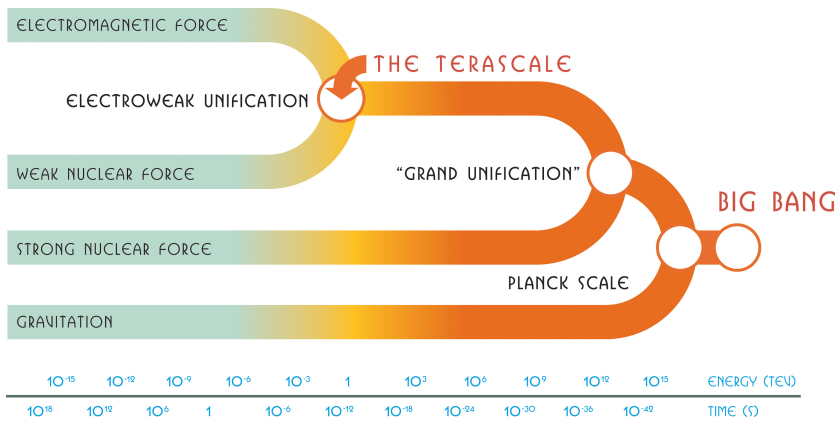
The Search for the Next Scale

After the Higgs: What next?

S. Dawson, BNL
February 6, 2014

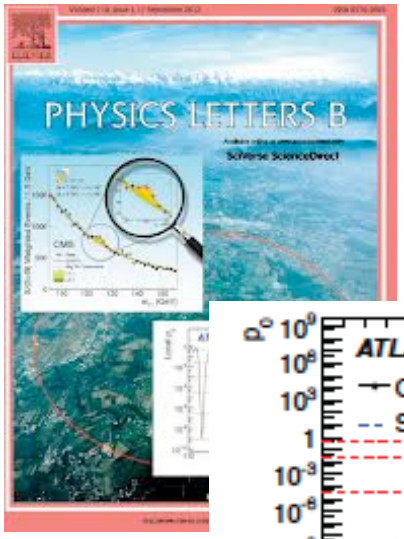


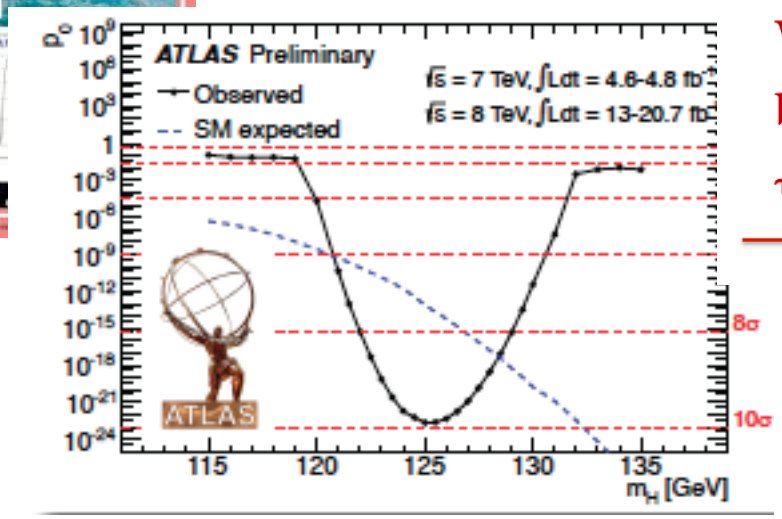
What's next?

- We found the Higgs
- We measured θ_{13} non-zero
- We excluded many regions of dark matter parameters
- *How do we put this together to find the next scale of new physics?*
- *I don't know the answer, but I believe this is one of the most important questions facing us*

We discovered a Higgs boson!

- The minimal Higgs model is very predictive
- Only free parameter is M_h





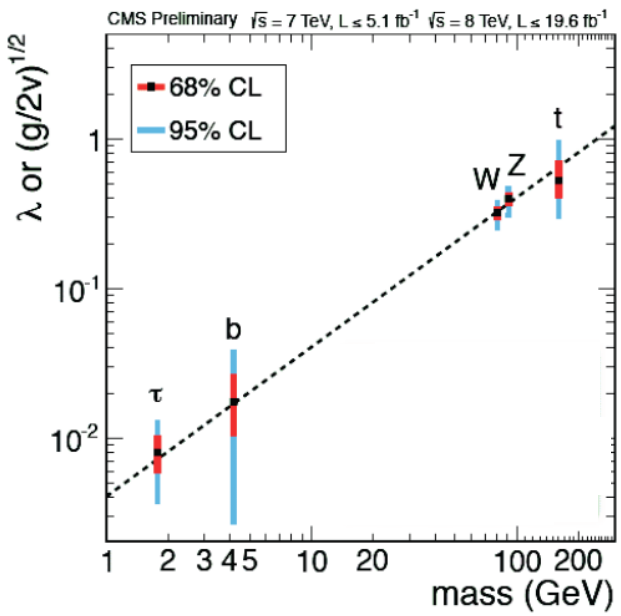
CMS

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	2.6 σ	2.8 σ

Both ATLAS and CMS have close to 10σ significance

All Higgs Couplings predicted in SM

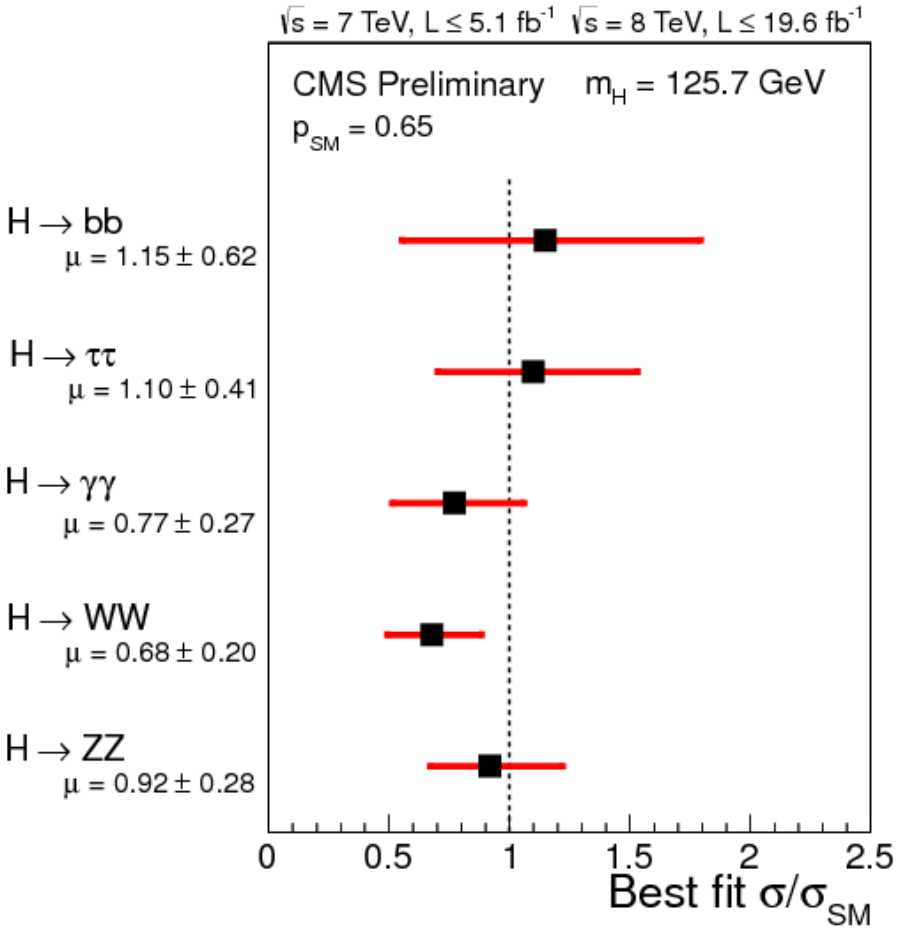
- Very precise predictions
  - Couplings to fermions proportional to mass
  - Couplings to gauge bosons proportional to (mass)^2
  - Higgs self-couplings proportional to M_h^2

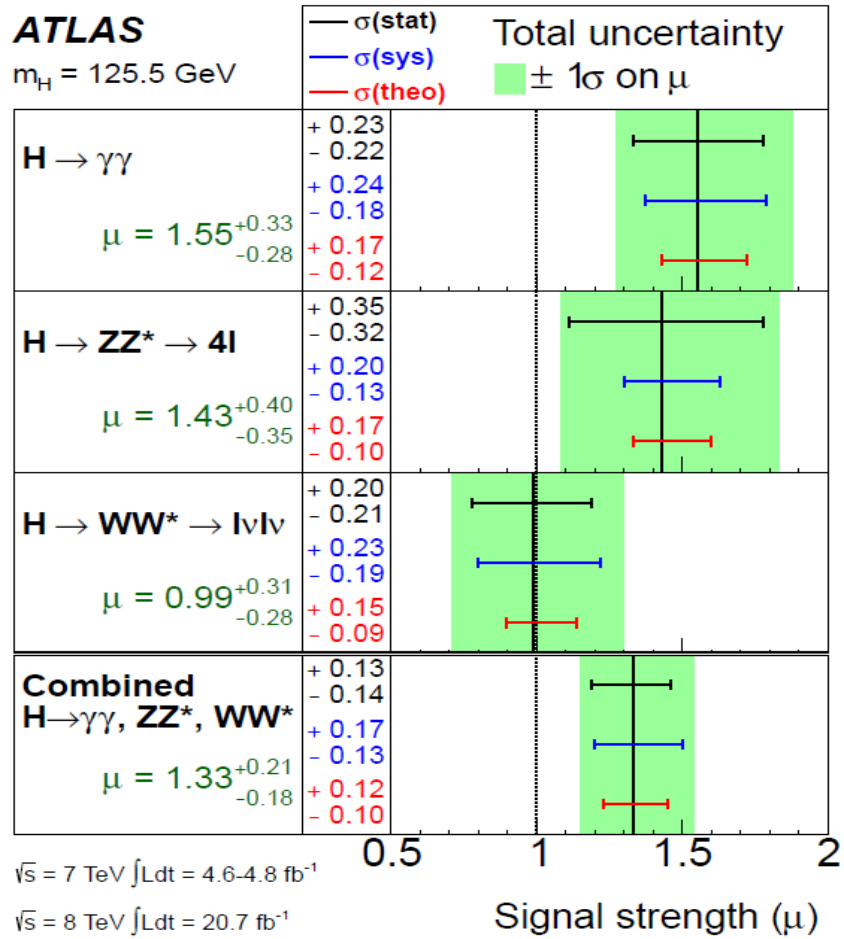


If couplings didn't have this pattern, it would indicate that not all mass comes from a single Higgs boson

