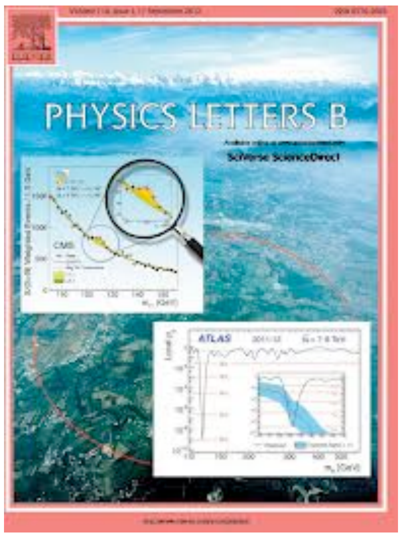
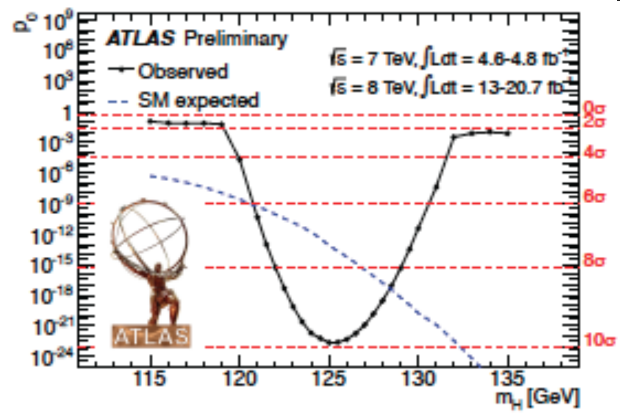
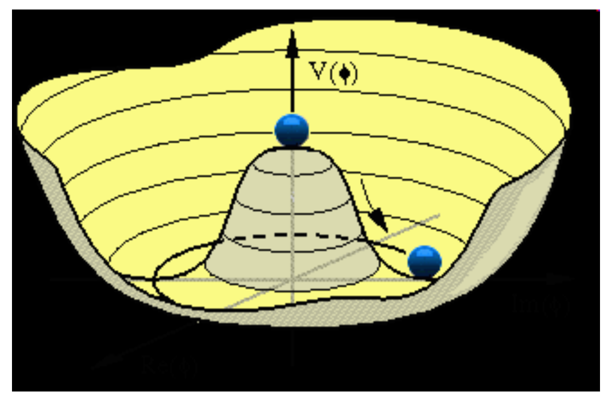
Why Higgs Couplings Matter



