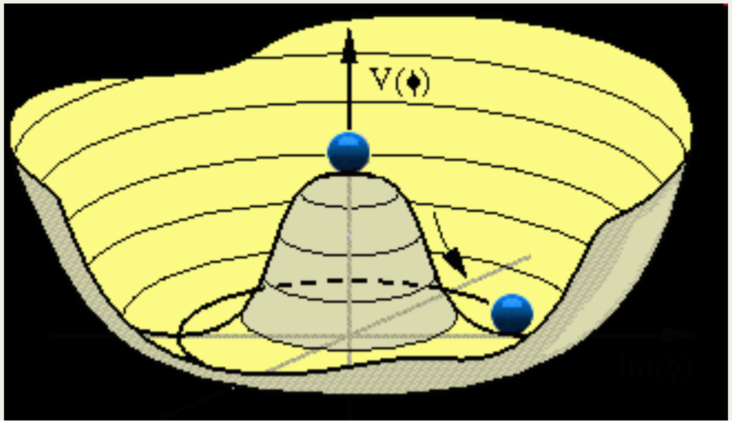
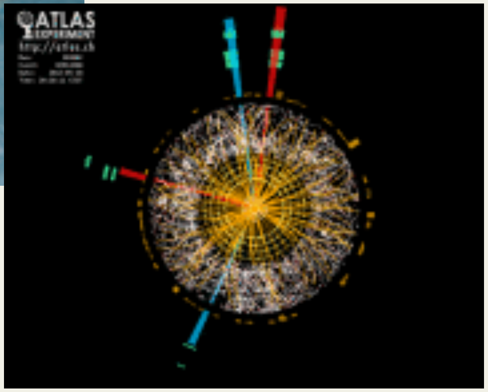
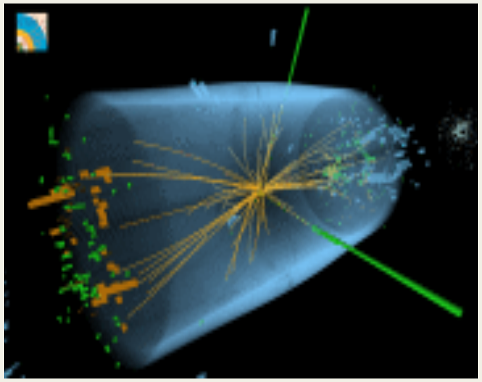


# Exploring the Higgs Sector

S. Dawson, BNL

May 20, 2014

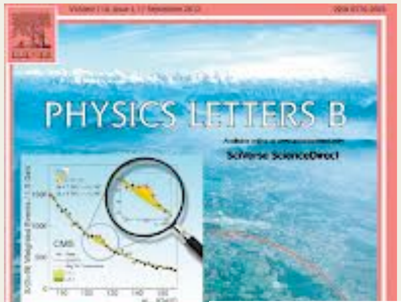


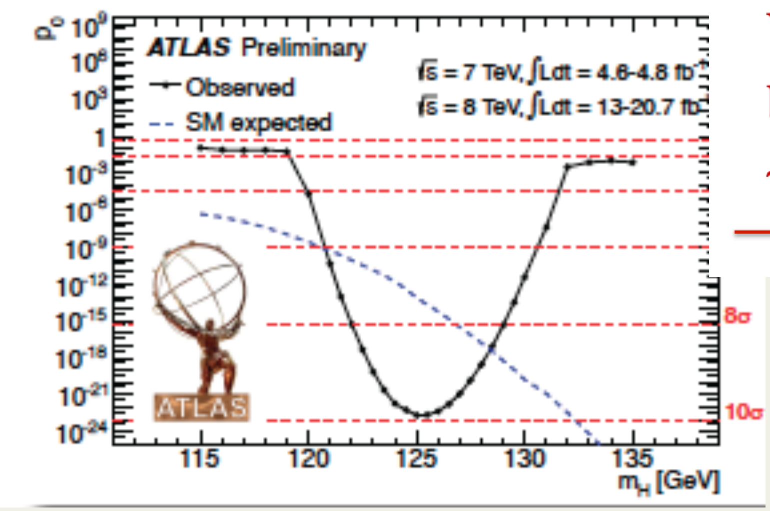


Rencontre de Blois, 2014

# We discovered a Higgs boson!

- The Standard Model is very predictive *(testable!)*
- Only free parameter is $M_H$





CMS

| **Decay** | **Expected** | **Observed** |
|---|---|---|
| **ZZ** | **7.1 σ** | **6.7 σ** |
| **γγ** | **3.9 σ** | **3.2 σ** |
| **WW** | **5.3 σ** | **3.9 σ** |
| **bb** | **2.2 σ** | **2.1 σ** |
| **ττ** | 3.4σ | 3.6σ |

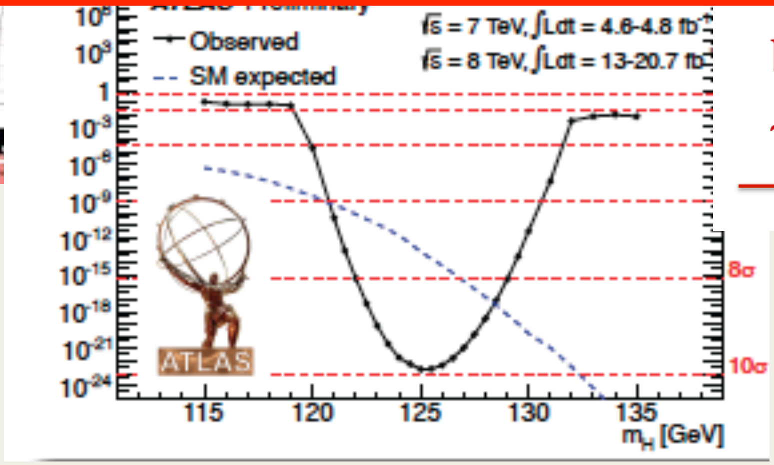
Both ATLAS and CMS have close to 10σ significance

