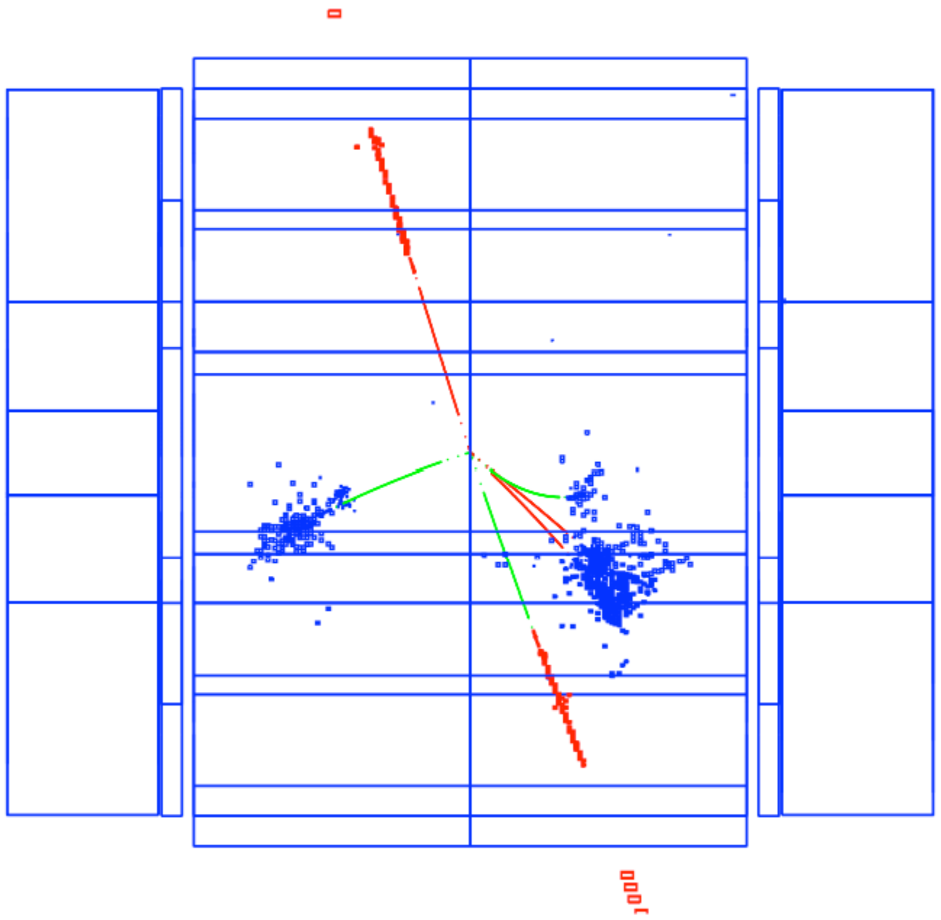
Superconducting RF and the Program of ILC



M. E. Peskin
SCRF Roadmap Workshop
at Fermilab
February 2017

High energy physicists have never needed accelerator R&D more desperately than at this moment.

We are caught in a situation in which we know there are discoveries to be made. But the conditions to make those discoveries seem just beyond our reach.

With your help, new strategies for discovery will become possible.

Superconducting RF is particularly relevant for the possibility of realizing the International Linear Collider.

Most of this talk will concern the general program of physics at future e+e- colliders. I will return very specifically to the ILC at the end of the lecture.

outline of the talk:

1. There must be physics beyond the Standard Model
2. Plan A
3. Plan B
4. Elements of Plan B, stepwise in energy

Why must there be physics beyond the Standard Model ?

Begin with the counterargument:

The Standard Model is a complete theory of strong, weak, and electromagnetic interactions.

It has no missing ingredients, no unitarity violation at high energy, no “anomalies”.

Unlike all theories that came before it, the SM does not predict an energy scale where it must break down.

Still, there are known phenomena of particle physics that cannot be explained within the SM:

dark matter in the universe

cosmic excess of baryons over antibaryons

neutrino masses

but, for all of these, new physics at $10^{12} - 10^{14}\ \mathrm{GeV}$ might be the explanation.

For this reason, if we are interested in models with new physics at accelerator energy scales, it is not enough to set limits.

We need to be able to prove that the SM is violated.

This will require experiments that allow clear signals and model-independent interpretation.

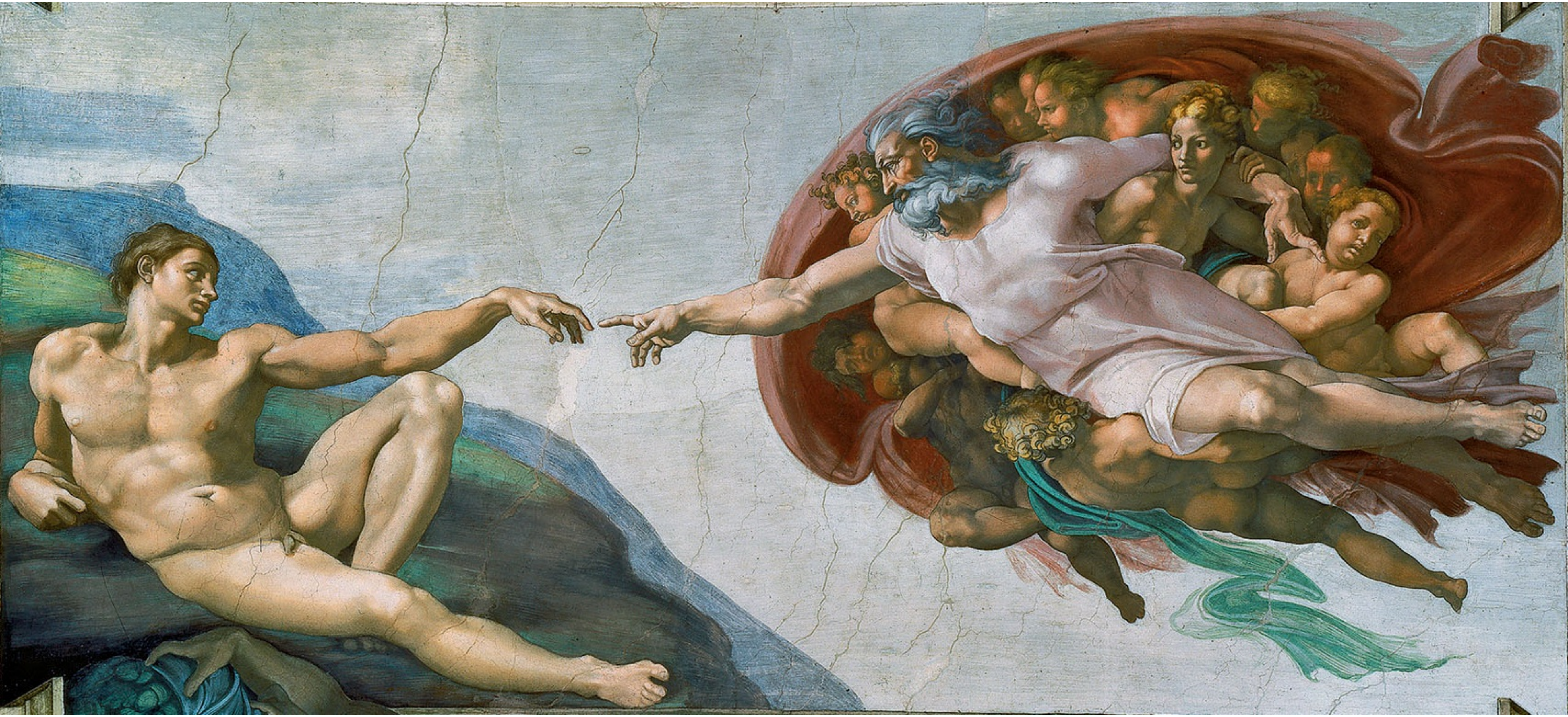
That is the strength of e+e- colliders.

For me, the strongest argument for new physics at energies just beyond our reach comes from the required properties of the Higgs boson.

The Higgs field is the order parameter of a phase transition, similar to phase transitions that we meet in condensed matter physics, in superconductivity, superfluidity, and magnetism.

In all of those systems, the phase transition happens for a reason. These reasons are fascinating, and lead us to new (emergent) laws of physics.

High energy theorists tend to think of the properties of the Higgs boson like this ➠



You, maybe, have a different perspective on how the properties of elementary particles are built ➠

I encourage you to think of the Higgs medium as a material, just as you think of metals and fluids.

Why shouldn’t we understand how it works ?

Once you start to think in this way, there is a more tantalizing idea:

In the SM, the phase transition in the Higgs theory is put in by hand. It cannot be explained by any SM interaction.

So, if this phase transition has a physics explanation, there must be new forces of nature unknown to us today. These forces must act to produce the mass scale of the Higgs, 100-250 GeV.

A comment on dark matter:

Although dark matter could come from almost any energy scale, theorists are continually drawn back to dark matter masses near 100 GeV.

If dark matter was produced thermally in the early universe and annihilated in pairs as the universe cooled and expanded, the current density would be

$$\Omega_N = \frac{s_0}{\rho_c}\left(\frac{45}{\pi g_*}\right)^{1/2}\frac{1}{\xi_F m_{\rm Pl}}\frac{1}{\langle\sigma v\rangle}$$

putting in the astrophysical numbers, we find

$$\langle\sigma v\rangle = 1 \ \mathrm{pb} = \frac{\pi\alpha^2}{2m^2}$$

where $m = 200 \ \mathrm{GeV}$. Weaker coupling implies smaller masses.

This brings us to Plan A:

Expect many particles of a sector coupled to the new interactions, including partners of the top quark and other heavy particles with QCD color.

Hadron colliders can search for these robustly.

It is easy for the lightest particle of the new type to carry a quantum number that makes it stable. If it is neutral, it is a dark matter candidate. There are exceptions, but generally direct detection cross sections

$$\sigma \sim 10^{-6} - 10^{-8}\ \mathrm{pb}$$

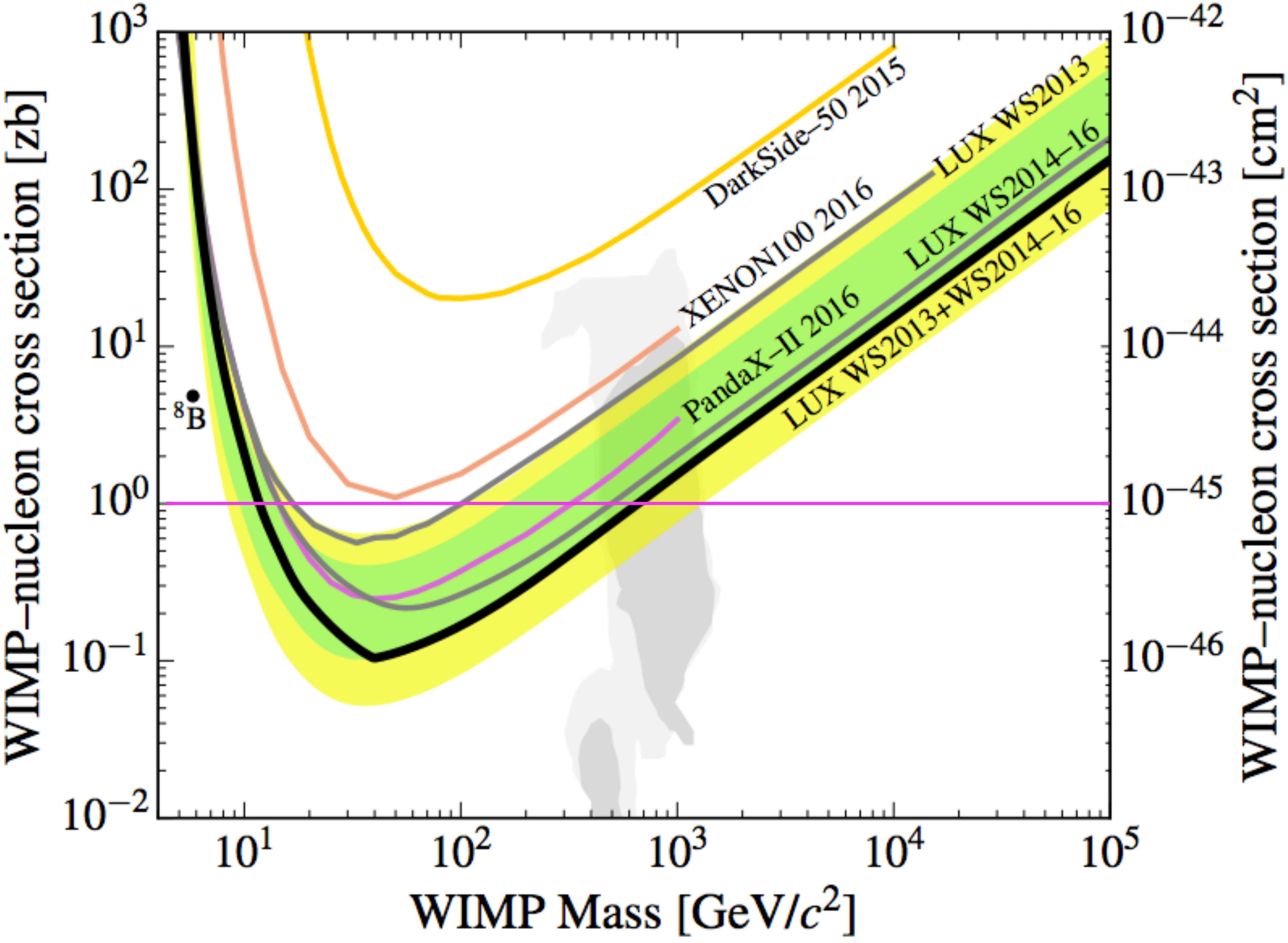
are expected.

Supersymmetry gives an example of such a model.

There is still room for hope, but, so far, this has not worked out. Strongly interacting particles expected to be copiously produced at the LHC are now excluded up to masses of 1 TeV and above. The gluino of SUSY is excluded almost up to 2 TeV.

The LHC still has much data to gather, but the reach is not expected to increase even by a factor 2 with 100 times more data.

Direct detection experiments have also been disappointing. We now need exceptional cases with very small direct detection cross sections.


WIMP–nucleon cross section [zb]
WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^1
10^2
10^3
10^4
10^5
DarkSide–50 2015
XENON100 2016
LUX WS2013
LUX WS2014–16
PandaX–II 2016
LUX WS2013+WS2014–16
^{8}B

LUX Aug 2016

How have theorists responded to this?

