ILC Higgs Physics Potential

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on behalf of ILC IDT WG3
(ILC International Development Team)

EPS-HEP 2021 @ Online
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Why We Need Precision on Higgs?

- Until today: SM-like Higgs boson and no new physics
- But we know there are missing elements such as nature of **dark matter**, **matter-antimatter asymmetry**, **neutrino mass**, **origin of EW symmetry breaking**, etc, that cannot be explained by SM. Thus, we need new physics.

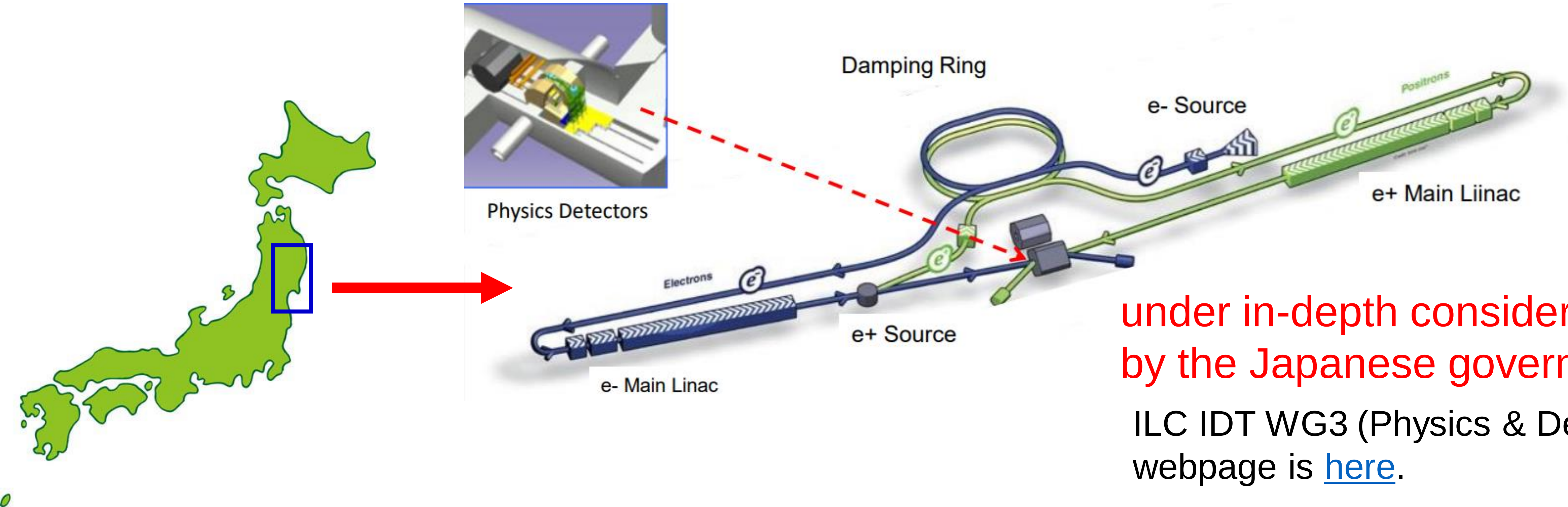
- Discovered Higgs boson is a window to new physics.
- Many new physics models predict small deviation from the SM (a few to 10%) ---> O(1%) level precision is necessary

Precision measurement on Higgs

The International Linear Collider (ILC)

- e^+e^- collider, $\sqrt{s}$ = 250 GeV (upgradable to 500 GeV, 1 TeV)
- polarized beam (e^-: $\mp$80%, e^+: $\pm$30%)
- clean environment, known initial state
- matured technology, TDR published

2000 fb^{-1} @ 250 GeV
200 fb^{-1} @ 350 GeV
4000 fb^{-1} @ 500 GeV



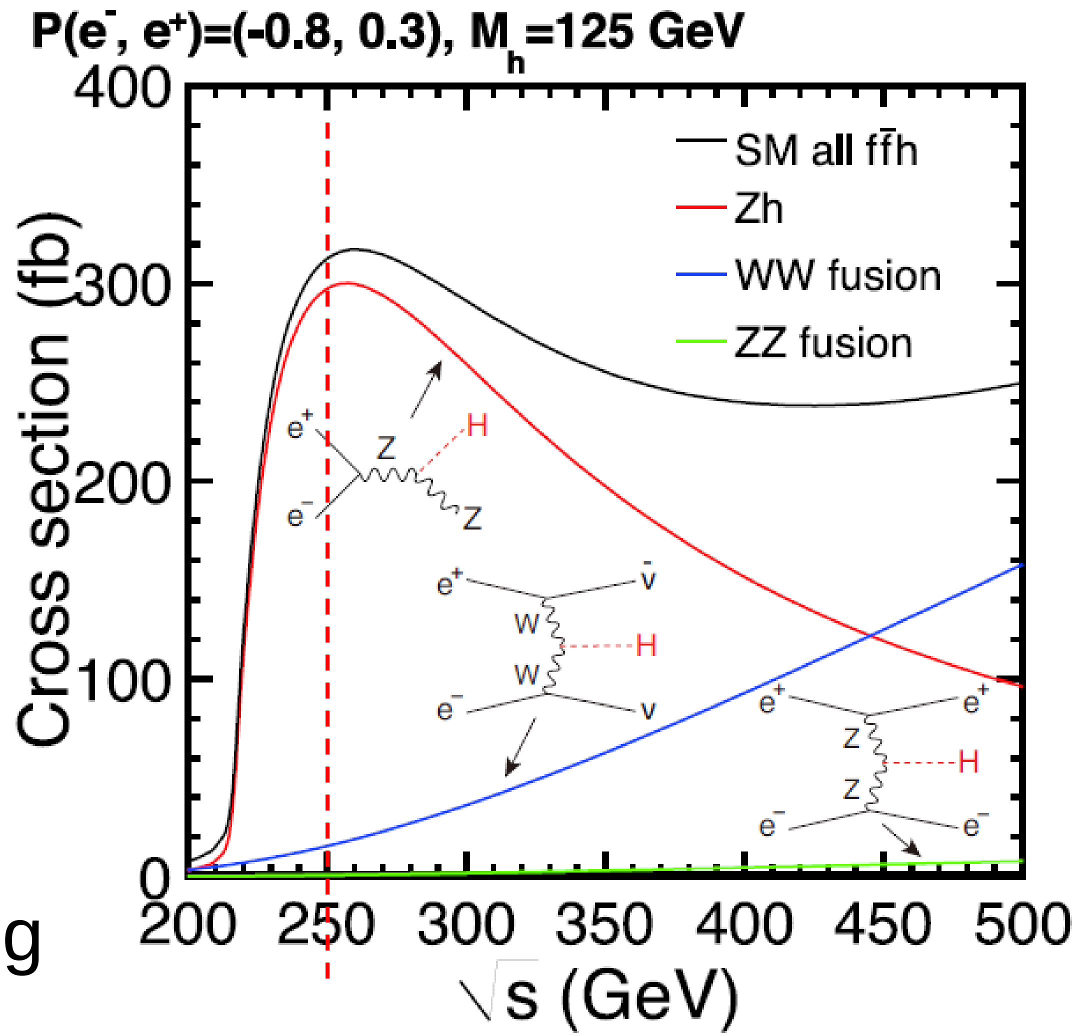
under in-depth consideration by the Japanese government

ILC IDT WG3 (Physics & Detectors) webpage is here.

Higgs Production at the ILC

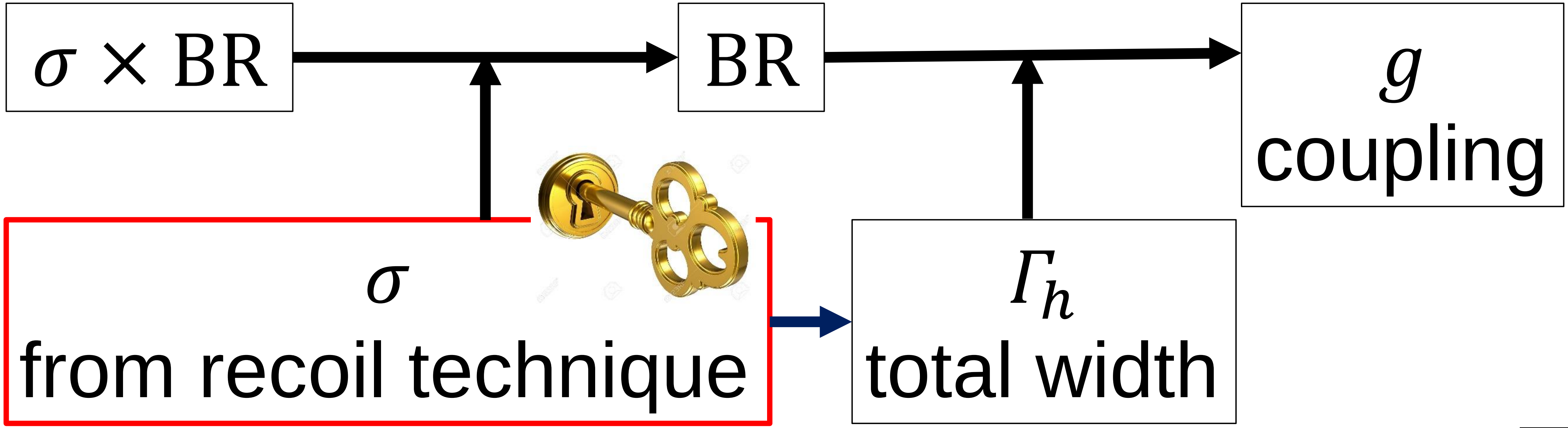
$\sqrt{s}$ = 250 GeV
Higgs-strahlung (Zh) dominant
maximum cross section around 250 GeV
---> Higgs factory, O(1M) Higgs events

$\sqrt{s}$ = 500 GeV
WW-fusion dominant
improve many couplings
access to Top-Yukawa, Higgs self-coupling



