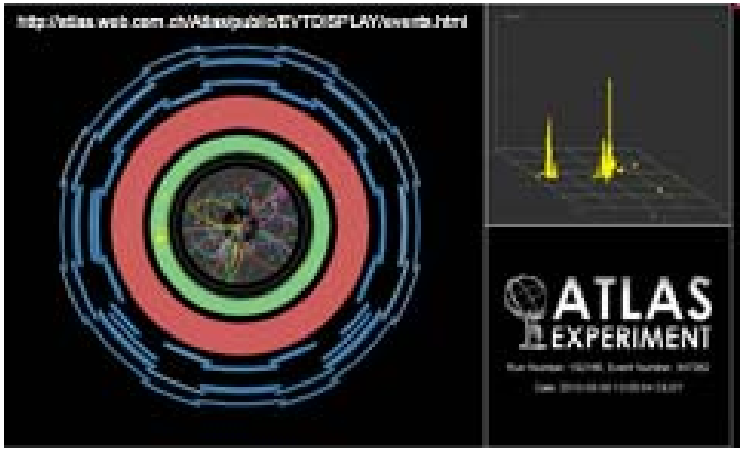
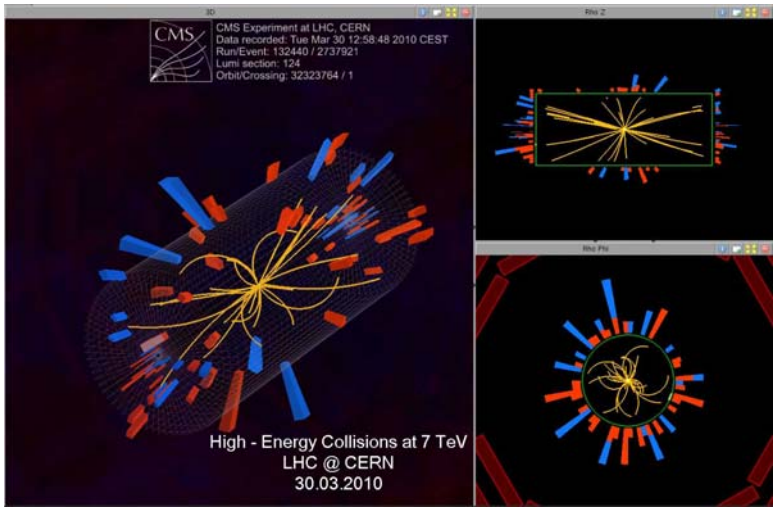
Exploring Electroweak Symmetry Breaking

Symposium in honor of G. Guralnik

Brown University, May 5, 2010

S. Dawson, BNL





Large Hadron Collider (LHC)

- pp collider at CERN
  - First collisions at 7 TeV energy, March 30, 2010!
- Goal: 14 TeV energy
  - 7 mph slower than the speed of light
  - *cf*. 2TeV @ Fermilab

    (307 mph slower than the speed of light)
- Typical energy of quarks and gluons 1-2 TeV

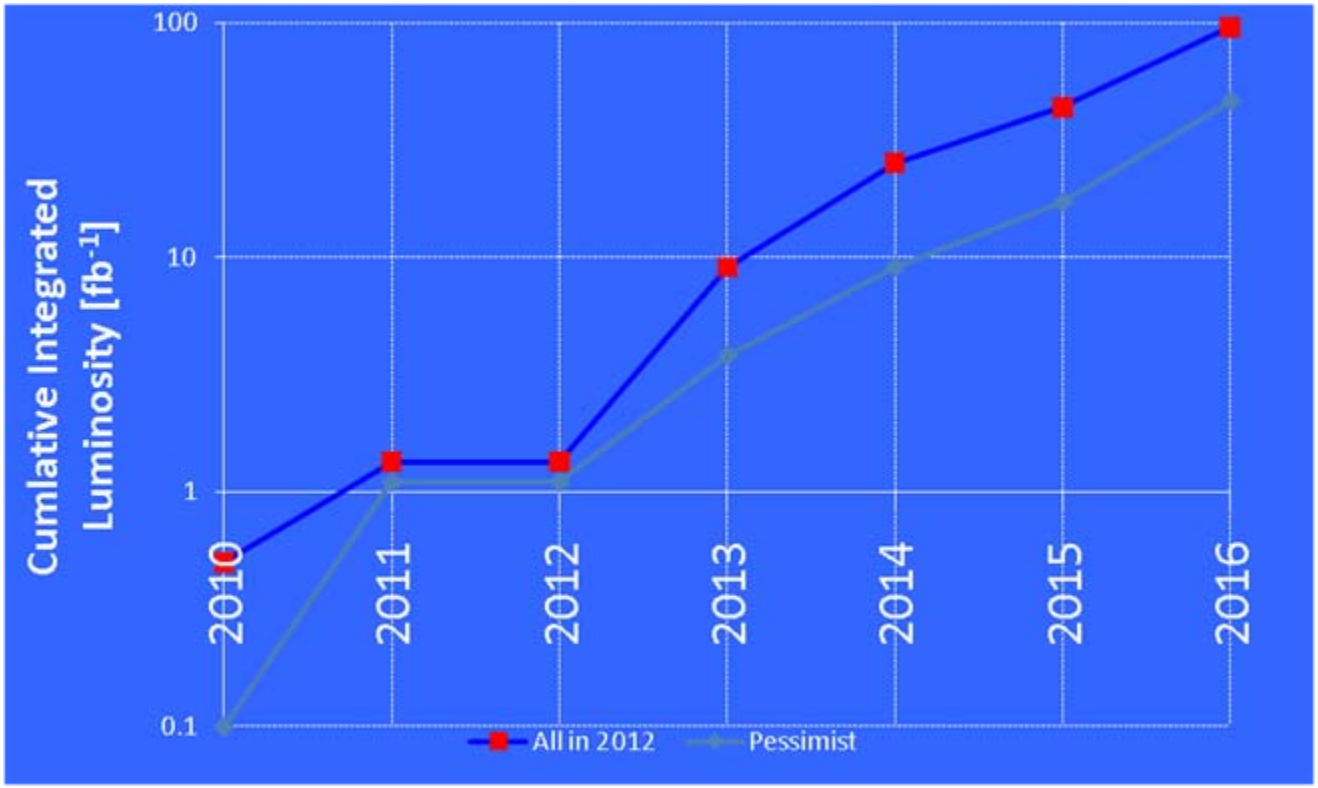
We have been waiting a long time

- SSC (pp @ 40 TeV) cancelled in 1993
  - Physics of the LHC much the same as the physics of the SSC
- LHC is running at $\sqrt{s}$=7 TeV until 1 fb^{-1} of data collected
  - What will we learn from this?

