Higgs Couplings at LHC and ILC

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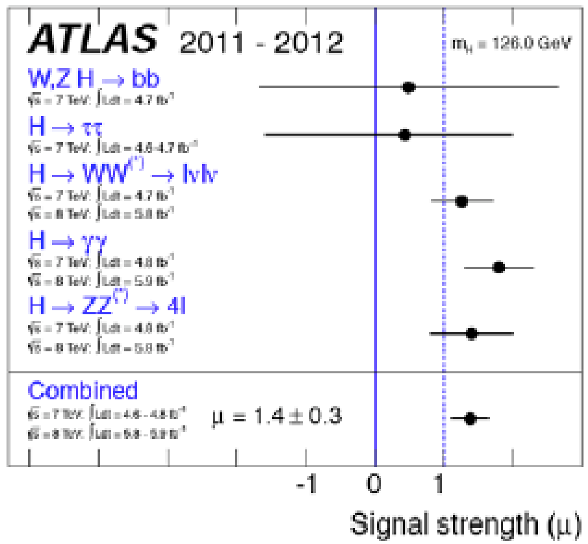
The discovery of a Higgs-like boson at the LHC seems to open a hitherto unexplored sector of particle physics to experimental investigation.

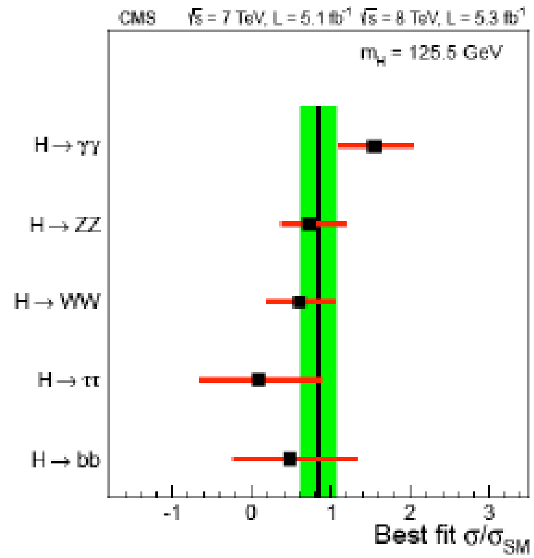
In the gauge sector of the Standard Model, all couplings are pinned down by SU(3)xSU(2)xU(1) symmetry.

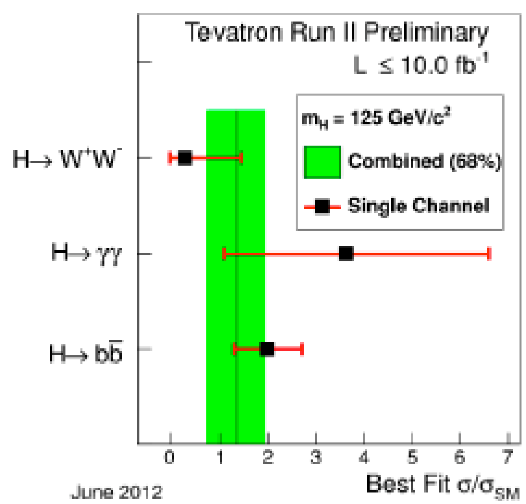
In the Higgs sector, there is no such principle. The "Standard Model predictions" are just a guess.

Thus, the measurement of the couplings of the Higgs particle is one of the very most important questions in particle physics.

Here are current measurements of Higgs process rates relative to the Standard Model expectations.   Large deviations are seen, but these might be statistical fluctuations.   Or maybe not ...







Even if the Higgs-like boson proves to have the Standard Model properties at the 20% level, this knowledge is not sufficient.

The challenge is given by the Decoupling Theorem, enunciated by Howard Haber:

If there is a light Higgs boson plus new physics at the scale M,

the couplings of the Higgs are precisely those of the Standard Model Higgs boson, up to corrections of order

$$m_h^2/M^2 \quad \text{or} \quad m_t^2/M^2$$

So, if we want to use the Higgs to probe for new physics, this level of accuracy is needed.

