Why We Need the ILC

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SiD Workshop
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The witching hour for the ILC is coming at the end of this year.

The GDE completes its task and goes out of existence. The ILC budget line for the US DOE is zeroed out.

It is lucky that, at just this moment, we have learned that the ILC is exactly the right machine for the next step in accelerator-based high energy physics.

There are two pieces to the argument to this conclusion.

The first involves the Higgs boson.

The second involves what is beyond the Higgs boson.

Rolf Heuer at LP 2011:

"Great oppotunities are in store at the TeV scale and a fuller understanding of Nature will come about through a clearer insight at this energy level. The LHC will provide a first indication of any new physics at energies up to several TeV. First results from the LHC will be decisive in indicating the direction that particle physics will take in the future."

"It is expected that the period of decision-making concerning the energy frontier will be in the next few years."

"It is mandatory to have accelerator laboratories in all regions as partners in accelerator development, construction, comissioning and exploitation.... The participation of CERN in global projects is to be enabled wherever they are sited."

We now have the story from the initial LHC running.

ATLAS and CMS have discovered a new particle, with properties very similar to the long-sought Higgs boson.

There are no other signs of new physics beyond the Standard Model.

From the new boson, the implications are clear.

From the new particle exclusions, the implications are less clear. It is not possible to look at the LHC data in a simple way and see that particles are not there.

For me, both lines of new knowledge point to the ILC.

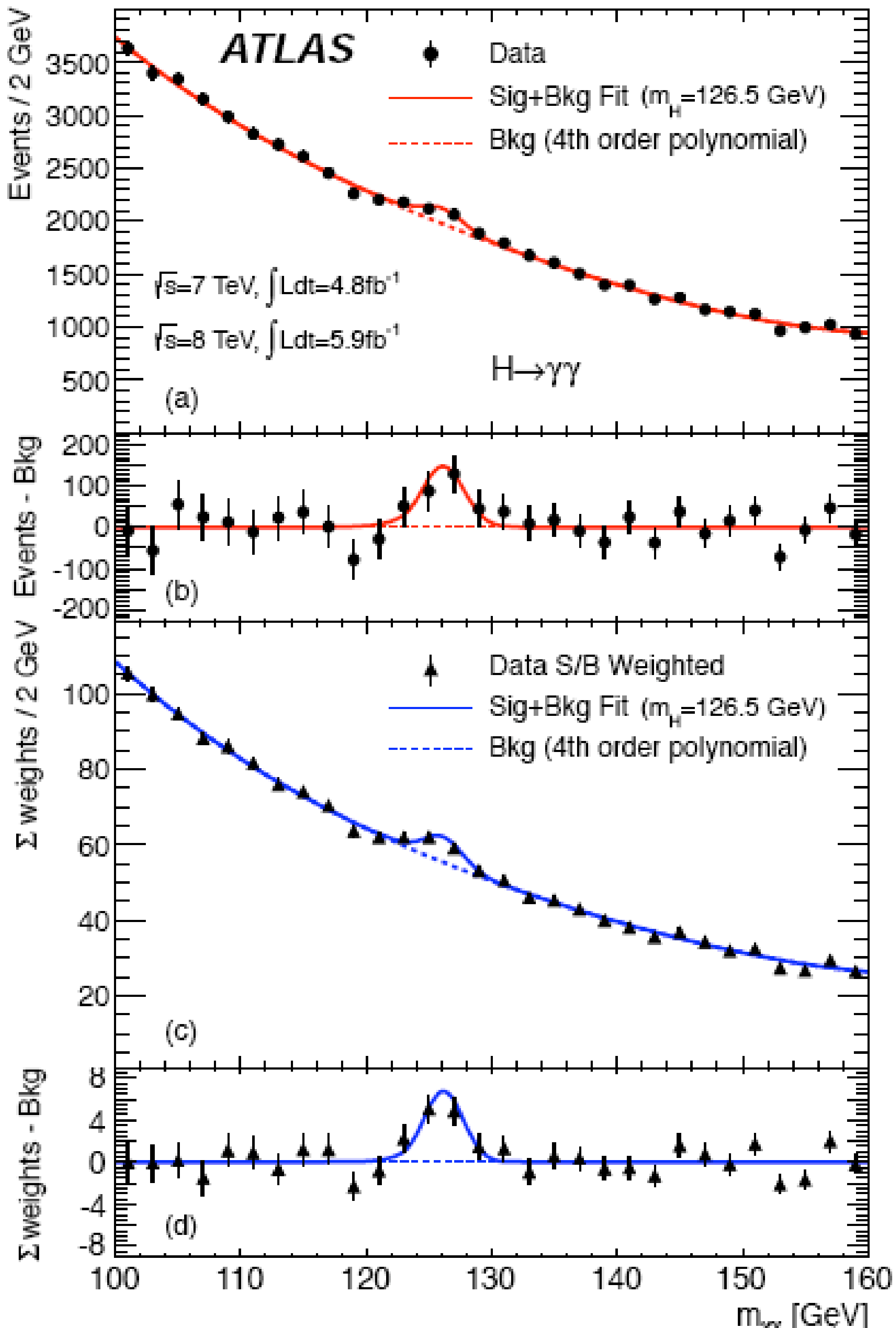
The physics case for the ILC has been written up in the

