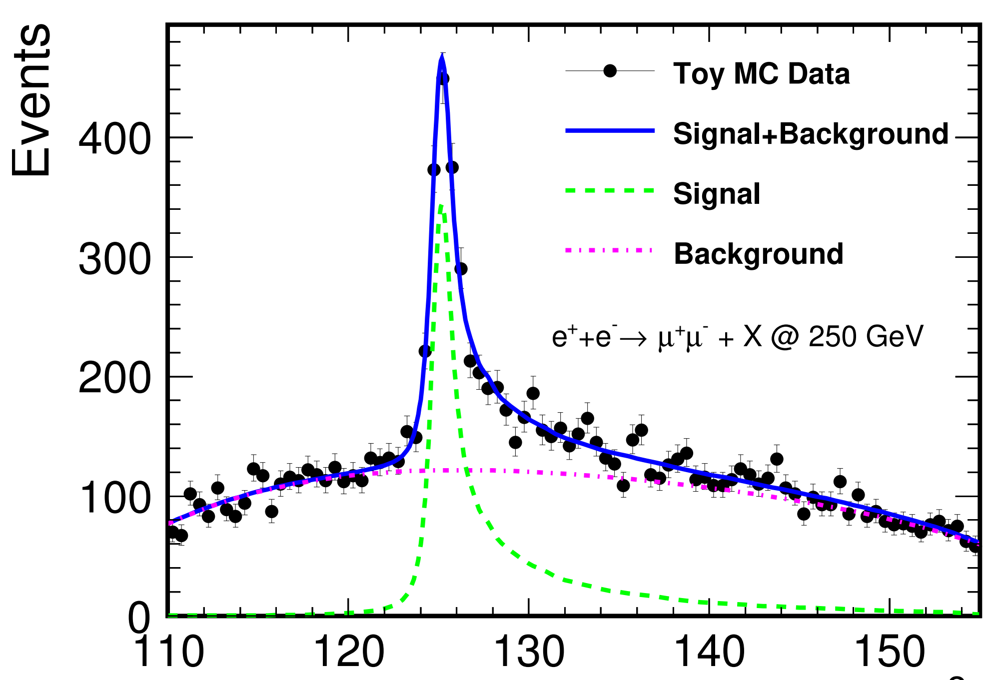
# Precision Higgs Physics at Future e+e- Colliders





M. E. Peskin
PASCOS - IBS
June 2021

The most important questions in particle physics today are:

How do we get beyond the Standard Model?

What do we hope to learn there?

In my opinion, the best route is to study the Higgs boson in much greater detail.

In this talk, I will discuss:

What is so important about studying the Higgs boson ?

What can we learn from studying the Higgs boson in e+e- collisions ?

Is there synergy between Higgs boson measurements and other tests of the Standard Model ?

What is the International Linear Collider ? What is its physics program ?

The Standard Model of particle physics is a very successful theory, but it cannot be a final one.

Too many parameters are unexplained. Too much of the structure seems ad hoc.

Among the many mysteries of the Standard Model, this one is particularly compelling to me:

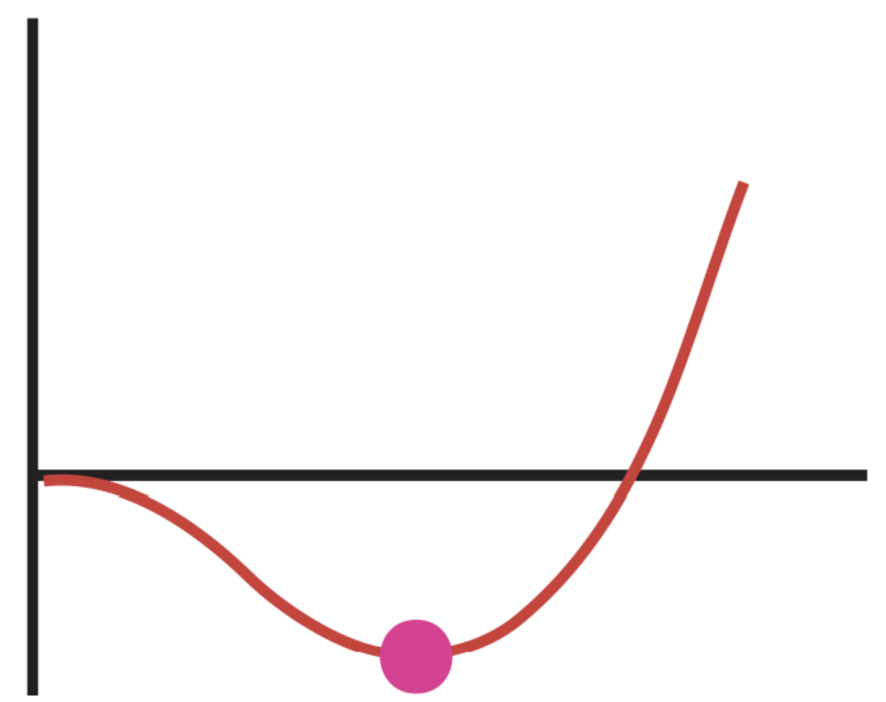
What physics leads to the phase transition to SU(2)xU(1) symmetry breaking ?

Here is the explanation for SU(2)xU(1) breaking given in the Standard Model:

Write the most general renormalizable potential for $\varphi$ :

$$V(\varphi) = \mu^2 |\varphi|^2 + \lambda |\varphi|^4$$

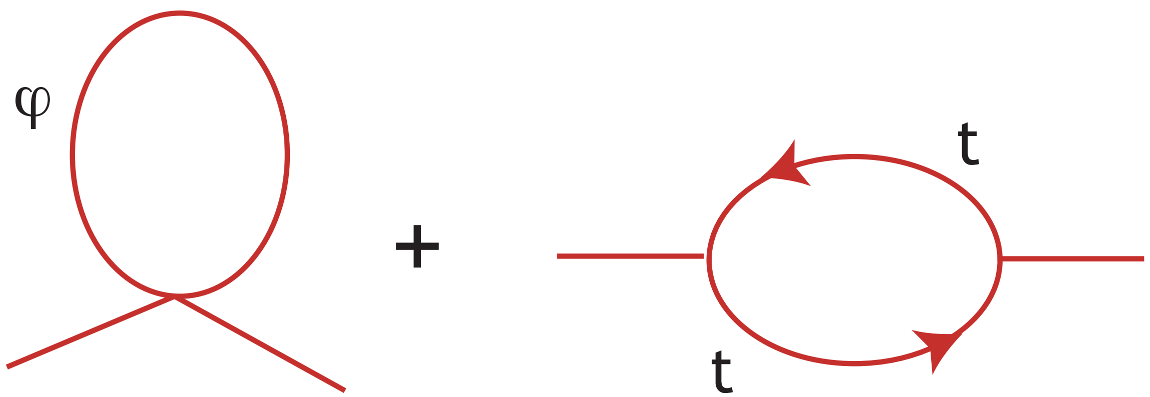
Assume $\mu^2 < 0$ . Then the potential has the correct shape for symmetry breaking.



Why is $\mu^2 < 0$ ? That question cannot be addressed within the model.

We get into deeper trouble if we try to pursue this question by higher-order computation.

If we compute the first quantum corrections to the picture on the previous slide, we find




$$\mu^2 = \mu^2_{\rm bare} + \frac{\lambda}{8\pi^2}\Lambda^2 - \frac{3y_t^2}{8\pi^2}\Lambda^2 + \cdots$$

This is not a promising route to explain why

$$|\mu^2| = (100\ \mathrm{GeV})^2 \ll \Lambda^2$$

This problem is not new to high-energy physics.

The question of the physical mechanism of spontaneous symmetry breaking comes up again and again, in condensed matter, nuclear, and hadron physics.

For superconductivity, the 1950 Landau-Ginzburg model explained account for the thermodynamics of the phase transition, the magnetic properties, the critical current, the existence of type I and type II superconductors. However, it could not explain why superconductivity occurs in the first place. For this, we needed the Bardeen-Cooper-Schrieffer theory.

In Higgs physics, we are still at the Landau-Ginzburg stage.

For superconductivity, physicists knew at least that the explanation had to be given in terms of the interactions of electrons and atoms.