*t coupling inferred from ggh top loop

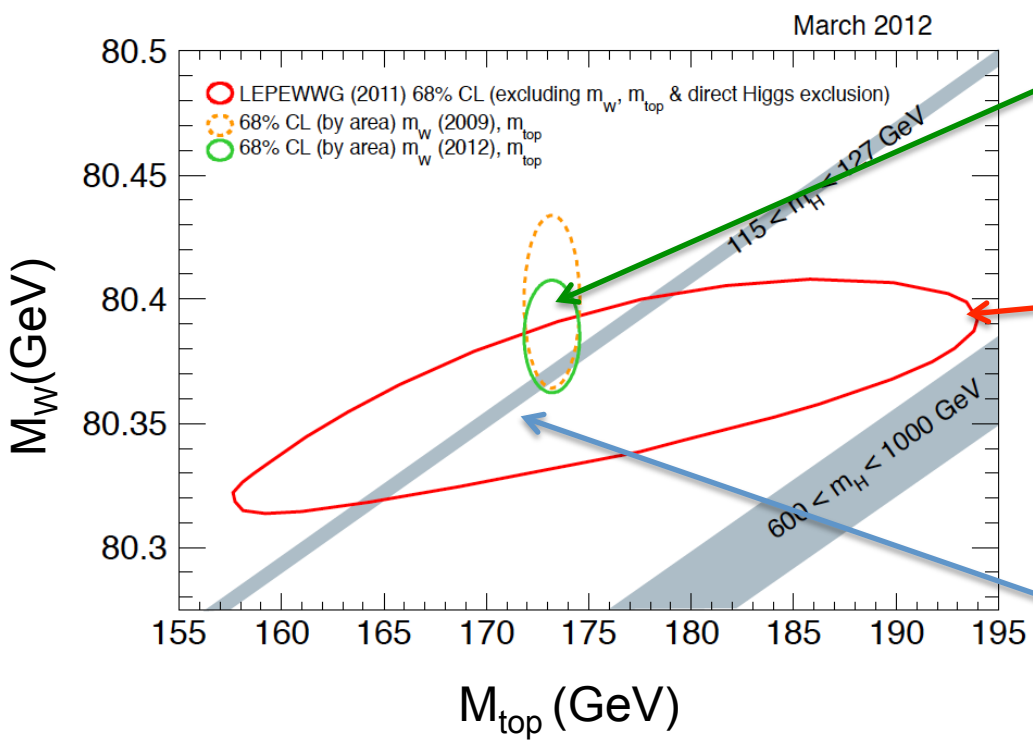
Consistent with SM Hypothesis





Note theory uncertainties

Precision Physics Before Higgs Discovery



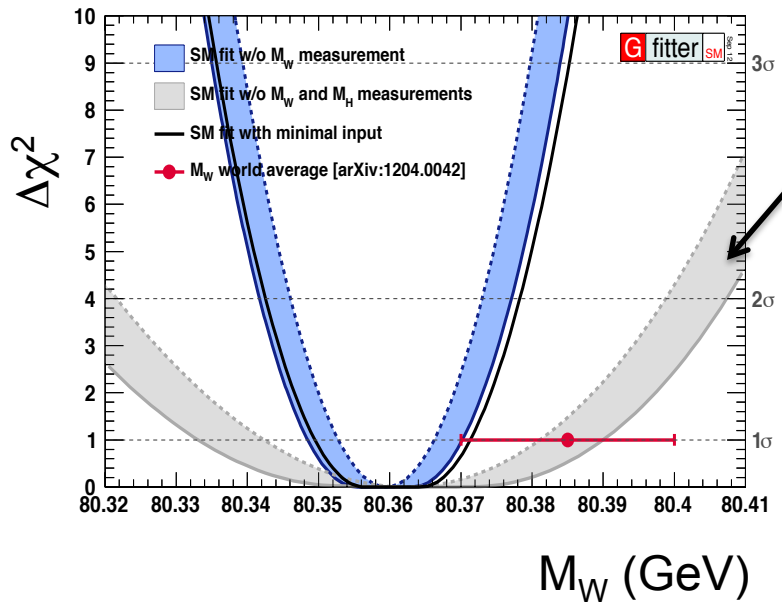
Experimental measurements from Fermilab

Inferred values of M_W and M_t from other experiments

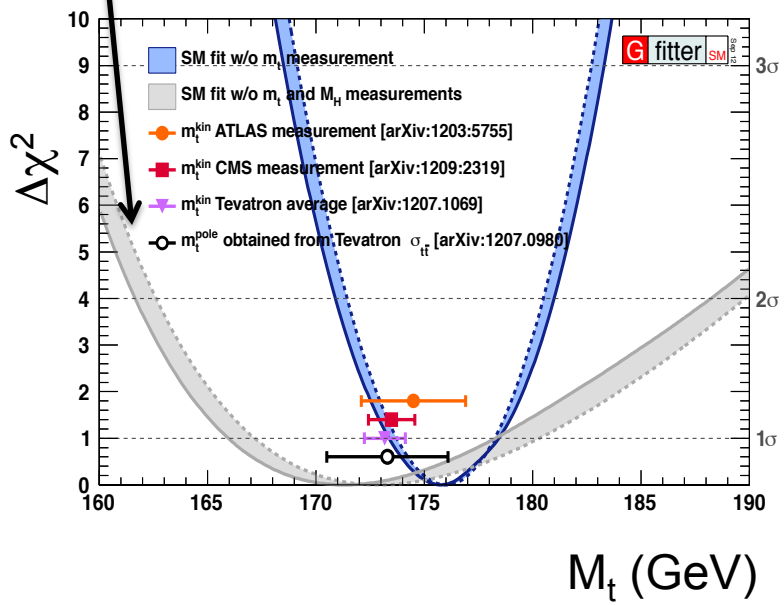
Theory predictions

Self-consistency of the theory told us the Higgs couldn't be too heavy without new physics

Precision Physics After Higgs Discovery



Fit without Higgs



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

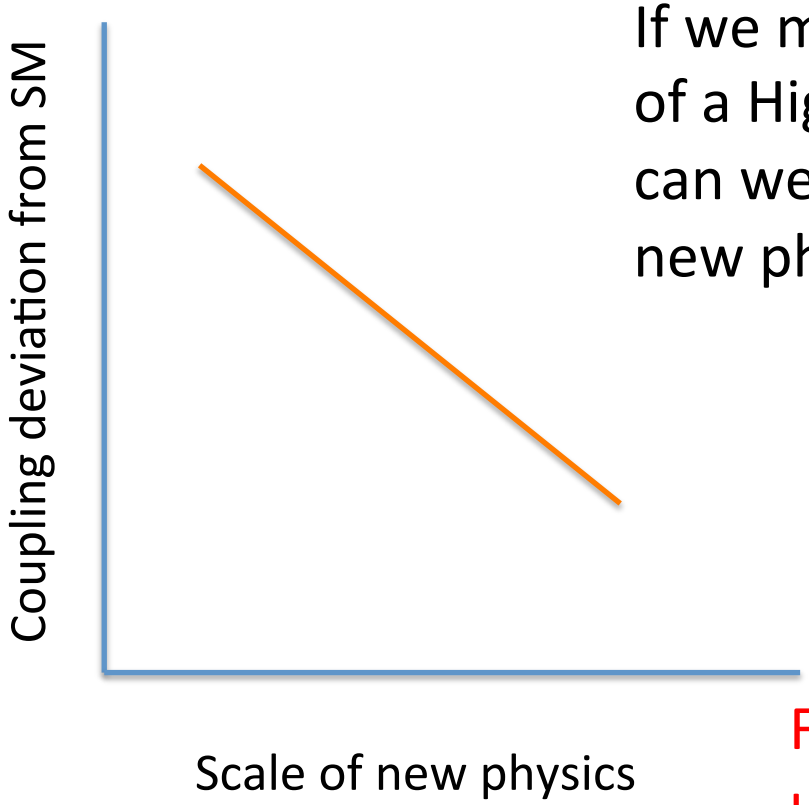
But the SM can't be complete

- It doesn't explain:
  - Neutrino masses
  - Dark matter
  - Baryon asymmetry
  - The pattern of fermion masses

If new physics explains any of this, how do we get a handle on the relevant energy scale?

The bottom line: The Higgs boson looks SM like and we haven't found any other new particles

What we hope for

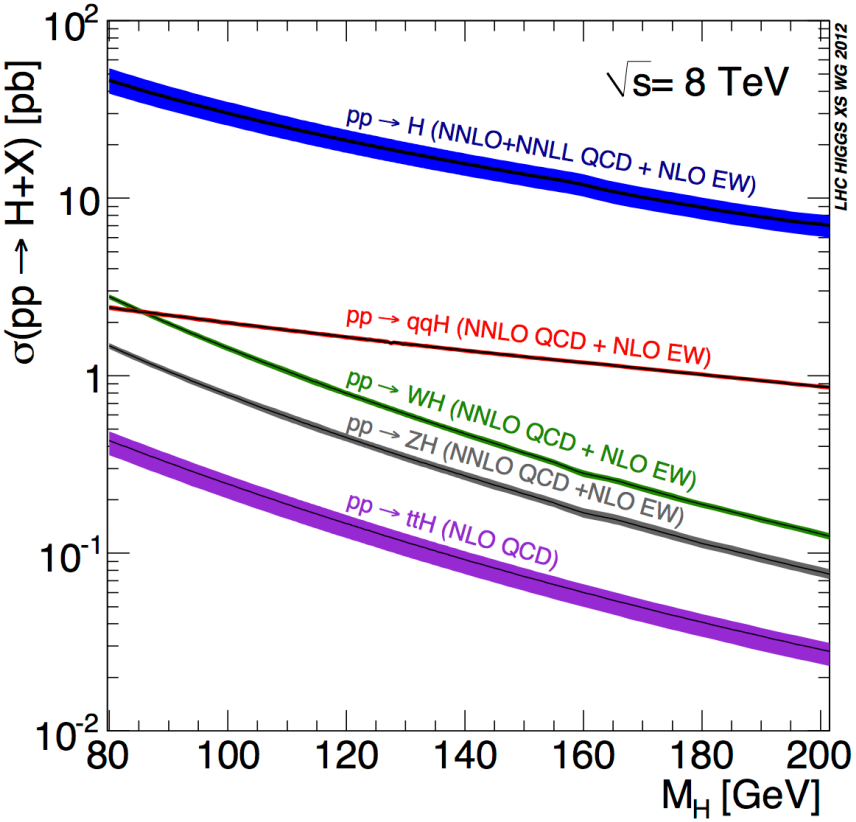


If we measure a large deviation of a Higgs coupling from the SM, can we associate it with a scale of new physics?

Proof by exhaustion

For this to work, we have to understand the SM first

Need to Understand SM First



NLO predictions now in MC programs, POWHEG, aMC@NLO

$$\sqrt{s} = 8\ TeV, M_H = 126\ GeV$$

$$\sigma_{gg} = 19^{+7.2\%+7.5\%}_{-7.8\%-6.9\%}\ pb$$

QCD Scale PDF+α_s

Theory uncertainties affect ability to extract couplings at LHC

[LHC Higgs Cross Section Working Group]

Precision Higgs Production

Uncertainties in Higgs production at 8 TeV

	Scale	PDF + α_s	Total (linear sum)
ggF	±8%	±8%	±15%
tth	±7%	±8%	±15%
VBF	±1%	±4%	±5%
VH	±1%	±4%	±5%

Uncertainties in Higgs production at 14 TeV

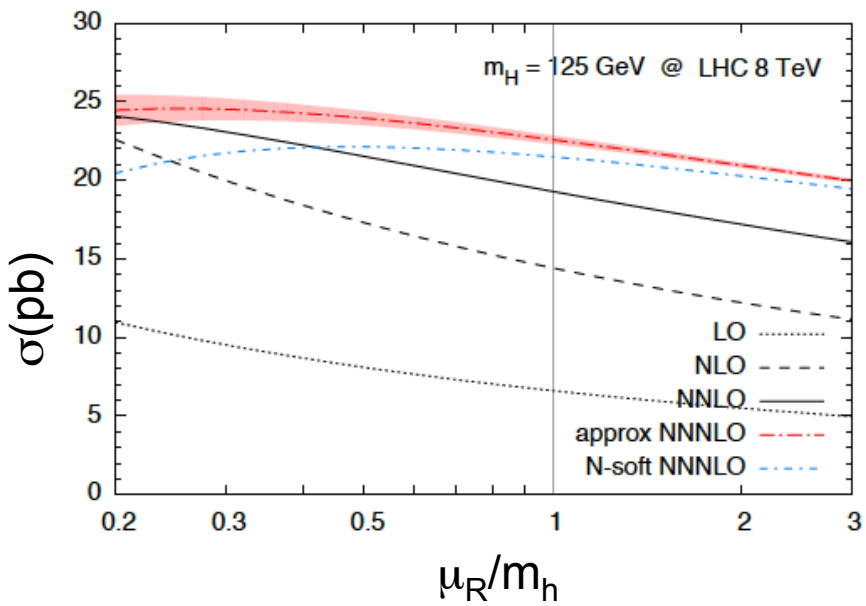
	Scale	PDF + a_s	Total (linear sum)
ggF	+12, -8%	±7%	+20, -15%
tth	+6, -9%	±9%	+15, -18%
VBF	+.7, -.4%	+2, -2.6%	±3%
VH	+.3, -.6%	±4%	±4%

Need to improve SM calculations and their inputs (especially PDFs) as we enter a new era of precision Higgs physics