Examples: (references in arXiv:1208.5152)

Supersymmetry:

$$g(\tau)/SM = 1 + 10\% \left(\frac{400\ \mathrm{GeV}}{m_A}\right)^2$$

$$g(b)/SM = g(\tau)/SM + (1-3)\%$$

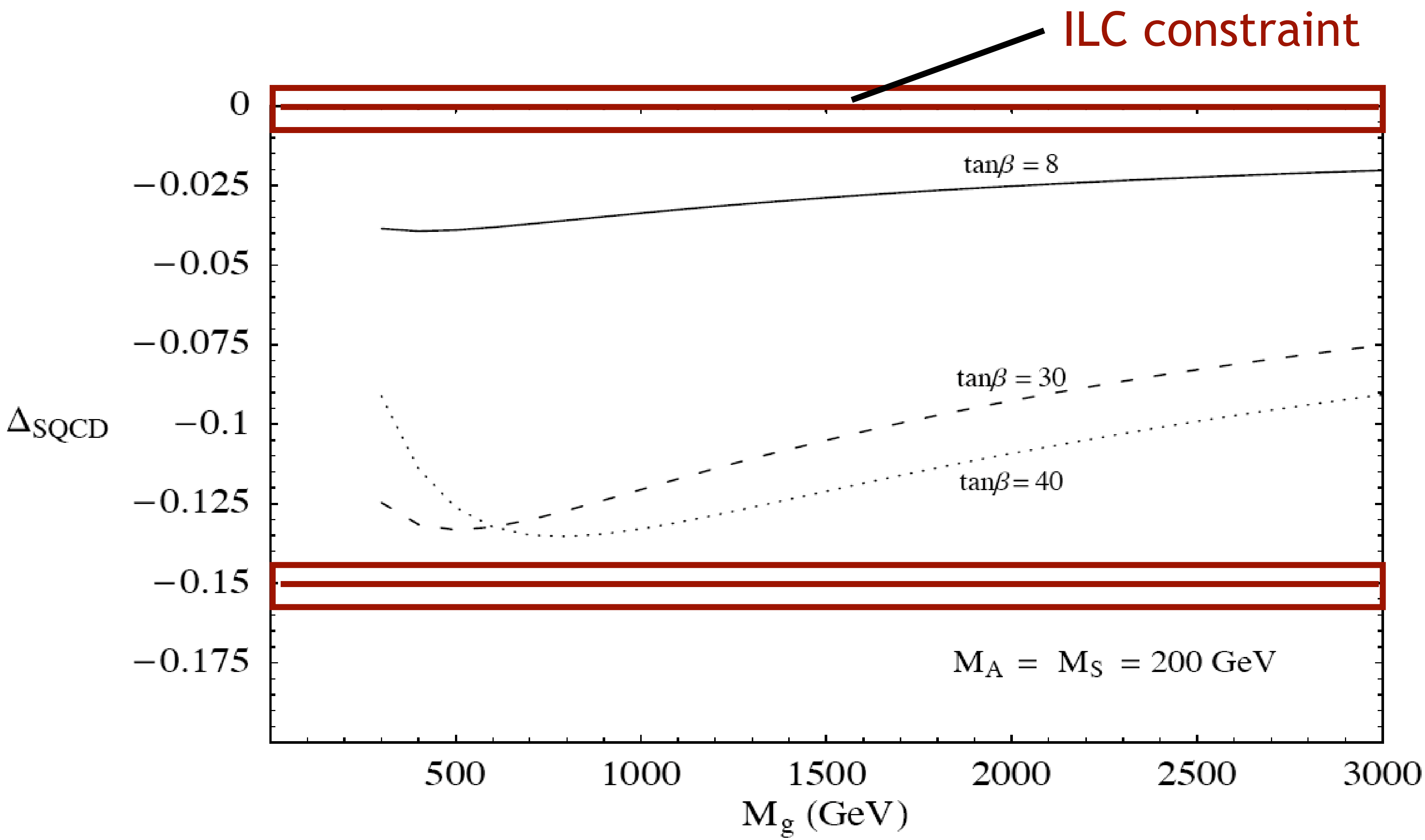
Little Higgs:

$$g(g)/SM = 1 + (5-9)\%$$
$$g(\gamma)/SM = 1 + (5-6)\%$$

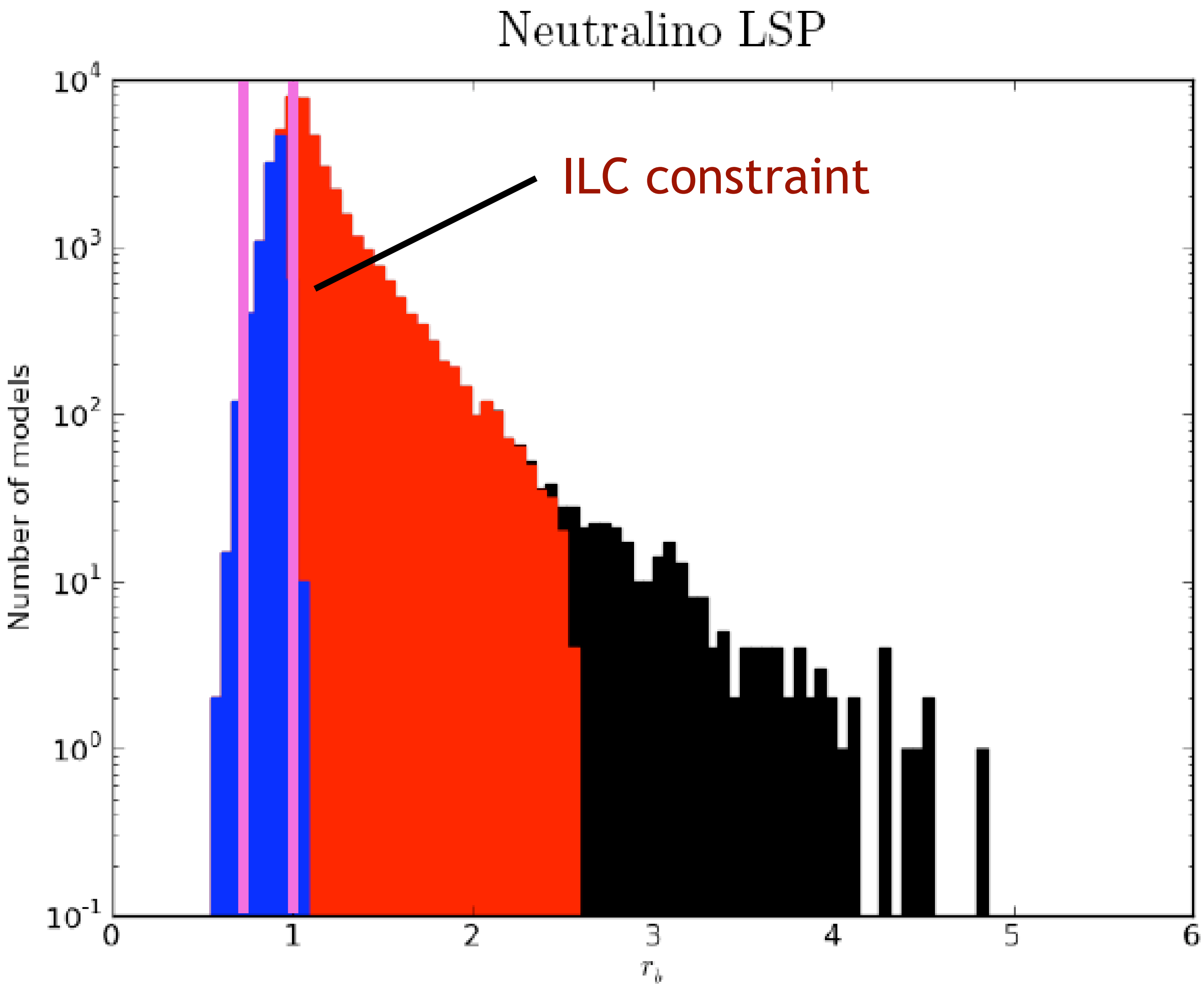
Composite Higgs:

$$g(f)/SM = 1 + (3-9)\% \cdot \left(\frac{1\ \mathrm{TeV}}{f}\right)^2$$

Specific models have higher sensitivity to heavy new particles.



Haber et al. “Decoupling Properties … “



Cahill-Rowley et al.   pMSSM

So:

1. New physics can potentially tweak any Higgs coupling independently of the others.

2. If we cannot reach 5% accuracy, we likely are not in the game.

3. If we are able to reach 1% accuracy, we can be sensitive to new particles at 3 TeV or higher.

The ILC gives new capabilities both for qualitative and quantitative improvement in our understanding of the Higgs boson.

Now, how do we measure the individual Higgs couplings?

The Standard Model Higgs boson couples to all Standard Model species precisely proportional to mass. Can we test this?

For convenience, let

$$\kappa_A = g(hA\overline{A})/g(hA\overline{A})|_{SM}$$

we would like to measure the individual κ_A.

Typical Higgs rate measurements are measurements of

$$\sigma(A\overline{A} \to h) BR(h \to B\overline{B})$$

This is proportional to

$$\mu_{AB} = \big(g^2(hA\overline{A}) g^2(hB\overline{B})/\Gamma_T\big)/(SM)$$

which is a complex function of the κ_A.