Key Point: Model Independence

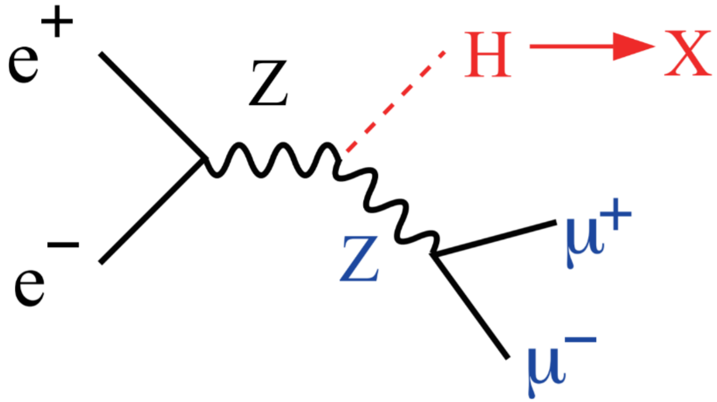
- LHC: all measurements are $\sigma \times \mathrm{BR}$
- ILC: $\sigma \times \mathrm{BR}$ measurements + **$\boldsymbol{\sigma}$ measurement**



leptonic: J. Yan, et al., Phys. Rev. D **94**, 113002 (2016)
hadronic: M. A. Thomson, Eur. Phys. J. C (2016) 76:72

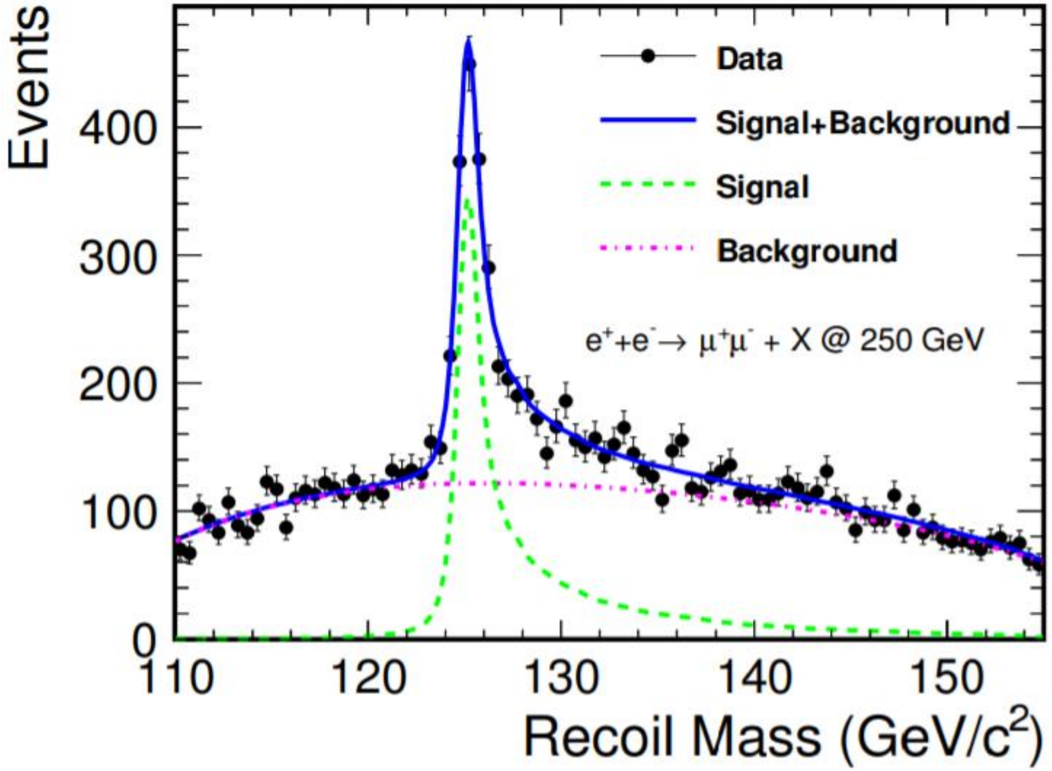
Key Measurement: σ_{Zh}

Unique measurement at lepton colliders



leptonic & hadronic

$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$



- well-defined initial states
- without looking into Higgs (recoil mass technique)

ILC250, 2 ab^{-1}

Δm_h = **14 MeV**, $\frac{\Delta\sigma_{Zh}}{\sigma_{Zh}}$ = **0.7%**

arXiv:2003.01116

Direct Higgs Observables at ILC250

σ_{Zh}

$\sigma_{Zh} \times \mathrm{BR}(h \to bb)$

$\sigma_{\nu\nu h} \times \mathrm{BR}(h \to bb)$

$\sigma_{Zh} \times \mathrm{BR}(h \to cc)$

$\sigma_{Zh} \times \mathrm{BR}(h \to gg)$

$\sigma_{Zh} \times \mathrm{BR}(h \to WW^*)$

$\sigma_{Zh} \times \mathrm{BR}(h \to ZZ^*)$

$\sigma_{Zh} \times \mathrm{BR}(h \to \tau\tau)$

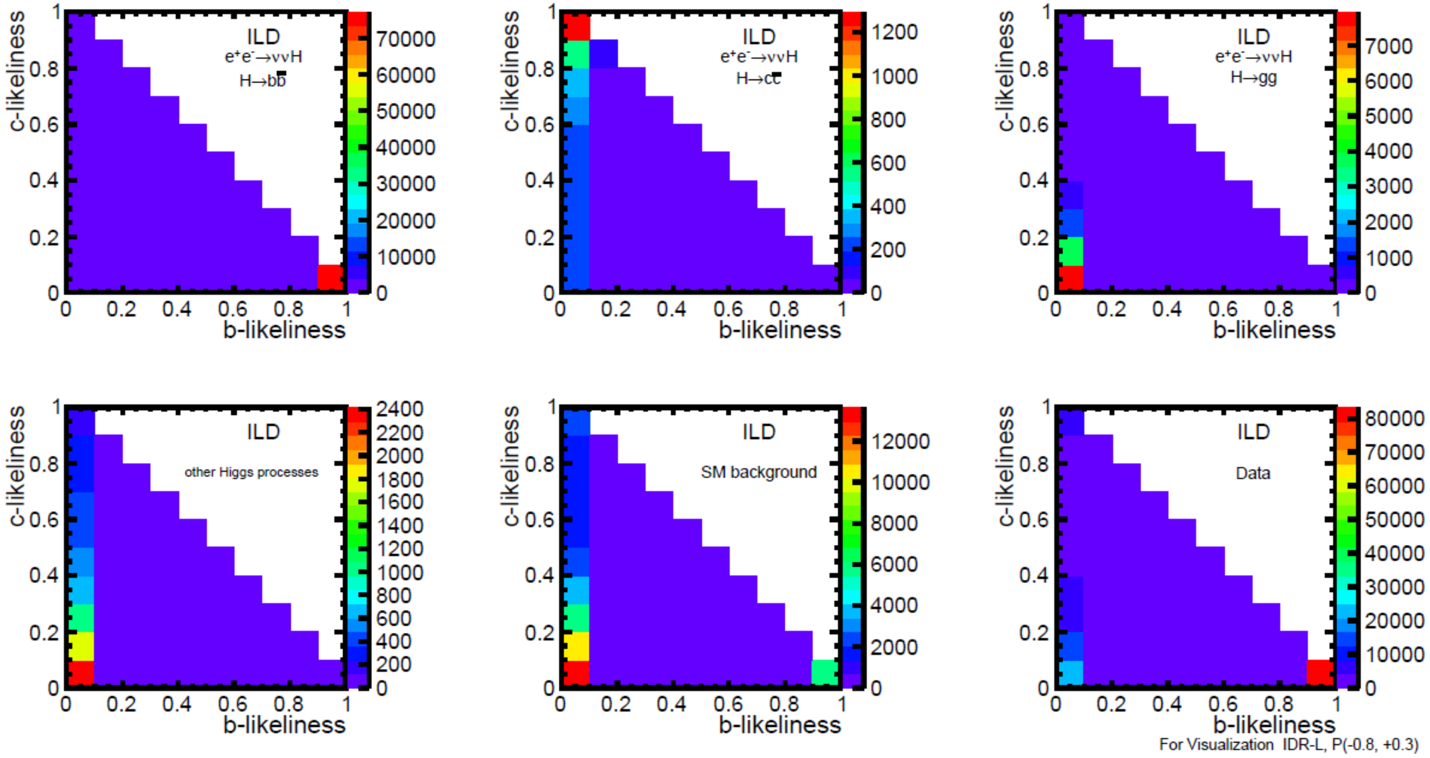
$\sigma_{Zh} \times \mathrm{BR}(h \to \gamma\gamma)$

$\sigma_{Zh} \times \mathrm{BR}(h \to \mu\mu)$ next talk

$\sigma_{Zh} \times \mathrm{BR}(h \to \mathrm{invisible})$

+ differential cross section

: speciality of e^+e^- colliders

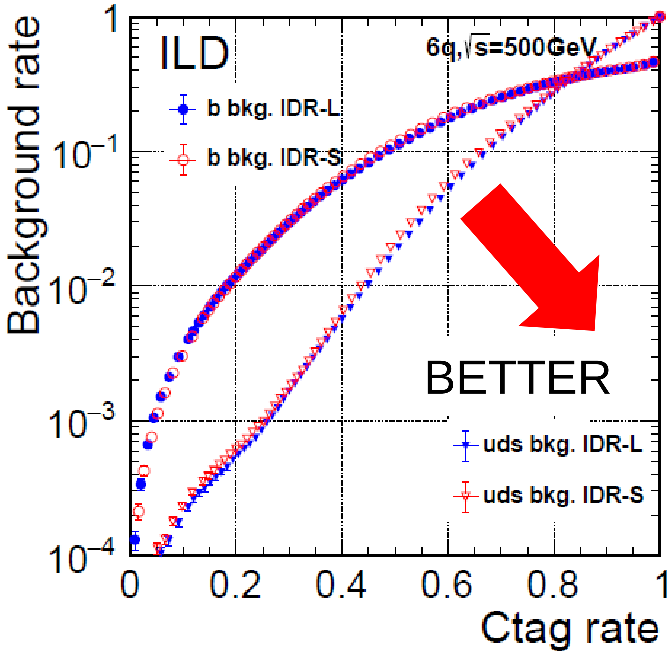


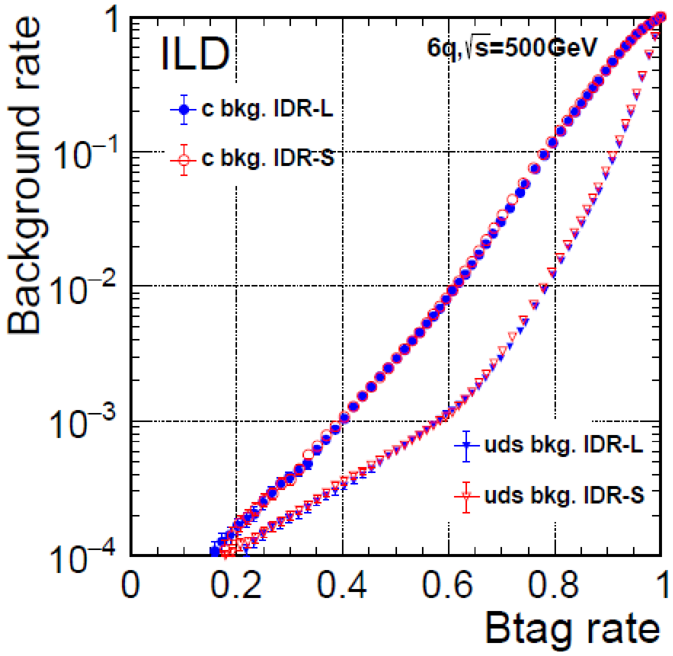
b- and c-likeliness for $h \to b\bar{b}$, $c\bar{c}$, gg, and other