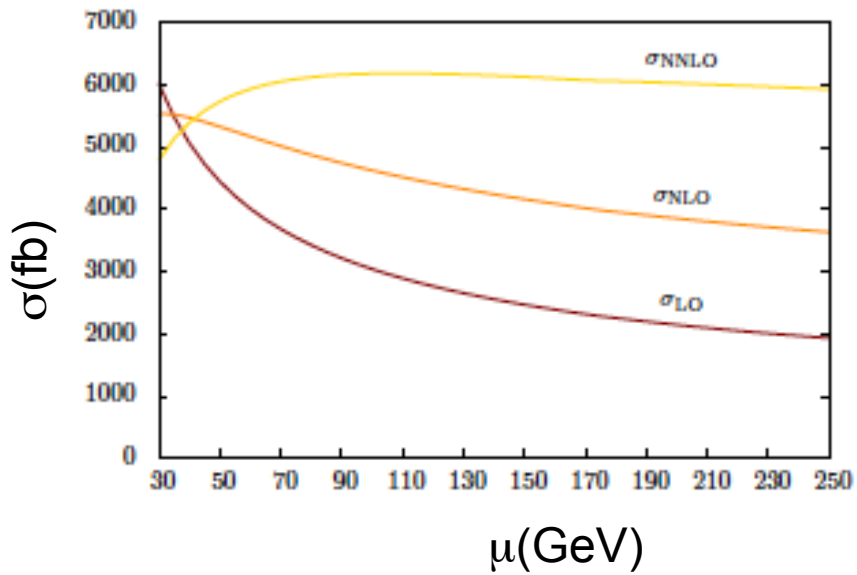
H+jet @NNLO, H@NNNLO

- Will decrease errors from scale uncertainty and jet binning

Higgs inclusive cross section



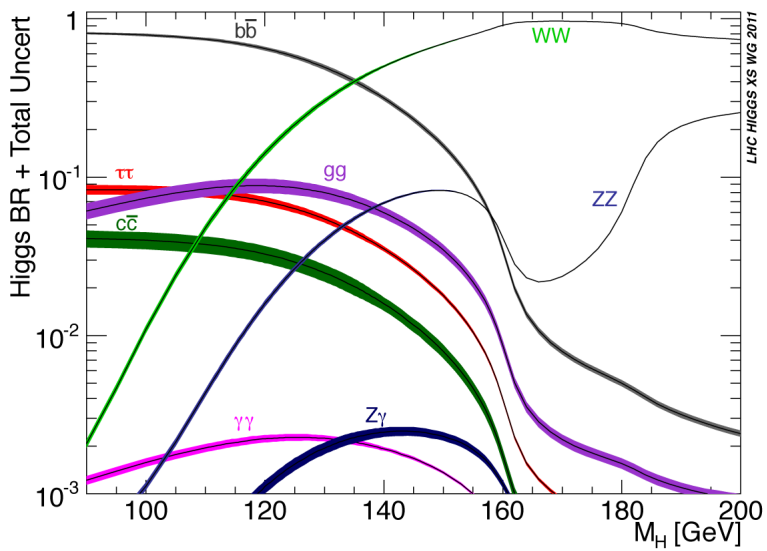
Higgs+jet at √s=8 TeV



Rates are increased with new results

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

Theory Predictions on Branching Ratios



- Parametric uncertainties can be reduced by better determination of m_b (lattice?)
- Theory uncertainties from missing EW corrections will be reduced

Target: Reduce theory uncertainties to ~1% to correspond to 1% measurements at lepton colliders

Decay	Theory Uncertainty (%)	Parametric Uncertainty (%)	Total Uncertainty on Branching Ratios (%)
$H \to \gamma\gamma$	± 2.7	± 2.2	± 4.9
$H \to b\bar{b}$	± 1.5	± 1.9	± 3.3
$H \to \tau^+\tau^-$	± 3.5	± 2.1	± 5.6
$H \to WW^*$	± 2.0	± 2.2	± 4.1
$H \to ZZ^*$	± 2.0	± 2.2	± 4.2

[LHC Higgs cross section working group]

Uncertainties on BR Predictions

- Example: h→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 ±.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) and for e^+e^- extractions (~2.7% at 250 GeV)

[LHC Higgs Cross Section Working Group, 1201.3084]

Precision Measurements vs Direct Observation

- Is there a clear answer to how precisely we need to measure Higgs couplings to get insight into new physics?
- If new particles are excluded to some scale, what does that tell us about the target for measuring Higgs couplings?
- Can we classify the types of new physics where *nothing new* shows up in the Higgs couplings?

Report of Snowmass Higgs Working Group, Dawson, Gritsen, Logan, Qian, Tully, van Kooten, arXiv: 1310.8361

How well do we *NEED* to measure Higgs Couplings?

- LHC measures $\sigma \cdot$BR (products of couplings)
- e^+e^- uses recoil method for model independence

0th order answer: We found a new particle which we hypothesize is the quanta of EWSB. We want to measure couplings as precisely as possible

1st order answer: Let's see what kind of deviations we might expect in reasonable scenarios

- To be sensitive to deviation Δ, need to measure to $\Delta/3$ or $\Delta/5$

Testing Higgs Couplings

- Assume 1 resonance/zero width approx/no new tensor structures

$$\sigma \cdot BR(ii \to h \to jj) = \frac{\sigma_{ii}\Gamma_{jj}}{\Gamma_h}$$

- Define scaling factors κ

$$\mu(gg \to h \to \tau^+\tau^-) = \frac{\sigma(gg \to h \to \tau^+\tau^-)}{\sigma(gg \to h \to \tau^+\tau^-)\,|_{SM}} = \frac{\kappa_g^2\kappa_\tau^2}{\kappa_h^2}$$

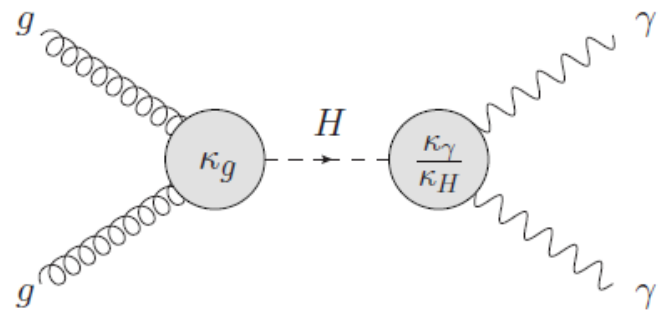
- Approaches to loops: κ_γ, κ_g can be
  - Written as function of SM scaling factors: eg $\kappa_g=\kappa_g(\kappa_t,\kappa_b)$
  - Treated as free parameters to look for BSM contributions
- Current fits have assumptions about Γ_h

All μ and κ experimentally consistent with 1

[LHC Higgs Cross Section Working group, arXiv1307.1346]

BSM Physics from Higgs Couplings

Example:
$gg \rightarrow H \rightarrow \gamma\gamma$



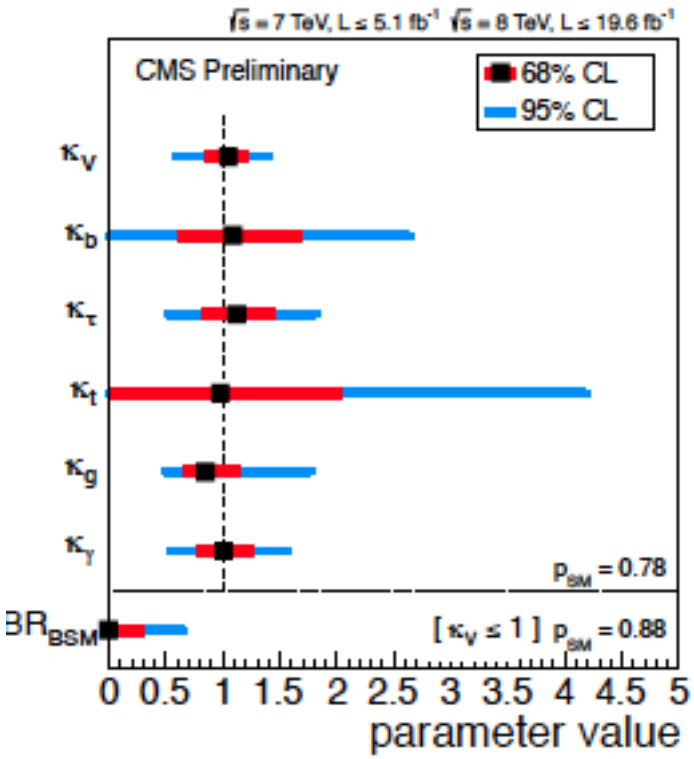
$$(\sigma \cdot BR)(gg \rightarrow H \rightarrow \gamma\gamma) = \left[\sigma(gg \rightarrow H) \cdot BR(H \rightarrow \gamma\gamma)\right]_{SM} \times \boxed{\frac{\kappa_g^2 \cdot \kappa_\gamma^2}{\kappa_H^2}}$$

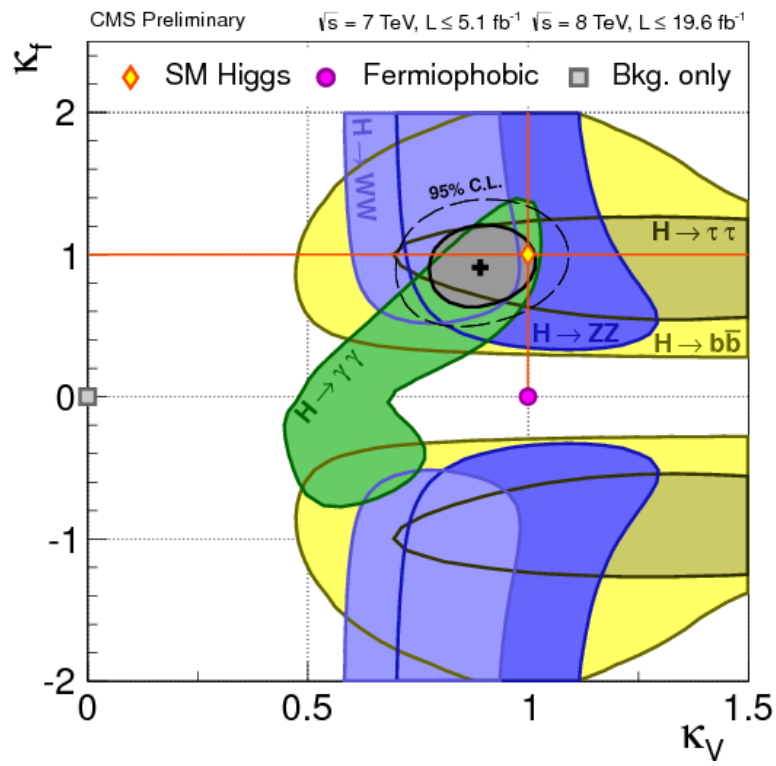
κ_H^2 is the scale factor to the total Higgs decay width

$$\kappa_H^2 = \sum_x \kappa_x^2 \cdot BR(H \rightarrow xx) \xrightarrow{\text{No BSM decays}} \kappa_H^2 = \sum_x \kappa_x^2 \cdot BR_{SM}(H \rightarrow xx)$$

$$\xrightarrow{\text{With BSM decays}} \kappa_H^2 = \sum \kappa_x^2 \cdot \frac{BR_{SM}(H \rightarrow xx)}{1 - BR_{BSM}}$$

Couplings Today:





Precision measurements yet to come

Snowmass Higgs group has 7 parameter fit

LHC Coupling Projections

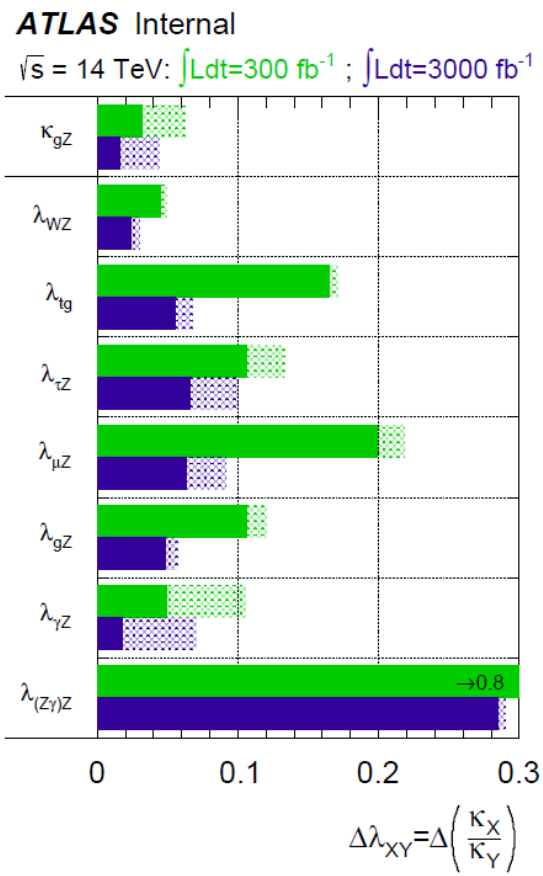
- Different scenarios assumed by CMS and ATLAS
  - ATLAS: with and without theory error (same syst.)
  - CMS: (a) Same systematics as today and (b) systematics scales as 1/√L and theory error halved

		κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ
300fb^{-1}	ATLAS	[8,13]	[6,8]	[7,8]	[8,11]	N/a	[20,22]	[13,18]	[78,79]	[21,23]
	CMS	[5,7]	[4,6]	[4,6]	[6,8]	[10,13]	[14,15]	[6,8]	[41,41]	[23,23]
3000fb^{-1}	ATLAS	[5,9]	[4,6]	[4,6]	[5,7]	N/a	[8,10]	[10,15]	[29,30]	[8,11]
	CMS	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]

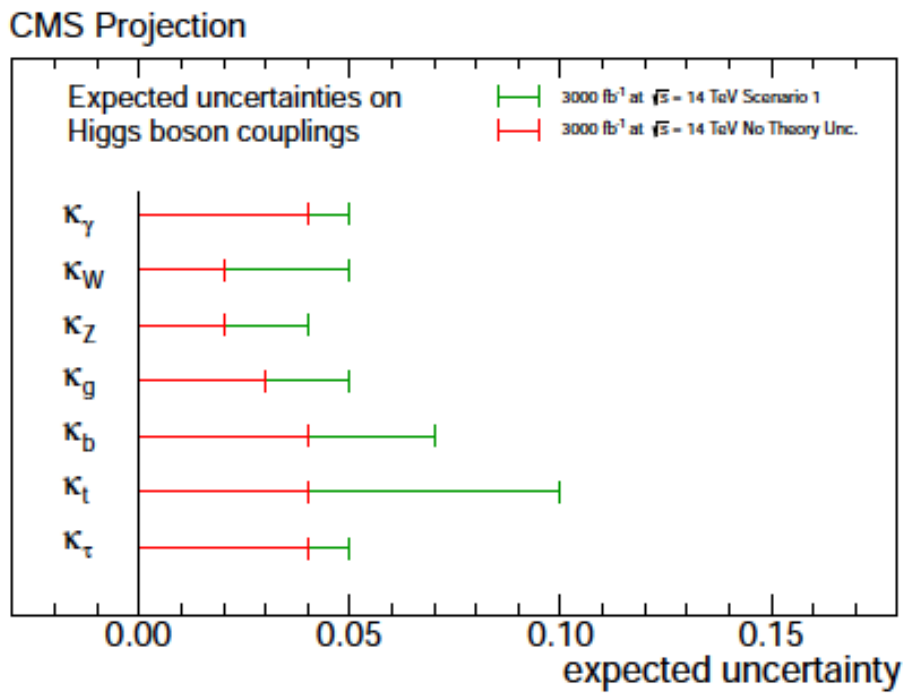
ECFA, 2013

Ultimately, 2-5% measurements

Theoretical Uncertainty Matters

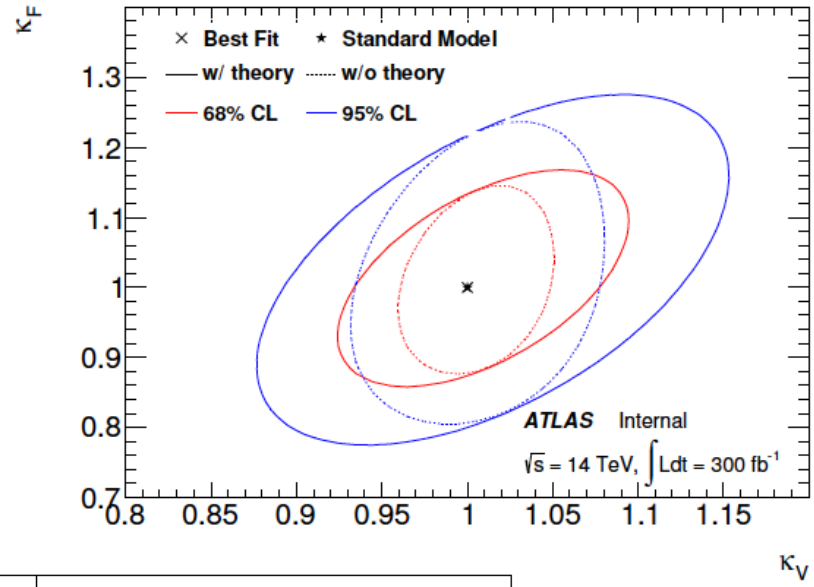


Normalized to H➔ZZ



Theory Uncertainty Matters

ATLAS Projections:



Coupling	With theory systematics	Without theory systematics
300 fb^{-1}		
κ_V	$^{+5.9\%}_{-5.4\%}$	$^{+3.0\%}_{-3.0\%}$
κ_F	$^{+10.6\%}_{-9.9\%}$	$^{+9.1\%}_{-8.6\%}$
3000 fb^{-1}		
κ_V	$^{+4.6\%}_{-4.3\%}$	$^{+1.9\%}_{-1.9\%}$
κ_F	$^{+6.1\%}_{-5.7\%}$	$^{+3.6\%}_{-3.6\%}$

~5-10% measurements

[ATLAS, Snowmass white paper]

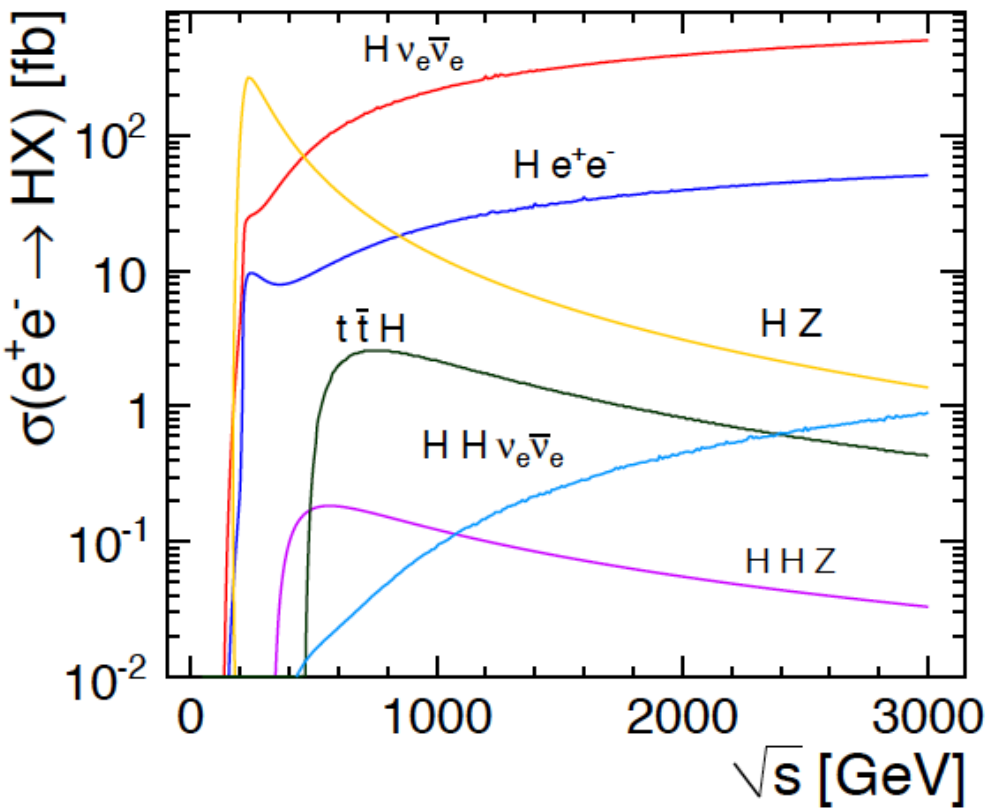
Can we do better?

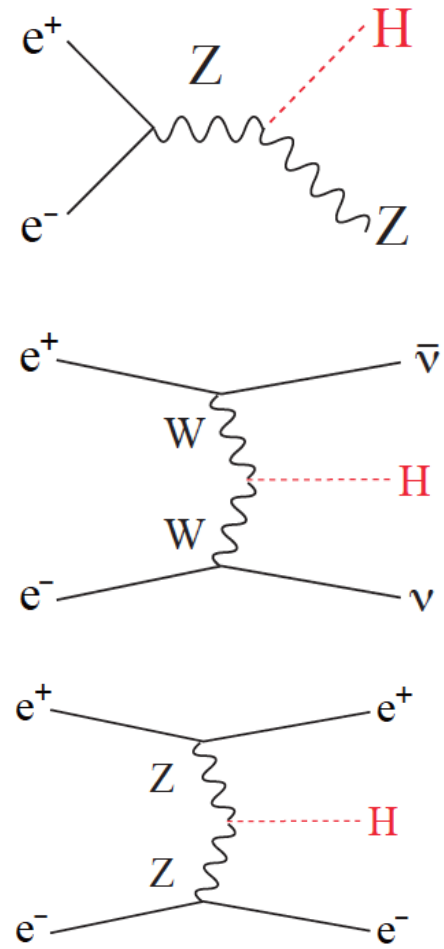
- Compare capabilities for extracting Higgs couplings at CLIC, $\gamma\gamma$, ILC, LHC (3000 fb^{-1}), 33 TeV LHC, 100 TeV LHC, μC, TLEP
- No value judgement about realities of machine parameters

Facility	HL-LHC	ILC	ILC(LumiUp)	CLIC	TLEP (4 IPs)	HE-LHC	VLHC
$\sqrt{s}$ (GeV)	14,000	250/500/1000	250/500/1000	350/1400/3000	240/350	33,000	100,000
$\int \mathcal{L}dt$ (fb^{-1})	3000/expt	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600	3000	3000
$\int dt$ (10^7s)	6	3+3+3	(ILC 3+3+3) + 3+3+3	3.1+4+3.3	5+5	6	6

[Snowmass Higgs Working Group Report, arXiv:1310.8361]

e^+e^- Colliders





Couplings at e^+e^- Colliders

- Recoil technique gives independent measurements of total width and branching ratios

- Get total Higgs width: $\Gamma_h = \frac{\Gamma(h \to ZZ)}{BR(h \to ZZ)} \sim \frac{\sigma(Zh)}{BR(h \to ZZ)}$

- At higher energies can also use $e^+e^- \to \nu\nu h$

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

Advantage: Coupling extractions don't need assumptions about total width

Couplings at e^+e^- Colliders

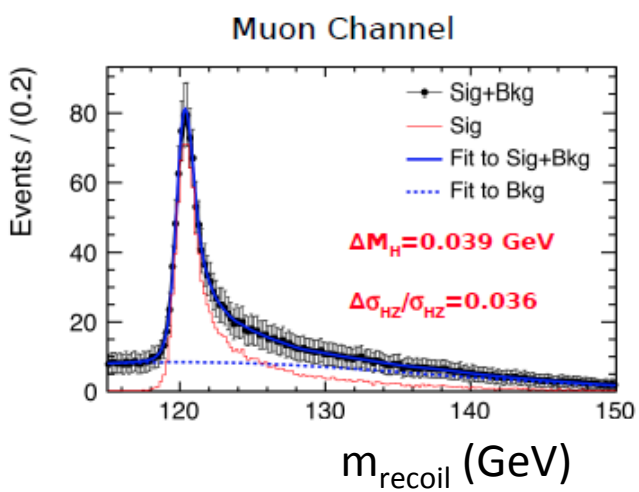
- Use recoil technique: $e^+e^- \to Zh$; tag $Z \to \mu^+\mu^-, e^+e^-$
  - Reconstruct recoil mass, $m^2_{\rm recoil} = (\sqrt{s} - E_{l^+l^-})^2 - |\vec{p}_{ll}|^2$
  - Identify Higgs independent of decay
  - This gives: $\sigma(Zh) \sim (g_{hZZ})^2$
  - Classify the rest of the events to measure BR ($h \to XX$)

