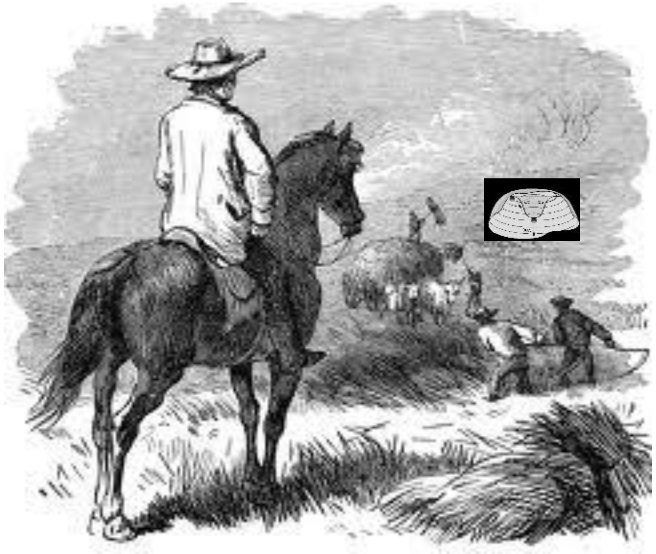
The Higgs Frontier: The Way Forward



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Princeton

April 26, 2013

The Higgs Frontier

- What have we found ?
  - Is it ***THE*** Higgs?
- What's next ?
  - Are there more Higgs particles?
  - Is there a next energy scale?

What are the important measurements/calculations to help us answer these questions?

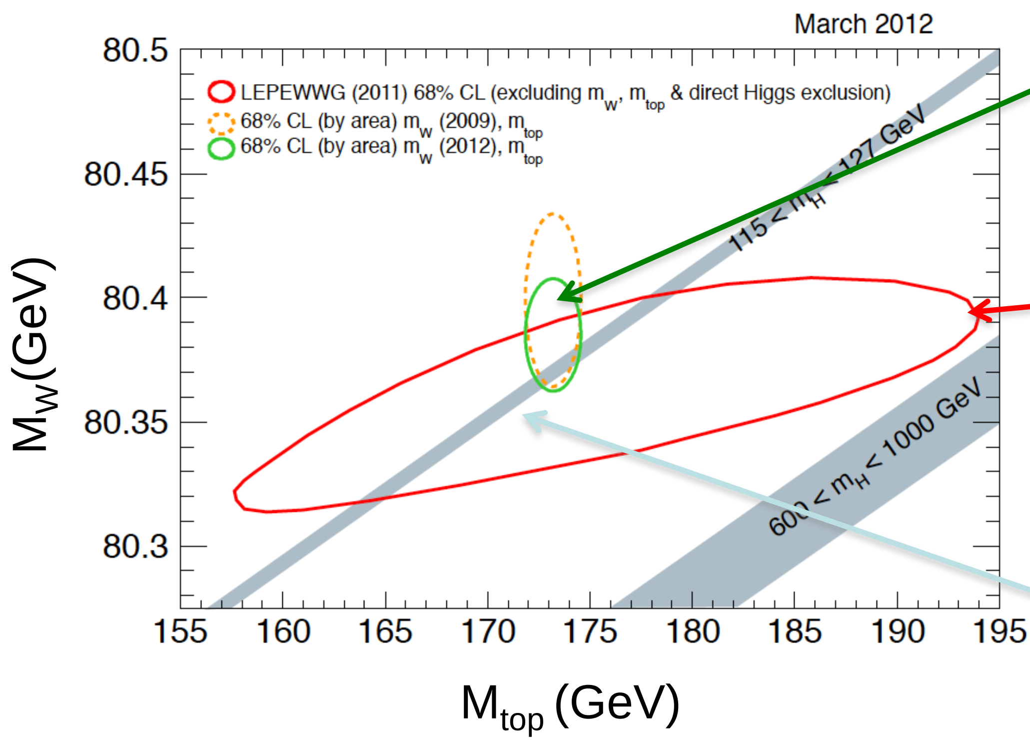
Please join the effort: snowmass2013.org

Needed Something like a Higgs

- Electroweak symmetry breaking needs to explain:
  - Non-zero mass of W and Z gauge bosons
  - Non-zero mass of fermions
  - Unitarity conservation at 1 TeV
- Precision electroweak data is consistent with SM

So the fact that the observed Higgs-like particle looks ***SM-like*** is no surprise

The 6 billion dollar plot



Experimental measurements from Fermilab

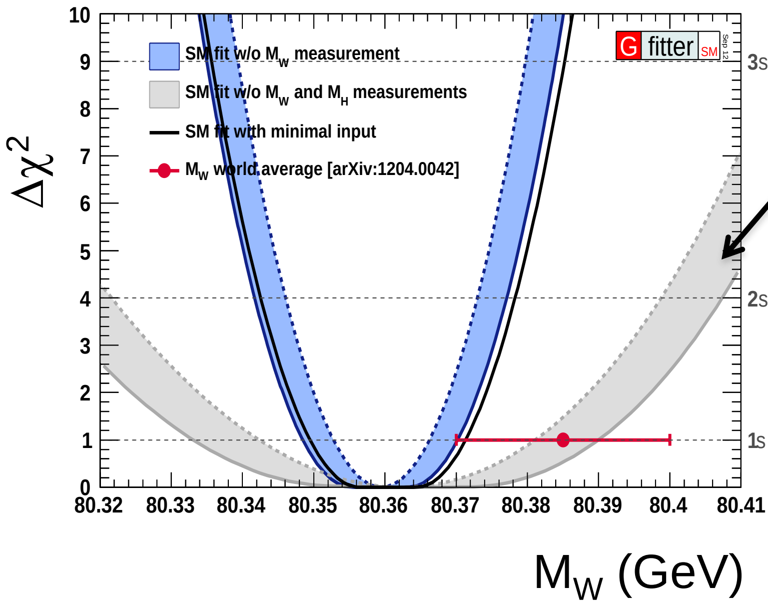
Inferred values of M_W and M_t from other experiments