We now have the tool we need to explore electroweak symmetry breaking

LHC Plan

- Run for 1 year at $\sqrt{s}$=7 TeV to get 1 fb^{-1}
- Shut down for a year, then $\sqrt{s}$=12-14 TeV



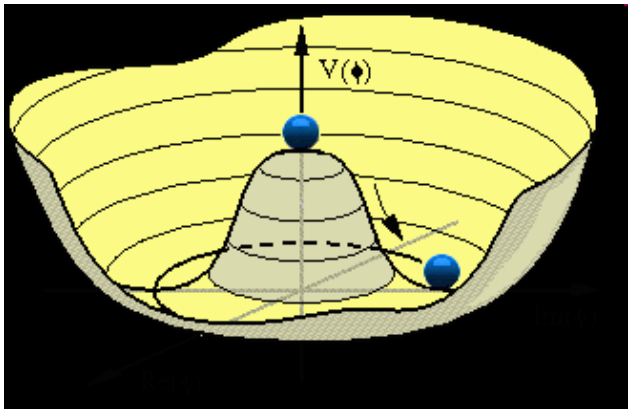
Standard Model in a Nutshell

- SM is SU(3) x SU(2) x U(1) gauge theory
- SM breaks SU(2) x U(1)symmetry and generates mass for the W and Z with a single scalar doublet, Φ
- Physical scalar, H, remains

$$\boxed{V = \lambda\left(\left|\Phi^{+}\Phi\right| - v^{2}\right)^{2}}$$

$$\lambda = \frac{M_H^2}{2v^2}, \quad v = \left(\sqrt{2}G_F\right)^{-1/2}$$

- Minimal approach



Scalar Couplings Fixed

- H couples to fermion mass
  - Largest coupling is to heaviest fermion
  - Top- H coupling plays special role?
  - No H coupling to neutrinos
- Scalar couples to gauge boson masses
  - No direct coupling to photons and gluons
- Only free parameter is scalar mass!
- Everything is calculable….***testable theory***

We have a *Standard Model*

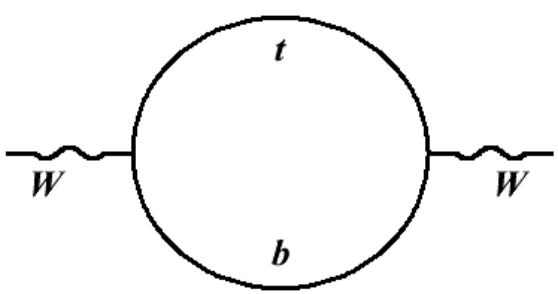
- Standard model provides excellent interpretation of experimental data
- Only unknown is the scalar sector

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

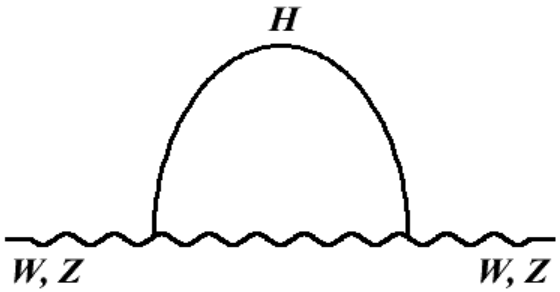
W Boson Mass

- Standard Model predicts W mass in terms of Z mass, electromagnetic coupling, Fermi constant
- Prediction sensitive to top and scalar masses

