Precision Higgs Physics at the International Linear Collider

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CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

Why We Need Precision on Higgs?

- Until today: SM-like Higgs boson and no new physics
- But we know SM is not a perfect theory, we need new physics.

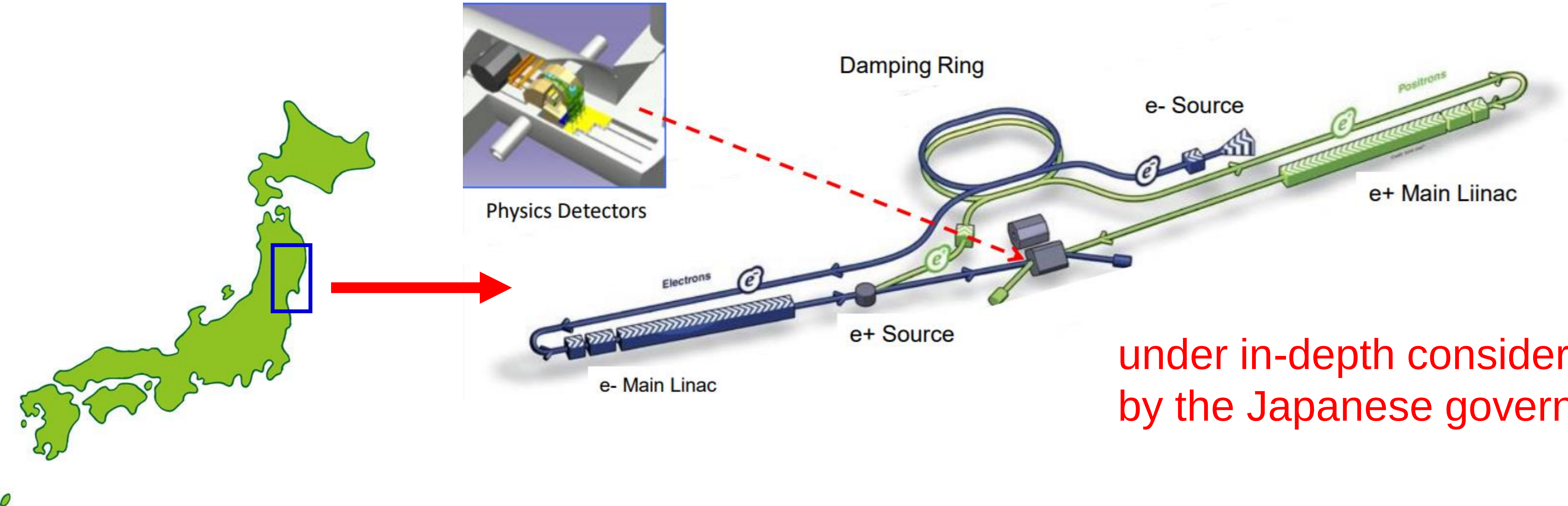
- Newly discovered Higgs boson is a window to new physics.
- Many new physics models predict small deviation from the SM (a few to 10%) ---> O(1%) level precision is necessary