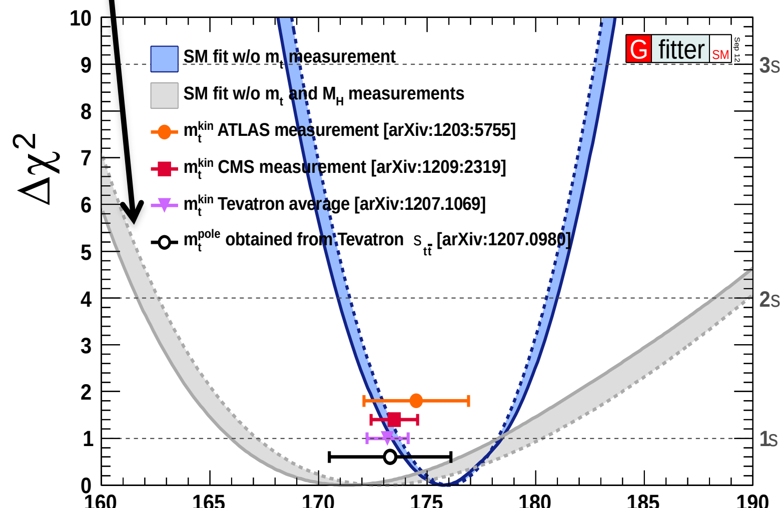
Theory predictions

Self-consistency of the theory told us the Higgs couldn't be too heavy

After Discovery

Fit without Higgs

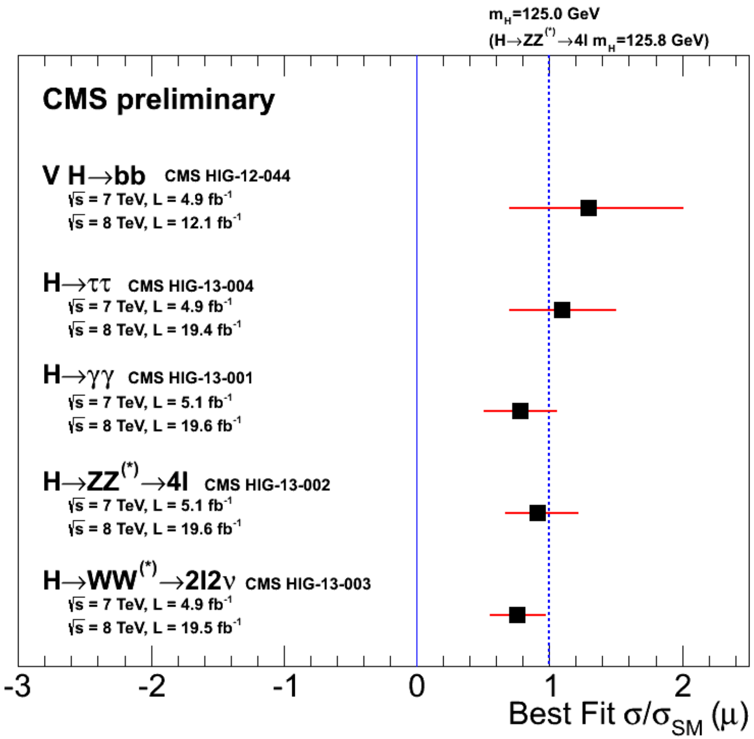


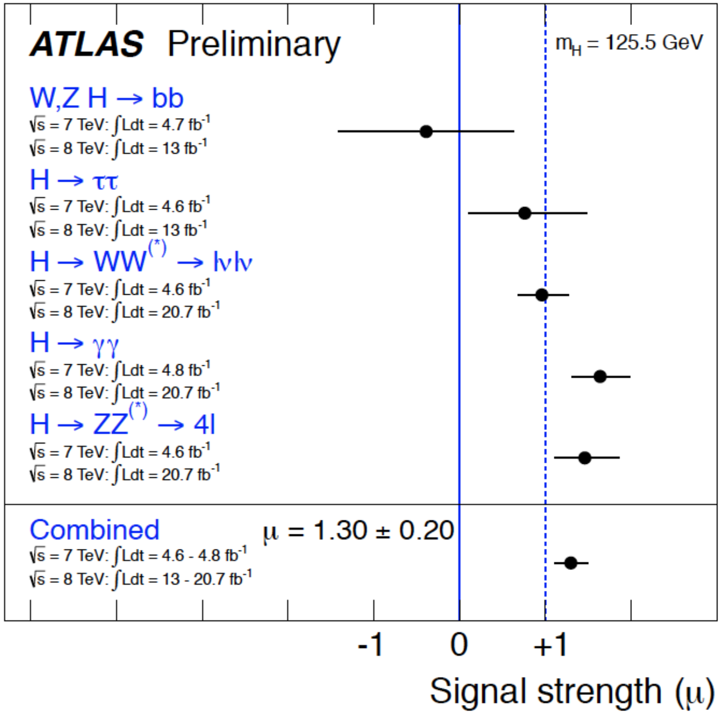


A consistent picture

The SM as an effective low energy theory is an extremely good approximation

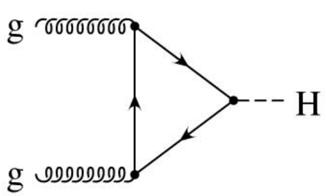
Higgs Rates look SM-like

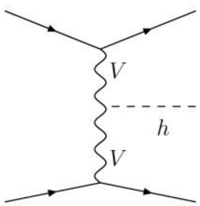


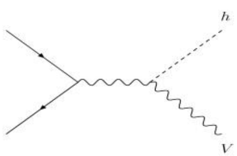


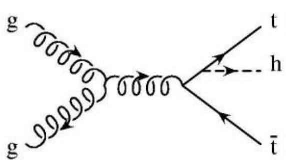
What goes into denominators?

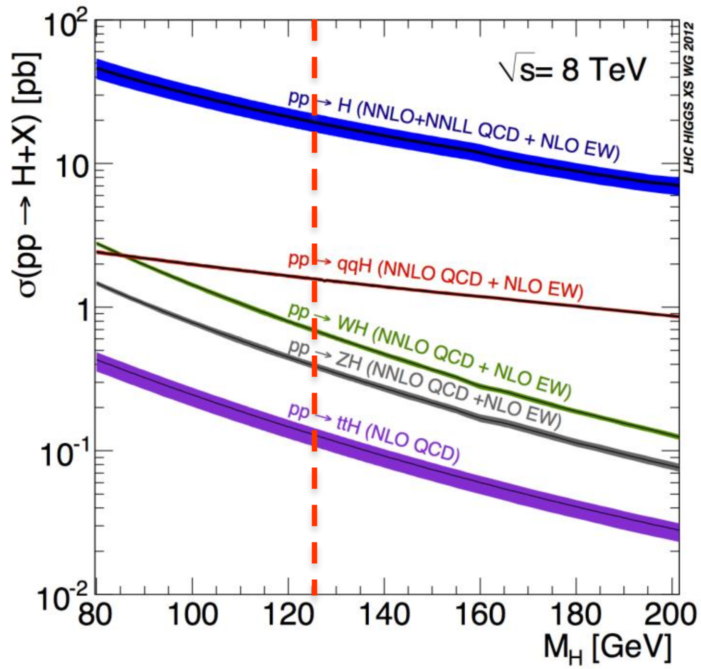
Precision Calculations











gg→h at 8 TeV: ±7% scale uncertainty ± 7%; PDF+α_s uncertainty (for m_h=125 GeV)

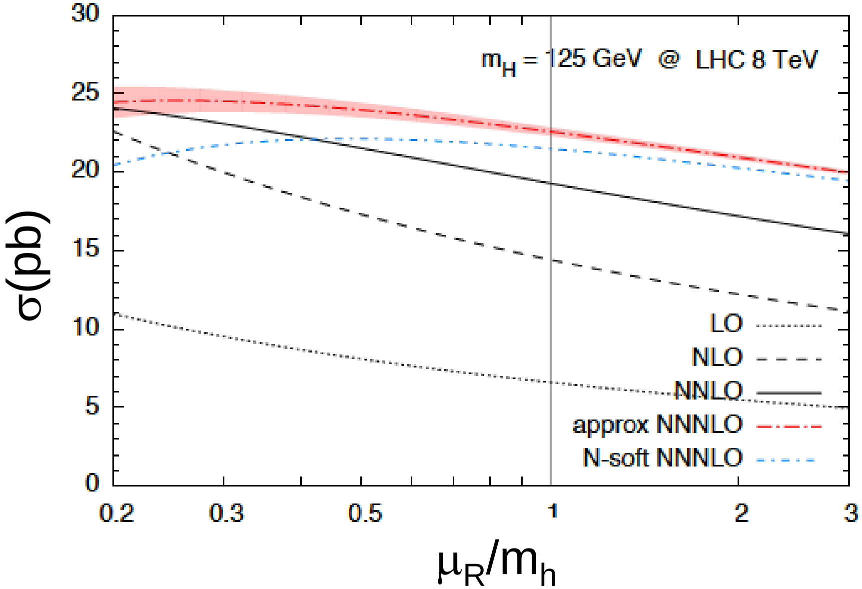
qq→Wh at 8 TeV: +.3,-.6% scale uncertainty;± 3.5% PDF+α_s uncertainty

[LHC Higgs Cross Section Working Group, 1201.3084]