The LHC experiments have two problems in turning Higgs rates into κ_A measurements:

1. The μ_{AB} problem: How do we disentangle the components of the μ_{AB} in terms of the κ_A ?

2. The Γ_T problem: The Higgs width is small and difficult to measure directly. It includes ALL κ_A . How do we fix this source of uncertainty?

Problem 1 is solvable if we have a large number of Higgs rate measurements and include them all in a global fit. At least 9 parameters are necessary.

Problem 2 is not solvable for LHC data in a completely model-independent way. However, it is solved by imposing the rather mild theoretical assumptions:

$$\Gamma(W) \leq \Gamma(W)|_{SM} \qquad \Gamma(Z) \leq \Gamma(Z)|_{SM}$$

To estimate the LHC capabilities for Higgs coupling measurements, we need to estimate the accuracies on the rate measurements that can be achieved in the future.

In 2003, Duehrssen made such estimates for a comprehensive LHC Higgs program. These estimates have been updated by the Sfitter team (cf. talk of Dirk Zerwas).

Recently, ATLAS and CMS have given new estimates, based on extrapolation of current detector performance, for 300 fb-1 and for 3000 fb-1 at 14 TeV.

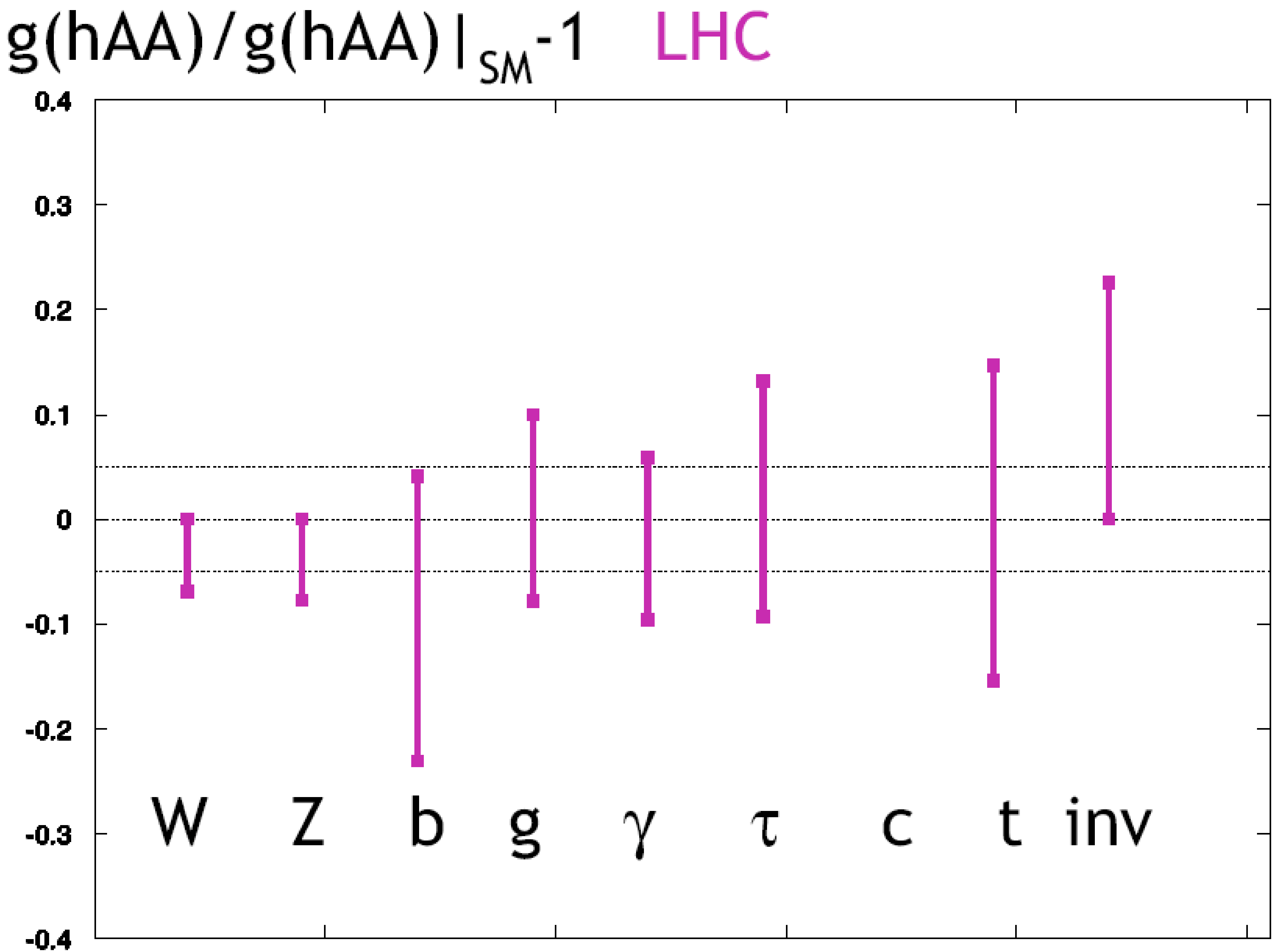
Estimates for 3000 fb-1 do not take account of the more difficult experimental conditions at the HL-LHC. In fact, serious simulation of these conditions has not yet begun.

