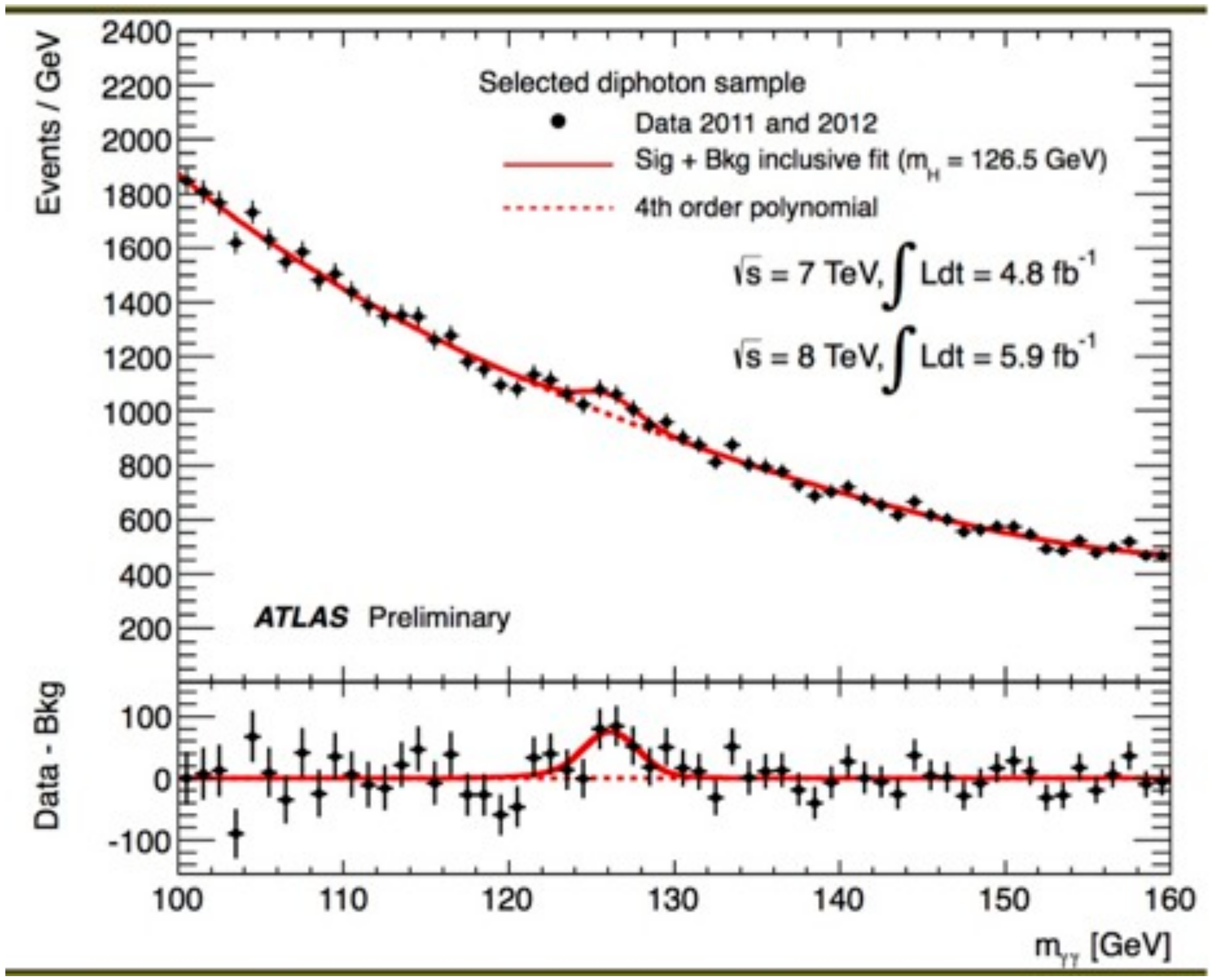
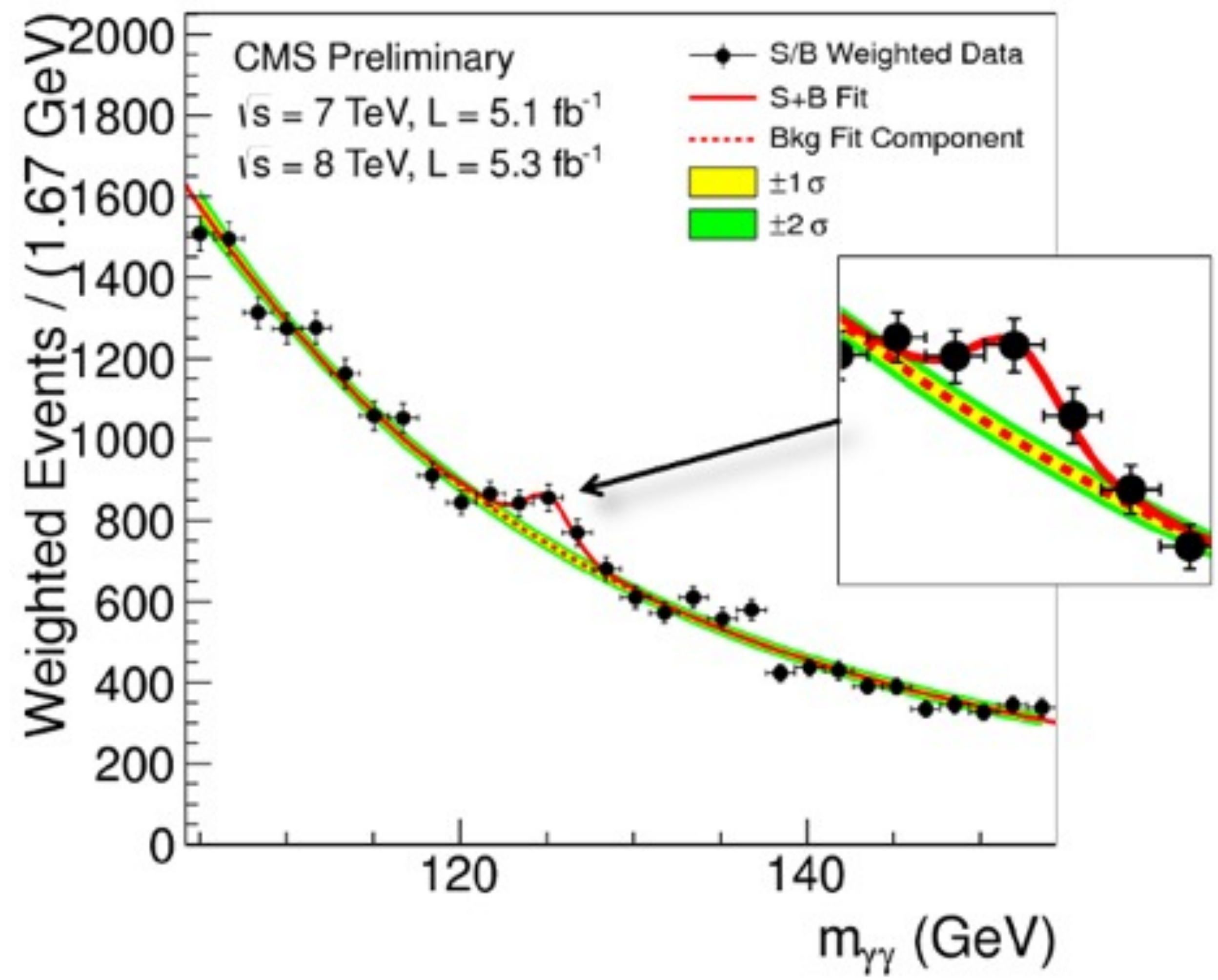
Implications of the `Higgs' discovery

Frank Petriello

ANL Higgs Retreat
October 5, 2012

You've all seen the following plots numerous times since July 4...





What comes next after discovery?