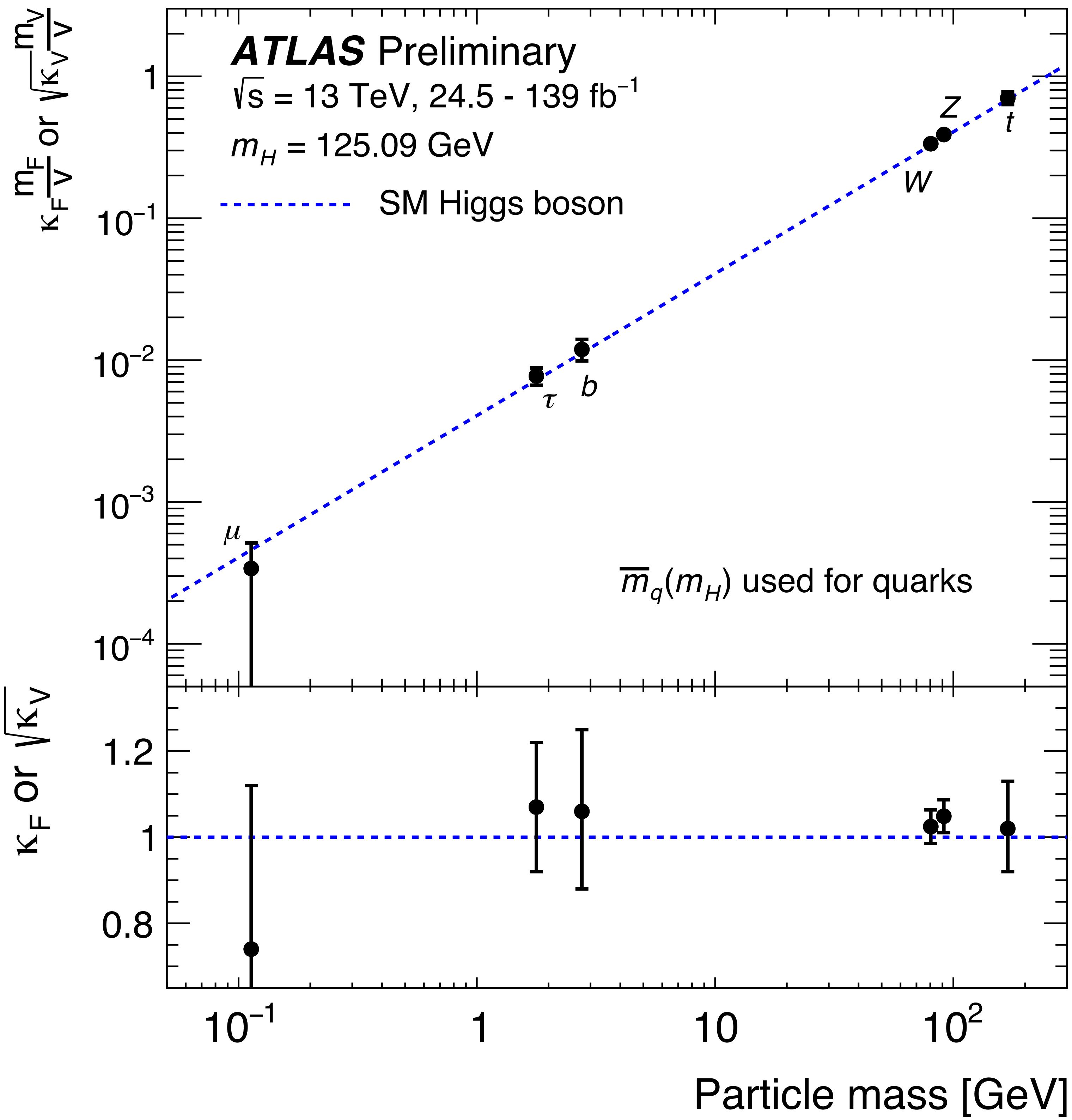
For SU(2)xU(1), we do not know the basic ingredients out of which we must build a theory of the symmetry-breaking potential. On general principles, these must be some particles and fields. We only know that we have not discovered them yet.

This is the biggest opportunity in physics, the opportunity to discover a new fundamental force of nature.

Since the discovery of the Higgs boson in 2012, many of its couplings have been measured by the LHC experiments.

We now know that, at the level of 10-20%, they follows the behavior predicted in the Standard Model.

Now these tests of the SM Higgs properties have become quantitative. Here is the ATLAS comparison of the proportionality of Higgs couplings to particle masses:



Even so, we know very little about the Higgs boson.

We know that it plays the role required for it in the SM.

We do not know whether it is fundamental or composite, whether there is only one or more Higgs fields, whether there is a new sector with additional particles related to the Higgs.

How can we have so much knowledge and so much ignorance at the same time ?

The explanation comes from Effective Field Theory:

If there are other particles that determine the physics of the Higgs field, and their masses are large, and we can form an Effective Field Theory in which they are integrated out.  Within this effective theory, the only source of SU(2)xU(1) symmetry breaking is the Higgs expectation value.

In this framework,

the masses of SM particle
reflect the Higgs couplings at $q^2 = 0$

the Higgs partial widths
reflect the Higgs couplings at $q^2 = m_h^2$

If the difference is due to heavy particles, it is small, of order $m_h^2/M^2$ .

This estimate can be proved as a theorem — called the Haber Decoupling Theorem — in Standard Model Effective Field Theory.

How do we know that the new particles associated with the Higgs field are heavy ?

We have not discovered them at the LHC.

Why are they so heavy ?

This is a definite, difficult model-building problem, called the Little Hierarchy Problem. In my opinion, it is this problem, rather than the one usually called the Hierarchy Problem, that deserves our attention.

However, it is quite consistent with everything we know that effects of order $m_h^2/M^2$ can be at the 5% level.

It is possible to search explicitly for these corrections. We are helped by two features:

1. The 125 GeV Higgs boson has a large number of possible decay modes, giving access to a large number of its couplings:

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

2. Within the Standard Model, the partial widths to these modes are completely computable, since, with the knowledge of $m_h$, all of the parameters of the Standard Model are determined.

The story is more interesting. The study of models shows that, at the few-% level of precision, each Higgs coupling has its own personality and is guided by different types of new physics. Very roughly, deviations appear in

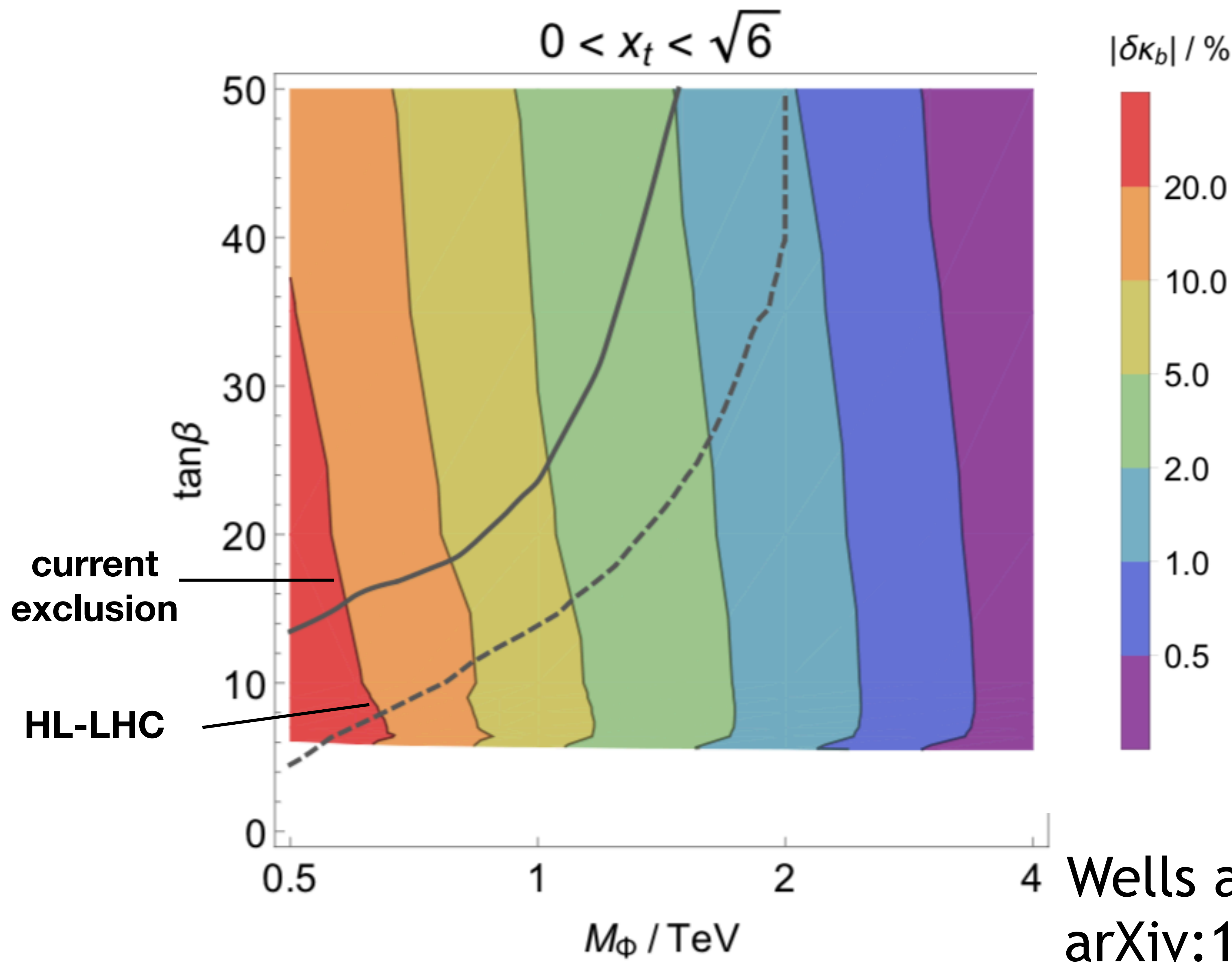
fermion couplings - multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