⇩

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

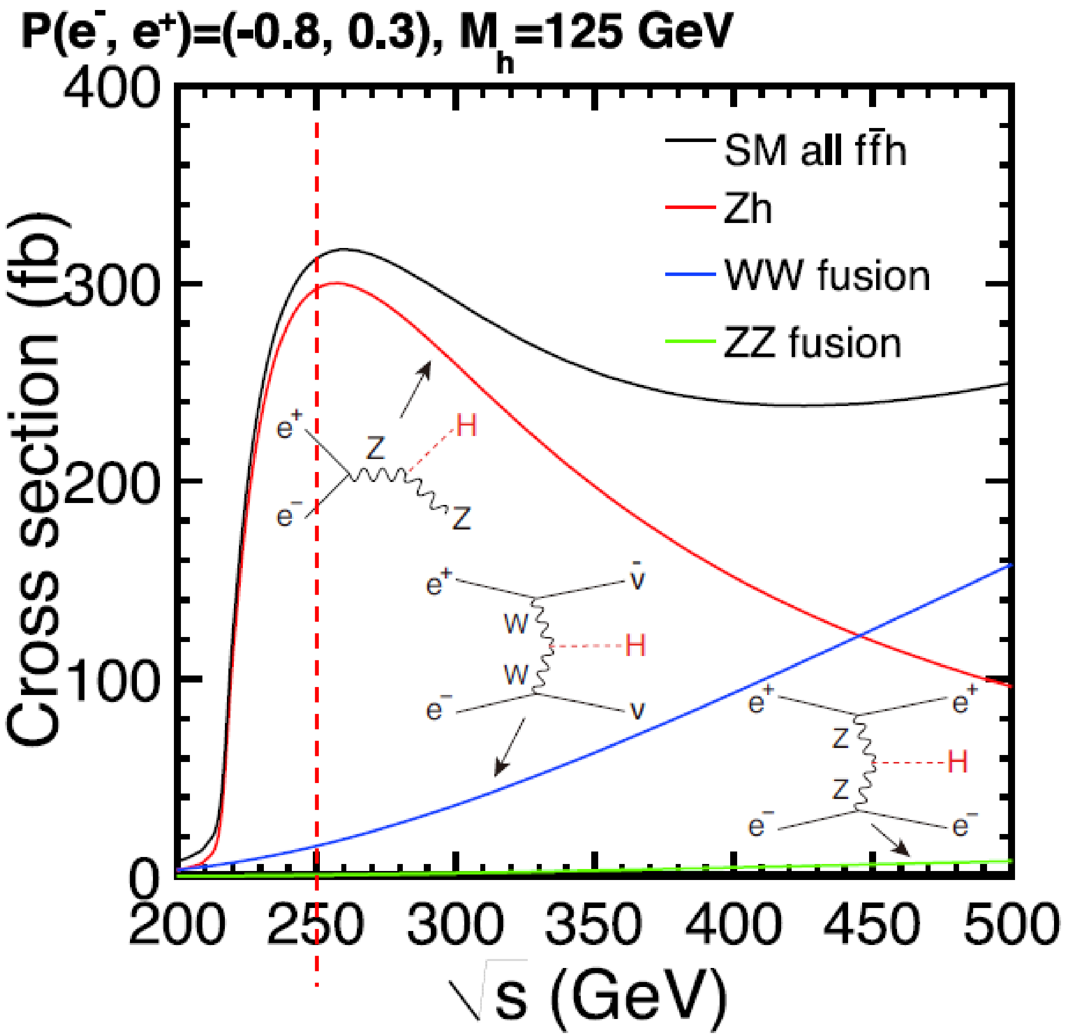


under in-depth consideration
by the Japanese government

Higgs Production at the ILC

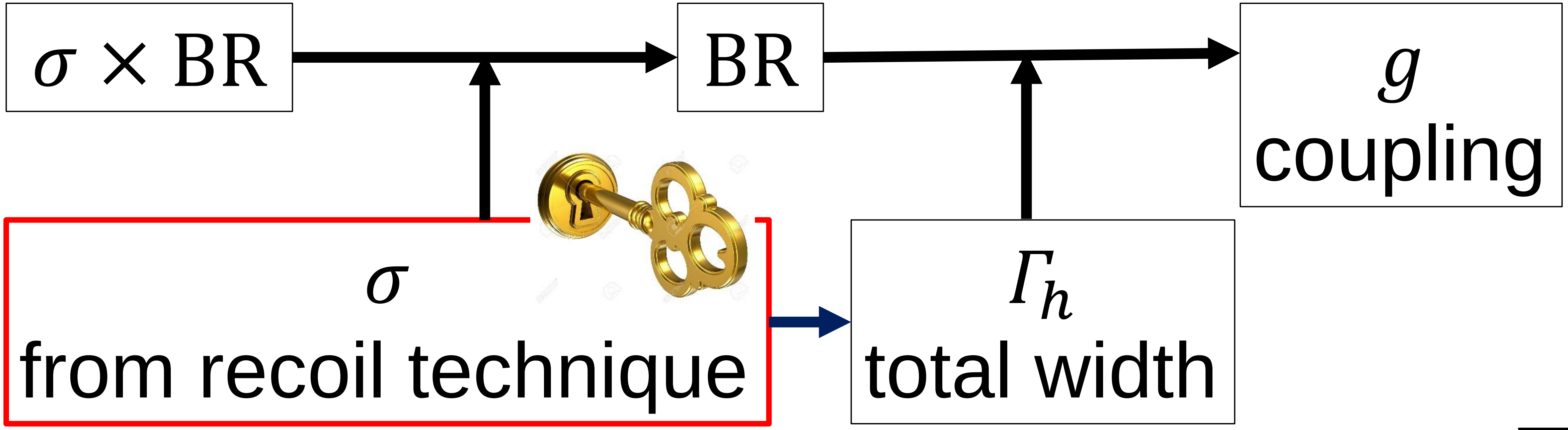
$\sqrt{s}$ = 250 GeV
Higgs-strahlung (Zh) dominant
maximum cross section around 250 GeV
---> Higgs factory

$\sqrt{s}$ = 500 GeV
WW-fusion dominant
improvements in many couplings
tth, Higgs self-coupling, rare decays



Key Point

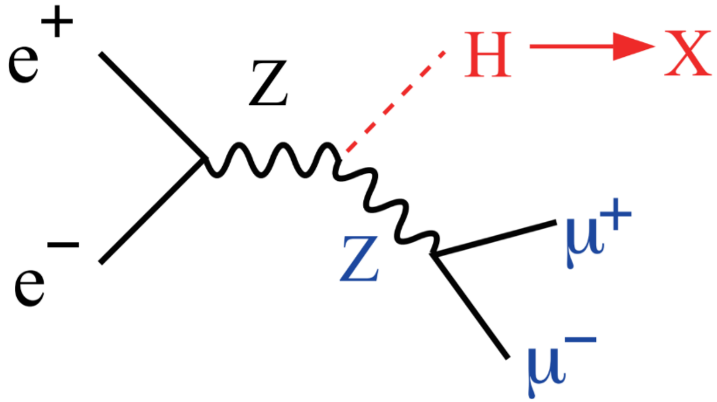
- LHC: all measurements are $\sigma \times \mathrm{BR}$
- ILC: $\sigma \times \mathrm{BR}$ measurements + **$\boldsymbol{\sigma}$ measurement**



