Expectations for Precision Tests of the Standard Model at the ILC

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Physics Working Group
ICHEP 2020, July 2020

Talks on ILC Physics at ICHEP 2020:

Higgs Physics 31/07

M. Peskin: Expectations for precision tests of the Standard Model at the ILC
D. Jeans: Precision Higgs physics at the ILC and its impact on detector design
J. Tian: A new way of understanding the role of each measurement in SMEFT

Top Quark and Electroweak Physics 28/07, 31/07

G. Wilson: Improving electroweak precision observables and TGCs with the ILD
A. Irles: Heavy quark production in high energy electron positron collisions

Computing and Data 29/07, 31/07

M. Berggren: Generating the full SM at linear colliders
R. Ete: The ILC software tools and detector performance

Detectors for future facilities 29/07, 31/07

A. White: The SiD detector for the International Linear Collider
T. Tanabe: ILD, a detector for the International Linear Collider

Accelerator Physics 30/07

J. List: Polarized beams at future e+e- colliders

Beyond the Standard Model 31/07

M. Núñez Pardo de Vera: ILC as a SUSY discovery and precision instrument

For off-line discussion of all of the ILC talks, we will open a Zoom room after the end of today's session: 4:00 pm July 31 CEST

https://stanford.zoom.us/j/99671238654?pwd=M2V2RCtYbTFrVi9Ub01kckh3WFVoZz09

Please bring your comments and questions.

There is now a well-established physics case for the construction of an “e+e– Higgs factory”, an accelerator designed to study the properties of the Higgs boson to high precision.

In this talk, I will review the expectations for the International Linear Collider (ILC) to test the SM predictions for the Higgs boson and to carry out other high-precision tests of the SM.

from the 2020 update of the European Strategy for Particle Physics:

“An electron positron Higgs factory is the highest-priority next collider.

The timely realization of the electron-positron International Linear Collider (ILC) in Japan would be compatible with this strategy and, in that case, the European particle physics community would wish to collaborate.”

In August 2020, the ILC will enter its next phase with the establishment of the International Development Team hosted by KEK.

Our current understanding of the next stages is:
(from S. Yamashita)

2022: establishment of the ILC pre-lab at KEK

2025: establishment of the ILC Laboratory;
start of construction

2034: first data at 250 GeV

The first goal of the ILC is to produce 0.5×10^6 Higgs bosons in the reaction

$$e^+e^- \to Zh$$

These are tagged Higgs bosons produced in an environment with little background. By counting, we can establish the Higgs boson branching ratios and search for invisible and exotic Higgs decays.

At the same time, we can study the reactions

$$e^+e^- \to W^+W^- \quad e^+e^- \to f\overline{f} \qquad e^+e^- \to Z\gamma$$

with high precision, providing additional tests of the SM.

Further reactions become available as the ILC is raised to higher energies.

In fact, the measurements on all of these reactions work together in a powerful way.

Assume that new physics beyond the SM is generated by heavy particles, with minimum mass M. To describe processes at the scale of m_h, integrate them out. The resulting effective Lagrangian (SMEFT) will be of the form

$$\mathcal{L} = \mathcal{L}_4 + \sum_i \frac{\bar{c}_i}{M^2}\mathcal{O}_i + \sum_j \frac{\bar{d}_i}{M^4}\mathcal{O}_j + \cdots$$

$\mathcal{L}_4$ is exactly the Standard Model. If the coefficients of the $\mathcal{O}_i$ can be determined, these give specific information on the nature of the heavy particles that give rise to them. Working with $1/M^2$ terms only, this is a finite problem, but many measurements are still required to see the full picture.

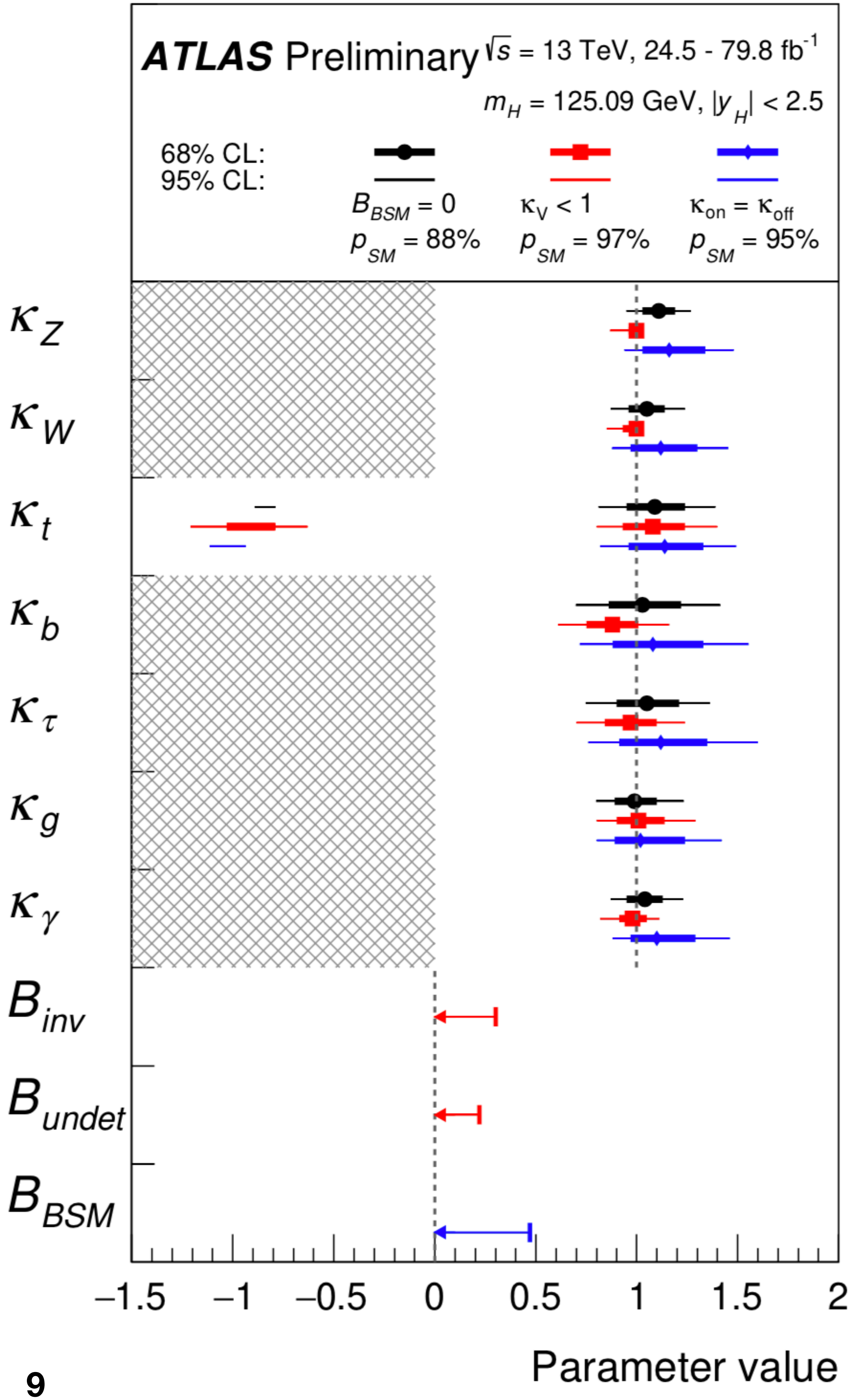
Begin by discussing the Higgs boson.