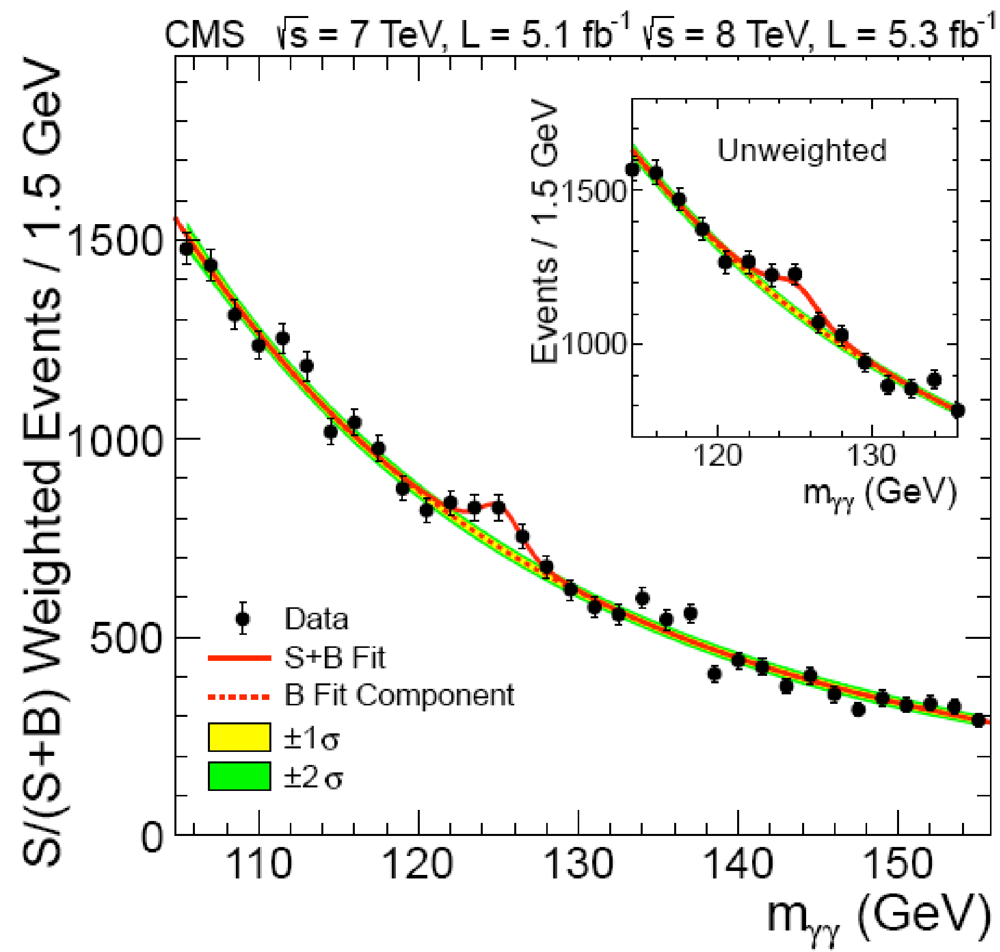
Physics Chapter of the ILC DBD

A first draft is available at : lcsim.org/paper/DBDPhysics.pdf

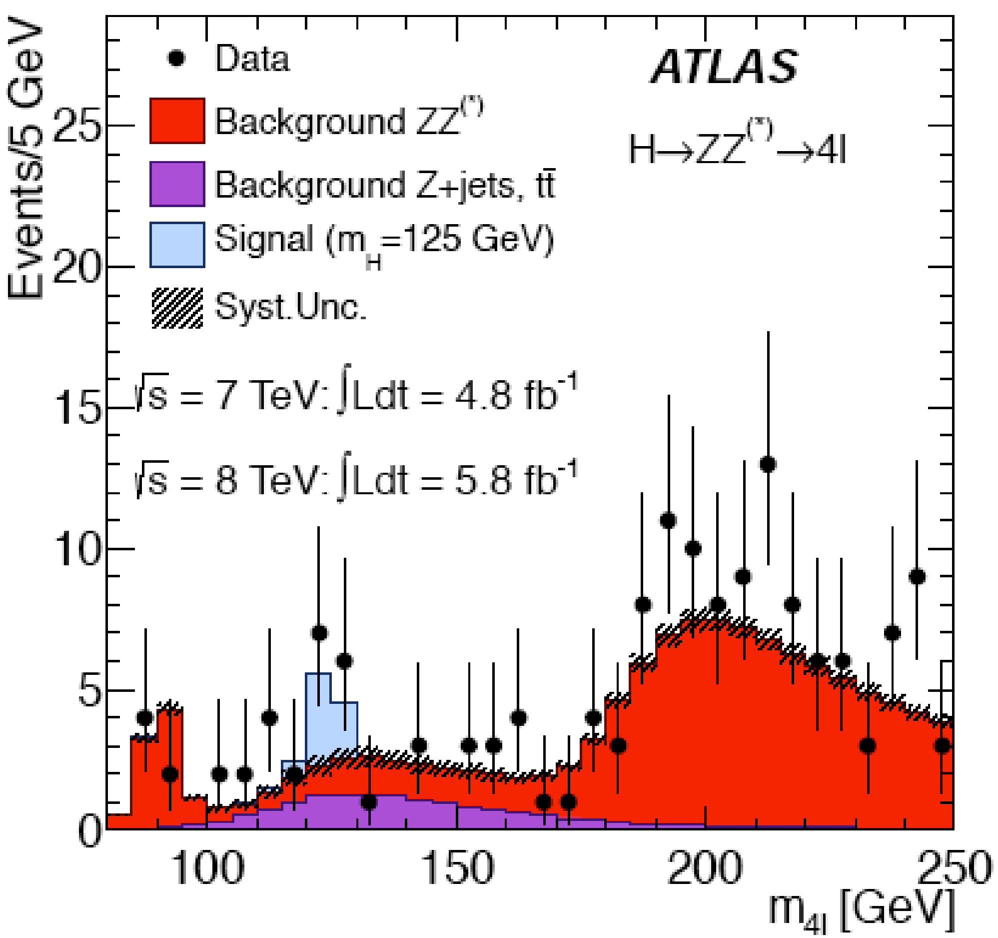
The editorial team is eager to receive feedback from the LC community. Please send email to: mpeskin@slac.stanford.edu and to the relevant section editors.

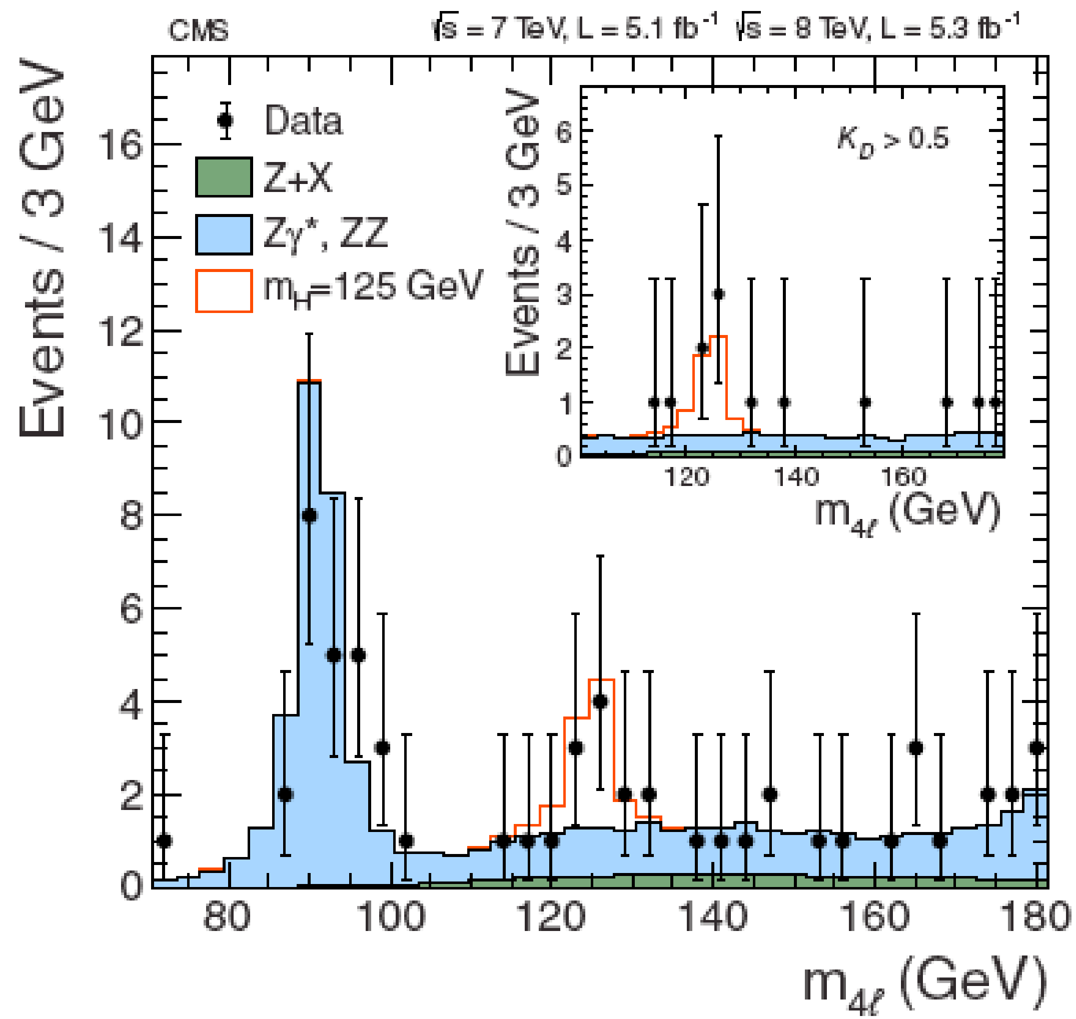
new boson discovered in $\gamma\gamma$





new boson discovered in ZZ^*





Now we must learn the properties of this particle:

Is it the Higgs boson ?

Are the expected major couplings present ?

Are its properties close to those of the Standard Model Higgs ?

Are there small deviations from the Standard Model predictions?

Is it the Higgs boson ?

Both ATLAS and CMS report strong signals for decays both to WW and to ZZ.

A scalar field with a vacuum expectation value can couple to WW and ZZ in order 1:

$$\begin{aligned} |D_\mu \varphi|^2 &\to \frac{g^2}{4}(v+h(x))^2 W^+ W^- \\ &\to m_W^2 W^+ W^- + \frac{2m_W^2}{v} h\, W^+ W^- + \cdots \end{aligned}$$

A field without a vacuum expectation value can couple to WW and ZZ through dimension-5 operators. In a weak-coupling theory, these operators come from loops.