$\gamma\gamma$, gg couplings - heavy vectorlike particles

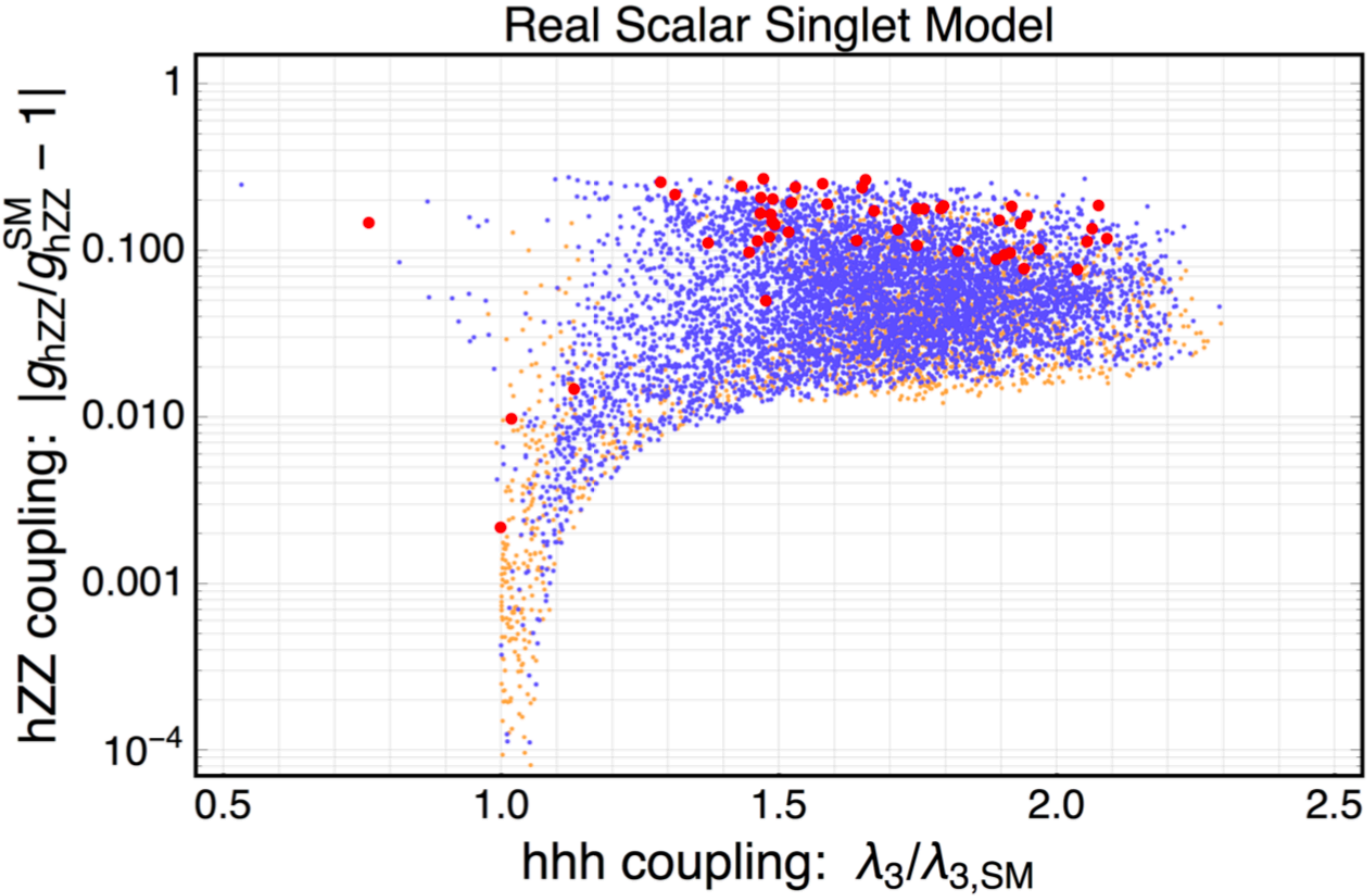
tt coupling - Higgs/top compositeness

hhh coupling (large deviations) - baryogenesis worked example: grand-unified SUSY



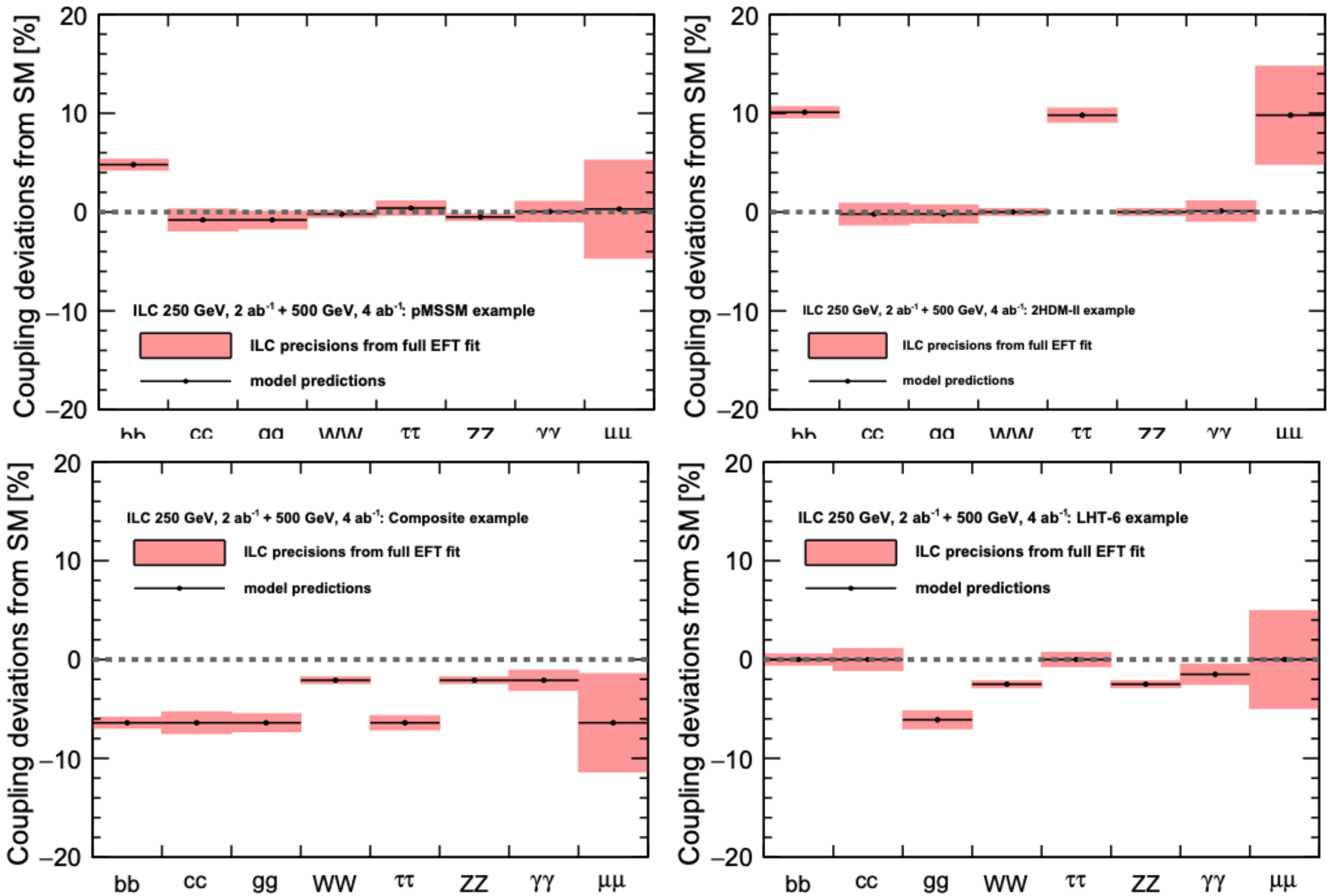

$(\kappa_b - 1)$ in %

Wells and Zhang, arXiv:1711.04774




Huang, Long, and Wang, arXiv:1608.06619

SUSY model | 2 Higgs doublet model




composite Higgs model | Little Higgs model

1708.08912

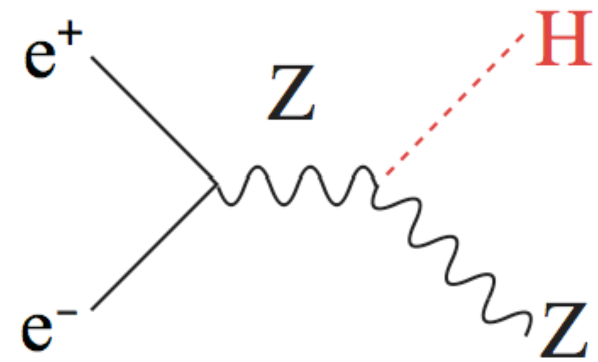
Now we should discuss the special advantages of studying the Higgs boson in e+e- annihilation.

These go beyond the usual advantages for any high-energy physics precision measurement:

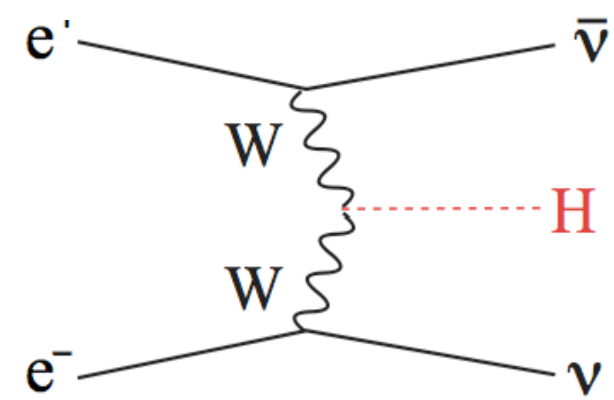
low backgrounds
ability to reconstruct the full event
access to W, Z in hadronic decay modes
use of beam polarization

