Physics Motivation for the ILC

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In 2001, the major physics advisory panels in Europe, the US, and Japan issued reports with a common conclusion:

The next major project in high energy physics should be an electron-positron linear collider with a CM energy of 500 GeV.

These reports set in motion a process of global planning and R&D that culminates in the presentation of the ILC TRD at this meeting.

The major points of the ILC physics case have been debated over the past decade.

We are re-examining them now in the light of the new results from the LHC.

The discovery of the "Higgs-like particle" at 125 GeV brings focus to the discussions.

The vision of the importance of ILC physics has been confirmed.

The motivations for the ILC come from two sources:

1. The recently discovered "Higgs-like boson" at 125 GeV.

2. The search for new physics beyond the Standard Model.

The arguments concerning the Higgs boson are the most straightfoward.

The arguments concerning the search for new physics are equally compelling.

Both are described in the Physics Volume of the ILC TDR.

1. The Higgs Boson

In this lecture, I will assume that the new resonance at 125 GeV is a Higgs boson -- the particle of a scalar field whose vacuum expectation breaks the SU(2)xU(1) symmetry of the electroweak interactions.

If this is not true, nevertheless, there must be at least one Higgs boson, its mass must be in the ILC energy range, and it must be copiously produced in e+e- collisions.

In this interesting case, both new bosons will be seen and will be studied at the ILC.

The Higgs boson is part of the "Standard Model", but it is too naive to say that we know all of its properties:

The gauge interactions of quarks, leptons, and gauge bosons follow from the SU(3)xSU(2)xU(1) symmetry of the Standard Model They depend only on the gauge group and quantum number assignments.

The quark and lepton masses and mixing come from their Higgs boson interactions. The Standard Model predictions for these is based only on the conjecture that a single Higgs field gives the full picture.

Lev Okun (1981) : "Problem number 1"

There are two ways that we can make progress in understanding the origin of quark and lepton masses:

1. Discover new particles that extend the Standard Model.

We hoped these would appear in the first stage of the LHC. Now, apparently, we must wait for 2016 or later.

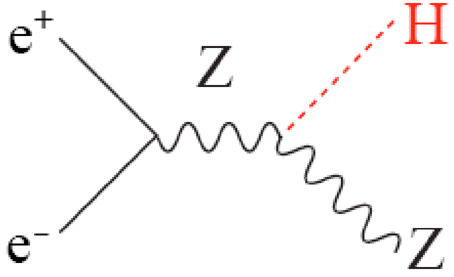
2. Study the new particle at 125 GeV that we have discovered.

This particle is likely to be the origin of mass. It could well be a gateway to new physics.

The Standard Model predicts that the Higgs boson couplings to each species are exactly proportional to the mass of that species. We need to test this prediction until it breaks.

In particular, we need a comprehensive program that can test each individual coupling of the Higgs boson to the percent level.

The ILC is the only machine proposed today that can do this.



At 250 GeV, study $e^+e^- \to Zh$

tagged Higgs production, branching ratios

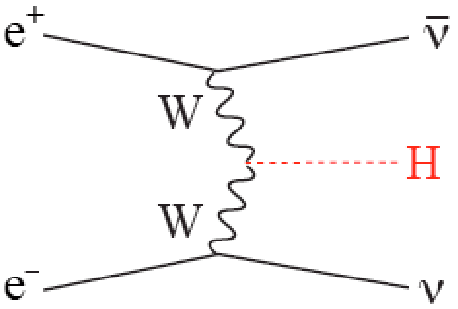
At 500 GeV, add $e^+e^- \to \nu\overline{\nu}h$, $e^+e^- \to t\overline{t}h$, $e^+e^- \to Zhh$

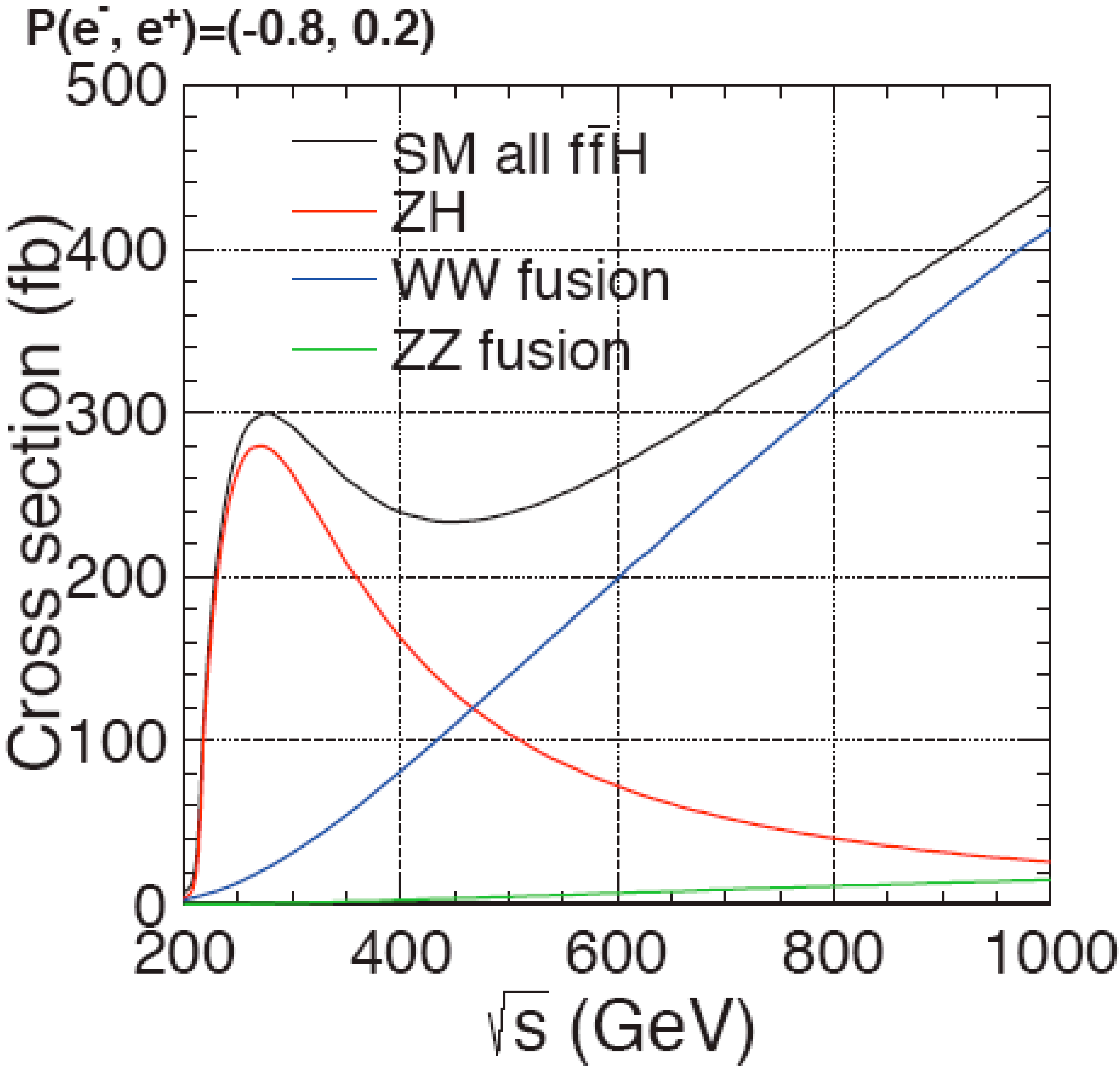
absolute normalization of couplings, begin t and h couplings

At 1000 GeV, add $e^+e^- \to \nu\overline{\nu}hh$, $e^+e^- \to \nu\overline{\nu}\mu^+\mu^-$

high statistics, refined t, h, μ couplings

All of the steps are needed for a full program.