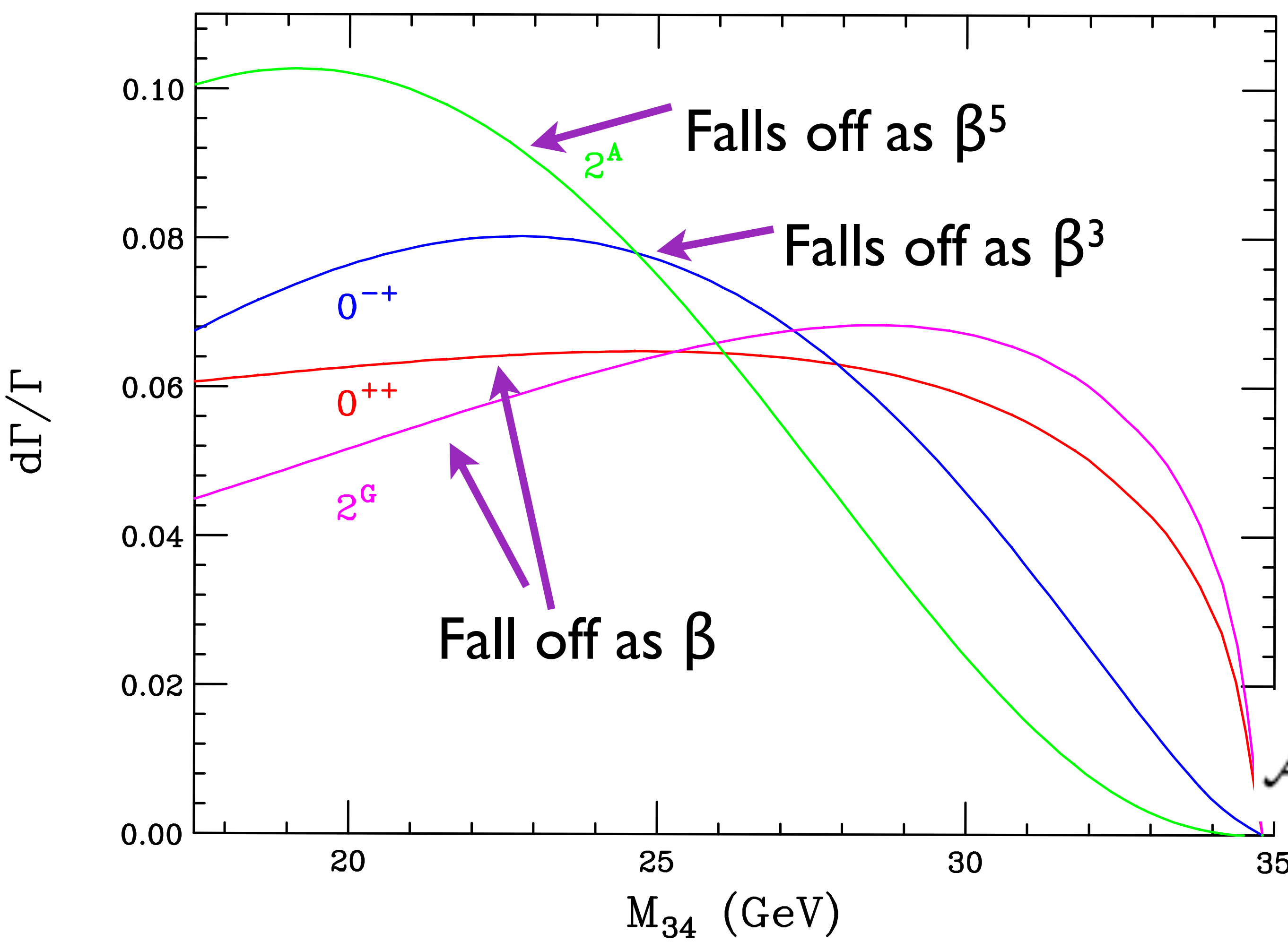
Outline

- Establishing the basic properties: spin and CP, is it a an EW-symmetry breaking scalar? SU(2) representation?
- What are the couplings? How well do we want to know them, and how do we get there?
- How well do we want to know the couplings?
- What future measurements should we do?

This will be a retreat-style talk: informal (i.e., quickly prepared at the last second), and meant to provoke discussion

Spin and CP

- Several ways to do this: single-variable measurements, multi-variate methods
- One way we've worked on here Boughezal, LeCompte, FP 1208.4311



- Consider an initial study of ATLAS+CMS events consistent with ZZ^* production:

$$\mathcal{A}_{26}^{sig+back}(0^{++}) = -0.060, \quad \mathcal{A}_{26}^{sig+back}(2^A) = -0.31$$

A_{26}(data) = 0±0.28

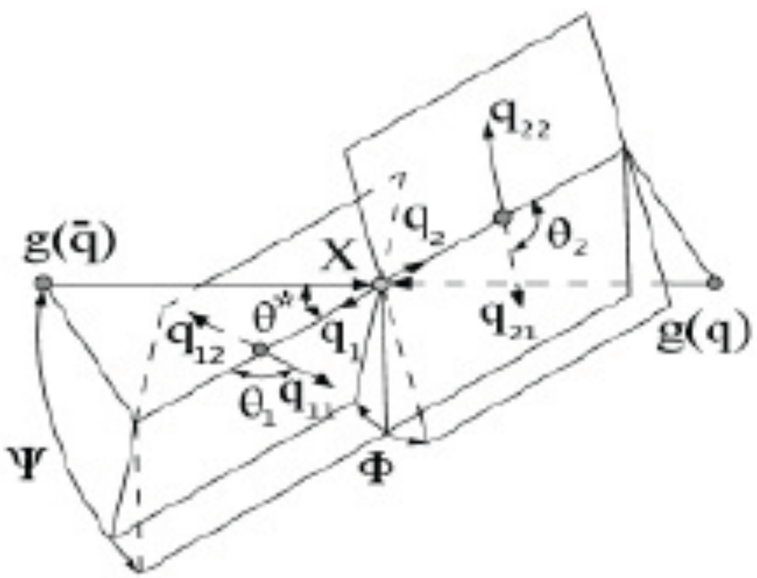
$$\mathcal{A}_{28}^{sig+back}(0^{++}) = -0.31, \quad \mathcal{A}_{28}^{sig+back}(0^{-+}) = -0.44$$

A_{28}(data) = -0.40±0.27

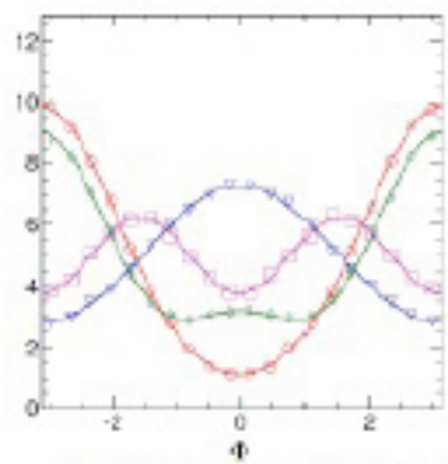
$$\mathcal{A}_{M_{cut}} = \frac{N(M_{34} > M_{cut}) - N(M_{34} < M_{cut})}{N(M_{34} > M_{cut}) + N(M_{34} < M_{cut})}$$

Spin and CP

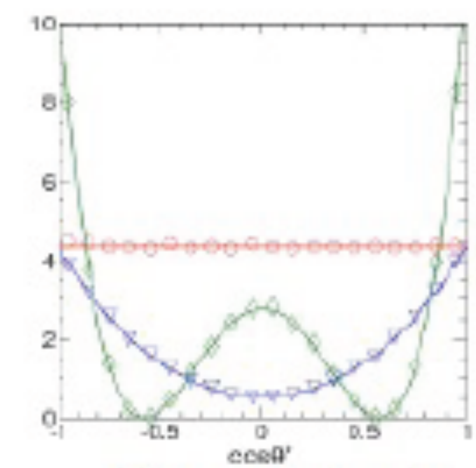
- MELA (matrix-element likelihood analysis): combine kinematic differences in multiple distributions into a single discriminant



