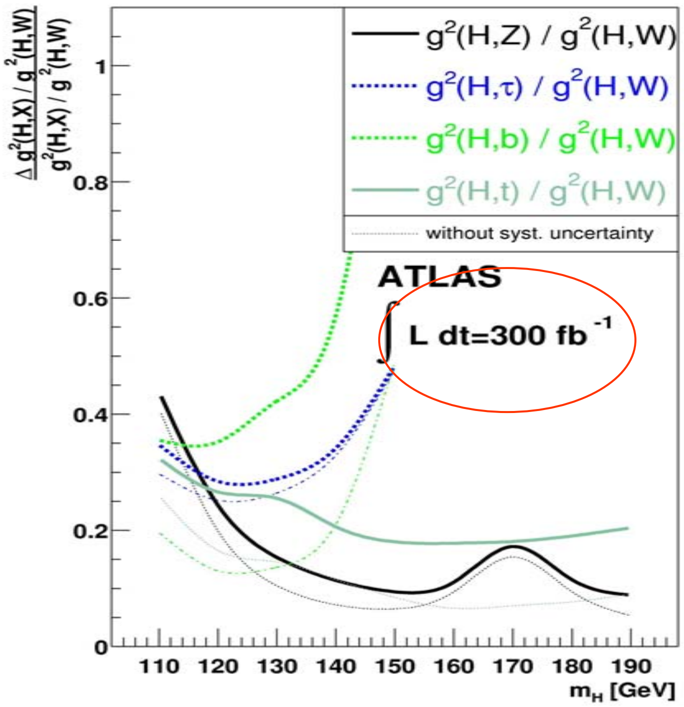
$$J^{PC} = 0^{++}$$

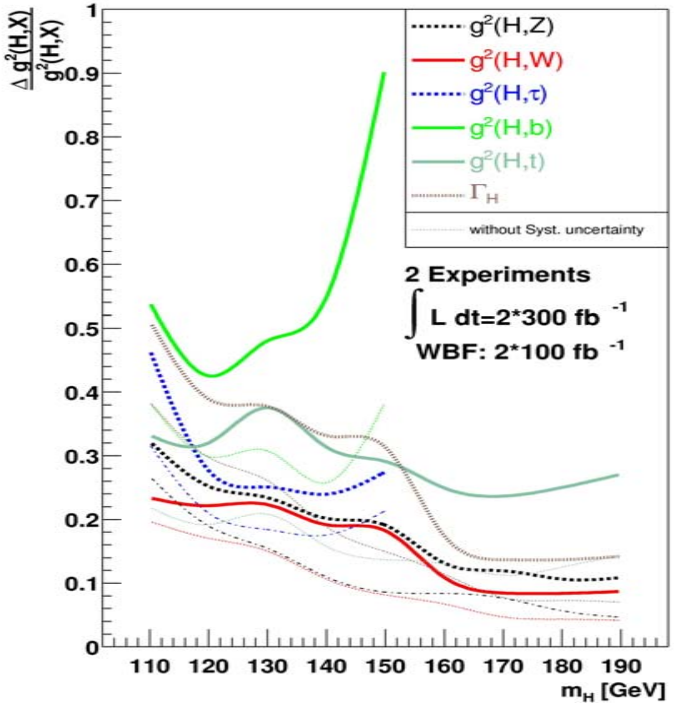
- Measure self interactions

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

Absolute Measurements of Higgs Couplings

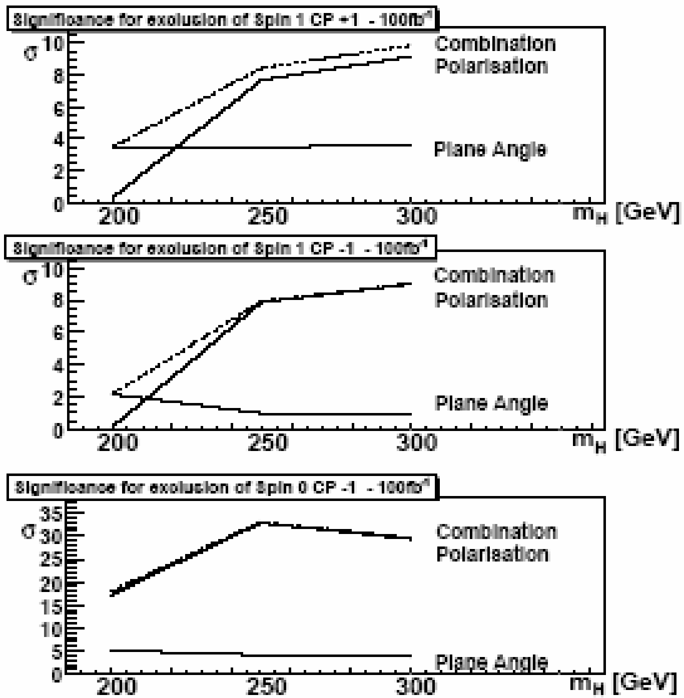
- Ratios of couplings more precisely measured than absolute couplings
- 10-40% measurements of most couplings





What about the Higgs Spin?

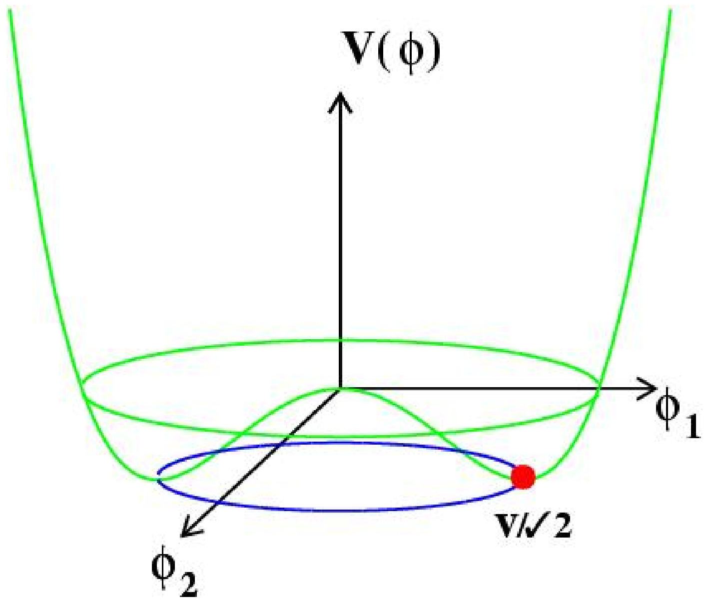
