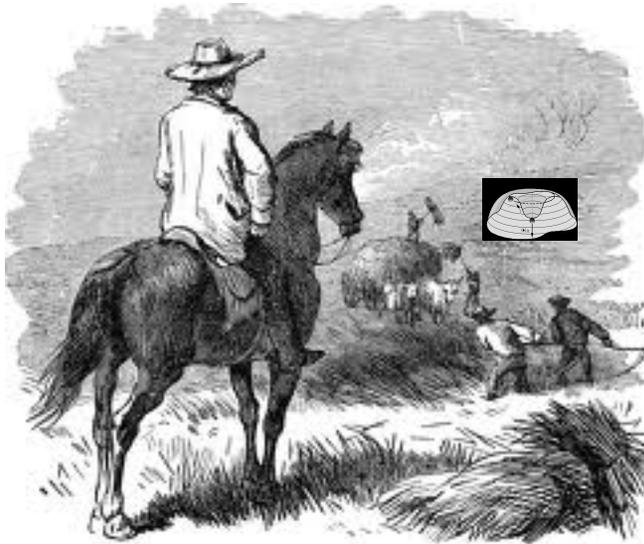


The Higgs Frontier: The Way Forward



S. Dawson
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?

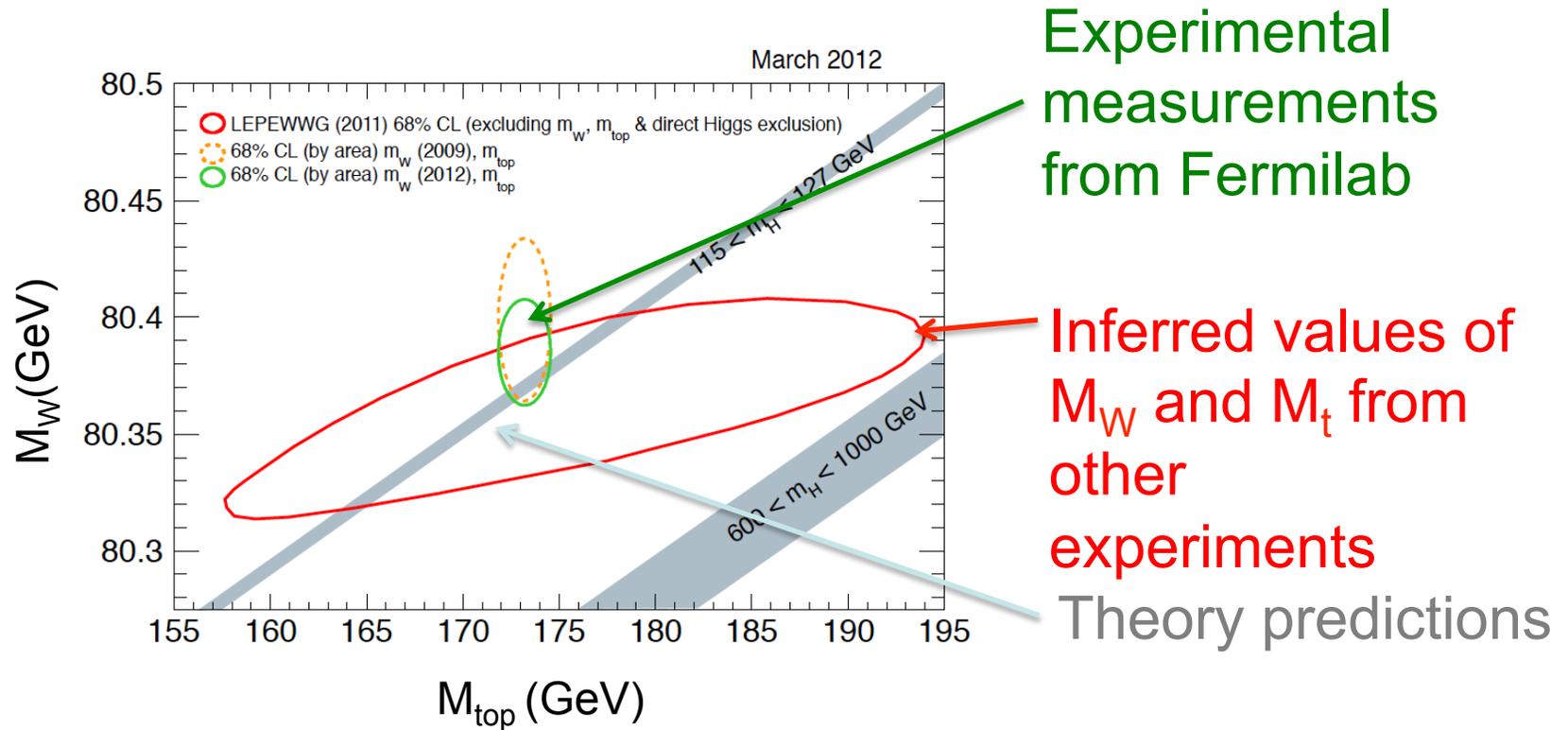
Please join the effort: snowmass2013.org

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

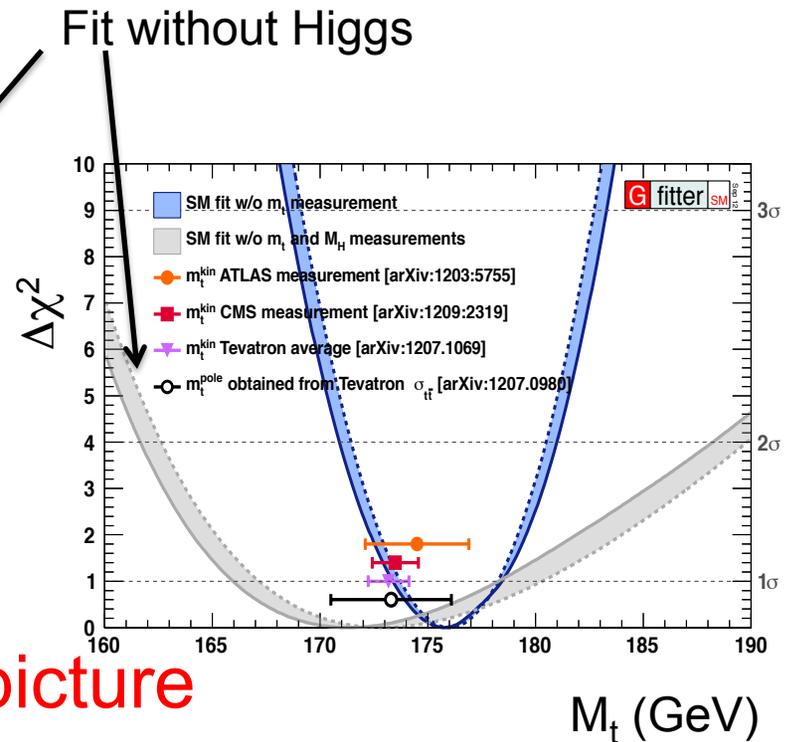
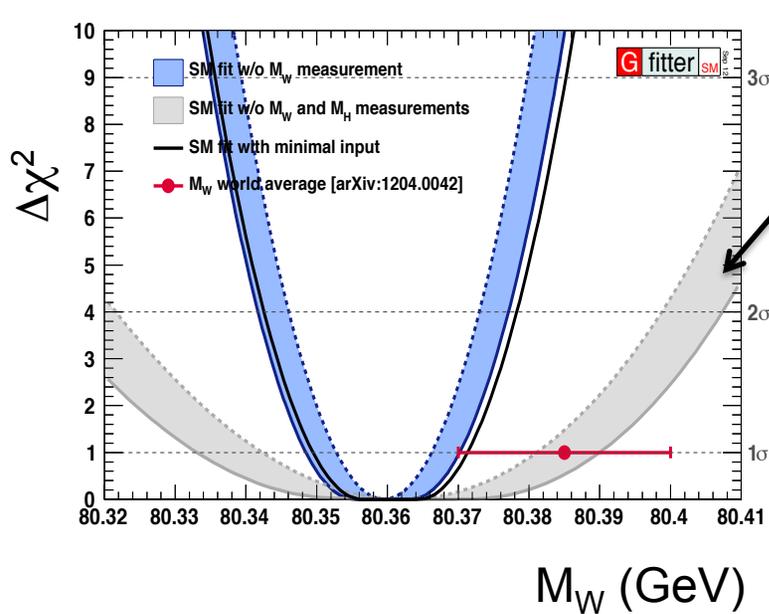
So the fact that the observed Higgs-like particle looks ***SM-like*** is no surprise

