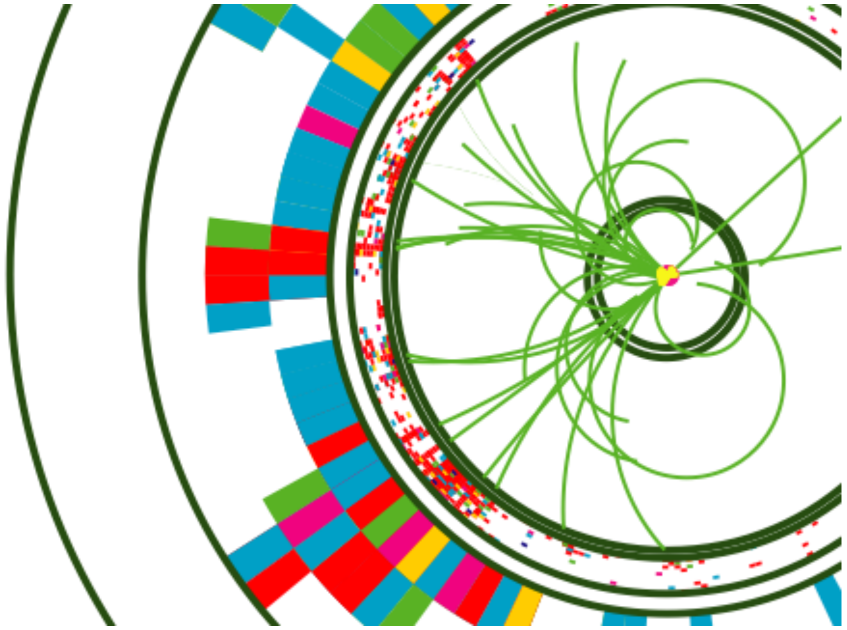
Physics Program of Future e+e- Colliders



M. E. Peskin
LPC Topic of the Week
September 2018

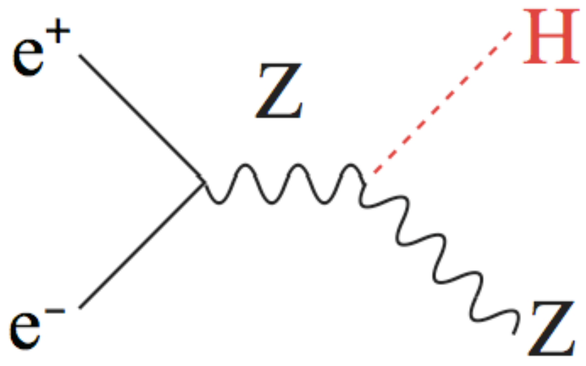
In the previous lecture, I discussed the physics opportunity available in the precision measurement of Higgs boson couplings.

In this lecture, I will explain how this opportunity can be realized through experiments at future e+e- colliders.

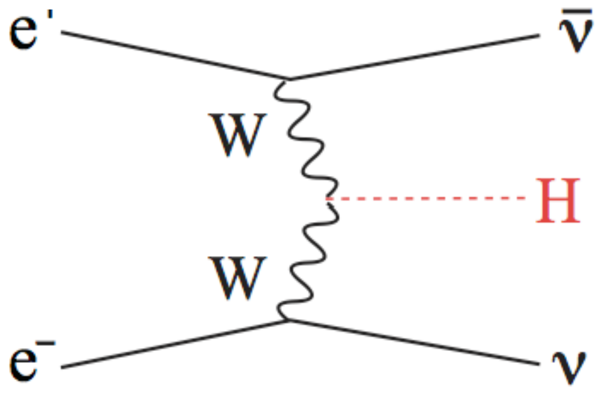
I will also briefly discuss some other experimental goals of these colliders.

The important production modes for the Higgs boson at e^+e^- colliders are:

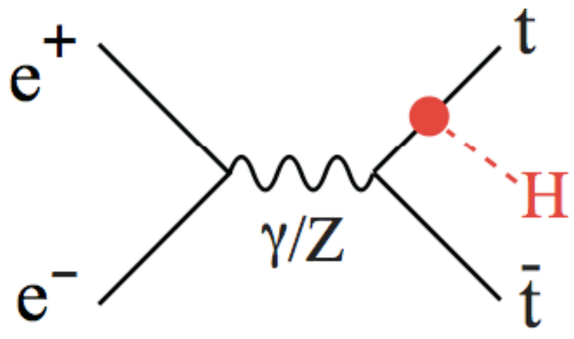
Higgsstrahlung



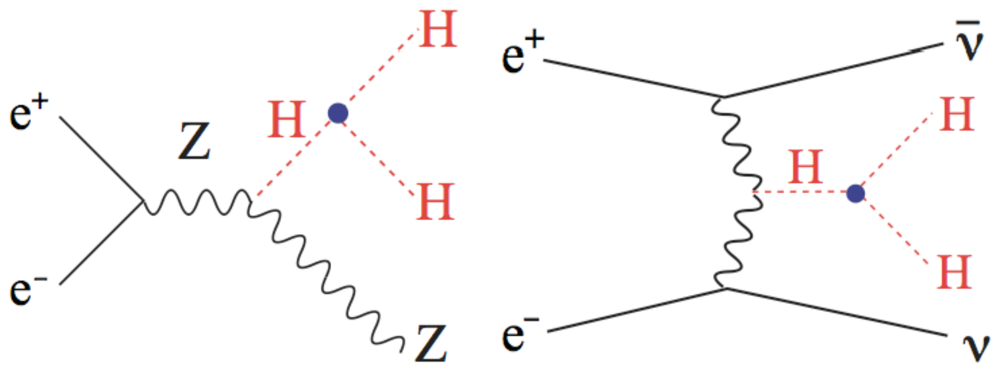
vector boson fusion

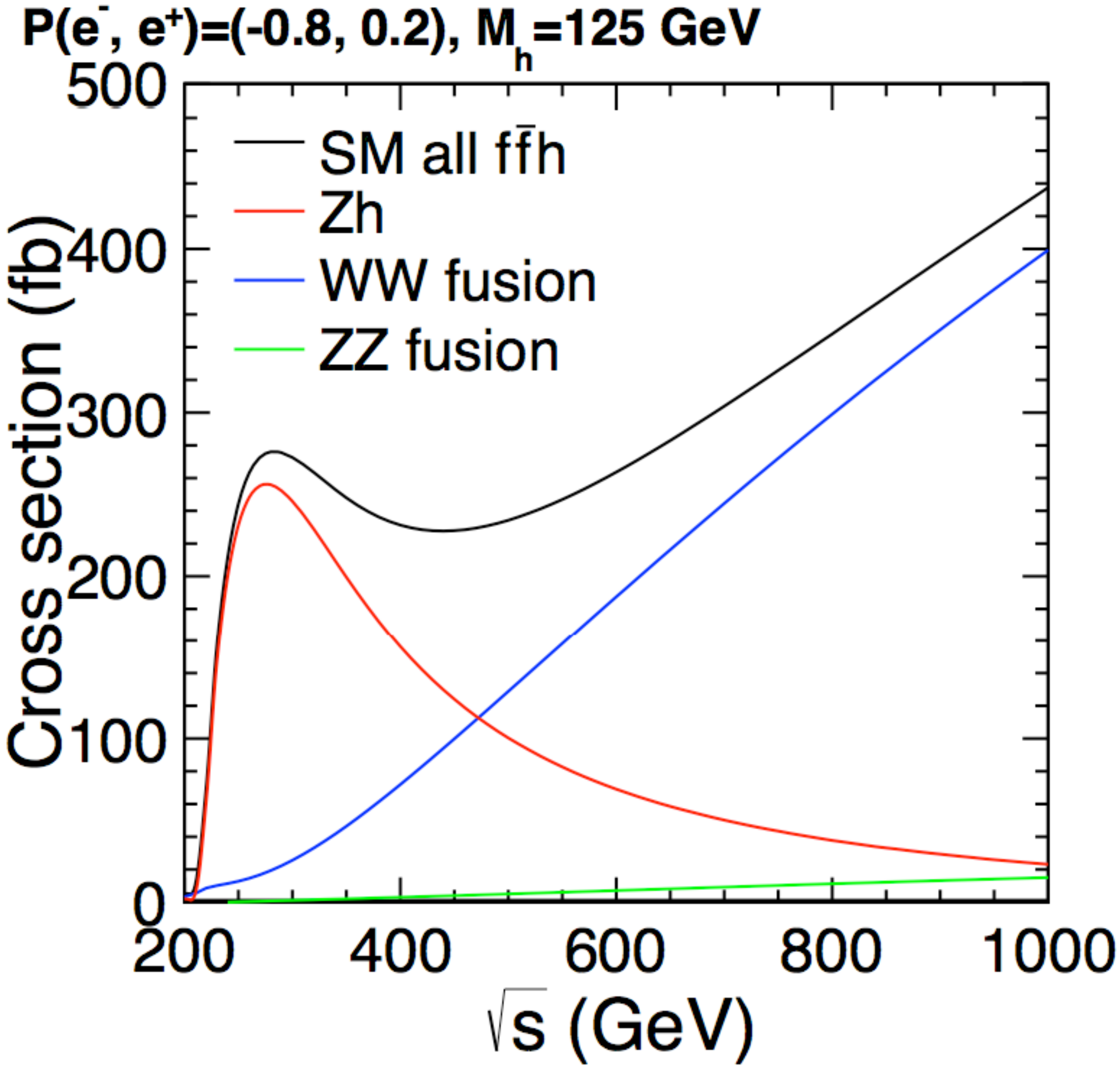


associated production with top



Higgs pair production





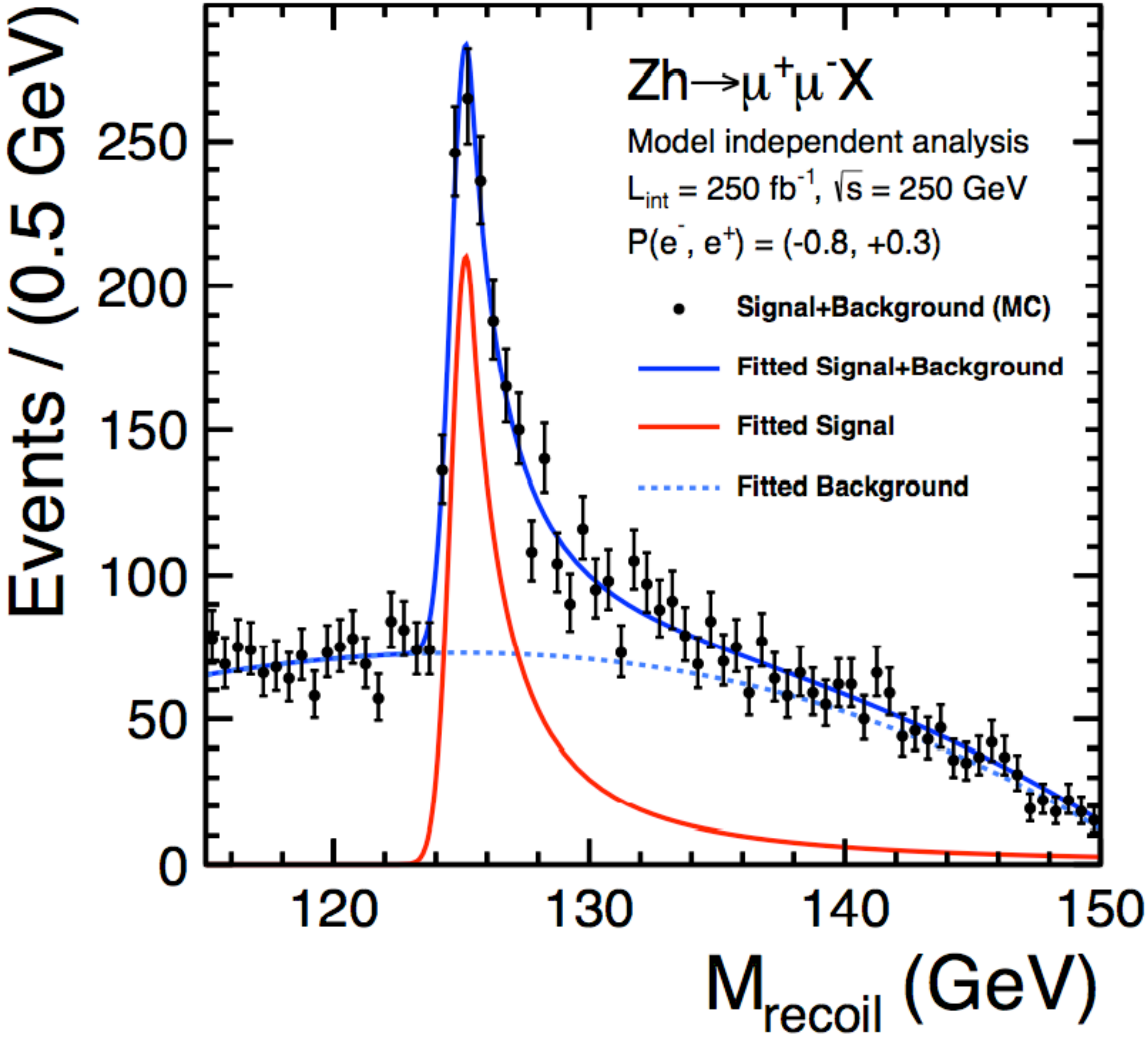
$P(e^-, e^+) = (-0.8, 0.2)$, $M_h = 125$ GeV
Cross section (fb)
500
400
300
200
100
0
200
400
600
800
1000
$\sqrt{s}$ (GeV)
SM all $f\bar{f}h$
Zh
WW fusion
ZZ fusion

The reaction $e^+e^- \to Zh$ is particularly attractive because it supplies tagged Higgs bosons.

