Physics at ILC

Higgs is the key to BSM

We have a very successful Standard Model (SM). However, ***all of its parameters are put in by hand*** to fit observations.

Except for the three gauge couplings, all of these parameters are of the Higgs field. The SM cannot predict any of these.

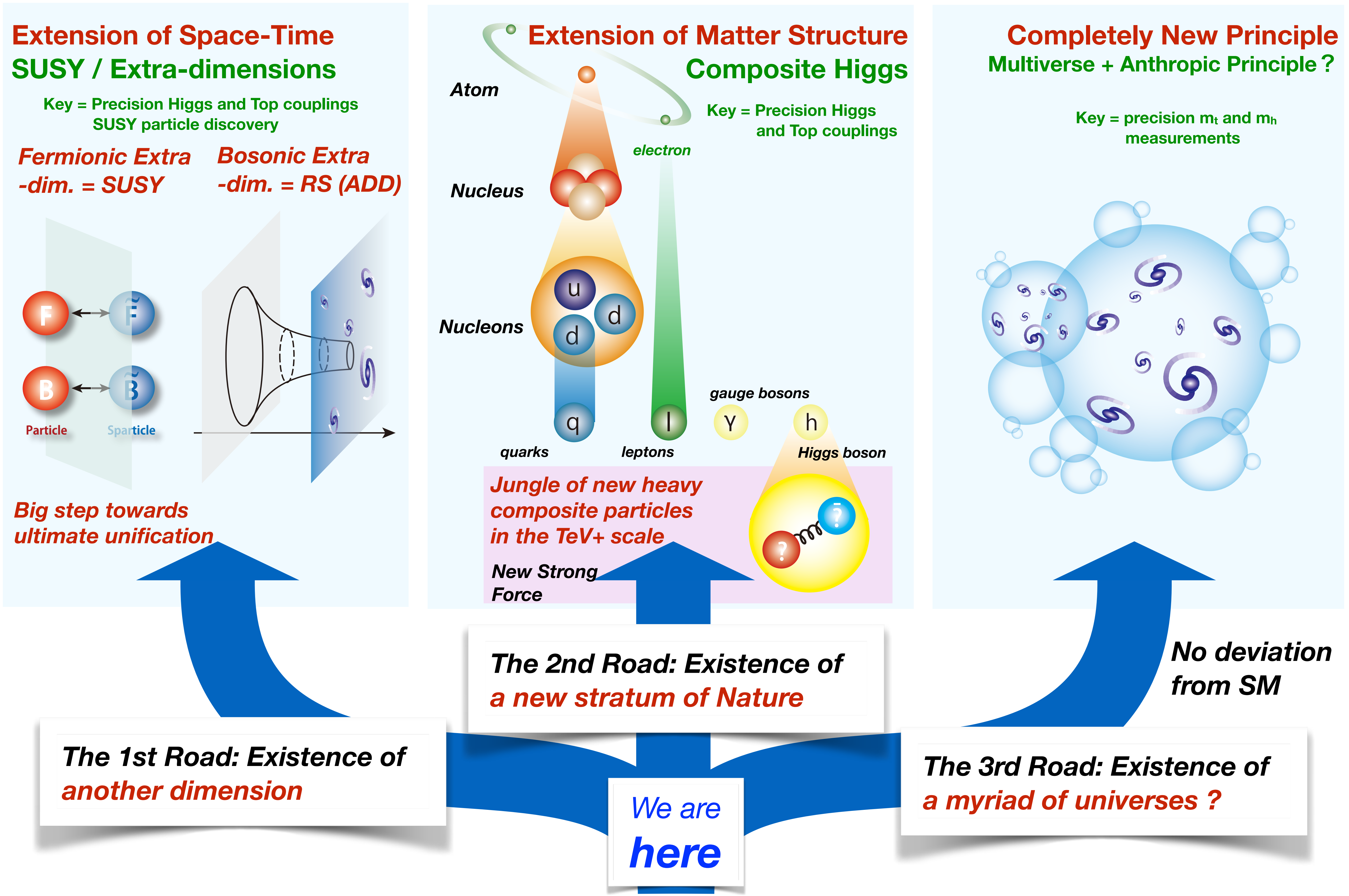
In particular, ***the SM cannot explain*** ***why the Higgs field filled the whole universe and why at the electroweak scale.***

We need ***physics beyond the SM*** to answer this question.

Answers to other big questions like ***dark matter, baryon asymmetry, neutrino masses/mixings, dark energy,*** etc. would change, depending on the answer to this question.

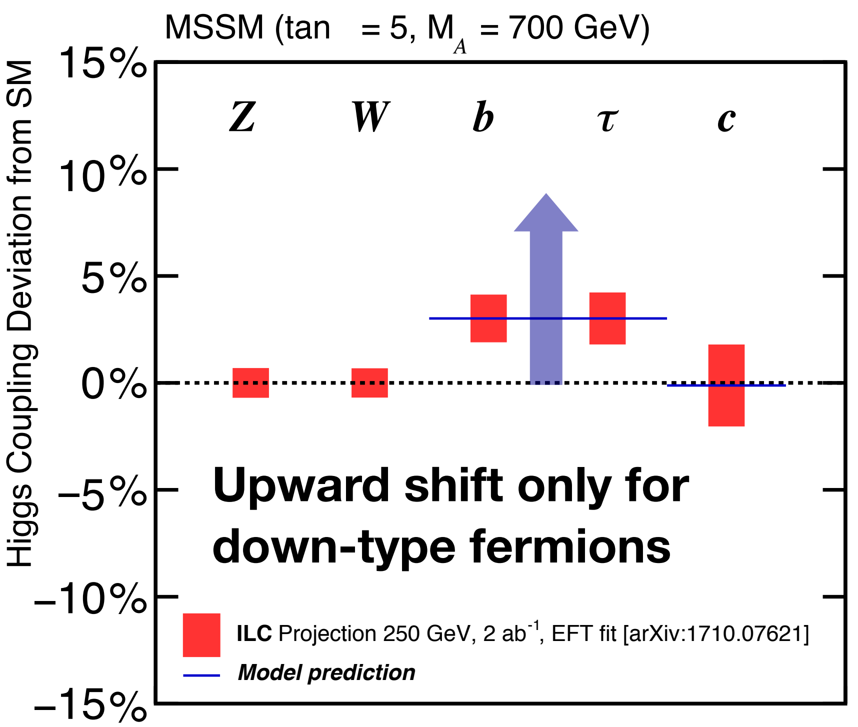
Our future forks in three ways

depending on the answer

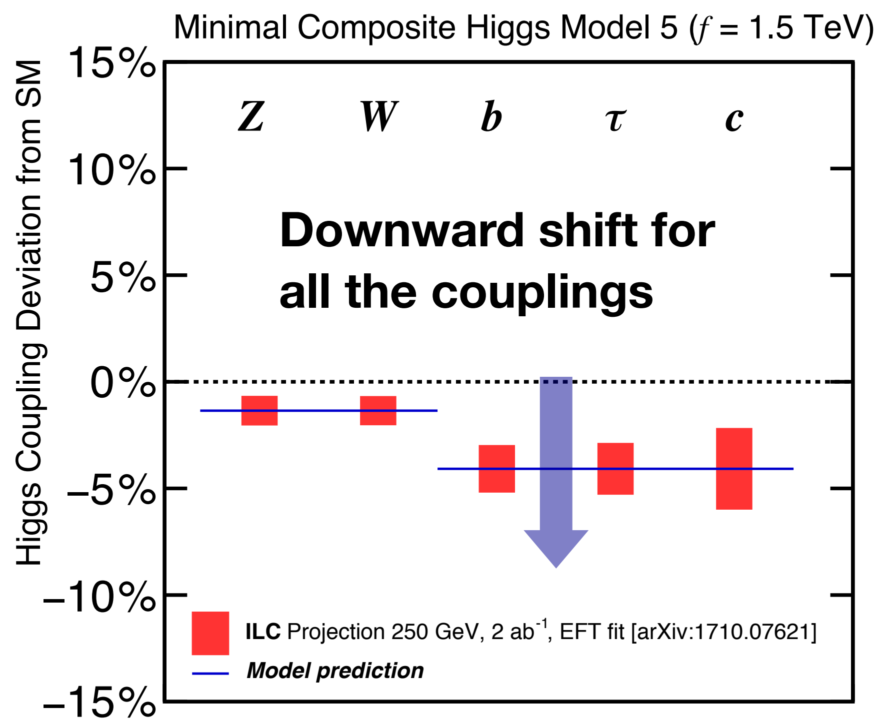


Higgs is the Key *to decide the direction*

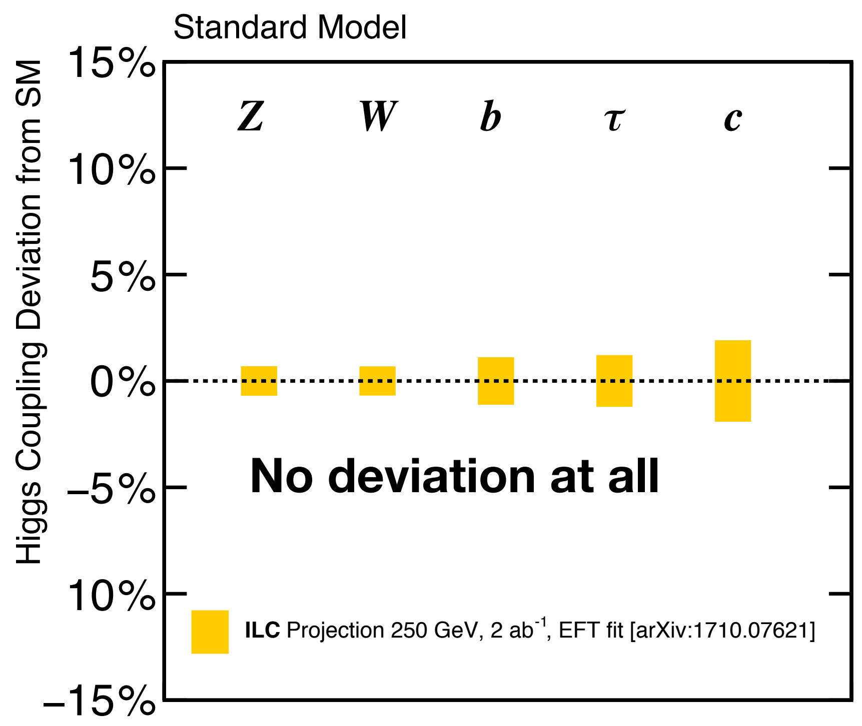
Supersymmetry
(MSSM)



Composite Higgs
(MCHM5)



Multi-verse?
(Standard Model)



example 1: **Minimal SUSY**

(tanβ=5, radiative correction factor ≈ 1)

$$\frac{g_{hbb}}{g_{h_{SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \text{TeV}}{m_A}\right)^2$$

heavy Higgs mass

example 2: **Minimal Composite Higgs Model**

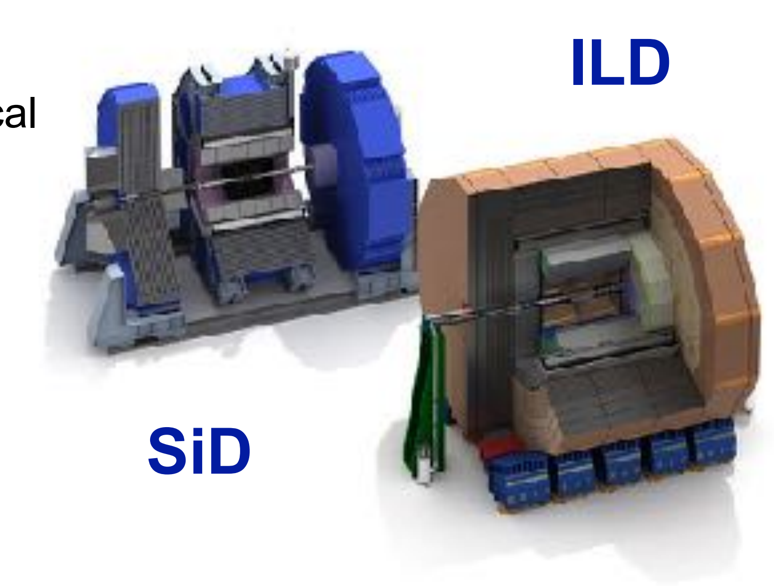
$$\frac{g_{hVV}}{g_{h_{SM}VV}} \simeq 1 - 8.3\% \left(\frac{1\ \text{TeV}}{f}\right)^2$$

$V=W/Z$ composite scal

New physics at 1 TeV → **deviation is at most ~10%**

We ***need 1%-level precision***

→ ***ILC Machine + ILD/SiD***



arXiv: 1901.09829
arXiv: 1903.01629

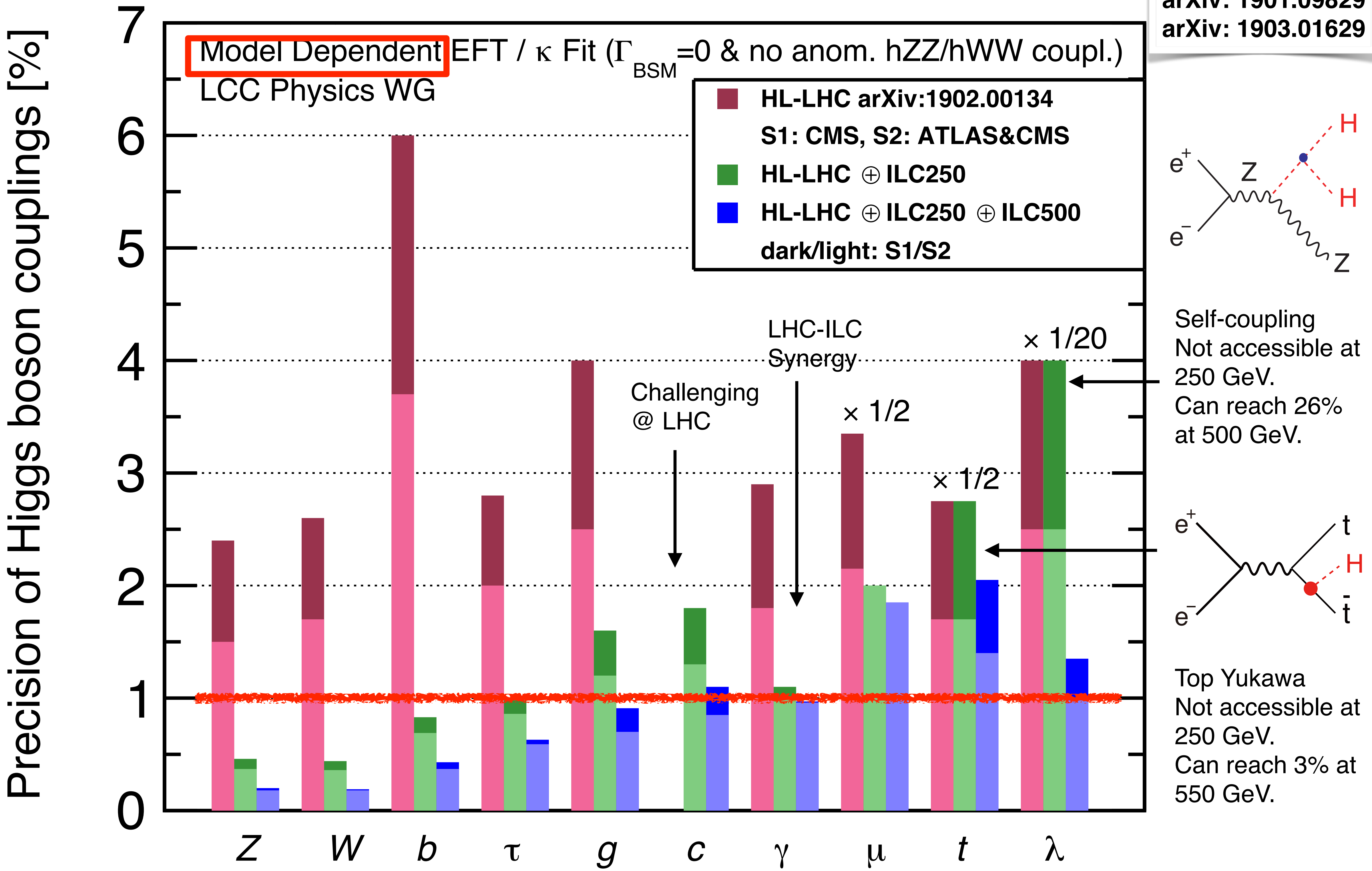


FIG. 1. Projected Higgs boson coupling uncertainties for the LHC and ILC using the model-dependent assumptions appropriate to the LHC Higgs coupling fit. The dark- and light-red bars represent the projections in the scenarios S1 and S2 presented in [9, 10]. The scenario S1 refers to analyses with our current understanding; the scenario S2 refers to more optimistic assumptions in which experimental errors decrease with experience. The dark- and light-green bars represent the projections in the ILC scenarios in similar S1 and S2 scenarios defined in [6]. The dark- and light-blue bars show the projections for scenarios S1 and S2 when data from the 500 GeV run of the ILC is included. The same integrated luminosities are assumed as for Figure 2. The projected uncertainties in the Higgs couplings to μμ, tt, and the self-coupling are divided by the indicated factors to fit on the scale of this plot.

With ILC, we can reach our goal of 1%-level precisions for all the major couplings.

- **The 250 GeV ILC will enable us to do precision measurements of absolutely normalized Higgs couplings.**

- **The 250 GeV ILC will show us the future direction of particle physics, by fingerprinting the deviation pattern of these precisely measured Higgs couplings.**

- **By adding experiments at higher energies (not covered today) in future which allow precision top studies and a measurement of the cubic Higgs self-coupling, we will be able to further narrow down viable new physics models.**

Backup

Details in the Support Documents

https://arxiv.org/abs/1903.01629

DESY 19-037, FERMILAB-FN-1067-PPD, IFIC/19-10
JLAB-PHY-19-2854, KEK Preprint 2018-92
LAL/RT 19-001, SLAC-PUB-17412
March 2019

The International Linear Collider
A Global Project

Prepared by: Philip Bambade[1], Tim Barklow[2], Ties Behnke[3], Mikael Berggren[3], James Brau[4], Dmitri Denisov[5,6], Angeles Faus-Golfe[1], Keisuke Fujii[7], Juan Fuster[8], Frank Gaede[3], Paul Grannis[9], Christophe Grojean[3], Andrew Hutton[10], Benno List[3], Jenny List[3], Shinichiro Michizono[7], Akiya Miyamoto[7], Olivier Napoly[11], Michael Peskin[2], Roman Pöschl[1], Frank Simon[12], Jan Strube[4,13], Junping Tian[14], Maksym Titov[11], Marcel Vos[8], Andrew White[15], Graham Wilson[16], Akira Yamamoto[7], Hitoshi Yamamoto[17], Kaoru Yokoya[7]

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[10]*Jefferson Lab*, [11]*CEA/Irfu*, [12]*Max Planck Inst., Munich*, [13]*PNNL*,
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(Representing the Linear Collider Collaboration and the global ILC community.)