ILC250:

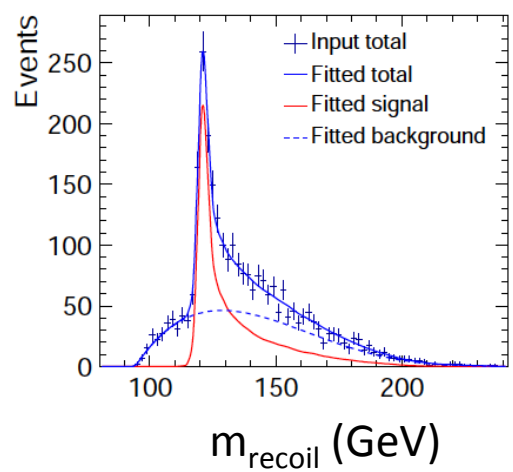
$$\frac{\Delta\sigma}{\sigma} = 2.5\%$$

$$\frac{\Delta g_{hZZ}}{g_{hZZ}} = 1.3\%$$

$$\Delta\Gamma_h = 11\%$$



$e^+e^- \to Zh$, ILC at $\sqrt{s}$=250 GeV, 250 fb^{-1}



$e^+e^- \to Zh$, CLIC at $\sqrt{s}$=350 GeV, 500 fb^{-1}

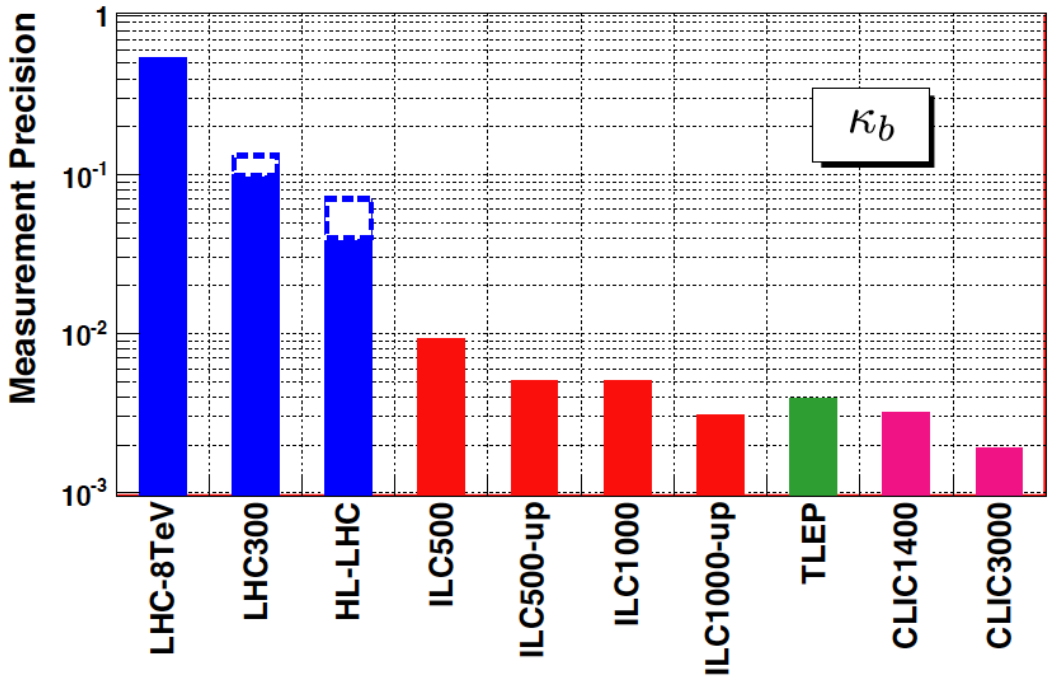
CLIC350:

$$\frac{\Delta\sigma}{\sigma} = 4\%$$

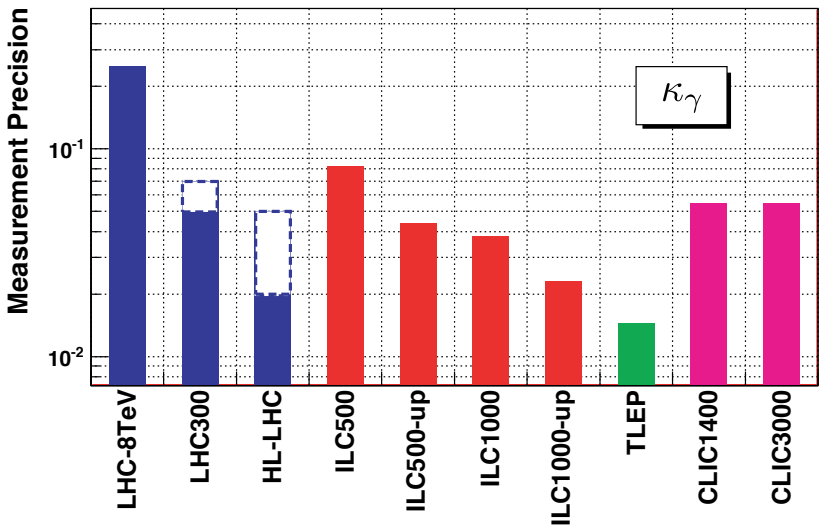
$$\frac{\Delta g_{hZZ}}{g_{hZZ}} = 2\%$$

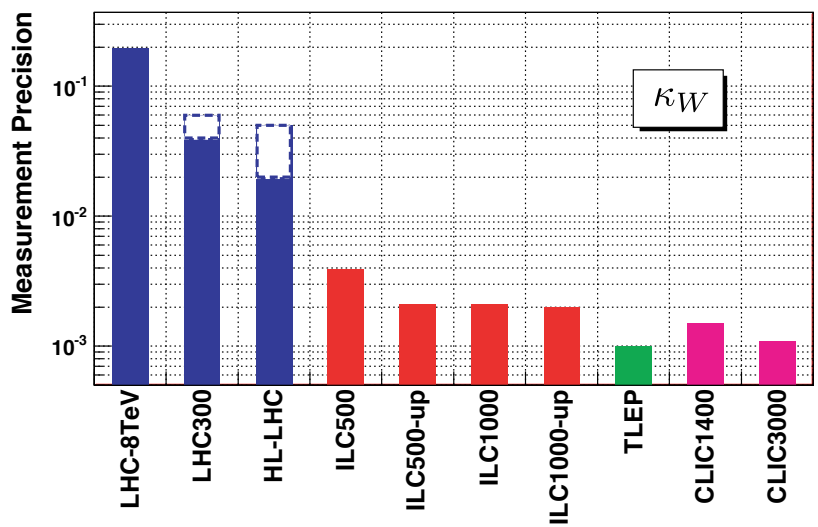
Examples of Comparisons

- Redo e^+e^- fits with SM Γ_H restrictions and 7 parameter fits



* This assumption not needed for e^+e^-


Measurement Precision
10^{-1}
10^{-2}
κ_γ
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000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ILC1000
ILC1000-up
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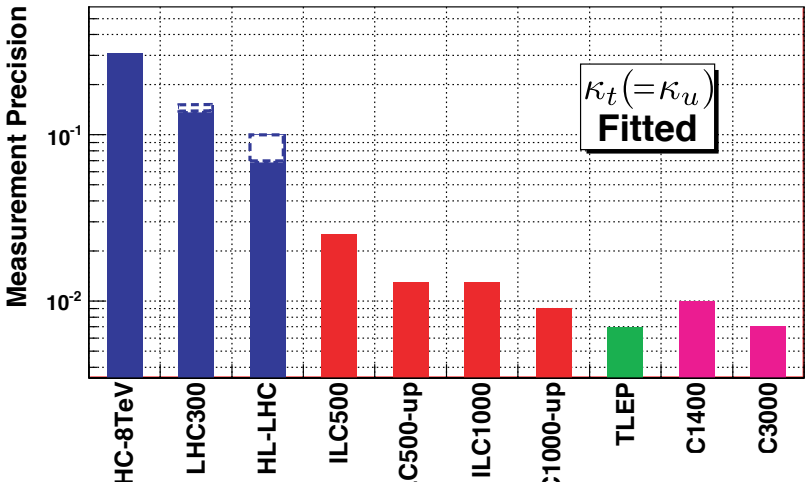
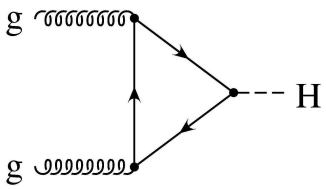
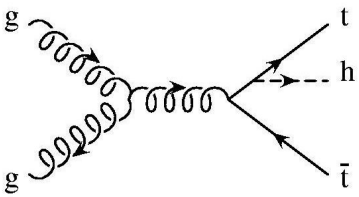
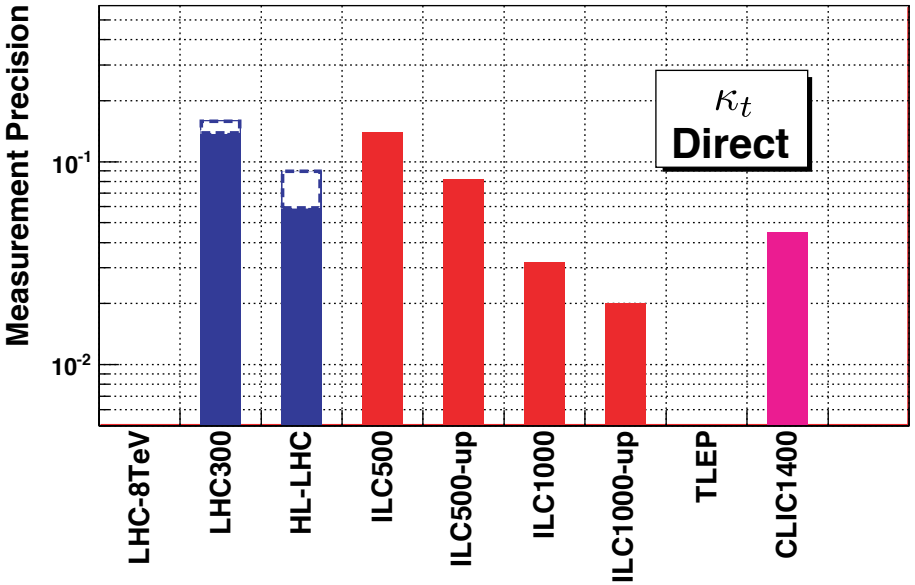
CLIC1400
CLIC3000

Top Yukawa Particularly Interesting



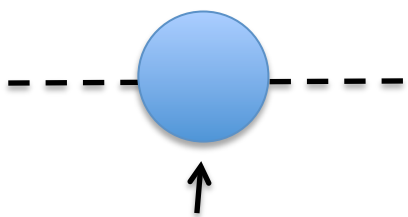






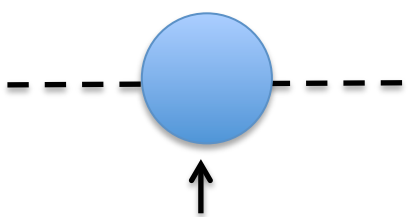
The Naturalness Connection

- Generically, solutions to naturalness involve new particles, which lead to deviations in Higgs couplings



SM particles

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



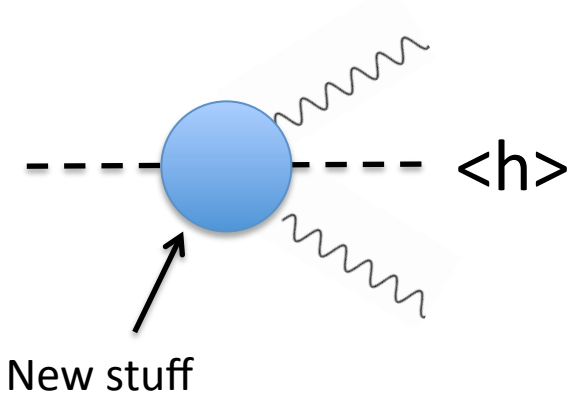
New stuff

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

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

The Naturalness Connection

- Generically, solutions to naturalness involve new particles, which lead to deviations in Higgs couplings



MSSM light stops generically contribute (no mixing):

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

Target precision < 3%

As LHC limits on new particles increases, target precision decreases

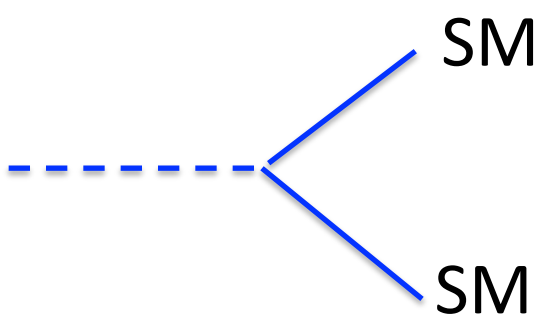
The Other Side of the Coin

- Suppose we measure Higgs couplings to 2-5%
- Suppose we reduce theory errors so that we can unambiguously claim difference from SM must be BSM physics

WHAT DO WE LEARN?