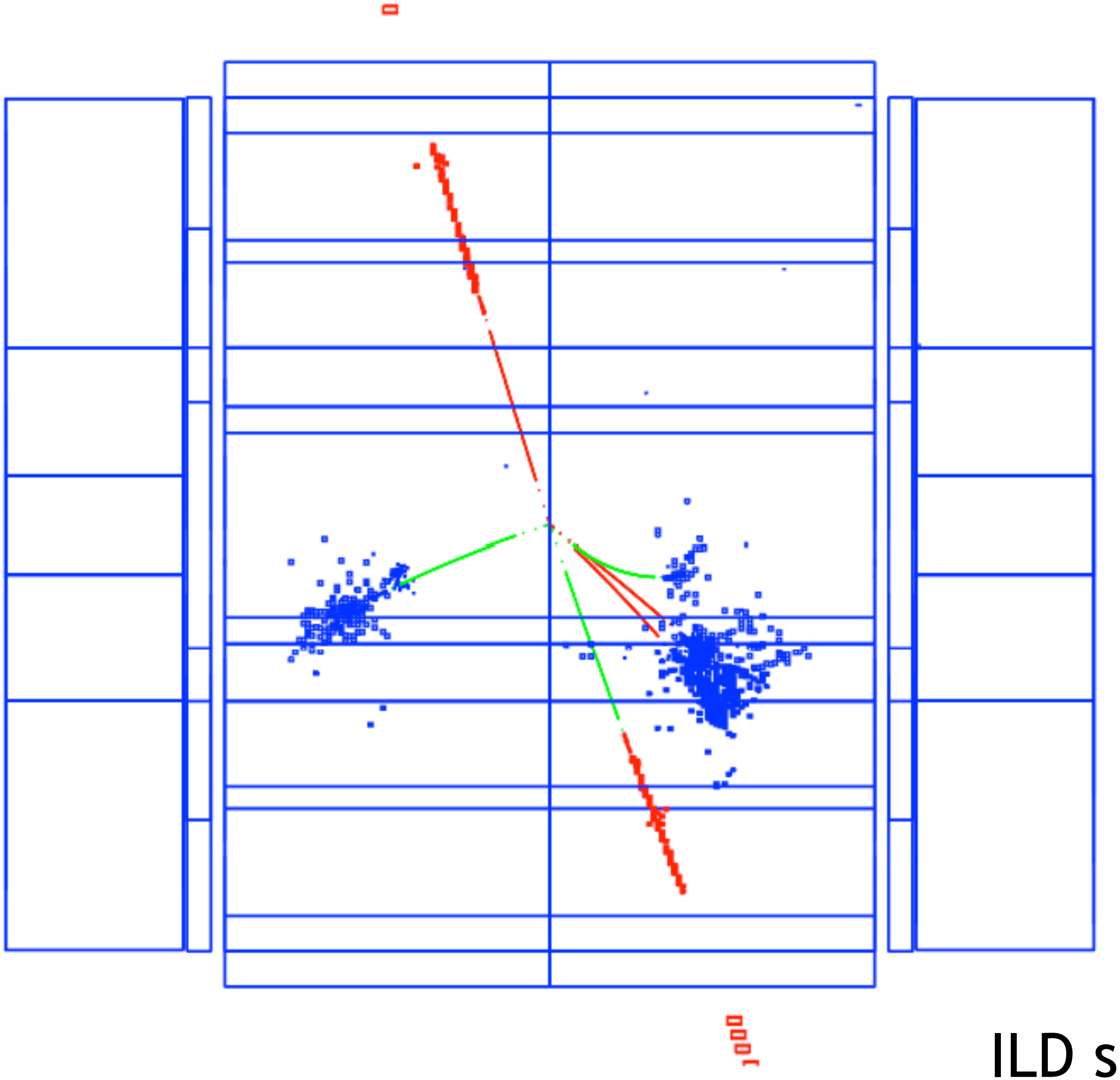
At 250 GeV, to a first approximation, any Z boson with a lab energy of 110 GeV is recoiling against a Higgs boson.

This selection is obviously very clean for leptonic Z decays, but it can also be made almost independent of the Higgs decay mode for hadronic Z decays.

m_h to 15 MeV using a recoil technique



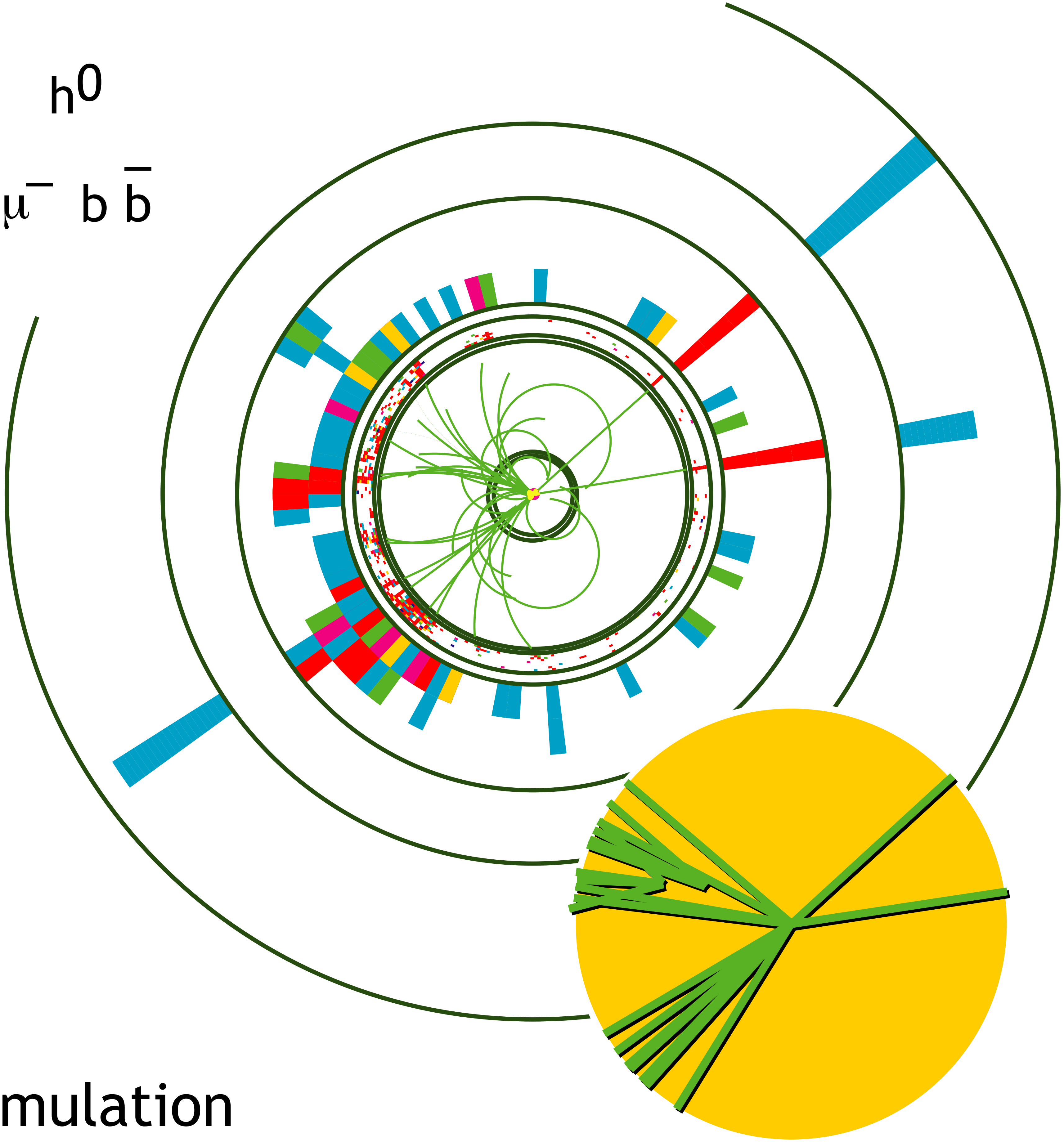
$$e^+e^- \to Zh \to (\mu^+\mu^-)(\tau^+\tau^-)$$