The 6 billion dollar plot



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

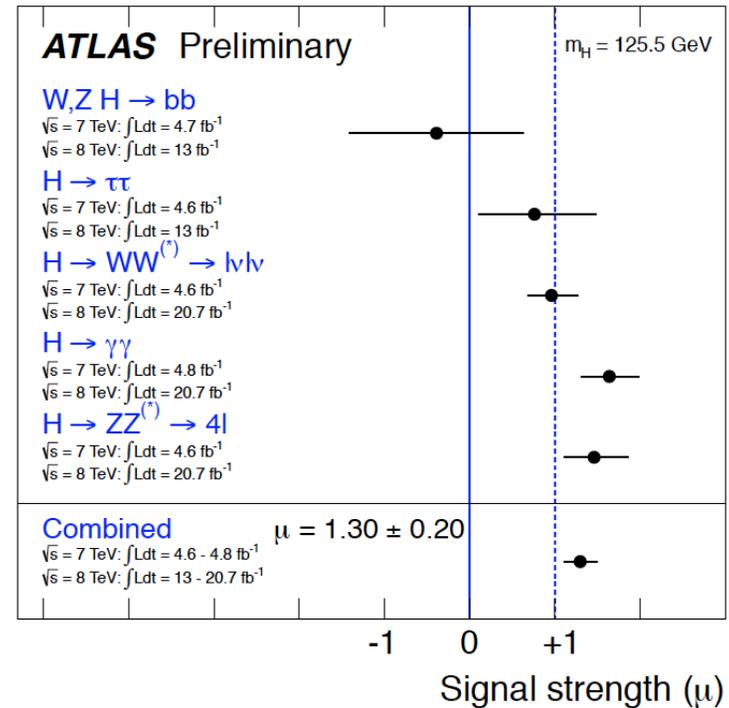
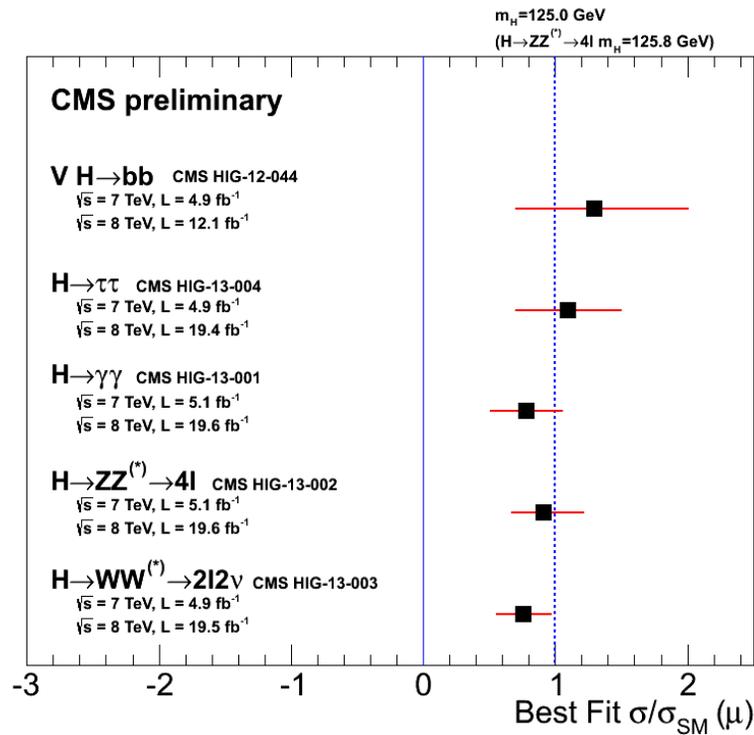
After Discovery



A consistent picture

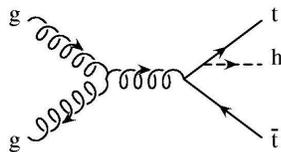
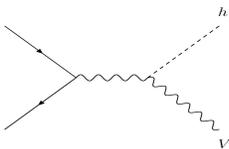
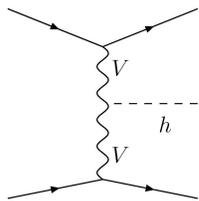
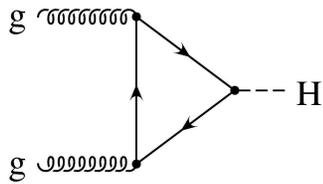
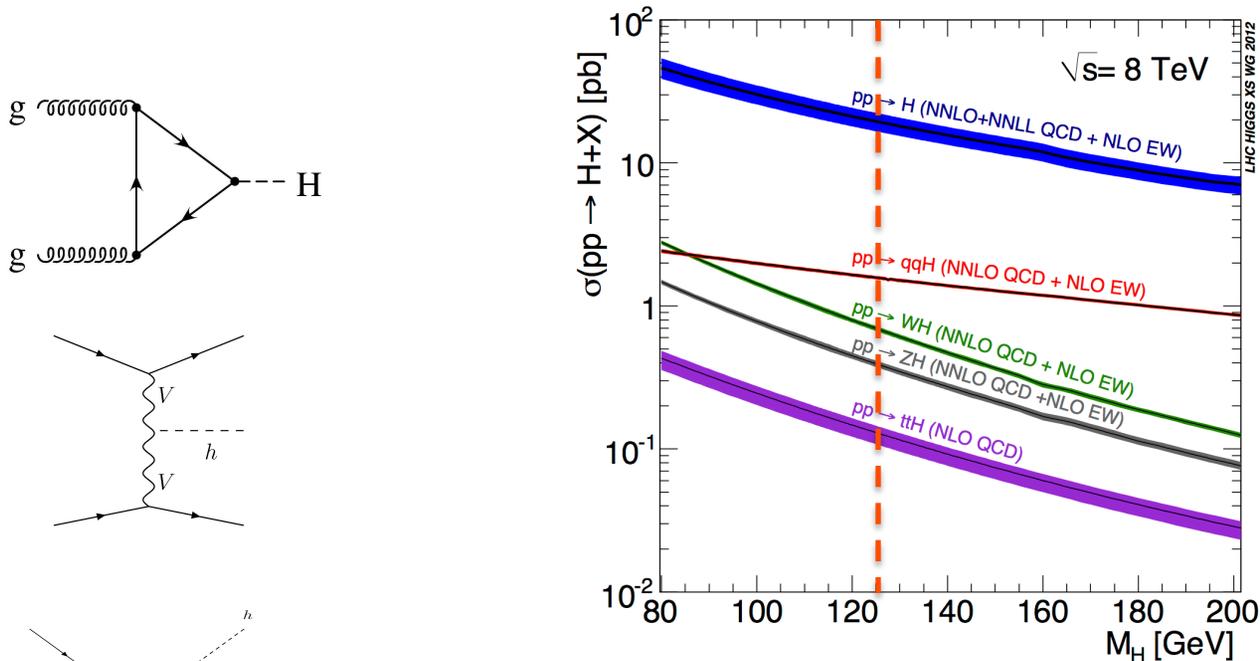
The SM as an effective low energy theory is an extremely good approximation

Higgs Rates look SM-like



What goes into denominators?