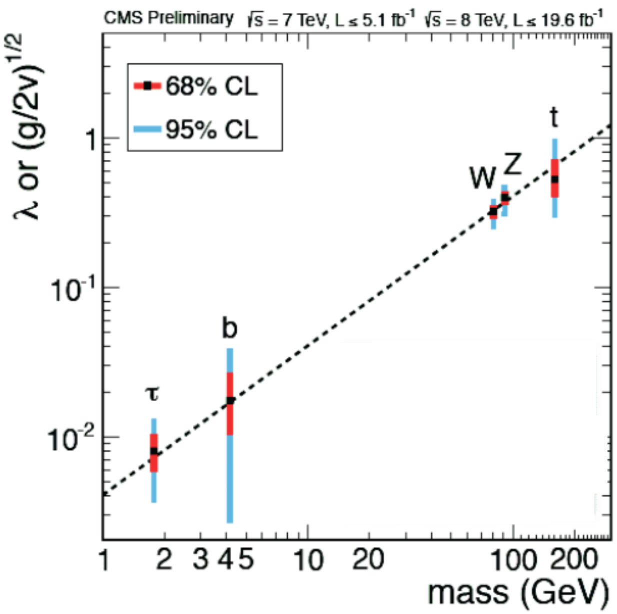
S. Dawson, BNL
March 7, 2014
Fermilab





All Higgs Couplings predicted in SM

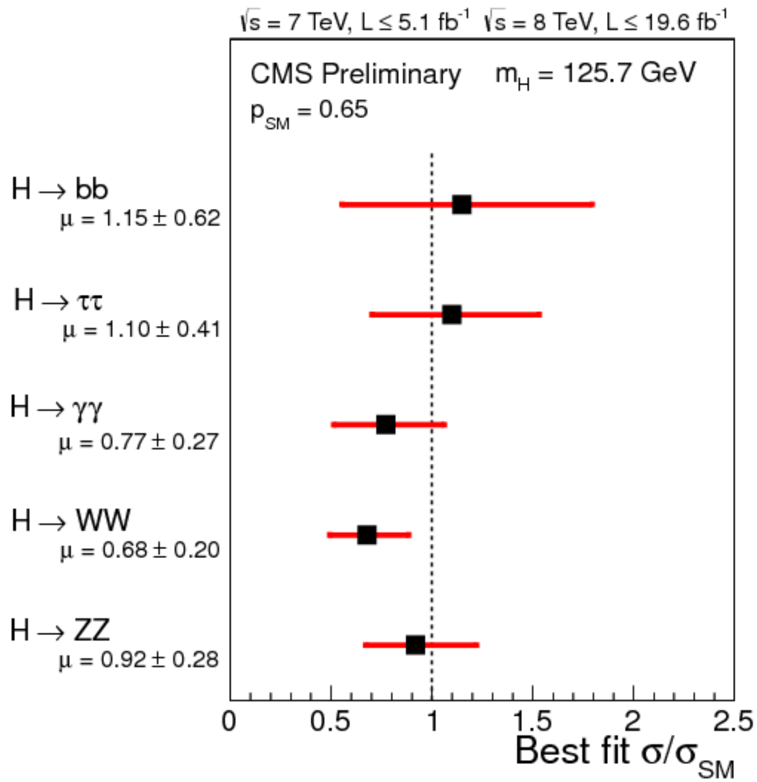
- Very precise predictions
  - Couplings to fermions proportional to mass
  - Couplings to gauge bosons proportional to gM_V
  - Higgs self-couplings proportional to M_H^2

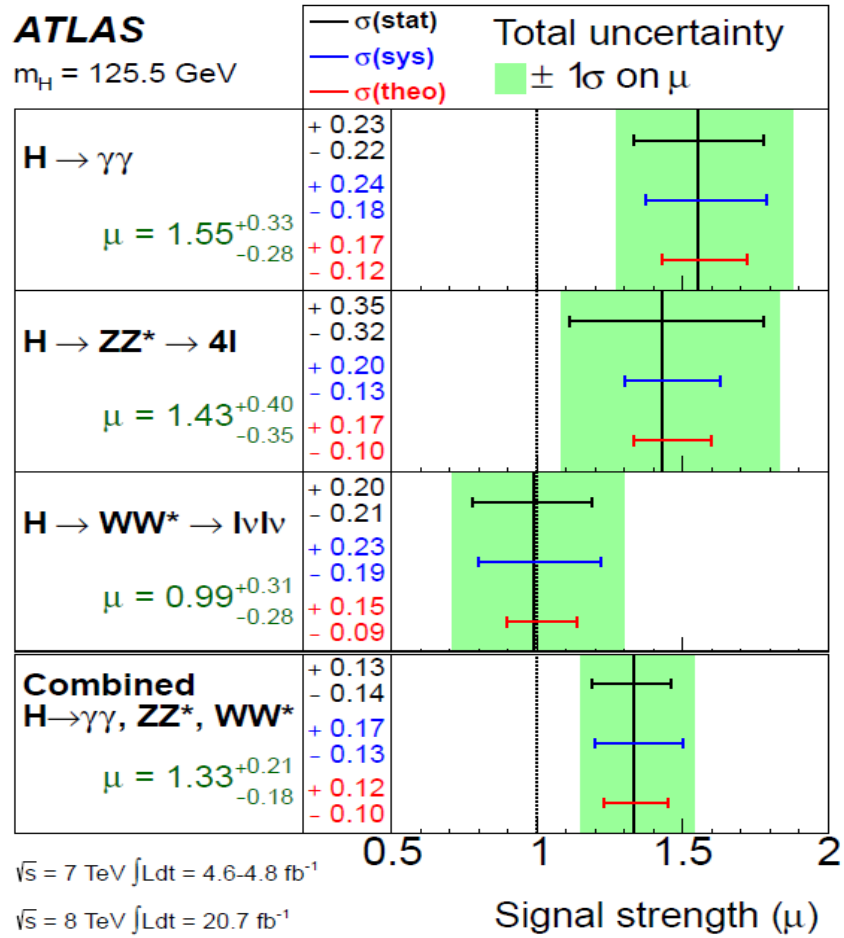


If couplings didn't have this pattern, it would indicate that not all mass comes from a single Higgs boson