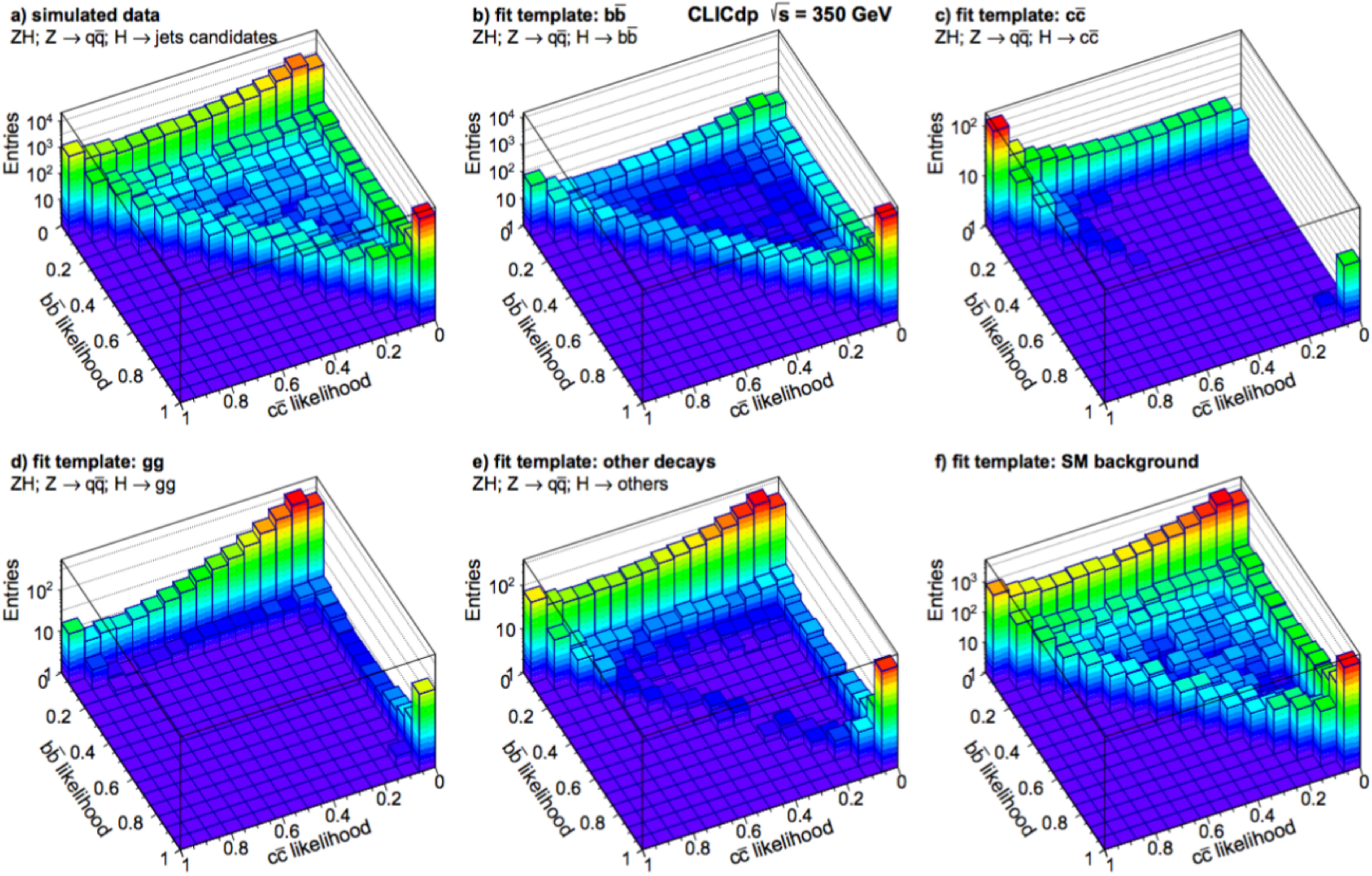
ILD simulation

$e^+e^- \to Z^0 \quad h^0$

$\to \mu^+\mu^- \; b\,\bar{b}$



SiD simulation


a) simulated data
ZH; Z → $q\bar{q}$; H → jets candidates

b) fit template: $b\bar{b}$
ZH; Z → $q\bar{q}$; H → $b\bar{b}$

CLICdp $\sqrt{s}$ = 350 GeV

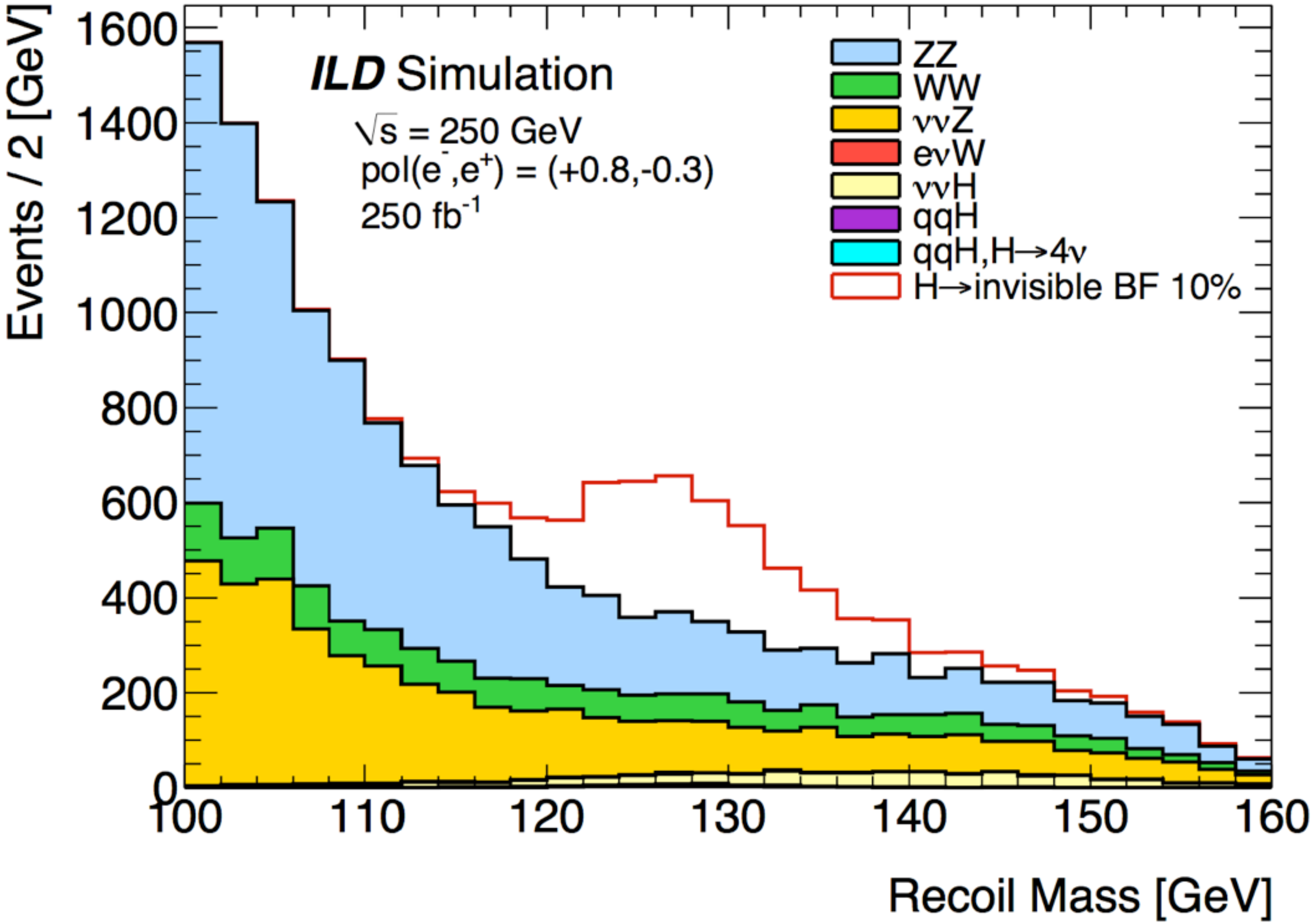
c) fit template: $c\bar{c}$
ZH; Z → $q\bar{q}$; H → $c\bar{c}$

d) fit template: gg
ZH; Z → $q\bar{q}$; H → gg

e) fit template: other decays
ZH; Z → $q\bar{q}$; H → others

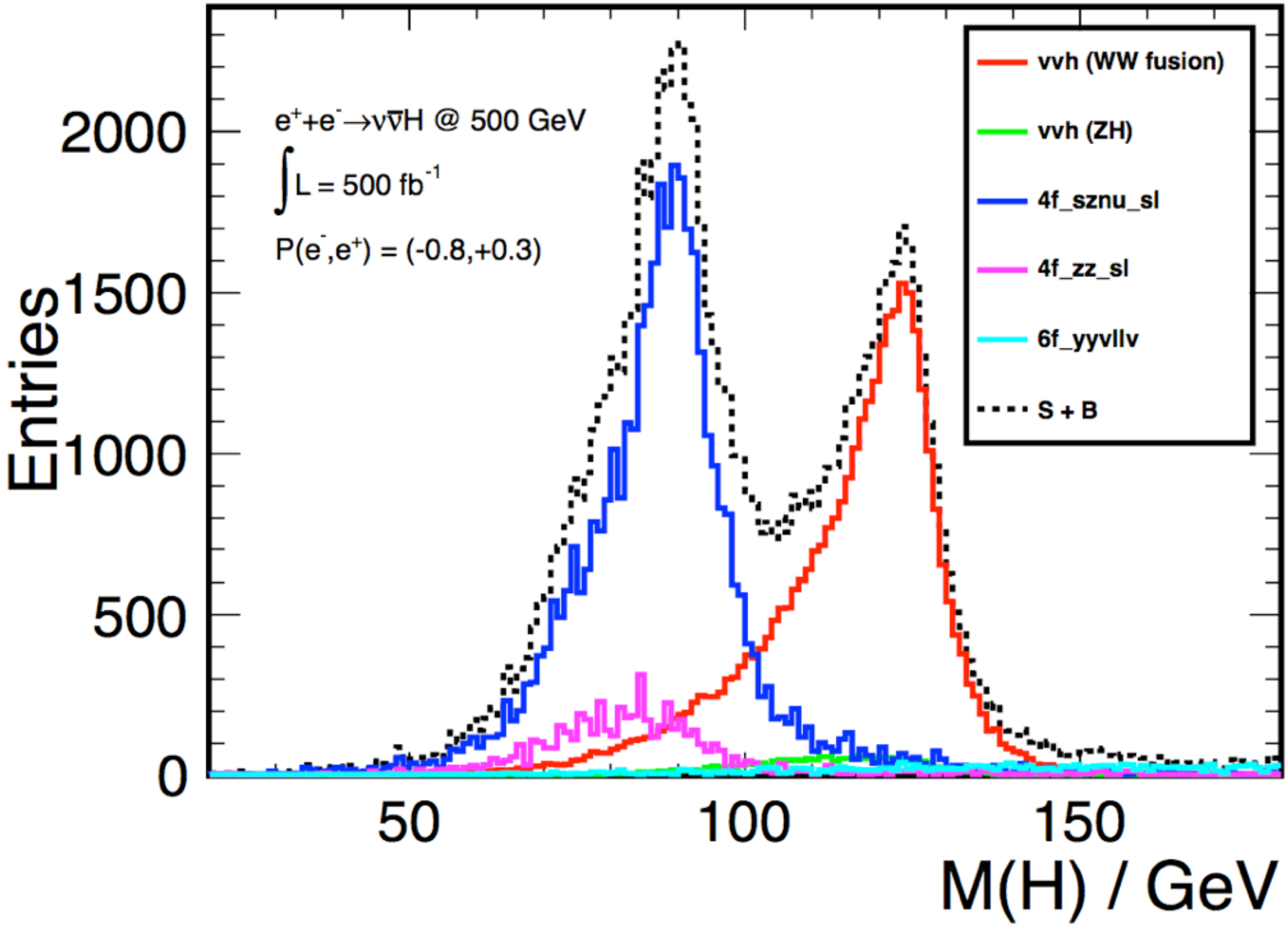
f) fit template: SM background

CLIC Higgs analysis group



Invisible Higgs decay can be limited to 0.3%. Observable exotic Higgs decays can be studied to the limits of their appearance — 0.1% - 0.01% .

observation of the Higgs in WW fusion is also very clean:



ILC Higgs White Paper for Snowmass 2013

However, this does not suffice for a program of precision Higgs measurements. Ideally, we should disentangle measurements of

$$\sigma \times BR(A\overline{A} \to h \to B\overline{B}) \sim \frac{\Gamma(h \to A\overline{A})\Gamma(h \to B\overline{B})}{\Gamma_{tot}}$$

to obtain values of $\Gamma(h \to A\overline{A})$, absolutely normalized.

At e+e- colliders, we can measure the absolute total cross section for $e^+e^- \to Zh$.

It is trickier to measure the Higgs total width. For example, in

$$\frac{\sigma(e^+e^- \to Zh)}{BR(h \to ZZ^*)} \sim \Gamma_{tot}$$

the denominator is a 3% BR, so we lose a factor 30 in statistics.

It is very helpful here to go to a larger context — the "Standard Model Effective Field Theory" (EFT).

We discussed yesterday that the SM is the most general renormalizable field theory with SU(2)xU(1) symmetry and the known particle content.   Deviations from the SM due to new physics are described by adding higher-dimension operators. If the new particles are heavy, dimension-6 operators suffice.

This is a standard method at LHC. Most LHC Higgs and TGV analyses are now done in this context.

The original example (Eichten et al.) was the search for quark and lepton compositeness in fermion-fermion scattering.

In Bhabha scattering ($e^+e^- \to e^+e^-$) there are three operators that can be added:

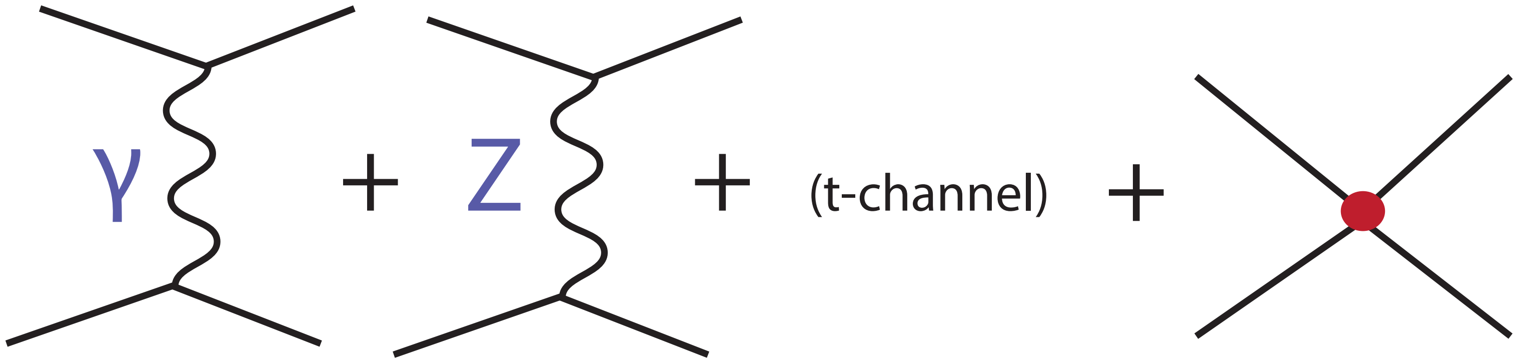
$$\Delta\mathcal{L} = \frac{2\pi}{\Lambda^2}\left[\eta_{LL} j_L^\mu j_{\mu L} + 2\eta_{LR} j_L^\mu j_{\mu R} + \eta_{LR} j_R^\mu j_{\mu R}\right]$$

with $j_L^\mu = e_L^\dagger \overline{\sigma} e_L \qquad j_R^\mu = e_R^\dagger \sigma e_R$

In quark-quark scattering, there are 17 possible operators of this type.

We set the largest η parameter equal to 1 and then interpret Λ as the compositeness scale.

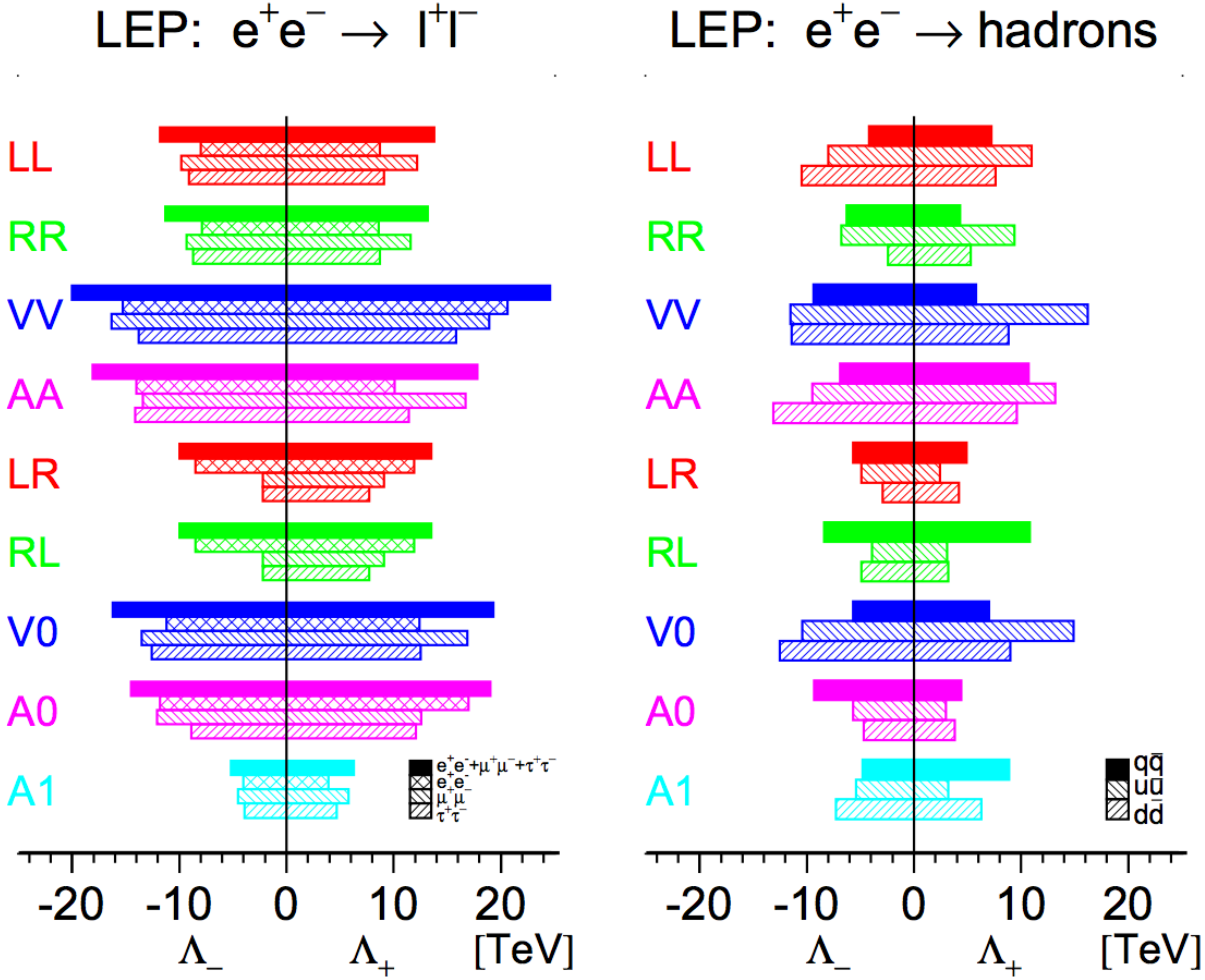
The complete amplitude for $e^+e^- \to e^+e^-$ is given by



so the contact interaction correction is of relative order

$$1/(\alpha\Lambda^2)$$

that is, it is surprisingly large. LEP 2 at 200 GeV set limits on the compositeness scale of 8 TeV.