Combined Higgs BR in next-next talk

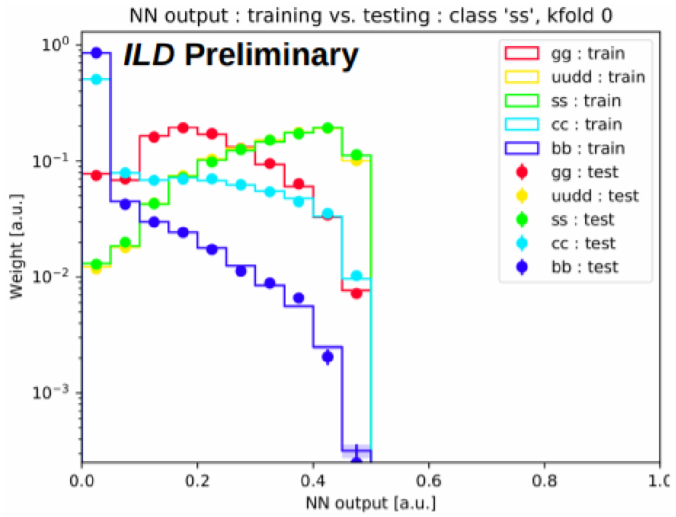
arXiv:2003.01116
Matthew Basso’s talk at LCWS2021

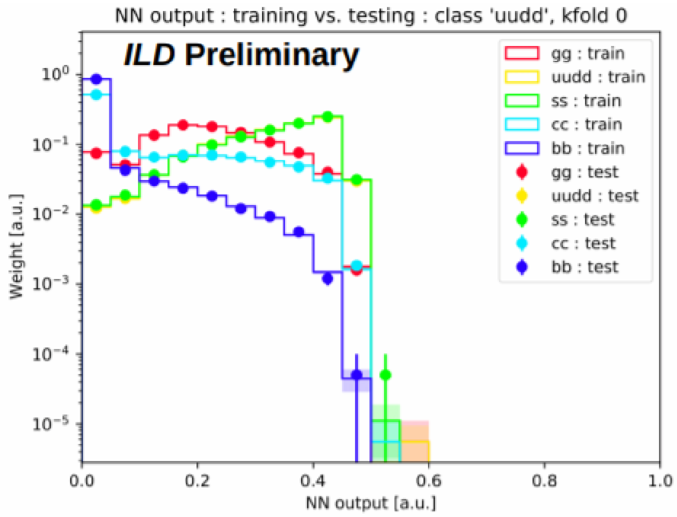
Example: Flavor Tagging





Performance of flavor tagging is essential for $h \to b\bar{b}$, $h \to c\bar{c}$, and $h \to gg$ study





Recent study: s-jet tagging for SM $h \to s\bar{s}$ and BSM $h \to c\bar{s}/\bar{c}s$

The first study report can be found here.

Tim Barklow, et al., Phys. Rev. D **97**, 053004 (2018)

Higgs Coupling Determination in SMEFT Formalism

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

“Warsaw” basis
- gauge invariant
- Lorentz invariant
- CP conserving
- **23** parameters

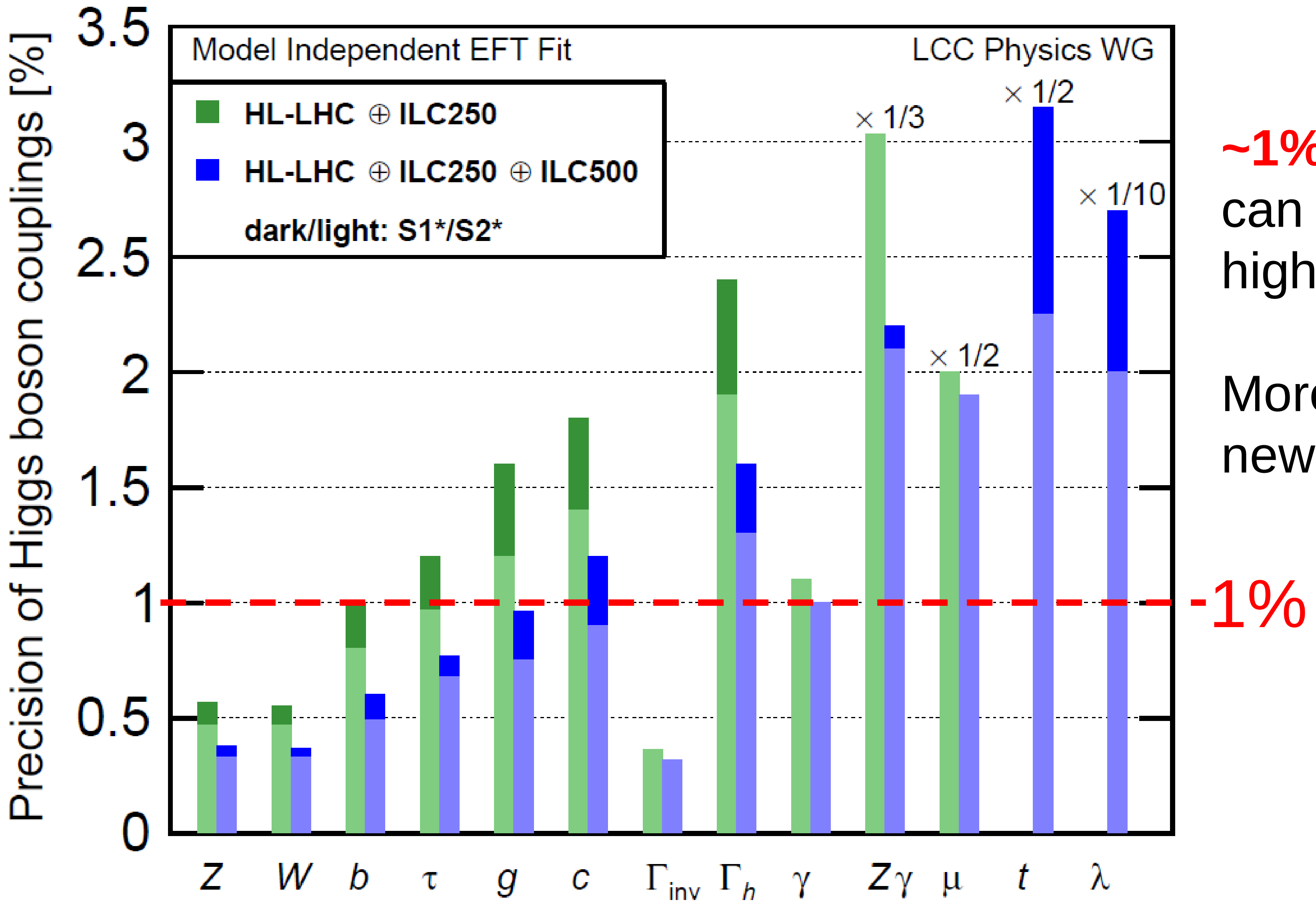
10 EFT operators (h, W, Z, γ): c_H, c_T, c_6, c_{WW}, c_{WB}, c_{BB}, c_{3W}, c_{HL}, c'_{HL}, c_{HE}
5 EFT operators modifying h couplings to b, c, τ, μ, g
2 EFT operators for contact interaction with quarks
4 SM parameters: g, g', v, λ
2 parameters for $h \to$ invisible and exotics

Observables in SMEFT

- In total: 39 observables
  - Electroweak Precision Observables (9)
  - Triple Gauge Coupling observables (3)
  - Higgs observables from LHC and ILC (3+12 × 2)
    - LHC: $\mathrm{BR}(h \to \gamma\gamma, \gamma Z, ZZ^*)$
    - ILC: multiplied by 2 because of beam polarization
- Systematics are considered in the global fit
- **At the ILC, it is possible to determine all the 23 parameters simultaneously.**