Currently, we know from LHC that the Higgs boson is “SM-like”.

7 of these couplings are observed and agree with the SM prediction within the errors.

$$\kappa_f = \Gamma(h \to f\overline{f})/SM$$

ATLAS-CONF-2019-005



According to the SMEFT, this is not an impressive verification of the SM.   Deviations in Higgs boson couplings are expected to be of order

$$m_h^2/M^2$$

that is, at the few-% level. Confident discovery of these signals requires sub-1% measurements.

You will hear about how the measurements are actually made in the following talk by Daniel Jeans.

On the other hand, many decay modes of the Higgs boson are accessible to experimental measurement.

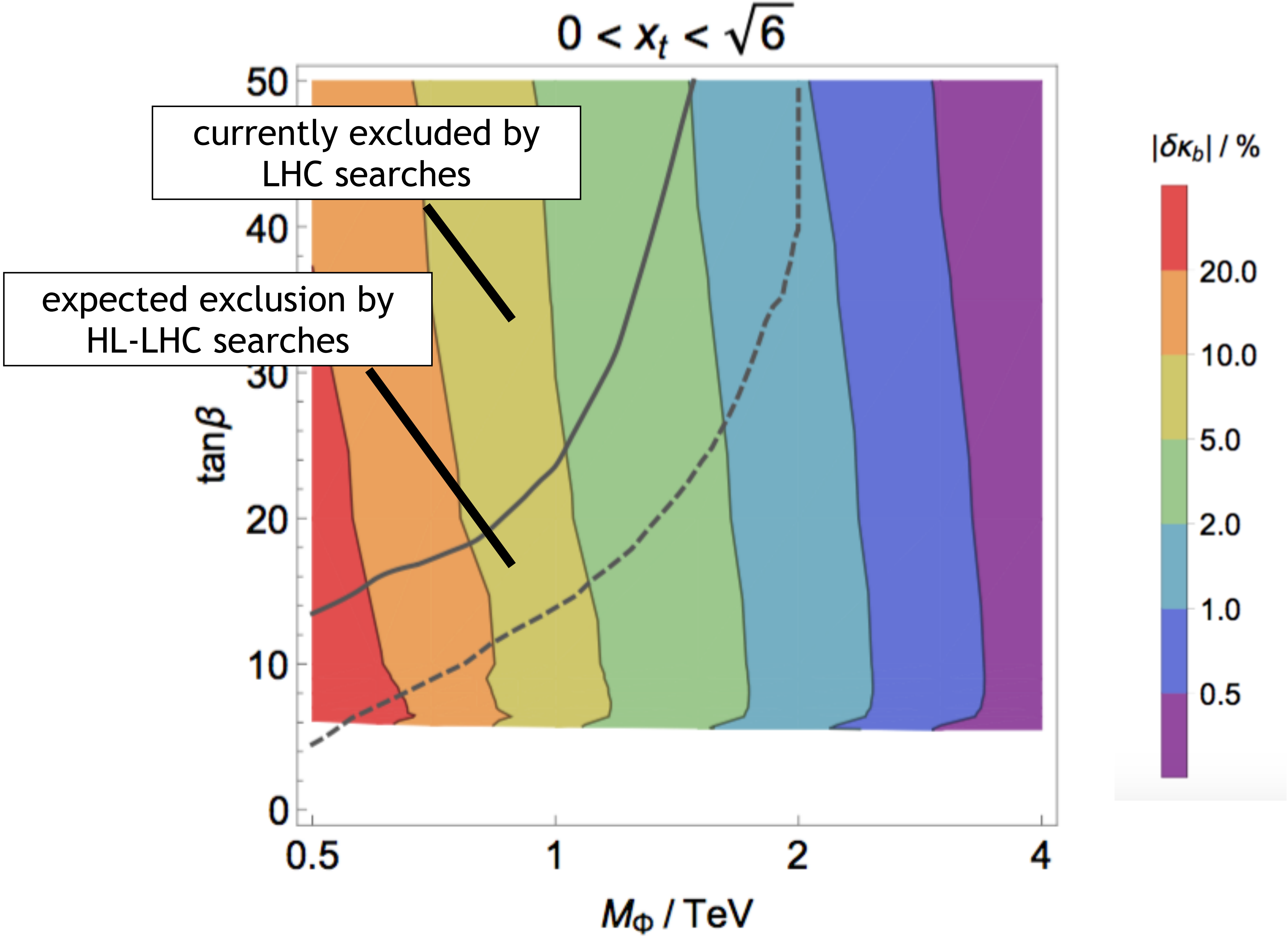
Different models of new physics affect the Higgs boson couplings in different ways. Roughly:

coupling to b, τ :   supersymmetry, 2-Higgs doublet

coupling to W, Z :   composite Higgs

coupling to γ, g, t : top condensation, top partners

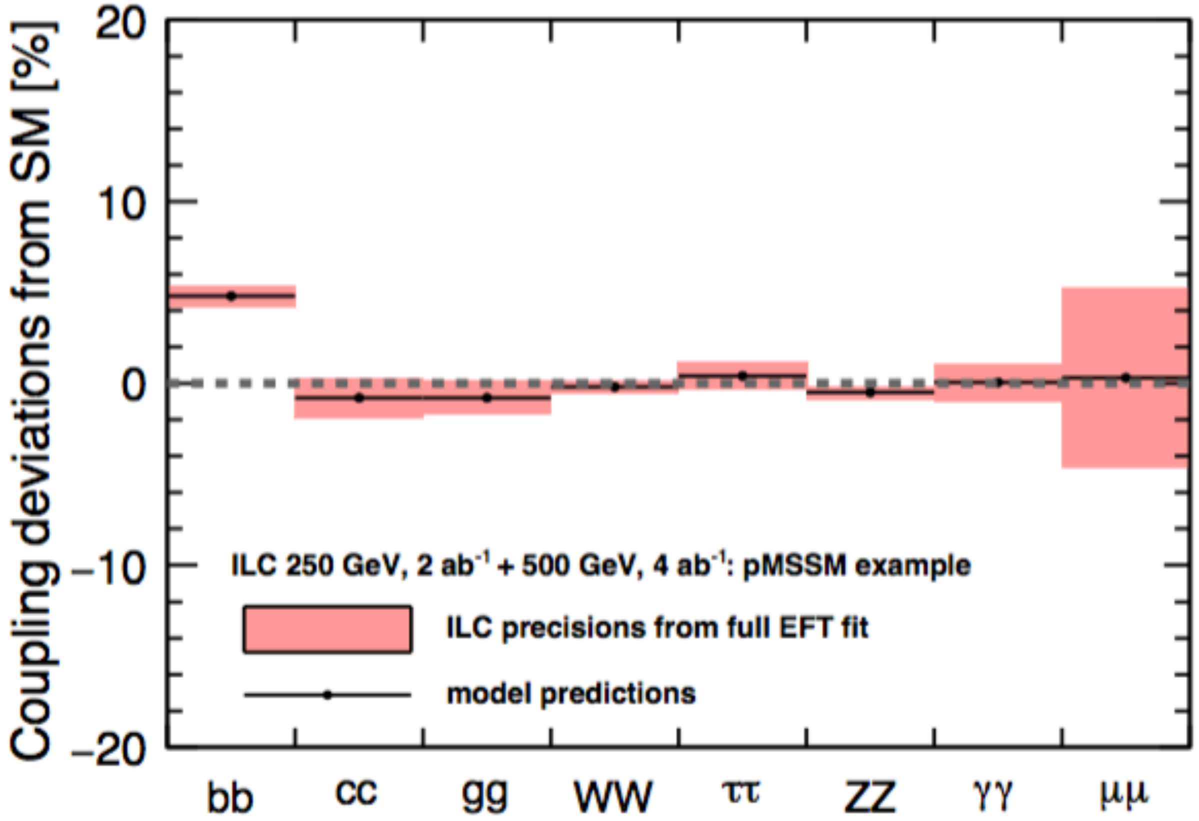
The measurement of anomalies in Higgs couplings cuts into parameter space in a matter orthogonal to the search for the new particles of these models.