Already at 300 fb-1, the measurements are limited to a great extent by theoretical systematics.

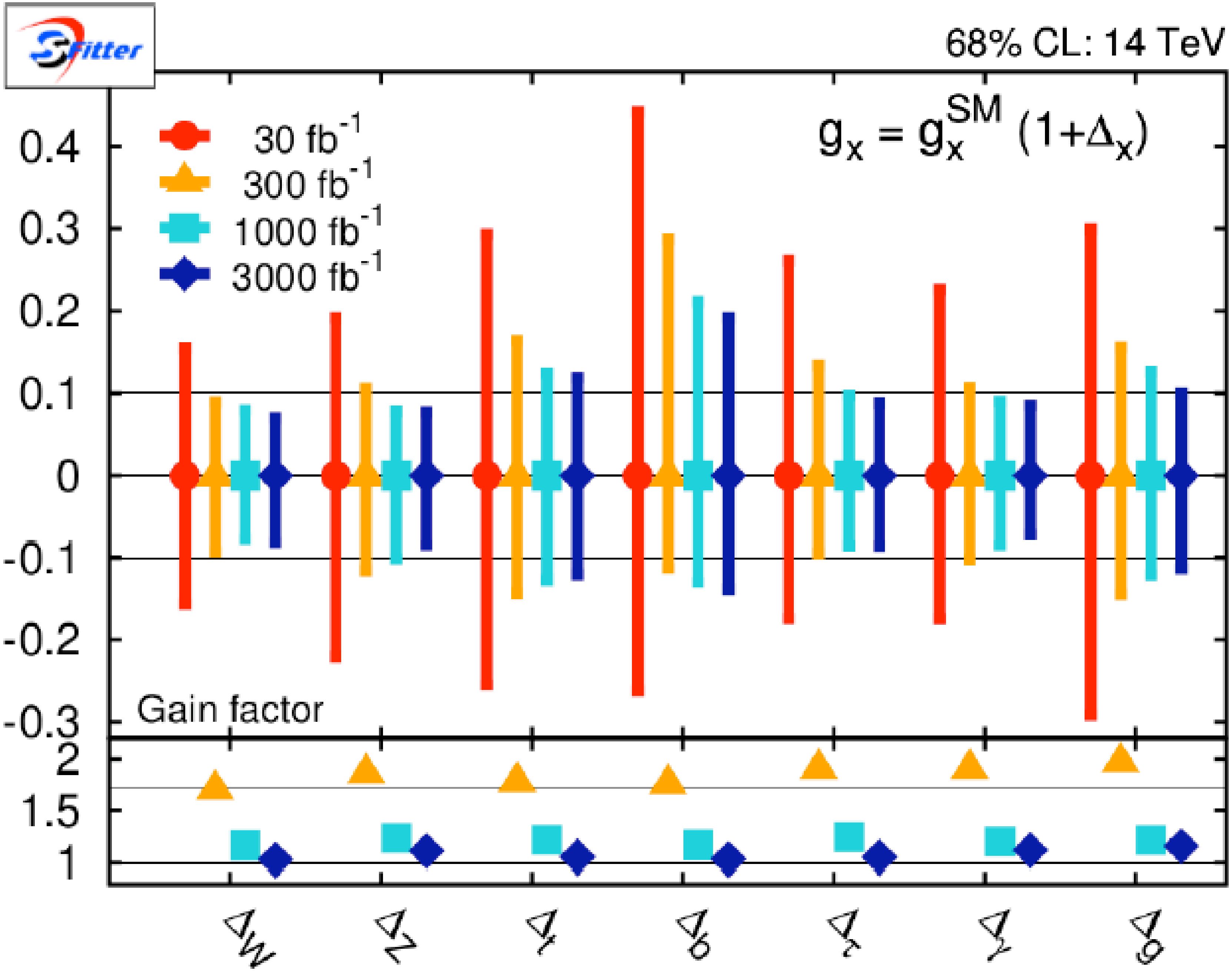
Observable	version 1	ATLAS	CMS
$\sigma(gg) \cdot BR(\gamma\gamma)$	$0.20 \oplus 0.15$	$0.15 \oplus 0.13$	$0.06 \oplus 0.13$
$\sigma(WW) \cdot BR(\gamma\gamma)$	$0.55 \oplus 0.10$	$0.15 \oplus 0.0$	—
$\sigma(gg) \cdot BR(ZZ)$	$0.21 \oplus 0.15$	$0.10 \oplus 0.10$	$0.08 \oplus 0.08$
$BR(\gamma\gamma)/BR(ZZ)$	0.21	0.19	—
$\sigma(gg) \cdot BR(WW)$	—	—	$0.09 \oplus 0.11$
$BR(\gamma\gamma)/BR(WW)$	0.21	—	—
$\sigma(gg) \cdot BR(\tau^+\tau^-)$	—	—	$0.11 \oplus a$
$\sigma(WW) \cdot BR(\tau^+\tau^-)$	$0.22 \oplus 0.10$	$0.41 \oplus 0.10$	$0.15 \oplus b$
$BR(\tau^+\tau^-)/BR(ZZ)$	0.38	—	—
$\sigma(Wh) \cdot BR(b\bar{b})$	$0.25 \oplus 0.20$		
$\sigma(Zh) \cdot BR(b\bar{b})$	$0.25 \oplus 0.20$		
$\sigma(Vh) \cdot BR(b\bar{b})$	—	—	$0.18 \oplus 0.0$
$\sigma(t\bar{t}h) \cdot BR(\gamma\gamma)$	$0.27 \oplus 0.20$	$0.42 \oplus 0.10$	—