Precision Calculations

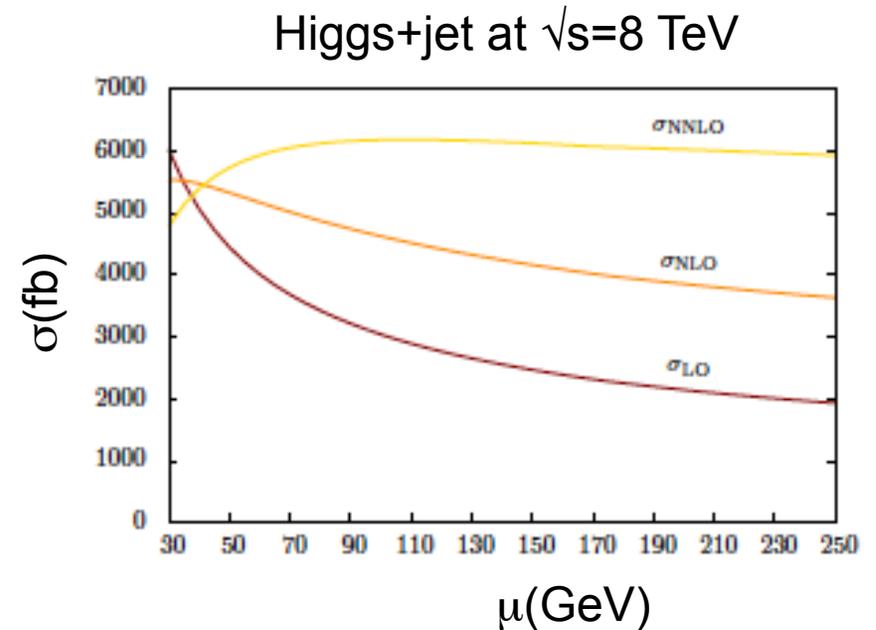
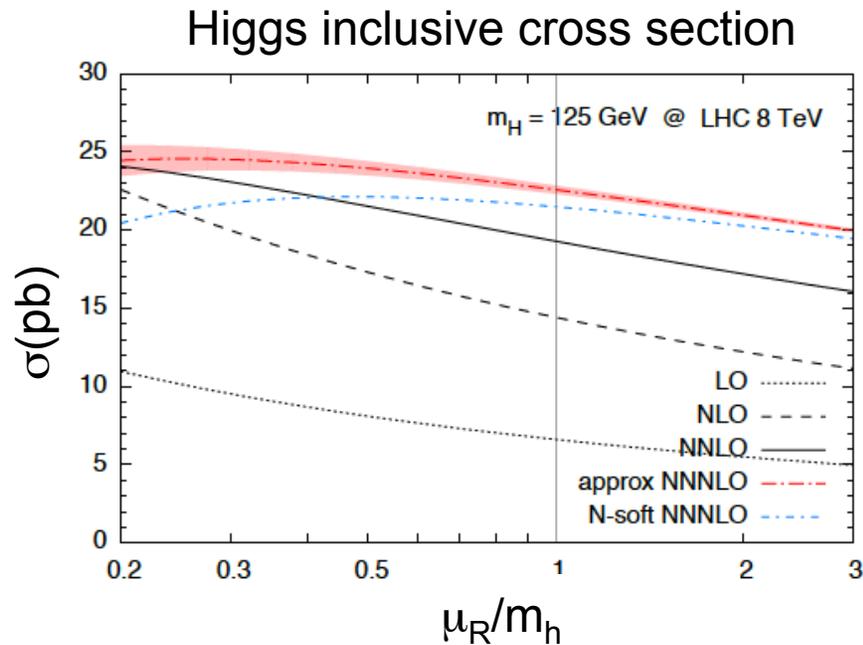


gg→h at 8 TeV: ±7% scale uncertainty ± 7%;
PDF+ α_s uncertainty (for $m_h=125$ GeV)

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

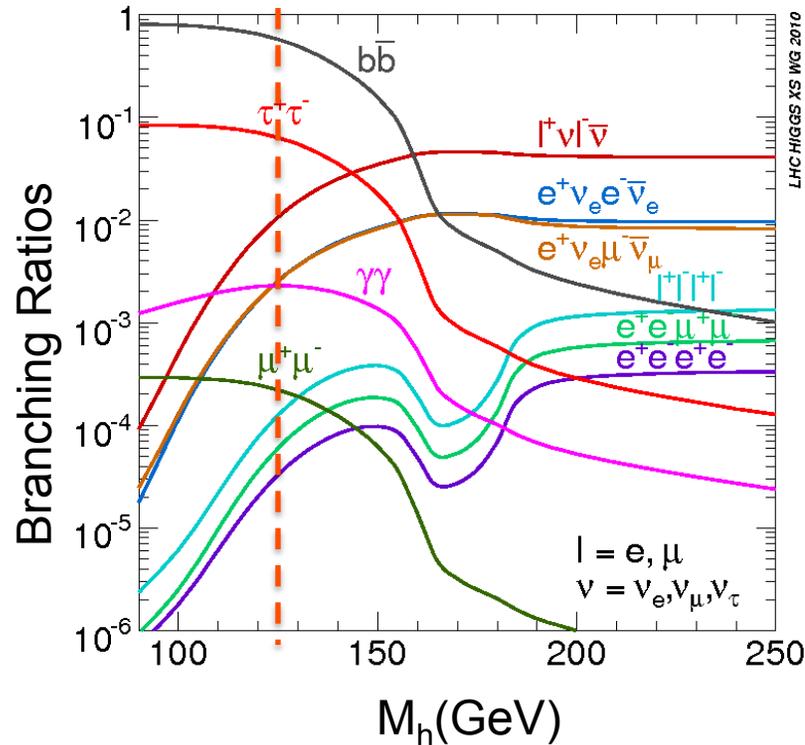
H+jet @NNLO, H@NNNLO

- Will decrease errors from scale uncertainty and jet binning



Rates are increased

Uncertainties: Branching Ratios



Theory Predictions

	$\delta\Gamma/\Gamma$
bb	$\pm 3\%$
$\tau\tau$	$\pm 5.7\%$
$\gamma\gamma$	$\pm 5\%$
WW	$\pm 4\%$
Γ_{tot}	$\pm 4\%$

Assumes no invisible width

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

Uncertainties on BR Predictions

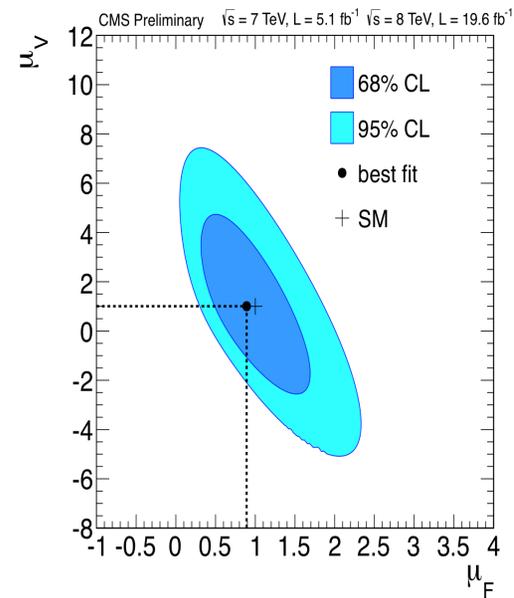
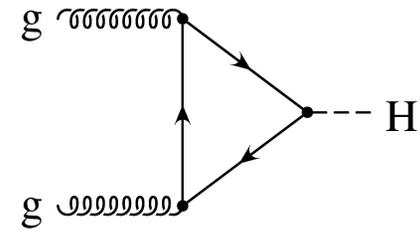
- Example: $h \rightarrow bb$
 - Error budget:
 - Theory (missing higher order corrections: QCD $\sim .1\%$, EW $\sim 1-2\%$)
 - Parametric errors from $\Delta m_b \sim 1.1\%$, $\Delta \alpha_s \sim 1\%$
 - Theory/parametric uncertainties roughly same size
 - Improve experimental value of $m_b = 4.49 \pm 0.06$ GeV
 - Use PDG central value, compromise on errors
 - Error on $\delta\Gamma_{bb}$ matters for 300 fb^{-1} extraction of hbb coupling ($\sim 6.9\%$ at CMS) [Olsen] and for ILC extractions ($\sim 2.7\%$ at 250 GeV)[van Kooten]

What we know

- ttH coupling exists
 - Indirectly from $gg \rightarrow h$, $h \rightarrow \gamma\gamma$
- WW h , ZZ h couplings exist
 - Rate appears to be SM-like
 - $h \rightarrow ZZ^* \rightarrow 4$ leptons

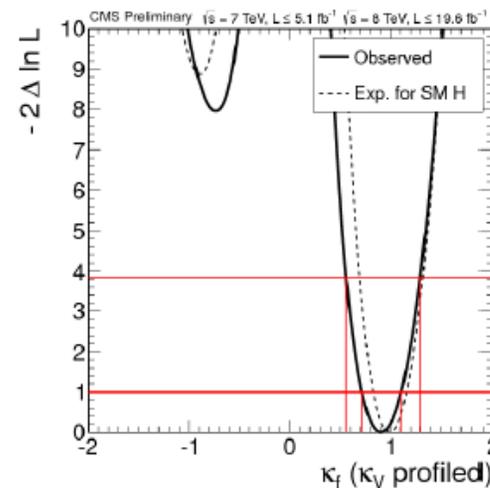
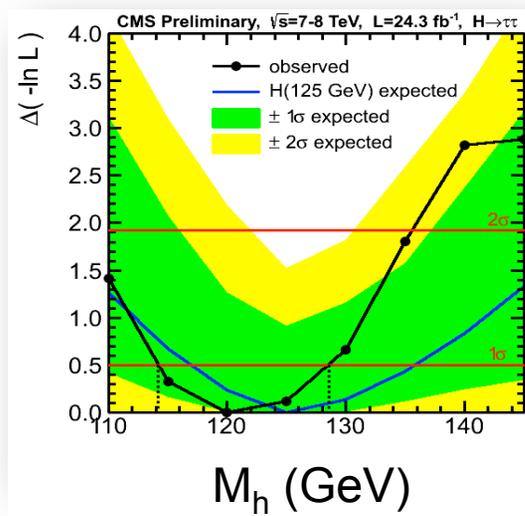
$$CMS : \sigma/\sigma_{SM} = \mu = 0.92 \pm 0.28$$