Gritsan, Melnikov, Schulze et al., 1001.3396



different spin 0 and 2 hypothessi in $X \to WW$



different spin 0 and 2 hypothessi in $X \to \gamma\gamma$

Expected separation significance (Gaussian σ) for 35 fb^{-1} integrated luminosity at the 8 TeV LHC

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$	combined
0_m^+ vs background	7.1	4.5	5.2	9.9
0_m^+ vs 0^-	4.1	1.1	0.0	4.2
0_m^+ vs 2_m^+	1.6	2.5	2.5	3.9

- These properties will be soon established (probably a reasonable picture by the end of the 2012 run)

EW symmetry breaking

- Let's assume a spin-0, CP-even scalar. Next need to know, is it associated with EW symmetry breaking (does it have a vev)?

$$A(X \to V_1 V_2) = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

a Higgs gives this term ($g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^*$)

Scalar without a vev would gives only this term ($g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}$)

MELA analysis:

Bolognesi et al., 1208.4018

scenario	$X \to ZZ$	$X \to WW$	$X \to \gamma\gamma$
0_m^+ vs background	5.0	5.0	5.0
0_m^+ vs 0_h^+	1.8	1.1	0.0
0_m^+ vs 0^-	2.9	1.2	0.0
0_m^+ vs 1^+	2.1	2.0	–
0_m^+ vs 1^-	2.8	3.2	–
0_m^+ vs 2_m^+	1.1	2.8	2.4
0_m^+ vs 2_h^+	∼5	1.1	3.1
0_m^+ vs 2_h^-	∼5	2.5	3.1

This will take a while to determine on kinematics alone

EW symmetry breaking

- Let's assume a spin-0, CP-even scalar. Next need to know, is it associated with EW symmetry breaking (does it have a vev)?

$$A(X \to V_1 V_2) = v^{-1}\left(g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^* + g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + g_3^{(0)} f^{*(1),\mu\nu} f_{\mu\alpha}^{*(2)} \frac{q_\nu q^\alpha}{\Lambda^2} + g_4^{(0)} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu}\right)$$

a Higgs gives this term → ($g_1^{(0)} m_V^2 \epsilon_1^* \epsilon_2^*$)

Scalar without a vev would gives only this term → ($g_2^{(0)} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu}$)

Another argument:

$$\begin{aligned}\mathcal{L}_{sV_1V_2} = {} & \kappa_W \frac{\alpha}{8\pi m_s s_w^2} s\, W_{\mu\nu}^+ W^{-\mu\nu} + \left(\kappa_W \frac{c_w^2}{s_w^2} + \kappa_B \frac{s_w^2}{c_w^2}\right) \frac{\alpha}{16\pi m_s} s\, Z_{\mu\nu} Z^{\mu\nu} \\ & + \kappa_g \frac{\alpha_s}{16\pi m_s} s\, G_{\mu\nu}^a G^{a\,\mu\nu} + (\kappa_W + \kappa_B) \frac{\alpha}{16\pi m_s} s\, F_{\mu\nu} F^{\mu\nu} \\ & + \left(\kappa_W \frac{c_w}{s_w} - \kappa_B \frac{s_w}{c_w}\right) \frac{\alpha}{8\pi m_s} s\, F_{\mu\nu} Z^{\mu\nu},\end{aligned}$$

- Best fit: $k_W/k_B \sim -1$, γZ/ZZ decay ratio predicted to be 500
- No γZ resonance signal disfavors such a scalar

Low, Lykken, Shaughnessy 1207.1093

SU(2) quantum numbers

- Ratio of W over Z branching ratios sensitive to the representation of the scalar (doublet, triplet)