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

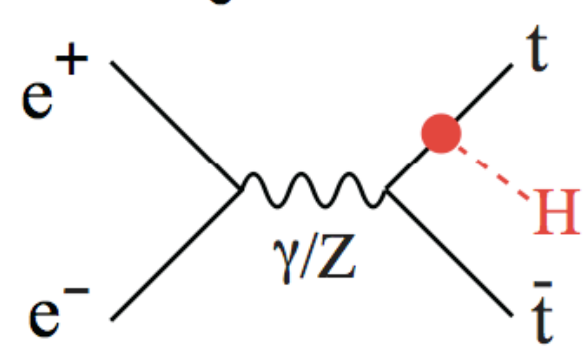
Higgsstrahlung



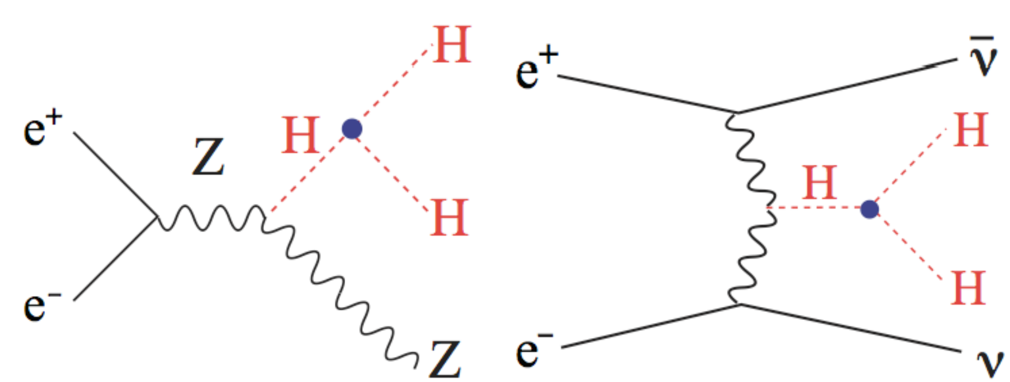

vector boson fusion

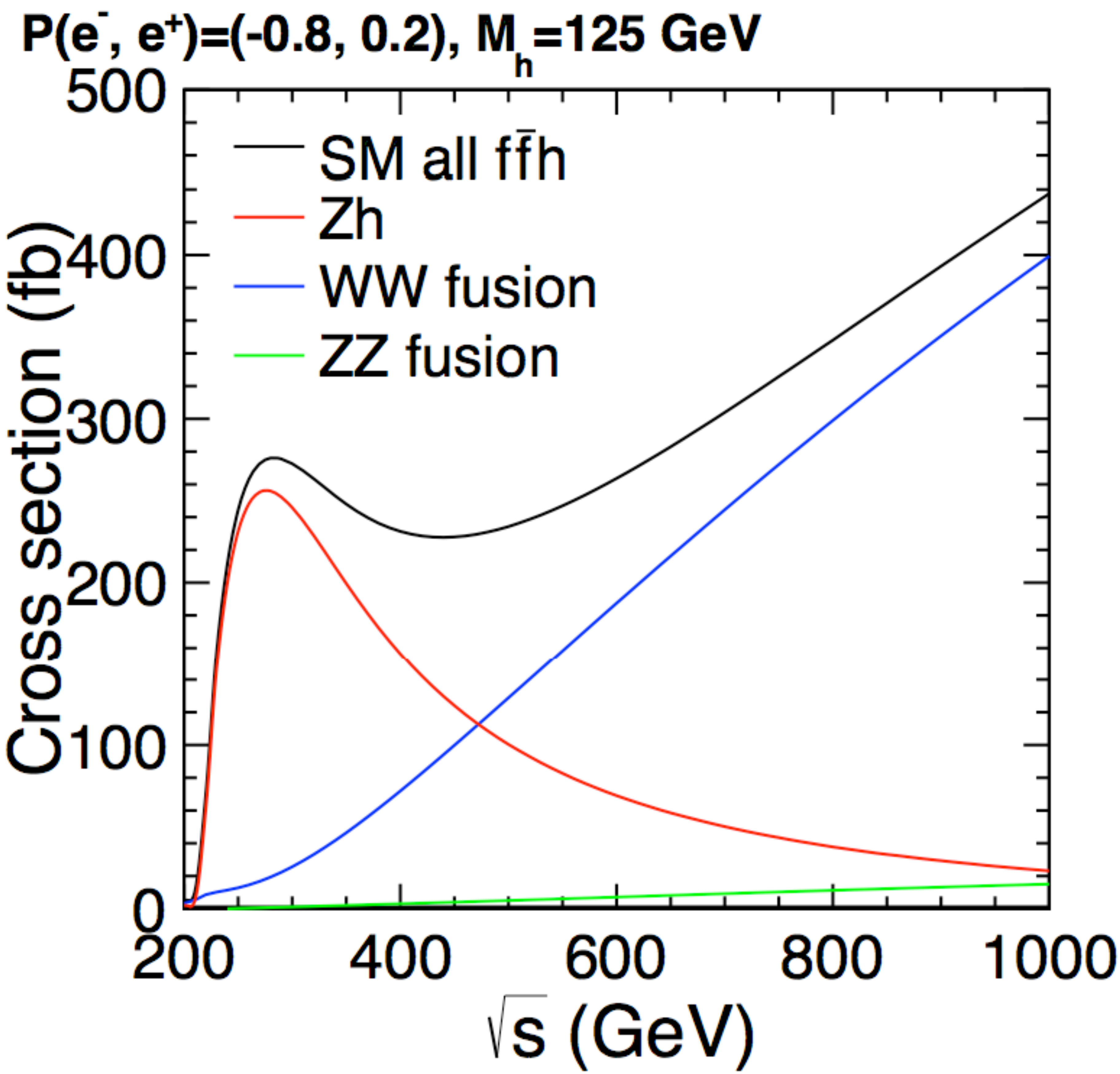



associated production with top



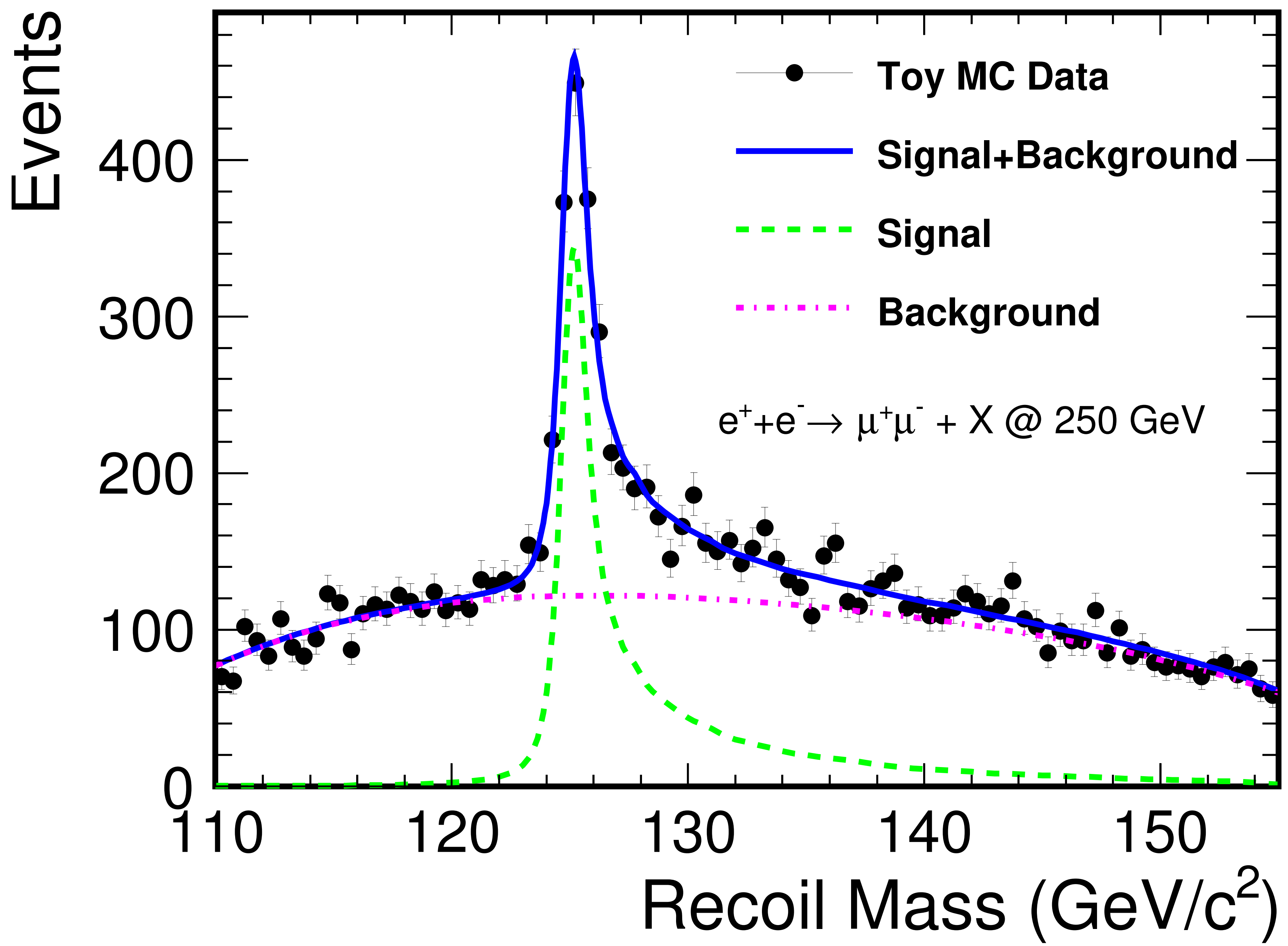

Higgs pair production



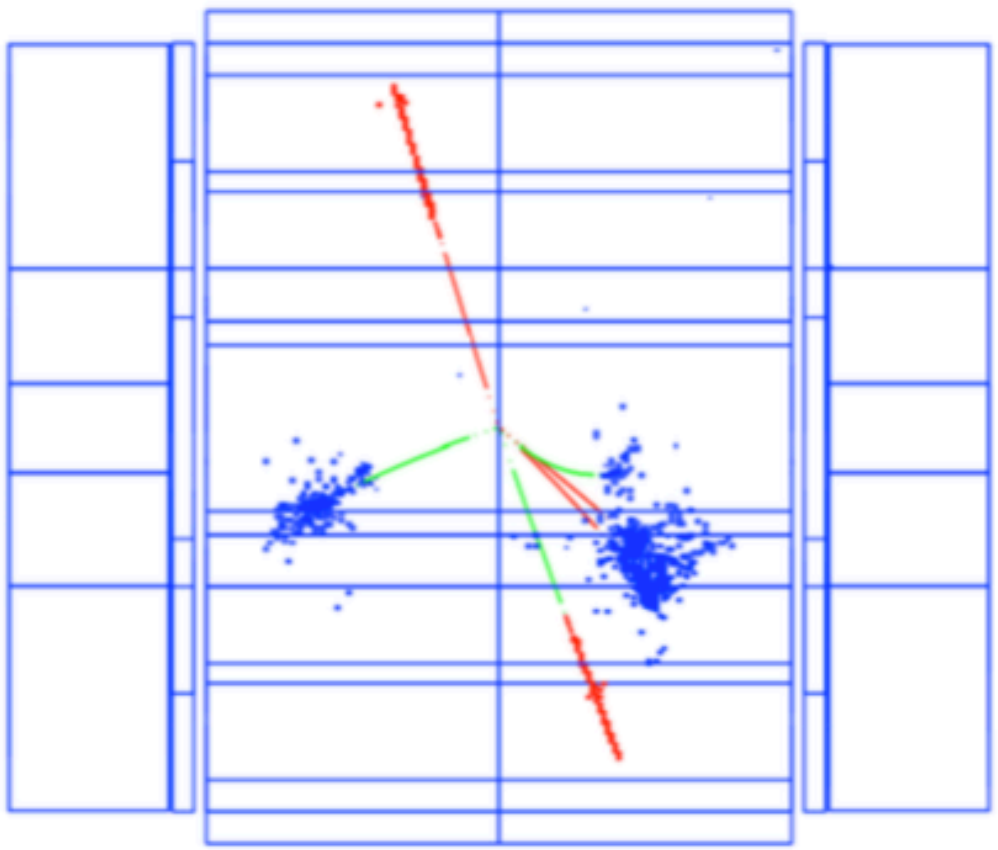


P(e-, e+)=(-0.8, 0.2), Mh=125 GeV
SM all ff̄h
Zh
WW fusion
ZZ fusion
Cross section (fb)
500
400
300
200
100
0
200
400
600
800
1000
√s (GeV)