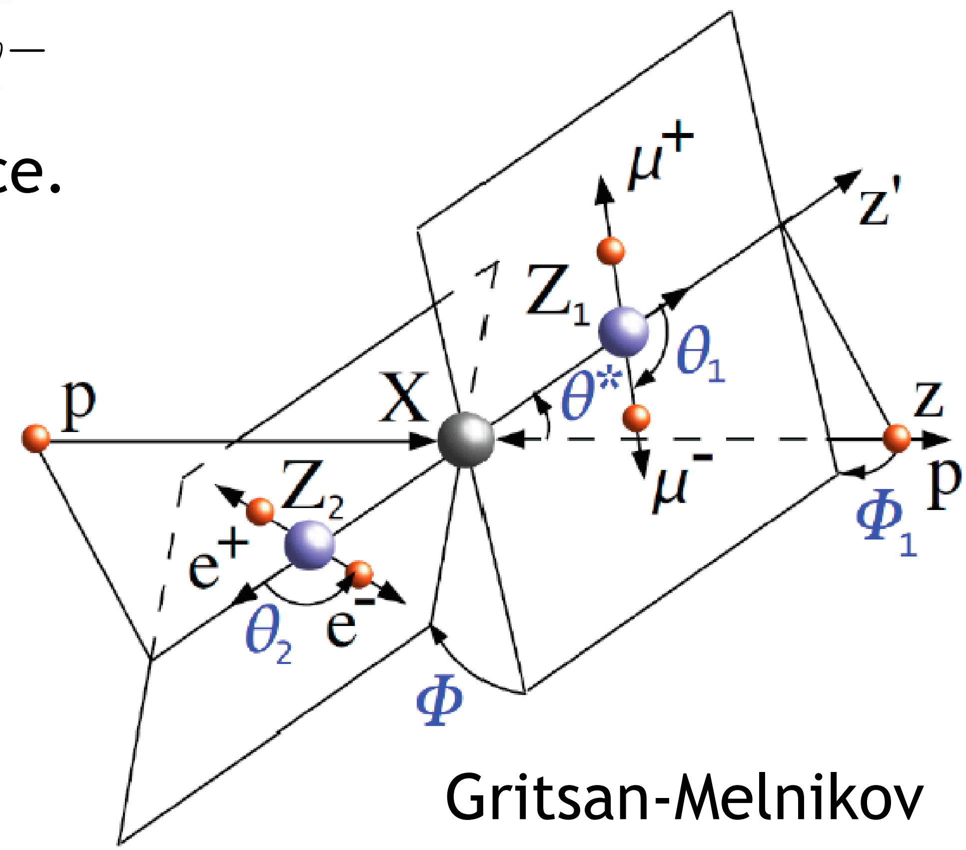
$$A \frac{\alpha}{4\pi} \frac{1}{M} h\, F_{\mu\nu} F^{\mu\nu} + B \frac{\alpha}{4\pi} \frac{1}{M} h\, \epsilon_{\mu\nu\lambda\sigma} F^{\mu\nu} F^{\lambda\sigma}$$

So, the fact that we see WW and ZZ at nearly Standard Model strength is prima facie evidence that the particle is a CP even spin 0 state from a field with a vacuum expectation value that breaks SU(2)xU(1).

The quantum numbers can be verified by angular analysis of

$$pp \to ZZ \to \ell^+\ell^-\ell^+\ell^-$$

This already enters the CMS evidence.



Gritsan-Melnikov

The hWW vertex gives dominantly longitudinal W polarization

The A and B vertices give transverse polarization.

CMS: MELA already favors the scalar hypothesis at about 1 sigma.
3 sigma separation between scalar and pseudoscalar hypostheses is possible with 30 fb-1.

From here on, I will call the new particle at 125 GeV "the Higgs boson" without further apology.

We still must find out whether this particle has the properties predicted in the Standard Model.

In the Standard Model, the Higgs boson is the unique source of mass for all quarks, leptons, and gauge bosons.   Is it really so ?

At 125 GeV, the Higgs boson is exceptionally hard to find.

However, once found, it offers us a large number of decay channels for study.

Gianotti: "Thank you, Nature."

$m_H \sim 126$ GeV

$\Gamma_H = 4.2$ MeV

$\lambda = (m_H/v)^2/2 = 0.131$

$H \to WW^*$ 23%*

$H \to ZZ^*$ 2.9%*

$H \to bb$ 56%*

$H \to cc$ 2.8%

$H \to \tau\tau$ 6.2%*

$H \to \mu\mu$ 0.21‰

$H \to gg$ 8.5%*

$H \to \gamma\gamma$ 2.3‰*

$H \to \gamma Z$ 1.6 ‰*

new set of reference SM parameters

many couplings accessible at LHC (*) !

Mele

the major decay modes present ?

Already, many of the key qualitative properties of the Higgs boson are falling into place:

$\gamma\gamma$ decay mode ✓

ZZ decay mode ✓

WW decay mode ✓

bb decay mode Tevatron only;
hopeful report from CMS (PAS-HIG-12-019)

$\tau\tau$ decay mode ? deficit at CMS

spin-parity	preliminary evidence from CMS
gg production mode	✓
VBF production mode	marginal (2.7 σ in ATLAS)
Higgsstrahlung mode	Tevatron only

All of these issues could be settled with the full 2012 LHC data set.

Are its properties close to those of the Standard Model Higgs ?

Recently, I tried to estimate how well LHC could do with 300 fb-1 of data, applying a model-independent (9 parameter) fit.

The only important theoretical assumption is

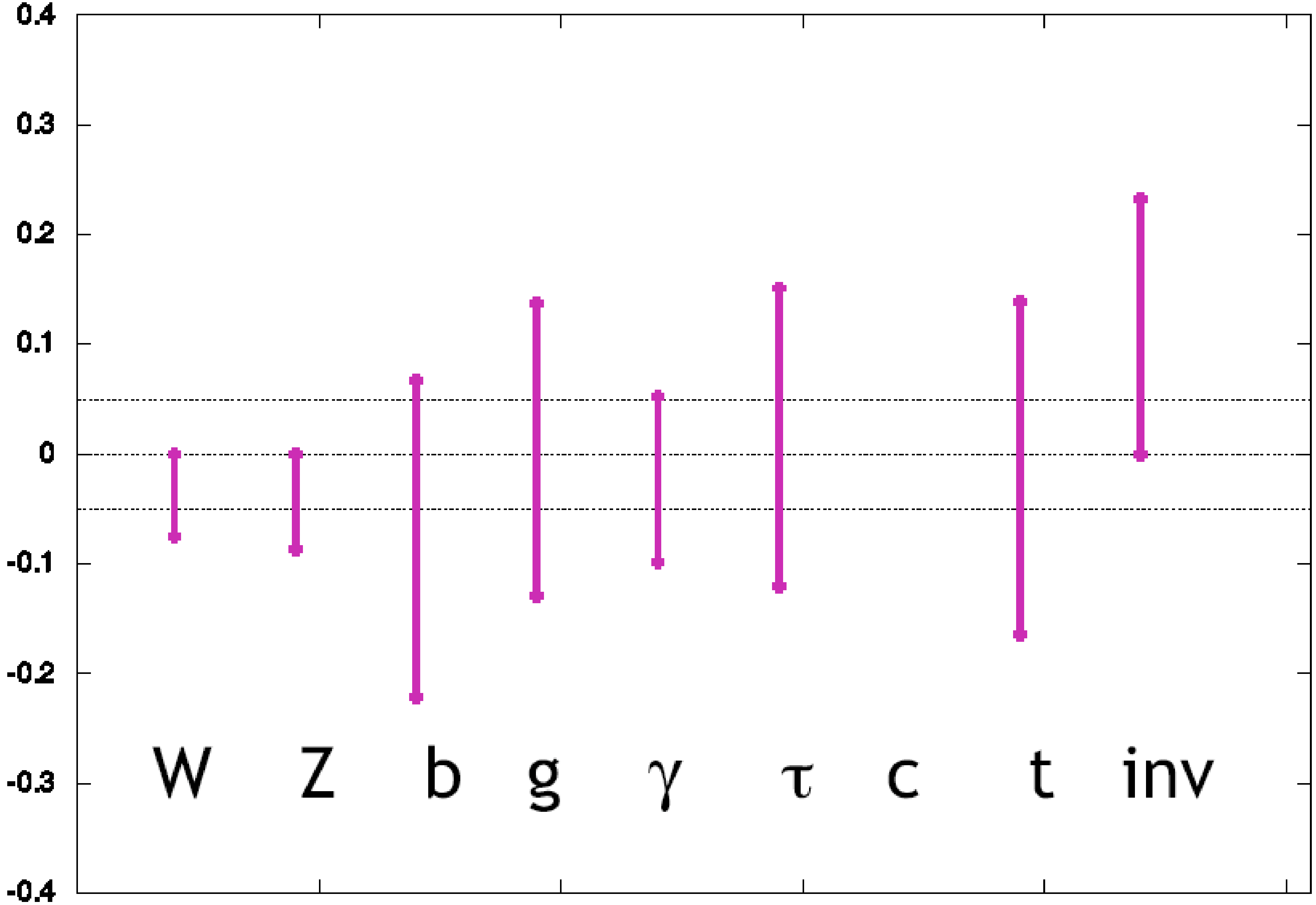
$$\Gamma(W) \leq \Gamma(W)|_{SM} \quad \Gamma(Z) \leq \Gamma(Z)|_{SM}$$

Violation of this assumption requires models with φ^{++}
(Gunion, Haber, and Wudka)

The loop couplings to g and γ are treated independently of the t and W couplings. Loops can be affected by unknown particles as well as by t and W.