$$\lambda_{WZ} = \kappa_W / \kappa_Z$$

deviation from SM W coupling

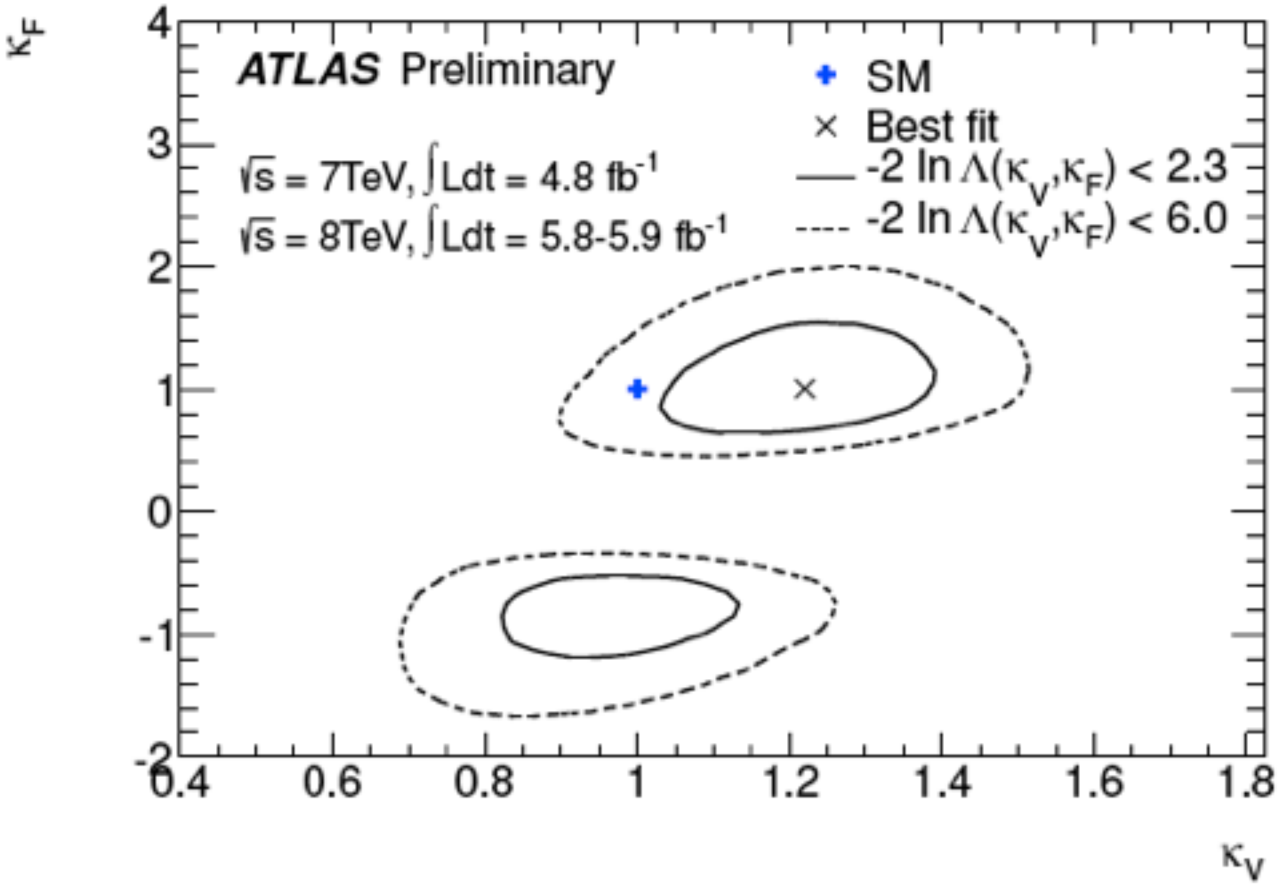
deviation from SM W coupling

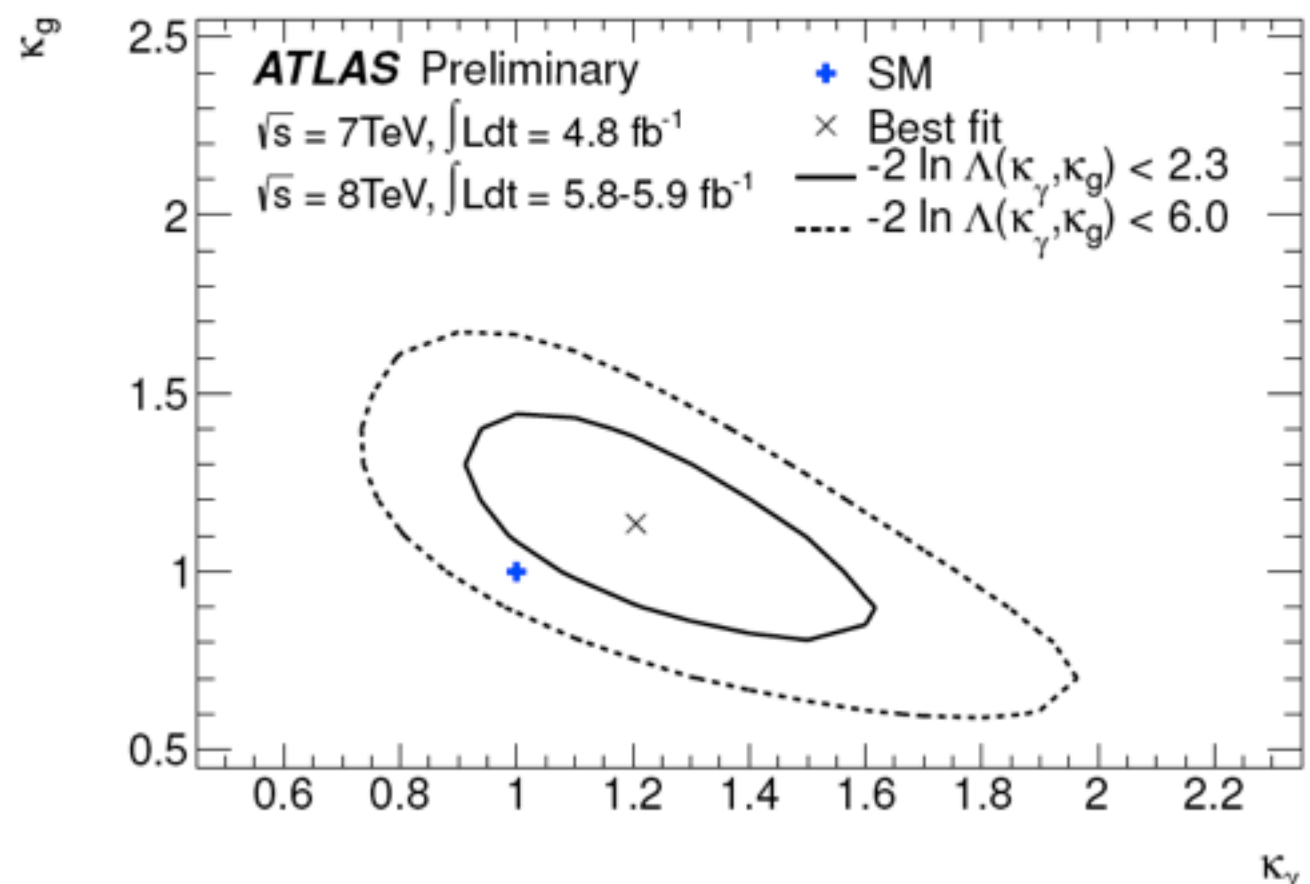
$\lambda_{WZ} = 1.07^{+0.35}_{-0.27}$ ⇒factor of 2 for a real triplet scalar

- Let's assume a CP-even, spin-0 doublet associated with EW symmetry breaking

Higgs couplings

- Are the couplings those of SM Higgs, or are there deviations?





$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau$$
$$\kappa_V = \kappa_W = \kappa_Z$$