Based on the above, here is a table of inputs for 1 expt. x 300 fb-1:

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



g(hAA) / g(hAA) |SM-1
LHC
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
W
Z
b
g
γ
τ
c
t
inv



Sfitter - Zerwas

The study of $e^+e^- \to Zh$ assists these problems in several ways.

In this reaction, Higgs bosons are tagged.

Then we can measure $\sigma(e^+e^- \to Zh)$ independently of the Higgs width.

We can also measure branching fractions independently of the production cross section.

We can also measure invisible and unexpected Higgs decays.

These advantages are in addition to the usual advantages of e+e- in precision, flavor tagging, etc.   Measurement of $h \to c\bar{c}$ is particularly demanding and may require the quiet environment of a linear e+e- collider.

In e+e-, there are actually three progressive Higgs programs as a function of CM energy:

250 GeV: $e^+e^- \to Zh$

Measure the pattern of BRs and measure κ_Z precisely. Measure invisible and exotic decay modes.

350 - 500 GeV $e^+e^- \to \nu\overline{\nu}h$

Measure κ_W precisely using $WW \to h$. This brings the fit to the 1% level for the major modes. Accumulate statistics for κ_τ , κ_γ .

700 GeV - 1 TeV $e^+e^- \to \nu\overline{\nu}h,\ e^+e^- \to t\overline{t}h,\ e^+e^- \to \nu\overline{\nu}hh$

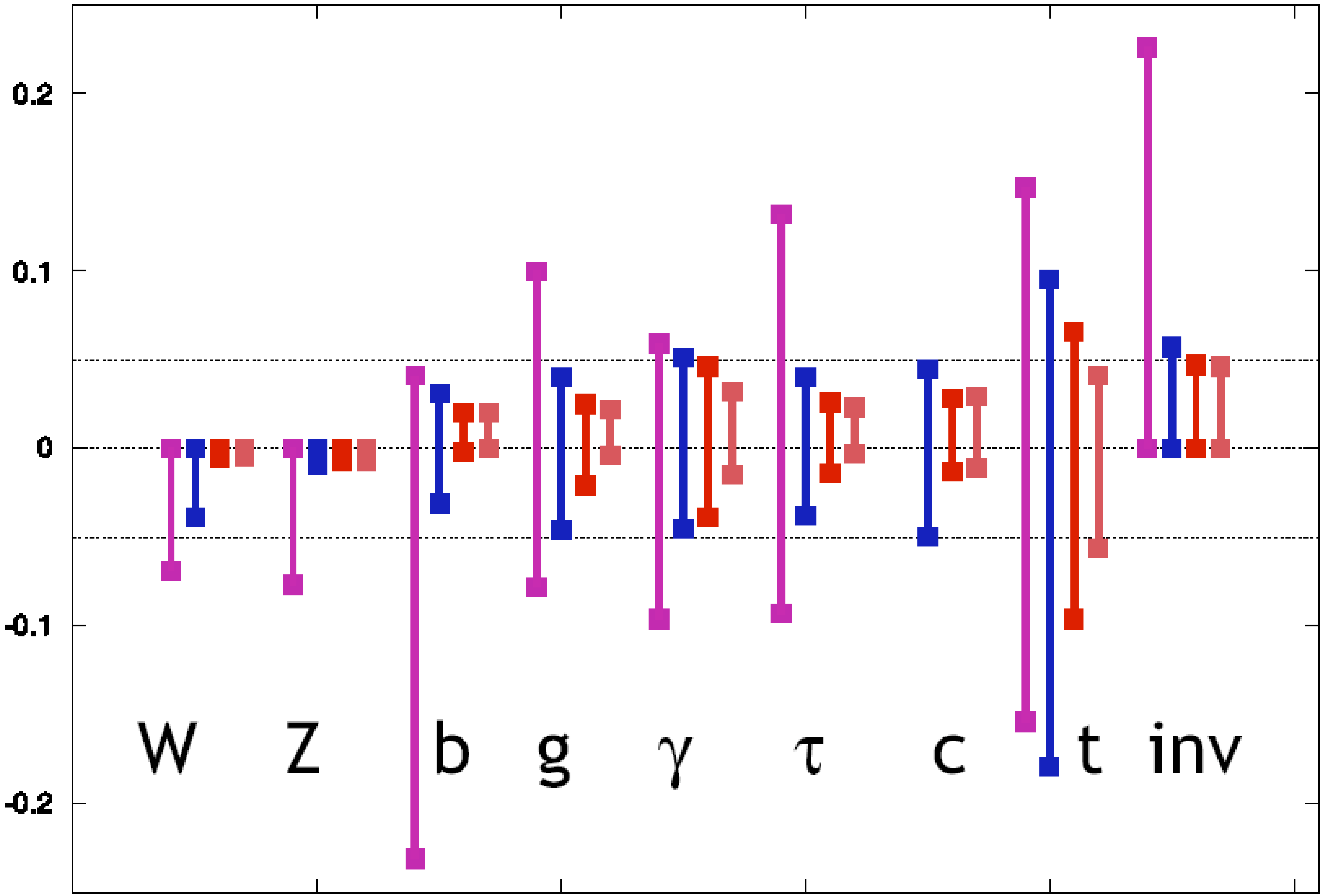
Accumulate more statistics for κ_τ , κ_γ .
Measure κ_μ , κ_t and the Higgs self-coupling.