$\Delta M_W \propto M_t^2$



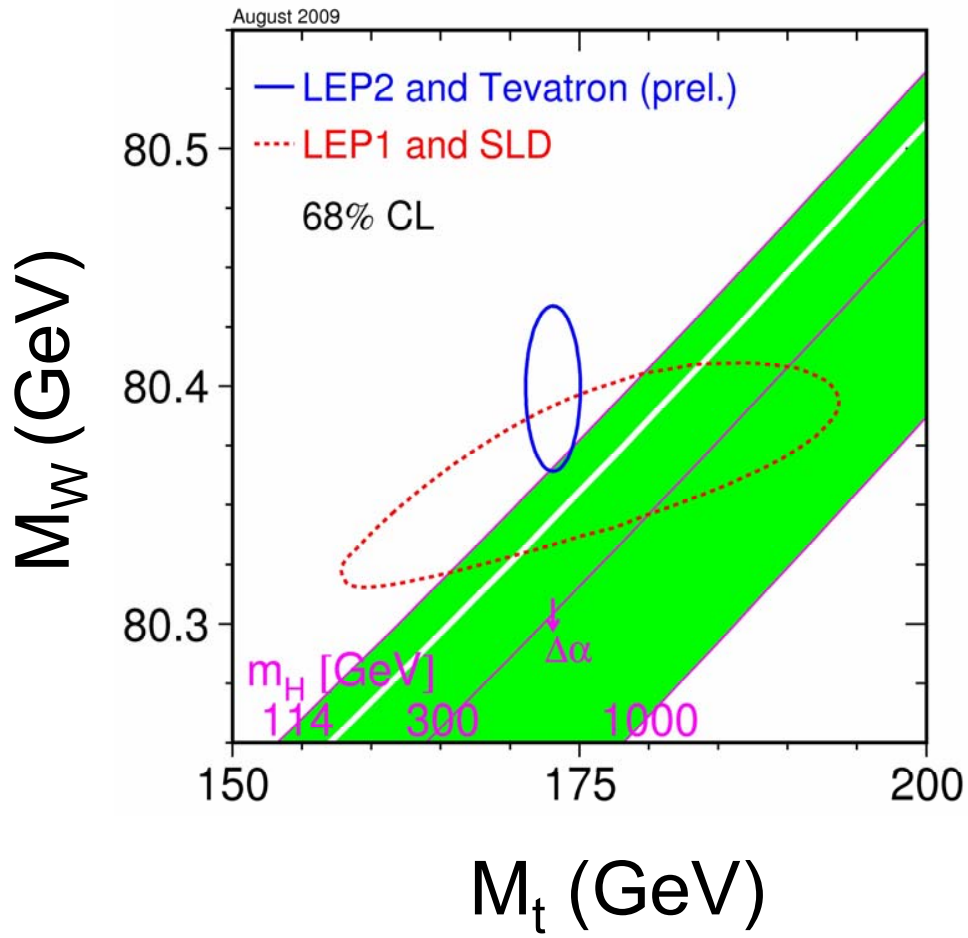
$\Delta M_W \propto \ln (M_H/M_Z)$



Top Quark Mass Restricts Scalar Mass

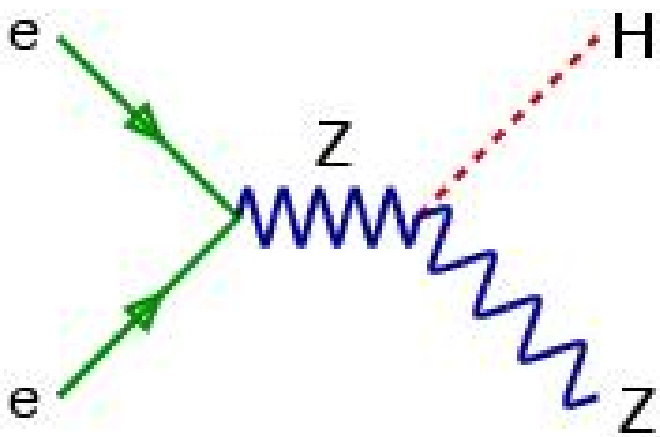
- Direct observation of W boson and top quark (blue)
- Inferred values from measurements (red)
- Consistency is triumph of theory!

Data prefer a light scalar

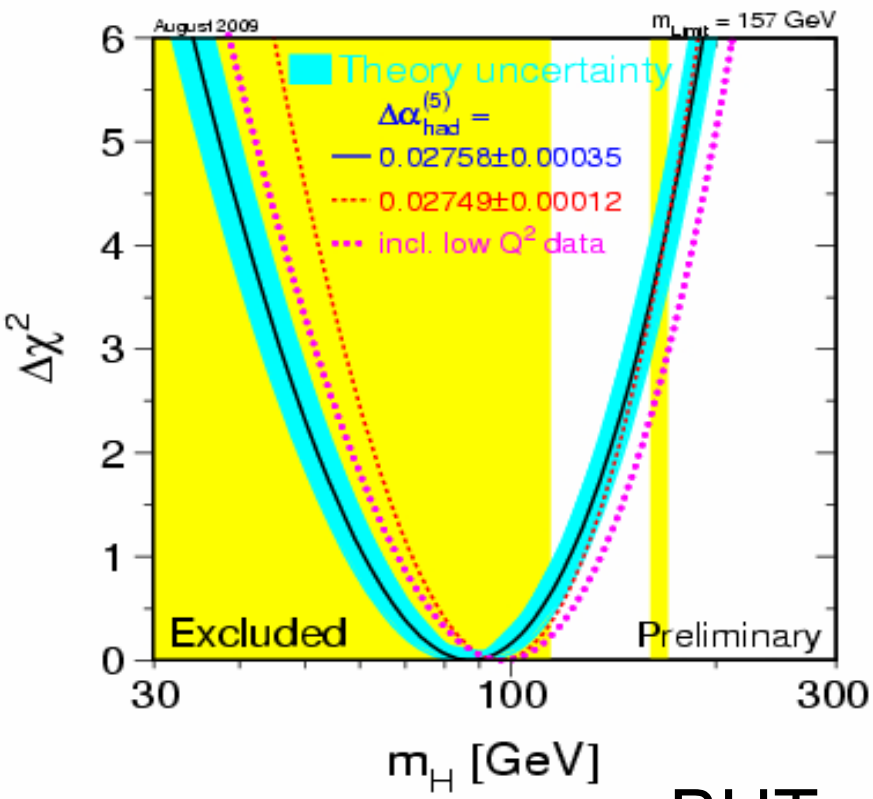


LEP Looked for the Scalar

- Looked for $e^+e^- \rightarrow Z\ H$
- Excluded a scalar boson up to M_H=114 GeV
- This limit assumes a scalar boson with the properties predicted by the Standard Model