The International Linear Collider (ILC) is now under consideration as the next global project in particle physics. In this report, we review of all aspects of the ILC program: the physics motivation, the accelerator design, the run plan, the proposed detectors, the experimental measurements on the Higgs boson, the top quark, the couplings of the W and Z bosons, and searches for new particles. We review the important role that polarized beams play in the ILC program. The first stage of the ILC is planned to be a Higgs factory at 250 GeV in the centre of mass. Energy upgrades can naturally be implemented based on the concept of a linear collider. We discuss in detail the ILC program of Higgs boson measurements and the expected precision in the determination of Higgs couplings. We compare the ILC capabilities to those of the HL-LHC and to those of other proposed e^+e^- Higgs factories. We emphasize throughout that the readiness of the accelerator and the estimates of ILC performance are based on detailed simulations backed by extensive R&D and, for the accelerator technology, operational experience.

https://arxiv.org/abs/1908.11299

DESY 19-146, IFIC/19-35
KEK Preprint 2019-22
SLAC-PUB-17467
August, 2019

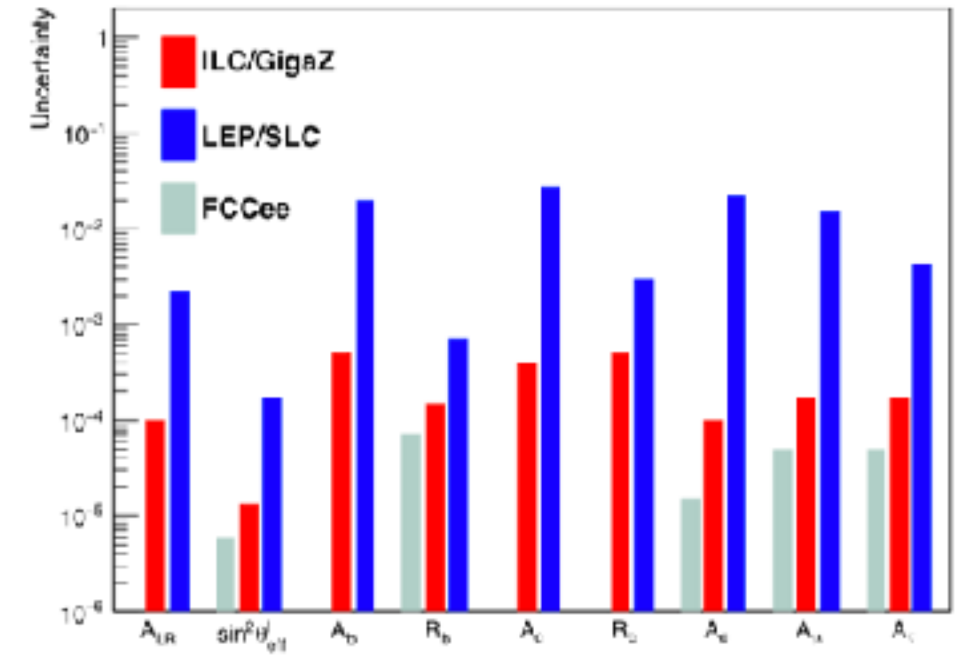
Tests of the Standard Model at the International Linear Collider

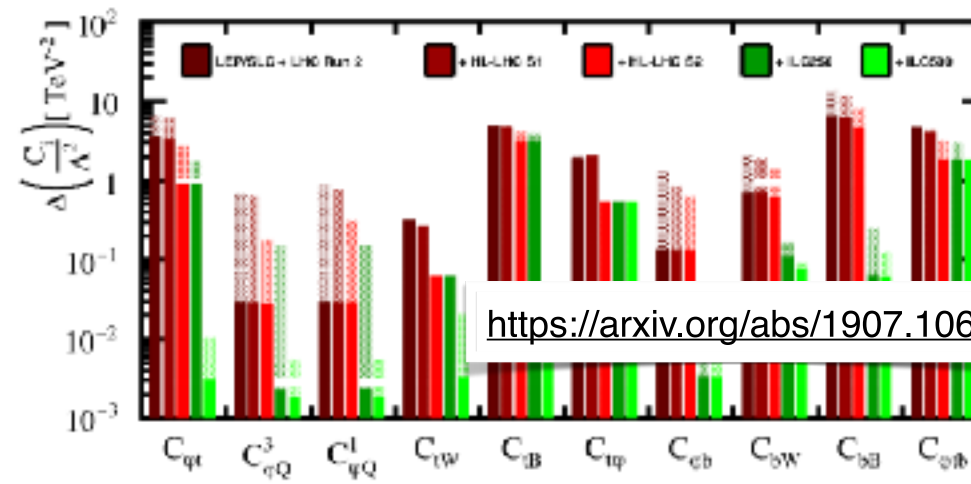
LCC Physics Working Group

Keisuke Fujii[1], Christophe Grojean[2,3], Michael E. Peskin[4] (Conveners); Tim Barklow[4], Yaunning Gao[5], Shinya Kanemura[6], Hyungdo Kim[7], Jenny List[2], Mihoko Nojiri[1,8], Maxim Perelstein[9], Roman Pöschl[10], Jürgen Reuter[2], Frank Simon[11], Tomohiko Tanabe[12], James D. Wells[13], Jaehoon Yu[14]; Junping Tian[12], Taikan Suehara[15], Marcel Vos[16], Graham Wilson[17]; James Brau[18], Hitoshi Murayama[8,19,20] (ex officio)

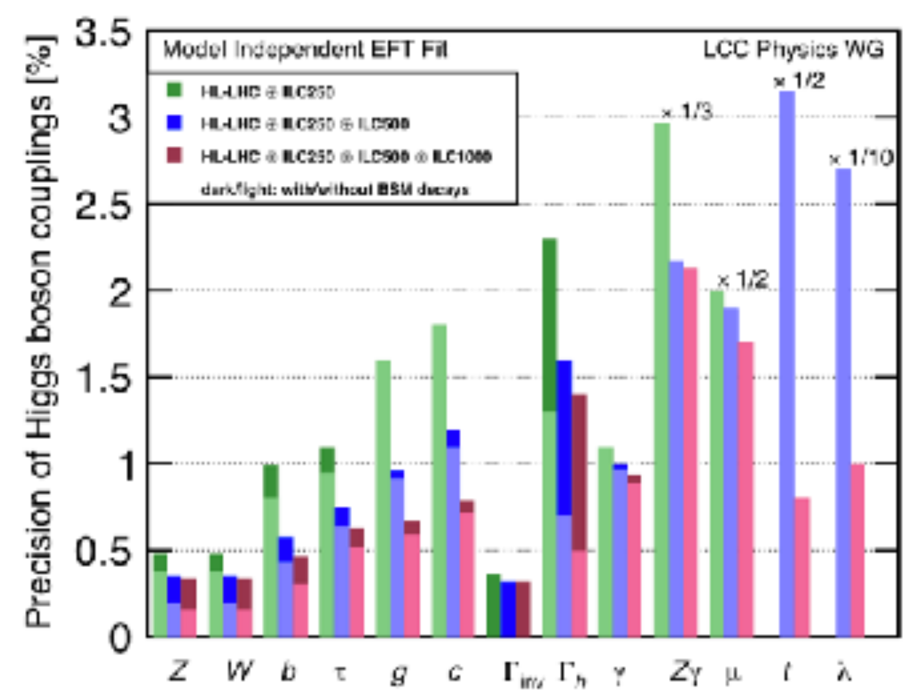
ABSTRACT

We present an overview of the capabilities that the International Linear Collider (ILC) offers for precision measurements that probe the Standard Model. First, we discuss the improvements that the ILC will make in precision electroweak observables, both from W boson production and radiative return to the Z at 250 GeV in the center of mass and from a dedicated GigaZ stage of running at the Z pole. We then present new results on precision measurements of fermion pair production, including the production of b and t quarks. We update the ILC projections for the determination of Higgs boson couplings through a Standard Model Effective Field Theory fit taking into account the new information on precision electroweak constraints. Finally, we review the capabilities of the ILC to measure the Higgs boson self-coupling.

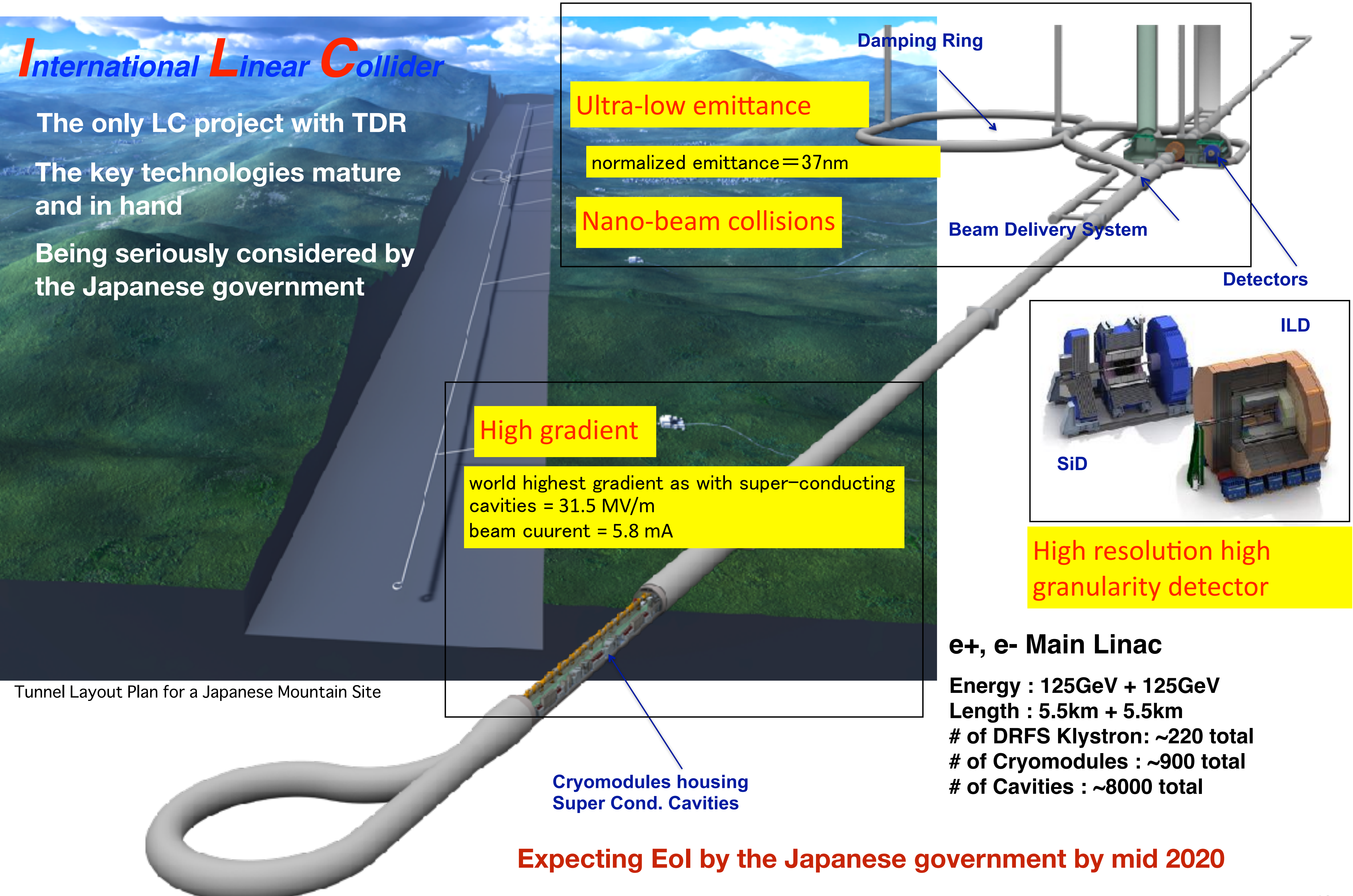




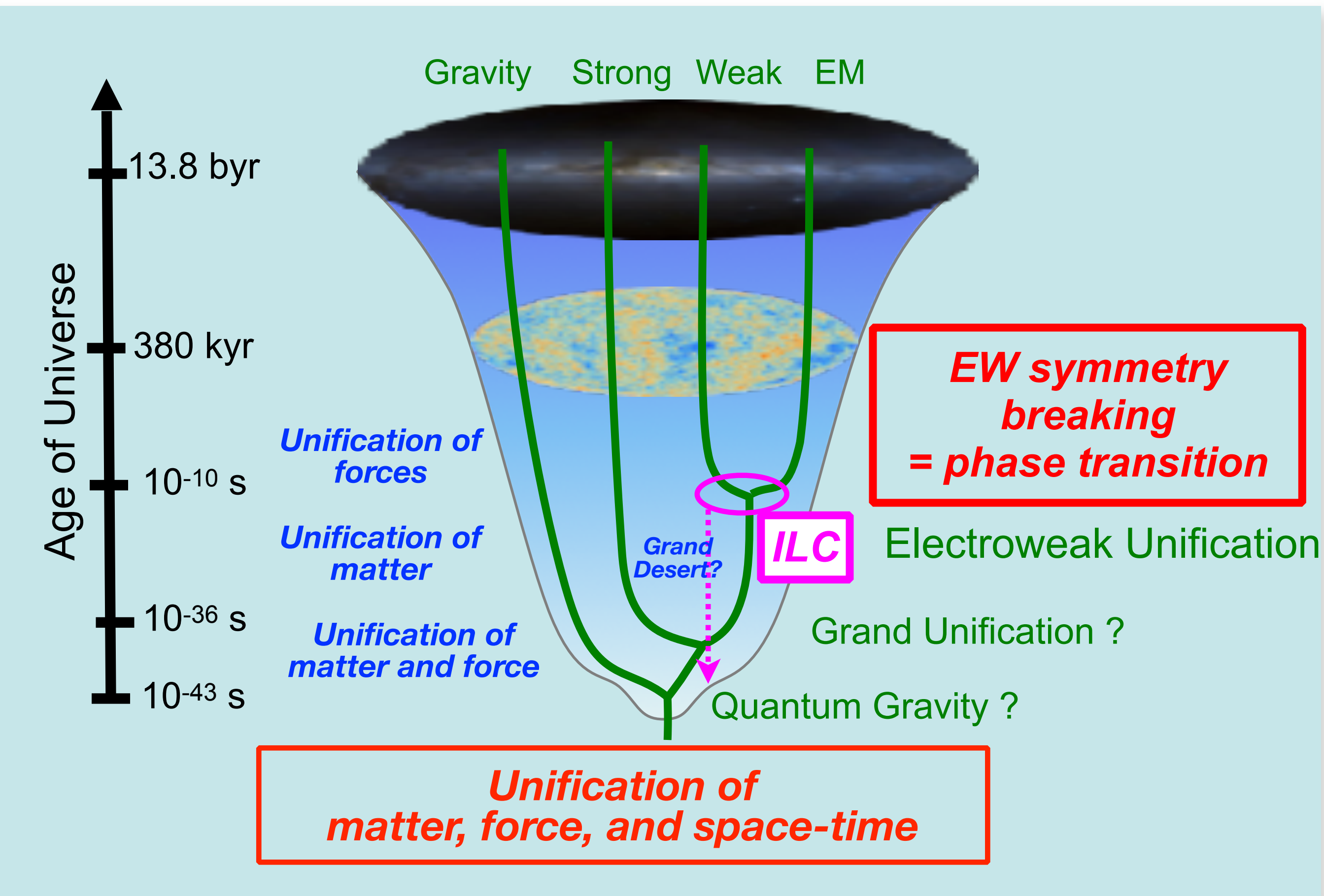
https://arxiv.org/abs/1907.10619

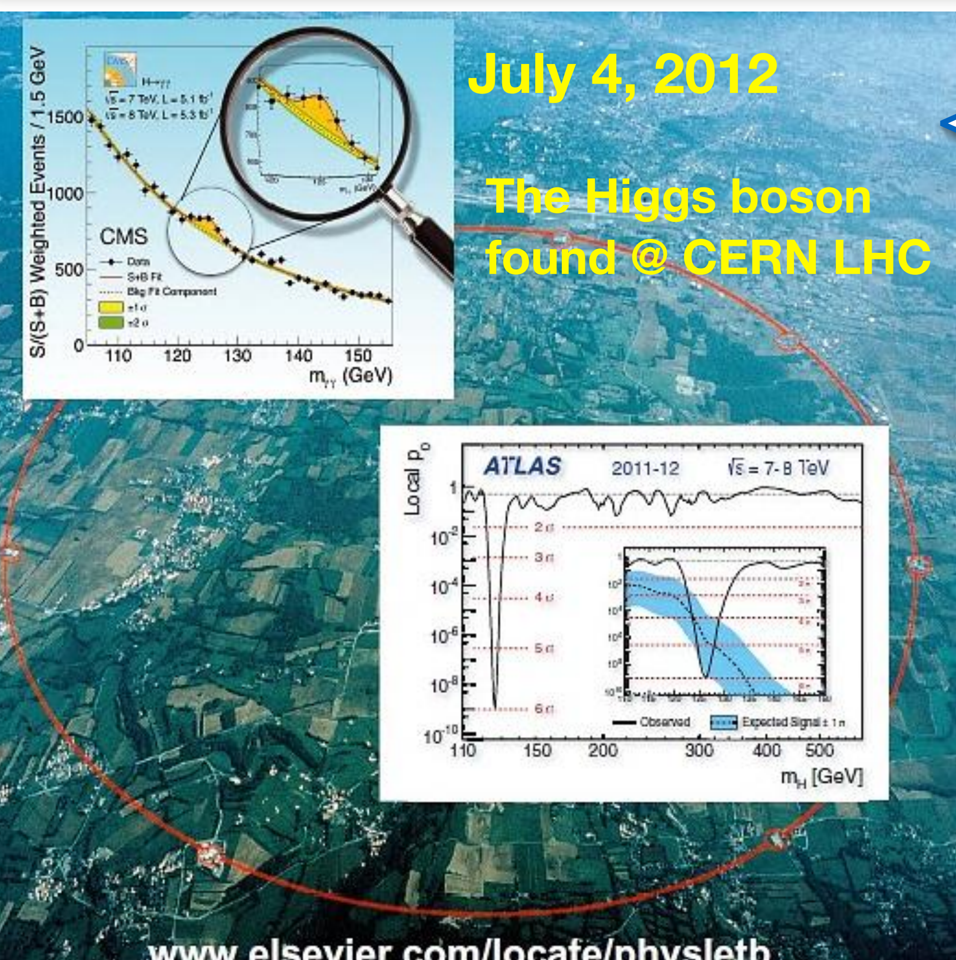


Bird's Eye View of the ILC Accelerator



Towards Ultimate Unification





Our goal is to go back in time to the moment of creation (Planck Scale), when everything, matter, force, and space-time, was conceived to be unified.

Standard Model (SM)
=Summary of Our Current Understanding

Gauge Symmetry = SU(3)xSU(2)xU(1)

Matter Fields = Quarks & Leptons (3 Gen.)

1995 Top discovery @ FNAL Tevatron
→3 generations of matter fields completed

Force Fields = Gauge Fields (γ,W/Z, g)

1983 W/Z discovery @ CERN SPPS
→ Gauge bosons for the 3 forces found

Symmetry Breaking Field = Higgs Field (H)
→ **2012 found @ LHC**: SM completed

Beyond the SM

The SM has been extremely successful.
→ Yet, there remain a lot of mysteries (Dark Matter, Baryon Number Asymmetry, Neutrino Mass/Mixing, Dark Energy, ..)

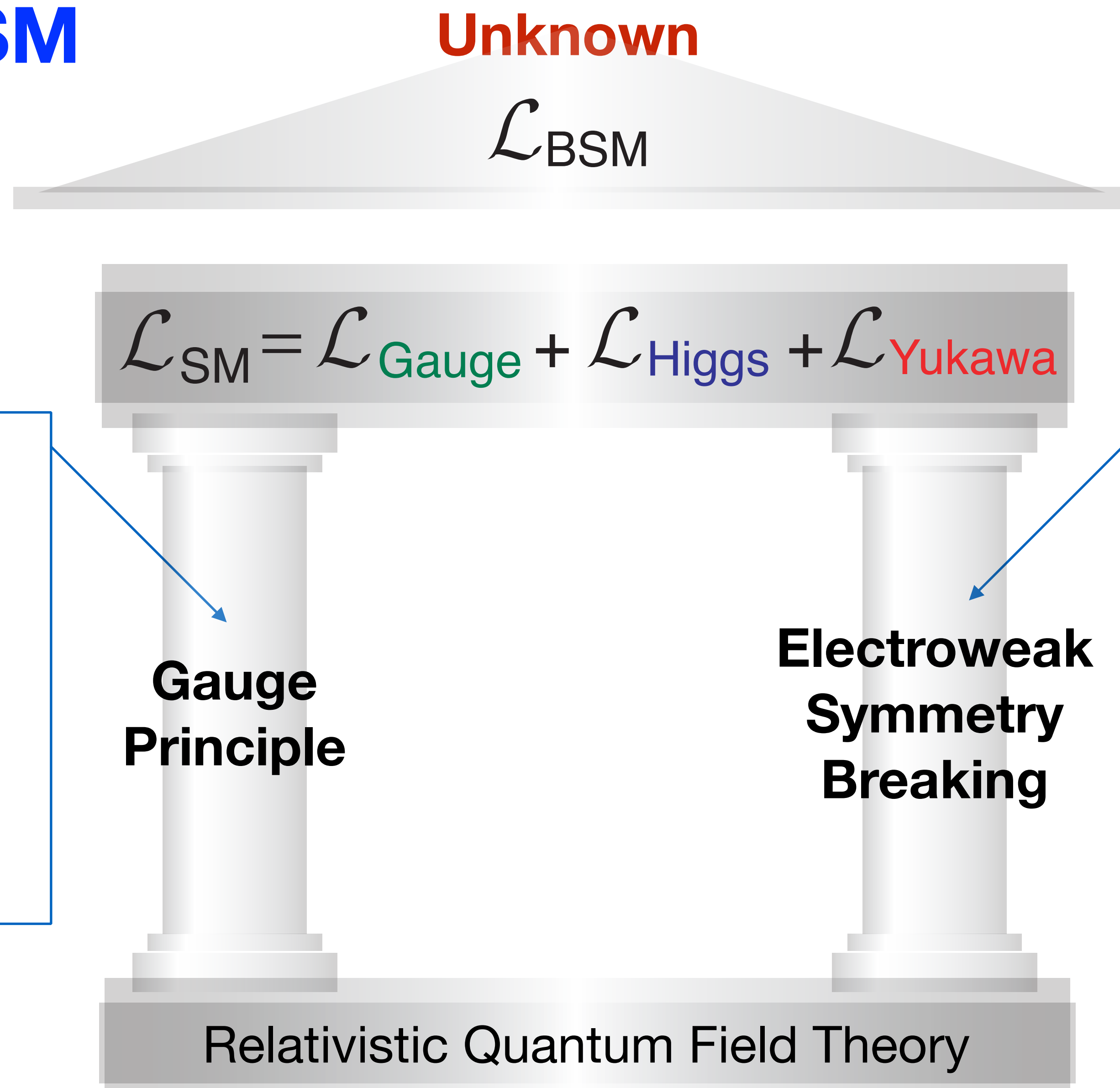
→ Start of new voyage to the Plank Scale: From the EW scale, there seems to be still a long way to go.

Why is the EW scale so important?

Why is the EW scale so important?

Mystery of the Higgs field filling the universe

2 Pillars of SM



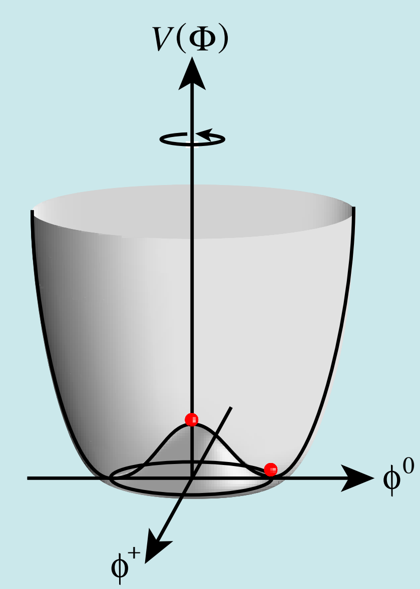
Success of SM
= success of
gauge theory
(left pillar)

Precisely tested!

Vacuum filled with weak charge (evidence: H125)

The nature of the Higgs field - its multiplet structure & dynamics behind it - **is all unknown!**

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



The SM does not explain **why the Higgs field filled the universe:**

Why $\mu^2 < 0$?

The EW scale is the key to answer this question.