- H→ZZ →4l useful above M_H=200 GeV
  - Study polar angle of leptons relative to Z boson
  - Study angle between decay planes of Z's in Higgs rest frame
- For M_H> 200 GeV, > 5σ discrimination between spin -1,0,1 hypothesis for L=100 fb^{-1}
- Spin 1 hypothesis ruled out by observing Hγγ or Hgg couplings



Can we reconstruct the Higgs potential?

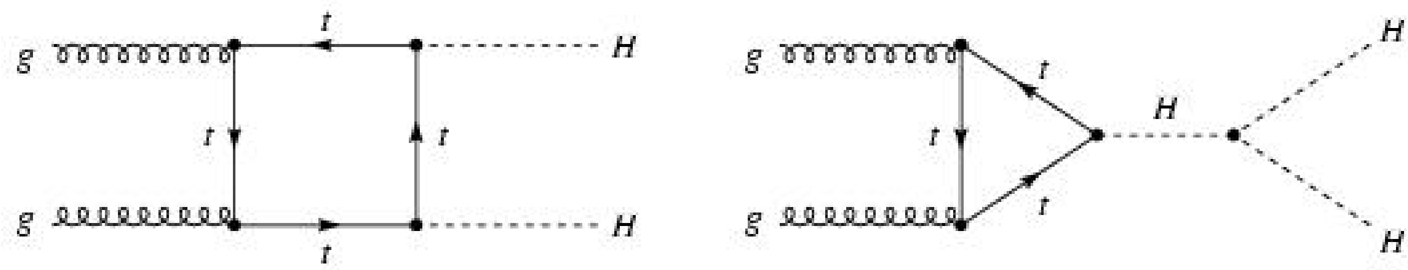
$$V = \frac{M_H^{\ 2}}{2} H^2 + \lambda_3 v H^3 + \frac{\lambda_4}{4} H^4$$