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

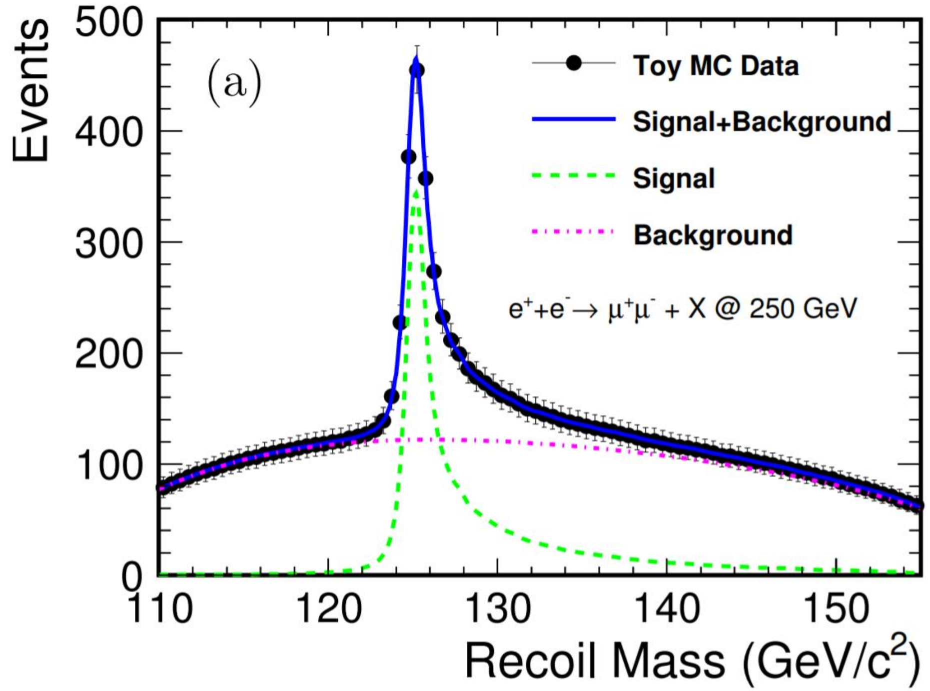
Key Measurement: σ_{Zh}

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 Higgs (recoil mass technique)

ILC250, 2 ab^{-1}

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

arXiv:1903.01629

Direct Higgs Observables at ILC250

σ_{Zh}

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

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

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

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

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

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

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

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

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

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

next talk

+ differential cross section

: speciality of e^+e^- colliders

-80% e^-, +30% e^+ polarization:

	250 GeV		350 GeV		500 GeV	
	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
σ	2.0		1.8		4.2	
$h \to invis.$	0.86		1.4		3.4	
$h \to b\bar{b}$	1.3	8.1	1.5	1.8	2.5	0.93
$h \to c\bar{c}$	8.3		11	19	18	8.8
$h \to gg$	7.0		8.4	7.7	15	5.8
$h \to WW$	4.6		5.6*	5.7*	7.7	3.4
$h \to \tau\tau$	3.2		4.0*	16*	6.1	9.8
$h \to ZZ$	18		25*	20*	35*	12*
$h \to \gamma\gamma$	34*		39*	45*	47	27
$h \to \mu\mu$	72		87*	160*	120	100
a	7.6		2.7*		4.0	
b	2.7		0.69*		0.70	
$\rho(a,b)$	-99.17		-95.6*		-84.8	

estimated from **full simulation** of ILD/SiD

numbers in %, nominal $\int L dt$ = 250 fb^{-1}

Dimension-6 SMEFT Formalism

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

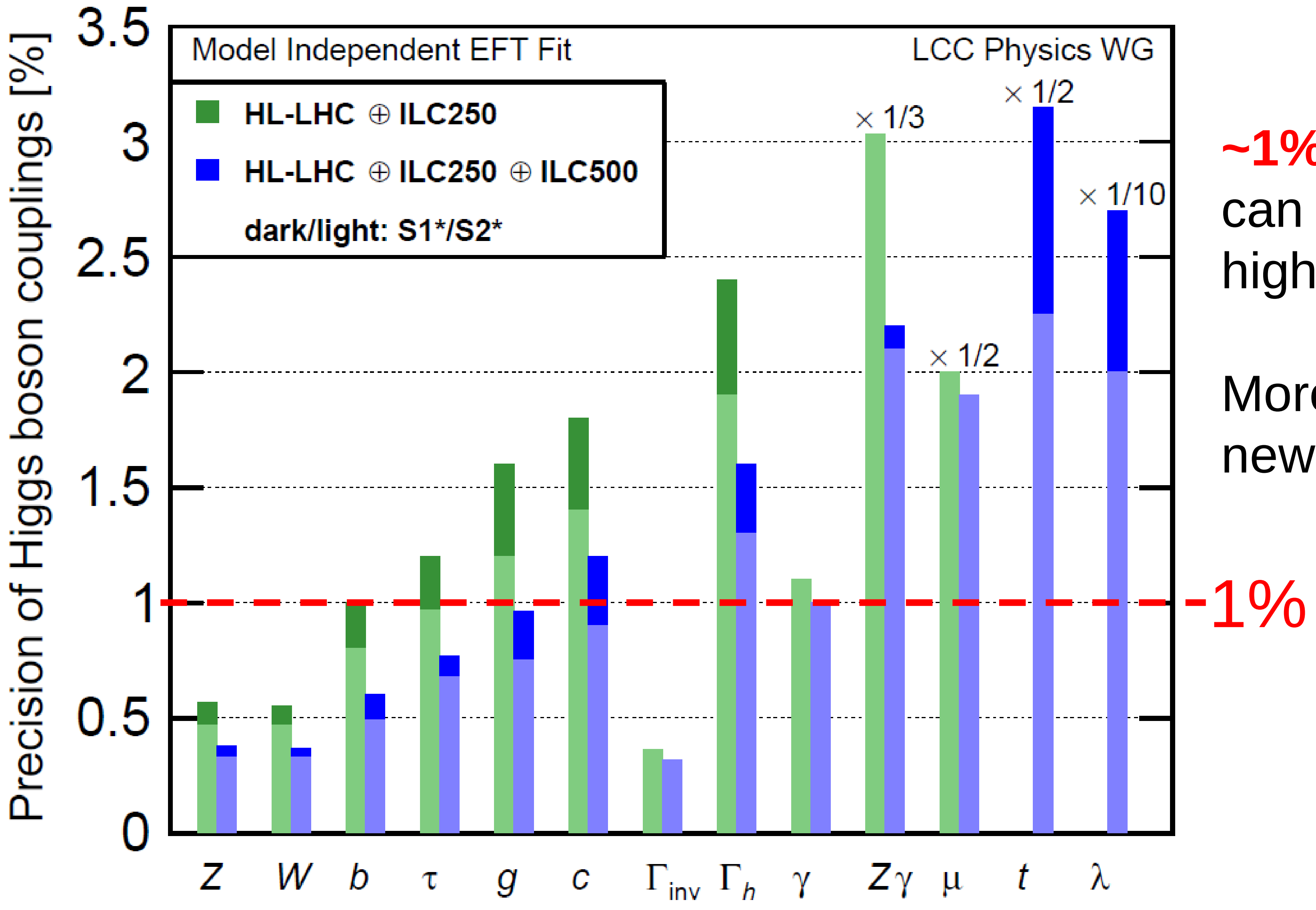
"Warsaw" basis
SMEFT full formalism
- gauge invariant
- Lorentz invariant
- CP conserving
- **23** parameters