EW Measurements Prefer Light Scalar

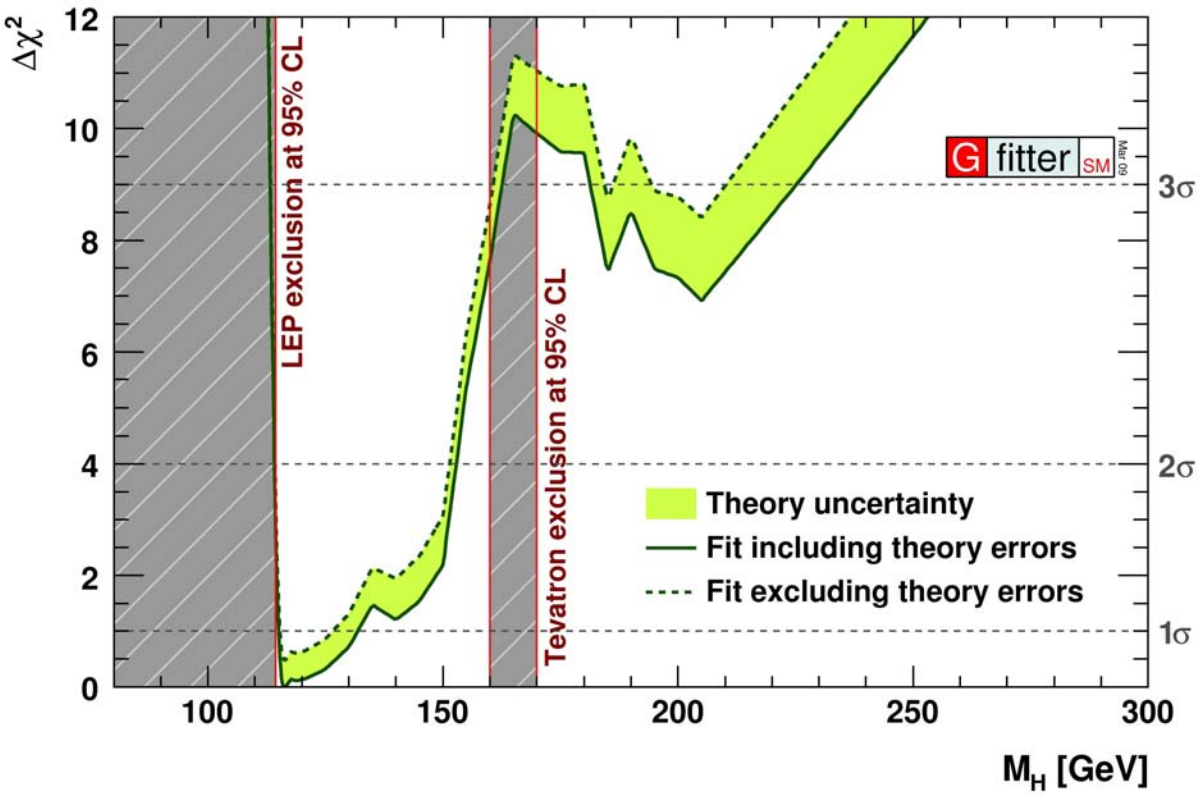


- $M_H = 87^{+35}_{-26}$ GeV (68% CL)
- M_H < 186 GeV (Precision measurements plus direct search limit)

BUT…..Fits assume SM with weakly interacting scalar

GFITTER Approach

- Includes direct search limits from Fermilab
- Includes estimate of theoretical uncertainties

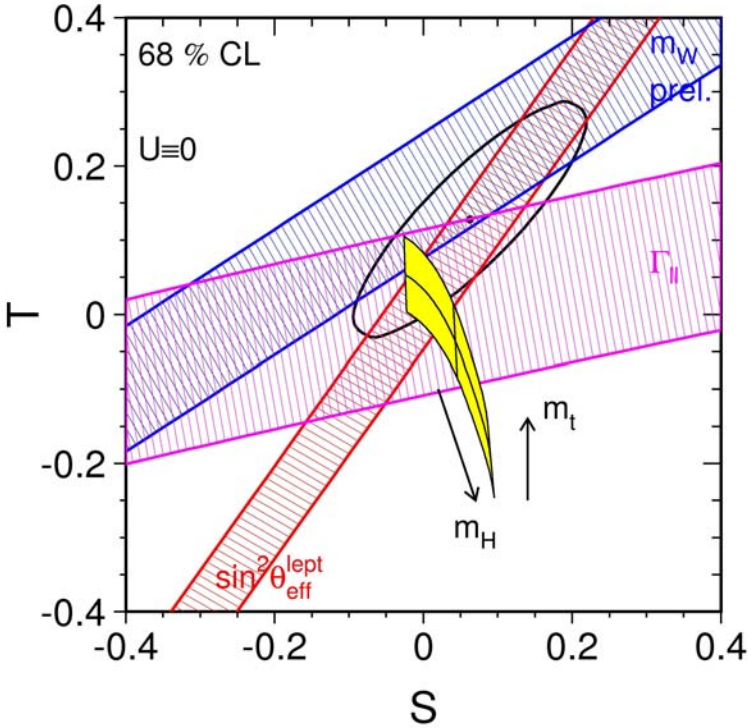


Who Needs a Scalar Boson Anyways?

Reason #1: To agree with precision electroweak measurements

SM isn't only theory that can fit precision measurements

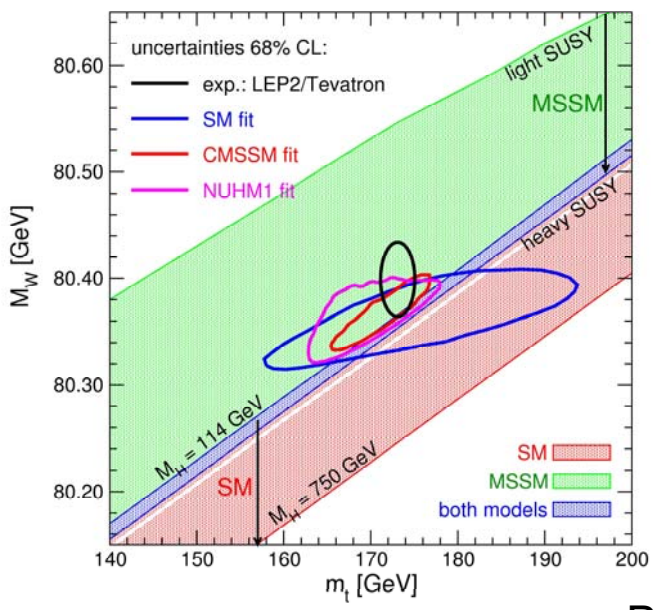
- Heavy scalar allowed with large ΔT ($\alpha\Delta T=\Delta\rho$)
- Straightforward to construct such models



Example: 4th generation of fermions with large mass splitting between charge 2/3 and charge -1/3 quarks

Supersymmetry is favorite alternative

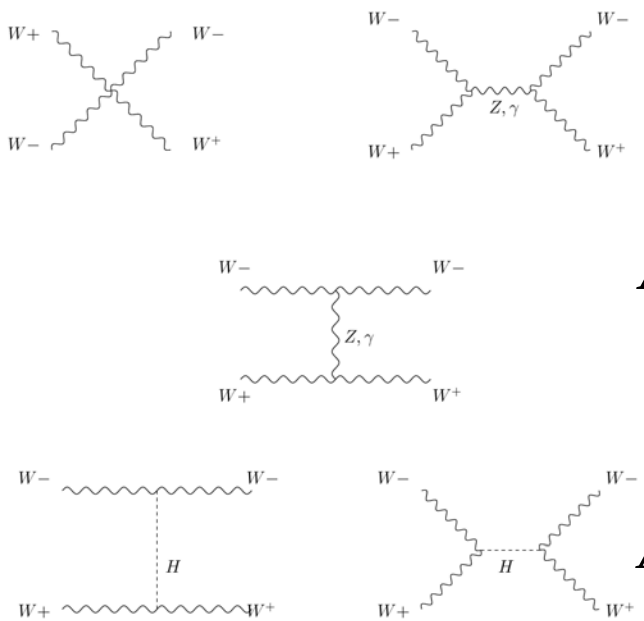
- SUSY: Introduce partner particles to all known particles
- Minimal version is extremely predictive
- Has 5 scalar particles!