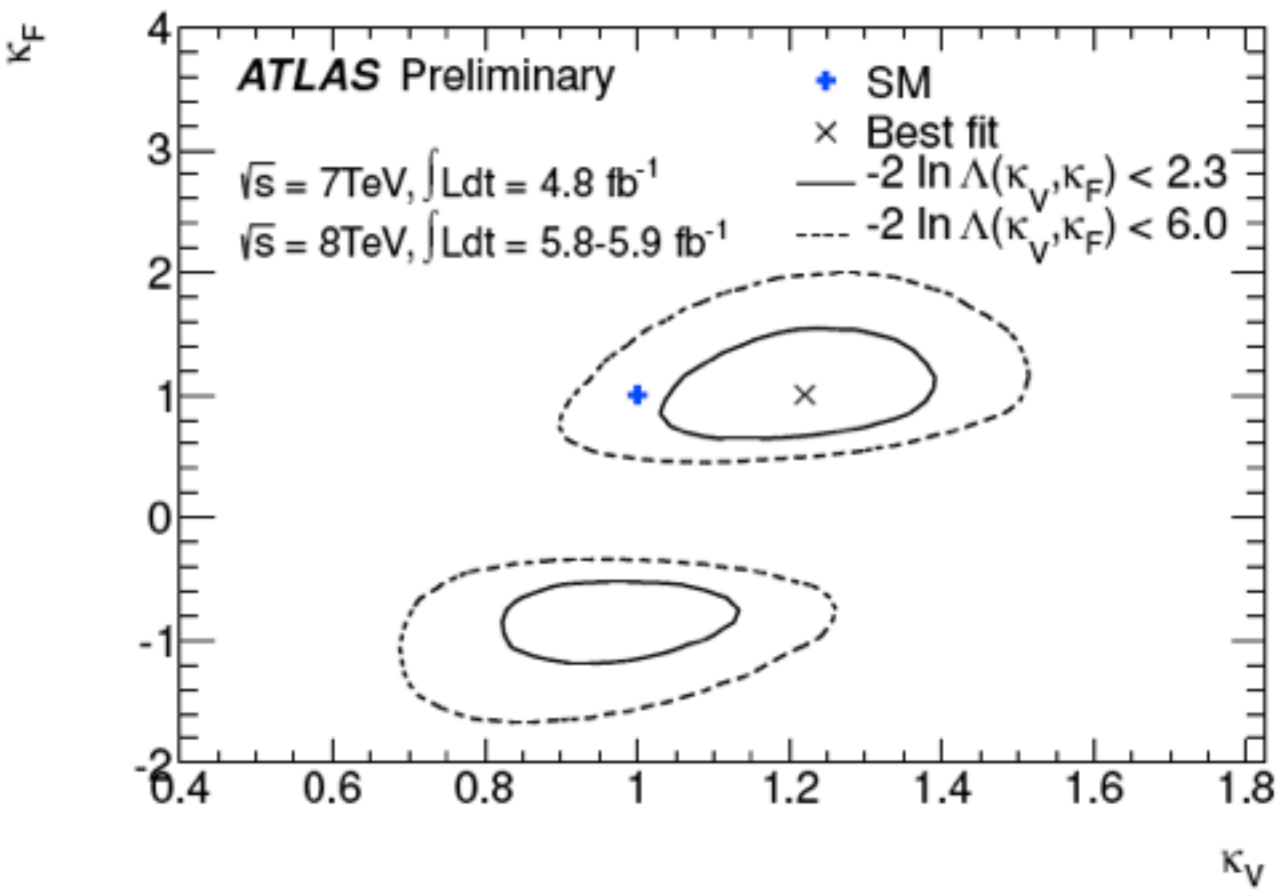
total width fixed to SM

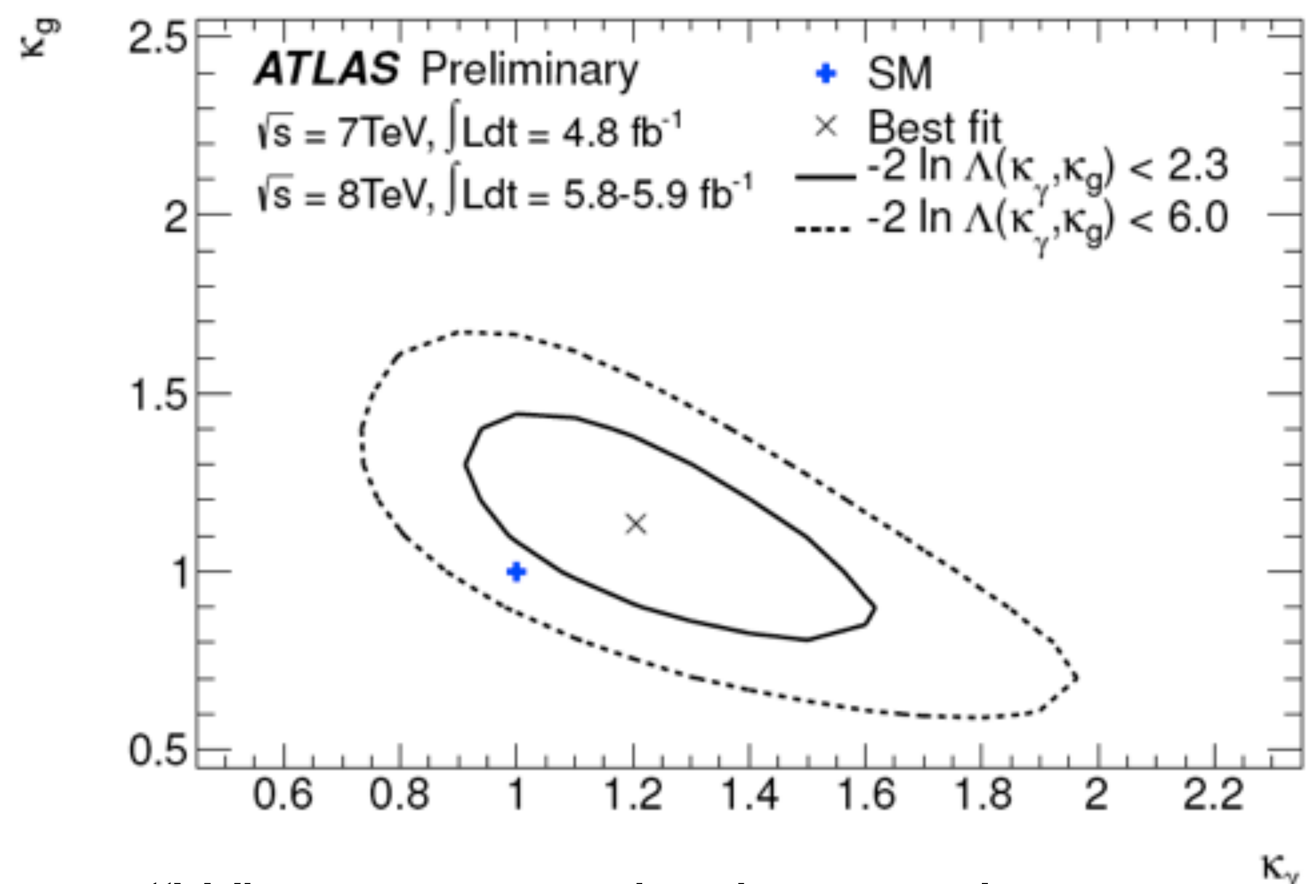
$$\kappa_g = 1.1^{+0.2}_{-0.3}$$
$$\kappa_\gamma = 1.2^{+0.3}_{-0.2}$$

- No deviations seen yet from the SM

Higgs couplings

- Are the couplings those of SM Higgs, or are there deviations?



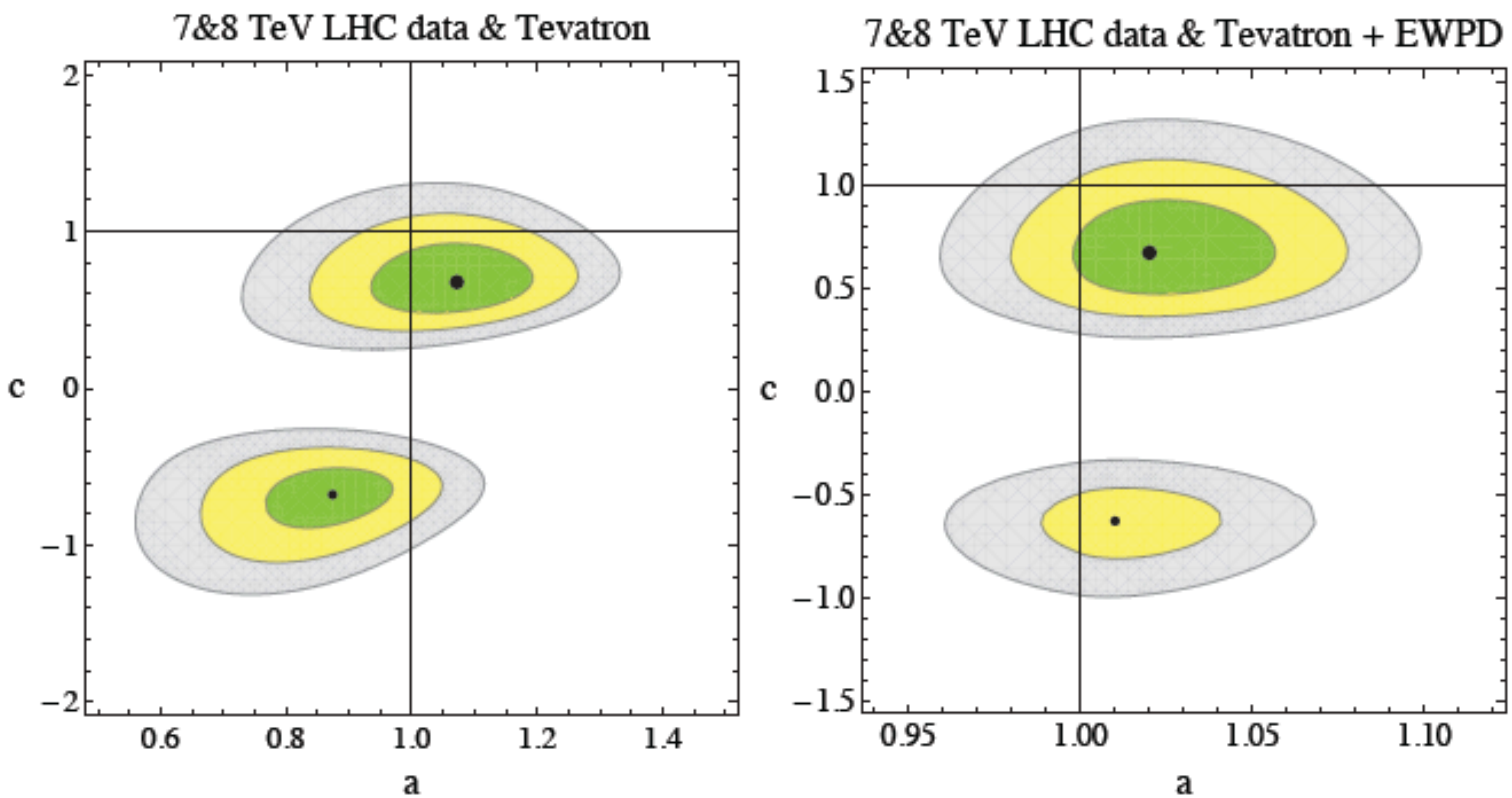


"The confidence intervals on k_V and k_F are reduced by approximately 20% when removing all theoretical systematic uncertainties"

"When removing the theoretical systematic uncertainties on the measurements of k_g and k_γ, the uncertainty is reduced by O(15%)"

Will this be a limiting factor in the future? What is driving this? Is it just the gluon-fusion rate? From an ATLAS experimenter: "The unsatisfying answer is that I am not sure."