*t coupling inferred from ggH top loop

Consistent with SM Hypothesis





Still room for new physics

Note theory uncertainties

The SM can't be complete

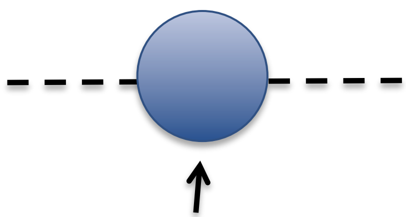
- It doesn't explain:
  - Neutrino masses
  - Dark matter
  - Baryon asymmetry
  - The pattern of fermion masses

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

Can Higgs couplings tell us something about new physics?

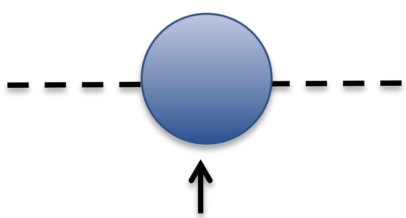
The Naturalness Connection

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



SM particles

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



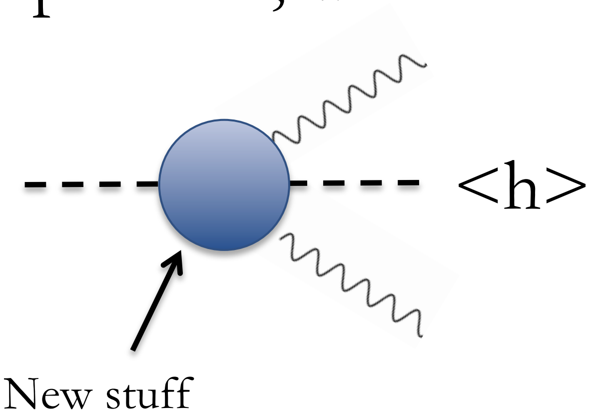
New stuff

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

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

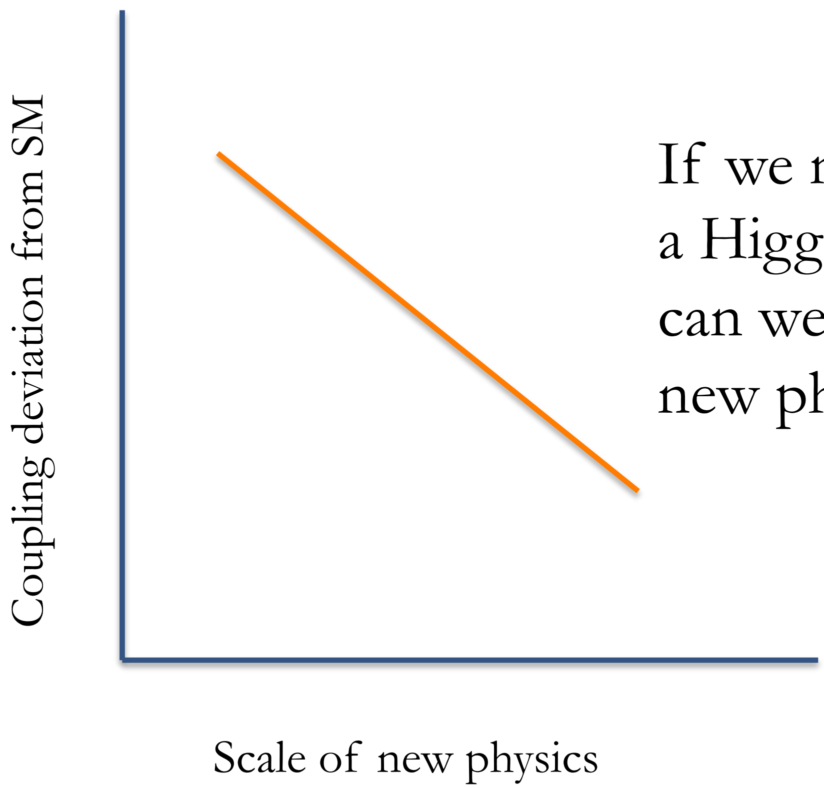


MSSM light stops generically contribute (no mixing):