Direct New Particle Searches

- $>10^3$ higher luminosity than LEP2
- beam polarizations
- much better detectors
- trigger-less data taking

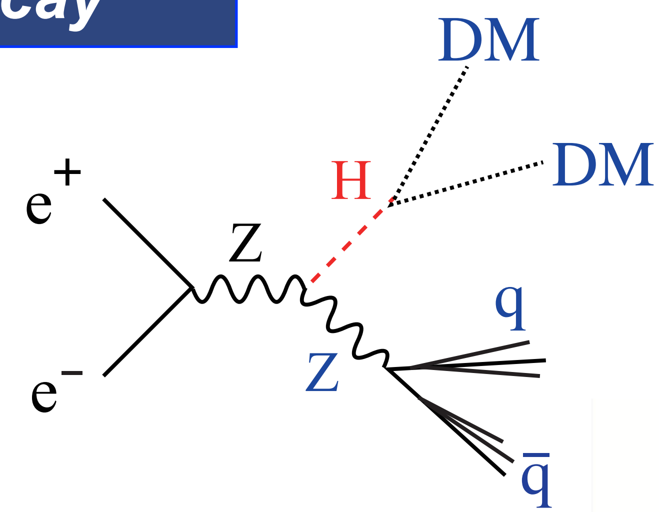
enhance sensitivities to regions with small cross sections and compressed mass spectrum, which are challenging at LHC

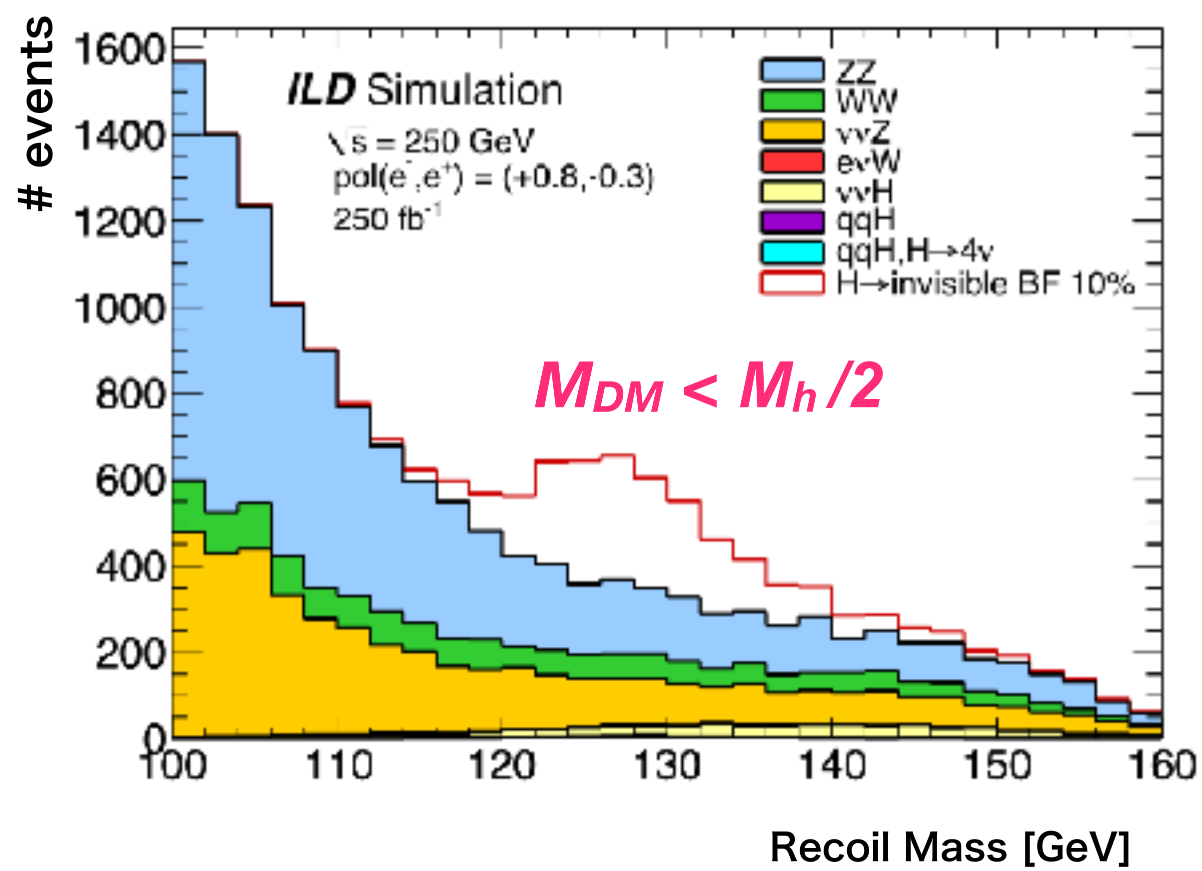
WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle

1. Higgs Invisible Decay

Effective when the Dark Matter particle interacts with the Higgs boson





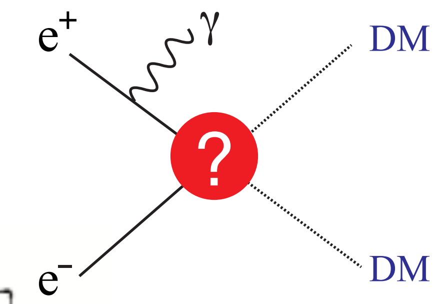
Possible to access BR_{inv} to 0.3%!

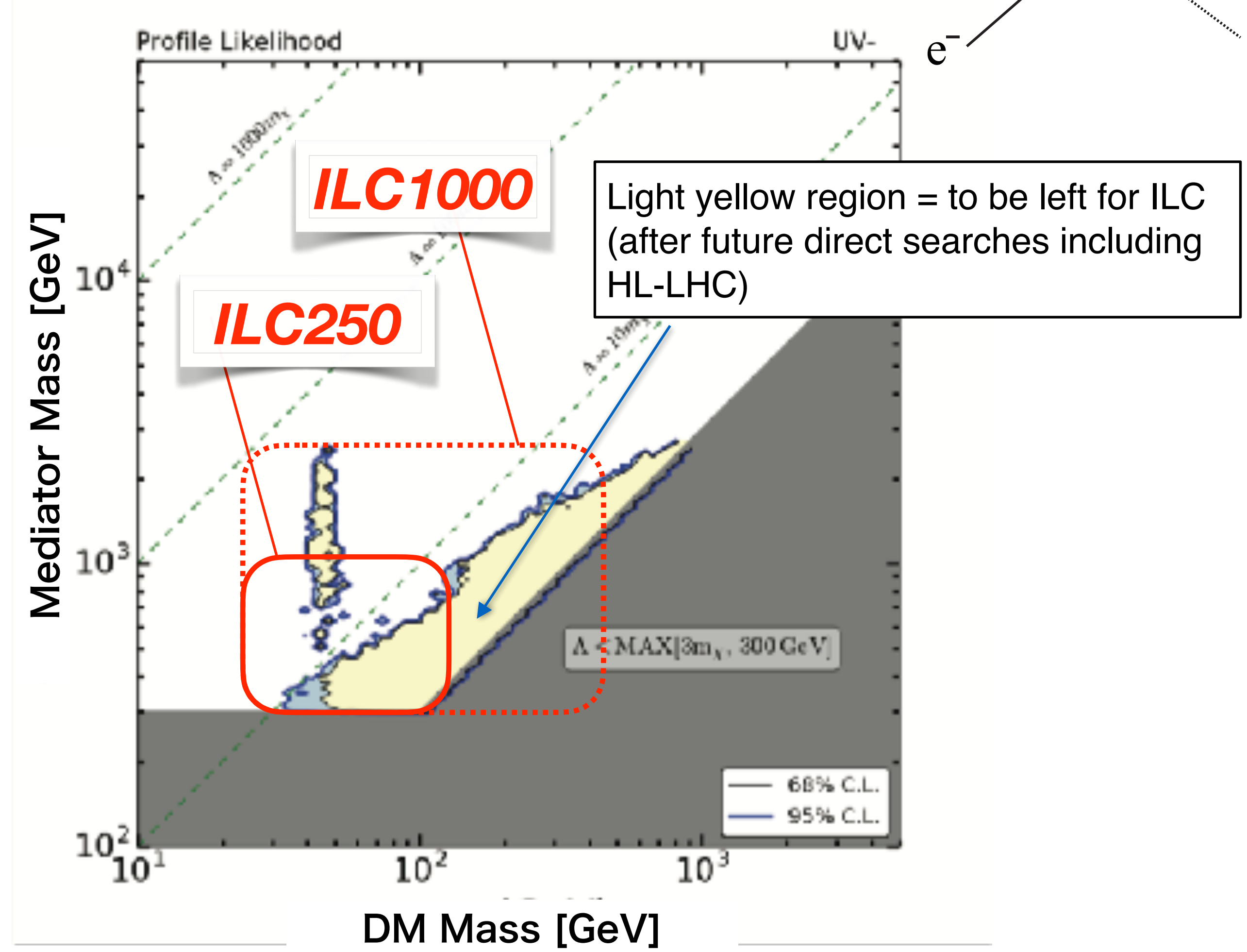
O(10) more sensitive than HL-LHC

2. Mono-photon Search

Sensitive to various types of Dark Matter particles

Effective in particular for DM particles which couple mostly to EW gauge bosons and leptons and hence difficult to find at the LHC.





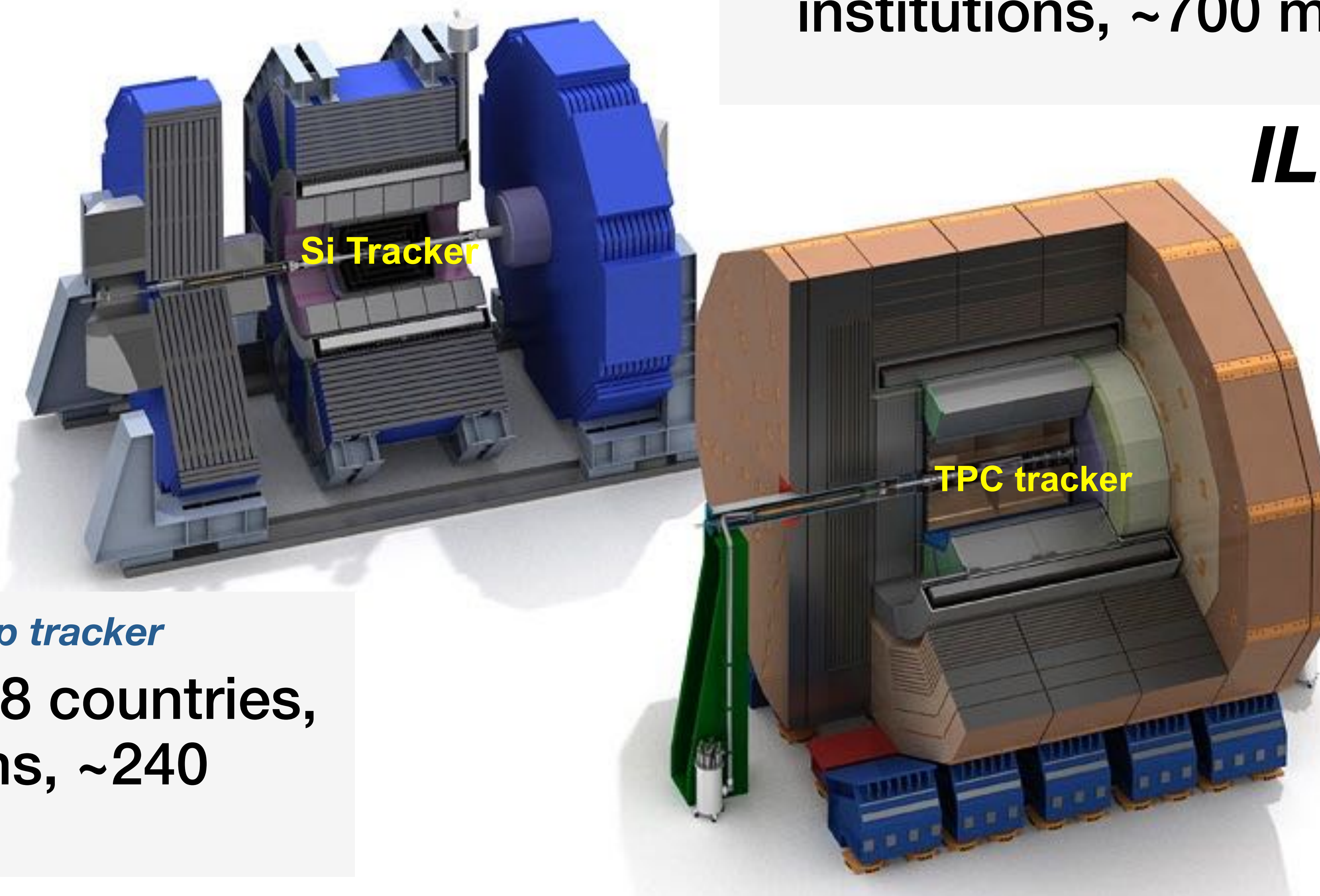
Significant chunk of region remains for ILC250!

Two ILC Detectors in the TDR

Design studies ongoing by international teams

- Compared with LHC detectors, ILC detectors have **~10 times better momentum resolution and 100~1000 times finer granularity.**
- This performance **can be achieved only in the clean environment of the ILC**, and cannot be achieved in the LHC environment.

- Large R with ***TPC tracker***
  - *LOI signatories:* 32 countries, 151 institutions, ~700 members



ILD

SiD

- High B with ***Si strip tracker***
  - *LOI signatories:* 18 countries, 77 institutions, ~240 members

Higgs Studies

Recent Development: EFT Analysis

Potential drawback:

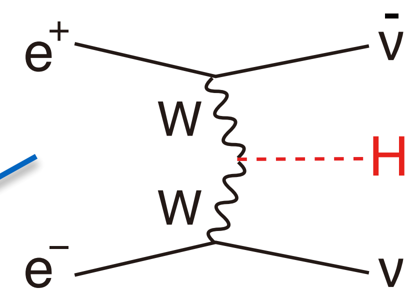
$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

SU(2)xU(1) inv. dim.6 operators

It has been said that Γ_h (Higgs total width) necessary for absolute coupling normalization requires >350GeV.

$$\Gamma_h = \frac{\Gamma(h \to WW^*)}{BR(h \to WW^*)}$$

$$\Gamma(h \to WW^*) \propto \sigma(\nu\bar{\nu}h)$$



cross section: small@250GeV

Solution: *EFT* (*Effective Field Theory*)

to relate **hZZ** and **hWW** couplings

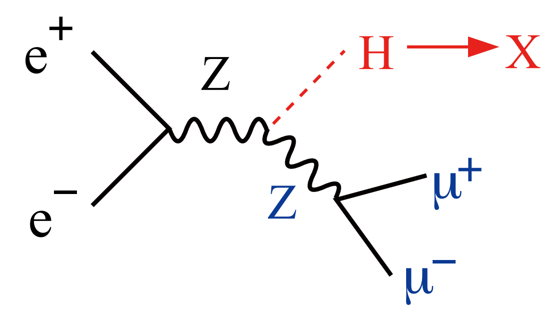
LHC Run II results suggest that **250 GeV** is likely **in the validity range of the EFT**

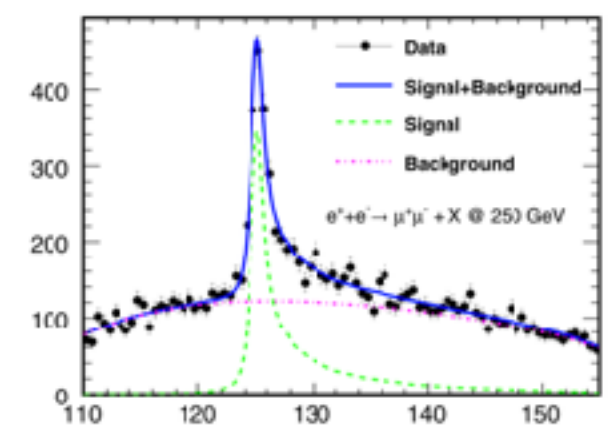
 # EFT coefficients to decide: 17 @ ILC

This ILC number is quite tractable.

Beam polarization doubles the number of usable observables.

The importance of ***the σ_{Zh} measurement by recoil mass technique*** remains the same.





W_L and Z_L are NGBs from the Higgs sector.
can use all the SM processes with W and Z to constrain the EFT coefficients.

Absolute and model-independent Higgs coupling measurements possible with the 250 GeV data alone.

EFT Lagrangian Before EW Symmetry Breaking

$$\mathcal{L} = \mathcal{L}_{SM} + \Delta\mathcal{L}$$

$$\begin{aligned}\Delta\mathcal{L} = &\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi) + \frac{c_T}{2v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi) - \frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3 \\ &+\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu} + \frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu} \\ &+\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g^3 c_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_\rho W^{c\rho\mu} \\ &+i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu L) + +4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu\Phi)(\overline{L}\gamma_\mu t^a L) \\ &+i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu\Phi)(\overline{e}\gamma_\mu e)\ . \\ &+\frac{g^2\tilde{c}_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + \frac{4gg'\tilde{c}_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{g'^2\tilde{c}_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\tilde{B}^{\mu\nu}\end{aligned}$$

Manifestly SU(2)xU(1) gauge invariant

10 parameters of which C_6 only affects Higgs self-coupling analysis.

5 parameters to account for Higgs coupling to b, c, τ, μ, g.

\+ **2** parameters to account for invisible and exotic Higgs decays.

\+ **4** parameters to account for the shifts of g, g’, v, and λ

\+ **2** parameters (CHL-type) to shift W, Z widths.

Example of Non-Higgs Process that plays an important role in the EFT fit

$e^+e^- \to W^+W^-$ (Triple Gauge Couplings)

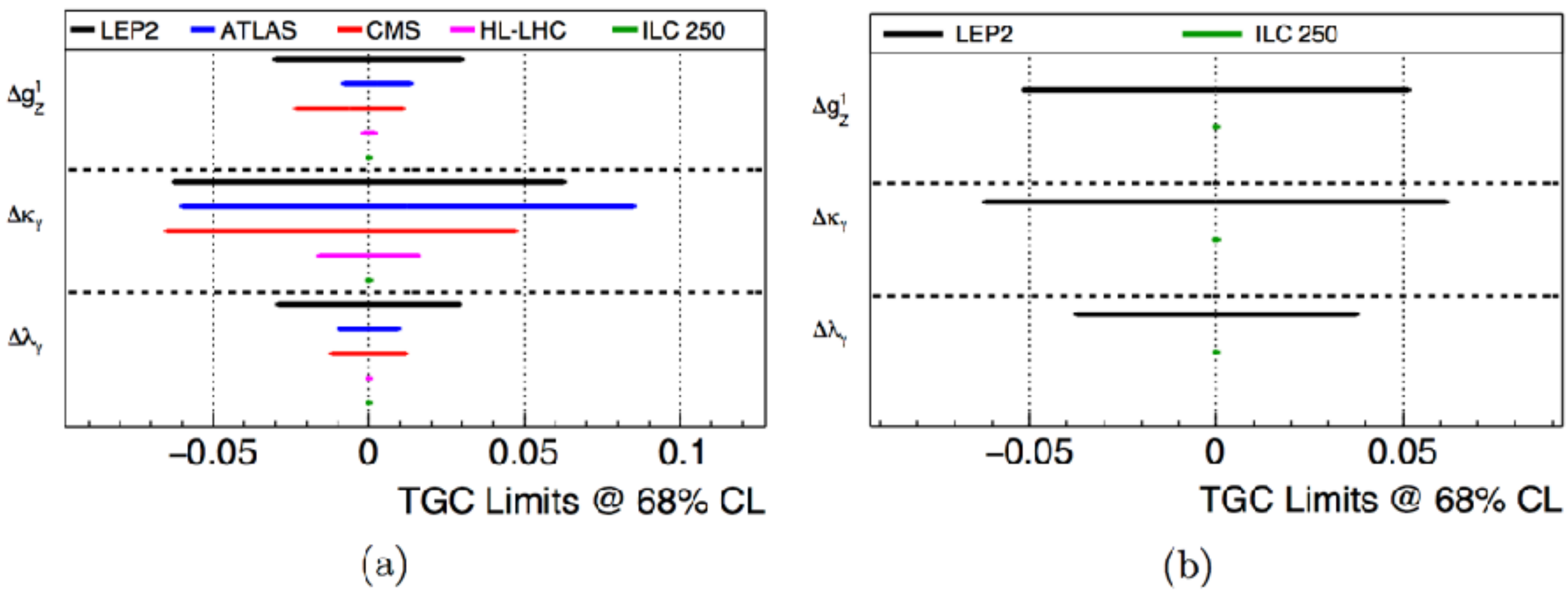


Figure 11: TGC precisions for LEP 2, Run1 at LHC, HL-LHC and the ILC at $\sqrt{s} = 250$ GeV with 2000 fb^{-1} luminosity (ILC 250) using one parameter fits (a) and for LEP 2 and ILC 250 using three parameter fits (b).