LEP Electroweak WG, arXiv:1302.3415

At an e+e- collider with beam polarization, it is possible to measure the contributions from individual operators and bound these separately.

At LHC, we are sensitive to combinations of operators, so limits are model-dependent.   The strongest current limit, from ATLAS is 40 TeV, on a current-current coupling of universal left-handed quark currents.

e+e- colliders at 250 GeV will not have much higher energy than LEP, but they will have higher luminosity and higher precision. Thus, they can push the separate sensitivities above 100 TeV.

Deviations of the Higgs couplings from the SM predictions can also be discussed in this framework.

For definiteness, consider $h \to \tau^+\tau^-$. The operator

$$\Delta\mathcal{L} = -c_{\tau\Phi}\frac{y_\tau}{v^2}(\Phi^\dagger\Phi)L^\dagger \cdot \Phi\tau_R + h.c.$$

gives

$$m_\tau = \frac{y_\tau v}{\sqrt{2}}(1+\frac{1}{2}c_{\tau\Phi}) \qquad g_{h\tau\tau} = y_\tau(1+\frac{3}{2}c_{\tau\Phi})$$

so the relation between the mass and Higgs coupling is broken. Also the operator

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi)$$

gives a field rescaling of the Higgs field that modifies all couplings. Finally,

$$\delta\Gamma(h \to \tau^+\tau^-) = 1 - c_H + 2c_{\tau\Phi}$$

The situation of $h \to W^+W^-$ is more complicated. The operators

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial_\mu(\Phi^\dagger\Phi)\partial^\mu(\Phi^\dagger\Phi) + \frac{g^2 c_{WW}}{m_W^2}(\Phi^\dagger\Phi)W^a_{\mu\nu}W^{a\mu\nu}$$

give modifications of the hWW vertex of two different structures

$$(1+\eta_W)\frac{2m_W^2}{v}hW^+_\mu W^{-\mu} + \zeta_W\frac{1}{v}W^+_{\mu\nu}W^{-\mu\nu}$$

These have different physical origin and so must be extracted separately from experimental data.

Fortunately, there is only one EFT Lagrangian and many possible observables. A strategy is to collect constraints to measure all relevant operator coefficients in a model-independent fashion.

This raises the question:

How many of these dimension-6 operators are there, anyway ? Actually, it is easy to write many dimension-6 operators, but probably this is an overcomplete basis, since we can remove operators that are zero by the equations of motion.

The correct list was given by

Grzadkowski, Iskrzynski, Misiak, and Rosiek,
arXiv:1008.4884

It turns out that there are 59 baryon- and lepton-number conserving SU(2)xU(1) invariant dimension-6 operators (for the case of 1 fermion generation).

At the LHC, where we have many species of quark that are not easily distinguished experimentally, and where quark-quark scattering contributes to many processes, it looks hopeless to perform a complete analysis with the full set of relevant operators.

In e+e- annihilation, where the initial particles are definitely e+e- and the quarks appear minimally, there is a chance to perform an analysis (tree-level, anyway) that is completely general.

We demonstrate this in

Barkow, Fujii, Jung, Karl, List, Ogawa, MEP, and Tian,
arXiv:1708.08912, arXiv:1708.09079

Using the equations of motion, we aggressively reduce the number of operators, removing operators with quarks.

First, consider only operators with γ, W, Z, h only (using equations of motion to minimize this set. There are 7 of these:

$$\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$

$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$

Add operators that modify the couplings of leptons to SM bosons. (Here I will assume lepton universality.)

$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$

$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

Add operators that modify the chirality-flip fermion-Higgs couplings $-c_{\tau\Phi}\frac{y_\tau}{v^2}(\Phi^\dagger\Phi)\overline{L}_3\cdot\Phi\tau_R + h.c.$

1 operator each for b, c, τ, μ — and g .

We will also need to include 2 more combinations of c_{HL}-type operators that shift the W and Z widths.

The total number of dimension-6 operators needed is 17. No other operators (except one eeμμ 4-fermion operator) contribute to any process we consider at the tree level.

CP - violating operators contribute to our observables in order c^2 . These can be bounded $c \lesssim 1\%$, by a different set of measurements. In this case, they are irrelevant to our analysis.

$$\Delta\mathcal{L} = \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)$$

Higgs Z factor

$$-\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

triple Higgs *

$$+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}$$
$$+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu}$$

h + W,Z,γ

$$+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L)$$
$$+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ .$$

precision EW

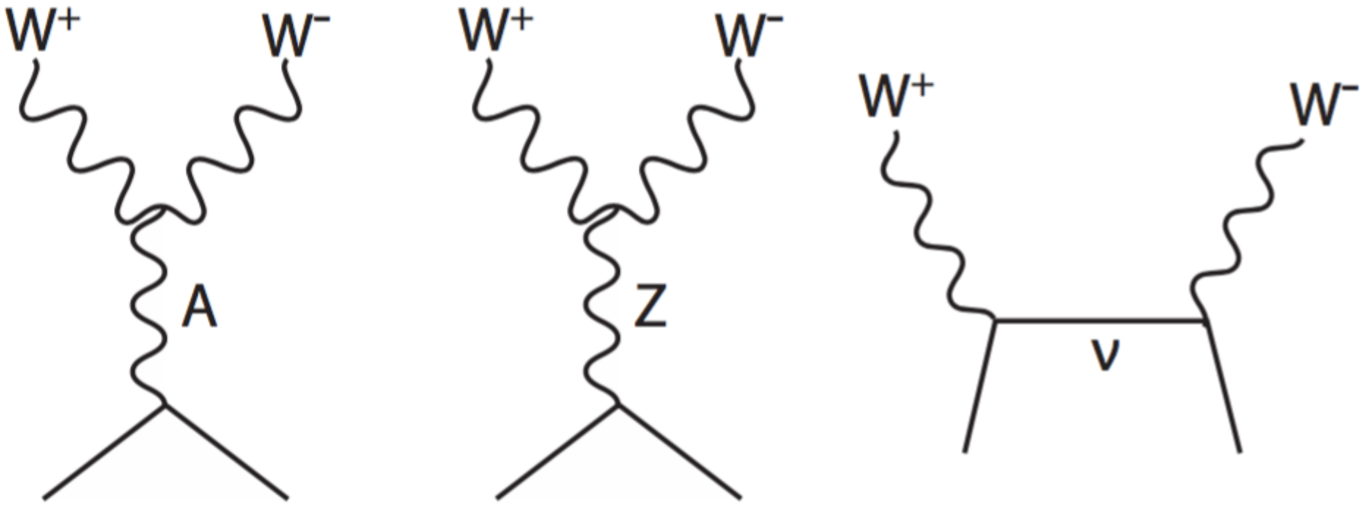
$$-\sum_i\left\{c_{\ell i\Phi}\frac{y_\tau \ell i}{v^2}(\Phi^\dagger\Phi)\overline{L}_i\cdot\Phi\,\ell_{iR} + c_{qi\Phi}\frac{y_\tau qi}{v^2}(\Phi^\dagger\Phi)\overline{Q}_i\cdot\Phi\,q_{iR}\right\}$$
$$+\mathcal{A}\frac{h}{v}G_{\mu\nu}G^{\mu\nu}\ .$$

h + q, l, g

* does not enter this analysis

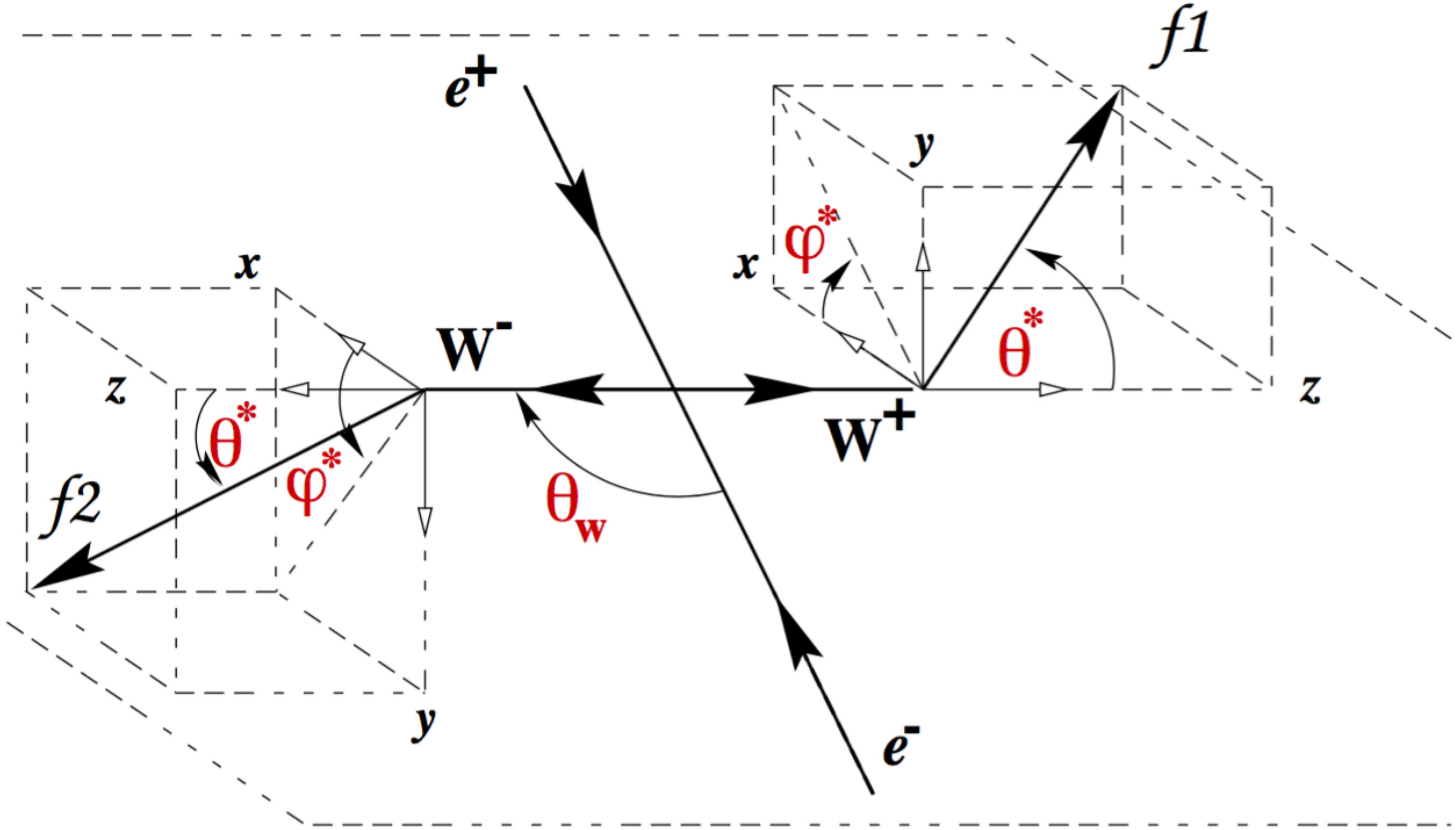
To determine the operator coefficients, we can use precision electroweak measurements, $e^+e^- \to Zh$ and $e^+e^- \to W^+W^-$.

The reaction $e^+e^- \to W^+W^-$ is a beautiful one to study in e+e- collisions. This is the largest single process in e+e- annihilation at 250 GeV.   The diagrams

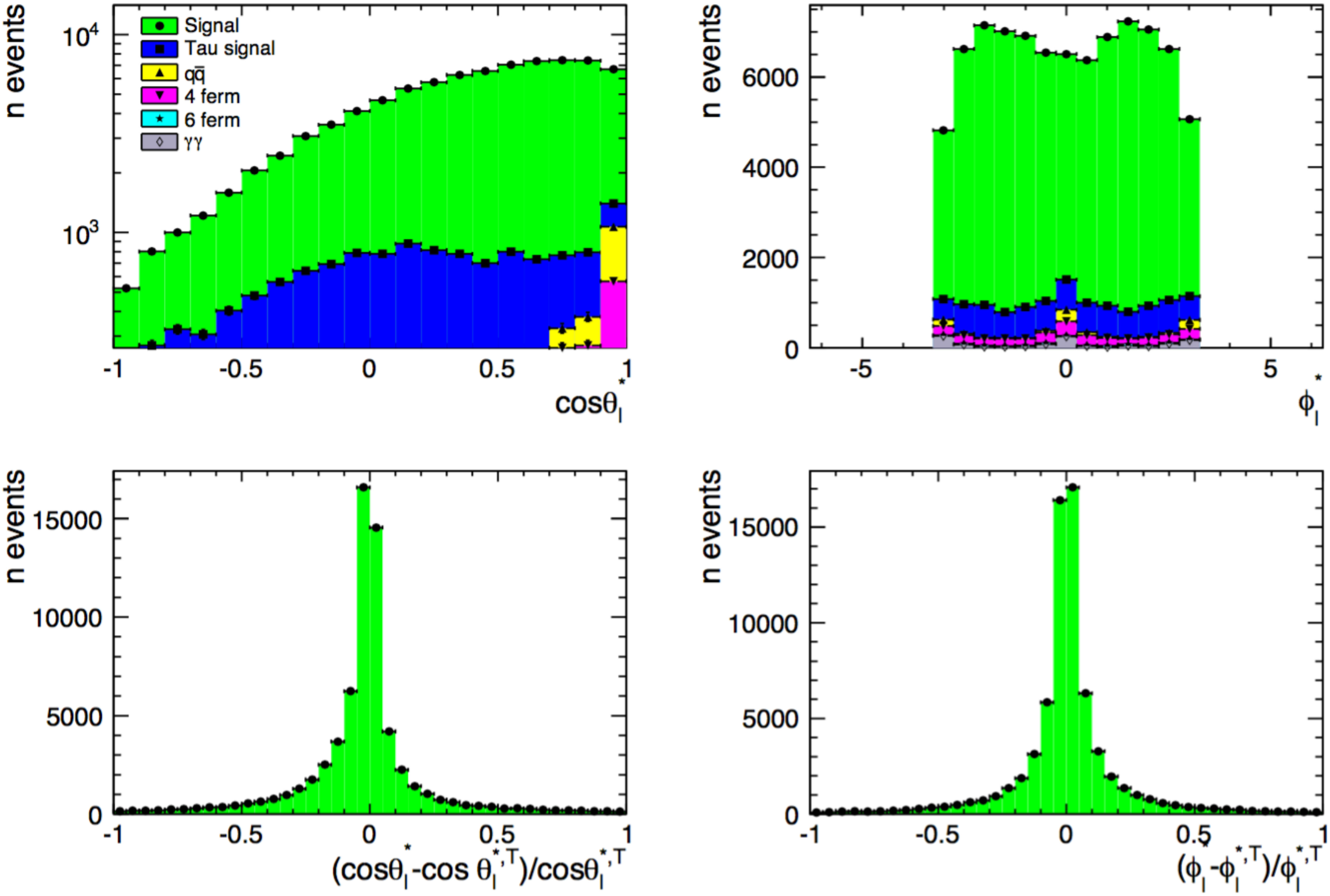


have strong dependence on the W polarizations and on the beam polarization. Actually, forward W production can be used as a polarimeter while wide-angle W production is used to test for anomalous W couplings.