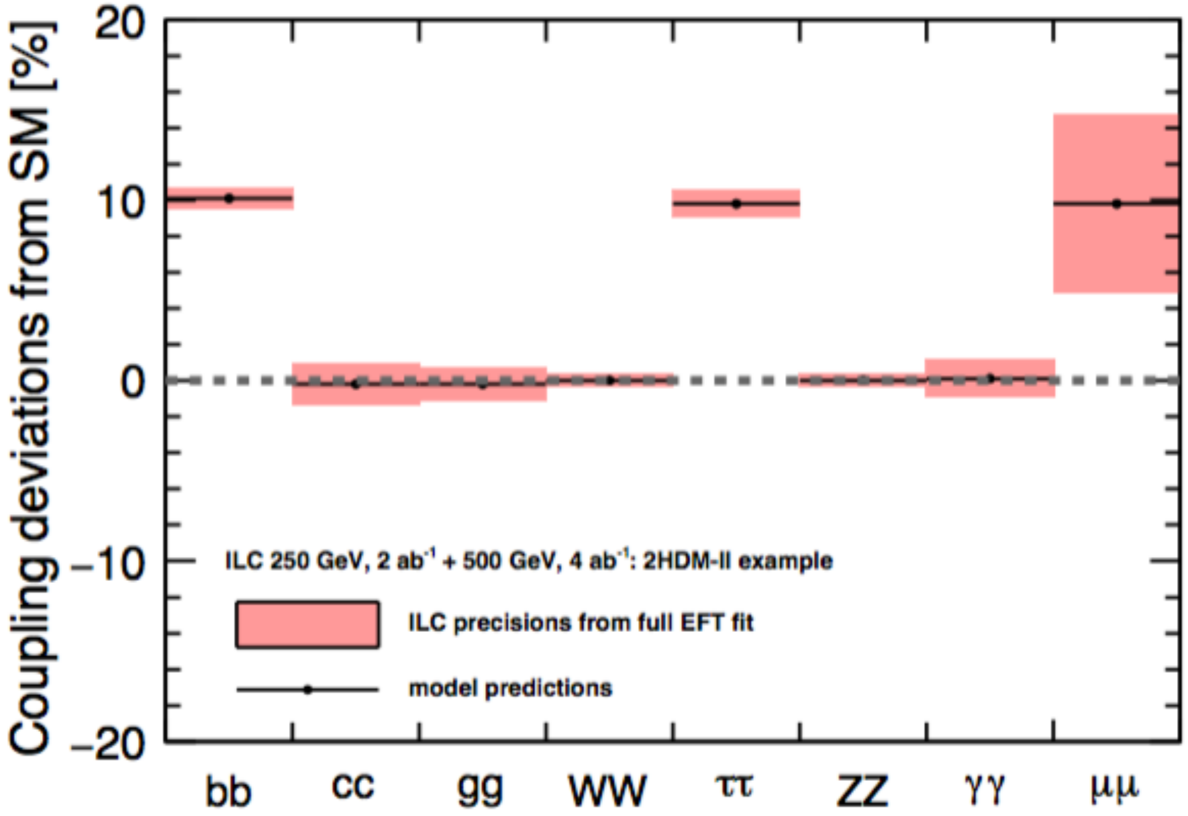
currently excluded by LHC searches

expected exclusion by HL-LHC searches

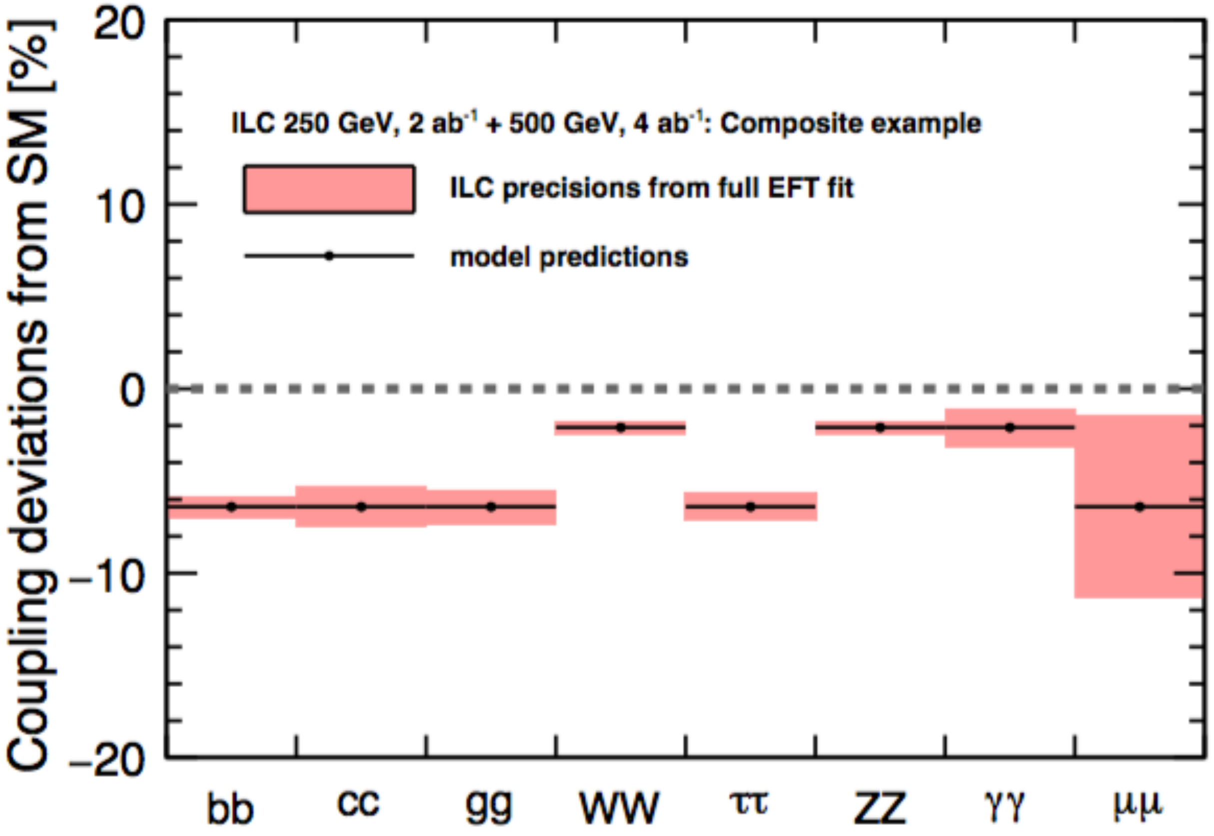
Wells and Zhang : models with b-τ unification