SUSY is slightly better fit than SM

Buchmueller et al, arXiv:0912.1036

Who Needs a Scalar Anyways?



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

Terms which grow with energy cancel for E >> M_H

This cancellation requires M_H < 800 GeV

Reason #2: SM scalar has just the right couplings so amplitudes don't grow with energy

On Very General Grounds…..

- We expect a light scalar

$$\varepsilon_L \approx \frac{p_W}{M_W}$$

$$A\left(W_L^+ W_L^- \to Z_L Z_L\right) = -\frac{G_F E^2}{8\sqrt{2}\pi}\left(\frac{M_H{}^2}{E^2 - M_H^2}\right)$$

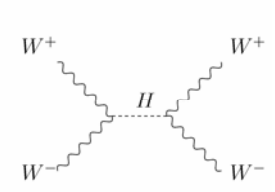
Unitarity → Light scalar: $M_H < 800$ GeV

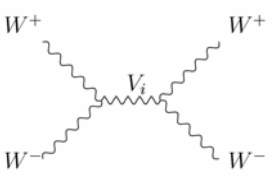
No scalar: $\Lambda_c \sim 1.2$ TeV ← Unitarity violation

Expect a light scalar or new physics below 1 TeV

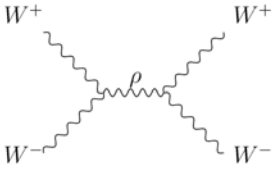
Question isn't: "Where is the Scalar?"

- Question is: ***"What unitarizes WW scattering?"***
- Symmetry breaking could be weakly coupled
  - SUSY, Lots of singlets, Extra-D with multiple vector bosons…..



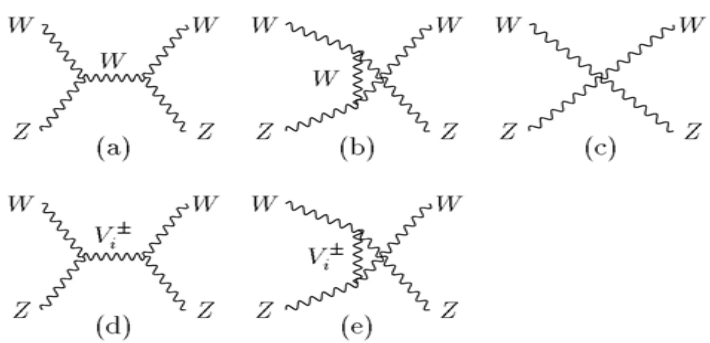


- Symmetry breaking could be strongly coupled
  - Technicolor, QCD like models, composite scalars…..

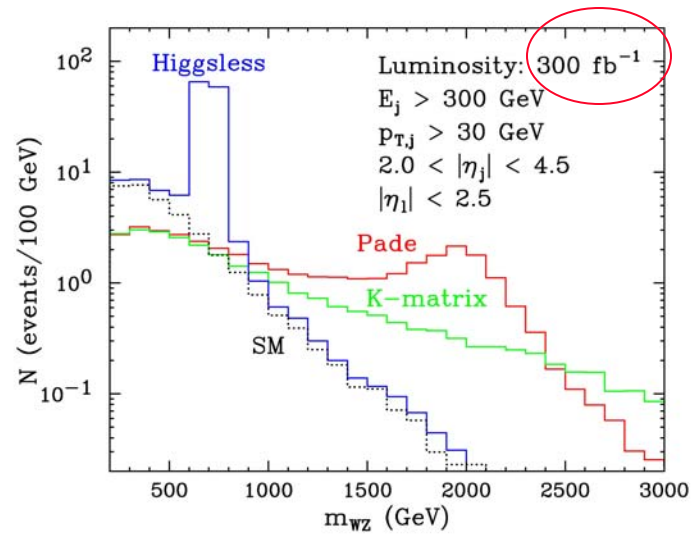


Extra-D Higgsless Models

- Look for massive W, Z, γ like particles in vector boson fusion
  - Need small couplings to fermions to avoid precision EW constraints
  - Narrow resonances in WZ channel



LHC

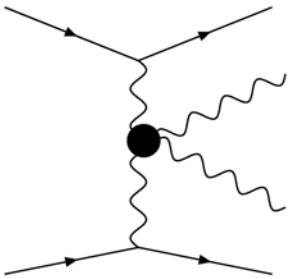


Different resonance structure from SM!