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



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

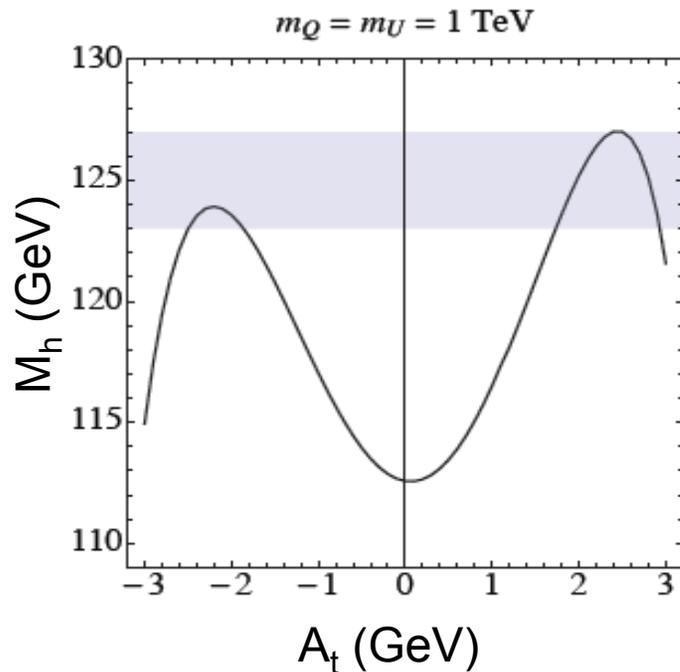
$$V = -\frac{\mu^2}{2}h^2 + \frac{\lambda}{4}h^4 \quad \lambda = \frac{M_h^2}{2v^2}$$

$$\lambda \sim .13, \mu \sim 90 \text{ GeV}$$

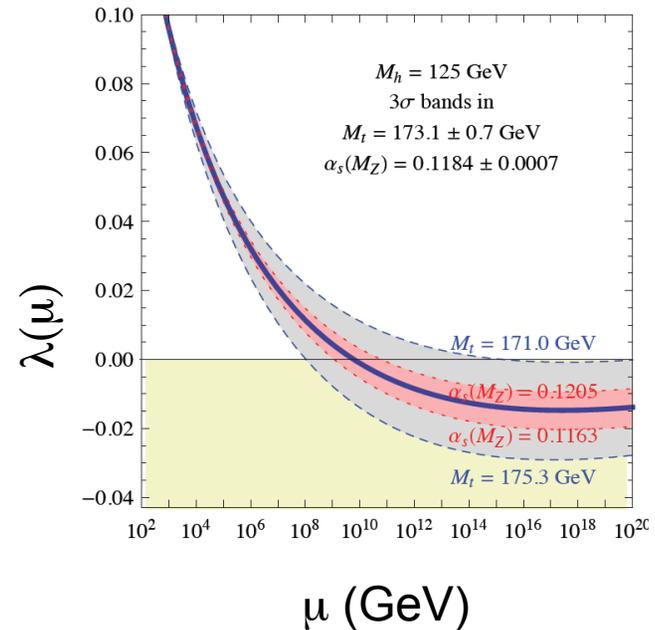
- We can sensibly calculate to high scales
- Is $M_h=125 \text{ GeV}$ special?

Is $M_h=125$ GeV Special?

$M_h=125$ GeV requires
 $M(\text{stop}) \sim 10$ TeV or large A_t in
the MSSM [Shih]



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



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 $\tan \beta = v_2/v_1, \alpha, m_h$
$$\sin 2\alpha = -\sin 2\beta \left(\frac{M_H^2 + m_h^2}{M_H^2 - m_h^2} \right)$$
 - Predictive models (MSSM is special case)

More than one 2HDM

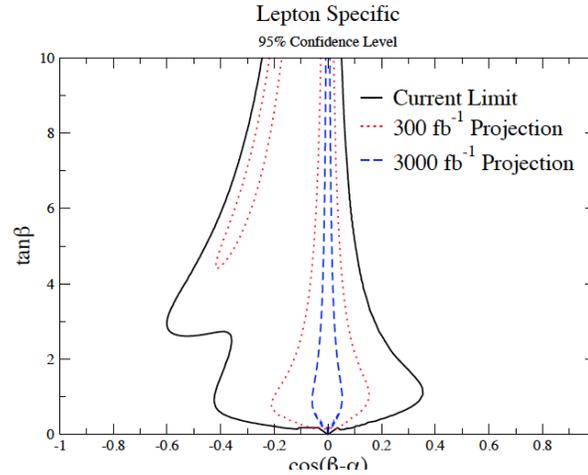
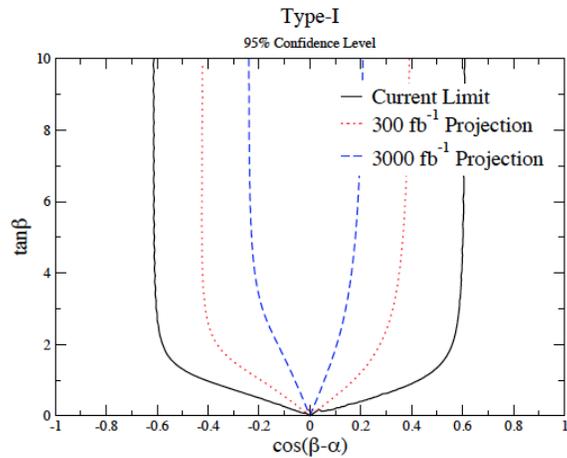
- Couplings to h :

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

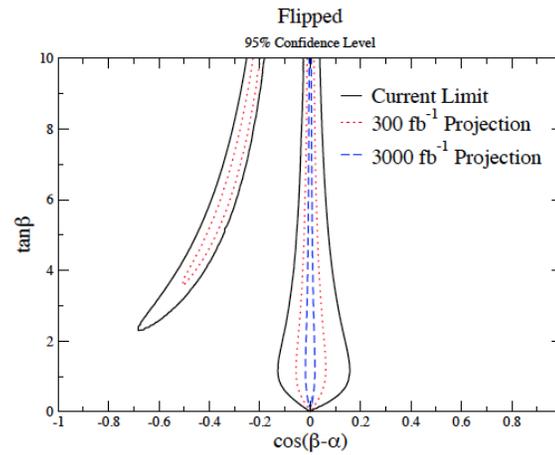
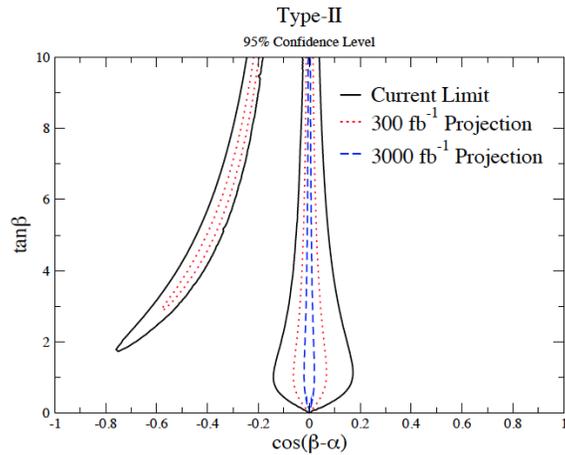
	I	II	Lepton-Specific	Flipped
g_{hVV}	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$	$\sin(\beta - \alpha)$
$g_{ht\bar{t}}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$	$\frac{\cos \alpha}{\sin \beta}$
$g_{hb\bar{b}}$	$\frac{\cos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

↑
Type II is MSSM-like

Updated 2HDM fits



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



We are near
SM couplings
already!