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

$\boxed{\text{Target precision} < 3\%}$

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

We have to understand the SM first

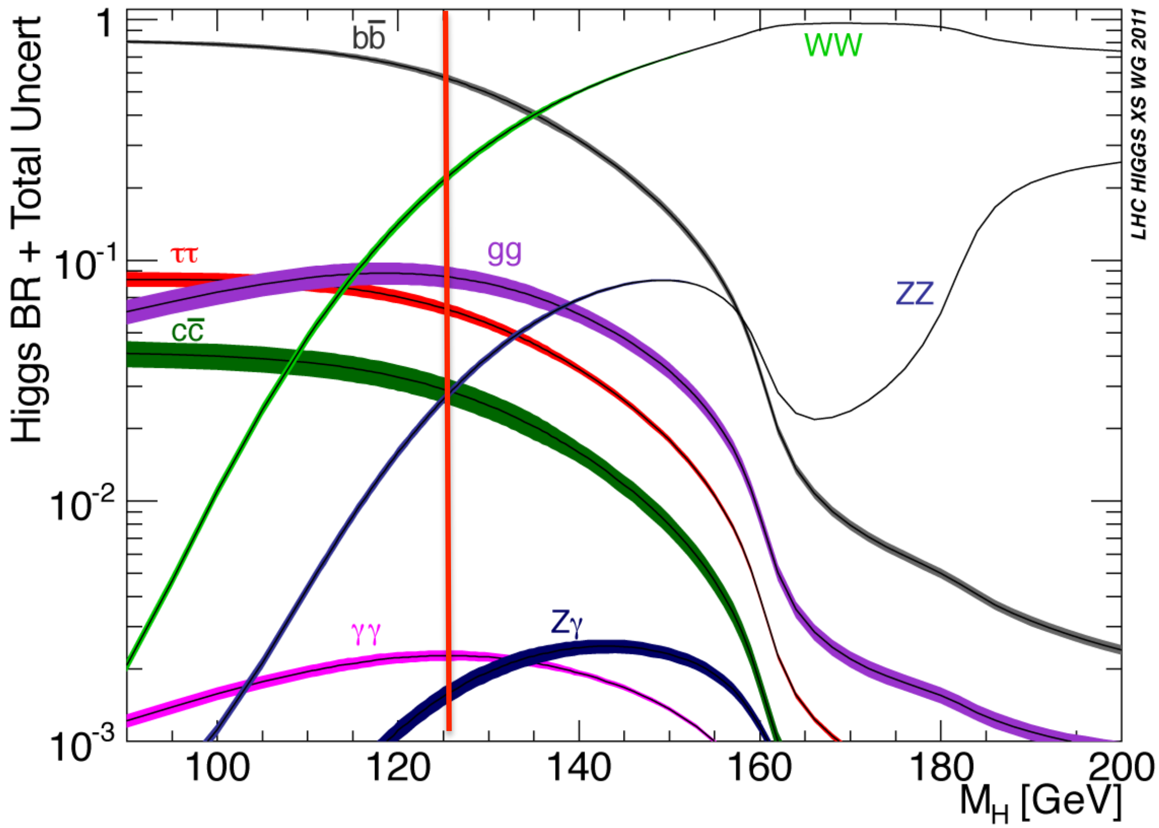
Precision Higgs Production

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%

Need to improve SM calculations and their inputs as we enter a new era of precision Higgs physics!

Theory Predictions of Branching Ratios



[LHC Higgs cross section working group]

Largest Higgs BR is to b's

- Sensitive to m_b: $$\boxed{\Gamma(H \to b\bar{b}) = \frac{G_\mu N_c}{4\sqrt{2}\pi} M_H \beta^3 m_b^2}$$
- QCD included to NNLO for H→bb predictions
- Calculate parametric uncertainties by varying m_t, m_c, m_b, α_s and finding maximum deviation from central value
- Add parametric uncertainties in quadrature

Input values for Higgs BR fits

Parameter	Central Value	Uncertainty
$\alpha_s(M_Z)$	0.119	±0.002 (90% CL)
m_c	1.42 GeV	±0.03 GeV
m_b	4.49 GeV	±0.06 GeV
m_t	172.5 GeV	±2.5 GeV