Example 1: Additional Higgs Singlet

- Models to explain dark matter, flavor often have more than 1 Higgs boson
  - Simple example: SM Higgs mixed with electroweak singlet, S



Coupling to light Higgs, h ~ cos θ
Coupling to heavy Higgs, H ~ sin θ

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

Measure Higgs couplings and/or look for heavy Higgs

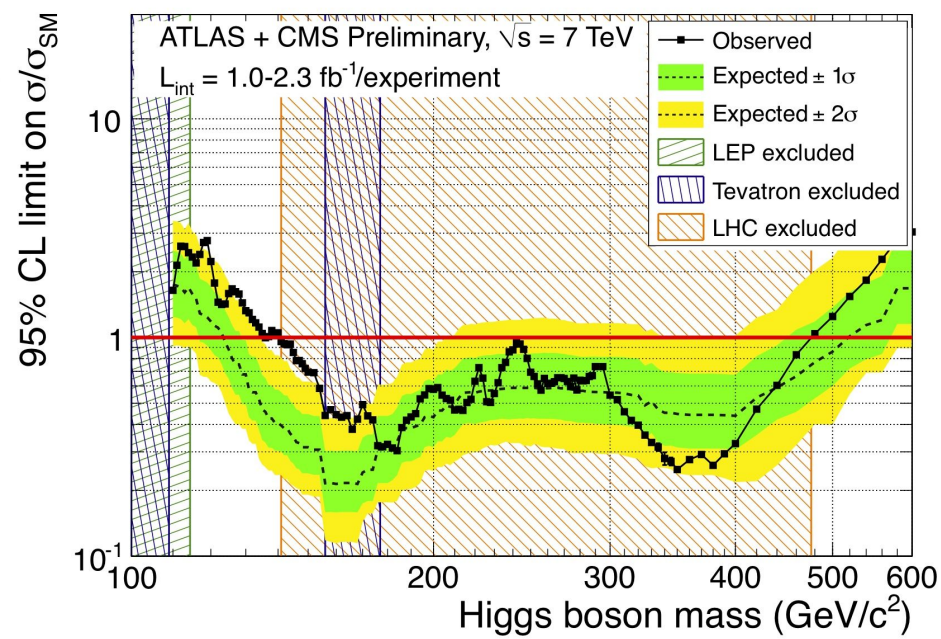
Higgs Couplings: 1 Parameter

- Higgs couplings modified

$$g^2_{hXX} = \cos^2\theta_h (g^{SM}_{hXX})^2, \quad g^2_{HXX} = \sin^2\theta_h (g^{SM}_{hXX})^2$$

- If no new decay channels, trivial interpretation of limits

$\sin^2\theta_h$



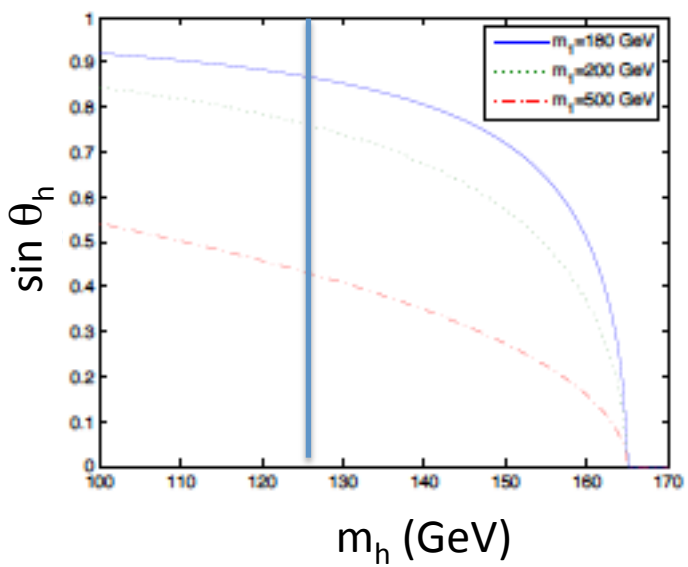
m_H

Higgs Couplings: 1 Parameter

- Modified Higgs couplings affect electroweak precision measurements:

$$\Delta T = (\ldots)\cos^2\theta_h \log(m_h) + (..)\sin^2\theta_h \log(m_H) + \ldots$$

95% CL allowed region (from STU) is below curves



m_H increasing

[Dawson, Yan]

Complementarity of Approaches

- Find the heavier Higgs and/or measure deviations in couplings
- What is largest sin θ such that we won't see H (heavier Higgs) at LHC with 100 fb^{-1}?
  - For M_H=1.1 TeV expect 13 signal events, 7 background ($S/\sqrt{B}$~5)
  - To see new physics (without observing H) need $(\sin\theta)^2 < .12$

Target precision: $\delta\kappa \sim -\frac{\sin^2\theta}{2} \sim -6\%$

[Gupta, Rzehak, Wells, arXiv:1206.3560]

Example 2: Top Partners

- Many possibilities
- Simplest:
  - Fermion with charge 2/3, $\mathcal{T}_L^2$, $\mathcal{T}_R^2$
  - $\mathcal{T}_L^2$, $\mathcal{T}_R^2$ have identical $SU(2)_L$ couplings (vector-like)
- Mixes with SM fermions: $\psi_L=(\mathcal{T}_L^1, \mathcal{B}_L^1)$, $\mathcal{T}_R^1$, $\mathcal{B}_R^1$
- Motivated by Little Higgs and composite Higgs models which have vector-like top partner

Top Partners can have Dirac Masses

- Physical t's are combinations of $\mathcal{T}^1, \mathcal{T}^2$

$$\chi_L = \begin{pmatrix} t_L \\ T_L \end{pmatrix} \equiv U_L \begin{pmatrix} \mathcal{T}_L^1 \\ \mathcal{T}_L^2 \end{pmatrix} \qquad \chi_R = \begin{pmatrix} t_R \\ T_R \end{pmatrix} \equiv U_R \begin{pmatrix} \mathcal{T}_R^1 \\ \mathcal{T}_R^2 \end{pmatrix}$$

- Most general mass terms:

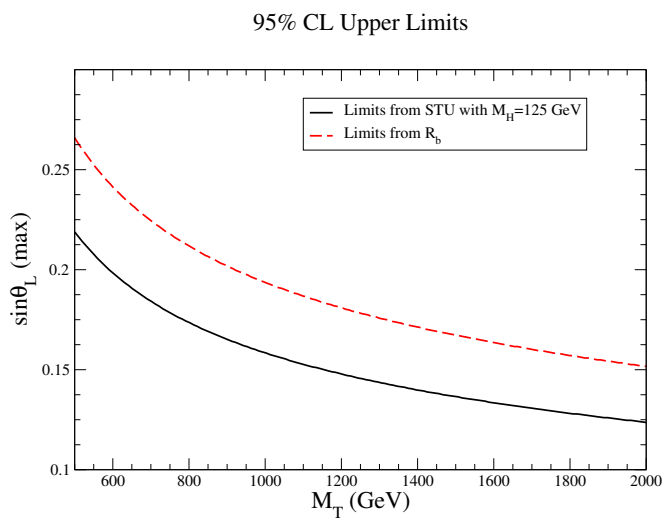
$$-\mathcal{L}_{M,SM} = \lambda_2 \overline{\psi}_L^1 \tilde{H} \mathcal{T}_R^1 + h.c.$$

$$-\mathcal{L}_{M,1} = \lambda_3 \overline{\psi}_L^1 \tilde{H} \mathcal{T}_R^2 + \lambda_4 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^1 + \lambda_5 \overline{\mathcal{T}}_L^2 \mathcal{T}_R^2 + h.c.$$

  – λ_4 can be rotated away by redefinition of $\mathcal{T}_R^2$
  – 4 physical parameters, m_b, m_t, M_T, θ_L
- Higgs, neutral current, charged couplings changed

Limits on Top partner Model

- Stringent limits from oblique parameters and R_b



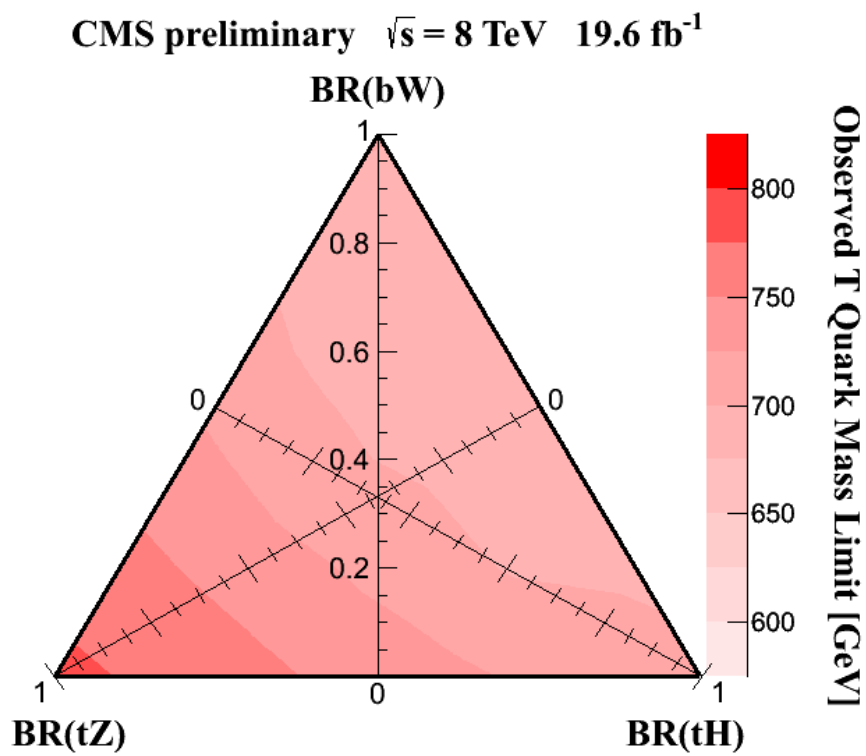
Large mixing not allowed

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

Top Partner limits

- LHC limits model dependent, but M_T>600-700 GeV
  - T➔bW, T➔tH, T➔tZ
  - gg➔$T\bar{T}$ model independent
- Unitarity