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.**

Model-independent Determination of Higgs Couplings



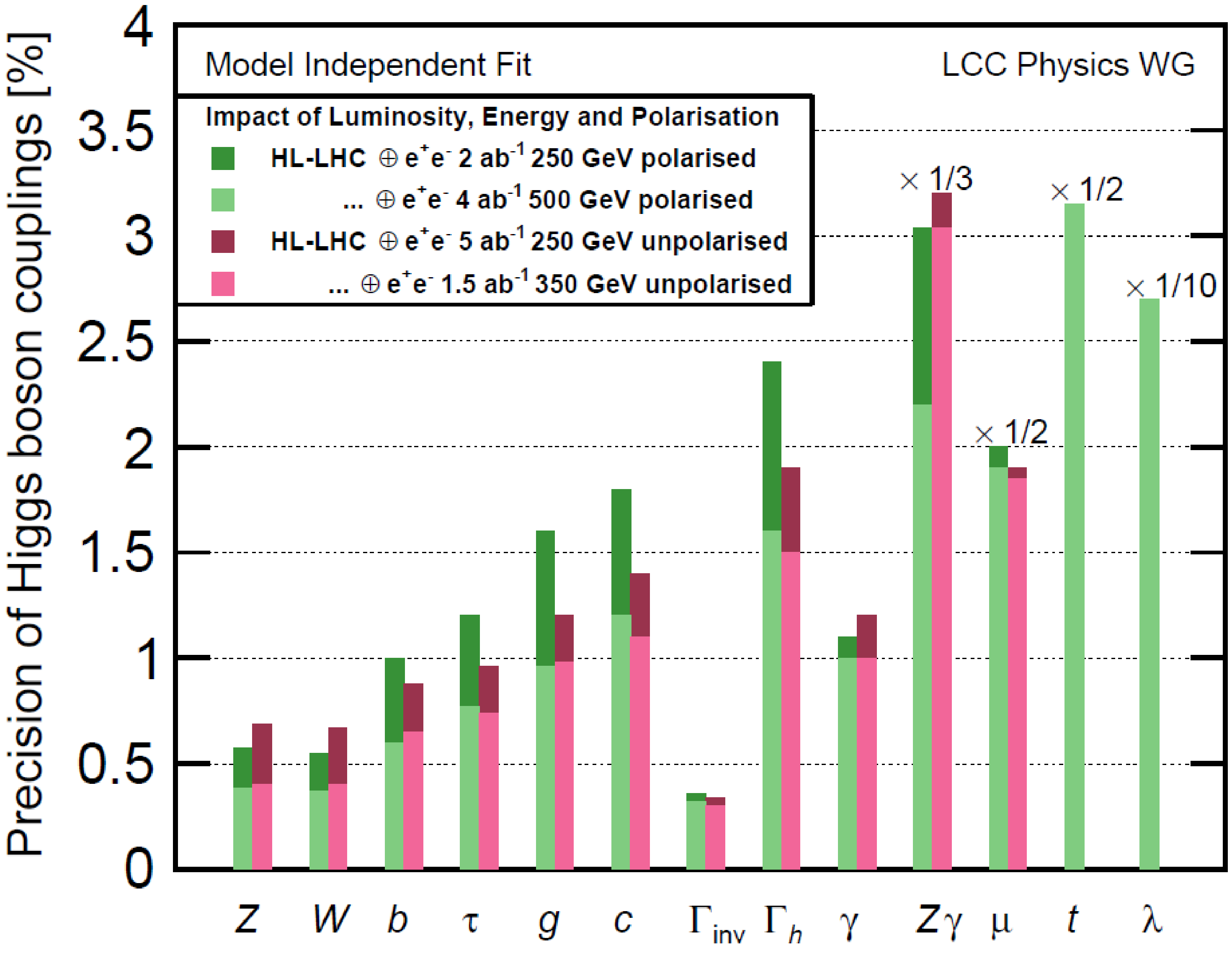
~1% or better precisions can be reached at ILC250 in a highly model-independent way.

