Higgs Physics and Future Colliders

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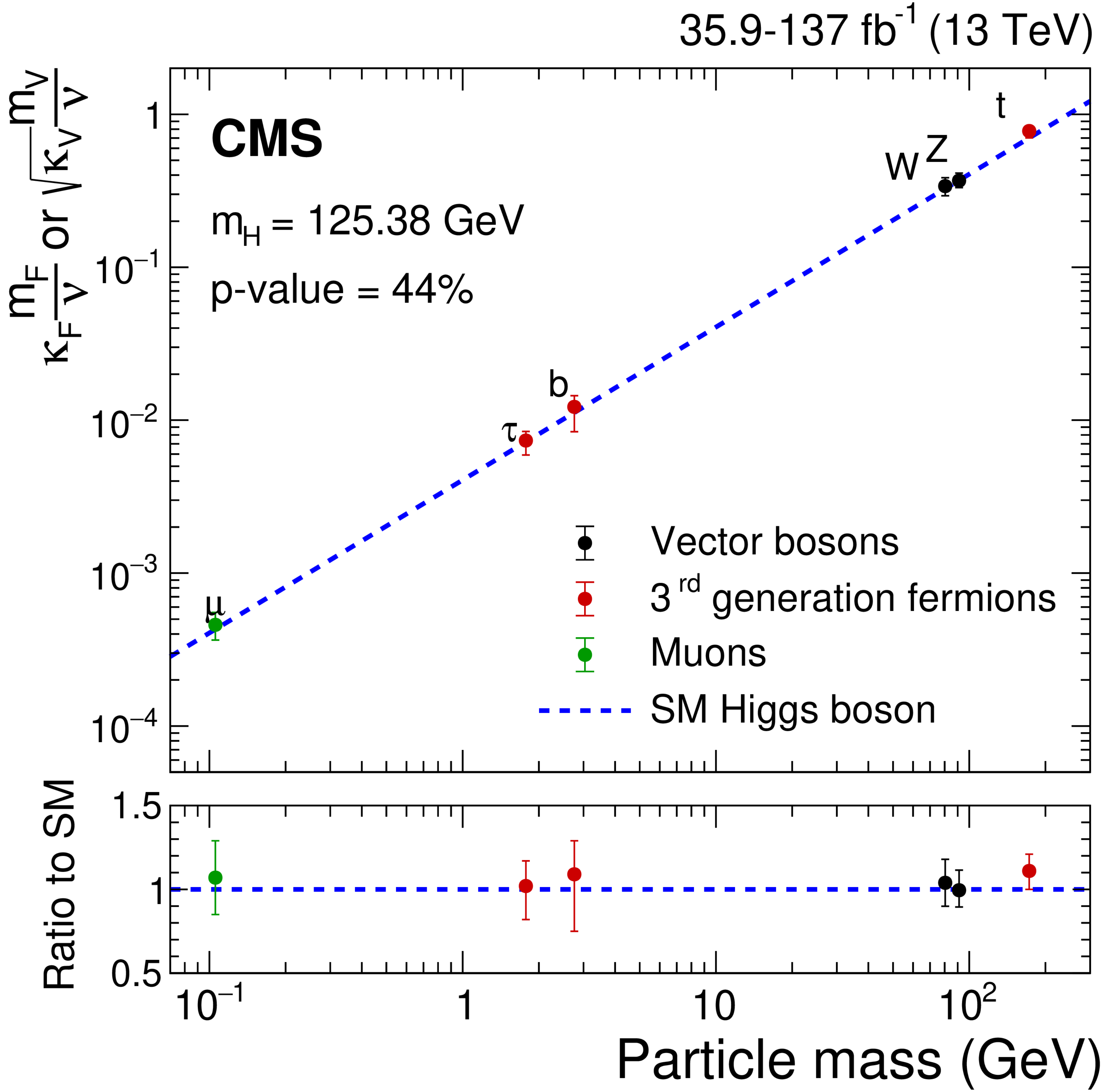
In this talk, I will highlight the next important goal of experimental particle physics
— the precision study of the Higgs boson.

Ten years ago, the Higgs boson was discovered at the CERN Large Hadron Collider. Actually, it was understood long before that this was a central element of the particle physics Standard Model.

Today, we have compelling evidence from the LHC that the Higgs boson is the source of mass at least for the heavier particles of the Standard Model — t, Z, W, b, τ .


35.9-137 fb^{-1} (13 TeV)
CMS
m_H = 125.38 GeV
p-value = 44%
$\kappa_F \frac{m_F}{v}$ or $\sqrt{\kappa_V}\frac{m_V}{v}$
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
t
W
Z
b
τ
μ
Vector bosons
3 rd generation fermions
Muons
SM Higgs boson
Ratio to SM
1.5
1
0.5
10^{-1}
1
10
10^2
Particle mass (GeV)

The Standard Model is surprisingly attractive as a final theory of elementary particles.

The Standard Model Lagrangian is the most general renormalizable Lagrangian with the gauge symmetry SU(2)xU(1) and the known particle content.   That is, writing out all of the possible terms and then simplifying with appropriate changes of variables, we can reduce any such Lagrangian to the form

$$\mathcal{L} = -\frac{1}{4}\sum_a (F^a_{\mu\nu})^2 + m_W^2 W^+_\mu W^{-\mu} + \frac{1}{2} m_Z^2 Z_\mu Z^\mu + \sum_f \overline{\Psi}_f (i\gamma \cdot D_f - m_f)\Psi_f + \frac{1}{2}(\partial_\mu h)^2 - V(h)$$

with, also, $m \to m(1 + h/v)$. This depends on there being only Higgs doublet field.

Unlike previous proposals for the theory of particle interactions (Fermi theory, chiral Lagrangians, models with no charm quark or no top quark, etc.), the Standard Model can be extended to higher energy with no clear limit (up to the Planck scale).

It is very tempting to say, “This is the theory of everything. We are done. All that remains is to stress-test the theory with higher precision measurements.”

I would like to persuade you not to accept this point of view.

The Standard Model is very good at parametrizing the physics we see.

It is very poor at explaining why.

Why do the quarks and leptons have the masses we see ?

Why is CP violated ?

Why is there mass at all ? Why is the gauge symmetry broken ?

The SM does not explain the why of Higgs symmetry breaking, a major phase transition in the early universe.

Many theorists are happy with the statement, “We postulate a scalar field and assume that its potential has a minimum away from $\Phi = 0$.”

This ignores many examples from condensed matter physics in which the presence of a broken symmetry state has a beautiful physics explanation:

magnetism, superconductivity, liquid crystals, …

If SU(2)xU(1) symmetry breaking has such an explanation, it must depend on new particles and forces outside the SM. We have the opportunity to find those new particles and forces, if only we don’t give up.

The example of superconductivity is particularly close to that of the SM.

The Landau-Ginzburg theory postulates a complex scalar field that exists inside a metal. This field acquires a thermodynamic nonzero expectation value. From that description, with only a few parameters, we explain:

the thermodynamics of the phase transition
the critical current
the Meissner effect
the Abrikosov vortex state (superconducting magnets)
the presence of Type I and Type II superconductors

However, this was a purely phenomenological description. To answer the why question, took further insights by Bardeen, Cooper, and Schrieffer.

The Standard Model is a similar “phenomenological effective theory”. We don’t know what lies behind it.

How is the low-energy Higgs field related to more fundamental Higgs fields ?

Is it one of large multiplet of scalar fields ?

Is it a mixture of fields (maybe one for each generation) ?

Is it a composite of more fundamental scalars, fermions, or superpartners ?

Is it a component of a gauge field, in universe with small extra dimensions ?

We need to answer these questions to address all other open question of particle physics.

How can we understand how the Higgs field couples to fermions, to explain the mass spectrum and CP violation, before we know what this Higgs is made of ?

Dark matter may not be a manifestation of the Higgs sector, but it is in many models.   SUSY Higgsinos and axions are compelling dark matter candidates.

According to SU(2)xU(1), neutrinos ultimately get their masses from the Higgs boson. So even here, we cannot escape the Higgs field's mysteries.

How can we address these questions experimentally ?

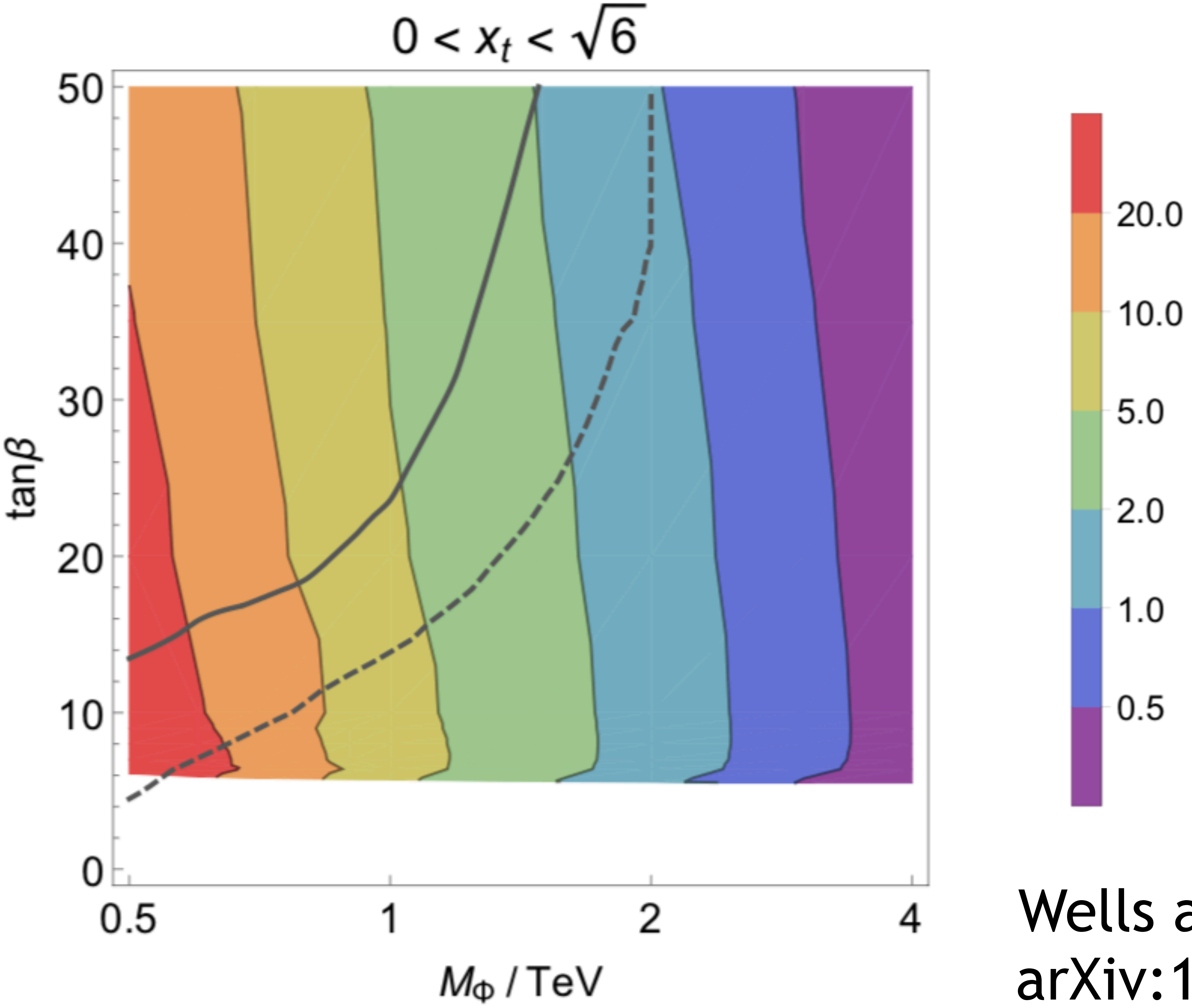
One way is to discover the new heavy particles.

This was the goal of the LHC. There is still an opportunity. Especially, if these new particles have only electroweak couplings, the HL-LHC will extend the reach in mass by almost a factor of 2.

Here, I will stress another probe, the precision study of the Higgs boson. This method has a similar reach in mass. But it is not competing, it is complementary. The models that have accessible new particles and those with large SM corrections are, in general, distinct.

Thus, precision measurements open a new window that we have not looked through yet.

worked example: grand-unified SUSY



$(\kappa_b - 1)$
in %

Wells and Zhang,
arXiv:1711.04774

Over the course of the High-Luminosity LHC, it is projected that we will measure the couplings of the Higgs boson more precisely,

for b quarks, to 4%, for W, Z, to 2%.

Unfortunately, this is not good enough.

The details of the coupling of the Higgs boson to beyond-Standard Model particles are hidden from us by the Standard Model’s special structure.

Because the Standard Model is the most general model with the known particle content and only dimension 4 operators, deviations from the Standard Model due to new particles of mass M — in particular, deviations in the Higgs boson couplings — are parametrically of order

$$v^2/M^2$$

Further, we need to prove that these deviations are real. This requires

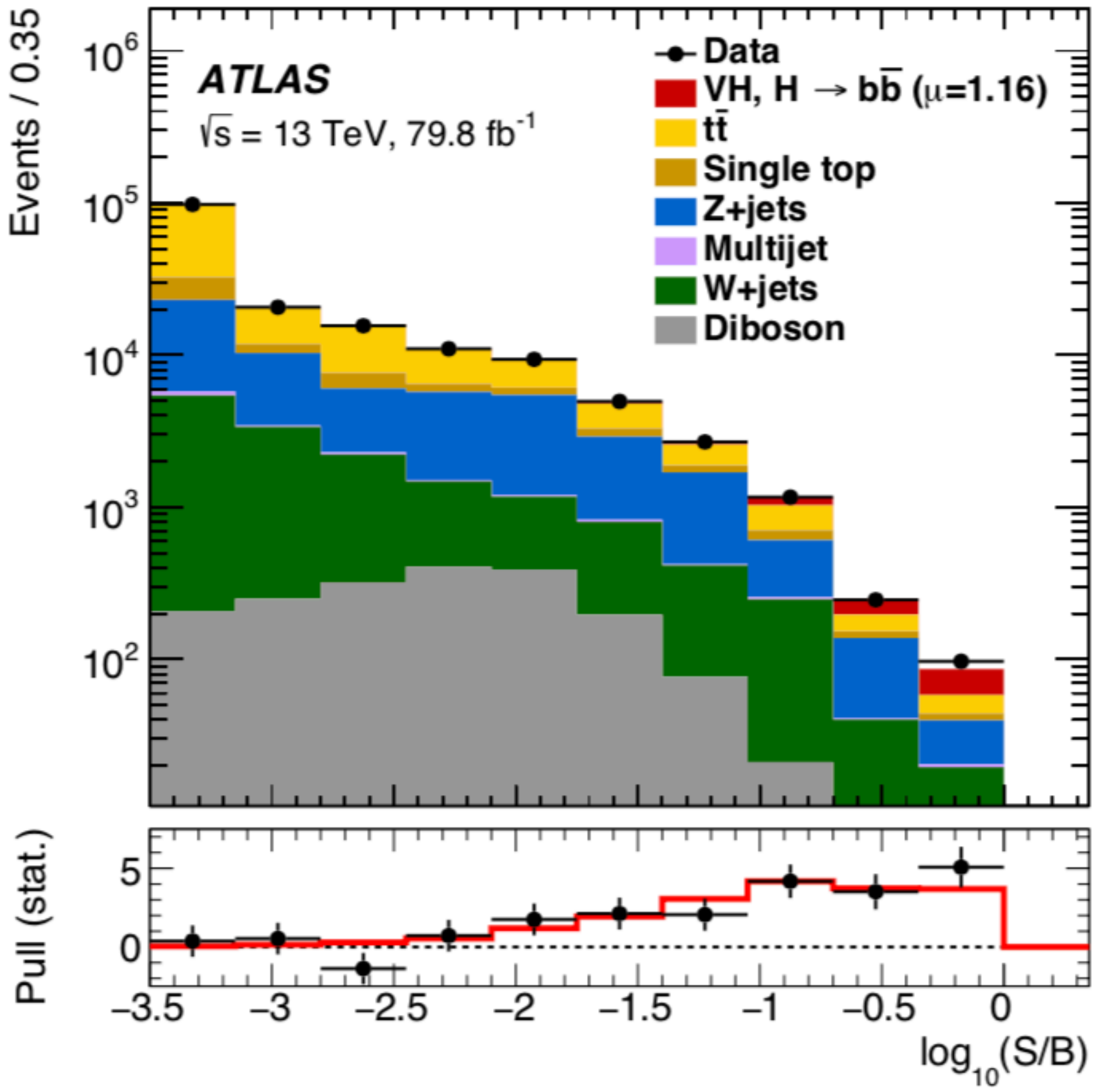
statistical significance of 5 σ or more
control of systematic errors to a still lower level