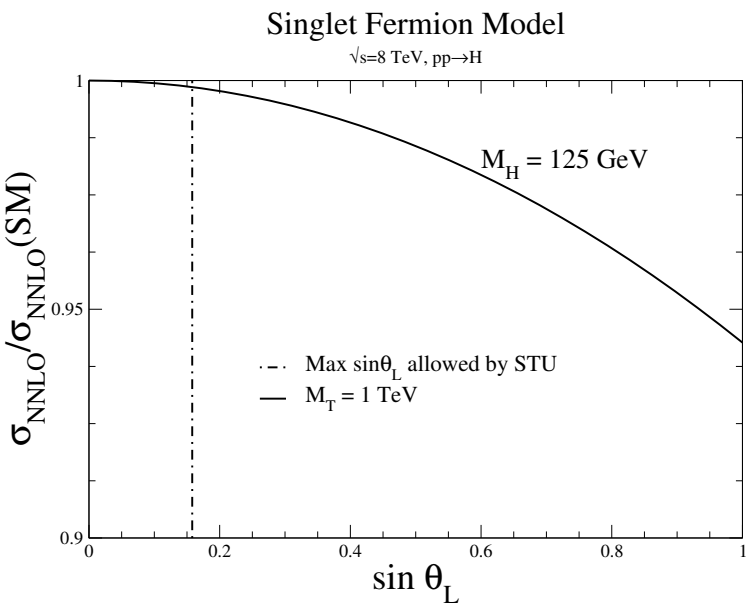
$$M_T < \frac{550\ GeV}{s_L^2}$$



CMS-PAS-B2G-12-015

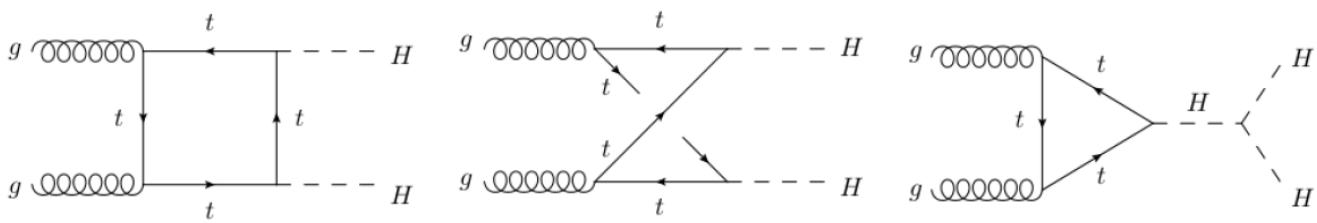
Top Partners and gluon fusion

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



Example of model where direct search beats Higgs coupling measurements for discovery

Two Higgs Production



- Sensitive to HHH coupling and new particles in loops
  - Cancellation between box and triangle reduces sensitivity
- Small rate: 3 fb at 8 TeV, 15 fb at 14 TeV
  - bbγγ gives 3σ with 3 ab^{-1} (270 events with 3 ab^{-1})
  - 30% measurement of λ_{HHH} with 2 experiments

[ATLAS/CMS HL-LHC study]

8% measurement at 100 TeV

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 (low energy theorem)

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

$$F_2 \to 0$$

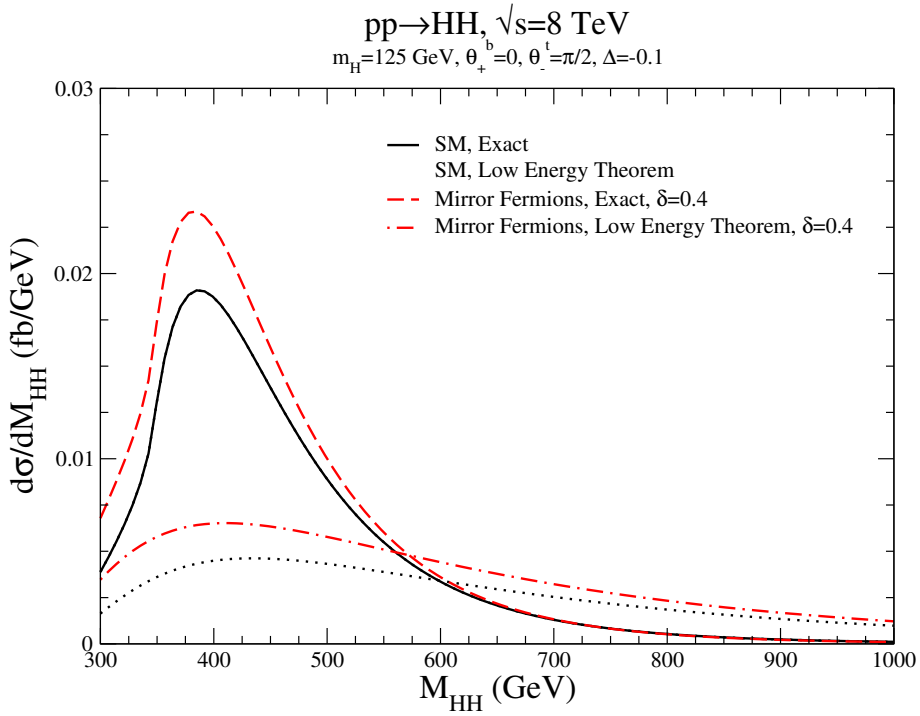
HHH coupling (1 for SM)

- Singlet top partner model has s_L and c_L in appropriate places
- Also has new diagrams with tTH vertices

*High energy doesn't help as much as you might think it would

Double Higgs Rate in Top Partner Model

- gg→HH rate increased by 17% relative to SM
- gg→H rate assumed to be 90% of SM



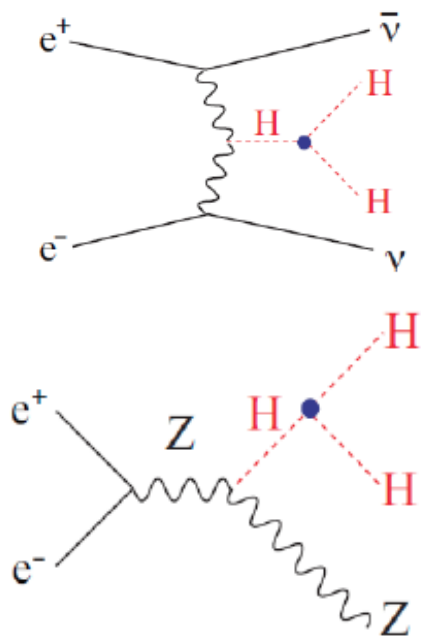
Parameters limited by requirement that single Higgs production agrees with measured rate

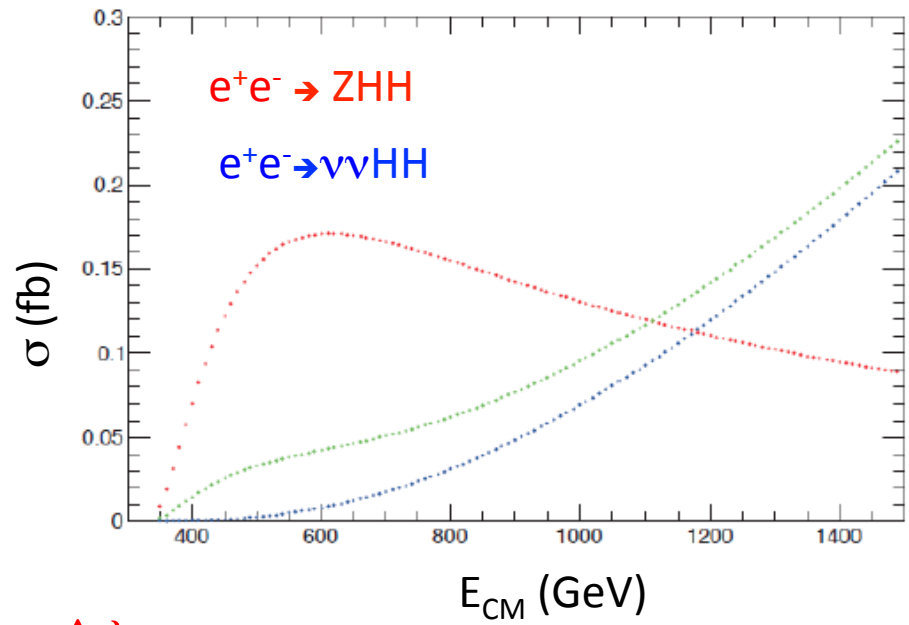
Optimal choice of parameters

[Dawson, Lewis, Furlan]

ILC doesn't do that much better with HHH

- Low rates: 400 events at 500 GeV, 1000 events at 3 TeV
- Large backgrounds





$$\frac{\Delta\lambda_{HHH}}{\lambda_{HHH}} \sim 25\%(ILC), 15\%(CLIC)$$

Example 3: Effective Lagrangian

- If no new particles, an effective Lagrangian can be used
  - Construct interactions which respect SU(2)xU(1) symmetry
  - Expand in powers of s/Λ^2: $L \sim L_{SM} + \Sigma f_i O_i/\Lambda^2 + \ldots$
- Simple model: Only Higgs and gauge boson operators participate in new physics

$$\mathcal{O}_{DW} \equiv -\frac{g^2}{4} Tr\left(\left[D_\mu, \sigma^a \cdot W^a_{\nu\rho}\right]\left[D^\mu, \sigma^b \cdot W^{b,\nu\rho}\right]\right)$$

$$\mathcal{O}_{DB} \equiv -\frac{g'^2}{2}(\partial_\mu B_{\nu\rho})(\partial^\mu B^{\nu\rho})$$

Renormalize kinetic energy

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

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

Modify gauge boson 2-point function at tree level

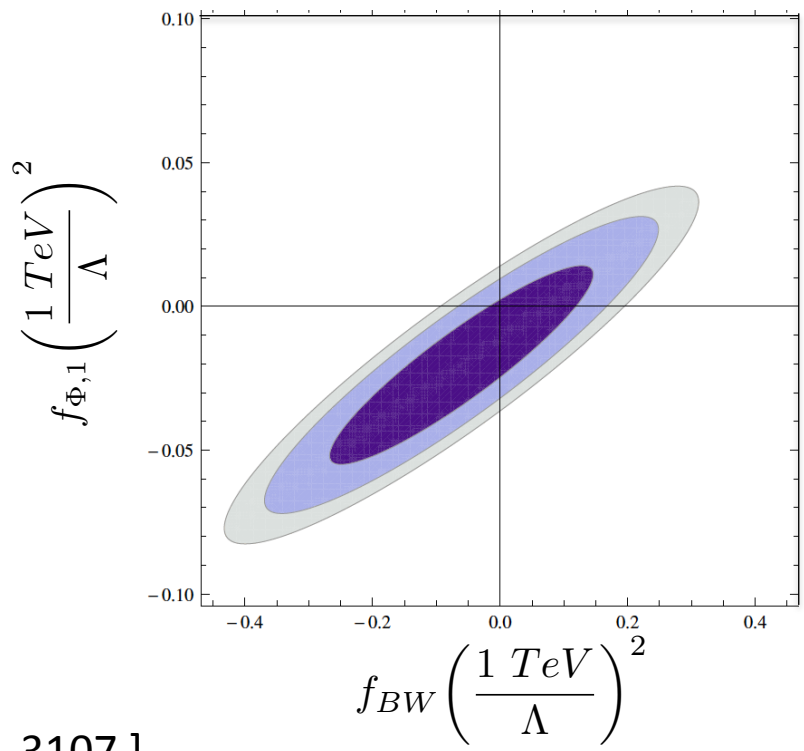
* Equations of motion relate bosonic operators to fermion operators

[Cen, Dawson, Zhang, arXiv: 1311.3107]

Scale from Oblique Parameters?

