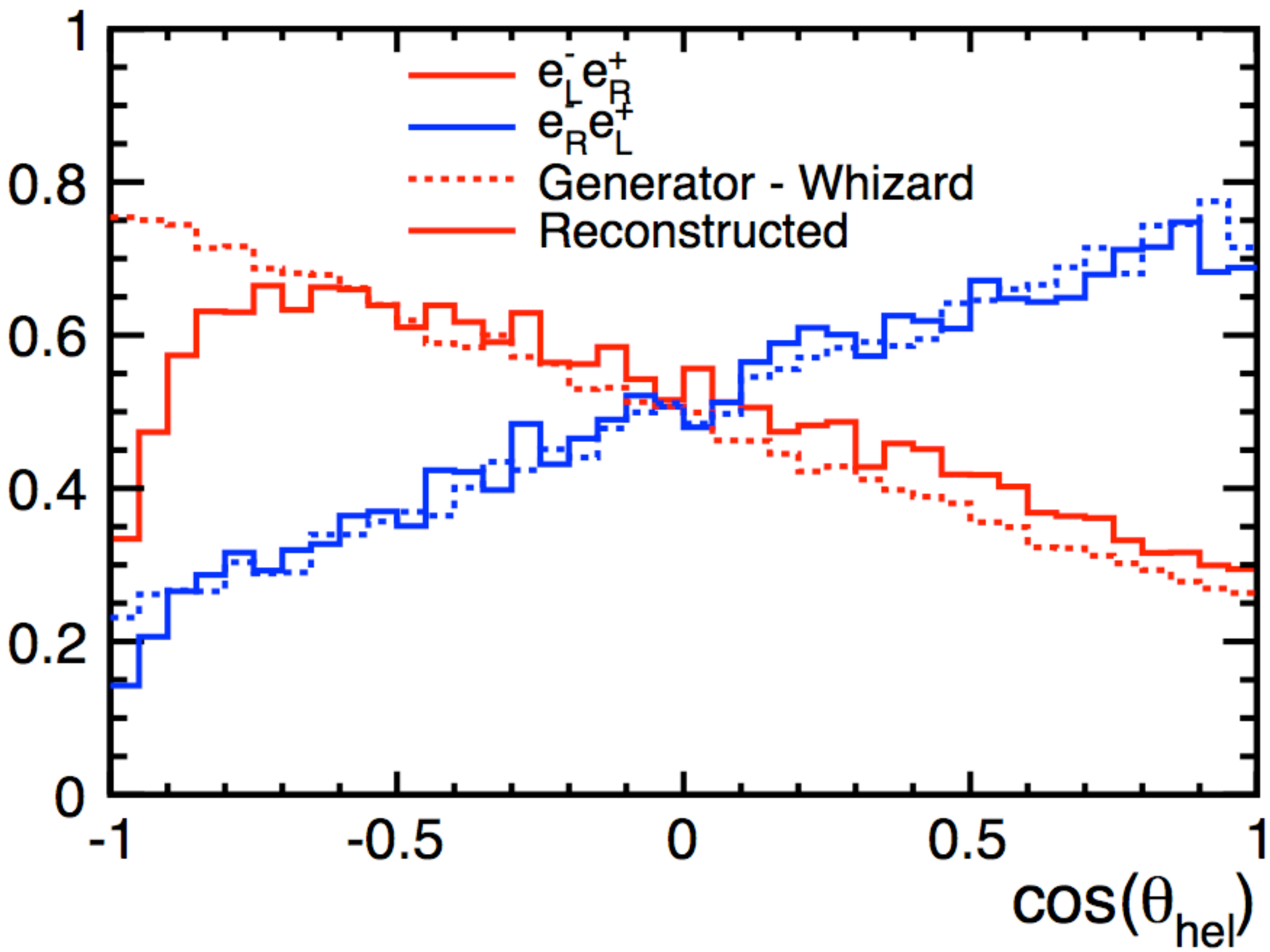
Physics Overview for Future Lepton Colliders



M. E. Peskin

MIT Lepton Collider Workshop
Snowmass Frontier Capabilities
April 2013

This is a workshop on accelerator capabilities for future lepton colliders. The requirements for future colliders are not only technical. They must be informed by the physics goals.

I am here in my role as convener -- with Chip Brock -- of the Energy Frontier segment on the Snowmass 2013 study. In this talk, I will discuss:

1. What are the structure and goals of the Energy Frontier study ?
2. What are the key physics objectives of lepton collider experiments ?
3. What do we need from your part of the study ?

The structure of our study is set out in detail on the Snowmass wiki:

http://www.snowmass2013.org/tiki-index.php?page=Energy+Frontier

Here are the highest-level goals, as expressed in the concluding talk at our recent workshop at Brookhaven:

Goals of the Energy Frontier study:

We need to articulate a scientific program and its motivation:

I. What scientific targets can be achieved before 2018 ?

II. What are the science cases that motivates the High Luminosity LHC ?

III. Is there a scientific necessity for a "Higgs Factory" ?

IV. Is there a scientific case today for experiments at higher energies beyond 2030 ?

For these issues, we must clarify in our own minds:

Where is the physics beyond the Standard Model ?

What did we learn from LHC 7/8 TeV ?

What does this tell us about the next step ?

Community goals:

I. Present our case to our HEP colleagues

II. Justify our ambitions to government

III. Explain our goals to scientists in other fields and to the general public

These require:

A clear expression of why we do what we do.

"Discovery stories" :

Concrete illustrations of discoveries that could take place before 2020,
and the experiments that would pursue the new direction that is opened

White paper on US participation in global projects

The physics topics that we are studying are divided among 6 working groups:

1. The Higgs Boson

Conveners: Sally Dawson (BNL), Andrei Gritsan (Johns Hopkins), Heather Logan (Carleton), Jianming Qian (Michigan), Chris Tully (Princeton), Rick Van Kooten (Indiana)

2. Precision Study of Electroweak Interactions

Conveners: Ashutosh Kotwal (Duke), Michael Schmitt (Northwestern), Doreen Wackeroth (SUNY Buffalo)

3. Fully Understanding the Top Quark

Conveners: Kaustubh Agashe (Maryland), Robin Erbacher (UC Davis), Cecilia Gerber (Illinois-Chicago), Kirill Melnikov (Johns Hopkins), Reinhard Schwienhorst (Michigan State)

4. The Path Beyond the Standard Model - New Particles, Forces, and Dimensions

Conveners: Yuri Gershtein (Rutgers), Markus Luty (UC Davis), Meenakshi Narain (Brown), Liantao Wang (Chicago), Daniel Whiteson (UC Irvine)

5. Quantum Chromodynamics and the Strong Force

Conveners: John Campbell (Fermilab), Kenichi Hatakeyama (Baylor), Joey Huston (Michigan State), Frank Petriello (ANL/Northwestern)

6. Flavor Mixing and CP Violation at High Energy

Conveners: Marina Artuso (Syracuse), Michele Papucci (LBL), Soeren Prell (Iowa State)

Technical Advisors

detectors and experimentation: Jeff Berryhill (Fermilab), Tom LeCompte (ANL), Eric Torrence (Oregon), Sergei Chekanov (ANL), Sanjay Padhi (UC San Diego)

accelerators: Eric Prebys (Fermilab), Tor Raubenheimer (SLAC)

and thank you to: Markus Klute, Mark Palmer

Our charge to the working group conveners includes:

Chip and Michael emphasize that you will own your working group reports. You have the final decision about all conclusions in these reports, and they will be public documents. We will reflect your conclusions in our summary report.

Energy Frontier Facilities List:

Hadron Colliders:

- LHC 13 TeV, 300/fb , spacing: 25 ns (50 ns), pileup: 19 (38) events/crossing
- LHC 13 TeV, 3000/fb (HL-LHC) , spacing: 25 ns, pileup: 95 events/crossing
- LHC 33 TeV, 3000/fb (HE-LHC) , spacing: 50 ns, pileup: 225 events/crossing
- VHE-LHC 100 TeV, 3000/fb, spacing: 50 ns, pileup: 263 events/crossing
- VLHC at 100 TeV, 1000/fb , spacing: 19 ns, pileup: 40 events/crossing

Lepton Colliders:

e+e- at 250 GeV (ILC: 500/fb , LEP3: 500/fb, TLEP: 2500/fb),
e-/e+ polarization: ILC: 80%/30%, LEP3, TLEP: 0/0

e+e- at 350 GeV (ILC: 350/fb, CLIC: 350/fb, TLEP: 350/fb) ,
e-/e+ polarization: ILC: 80%/30%, CLIC: 80%/0, TLEP: 0/0

e+e- at 500 GeV (ILC: 500/fb), e-/e+ polarization: ILC: 80%/30%

e+e- at 1000 GeV (ILC: 1000/fb) , e-/e+ polarization: ILC: 80%/20%

e+e- at 1400 GeV (CLIC: 1400/fb) , e-/e+ polarization: CLIC: 80%/0%

e+e- at 3000 GeV (CLIC: 3000/fb) , e-/e+ polarization: CLIC: 80%/ 0%

mu+mu- at 125 GeV 2/fb , 0 polarization

mu+mu- at 1500 GeV 1000/fb , 0 polarization

mu+mu- at 3000 GeV 3000/fb , 0 polarization

Gamma Colliders:

gamma-gamma at 125 GeV, 100/fb ,
80% e- polarization to generate the photon beams

gamma-gamma at 200 GeV, gamma-e at 225 GeV, 200/fb ,
80% e- polarization to generate the photon beams

gamma-gamma at 800 GeV, gamma-e at 900 GeV, 800/fb ,
80% e- polarization to generate the photon beams

Electron-Hadron Colliders:

LHeC 60 GeV e- or e+ on 7 TeV p 50/fb , 90% e- / 0% e+ polarization

Our timeline:

April 3 meeting of all working groups at Brookhaven

finalization of fast simulation framework, definition of projects that must be completed for the reports

June 30 meeting of all working groups at UW, Seattle

due date for white papers from the community and talks on these white papers

draft bulleted lists of conclusions from each working group for public discussion and comment

July 29 working group reports completed; presentation at Snowmass/Minnesota

August 16 presentation of final conclusions at DPF

August 30 finalization of all reports

Most of the people working in our study are collaborators in LHC experiments or are theorists actively engaging with LHC data.

We see an important role for our study in defining the physics case for the LHC luminosity upgrades, and thus motivating continued US contributions to the LHC accelerator and experiments.

The ILC and CLIC physics communities have engaged with our study and presented a number of papers at our recent meeting at Brookhaven. This meeting also included a Higgs Factory session with presentations from TLEP, Muon Collider, and Gamma-Gamma.

We are expecting to receive white papers on the physics capabilities from ILC, CLIC, Muon Collider, and Gamma-Gamma collider enthusiasts.

We encourage other groups to submit white papers on lepton collider physics to the Snowmass study. These papers would be most useful to us if submitted before our Seattle meeting, June 30.

We intend to answer the relevant questions about the physics goals of future lepton colliders. For example:

1) Summarize precisions of Higgs coupling measurements across the Energy Frontier facilities and compare their sensitivities to Higgs-coupling deviations in simplified benchmark models

Working Group Output

- General coupling fits+ fits within specific models

	LHC300	LHC3000	ILC250	ILC500	ILC1TeV	CLIC 3 TEV	$\mu\mu$
Δ_H							
Δ_V							
Δ_f							
Δ_b							
Δ_τ							
Δ_V							
...							

See recommendations of LHC Higgs Cross Section Working Group

We are happy to add columns if people are willing to generate the entries.

Heather Logan (Carleton U) *Higgs WG summary* *Snowmass EF workshop BNL*

What are the key goals for lepton collider experiments of the next generation ?

1. Higgs Boson

2. Top Quark

3. W boson

4. Two-Fermion Reactions

5. Extended Higgs Sector

6. Supersymmetry

In the following, most analyses labelled “ILC” apply to any lepton collider operating at that CM energy

1. Higgs Boson

The discovery of the Higgs Boson gives us a toehold in a new sector of particle physics.

The couplings of quarks, leptons, and vector bosons are controlled by the principle of local gauge invariance. Given the quantum numbers, these couplings are specified precisely.

The structure of the symmetry-breaking sector, and the couplings of the Higgs boson to quarks and leptons, have no such constraints. Any a priori statements are simply guesses. It is no surprise that almost all of the input parameters of the Standard Model are in this sector.