P(e$^-$, e$^+$)=(-0.8, 0.2)
SM all $f\bar{f}H$
ZH
WW fusion
ZZ fusion
Cross section (fb)
0
100
200
300
400
500
200
400
600
800
1000
$\sqrt{s}$ (GeV)

What is the imporance of percent accuracy ? This is the typical scale of deviations in the Higgs couplings if only very massive new particles are seen at the LHC.

Examples:

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:

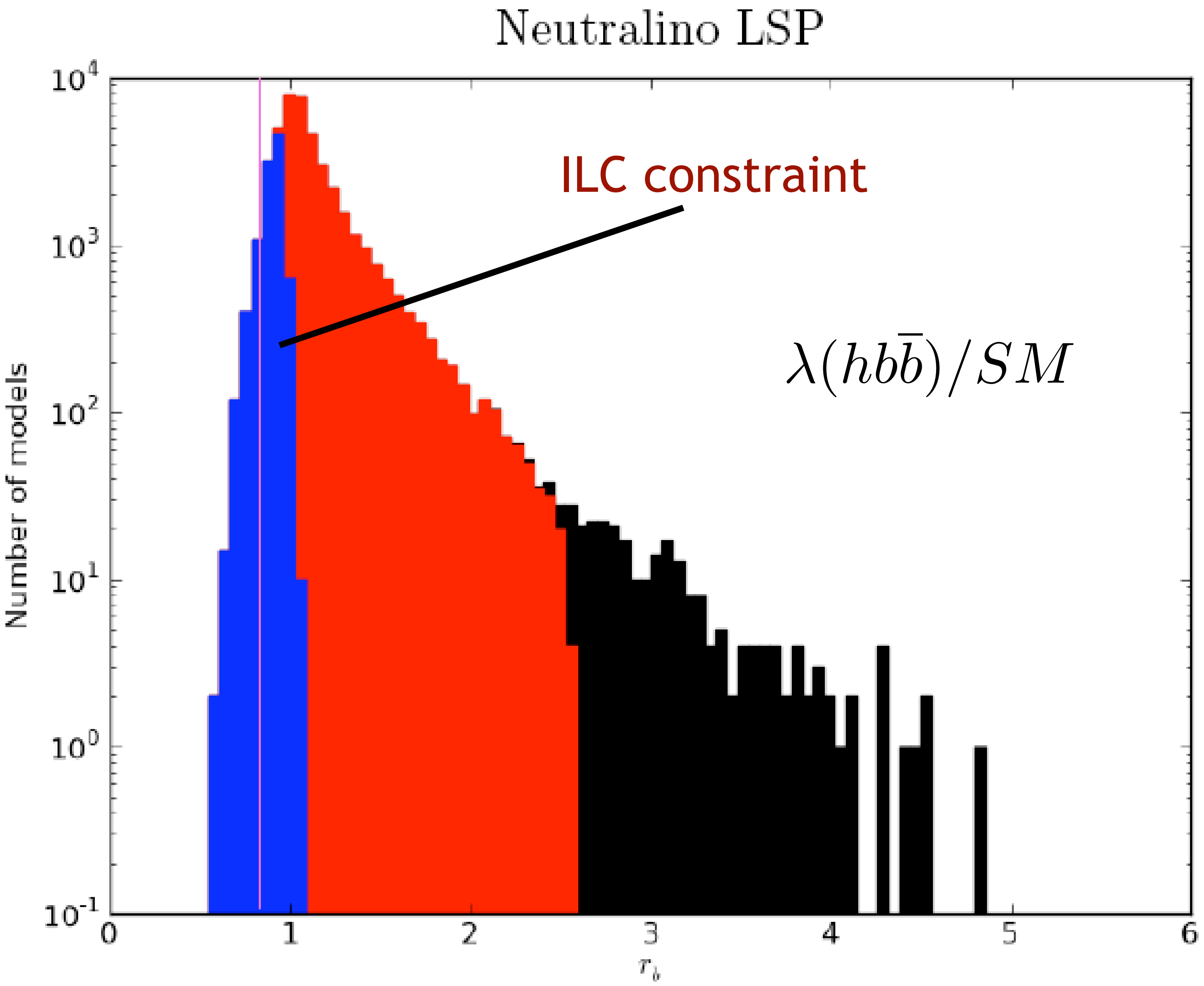
$$g(g)/SM = 1 + (5-9)\%$$

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

Composite Higgs:

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

reach: roughly 3 TeV in new particle masses for the most sensitive deviations.



ILC constraint

$\lambda(hb\bar{b})/SM$

Cahill-Rowley et al. pMSSM

Many Higgs reactions are measured at LHC ? Isn't this sufficient ?