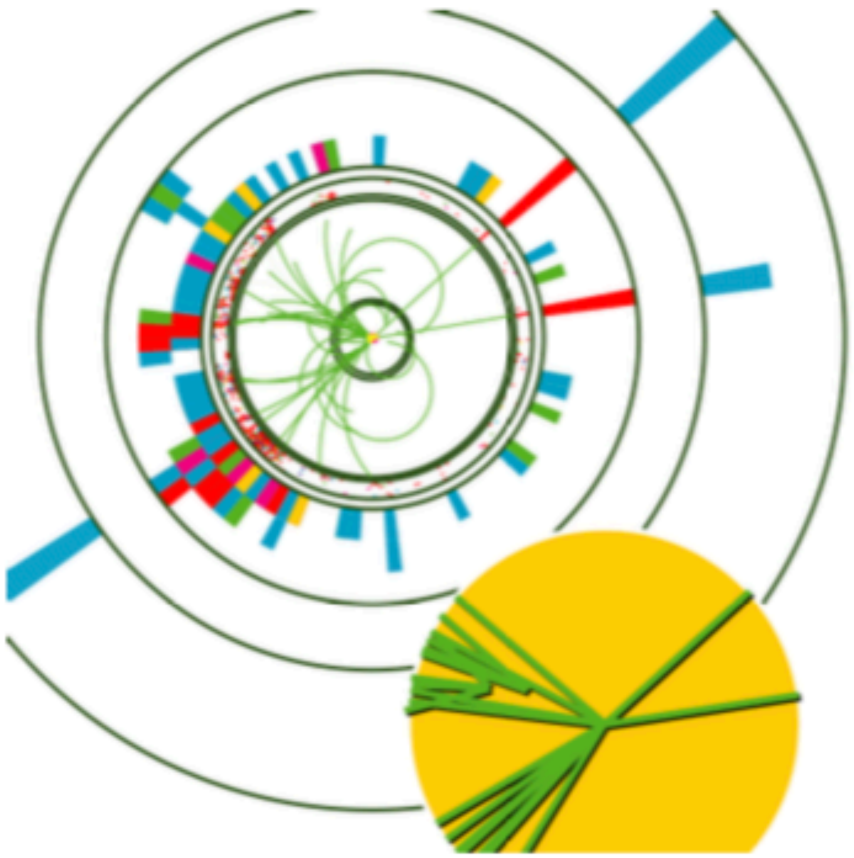
# measurement of the Higgs boson mass by the recoil technique ($\sigma$ = 15 MeV)




arXiv:1903.01629

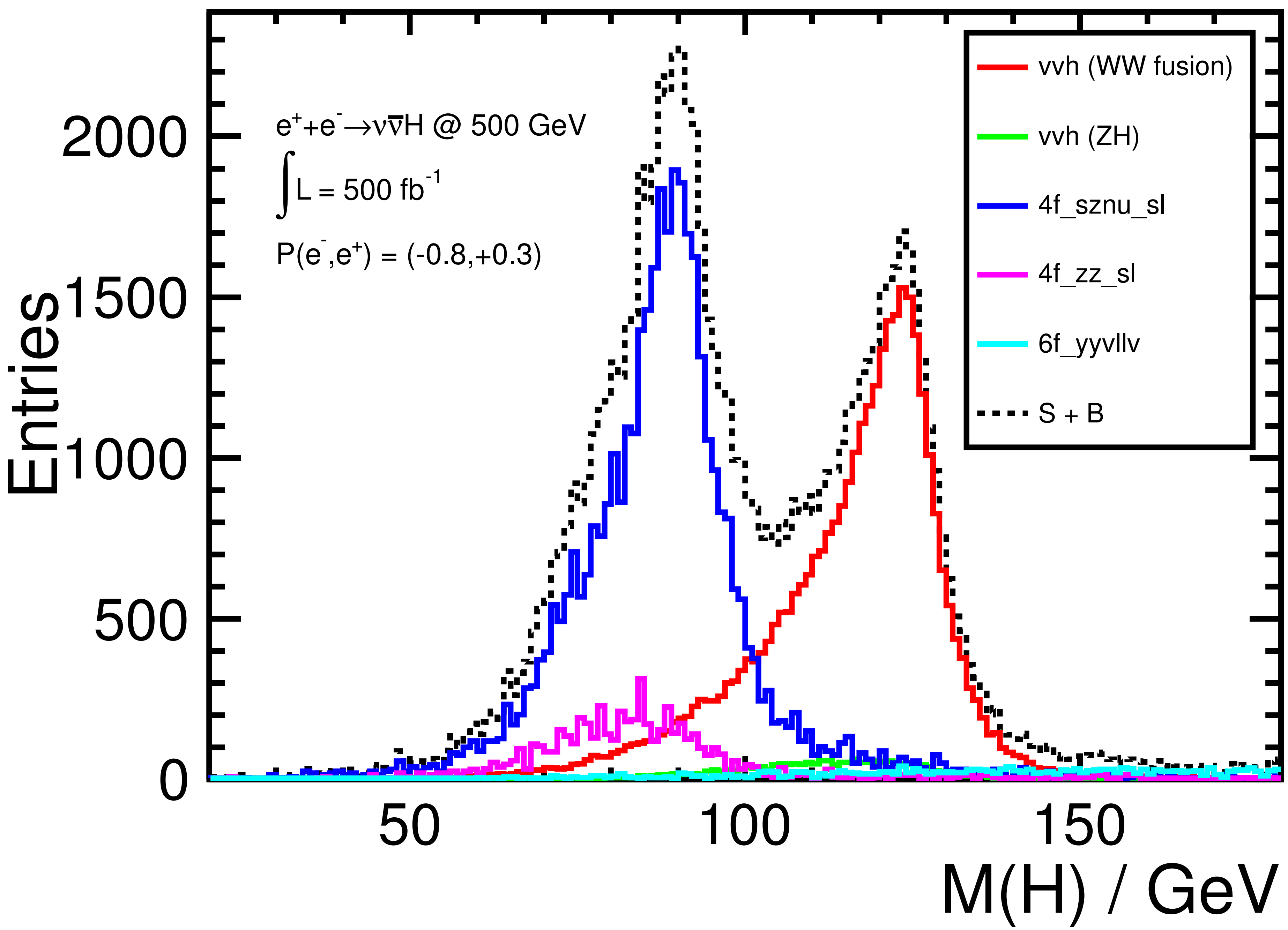


$h \to \tau^+\tau^-$

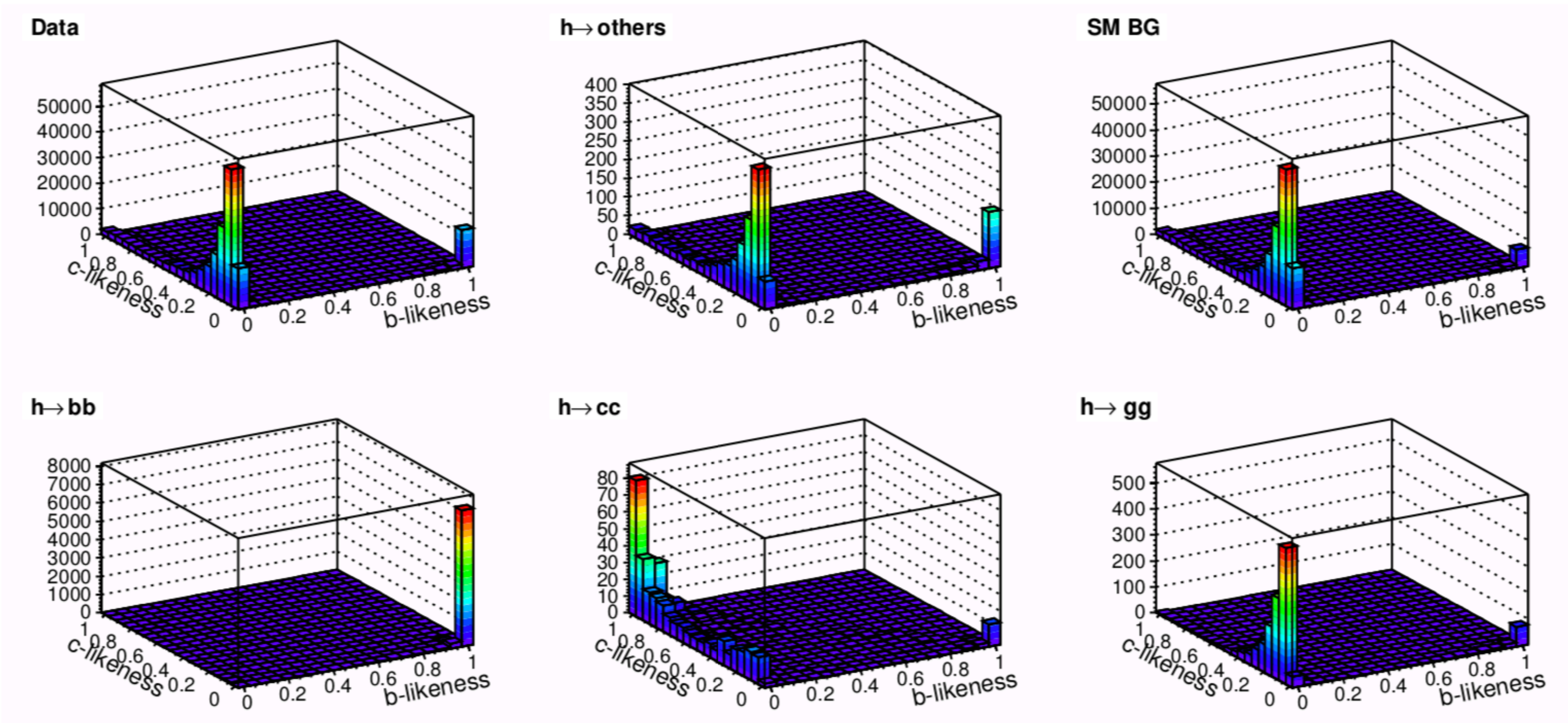


$h \to b\bar{b}$

$$e^+e^- \to \nu\bar{\nu} + b\bar{b}$$




arXiv:1903.01629




discrimination of hadronic Higgs decays - ILD simulation

The measurement of Higgs boson branching ratios is quite straightforward for the ILC at 250 GeV.