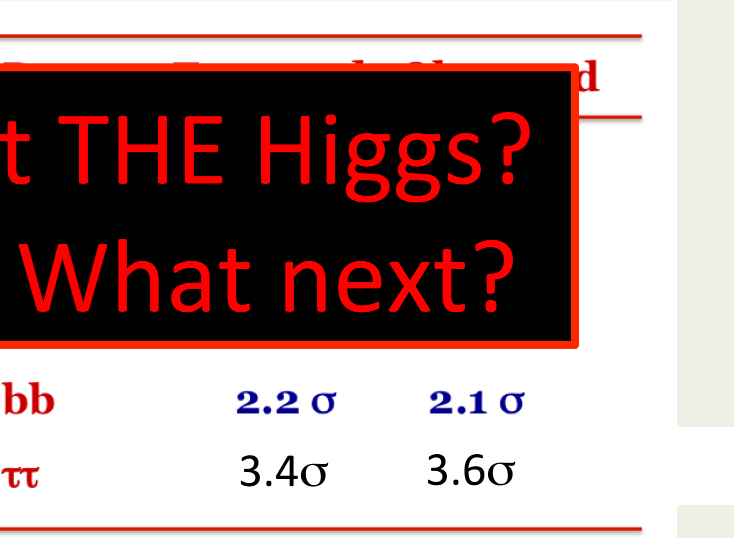
Probability of 10 σ event being random is $10^{-23}$

# We discovered a Higgs boson!

- The Standard Model is very predictive *(testable!)*
- Only free parameter is $M_H$

CMS





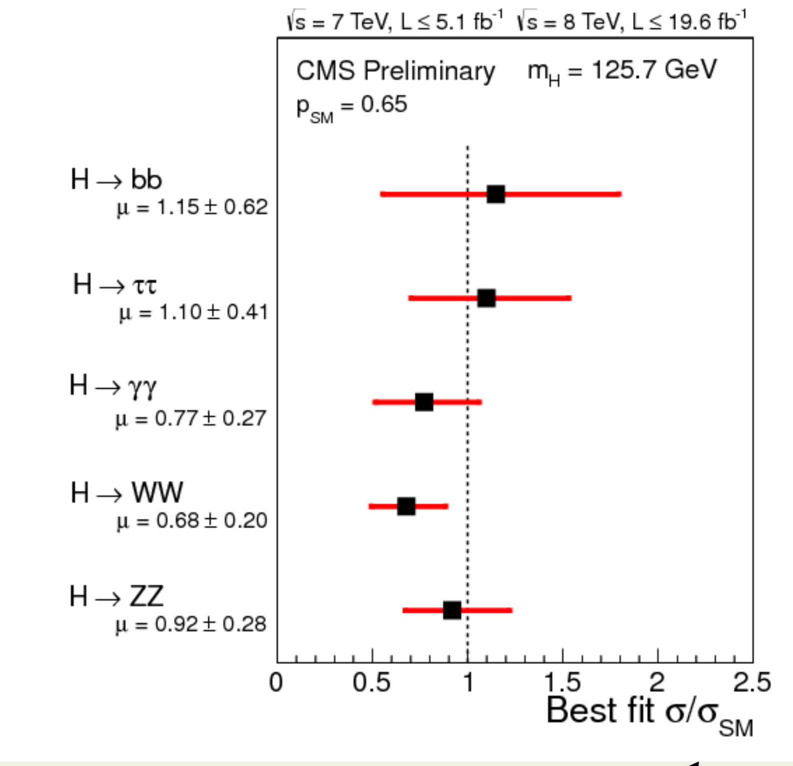
| | | |
|---|---|---|
| **bb** | **2.2 σ** | **2.1 σ** |
| ττ | 3.4σ | 3.6σ |

It's for real. But is it THE Higgs? And is there more? What next?

Both ATLAS and CMS have close to 10σ significance

Probability of 10 σ event being random is $10^{-23}$

# Data Consistent with SM Hypothesis



Couplings to both fermions and gauge bosons observed with rates which are consistent with predictions

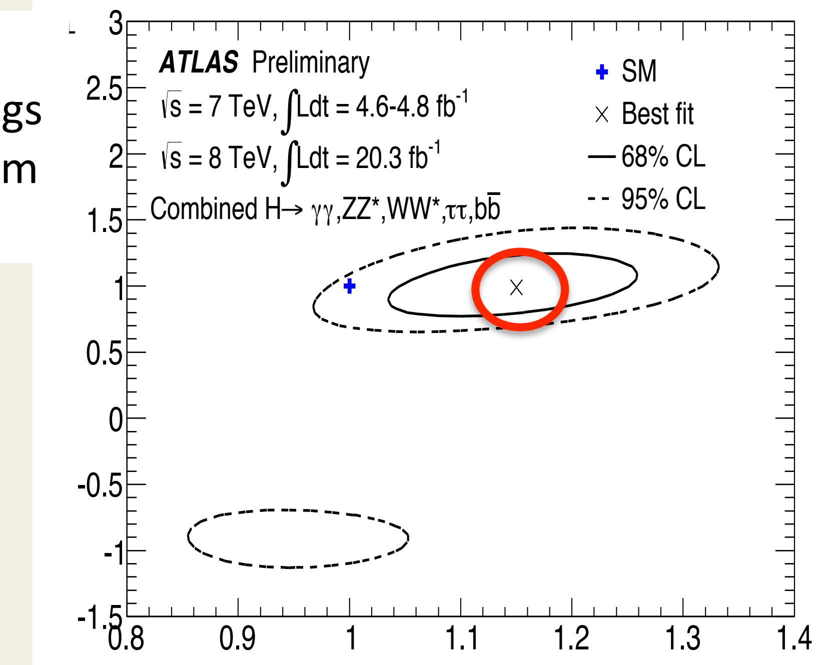
**CMS : Data/theory = 0.80± 0.14**
**ATLAS : Data/theory =1.30± 0.18**

Lots of theory dependence in the denominator!