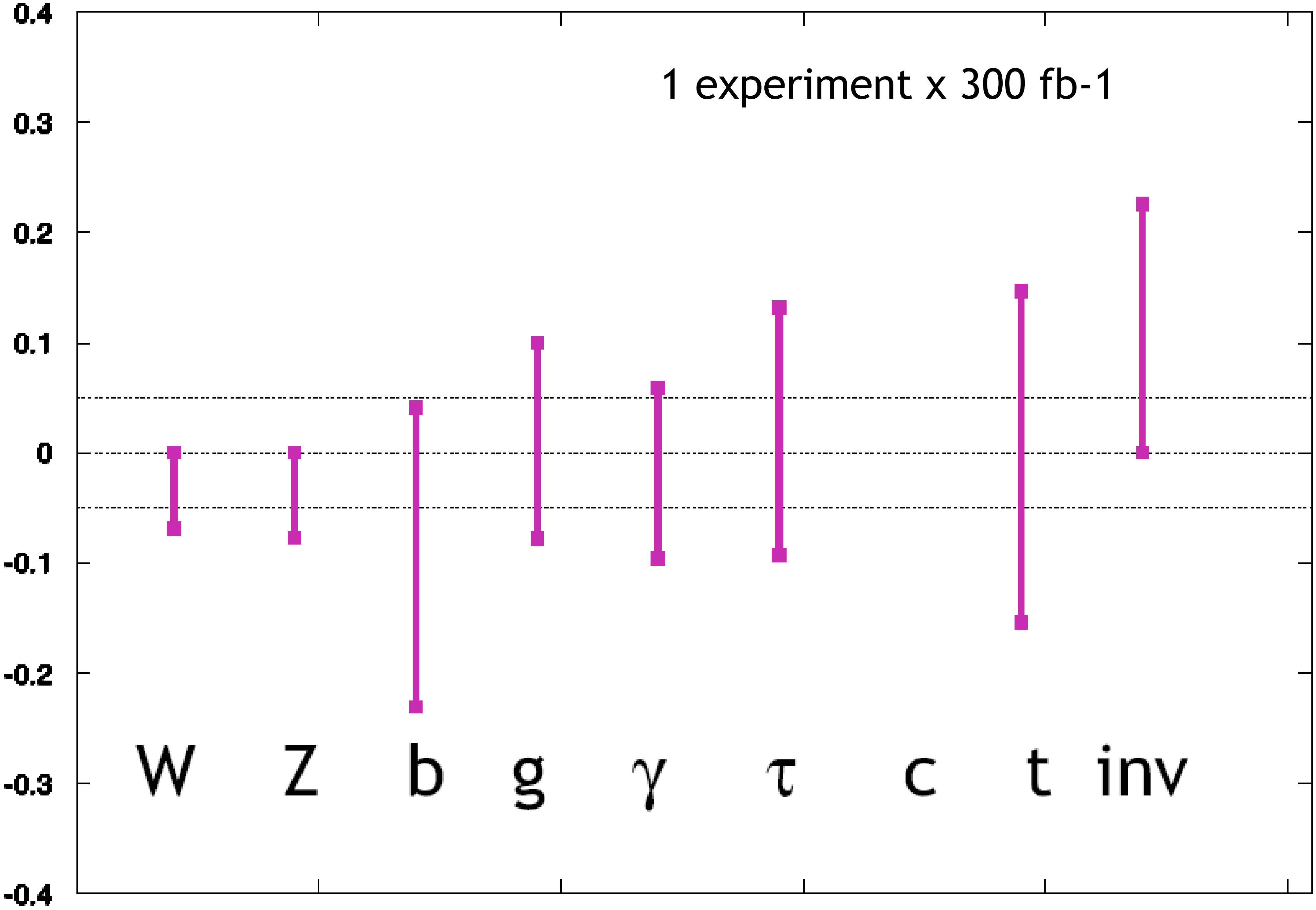
LHC experiments measure $\sigma(A\overline{A} \to h) BR(h \to B\overline{B})$
which depends on Higgs couplings through:

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

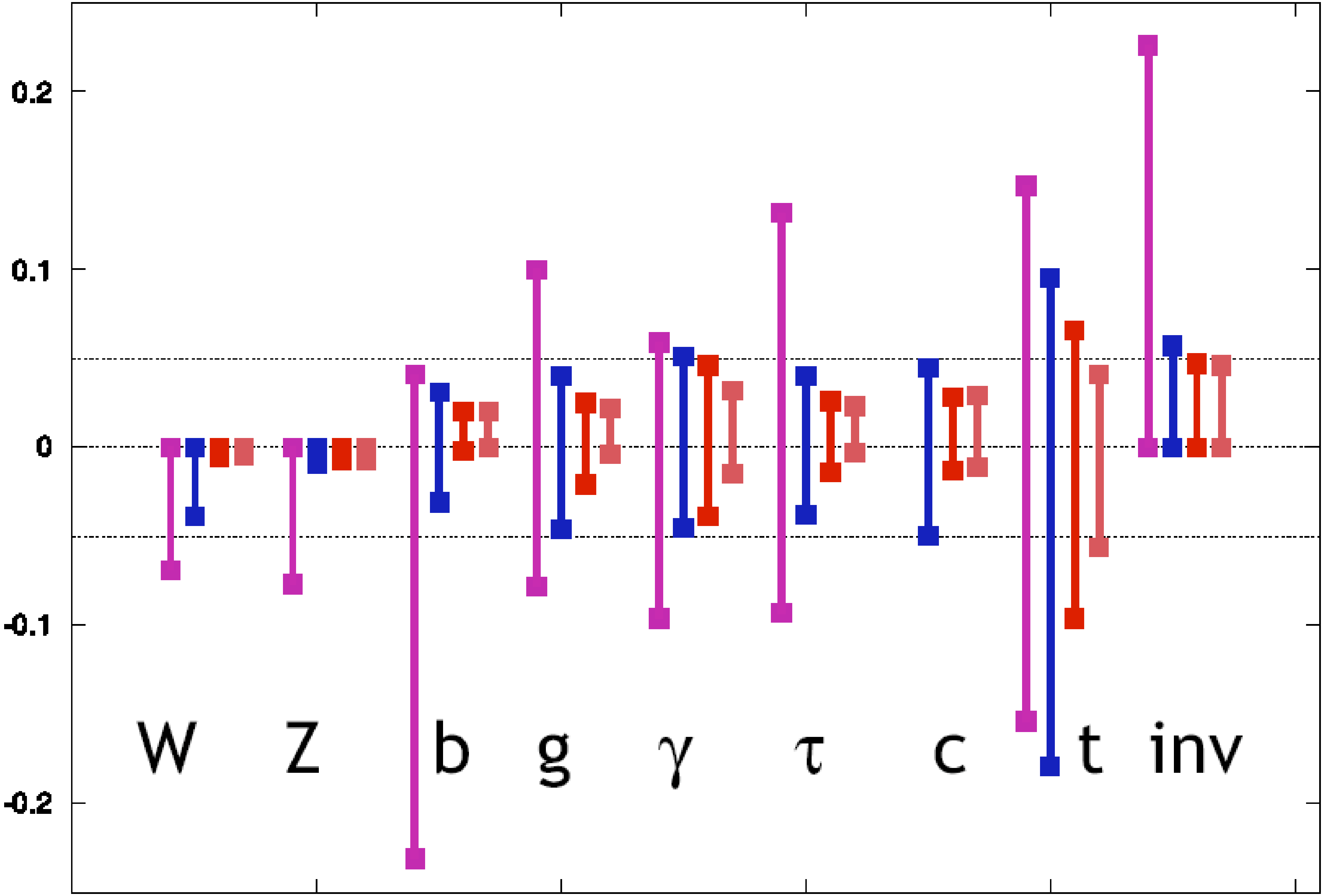
Requires a global fit, plus some theoretical assumptions to control the total width.