arXiv:1903.01629

Model-independent Determination of Higgs Couplings



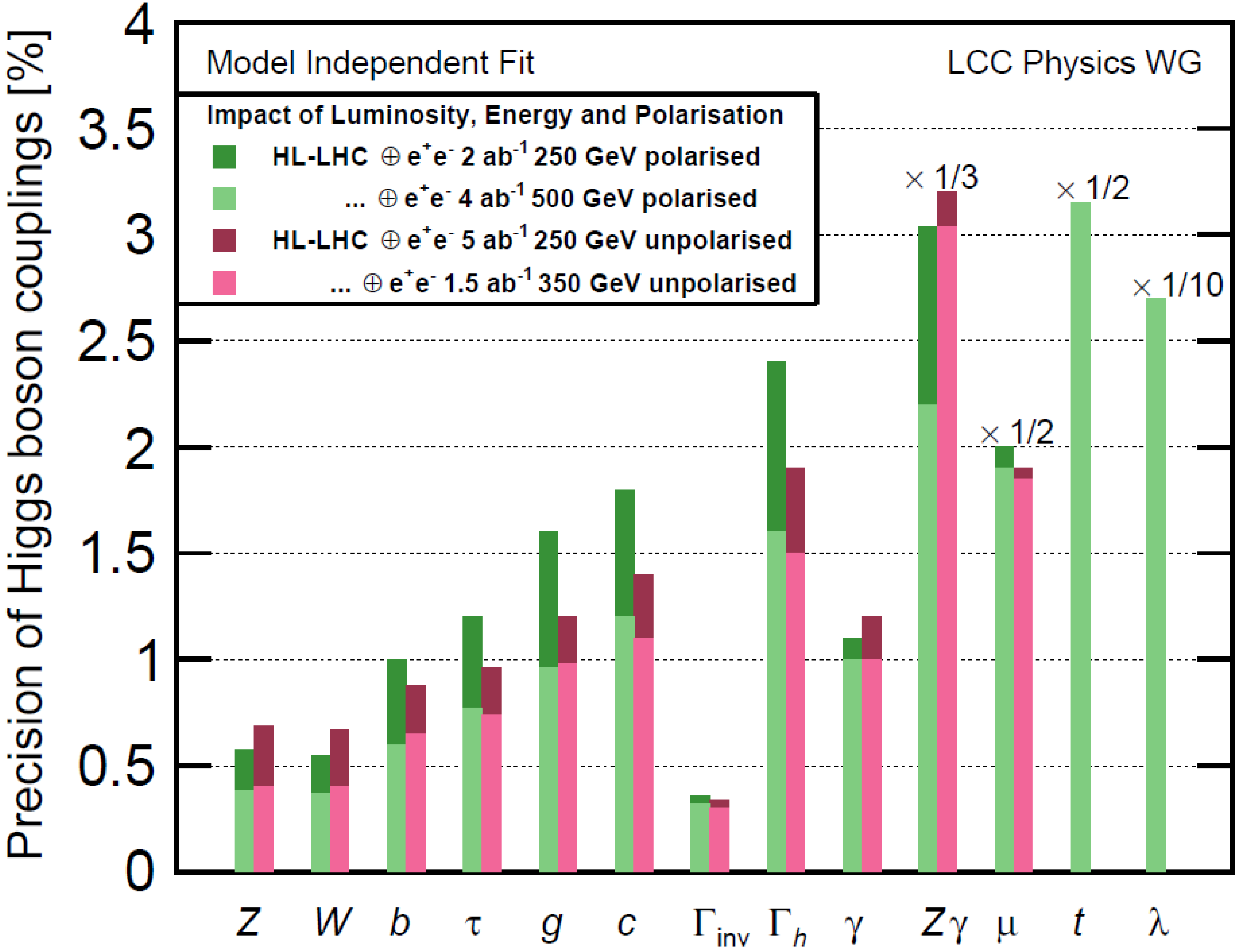
~1% or better precisions can be reached at ILC250 in a highly model-independent way.

More improvements and new results with ILC500.

S1*: based on current results
S2*: assume improvements in jet clustering, flavor tagging,,, (see backup for details)

arXiv:1903.01629

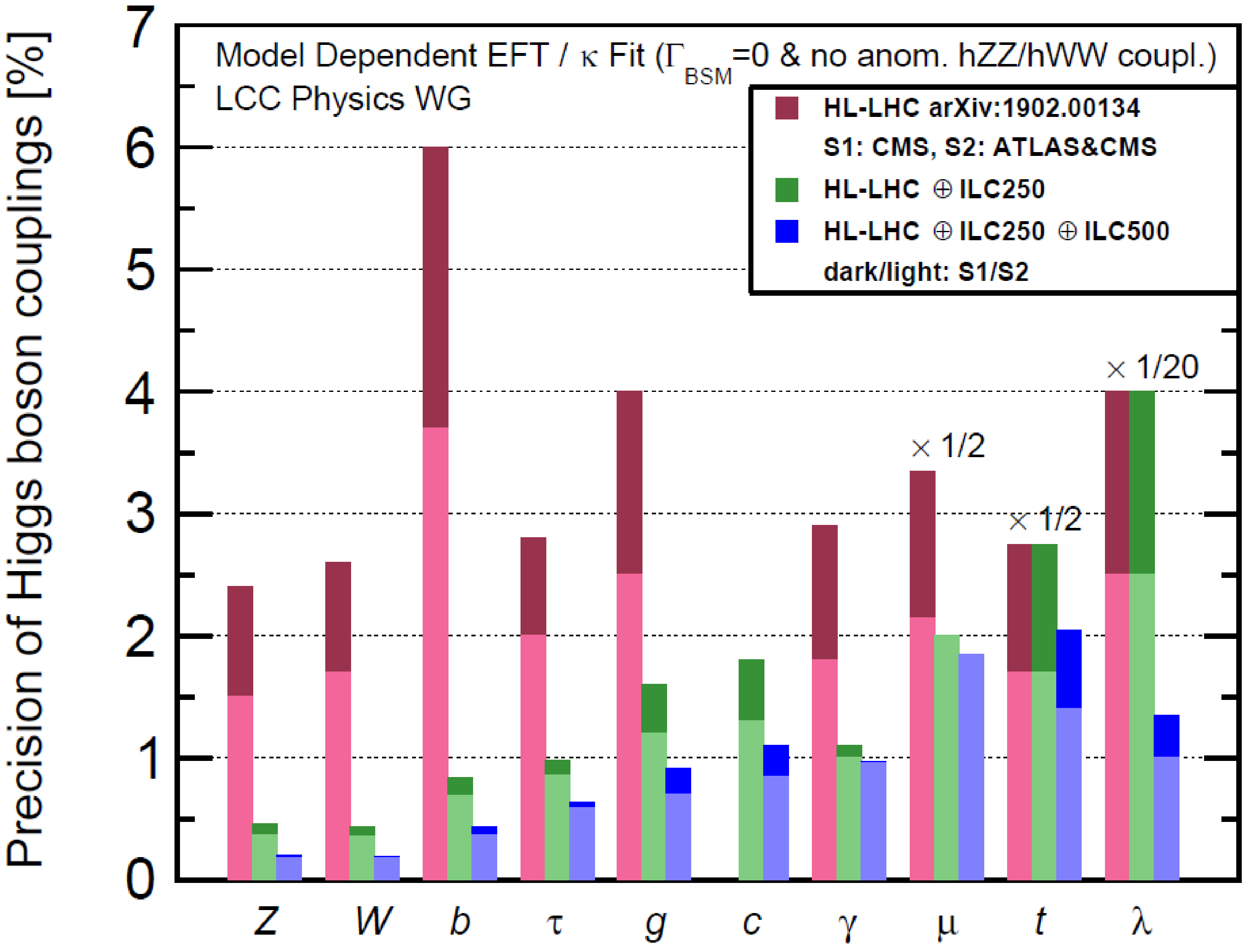
Power of Beam Polarization



There are no drastic difference between precision with **2 ab^{-1}, polarized beam** and
precision with **5 ab^{-1}, unpolarized beam** at 250 GeV.

The polarization is very powerful, essentially compensating the advantage of large data set.

Comparison with HL-LHC Higgs Capabilities

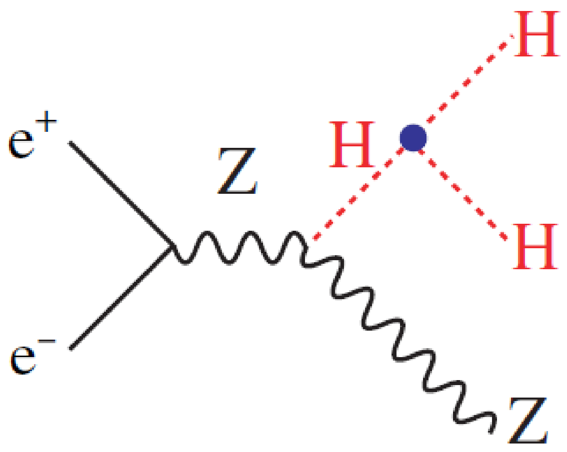


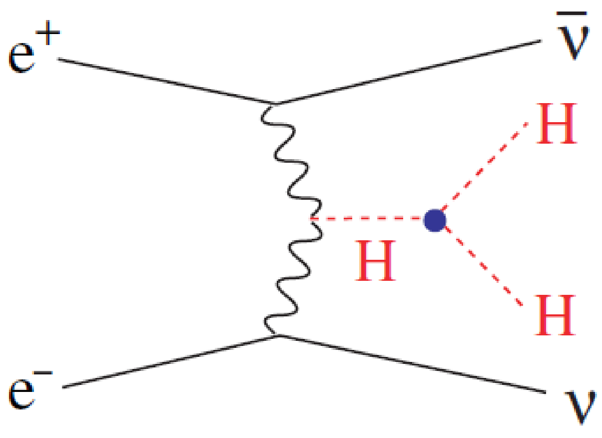
Not simple comparison due to different framework.
---> add assumptions in EFT fit (model-dependent fit)
(1) no BSM decay of Higgs
(2) no anomalous couplings in hWW and hZZ

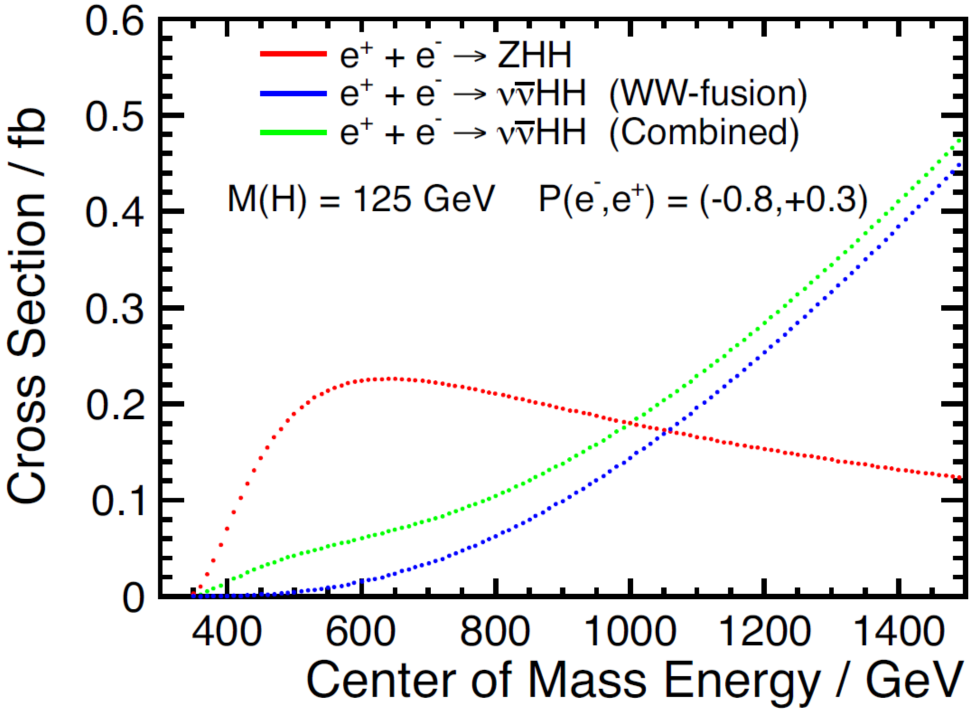
Great improvement at the ILC in many channels.
Nice synergy with HL-LHC, typically in rare channel.