Similar work by Klute et al. comes to similar conclusions. My fit is more naive, but more transparent. For its complete details, see arXiv:1207.2516.

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



MEP, arXiv:1207.2516

Are there small deviations from the Standard Model ?

Why should we care about this ?   In fact, it is crucial.

1. The Higgs might turn out to look Standard Model like. But, the Standard Model Higgs makes no sense. In this model, the complete explanation for spontaneous symmetry breaking is

$$\mu^2|_{\mathrm{TeV}} < 0$$

As physicists, we should be ashamed of ourselves to be satisfied with this.

At this moment, the study of the Higgs boson is our best path to the discovery of new physics beyond the Standard Model.

2. In dynamical models of electroweak symmetry breaking (supersymmetry, Little Higgs, Randall-Sundrum, ...), there is a light Higgs boson. If all other particles are heavy (TeV mass), we are in the Decoupling Limit described by Haber.

The properties of the Higgs are those of the Standard Model Higgs up to corrections of order $(m_h^2, m_t^2)/M^2$.

Examples: (see also Gupta, Rzehak, Wells (2012))

SUSY:

$$\begin{aligned} g(\tau\tau)/SM &= 1 + 10\% \left(\frac{400 \text{ GeV}}{m_A}\right)^2 \\ g(b\bar{b})/SM &= g(\tau\tau)/SM + (1-4)\% \end{aligned}$$

Composite Higgs:

$$g(f\bar{f})/SM = 1 + (3-9)\% \left(\frac{1 \text{ TeV}}{f}\right)$$

Littlest Higgs:

$$\begin{aligned} g(gg)/SM &= 1 + (5-9)\% \\ g(\gamma\gamma)/SM &= 1 + (5-6)\% \end{aligned}$$

In general, corrections to the Decoupling Limit can tweak any individual Higgs coupling independently of the others.

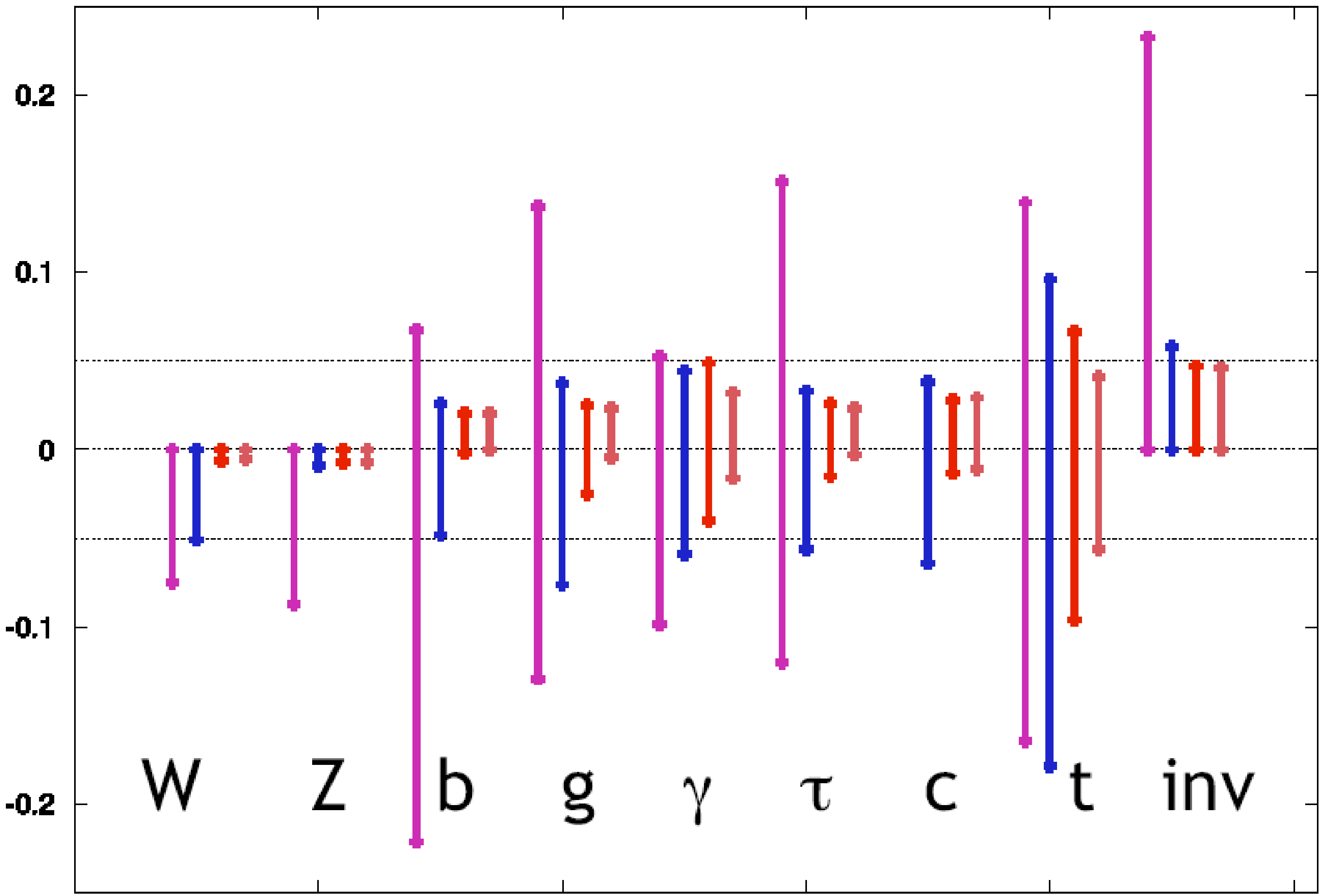
After July 4,

the issue of the precise values of the Higgs couplings has vaulted to the top of the list of problems in high energy physics.

The level of precision that is needed is very high.

Can we get there ?