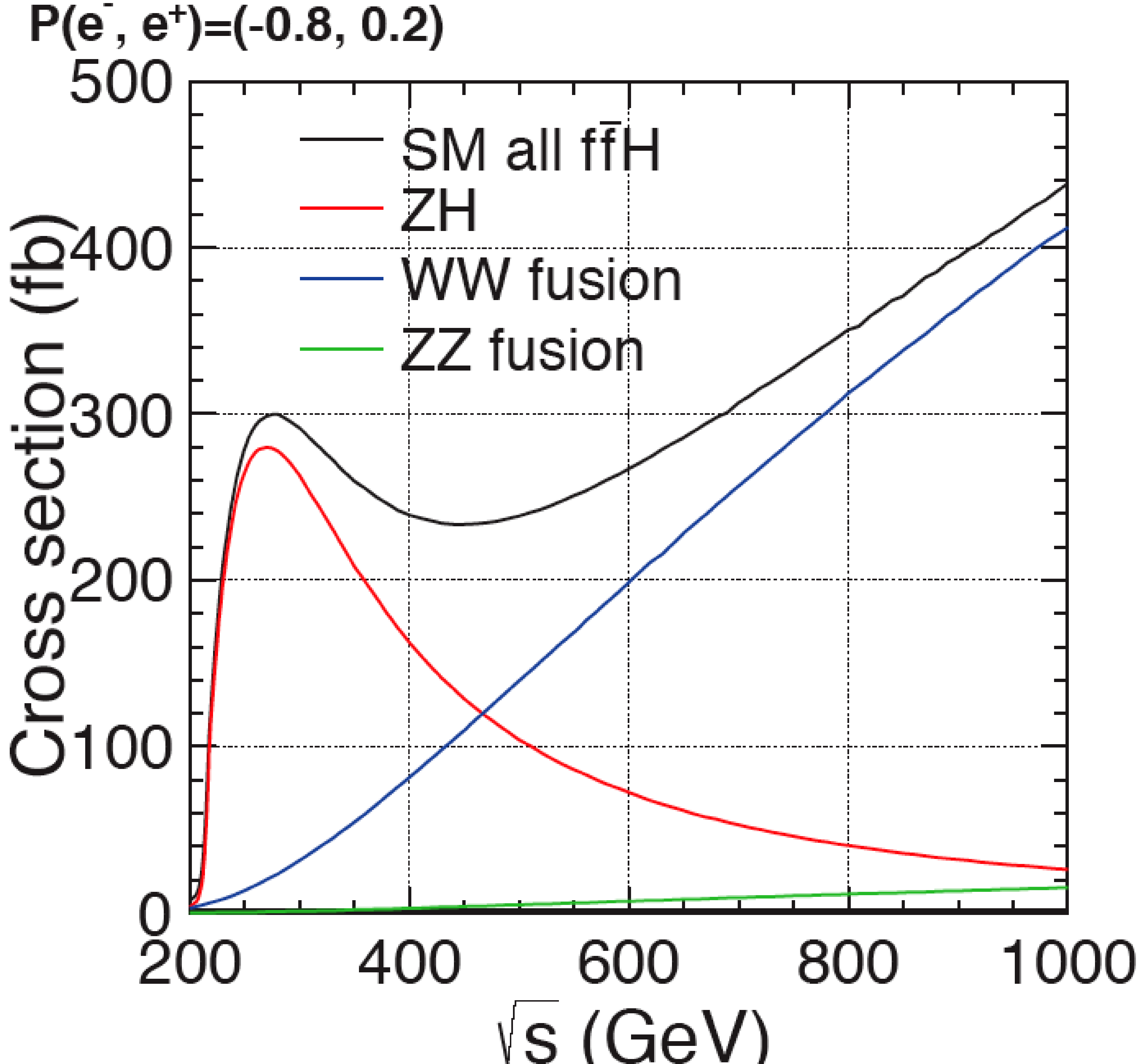
It is thus imperative to measure the couplings of the Higgs Boson as accurately as possible. This is a new road to what lies beyond or behind the Standard Model.

Lepton colliders bring important advantages to the study of the Higgs Boson couplings:

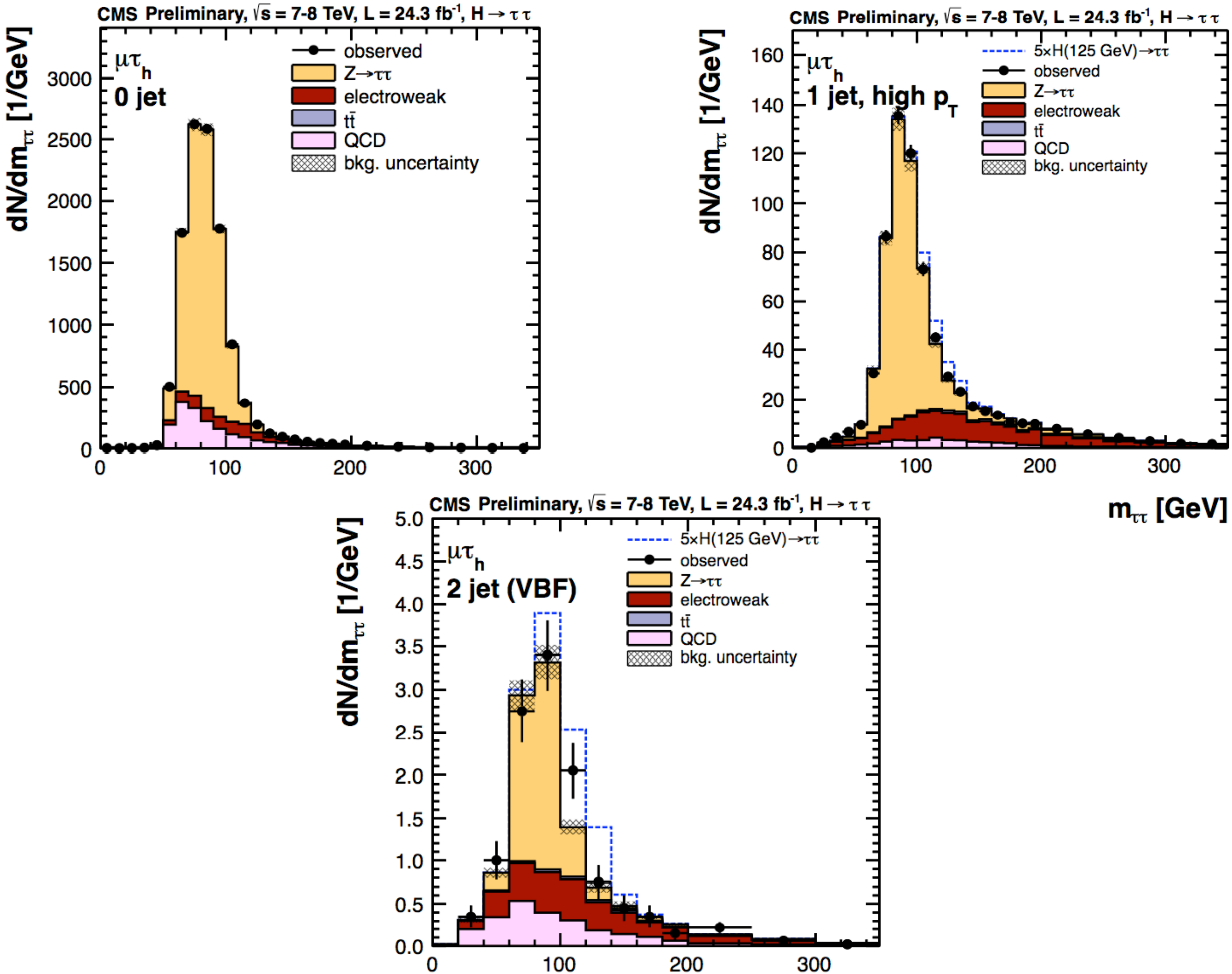
Higgs rates are 1% of the total cross section, not 10^{-10}.

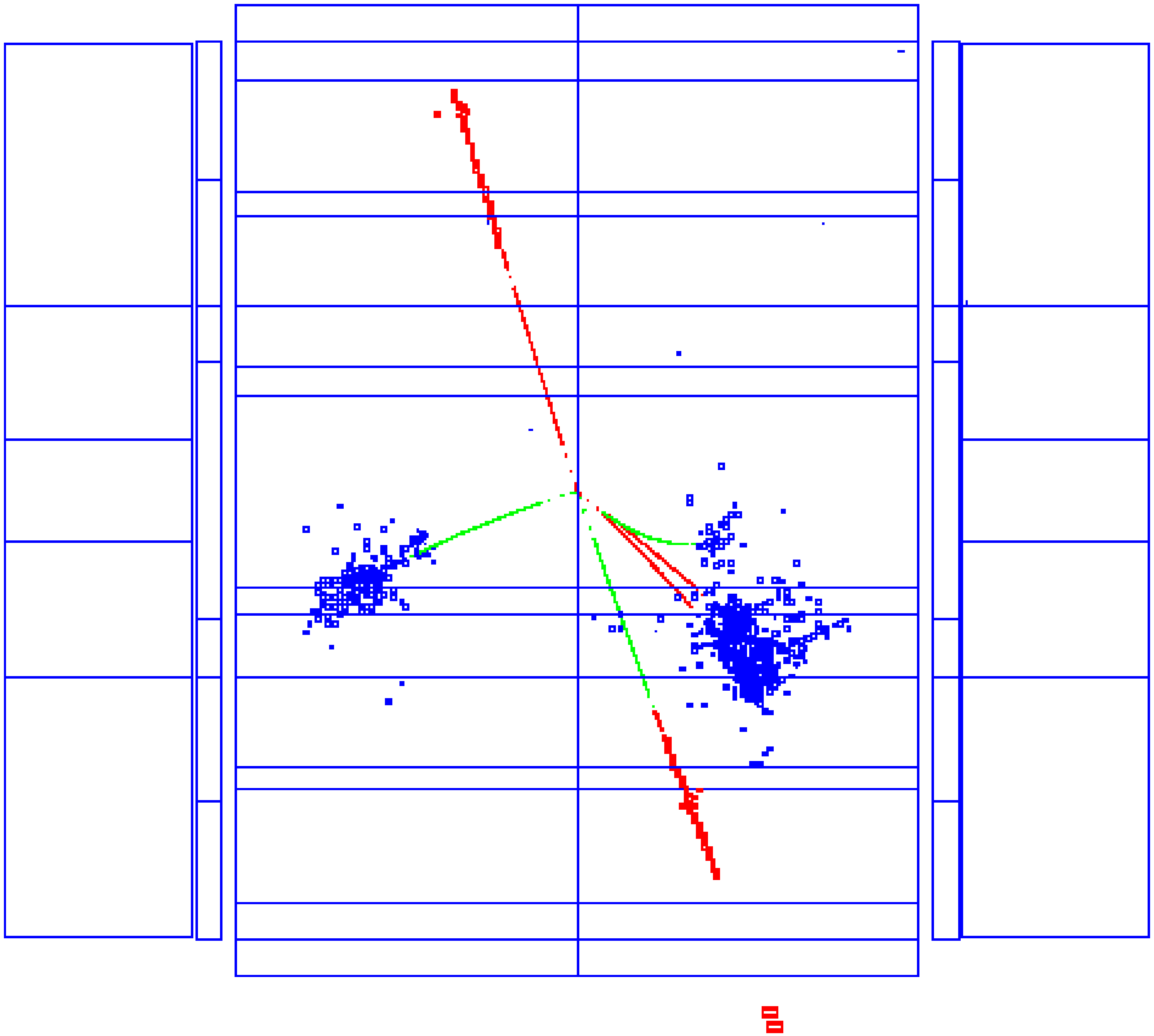
Low backgrounds and high flavor tagging efficiency make possible the direct observation of hadronic decay channels $h \to b\bar{b}, c\bar{c}, gg$.

The reaction $e^+e^- \to Zh$ provides tagged Higgs decay. This gives a tool for measuring branching fractions and a way to discover invisible and otherwise unexpected Higgs decays.