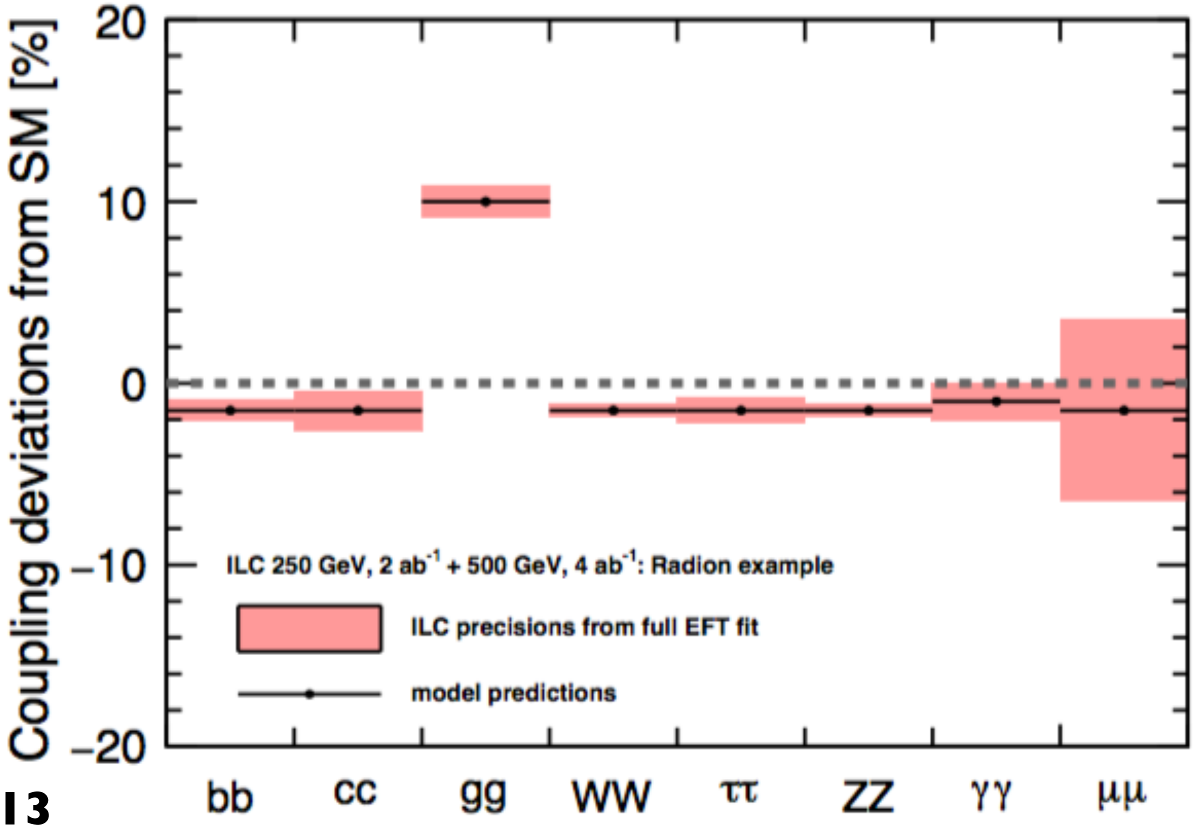
heavy SUSY



2 Higgs doublet



Composite Higgs



Higgs-Radion mixing

In general, the SMEFT contains 59 baryon- and lepton-number conserving dimension-6 operators for 1 generation and 2499 for 3 generations. It is a challenge to fix all of these coefficients uniquely.

However, e+e- reactions give a special situation. There are only 7 (CP-conserving) operators that involve γ, Z, W, h only, and for operators with fermion fields, we usually deal with the electron fields specifically.

Thus, the Higgs couplings are determined by a system of 17 CP-conserving operators only. Further, $e^+e^- \to W^+W^-$ and precision electroweak involve the same set of operators, so we can use these processes together to generate the most powerful constraints.

$$
\begin{aligned}
\Delta\mathcal{L} = {} & \frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) \\
& - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\
& + \frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a \Phi W^a_{\mu\nu}B^{\mu\nu} \\
& + \frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\
& + i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L) + 4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu t^a L) \\
& + i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{e}\gamma_\mu e)\ . \\
& - \sum_i \left\{ c_{\ell i\Phi}\frac{y_\tau \ell i}{v^2}(\Phi^\dagger\Phi)\overline{L}_i \cdot \Phi\, \ell_{iR} + c_{qi\Phi}\frac{y_\tau q i}{v^2}(\Phi^\dagger\Phi)\overline{Q}_i \cdot \Phi\, q_{iR} \right\} \\
& + \mathcal{A}\frac{h}{v}G_{\mu\nu}G^{\mu\nu}\ .
\end{aligned}
$$

Higgs Z factor

triple Higgs

h + W,Z,γ

Precision EW

h + q, l, g

Precision electroweak can be studied at the ILC via radiative return at 250 GeV or by a dedicated “Giga-Z” run at 91 GeV (5×10^9 Z’s).

In either case, polarized e- and e+ beams provide major advantages, allowing the measurement of polarized observables and crucial checks on systematic errors. For details, see yesterday’s talk by Jenny List.

projected errors on Precision EW observables

			Z pole		radiative return	
Quantity	Value	current	GigaZ		ILC250	
		$\delta[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$	$\delta_{stat}[10^{-4}]$	$\delta_{sys}[10^{-4}]$
boson properties						
m_W	80.379	1.5	-	-	~ 0	0.3
m_Z	91.1876	0.23	-	-	-	-
Γ_Z	2.4952	9.4	~ 0	4.	-	-
$\Gamma_Z(had)$	1.7444	11.5	~ 0	4.	-	-
Z-e couplings						
$1/R_e$	0.0482	24.	2.	5	5.5	10
A_e	0.1513	139.	1	5.	9.5	3.
$\sin^2\theta_w$	**0.2312**	**12.**	**0.08**	**0.4**	**0.8**	**0.2**
Z-ℓ couplings						
$1/R_\mu$	0.0482	16.	2.	2.	5.5	10
$1/R_\tau$	0.0482	22.	2.	4.	5.7	10
A_μ	0.1515	991.	2.	5	54.	3.
A_τ	0.1515	271.	2.	5.	57.	3
Z-b couplings						
R_b	0.2163	31.	0.4	7.	3.5	10
A_b	**0.935**	**214.**	**1.**	**5.**	**5.7**	**3.**
Z-c couplings						
R_c	0.1721	174.	2.	30	5.8	50
A_c	**0.668**	**404.**	**3.**	**5.**	**21.**	**3.**