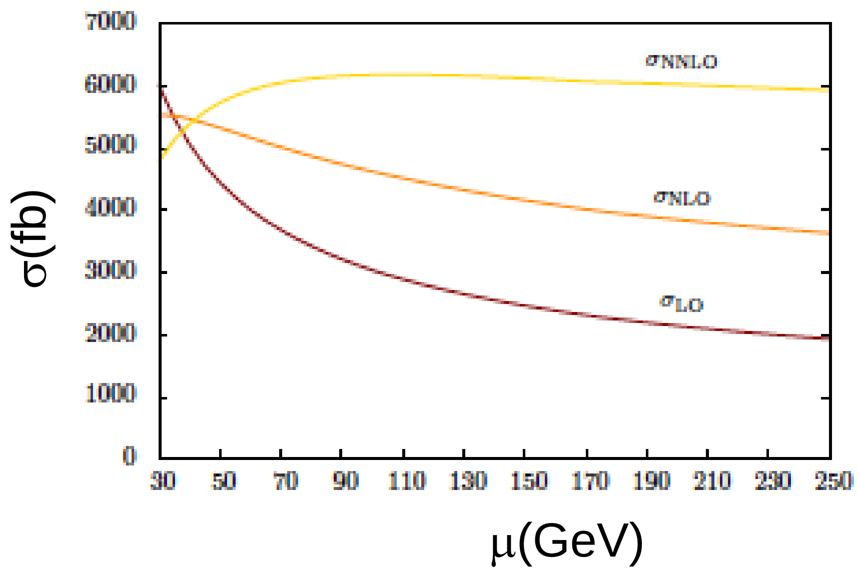
H+jet @NNLO, H@NNNLO

- Will decrease errors from scale uncertainty and jet binning

Higgs inclusive cross section



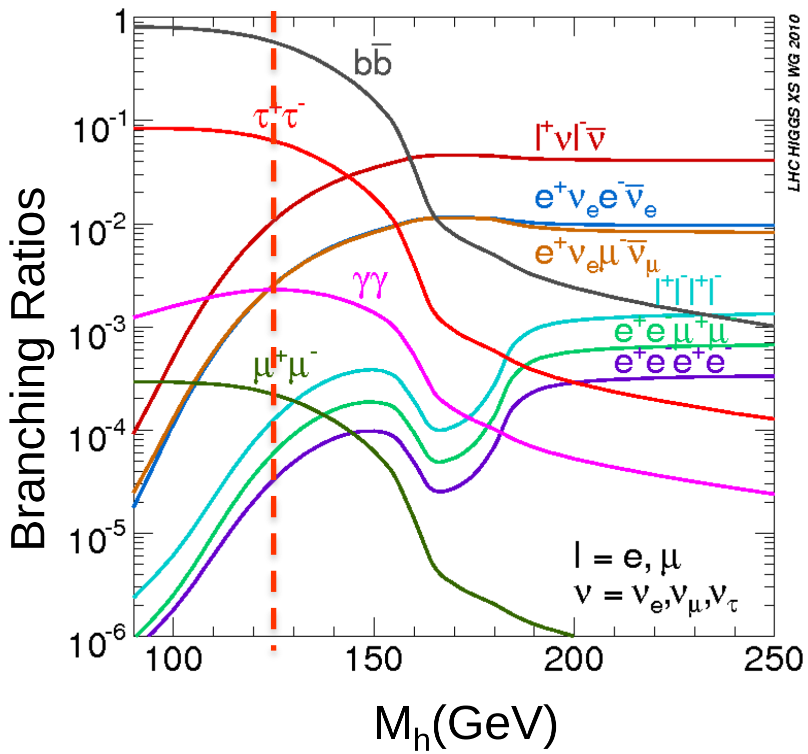
Higgs+jet at √s=8 TeV



Rates are increased

[Ball et al, 1303.3590; Boughezal et al, 1302.6216]

Uncertainties: Branching Ratios



Theory Predictions

	$\delta\Gamma/\Gamma$
bb	±3%
ττ	±5.7 %
γγ	±5%
WW	±4%
Γ_{tot} ↑	±4%

Assumes no invisible width

Parametric uncertainties (mostly m_b) and uncertainties from unknown higher order EW corrections

[LHC Higgs Cross Section Working Group, 1201.3084]

Uncertainties on BR Predictions

- Example: $h \rightarrow bb$
  - Error budget:
    - Theory (missing higher order corrections: QCD ~.1%, EW~1-2%)
    - Parametric errors from Δm_b~1.1%, $\Delta\alpha_s$~1%
  - Theory/parametric uncertainties roughly same size
    - Improve experimental value of m_b=4.49 $\pm$.06 GeV
    - Use PDG central value, compromise on errors
  - Error on $\delta\Gamma_{bb}$ matters for 300 fb^{-1} extraction of hbb coupling (~6.9% at CMS) [Olsen] and for ILC extractions (~2.7% at 250 GeV)[van Kooten]

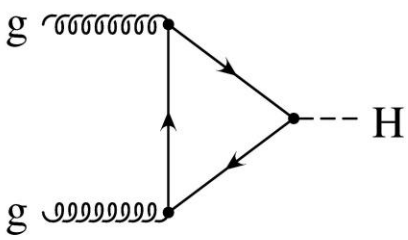
[LHC Higgs Cross Section Working Group, 1201.3084]

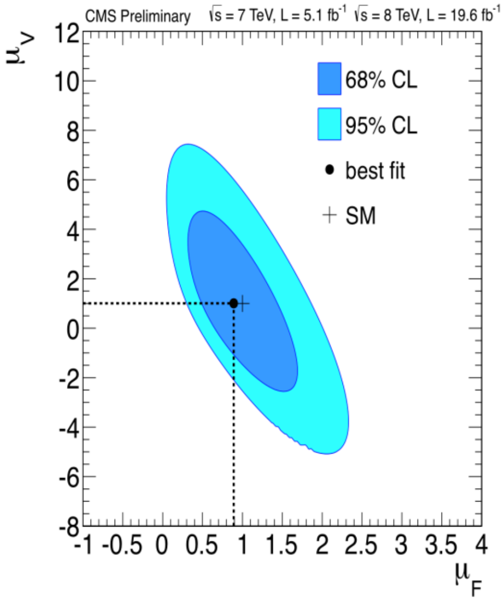
What we know

- ttH coupling exists
  - Indirectly from gg→h, h→γγ
- WWh, ZZh couplings exist
  - Rate appears to be SM-like
  - h→ZZ*→4 leptons

$$CMS : \sigma/\sigma_{SM} = \mu = 0.92 \pm 0.28$$

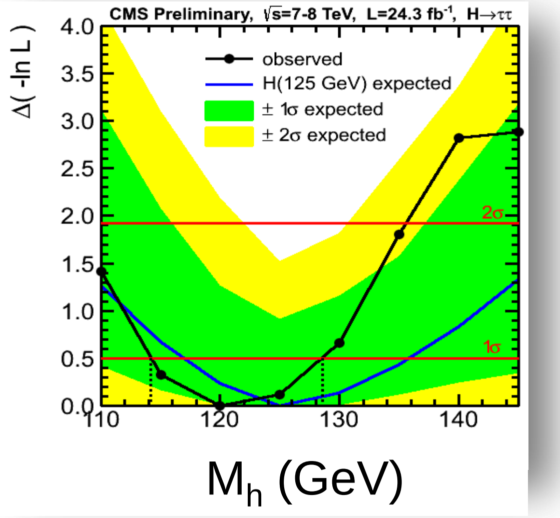
$$ATLAS : \sigma/\sigma_{SM} = \mu = 1.7^{+0.5}_{-0.4}$$

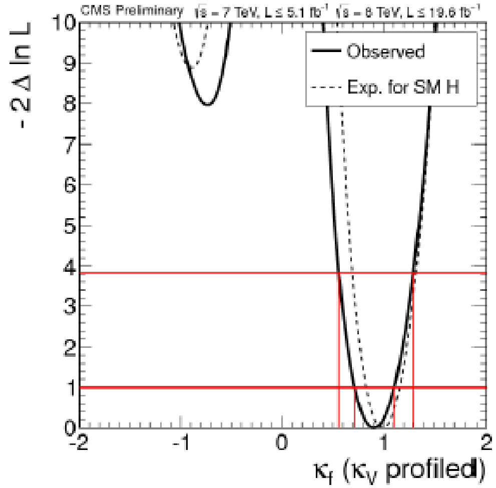




What we know

- Higgs couples to fermions (2.8σ in $\tau^+\tau^-$)
  - Fermion couplings are non-universal
  - We see $\tau\tau$, not $\mu\mu$





No more fermiophobic models

What we know

- The Higgs sector is perturbative

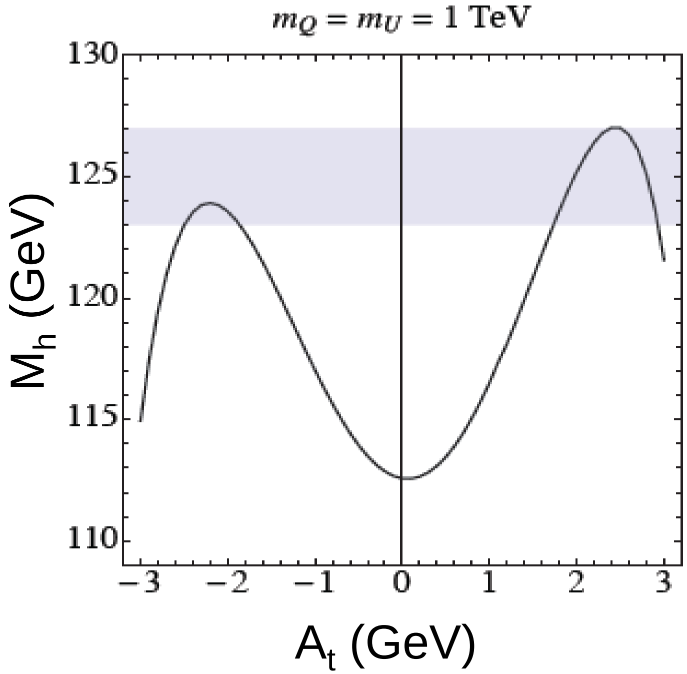
$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 \qquad \lambda = \frac{M_h^2}{2v^2}$$

$$\lambda \sim .13, \mu \sim 90\ GeV$$

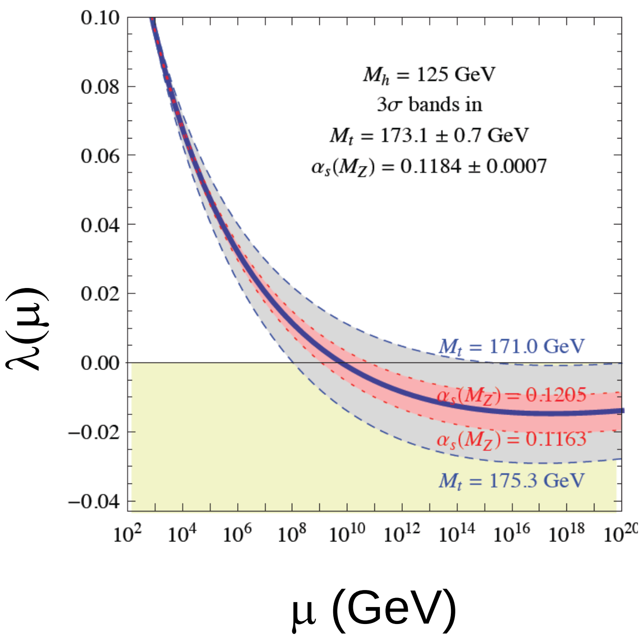
- We can sensibly calculate to high scales
- Is M_h=125 GeV special?