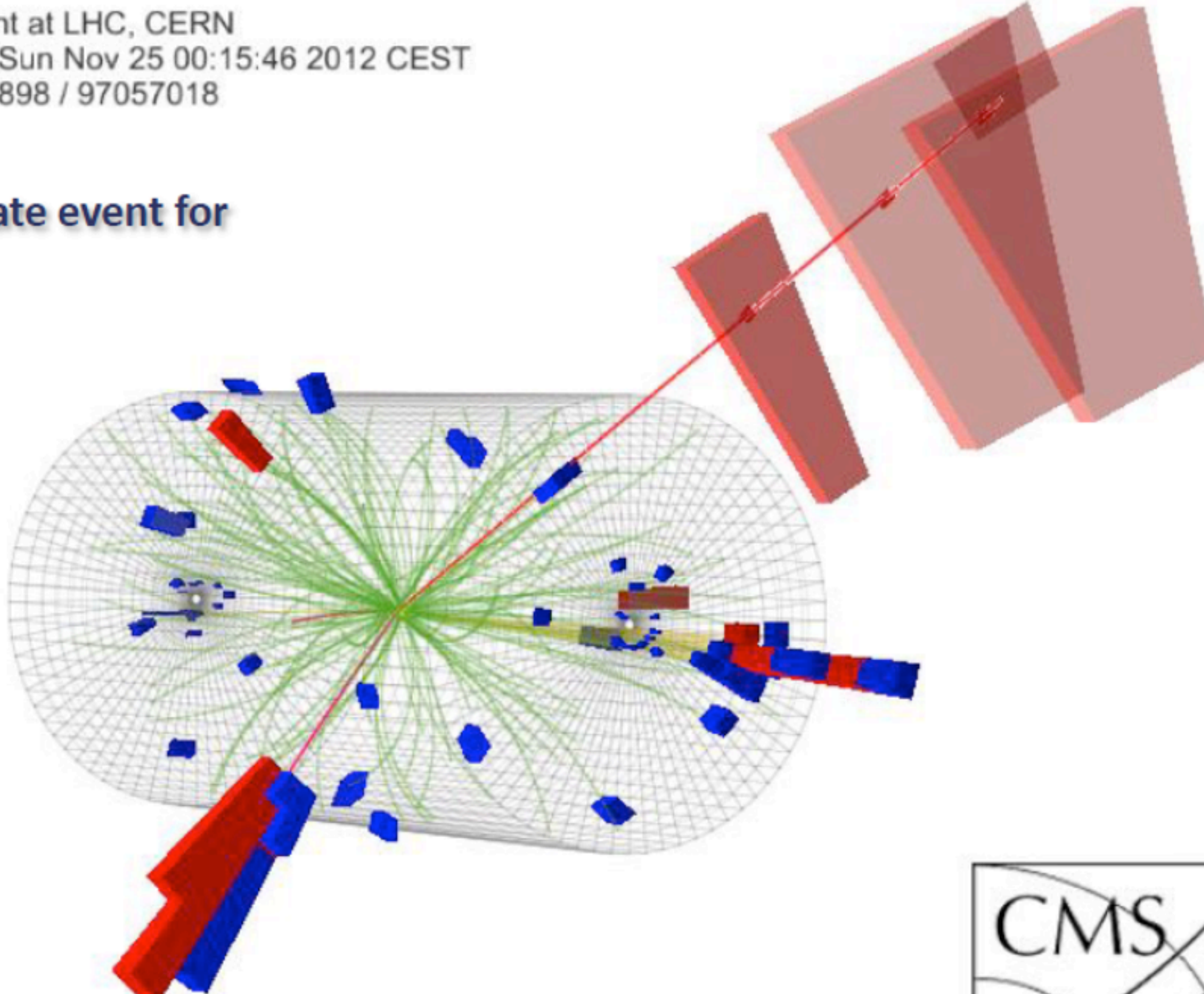
P(e⁻, e⁺)=(-0.8, 0.2)
SM all ff̄H
ZH
WW fusion
ZZ fusion
Cross section (fb)
0
100
200
300
400
500
200
400
600
800
1000
√s (GeV)


CMS Preliminary, √s = 7-8 TeV, L = 24.3 fb-1, H → τ τ
μτh
0 jet
observed
Z→ττ
electroweak
tt̄
QCD
bkg. uncertainty
dN/dmττ [1/GeV]
CMS Preliminary, √s = 7-8 TeV, L = 24.3 fb-1, H → τ τ
μτh
1 jet, high pT
5×H(125 GeV)→ττ
observed
Z→ττ
electroweak
tt̄
QCD
bkg. uncertainty
dN/dmττ [1/GeV]
mττ [GeV]
CMS Preliminary, √s = 7-8 TeV, L = 24.3 fb-1, H → τ τ
μτh
2 jet (VBF)
5×H(125 GeV)→ττ
observed
Z→ττ
electroweak
tt̄
QCD
bkg. uncertainty
dN/dmττ [1/GeV]

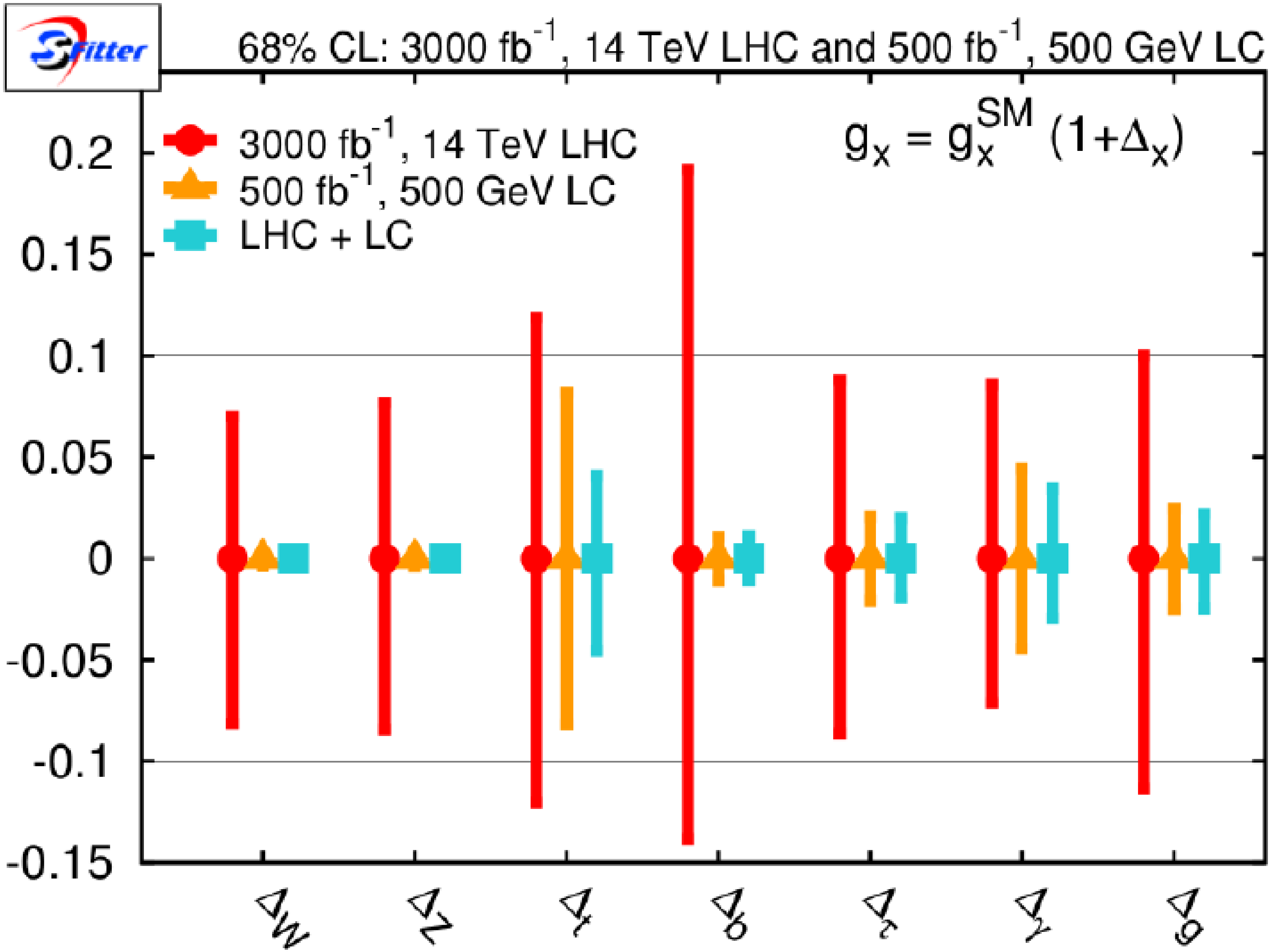


CMS Experiment at LHC, CERN
Data recorded: Sun Nov 25 00:15:46 2012 CEST
Run/Event: 207898 / 97057018

VBF candidate event for $H \rightarrow \tau\tau \rightarrow \mu\tau_h$



CMS



Sfitter - Zerwas

It is important to realize that a comprehensive Higgs program requires running at multiple energies:

250 GeV: tagged Higgs, branching ratios

350-500 GeV: W fusion production, absoluted normalization of the couplings

> 700 GeV: Higgs coupling to top

> 700 GeV: Higgs self-coupling

One difficulty should be noted: Higgs reaction rates involve the Higgs total width:

$$\sigma \cdot BR \sim \frac{\Gamma(h \to A\overline{A})\Gamma(h \to B\overline{B})}{\Gamma_T}$$

It is not possible to measure the Higgs boson width directly at an e+e- collider if it is as small as predicted in the Standard Model (4 MeV).

The Higgs width can be determined in a model-independent way using

$$\Gamma_T = \Gamma(h \to ZZ)/BR(h \to ZZ)$$

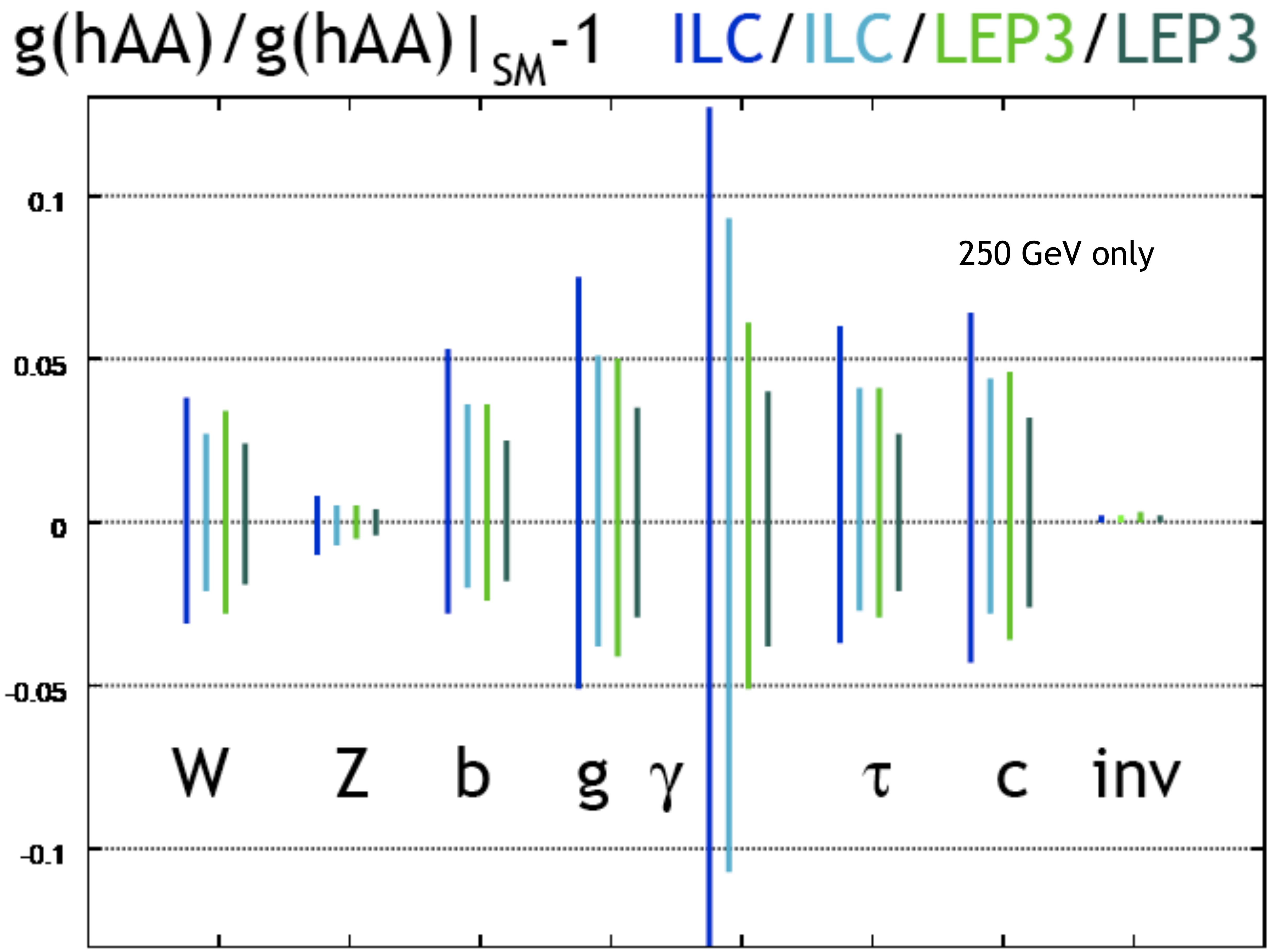
But because the ZZ mode is relatively rare this BR is difficult to measure. This method is typically statistics limited.