Significant improvements from HL-LHC and LEP2 !

coupling	current	S1*	S1	S2*	S2
hZZ - LHC	11.		2.5		1.7
- ILC 250		0.67	0.46	0.64	0.36
- ILC 500		0.35	0.20	0.32	0.18
hWW - LHC	15.		3.0		2.1
- ILC 250		0.66	0.44	0.62	0.36
- ILC 500		0.34	0.19	0.32	0.18
hbb - LHC	29.		5.5		4.0
- ILC 250		1.1	0.83	0.90	0.68
- ILC 500		0.58	0.42	0.48	0.36
$h\tau\tau$ - LHC	17.		3.6		2.8
- ILC 250		1.2	0.98	1.0	0.86
- ILC 500		0.74	0.63	0.67	0.59
hgg - LHC	15.		4.0		2.8
- ILC 250		1.7	1.6	1.3	1.2
- ILC 500		0.95	0.91	0.74	0.70
hcc - LHC	-		-		-
- ILC 250		1.9	1.8	1.4	1.3
- ILC 500		1.2	1.1	0.9	0.84
$h\gamma\gamma$ - LHC	15.		3.6		2.8
- ILC 250		1.2	1.1	1.2	1.0
- ILC 500		1.0	0.99	1.0	0.97
$h\mu\mu$ - LHC	70.		7.6		7.0
- ILC 250		5.6	5.6	5.5	5.5
- ILC 500		5.1	5.1	5.0	5.0
htt - LHC	14.		5.5		3.6
- ILC 250		-	5.5	-	3.6
- ILC 500		6.3	4.1	4.5	2.8
hhh - LHC			80		60
- ILC 500		-	80	-	60
- ILC 500		27	27	20	20
Γ_{tot} - ILC 250		2.5	1.3	2.1	1.1
- ILC 500		1.6	0.69	1.3	0.59
Γ_{inv} - ILC 250		0.32	-	0.32	-
- ILC 500		0.29	-	0.28	-

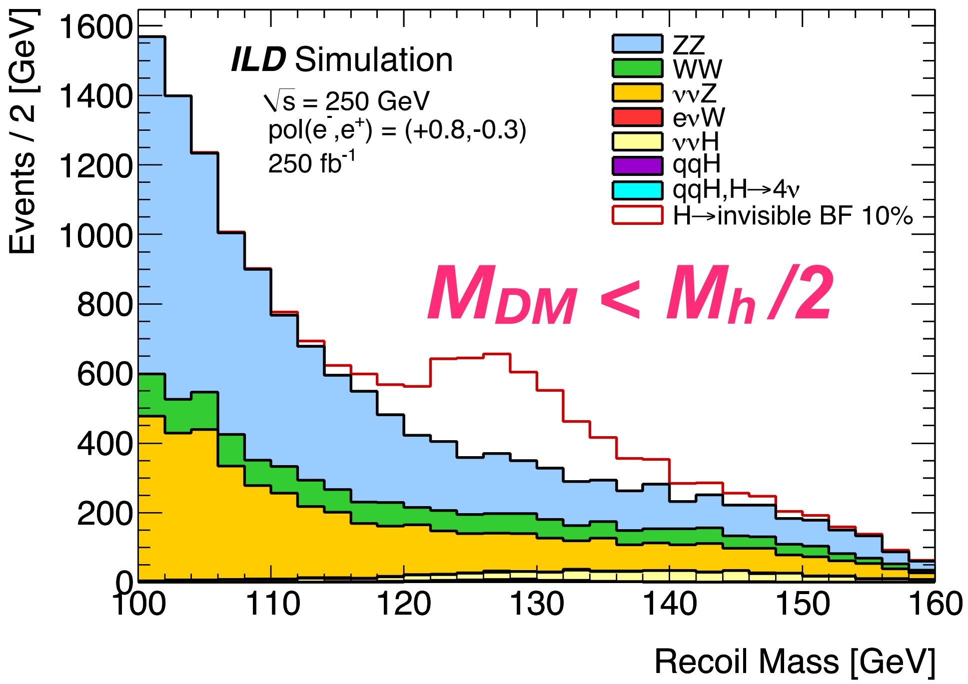
TABLE XV: Projected uncertainties in the Higgs boson couplings for LHC and for and for ILC at 250 GeV, with precision LHC input, in various scenarios. All values are given in percent (%). The values labeled "current" are taken from Table 8 of the CMS publication [240]. The LHC S1 and S2 values are taken from [239]. The ILC scenarios are as described in this paper. We also include our S1* and S1 projections including the full ILC data set with running at 250 GeV and 500 GeV. The ILC at 250 GeV only does not have direct sensitivity to the *htt* and *hhh* couplings; thus no model-independent values are given in these lines. The bottom lines give, for reference, the projected uncertainties in the Higgs boson total width and the 95% confidence limits on the Higgs boson invisible width. One should remember that one of the assumptions in the model-dependent S1/S2 fits is that the Higgs boson has no invisible or other exotic decay models. We believe that the comparison of the S1 values gives the sharpest comparison between the capabilities of LHC alone and the capabilities after adding the ILC measurements.

Invisible/Exotic※1 Higgs Decays

By making maximum use of Z-tagged Higgs bosons,
all kinds of invisible/exotic decays can be searched
for with high sensitivity

Invisible Higgs Decay

※1: exotic decays = non−SM decays



BR(H→invis.) < 0.3% at 95%CL
2ab⁻¹@ 250GeV

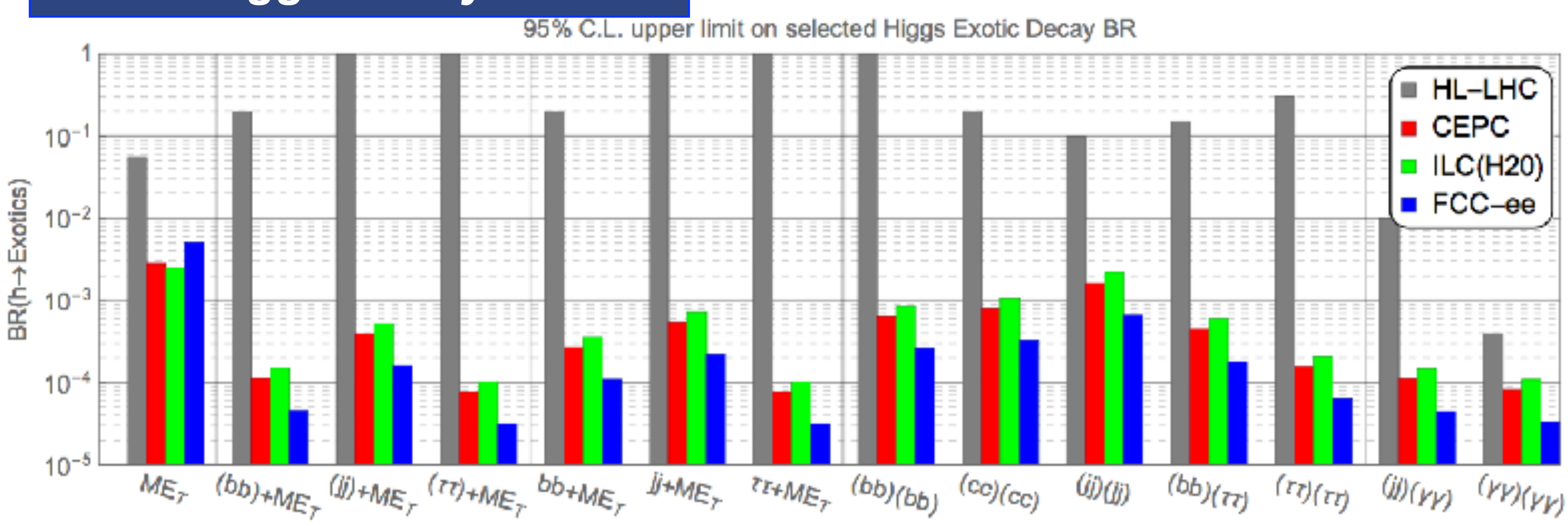
An attractive way to build a model of Dark Matter
= to assume a "Hidden Sector"

Invisible / Exotic Higgs Decays
= ideal hunting ground for

Higgs Portal $\epsilon|\varphi|^2|\hat{S}|^2$

Neutrino Portal $\epsilon\, L^\dagger \cdot \varphi \hat{N}$

Exotic Higgs Decays

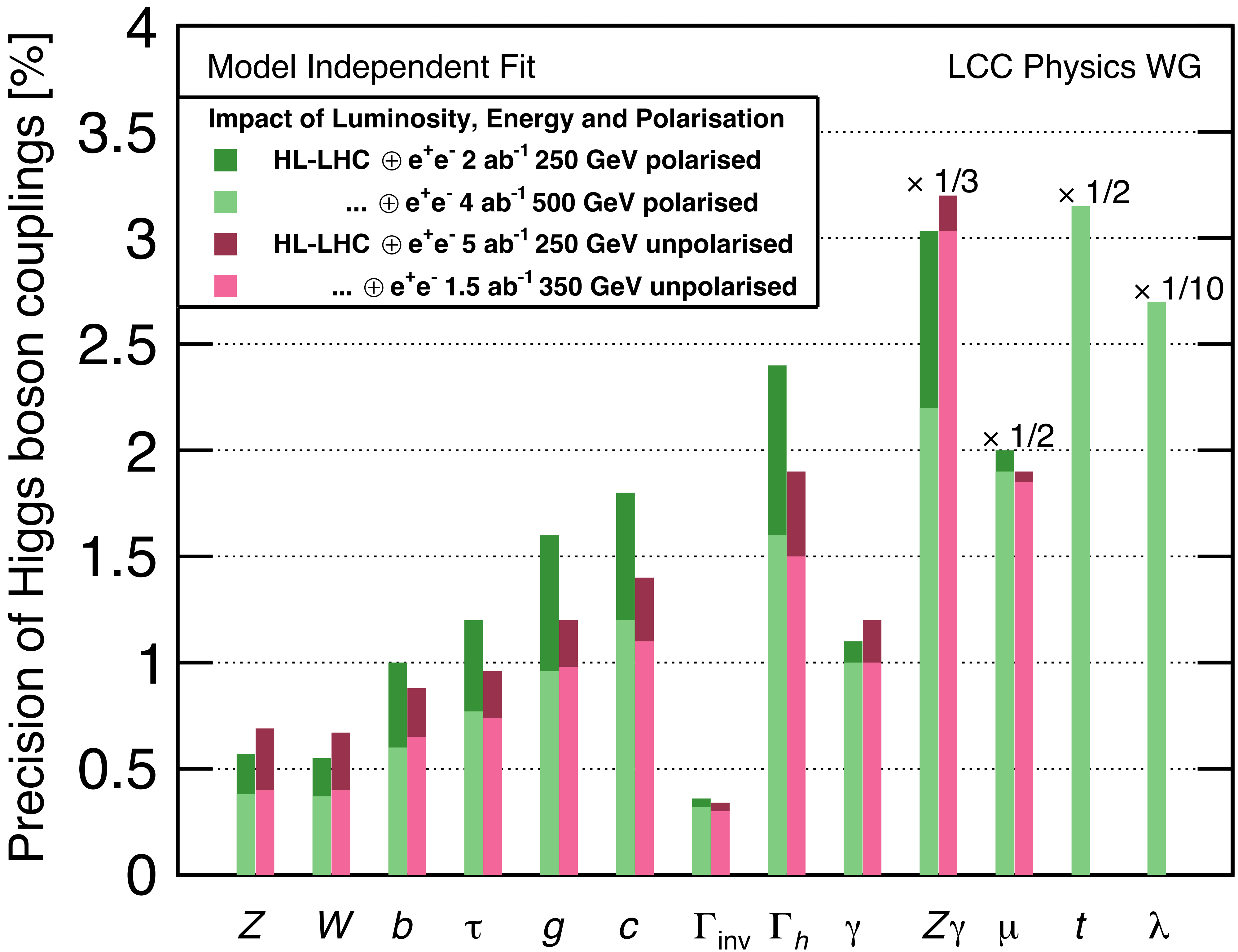


Liu, Wang, Zhang
arXiv: 1612.09284

BR= 0.1%
→ >500 events
2ab⁻¹@ 250GeV

Power of Polarization

arXiv: 1903.01629

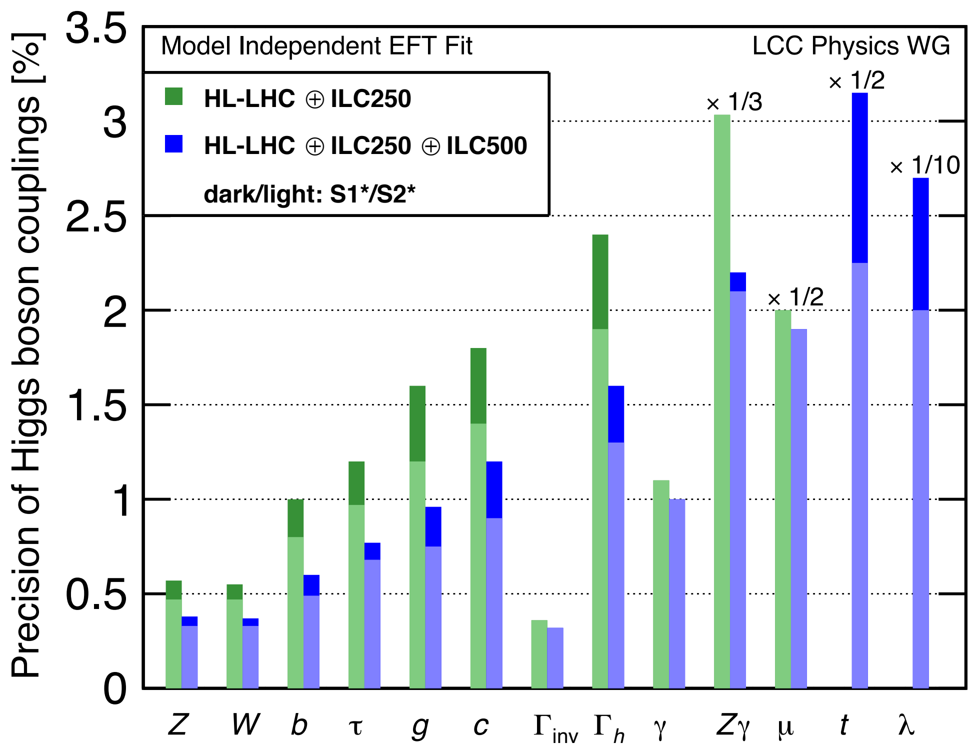


Polarized 2 ab^{-1} is roughly equivalent to unpolarized 5 ab^{-1}!

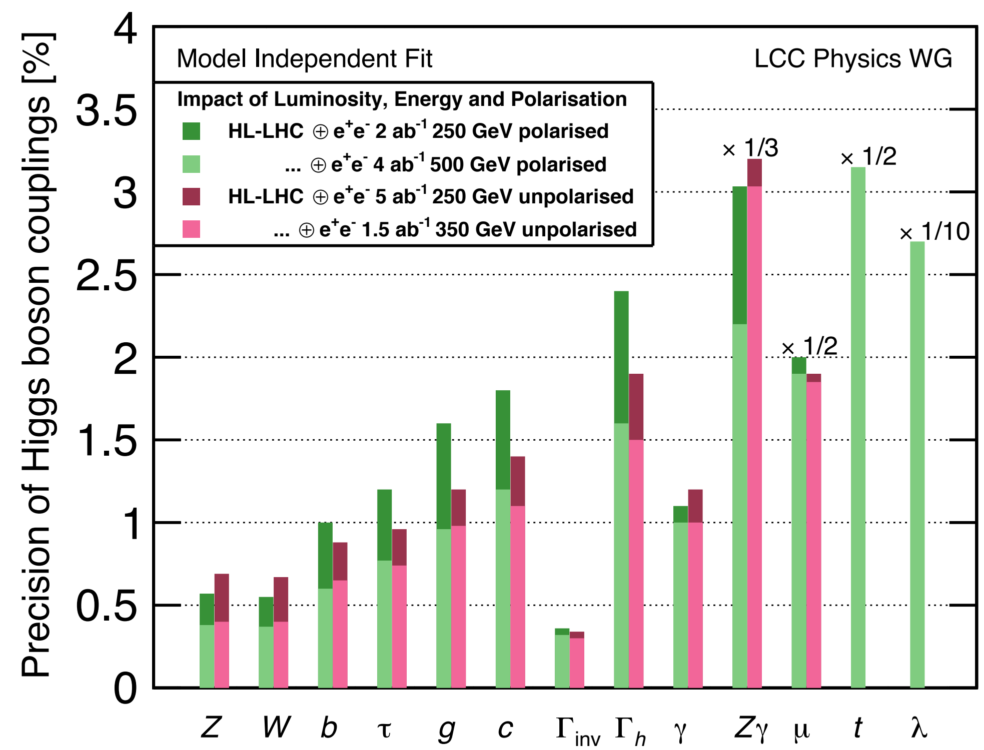
New Manhattan Plots

arXiv: 1903.01629

w/ (S2*) and w/o (S1*) foreseen improvements

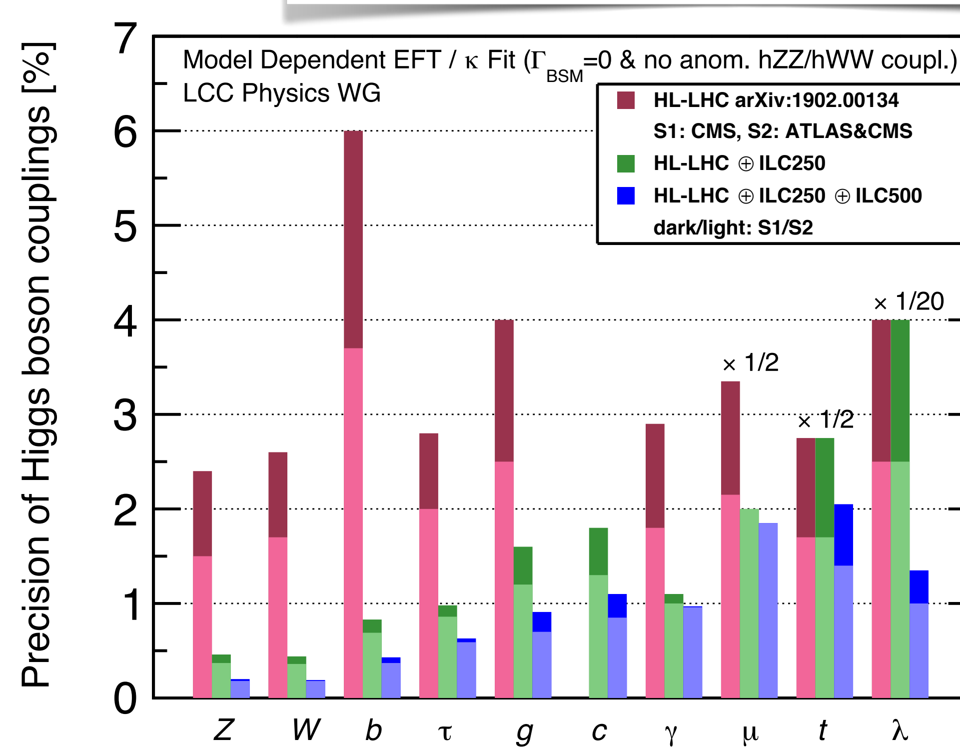


Unpol. 5ab^{-1} ~ Pol. 2ab^{-1}



<1% level precision for most couplings

Significant improvement from HL-LHC



systematic errors included in the global fit

for every σ and σxBR measurement

- 0.1% from theory computations
- 0.1% from luminosity
- 0.1% from beam polarizations
- 0.1%⊕0.3%/sqrt(L/250) from b-tagging and analysis

newly added a limit of 0.1% systematic errors from experimental analysis

same systematic errors are used for unpolarized case, except without item 3

ILC Higgs Capabilities at 1 TeV

JENNY LIST, MICHAEL PESKIN, JUNPING TIAN, MARCEL VOS
(REPRESENTING THE LCC PHYSICS WORKING GROUP)

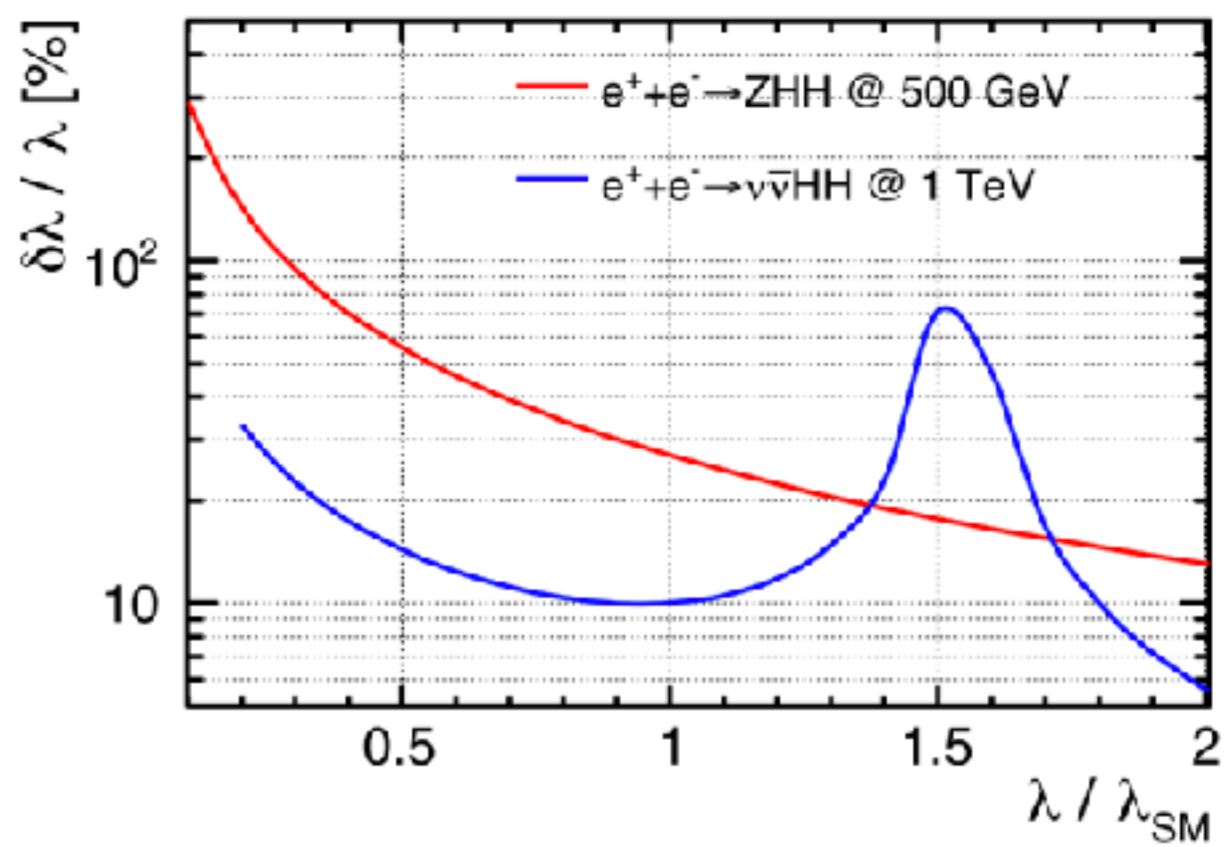
8ab-1 split into 4 pol. combinations:
(-+, +-, ++, - -) = (40%,40%,10%,10%)

coupling	2 ab^{-1} at 250	+ 4 ab^{-1} at 500	+8 ab^{-1} at 1000
HZZ	0.48 / 0.38	0.35 / 0.20	0.34 / 0.16
HWW	0.48 / 0.38	0.35 / 0.20	0.34 / 0.16
Hbb	0.99 / 0.80	0.58 /0.43	0.47 / 0.31
$H\tau\tau$	1.1 / 0.95	0.75 / 0.64	0.63 / 0.52
Hgg	1.6 / 1.6	0.96 / 0.92	0.67 / 0.59
Hcc	1.8 / 1.8	1.2 / 1.1	0.79 / 0.72
$H\gamma\gamma$	1.1 / 1.1	1.0 / 0.97	0.94 / 0.89
$H\gamma Z$	8.9 / 8.9	6.5 / 6.5	6.4 / 6.4
$H\mu\mu$	4.0 / 4.0	3.8 / 3.8	3.4 / 3.4
Htt	—	6.3	1.6
HHH	—	27	10
Γ_{tot}	2.3 / 1.3	1.6 / 0.70	1.4 / 0.50
Γ_{inv}	0.36 / —	0.32 / —	0.32 / —