in $e^+e^- \to WW \to \ell\nu q\bar{q}$ events, all of these angles are separately measureable



from the DESY thesis of Ivan Marchesini


n events
10^4
10^3
Signal
Tau signal
$q\bar{q}$
4 ferm
6 ferm
$\gamma\gamma$
-1
-0.5
0
0.5
1
$\cos\theta_l^*$
n events
6000
4000
2000
0
-5
0
5
ϕ_l^*
n events
15000
10000
5000
0
-1
-0.5
0
0.5
1
$(\cos\theta_l^* - \cos\theta_l^{*,T})/\cos\theta_l^{*,T}$
n events
15000
10000
5000
0
-1
-0.5
0
0.5
1
$(\phi_l^* - \phi_l^{*,T})/\phi_l^{*,T}$

In the literature, the γWW and ZWW vertices are parametrized by an effective interaction

$$\Delta\mathcal{L}_{TGC} = ig_V\Big\{V^\mu(\hat{W}^-_{\mu\nu}W^{+\nu} - \hat{W}^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu \hat{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2}\hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu}\hat{V}^{\mu\nu}\Big\} ,$$

The effect of the new operators is to modify 5 of the 6 parameters ($g_A = e$ by QED gauge invariance) through 3 combinations of EFT parameters.

$$g_Z = gc_w(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ})$$

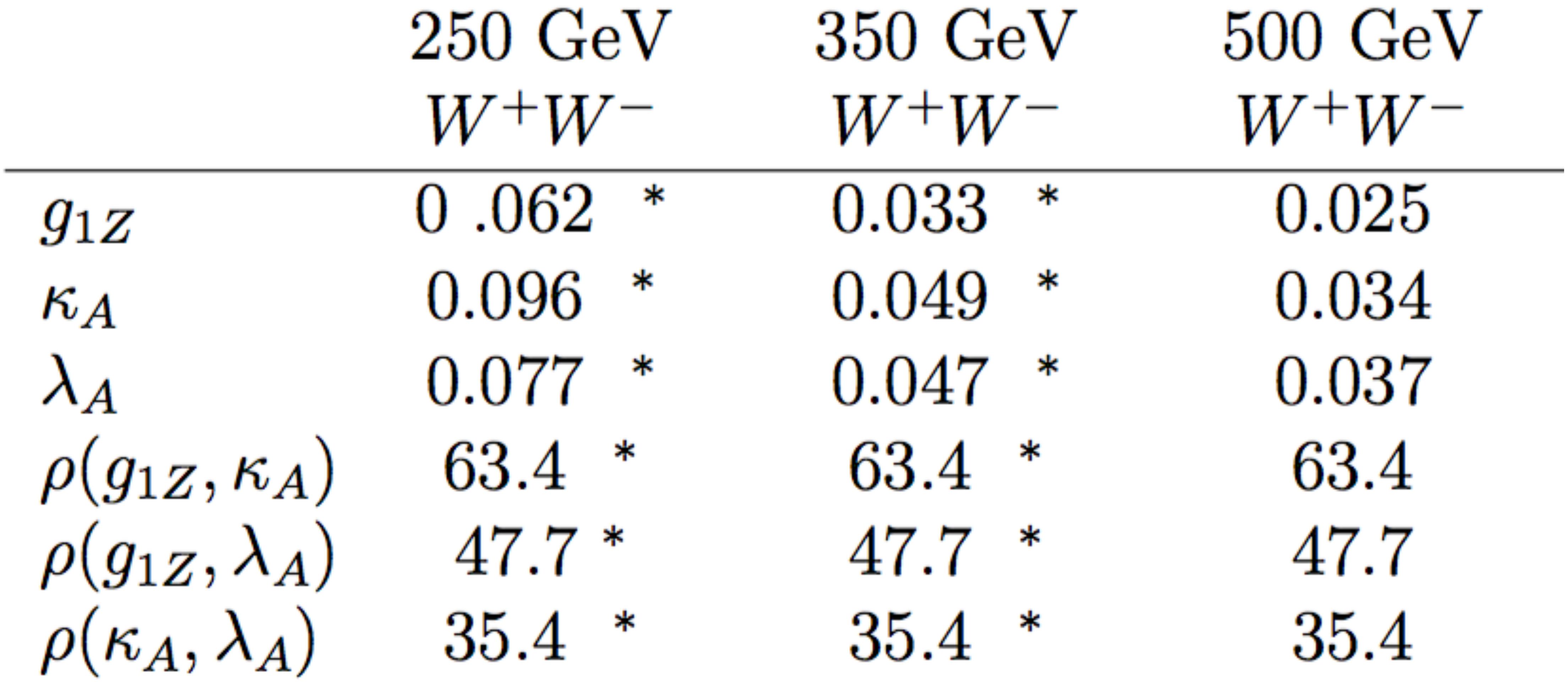
$$\kappa_A = 1 + (8c_{WB})$$

$$\kappa_Z = 1 - \frac{s_w^2}{c_w^2}(8c_{WB})$$

$$\lambda_A = \lambda_Z = -6g^2 c_{3W}$$

Polarization plays an important role: g_Z, κ_A, κ_Z mainly affect the longitudinally polarized W’s, λ_A, λ_Z the transversely polarized W’s.

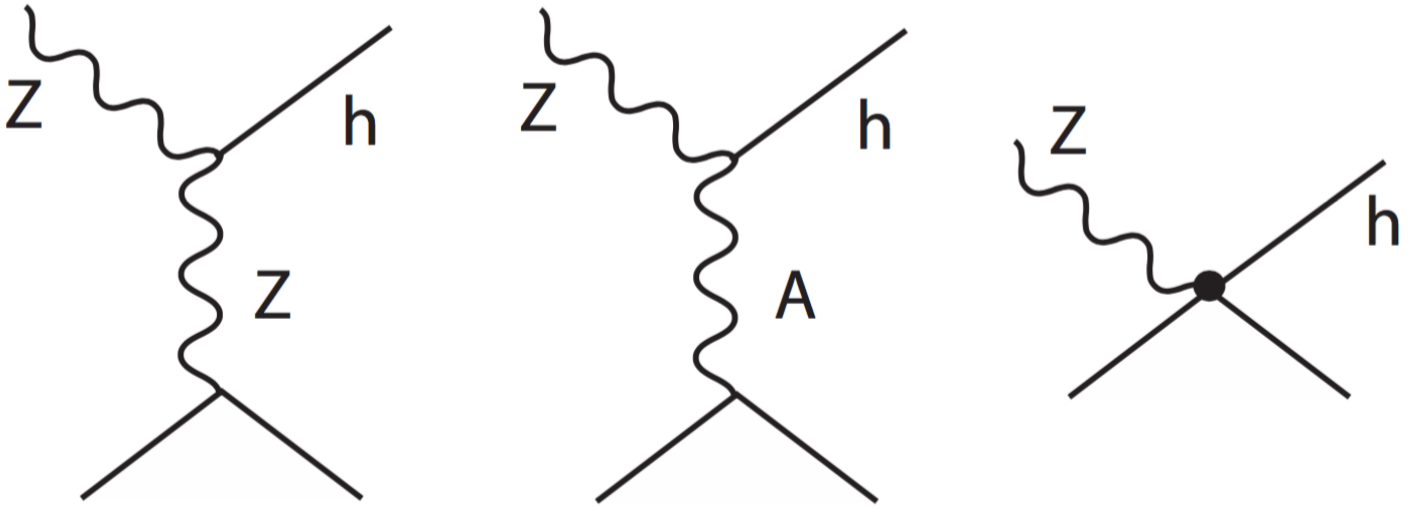
projected errors (in %) for 500 fb-1 samples:



	250 GeV	350 GeV	500 GeV
	W^+W^-	W^+W^-	W^+W^-
g_{1Z}	0 .062 *	0.033 *	0.025
κ_A	0.096 *	0.049 *	0.034
λ_A	0.077 *	0.047 *	0.037
$\rho(g_{1Z}, \kappa_A)$	63.4 *	63.4 *	63.4
$\rho(g_{1Z}, \lambda_A)$	47.7 *	47.7 *	47.7
$\rho(\kappa_A, \lambda_A)$	35.4 *	35.4 *	35.4

The 500 GeV results are from Marchesini’s analysis; the results at lower energy are obtained by extrapolation. $\sqrt{N}$ scaling is correct to ILC luminosities.

The cross section for $e^+e^- \to Zh$ depends strongly on the EFT parameters c_H, c_{WW}, corresponding to the two Lorentz structures discussed earlier. The diagrams are

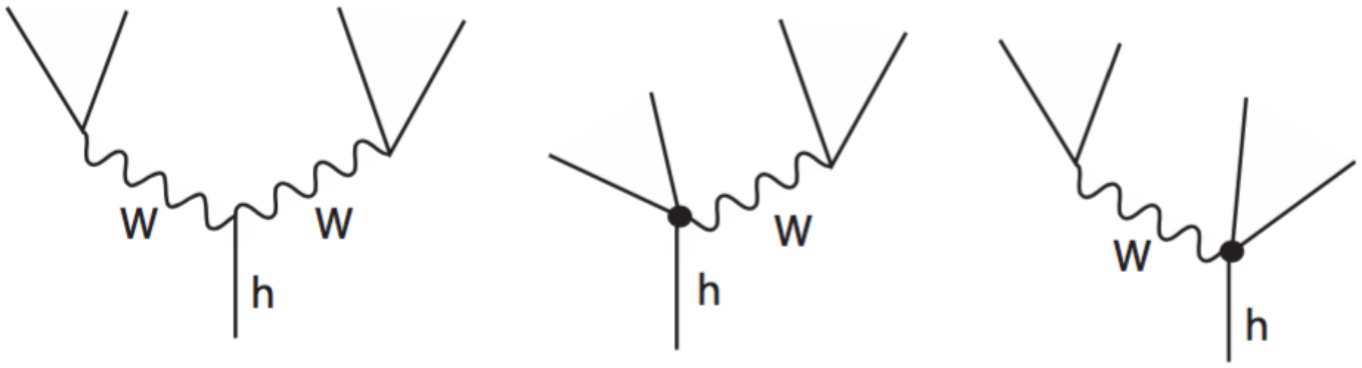


Under $e^-_L \leftrightarrow e^-_R$, the Z diagram changes sign; the A diagram does not. The resulting polarization asymmetry is approximately proportional to c_{WW} .

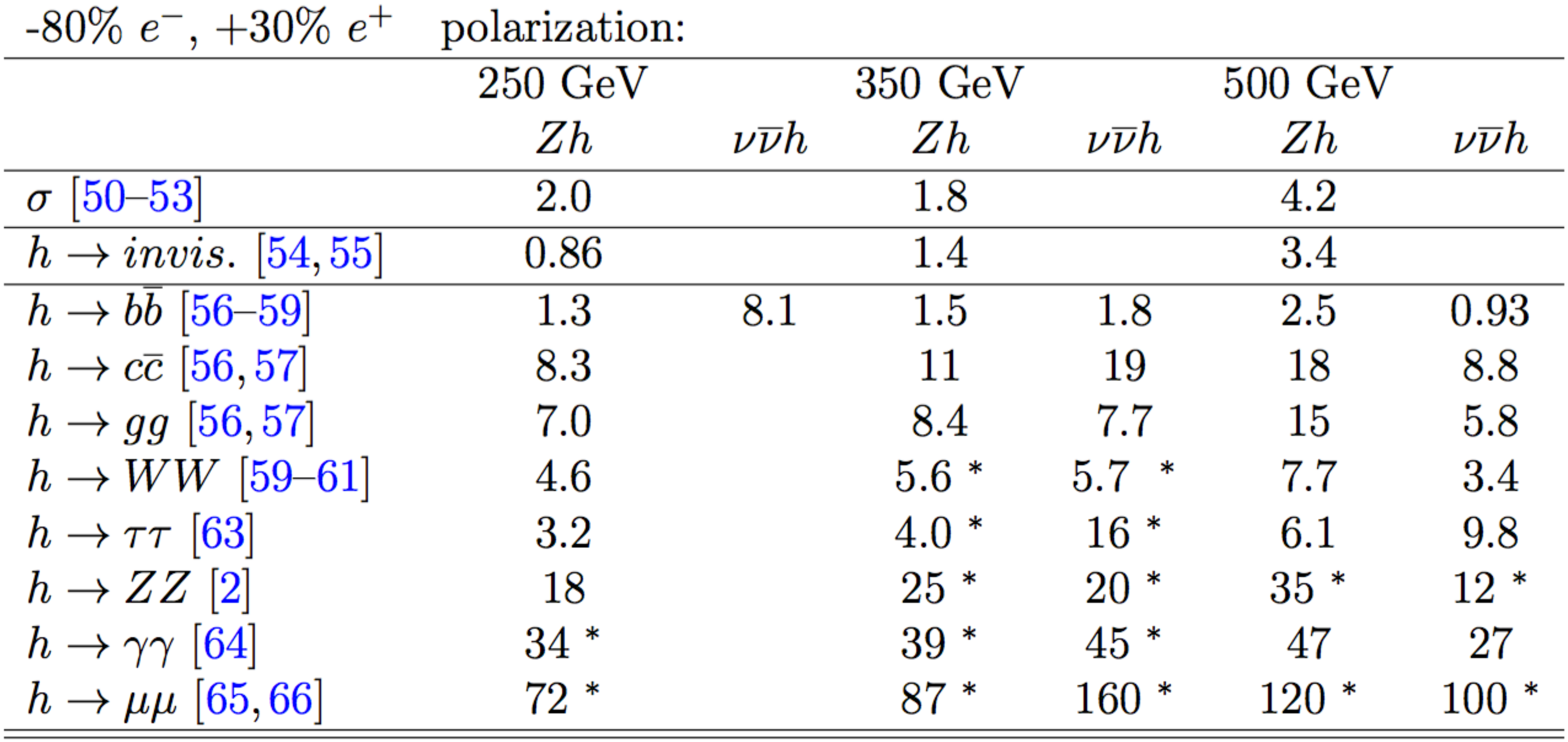
We can also add information from the h branching ratios.