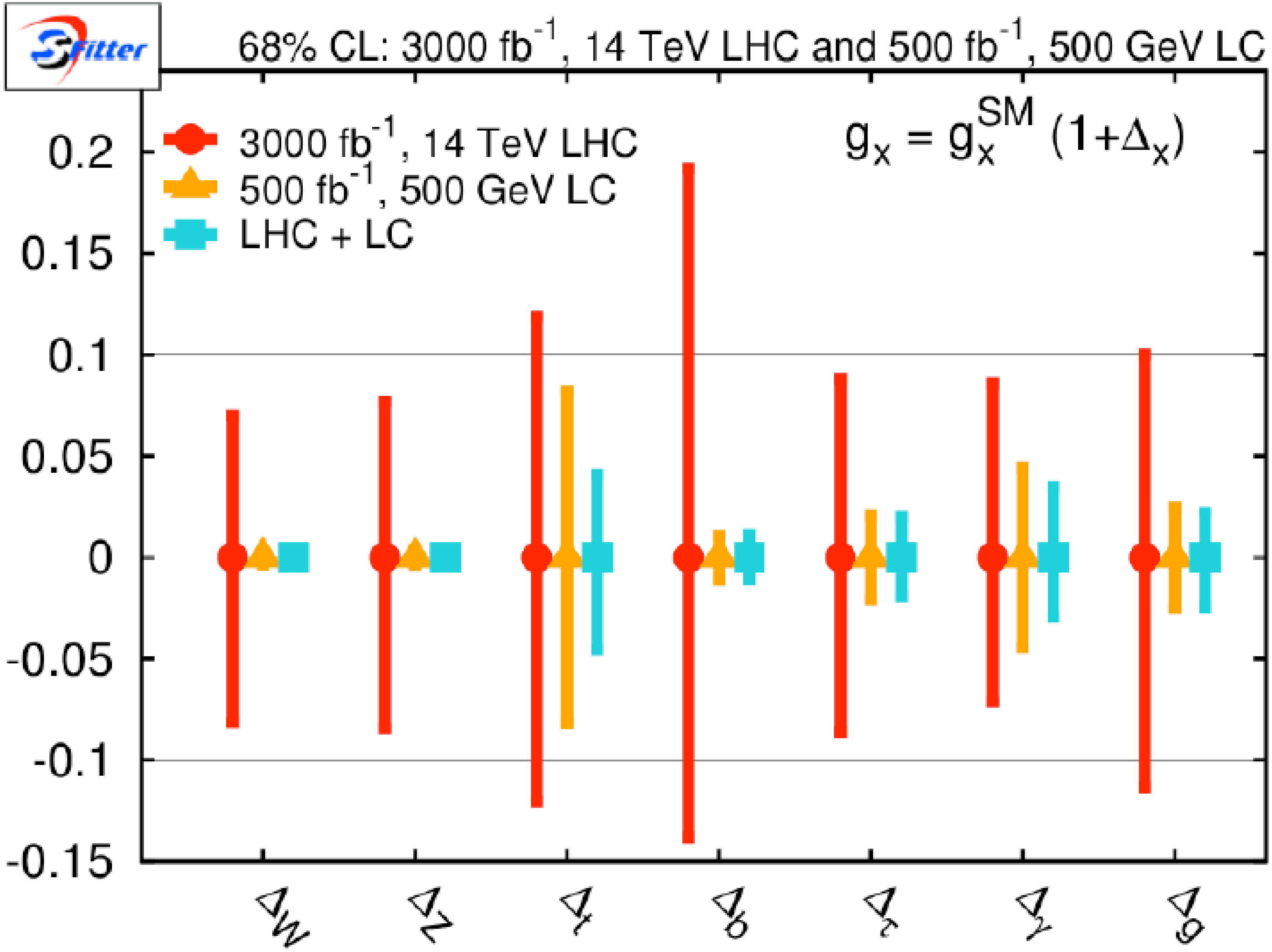
Even in the best case, it is difficult for LHC to reach the required level of precision.

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



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



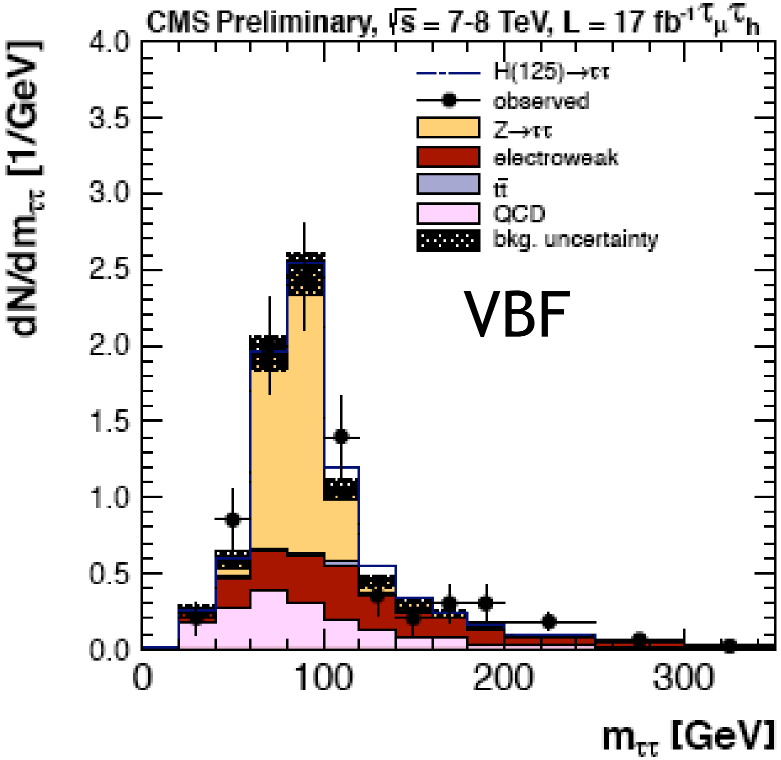


Sfitter - Zerwas

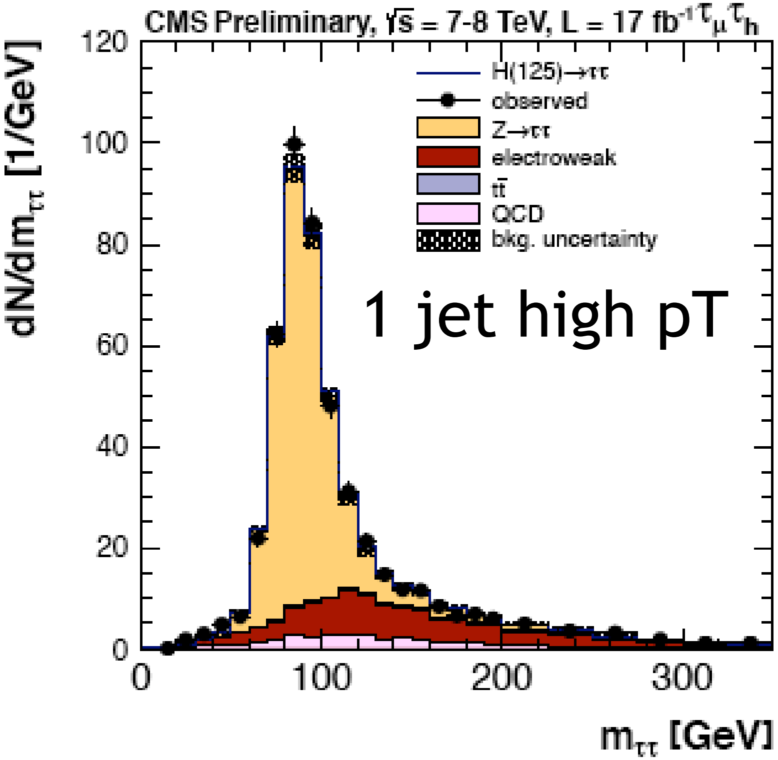
And, do not forget the qualitative differences between electron-positron and hadron collider experimentation.