2nd number assumes Σ BR(SM)_i = 1

Significant improvements in single Higgs and WW productions

Significant improvements in Top Yukawa and Triple Higgs couplings



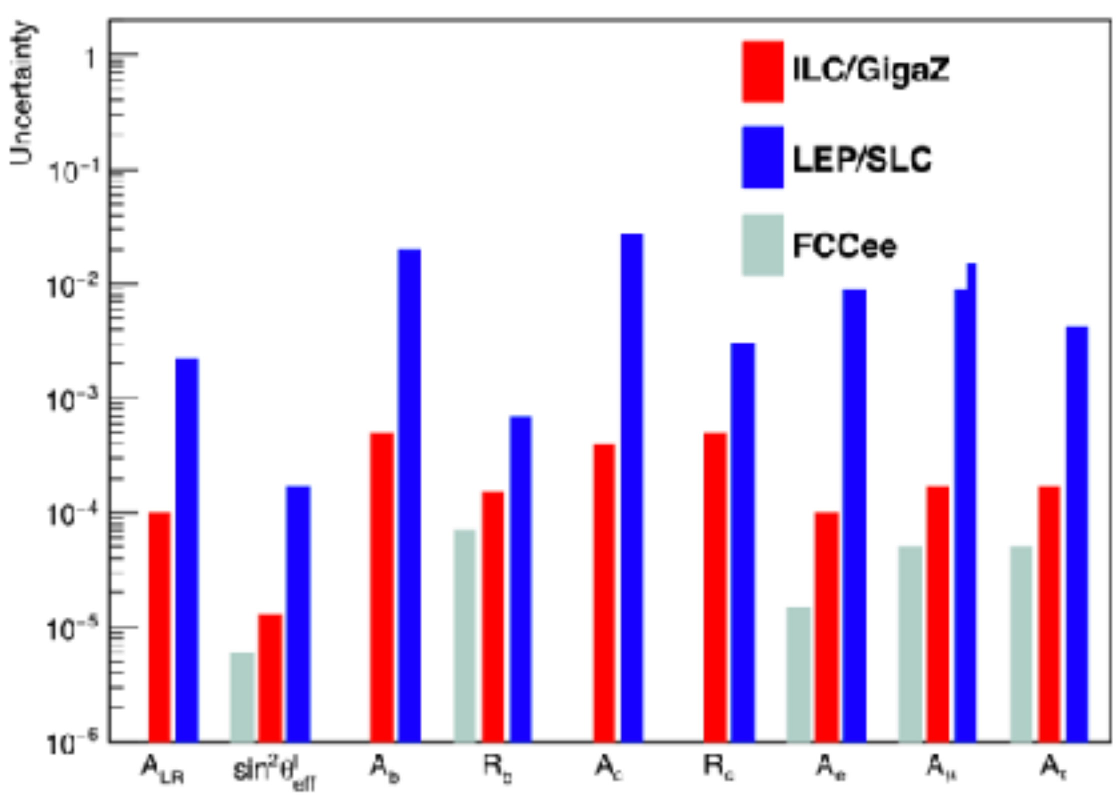
ILC Capabilities for Precision Electroweak Measurements

Keisuke Fujii, Daniel Jeans, Masakazu Kurata, Jenny List,
Michael Peskin, Roman Pöschl, Francois Richard,
Taikan Suehara, Junping Tian, Hitoshi Yamamoto
(representing the LCC Physics Working Group
and the ILC Technical Change and Management Board)

	sgn($P(e^-)$, $P(e^+)$) = (-,+)	(+,-)	(-,-)	(+,+)	sum
luminosity [fb^{-1}]	40	40	10	10	
$\sigma(P_{e^-}, P_{e^+})$ [nb]	83.5	63.7	50.0	40.6	
Z events [10^9]	3.3	2.5	0.50	0.41	6.8
hadronic Z events [10^9]	2.3	1.8	0.35	0.28	4.7

Quantity	Value	current $\delta[10^{-4}]$	GigaZ $\delta_{stat}[10^{-4}]$	GigaZ $\delta_{sys}[10^{-4}]$	250 GeV $\delta_{stat}[10^{-4}]$	250 GeV $\delta_{sys}[10^{-4}]$
boson properties						
m_W	80.379	1.5	-	-		0.3 °
m_Z	91.1876	0.23	-	-	-	-
Γ_Z	2.4952	9.4		3.2	-	-
$\Gamma_Z(had)$	1.7444	11.5		3.2	-	-
Z-e couplings						
$1/R_e$	0.0482	24.	2.	4 †	5.5	10 +
A_e	0.1515	139.	0.1	5 *	9.5	3 *
g_L^e	-0.632	16.	1.	2.5	2.8	7.6
g_R^e	0.551	18.	1.	2.5	2.9	7.6

The source of the dominant systematic error:
† acceptance; ○ energy scale; * beam polarization;
# jet correlations; + flavor tag.

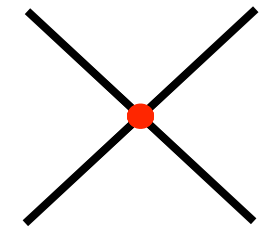


Radiative Return to Z @ 250 GeV already gives a factor of 10 better A_e than LEP/SLC. Giga-Z further improves precisions.

Update on ILC capabilities for the ESPP BSM working group on Resonances and New Strong Interactions

Keisuke Fujii, Jenny List, Maxim Perelstein, Michael Peskin, Roman Pöschl, Taikan Suehara, Junping Tian, Marcel Vos
(representing the LCC Physics Working Group)

4-fermion contact int.



$$\mathcal{L}_{LL} = \frac{g^2_{\rm contact}}{2\Lambda^2}\sum_j \eta^j_{LL}(\bar{e}_L\gamma_\mu e_L)(\bar{\psi}^j_L\gamma^\mu\psi^j_L),$$

$$\mathcal{L}_{LR} = \frac{g^2_{\rm contact}}{2\Lambda^2}\sum_j \eta^j_{LR}(\bar{e}_L\gamma_\mu e_L)(\bar{\psi}^j_R\gamma^\mu\psi^j_R),$$

$$\mathcal{L}_{RL} = \frac{g^2_{\rm contact}}{2\Lambda^2}\sum_j \eta^j_{RL}(\bar{e}_R\gamma_\mu e_R)(\bar{\psi}^j_L\gamma^\mu\psi^j_L),$$

$$\mathcal{L}_{RR} = \frac{g^2_{\rm contact}}{2\Lambda^2}\sum_j \eta^j_{RR}(\bar{e}_R\gamma_\mu e_R)\bar{\psi}^j_R\gamma^\mu\psi^j_R),$$

CL^{95} [TeV]	ILC250	ILC500	ILC1000
Λ^+_{LL}	108	189	323
Λ^-_{LL}	108	189	323
Λ^+_{RR}	106	185	314
Λ^-_{RR}	106	185	314
Λ^+_{VV}	161	280	478
Λ^-_{VV}	161	280	478
Λ^+_{AA}	139	240	403
Λ^-_{AA}	139	240	403
$\Lambda^+_{(V-A)}$	122	208	350
$\Lambda^-_{(V-A)}$	122	208	350

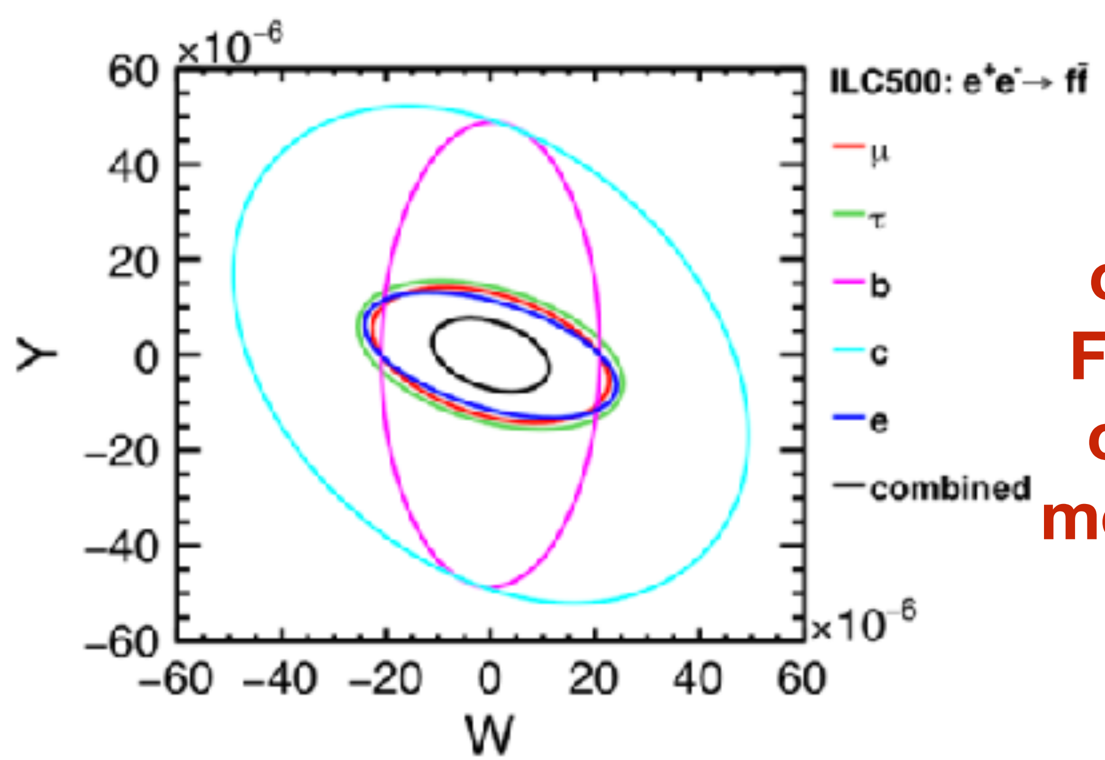
Λ >200 x E_{cm}

Z' mass: 95% excl. lim. & 5-σ disc. reach in TeV

Model	250 GeV, 2 ab^{-1} excl.	disc.	500 GeV, 4 ab^{-1} excl.	disc.	1000 GeV, 8 ab^{-1} excl.	disc.
SSM	7.8	4.9	13	8.4	22	14
ALR	9.5	6.0	17	11	25	18
χ	7.0	4.5	12	7.8	21	13
ψ	3.7	2.4	6.4	4.1	11	6.8
η	4.2	2.7	7.3	4.6	12	7.9

W/Y param. Higgs Compositeness Scale

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{g^2\mathbf{W}}{2m_W^2}J^a_{L\mu}J^{a\mu}_L - \frac{g'^2\mathbf{Y}}{2m_W^2}J_{Y\mu}J^\mu_Y$$



Sensitivity comparable to FCC-ee & CLIC, can separately measure different fermions

CERN-ESU-004
1 October 2019

Physics Briefing Book

Input for the European Strategy for Particle Physics Update 2020

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From Introduction

The readiness of these projects (CLIC, FCC, HE-LHC) was subject to intense scrutiny during the Granada Symposium and the conclusions are summarised in Chapter 10. No show-stoppers were found on the technical side, however **there are still challenges ahead with time scales for addressing them quite uncertain, more so in the case of FCC-hh than for CLIC**. In the global context, CLIC and FCC-ee are "competing" with the International Linear Collider (ILC) project proposed to be built in Japan [ID77], and with the circular CEPC of China [ID29]. In the latter case, the CEPC could be turned at a later stage into a *pp* collider similarly to the FCC project. **As Higgs factories, all the four contenders have a similar reach**, as established during the Open Symposium (see Chapter 3).

… the estimated time quoted for development of 16 T magnets for the FCC-hh is comparable to the one projected, albeit with lesser confidence level, for the development of the novel acceleration technologies from proof-of-principle towards an accelerator conceptual design.

Already the previous Strategy update expressed interest in the initiative of the Japanese particle physics community to host the ILC and welcomed this initiative. **The negotiations in Japan are ongoing but no clear statement has been made at this time.**

From the national inputs submitted to the present Strategy update process, **a clear support is evident for an e^+e^- Higgs factory as the next large-scale facility after the LHC.**

https://arxiv.org/pdf/1910.11775.pdf

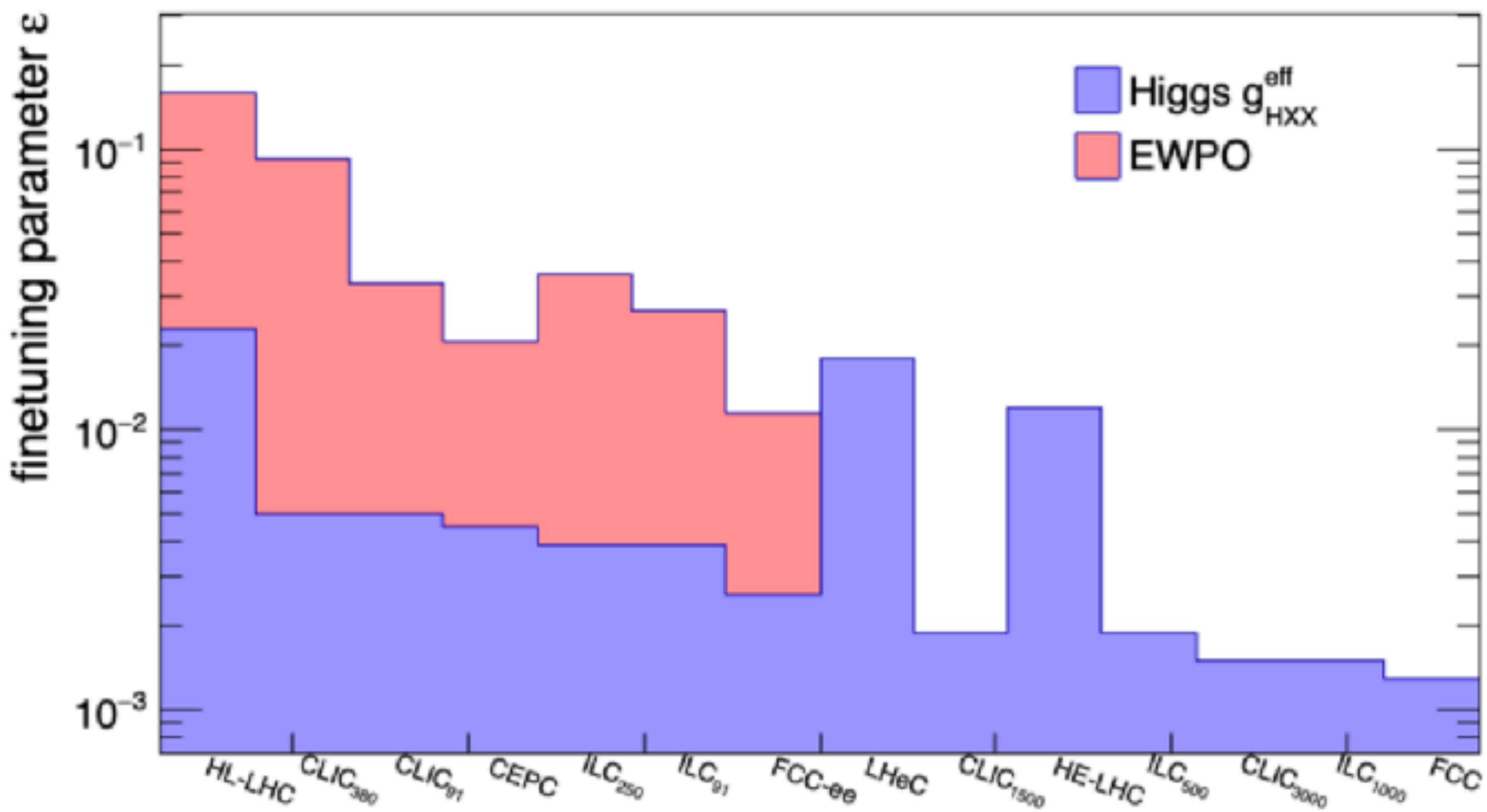


Fig. 3.11: Fine-tuning sensitivity as defined in Sect. 3.1 based on the Higgs coupling and EWPO precision projections. In each case the highest precision Higgs measurement is shown based on the EFT analysis: for HL-LHC, HE-LHC and LHeC this is the ggH coupling, and for all others it is the VVH coupling. For the EWPO the value of S is chosen, multiplied by three to be a measure of ε, and only the low-energy stages of the lepton colliders are shown. The colliders are roughly ordered by the time it takes to take the data after a project start time t_0. For projects with multiple stages, t_0 is defined as start of data taking for the first stage.

Linear vs Circular Discussion

Political support: ILC has been considered in depth over a number of years by the government of Japan, which, **for the first time, officially showed its interest in the ILC**.

Politicians, governments, and funding agencies in Japan have been discussing the ILC with their counterparts in Europe and the US for a number of years, and have been encouraged by these discussions.

Other large collider projects have not yet reached a similar stage.

Technical maturity:

The RDR (CDR equivalent) for the ILC was published in 2007 and the **TDR in 2013**.

Circular collider projects have only recently published their CDRs.

The ILC's quoted performance and costs are deeply understood and thus reliable.

Timeline: Given a go-ahead, the ILC will very soon be ready to start construction. First collisions can occur within around 15 years from now.

According to current run plans, the ILC will complete its 2 ab-1 250 GeV run at about the time FCCee begins its ZH run.

Physics: Beam polarization is a powerful tool not available at high energy circular colliders.

When measuring Higgs couplings, **polarization compensates for the lower integrated luminosity at 250 GeV compared to FCCee (2 vs 5 ab-1)** not just by the increased rates but also by its power to remove some correlations among different EFT operators.

In the case that ILC observes new phenomena other than in the Higgs couplings, polarization will play an essential role in determining their chiral properties.

Polarization will also allow **systematic uncertainties** on many measurements **to be significantly reduced**.

Upgradeability: The ILC's collision energy can be readily upgraded to 500 GeV and above.

A technical design for a 500 GeV stage exists.

Likewise, **a technical design exists for upgrading the luminosity:**

- **by a factor 2 by doubling the number of bunches per pulse,**
- **another factor 2 by doubling the repetition rate.**

The ILC250 infrastructure is reusable. It provides long-term perspectives beyond current technologies (e.g. a plasma-based accelerator).

arXiv: 1905.00220

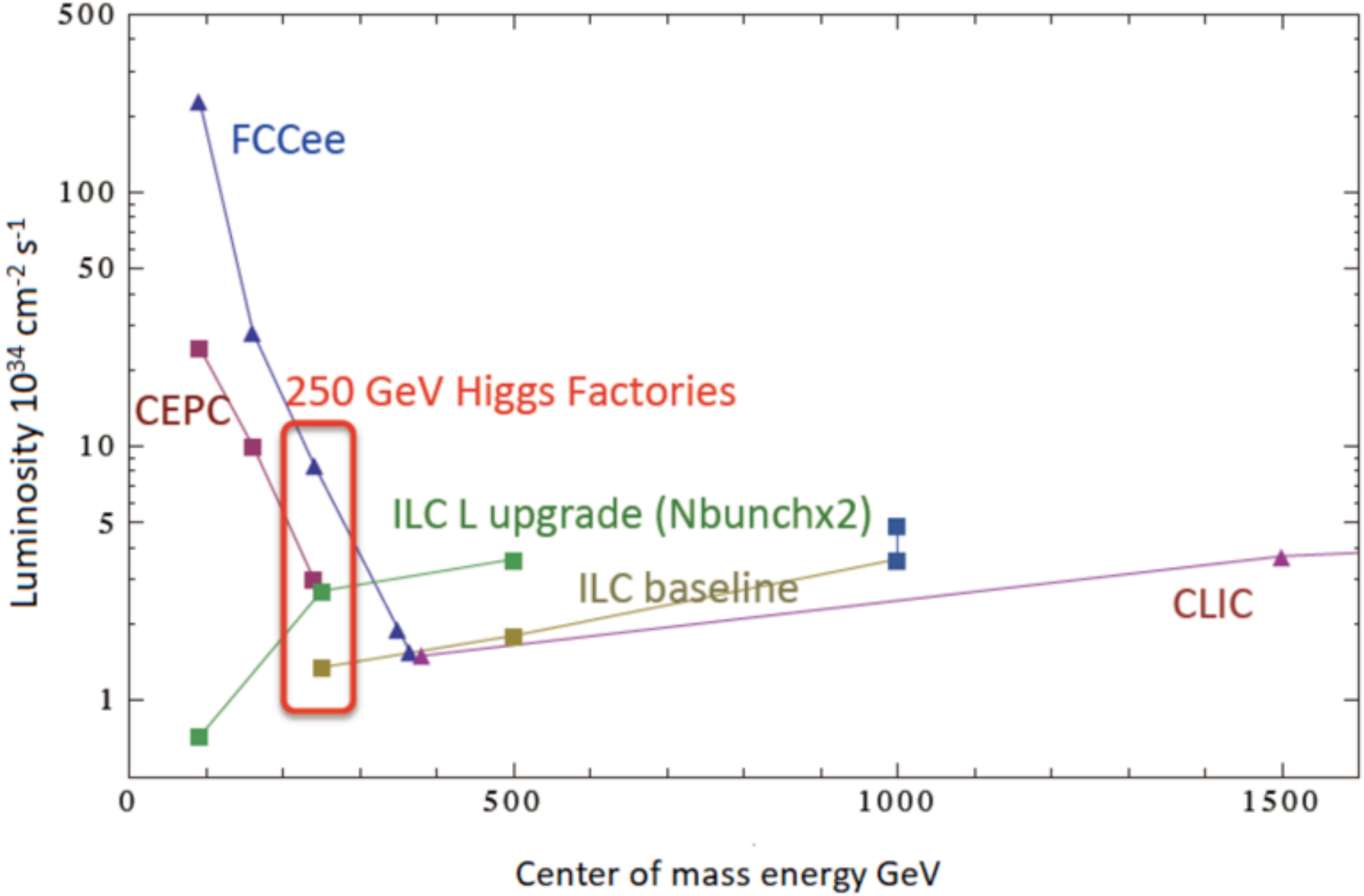


Figure 1: Comparison between luminosities vs. energy. FCC-ee adding two detectors (dark blue), CEPC (magenta), CLIC (pink) and high-luminosity ILC scenario (green). ILC green is extrapolated to Z as explained in the text

Beyond 250 GeV

What we can do at higher energies

Precision EW coupling measurement of Top
Precision Top mass measurement
Direct measurement of Top Yukawa coupling