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

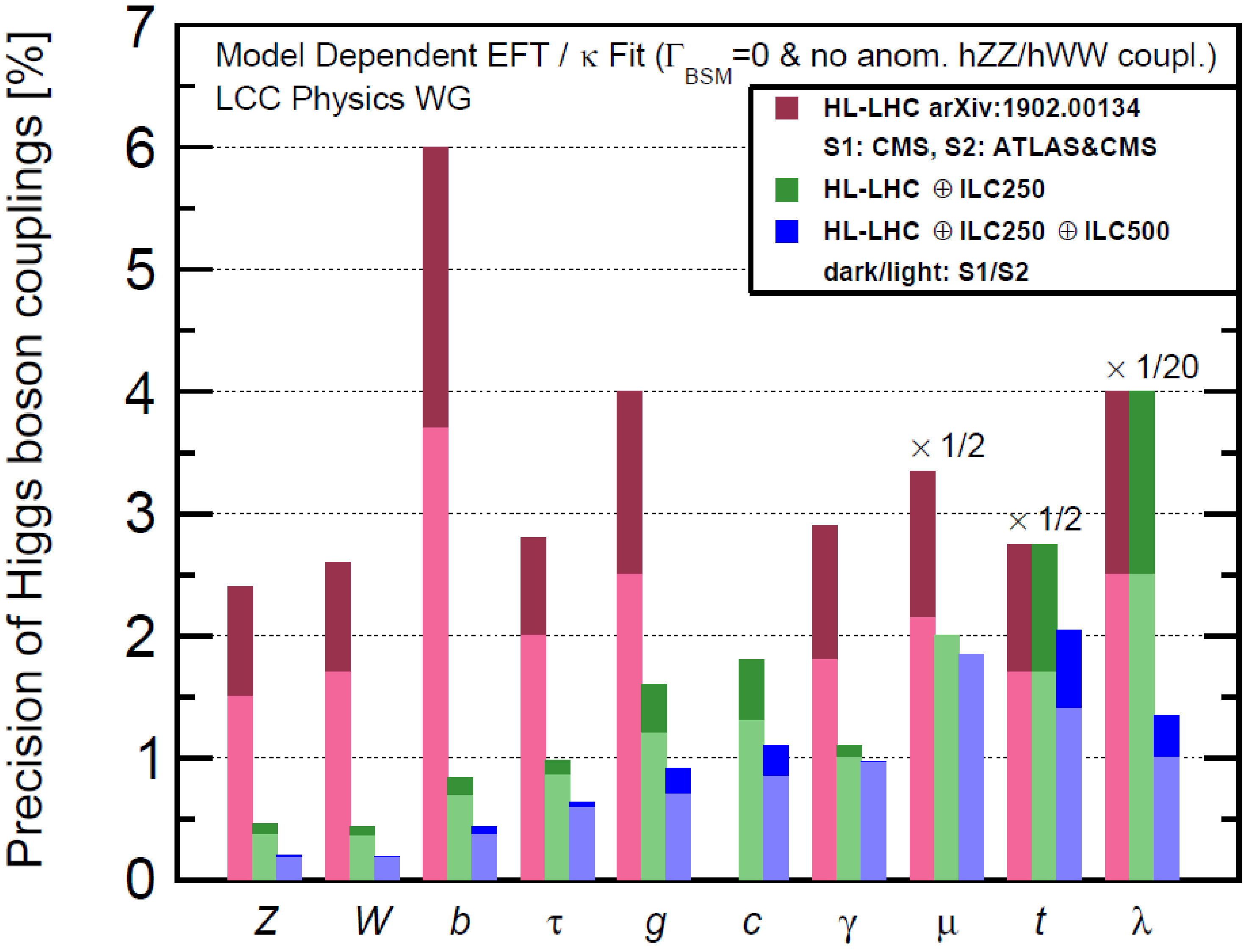


There are no drastic difference between precision with **2 ab^{-1}, polarized beam** and precision with **5 ab^{-1}, unpolarized beam** at 250 GeV.

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

arXiv:1903.01629

Comparison with HL-LHC Higgs Capabilities



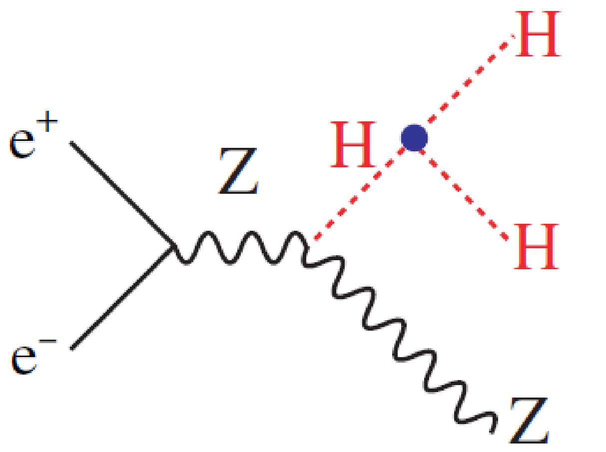
Not simple comparison due to different framework.
---> add assumptions in EFT fit (model-dependent fit)
(1) no BSM decay of Higgs
(2) no anomalous couplings in hWW and hZZ

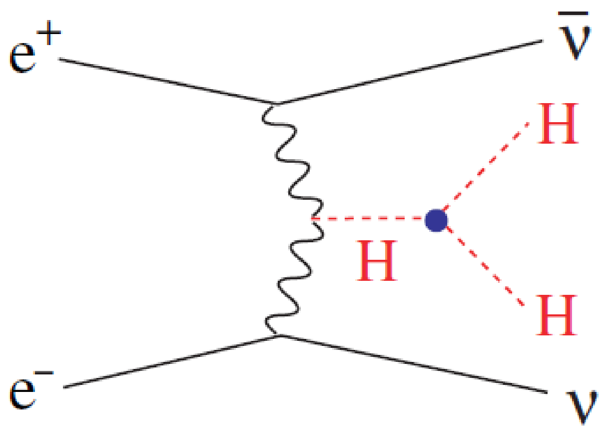
Great improvement at the ILC in many channels.
Nice synergy with HL-LHC, typically in rare channel.