Birkedal, Matchev, Perelstein, hep-ph/0412278

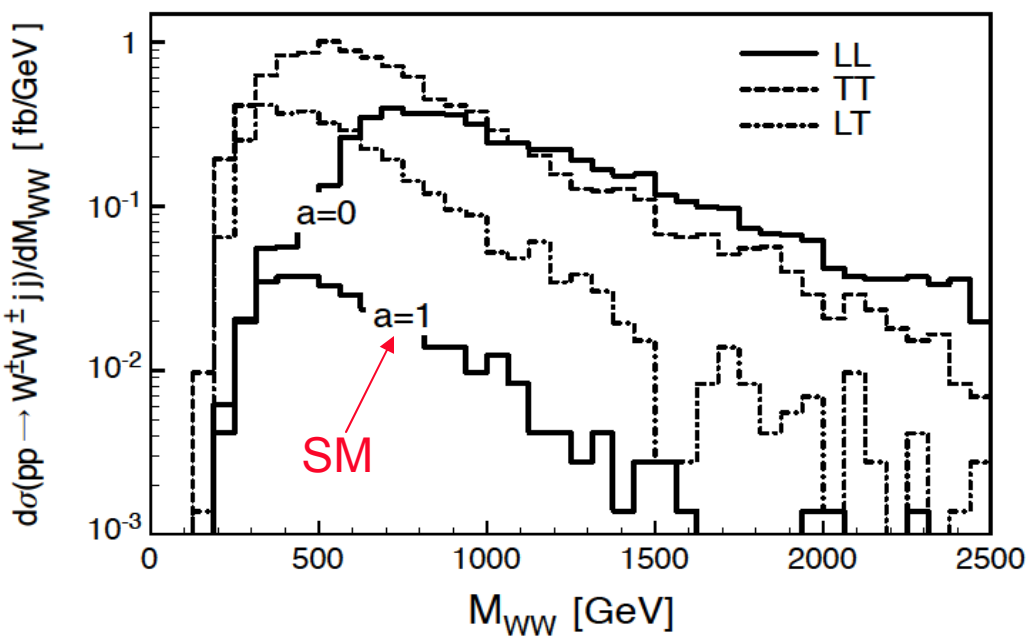
WW Scattering can be Measured

- No scalar → longitudinal gauge boson cross sections rise with energy
- Can we see this effect?
  - Electroweak process with no color exchange
  - Outgoing quarks make forward jets which can be tagged
  - Tends to produce fewer central jets than background
  - Many backgrounds with large interference
  - Very small effects → requires large luminosity (~300 fb^{-1})



Non-SM Interactions grow with energy

- $V_L V_L \rightarrow V_L V_L$, $\sigma \sim (\ldots)\, s^2/M_W^4$
- Can we see rising cross sections?



- Only win for large M_{WW}, where σ is small

Contino, Grojean, Moretti, Piccinini, Rattazzi, arXiv:1002.1011

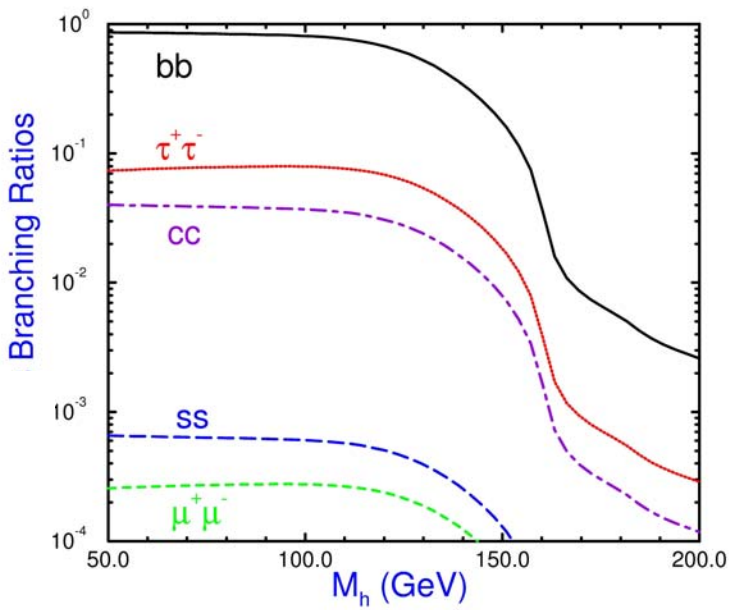
Who Needs a Scalar Anyways?

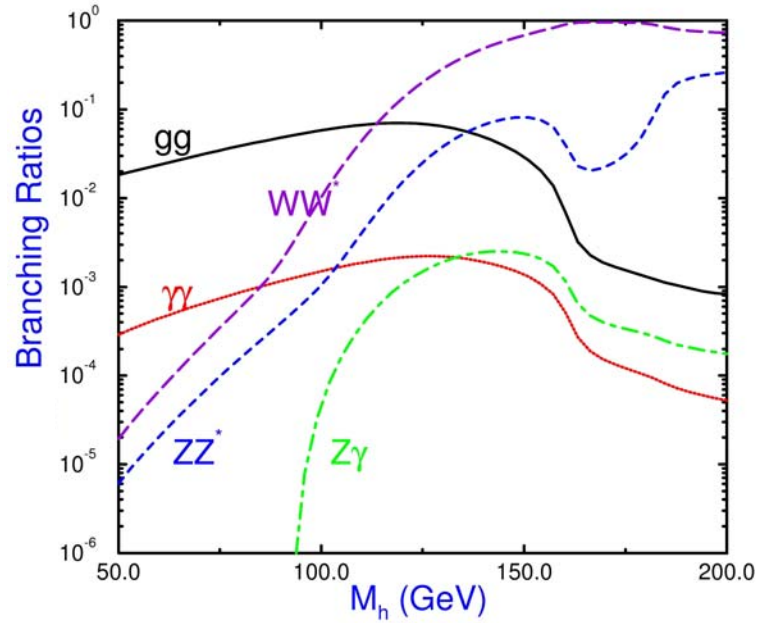
- Standard model is a chiral theory
  - Example:
    - t_L is SU(2) doublet, t_R is SU(2) singlet
  - Quark and lepton masses are forbidden by SU(2) x U(1) gauge symmetry
    - Mass term connects left and right-handed fermions: $L \approx m\bar{f}_L f_R$
    - Scalar provide gauge invariant mass term: $L \approx \frac{m_f}{v} \bar{f}_L \Phi f_R$