Need to reduce uncertainty on m_b, α_s

M_b is pole mass calculated with 1 loop running of $m_b(m_b)$=4.16 GeV

Uncertainties on Partial Widths

	Γ(MeV)	$\Delta\alpha_s$	Δm_b	Δm_c	Theory
$H \rightarrow bb$	2.36	-2.3%	+3.3%	0	+2%
		+2.3%	-3.2%	0	-2%
$H \rightarrow \tau\tau$	.259	0	0	0	+2%
		0	0	0	-2%
$H \rightarrow W^+W^-$	.973	0	0	0	+.5%
		0	0	0	-.5%

- Parametric and theory errors roughly the same size and added linearly
- Theory uncertainties mostly from estimate of missing 2-loop EW corrections

Errors in BRs are correlated

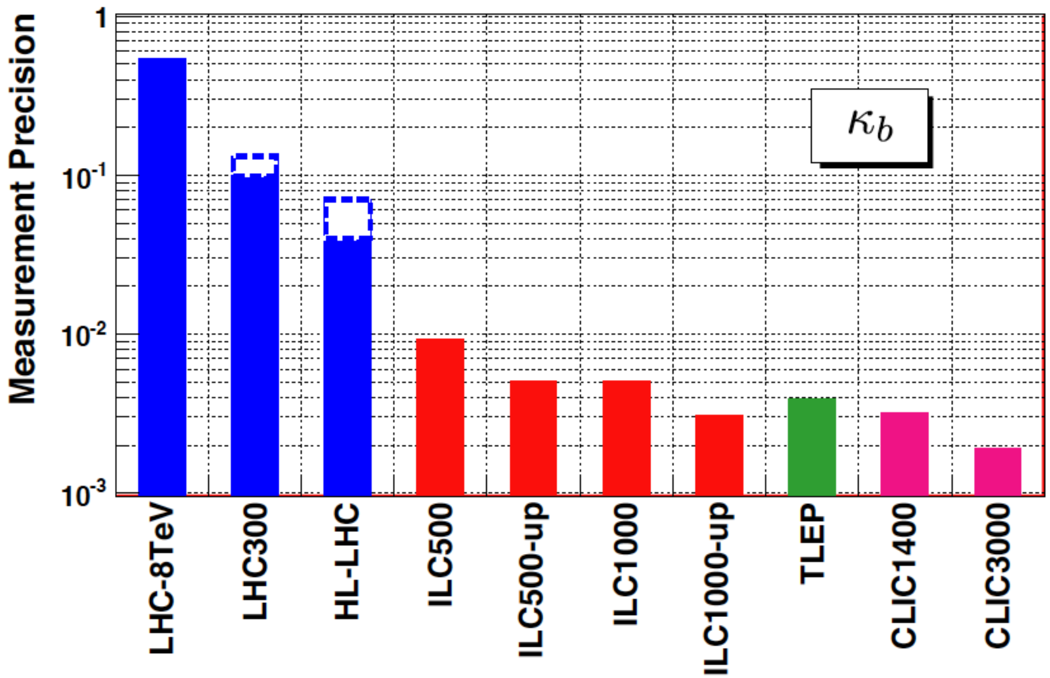
- Total width found by adding all observed BRs

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

Higgs cross section working group

Projections for Future Colliders

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



Percent level measurements need theory at the same level

κ_b is ratio of b-Higgs coupling to SM value

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

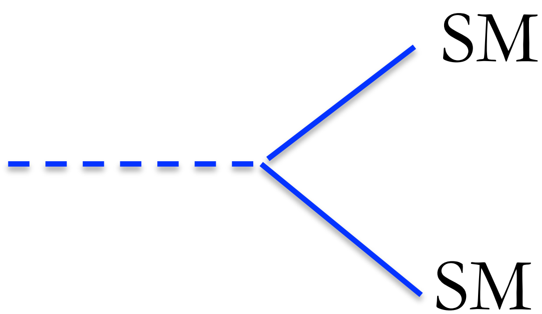
0th order answer: We found a new particle which we hypothesize is the quanta of EWSB. We want to measure couplings as precisely as possible

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 $\Delta/5$

Example: 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

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 ($S/\sqrt{B}\sim5$)
  - To see new physics (without observing H) need $(\sin\theta)^2 < .12$