Higgs events are readily isolated from background. All standard Higgs decay modes are visible.

Measurement accuracies are such that 1% coupling measurements are feasible.

The absolute cross section for $e^+e^- \to Zh$ can be measured.

At 250 GeV, to first approximation, any Z boson with $E_{lab} = 110 \text{ GeV}$ is recoiling against a Higgs boson.

Though we can measure BR's, there is a potential problem in converting these to absolute coupling strengths. The width of the Higgs boson is predicted to be 4 MeV in the SM. This would not be directly measurable at any collider.

At e+e- colliders, there is an apparently model-independent way to determine the Higgs width. This uses

$$\frac{\sigma(e^+e^- \to Zh)}{BR(h \to ZZ^*)} = \frac{\sigma(e^+e^- \to Zh)}{\Gamma(h \to ZZ^*)/\Gamma_h} \sim \Gamma_h$$

Still , in the SM, $BR(h \to ZZ^*) \sim 3\%$ . Then we lose a factor 30 in statistics to measure this ratio. For 2 ab-1 of data, this gives normalization errors on the Higgs couplings of 3%.

Fortunately, we can improve this situation by the systematic use of Standard Model Effective Field Theory (SMEFT).

Given that the corrections to the SM are small, we can parametrize them as corrections to the SM from operators of the leading dimension — dimension 6.

This leads to a method for the (almost) model-independent absolute determinations of the Higgs boson couplings from data.

Deviations in the Higgs boson couplings to b, c, τ, g are each controlled by a single coefficient in the dim-6 Lagrangian. The couplings of W and Z have two possible independent structures:

$$\Delta L_{hWW} = 2(1+\eta_W) m_h^2 \frac{h}{v} W_\mu^+ W^{-\mu} + \zeta_W \frac{h}{v} W_{\mu\nu}^+ W^{-\mu\nu}$$

$$\Delta L_{hZZ} = (1+\eta_Z) m_h^2 \frac{h}{v} Z_\mu Z^\mu + \frac{1}{2}\zeta_Z \frac{h}{v} Z_{\mu\nu} Z^{\mu\nu}$$

So, actually, the simple extraction of the Higgs boson width presented above is not model-independent within the dimension-6 SMEFT framework.

Fortunately, this problem has a nice solution when one fits all of the e+e- data, not just the Higgs data, using the same SMEFT Lagrangian.

The dim-6 Lagrangian gives nontrivial but tractable relations between the Z and W parameters:

$$\eta_W = -\frac{1}{2} c_H \qquad \eta_Z = -\frac{1}{2} c_H - c_T$$

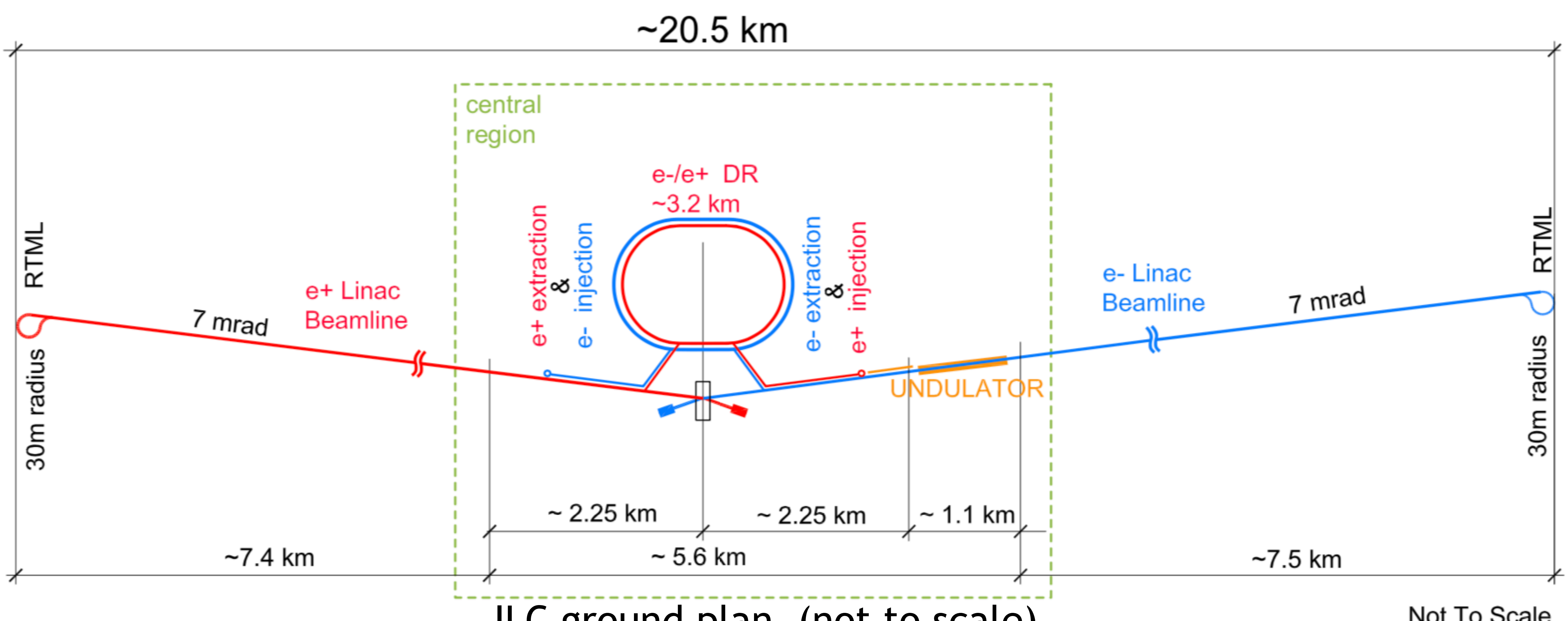
$$\zeta_W = (8 c_{WW})$$

$$\zeta_Z = c_w^2 (8 c_{WW}) + 2 s_w^2 (8 c_{WB}) + (s_w^4 / c_w^2)(8 c_{BB})$$

The parameter $\zeta_Z$ is very sensitive to the polarization asymmetry in $\sigma(e^+ e^- \to Zh)$ . This gives special power to an accelerator with beam polarization.

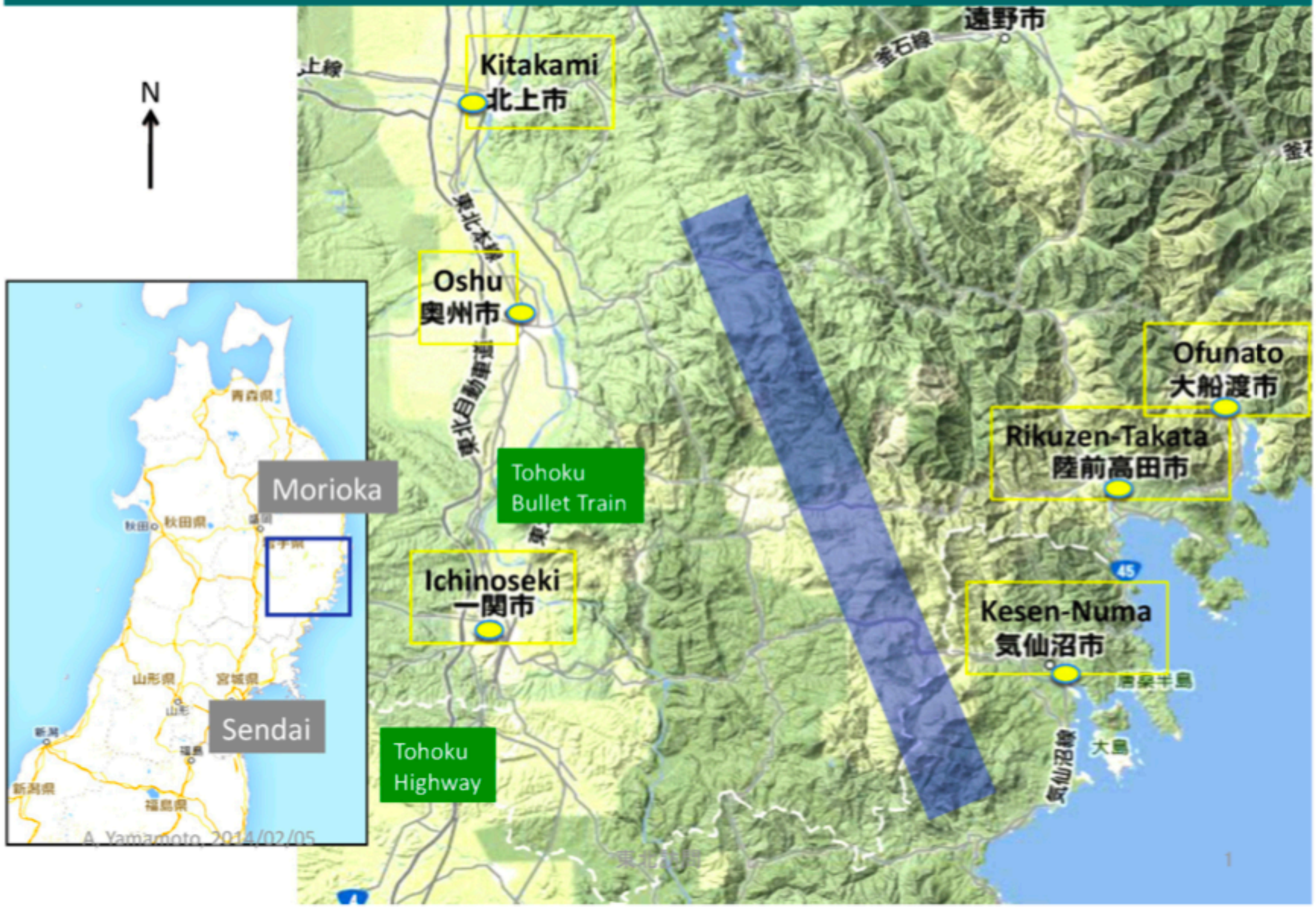
There are now a number of proposals for e+e- Higgs factories around the world: CEPC in China, FCC-ee and CLIC at CERN, ILC in Japan.