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



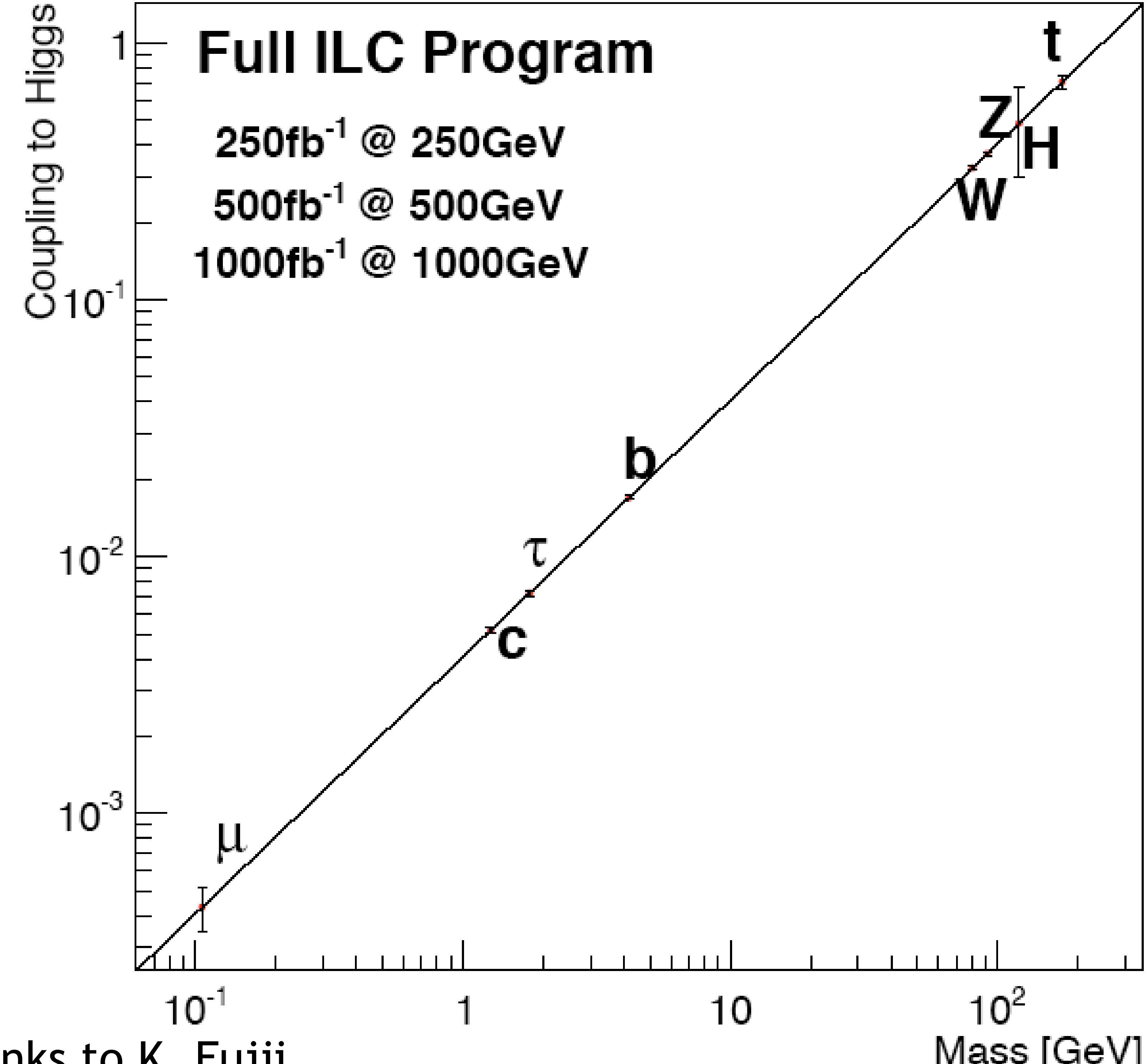
MEP, arXiv:1207.2516

We know now that the Higgs boson exists, at a mass that gives the possibility of a very rich experimental program.

We know that high-precision measurement of couplings, to few percent or even 1% accuracy, is needed to fully understand the Higgs boson.

We know that the WW and ZZ couplings are large enough that the Higgs boson can be studied with large samples in e+e- .

So, it is compelling - now! - to propose a Higgs factory to study the Higgs boson in e+e- collisions.



thanks to K. Fujii

I have now argued that there is a very strong case for the ILC based on the Higgs boson alone.

The LHC has discovered no other new particles, so at the moment there is no motivation to ask for a collider at higher energy that that required to carry out the Higgs program.

But, the LHC might discover new particles at 14 TeV, or maybe even in 2012.

Where will they be ?   What will they be ?

There are three major classes of models of electroweak symmetry breaking at the TeV mass scale.

1. Technicolor models: Electroweak symmetry breaking is due to new strong interaction condensates at TeV energies.

2. Supersymmetry models: Electroweak symmetry breaking is due to a fundamental Higgs boson that is stabilized through its symmetry relation to fundamental fermions.

3. Composite Higgs models: Electroweak symmetry is broken by an effective Higgs boson that is a composite formed by new interactions at 10 TeV.

If indeed the new boson has a vev that breaks SU(2)xU(1), the class 1 models are dead. We must consider the other two classes.

The ATLAS and CMS experiments have published very stringent exclusions of SUSY, excluding squarks and gluinos up to 1 TeV in the MSUGRA/cMSSM scenario.

But, are light SUSY particles really excluded at the LHC ?

I will first give some sociological evidence against this statement:

1. No theorist who believed in SUSY before 2009 has renounced SUSY in the light of the LHC exclusions. (*)

2. Model builders are still building models with 200 GeV charginos.

(* Gordy Kane might be considered an exception.)

Blum, D'Agnolo, and Fan, arXiv:1206.5303

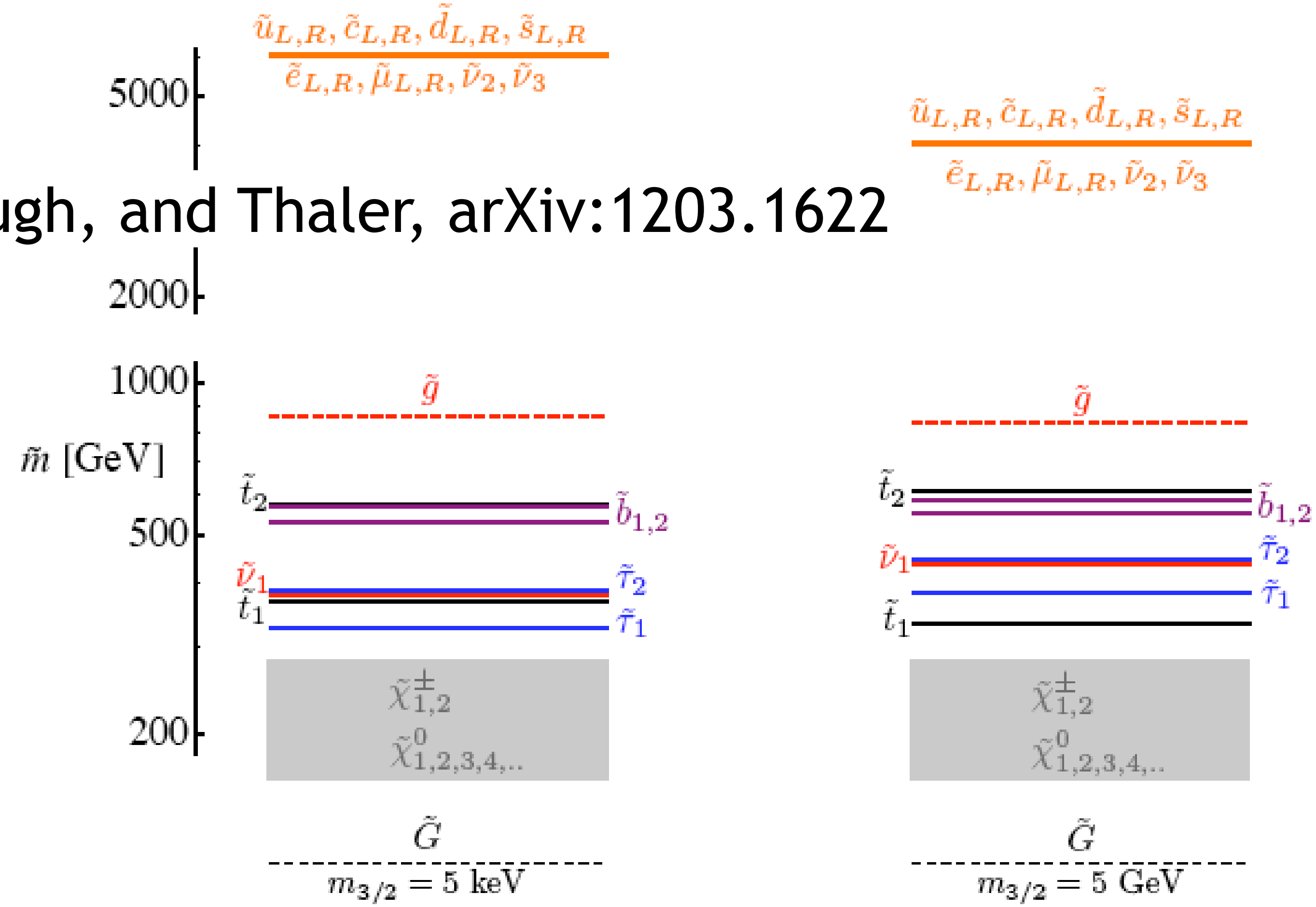
Naturalness dictates that at least one chargino must be light, $m_{\tilde{\chi}^\pm} \lesssim 200$ GeV. Hence, the chargino contribution to r_γ may be expected to become relevant [73–75]. What limits the effect to be modest is the direct bound, that we take to be $m_{\tilde{\chi}^\pm} > 94\,\mathrm{GeV}$ [76]. Imposing this bound, we compute