Is M_h=125 GeV Special?

M_h=125 GeV requires M(stop)~10 TeV or large A_t in the MSSM [Shih]



Quartic coupling evolves to 0. What does this mean? [Reese]



[Draper et al,1112.3068;
Degrassi, 1205.6497]

Multi- Prong Approach to Future

- Measure everything in sight
  - There are a lot more Higgs channels to measure
  - Corollary: Calculate as precisely as possible
- Look for more Higgs candidates
  - Look for non-standard Higgs production/decays
- Use effective field theory to limit deviations
  - Look for new particles connected with EWSB
- Make connections
  - Dark matter, intensity frontier

Explore NP-Higgs Connections

- Many possibilities:
  - Supersymmetry (squarks in loop)
  - Color octet scalars [Kribs]
  - More scalars (neutral or charged) [Thomas]
  - New operators involving Higgs particle
  - New fermions (top partners)
  - Higgs produced in NP particle decays[Haas, Kribs, Thomas]

How far can Higgs production get from the SM prediction?

What is the Higgs telling us?

Example 1: 2HDMs

- Many models have extended Higgs sectors
  - Two Higgs doublet models can be used as effective theories for many of these models
  - 5 Higgs bosons: h, H, A, $H^{\pm}$
  - 4 types of 2HDM models which avoid tree level FCNCs
  - Classified in terms of tan $\beta = v_2/v_1$, α, m_h

$$\sin 2\alpha = -\sin 2\beta \left(\frac{M_H^2 + m_h^2}{M_H^2 - m_h^2} \right)$$

  - Predictive models (MSSM is special case)

More than one 2HDM

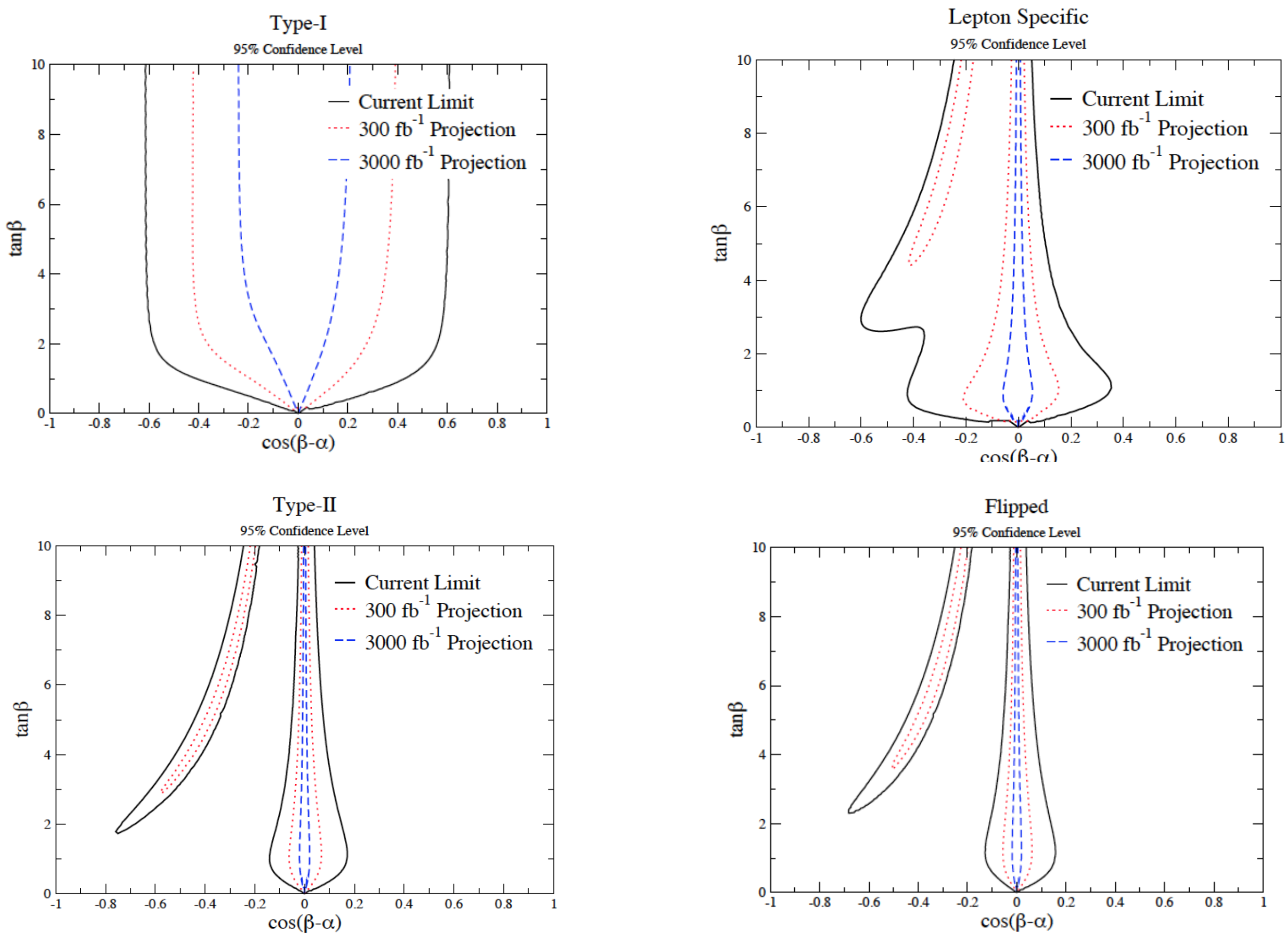
- Couplings to h:

$$L \sim -\Sigma_i g_{hii} \frac{m_i}{v} \overline{f}_i f_i h - \Sigma_{i=W,Z} g_{hVV} \frac{2M_V^2}{v} V_\mu V^\mu h$$

	I	II	Lepton-Specific	Flipped
g_{hVV}	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
$g_{ht\bar{t}}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$\frac{\cos\alpha}{\sin\beta}$
$g_{hb\bar{b}}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$
$g_{h\tau^+\tau^-}$	$\frac{\cos\alpha}{\sin\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$-\frac{\sin\alpha}{\cos\beta}$	$\frac{\cos\alpha}{\sin\beta}$

Type II is MSSM-like

Updated 2HDM fits



SM limit is $\cos(\alpha-\beta)=0$

We are near SM couplings already!