Decoupling Limit: Type II 2HDMs

Assume $M_{H^+}, M_A \gg M_Z$

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

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

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

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

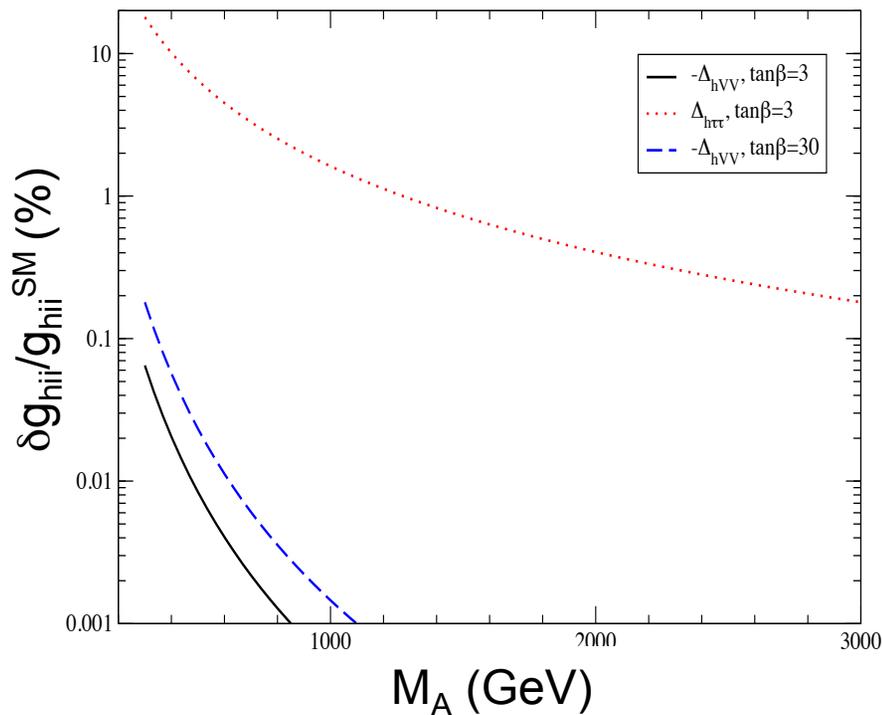
$$\frac{\delta g_{ht\bar{t}}}{g_{ht\bar{t}}^{SM}} = -\frac{2M_Z^2 \cot^2 \beta}{M_A^2}$$

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

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 $\sigma \cdot \text{BR}$

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

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

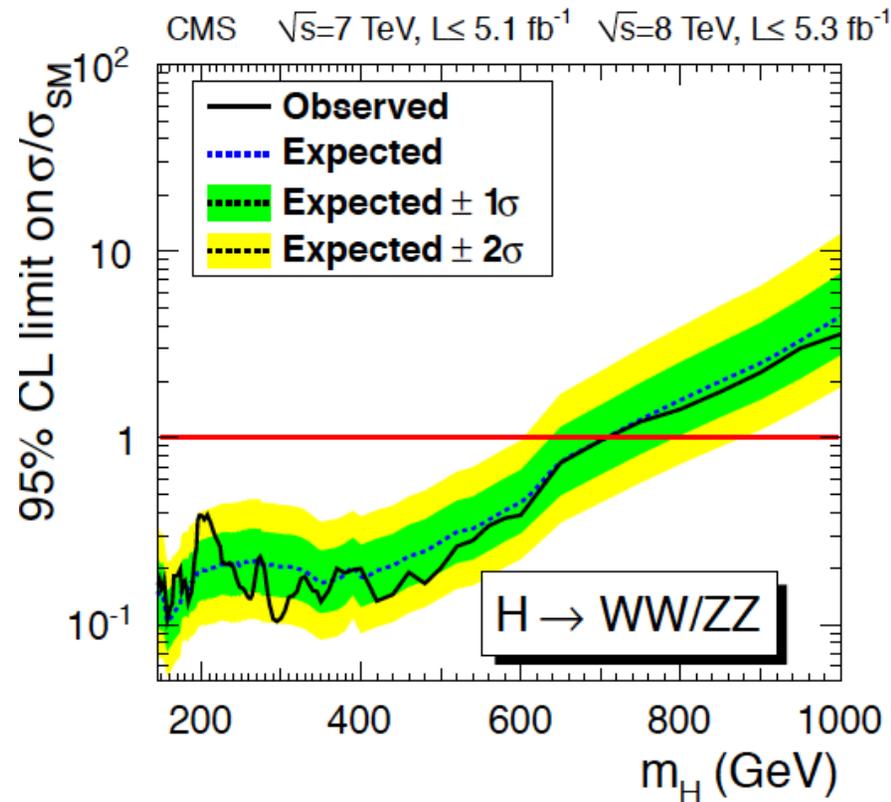
	LHC (300 fb ⁻¹ /exp)	LHC (3 ab ⁻¹ /exp)	ILC 250 (250 fb ⁻¹)
$\frac{\delta g_{hWW}}{g_{hWW}^{SM}}$	2.7 – 5.7%	1.0 – 4.5%	4.3%
$\frac{\delta g_{h\tau\tau}}{g_{h\tau\tau}^{SM}}$	5.1 – 8.5%	2.0 – 5.4%	3.5%

Assume systematics $\sim 1/\sqrt{L}$

S. Dawson

Complementary Approach

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

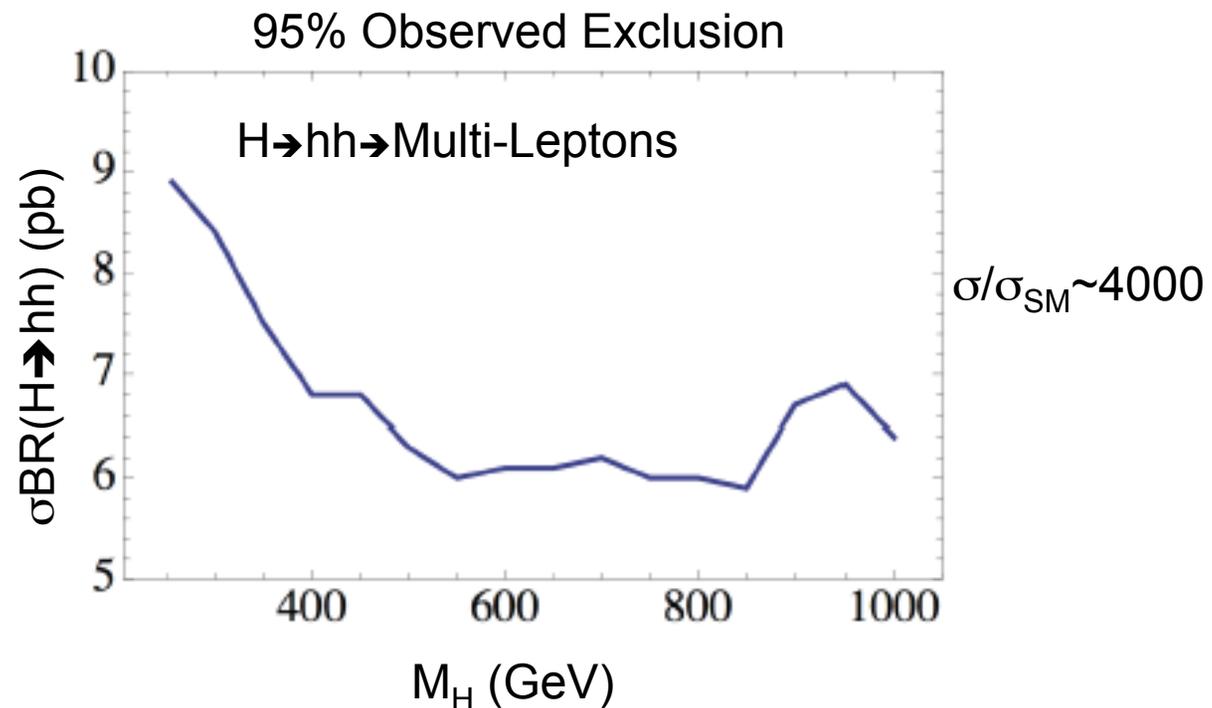


$$g_{HVV} = \cos(\beta - \alpha)$$

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

New Decay Channels Possible

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

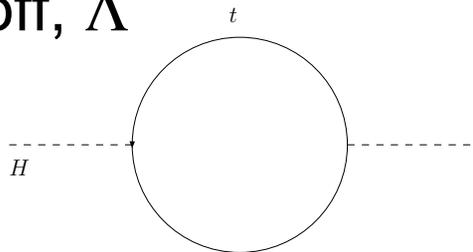


At $\sqrt{s}=7$ TeV:
 $\sigma_{\text{HH}}(\text{SM})=2$ fb

Does Naturalness matter?