With EW precision data



Espinosa et al., 1207.1717

$$\mathcal{L}_{eff} = \frac{1}{2}(\partial_\mu h)^2 - V(h) + \frac{v^2}{4}\mathrm{Tr}(D_\mu \Sigma^\dagger D^\mu \Sigma)\left[1 + 2\,a\,\frac{h}{v} + b\,\frac{h^2}{v^2} + b_3\,\frac{h^3}{v^3} + \cdots\right],$$

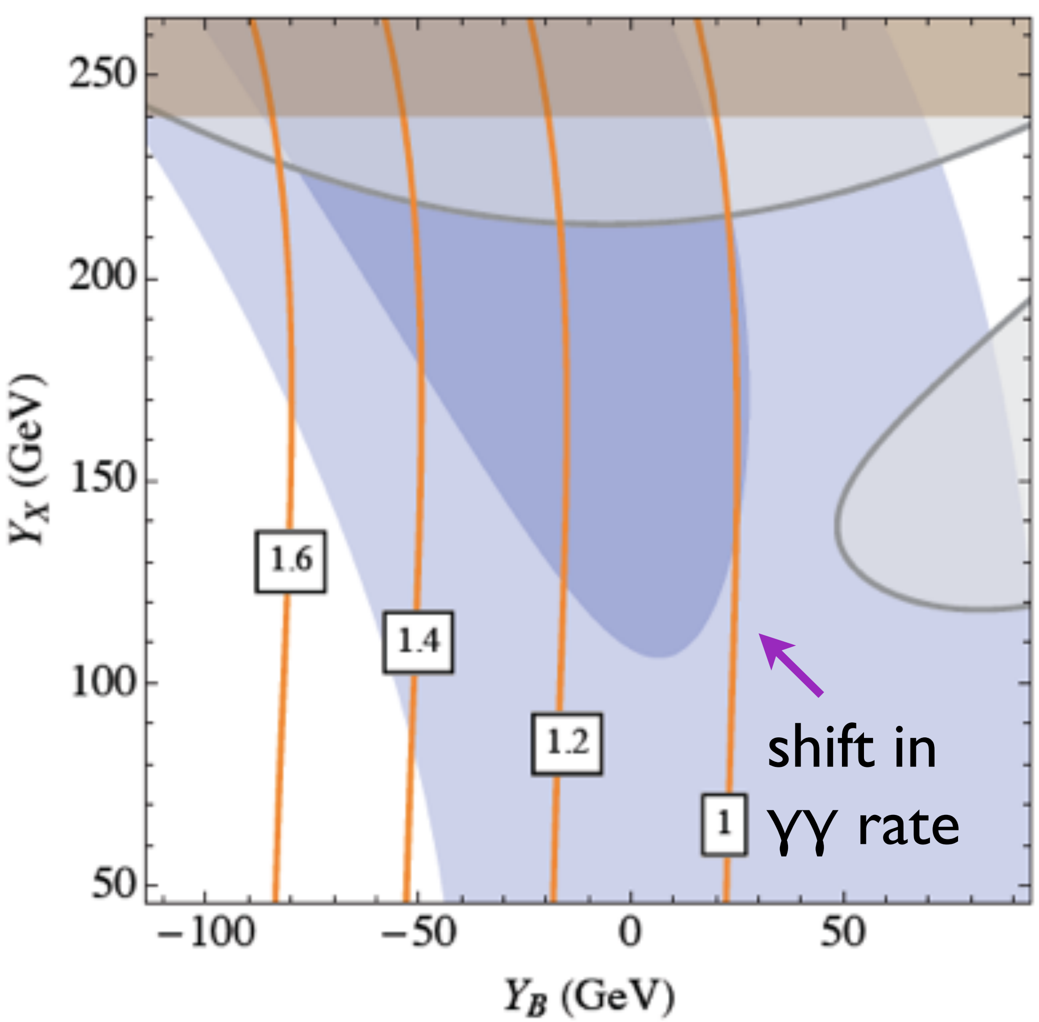
$$-\frac{v}{\sqrt{2}}(\bar{u}_L^i \bar{d}_L^i)\,\Sigma\left[1 + c_j\,\frac{h}{v} + c_2\,\frac{h^2}{v^2} + \cdots\right]\begin{pmatrix} y_{ij}^u\, u_R^j \\ y_{ij}^d\, d_R^j \end{pmatrix} + h.c. \cdots,$$

$$\Delta S \approx \frac{-(1-a^2)}{6\,\pi}\log\left(\frac{m_h}{\Lambda}\right), \qquad \Delta T \approx \frac{3(1-a^2)}{8\,\pi\,\cos^2\theta_W}\log\left(\frac{m_h}{\Lambda}\right)$$

- strong preference for a~1 from S,T parameters

How much is enough?

- This begins to get at the question, how precisely do we want to measure these couplings?
- Besides "as well as possible," can answer in two ways
- In motivated models, what deviations are expected in parameter-space regions that agree with EW data?

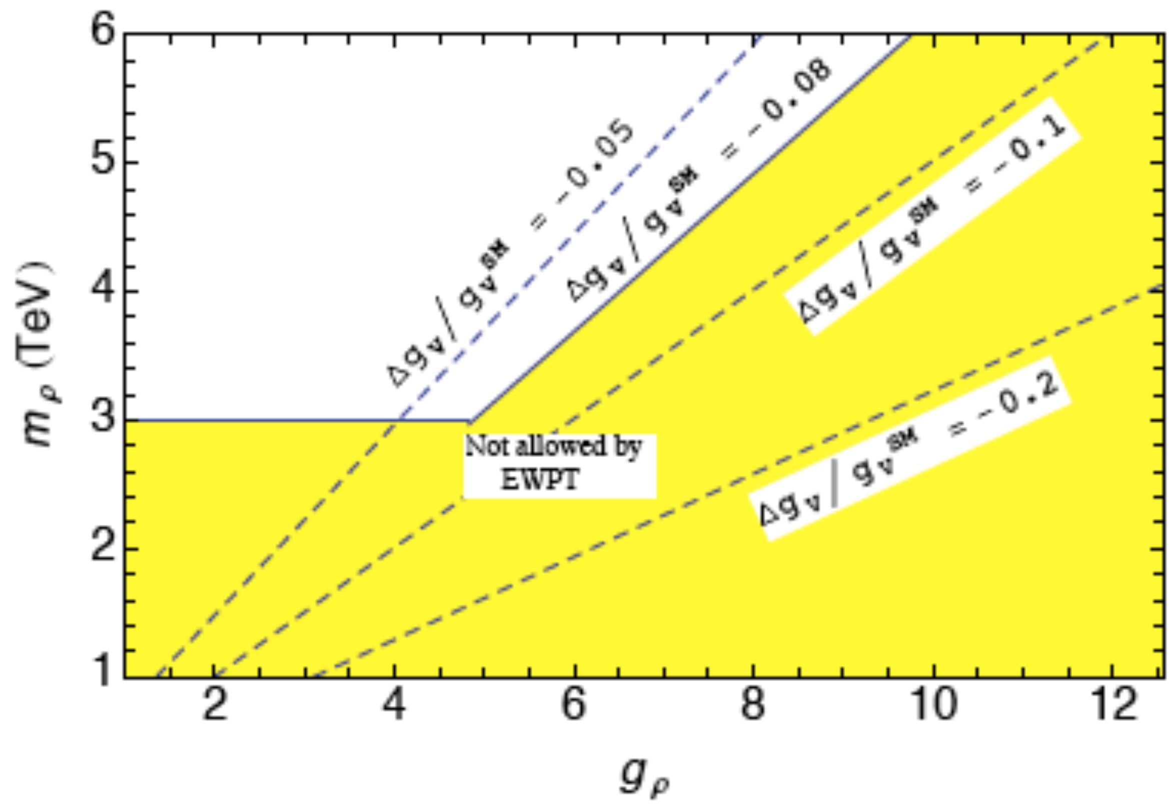


- Model with vector-like fermions to explain A_{FB} (Batell, Gori, Wang 1209.6382)

- Note: $\Gamma \sim g^2$, $\delta\Gamma/\Gamma \sim 2\delta g/g$, so 30% in rate corresponds to 15% in coupling

How much is enough?