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



- Fundamental test of model!
- We have no idea how to measure λ_4

Reconstructing the Higgs potential



- λ_3 requires 2 Higgs production
- M_H<140 GeV, $H \rightarrow bb\underline{b}b\_$
- Overwhelming QCD background

Can determine whether λ_3=0 at 95% cl with 300 fb^{-1} for 150 <M_H <200 GeV

So we can probably find the Higgs

- Can we learn anything about the Higgs from places other than direct searches?

Basics

- SM is SU(2) x U(1) theory
  - Two gauge couplings: g and g'
- Higgs potential is $V=-\mu^2\phi^2+\lambda\phi^4$
  - Two free parameters
- Four free parameters in gauge-Higgs sector

Basics, #2

- Chose parameters in gauge/Higgs sector
  - 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

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

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

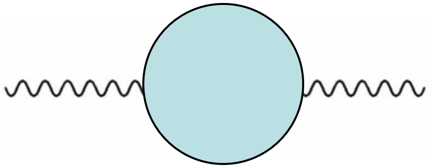
$$M_W^2 = \pi\sqrt{2}\frac{\alpha}{G_F}\left(1-\sqrt{1-\frac{4\pi\alpha}{\sqrt{2}G_F M_Z^2}}\right)^{-1}$$

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

  - Plug in numbers:
    - M_W predicted =80.939 GeV
    - M_W(exp) =80.399 $\pm$ 0.025 GeV
  - Need to calculate beyond tree level

Quantum Corrections

- Relate tree level to one-loop corrected masses

$$-i\Pi^{\mu\nu}_{XY} =$$ 

$$\Pi^{\mu\nu}_{XY}(k^2) = g^{\mu\nu}\Pi_{XY}(k^2) + k^{\mu}k^{\nu}B_{XY}(k^2)$$

$$M^2_{V0} = M^2_V + \Pi_{VV}(M^2_V)$$

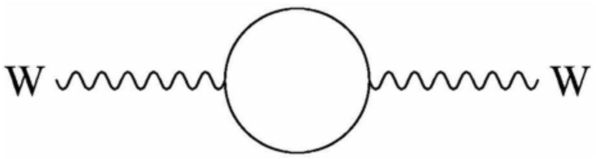
- Majority of corrections at one-loop are from 2-point functions

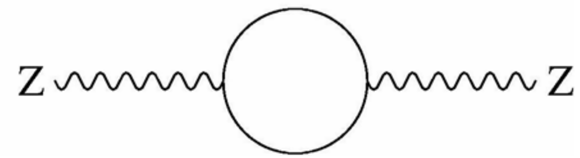
Note sign conventions for 2-point functions

Example of Quantum Corrections

- Example: $$\rho = \frac{M_W^2}{M_Z^2 \cos_W^2} = 1 + \delta\rho$$

$$\boxed{\delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2}}$$





Top quark contributes to W and Z 2-point functions

Top Quark Corrections to ρ Parameter

- 2-point functions of W, Z

$$\Pi_{ZZ}(0) = \frac{g^2 N_c}{32\pi^2 c_W^2}\left(\frac{4\pi}{m_t^2}\right)^{\varepsilon} \frac{m_t^2}{\varepsilon}\left(R_t - L_t\right)^2$$

$$\Pi_{WW}(0) = \frac{g^2 N_c}{32\pi^2}\left(\frac{4\pi}{m_t^2}\right)^{\varepsilon} m_t^2\left(\frac{1}{\varepsilon} + \frac{1}{2}\right)$$