Cohen, Hook, Torroba, arXiv:1204.1337

v	M_3	M_2	M_1
350 TeV	2.5 TeV	1.0 TeV	530 GeV
$\widetilde{m}_3^2$	$\widetilde{m}_{1,2}^2$	$\widetilde{m}_{H_u}^2$	$\widetilde{m}_{H_d}^2$
$(1.2\ \mathrm{TeV})^2$	$(5\ \mathrm{TeV})^2$	$-(220\ \mathrm{GeV})^2$	$(300\ \mathrm{GeV})^2$
μ	b_μ	M_A	$\tan\beta$
220 GeV	- 0.030 GeV^2	135 GeV	4.2

Table 3: An example set of consistent parameters with the solution to the μ problem given in Eq. (24). We have assumed gaugino mass unification and to good approximation $\widetilde{m}^2_{Q_i} = \widetilde{m}^2_{u_i} =$

Craig, McCullough, and Thaler, arXiv:1203.1622



Randall and Reece, arXiv:1206.6540

We are now in a position to try to put everything together. In terms of the low-energy effective theory, one set of numbers that gives a good solution in the tree-level potential: $\lambda = 1.1$, $f = (100 \text{ GeV})^2$, $T = 1.8 \times 10^6 \text{ GeV}^3$, $A_\lambda = 200$ GeV, $m^2_{H_u} = -(70 \text{ GeV})^2$, $m^2_{H_d} = (120 \text{ GeV})^2$, $m^2_S = (100 \text{ GeV})^2$. This leads to $\tan\beta = 1.7$, a 121 GeV mostly-up-type Higgs, and Higgses at 214 and 252 GeV that are mixtures of mostly S and H_d. The effective μ-term $\lambda \langle S \rangle = -148$ GeV.

The reason for this is easy to understand. The μ parameter enters directly into the expression for the Z mass in SUSY, so at the very least, small μ is needed for naturalness.

$$m_Z^2 = 2\,\frac{M_{Hd}^2 - \tan^2\beta M_{Hu}^2}{\tan^2\beta - 1} - 2\mu^2$$

This has led to a number of proposals for SUSY spectra with a few particles important for naturalness light and all others much heavier. This strategy has been given the name "natural SUSY". See, e.g.

Papucci, Ruderman, Weiler, arXiv:1110.6926
Baer, Barger, Huang, Tata, arXiv:1203.5539

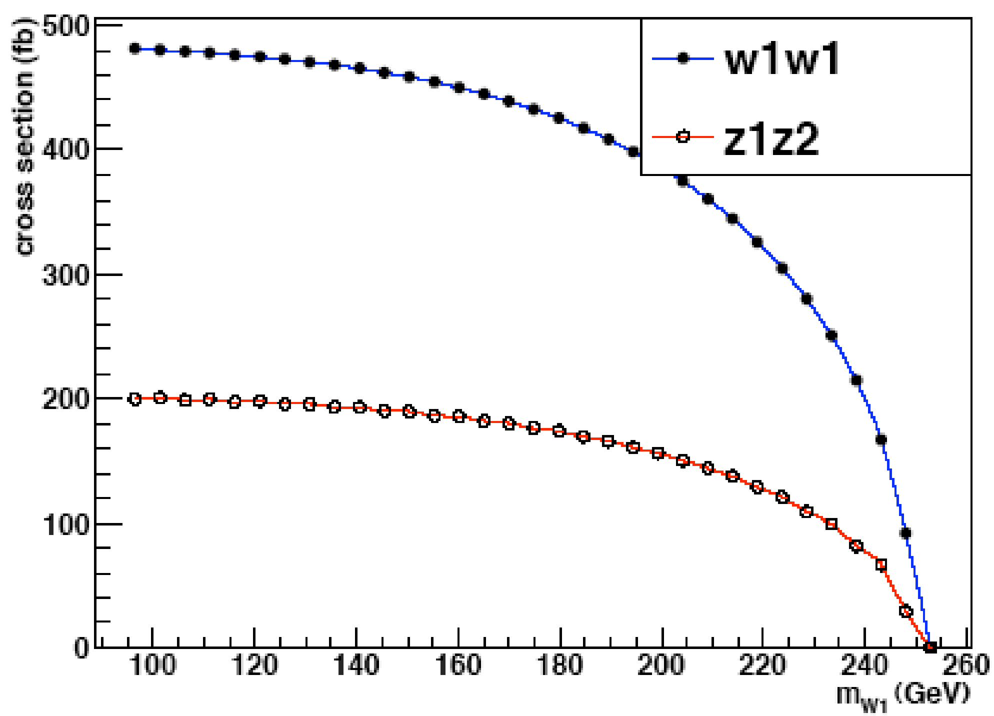
The minimal scenario is that the only light particles of SUSY are the Higgsinos.

This is a sector $\widetilde{\chi}_1^0\ ,\ \widetilde{\chi}_2^0\ ,\ \widetilde{\chi}_1^\pm$

below 200 GeV, with mass splittings of order 10 GeV. It is very difficult for LHC to observe these particles.

At the ILC, the cross sections are large. Observation is not trivial, but Baer, Barger, Huang, arXiv:1107.5581 give a straightfoward set of cuts.

The cross sections are strongly dependent on beam polarization, allowing a test of the Higgsino/chargino mixture.



The Higgsino is not a good dark matter candidate, having too large an annihilation cross section to WW, ZZ.

However, we might need to go to the NMSSM to raise the Higgs mass to 125 GeV. Then a singlino LSP below the Higgsino can be a good dark matter candidate, with

$$\sigma(\widetilde{S}\widetilde{S} \to W^+W^-) \sim \lambda^4 \sigma(\widetilde{H}\widetilde{H} \to W^+W^-)$$

The Higgsino decays to the singlino with

$$\Gamma(\widetilde{H}) \sim \lambda^2 \cdot \mathrm{GeV}$$

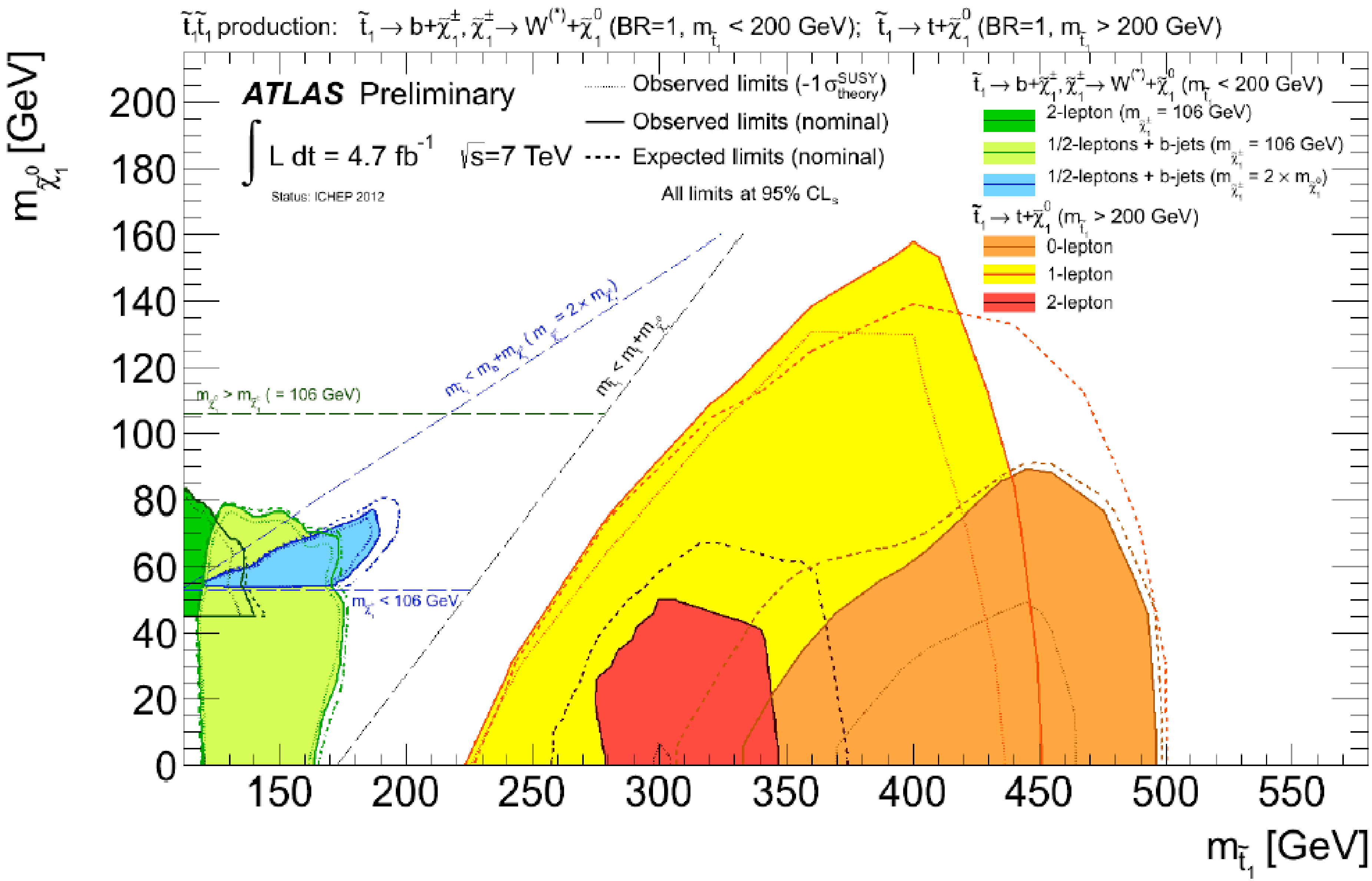
This can be measured down to tens of MeV in a threshold scan.