- More detailed analysis of exactly this point in Gupta et al., 1206.3560



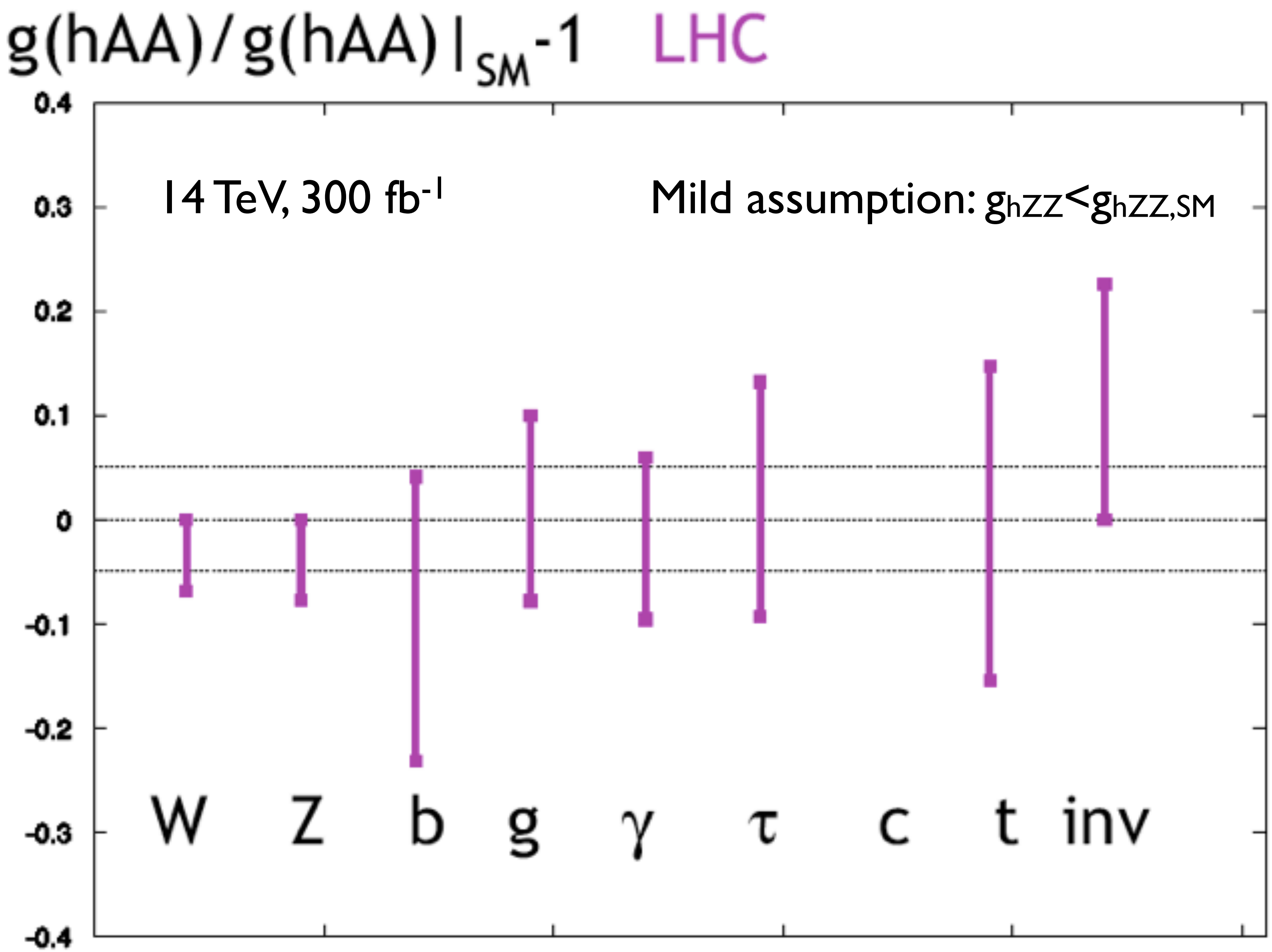
Composite Higgs models

	ΔhVV	$\Delta h\bar{t}t$	Δhbb
Mixed-in Singlet	6%	6%	6%
Composite Higgs	8%	tens of %	tens of %
Minimal Supersymmetry	< 1%	3%	10%[a], 100%[b]
LHC 14 TeV, 3 ab^{-1}	8%	10%	15%

- LHC misses the target precision for bb, tt couplings

- Message (probably a gross oversimplification): while some models deviate by up to 15-20%, a 5% measurement of couplings is required to start eating into parameter space of all models

LHC capabilities



Peskin, 1207.2516

- Peskin's horizontal lines define a 5% target; b, t, c miss badly, g and tau miss somewhat. Experimental error largest for b, t but theory not negligible; mix of theory, experiment for tau

LHC capabilities

In more detail:

Observable	Expected Error (experiment $\oplus$ theory)
LHC at 14 TeV with 300 fb^{-1}	
$\sigma(gg) \cdot BR(\gamma\gamma)$	$0.06 \oplus 0.13$
$\sigma(WW) \cdot BR(\gamma\gamma)$	$0.15 \oplus 0.10$
$\sigma(gg) \cdot BR(ZZ)$	$0.08 \oplus 0.08$
$\sigma(gg) \cdot BR(WW)$	$0.09 \oplus 0.11$
$\sigma(WW) \cdot BR(WW)$	$0.27 \oplus 0.10$
$\sigma(gg) \cdot BR(\tau^+\tau^-)$	$0.11 \oplus 0.13$
$\sigma(WW) \cdot BR(\tau^+\tau^-)$	$0.15 \oplus 0.10$
$\sigma(Wh) \cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(Wh) \cdot BR(\gamma\gamma)$	$0.24 \oplus 0.10$
$\sigma(Zh) \cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(Zh) \cdot BR(\gamma\gamma)$	$0.24 \oplus 0.10$
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	$0.25 \oplus 0.20$
$\sigma(t\bar{t}h) \cdot BR(\gamma\gamma)$	$0.42 \oplus 0.10$
$\sigma(WW) \cdot BR(\text{invisible})$	$0.2 \oplus 0.24$

Table 1: Input data for the fits to Higgs couplings from LHC measurements.

Experimental errors larger; Wh, Zh, tth largest theory errors

Theory improvements

- Would first be good to confirm what exactly is driving the error in the current ATLAS fit. The collaborations should strive to understand and make this information available
- N^3LO inclusive cross section calculation might be feasible (5 years?), efforts underway. PDFs will improve.
- Not clear what the prospect for reducing uncertainties from dividing into jet bins; an area of active study

Summary

- LHC will do a remarkable job of measuring the couplings down to the interesting level
- IMHO, the primary problem is the poor precision on the htt coupling; top is heaviest fundamental particle, a very likely place for deviation to occur. How well can this coupling be measured at an energy-upgraded LHC?