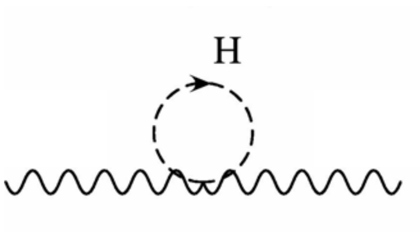
$L_t = 1 - 4s_W^2/3$

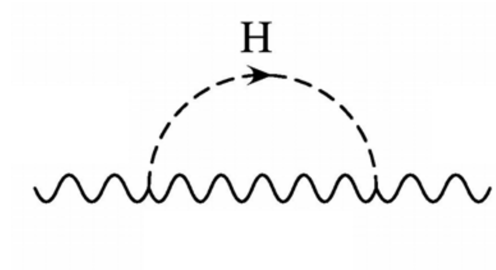
$R_t = -4s_W^2/3$

$$\delta\rho = \frac{\Pi_{WW}(0)}{M_W^2} - \frac{\Pi_{ZZ}(0)}{M_Z^2} = \frac{G_F}{\sqrt{2}}\frac{N_c}{8\pi^2}\left(\frac{m_t^2}{M_W^2}\right)$$

(Neglecting $\log(m_t)$ pieces and using on-shell definition of $\sin\theta_W$)

Heavy Higgs Contribution to δρ





$$\rho = \frac{-3\alpha}{16\pi c_W^2} \log\left(\frac{M_H^2}{M_W^2}\right)$$

- In on-shell scheme, Higgs contributes logarithmically to quantum corrections & top quark contributes quadratically

Modification of tree level relations

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

- Δr is a physical quantity which incorporates 1-loop corrections

- Contributions to Δr from top quark and Higgs loops

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

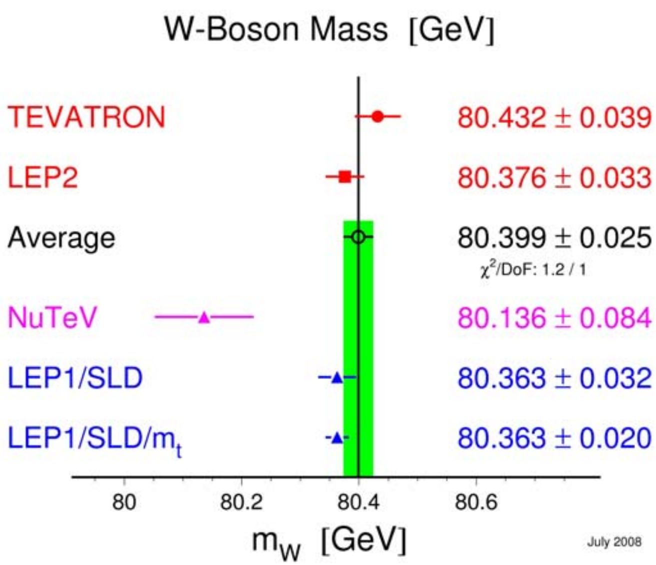
$$\Delta r^H = \frac{11 G_F M_W^2}{24\sqrt{2}\pi^2}\left(\ln\frac{M_H^2}{M_W^2} - \frac{5}{6}\right)$$

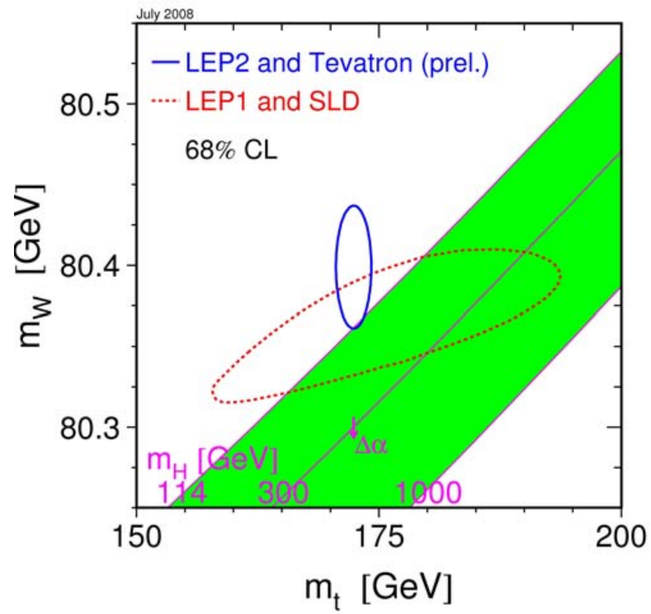
Extreme sensitivity of precision measurements to m_t