$$\delta\mathcal{O} = \Delta\mathcal{O}/\mathcal{O}$$

arXiv:1908.11299

At the same time, the ILC will measure

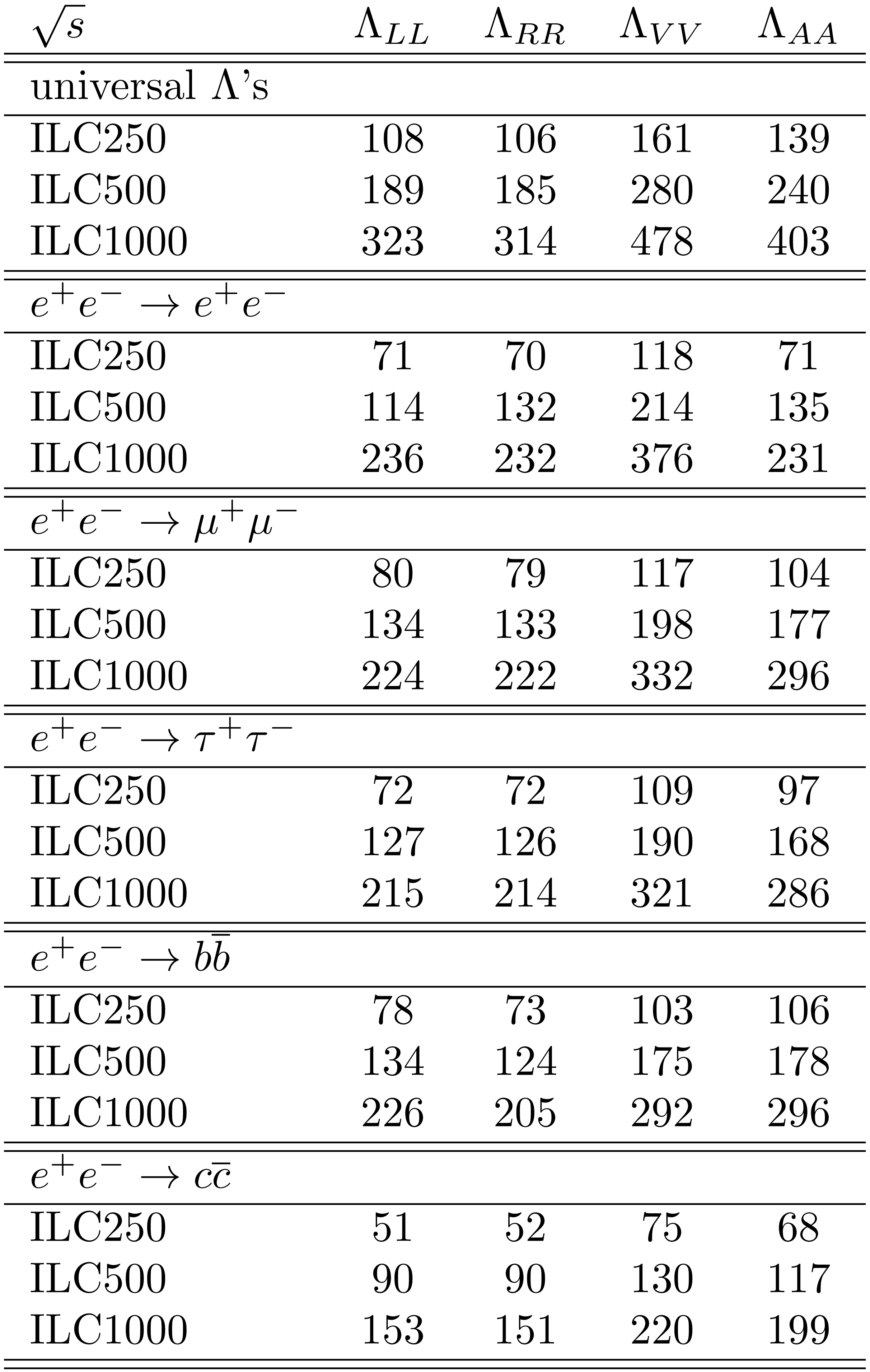
$$e^+e^- \to f\overline{f}$$

production with high precision. Each reaction is modified by 4 dimension-6 contact interactions. With the measurement of the forward- and backward-hemisphere cross sections from 2 states of initial beam polarization, ILC can measure these 4 coefficients independently.

This allows searches and coupling measurements for Z' bosons and very high sensitivity to fermion compositeness.

Assuming no deviation from the SM, limits on the compositeness scale (TeV).

arXiv:1908.11299



$\sqrt{s}$	Λ_{LL}	Λ_{RR}	Λ_{VV}	Λ_{AA}
universal Λ's				
ILC250	108	106	161	139
ILC500	189	185	280	240
ILC1000	323	314	478	403
$e^+e^- \to e^+e^-$				
ILC250	71	70	118	71
ILC500	114	132	214	135
ILC1000	236	232	376	231
$e^+e^- \to \mu^+\mu^-$				
ILC250	80	79	117	104
ILC500	134	133	198	177
ILC1000	224	222	332	296
$e^+e^- \to \tau^+\tau^-$				
ILC250	72	72	109	97
ILC500	127	126	190	168
ILC1000	215	214	321	286
$e^+e^- \to b\bar{b}$				
ILC250	78	73	103	106
ILC500	134	124	175	178
ILC1000	226	205	292	296
$e^+e^- \to c\bar{c}$				
ILC250	51	52	75	68
ILC500	90	90	130	117
ILC1000	153	151	220	199