Each quark or lepton BR brings one more parameter.

The Higgs partial widths to WW, ZZ depend on the parameters we have already discussed. They also involve quark contact terms c_{HQ} . But these same parameters also modify, and are determined by, the W and Z total widths.



Here is part of a table of projected errors σ x BR from the ILD collaboration (in %) for luminosity samples of 250 fb-1. Again, scale with $\sqrt{N}$ plus systematics.



-80% e^-, +30% e^+ polarization:

	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ [50–53]	2.0		1.8		4.2	
$h \to invis.$ [54, 55]	0.86		1.4		3.4	
$h \to b\bar{b}$ [56–59]	1.3	8.1	1.5	1.8	2.5	0.93
$h \to c\bar{c}$ [56, 57]	8.3		11	19	18	8.8
$h \to gg$ [56, 57]	7.0		8.4	7.7	15	5.8
$h \to WW$ [59–61]	4.6		5.6 *	5.7 *	7.7	3.4
$h \to \tau\tau$ [63]	3.2		4.0 *	16 *	6.1	9.8
$h \to ZZ$ [2]	18		25 *	20 *	35 *	12 *
$h \to \gamma\gamma$ [64]	34 *		39 *	45 *	47	27
$h \to \mu\mu$ [65, 66]	72 *		87 *	160 *	120 *	100 *

Most of the numbers are from full simulations; numbers with * are extrapolations.

Put all sources of information together! Count parameters and constraints:

Parameters (22):

4 SM + 16 EFT + 2 (invisible and exotic decays)

Measurements (22):

9 precision EW + 3 WW + 2 Zh + 7 BR's + invisible BR

The system is well determined. Then we can solve for all of the parameters independently.

Actually, with polarization, there are more independent observables, and we have LHC inputs (BR(γγ)/BR(4l)).

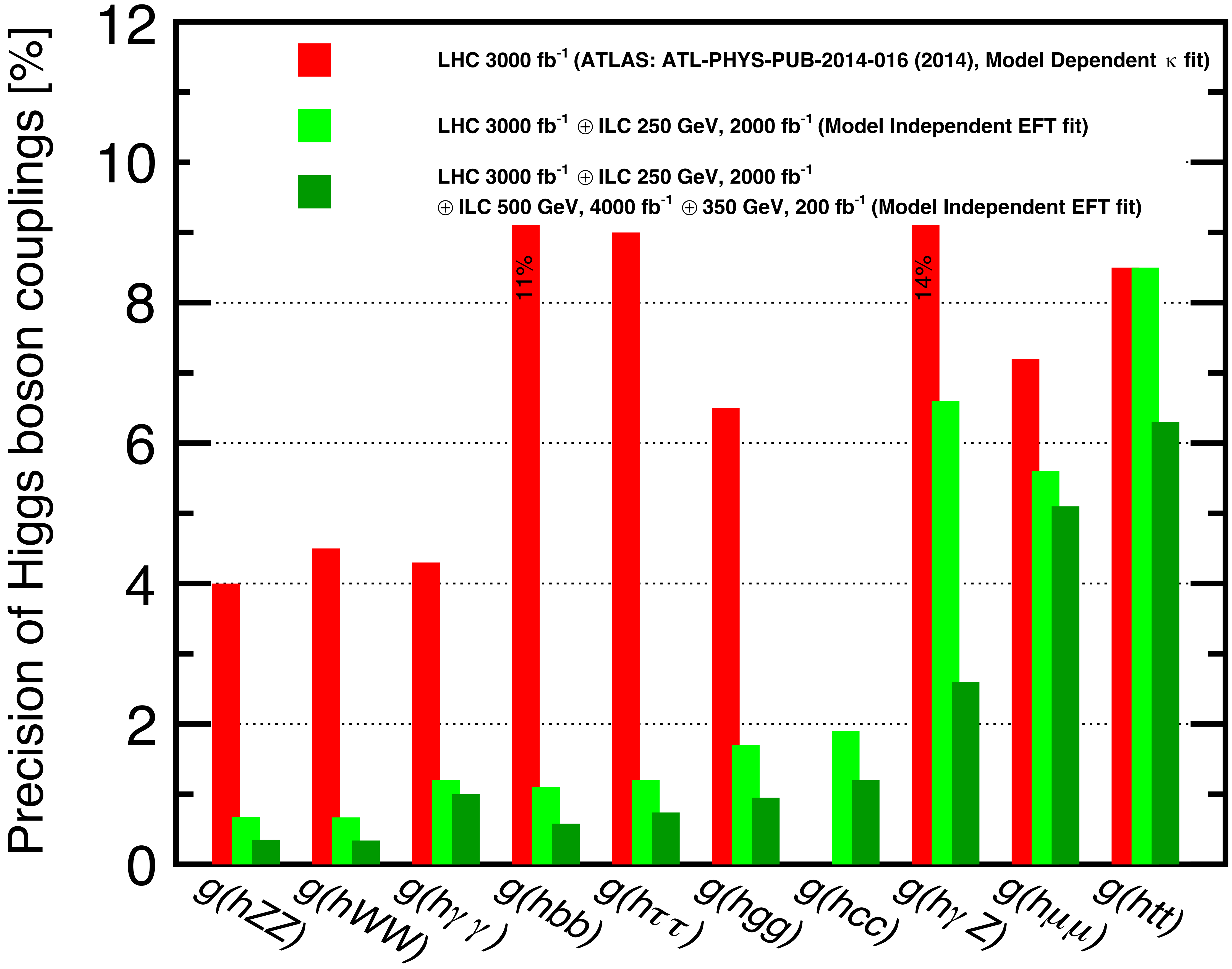
It would be ideal to add data at a higher energy, e.g. at 500 GeV.

This adds two new sources of information:

The WW fusion reaction turns on. Then we add a new set of σ x BR measurements.

The contact vertices in $e^+e^- \to Zh$ enter the cross section with factors of s/m_Z^2. Using measurements at two different energies, we strongly constrain (or measure) these parameters.

These coefficients were originally determined by precision electroweak; this method improves upon the results of precision electroweak.



arXiv:1710.07621

The extension of e+e- experiments to 500 GeV also opens up additional physics investigations:

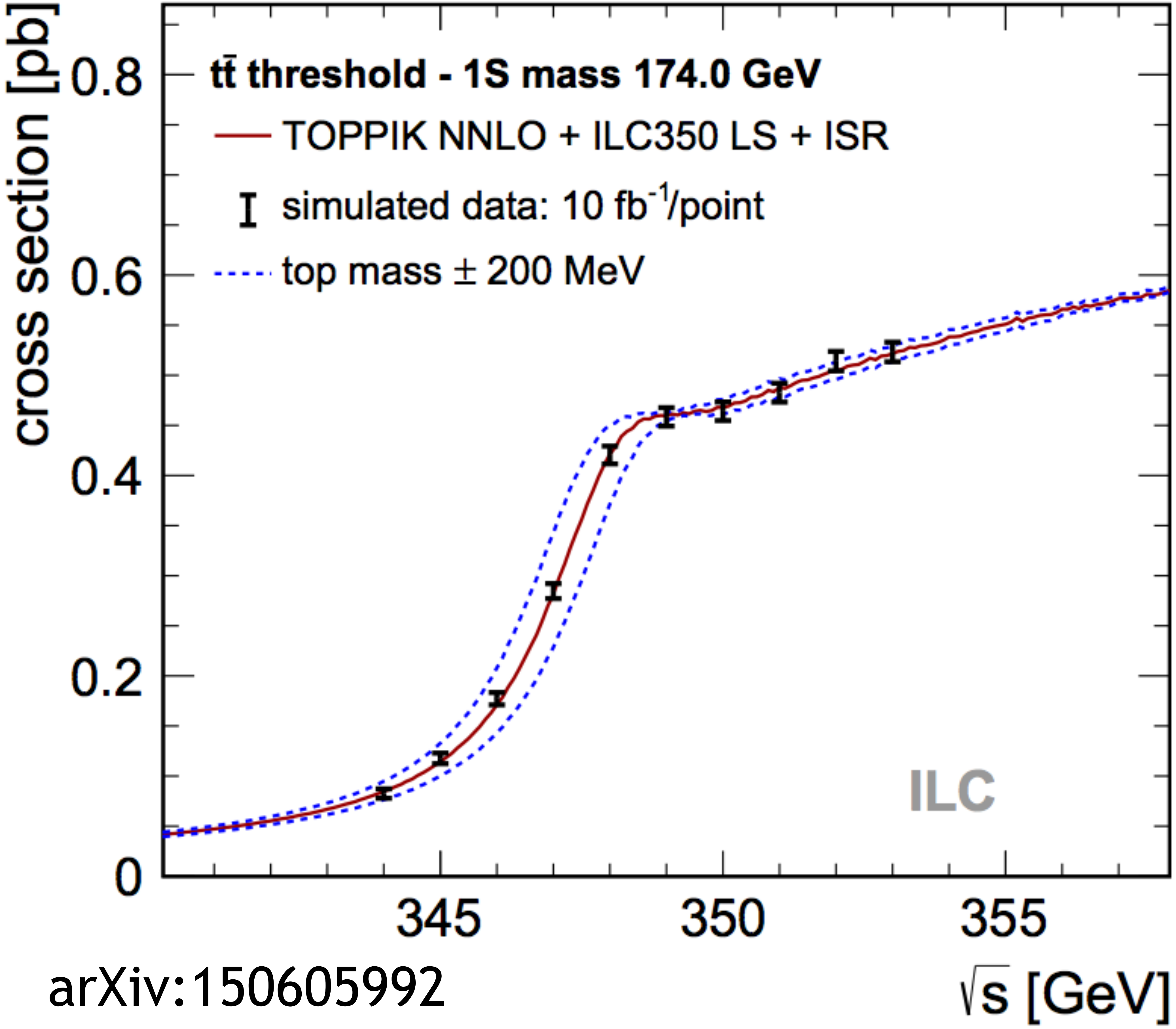
Measurement of the top quark mass to 40 MeV by determination of the energy of the top quark threshold.

Measurement of top quark electromagnetic form factors to accuracies below 1%.

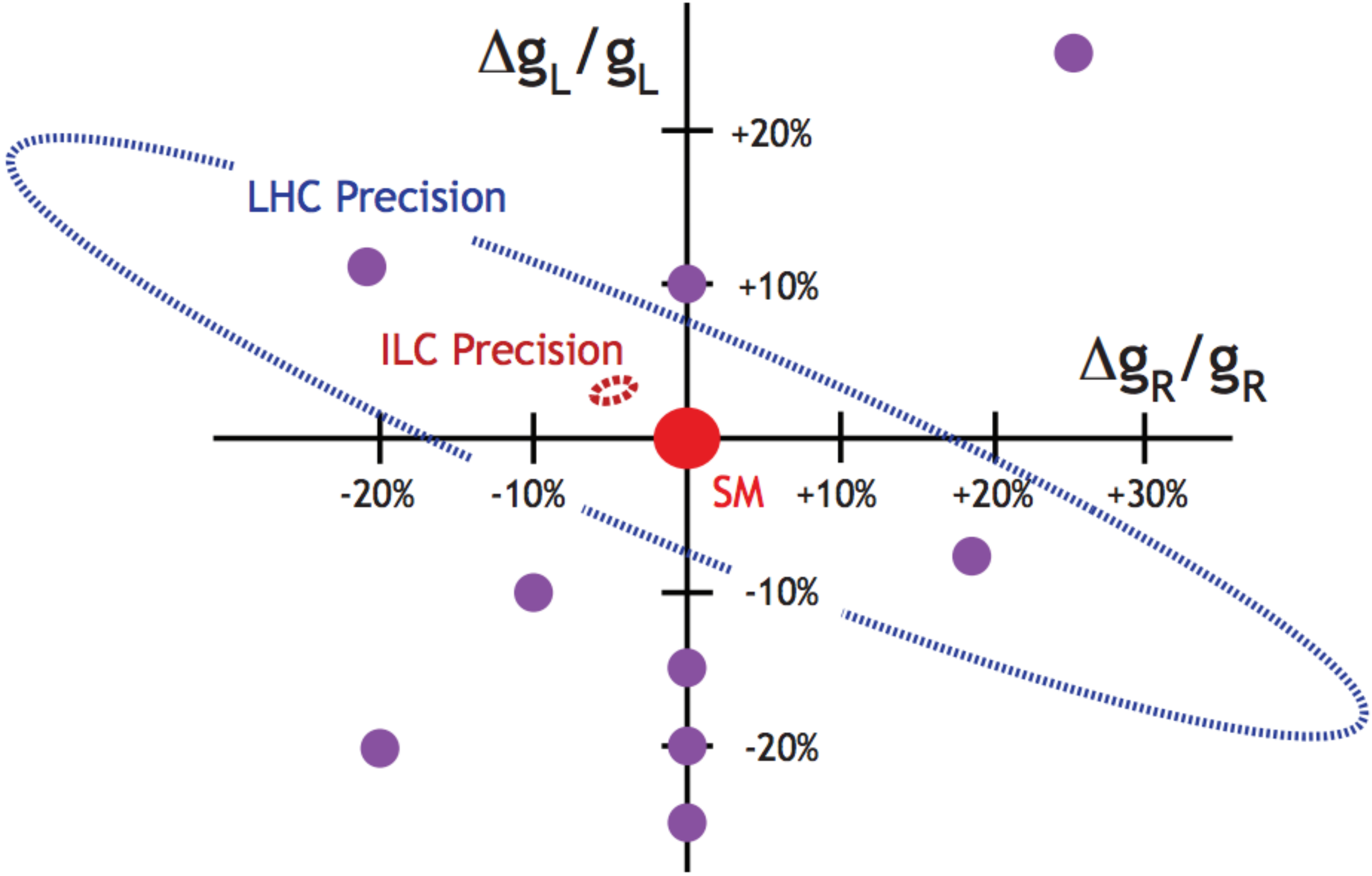
Measurement of the top quark - Higgs Yukawa coupling, to 6% at 500 GeV, to 2% at 1 TeV.