Understanding Higgs Limit

Theory: Input M_Z, G_F, α

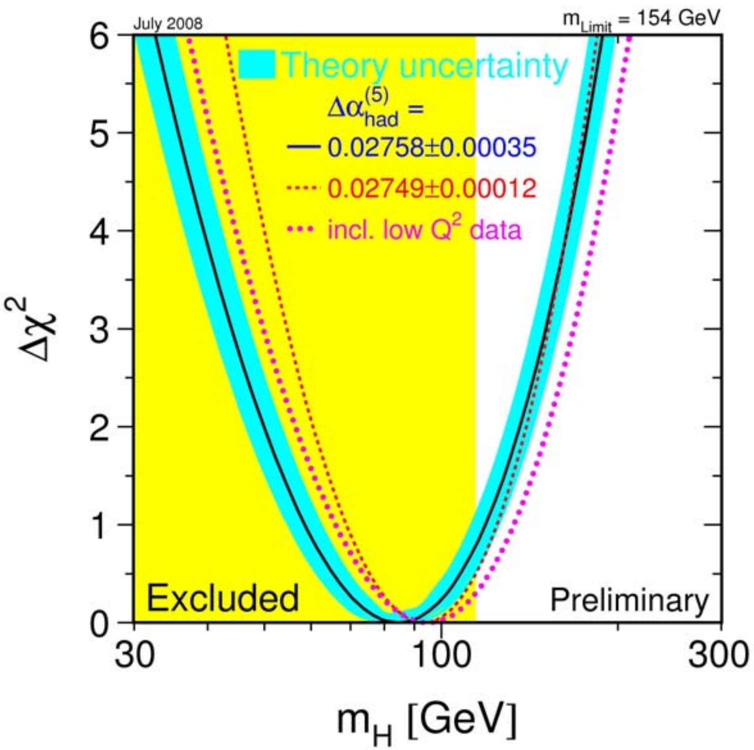
$\rightarrow$ Predict M_W





Consistency between direct and indirect measurements of M_W and m_t a strong test of theory!

Precision Measurements Limit M_H



- LEP EWWG (July, 2008):
  - m_t=172.4 ± 1.2 GeV
  - M_H=84^{+34}_{-26} GeV
  - M_H < 154 GeV (one-sided 95% cl)
  - M_H < 185 GeV (Precision measurements plus direct search limit)

Best fit in region excluded from direct searches

Caveats

- Low Q^2 data not included in fit
  - Doesn't include atomic parity violation in cesium, parity violation in Moller scattering, & neutrino-nucleon scattering (NuTeV)
  - Higgs fit not hugely sensitive to low Q^2 data
- $M_H < 185$ GeV
  - Higgs limit moves around with m_t

Higgs limit assumes SM!

Theoretical Limits on M_H

- Unitarity
  - If unitarity is violated, interactions grow with energy (cf longitudinal W's)
- Perturbativity of couplings
  - If perturbativity is violated, loop corrections may be larger than tree
- Limits tell us where minimal SM is valid
  - Unitarity and perturbativity provide strong limits on beyond the SM physics
  - These are model builders tools
- Renormalization of Higgs mass
  - What about naturalness?

Unitarity

- Consider 2 $\rightarrow$ 2 elastic scattering

$$\frac{d\sigma}{d\Omega} = \frac{1}{64\pi^2 s}|A|^2$$

- Partial wave decomposition of amplitude

$$A = 16\pi \sum_{l=0}^{\infty} (2l+1) P_l(\cos\theta) a_l$$

- a_l are the spin *l* partial waves

Unitarity

- $P_l(\cos\theta)$ are Legendre polynomials:

$$\int_{-1}^{1} dx P_l(x) P_{l'}(x) = \frac{2\delta_{l,l'}}{2l+1}$$

$$\sigma = \frac{8\pi}{s} \sum_{l=0}^{\infty} (2l+1) \sum_{l'=0}^{\infty} (2l'+1) a_l a_{l'}^{*} \int_{-1}^{1} d\cos\theta P_l(\cos\theta) P_{l'}(\cos\theta)$$