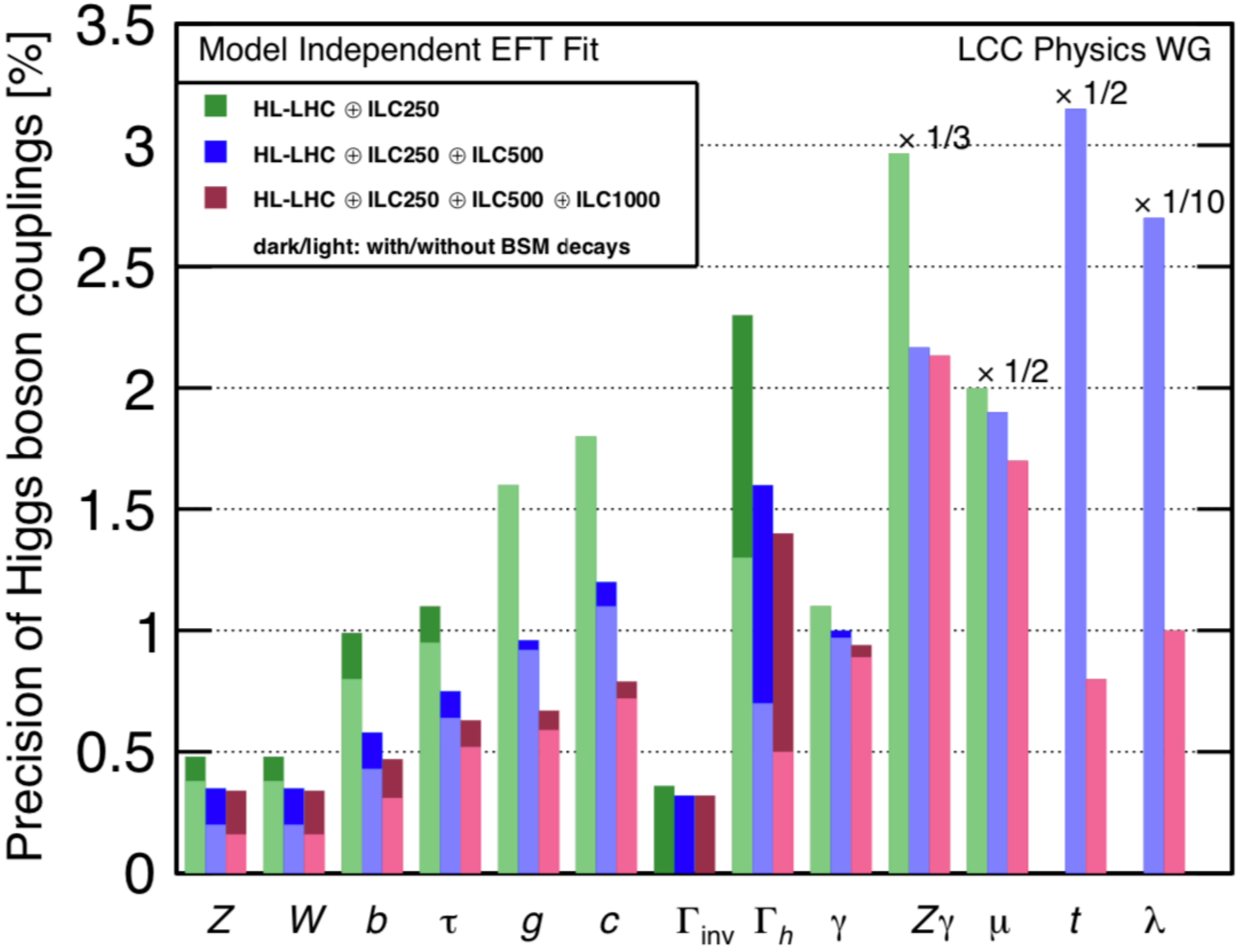
We envision “model-independent” extraction of absolute Higgs boson couplings using a fit to SM Effective Field Theory.

This requires independent variation of 22 parameters:

4 SM parameters
16 coefficients of dimension-6 operators
2 parameters for invisible and unclassified exotic decays

Precision electroweak measurements, precision measurement of $e^+e^- \to W^+W^-$, and some HL-LHC inputs assist in the determination of these parameters.

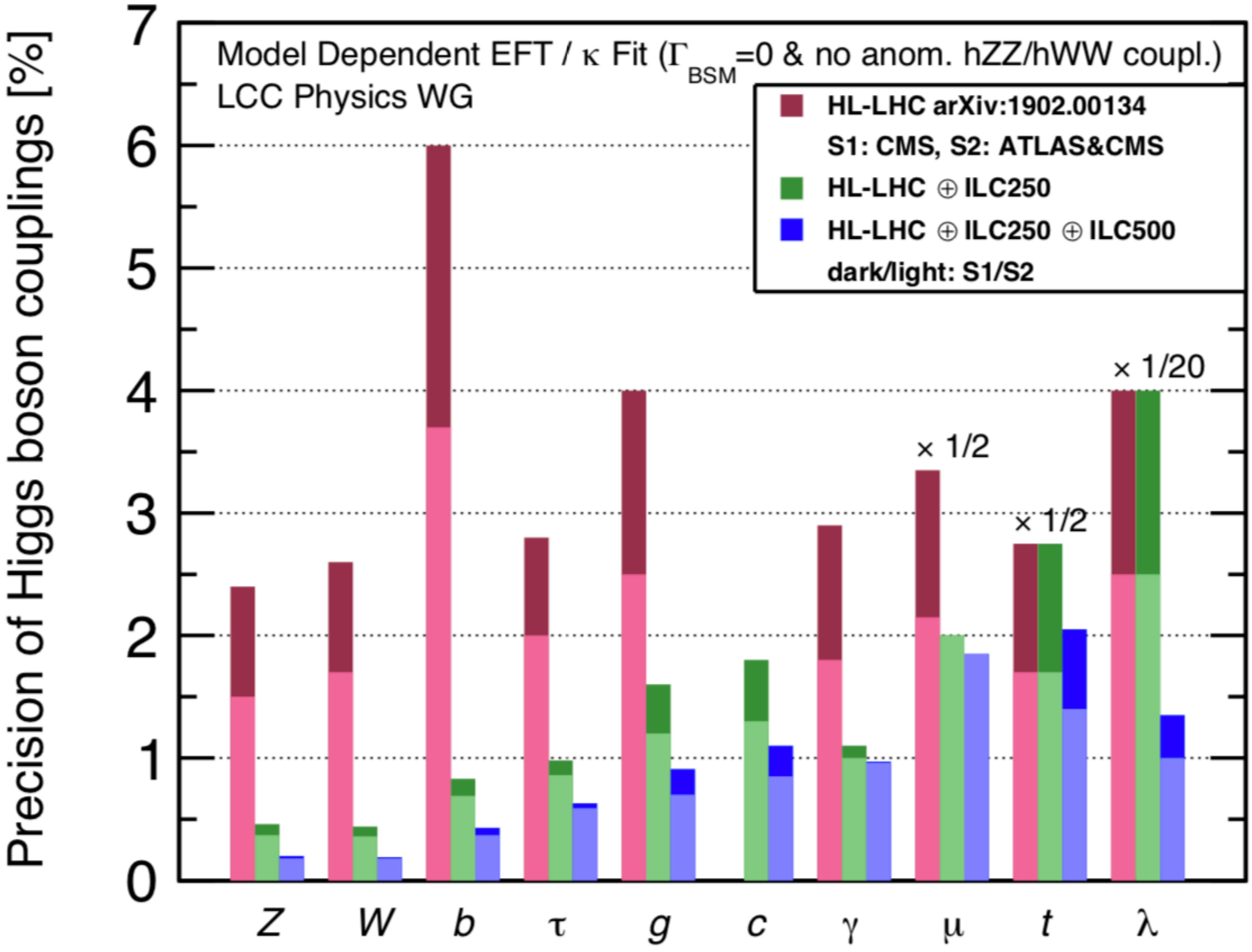
see: arXiv:1908.11299, 2003.0543 [hep-ph]