Measurement of the triple Higgs coupling, to 27% at 500 GeV, to 10% at 1 TeV.

Search for invisible particle pair production (dark matter) in $e^+e^- \to \gamma + \chi\chi$.



arXiv:150605992



arXiv:150605992

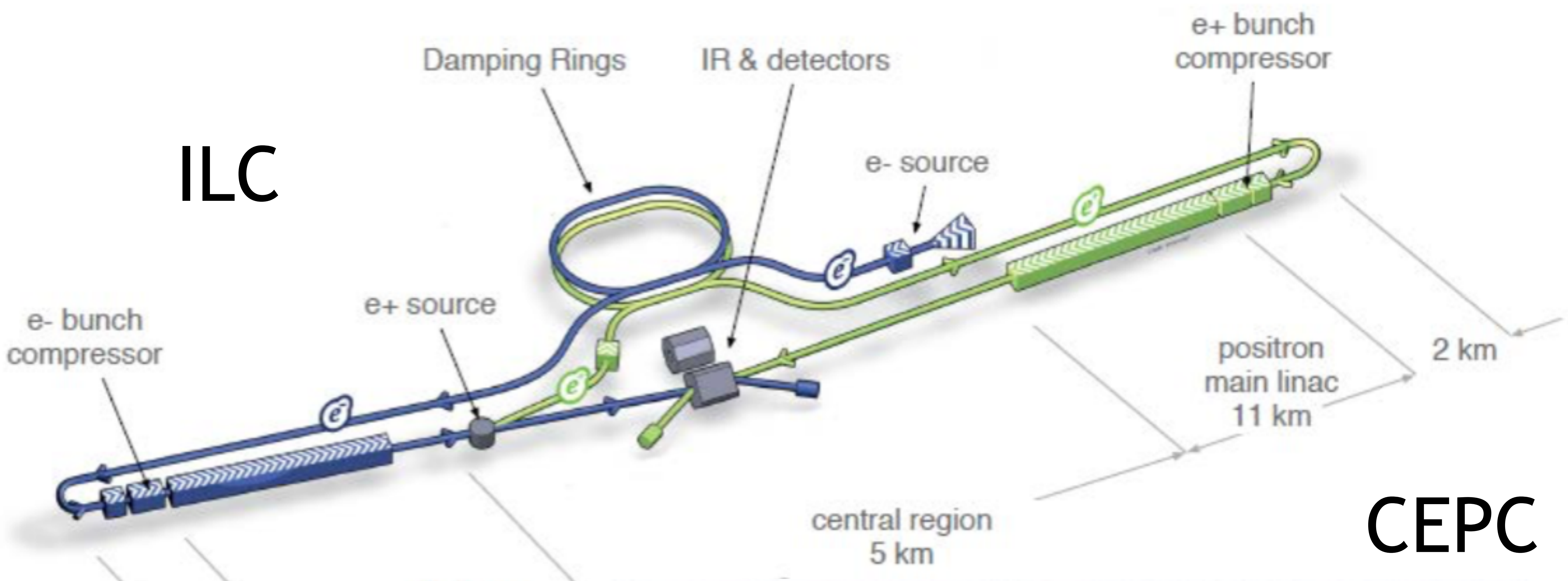
The study of the possible anomalous properties of top and the top Yukawa coupling (measured in tth events) also properly requires an EFT treatment.

A new paper by Durieux, Perello, Vos, and Zhang (arXiv: 1807.02121) describes the model-independent determination of the coefficients of 8 CP-conserving operators contributing to $e^+e^- \to t\bar{t}$. This requires measurements of the cross section, polarization asymmetry, and final-state polarizations at 2 different energies.

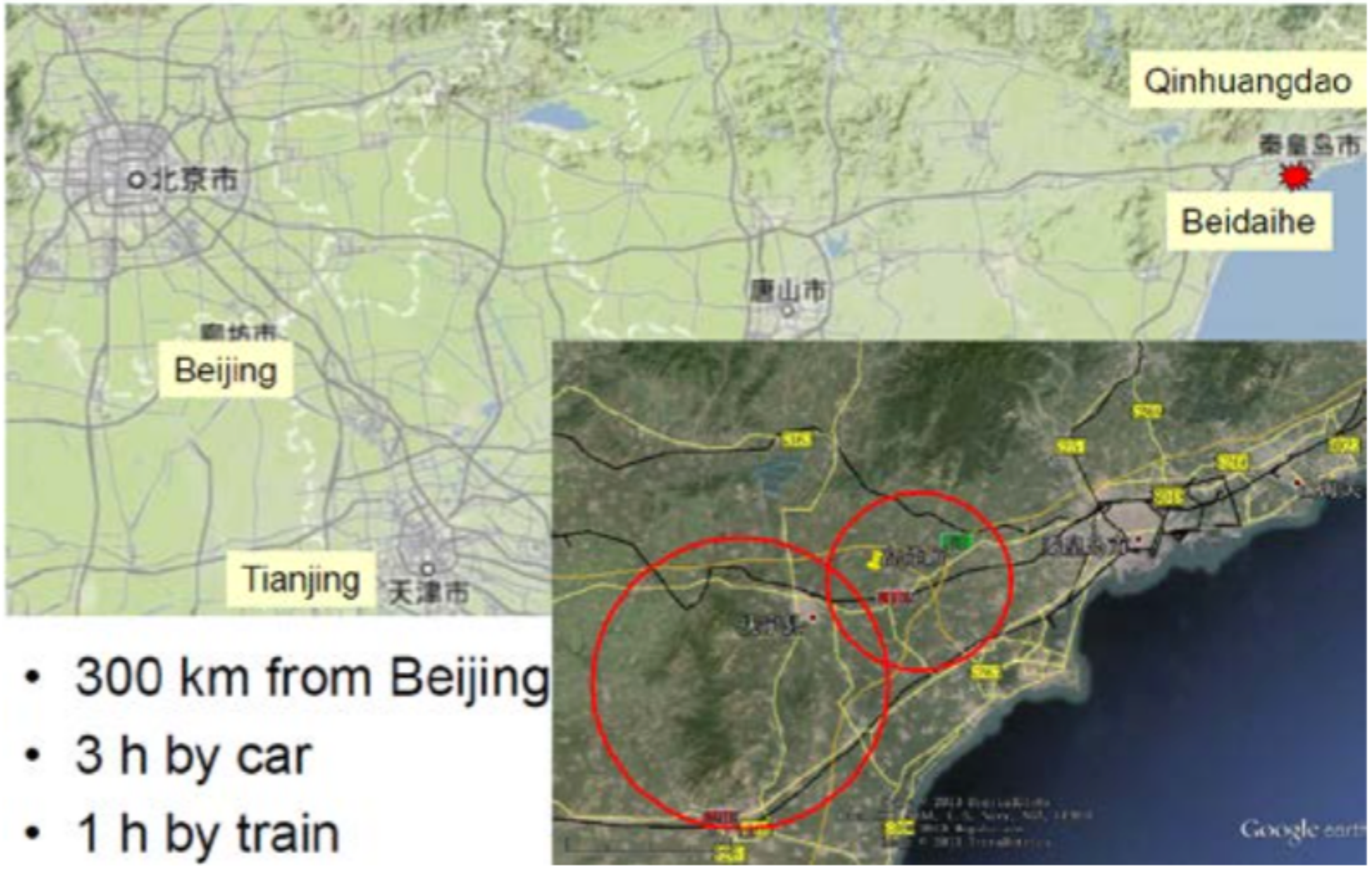
Finally, these experiments are very beautiful, but will we actually see them?

The US seems not to be interested in hosting new energy frontier colliders.   The possible colliders discussed are in Europe and Asia.