Color neutral symmetry breaking sectors

Higgs compositeness, with resonances at higher mass

Dark matter in complex “dark sectors”, very weakly coupled to the SM (implying also lower mass)

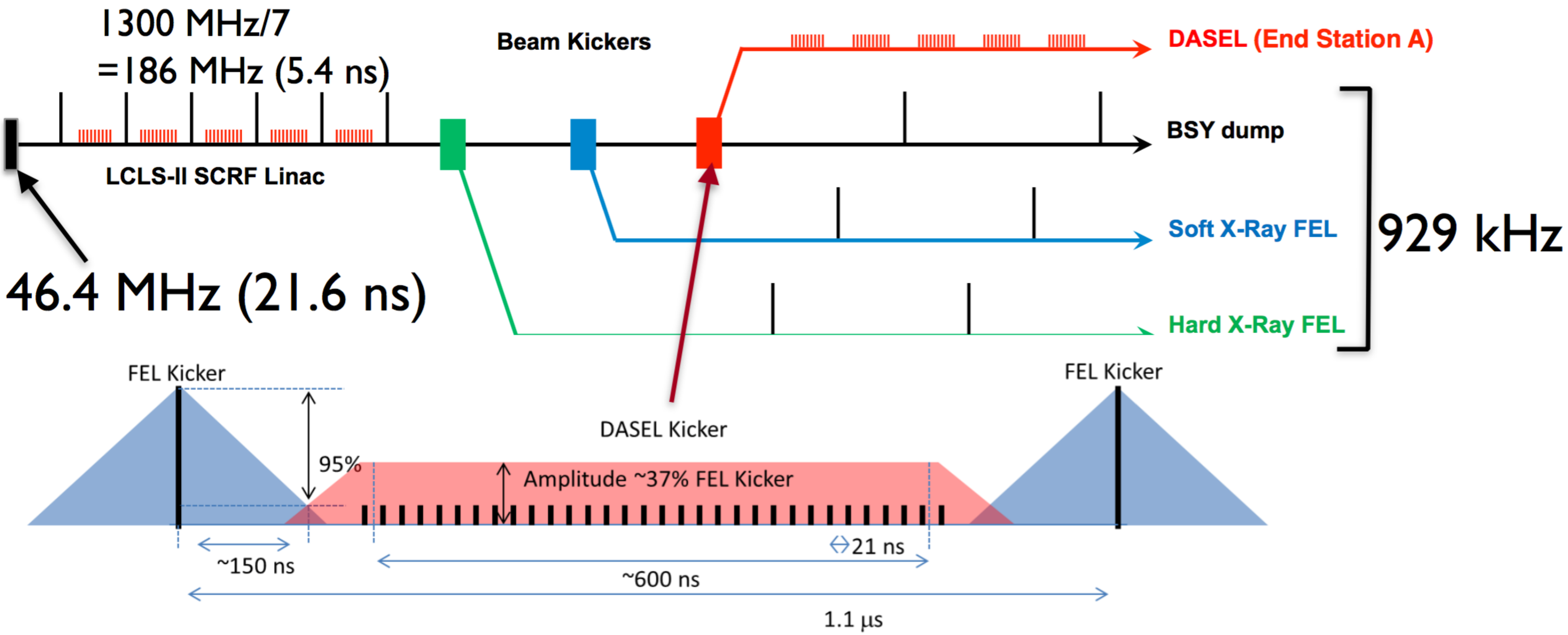
We need a Plan B, a very different approach to the search for new physics.

One aspect, which might suffice for dark matter, is to search for light, weakly coupled particles at low mass using extremely intense beams.

For high energy accelerators, we must

use the Higgs boson and the top quark as probes of new physics by making precision measurements of their properties

search for color-neutral particles that are invisible or leave very small energy deposition in detectors (parenthetically, SCRF also has a solution for the discovery of very light (MeV - GeV) dark matter particles: DASEL at LCLS II)



(detector ? ask Nhan Tran in the LPC)

Higgs and top quark measurements and dark matter searches are actively pursued at LHC.   But there are limits:

At an e+e- collider, Higgs bosons are produced in 1 in 100 annihilation events.

At the LHC, Higgs bosons are produced in 1 in 2 billion pp collisions.

R. Talman:

> “That’s like doing astronomy in the daytime.”

Similarly, for weakly coupled color-neutral particles, products with pT < 5 GeV for leptons and < 20 GeV for quarks are buried in the noise of typical events.

For both of these questions,

Higgs boson and top quark precision measurement

the search for neutral, weakly coupled particles

LHC is the wrong tool. We use it for lack of a better one.

These questions cry out for a new e+e- collider at higher energy.

Precision measurement of the Higgs boson couplings is a well-defined goal.

In the SM, once the mass of the Higgs is known, these couplings are precisely predicted. Any deviation from those predictions signals new interactions beyond the SM.

For $m_h = 125\ \mathrm{GeV}$, many couplings are available in Higgs decays. The branching ratios are predicted to be

$b\bar{b}$	56%	$\tau^+\tau^-$	6.2%	$\gamma\gamma$	0.23%
WW^*	23%	ZZ^*	2.9%	γZ	0.16%
gg	8.5%	$c\bar{c}$	2.8%	$\mu^+\mu^-$	0.02%

To obtain the couplings, we must also the total width, predicted to be $\Gamma_h = 4.3\ \mathrm{MeV}$. The program should also include measurement of the $t\bar{t}h$ and hhh couplings.

Higgs
yurukyaya
at
LCWS2016

What are the expectations for new physics effects ?
These are set by Haber's Decoupling Theorem:

If the spectrum of the Higgs sector contains one Higgs boson of mass m_h and all other particles have mass at least M , then the influence of these particles on the properties of the light Higgs boson is proportional to

$$m_h^2/M^2$$

Then the effects of new physics at 1 TeV on the properties of the Higgs are at the percent level.

In this context, the current 30% agreement of the Higgs properties with the predictions of the Standard Model is completely expected. But more accurate experiments could potentially show deviations in all of the visible Higgs decay modes.

Here are some examples of effects on the Higgs boson in explicit models of new physics:

Note that different models produce different patterns of deviations from the precise SM predictions.

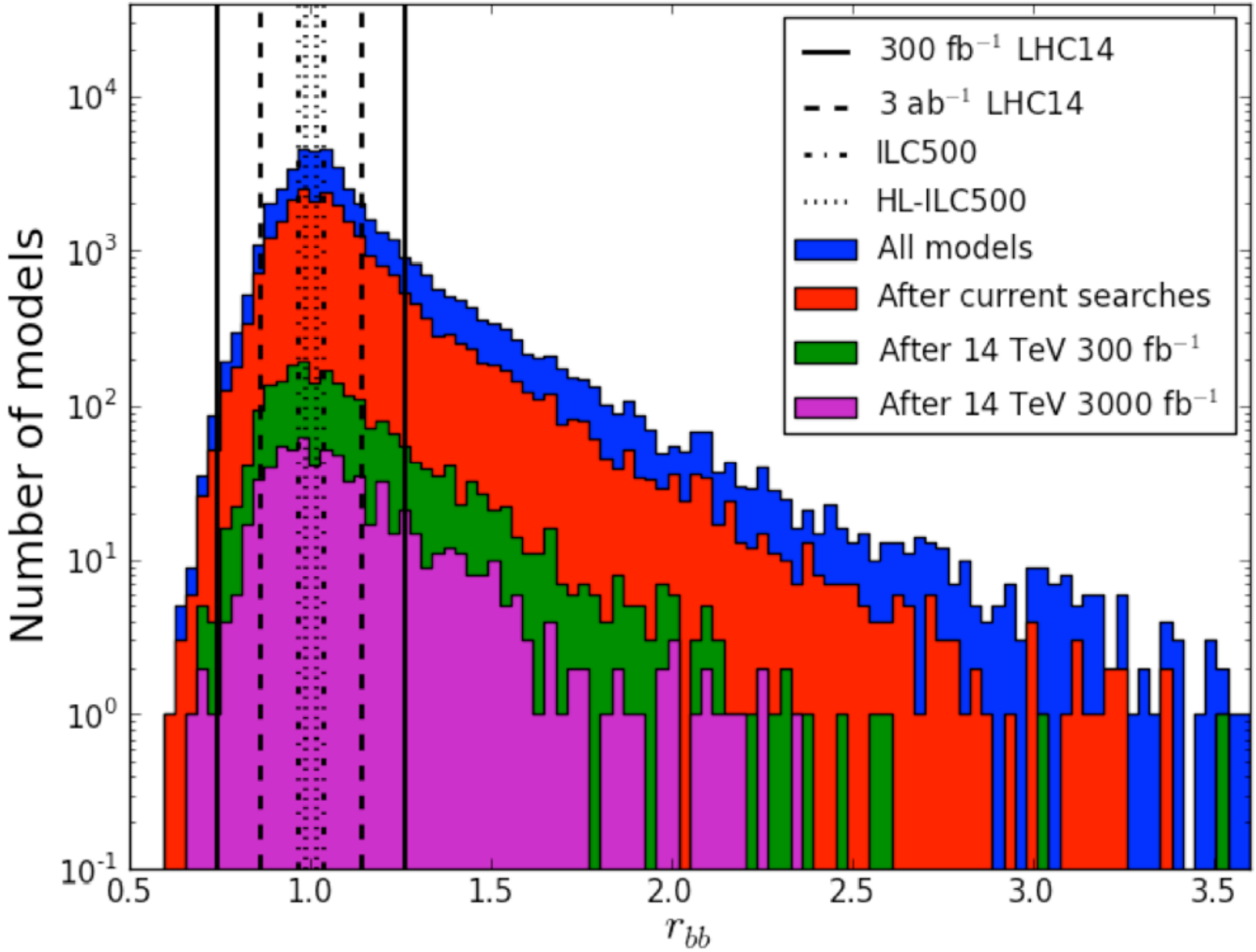
Models with weakly coupled particles explaining the Higgs potential typically contain more than one Higgs doublet.

This leads to anomalies in the hbb and hττ couplings.

$$g(b\overline{b}) = -\frac{\sin\alpha}{\cos\beta}\frac{m_b}{v} \qquad g(c\overline{c}) = \frac{\cos\alpha}{\sin\beta}\frac{m_c}{v}$$

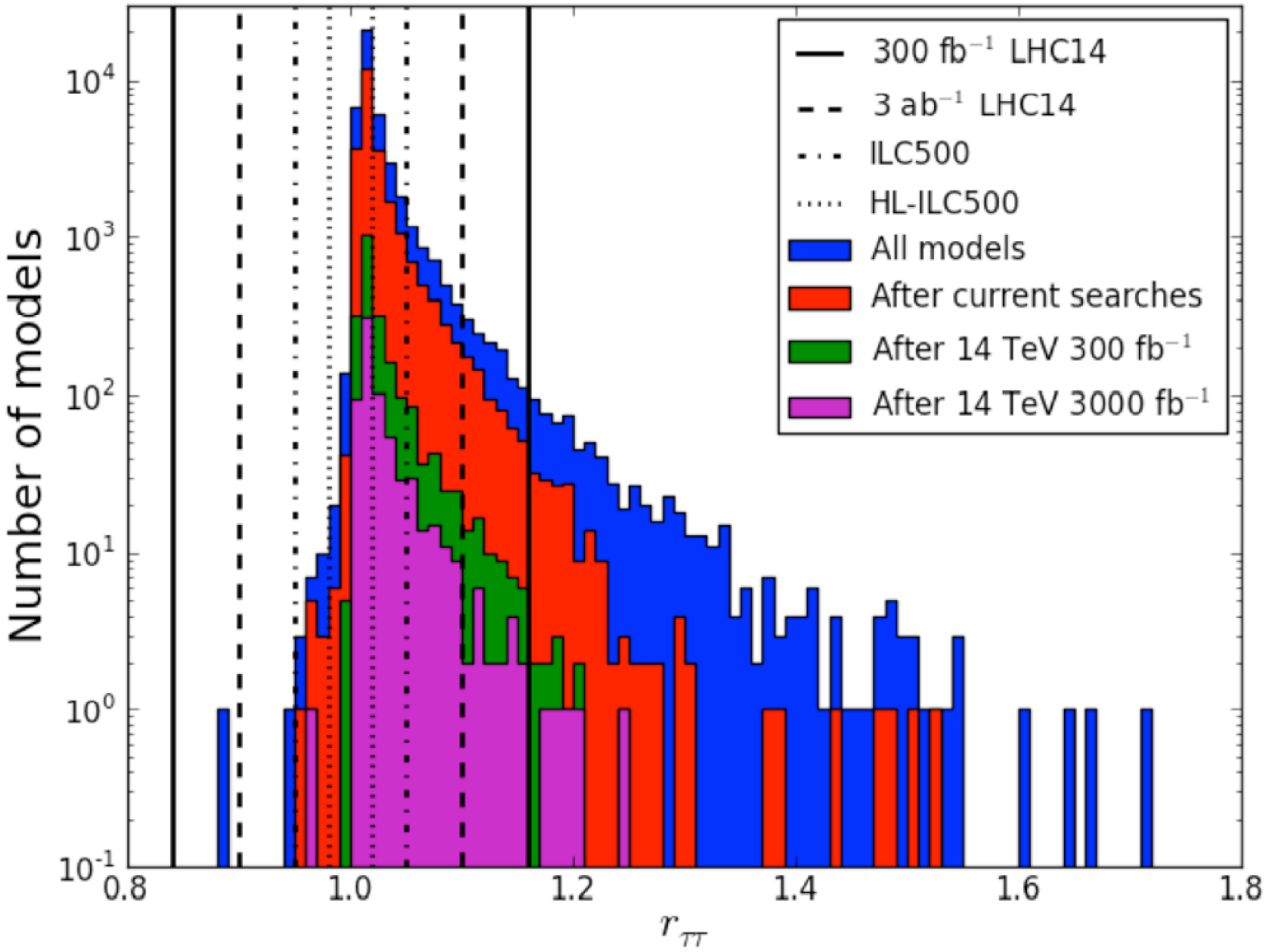
These effects are restricted by decoupling but can be at the 5% level. They can be enhanced by loop diagrams involving the heavy partners of b, τ.

$\Gamma(h \to b\bar{b})$



Cahill-Rowley, Hewett, Ismail, Rizzo

$\Gamma(h \to \tau^+\tau^-)$



Cahill-Rowley, Hewett, Ismail, Rizzo

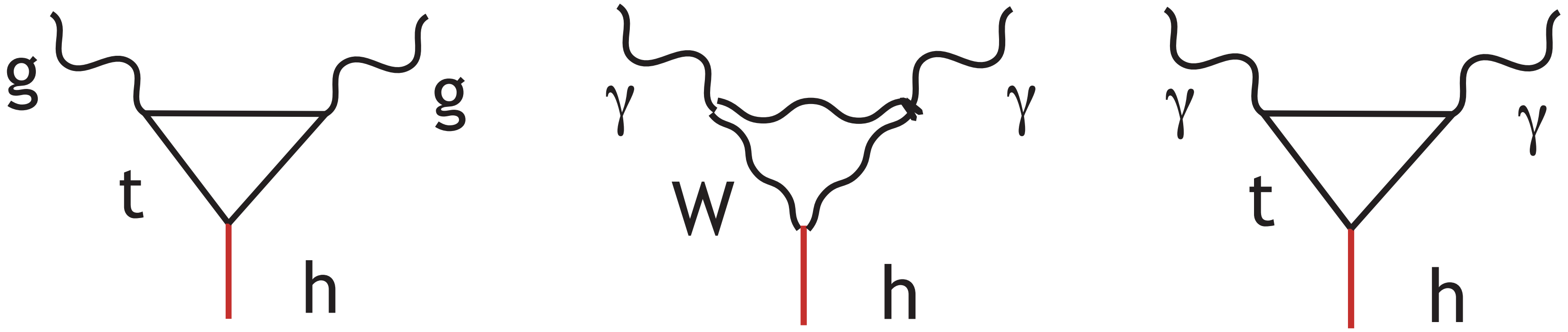
Models with additional scalar fields that do not have SM quantum numbers affect the hZZ and hWW couplings. This structure appears in Higgs portal dark matter.

$$g(hVV) \sim \cos\phi \sim (1 - \phi^2/2)$$

Models with composite Higgs bosons also may have significant suppression of the hZZ and hWW couplings.

$$g(hVV) = (1 - v^2/f^2)^{1/2} \approx 1 - v^2/2f^2 \approx 1 - 3\%$$

The decays $h \to gg$, $h \to \gamma\gamma$ go through loop diagrams.



Models in which new heavy fermions create the Higgs potential give additional contributions to these loops.