All four projects have very similar physics programs and expected reach. In the next few slides, I will show some plans and projections for ILC.

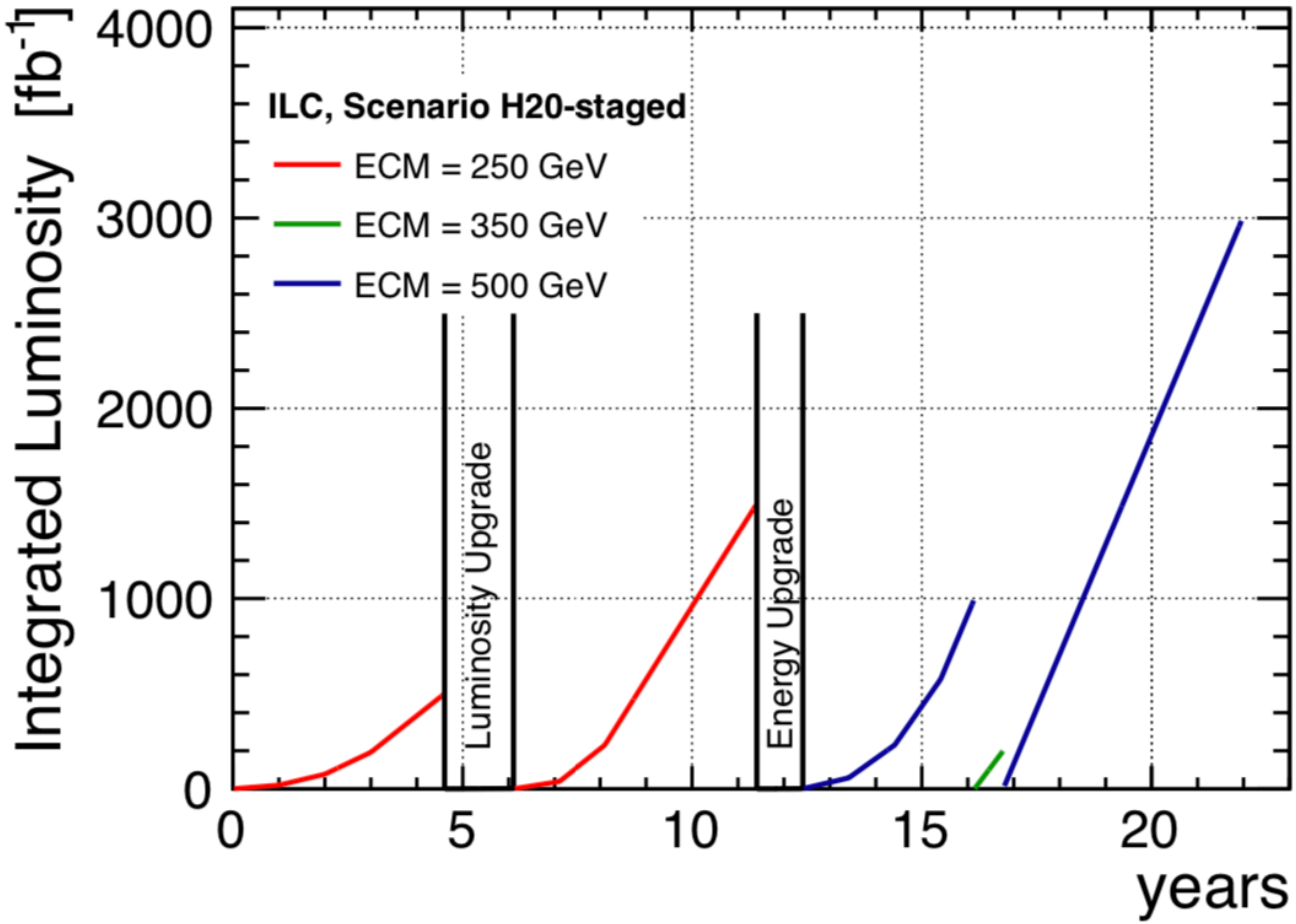



ILC ground plan (not to scale)

# ILC Candidate site in Kitakami, Tohoku



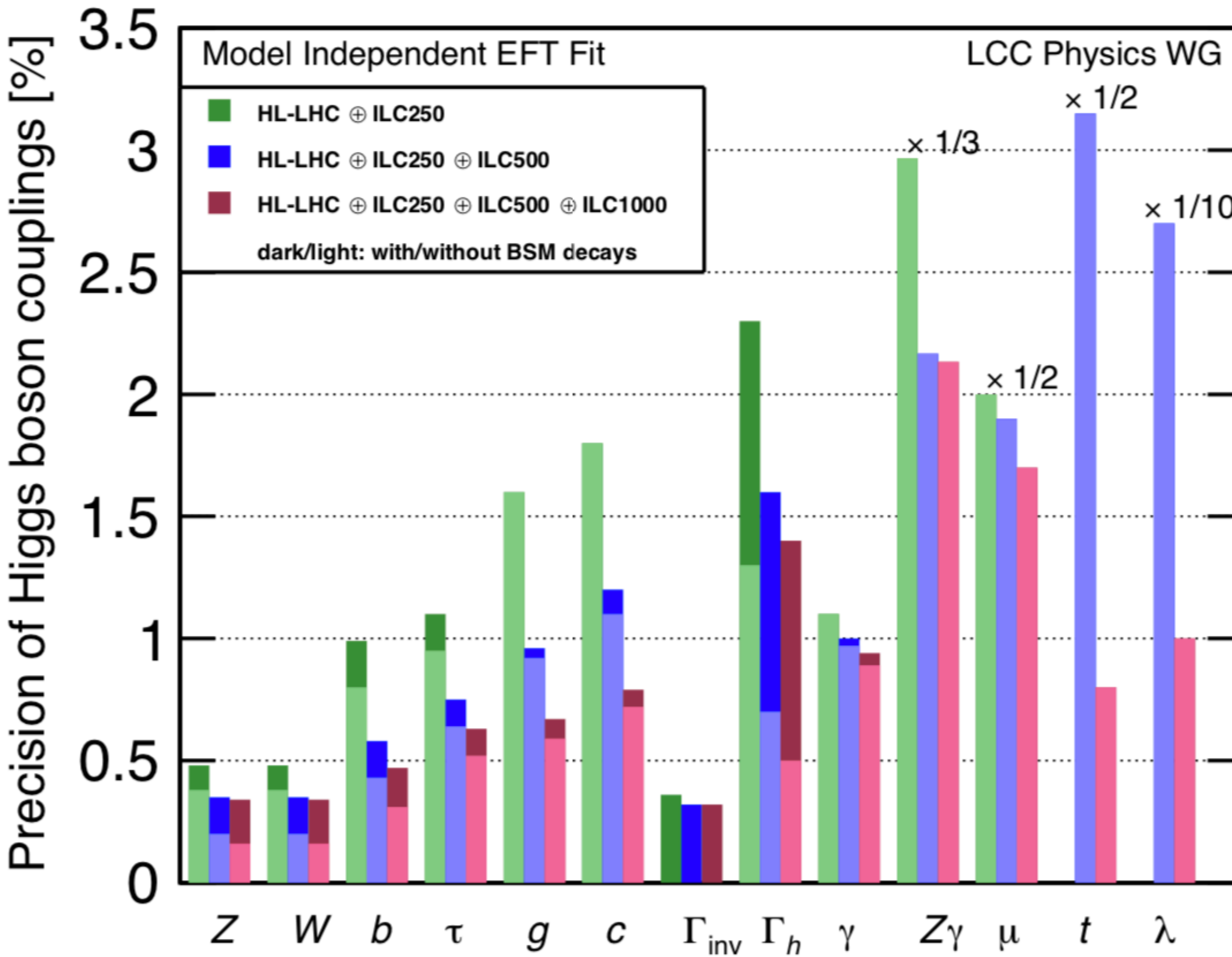
# ILC proposed run plan



total integrated luminosity at each stage:

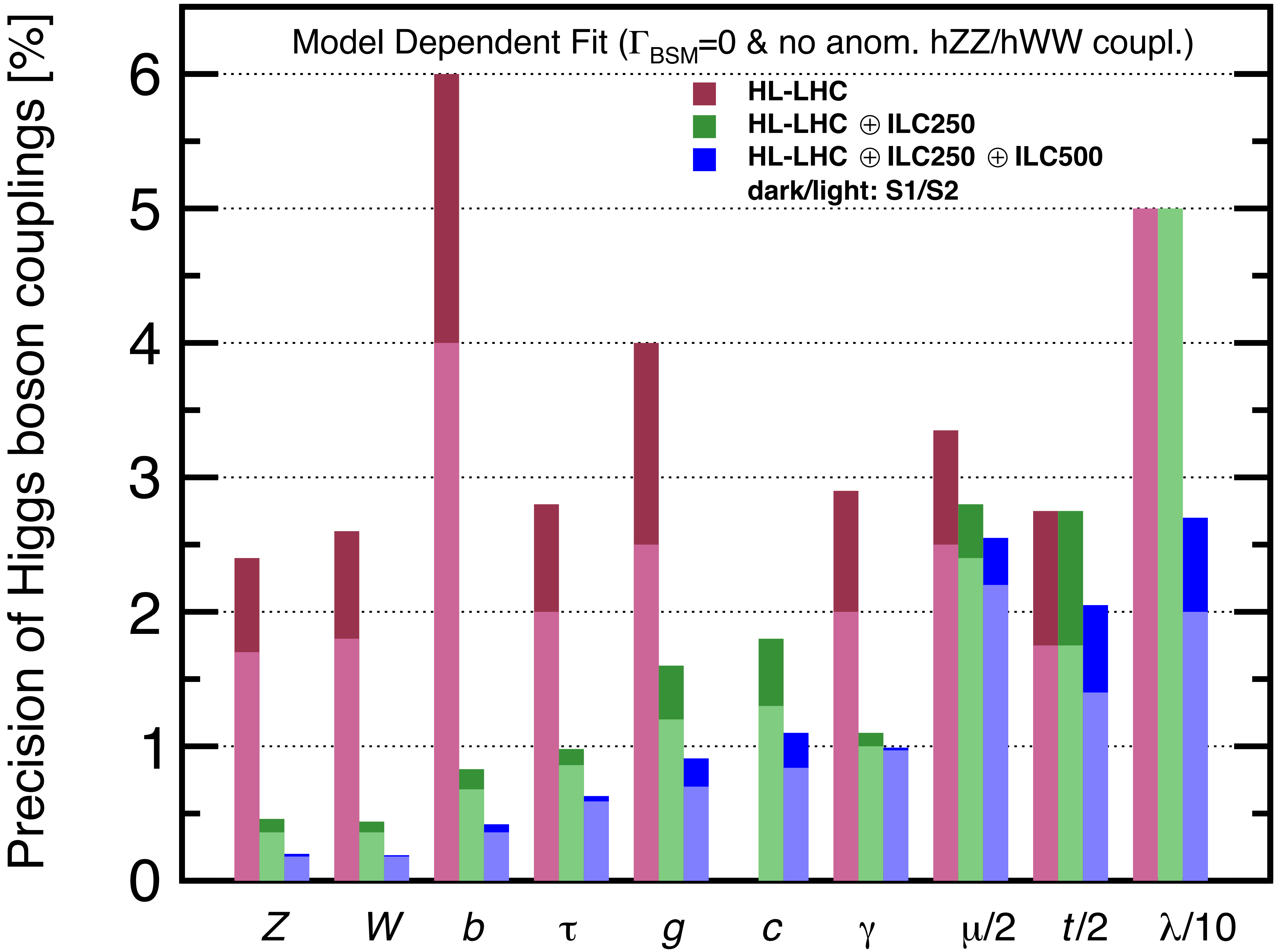
| | $E_{CM}$ (GeV) | $\int \mathcal{L}$ ($\mathrm{fb}^{-1}$) |
|---|---|---|
| ILC250 | 250 | 2000 |
| ILC350 | 350 | 200 |
| ILC500 | 500 | 4000 |
| GigaZ | 91.19 | 100 |
| ILC1000 | 1000 | 8000 |

with e- and e+ beam polarization: 80% / 30%




arXiv:1908.11299

# HL-LHC and ILC projections of Higgs coupling precision (in %) with the same model-dependent assumptions

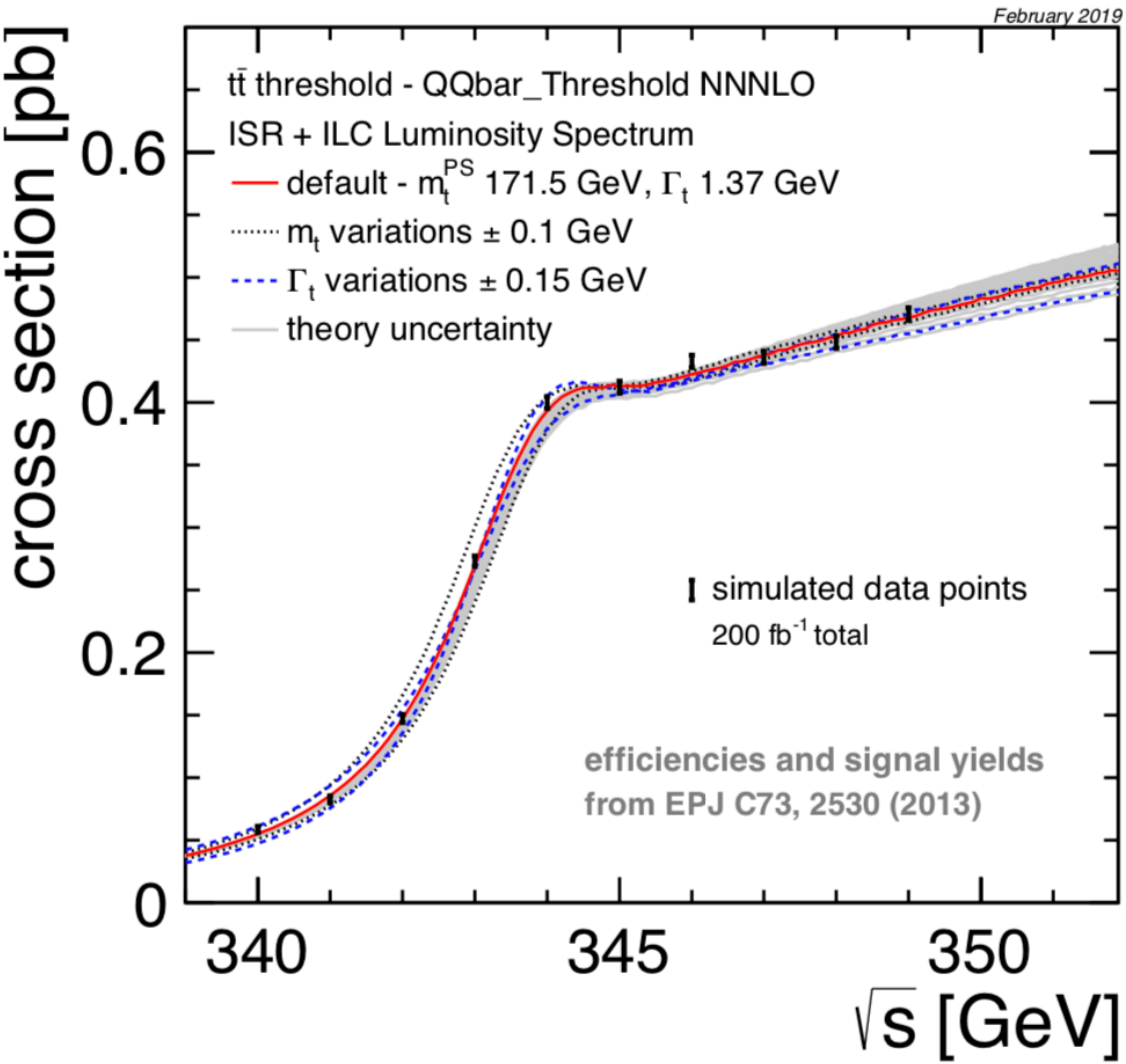



arXiv:1903.01629

At energies above 250 GeV, the precision study of the top quark becomes another important target of the ILC.

The reactions $e^+e^- \to f\overline{f}$ probe for new vector resonances in the mass range 15-20 TeV and for compositeness scales of 200-300 TeV.

Details of these studies can be found in arXiv: 1908.11299 .


February 2019
$t\bar{t}$ threshold - QQbar_Threshold NNNLO
ISR + ILC Luminosity Spectrum
default - $m_t^{PS}$ 171.5 GeV, $\Gamma_t$ 1.37 GeV
$m_t$ variations ± 0.1 GeV
$\Gamma_t$ variations ± 0.15 GeV
theory uncertainty
simulated data points
200 $fb^{-1}$ total
efficiencies and signal yields
from EPJ C73, 2530 (2013)
cross section [pb]
0.6
0.4
0.2
0
340
345
350
$\sqrt{s}$ [GeV]

Finally, I will say a little about the timeline for funding and construction of the ILC.

The ILC is an expensive project, with cost comparable to the LHC. There is interest in Japan in hosting the ILC, and in fact a site is chosen, but this will not happen without the promise of substantial funding from other parts of the world.

Last summer, the ILC International Development Team was formed to begin a gradual process toward the required international collaboration.

The schedule envisioned for this process was shown by the IDT chair Tatsuya Nakada at the October 2020 Americas Workshop on Linear Colliders:

https://agenda.linearcollider.org/event/8622/

# *Rough timeline of the ILC under discussion*

ILC IDT (~1.5 years)

- Prepare the work and deliverables of the ILC Pre-laboratory and workout with national and regional laboratories a scenario for their contributions
- Prepare a proposal for the organisation and governance of the ILC Pre-laboratory

In parallel:
Positive “signs” from the host country (Japan) government and agreements by the national/regional laboratories for providing their contributions.

ILC Pre-laboratory (~4 years) **begin: 2022**

- Complete all the technical preparation necessary to start the ILC project (infrastructure, environmental impact and accelerator facility)
- Prepare scenarios for the regional contributions to and organisation for the ILC.

In parallel:
Positive outcomes of the inter-governmental negotiation for the responsibility and cost sharing among the host (Japan) and partner countries

**begin: 2026**

ILC laboratory

- Construction and commissioning of the ILC (~10 years)
- Followed by the operation of the ILC
- Managing the scientific programme of the ILC

T. Nakada,

**first data: 2037**

T. Nakada at AWLC 2020

A proposal for the ILC Pre-Lab, including governance, tasks, and budget, is now available as

arXiv:2106.00602 [physics.acc-ph]

A specific funding proposal will be submitted by KEK this summer, and we anticipate approval in the FY 2022 Japanese budget.

ICFA, the European Strategy Report, and the US DOE and State Depts. have explicitly encouraged this process.

The Physics and Detector Organization under the IDT (and hopefully continuing under the Pre-Lab) is described at https://linearcollider.org/team/wg3 .

We are on a path now to learn from experiment about the nature of the Higgs boson and the mechanism of electroweak symmetry breaking.   These experiments have a good prospect to discover a new force of nature that plays an essential role in fundamental physics.

I strongly encourage you to learn more about this direction and to join this program.