Corollary: New physics effects will be subtle

# Room for New Physics in Higgs Sector

Deviation of fermion –Higgs couplings from SM



$\kappa_V$=1.15 ± .08

$\kappa_F=.99^{+.17}_{-.15}$

~20% deviations allowed

Deviation of WWH and ZZH couplings from SM

13 TeV run will clarify the situation!

*Assumes only SM contributions

# New Physics in Loops

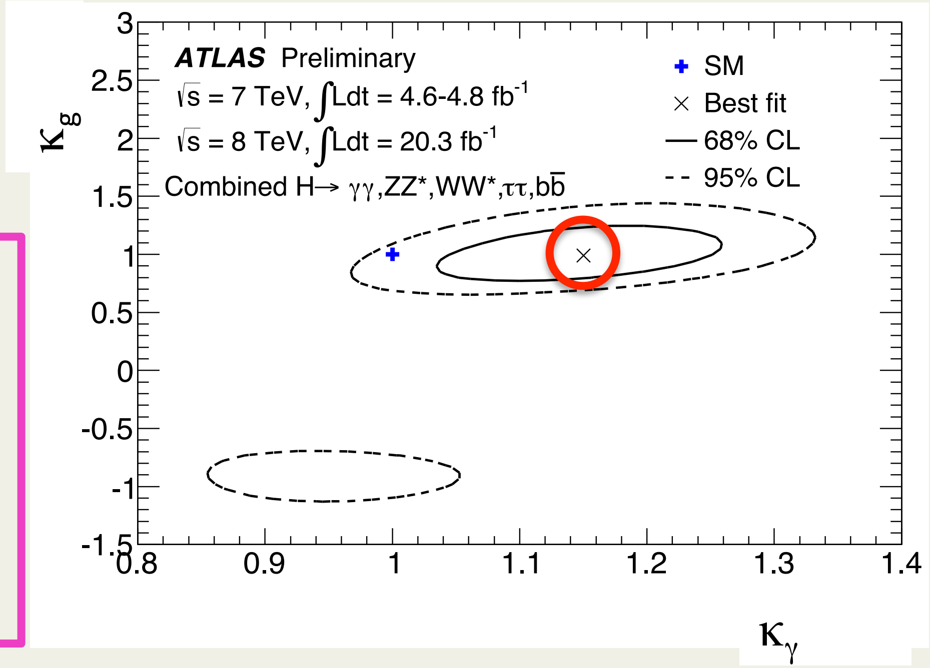
- Might expect to see deviations in loop processes first
  - New heavy particles could make significant contributions

ATLAS @68% CL

$k_g = 1.08 \pm 0.14$

$k_\gamma = 1.19 \pm 0.13$

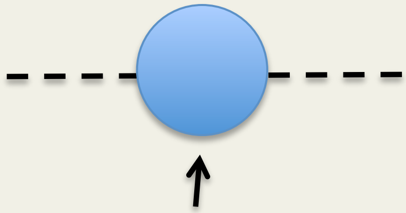
The hope that we can discover new physics by observing large deviations in Higgs processes is under tension



The LHC 13 TeV run should clarify this!

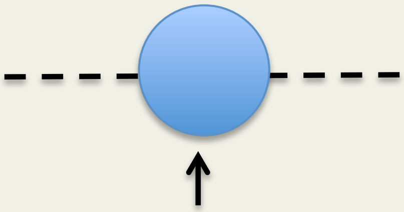
# Why do we expect New Physics?

- Generically, solutions to naturalness involve new particles



SM particles

$$\delta M_H^2 \sim -(125\ GeV)^2 \left(\frac{\Lambda}{600\ GeV}\right)^2$$



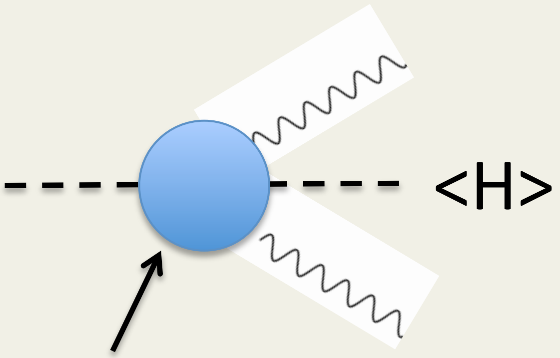
New stuff

$$\delta M_H^2 \sim +(125\ GeV)^2 \left(\frac{\Lambda}{M_{new}}\right)^2$$

*For this cancellation to work, new stuff can't be too much above TeV scale*

# New Physics From Loops

- New particles lead to deviations in Higgs couplings



MSSM light stops generically contribute (no mixing):

$$\kappa_g^2 = \frac{\sigma(gg \to H)}{\sigma(gg \to H)\mid_{SM}} \sim 1 + \left(\frac{700\ GeV}{\tilde{m}_t}\right)^2 3\%$$

Target precision < 3%

***As LHC limits on new particles increase, target precision decreases***

# Naturalness

- Higgs mass effects from high scale physics at $\Lambda$ canceled by particles with symmetry:
  - SUSY: $\delta M_H^2 \sim G_F \Lambda^2 (m_{stop}^2 - m_t^2)$
  - Little Higgs: $\delta M_H^2 \sim G_F \Lambda^2 (m_{top\ partner}^2 - m_t^2)$
- No high scale physics…. $m_t$ Is highest scale
  - No problem: $\delta M_H^2 \sim m_t^2$

- Where is the new physics?
- New TeV scale particles give 2-5% deviations to Higgs couplings (extremely model dependent)

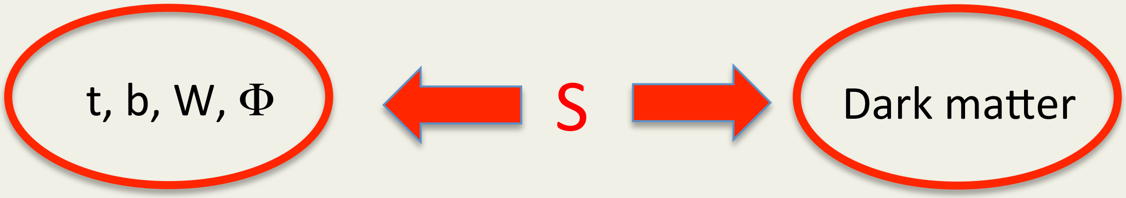
# 2 Pathways Forward

- More particles exist at ~ TeV energies
  - – Find the new particles
  - – Measure any deviations from predictions
- There are no new particles observable at the LHC
  - – Measure any deviations from predictions
  - – Explore new physics via effective Lagrangians

*New particle searches and Higgs coupling measurements linked*

# Example 1: Additional Higgs Singlet

- Dark matter models often have Higgs singlet



t, b, W, $\Phi$

S

Dark matter

- Communication with SM particles through mixing
  - SM Higgs mixed with electroweak singlet, S

$$V_4 = \lambda_m \mid \Phi \mid^2 S^2 + \frac{\lambda_{SM}}{2} \mid \Phi \mid^4 + \frac{\lambda_S}{2} S^4$$

$$h = \cos\theta \phi_0 + \sin\theta S$$

$$H = -\sin\theta \phi_0 + \cos\theta S$$

- Universal rescaling of Higgs couplings, $\kappa_F = \kappa_V = \cos\theta$

# Higgs Singlet

- Small mixing, $\theta \sim -\frac{\lambda_m}{\lambda_S}\left(\frac{v_{SM}}{v_S}\right)$ →