[Thomas]

[Chen, Dawson, 1301.0309; Chen, Dawson, Sher]

Decoupling Limit: Type II 2HDMs

Assume M_{H+}, $M_A >> M_Z$

$$\alpha \Delta T \sim \mathcal{O}\left(\frac{M_Z^2}{M_A^2}\right)$$

$$\Delta S \sim \frac{1}{12\pi} \cos^2(\beta - \alpha)\left[\log\left(\frac{M_A^2}{M_h^2}\right) - \frac{5}{6}\right]$$

Coupling shifts are small: $g_{hii} \equiv g_{hii}^{SM}\left(1 + \frac{\delta g_{hii}}{g_{hii}^{SM}}\right)$

$$\frac{\delta g_{hVV}}{g_{hVV}^{SM}} = -\frac{2M_Z^4 \cot^2\beta}{M_A^4}$$

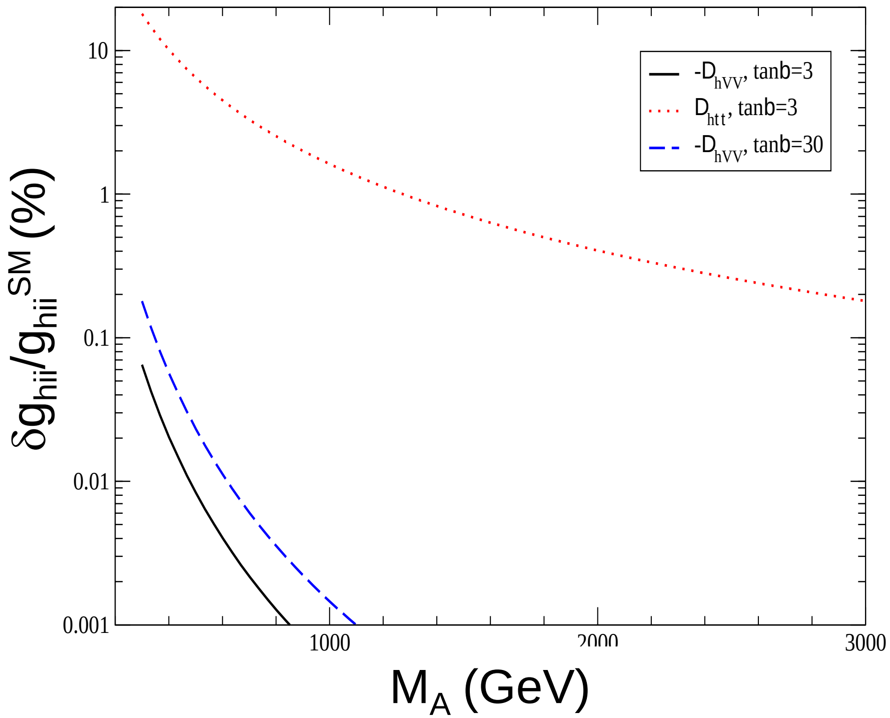
$$\frac{\delta g_{ht\bar{t}}}{g_{ht\bar{t}}^{SM}} = -\frac{2M_Z^2 \cot^2\beta}{M_A^2}$$

$$\frac{\delta g_{hb\bar{b}}}{g_{hb\bar{b}}^{SM}} = \frac{2M_Z^2}{M_A^2}$$

Higgs physics is new precision electroweak physics

The world looks SM-Like

Higgs Couplings in Type-II 2HDM



This requires sub-percent level measurements of Higgs couplings to distinguish the 2HDM model from the Standard Model

➔If we don't see any new particles, this will be very hard!

Higgs Coupling Measurements

- Higgs coupling extracted from global fit
  - Measure σ•BR

$$L \sim g_{hii} f_i \overline{f}_i h$$

$$g_{hii} \equiv \left(1 + \frac{\delta g_{hii}}{g_{hii}^{SM}}\right) g_{hii}^{SM}$$

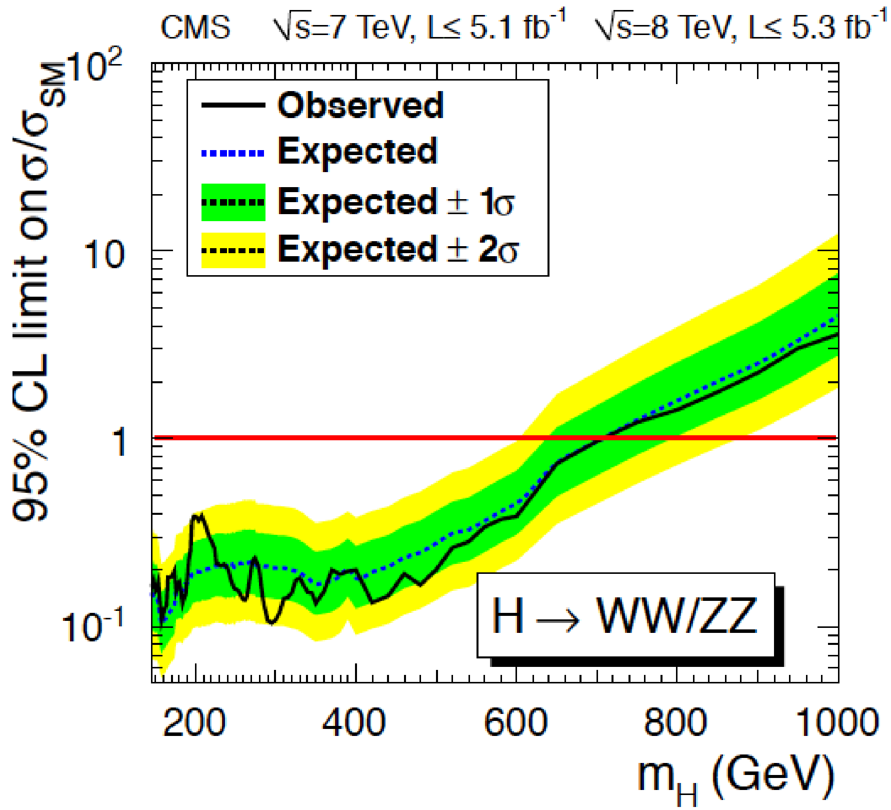
	LHC (300 fb^{-1}/exp)	**LHC (3 ab^{-1}/exp)**	**ILC 250 (250 fb^{-1})**
$\frac{\delta g_{hWW}}{g_{hWW}^{SM}}$	$2.7 - 5.7\%$	$1.0 - 4.5\%$	4.3%
$\frac{\delta g_{h\tau\tau}}{g_{h\tau\tau}^{SM}}$	$5.1 - 8.5\%$	$2.0 - 5.4\%$	3.5%

Assume systematics ~1/√L

[Janot, ICFA Higgs factor workshop, European Strategy Report]

Complementary Approach

- Look for new particles of 2HDM (H,A,$H^{\pm}$)



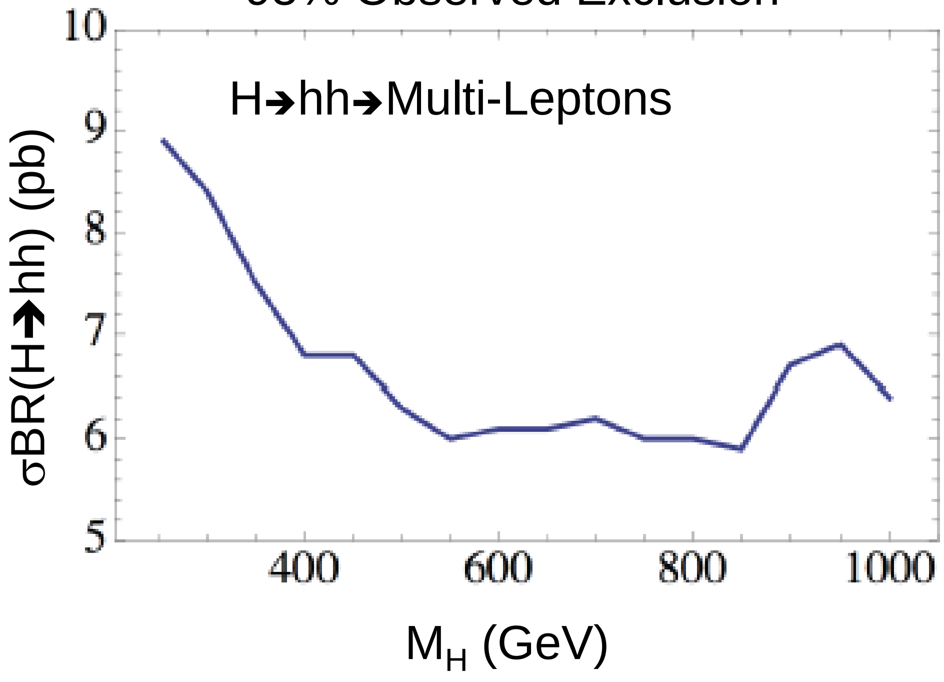
$$g_{HVV} = cos(\beta - \alpha)$$

$$g_{Ht\bar{t}} = \left(\frac{\sin\alpha}{\sin\beta}\right)$$

New Decay Channels Possible

- H➔hh [Thomas]
- First limit on di-Higgs production from CMS multi-lepton search

95% Observed Exclusion



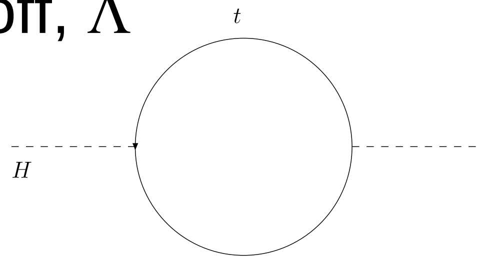
σ/σ_{SM}~4000

At □s=7 TeV:
σ_{HH}(SM)=2 fb

Does Naturalness matter?