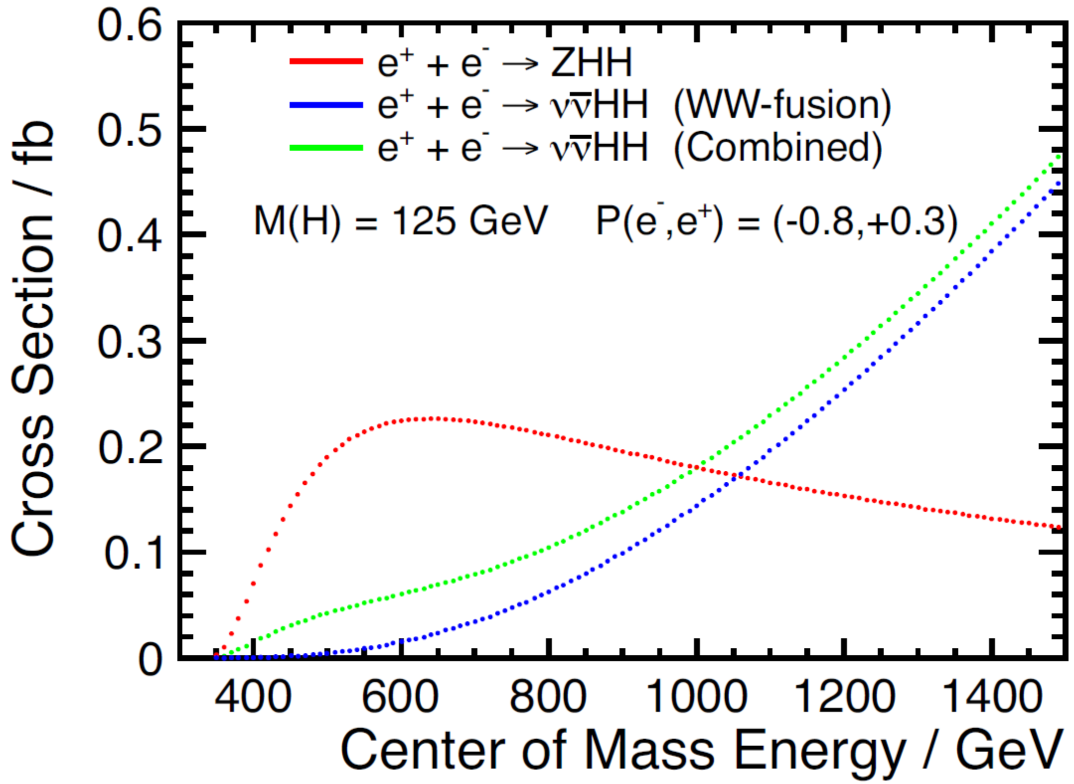
arXiv:1903.01629
Claude Dürig, DESY-THESIS-2016-027