Reason #3: To give gauge invariant masses to fermions

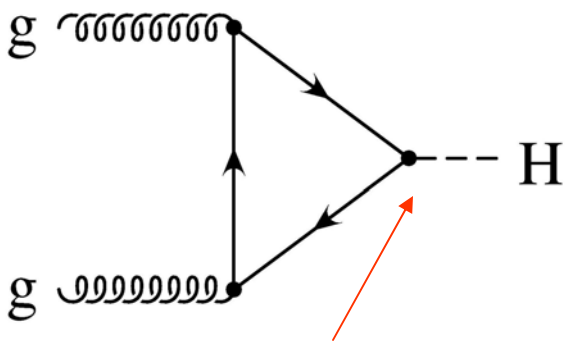
H Decays to Heaviest Possible Particles

- This is SM property

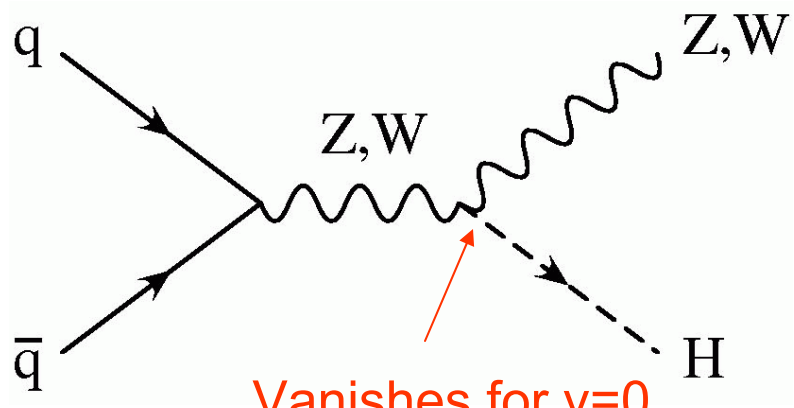




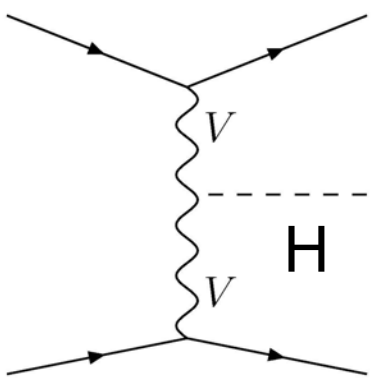
Producing the Scalar



Probes top-H coupling



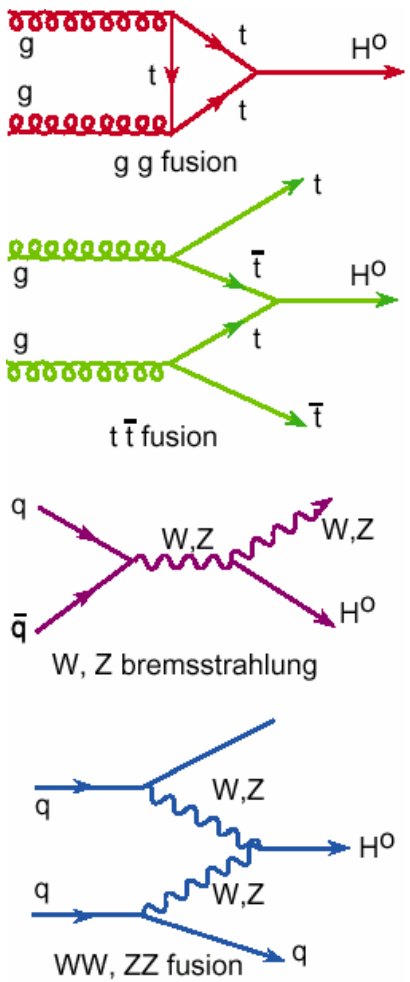
Vanishes for v=0

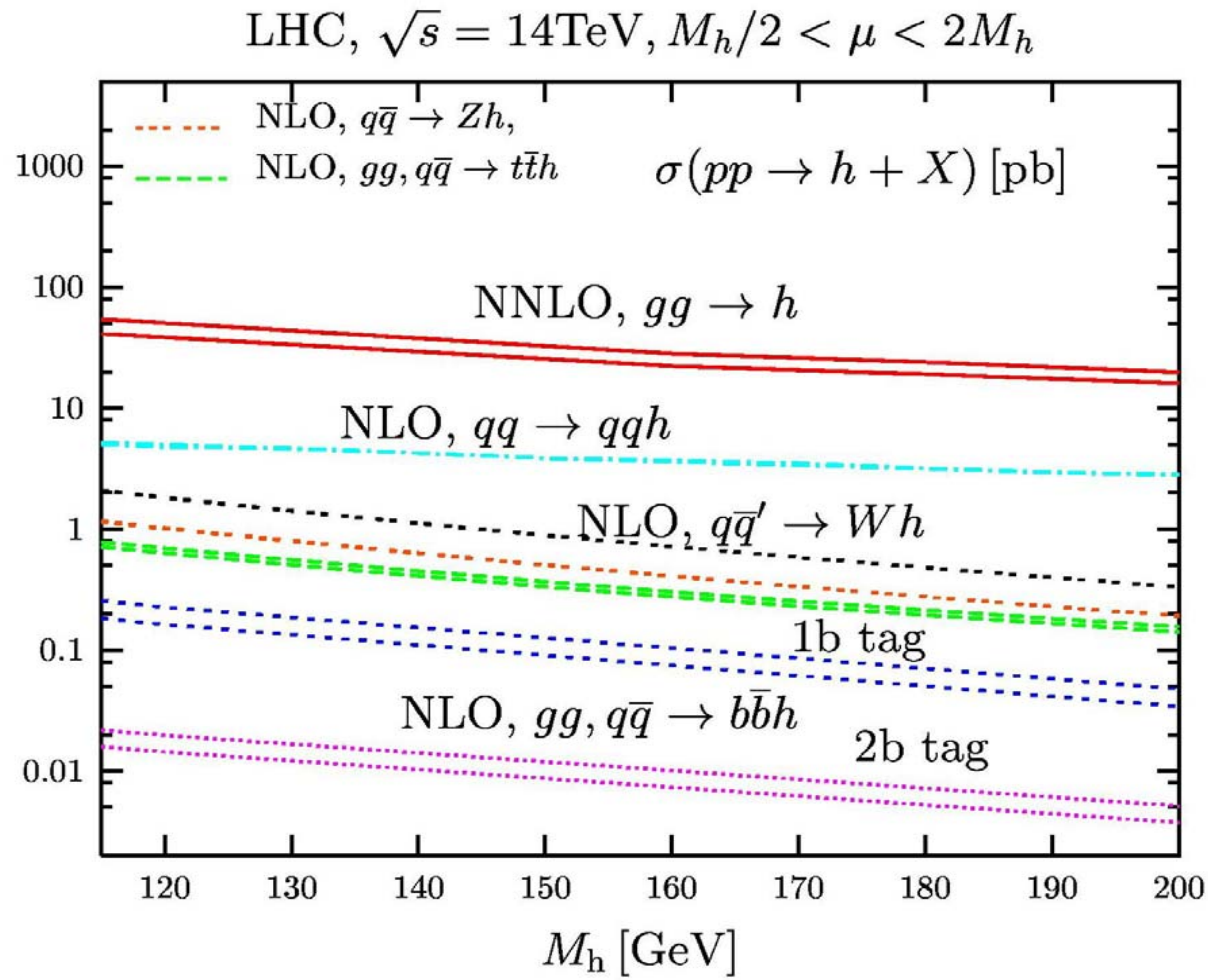


Different mechanisms important for different M_H

Sensitive to rising cross sections

Standard Model Scalar at the LHC





Discovery isn't Enough

- Is this the SM scalar or something else?
- We must answer critical questions
  - Does the scalar generate mass for the W,Z bosons?
  - Does the scalar generate mass for fermions?
  - Does the scalar generate its own mass?