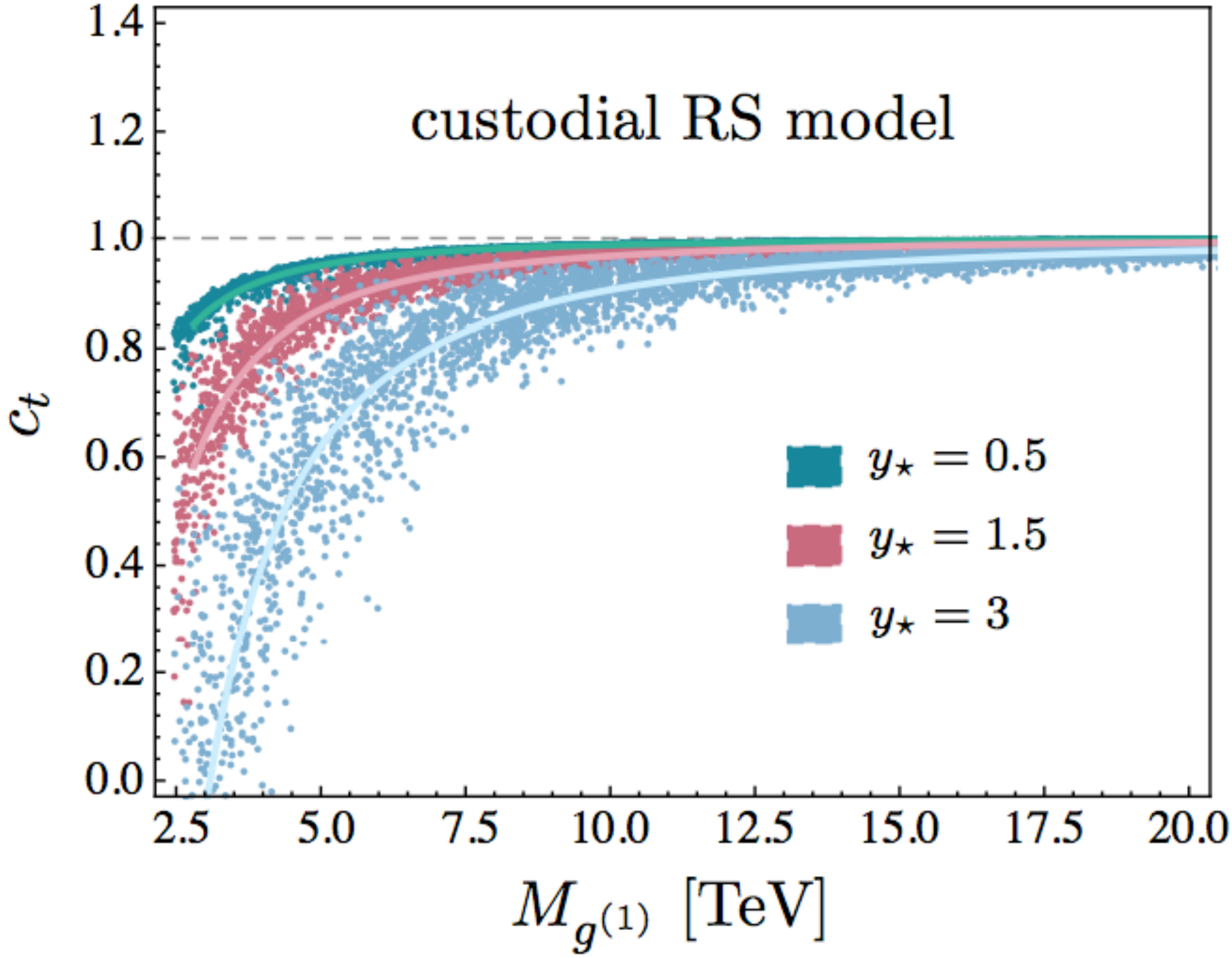
For example, one new vectorlike T quark gives

$$g(hgg)/SM = 1 + 2.9\% (\frac{1 \text{ TeV}}{m_T})^2$$

In composite Higgs models, the shifts in the γγ and gg partial widths come both from the modification of the top quark coupling and from the contributions of heavy vectorlike particles.

These effects are disentangled by direct measurement of the Higgs coupling to $t\bar{t}$.

Substantial effects are expected in 5-dimensional models, such as Randall-Sundrum models, especially those that have a special role for the top quark in SU(2)xU(1) symmetry breaking.



Malm, Neubert, Schmell

The Higgs self-coupling is a special case in this story.

Whereas we can expect the other Higgs couplings to be measured at the percent level, the hhh coupling is much more difficult to access.

However, factor of 2 deviations in the hhh coupling are expected in some scenarios, in particular, in models of baryogenesis at the electroweak scale. These may be the only models of baryogenesis testable with accelerator data.

The result of this survey is that each Higgs coupling has its own personality and is guided by different types of new physics.   This is something of a caricature, but, still, a useful one.

fermion couplings -   multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

γγ, gg couplings - heavy vectorlike particles

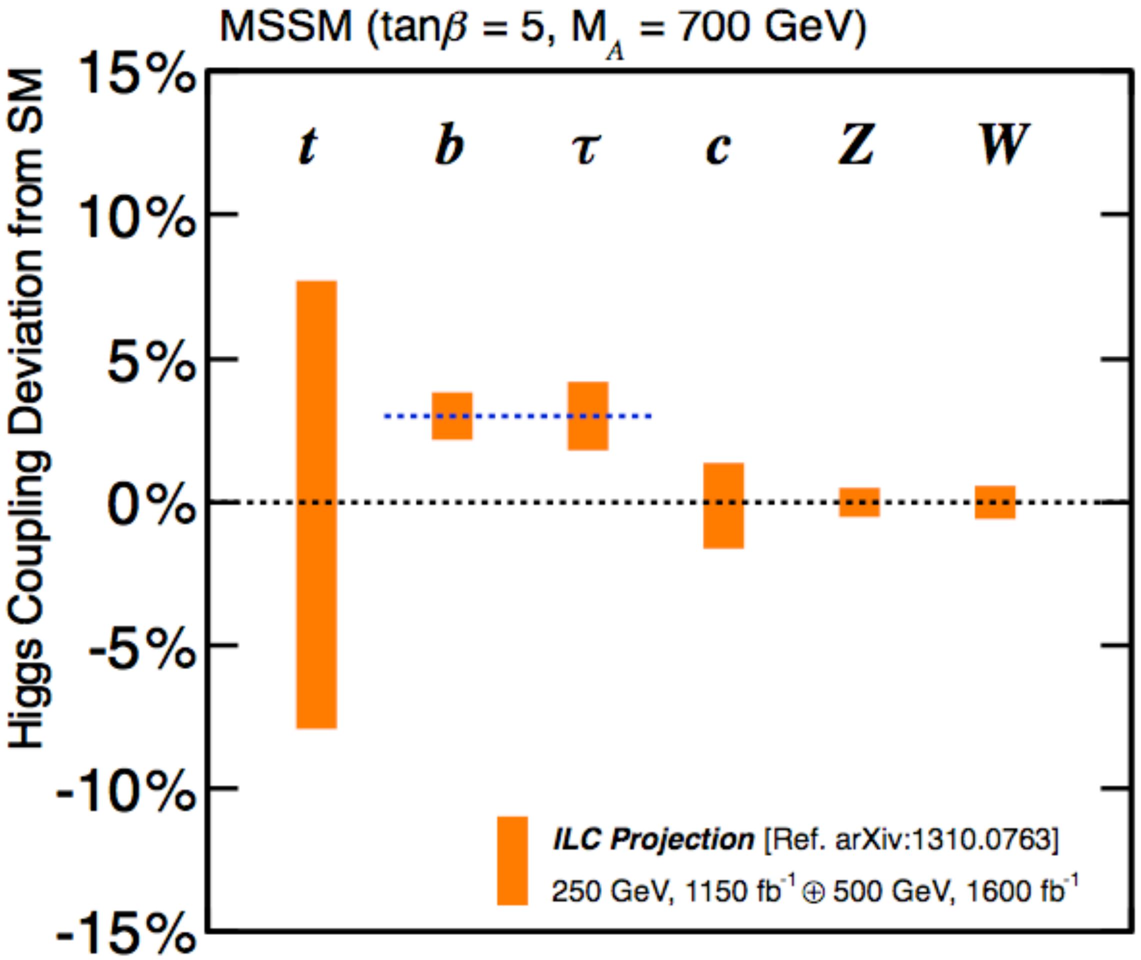
tt coupling -   Higgs/top compositeness

hhh coupling (large deviations) - baryogenesis

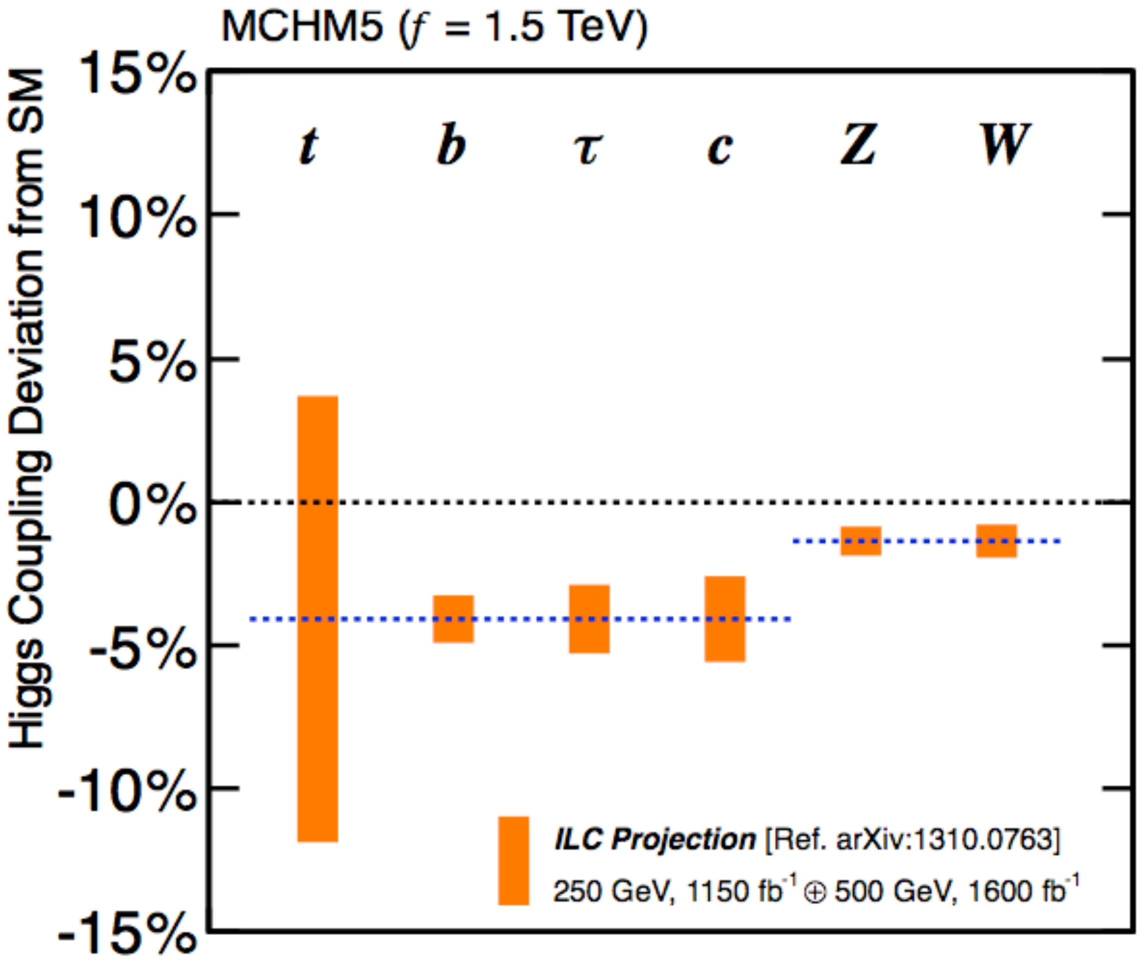
Putting all of these effects together, we find patterns of deviations from the SM predictions that are different for different schemes of new physics.

For example:

SUSY



Composite Higgs

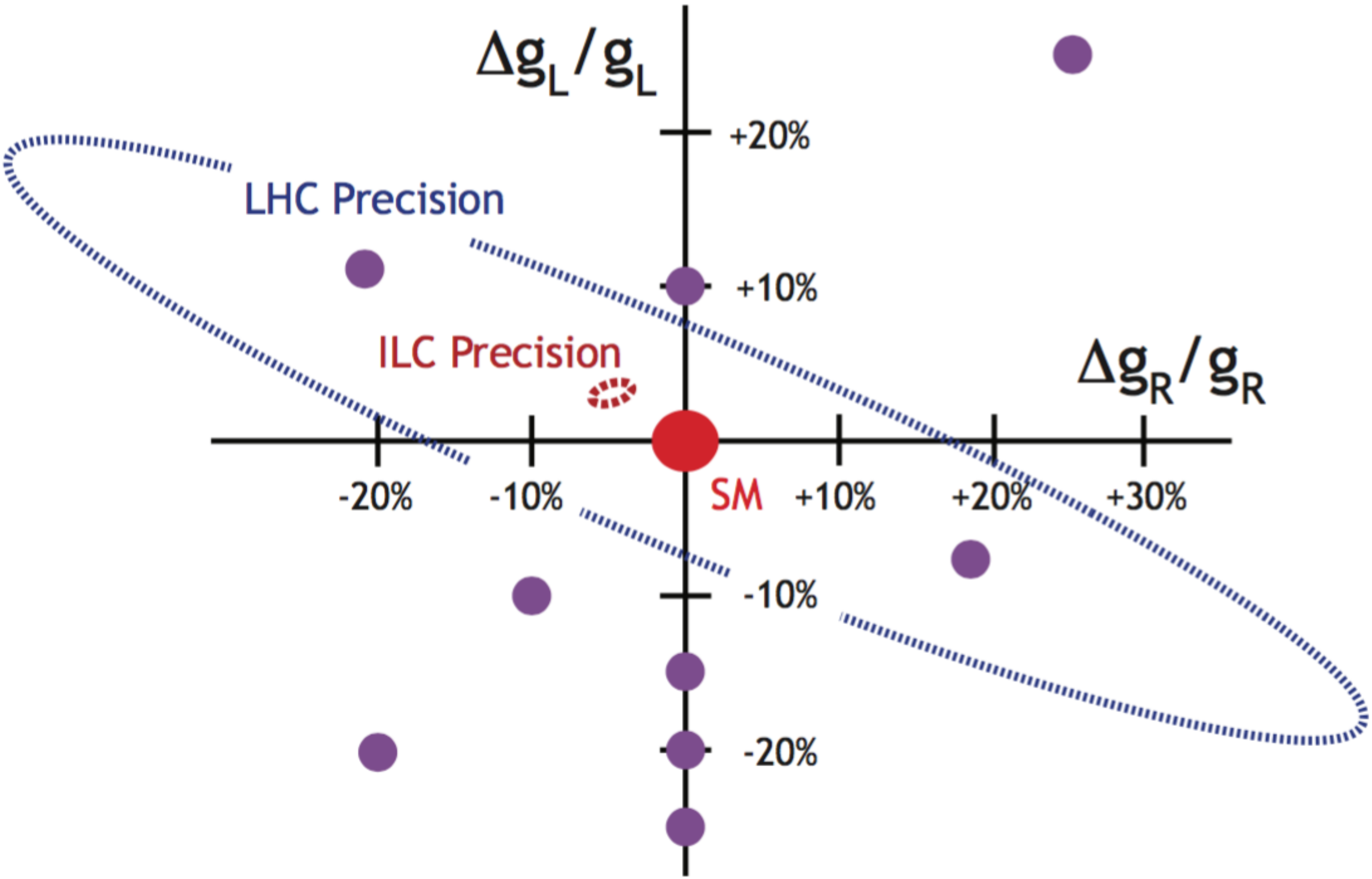


Kanemura, Tsumura, Yagyu, Yokoya

A similar story applies to the weak and electromagnetic couplings of the top quark.