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

[Gupta, Rzehak, Wells, arXiv:1206.3560]

Example: Type II 2HDMs

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

Coupling shifts are typically small:

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

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

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

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

* Large effects require small tan β, which is excluded by B physics

Some Possibilities

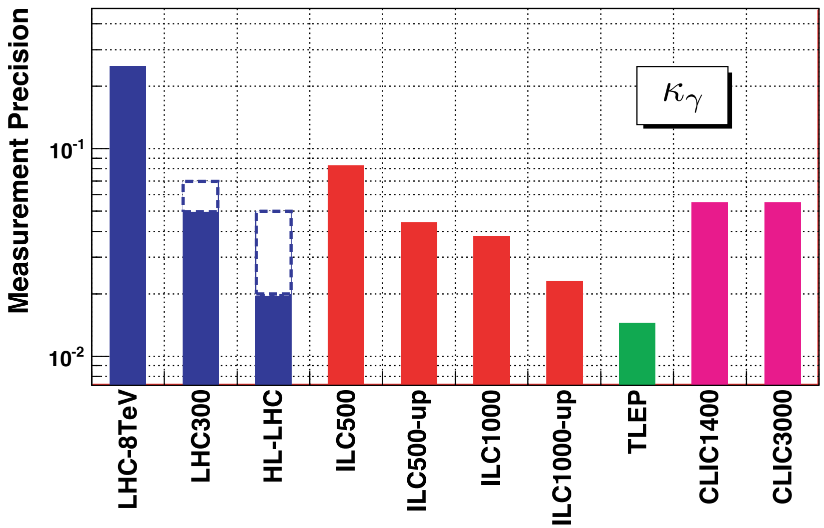
- Assume new physics (M) is at 1 TeV:
  - Generic effects on Higgs couplings $\delta\kappa \sim (M_Z/M)^2$
  - The pattern of deviations is what pinpoints new physics

Model	$\delta\kappa_W$, $\delta\kappa_Z$	$\delta\kappa_b$	$\delta\kappa_\gamma$
Singlet Mixing	~-6%	~-6%	~-6%
Decoupling MSSM	~-.01%	~-2%	-.4%
Composite	~-3%	-(3-9)%	-9%
Top partner	~-2%	~-2%	~1%

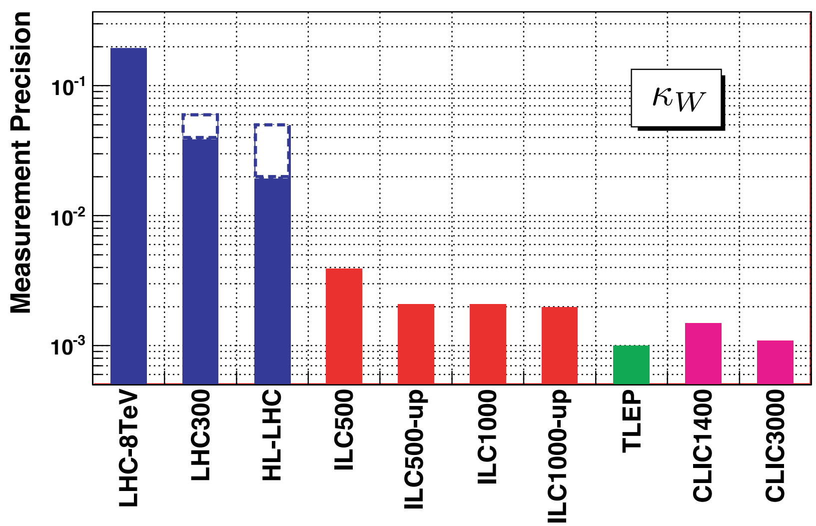
Largest deviations typically in b couplings

Conclusions

- Can we find new physics by precision measurements of Higgs couplings?
  - To start, we have to get SM theory under better control
- Future e^+e^- measurements will require theory improvements
  - Lattice measurements of m_b and α_s important ingredient



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



κ_W
Measurement Precision
10^{-1}
10^{-2}
10^{-3}
LHC-8TeV
LHC300
HL-LHC
ILC500
ILC500-up
ILC1000
ILC1000-up
TLEP
CLIC1400
CLIC3000