- Limits highly correlated
- In any particular model, relationships between f_i
- If $f_i \sim 1$ then $\Lambda > 1.4$ TeV

Not sensitive to multi-TeV scales in a model independent manner



[Chen, Dawson, Zhang, arXiv:1311.3107]

Effective Lagrangians at 1-loop

- At 1-loop more operators contribute to S,T,U; Also to Higgs decays, and VV production

$$
\begin{aligned}
\mathcal{O}_{WWW} &= -i\frac{g^3}{8}Tr\left(\sigma^a \cdot W_\nu^{a,\mu}\sigma^b \cdot W_\rho^{b,\nu}\sigma^c \cdot W_\mu^{c,\rho}\right) \\
\mathcal{O}_W &= i\frac{g}{2}(D_\mu\Phi)^\dagger\sigma^a \cdot W^{a,\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_B &= i\frac{g'}{2}(D_\mu\Phi)^\dagger B^{\mu\nu}(D_\nu\Phi) \\
\mathcal{O}_{WW} &= -\frac{g^2}{4}\Phi^\dagger\sigma^a \cdot W^{a,\mu\nu}\sigma^b \cdot W_{\mu\nu}^b\Phi \\
\mathcal{O}_{BB} &= -\frac{g'^2}{4}\Phi^\dagger B^{\mu\nu}B_{\mu\nu}\Phi\,.
\end{aligned}
$$

  - Contributions to oblique parameters are divergent

$$
\begin{aligned}
\Delta S &= C_S\frac{1}{\epsilon}\left(\frac{4\pi\mu^2}{m_Z^2}\right)^\epsilon\Gamma(1+\epsilon) + R_S \\
\Delta T &= C_T\frac{1}{\epsilon}\left(\frac{4\pi\mu^2}{m_Z^2}\right)^\epsilon\Gamma(1+\epsilon) + R_T \\
\Delta U &= C_U\frac{1}{\epsilon}\left(\frac{4\pi\mu^2}{m_Z^2}\right)^\epsilon\Gamma(1+\epsilon) + R_U
\end{aligned}
$$

The Point about Effective Theories

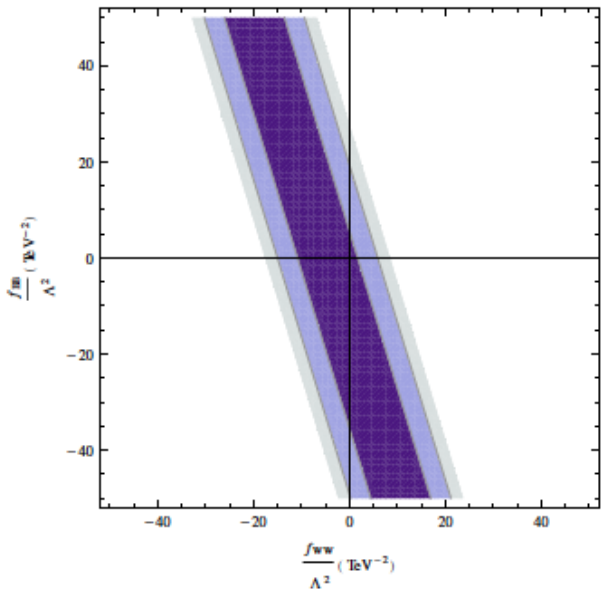
- 1-loop divergences absorbed into renormalization of operators which contribute at tree level at any given order in $1/\Lambda^2$

$$
\begin{aligned}
f_{BW}(\mu) &= f_{BW} - \frac{1}{\epsilon}(4\pi)^\epsilon \Gamma(1+\epsilon) C_S \\
f_{DW}(\mu) &= f_{DW} - \frac{1}{\epsilon}(4\pi)^\epsilon \Gamma(1+\epsilon) C_U \\
f_{\Phi,1}(\mu) &= f_{\Phi,1} - \frac{1}{\epsilon}(4\pi)^\epsilon \Gamma(1+\epsilon) C_T \,.
\end{aligned}
$$

- Effective theory is finite order by order in $1/\Lambda^2$ expansion
- After renormalization, no logarithmic enhancements
- This has drastic effects on limits from oblique parameters

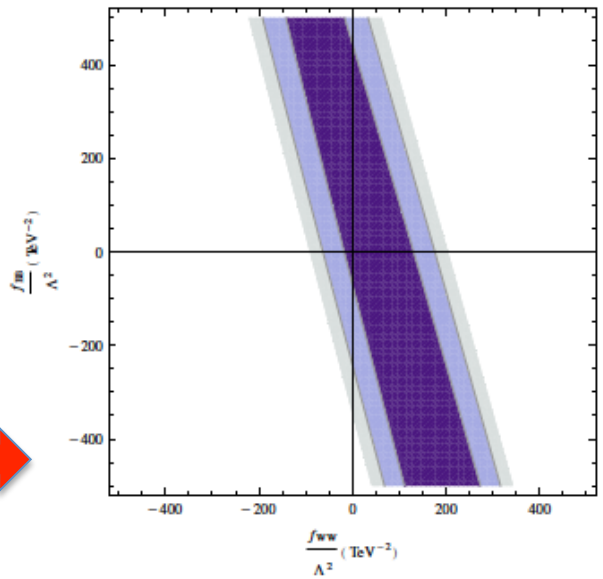
Old result [Hagiwara (1993)] but not appreciated until lately [Melbane, arXiv:1304.1789]

No Limits from Oblique Parameters



Leading logarithm

Complete renormalized result



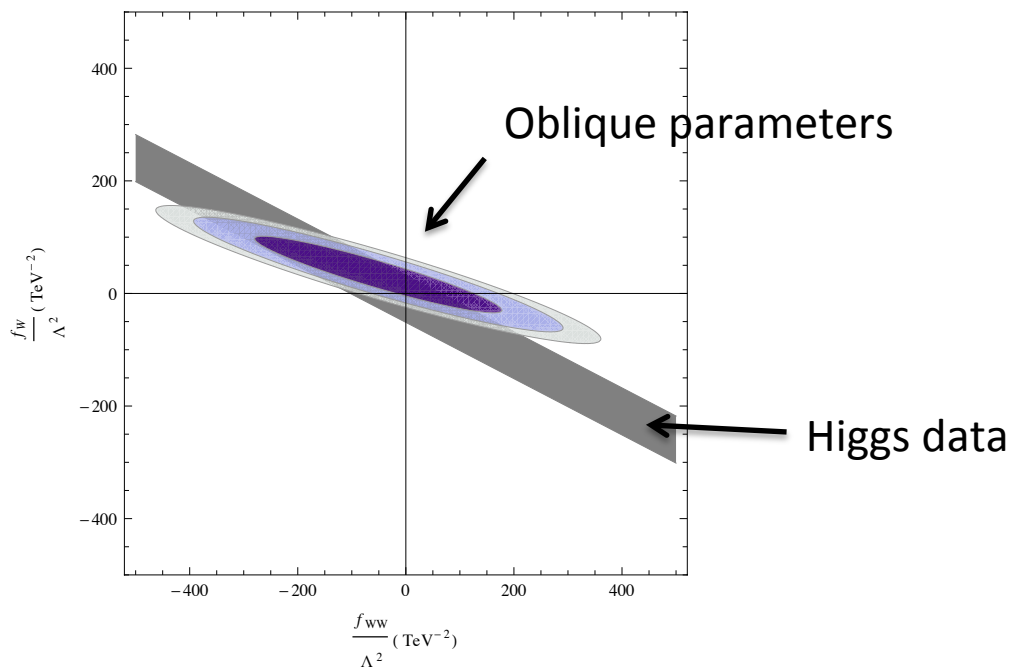
Hint: check scales

[Alam, Dawson, Szalapski,hep-ph/9706542]

[Chen, Dawson, Zhang, arXiv: 1311.3107]

One Interesting Case

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



In principle, complementary data from oblique parameters and Higgs data

Need Global fit for meaningful limits

- Fit to Higgs data + 3 gauge boson couplings:
- Sensitive to scales $\Lambda \sim 1$ TeV if $f \sim 1$
  - Loop contributions would give $f \sim 1/(16\pi^2)$
- Scale with $1/\sqrt{L}$ to 3000 fb $^{-1}$ then $\Lambda \sim 3$ TeV

	Best fit	90% CL allowed range
f_{WW}/Λ^2 (TeV^{-2})	1.5	[-3.2,8.2]
f_{BB}/Λ^2(TeV^{-2})	-1.6	[-7.5,5.3]
f_W/Λ^2(TeV^{-2})	2.1	[-5.6,9.6]
f_B/Λ^2(TeV^{-2})	-10	[-29,8.9]

[Gonzalez-Garcia at Higgs Couplings 2013; Brivio et al, arXiv: 1311.1823, Corbett, arXiv:1306.0006]

Conclusions

- Can we find new physics by precision measurements of Higgs couplings?
  - *To start, we have to get SM theory and PDFs under better control*
- I haven't found examples where lever arm gets you to multi-TeV scale BSM physics

  - However….. Predictions are always tricky

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 $\beta = v_2/v_1$, 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)

Decoupling Limit: Type II 2HDMs

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

Coupling shifts are typically small:

$$\delta\kappa_V = -\frac{2M_Z^4 \cot^2\beta}{M_A^4} \sim .1\% \left(\frac{600}{M_A}\right)^2$$

$$\delta\kappa_t = -\frac{2M_Z^2 \cot^2\beta}{M_A^2} \sim -5\% \cot^2\beta \left(\frac{600}{M_A}\right)^2$$

$$\delta\kappa_b = \frac{2M_Z^2}{M_A^2} \sim 5\% \left(\frac{600}{M_A}\right)^2$$

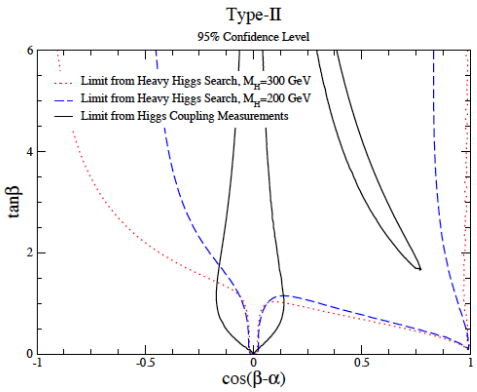
Target precision: $\delta\kappa < 5\%$

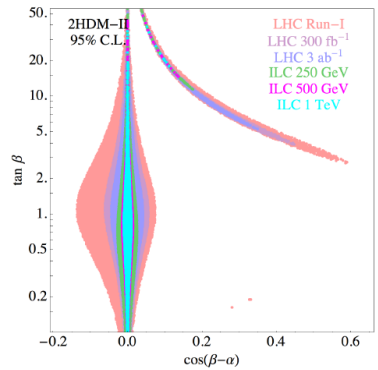
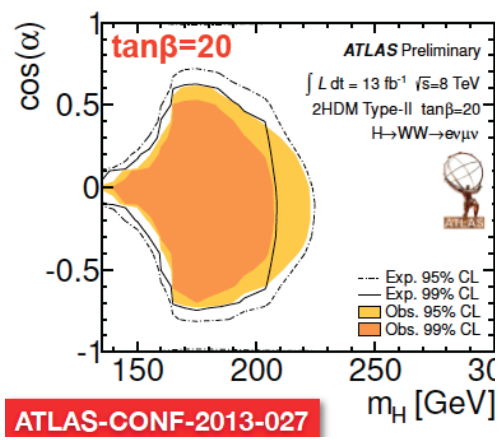
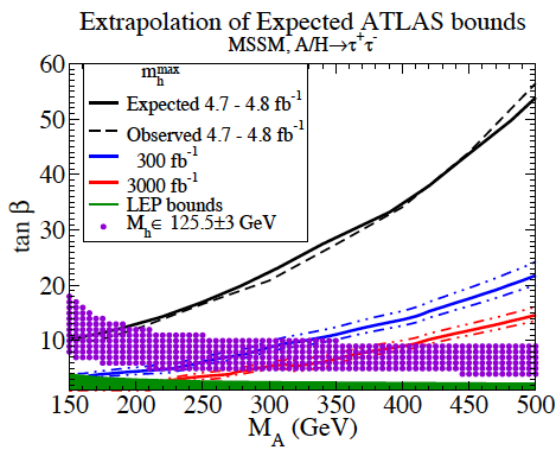
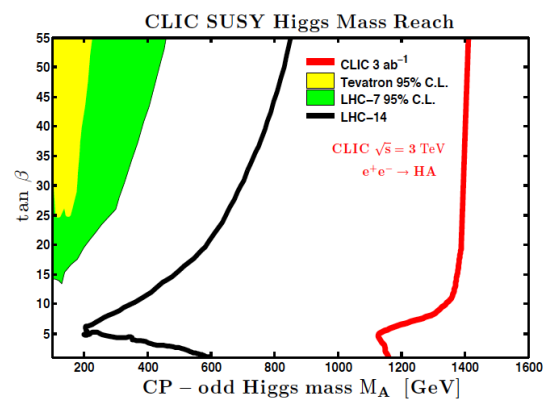
Coupling shifts depend on mass scale of new physics

Different models have different patterns of Higgs coupling shifts ➡ requires comprehensive set of measurements

Complementarity in 2HDMs

- Coupling fits vs direct search for H/A at LHC, e^+e^-, $\mu^+\mu^-$





Direct search at e^+e^- typically reaches $M \sim E_{CM}/2$