λ can also be determined using precision measurements of the 5 neutralino mass eigenvalues.

There are many other possibilities.

Sleptons are not yet excluded above the LEP limits.

Limits on the top squarks depend on the spectrum of color-singlet superparticles. Light top and bottom squarks are expected in Natural SUSY models.

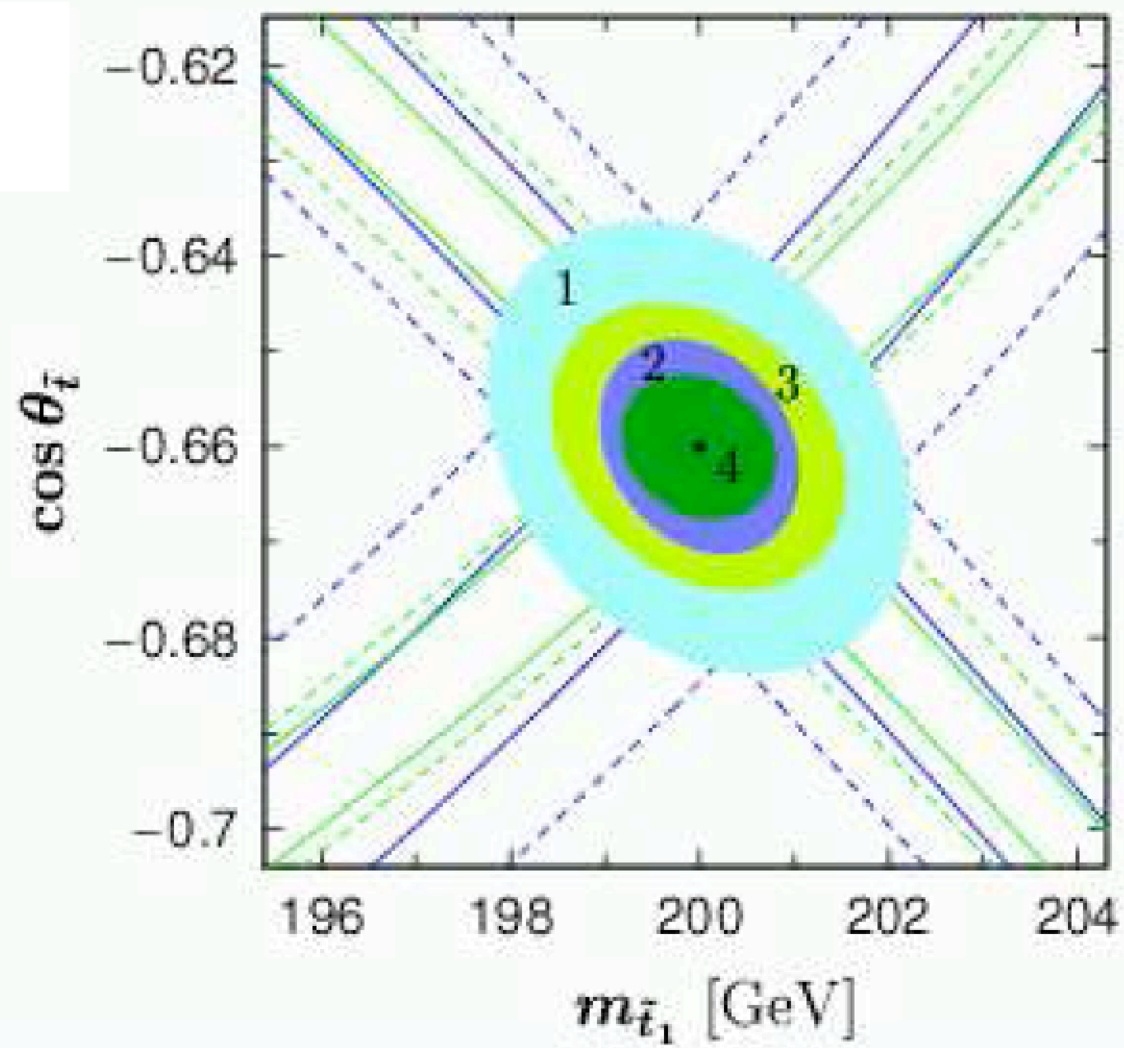


$\tilde{t}_1\tilde{t}_1$ production: $\tilde{t}_1 \rightarrow b+\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \rightarrow W^{(*)}+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1}$ < 200 GeV); $\tilde{t}_1 \rightarrow t+\tilde{\chi}_1^0$ (BR=1, $m_{\tilde{t}_1}$ > 200 GeV)
ATLAS Preliminary
$\int L\,dt = 4.7\ fb^{-1}$ $\sqrt{s}$=7 TeV
Status: ICHEP 2012
Observed limits ($-1\sigma^{SUSY}_{theory}$)
Observed limits (nominal)
Expected limits (nominal)
All limits at 95% CL_s
$\tilde{t}_1 \rightarrow b+\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \rightarrow W^{(*)}+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1}$ < 200 GeV)
2-lepton ($m_{\tilde{\chi}_1^{\pm}}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^{\pm}}$ = 106 GeV)
1/2-leptons + b-jets ($m_{\tilde{\chi}_1^{\pm}} = 2 \times m_{\tilde{\chi}_1^0}$)
$\tilde{t}_1 \rightarrow t+\tilde{\chi}_1^0$ ($m_{\tilde{t}_1}$ > 200 GeV)
0-lepton
1-lepton
2-lepton
$m_{\tilde{\chi}_1^0} > m_{\tilde{\chi}_1^{\pm}}$ (= 106 GeV)
$m_{\tilde{t}_1} < m_b+m_{\tilde{\chi}_1^{\pm}}$ ($m_{\tilde{\chi}_1^{\pm}} = 2 \times m_{\tilde{\chi}_1^0}$)
$m_{\tilde{t}_1} < m_t+m_{\tilde{\chi}_1^0}$
$m_{\tilde{\chi}_1^0}$ < 106 GeV
$m_{\tilde{\chi}_1^0}$ [GeV]
$m_{\tilde{t}_1}$ [GeV]
0
20
40
60
80
100
120
140
160
180
200
150
200
250
300
350
400
450
500
550

I remind you that measurement of the polarized cross sections

$$\sigma(e^-_L e^+_R \to \widetilde{t}_1 \widetilde{t}_1^*)\ ,\ \sigma(e^-_R e^+_L \to \widetilde{t}_1 \widetilde{t}_1^*)$$

determines the stop mixing angle. This is crucial information for understanding whether m(h) = 125 GeV is possible within the MSSM.



Bartl et al.