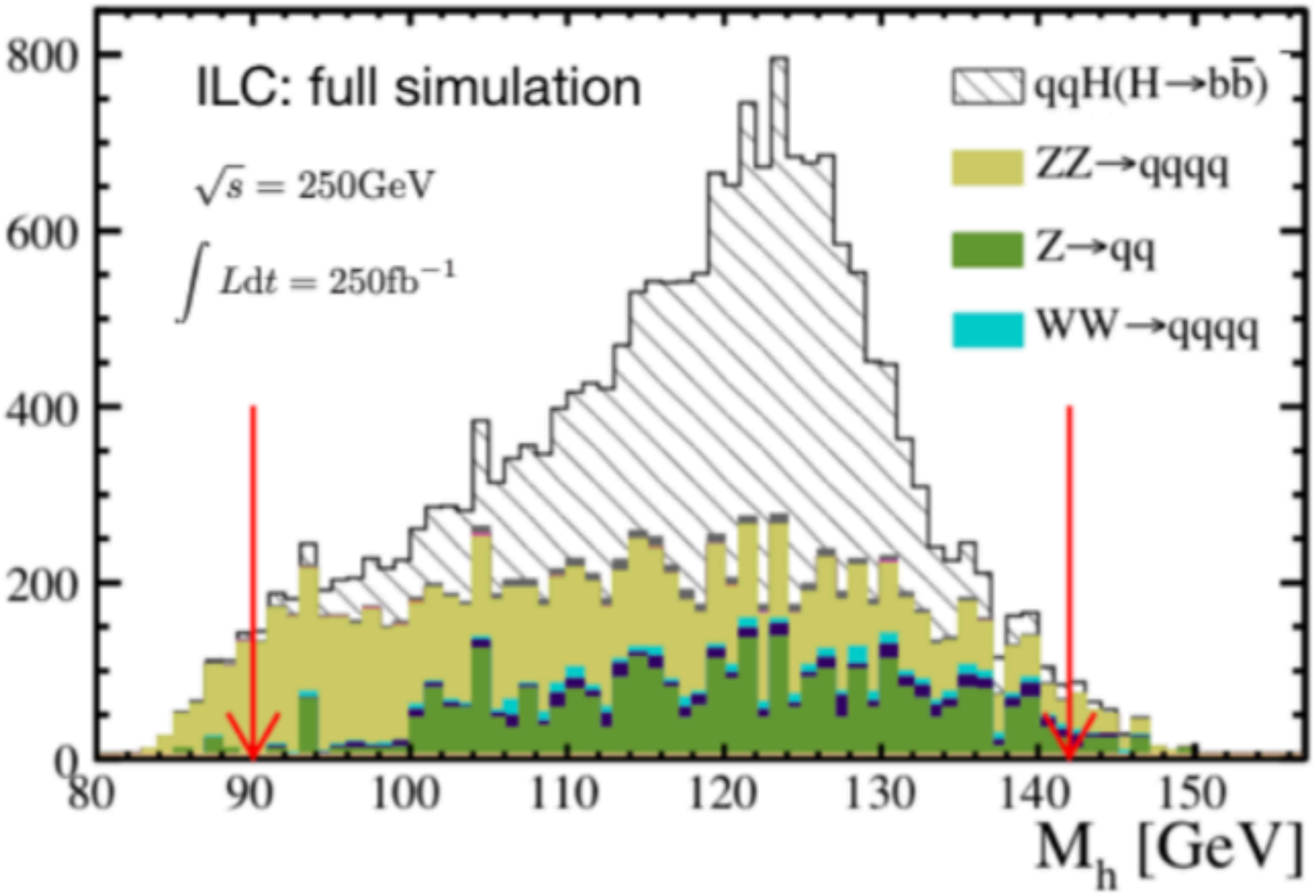
These requirements call for measurement of the Higgs boson properties at an e+e- collider.

much lower and computable backgrounds
very low material tracking, much simpler calorimetry
very high efficiency for b, c quark tagging

General reference on e+e- Higgs factory physics:
ILC Report to Snowmass 2021: arXiv:2203.07622

measurement of $h \to b\bar{b}$





(1/8 of the ILC data set at 250 GeV)

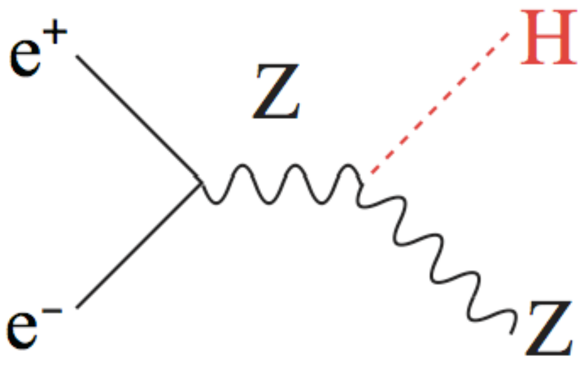
There are multiple proposals for new e+e- colliders that can access the Higgs physics.

There are differences among these — especially between linear and circular colliders — but the similarities in the experimental programs are greater.

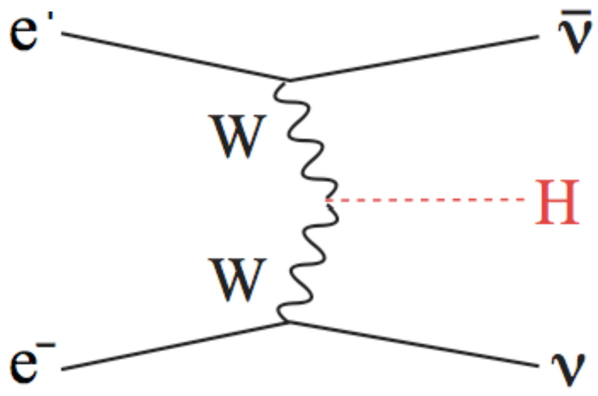
So, I will discuss the experimentation and extraction of Higgs boson couplings and then compare the various proposed facilities.

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

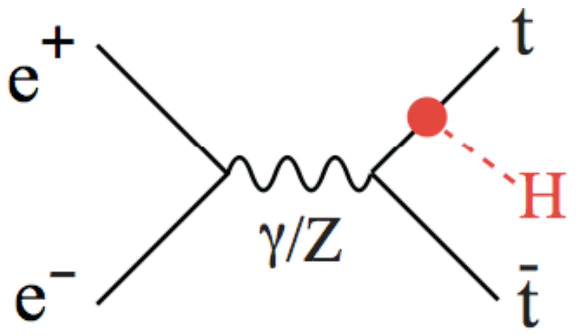
Higgsstrahlung



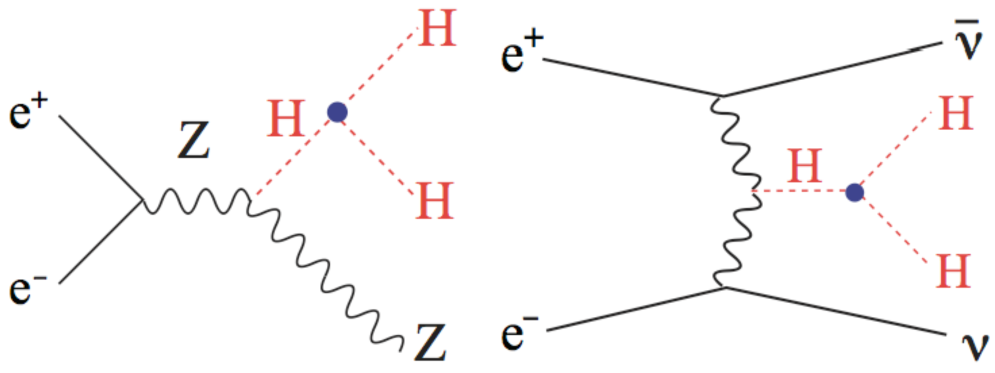
vector boson fusion

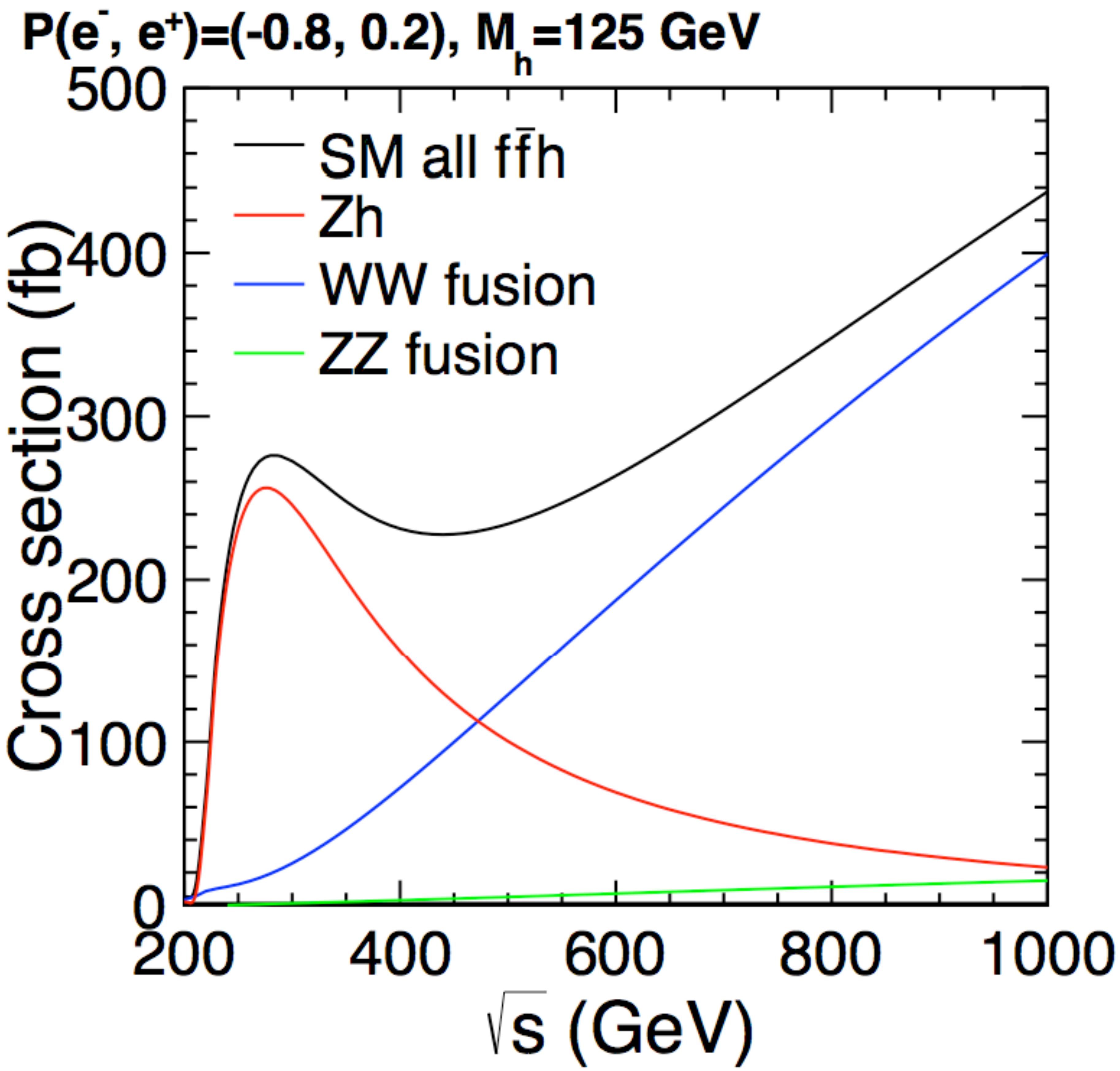


associated production with top



Higgs pair production




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

First energy stage: 240-250 GeV

Higgs production dominated by the Higgsstrahlung process

Higgs bosons are tagged by the recoil Z boson at a lab energy of 110 GeV. This allows:

direct measurement of Higgs boson branching ratios

searches for invisible, partially invisible, and other exotic Higgs final states

measurement of $\sigma(e^+e^- \to hZ)$ independently of the Higgs boson final state. This allows determination of the absolute normalization of Higgs partial widths.

measurement of the Higgs boson mass in recoil

Second energy stage: 360 - 600 GeV

Higgs production dominated by the WW fusion process

This is gives an independent data set that can confirm anomalies found at the first stage.

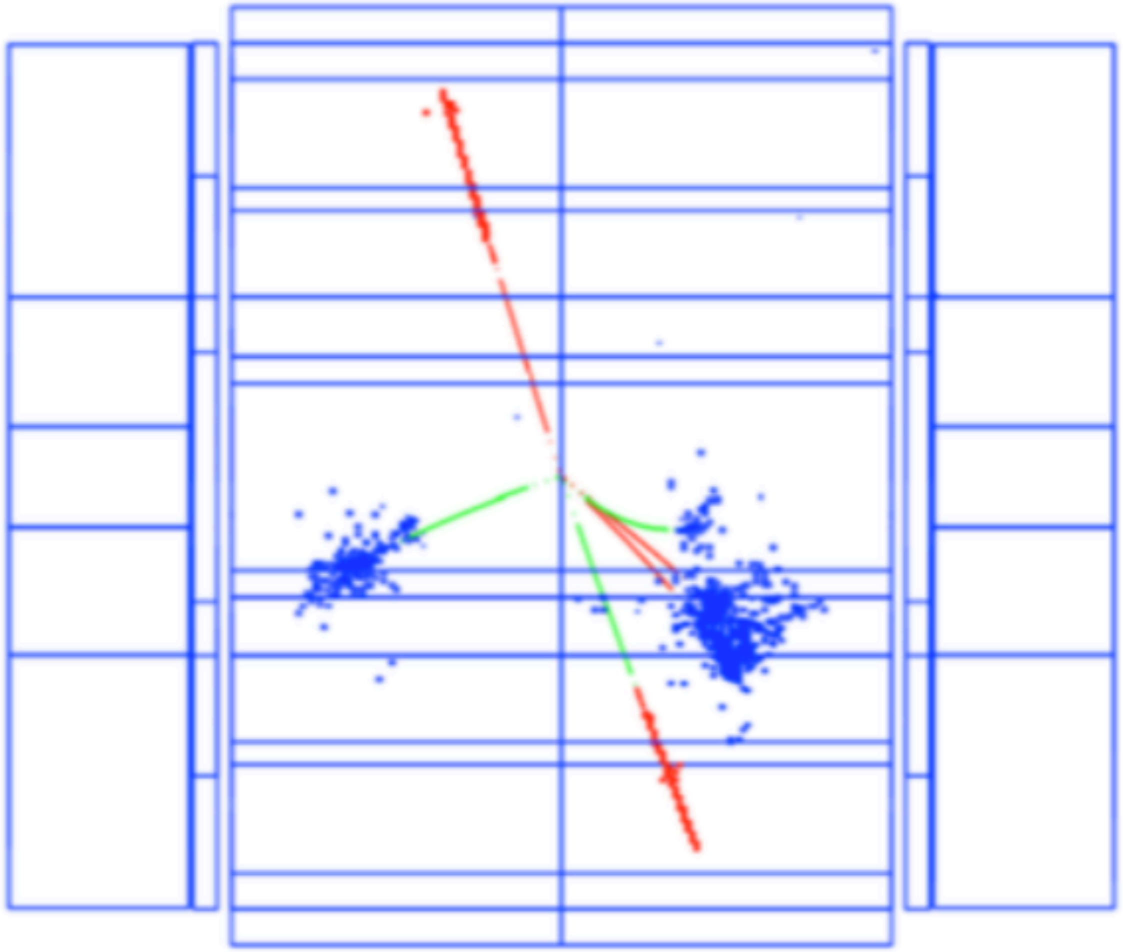
Additional and complementary Higgs measurements:

top-Higgs coupling: $e^+e^- \to t\bar{t}h$

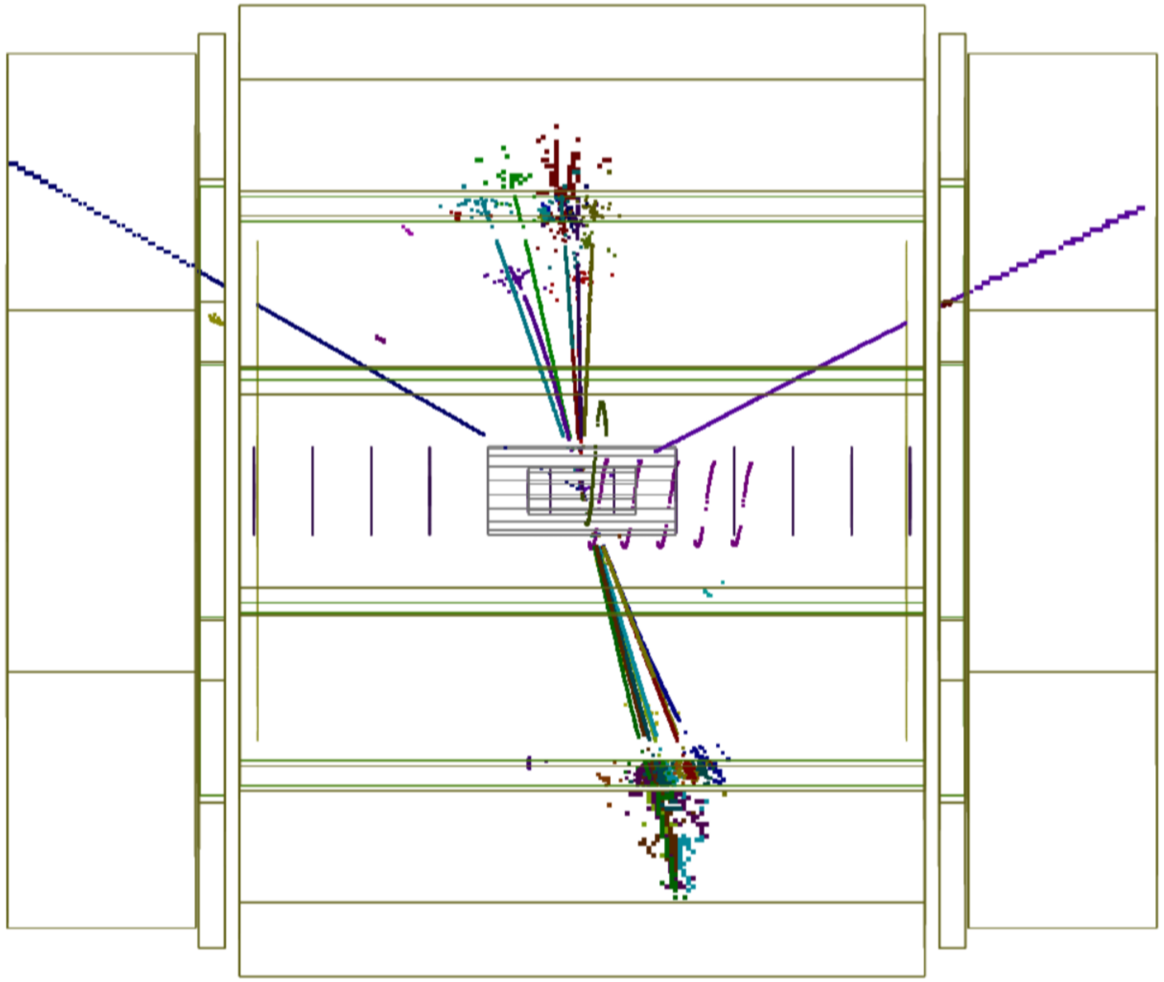
Higgs self-coupling: $e^+e^- \to Zhh$

precision measurement of top quark electroweak form factors in $e^+e^- \to t\bar{t}$

ILD simulation of $e^+e^- \to Zh\ ,\ Z \to \mu^+\mu^-$



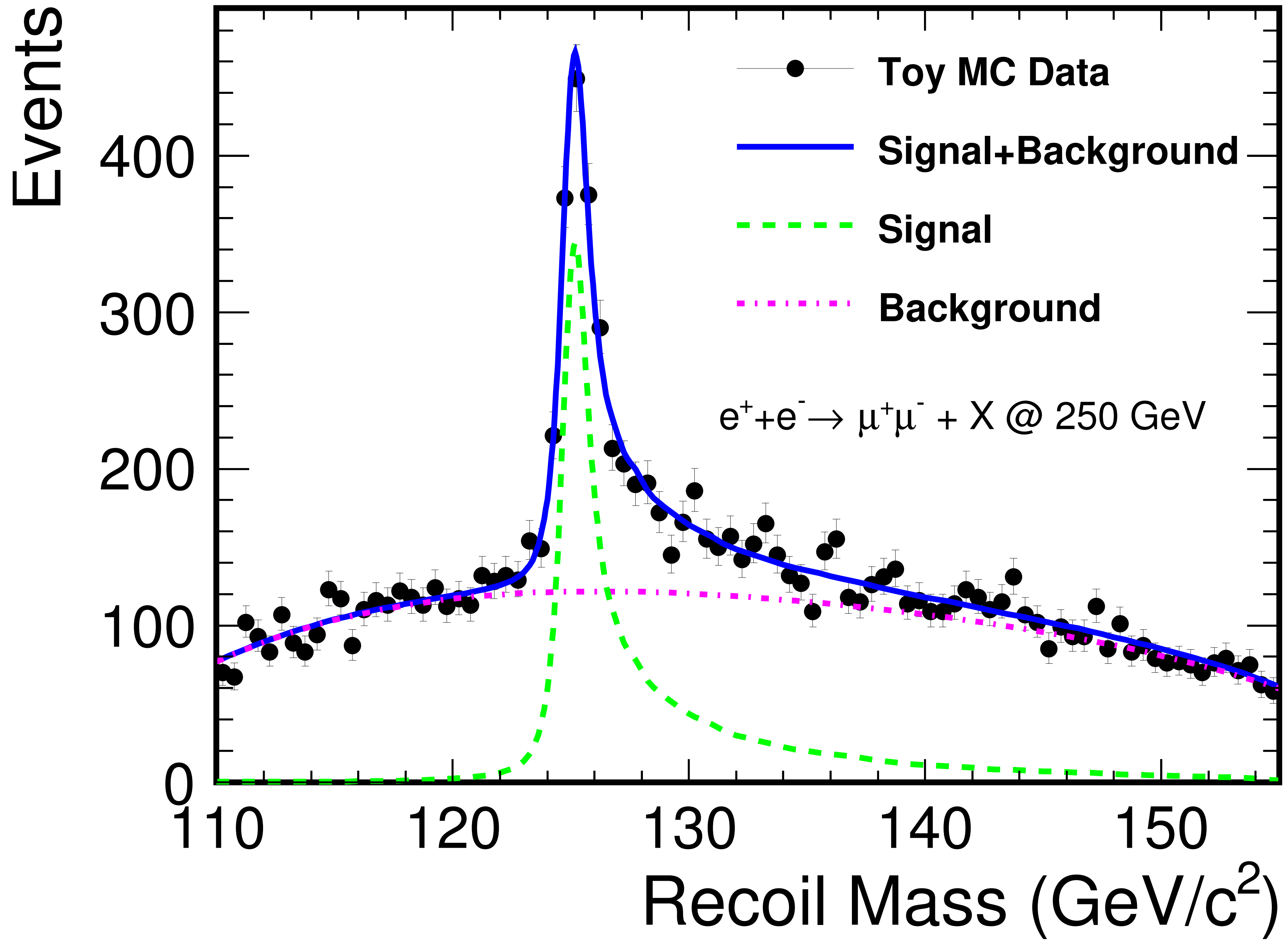
$h \to \tau^+\tau^-$



$h \to b\bar{b}$

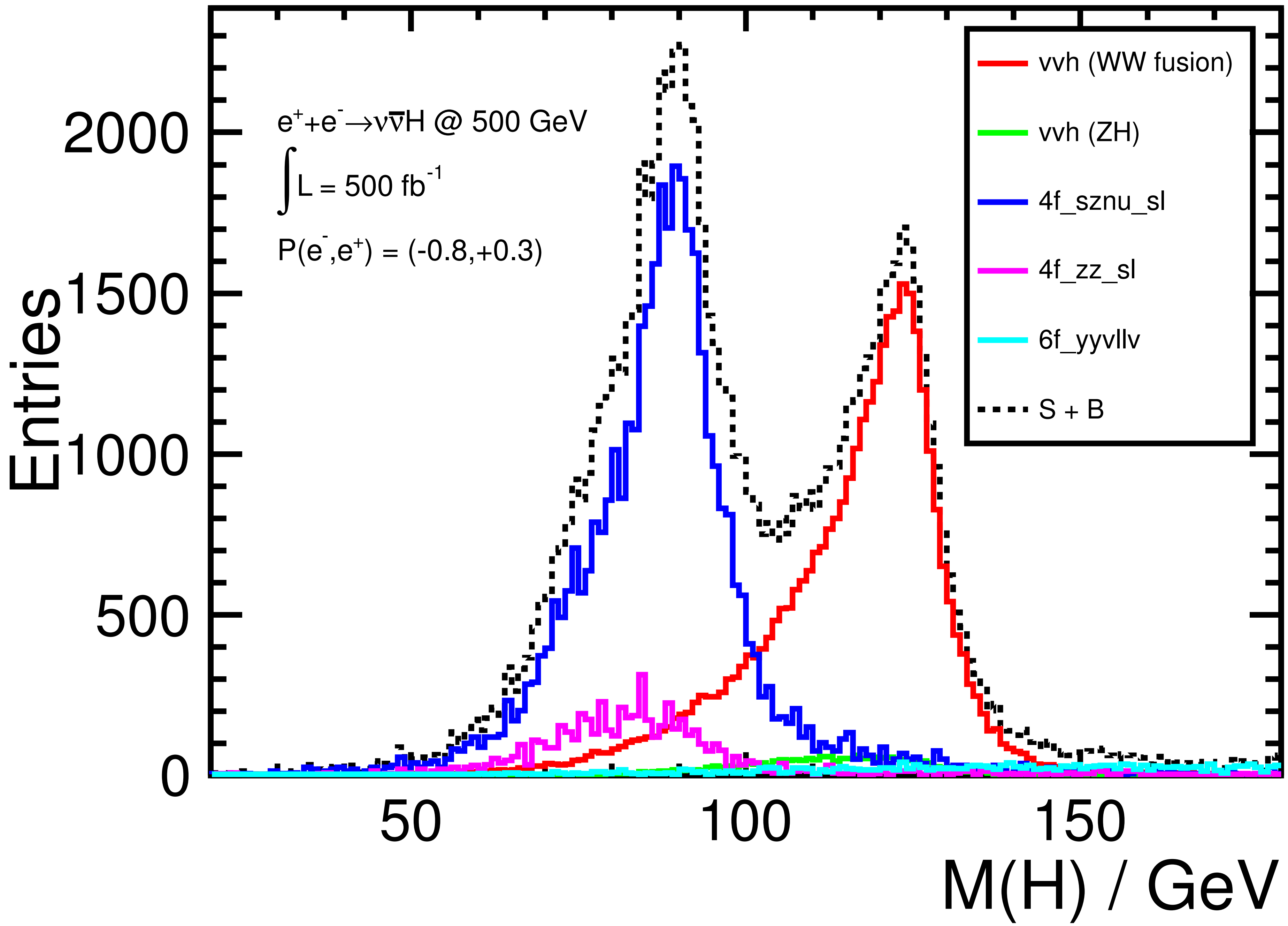
(thanks to M. Ruan)

measurement of the Higgs boson mass by the recoil technique (σ = 15 MeV)

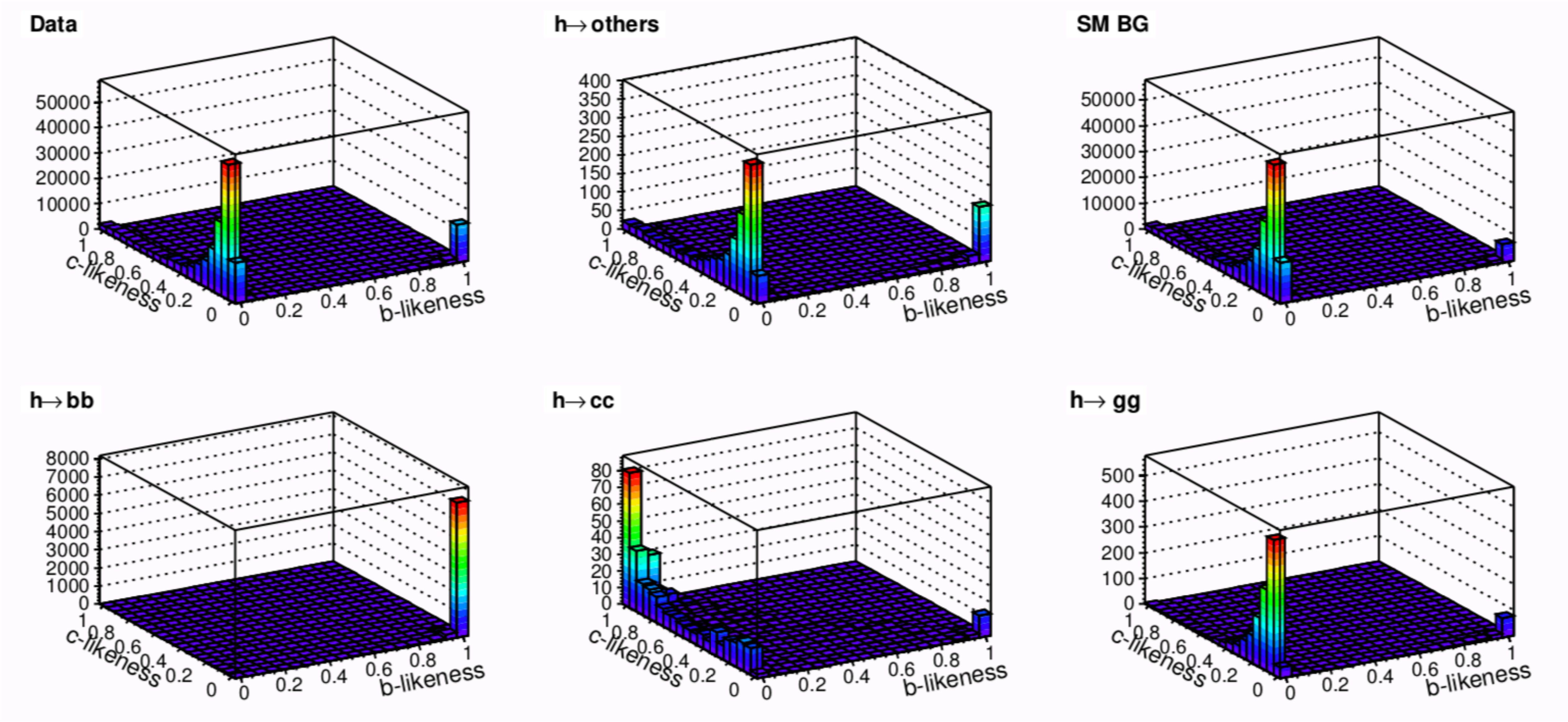


arXiv:1903.01629

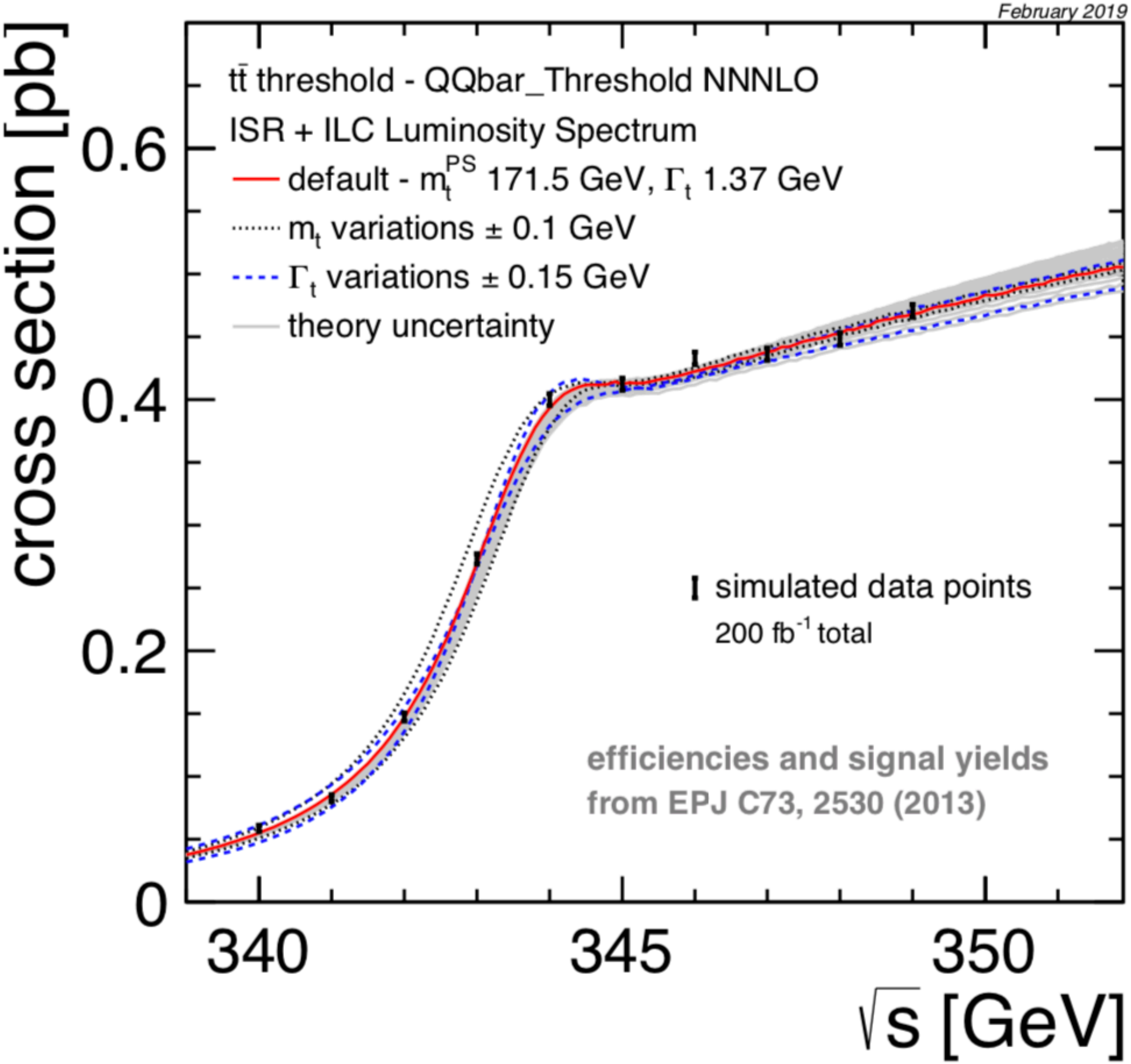
$$e^+e^- \rightarrow \nu\overline{\nu} + b\overline{b}$$