$$= \frac{16\pi}{s} \sum_{l=0}^{\infty} (2l+1) \left| a_l \right|^2$$

- Sum of positive definite terms

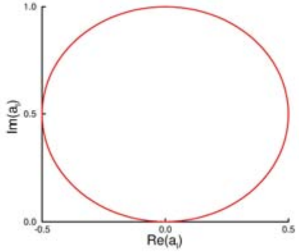
More on Unitarity

- Optical theorem $\sigma = \frac{1}{s}\mathrm{Im}\left[A(\theta = 0)\right] = \frac{16\pi}{s}\sum_{l=0}^{\infty}(2l+1)\left|a_l\right|^2$

$$\mathrm{Im}(a_l) = \left|a_l\right|^2$$

Optical theorem derived assuming only conservation of probability

- Unitarity requirement:



$$\left|\mathrm{Re}(a_l)\right| \le \frac{1}{2}$$

More on Unitarity

- Idea: Use unitarity to limit parameters of theory

Cross sections which grow with energy always violate unitarity at some energy scale

- Remember $W_L(p)$ with $\varepsilon_L \sim p/M_W$

Aside on WW Scattering

$$A(V_L^1 \ldots V_L^N \to V_L^1 \ldots V_L^{N'}) = (i)^N (-i)^{N'} A(\omega_1 \ldots \omega_N \to \omega_1 \ldots \omega_{N'})$$
$$+O\left(\frac{M_W^2}{E^2}\right)$$

This is a statement about scattering amplitudes, NOT individual Feynman diagrams

$\omega^\pm$, z are Goldstone bosons which are eaten by the Higgs mechanism to give the W & Z bosons their longitudinal components

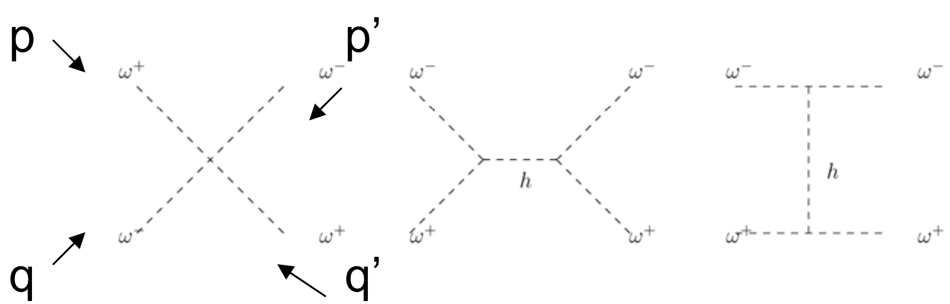
$W^+W^- \to W^+W^-$

- Recall scalar potential

$$V = \frac{M_H^2}{2} H^2 + \frac{M_H^2}{2v} H\left(H^2 + z^2 + 2\omega^+\omega^-\right) + \frac{M_H^2}{8v^2}\left(H^2 + z^2 + 2\omega^+\omega^-\right)^2$$

- $\omega^+\omega^- \to \omega^+\omega$

$$iA(\omega^+\omega \to \omega^+\omega^-) = -2i\frac{M_H^2}{v^2} + \left(-i\frac{M_H^2}{v}\right)^2 \frac{i}{t - M_H^2} + \left(-i\frac{M_H^2}{v}\right)^2 \frac{i}{s - M_H^2}$$