Higgs Self-coupling

Direct probe of Higgs potential







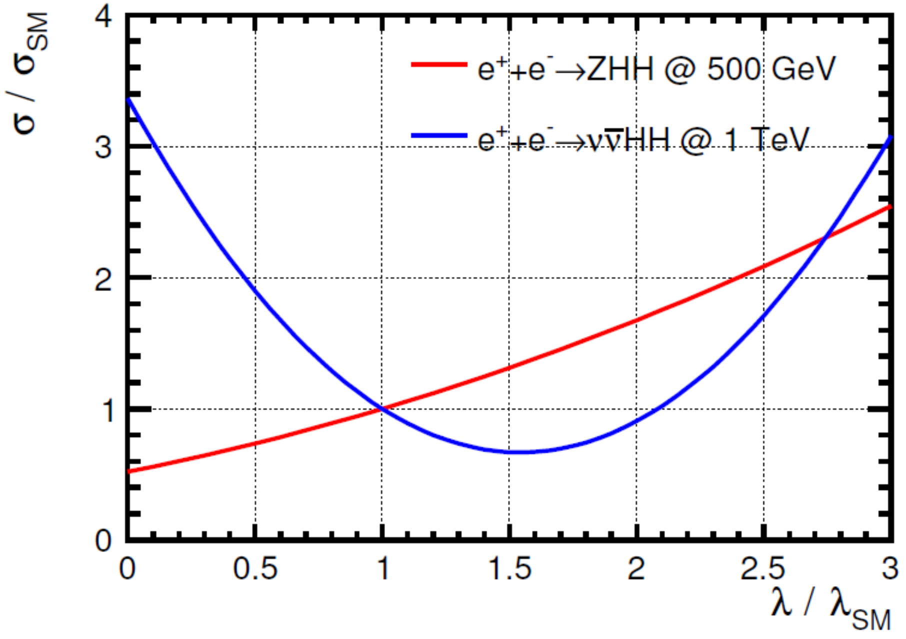
	$\Delta\lambda_{hhh}/\lambda_{hhh}$
4 ab^{-1} at ILC500	27%
+8 ab^{-1} at ILC1000	10%

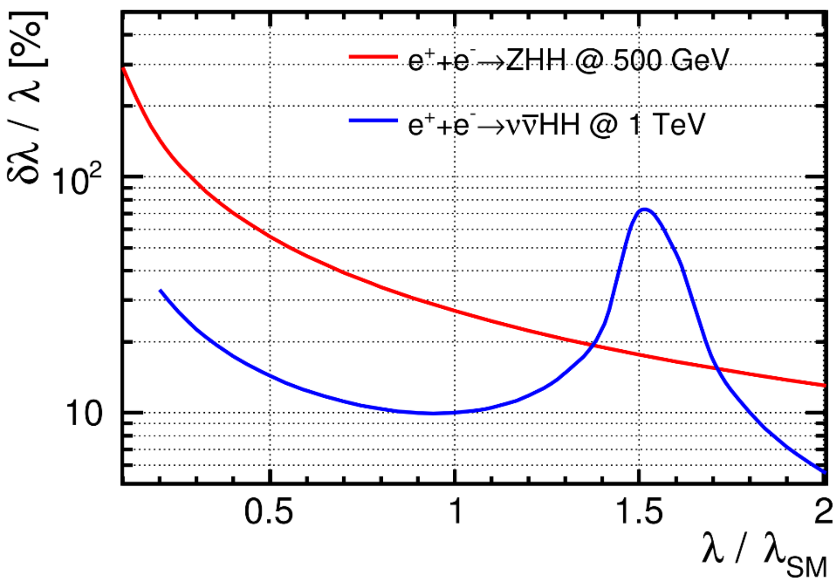
More improvements are expected:
- b-tagging
- jet reconstruction
- kinematic fitting
- ...

see poster by Yasser Radkhorrami (DESY) about kinematic fitting

Higgs Self-coupling: What Happens If $\lambda_{hhh} \neq \lambda_{\mathrm{SM}}$

- λ_{hhh} can be significantly enhanced in BSM such as EW baryogenesis models.
- Complementarity in $Zhh/\nu\bar{\nu}hh$ (and LHC): interferences different
- If $\lambda_{hhh}/\lambda_{\mathrm{SM}}$ = 2, $\Delta\lambda_{hhh}/\lambda_{hhh}$ ~ 15% at ILC500 with Zhh



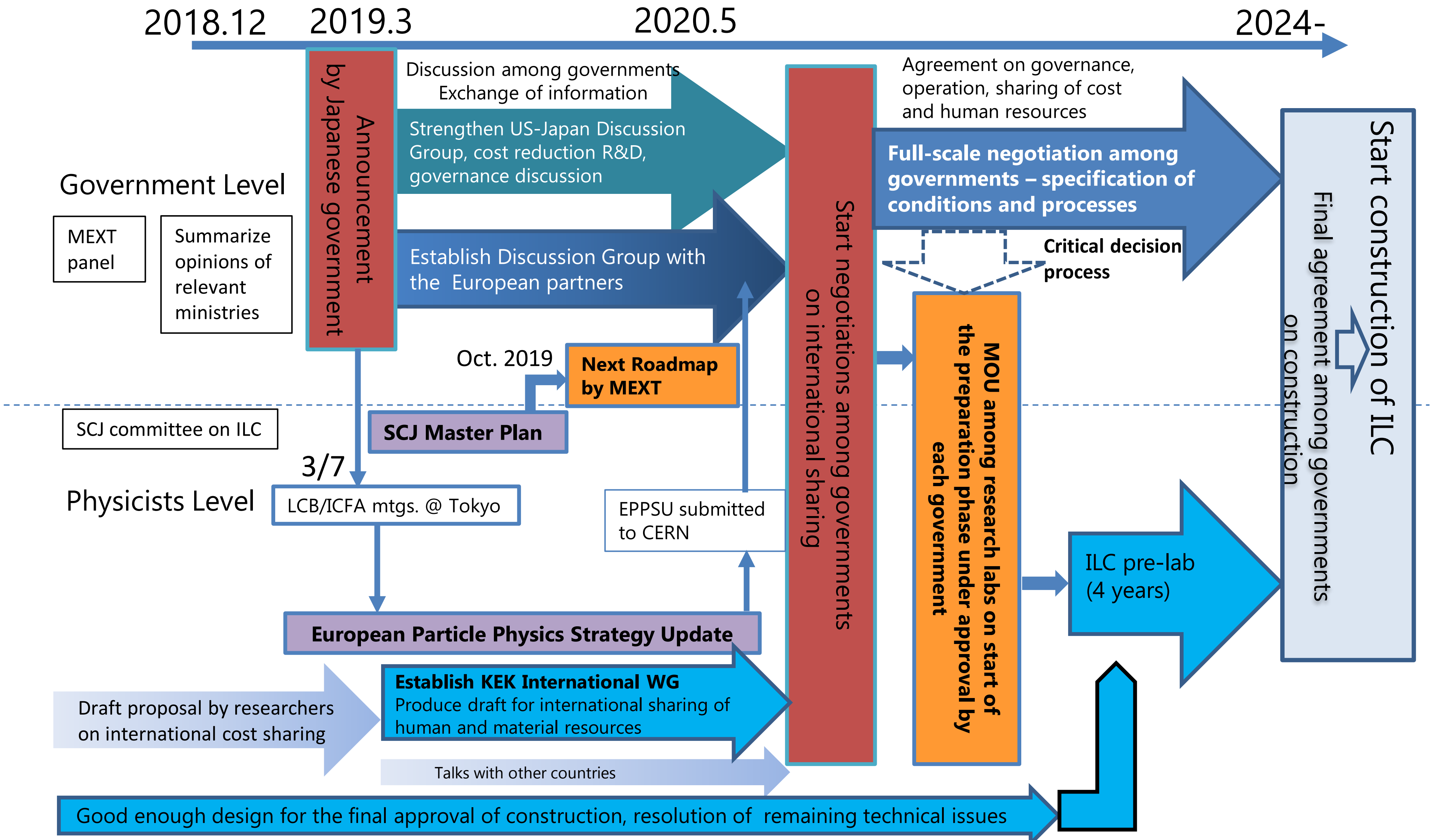


Summary

- Precision measurement on Higgs is a window to new physics.
- Precise and highly model-independent measurements of Higgs boson are possible at the ILC under EFT framework.
- Many couplings can be reached ~1% precision at ILC250.
- Beam polarization is very powerful, essentially compensating ×2.5 luminosity.
- At ILC500 and above, top-Yukawa and Higgs self-coupling can be measured.