The case for new TeV Scale particles

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

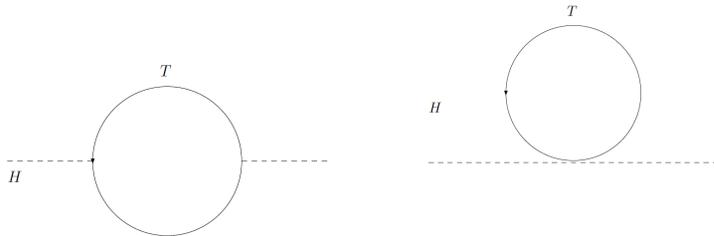

$$\delta m_H^2 \sim -\frac{3\lambda_t^2}{8\pi^2} \Lambda^2$$

- 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** $\delta M_h^2 \sim \left(\dots \right) (M_T^2 - m_t^2) \log \left(\frac{M_T^2}{m_t^2} \right)$



- **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)

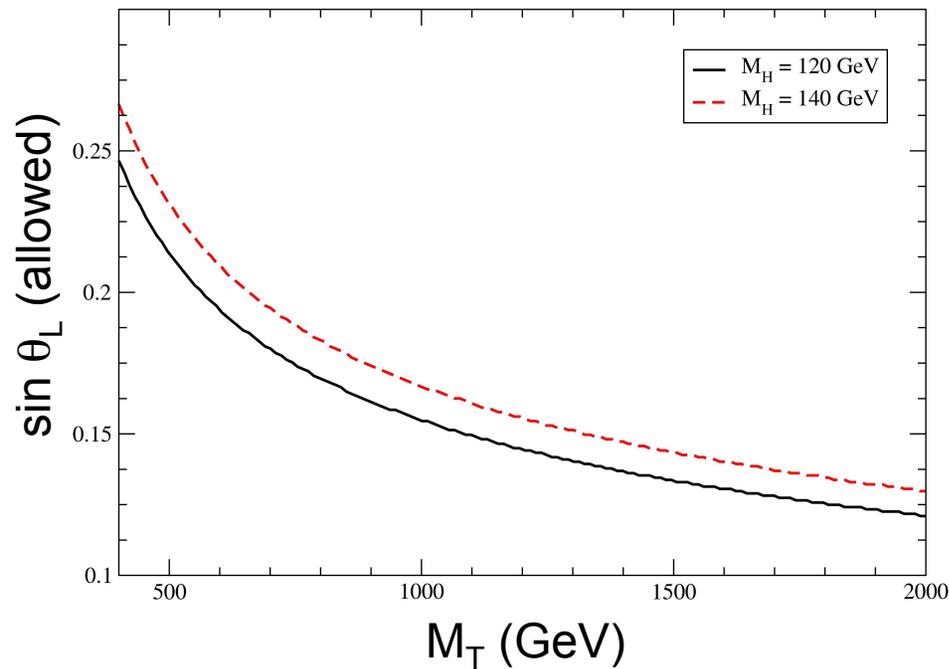
$$\begin{pmatrix} t_L \\ T_L \end{pmatrix} = \begin{pmatrix} c_L & -s_L \\ s_L & c_L \end{pmatrix} \begin{pmatrix} u_L \\ U_L \end{pmatrix}$$

T is charge 2/3 top partner

2 parameters: M_T , θ_L

Top Mixing with Top Partner

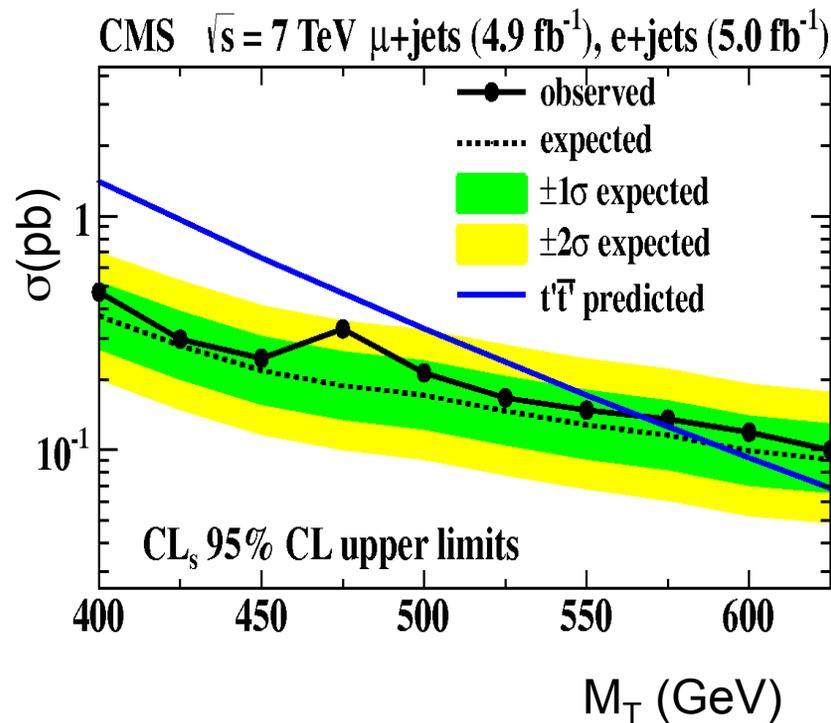
STU 95% CL Allowed Region
(below curves)



As Higgs mass gets larger, allowed parameter space shrinks

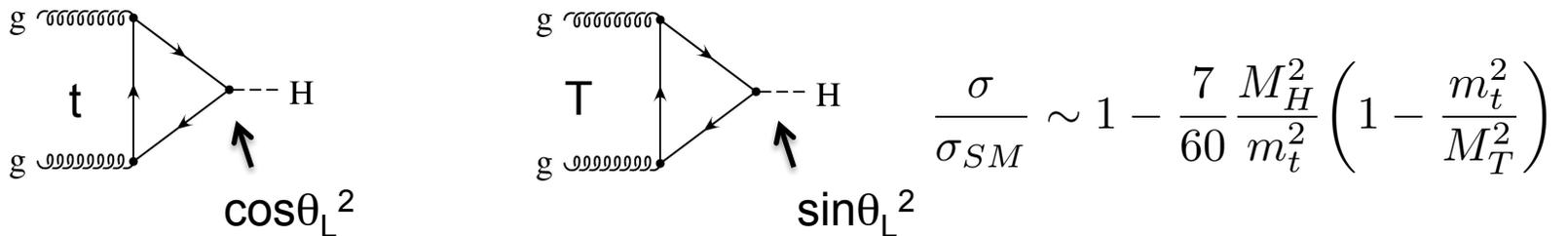
Experimental Limit

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

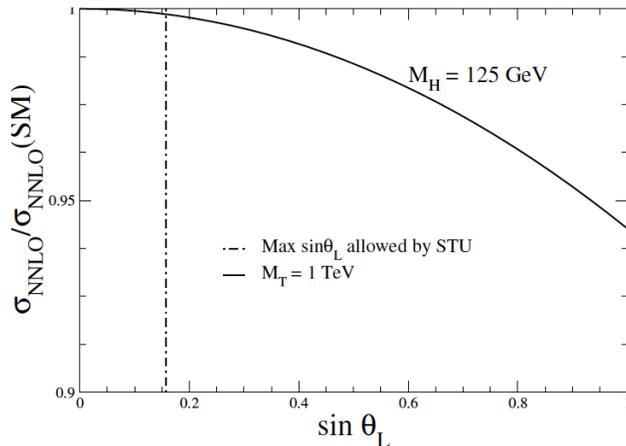


Higgs Production and Top Partners

- Production suppressed (but not observably so)