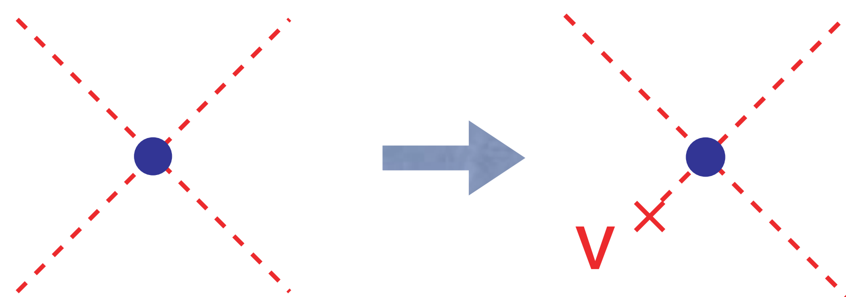
Measurement of 3-point Higgs self-coupling

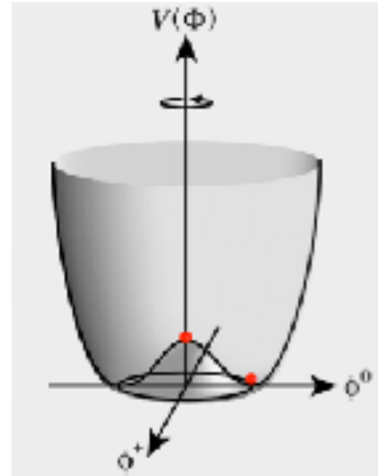
Expansion of search region of new particles

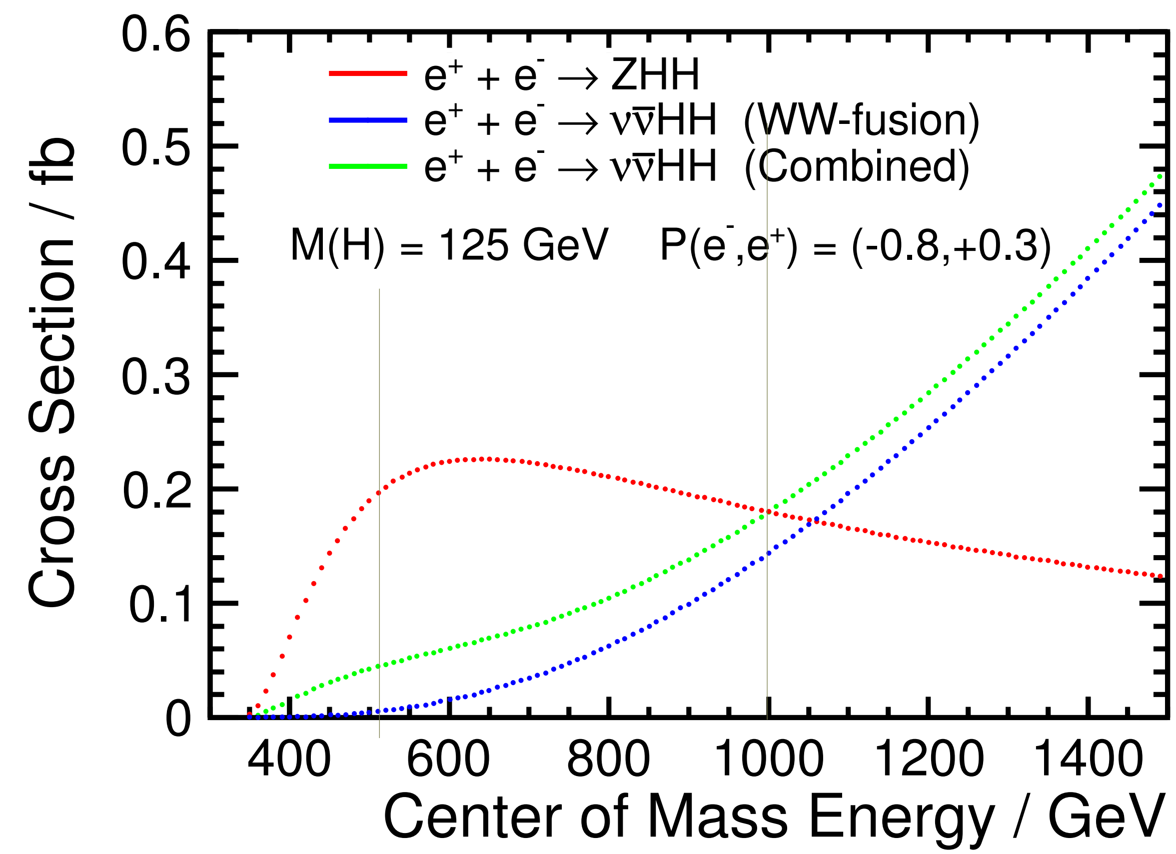
If no deviations at all would be seen?

Higgs Self-Coupling

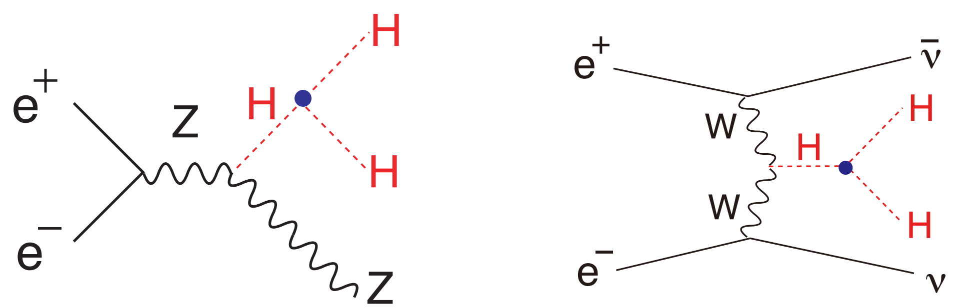
The ***Higgs cubic self-coupling*** is at the heart of EWSB, so should be measured in its own right!







There are ***two ways to measure it*** at ILC



Challenging even at ILC because of

- Small cross section
- ***Presence of irreducible BG diagrams that dilute the self-coupling contribution!***
- ***Separation of BSM effects that appear other than in self-coupling (possible in EFT: same impossible at LHC)***

ILC

	500 GeV	+ 1 TeV
Snowmass	46%	13%
H20	**26%**	10%

H20 arXiv: 1506.07870

J. Tian, LC-REP-2013-003

C. Dürig @ ALCW16

M. Kurata, LC-REP-2014-025

CLIC

1.4 TeV ($1.5\ ab^{-1}$)	+3 TeV ($2\ ab^{-1}$)
21%	10%

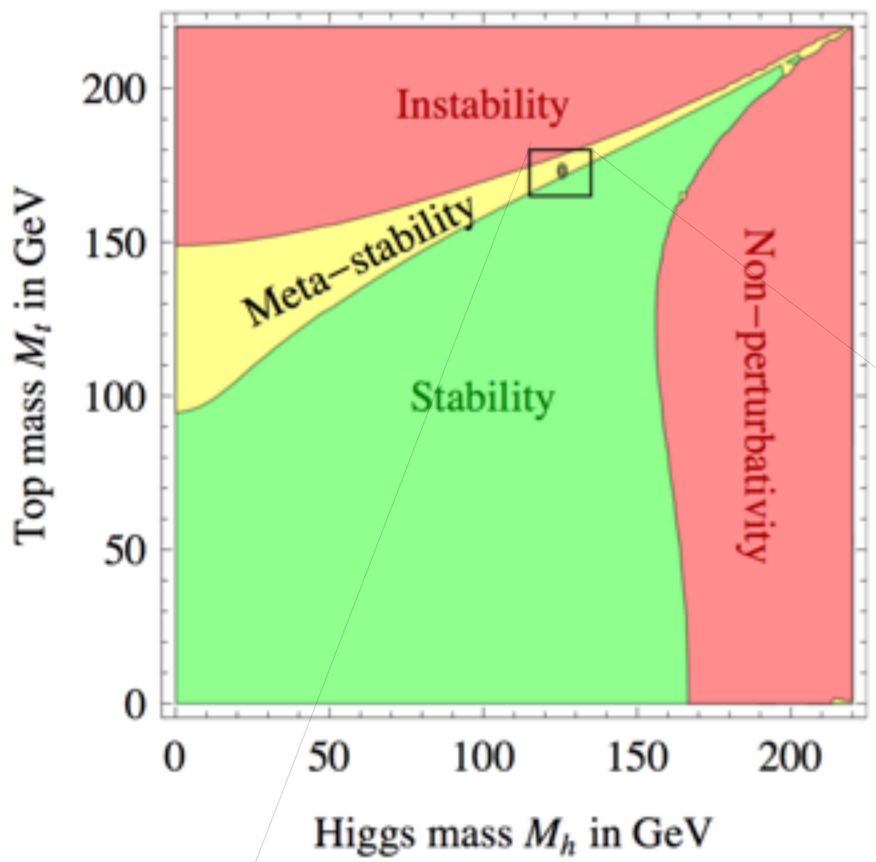
(arXiv: 1307.5288)

Ongoing effort ***towards O(10)% measurement***

If +100% deviation as possible in EWBG scenario, Δλ/λ=14%!

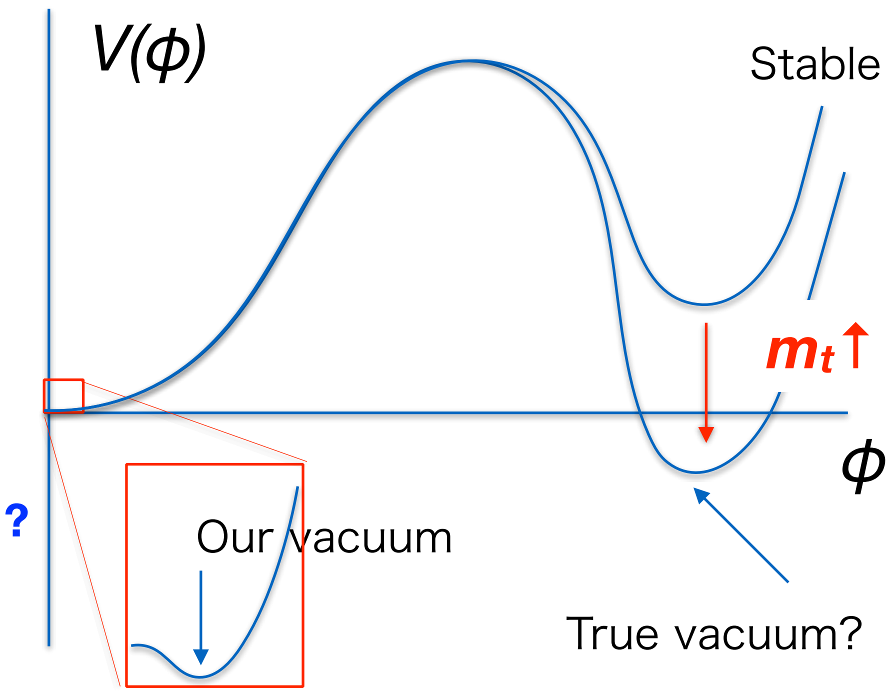
Clarify the Range of Validity of SM

Stability of SM Vacuum



Top Yukawa coupling drives the 4-point Higgs coupling (λ) to negative!
→ The true vacuum could be somewhere else at a high φ value.

The current values of mt and mh seem to be in **subtle point of meta-stability!**

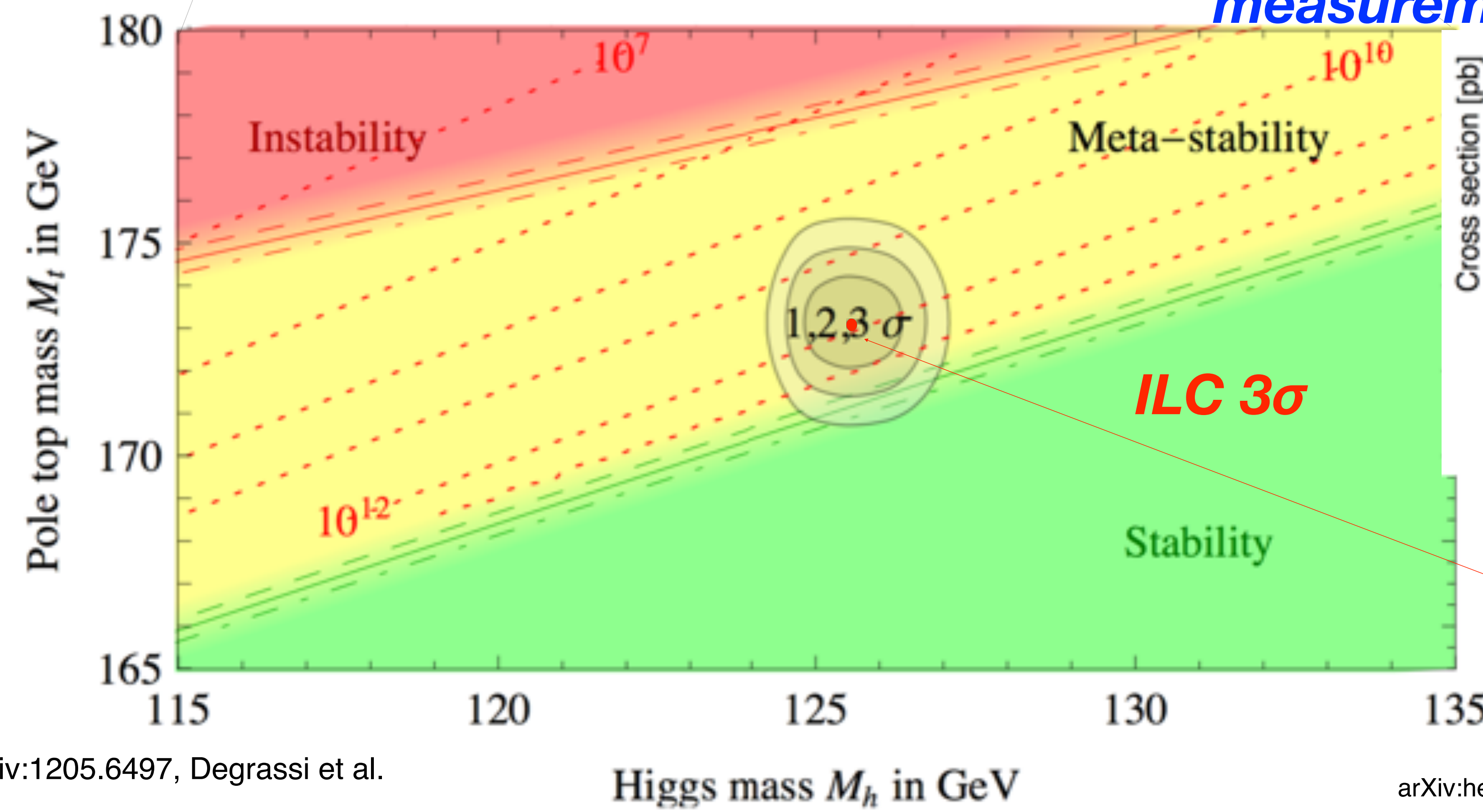


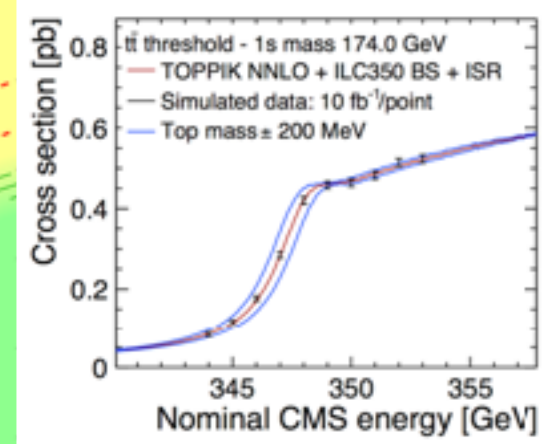
Does λ go to negative below Λ_P?
or $\lambda(\Lambda_{Pl})$ = 0 (suggesting new principle) ?

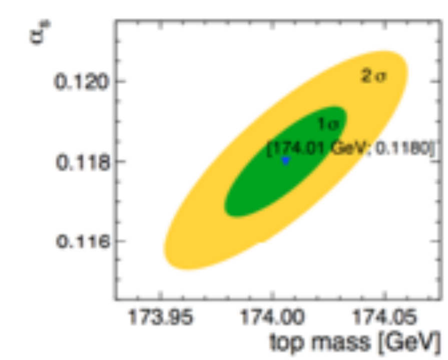
To answer this, we need precision m_t measurement!

At LHC, theory error limits the precision to ~500MeV.

TTbar Threshold Scan @ILC allows very clean measurement of theoretically well defined mt







$$\Delta m_t(\overline{MS}) \lesssim 50\,\mathrm{MeV}$$
$$\Delta m_H = 14\,\mathrm{MeV}$$

ILC pinpoints the vacuum location

arXiv:1205.6497, Degrassi et al.

arXiv:hep-ph/1502.01030: Quark mass relation to 4-loop order
arXiv:hep-ph/1506.06864: NNNLO QCD
arXiv:hep-ph/1506.06542: possibility of MSbar mass to 20MeV

EW Baryogenesis?

Impossible in SM

EW Phase Transition＝Strong 1st Order

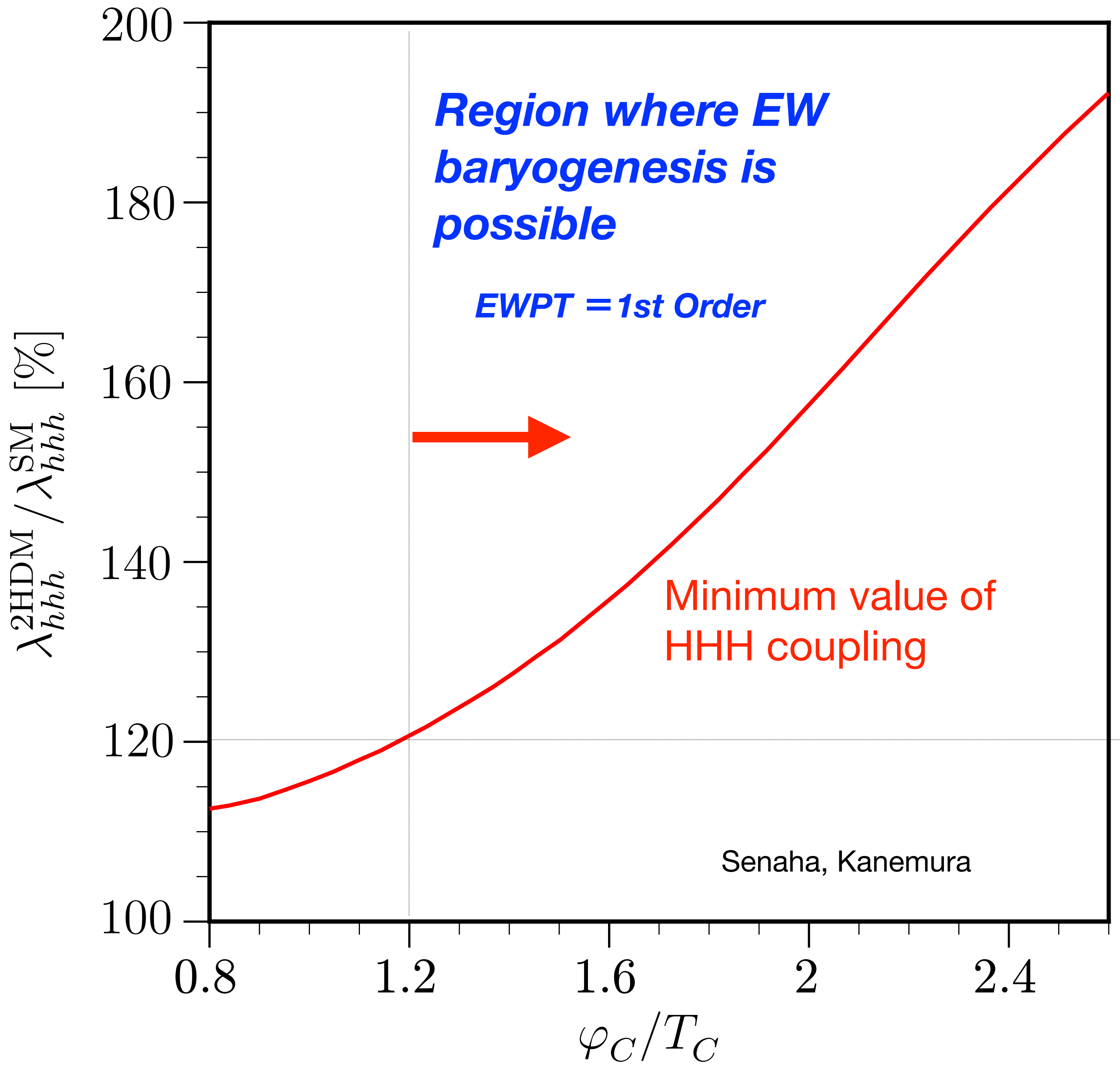
Necessary to deviate from equilibrium
→ Shifts in HXX couplings
Expect a large deviation in the HHH coupling

Big enough CP violation (δ_{KM} too small) at the bubble wall
→ CP violation in the Higgs sector

→ Extended Higgs Sector

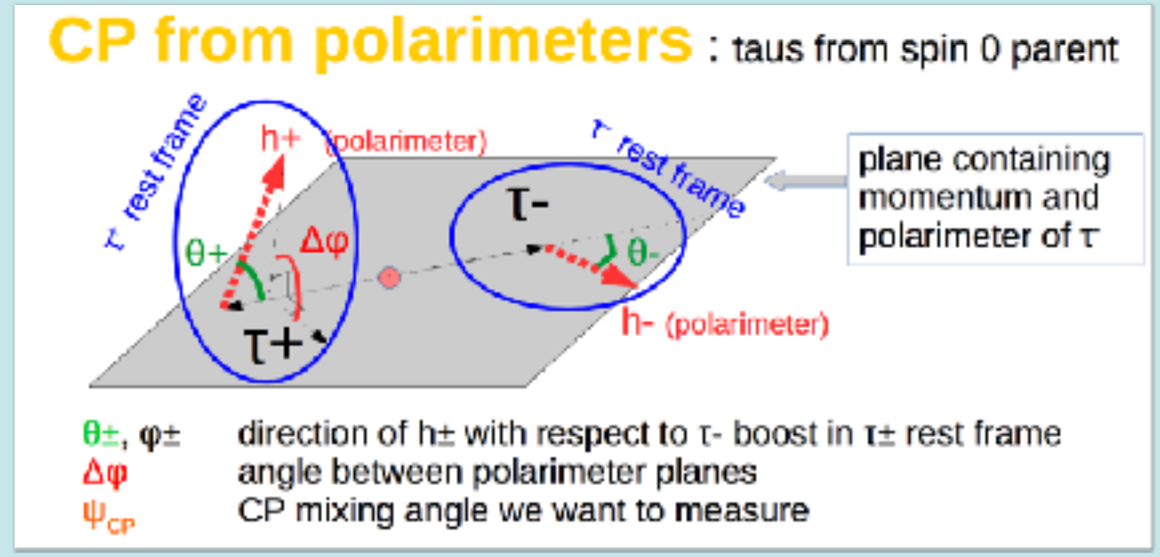
EW Baryogenesis?