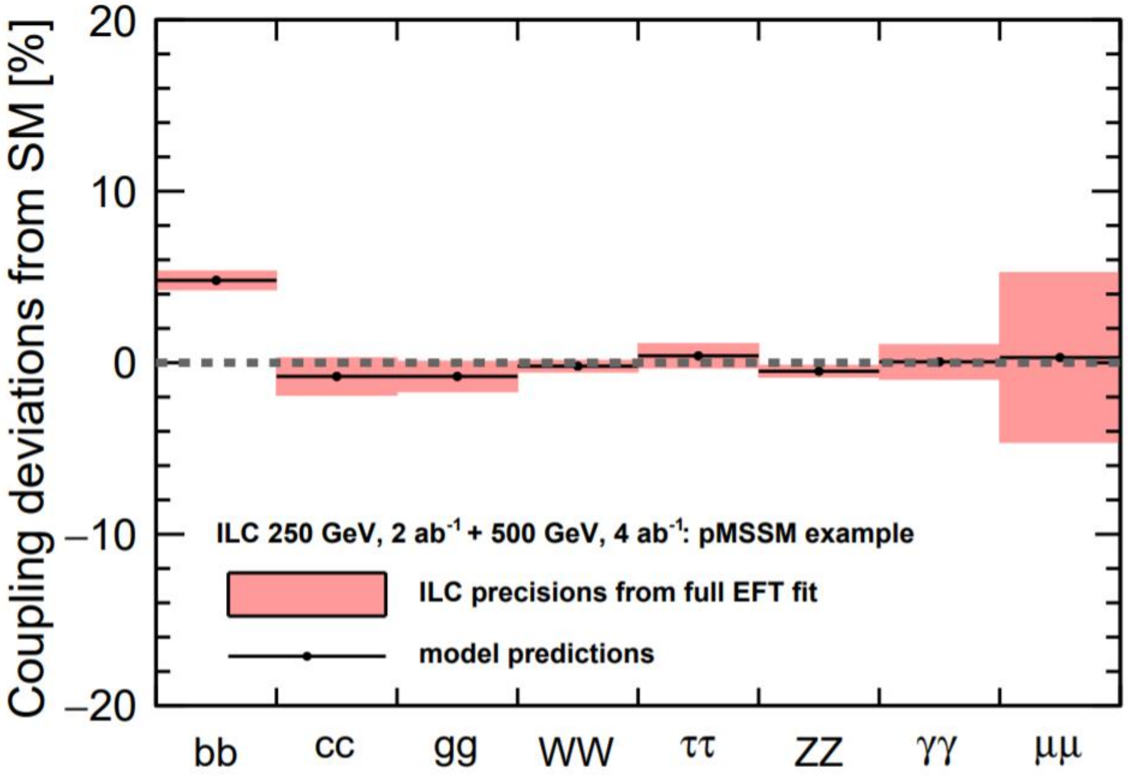
BACKUP

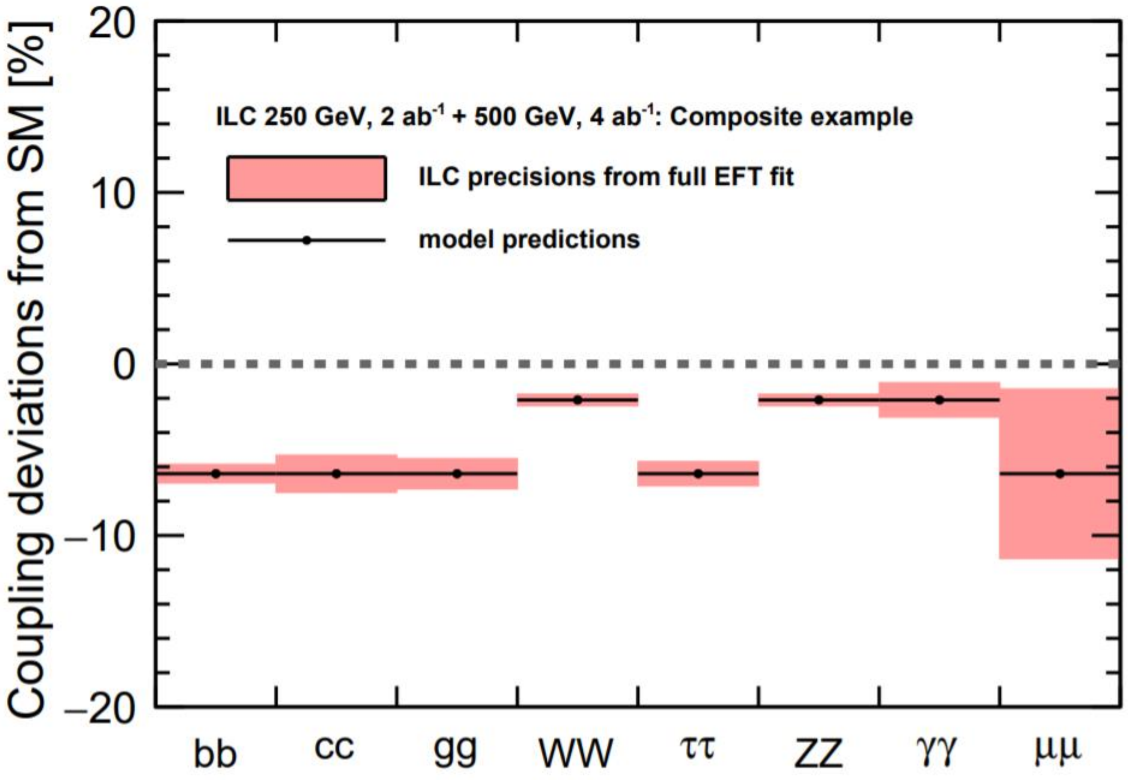
Processes toward Realization of ILC



＊ICFA: international organization of researchers consisting of directors of world's major accelerator labs and representatives of researchers
＊ILC pre-lab: International research organization for the preparation of ILC based on agreements among world's major accelerator labs such as KEK, CERN, FNAL, DESY etc.

Example of Deviation From SM

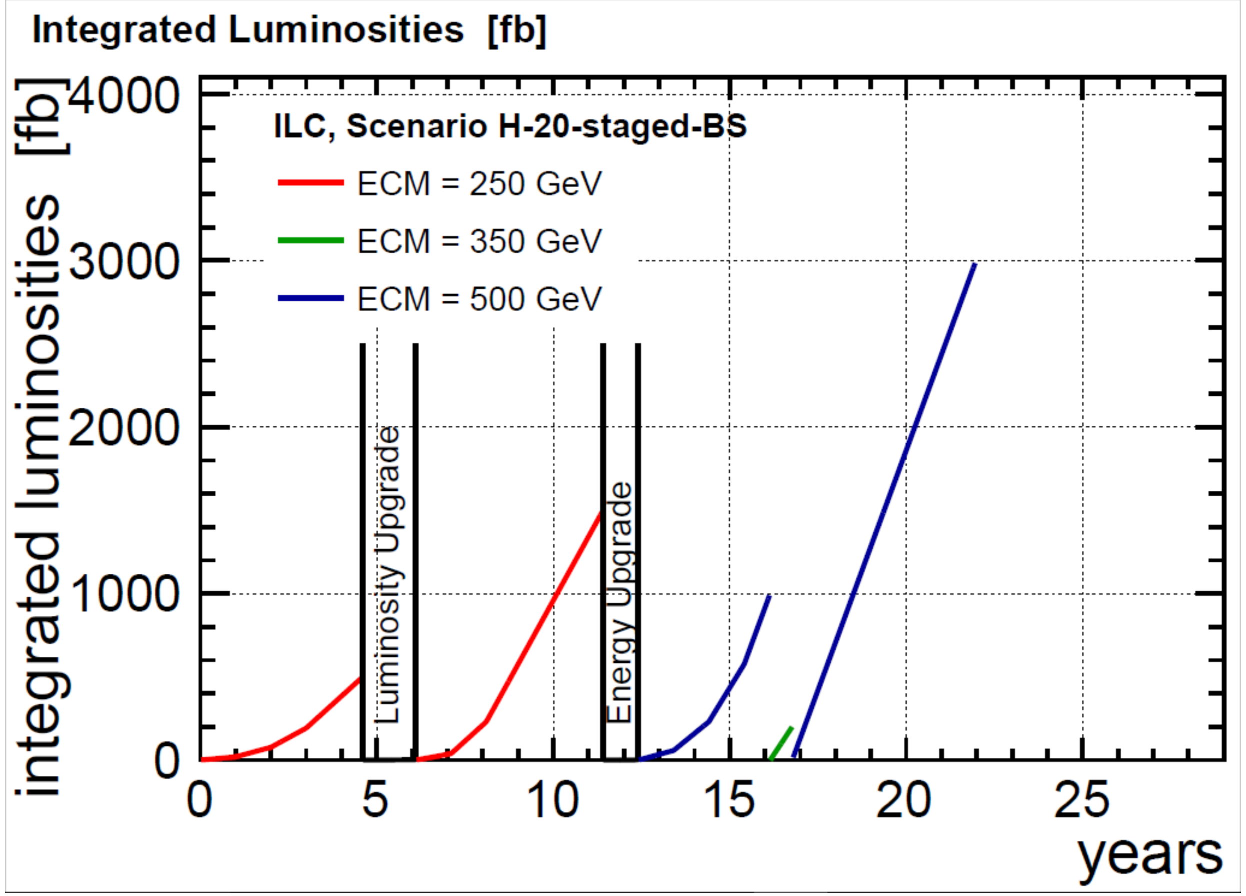




ILC Running Scenario

optimized scenario with considering Higgs/Top/New physics

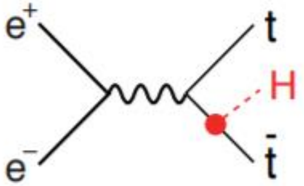
~20 years running with energy range [250-500] GeV, beam polarization sharing



2000 fb^{-1} @ 250 GeV
200 fb^{-1} @ 350 GeV
4000 fb^{-1} @ 500 GeV

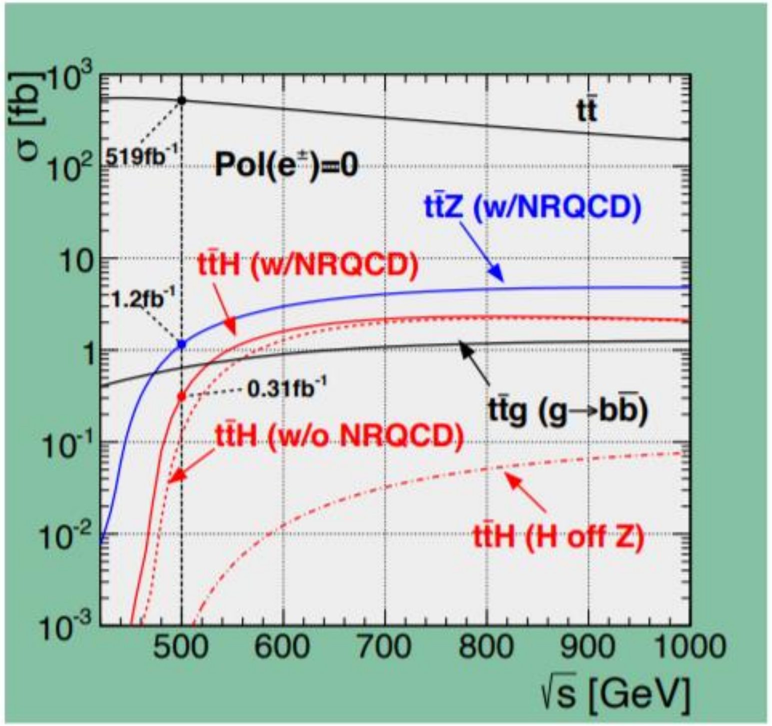
(iii.2.7) Top-Yukawa coupling

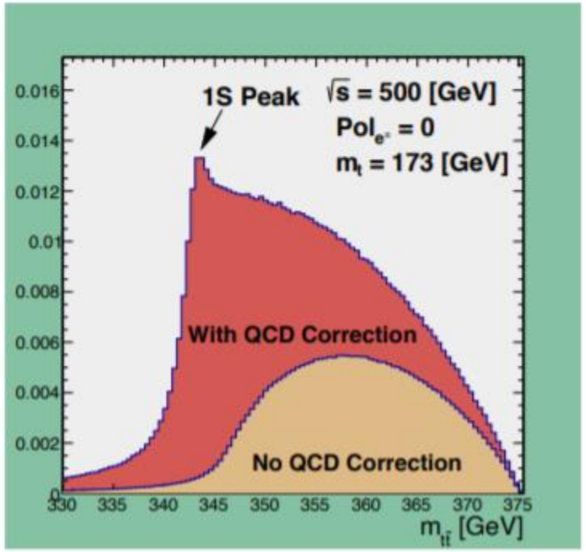
- largest Yukawa coupling; crucial role
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