arXiv:1903.01629



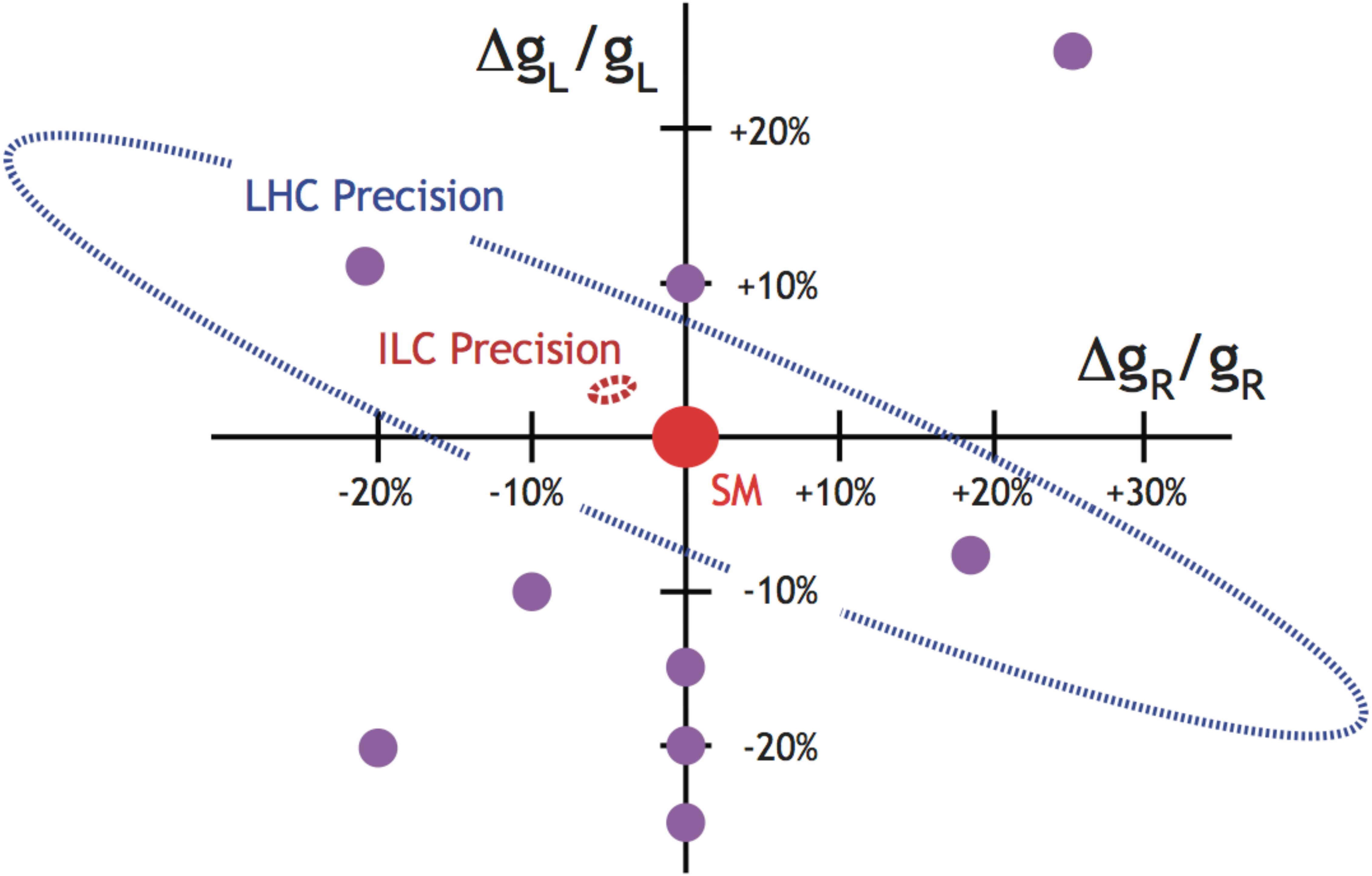
discrimination of hadronic Higgs decays - ILD simulation



February 2019

efficiencies and signal yields from EPJ C73, 2530 (2013)

LHC and ILC opportunities to measure the t_L and t_R form factors for coupling to the Z:



arXiv:1506.05992

The Higgs boson measurements can be combined most powerfully by 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.

The coefficients of all dimension-6 operators entering the Higgs factory processes at tree level can be determined independently.

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:

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

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

We need additional information to separate these contributions.

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. Both precision electroweak and $e^+e^- \to W^+W^-$ are used.

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

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

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

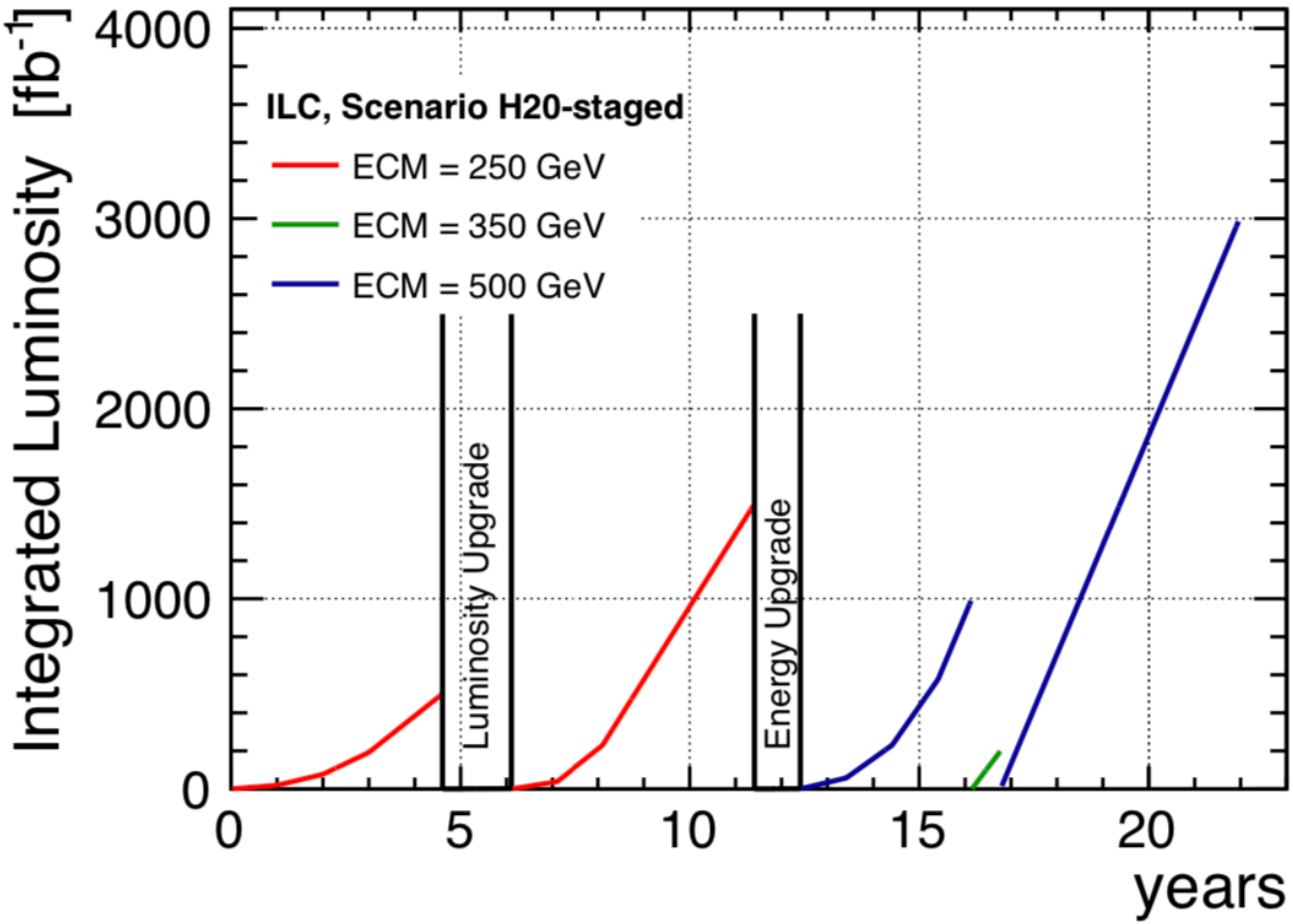
The parameter ζ_Z is very sensitive to the polarization asymmetry in $\sigma(e^+e^- \to Zh)$. This gives special power to an accelerator with beam polarization.

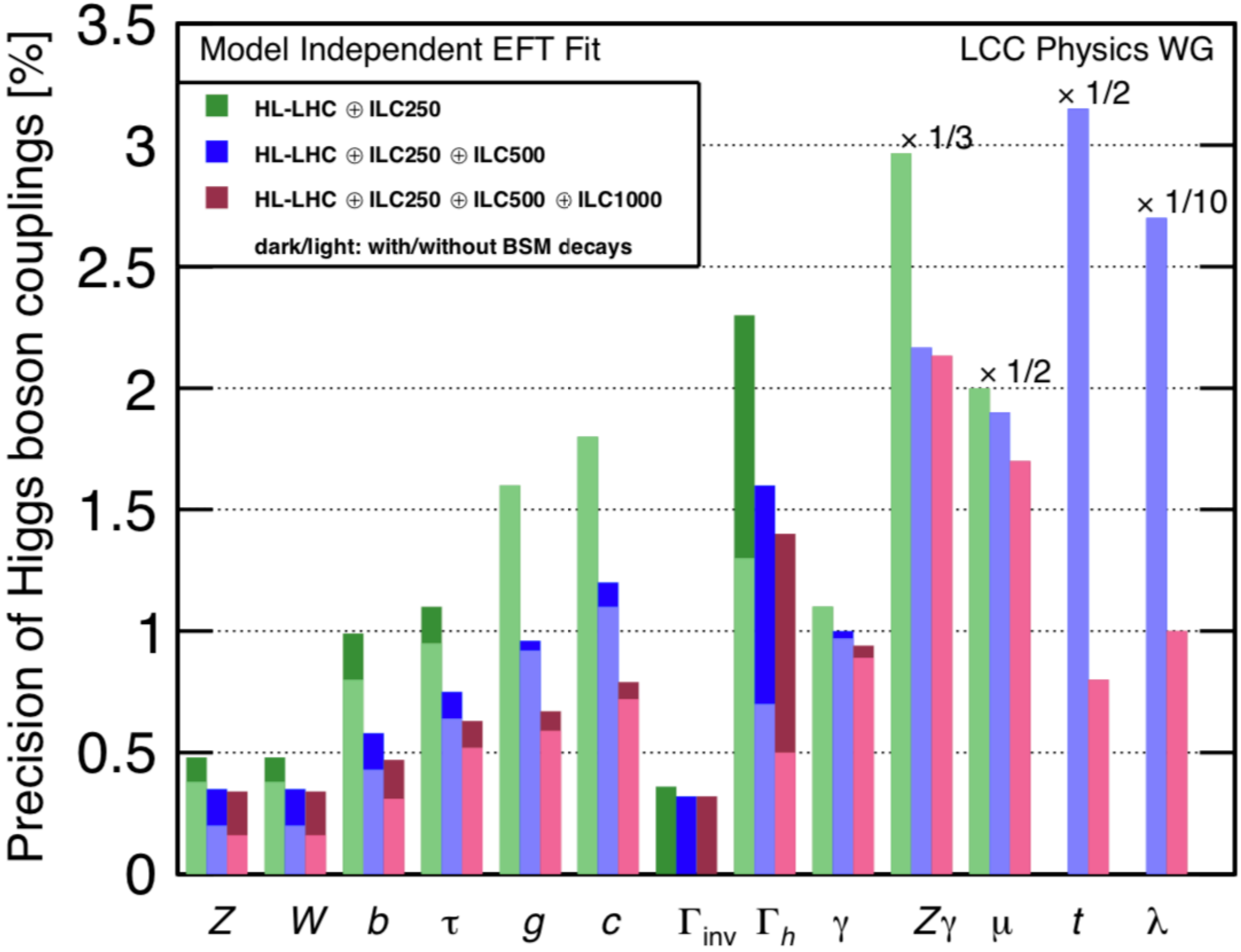
Higgs factories promise improvements in our knowledge of these auxiliary processes.

At a polarized e+e- Higgs factory, the study of radiative return to the Z at 250 GeV, $e^+e^- \to Z\gamma$, is expected to improve the current precision in $\sin^2\theta_w$ by a factor 8.

Dedicated runs at the Z resonance
  linear colliders: 5×10^9 polarized Z’s
  circular colliders: 5×10^{12} unpolarized Z’s
can lead to further improvements.