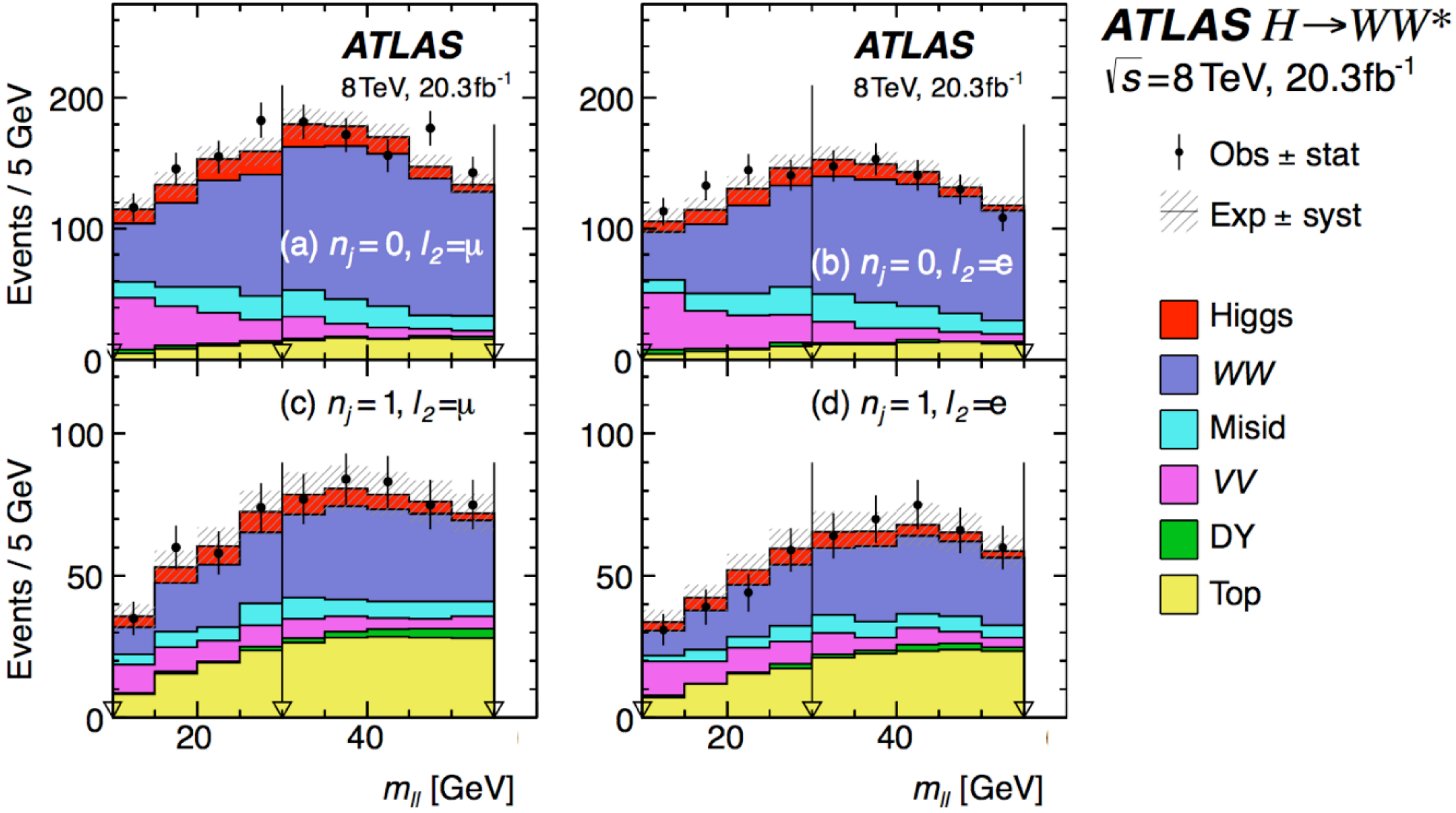
In particular, the Ztt couplings are relatively unconstrained by gauge invariance. In weakly coupled models (e.g. SUSY), the deviations from the SM are small.   But models in which the Higgs boson is composite typically also have mixing of the top quark with heavy composite states, leading to sizable effects.

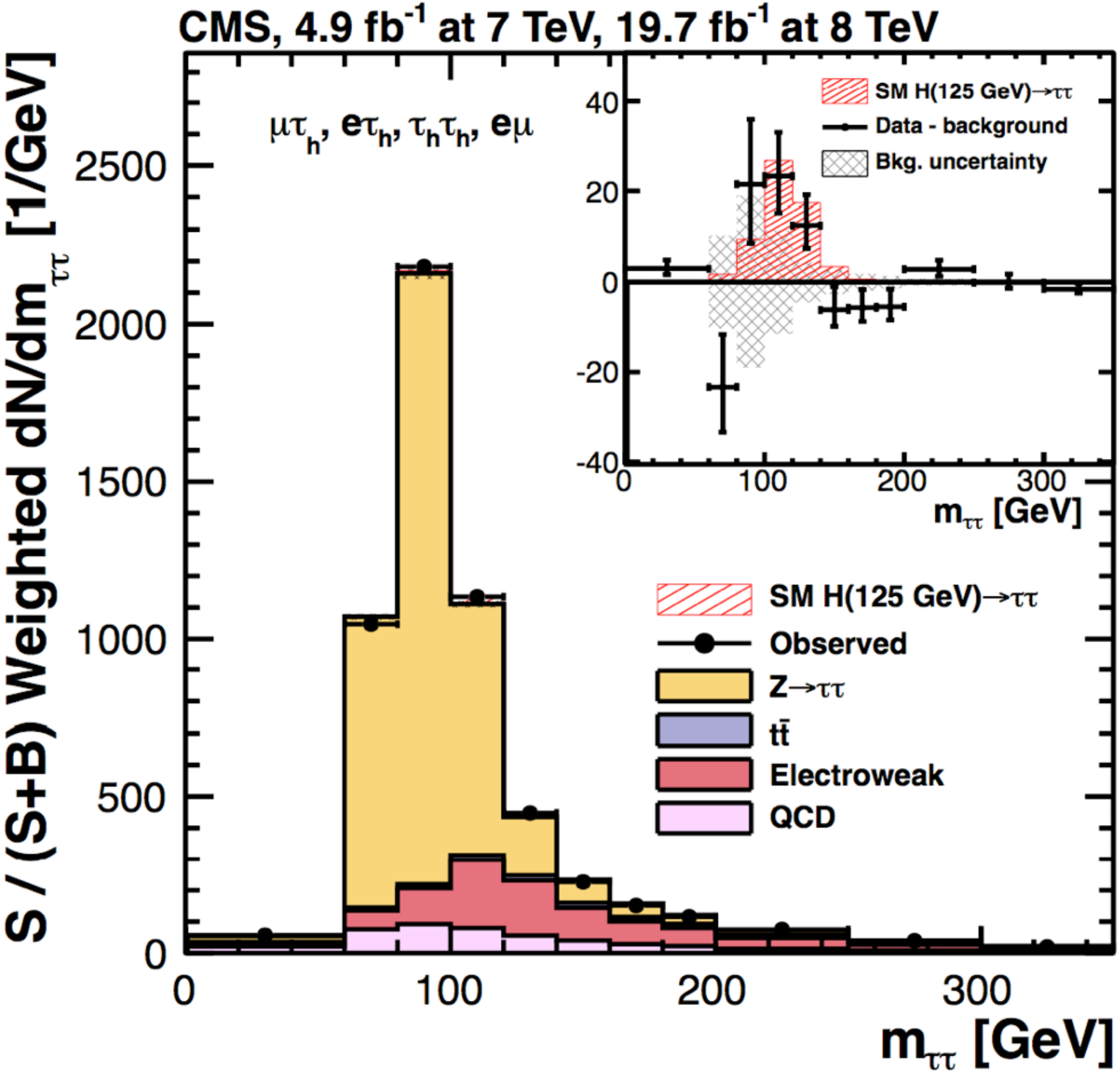
The sign and chirality of the deviations is an important diagnostic of these models.


$\Delta g_L / g_L$
+20%
LHC Precision
+10%
ILC Precision
$\Delta g_R / g_R$
-20%
-10%
SM
+10%
+20%
+30%
-10%
-20%

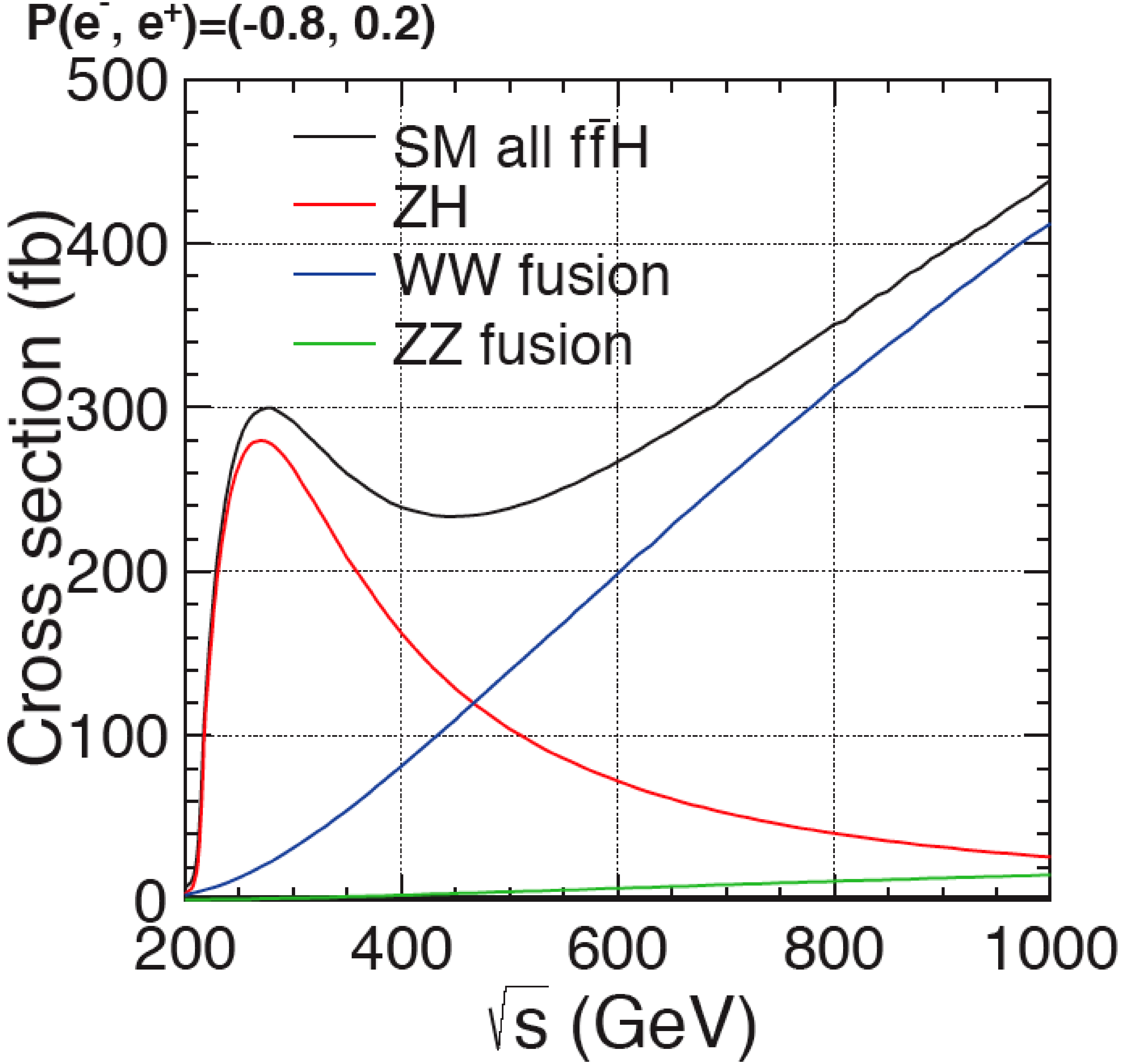
The accuracies needed for these study go well beyond what is possible at hadron colliders.

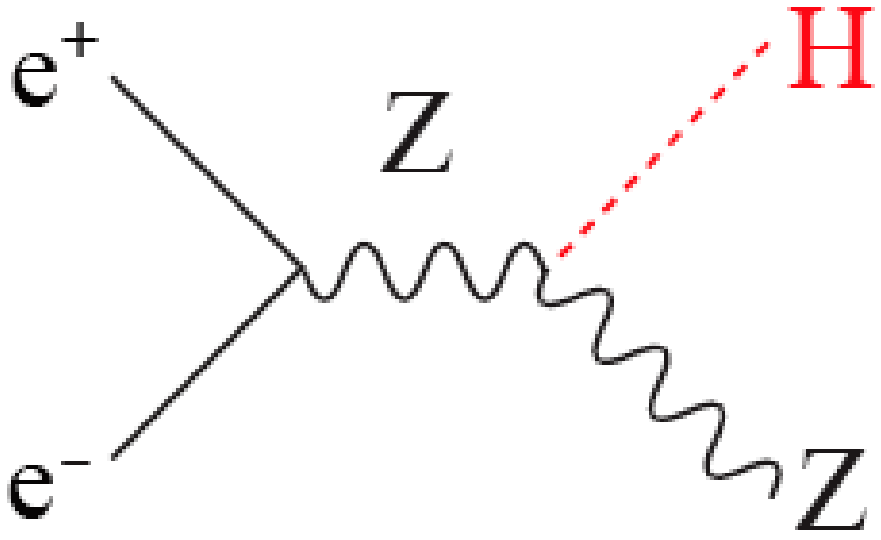
This is especially true because an upper limit is not interesting. We need a 5σ discovery.


ATLAS
8 TeV, 20.3fb-1
(a) $n_j = 0, l_2 = \mu$
(b) $n_j = 0, l_2 = e$
(c) $n_j = 1, l_2 = \mu$
(d) $n_j = 1, l_2 = e$
Events / 5 GeV
0
100
200
50
20
40
m_{ll} [GeV]
ATLAS $H \rightarrow WW^*$
$\sqrt{s} = 8$ TeV, 20.3fb^{-1}
Obs ± stat
Exp ± syst
Higgs
WW
Misid
VV
DY
Top

CMS, 4.9 fb^{-1} at 7 TeV, 19.7 fb^{-1} at 8 TeV
$\mu\tau_h$, $e\tau_h$, $\tau_h\tau_h$, $e\mu$
S / (S+B) Weighted dN/dm$_{\tau\tau}$ [1/GeV]
0
500
1000
1500
2000
2500
0
100
200
300
m$_{\tau\tau}$ [GeV]
SM H(125 GeV)→ττ
Observed
Z→ττ
$t\bar{t}$
Electroweak
QCD
SM H(125 GeV)→ττ
Data - background
Bkg. uncertainty
-40
-20
0
20
40
0
100
200
300
m$_{\tau\tau}$ [GeV]

How can we carry out this program at e+e- colliders ?