The case for new TeV Scale particles

- Calculate top quark contribution in SM with a high scale cutoff, Λ



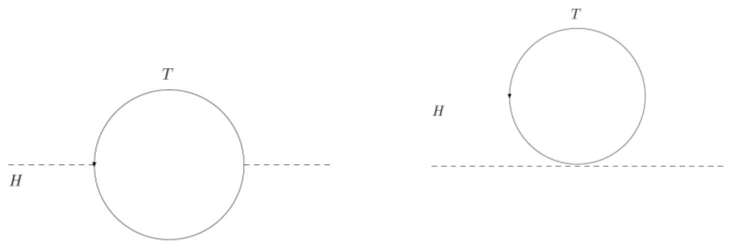
$$\delta m_H^2 \sim -\frac{3\lambda_t^2}{8\pi^2}\Lambda^2$$

- Cancel with new particle contribution:
  - Stop in SUSY models
  - Top partner in composite/Little Higgs models

Logical proposition: forget about naturalness and use dimensional regularization for δm_H

Consequences of Naturalness

- If we accept naturalness as a fundamental requirement, then there must be new light particles at the TeV scale
- Example: top partners $\delta M_h^2 \sim \left(\ldots\right)(M_T^2 - m_t^2)\log\left(\frac{M_T^2}{m_t^2}\right)$



  – Quadratic contribution to Higgs mass cancels with SM
    - This requirement fixes couplings
  – New TThh vertex has implications for hh production

Example 2: Top Seesaw, Little Higgs, Composite Higgs…..

- Special cases of models with weak singlet vector like charge 2/3 quark, U_L, which mixes with SM-like third generation $q_L \sim (u_L, d_L)$, u_R, d_R
- Generic mass matrix

$$L_M = -a\bar{q}_L\tilde{H}u_R - b\bar{q}_L\tilde{H}U_R - c\bar{U}_L u_R - d\bar{U}_L U_R + hc$$

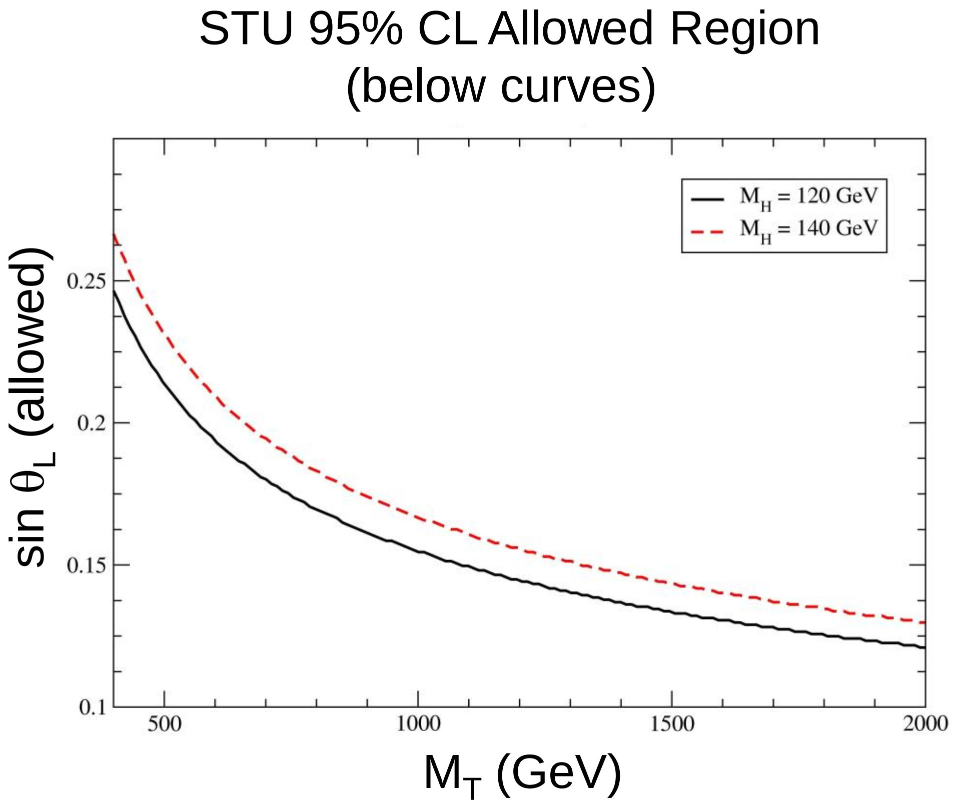
- Physical top is mixture of (u, U)

$$\begin{pmatrix} t_L \\ T_L \end{pmatrix} = \begin{pmatrix} c_L & -s_L \\ s_L & c_L \end{pmatrix} \begin{pmatrix} u_L \\ U_L \end{pmatrix}$$

T is charge 2/3 top partner

2 parameters: M_T, θ_L

Top Mixing with Top Partner

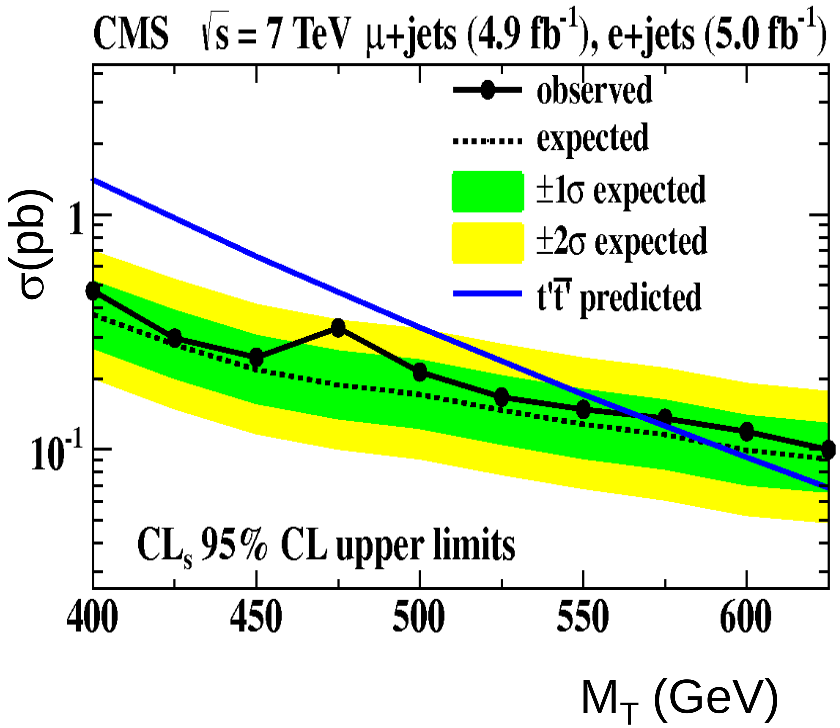


As Higgs mass gets larger, allowed parameter space shrinks

[Dawson, Furlan, 1205.4733]

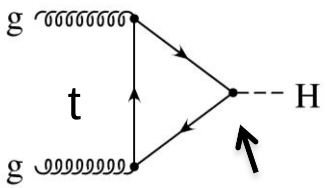
Experimental Limit

- Assumes BR($T \rightarrow bW$)=1
- Here, additional suppression of $(\sin\theta_L)^4$

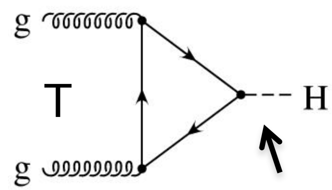


Higgs Production and Top Partners

- Production suppressed (but not observably so)



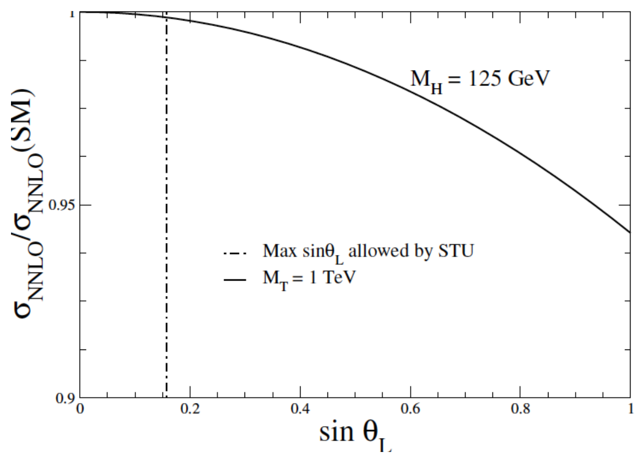
$\cos\theta_L{}^2$



$\sin\theta_L{}^2$

$$\frac{\sigma}{\sigma_{SM}} \sim 1 - \frac{7}{60}\frac{M_H^2}{m_t^2}\left(1 - \frac{m_t^2}{M_T^2}\right)$$