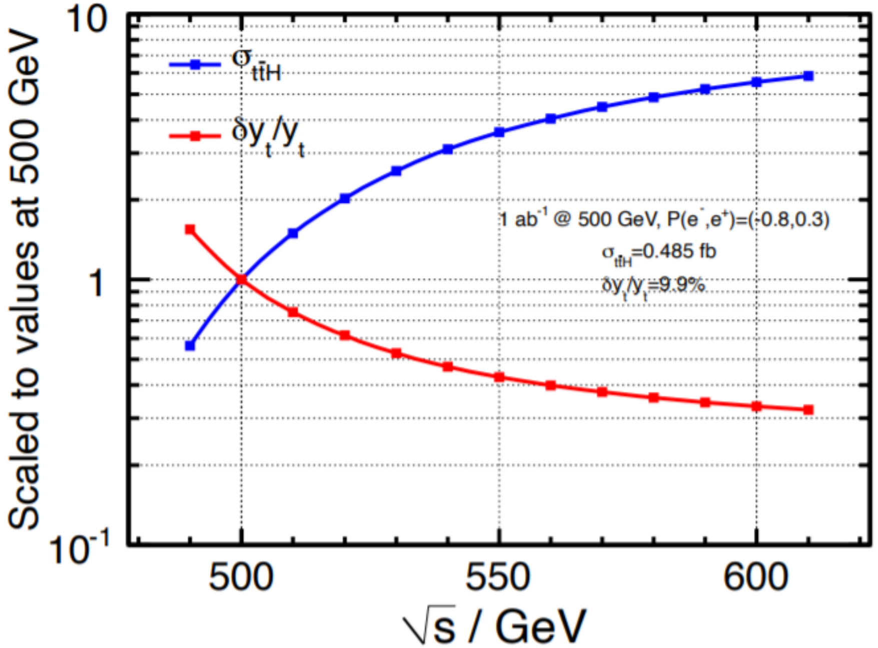
H-> bb

$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
Snowmass	7.8%	2.0%
H20	6.3%	1.5%





Yonamine, et al., PRD84, 014033;
Price, et al., Eur. Phys. J. C75 (2015) 309



Y. Sudo

LABORATOIRE DE L'ACCÉLÉRATEUR LINÉAIRE

GigaZ – Basic facts

arXiv:1506.07830	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]	2.4	1.8	0.36	0.29	4.9	
hadronic Z events [10^9]	1.7	1.3	0.25	0.21	3.4	=230xLEP, 8500xSLC

- Accelerator scenario 3.7Hz@M_Z/2 + 3.7 Hz@125 GeV to produce positrons
- With 2625 bunches an instantaneous luminosity of 5×10^{33} cm^{-2}s-1 => 100 fb^{-1} in 1.3 years after lumi upgrade
- More possible by improved damping rings and BDS system

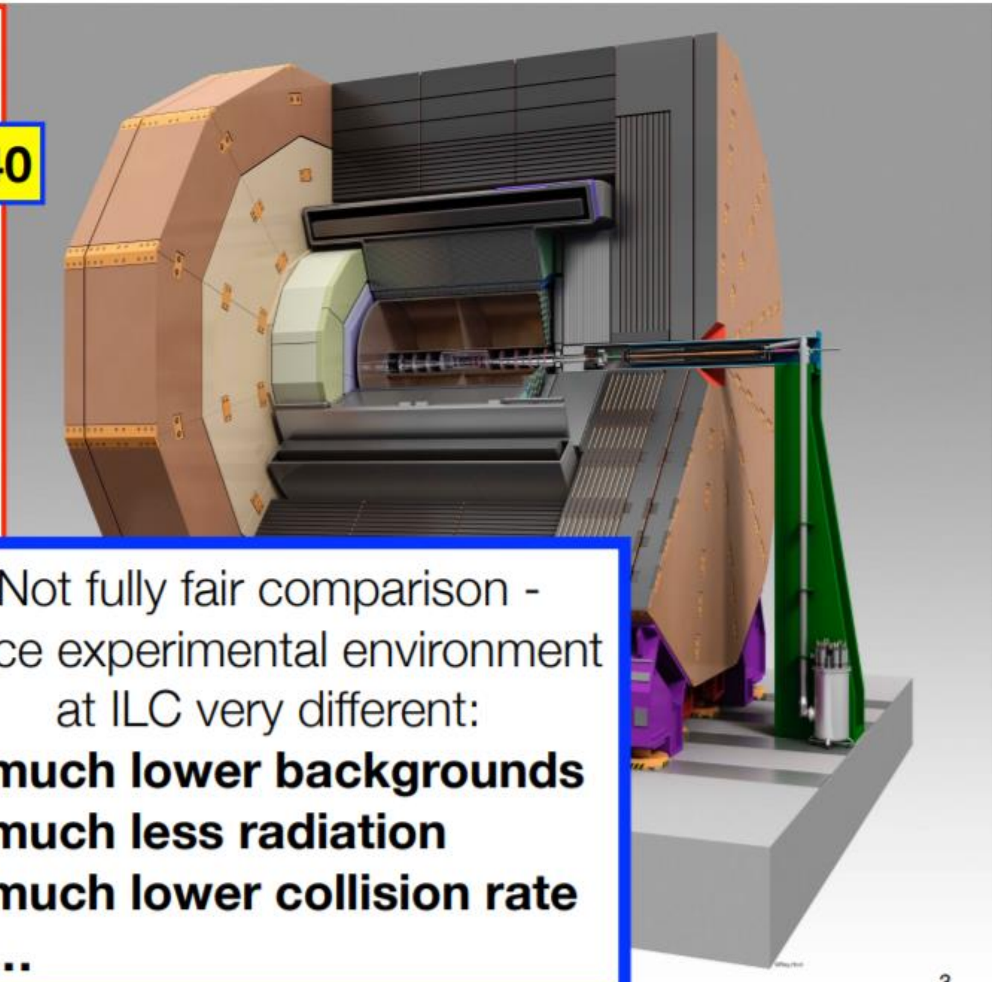
The ILD Concept

From key requirements from physics:

- **p_t resolution** (total ZH x-section)
  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$ **≈ CMS / 40**
- **vertexing** ($H \rightarrow bb/cc/\tau\tau$)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$ **≈ CMS / 4**
- **jet energy resolution** 3-4% **≈ ATLAS / 2**
  ($H \rightarrow$ invisible)
- **hermeticity** θ_{min} = 5 mrad **≈ ATLAS / 3**
  ($H \rightarrow$ invis, BSM)

To key features of the detector:

- **low mass tracker:**
  - main device: **Time Projection Chamber** (dE/dx !)
  - add. silicon: eg VTX: 0.15% rad. length / layer)
- **high granularity calorimeters**
  optimised for particle flow



Not fully fair comparison - since experimental environment at ILC very different:

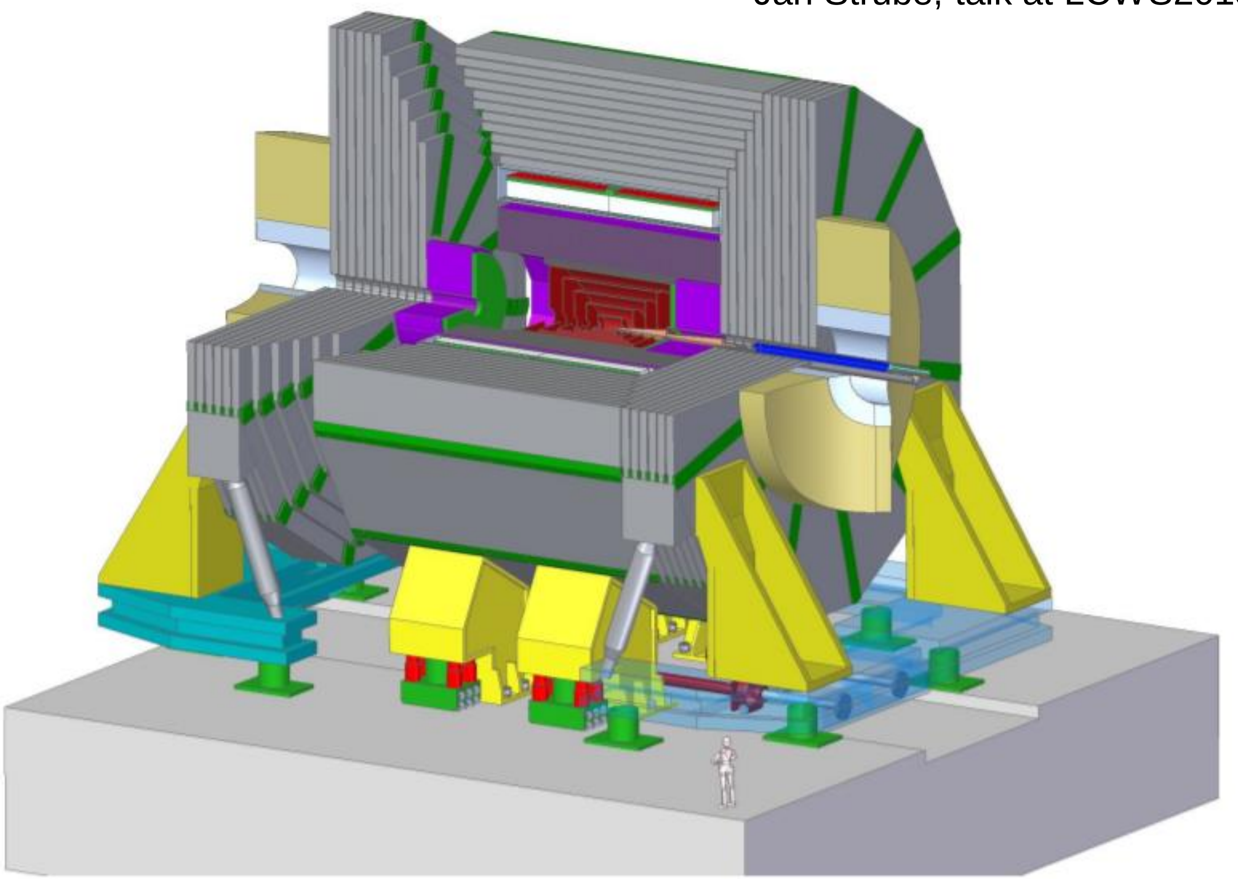
- **much lower backgrounds**
- **much less radiation**
- **much lower collision rate**
- **...**