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



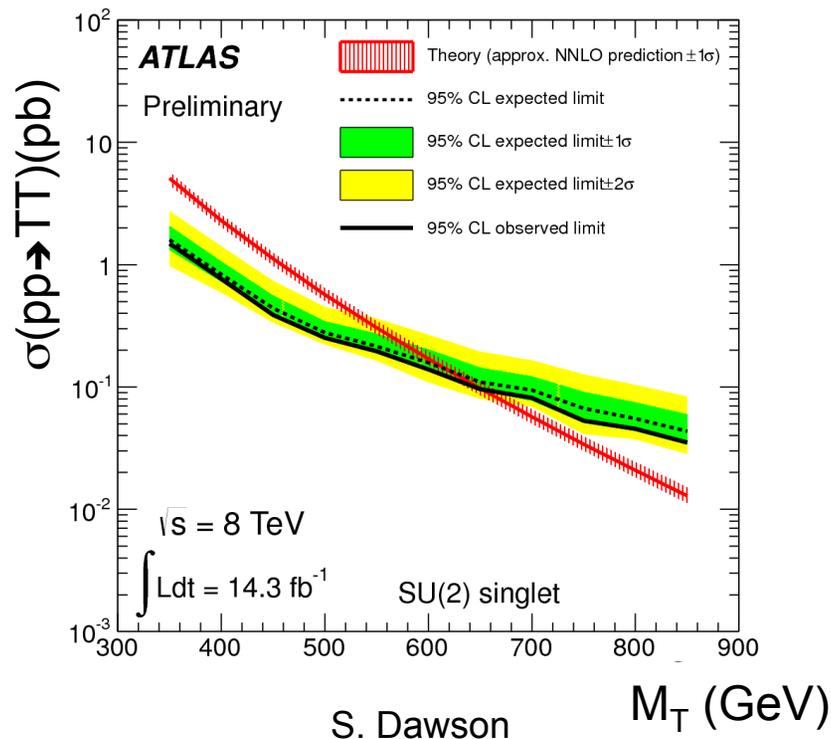
Example of model where new physics will be observed by top partner production, not by measuring Higgs properties

Higgs Production and Top Partners

- $T \rightarrow th$

- 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

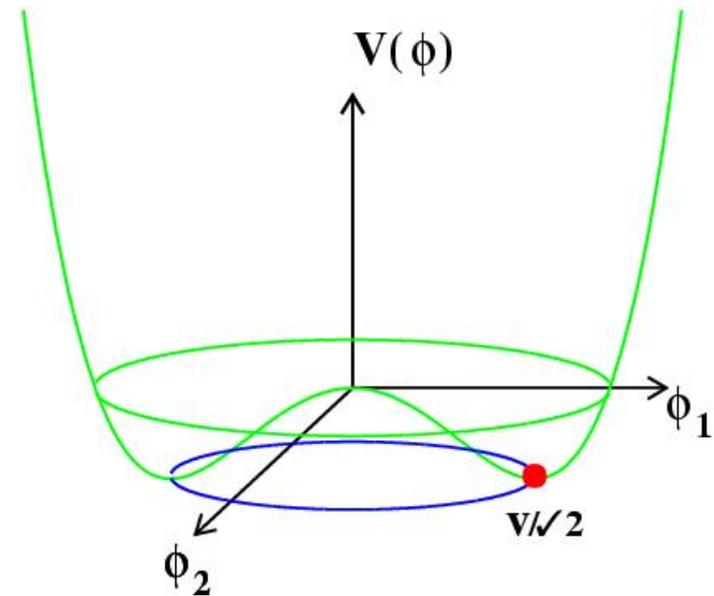
BUT.....all of these models have new particles not present in the SM

Reconstruct the Higgs potential

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

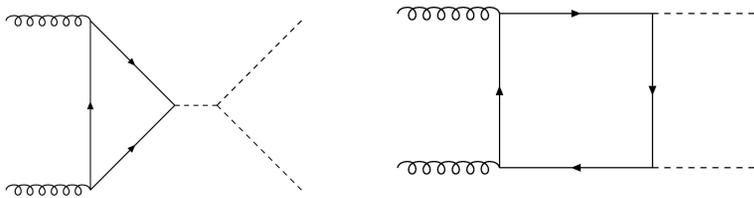
$$SM : \lambda_3 = \lambda_4 = \frac{m_h^2}{2v^2}$$

- Fundamental test of model
- $\lambda_3 \sim .13$ is perturbative

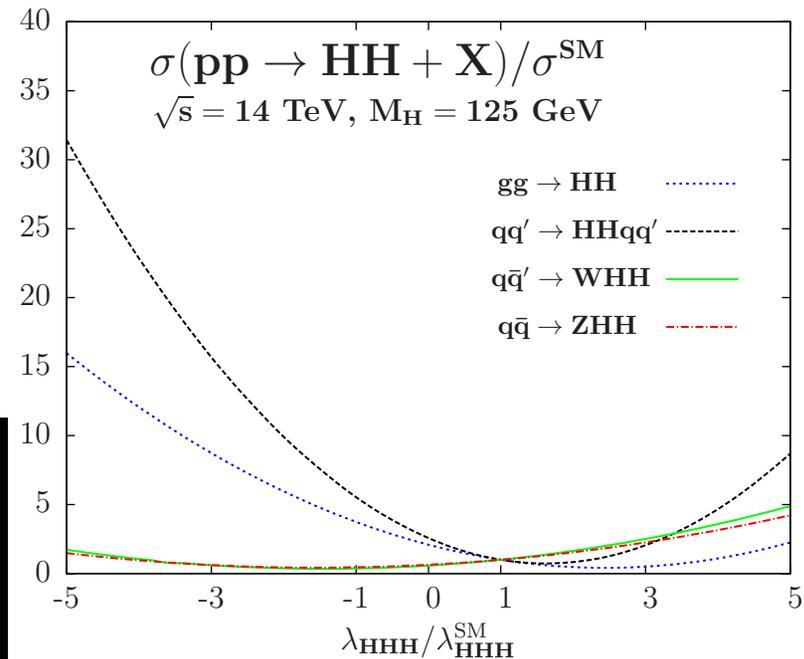


Double Higgs Production

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



Contributions tend to cancel



Needs high luminosity LHC: $\sim 3\sigma$ observation with 3000 fb^{-1} and both experiments

Double Higgs Production

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

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

- An effective theory could generate

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

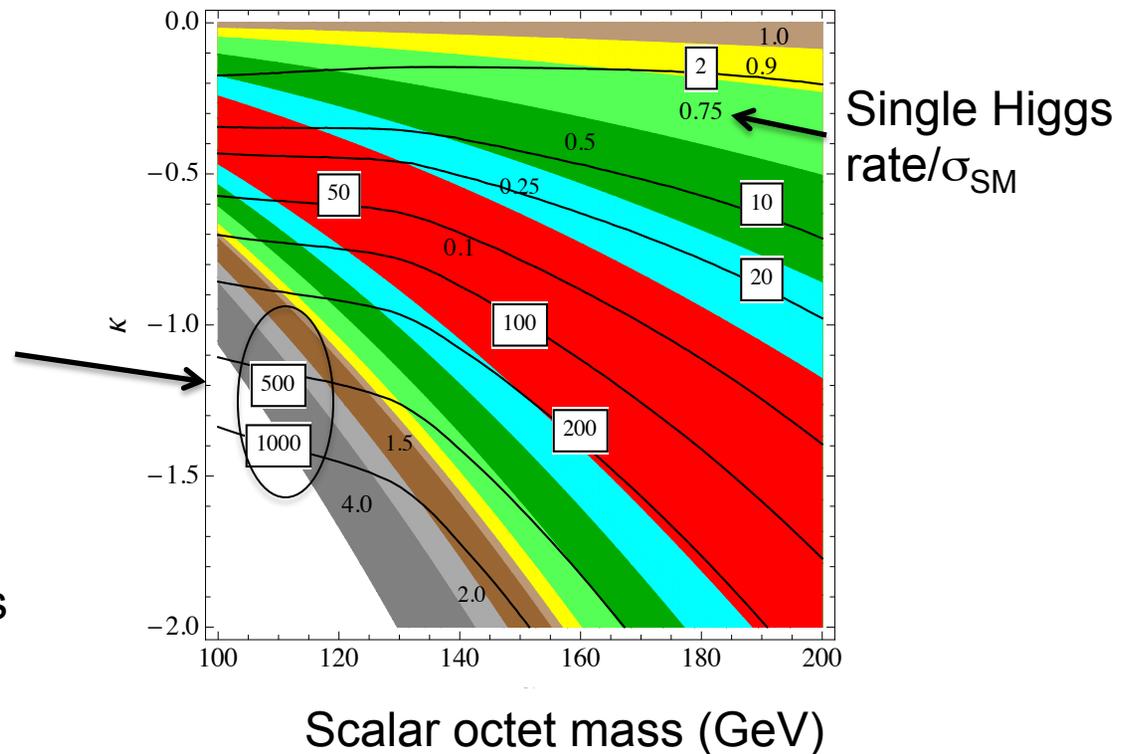
- Measuring single and double Higgs production is window into source of EWSB
- Non-renormalizable ttHH coupling in composite models