Top partner model, $\sqrt{s}$=7 TeV

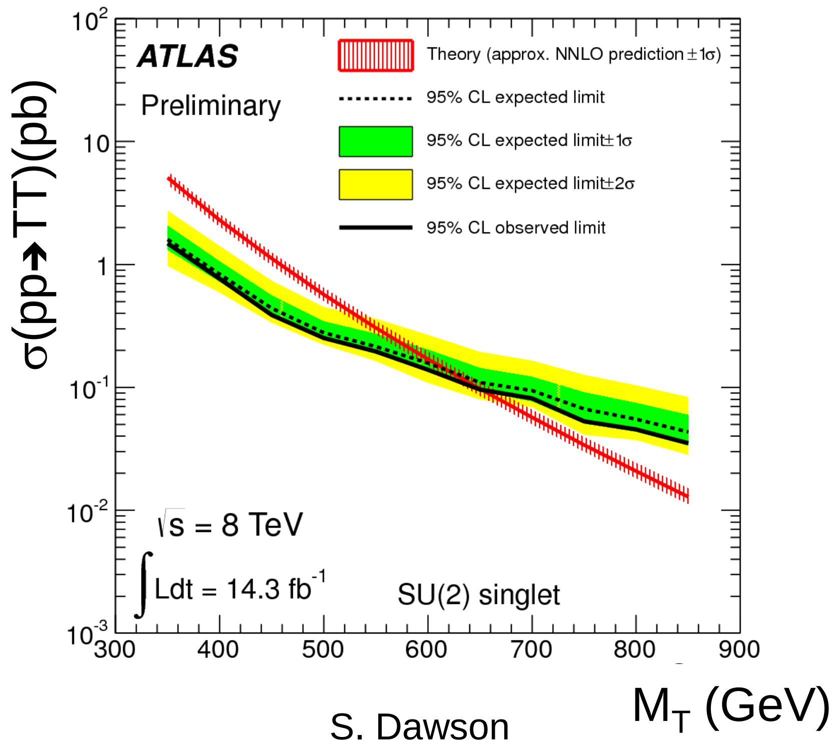


Example of model where new physics will be observed by top partner production, not by measuring Higgs properties

Higgs Production and Top Partners

- T→th
  - Branching ratio can be O(30%)

$$Tth :\sim \sin(2\theta_L)^2$$



Recap: 2 Examples

- 2HDMs, Top Partner models

These models have parameter spaces restricted by experimental Higgs measurements

Knowledge about NP from coupling constant measurements requires 1-10% percentage accuracy

BUT…..all of these models have new particles not present in the SM

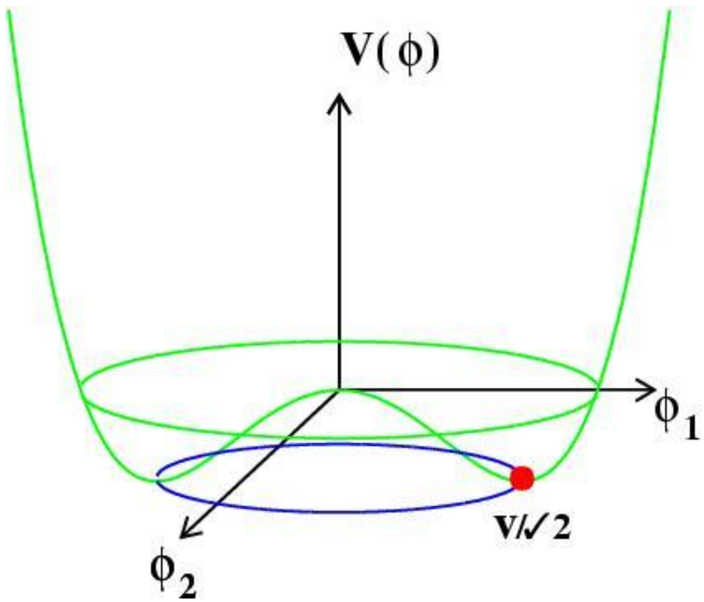
Reconstruct the Higgs potential

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

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

- Fundamental test of model

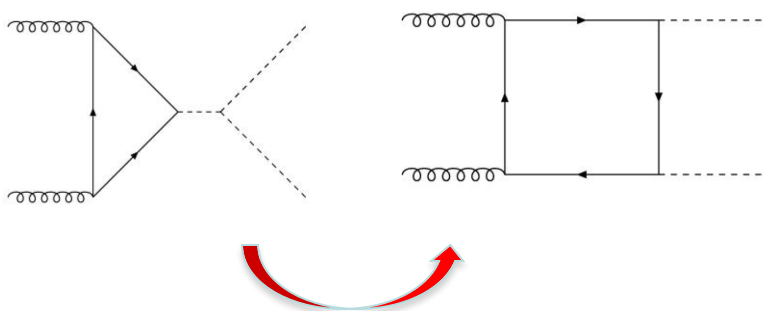
□ $\lambda_3 \sim .13$ is perturbative



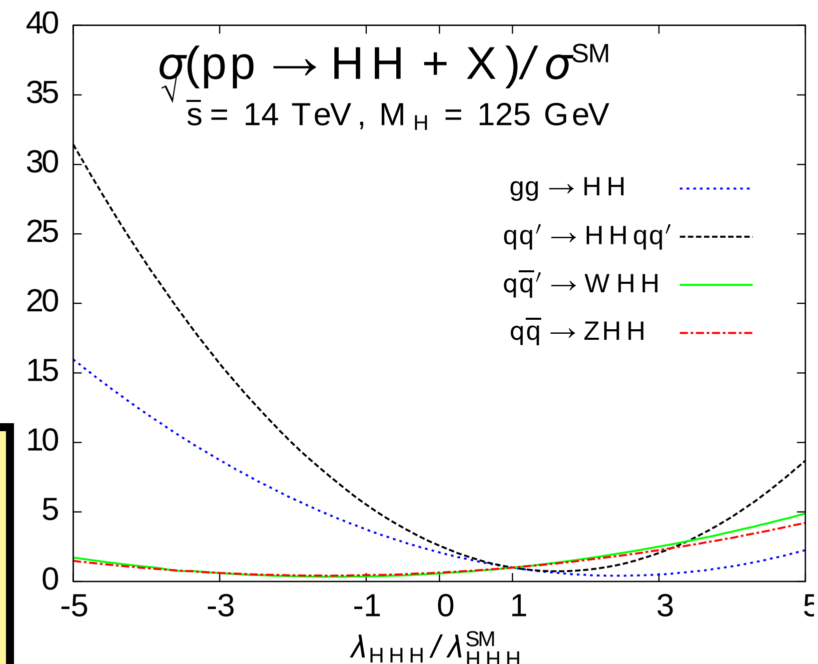
Double Higgs Production

- Sensitive to hhh coupling, $\lambda_{hhh} = 3M_h^2/v$
  - SM has small rates: At 14 TeV $\sigma(gg \to hh) = 34\ fb$

$$\sigma(qq' \to qq'hh) = 2\ fb$$



Contributions tend to cancel



Needs high luminosity LHC: ~3σ observation with 3000 fb^{-1} and both experiments

[Baglio et al, 1212.5581]

Double Higgs Production

- If fermion masses arise from electroweak symmetry breaking, they have the form

$$O_{LE} = \frac{\alpha_s}{24\pi} G^A_{\mu\nu} G^{A,\mu\nu} \log\left(\frac{H^+ H}{v^2}\right) = \frac{\alpha_s}{12\pi} G^A_{\mu\nu} G^{A,\mu\nu}\left(\frac{H}{v} - \frac{H^2}{2v^2}\right)$$

- An effective theory could generate

$$O_{eff} = \frac{\alpha_s}{4\pi} C_1 G^A_{\mu\nu} G^{A,\mu\nu} \left|\frac{H^+ H}{v^2}\right|^2 = \frac{\alpha_s}{4\pi} C_1 G^A_{\mu\nu} G^{A,\mu\nu}\left(\frac{H}{v} + \frac{H^2}{2v^2}\right)$$

- Measuring single and double Higgs production is window into source of EWSB
- Non-renormalizable ttHH coupling in composite models

Double Higgs Production from Colored Octet Scalars

- Single Higgs production can be SM-like, while double Higgs production greatly enhanced [Kribs]