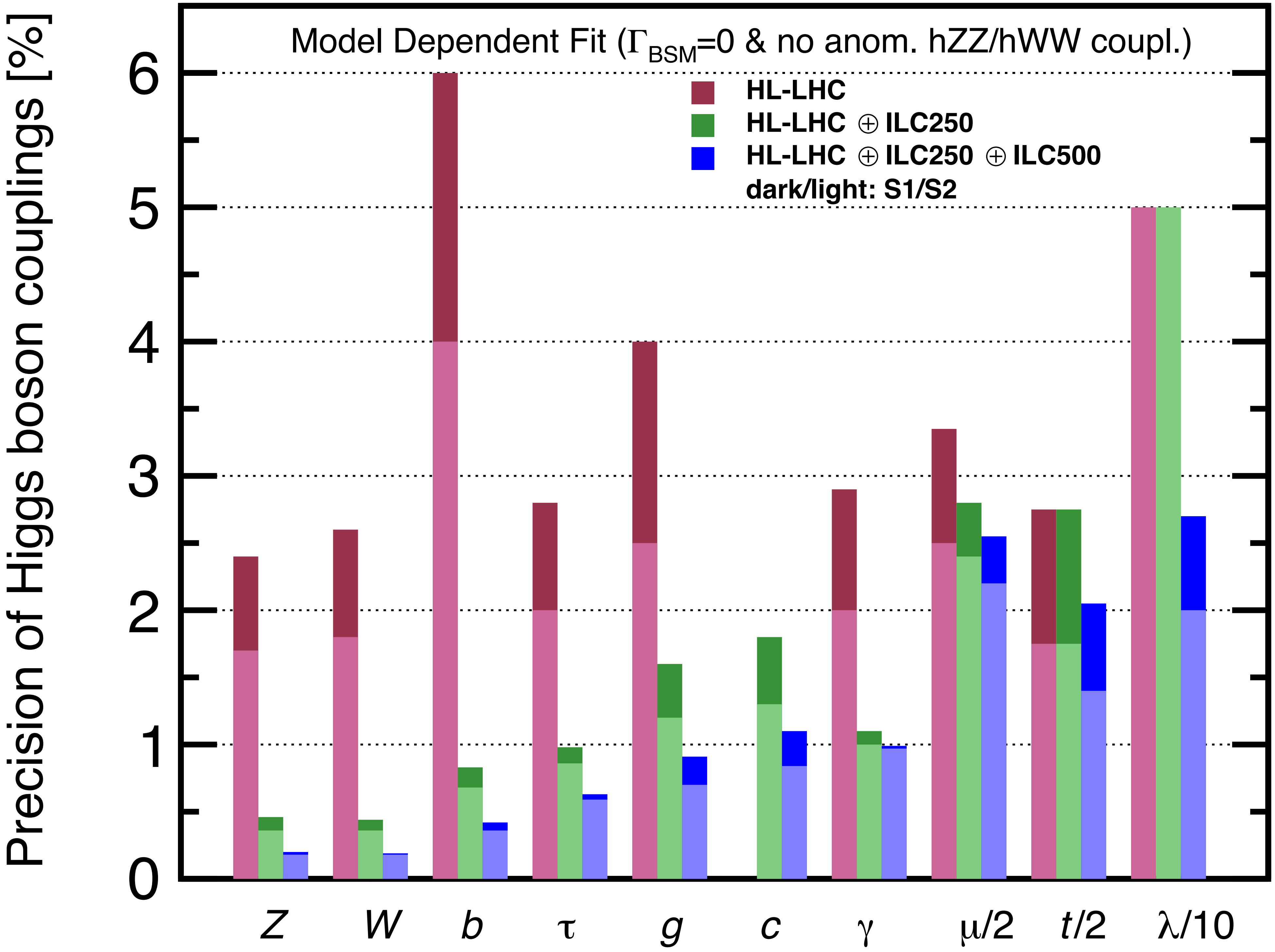
ILC proposed run plan





arXiv:1908.11299

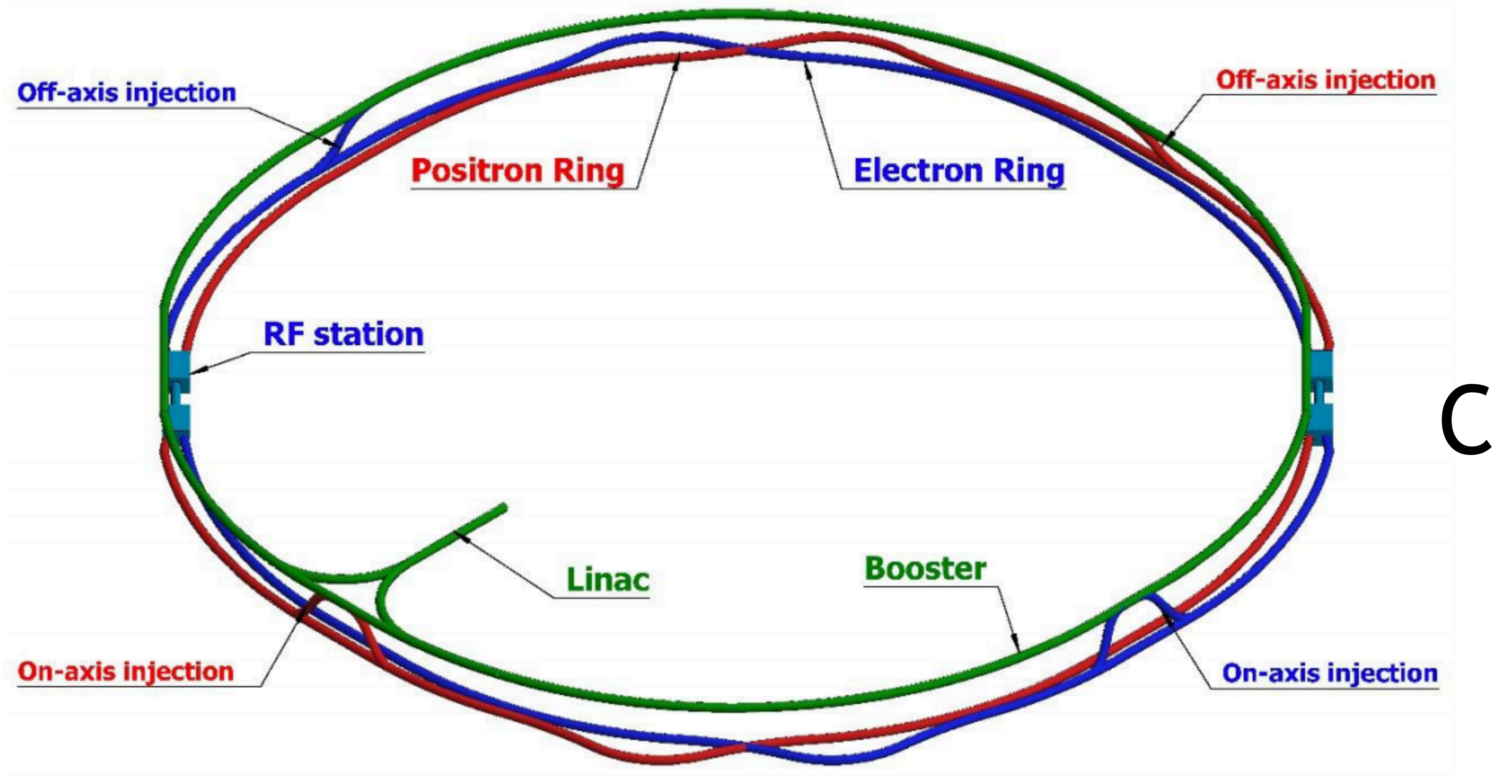
HL-LHC and ILC projections of Higgs coupling precision (in %) with the same model-dependent assumptions



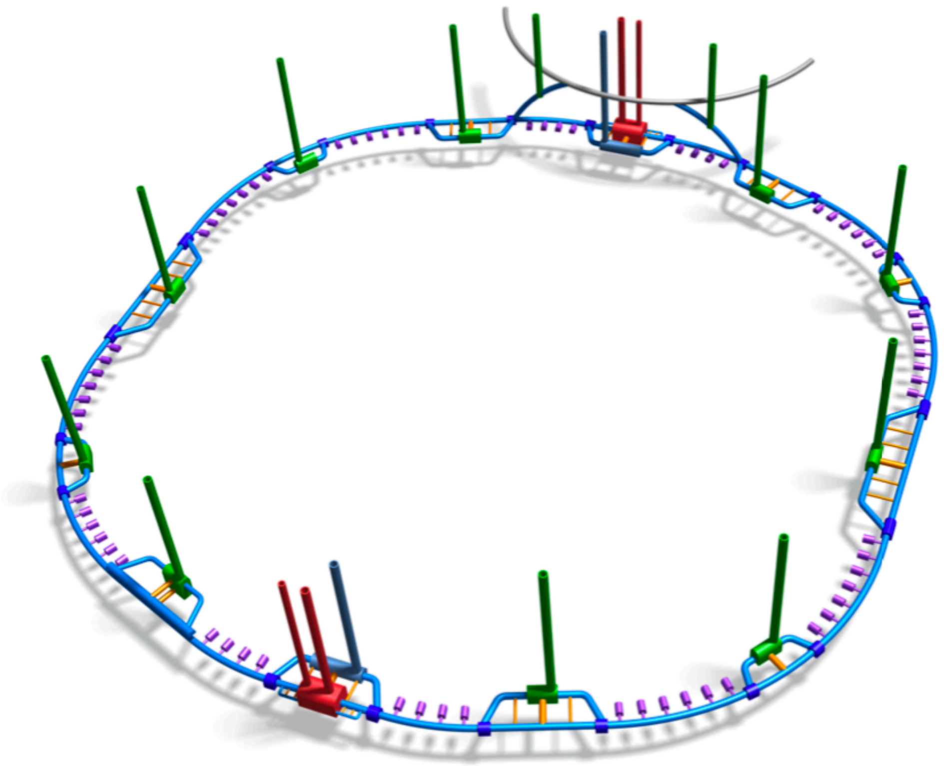
arXiv:1903.01629

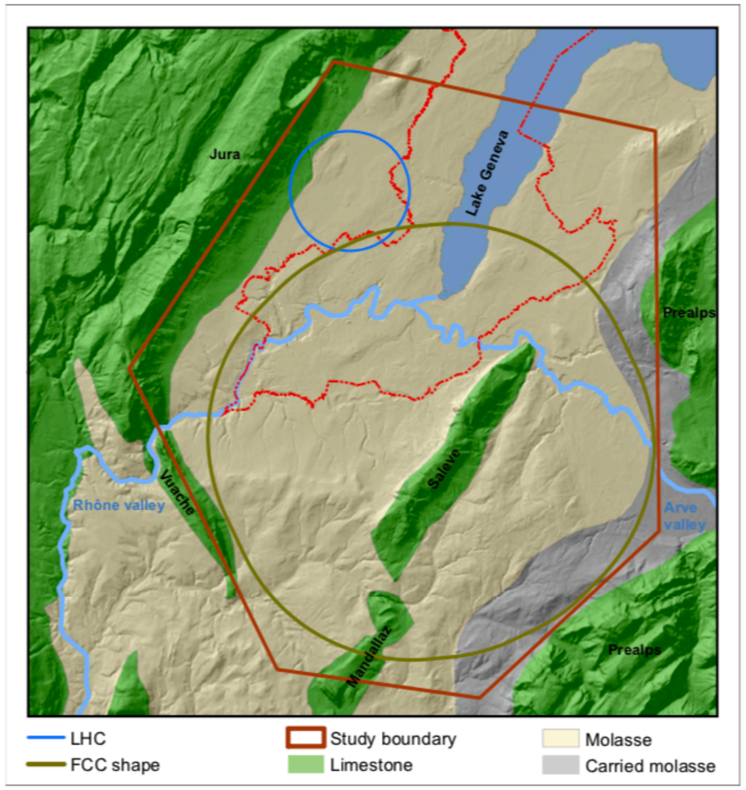
Now discuss the various Higgs factor proposals:

circular colliders



CEPC

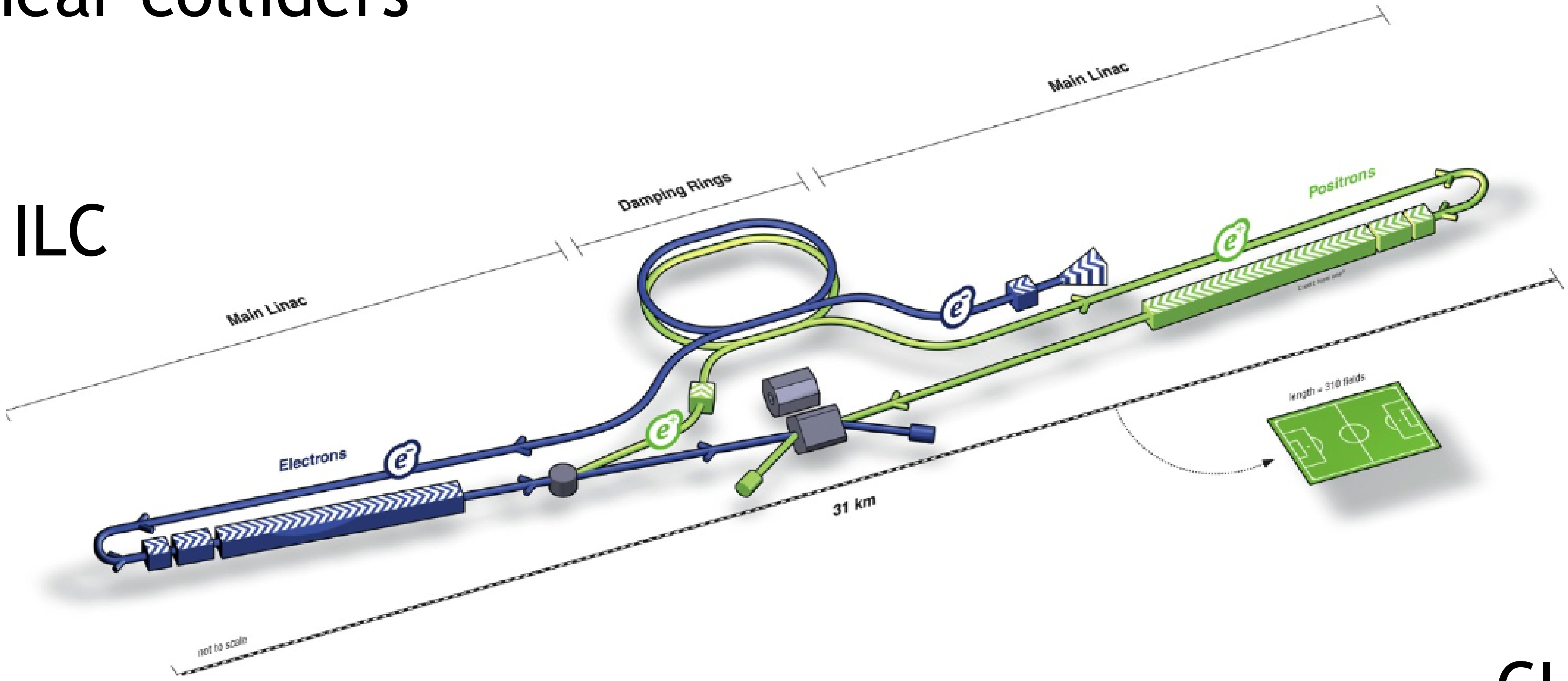


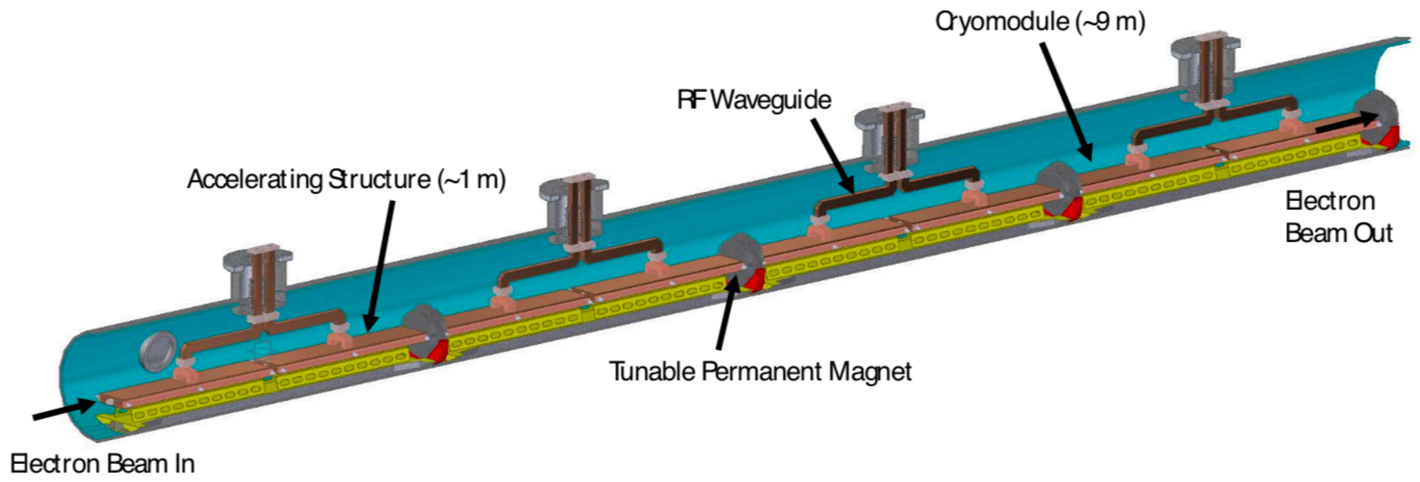


FCC-ee

Linear colliders

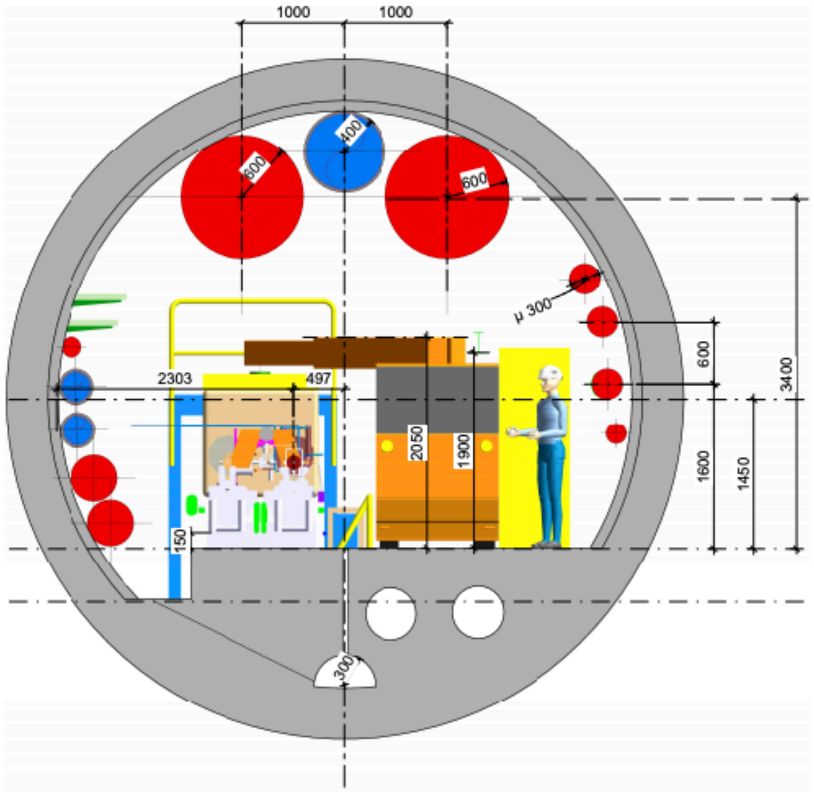
ILC



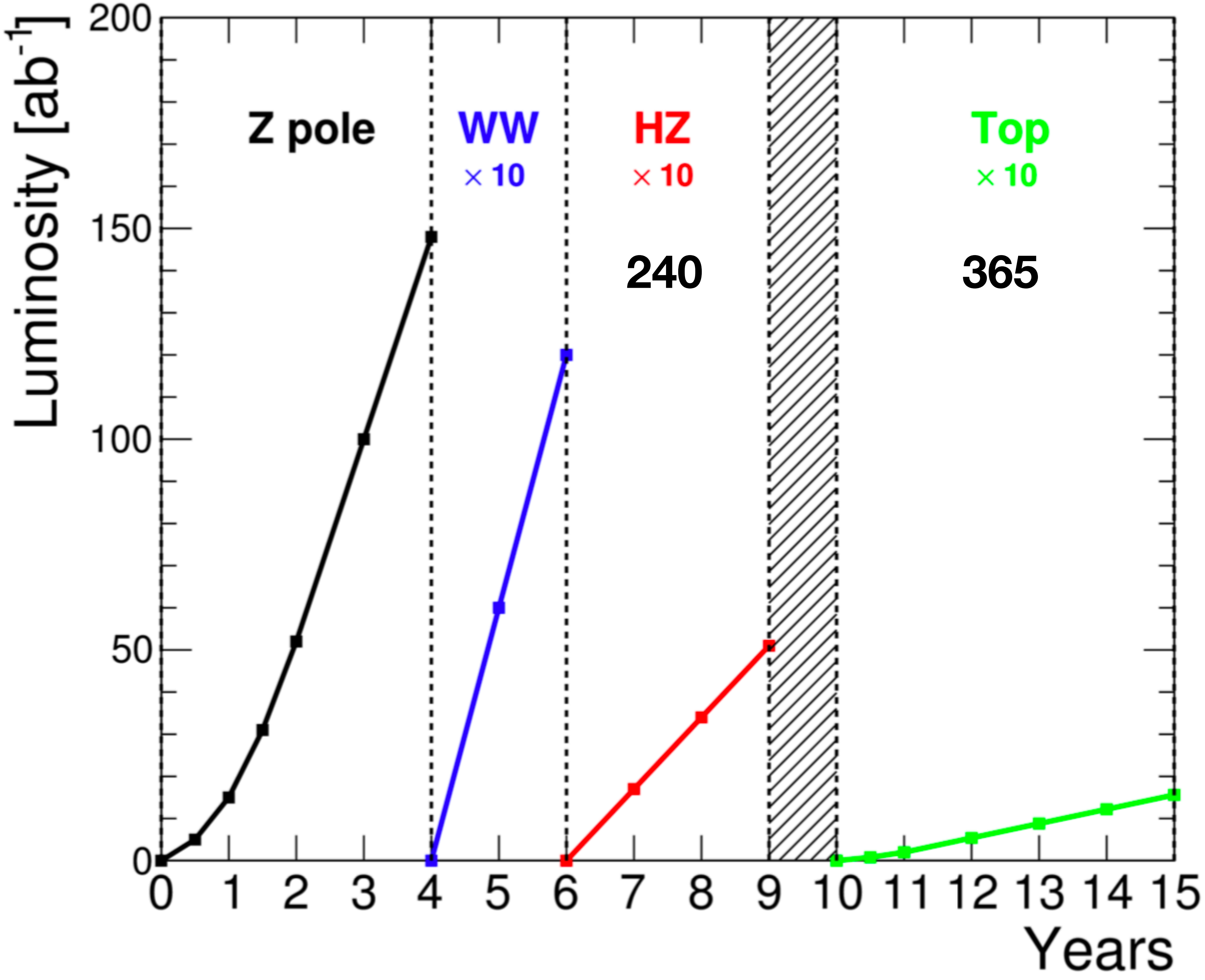


C3

CLIC

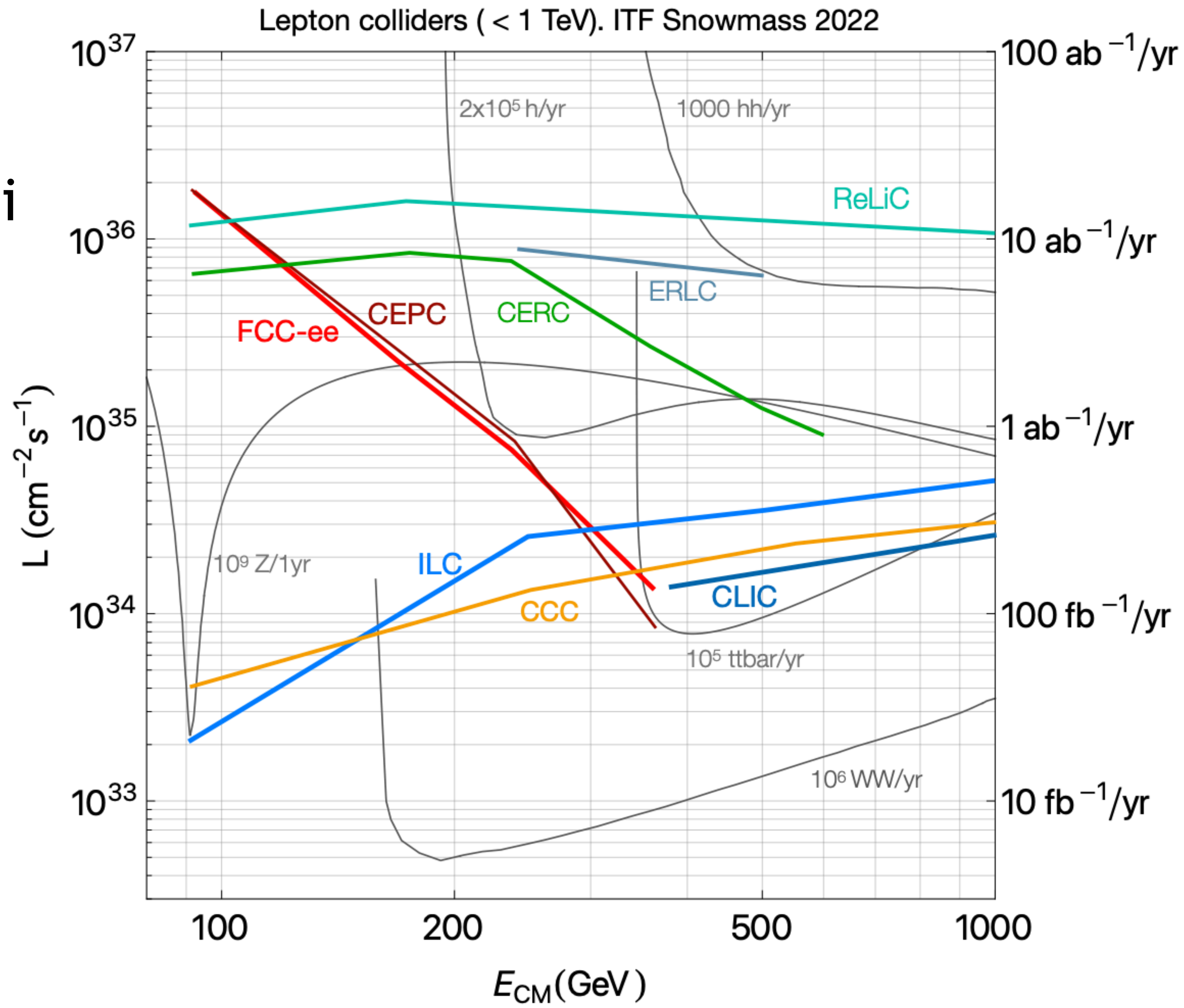


FCC-ee run plan: (unpolarized beams)



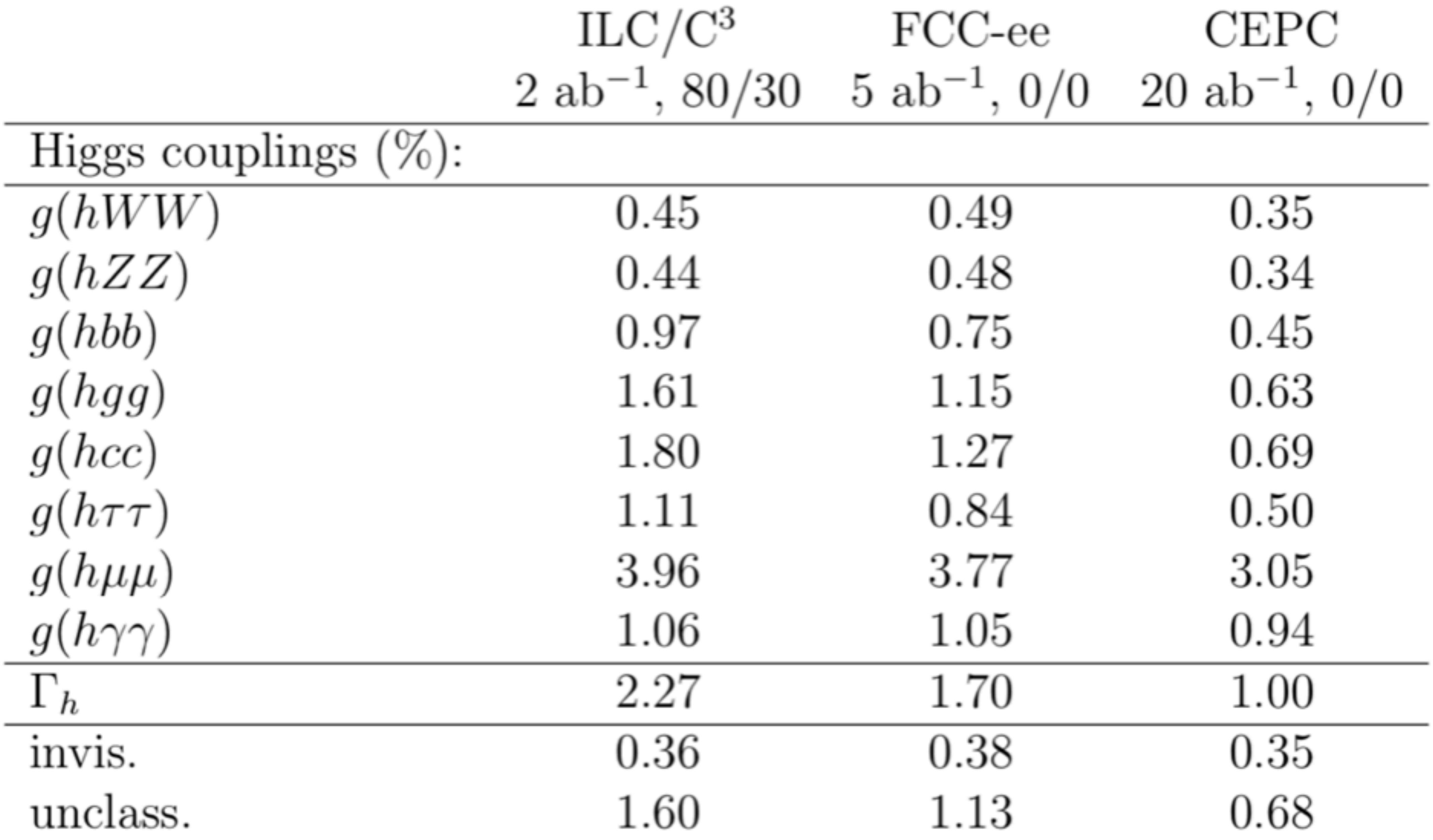
The CEPC run plan calls for 10 years and 20 ab-1 at 240 GeV.

peak lumi
per IP



Snowmass Collider Implementation Task Force
arXiv:2208.06030

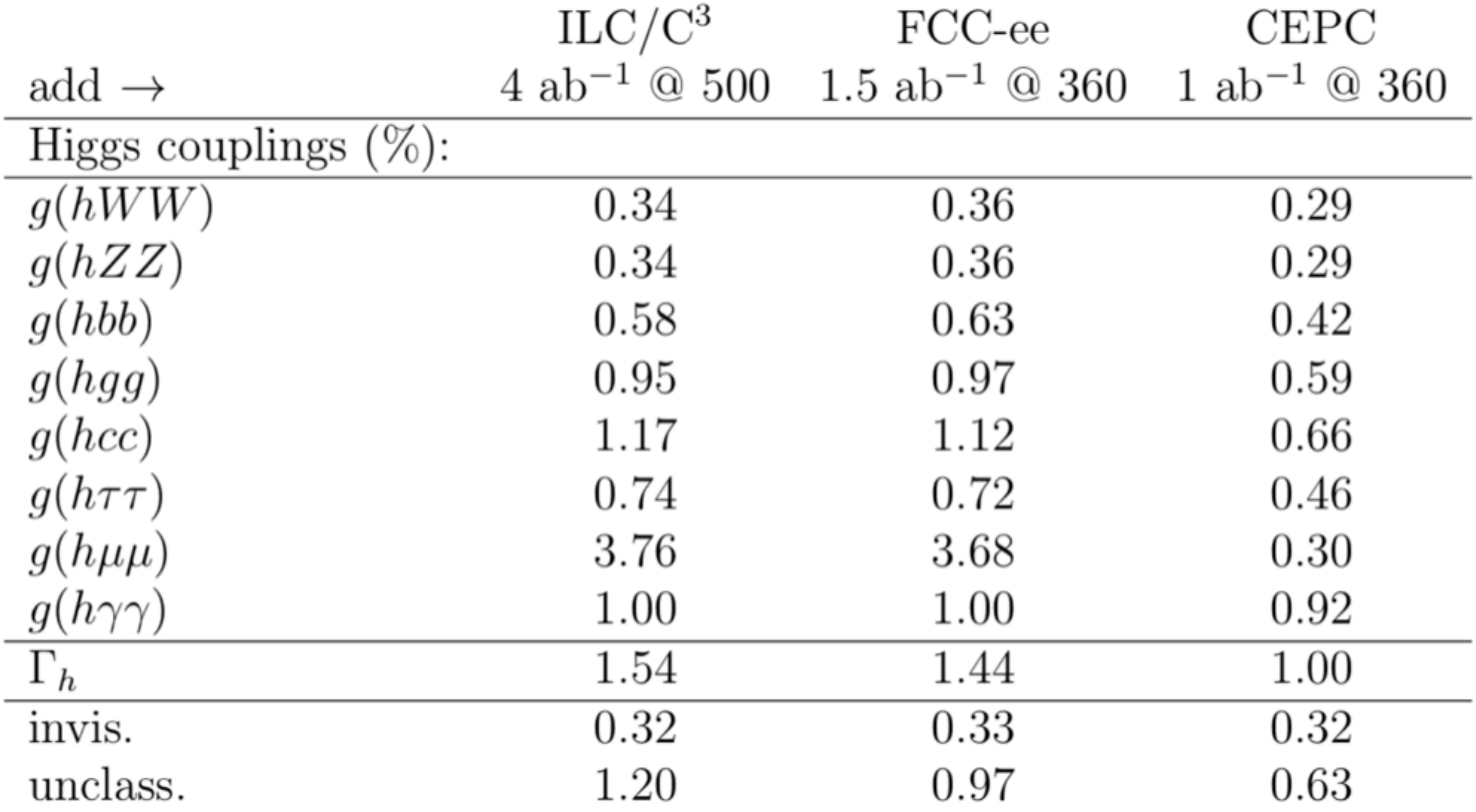
Projected Higgs coupling uncertainties (absolute) from the 240-250 GeV runs