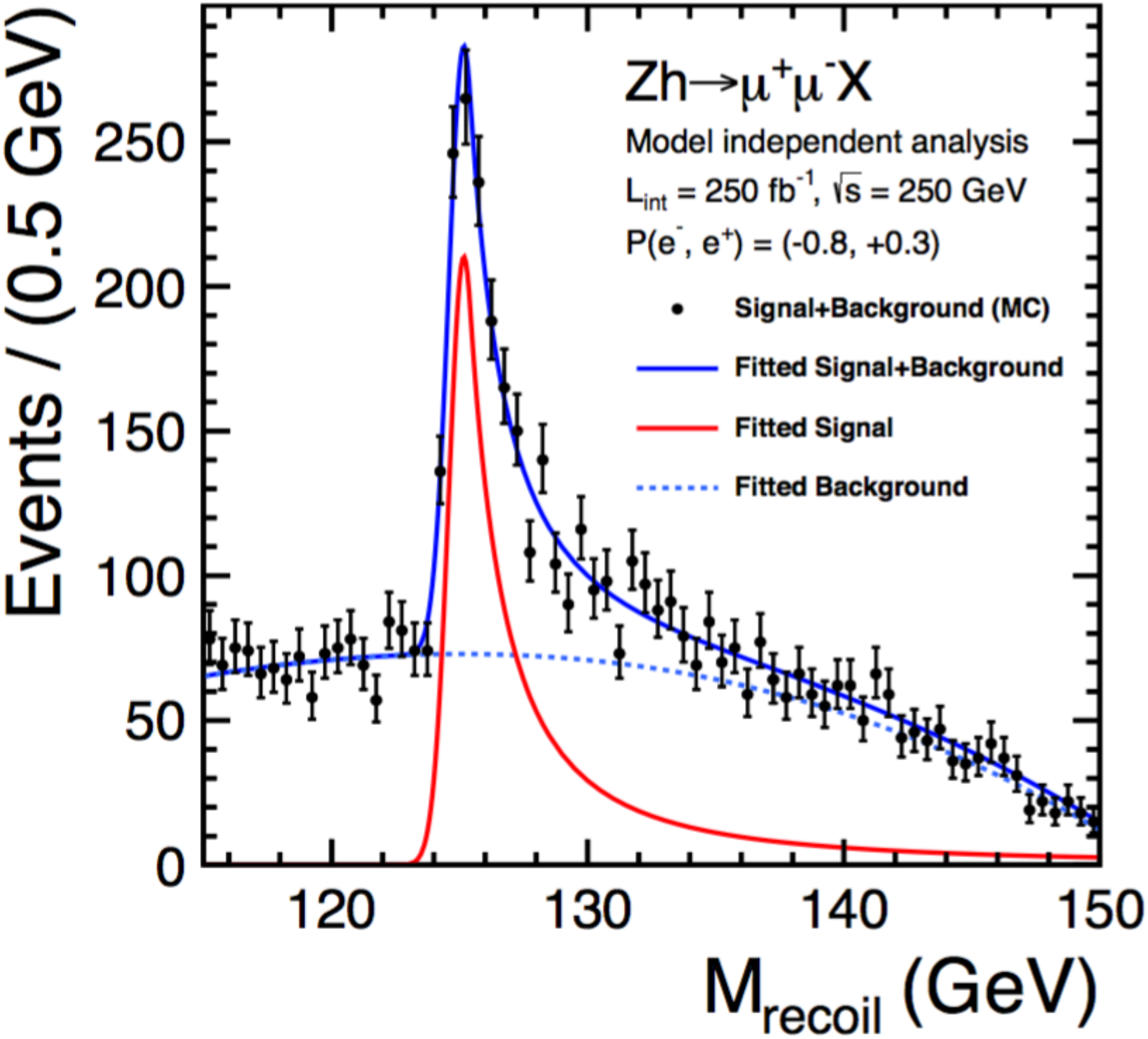

P(e⁻, e⁺)=(-0.8, 0.2)
SM all ff̄H
ZH
WW fusion
ZZ fusion
Cross section (fb)
0
100
200
300
400
500
200
400
600
800
1000
√s (GeV)



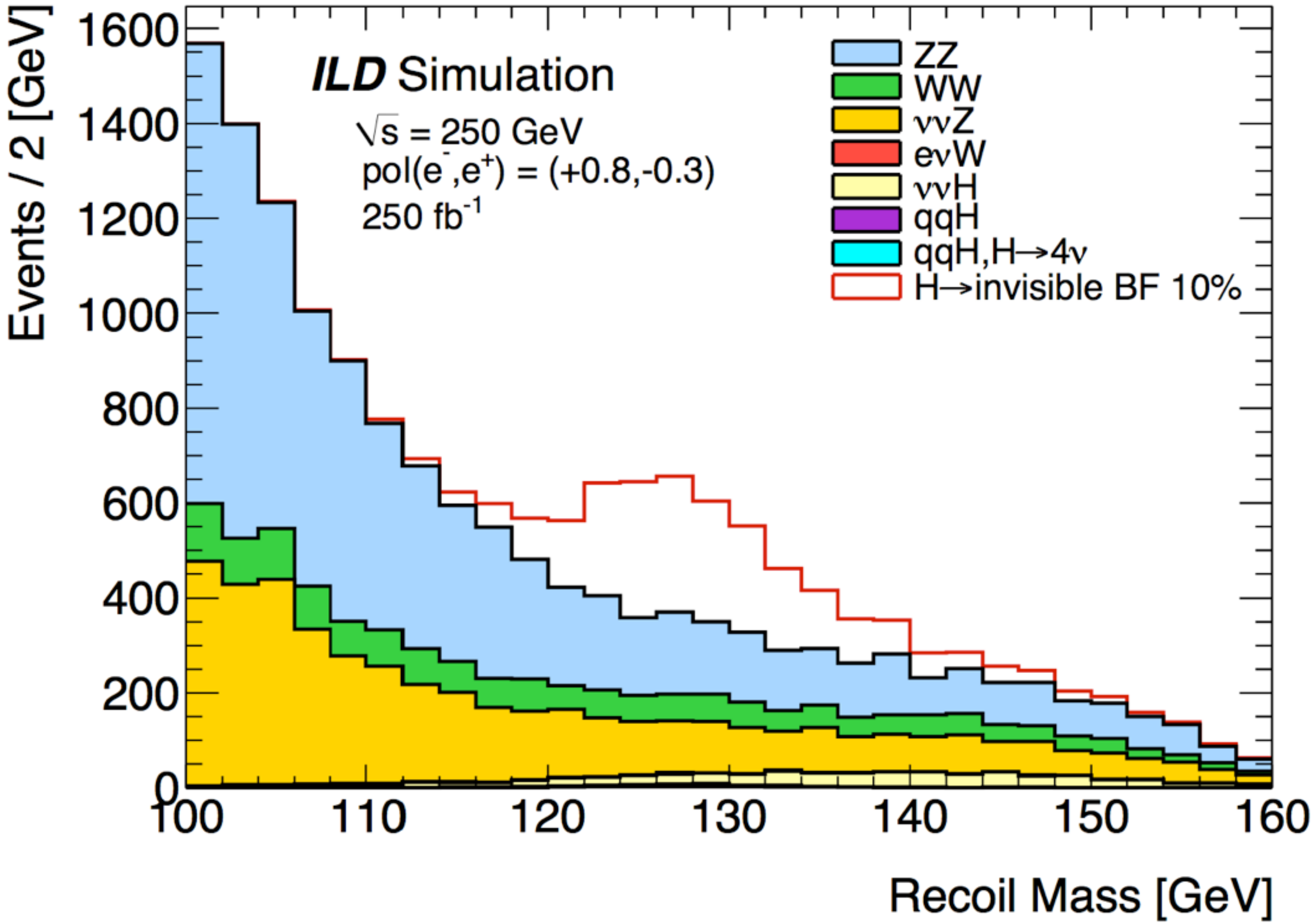
250 GeV:

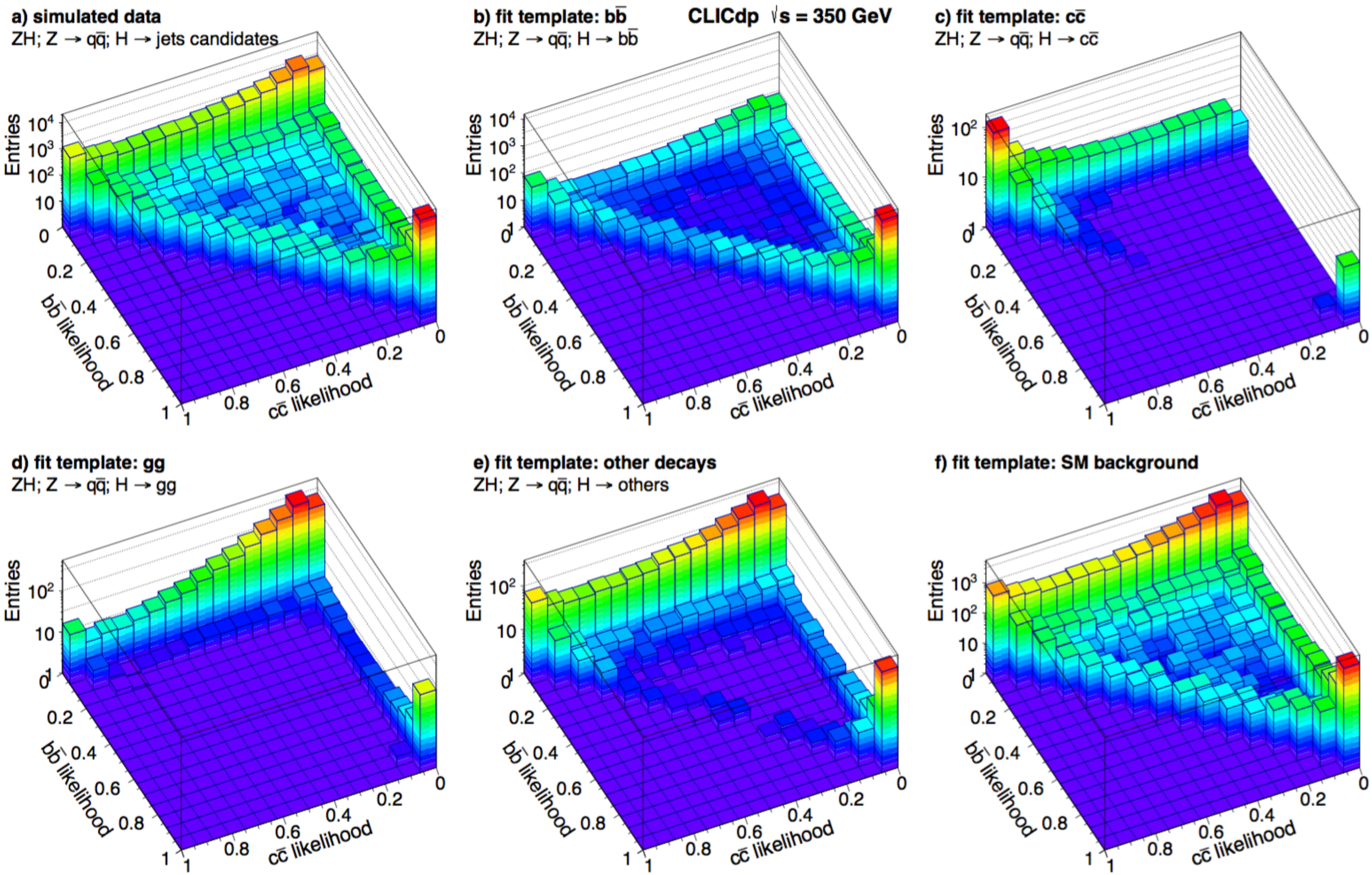
This is the peak of the cross section for $e^+e^- \to Zh$. About 200,000 Higgs bosons are produced per $500 fb^{-1}$ of luminosity.

Higgs bosons are tagged by a Z at the recoil energy (113 GeV), giving sensitivity to all, even very unusual, decay modes. Hadronic and invisible or partially visible decay modes can be identified.



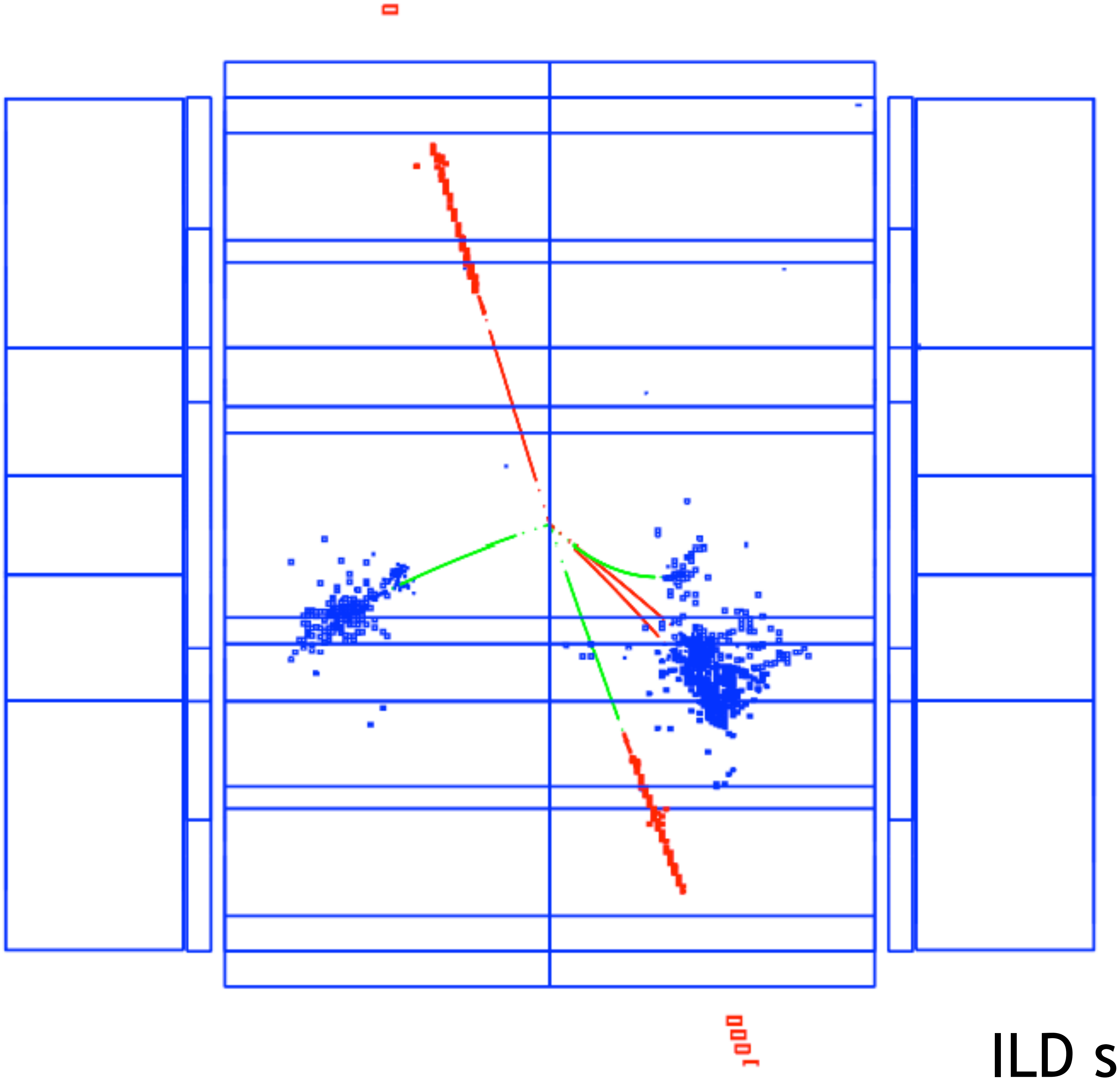
This technique can determine m_h to 15 MeV. This is needed to determine the hWW and hZZ couplings to 0.1%.


ILD Simulation
$\sqrt{s}$ = 250 GeV
pol(e⁻,e⁺) = (+0.8,-0.3)
250 fb⁻¹
ZZ
WW
νν Z
eνW
ννH
qqH
qqH,H→4ν
H→invisible BF 10%
Events / 2 [GeV]
Recoil Mass [GeV]
0
200
400
600
800
1000
1200
1400
1600
100
110
120
130
140
150
160