Single Higgs rate/σ_{SM}

Huge enhancements of double Higgs rate

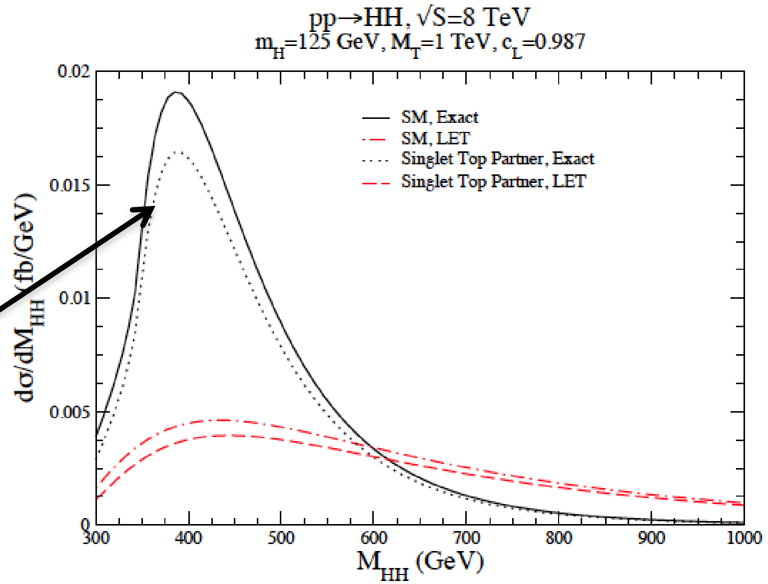
[Reese] Quartic coupling gets large in this class of models

Scalar octet mass (GeV)

[Kribs, Martin, 1207.4496]

Double Higgs Production from Top Partners

Small sensitivity to top partners (no ttHH vertex)

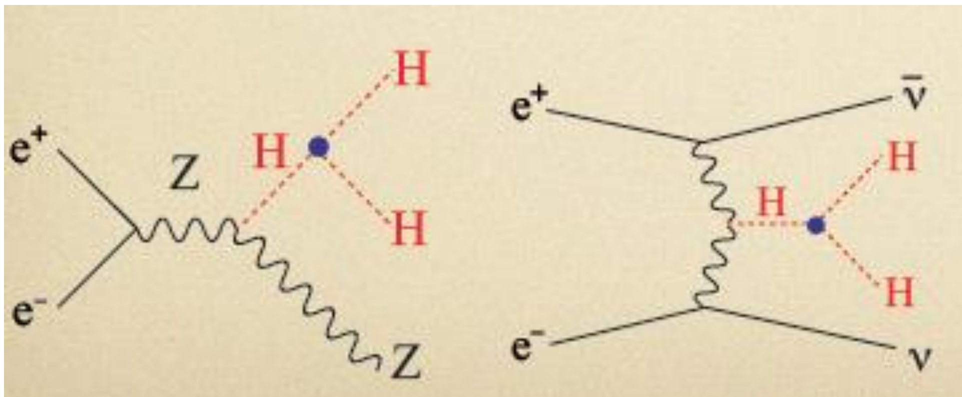


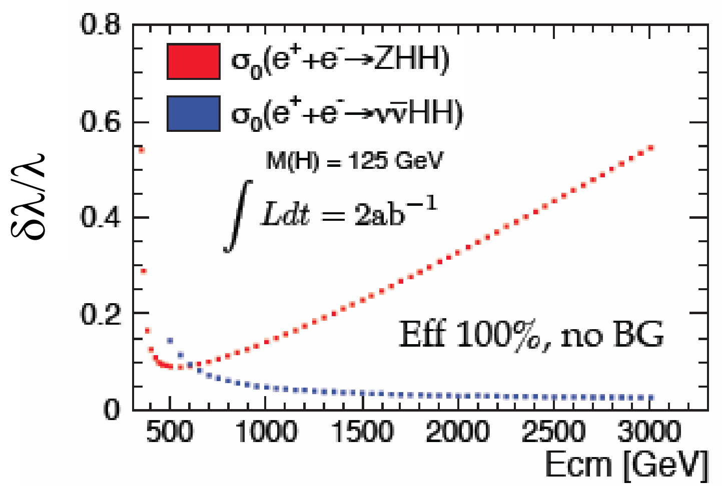
Parameters chosen to give SM (within 15%) single Higgs rate and to be consistent with precision EW

[Dawson, Furlan, Low, 1210.6663]

Double Higgs Production in e^+e^-

- At √s=500 GeV, rate for Zhh is larger (σ~.22 fb)





Including background and efficiencies at √s=500 GeV:

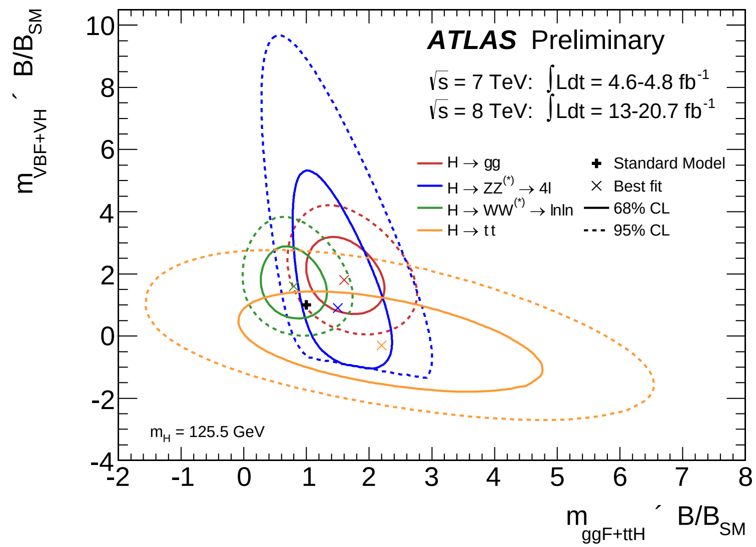
$$\frac{\delta\lambda}{\lambda} = 53\%$$

This improves at √s=1 TeV

Measure ratios of BRs

- Avoids large theory uncertainty on σ_{ggF} (necessary to claim new physics)
- Eventually get 5% measurement
- ATLAS current limit:

$$\frac{BR(h\rightarrow\gamma\gamma)}{BR(h\rightarrow ZZ^*)}\frac{BR(h\rightarrow ZZ^*)}{BR(h\rightarrow\gamma\gamma)}|_{SM}=1.1^{+0.4}_{-0.3}$$



[Cranmer]

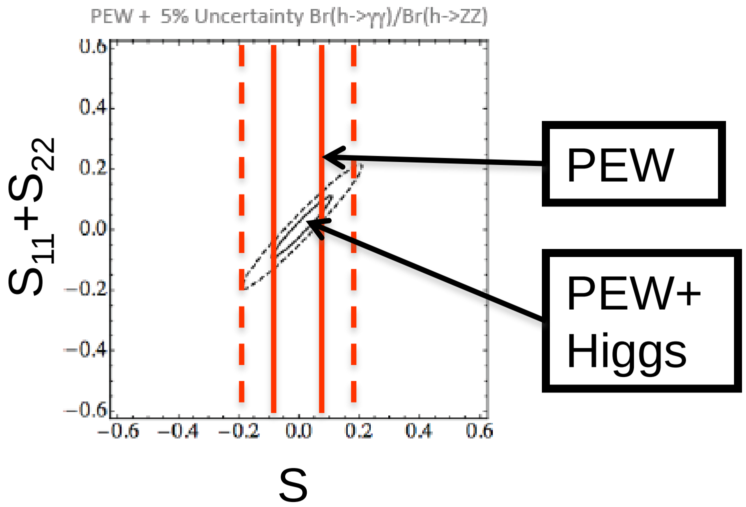
Effective Field Theories & Higgs

- Suppose we don't find any new particles
  - SM is a valid effective theory up to some scale
  - Look at contributions from dimension-6 operators
  - Higgs physics is the new precision EW physics

$$\frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to ZZ)}$$ is sensitive to new operators

$$\frac{\zeta}{2M^2}\left(g_1^2 S_{11} H^\dagger H B_{\mu\nu}B^{\mu\nu} + g_2^2 S_{22} H^\dagger H W_{\mu\nu}W^{\mu\nu}\right)$$

[Thomas]



Conclusions

- We are in the era of precision Higgs physics
  - Calculations + experiment
  - Theory may be limiting factor in precision coupling extraction
- Higgs production is a window to high scale physics
  - Need to look at big picture—new physics in the Higgs sector is typically associated with new particles (more Higgs particles, SUSY particles, top partners…)
  - 2 Higgs production can discriminate between models

The SM is an extremely good effective theory

Look at the Big Picture

- Higgs measurements and new physics searches are all part of the same exploration of physics

Thanks to the organizers!