	ILC/C^3 2 ab^{-1}, 80/30	FCC-ee 5 ab^{-1}, 0/0	CEPC 20 ab^{-1}, 0/0
Higgs couplings (%):			
$g(hWW)$	0.45	0.49	0.35
$g(hZZ)$	0.44	0.48	0.34
$g(hbb)$	0.97	0.75	0.45
$g(hgg)$	1.61	1.15	0.63
$g(hcc)$	1.80	1.27	0.69
$g(h\tau\tau)$	1.11	0.84	0.50
$g(h\mu\mu)$	3.96	3.77	3.05
$g(h\gamma\gamma)$	1.06	1.05	0.94
Γ_h	2.27	1.70	1.00
invis.	0.36	0.38	0.35
unclass.	1.60	1.13	0.68

note that, with SMEFT analysis, the use of beam polarization compensates a factor ~ 2.5 in luminosity

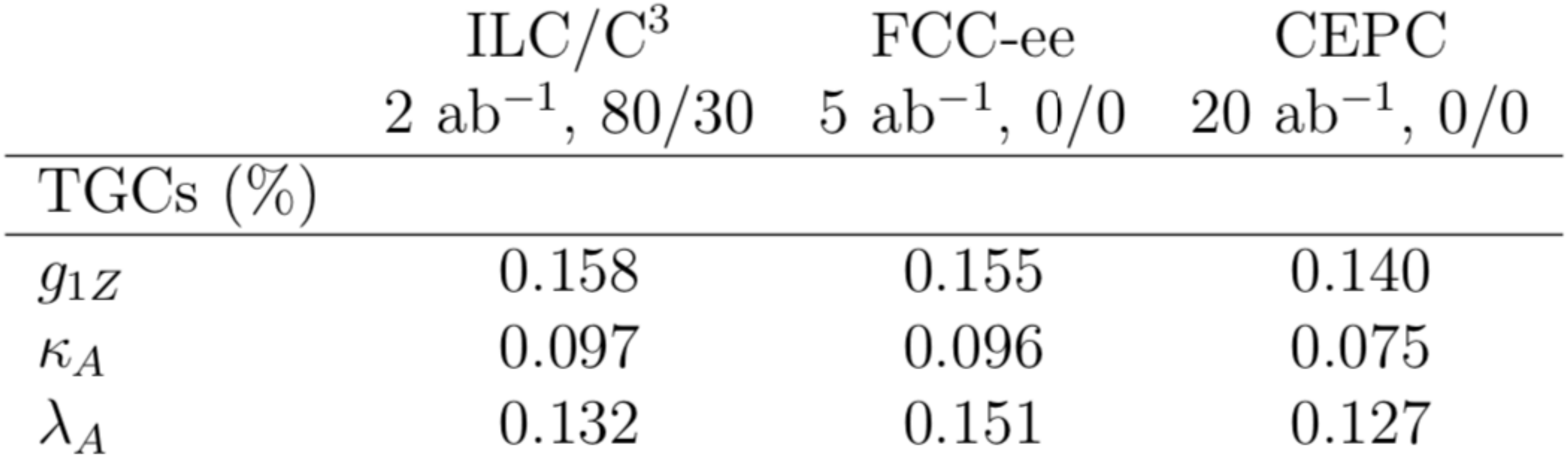
Projected Higgs coupling uncertainties (absolute) including the higher energy runs



	ILC/C^3	FCC-ee	CEPC
add →	4 ab^{-1} @ 500	1.5 ab^{-1} @ 360	1 ab^{-1} @ 360
Higgs couplings (%):			
$g(hWW)$	0.34	0.36	0.29
$g(hZZ)$	0.34	0.36	0.29
$g(hbb)$	0.58	0.63	0.42
$g(hgg)$	0.95	0.97	0.59
$g(hcc)$	1.17	1.12	0.66
$g(h\tau\tau)$	0.74	0.72	0.46
$g(h\mu\mu)$	3.76	3.68	0.30
$g(h\gamma\gamma)$	1.00	1.00	0.92
Γ_h	1.54	1.44	1.00
invis.	0.32	0.33	0.32
unclass.	1.20	0.97	0.63

the increasing luminosity of linear colliders with increasing energy is also an advantage

The tradeoff of polarization against luminosity is also apparent in the uncertainties on triple gauge boson couplings:



	ILC/C^3 2 ab^{-1}, 80/30	FCC-ee 5 ab^{-1}, 0/0	CEPC 20 ab^{-1}, 0/0
TGCs (%)			
g_{1Z}	0.158	0.155	0.140
κ_A	0.097	0.096	0.075
λ_A	0.132	0.151	0.127

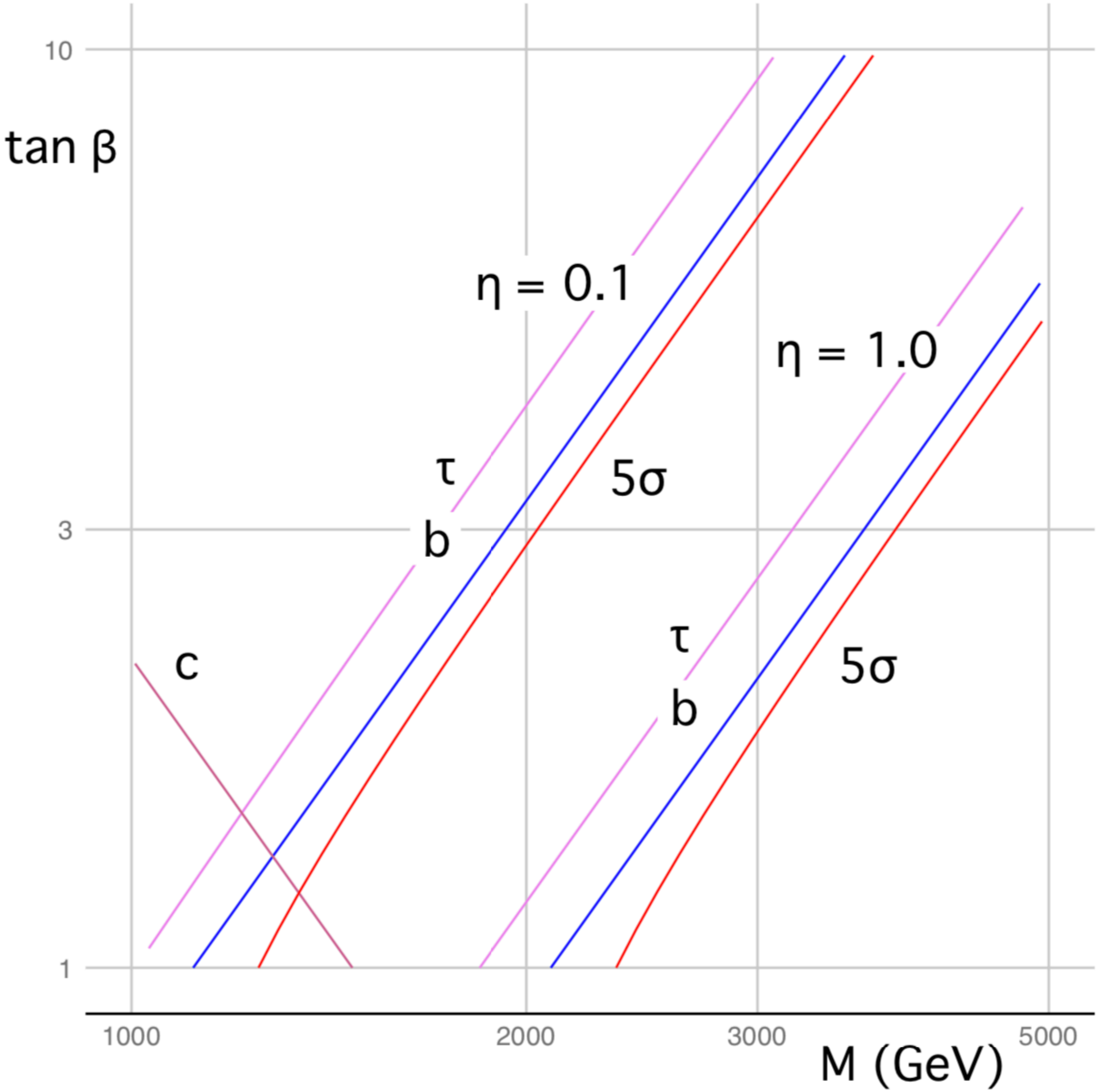
I noted earlier that searches for BSM effects from Higgs precision measurement complements direct searches for BSM particles.   For different classes of models, the two approaches offer different reach in particle mass.

I would like to show some examples in which the reach of precision Higgs measurements is superior.

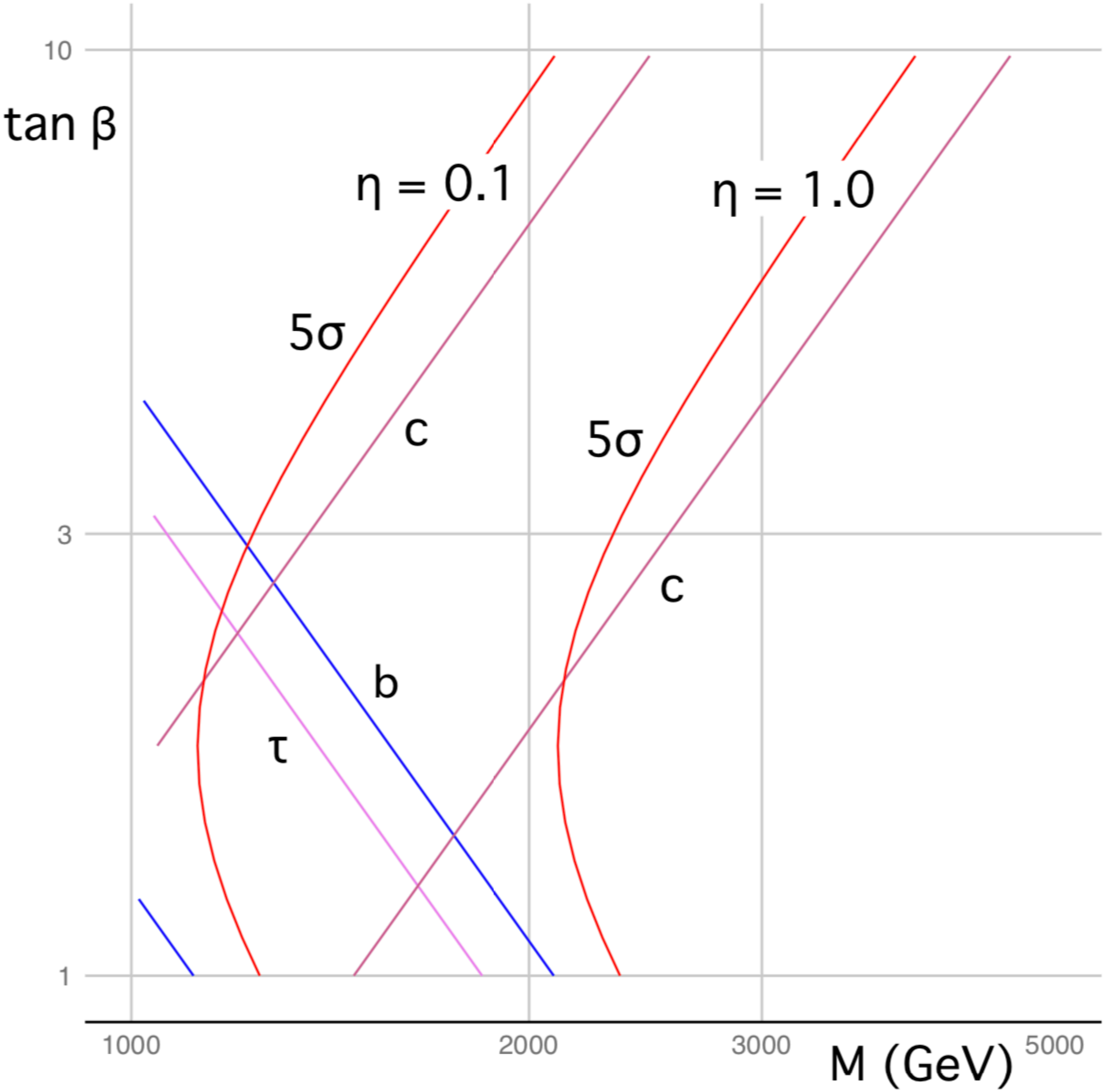
The curves I will show give the 3σ contours for individual Higgs couplings from the SMEFT fit, and the 5σ contour for the complete fit. The analysis includes only linear effects from dimension-6 operators.