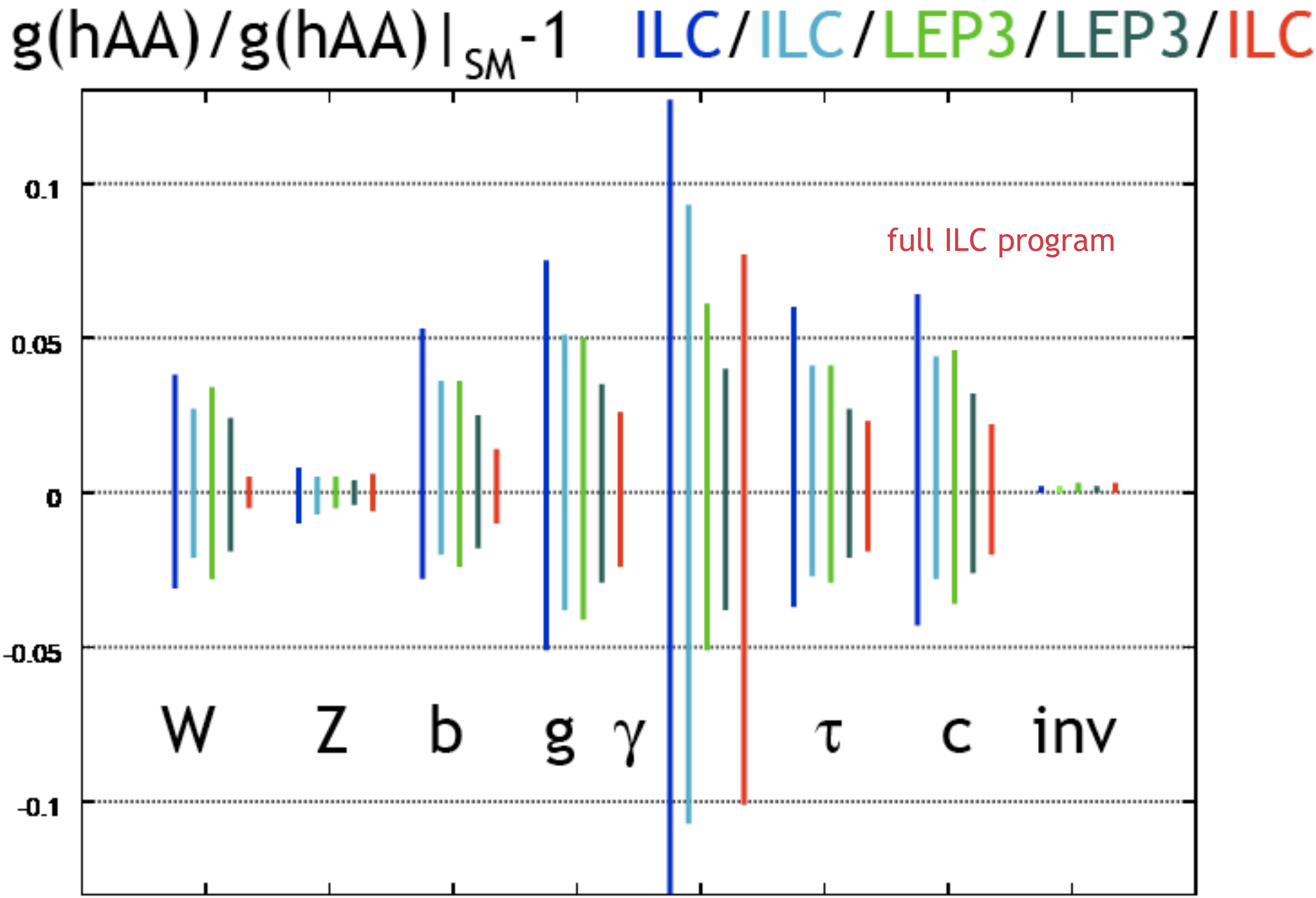
There are two solutions:

acquire very high integrated luminosity (TLEP: 2.5 - 5 ab-1)

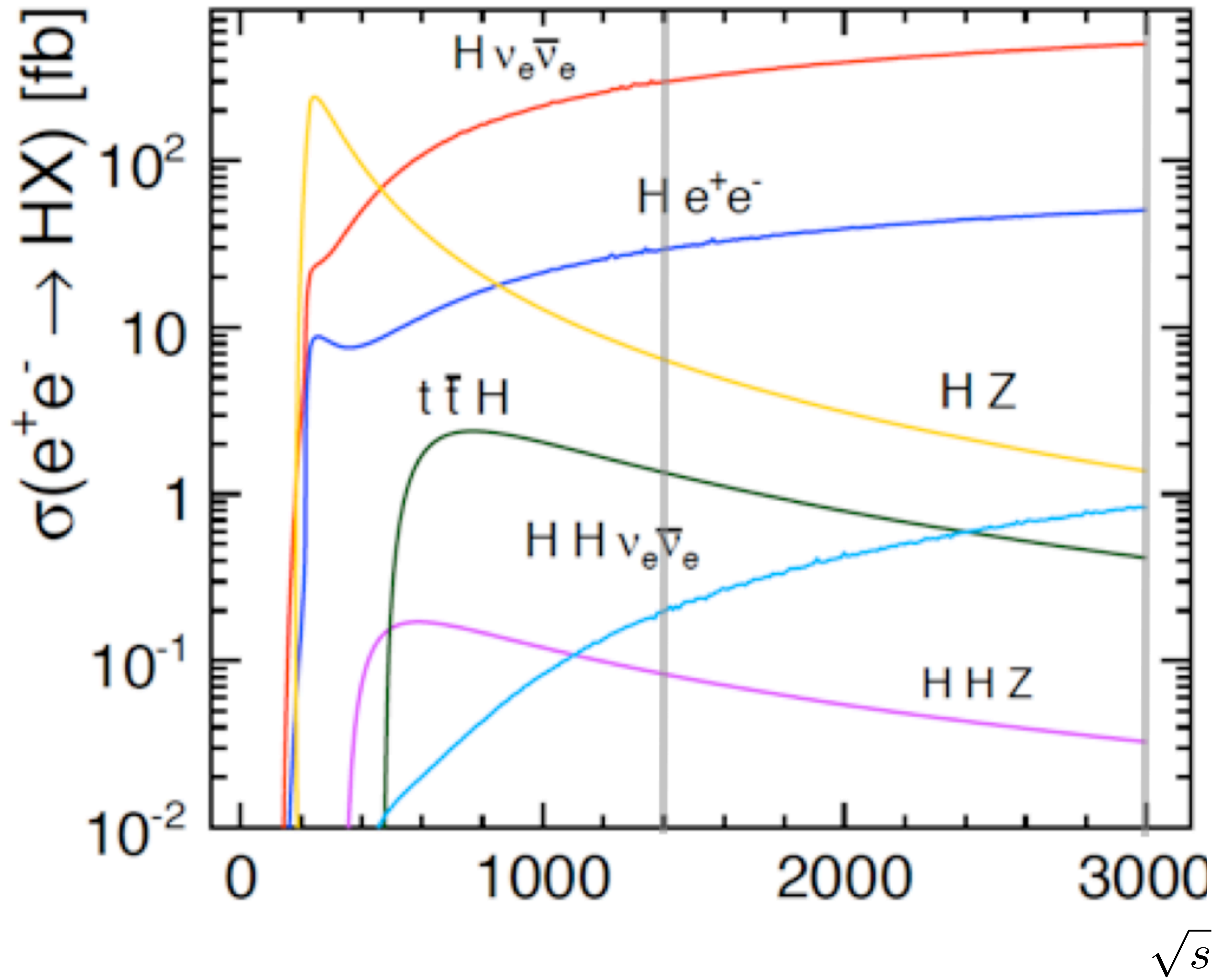
or

run at higher energy, at least 350 GeV, to access the W fusion Higgs production reaction.


g(hAA)/g(hAA)|SM-1
ILC/ILC/LEP3/LEP3
250 GeV only
0.1
0.05
0
-0.05
-0.1
W
Z
b
g
γ
τ
c
inv


g(hAA)/g(hAA)|SM-1 ILC/ILC/LEP3/LEP3/ILC
0.1
0.05
0
-0.05
-0.1
full ILC program
W
Z
b
g
γ
τ
c
inv

a high energy collider, above 1 TeV, can take advantage of logarithmically increasing cross sections for key processes:



CLIC: Higgs self-coupling to 16% with 3 TeV running.

Velasco

ζ_2 is the degree of circular polarization
(ζ_3, ζ_1) are the degrees of linear polarization

Only with $\gamma\gamma$C

In s-channel production of Higgs:

$$\overline{|\mathcal{M}^{H_i}|^2} = \overline{|\mathcal{M}^{H_i}|_0^2} \left\{ [1+\zeta_2\tilde{\zeta}_2] + \mathcal{A}_1 \left[\zeta_2 + \tilde{\zeta}_2\right] + \mathcal{A}_2 \left[\zeta_1\tilde{\zeta}_3 + \zeta_3\tilde{\zeta}_1\right] - \mathcal{A}_3 \left[\zeta_1\tilde{\zeta}_1 - \zeta_3\tilde{\zeta}_3\right] \right\}$$

== 0 if CP is conserved

== +1 (-1) if CP is conserved for a CP-Even (CP-Odd) Higgs

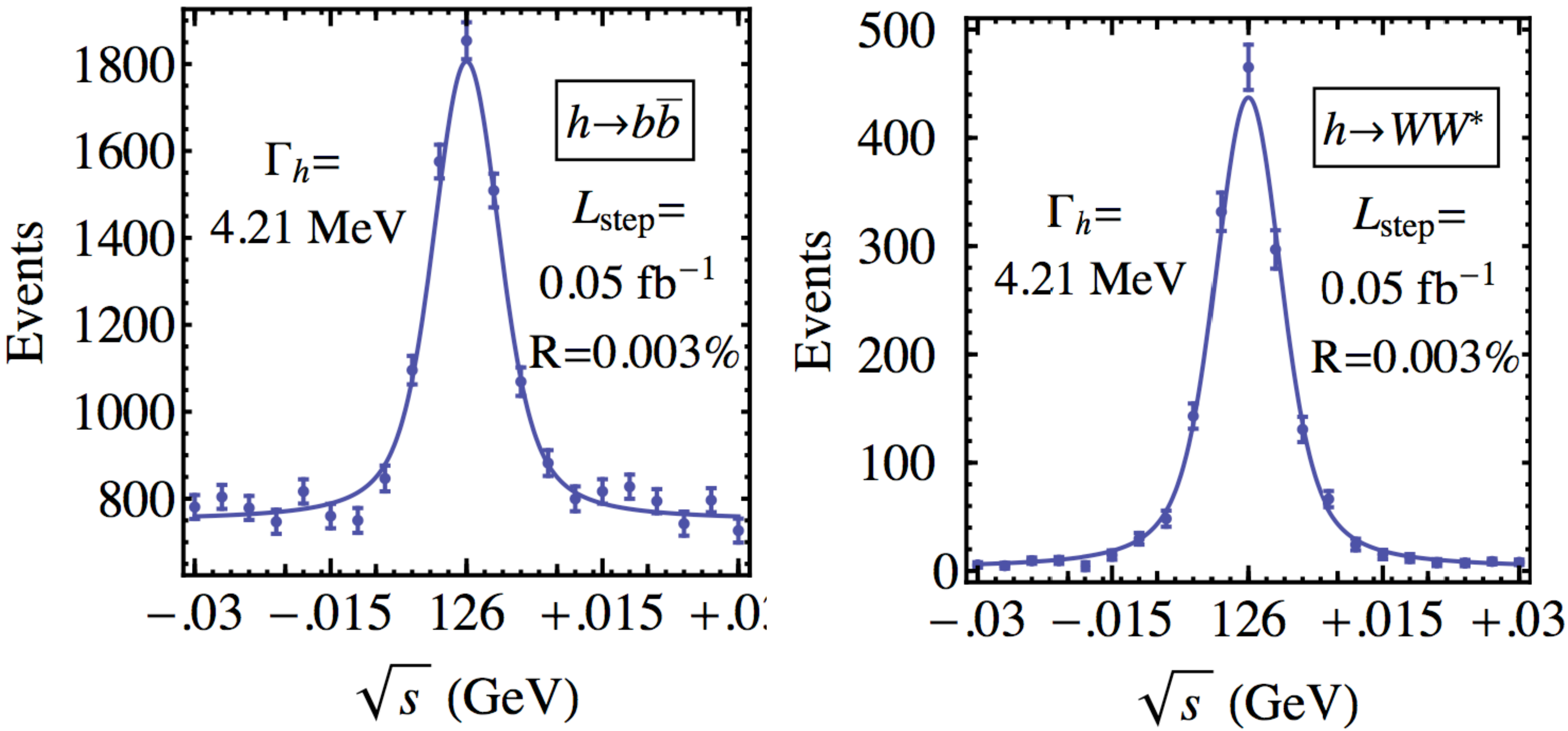
→ If $A_1 \neq 0$, $A_2 \neq 0$ and/or $|A_3| < 1$, the Higgs is a mixture of CP-Even and CP-Odd states