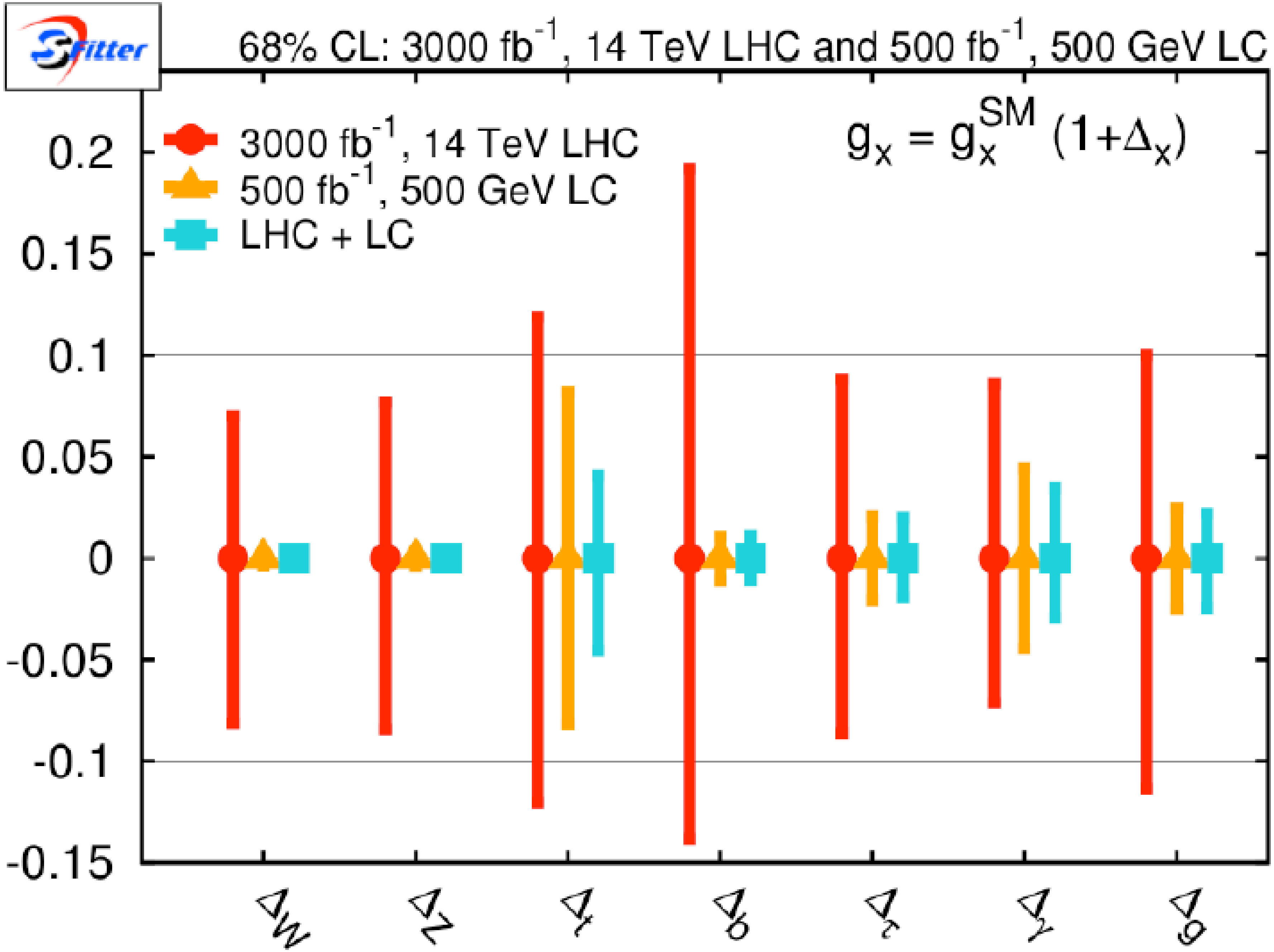
Observable	Expected Error
ILC at 250 GeV with 250 fb^{-1}	
$\sigma(Zh)$	0.025
$\sigma(Zh) \cdot BR(b\bar{b})$	0.010
$\sigma(Zh) \cdot BR(c\bar{c})$	0.069
$\sigma(Zh) \cdot BR(gg)$	0.085
$\sigma(Zh) \cdot BR(WW)$	0.08
$\sigma(Zh) \cdot BR(ZZ)$	0.28
$\sigma(Zh) \cdot BR(\tau^+\tau^-)$	0.05
$\sigma(Zh) \cdot BR(\gamma\gamma)$	0.27
$\sigma(Zh) \cdot BR(\text{invisible})$	0.005

Fujii, Miyamoto, Ono, Tian

ILC at 500 GeV with 500 fb^{-1}	
$\sigma(Zh) \cdot BR(b\bar{b})$	0.016
$\sigma(Zh) \cdot BR(c\bar{c})$	0.11
$\sigma(Zh) \cdot BR(gg)$	0.13
$\sigma(Zh) \cdot BR(\tau^+\tau^-)$	0.07
$\sigma(Zh) \cdot BR(\gamma\gamma)$	0.36
$\sigma(WW) \cdot BR(b\bar{b})$	0.006
$\sigma(WW) \cdot BR(c\bar{c})$	0.04
$\sigma(WW) \cdot BR(gg)$	0.049
$\sigma(WW) \cdot BR(WW)$	0.03
$\sigma(WW) \cdot BR(\tau^+\tau^-)$	0.05
$\sigma(WW) \cdot BR(\gamma\gamma)$	0.28
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	0.2
ILC at 1 TeV with 1000 fb^{-1}	
$\sigma(WW) \cdot BR(WW)$	0.01
$\sigma(WW) \cdot BR(gg)$	0.018
$\sigma(WW) \cdot BR(\tau + \tau -)$	0.02
$\sigma(WW) \cdot BR(\gamma\gamma)$	0.05
$\sigma(t\bar{t}h) \cdot BR(b\bar{b})$	0.12

$g(hAA)/g(hAA)|_{SM}-1$ LHC / ILC1 / ILC / ILCTeV





Sfitter - Zerwas

In this talk, I have set out a simple and not obviously incorrect way to visualize the improvement of ILC over LHC measurements of Higgs couplings.

This is just the beginning of a discussion that will continue throughout the next year.

Such comparisons are not the whole story. They ignore the qualitative improvements in the ILC picture of the Higgs boson through democratic production, control of backgrounds, and tagged Higgs measurements.