arXiv:2209.03303

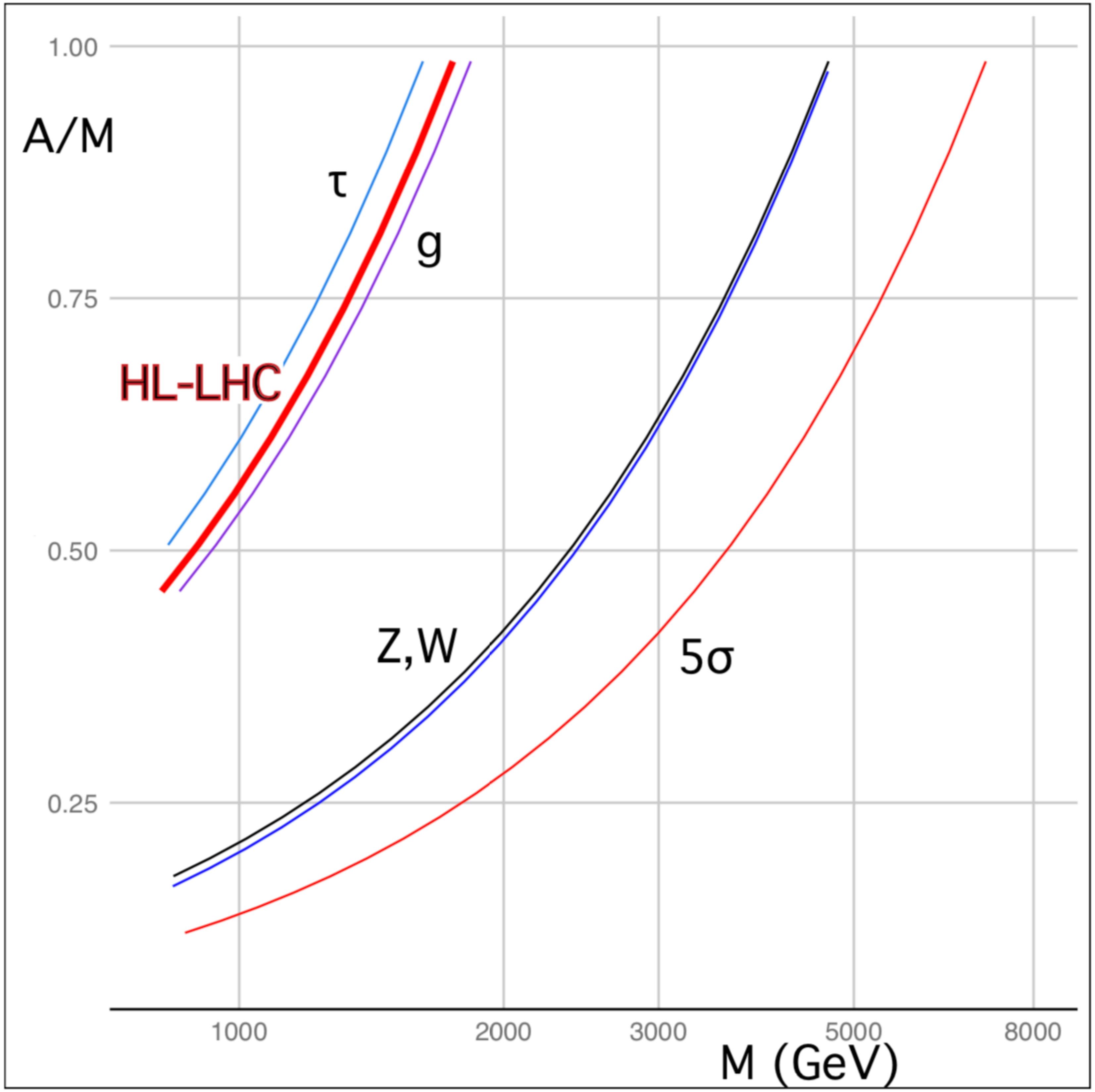
Type II 2-Higgs-doublet models



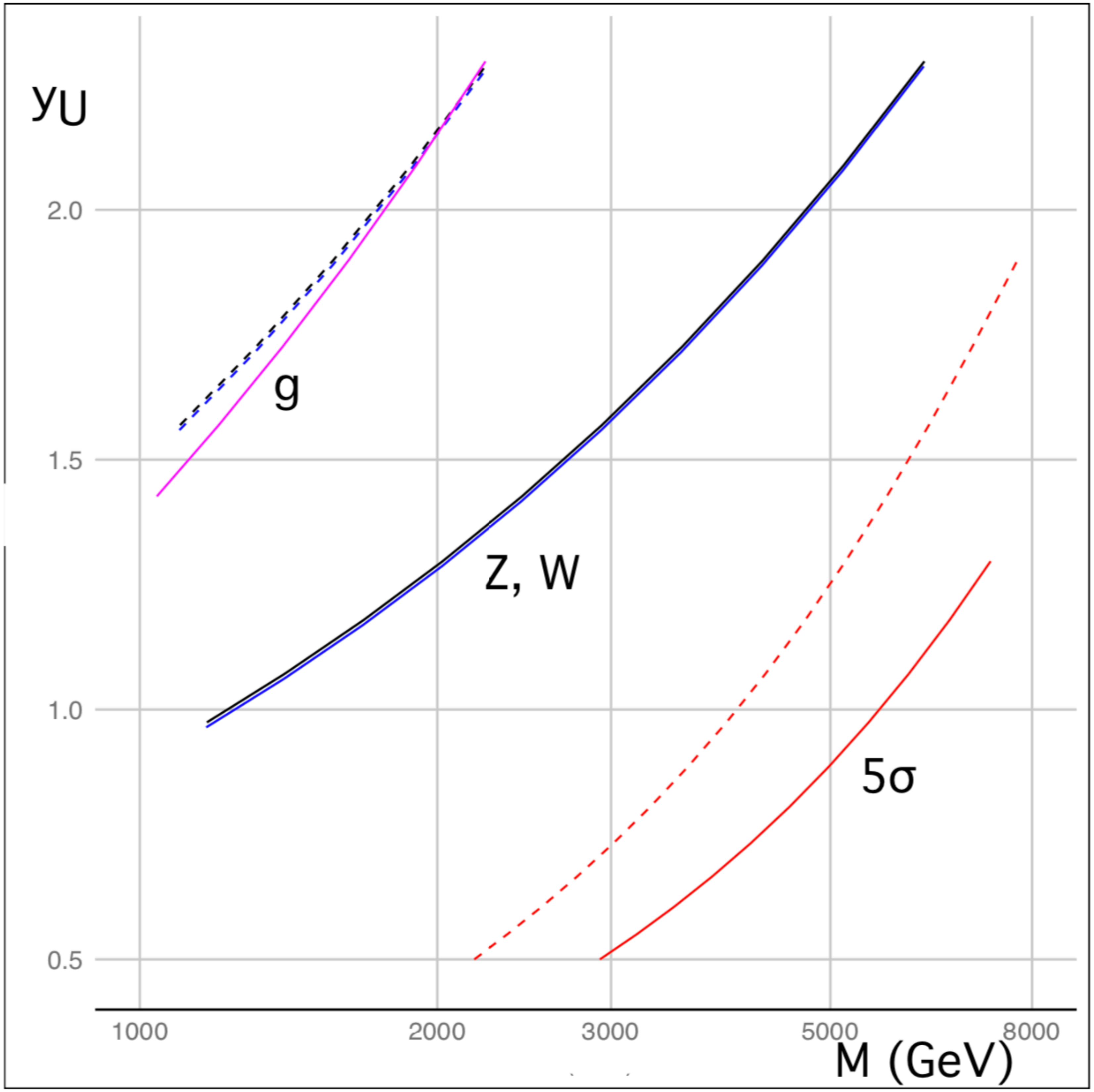
Flavored 2-Higgs-doublet models



Mixing of a scalar singlet with the Higgs



Heavy vectorlike quark doublet



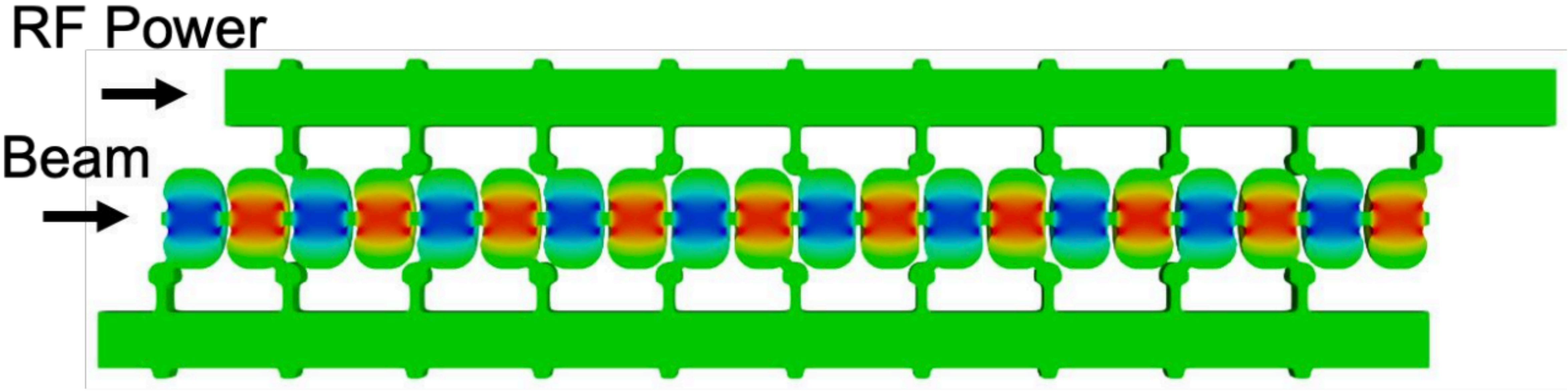
Finally, I would like to call attention to the newest entry into this list, the "Cool Copper Collider" (C^3) linear collider.

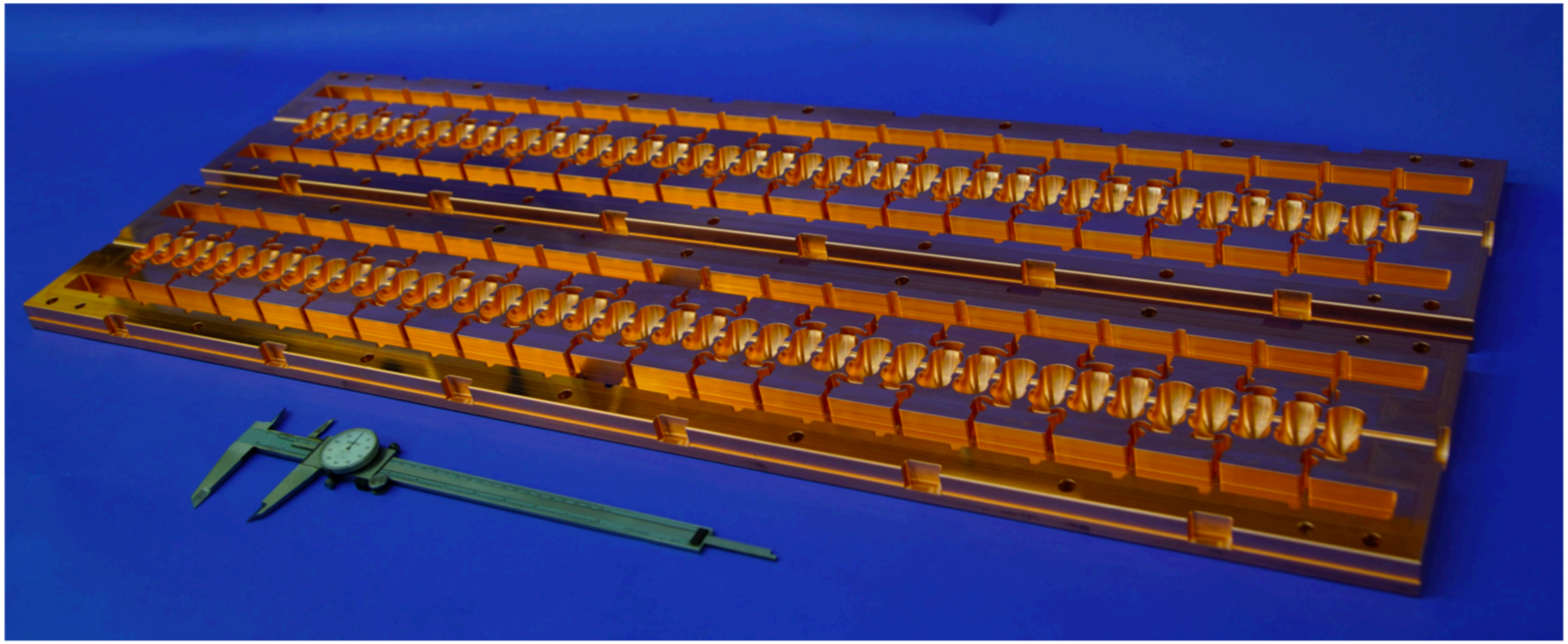
arXiv: 2110.15800

This is the result of a decade of work by my SLAC RF accelerator colleagues, in particular, Sami Tanawi, to overcome the problem of electrostatic breakdown in very high gradient normal conducting accelerators.

In a normal-conducting linear accelerator, the cells of the accelerator must be filled rapidly with RF power. This conflicts with the requirement of small irises needed to produce high gradients.

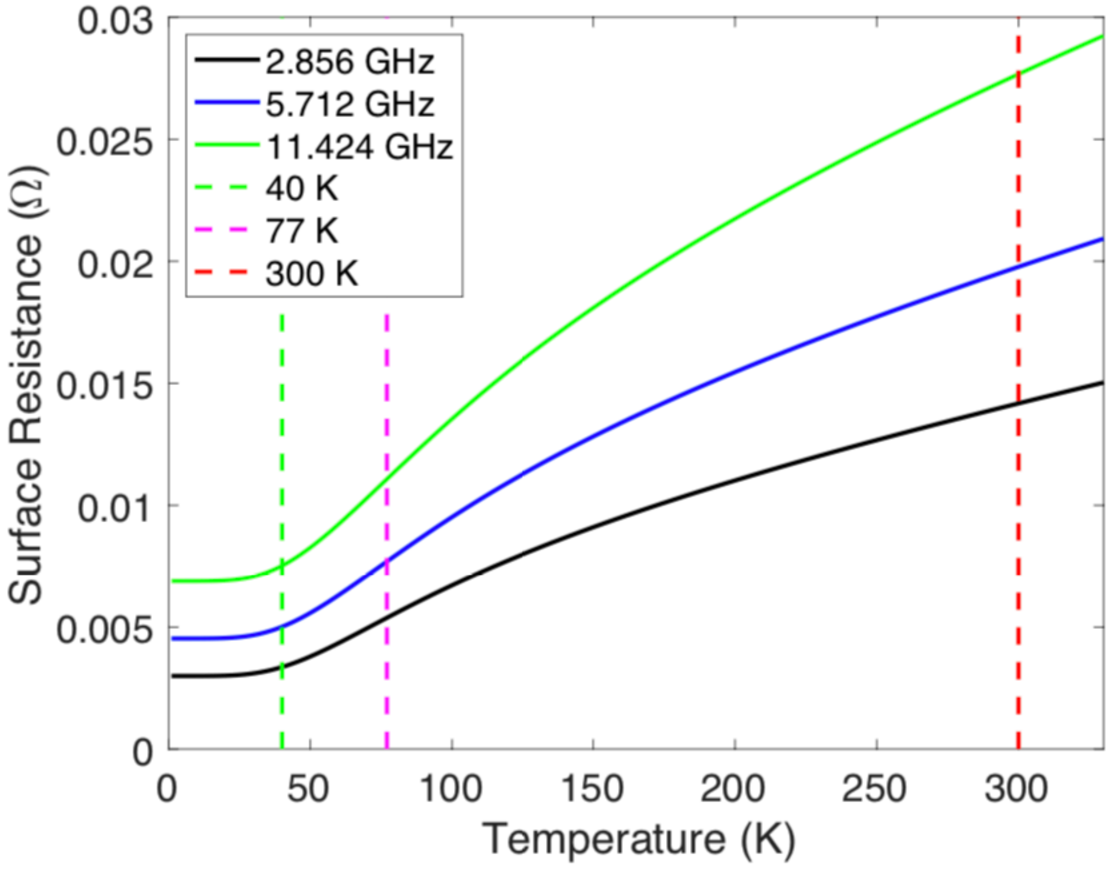
The solution is a “standing-wave structure” in which RF power is supplied individually to each cell. This is made possible by computer-aided manufacturing.

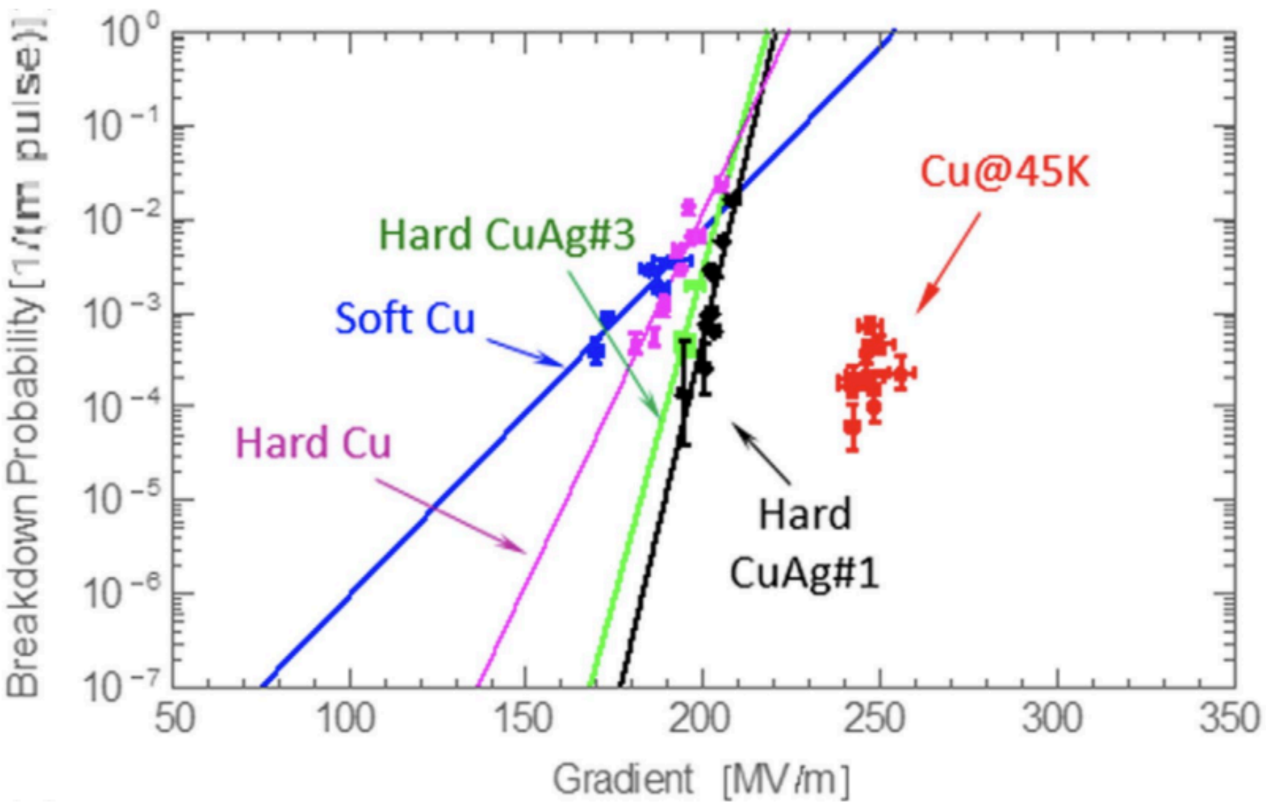

RF Power
Beam



If you immerse the system in Liquid Nitrogen, it works even better!

150 MeV/m demonstrated in 1 m structures at X-band





Cahill, A. D., et al. *PRAB* 21.10 (2018): 102002.

see: C^3 development plan arXiv:2203.09076

Our concept: (Caterina Vernieri, Emilio Nanni)

70 MeV/m C-band accelerator to reach 250 GeV
with an 8 km footprint

add RF power (only) to reach 120 GeV/m and 550 GeV

We expect that this will have the same luminosity and performance as ILC.

We believe that this is will be the least expensive solution for an e+e- Higgs factory.

The technology is not mature. Many questions remain. We believe that these can be addressed with a 5-year R&D program in the US.

Summary:

To make progress in understanding fundamental particle physics, it is urgent that we learn more about the nature of the Higgs boson.

One practical route, for which the technology is available now, is to build an e+e- Higgs factory. There are proposals for linear and for circular machines. These have very similar capabilities for physics measurments.

The e+e- Higgs factory should be the next global accelerator project. As a community, we need to make a plan and get on with it!