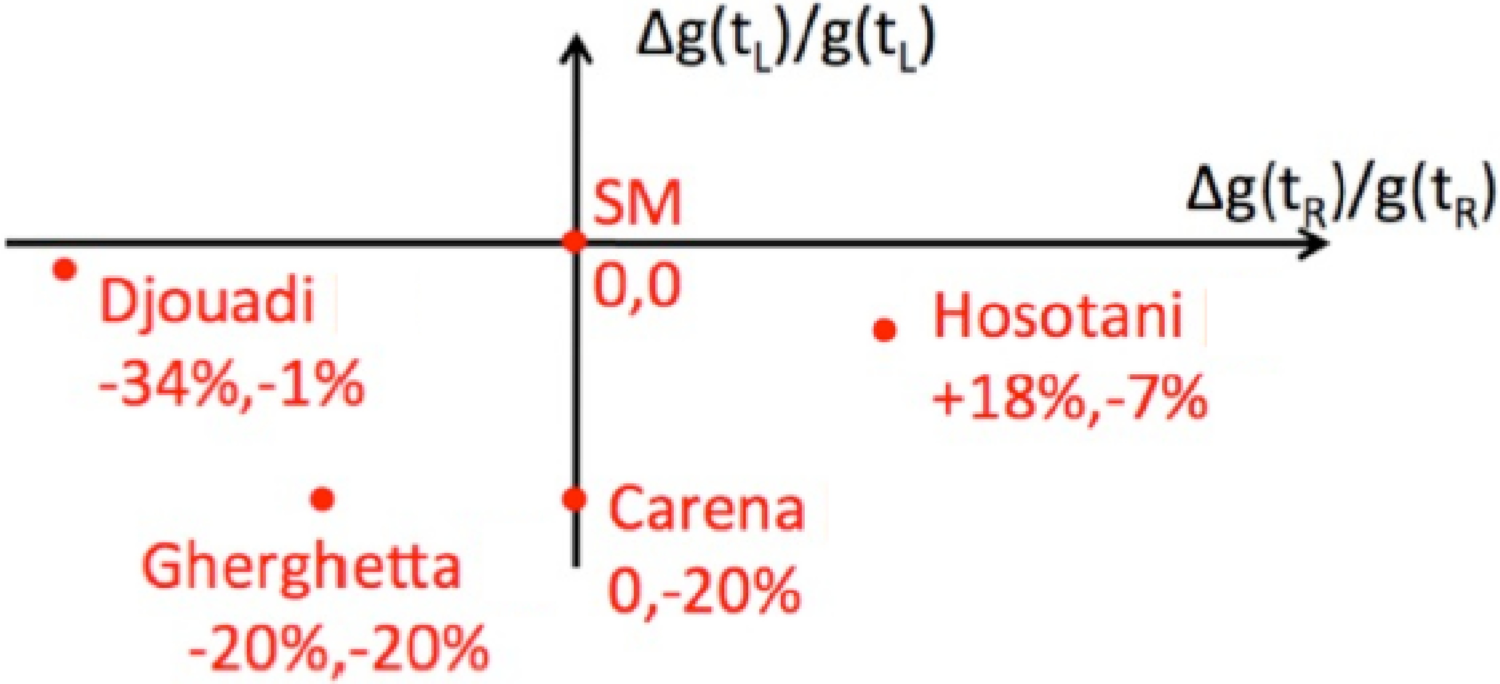
Composite Higgs models predict new vectorlike top quarks. These particles are needed to cancel the quadratically divergent corrections in the Higgs mass from the known top quark.

These particles might appear at the LHC soon, but it is equally likely that their masses are at 2 TeV or higher.

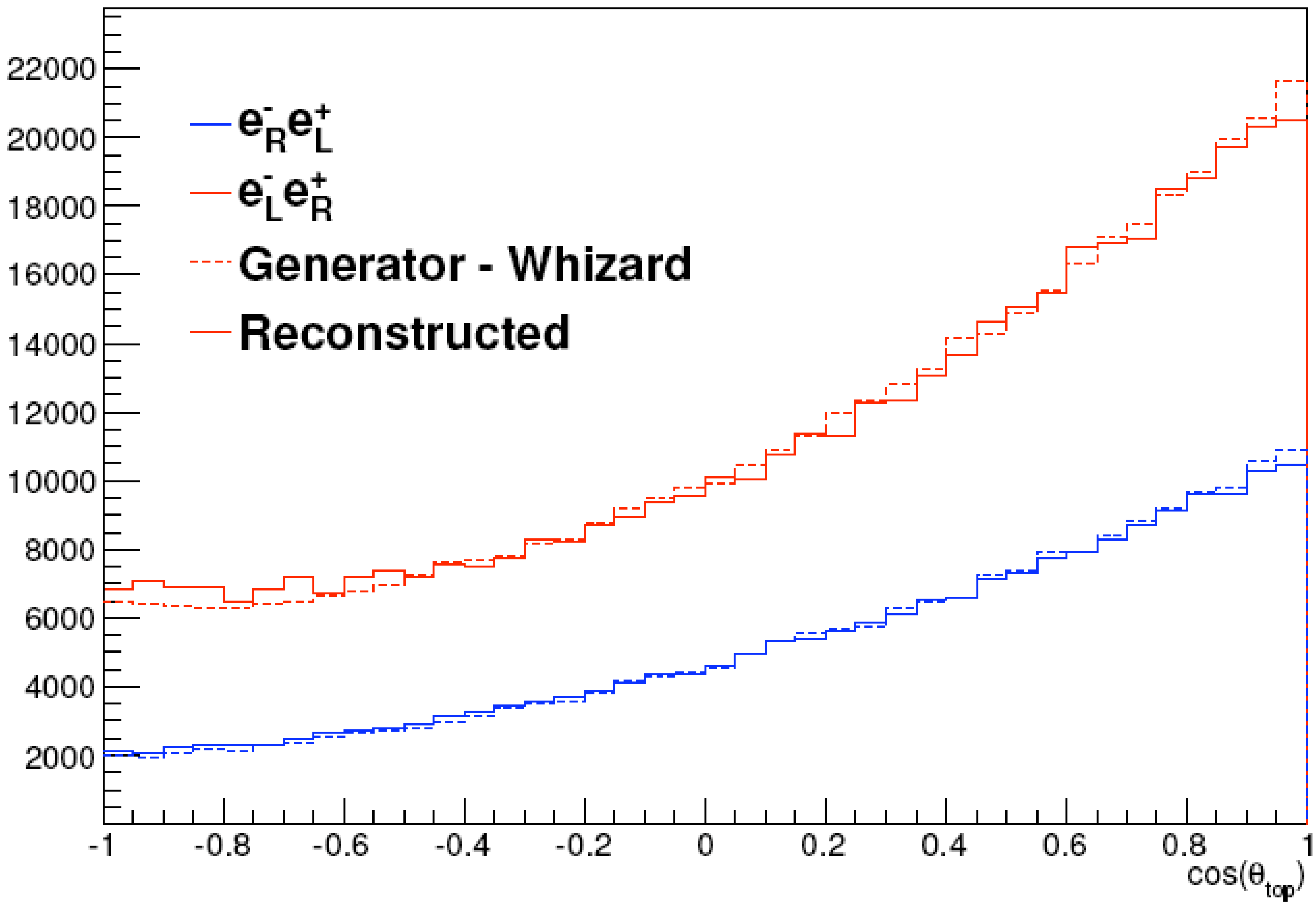
We will need to wait some time for the LHC to clarify this.

But, composite Higgs particles and associated structure must modify the couplings of Higgs, W, Z, and top. The gives anomalies that are detectable in precision experiments. We already know the energy scale needed for those experiments. It is 350-400 GeV.

Composite Higgs models predict a wide range of values for the couplings of the Z boson to the top. Here is an example of predictions from Randall-Sundrum extra-dimensional models:



These couplings can be measured to few-percent accuracy using the ILC beam polarization and the excellent ILC capabilities for tracking, calorimetry, and vertex measurements.



Conclusions:

The discovery of the Higgs boson at the LHC already leads to a compelling case for the ILC as the next step in accelerator-based high energy physics.   The ILC will be able to measure the complete phenomenological profile of the Higgs boson at the required high level of precision.

The LHC has winnowed possible models of new physics at the TeV energy scale. The models still standing crucially require information from the ILC.

The LHC discoveries of the coming decade are likely to make the case for the ILC even stronger.