Future linear colliders

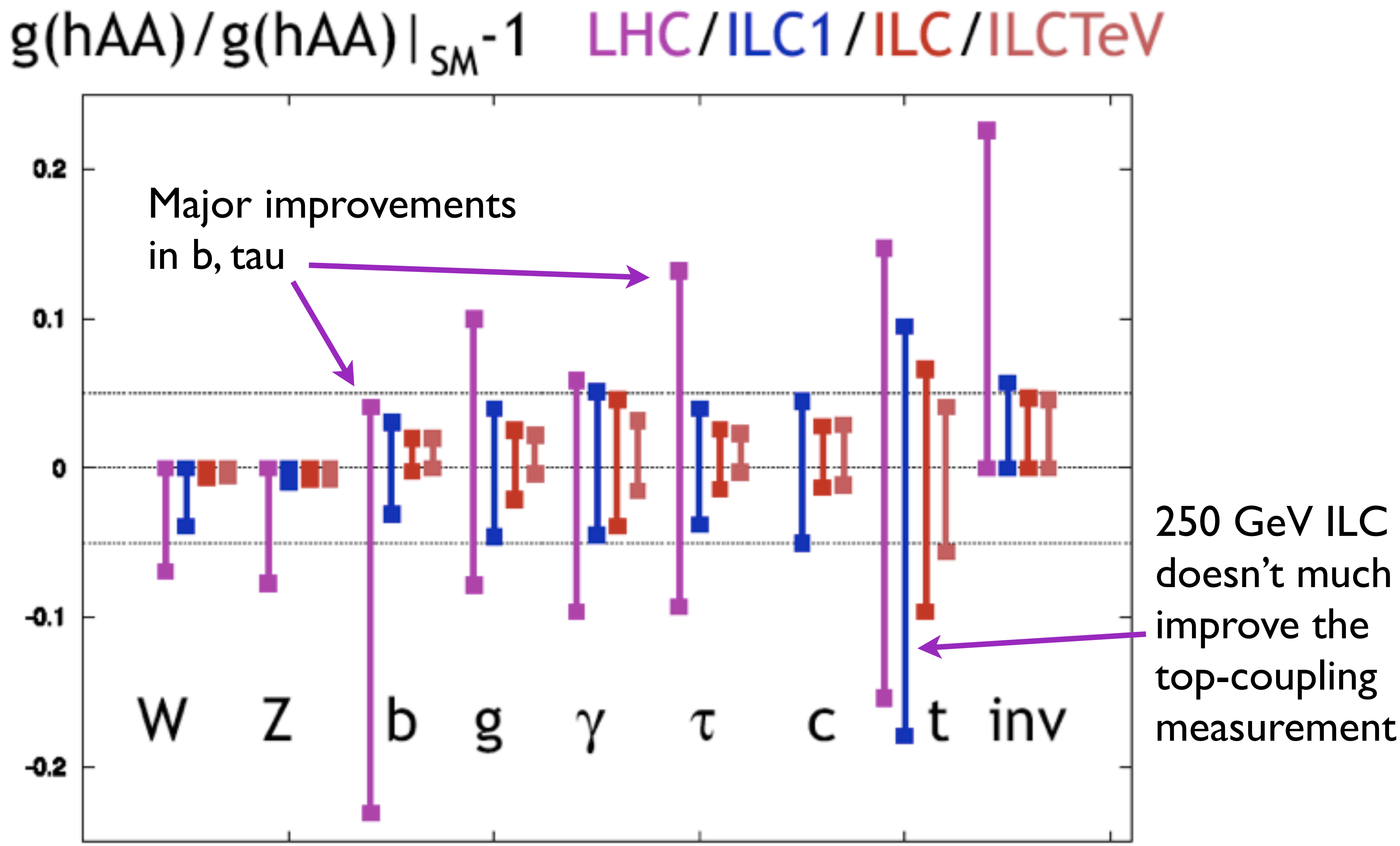
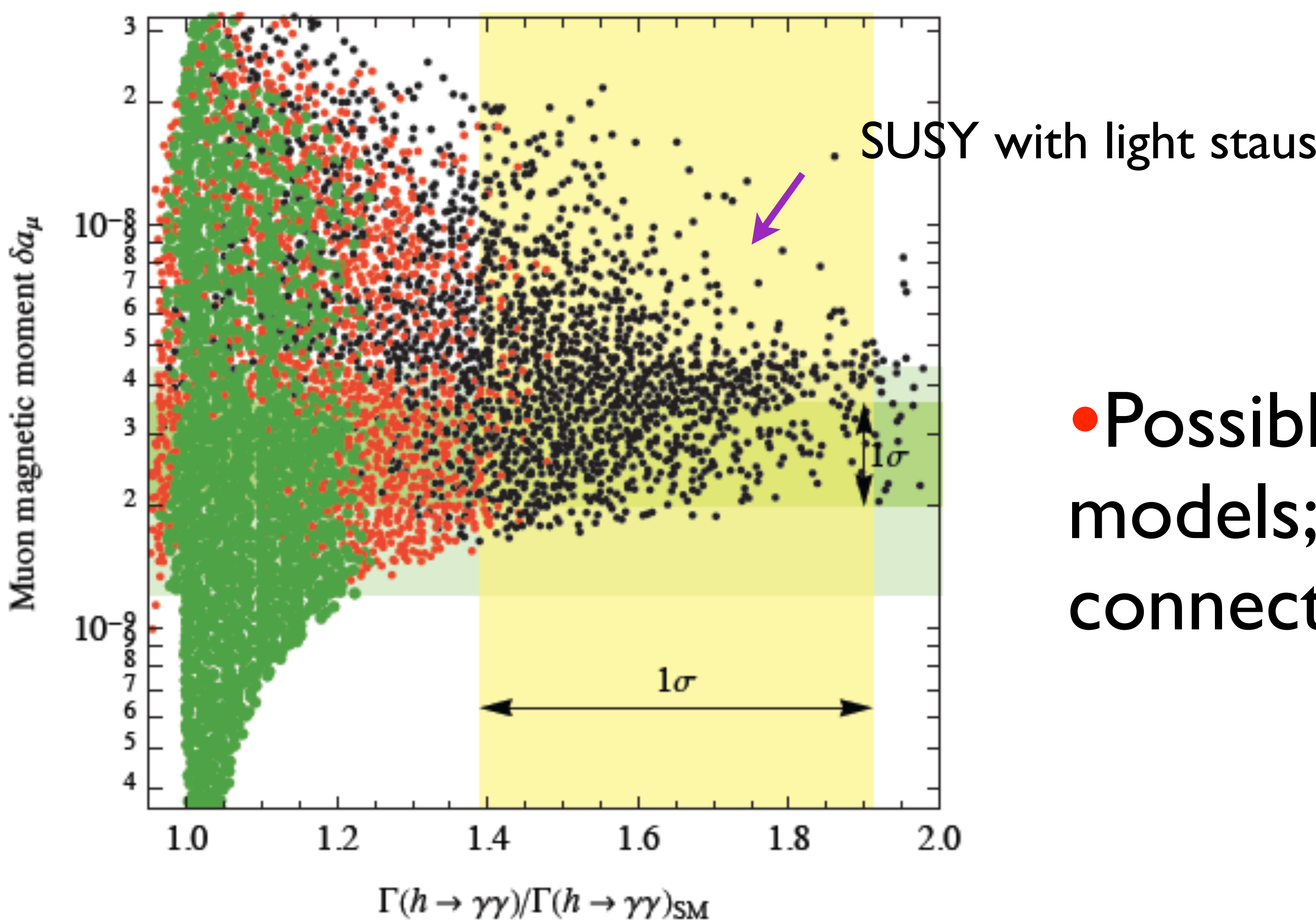


Figure 2: Comparison of the capabilities of LHC and ILC for model-independent measurements of Higgs boson couplings. The plot shows (from left to right in each set of error bars) 1 σ confidence intervals for LHC at 14 TeV with 300 fb^{-1}, for ILC at 250 GeV and 250 fb^{-1} ('ILC1'), for the full ILC program up to 500 GeV with 500 fb^{-1} ('ILC'), and for a program with 1000 fb^{-1} for an upgraded ILC at 1 TeV ('ILCTeV'). The marked horizontal band represents a 5% deviation from the Standard Model prediction for the coupling.

Other future measurements

- Vital at the LHC to determine whether the Higgs unitarizes WW scattering; a major physics goal for the 14 TeV program
- What about correlations between Higgs and such future experiments as g-2?



Giudice, Paradisi, Strumia 1207.6393

- Possible in particular models; IMHO no robust connection

Conclusions

- LHC will do an amazing job in determining Higgs couplings; only a few areas will be definitely missed
- My (provocative) conclusion: not clear an ILC is the next machine to build. Maybe an energy-upgraded LHC will measure the htt coupling better? Also possible to do Higgs potential measurement there? Probably better to determine WW unitarization there
- Regarding future experiments such as g-2, connections to Higgs physics model-dependent