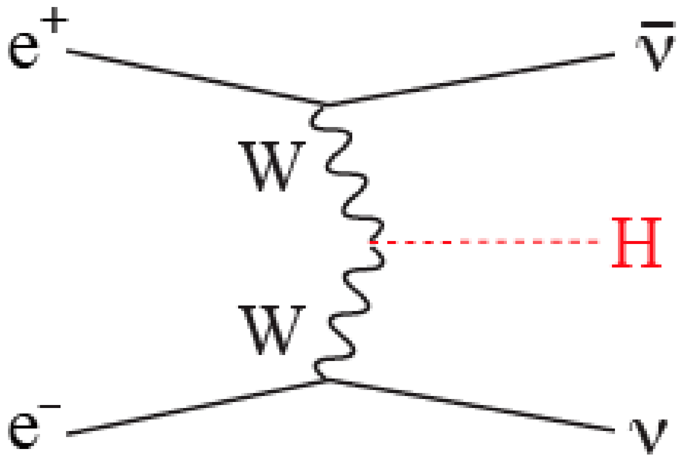
CLIC study at 350 GeV

$$e^+e^- \to Zh \to (\mu^+\mu^-)(\tau^+\tau^-)$$



ILD simulation

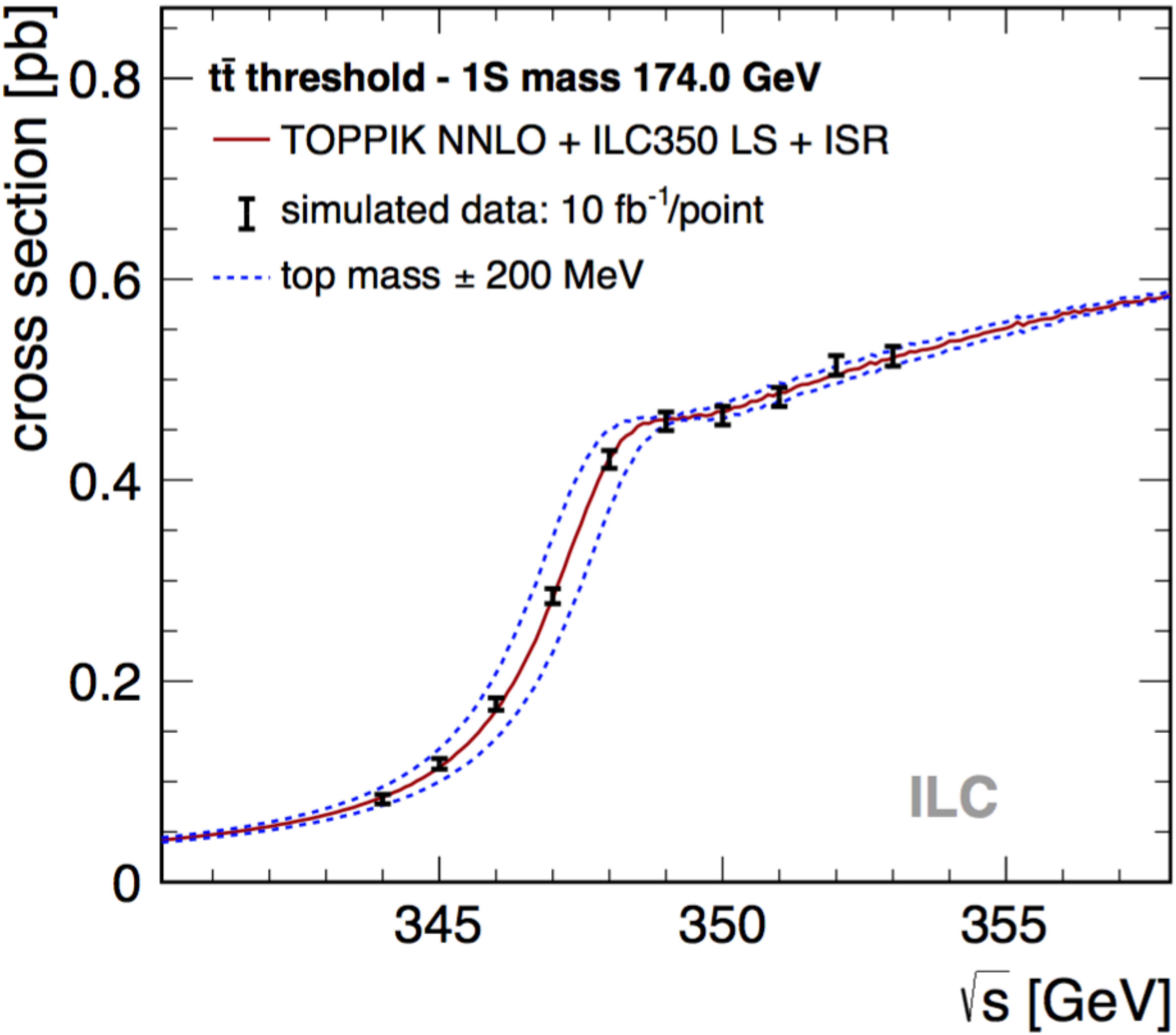
500 GeV:



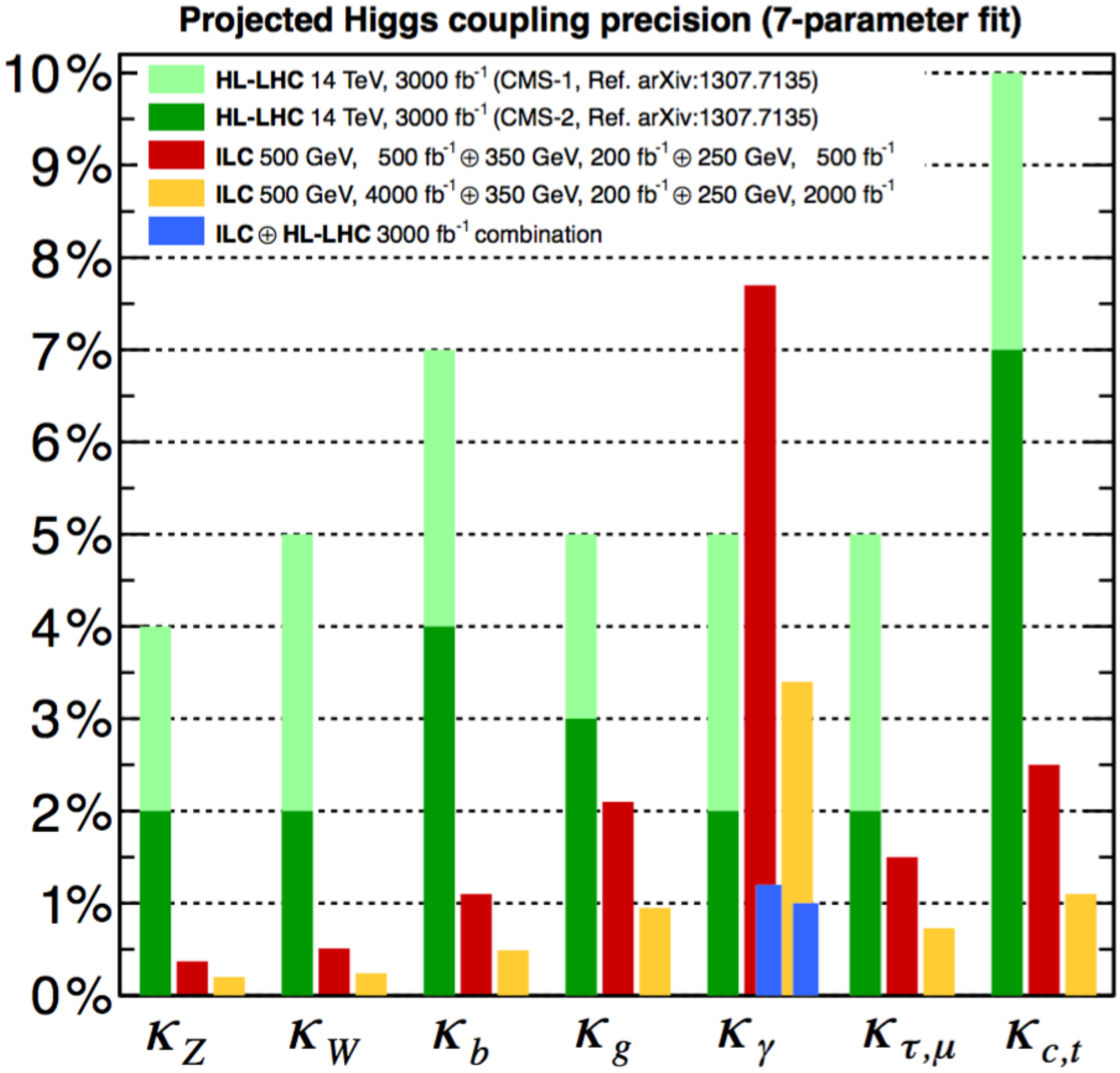
The main process studied at this energy is $e^+e^- \to \nu\bar{\nu}h$, that is, WW fusion to Higgs.

The measurement of $\sigma(e^+e^- \to \nu\bar{\nu}h \to b\bar{b})$ combined with the very accurate measurement of $BR(h \to b\bar{b})$ at 250 GeV, allows a model-independent determination of the Higgs total width and the absolute normalization of Higgs couplings

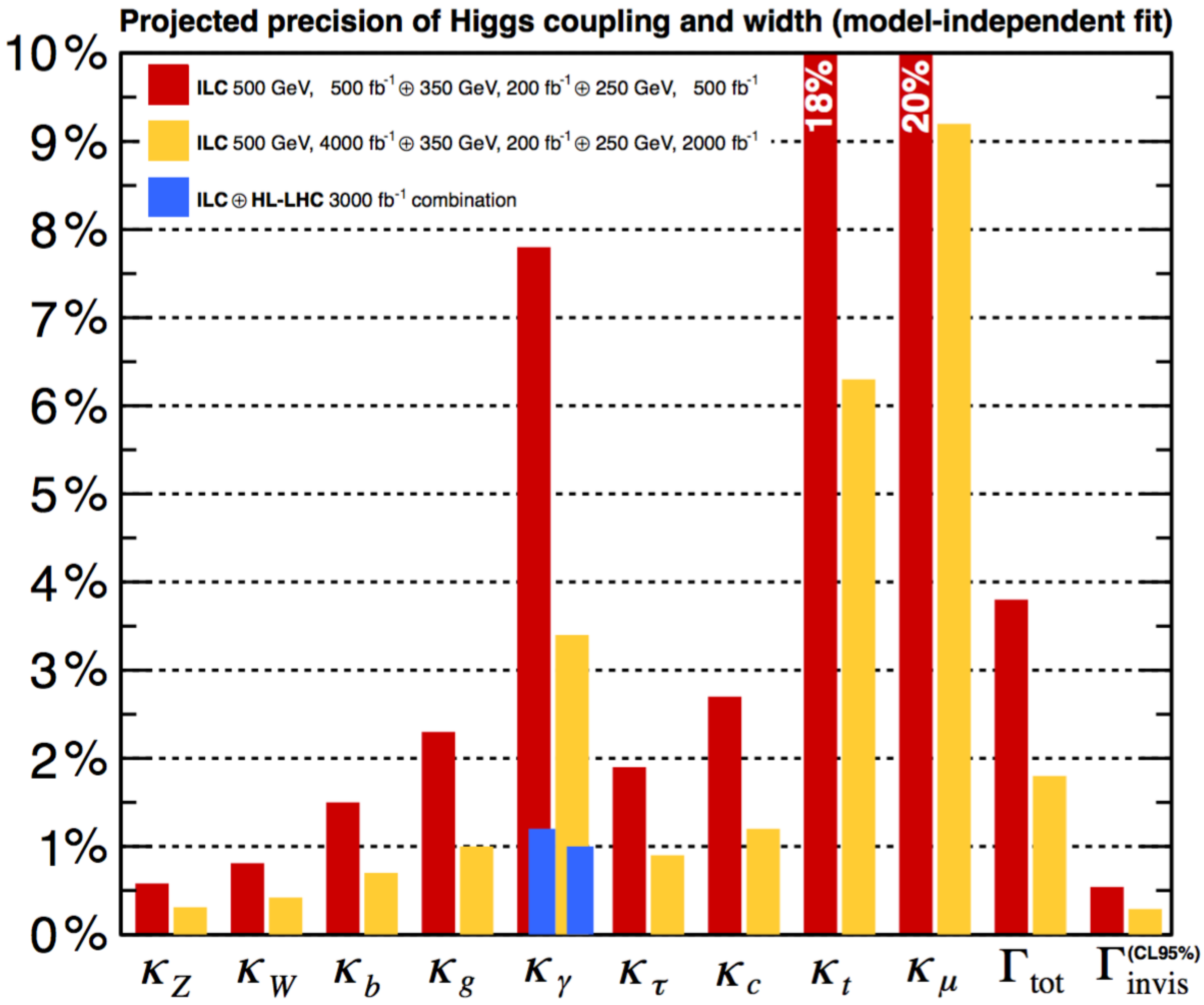
This energy also gives access to the $ht\bar{t}$ coupling and the Higgs self-coupling.



$t\bar{t}$ threshold - 1S mass 174.0 GeV
TOPPIK NNLO + ILC350 LS + ISR
simulated data: 10 fb^{-1}/point
top mass ± 200 MeV
ILC
cross section [pb]
0
0.2
0.4
0.6
0.8
345
350
355
$\sqrt{s}$ [GeV]

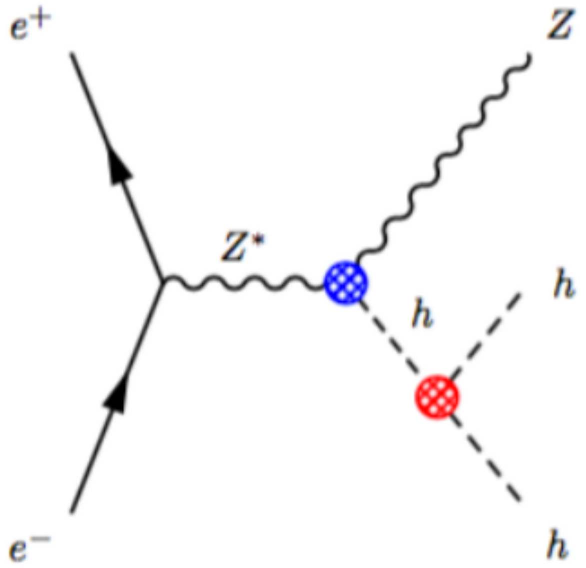


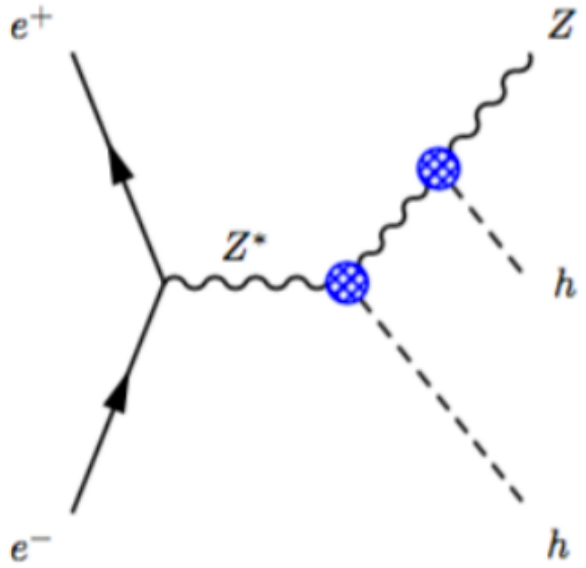
Higgs couplings: Snowmass model-dependent fit

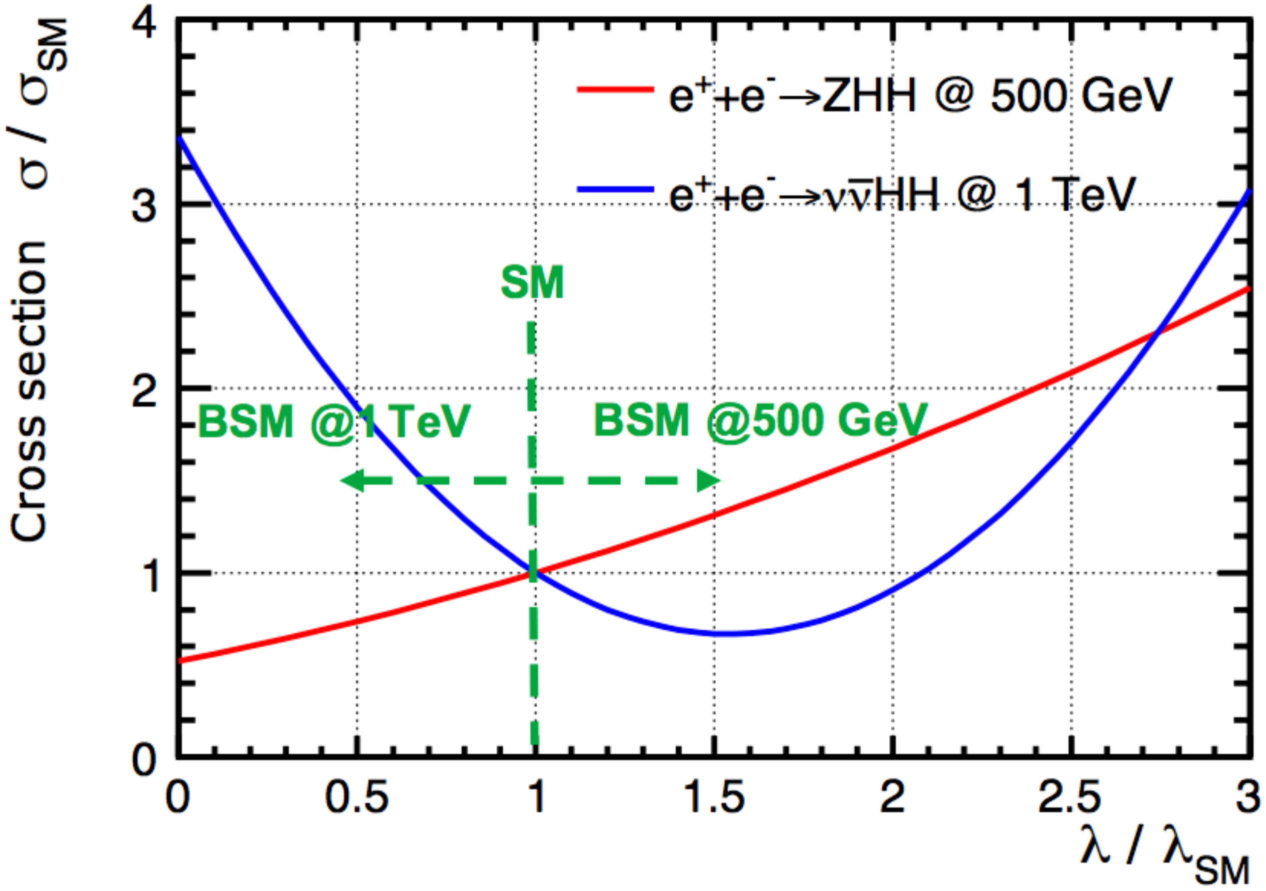


model-independent fit (e+e- colliders only)