In pp, Higgs production is 10^{-9} of the total cross section.

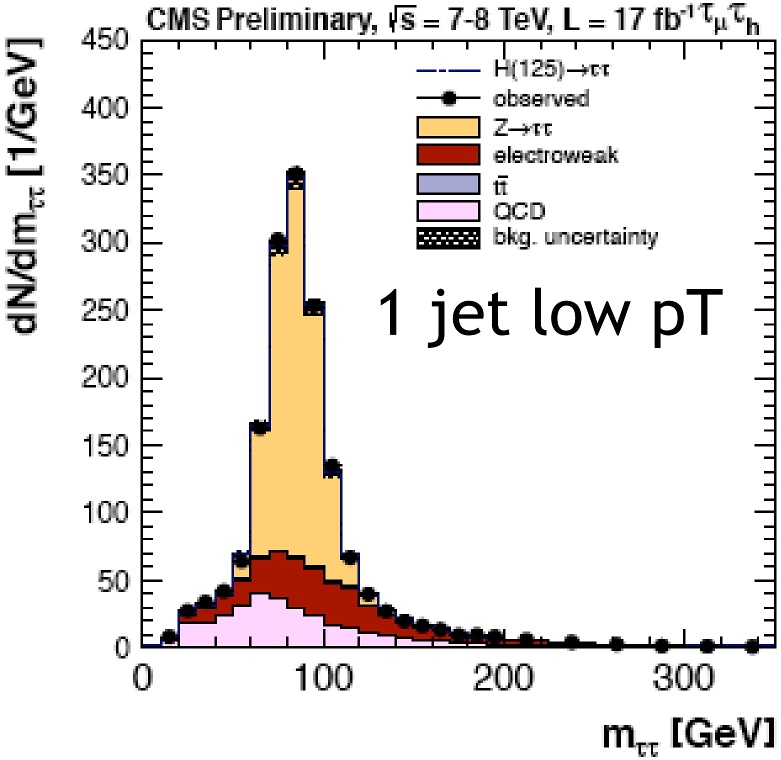
In e^+e^-, Higgs production is 1% of the total cross section.