dark/light : allowing/not allowing
invisible and exotic decays

arXiv:1908.11299

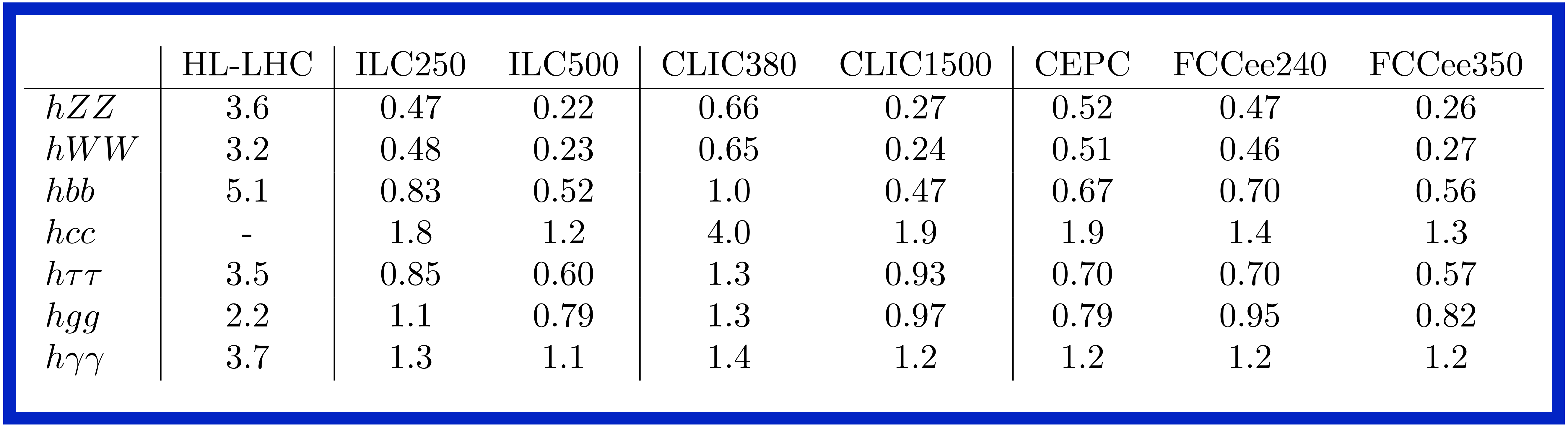
comparison to HL-LHC expectations:



dark/light : scenarios S1/S2

arXiv:1903.01629

Comparing the Higgs factory proposals, it turns out that they all have essentially equivalent projected performance. Polarized beams at linear machines compensate higher luminosity at circular machines.



	HL-LHC	ILC250	ILC500	CLIC380	CLIC1500	CEPC	FCCee240	FCCee350
hZZ	3.6	0.47	0.22	0.66	0.27	0.52	0.47	0.26
hWW	3.2	0.48	0.23	0.65	0.24	0.51	0.46	0.27
hbb	5.1	0.83	0.52	1.0	0.47	0.67	0.70	0.56
hcc	-	1.8	1.2	4.0	1.9	1.9	1.4	1.3
$h\tau\tau$	3.5	0.85	0.60	1.3	0.93	0.70	0.70	0.57
hgg	2.2	1.1	0.79	1.3	0.97	0.79	0.95	0.82
$h\gamma\gamma$	3.7	1.3	1.1	1.4	1.2	1.2	1.2	1.2

projected uncertainties in Higgs boson couplings, in %
(SMEFT without flavor universality)

ECFA Higgs@Future Colliders arXiv:1905.03764v1

Finally, how can you enter the field of e+e- physics and prepare to make these measurements ?

It is an opportune time.   In the US, the APS-DPF is conducting a community study of the future of particle physics, “Snowmass 2021”. Many US LHC experimenters will dip their toes in the e+e- water and see if it is congenial.

Because of the coronavirus, all meetings so far are by video. So, set your clock back 8 hours and join us !

https://www.snowmass21.org/energy/start

We have written an introductory handbook for studies of physics at e+e- Higgs factories:

“ILC Study Questions for Snowmass 2021”,
arXiv:2007.03650

We have prepared a new version of Delphes for e+e- studies. We are making available large samples of e+e- events at 250, 350, 500, and 1000 GeV in stdhep and other formats. These can be accessed at

http://ilcsnowmass.org .

We believe it is time now to prepare for the adventure of studying the Higgs boson and other windows into the Standard Model with high precision.

This will open a new door through which we can finally glimpse new fundamental interactions beyond the SM.