→ Possible to search for CP violation in $\gamma\gamma \rightarrow H \rightarrow$ fermions without having to measure their polarization

→ In bb, a $\leq 1\%$ asymmetry can be measure with 100 fb^{-1} that is, in 1/2 years

arXiv:0705.1089v2

Muon Collider: possibility of observing the Higgs boson as a resonance



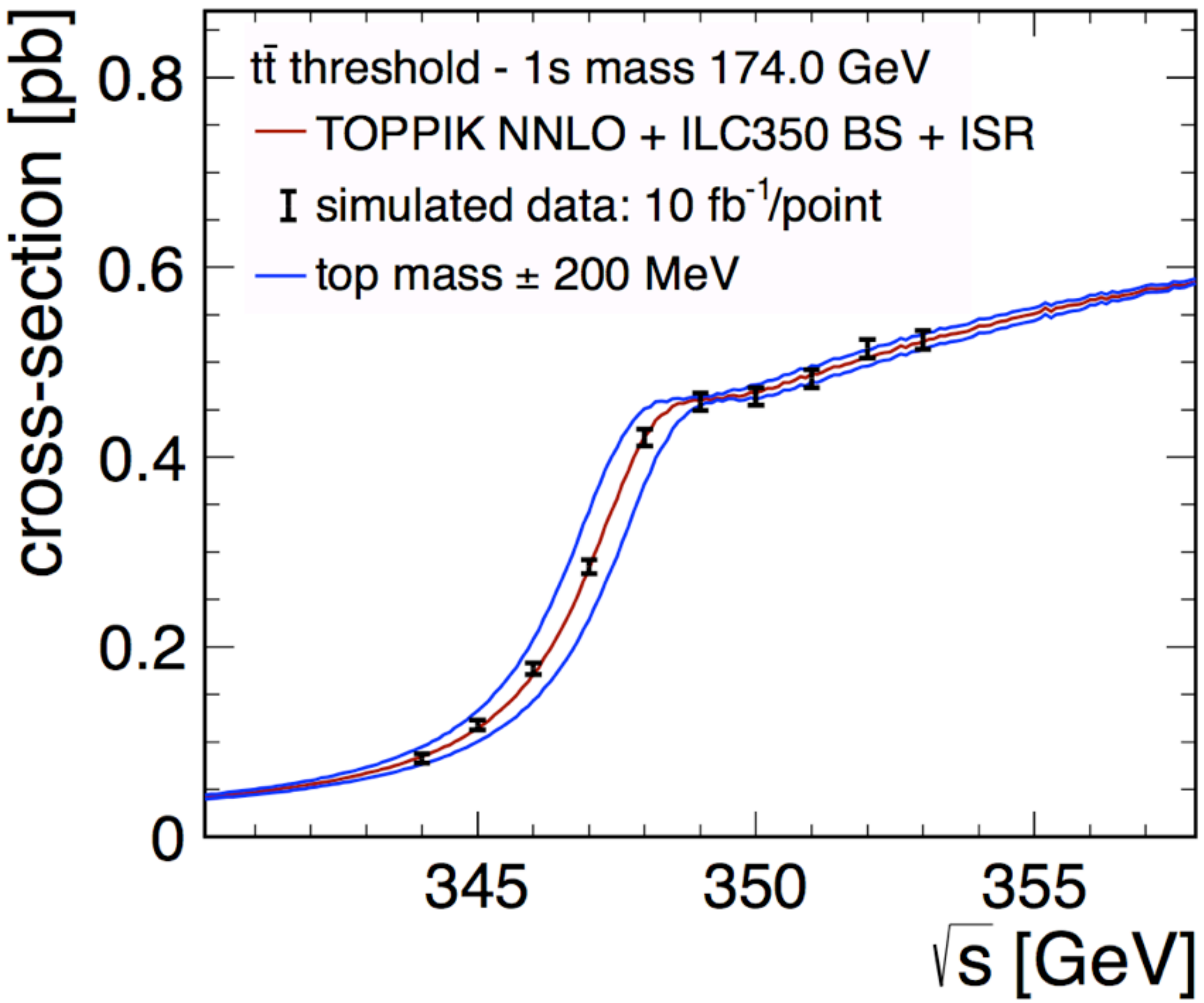
Han and Liu;   detection and machine backgrounds not yet included

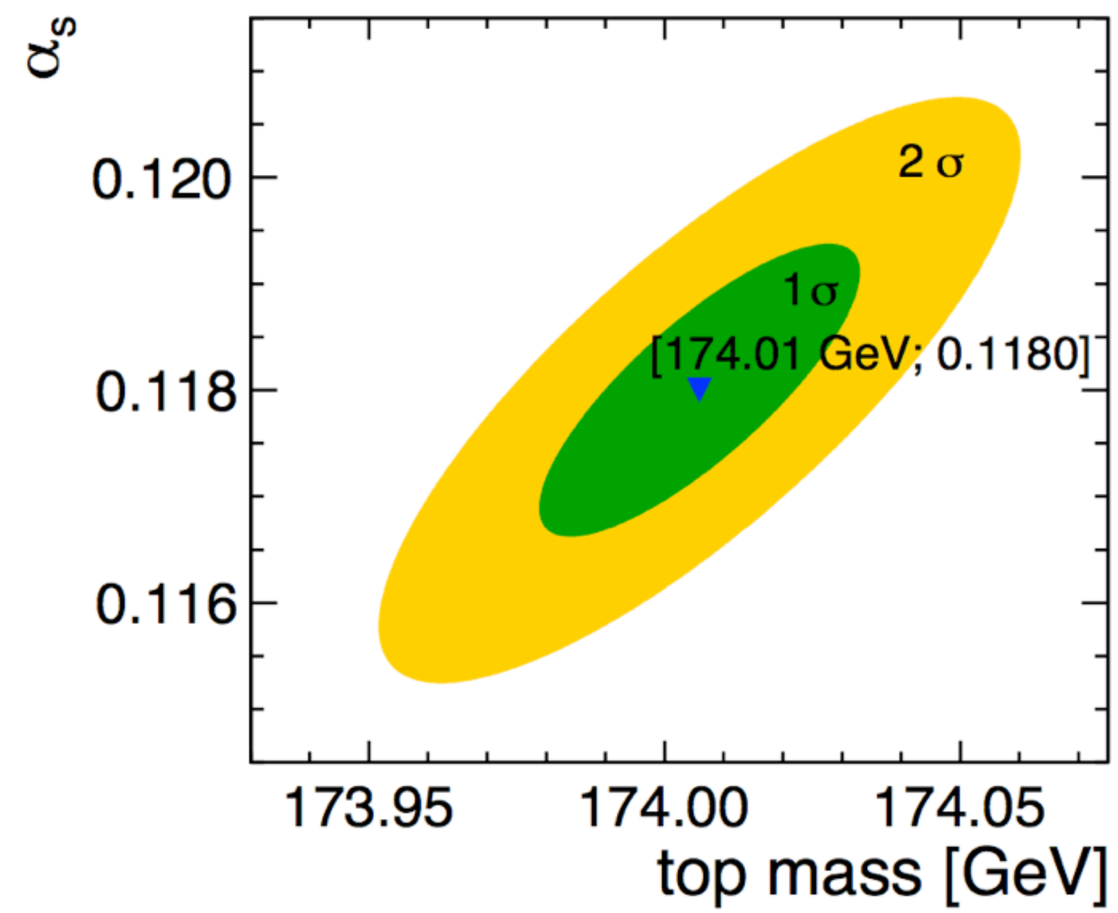
2. Top Quark

The top quark is the heaviest quark, and is still the most mysterious. Many questions remain that call for a precision study of top.

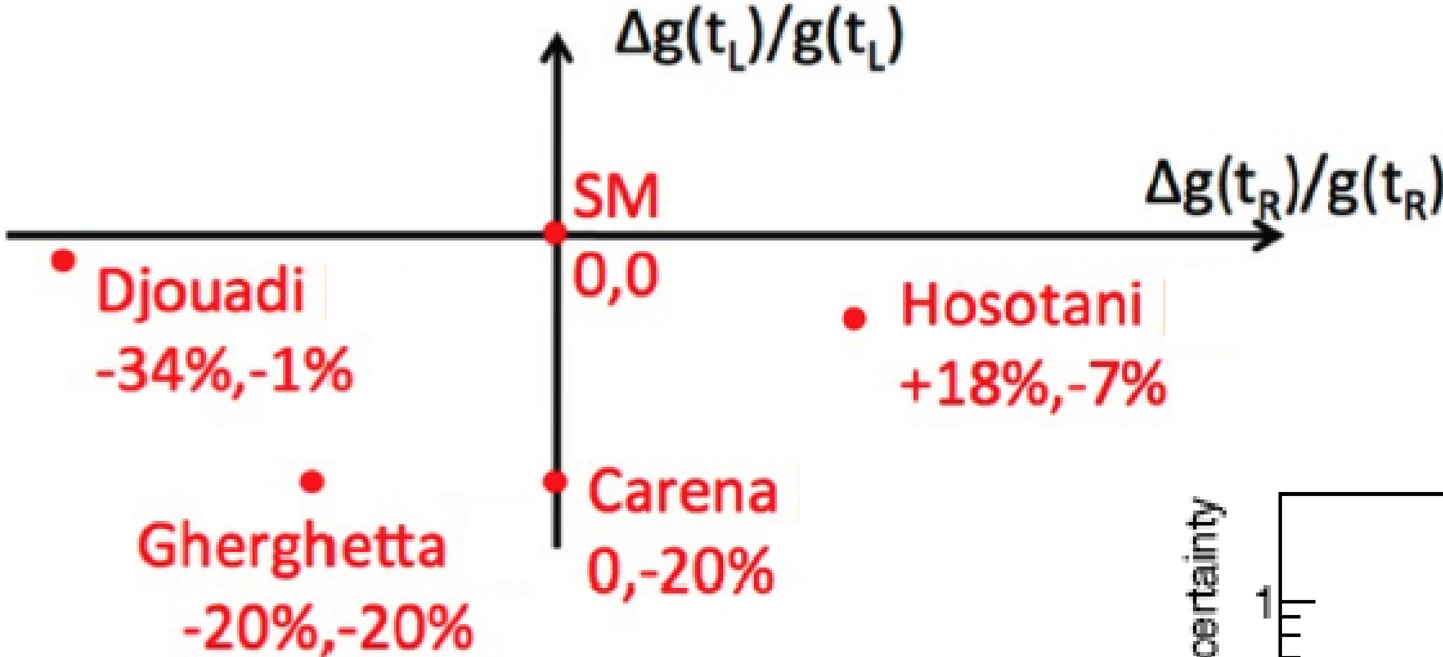
The top quark mass is a key input to any model of particle physics. It would be beneficial to improve the accuracy in this parameter from the current error of 1-2 GeV to 100 MeV.