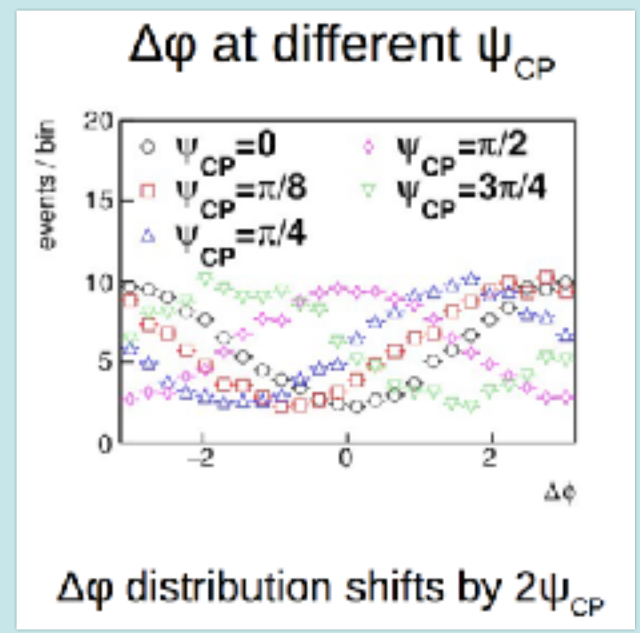
e.g.: ***2 Higgs Doublet Model (2HDM)***



Measuring CP in H → τ⁺τ⁻ at ILC

$$\mathcal{L}_{h\tau\tau} = g\bar{\tau}\left(\cos\Psi_{CP} + i\gamma_5 \sin\Psi_{CP}\right)\tau\, h$$





2ab⁻¹ @ 250 GeV

$$\delta\Psi_{CP} \simeq 4^\circ$$

D. Jeans 2018

Measurement of HHH coupling at ILC

At 500 GeV signal and background diagrams constructively interfere.強め合う

→ ***If there is 100% upward shift→ Δλ/λ=14%***

ILC will test EW baryogenesis.

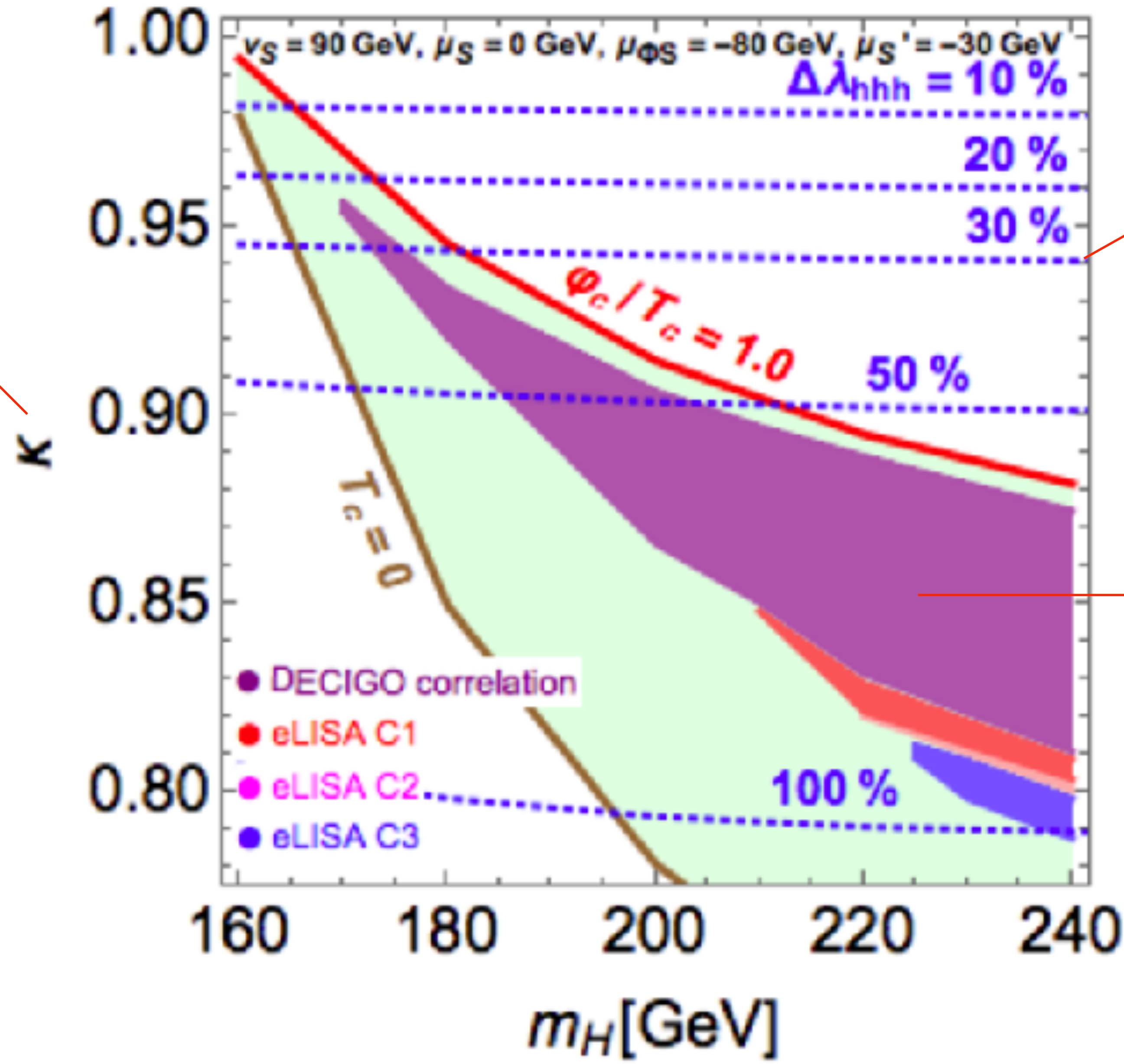
Strong 1st Order EW Phase Transition

e.g.: ***Doublet-Singlet Mixing Model (HSM)***

Precision Higgs Coupling Measurements

Uniform Shift

$\kappa_V = \kappa_f = \kappa$



g_{HHH} shift

Gravitational Wave

FIG. 2: The detectability of GWs and the contours of the deviations in the hhh coupling $\Delta\lambda_{hhh}$ in the m_H-κ plane. The projected region of a higher sensitive detector design is overlaid with that of weaker one. The region which satisfies both $\varphi_c/T_c > 1$ and $T_c > 0$ is also shown for a reference. The input parameters and legends are same as in Fig. 1

Fuyuno, Senaha: arXiv: 1406.0433

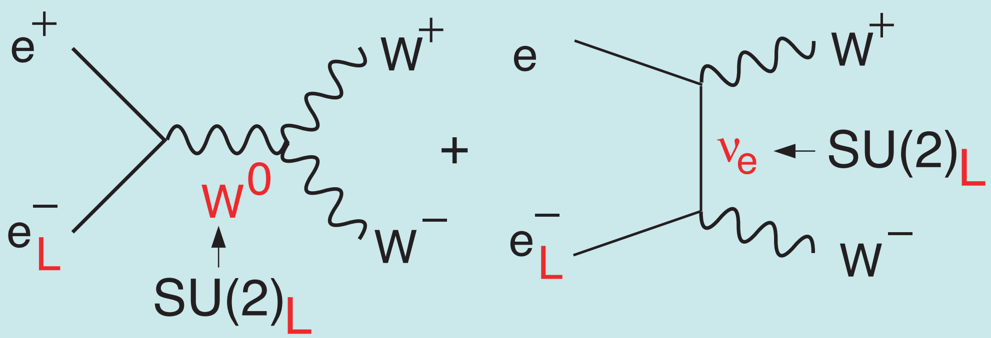
Hashino, Kakizaki, Kanemura, Matsui, Ko: arXiv 1609.00297

Direct/Indirect Searches

Power of Beam Polarization

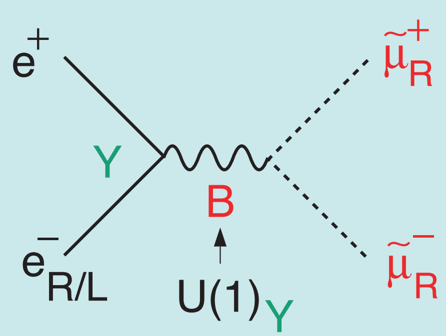
BG Suppression

***W^+W^-** (Largest SM BG in SUSY searches)*



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

Slepton Pair



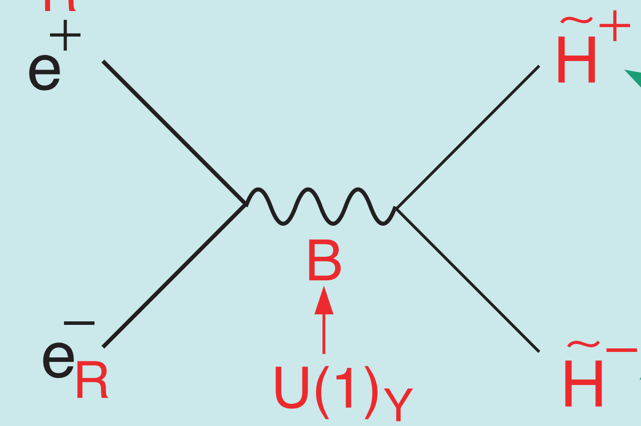
$Y_L = -1/2 : e^-_L$

$Y_R = -1 : e^-_R$

In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

Chargino Pair

e^-_R Beam



Only $\tilde{H}^\pm$ components in $\tilde{\chi}^\pm_1$ contribute !

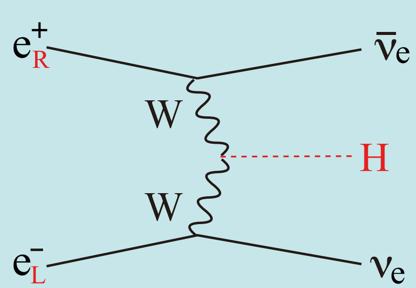
cf.) $e^+e^- \to W^+W^-$

$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

$$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$$

Decomposition

WW-fusion Higgs Prod.



	ILC
Pol (e-)	-0.8
Pol (e+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

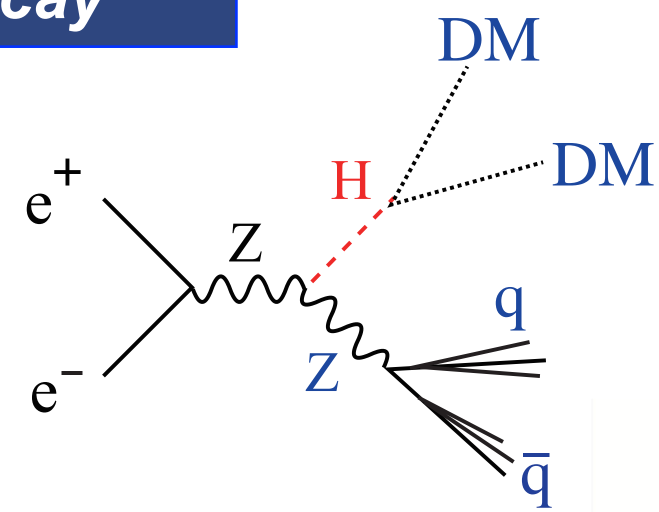
Signal Enhancement

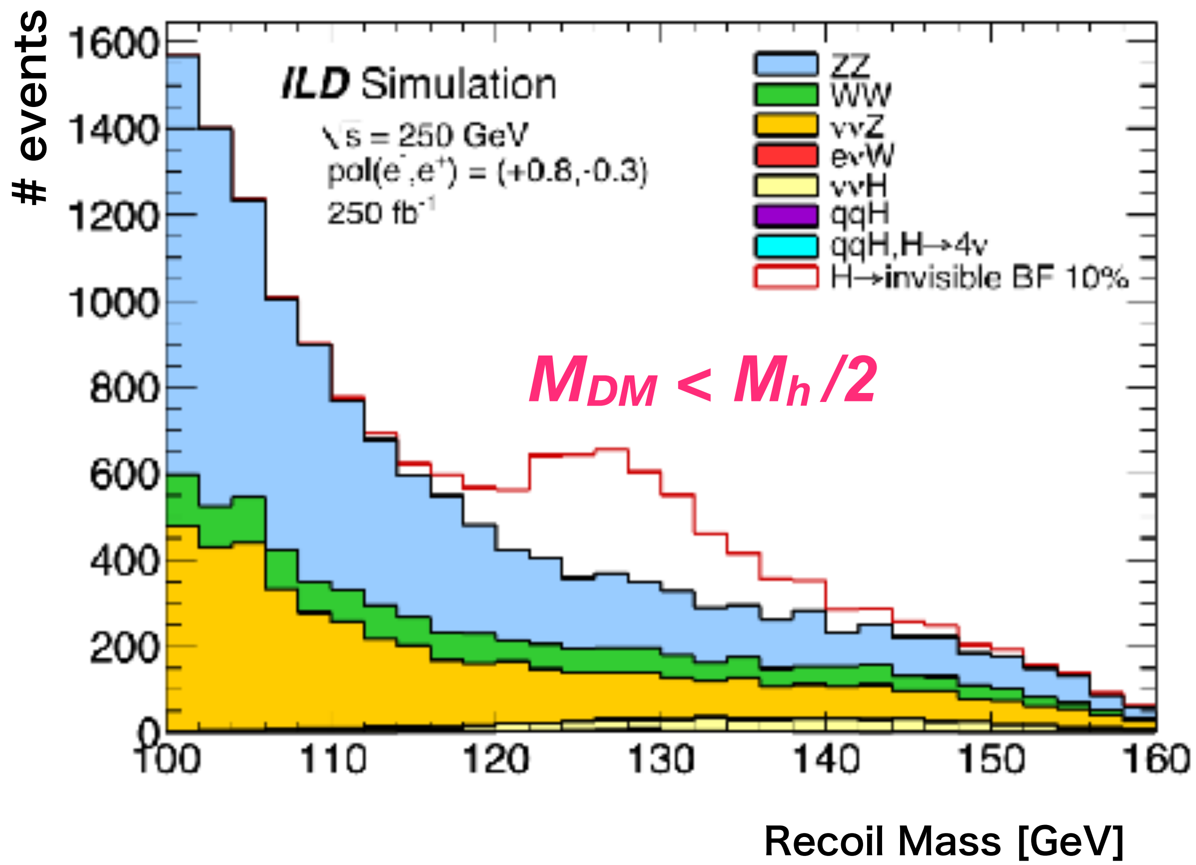
WIMP Dark Matter Search @ ILC

Weakly Interacting Massive Particle

1. Higgs Invisible Decay

Effective when the Dark Matter particle interacts with the Higgs boson





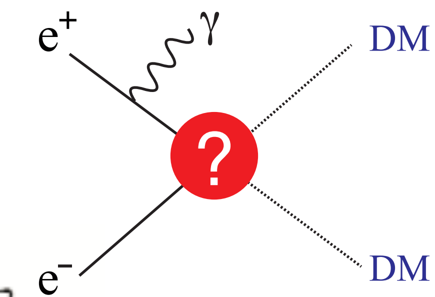
Possible to access BR_{inv} to 0.3%!

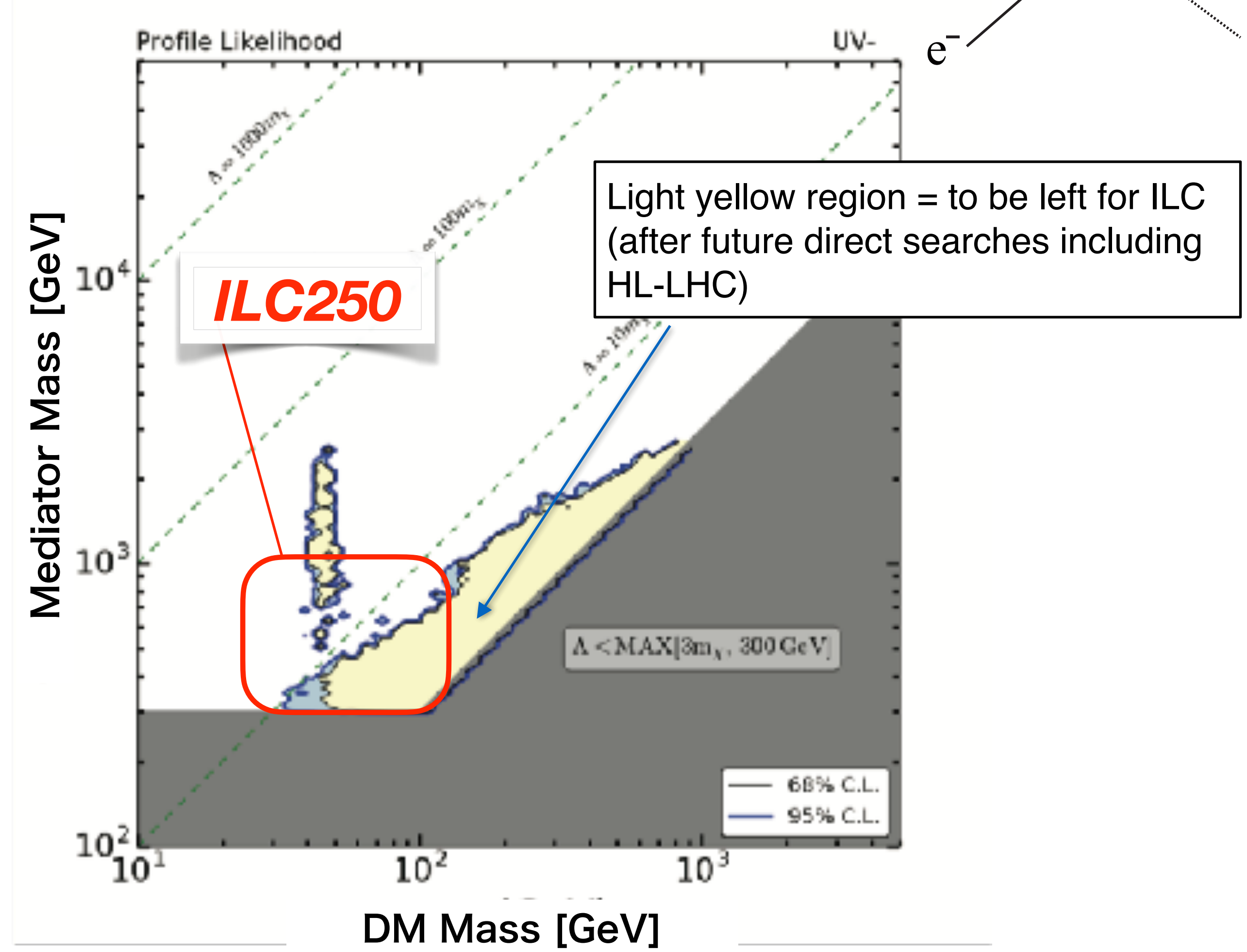
O(10) more sensitive than HL-LHC

2. Mono-photon Search

Sensitive to various types of Dark Matter particles

Effective in particular for DM particles which couple mostly to EW gauge bosons and leptons and hence difficult to find at the LHC.



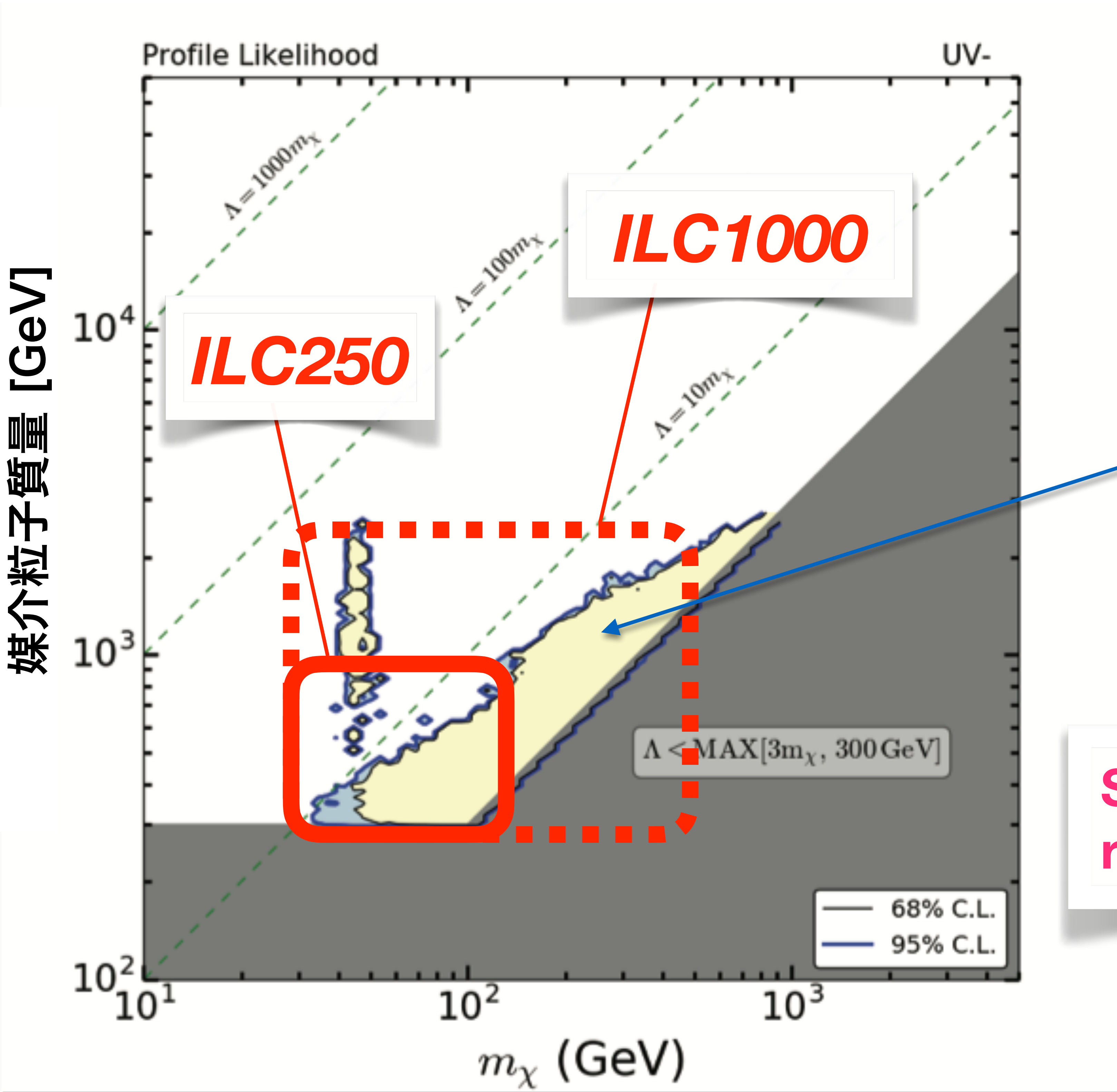


Significant chunk of region remains for ILC250!