Couplings to heavier H suppressed by sin θ

- Current limit from ATLAS, $\theta \sim .4$
- Mass eigenstates for small mixing:

$$
\begin{aligned}
M_h^2 &= \lambda_{SM} v_{SM}^2 - M_H^2 \sin^2\theta \\
M_H^2 &= \lambda_S v_s^2 + M_H^2 \sin^2\theta
\end{aligned}
$$

$$\boxed{M_H < \sqrt{2}\frac{M_h}{\sin\theta}}$$

As coupling measurements at HL-LHC achieve % level, limit on $M_H$ is O(1-2) TeV

Complementarity between precision coupling measurements and direct searches

# Example 2: Two Higgs Doublets

- 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 $\beta = v_2/v_1$, $\alpha$, $m_h$

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

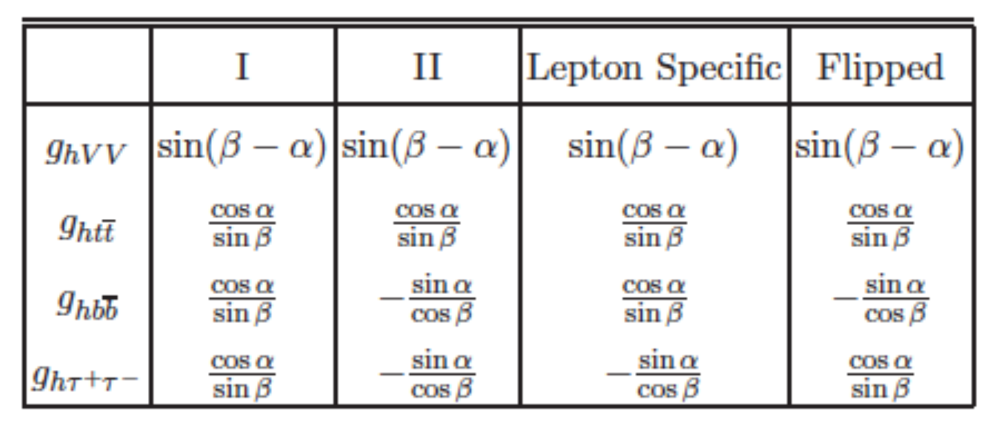
  - Predictive models (MSSM is special case)

Rich Phenomenology

# Higgs Couplings: 2 Parameters

- 2 Higgs doublet models with no FCNC
  - Parameters are $\alpha$ (mixing in neutral h), tan $\beta$
  - 4 possibilities for Higgs coupling assignments

$$L = -g_{hii}\frac{m_i}{v}\overline{f}_i f_i h - g_{hVV}\frac{2M_V^2}{v}V_\mu V^\mu h$$



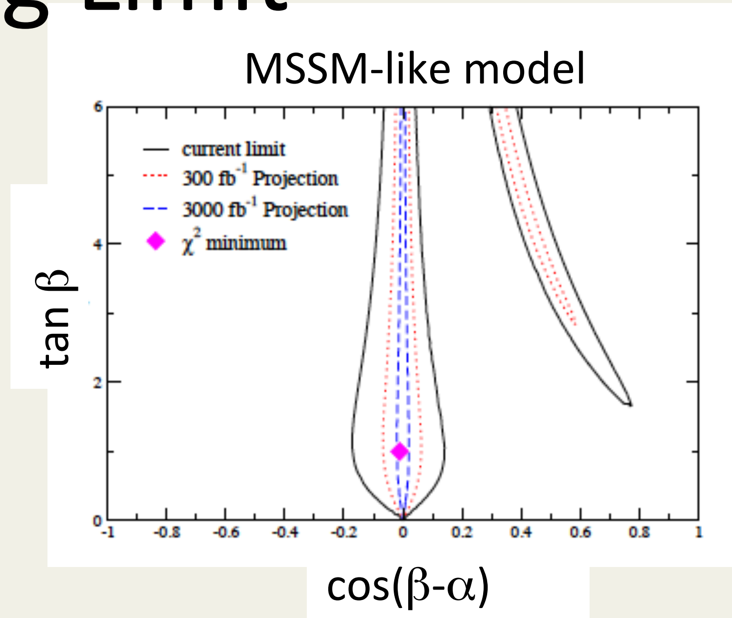
|  | I | II | Lepton Specific | Flipped |
|---|---|---|---|---|
| $g_{hVV}$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ | $\sin(\beta-\alpha)$ |
| $g_{ht\overline{t}}$ | $\frac{\cos\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\sin\beta}$ | $\frac{\cos\alpha}{\sin\beta}$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

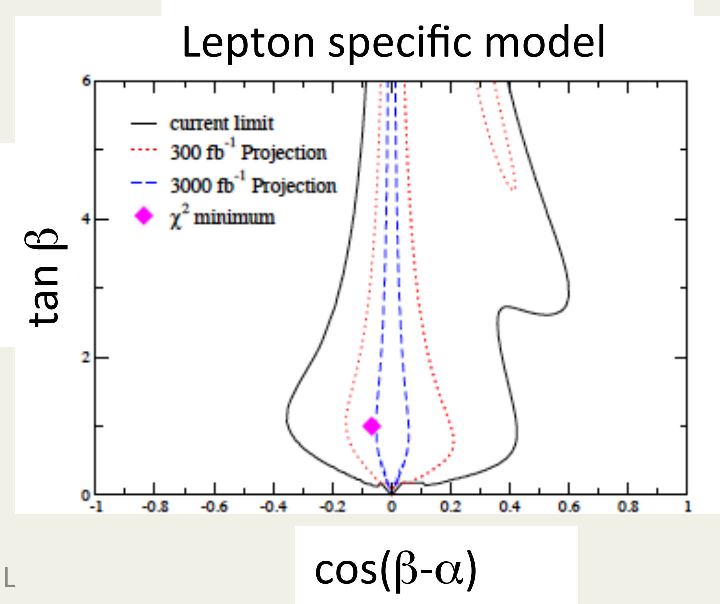
Type II is MSSM – like 2 Higgs doublet model

# Decoupling Limit

- 2HDMs approach SM when $\cos(\beta-\alpha) \rightarrow 0$
- Current limits allow non-SM like couplings
- $\tan\beta < .4$ excluded by $\Delta M_{Bd}$ for $M_{H+} < 2$ TeV
  - Higgs coupling measurements sensitive probes of theory even if new Higgs particles too heavy to be produced
  - Prefer small $\tan\beta$