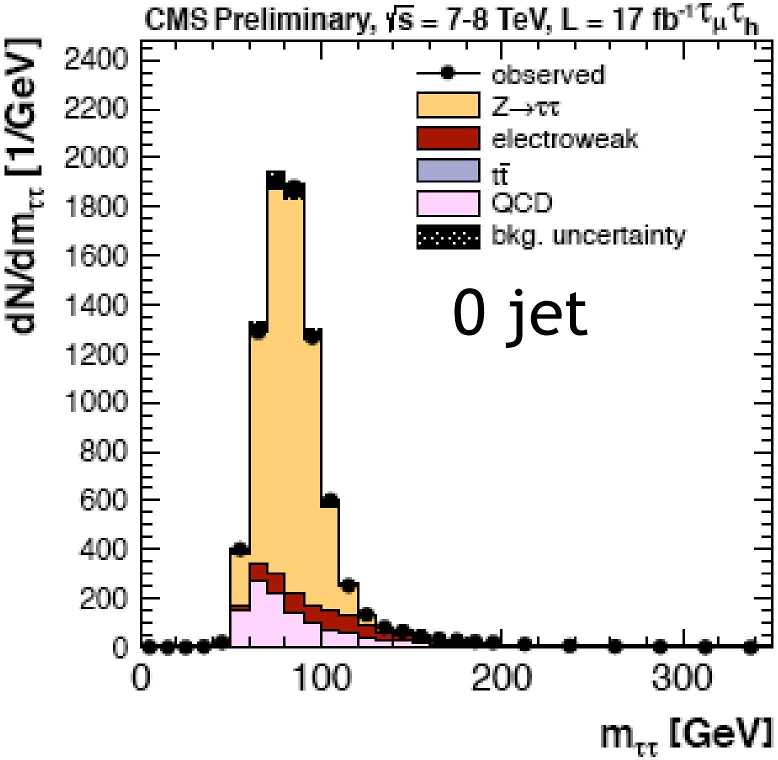
VBF



1 jet high pT

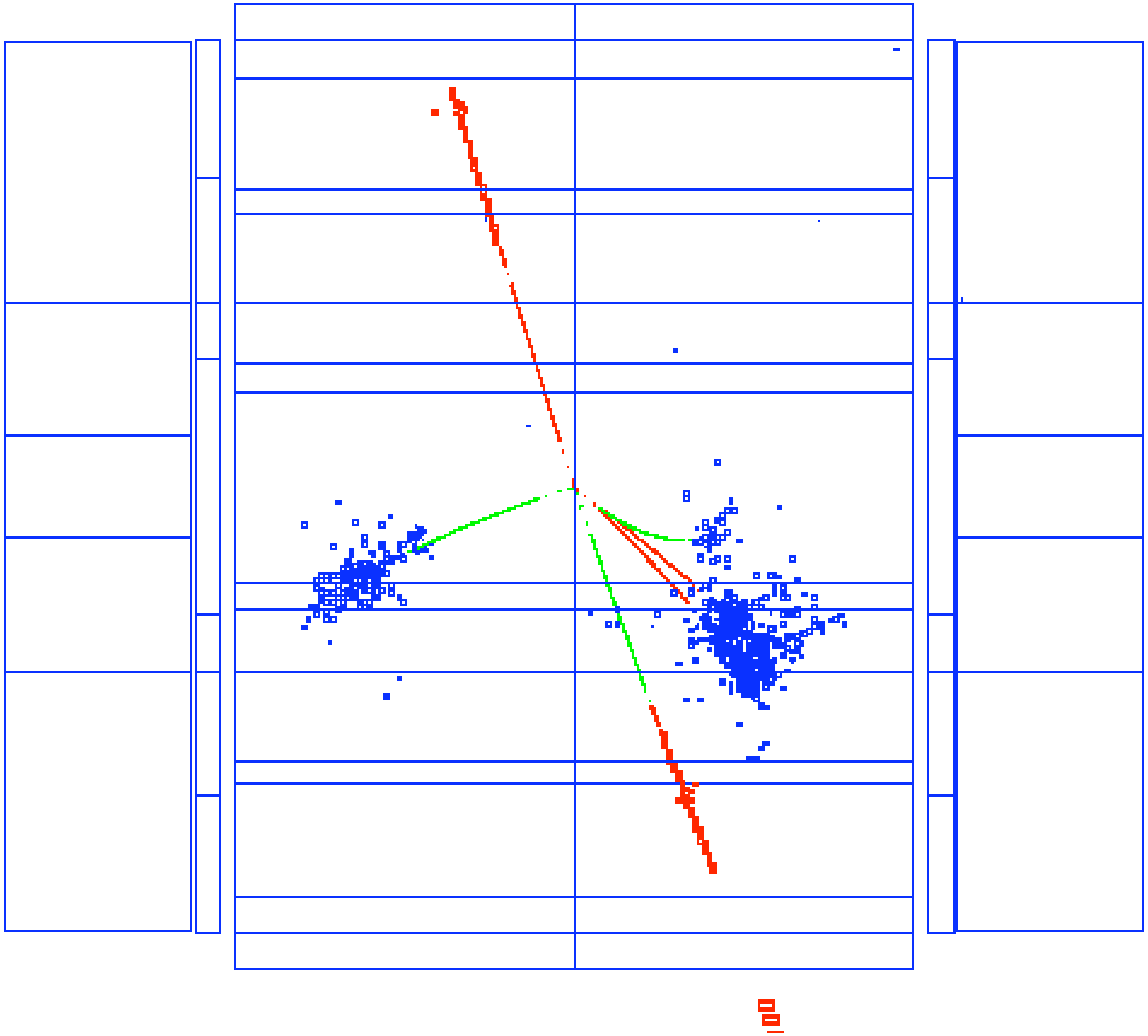


1 jet low pT

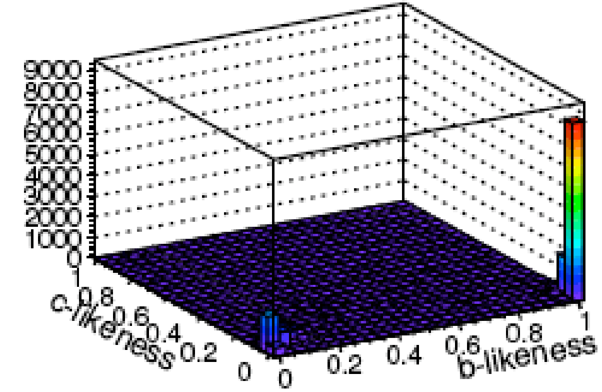


0 jet

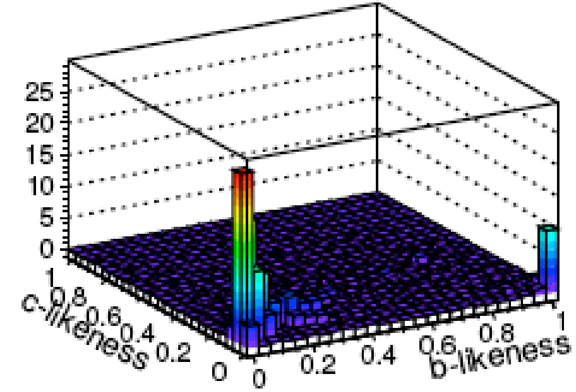
CMS



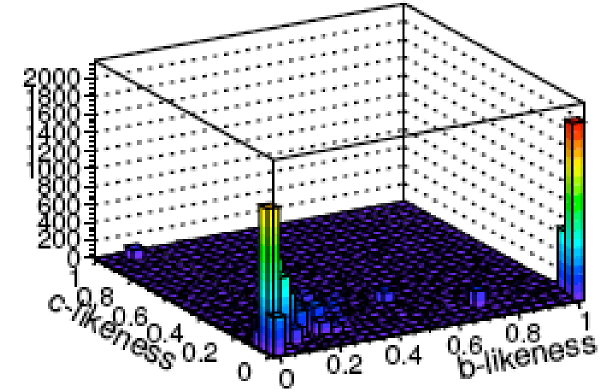
Data



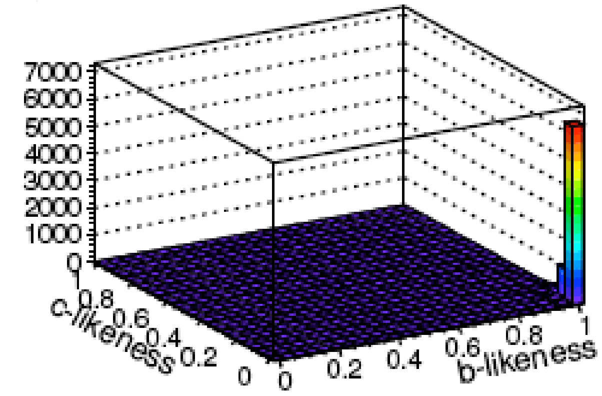
h→ others



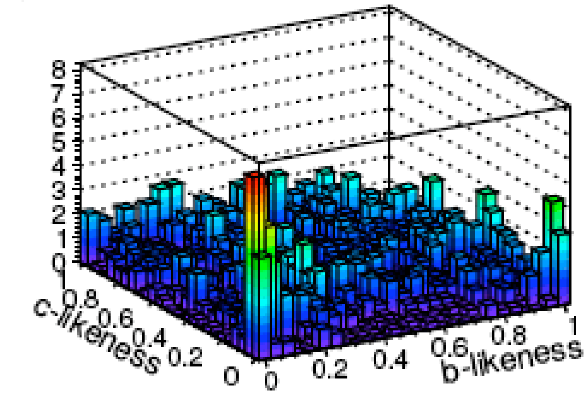
SM BG



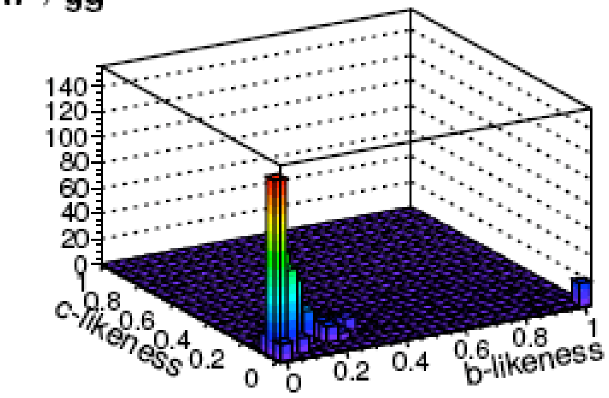
h→ bb



h→ cc



h→ gg



Asian ILD group

In addition, the ILC offers:

At 250 GeV, sensitivity to invisible and all unexpected decay modes of the Higgs to the 1% level.

At 1000 GeV, sensitivity to
    the $t\bar{t}h$ coupling to 4%
    the $\mu\mu h$ coupling to 20%
    the Higgs self-coupling at 24%

2. New physics beyond the Standard Model

The exploration of new particles at the LHC has put us into a new era of the study of physics beyond the Standard Model.

So far, the LHC has given us no discoveries (beyond the Higgs boson) and many exclusions.

However, the basic incompleteness of the Standard Model has not gone away.

We need to analyze: What models are still alive? What can the ILC do to study new particles and interactions within those models ?

There is a simple argument, expressed often:

The LHC operates at a higher parton-parton center of mass energy than the ILC. If the LHC sees nothing, the ILC has no chance.

This argument is not completely incorrect, but it is naive.

It ignores the difficulty that the LHC experiments have in detecting

color singlet particles
particles with small mass differences
particles of a Higgs sector larger than the Standard one

It also ignores the power of precision top and W physics at the ILC.

There is no time here for a full discussion of this question. Please see the analysis in the Physics Volume of the TDR.