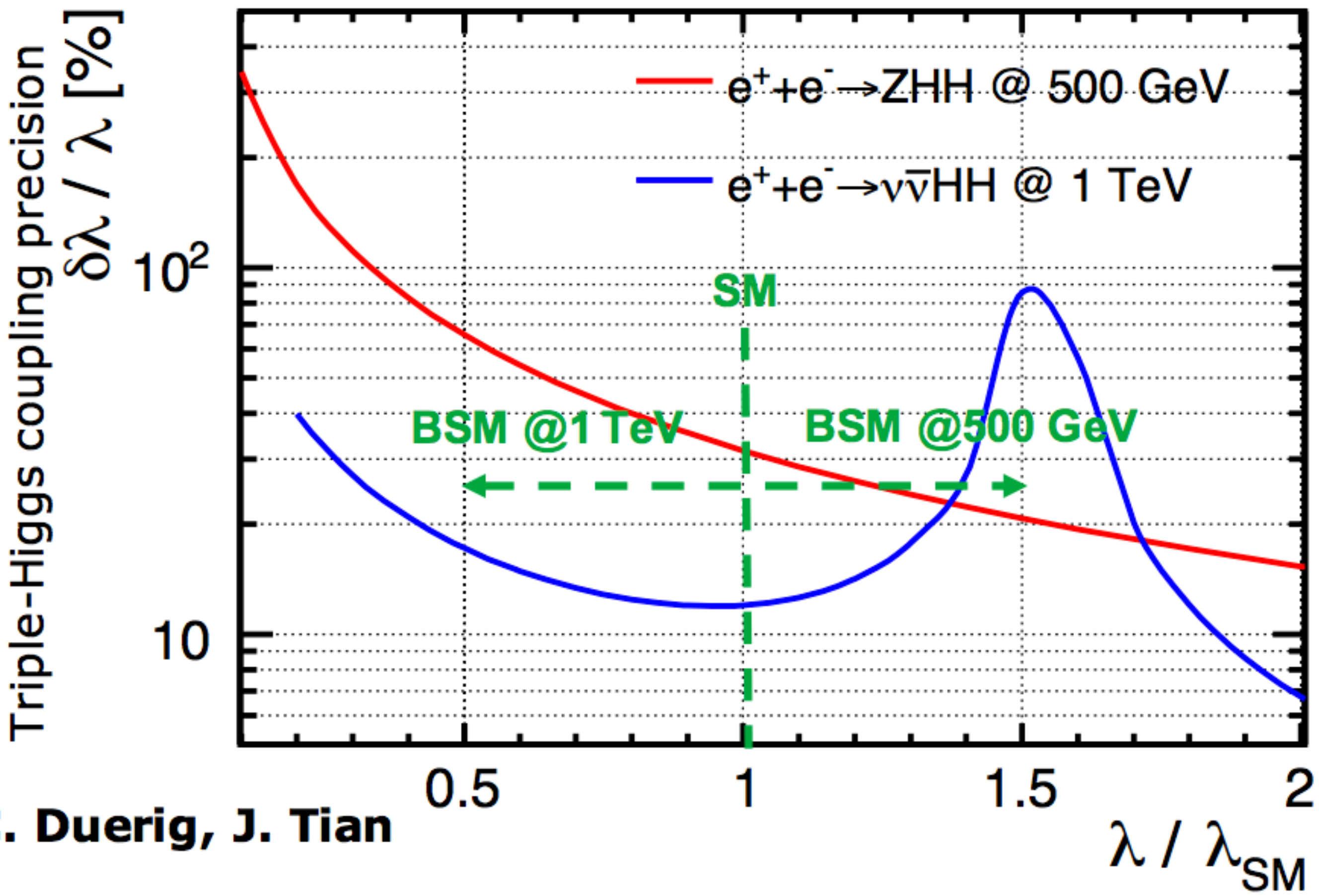
Already at 500 GeV, it is possible to measure the triple Higgs coupling at a level interesting for baryogenesis models.



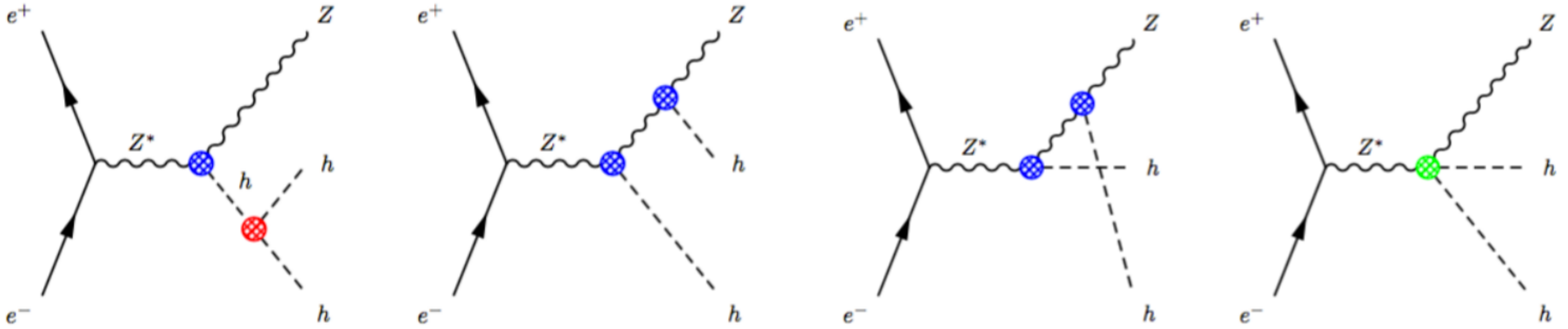




C. Duerig, J. Tian



Just as with the other Higgs couplings, a model-independent measurement is possible only at e+e- colliders.



$$\frac{\sigma(e^+e^- \to Zhh)}{\sigma_{SM}} = 1 - \underbrace{3.6\, c_H} + \underbrace{7.4\,(16 c_{WW})} + 0.56\, c_6$$

Higgs wavefunction renormalization & new vertex $\Delta\mathcal{L} = \frac{c_H}{v_0} h\partial_\mu h \partial^\mu h$

dim-6 vertices enhanced by (s/m_Z^2)

1000 GeV:

Running at still higher energies gives:

further improvement in Higgs statistics

opening up of $e^+e^- \to t\bar{t}h$:
coupling measurement to 2%

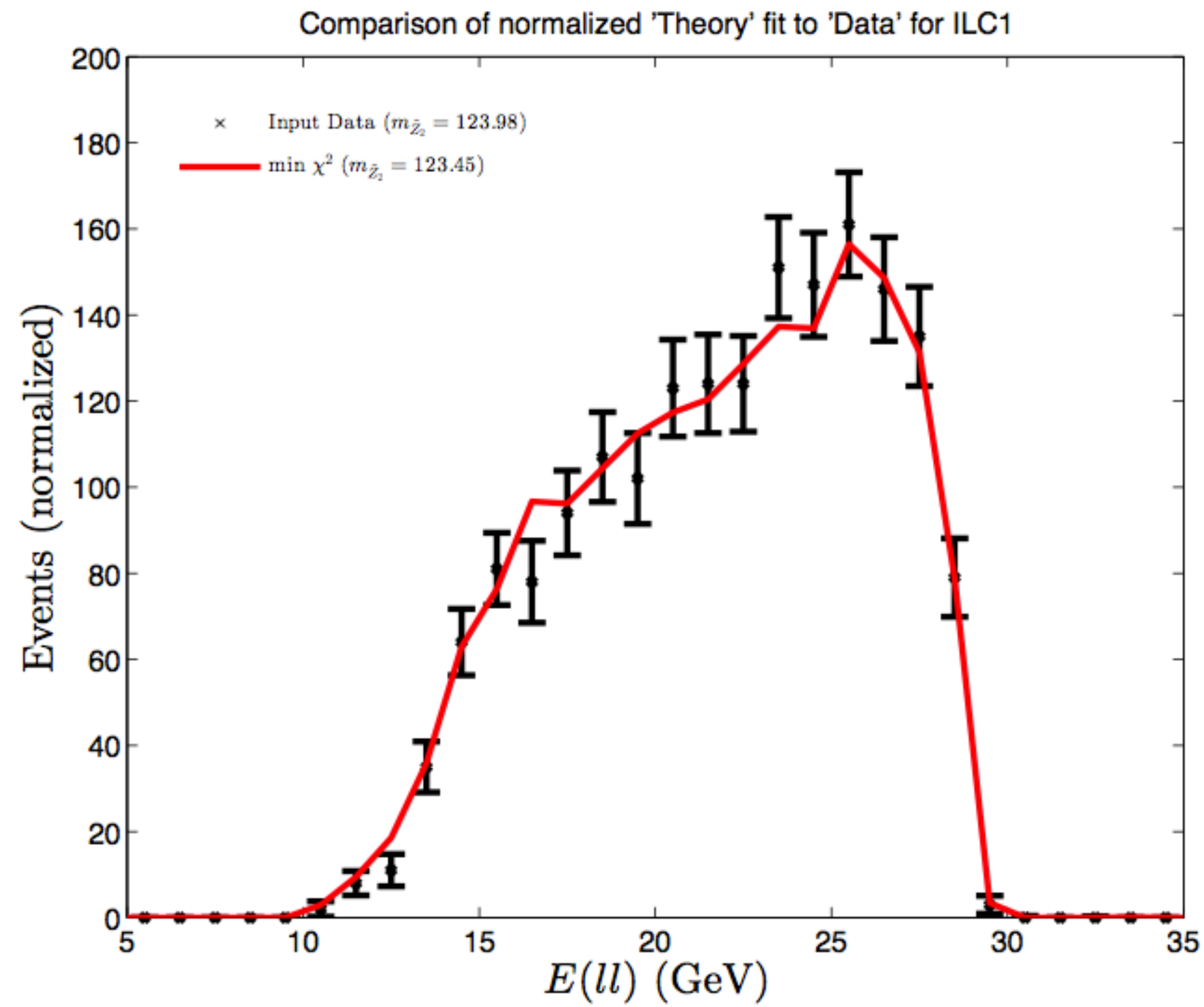
study of Higgs self-coupling with $e^+e^- \to Zhh$ and
$e^+e^- \to \nu\bar{\nu}hh$: coupling measurement to 10%

some statistics on $h \to \mu^+\mu^-$: coupling
measurement to 20%

Linear colliders also have exceptional capabilities for discovering new particles with very low energy transfer to the detector.

e+e- experiments do not need a trigger — so we do not have to know in advance what we are looking for.

Study of $e^+e^- \to \widetilde{H}_1^0 \widetilde{H}_2^0 \to \ell^+\ell^- + (\text{invisible})$

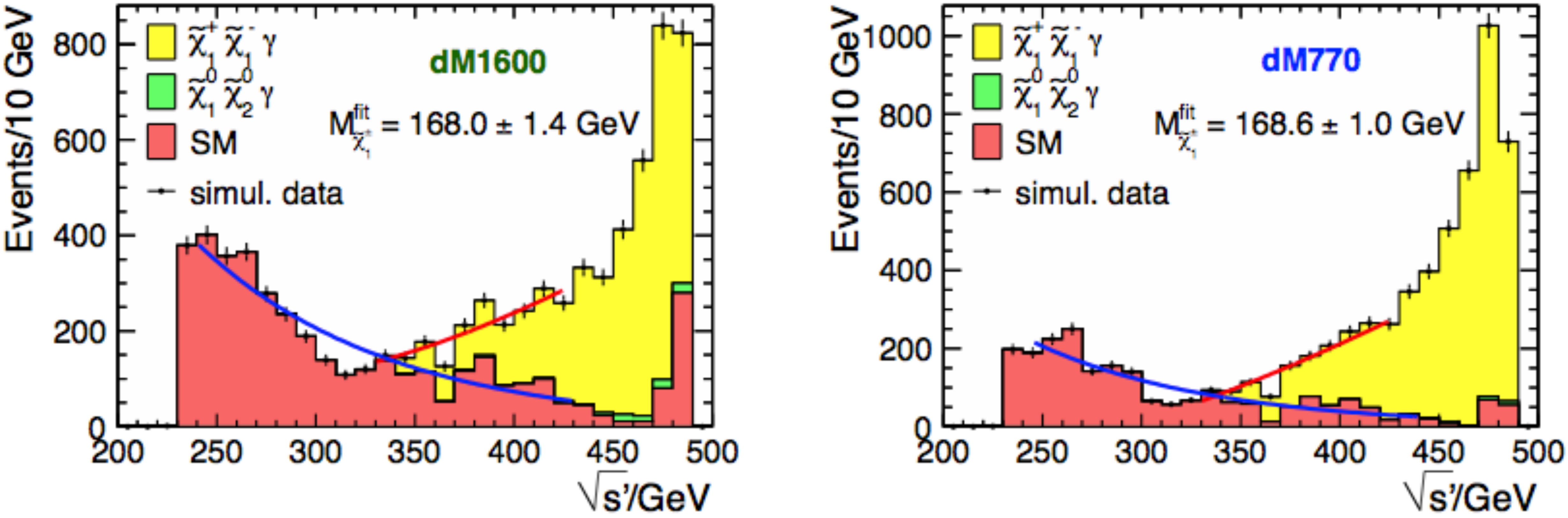


$m(\widetilde{H}_1^0) = 102.7 \pm 0.3$ GeV

$m(\widetilde{H}_2^0) = 123.7 \pm 0.2$ GeV

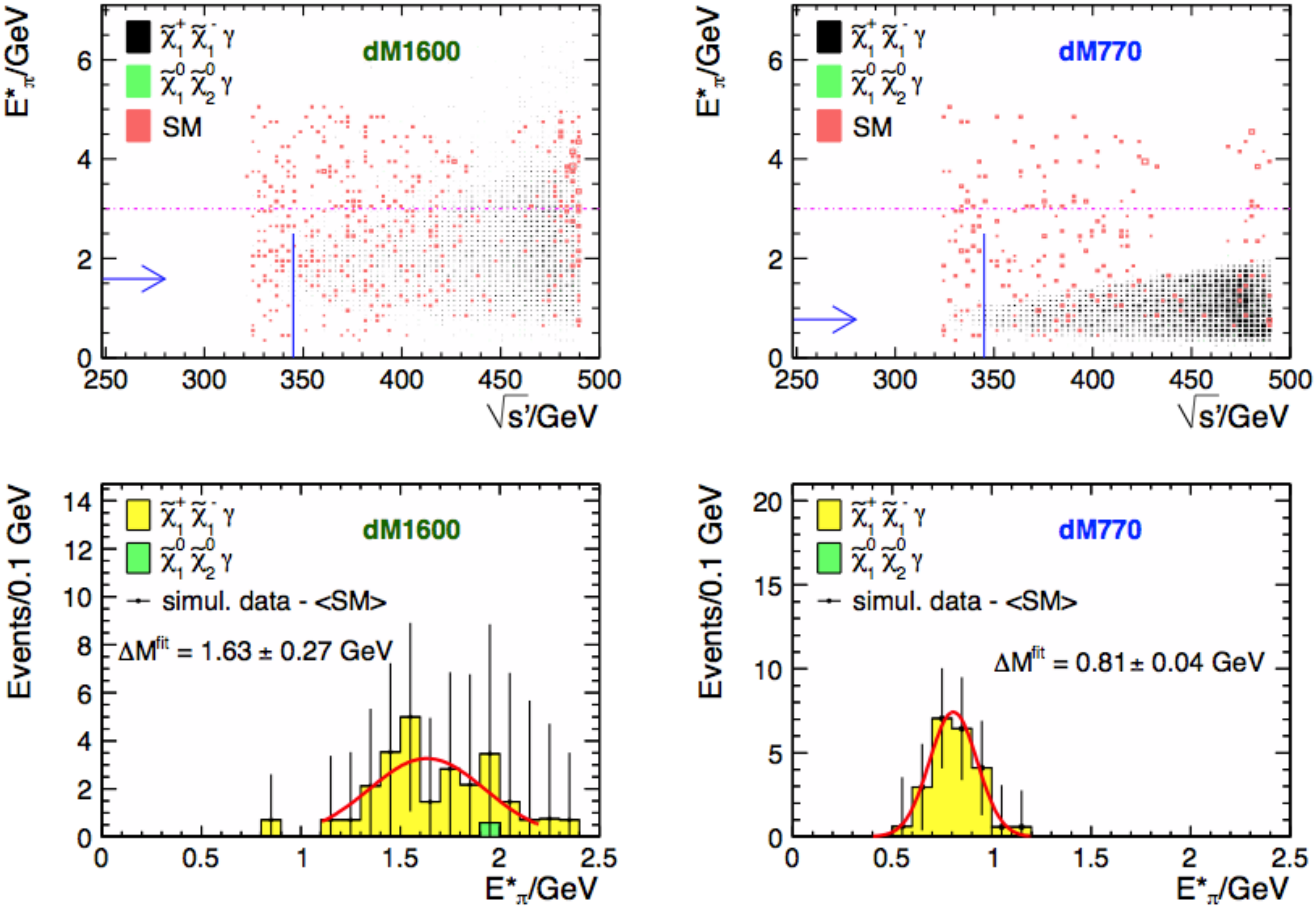
Baer, Barger, Mickelson, Mustafayev, Tata