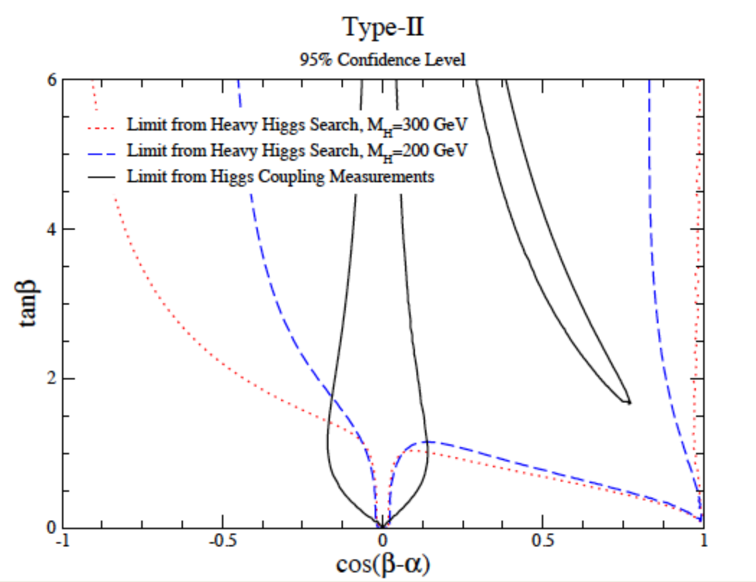
Chen, Dawson, Sher, arXiv:1305.1624;
Chen, Dawson, arXiv:1301.0309


MSSM-like model


Lepton specific model

# Complementarity in 2HDMs

- Coupling fits vs direct search for H/A at LHC

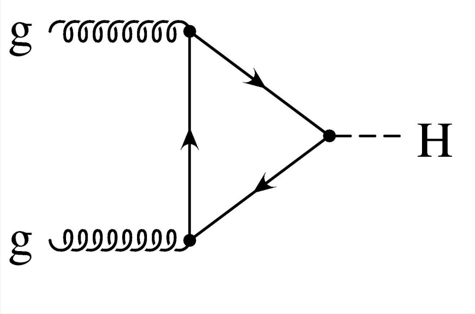


- Small tan $\beta$ direct searches most sensitive
- Larger tan $\beta$ coupling measurements most sensitive

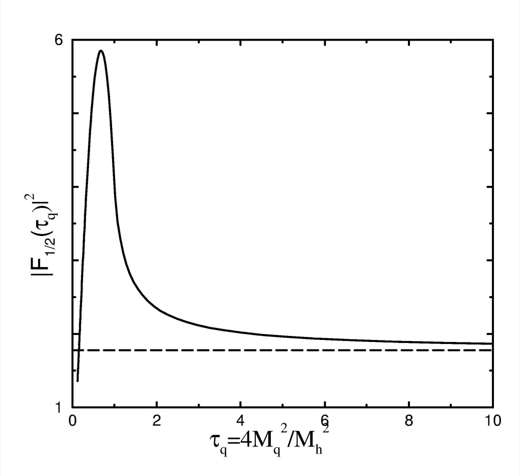
- Direct search at $e^+e^-$ collider typically reaches M~$E_{CM}/2$
- Plot assumes H→hh has small rate

# Understanding Fermion Masses

- gg→h sensitive to new colored fermions
  - Heavy quarks: $F_{1/2} \to -4/3$



$$\hat{\sigma}_{gg\to h}(\hat{s}) = \frac{\alpha_s(\mu_R)^2}{1024\pi v^2}\left|\sum_q F_{1/2}(\tau_q)\right|^2 \delta\left(1-\frac{M_h^2}{\hat{s}}\right)$$



Chiral 4th generation excluded

Is the Higgs particle the source of fermion masses?

# Example 3: Vector Fermions

- What are they?
  - Vector fermions, $\psi_L$ and $\psi_{R,}$ have identical EW quantum numbers
  - Can be either quarks or leptons
- Why?
  - Allowed by LHC data
  - Can mix with SM fermions and modify couplings to Z,W,H
  - Easy to study in model independent fashion
  - Motivated by models where Higgs is a pseudo-Goldstone Boson (Little Higgs, Composite Higgs)

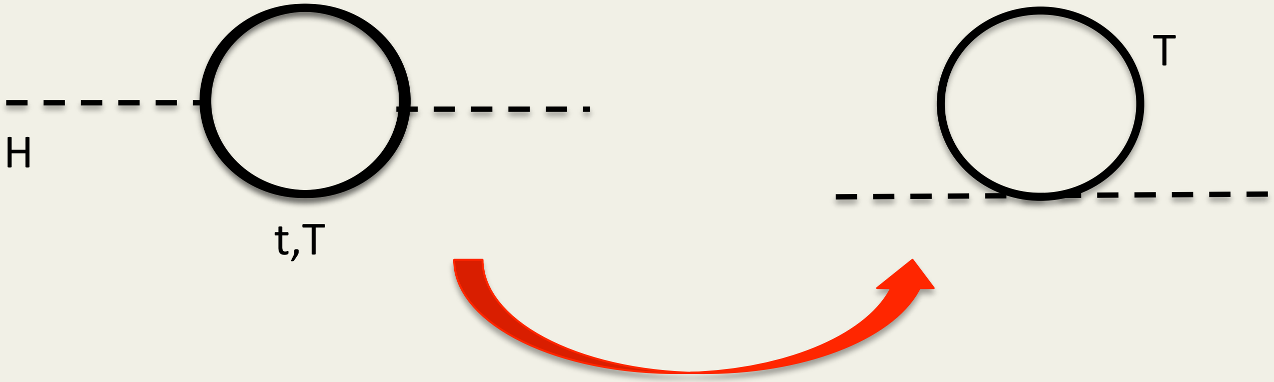
*Smoking gun for new physics in the Higgs sector*

# Top Partners

- Many possibilities for vector fermion multiplets
- Simplest is top partner:
  - Fermion with charge 2/3, $T_L^2$, $T_R^2$
  - $T_L^2$, $T_R^2$ have identical $SU(2)_L$ couplings
- Mixes with SM fermions: $\psi_L=(T_L^1, B_L^1)$, $T_R^1$, $B_R^1$
- Motivated by Little Higgs and composite Higgs models which have vector-like top partner