Here are some snapshots:

observations on supersymmetry models:

1. No theorist who believed in supersymmetry in 2008 has renounced supersymmetry in the light of current LHC results.

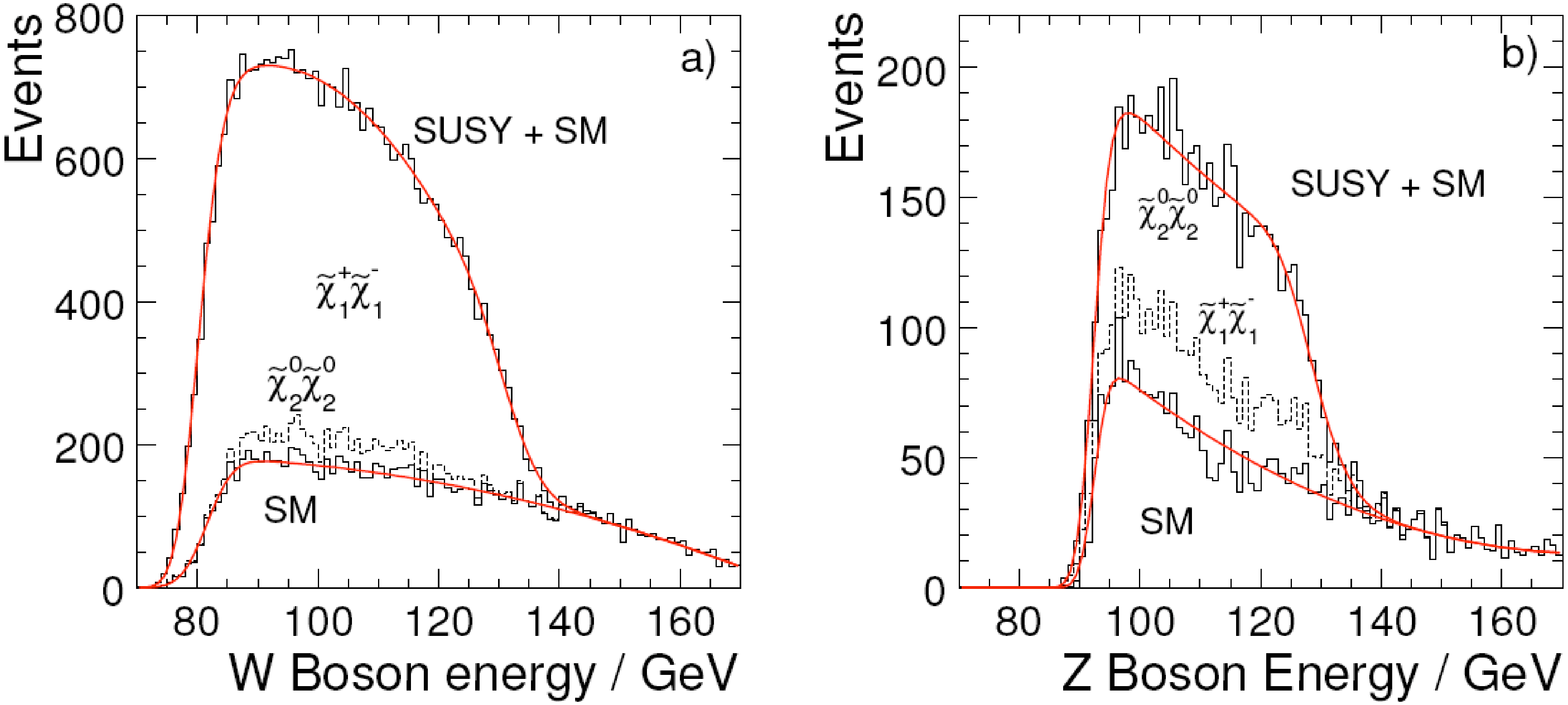
2. Young SUSY theorists are still proposing models with charginos below 250 GeV ("natural SUSY")

Cohen, Hook, Torroba, arXiv:1204.1337 μ = 220 GeV

Randall, Reece, arXiv:1206.6540 μ = 148 GeV

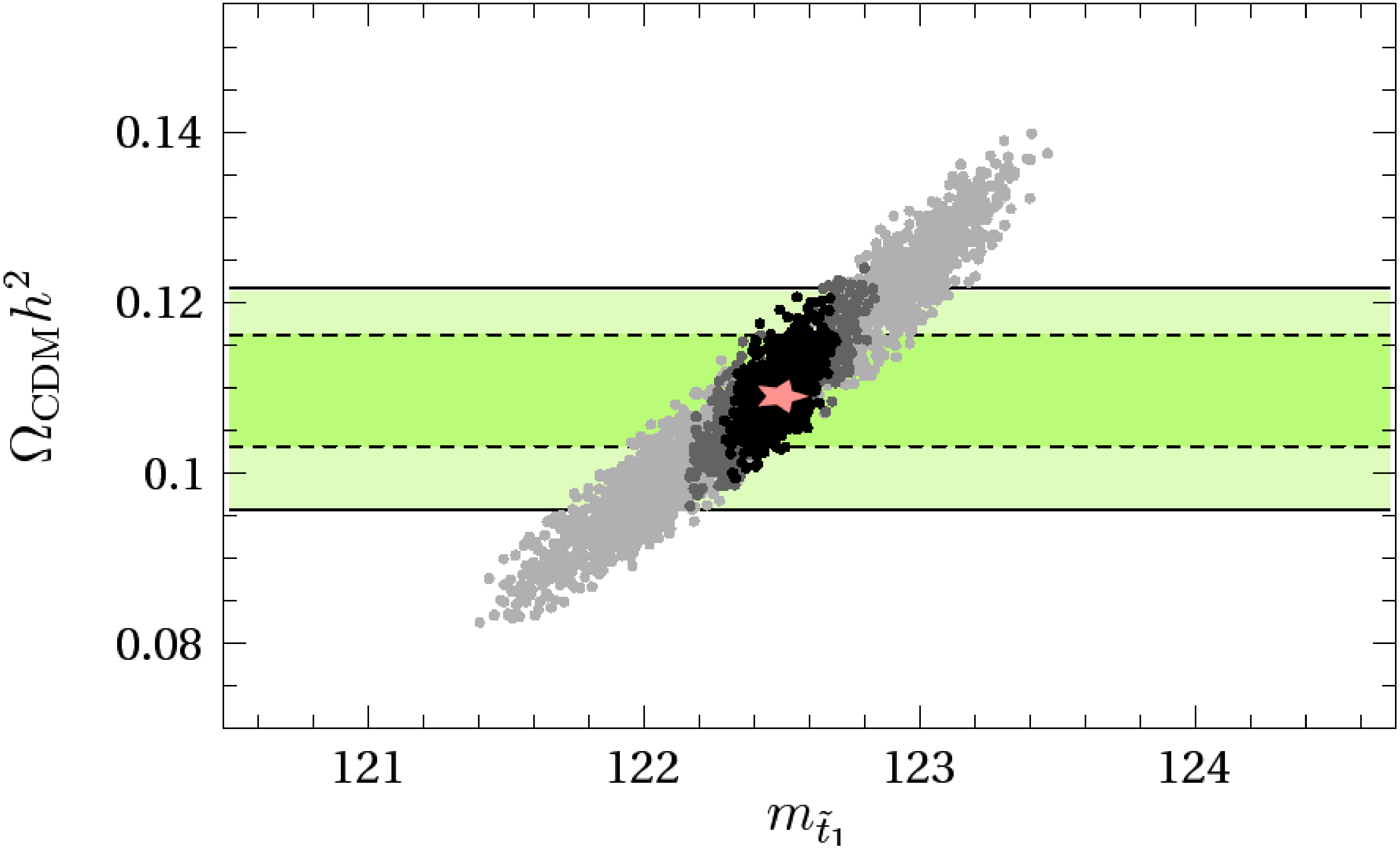
Craig, McCullough, Thaler, arXiv:1203.1622 μ = 200-300 GeV

In these models, ILC is not only a Higgs factory but also a Higgsino factory.