WIMP Search

Mono-photon search

arXiv: 1702.05377



Light yellow region
= to be left for ILC
(after future direct searches
including HL-LHC)

Significant chunk of region remains for ILC250!

3. Higgsino Search

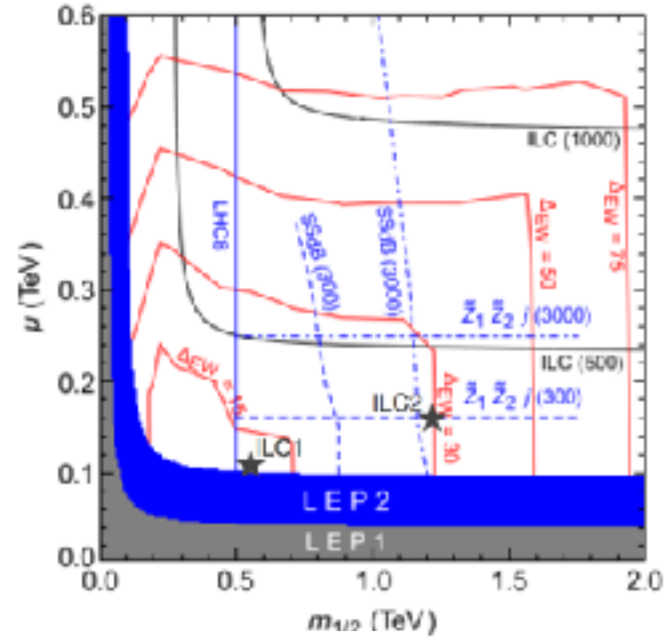
Radiatively driven Natural SUSY

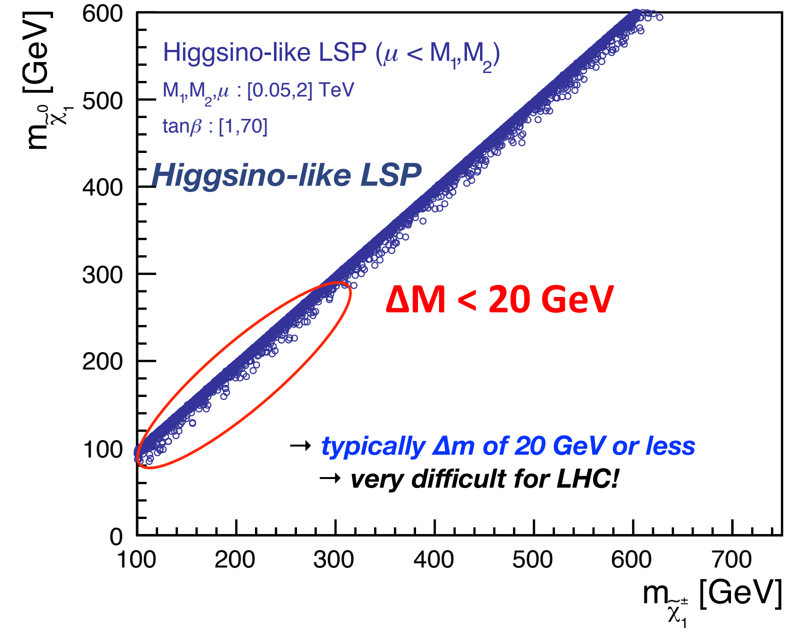
μ not far above 100GeV

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

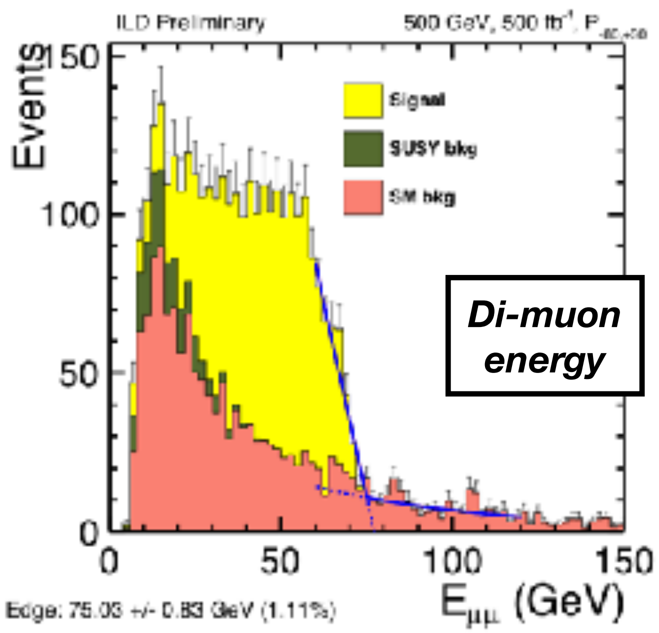
Chargino & neutralino production (ILC1)

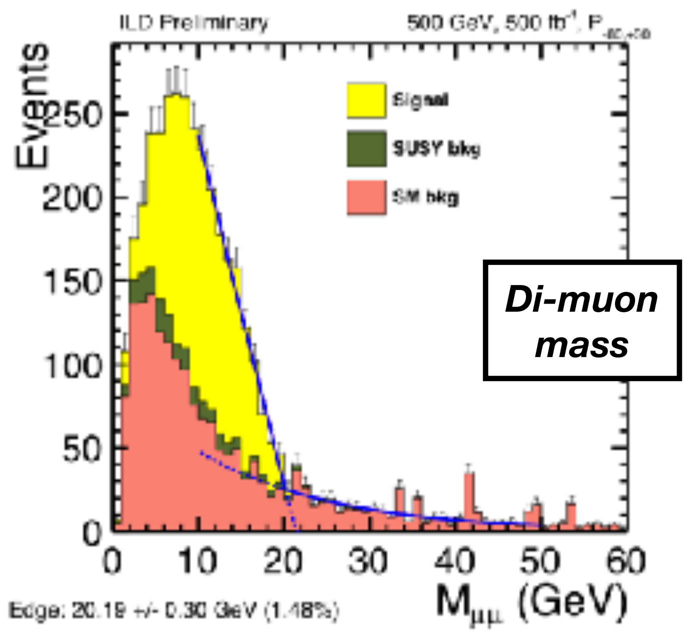
$$e^+e^- \to \tilde{\chi}_1^0\,\tilde{\chi}_2^0 \to \tilde{\chi}_1^0\tilde{\chi}_1^0\ell^+\ell^-$$





T. Tanabe: LCWS2017





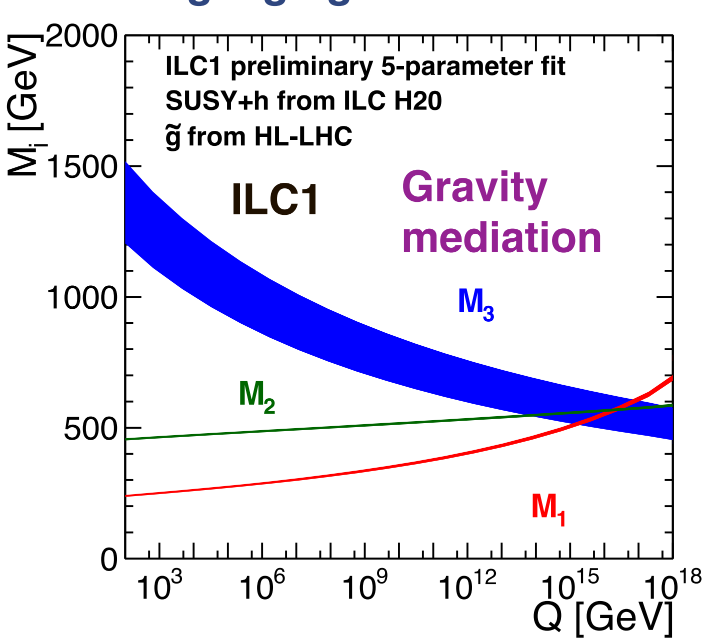
cross section and mass measurements

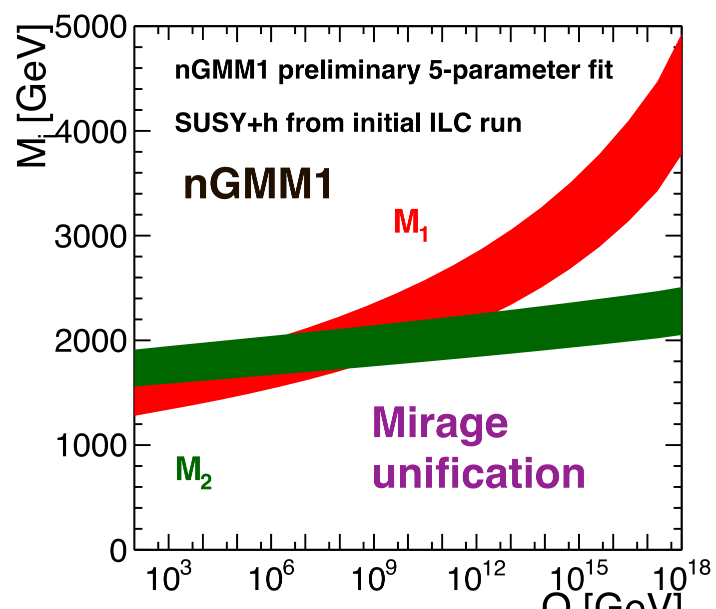
Kinematical edges→ M_X

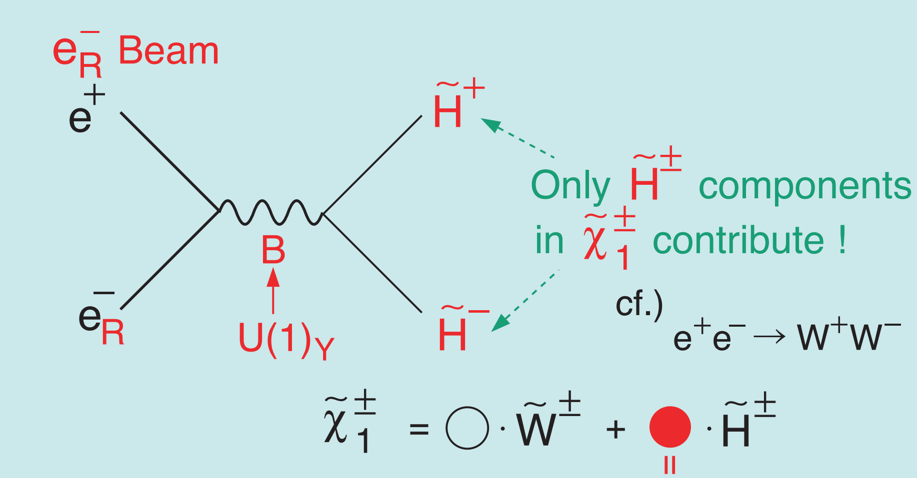
"ILC1 benchmark": ΔM∼ 20GeV
σ_M to ~2% M to ~1% (H20)

Power of beam polarization
→ Higgsino/gaugino decomposition

Test of gauging mass unification







Polarized σ → mixing angle

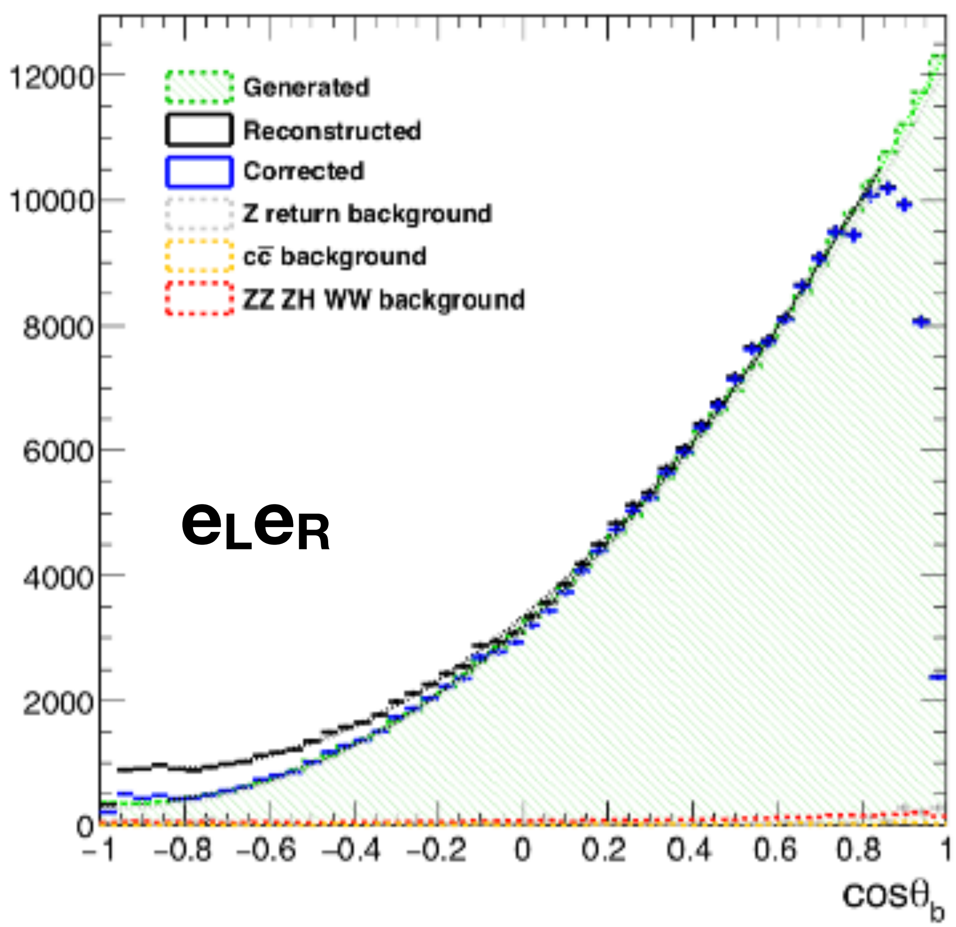
500GeV → *ILC1: 250GeV*
ILC2: 350GeV

b-quark EW Form Factors

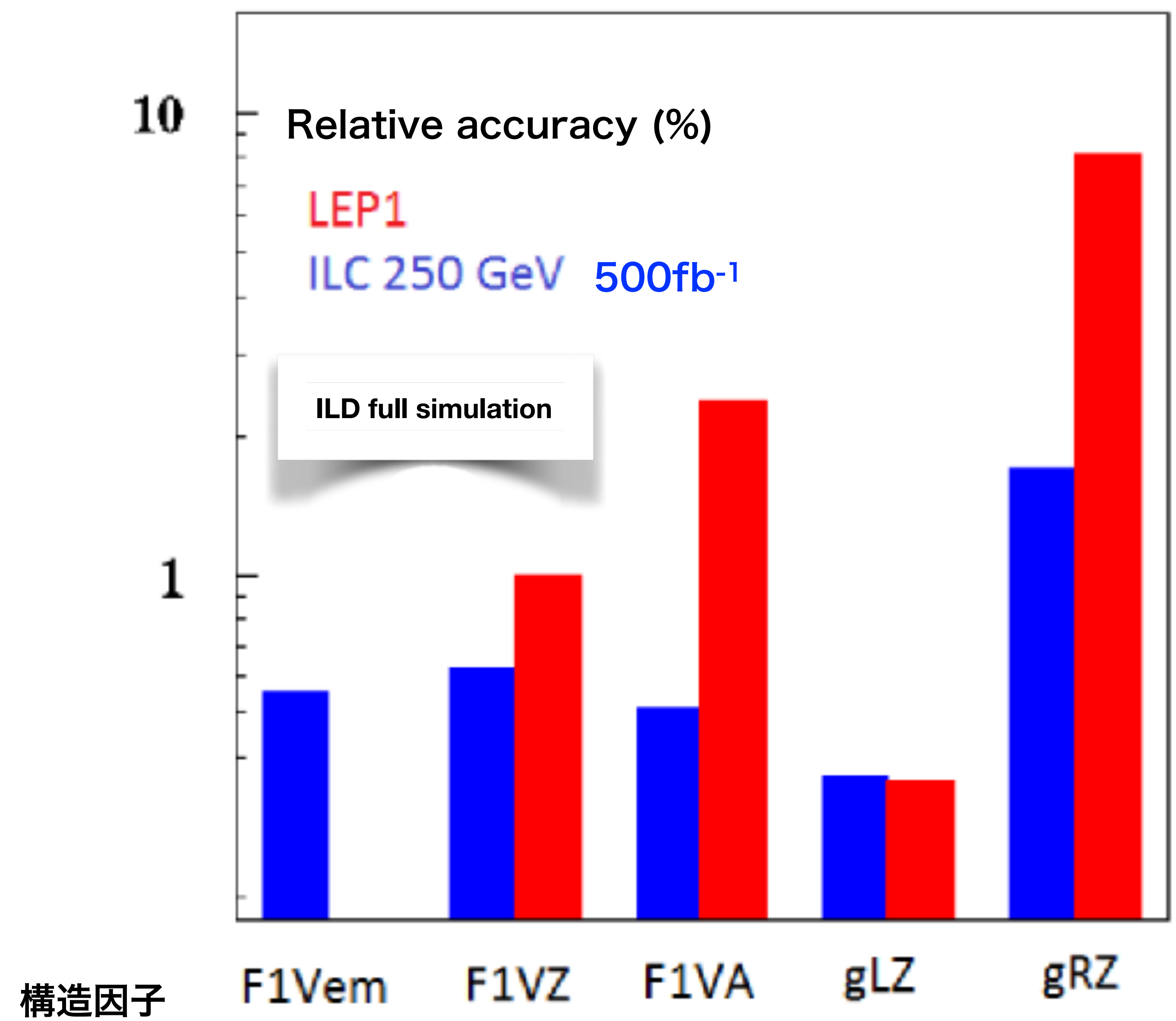
$$e^+e^- \to b\bar{b}$$

arXiv: 1709.04289

Vertex charge + K ID with dE/dx



Bilokhin, Poeschl, Richard



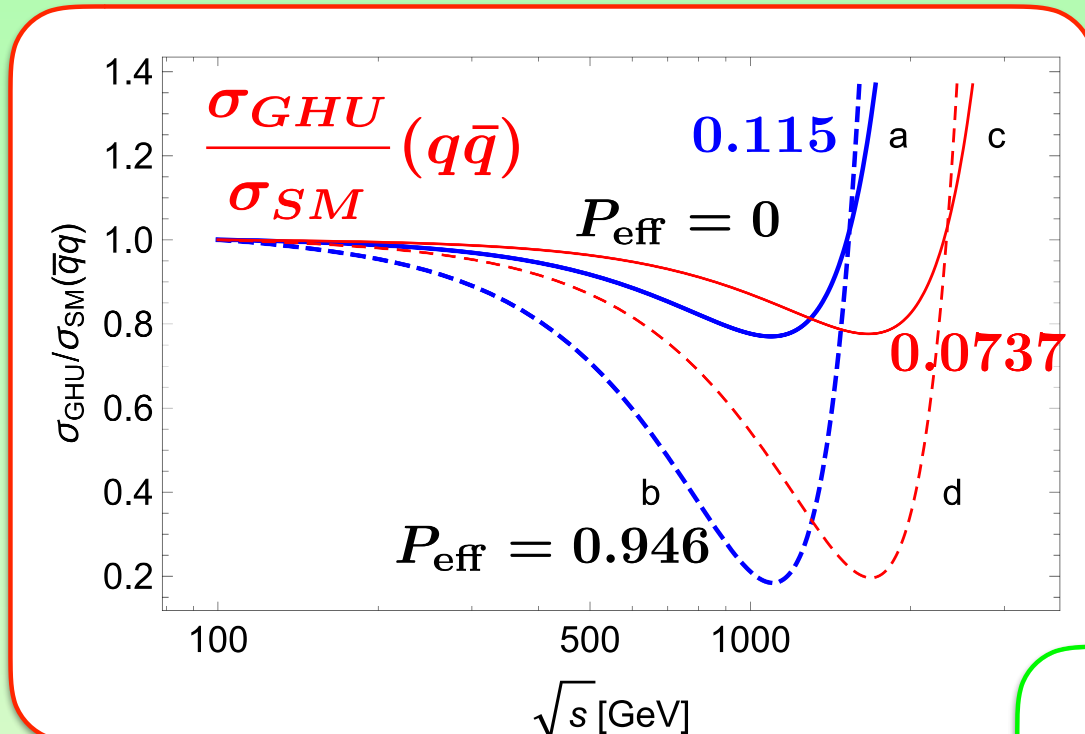
ILC has
- **10^3 times higher luminosity**
- **much improved detectors**
- **polarized beams**

as compared to LEP

ILC will put a period to long outstanding LEP $A_{FB}(b)$ anomaly.
Once confirmed → BSM study

Gauge Higgs Unification

PL B 775 (2017) 297 (arXiv:1705.05282) : Funatsu, Hatanaka, **Hosotani**, Orikasa



ILC

$$\frac{\sigma^{\rm GHU}}{\sigma^{\rm SM}}(\bar{q}q)$$

$$q = u, d, s, c, b$$

Measurable deviations even at 250GeV