# Top Partners and Naturalness

- In minimal Little Higgs Model,

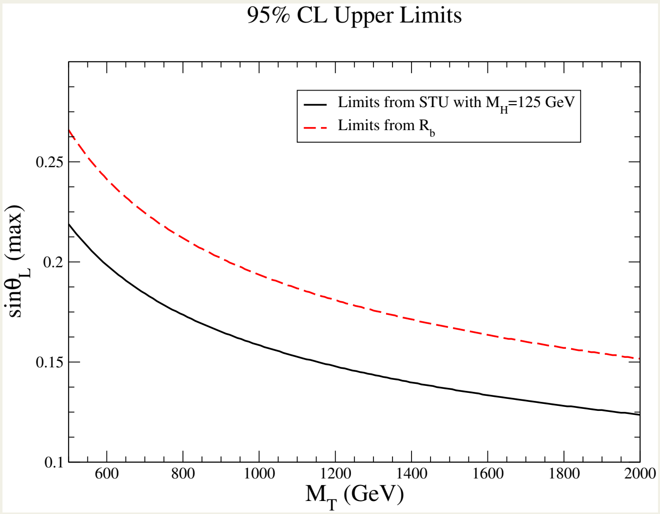


- Cancellation of $\Lambda^2$ contributions

$$\delta M_H^2 \sim -\frac{3}{8\pi^2}\left(\frac{m_t M_T}{v}\right)^2 \ln\left(\frac{\Lambda^2}{M_T^2}\right)$$

# Limits on Top Partner Models

- Stringent limits from oblique parameters and $R_b$



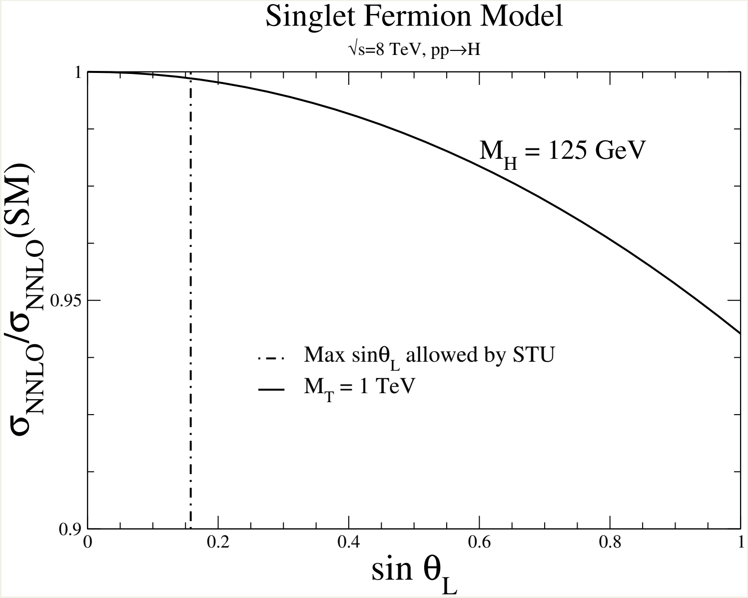
*Large mixing with SM particles not allowed*

- Top partners decouple as $M_T \rightarrow \infty$ for perturbative Yukawas
- General feature of vector-like particles

[Dawson, Furlan, arXiv.1205.4733, arXiv.1310.7593; Dawson, Furlan, Lewis, arXiv:1210.663]

# Top Partners and Gluon Fusion

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



Large effects not possible due to precision EW

$$L_H \sim \frac{m_t}{v}c_L^2 t\bar{t}H + \frac{M_T}{v}s_L^2 T\overline{T}H$$

→ Leading piece in $M_H^2/M_t^2$ expansion independent of top partner mixing

# Simple Example

- Add vector-like quark doublet Q and top partner T

$$L \sim M\overline{Q}Q + M_T\overline{T}T + \left(\lambda_1\overline{Q}_L H T_R + \lambda_2\overline{Q}_R H T_L + h.c.\right)$$

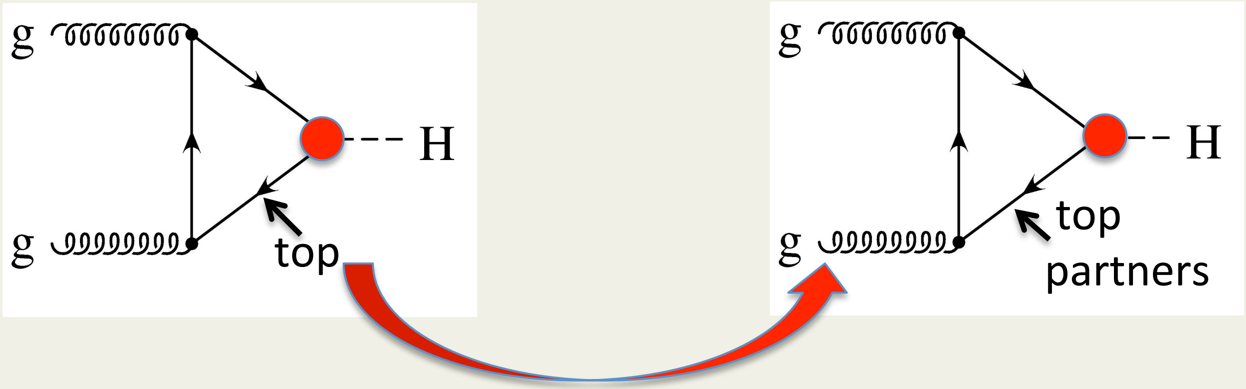
$$L \sim \frac{\alpha_s}{12\pi}\frac{H}{v}\frac{\partial\log(Det M_F)}{\partial\log(v)}G^A_{\mu\nu}G^{A,\mu\nu}$$

- ggH coupling: $\frac{\partial \ln det\mathcal{M}_F}{\partial v} \sim -\frac{2\lambda_1\lambda_2}{M M_T}$ ←

Decoupling for large top partner masses

Model is too simple to deviate much from SM

# Gluon Fusion and Higgs Masses

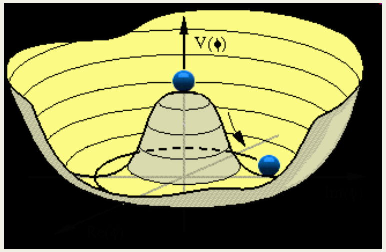


Cancellation of new physics effects

- Often has SM rate, despite new physics in loop
- Vector like fermions allow Dirac masses: $L \sim Y_{ij}\overline{f}_i f_j H + M_i \overline{f}_i f_i$
- In general, Higgs and fermions not simultaneously diagonalized.
- Flavor violating Higgs couplings, eg tTH (affects HH, but not single H production)