$$s = (p+q)^2$$
$$t = (p-p')^2$$
$$u = (q-p')^2$$

$\omega^+\omega^- \to \omega^+\omega^-$

- Two interesting limits:
  - s, t >> M_H^2

$$A(\omega^+\omega^- \to \omega^+\omega^-) \to -2\frac{M_H^2}{v^2}$$

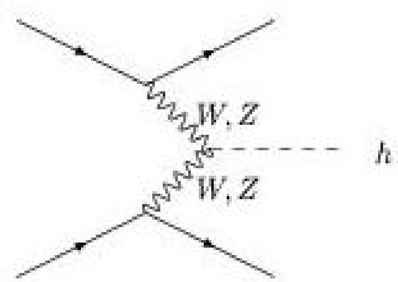
$$a_0^0 \to -\frac{M_H^2}{8\pi v^2}$$

  - s, t << M_H^2

$$A(\omega^+\omega^- \to \omega^+\omega^-) \to -\frac{u}{v^2}$$

$$a_0^0 \to -\frac{s}{32\pi v^2}$$

Remember: This is physical process



Use Unitarity to Bound Higgs

$$\left|\mathrm{Re}(a_l)\right| \leq \frac{1}{2}$$

- High energy limit:

$$a_0^0 \to -\frac{M_H^2}{8\pi v^2}$$

$M_H < 800$ GeV

- Heavy Higgs limit

$$a_0^0 \to -\frac{s}{32\pi v^2}$$

$E_c \sim 1.7$ TeV

$\to$ ***New physics at the TeV scale***

Can get more stringent bound from coupled channel analysis

Another Sort of Limit: Landau Pole

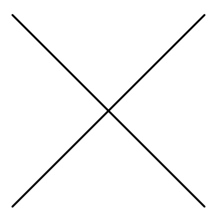
- M_H is a free parameter in the Standard Model
- Can we derive limits from consistency?
- Consider a scalar potential:

$$V = \frac{M_H^2}{2} H^2 + \frac{\lambda}{4} H^4$$

- This is potential at electroweak scale
- Parameters evolve with energy in a calculable way

Consider HH→HH

- Real scattering, $s+t+u=4M_H^2$
- Consider momentum space-like and off-shell: $s=t=u=Q^2<0$
- Tree level: $iA_0=-6i\lambda$

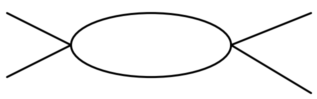


HH→HH, #2

- One loop:

$$iA_s = (-6i\lambda)^2 \frac{1}{2}\int \frac{d^n k}{(2\pi)^2}\frac{i}{k^2 - M_H^2}\frac{i}{(k+p+q)^2 - M_H^2}$$

$$= \frac{9\lambda^2}{8\pi^2}(4\pi\mu^2)\Gamma(\varepsilon)\left(M_H^2 - Q^2 x(1-x)\right)^{-\varepsilon}$$



- $A = A_0 + A_s + A_t + A_u$

$$A = -6\lambda\left(1 + \frac{9\lambda}{16\pi^2}(4\pi\mu^2)\Gamma(\varepsilon)\left(M_H^2 - Q^2 x(1-x)\right)^{-\varepsilon} + \ldots\right)$$

HH→HH, #3

- Sum the geometric series to define running coupling

$$A = -6\lambda\left(1 + \frac{9\lambda}{16\pi^2}\log\frac{Q^2}{M_H^2}\right) + \ldots$$

$$A = \frac{6\lambda}{1 - \frac{9\lambda}{8\pi^2}\log\left(\frac{Q}{M_H}\right)} \equiv 6\lambda(Q)$$

- $\lambda(Q)$ blows up as $Q \to \infty$ (called Landau pole)

HH$\rightarrow$HH, #4

- This is independent of starting point
- BUT…. Without $\lambda\phi^4$ interactions, theory is non-interacting
- Require quartic coupling be finite

$$\frac{1}{\lambda(Q)} > 0$$

HH→HH, #5

- Use $\lambda = M_H^2/(2v^2)$ and approximate $\log(Q/M_H) \to \log(Q/v)$
- Requirement for $1/\lambda(Q)>0$ gives upper limit on M_H

$$M_H^2 < \frac{32\pi^2 v^2}{9\log\left(\frac{Q^2}{v^2}\right)}$$

- Assume theory is valid to 10^{16} GeV
  - Gives upper limit on $M_H < 180$ GeV
- Can add fermions, gauge bosons, etc.