Is it the Standard Model scalar?

- 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

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

Scalar Couplings very hard at LHC

- At the LHC with $\sqrt{s}$=14 Tev and L=30 fb^{-1} (for M_H=120 GeV)

$$g_{XXH}=g_{XXH}^{SM}(1+\Delta_{XXH})$$

  - Δ_{WWH} ~ 30%
  - Δ_{bbH} ~ 50%
  - $\Delta_{\tau\tau H}$ ~ 50%

High energy e^+e^- collider could get couplings to a few %!

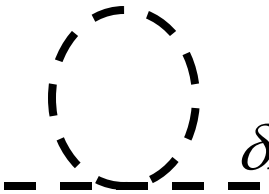
Lafaye et al, arXiv: 0904.3866

What's Wrong with the SM?

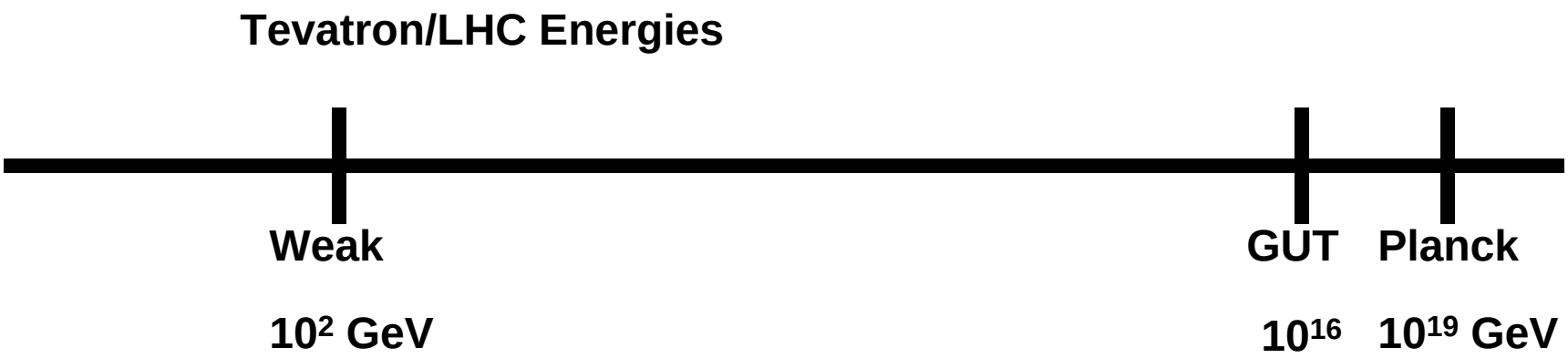
- We haven't seen the scalar!
  - If a SM scalar exists, we will see it at the LHC
- Many (theoretically attractive) models beyond the SM exist
  - These models will be tested at the LHC
  - Typically predict more new particles
- Theoretical worries about minimal Standard Model
  - (These only bother theorists)

Quantum Corrections Connect Weak and Planck Scales

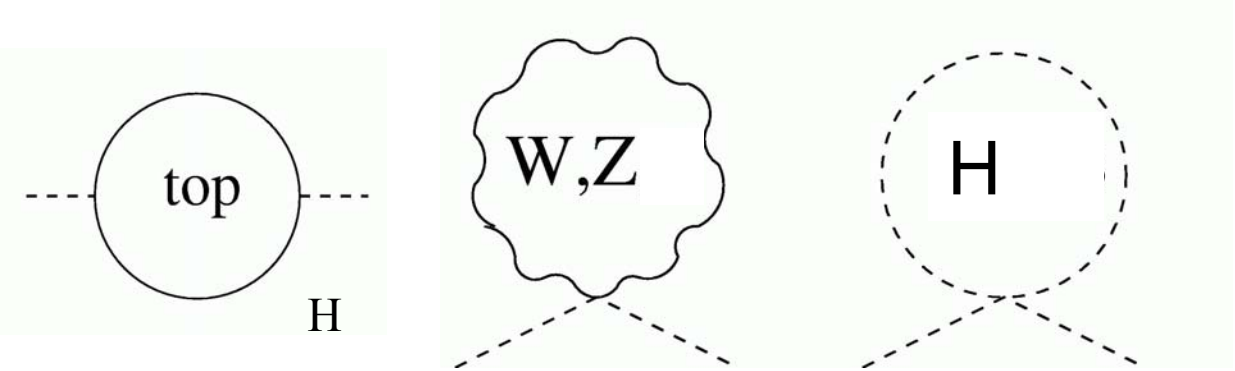
Quantum corrections drag weak scale to Planck scale



$$\delta M_H^2 \approx M_{Pl}^2$$



Why 1 TeV?



- Scalar mass grows with high scale, Λ (*a priori* Λ=M_{pl})

$$\delta M_H^2 = \frac{G_F}{4\sqrt{2}\pi^2}\Lambda^2\left(6M_W^2 + 3M_Z^2 + M_H^2 - 12M_t^2\right)$$

$$= -\left(\frac{\Lambda}{0.7\ \mathrm{TeV}}\ 200\ \mathrm{GeV}\right)^2$$

$M_H \leq 200$ GeV requires $\Lambda \sim$ TeV

Conclusions

- A new era of particle physics has begun
- Our expectations are high
- It all hinges on finding the SM scalar!