# Does the Higgs come from the SM Potential?

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



We know the the Higgs self interactions are weak: $\frac{M_H^2}{2v^2} \sim .13$

- Need to measure HHH and HHHH couplings
- HHH coupling can be measured with HH production

$$14\ TeV: \quad \sigma(gg \to HH) \sim 34 fb$$
$$\sigma(gg \to HHH) \sim .04 fb$$

BSM models can change the HHH and HHHH couplings

# Double Higgs Production

- Can we measure it?
  - Small rate!
- Can we construct models where it is enhanced?
  - Non-SM couplings ($\lambda_3$ or ttHH vertex, eg)
  - New particles in loops
  - Resonances: gg→X→HH (MSSM, eg)

Creativity restricted by requiring single H production to have experimentally measured value and by precision EW measurements

# Two Higgs Production at LHC

- Cross section has spin-0 and spin-2 contributions

$$\frac{d\sigma(gg \to HH)}{dt} = \frac{\alpha_s^2}{32768\pi^3 v^4}\left(\mid F_0 \mid^2 + \mid F_2 \mid^2\right)$$

- $M_t^2 >> s, p_T^2$ (low energy theorem)

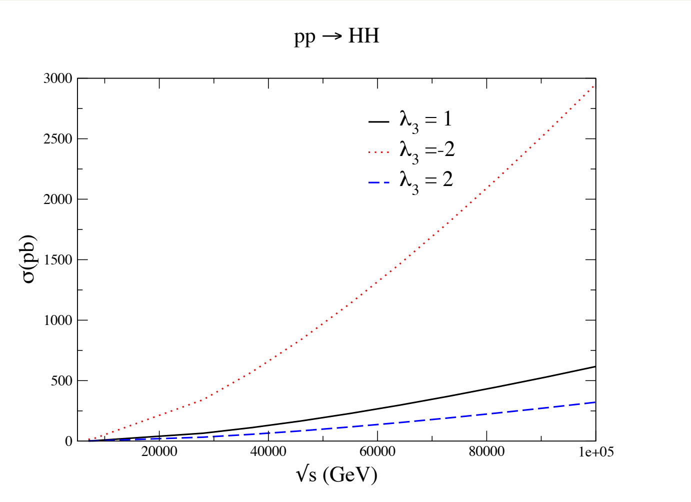
$$F_0 \to -\frac{4}{3} + \frac{4M_H^2}{s - M_H^2}(\lambda_3)$$

$$F_2 \to 0$$

HHH coupling (1 for SM)

- For large s, dependence on $\lambda_3$ suppressed
- More sensitivity to negative $\lambda_3$
- Exact cancellation at threshold

# Small Rates



For √ S=14 TeV,
K ~ 2 in $m_t \rightarrow \infty$ limit
(not in plot)

Sensitivity to HHH coupling; also to sign($\lambda_3$)

* Exact calculation, not low energy theorem

# $\lambda_3$ comes from Potential

- Assume no new particle seen
- Effective Lagrangian parameterizes high scale Higgs physics

$$V = \mu_0^2 \mid \Phi^\dagger \Phi \mid + \lambda_0 (\mid \Phi^\dagger \Phi \mid)^2 - \frac{f}{3\Lambda^2} (\mid \Phi^\dagger \Phi \mid)^3$$

*Just a toy example

- Only 1 new parameter, take it to be

$$\delta\kappa_W = \frac{f v^2}{2\Lambda^2}(1-\zeta) \sim .8 \left(\frac{1\ TeV}{\Lambda}\right)^2 \qquad \zeta = \frac{2v^2}{M_H^2} \sim 7.7$$

- Coupling deviations predicted in terms of $\delta\kappa_W$
- $\lambda_3$ NOT free

$$\lambda_{HHH} = \frac{3M_H^2}{v}\left(1 + \delta_{HHH}\right)$$

$$\delta_{HHH} = \left(1 + \frac{2\zeta}{3(\zeta - 1)}\right)\delta\kappa_W$$

# Double Higgs and the Source of Mass

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

$$C_2 O_{LE} = \frac{\alpha_s}{24\pi} C_2 G^A_{\mu\nu} G^{A,\mu\nu} \log\left(\frac{H^+ H}{v^2}\right) = \frac{\alpha_s}{12\pi} C_2 G^A_{\mu\nu} G^{A,\mu\nu} \left(\frac{H}{v} - \frac{H^2}{2v^2}\right)$$

- A general expansion could generate

SM: $C_1=0$, $C_2=1$

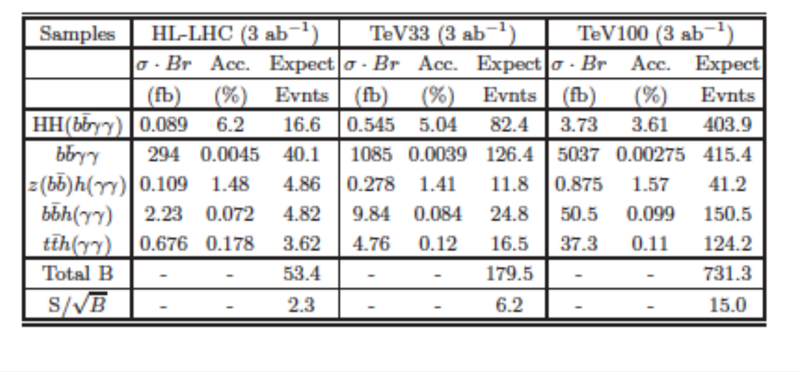
$$C_1 O_{eff} = \frac{\alpha_s}{12\pi} C_1 G^A_{\mu\nu} G^{A,\mu\nu} \left|\frac{H^+ H}{v^2}\right|^2 = \frac{\alpha_s}{12\pi} C_1 G^A_{\mu\nu} G^{A,\mu\nu} \left(\frac{H}{v} + \frac{H^2}{2v^2}\right)$$