ILC

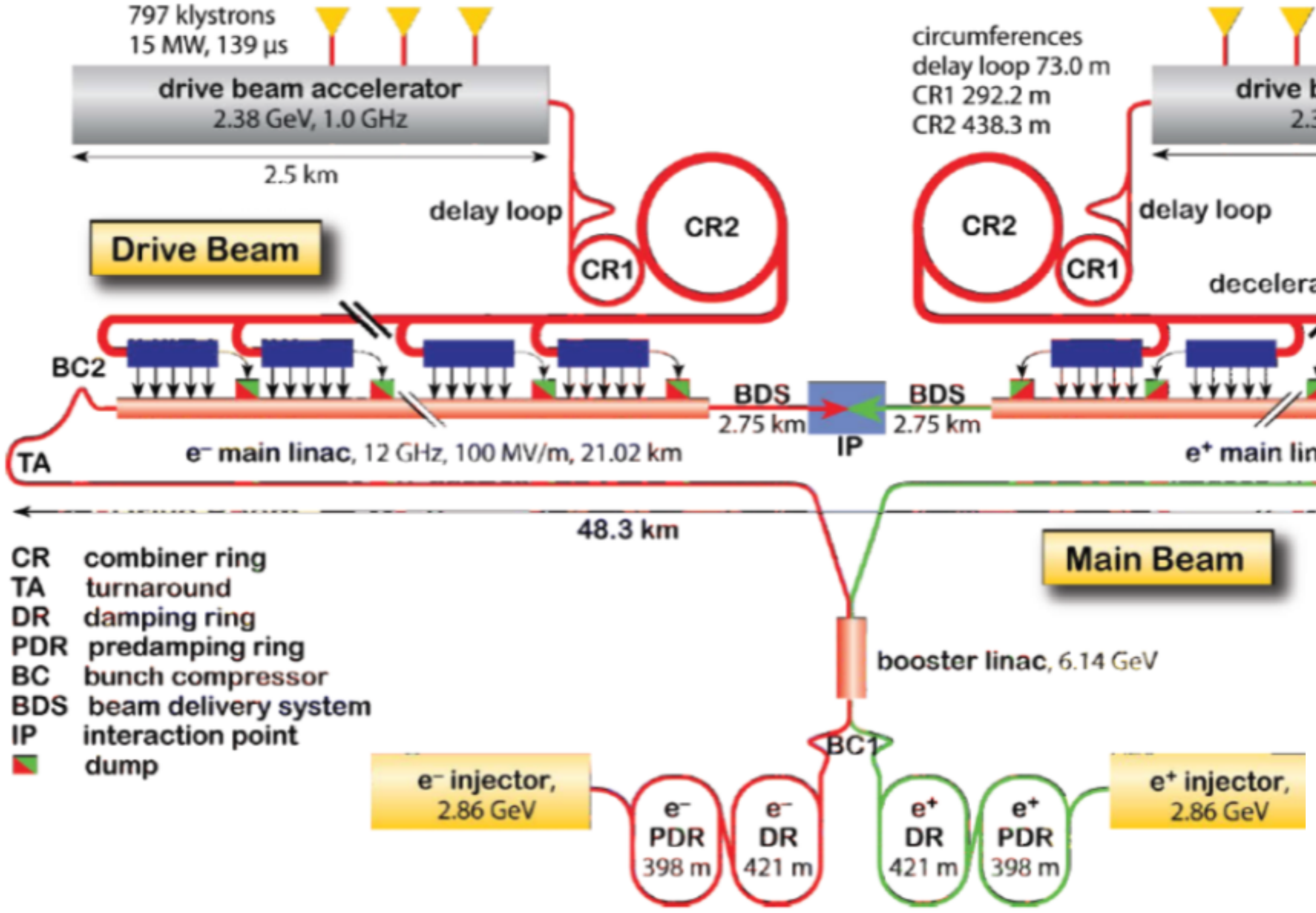


CEPC



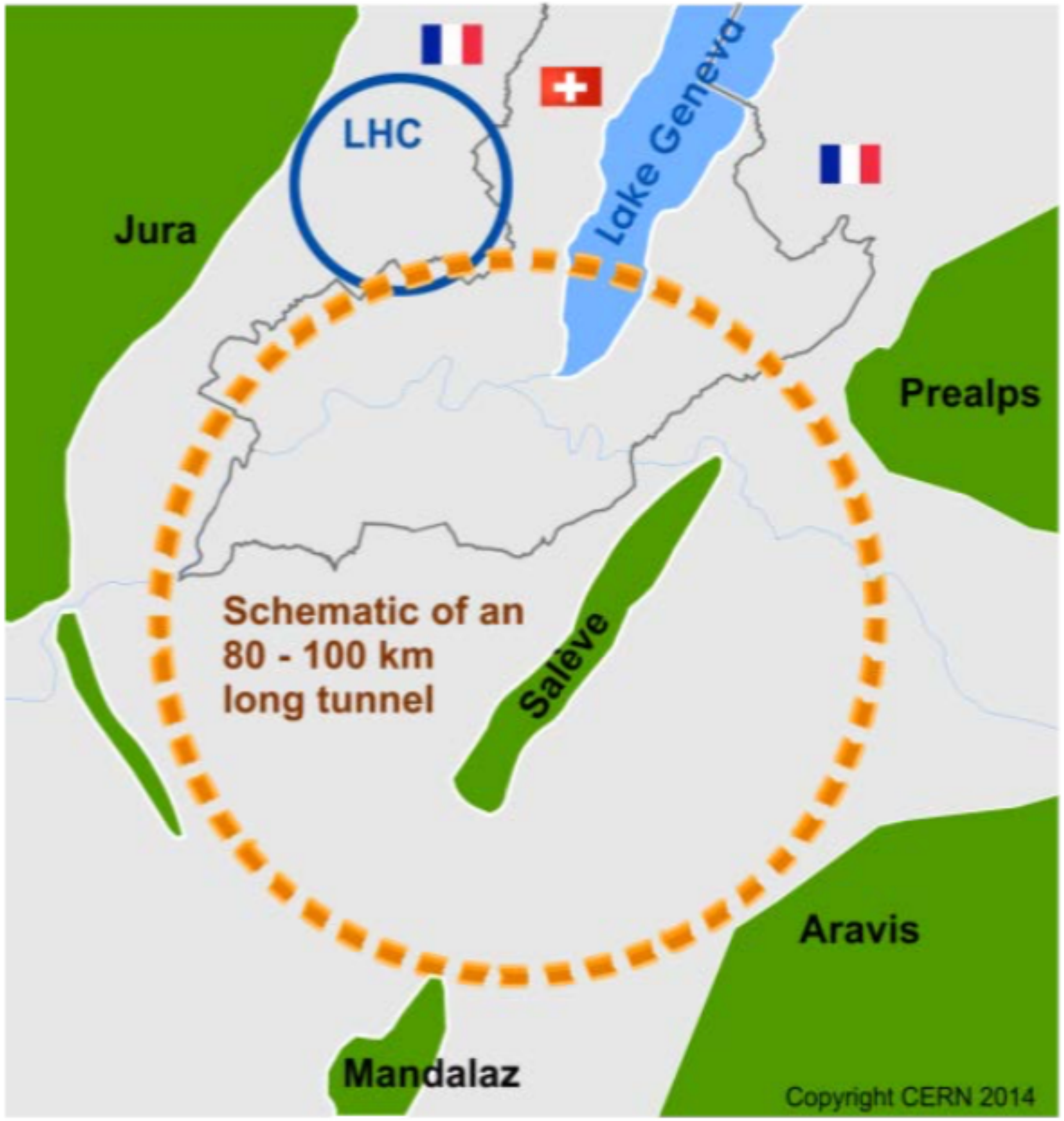
- 300 km from Beijing
- 3 h by car
- 1 h by train

new accelerators proposed in Asia



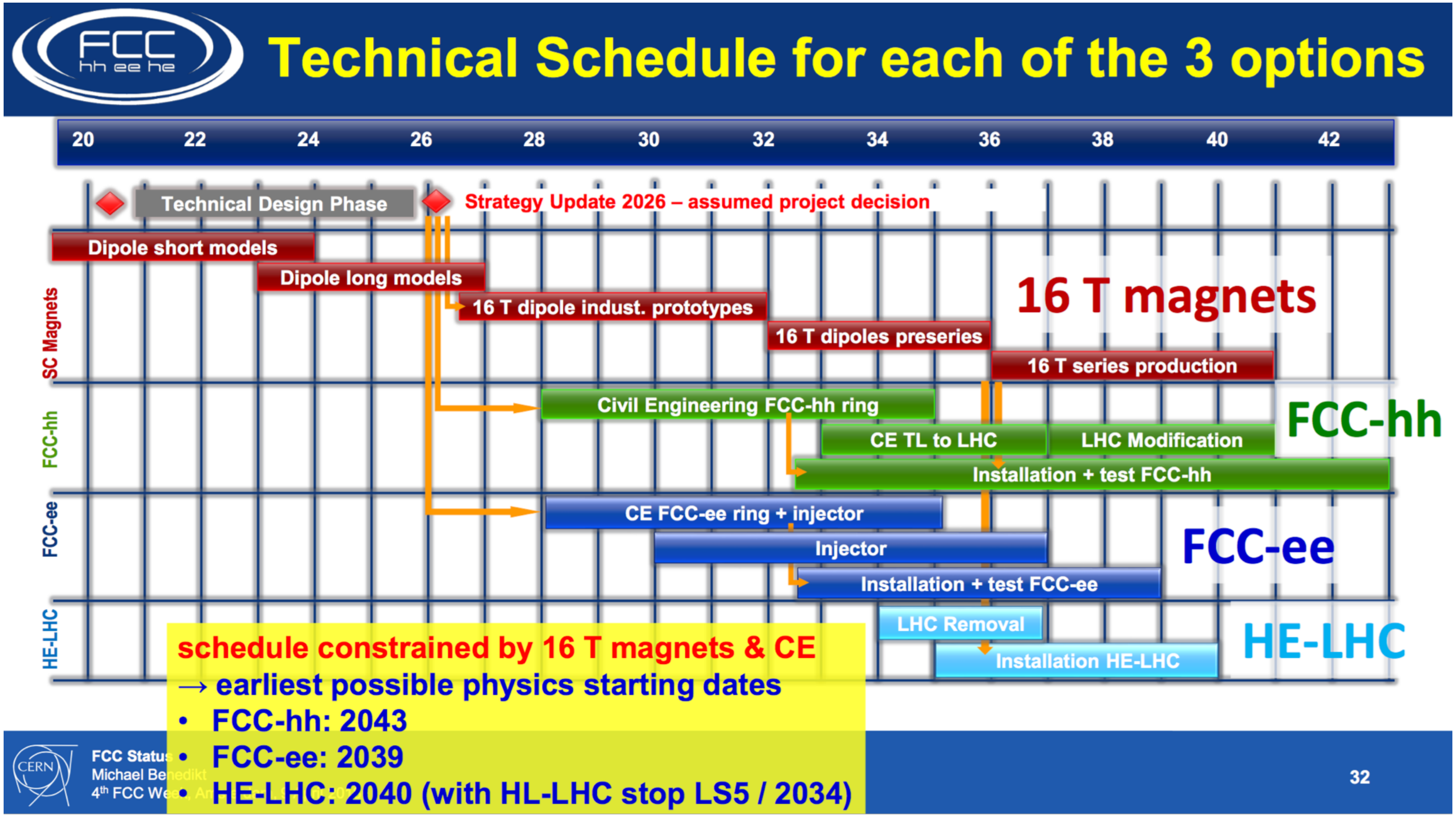
CLIC

FCC-ee



new accelerators proposed for the next CERN project after LHC

Michael Benedikt - FCC week 2018:



Technical Schedule for each of the 3 options

schedule constrained by 16 T magnets & CE
→ earliest possible physics starting dates
- FCC-hh: 2043
- FCC-ee: 2039
- HE-LHC: 2040 (with HL-LHC stop LS5 / 2034)

These projects are far away. CLIC might be closer;
its start is limited by CERN's borrowing to pay for HL-LHC.

Geoffrey Taylor (chair of ACFA) - FCC week 2018

China New Scientific Policies

January 23, 2018 : The China Reform and Development Committee (led by President J.P. Xi) had the meeting on Jan 23, 2018, and passed the plan of "Chinese Initiated International Large Scientific Plan and Large Scientific Project"

March 28, 2018 : Chinese Government (led by Premier Minister Keqiang Li) made public details of "Chinese Initiated International Large Scientific Plan and Large Scientific Project" :

...till 2020 China will prepare 3~5 projects (hopefully, CEPC is inside)and finally select 1~2 projects to construct...(hopefully, CEPC will be selected)

...Actively participate in other country or multinational initiated Large Scientific Projects (hopefully, ILC will have good news from Japan at the end of 2018)

...Actively participate important international scientific organisations' scientific projects and activities...

translation and interpretation by Jie Gao, IHEP

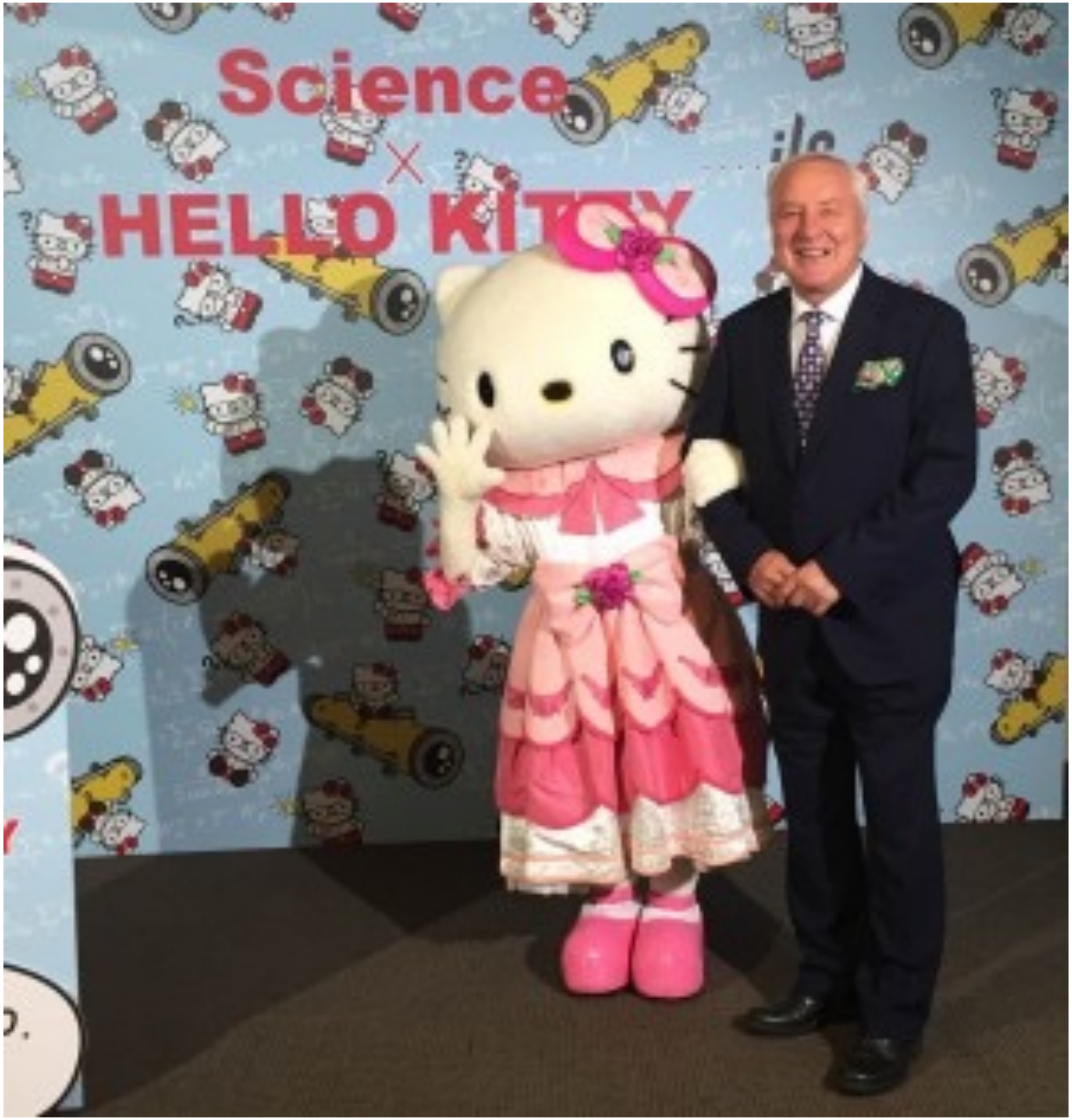
This year, there is new hope that for the funding and construction of the ILC in Japan:

- staged design with the first state at 250 GeV and 40% cost reduction (arXiv:1711.00568)
- reworking of the physics case for precision Higgs and other aspects of 250 GeV program (arXiv:1710.07621)
- endorsement of this plan by the Japanese particle physics community (JAHEP), July 2017
- endorsement of this plan by ICFA, November 2017
- warm final report from MEXT study after a 5-year study, July 2018

deadline for a decision by the Japanese government for inclusion in the European Strategy Study, fall 2018

Hon. Shintaro Ito (Sendai) meeting with the American Linear Collider Coordinating Committee, AWLC 2017 at SLAC, June 2017

Higgs Boson yurukyara


Science
×
HELLO KITTY
ilc

I am cautiously optimistic about ILC and/or CEPC going forward.

Full approval would require collaboration agreements negotiated with CERN and US, then 8-10 years of construction. This corresponds to detector TDRs in the mid-2020’s, physics start in 2030-32.

For those of you now fully involved in the development of the HL-LHC detectors, this could be well timed for your future.

If neither ILC nor CEPC is approved, we wait another 10 years.

In these lectures, I have argued that next-generation e+e- colliders offer an excellent opportunity.

They represent a new path, and a very promising one, for the discovery of physics beyond the Standard Model.

The experiments are beautiful and make powerful use of all aspects of the known particle physics.

If you would like to be a leader of a major experiment at the energy frontier, this your one chance. Grab it!

If you would like to get involved now, please attend:

www.uta.edu/physics/lcws18/

We would love to have more talks on detector R&D for the ATLAS and CMS HL-LHC upgrades. Early registration is extended to Sept. 14.