study of $e^+e^- \to \widetilde{H}^+\widetilde{H}^- + \gamma$



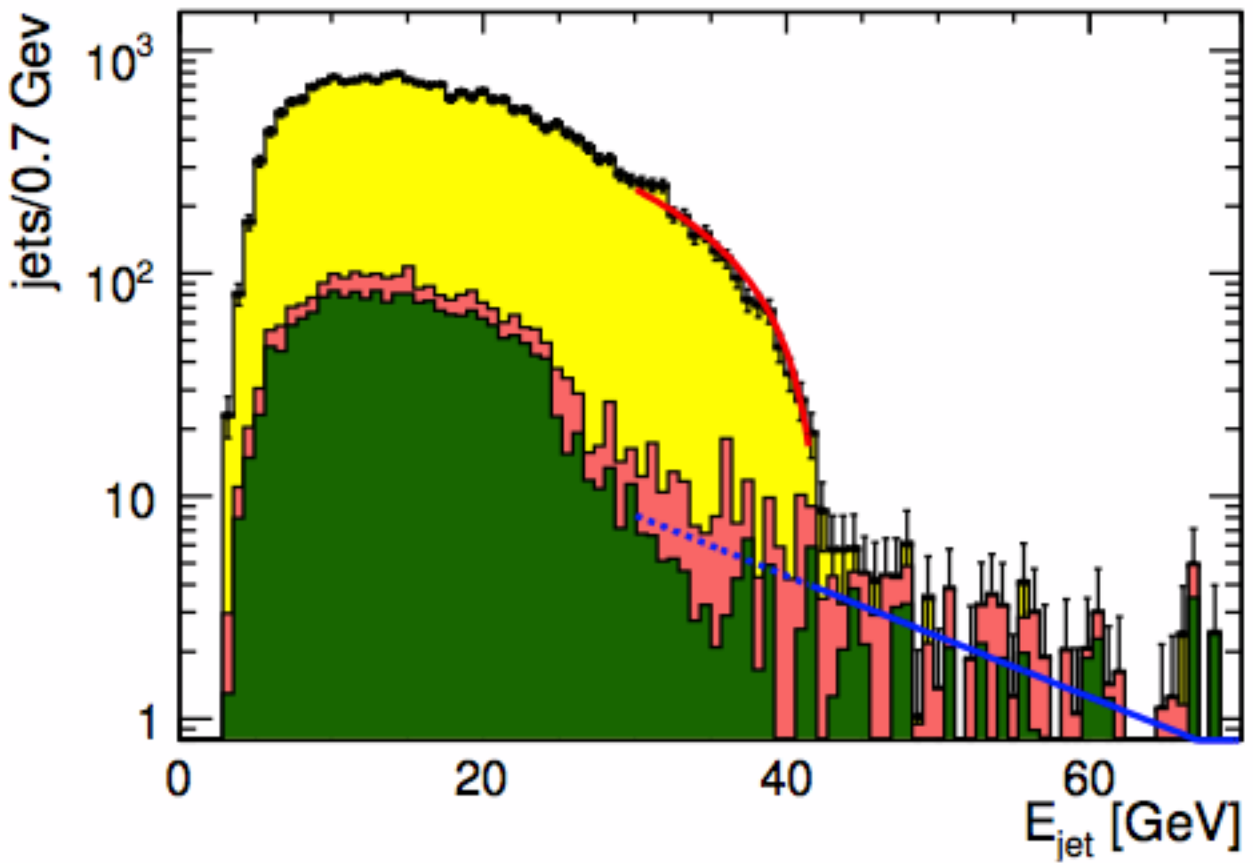
M. Berggren, et al.

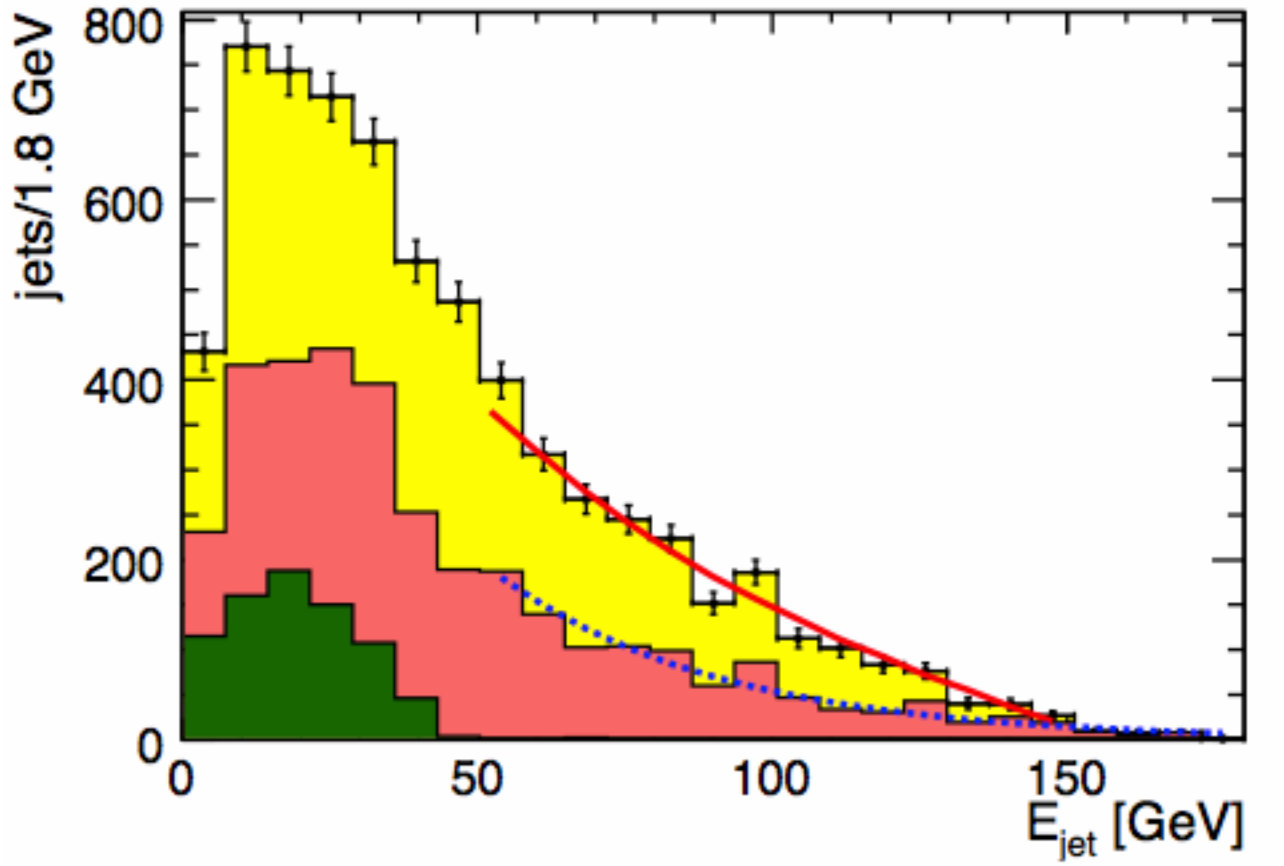
observation of a low-energy π^+ from the Higgsino -> DM decay, and precision measurement of the mass difference.



M. Berggren, et al., arXiv:1307.3566

Observation of lighter and heavier stau states with decay to DM + hadronic tau





$$m(\widetilde{\tau}_1) = 107.7 \pm 2.2 \text{ GeV}$$

$$m(\widetilde{\tau}_2) = 183 \pm 1.7 \text{ GeV}$$

Bechtle, Berggren, List, Schade, Stempel

Turn now to the specific case of the ILC.

The ILC is now moving very slowly toward approval as a global project based in Japan:

2010 foundation of AAA and Diet Members for ILC
2012 Technical Design Report
2013 site selection * * not 100% resolved
2014 MEXT Advisory Panel
questions on physics case, costing,
human resources, environment

go-to reference on ILC physics capabilities:
arXiv:1506.05992

In Japan, there is wide name recognition of the ILC as a project, and vocal support from many politicians and industrialists.

ILC appeared by name twice in Prime Minister Abe’s 2012 platform.

Somewhere on the road to Morioka:

near the ILC site outside Ichi-no-Seki

The ILC Support Committee is comprised of a group of international residents living in Iwate Prefecture, Japan. Working in collaboration with the Oshu International Relations Association, the committee strives to provide insight to government and non-government organizations regarding the needs of the international researchers, engineers and their families who will come as part of the proposed International Linear Collider (ILC) project in Tohoku. Drawing on their wealth of experience as international residents in Iwate, the members of the committee are dedicated to provide both knowledge and support to help the local community further show their gracious hospitality the members have come to know and love to the ILC newcomers.

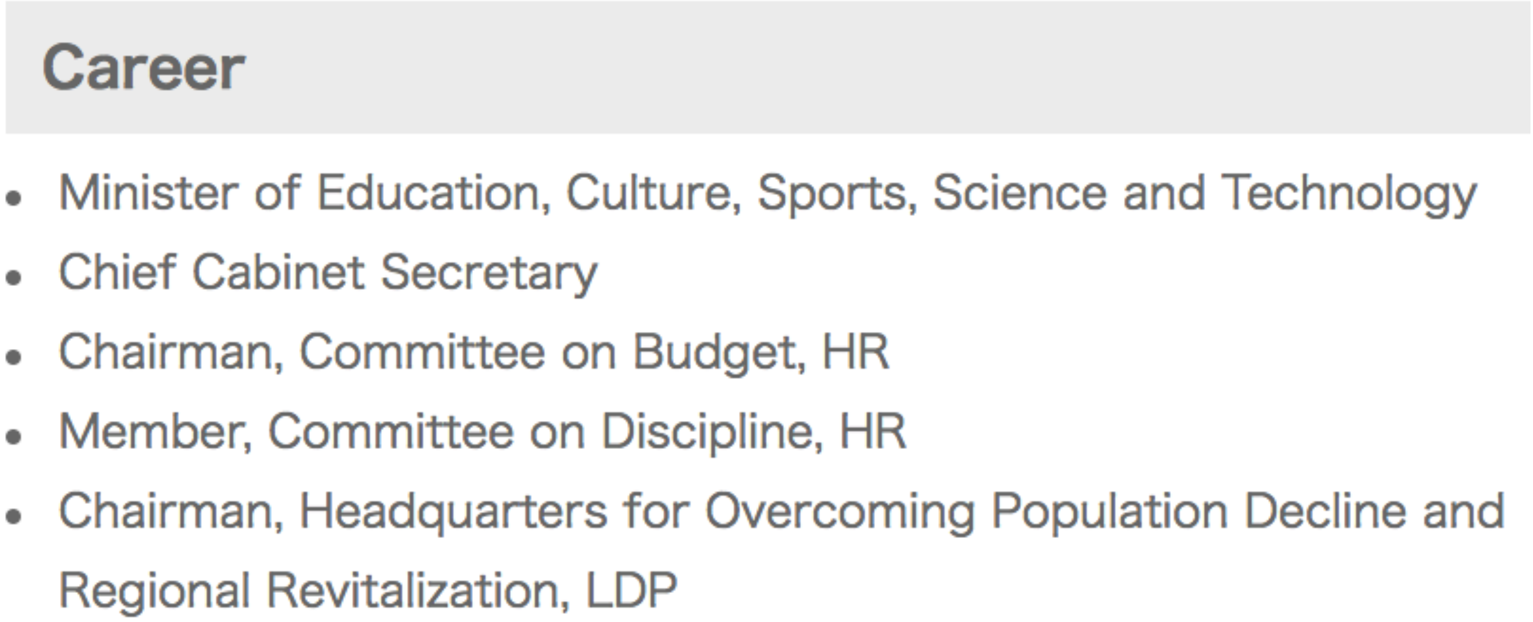
English-speaking aides at LCWS 2016

government officials attending LCWS 2016 included

Diet members

- Takeo Kawamura (Yamaguchi)
- Takeji Shino (Morioka)
- Hinako Takahashi (Iwate prop.)

Governor Takuya Tasso



Career

- Minister of Education, Culture, Sports, Science and Technology
- Chief Cabinet Secretary
- Chairman, Committee on Budget, HR
- Member, Committee on Discipline, HR
- Chairman, Headquarters for Overcoming Population Decline and Regional Revitalization, LDP

Currently , the sticking point between the politicians and MEXT seems to be the cost of the facility, even with the vision that this is to be split 50/50 with foreign partners.

Strategies of lowering the initial cost of ILC:

Staging
(but, 250 GeV needs 70% of the total cost)

Cost reduction of SCRF
(for which we thank you!)

a straw man staging plan (first 15 years)

500 fb-1 at 250 GeV

hZZ couping to 0.75%
hbb/hWW, $h\tau\tau$/hWW coupling ratios to 2.5%
h -> invisible 95% CL = 0.6%

500 fb-1 at 350 GeV

top quark $\overline{MS}$ mass to 50 MeV
first absolutely normalized Higgs couplings:
hWW to 1%, hbb to 1.9%

500 fb-1 at 550 GeV

htt coupling to 6%
Higgs total width to 3.5%
full set of Ztt couplings to 2% in a joint fit

Further stages can be at increased luminosity and energy. Current technology allows many ab-1 at 550 and 1000 GeV. The precise plan will depend on the efficiency of RF power generation and the gradients of cavities for the energy upgrade stages.

e.g. if the energy upgrades are made with 40 MeV/m, the energy can be raised to 600 GeV, or the upgrade cost can be lowered.

I hope that your R&D plan will reflect this:

1. Consolidate the recent progress: Give a practical plan assuming SCRF orders in 2020. Let’s get this machine started!

2. Give a plan for 40 MeV/m in the upgrade stages to 350 GeV and 550 GeV. This will give increased physics potential or cost saving in these stages.

3. Give a plan for 80 MeV/m over a 20-year timeline. This will greatly assist the extension of ILC to 1 TeV and beyond.

Can we break through to discover new physics beyond the Standard Model and solve the mysteries of the Higgs boson ?

With your help, it is possible.

Please, we should not miss this opportunity.