We expect Higgs at electroweak scale

High Energy Behavior of λ

- Renormalization group scaling $\frac{1}{\lambda(Q)} = \frac{1}{\lambda(\mu)} + (\ldots)\log\left(\frac{Q}{\mu}\right)$

$$16\pi^2 \frac{d\lambda}{dt} = 12\lambda^2 + 12\lambda g_t^2 - 12 g_t^4 + (gauge)$$

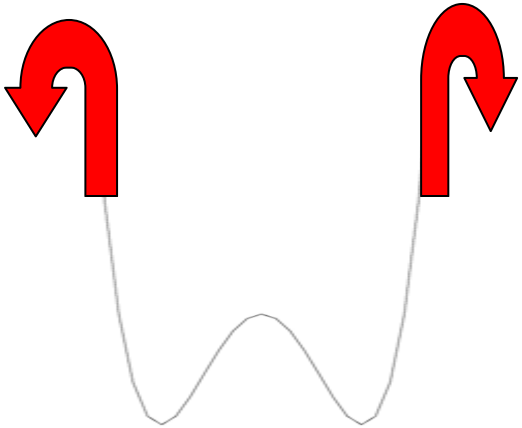
$$t \equiv \log\left(\frac{Q^2}{\mu^2}\right) \qquad g_t = \frac{M_t}{v}$$

- *Large λ (Heavy Higgs):* self coupling causes λ to grow with scale
- *Small λ (Light Higgs):* coupling to top quark causes λ to become negative

Does Spontaneous Symmetry Breaking Happen?

- SM requires spontaneous symmetry
- This requires $V(v) < V(0)$
- For small λ

$$16\pi^2 \frac{d\lambda}{dt} \approx -16 g_t^4$$



- Solve

$$\lambda(\Lambda) \approx \lambda(v) - \frac{3g_t^4}{4\pi^2}\log\left(\frac{\Lambda^2}{v^2}\right)$$

Does Spontaneous Symmetry Breaking Happen? (#2)

- $\lambda(\Lambda) > 0$ gives lower bound on M_H

$$M_H^2 > \frac{3v^2}{2\pi^2}\log\left(\frac{\Lambda^2}{v^2}\right)$$

- If Standard Model valid to 10^{16} GeV

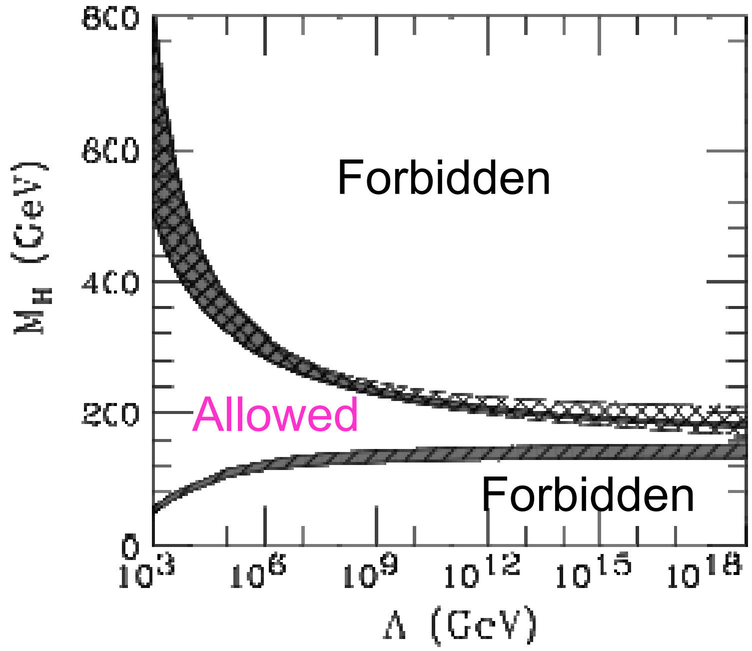
$$M_H > 130\ GeV$$

- For any given scale, Λ, there is a theoretically consistent range for M_H

Light Higgs Theoretically Attractive

➢Extrapolate Higgs potential to high scale Λ

$$V = \lambda\,(\Phi^{+}\Phi - v^2)^2$$



- Standard Model is only consistent to GUT scale for small range of Higgs masses
- Heavy Higgs implies new physics at some low scale