Higgs Self-coupling

Direct measurement of Higgs potential





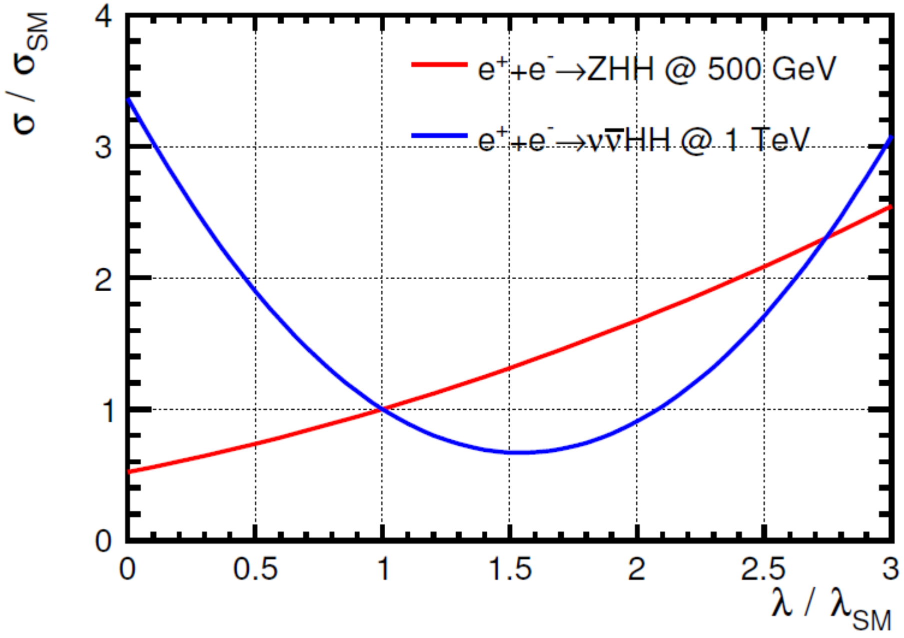


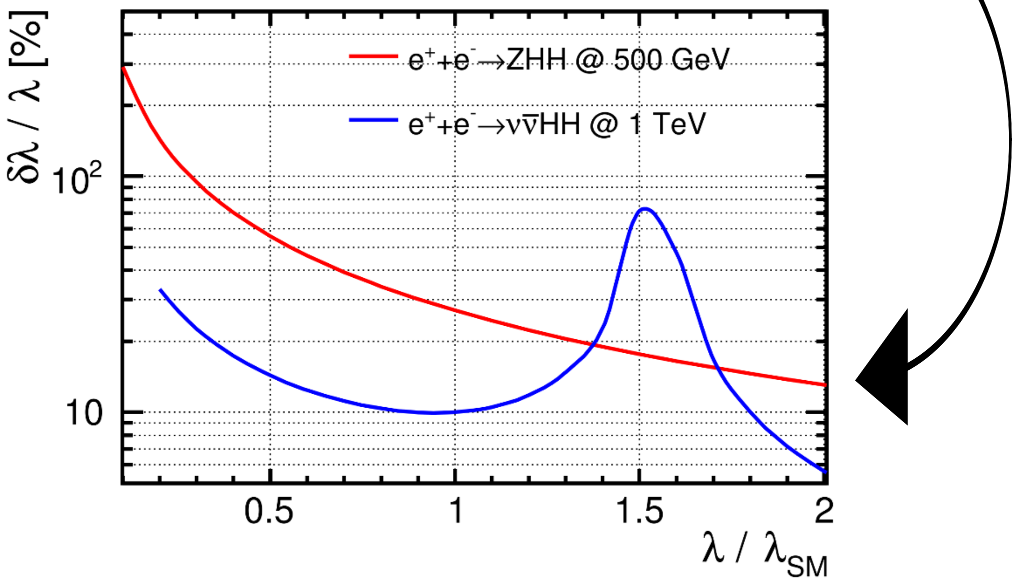
4 ab^{-1} at ILC500 ---> $\Delta\lambda_{hhh}/\lambda_{hhh}$ = 27%

+8 ab^{-1} at ILC1000 --> $\Delta\lambda_{hhh}/\lambda_{hhh}$ = 10%

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

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





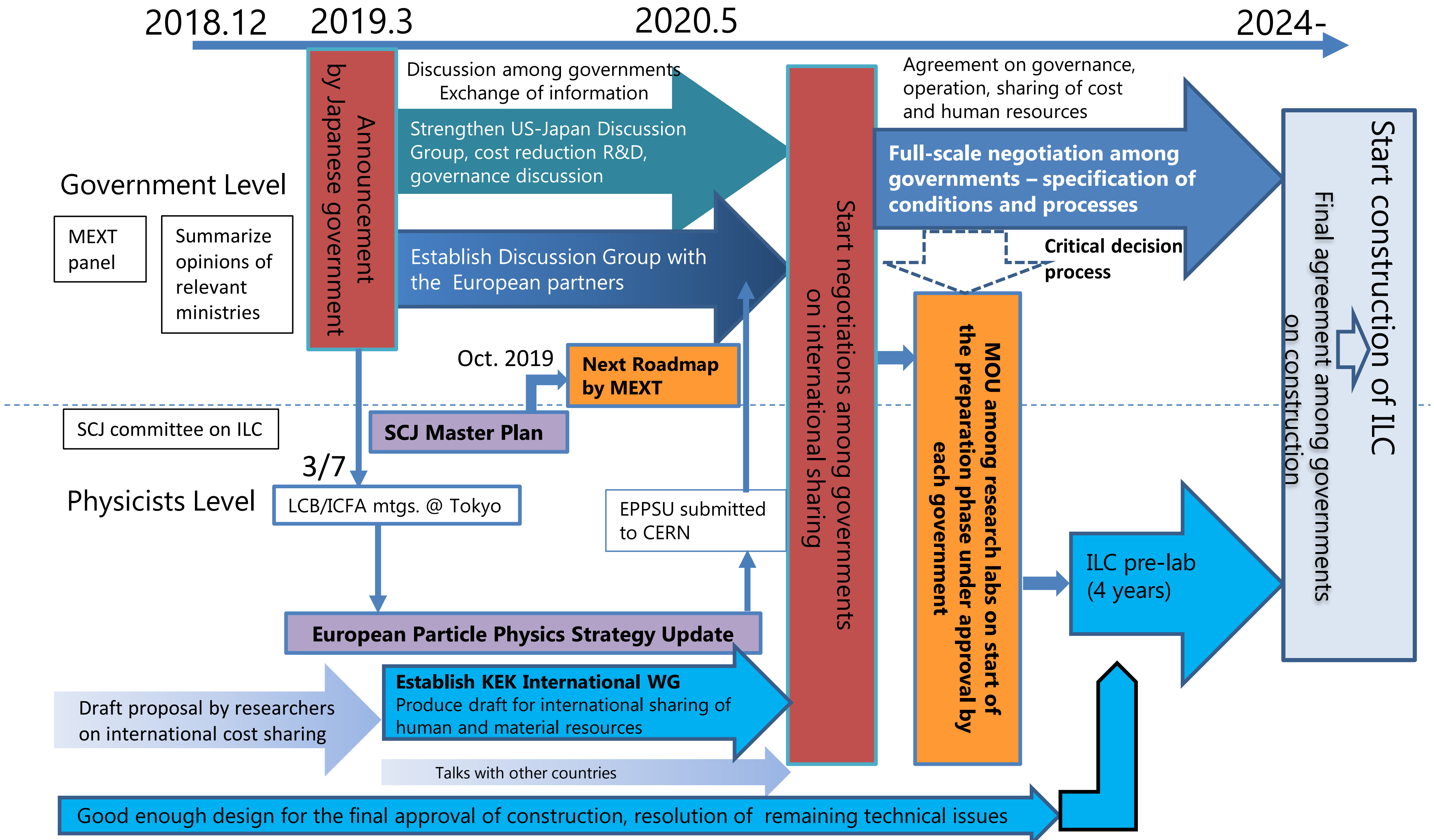
Summary

- 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 $\times 2.5$ luminosity.
- At ILC500 and above, rare channels and Higgs self-coupling can be measured.