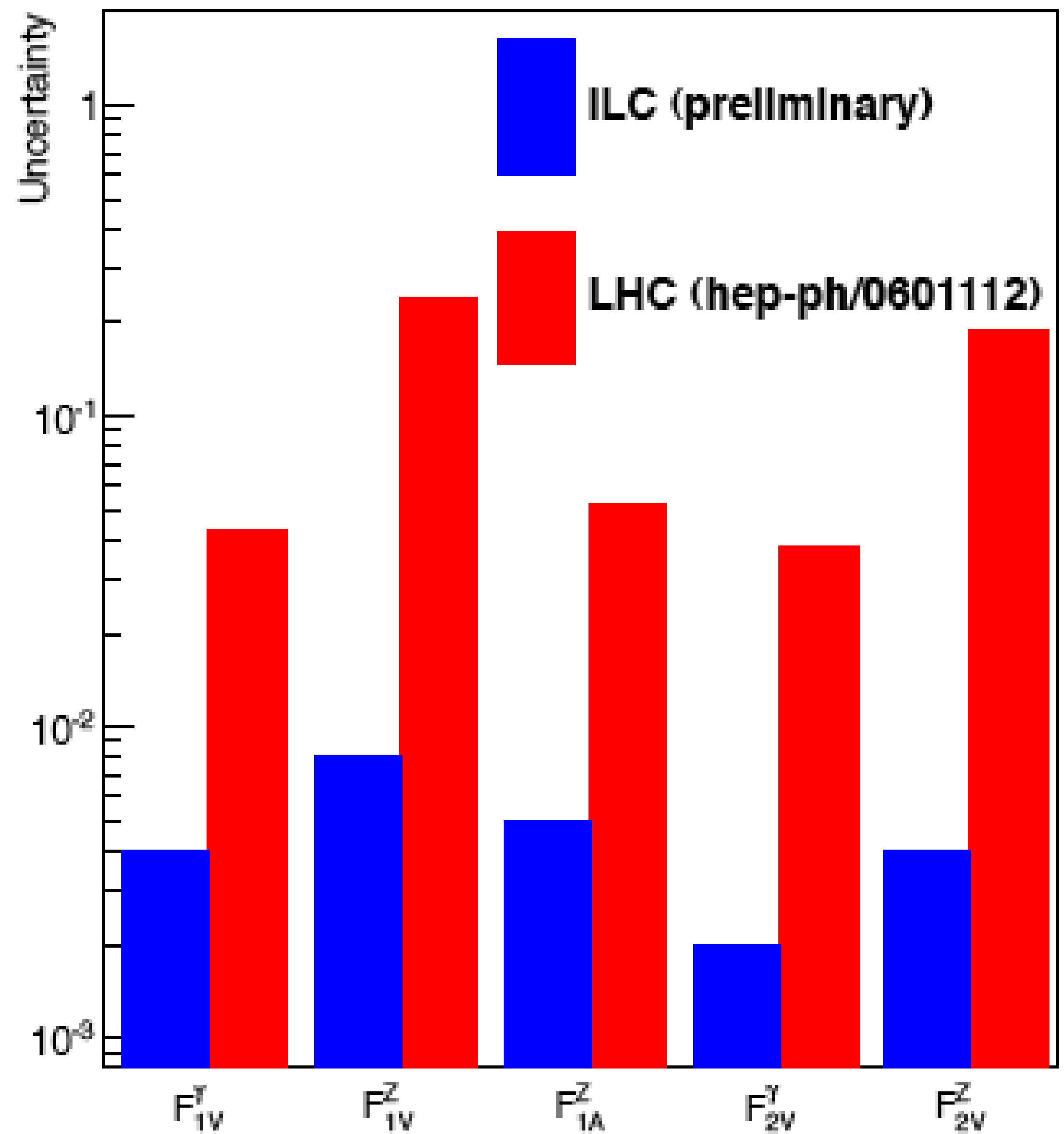
The top quark has the strongest couplings of any Standard Model particle to the Higgs sector. Models of composite or strongly interacting Higgs typically predict modifications of the couplings of top to vector bosons. Of special interest are the chiral couplings to the Z boson. These are difficult to measure at the LHC and are difficult disentangle without the use of beam polarization.





Simon similar results for CLIC350





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

Richard

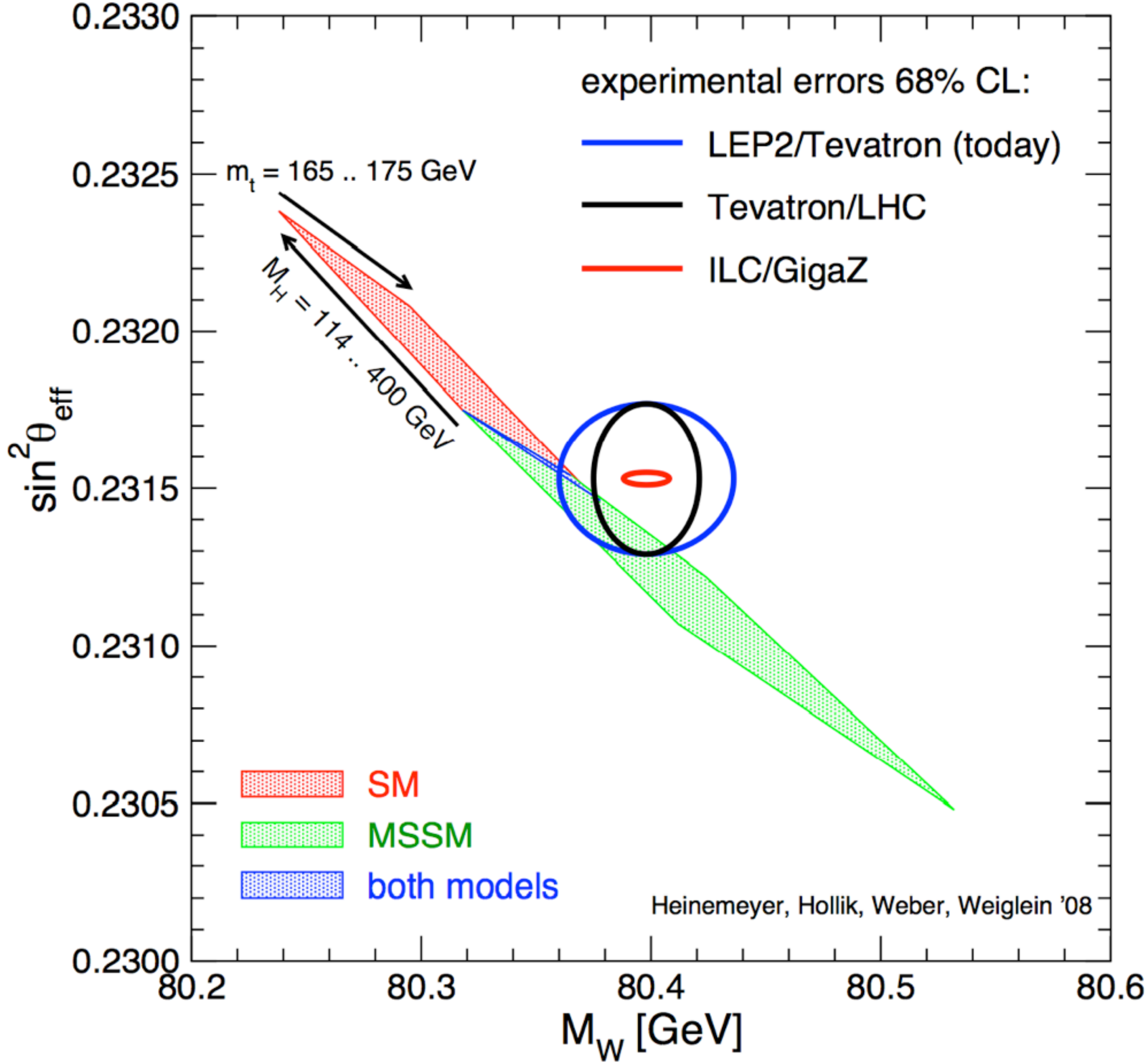
3. W boson and precision electroweak

Lepton colliders offer the opportunity to further improve the inputs to precision electroweak fits to the Standard Model.

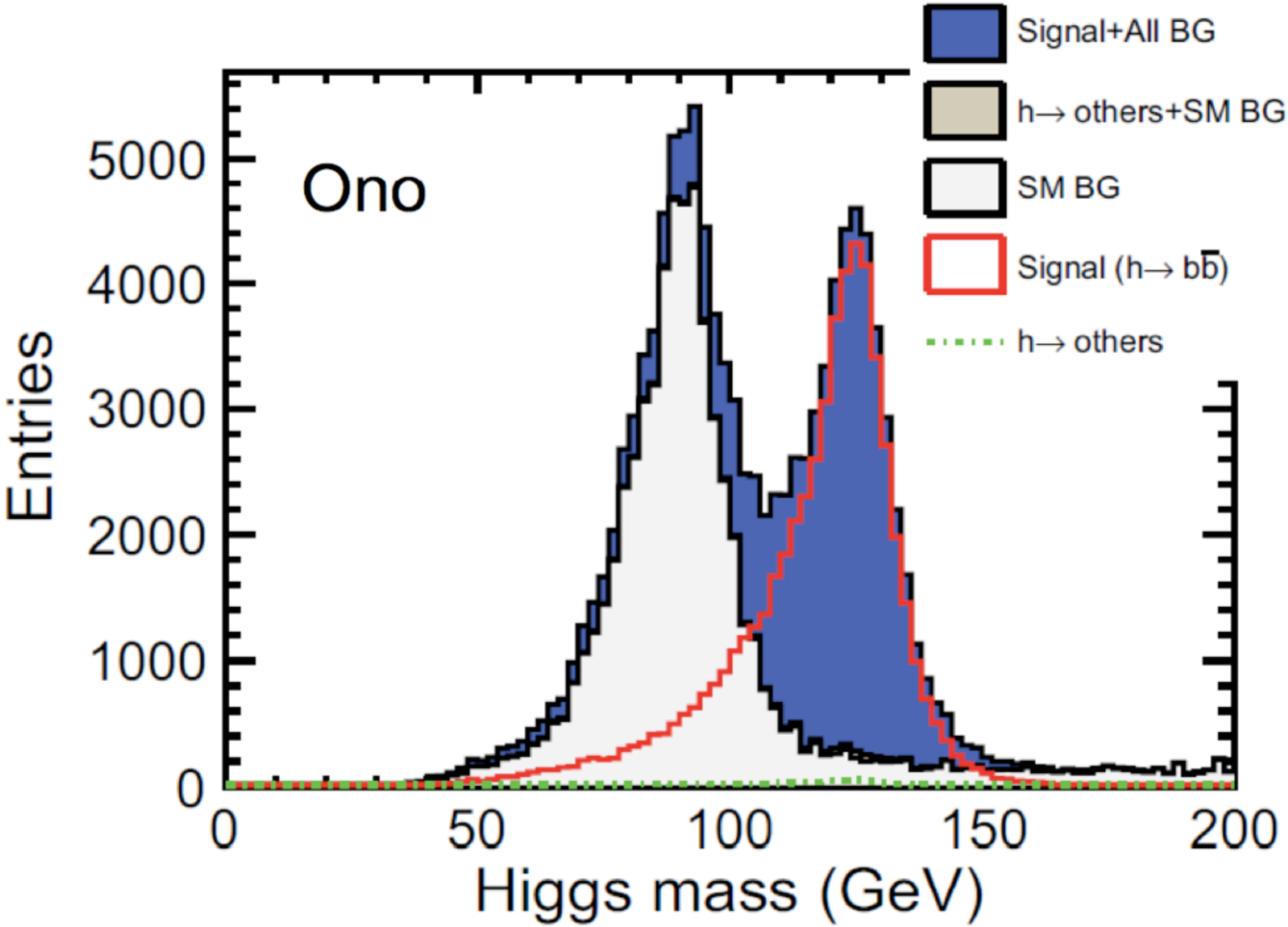
A Giga-Z program can access the 5th decimal place in $\sin^2\theta_w$.

W mass measurements at threshold or in the continuum can access the 5th decimal place in m_W.

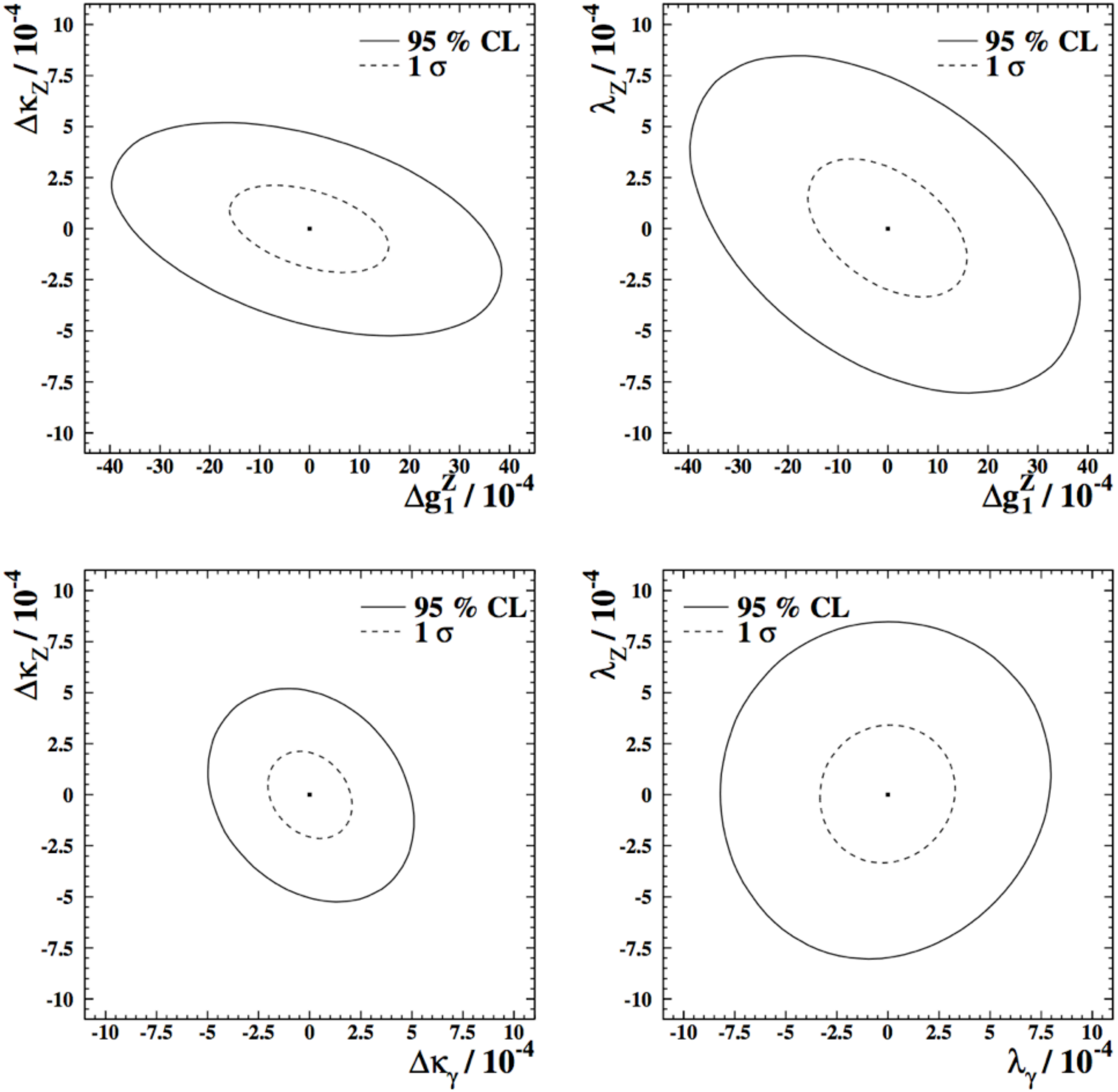
Measurements of $e^+e^- \to W^+W^-$ can access the 4th decimal place in the W nonlinear couplings. This is the level expected for effects of composite Higgs models.