Suehara and List

prediction of dark matter relic density in a stop co-annihilaton scenario:

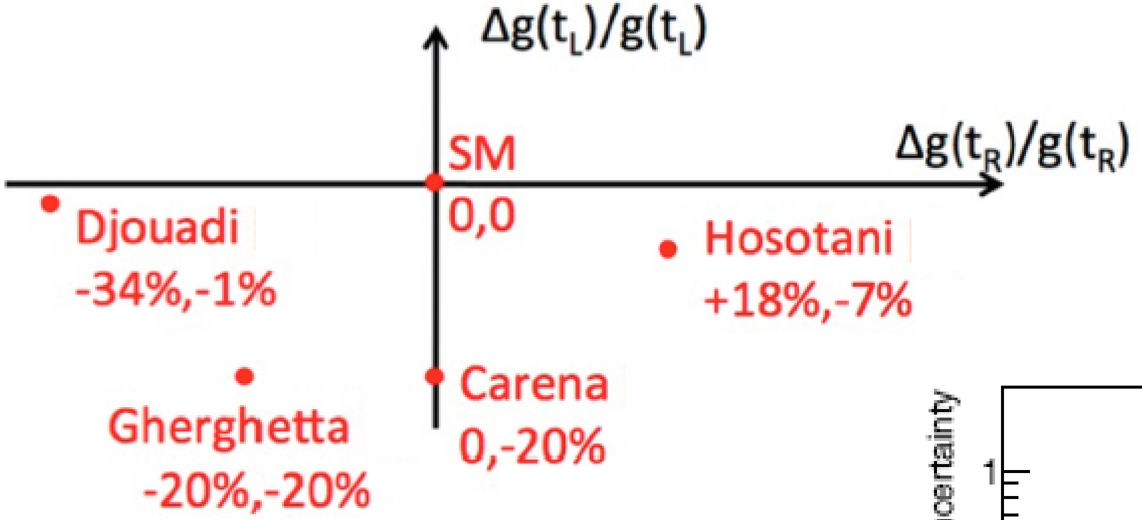


Frietas et al.

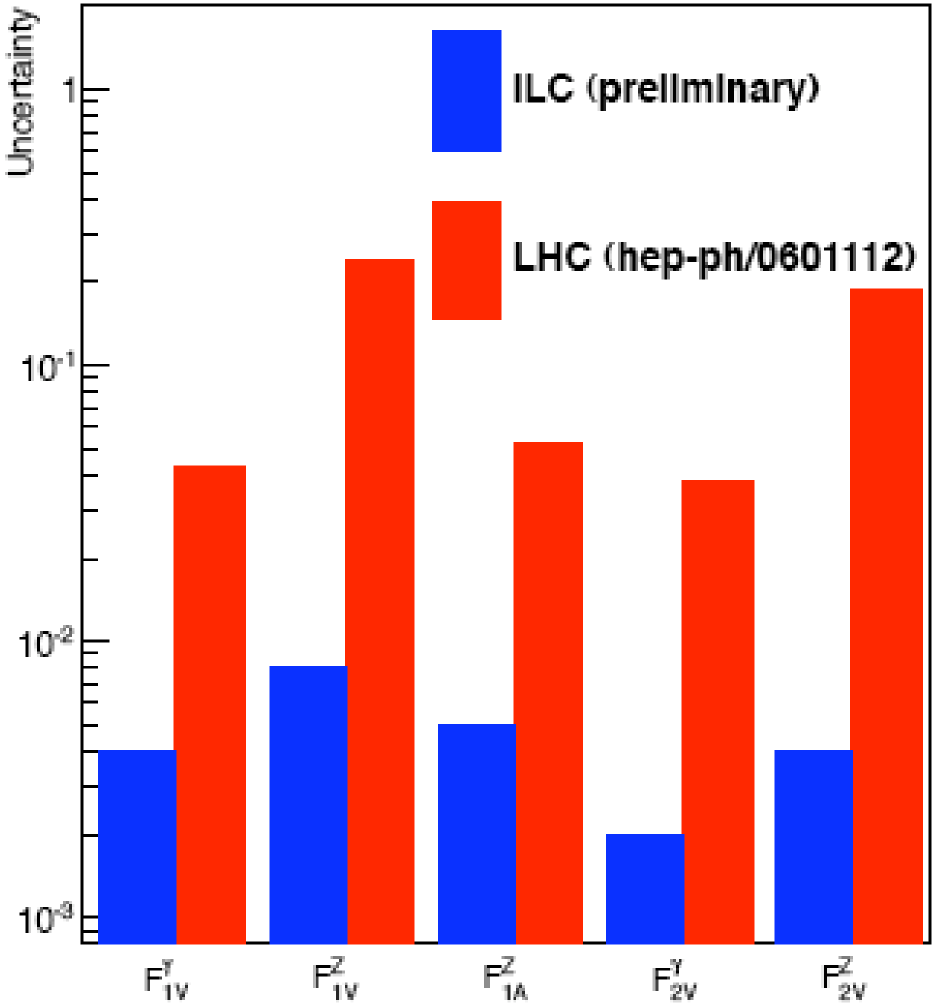
The alternatives to SUSY are models with an effective or composite light Higgs boson -- Little Higgs, Randall-Sundrum, etc.

These models predict new W, Z, t bosons at multi-TeV masses.
LHC is not yet challenging these models.

These models also predict substantial corrections to the couplings of the familiar W, Z, t.   We can search for these at ILC energies.



predicted deviations in $t\bar{t}Z$ couplings, and LHC and ILC sensitivity



Richard

Conclusions:

ILC offers a systematic program of Higgs boson studies. ILC gives the complete profile of Higgs boson couplings with high precision in a model-independent way. No other currently proposed collider has that capability.

ILC has an important role in the study of physics beyond the Standard Model. LHC has excluded many possible models. Of those that remain, many have crucial measurements for which ILC is needed.

We are grateful to Barry Barish and his team for their foresight and persistence in developing this technology.

I thank the editorial team for the Physics Volume:

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Extended Higgs: Shinya Kanemura, Aurore Savoy-Navarro
Supersymmetry: Howard Baer, Jenny List
Cosmology: Geraldine Servant, Tim Tait

and the many authors cited in the report who have investigated the physics capabilities of the ILC !