- Measuring single and double Higgs production is window into source of EWSB

$C_H = C_1+C_2$
$C_{HH}= C_1-C_2$

# Snowmass Simulation: HH→ bb$\gamma\gamma$

- After cuts:



| Samples | HL-LHC (3 $\text{ab}^{-1}$) | | | TeV33 (3 $\text{ab}^{-1}$) | | | TeV100 (3 $\text{ab}^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| | $\sigma \cdot Br$ | Acc. | Expect | $\sigma \cdot Br$ | Acc. | Expect | $\sigma \cdot Br$ | Acc. | Expect |
| | (fb) | (%) | Evnts | (fb) | (%) | Evnts | (fb) | (%) | Evnts |
| HH($b\bar{b}\gamma\gamma$) | 0.089 | 6.2 | 16.6 | 0.545 | 5.04 | 82.4 | 3.73 | 3.61 | 403.9 |
| $b\bar{b}\gamma\gamma$ | 294 | 0.0045 | 40.1 | 1085 | 0.0039 | 126.4 | 5037 | 0.00275 | 415.4 |
| $z(b\bar{b})h(\gamma\gamma)$ | 0.109 | 1.48 | 4.86 | 0.278 | 1.41 | 11.8 | 0.875 | 1.57 | 41.2 |
| $b\bar{b}h(\gamma\gamma)$ | 2.23 | 0.072 | 4.82 | 9.84 | 0.084 | 24.8 | 50.5 | 0.099 | 150.5 |
| $t\bar{t}h(\gamma\gamma)$ | 0.676 | 0.178 | 3.62 | 4.76 | 0.12 | 16.5 | 37.3 | 0.11 | 124.2 |
| Total B | - | - | 53.4 | - | - | 179.5 | - | - | 731.3 |
| S/$\sqrt{B}$ | - | - | 2.3 | - | - | 6.2 | - | - | 15.0 |

$$\frac{d(\sigma/\sigma_{SM})}{d(\lambda_3/\lambda_{3,SM})} \sim -.8$$

- Statistical accuracy on $\lambda_3$:
  - 50% (8%) at 14 (100) TeV with 3000 $\text{fb}^{-1}$ at one experiment

Need to improve this!

# If no new particles at LHC……

- Effective Lagrangians used to describe physics
  - Interactions which respect SU(2) x U(1) symmetry
  - Expand in powers of $1/\Lambda^2$:
    - $L_{SM}+\Sigma\, f_i\, O_i/\Lambda^2+\ldots$
    - Contributions to oblique parameters at tree level:

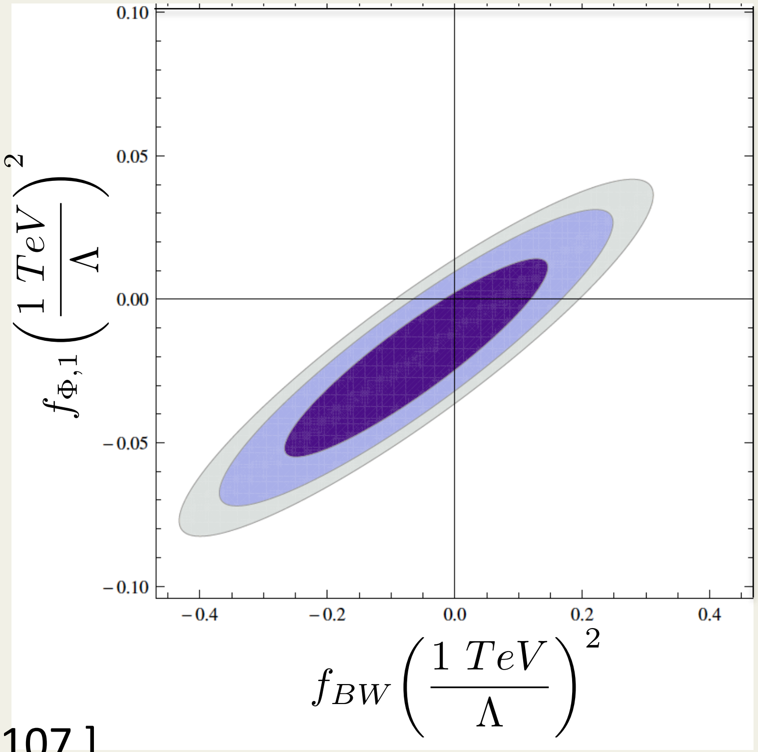
$$\mathcal{O}_{BW} \equiv -\frac{gg'}{4}\Phi^\dagger B_{\mu\nu}\sigma^a \cdot W^{a,\mu\nu}\Phi \quad \Rightarrow \quad S$$

$$\mathcal{O}_{\Phi 1} \equiv (D_\mu\Phi)^\dagger(\Phi\Phi^\dagger)(D^\mu\Phi) \quad \Rightarrow \quad T$$

# Where is the New Physics?

- Limits highly correlated: Need global fits
- In any particular model, relationships between $f_i$
- If $f_i \sim 1$ then $\Lambda > 2$ TeV

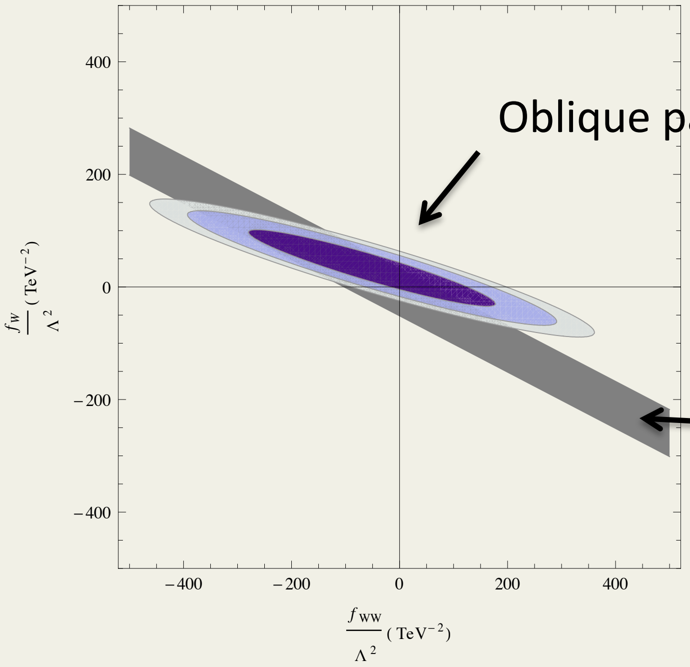
Where is new physics?



[Chen, Dawson, Zhang, arXiv:1311.3107 ]

# One Interesting Case

$$\frac{\Gamma(H \rightarrow W^+W^-)}{\Gamma(H \rightarrow W^+W^-)_{SM}} \sim 1 + \left[.0086 f_{WW}(m_Z) + .017 f_W(m_Z)\right]\left(\frac{1\ TeV}{\Lambda}\right)^2$$



Oblique parameters

Higgs data

In principle, complementary data from oblique parameters and Higgs data

# Conclusion

- If we don't find new particles…..
  - Higgs searches and coupling measurements are complementary
  - *Effects on Higgs physics from high scales expected to be small*
  - We are just starting to probe the interesting region
- *It's all about decoupling and effective theories*