experimental errors 68% CL:
LEP2/Tevatron (today)
Tevatron/LHC
ILC/GigaZ
m_t = 165 .. 175 GeV
M_H = 114 ... 400 GeV
SM
MSSM
both models
Heinemeyer, Hollik, Weber, Weiglein '08
0.2330
0.2325
0.2320
0.2315
0.2310
0.2305
0.2300
80.2
80.3
80.4
80.5
80.6
M_W [GeV]
sin²θ_eff



Signal+All BG
h→ others+SM BG
SM BG
Signal (h→ bb̄)
h→ others
Ono
Entries
0
1000
2000
3000
4000
5000
0
50
100
150
200
Higgs mass (GeV)



ILC 800 GeV 1000 fb-1 80%/60% ECFA/DESY study

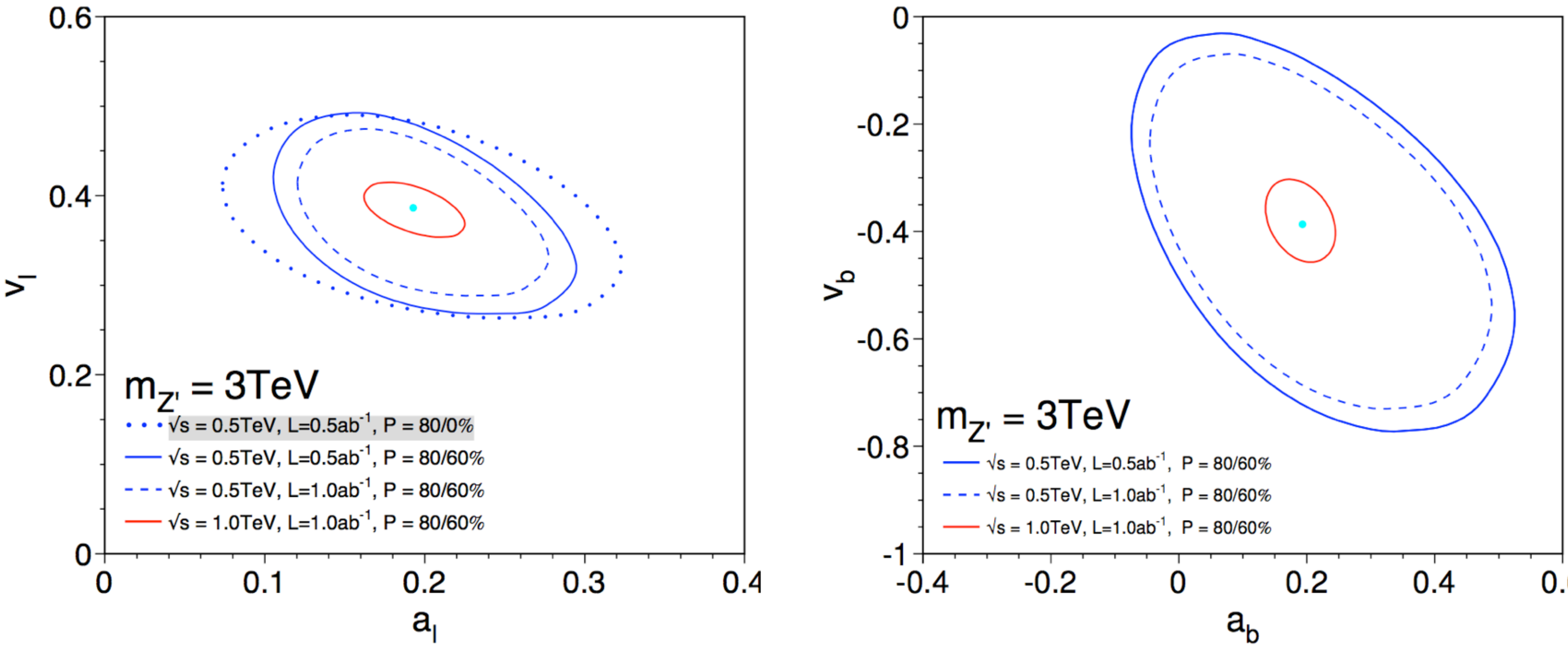
4. Two-Fermion Reactions

The two fermion processes $e^+e^- \to f\overline{f}$ are the most powerful probes of possible lepton and quark compositeness.

In the search for new vector bosons, the search for deviations from the Standard Model in two fermion reactions has comparable reach to the direct search for resonances at the LHC.

The two methods are complementary: LHC gives the resonance mass. Lepton colliders, using beam polarization and flavor tagging, give the full set of couplings.

If the resonance is sufficiently low in mass, our lepton collider technology might get us there.



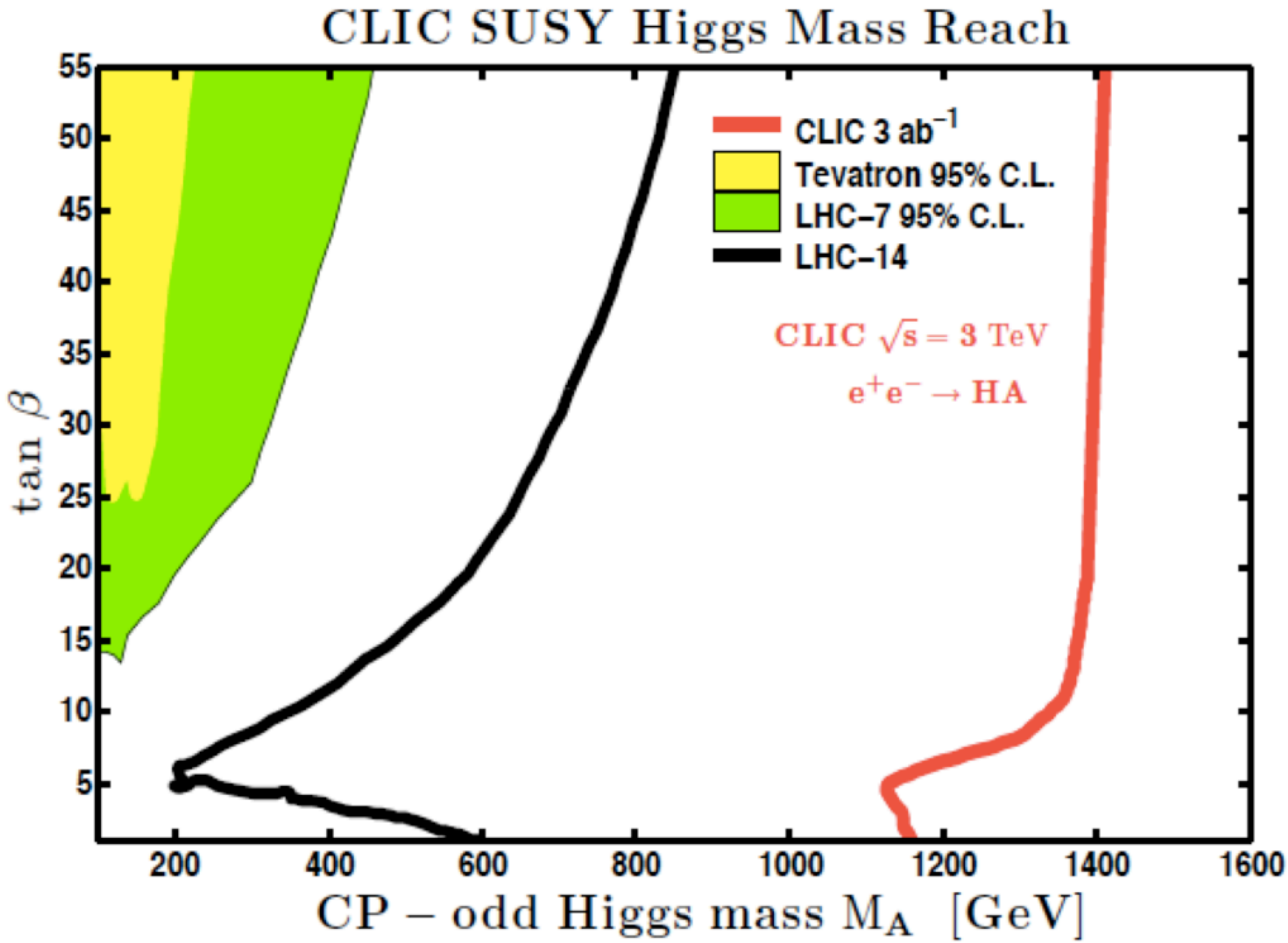
coupling determination for an SO(10) Z' boson at 3 TeV
Riemann

5. Extended Higgs sector

There could well be more particles in the Higgs sector beyond the simplest Higgs Boson. These -- and other new particles with zero color charge -- are difficult to discover at the LHC.

Extended Higgs particles can have complex decay patterns, for which only a subset of decays can be seen at the LHC.

In a 2-Higgs doublet model, a crucial parameter is the mixing angle $\tan\beta$. It is important to measure this angle with precision, in a model-independent way. This can be done by measuring ratios of branching ratios of extended Higgs bosons.


CLIC SUSY Higgs Mass Reach
CLIC 3 ab^{-1}
Tevatron 95% C.L.
LHC–7 95% C.L.
LHC–14
CLIC $\sqrt{s} = 3$ TeV
$e^+e^- \to HA$
tan β
CP – odd Higgs mass M_A [GeV]
55
50
45
40
35
30
25
20
15
10
5
200
400
600
800
1000
1200
1400
1600

Linssen

6. Supersymmetry

Supersymmetry is a leading candidate for new physics beyond the Standard Model.

Today, one often hears the following statements:

1. Supersymmetry is dead, or at least on the ropes, because of LHC exclusions.

2. Since supersymmetry has not been found at the LHC, it cannot be found at a 500 GeV e^+e^- collider

Both statements are incorrect.