3

Pacific Northwest
NATIONAL LABORATORY

SiD Overview

- Compact design in a 5 T field
- Robust all-silicon tracking with excellent momentum resolution
- Time-stamping for single bunch crossings
- Highly granular calorimetry optimized for Particle Flow
- Integrated design: All parts work in tandem
- Iron flux return / muon identifier is part of SiD self-shielding



A compact, cost-constrained detector designed to make precision measurements and be sensitive to a wide range of new phenomena

Observables To Couplings: κ-formalism (1)

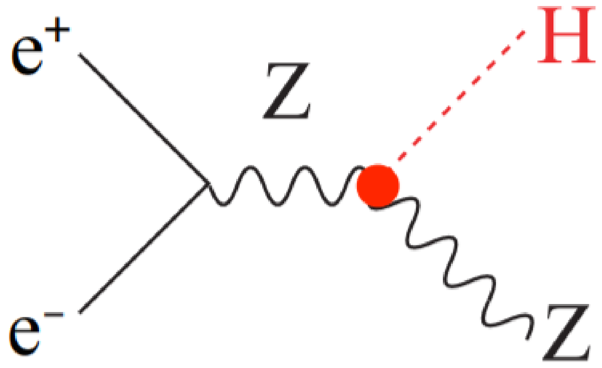
(1) recoil mass technique ---> σ_{Zh}
(2) σ_{Zh} ---> κ_Z ---> $\Gamma(h \to ZZ^*)$
(3) WW-fusion measurement ---> κ_W ---> $\Gamma(h \to WW^*)$
(4) total width $\Gamma_h = \frac{\Gamma(h \to ZZ^*)}{\mathrm{BR}(h \to ZZ^*)}$, or $\Gamma_h = \frac{\Gamma(h \to WW^*)}{\mathrm{BR}(h \to WW^*)}$
(5) then all other couplings $\Gamma_h \times \mathrm{BR}(h \to XX)$ ---> κ_X

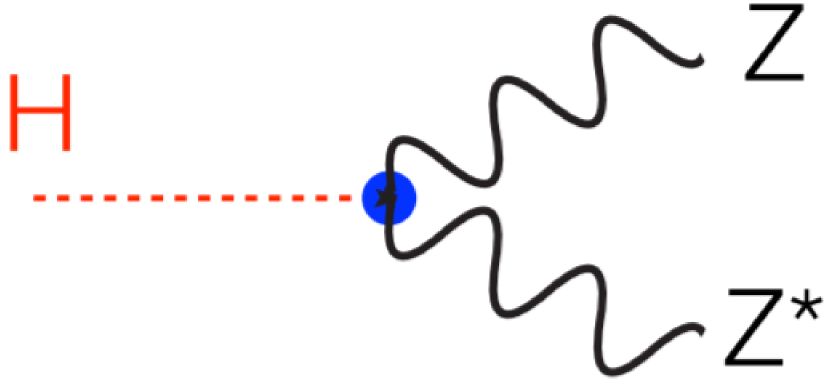
Simple, but **model-dependent**
anomalous coupling is not considered

Observables To Couplings: κ-formalism (2)

assume $\zeta_Z = 0$ in κ-formalism: model-dependent

$$\delta\mathcal{L} = \frac{m_Z^2}{v}(1+\eta_Z)hZ_\mu Z^\mu + \frac{1}{2v}\zeta_Z hZ_{\mu\nu}Z^{\mu\nu}$$





$$\frac{\sigma(e^+e^- \to Zh)}{SM} = 1 + 2\eta_Z + 5.7\zeta_Z$$

$$\frac{\Gamma(h \to ZZ^*)}{SM} = 1 + 2\eta_Z - 0.5\zeta_Z$$

Synergy with HL-LHC

LHC meas.: BR(h->γγ)/BR(h->ZZ*), BR(h->γZ)/BR(h->ZZ*)

$$\delta\Gamma(h \to \gamma\gamma) = 528\,\delta Z_A - c_H \quad + \ldots$$

$$\delta\Gamma(h \to Z\gamma) = 290\,\delta Z_{AZ} - c_H \quad + \ldots$$

$$\delta\Gamma(h \to ZZ^*) = -0.50\delta Z_Z - c_H \quad + \ldots$$

- loop induced h->γγ/γZ provide two very strong constraints

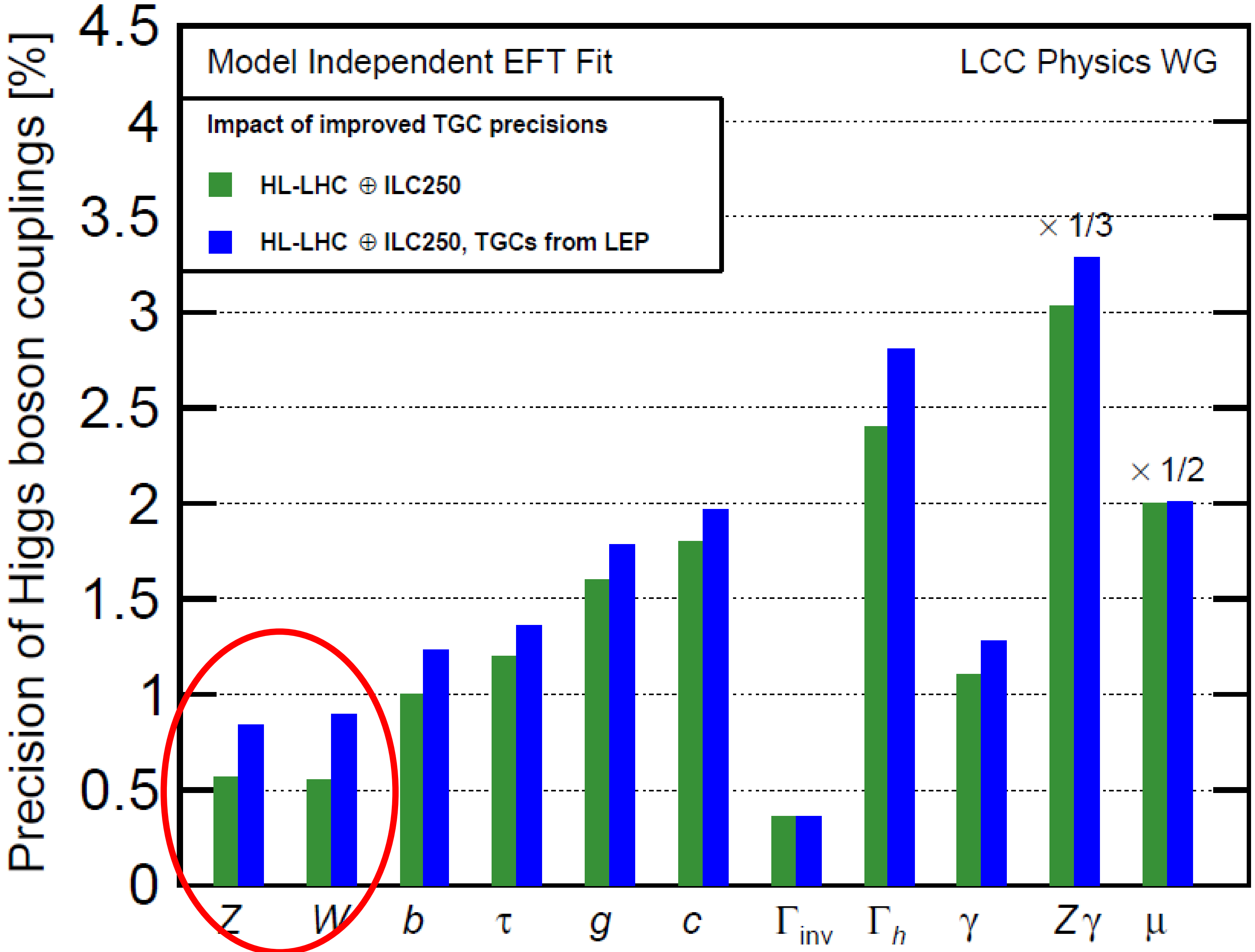
Systematic Errors

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

S2 Assumption

- 10% improvement in signal efficiency of the jet clustering algorithm
- 20% improvement in the performance of the flavor tagging algorithm
- 20% improvement in statistics by including more signal channels in $\sigma_{Zh} \times \mathrm{BR}(h \to WW^*)$
- a factor of 10 improvement in the precision electroweak input A_{LR} through the measurement of $e^+e^- \to \gamma Z$ with polarized beams at ILC250
- 30% improvement in the precision of Higgs self-coupling and top Yukawa coupling at ILC500

Power of TGC


Precision of Higgs boson couplings [%]
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Model Independent EFT Fit
LCC Physics WG
Impact of improved TGC precisions
HL-LHC ⊕ ILC250
HL-LHC ⊕ ILC250, TGCs from LEP
× 1/3
× 1/2
Z
W
b
τ
g
c
Γinv
Γh
γ
Zγ
μ