Double Higgs Production from Colored Octet Scalars

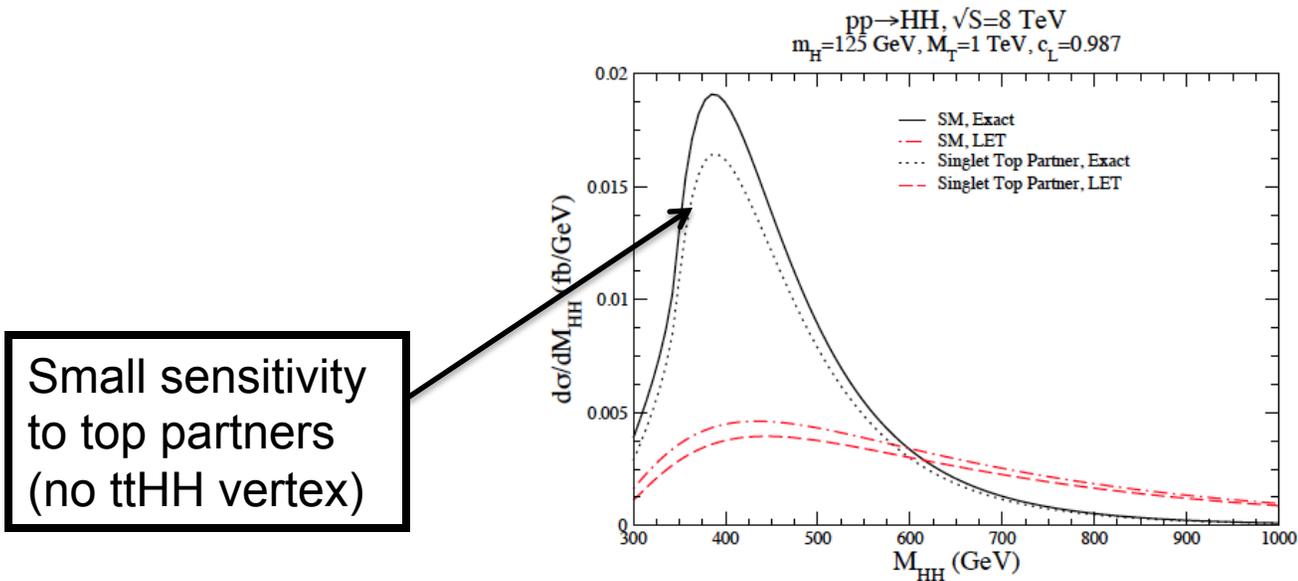
- Single Higgs production can be SM-like, while double Higgs production greatly enhanced [Kribs]

Huge enhancements of double Higgs rate

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



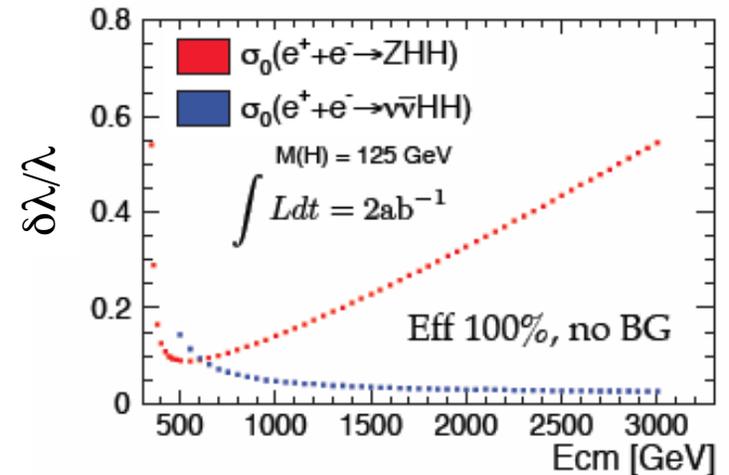
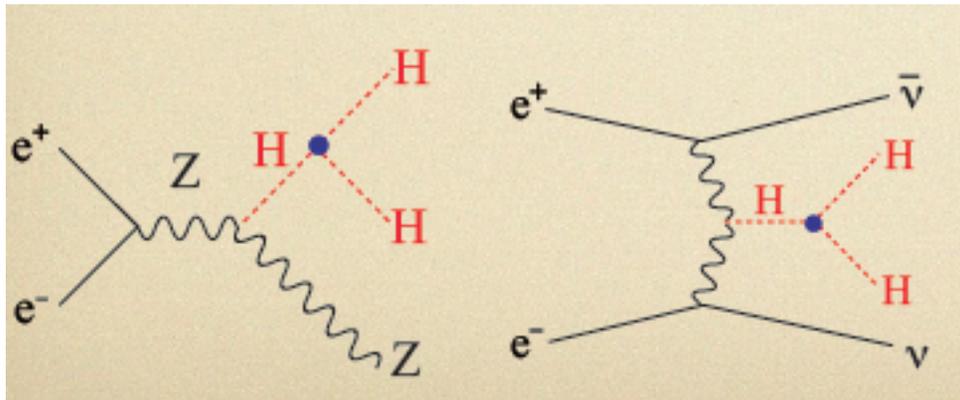
Double Higgs Production from Top Partners



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

Double Higgs Production in e^+e^-

- At $\sqrt{s}=500$ GeV, rate for Zhh is larger ($\sigma \sim .22$ fb)



Including background
and efficiencies at
 $\sqrt{s}=500$ GeV:

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

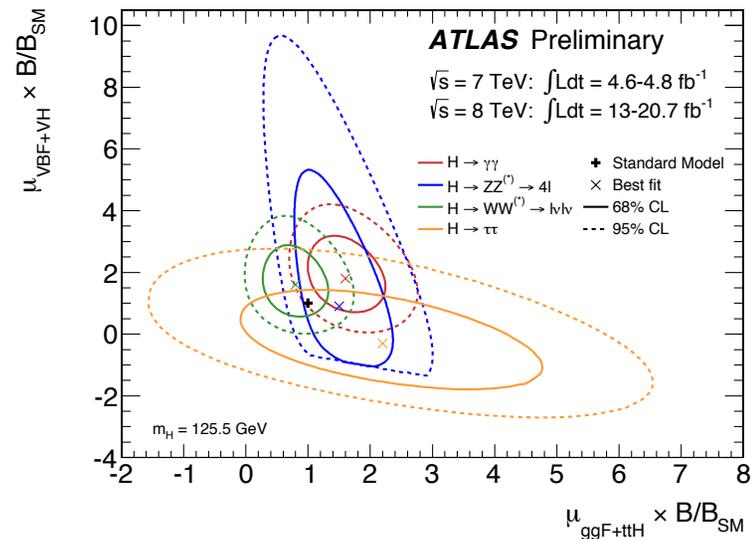
This improves at
 $\sqrt{s}=1$ TeV

Measure ratios of BRs

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

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

[Cranmer]



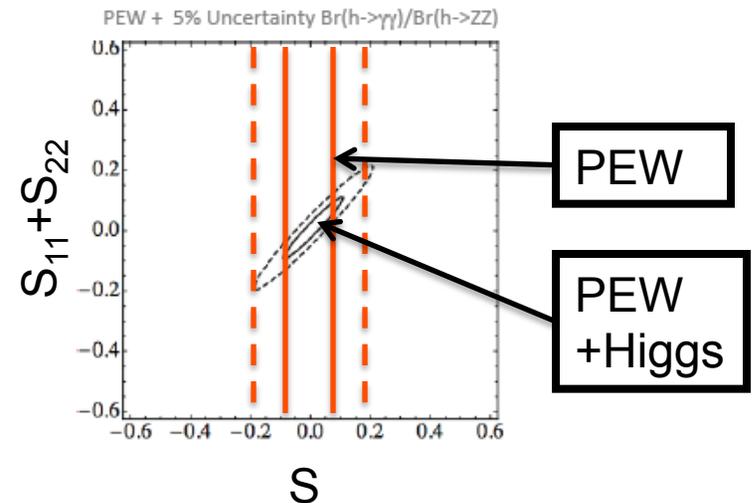
Effective Field Theories & Higgs

- 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

$\frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma(h \rightarrow ZZ)}$ 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!