Here is some evidence:

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")

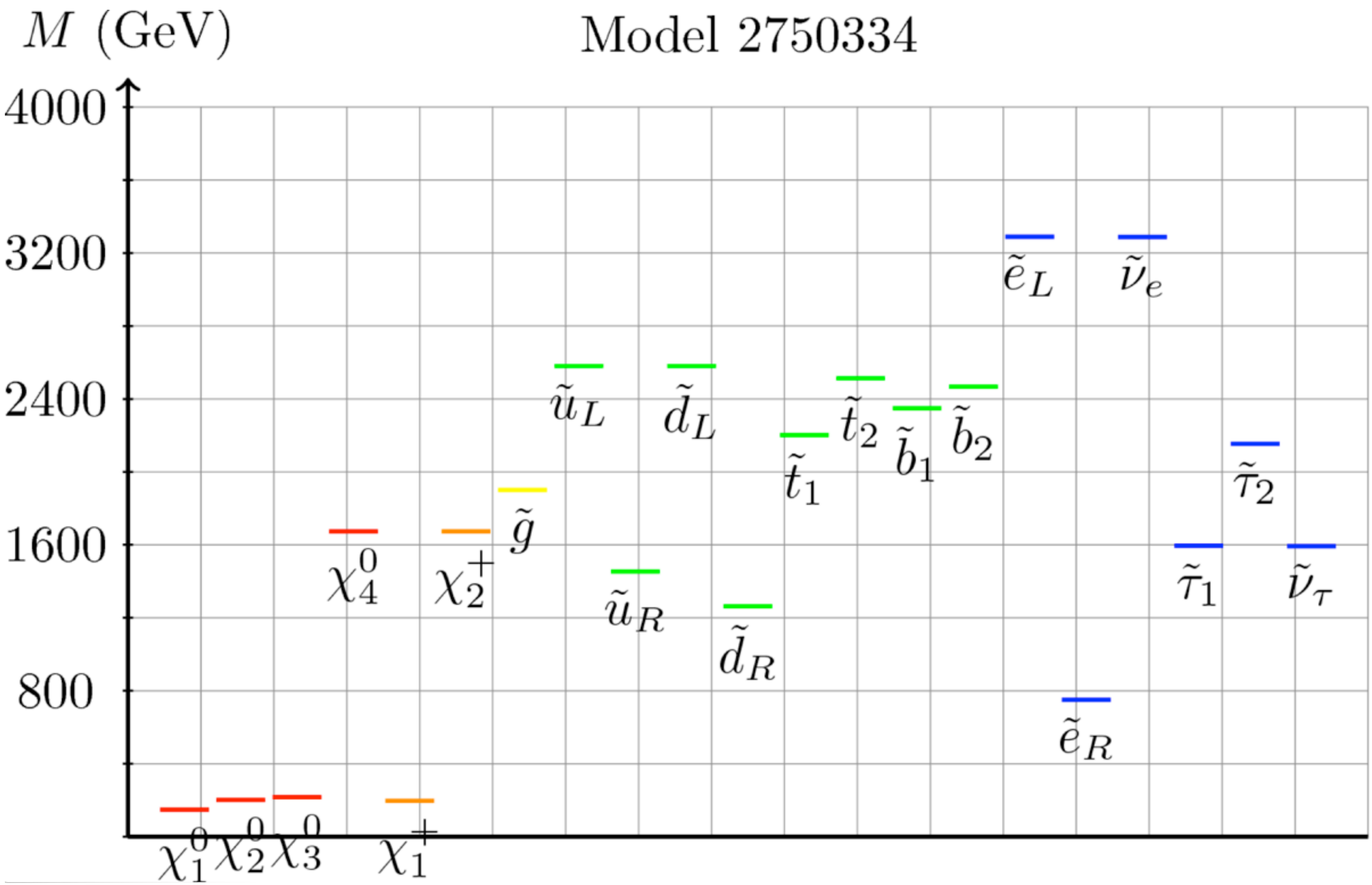
Cohen, Hook, Torroba, arXiv:1204.1337 μ = 220 GeV

Randall, Reece, arXiv:1206.6540 μ = 148 GeV

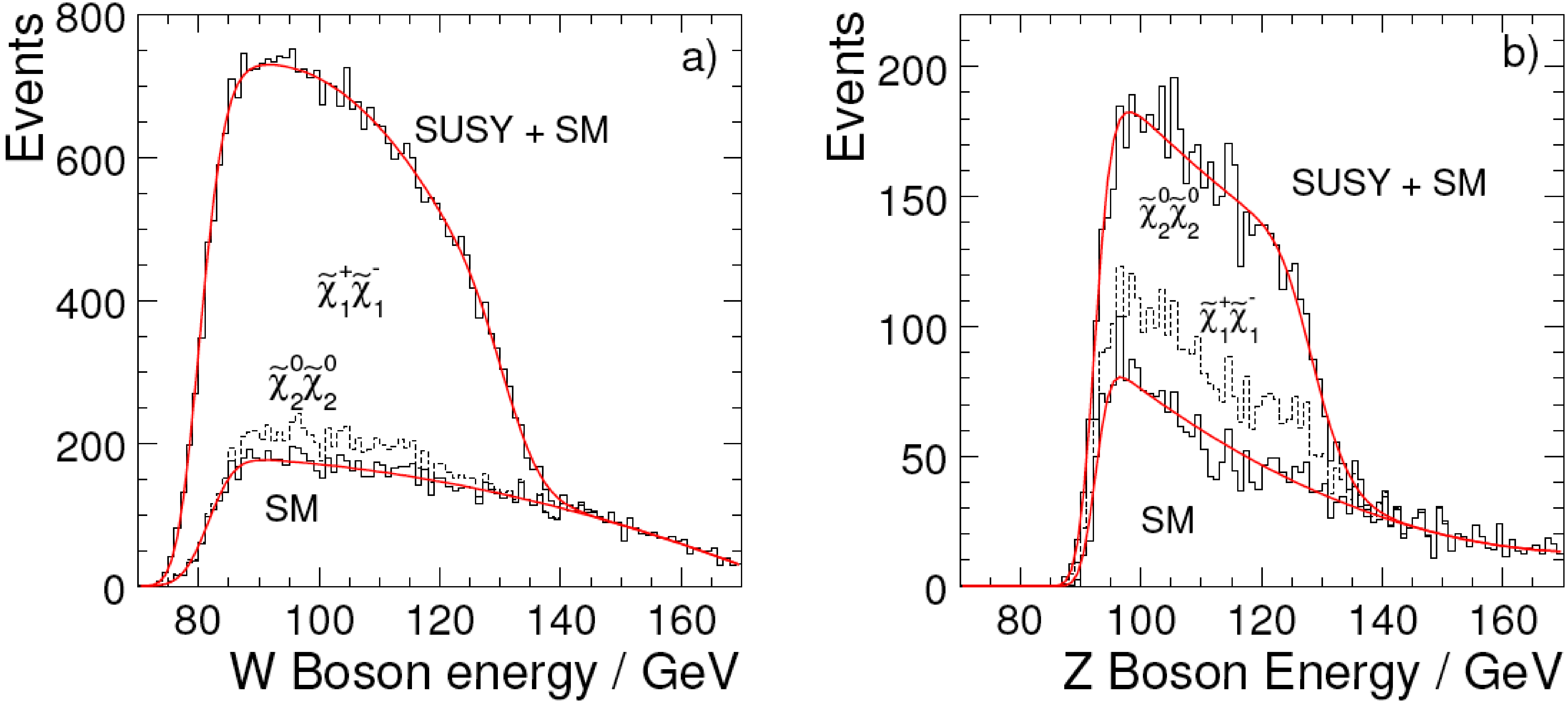
Craig, McCullough, Thaler, arXiv:1203.1622 μ = 200-300 GeV

In these models, an e+e- collider at 500 GeV is not only a Higgs factory but also a Higgsino factory.

an interesting model that is one of our Snowmass benchmark points. In this model, the lightest SUSY particle would make up the cosmic dark matter.

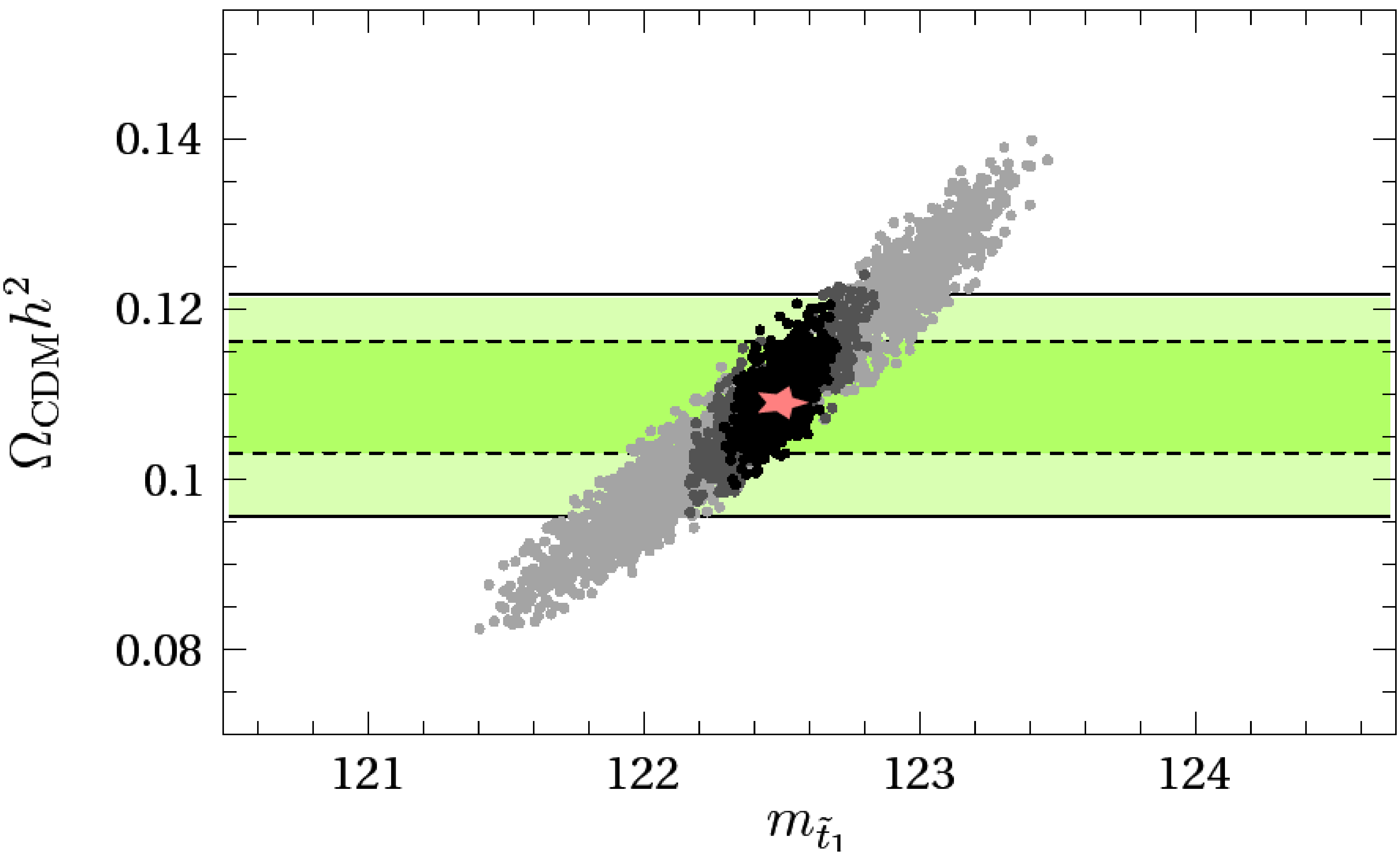


Supersymmetry gives many illustrations of the wonderful capabilities of lepton collider experiments to make precision measurements and uncover the underlying Lagrangian parameters of a new physics model.



Suehara and List

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



Frietas et al.

Finally, what do we need from you ?

The Energy Frontier study is well equipped to answer the questions that arise on the physics side.

e.g., for Higgs couplings

What is the eventual capability of the LHC at high luminosity ?

What are the capabilities of proposed lepton colliders ?

What are the goals of precision Higgs study ? What is the size of deviations from the Standard Model expected in new physics models ?

What we cannot do effectively is evaluate the technical status of the various proposals for Higgs factories and, more generally, for higher-energy lepton colliders.

The perspective on this question must come from your working group.

First, we need an evaluation of the ILC Technical Design Report.

The ILC needs to have a special place in your report because

- it can plausibly begin construction in this decade
- it has political traction in Japan

The next P5 must discuss the ILC, and it needs your input.

You should give you opinion on the questions:

In their presentation to the European Strategy Study, the ILC GDE claimed that the ILC could be constructed today on the basis of the (now finished) TDR. Is this a correct statement ?

What R&D elements remain ? How serious are the issues ? How complete is the ILC cost estimate included in the TDR ?

Are the ILC luminosity projections sufficiently conservative that we can use these as a basis for evaluating the physics potential ?

meeting of Lyn Evans and Prime Minister Abe, March 27, 2013

The other machines being considered today -- CLIC, TLEP, Muon Collider, etc. -- need both R&D and engineering design to be ready for construction.

We need your detailed evaluation of what is required to propose construction of these machines.

What are the important issues that still must be resolved by R&D ?

What is the scale of the engineering effort needed to write a Technical Design Report and to make a credible cost accounting ?

In his talk at our Brookhaven meeting, Patrick Janot said about TLEP:

The goal is to have a technically-ready proposal by 2018.

We aim for physics in 2030.

The physics study and the next P5 need the specific information that will allow us to evaluate claims such as these.

With our evaluation of physics requirements and capabilities of each project, and your assessment for each of the technical requirements and readiness,

we can provide the information that the HEP community needs to make the best decisions about its future.