#ILCsupporters

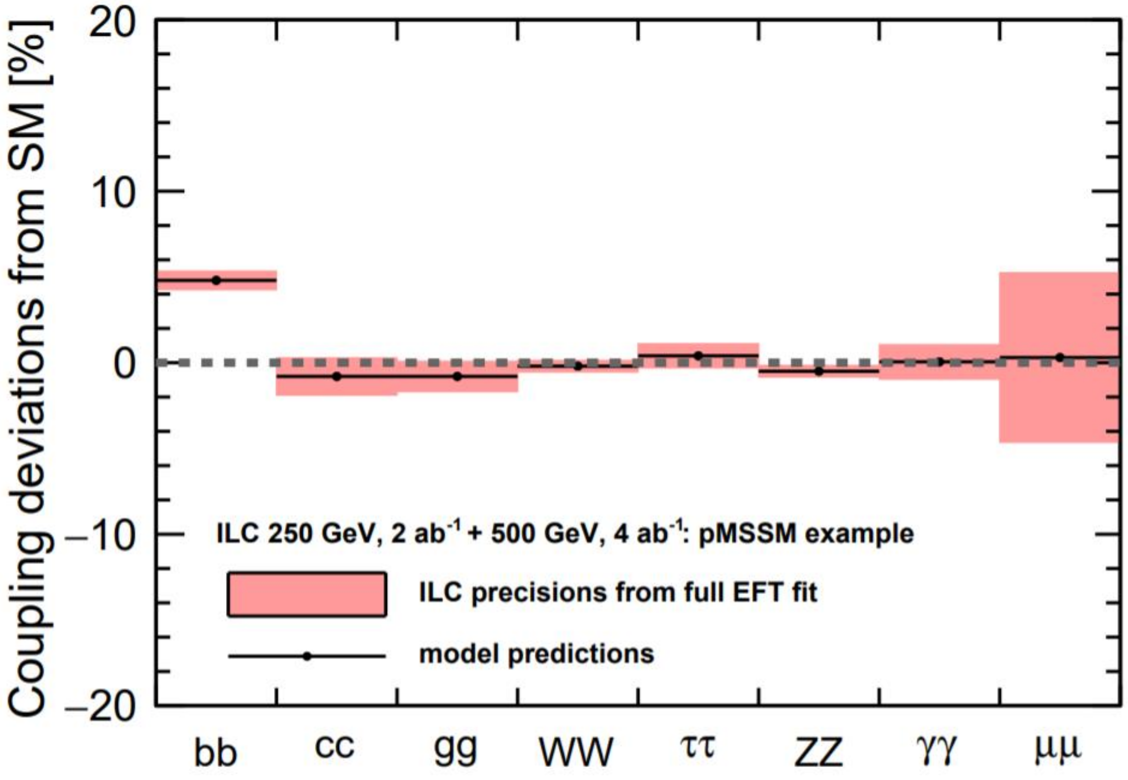
BACKUP

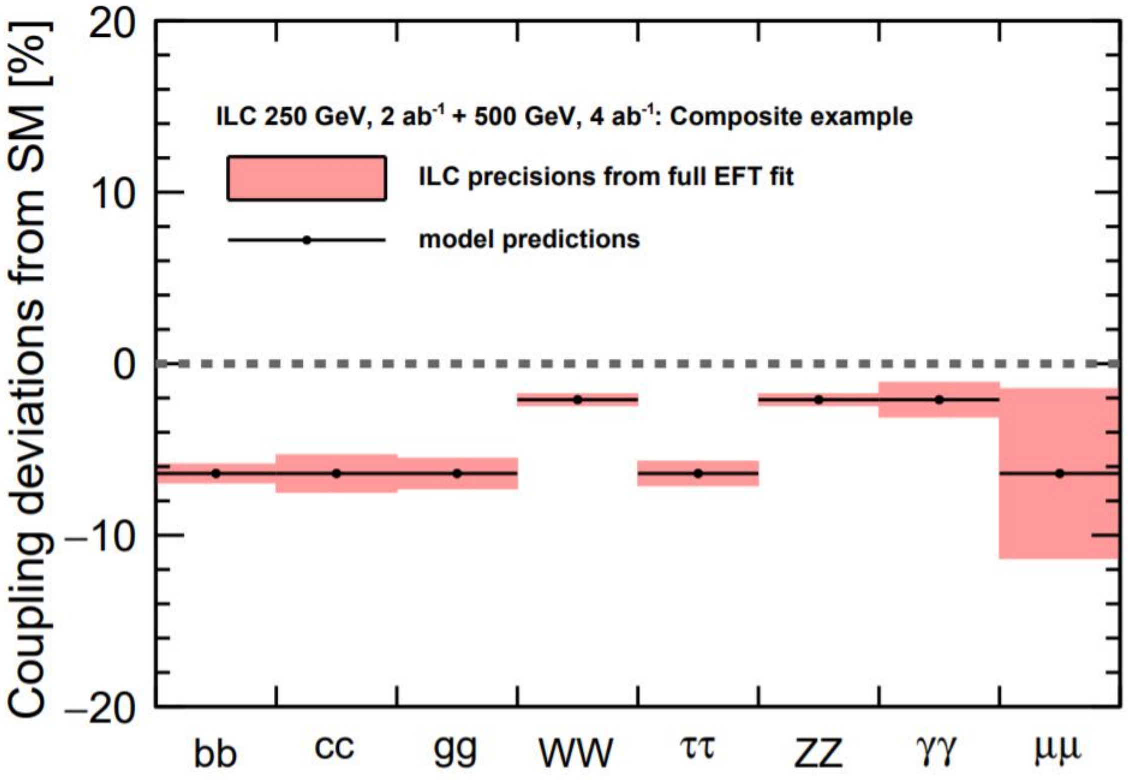
Processes toward Realization of ILC



* 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

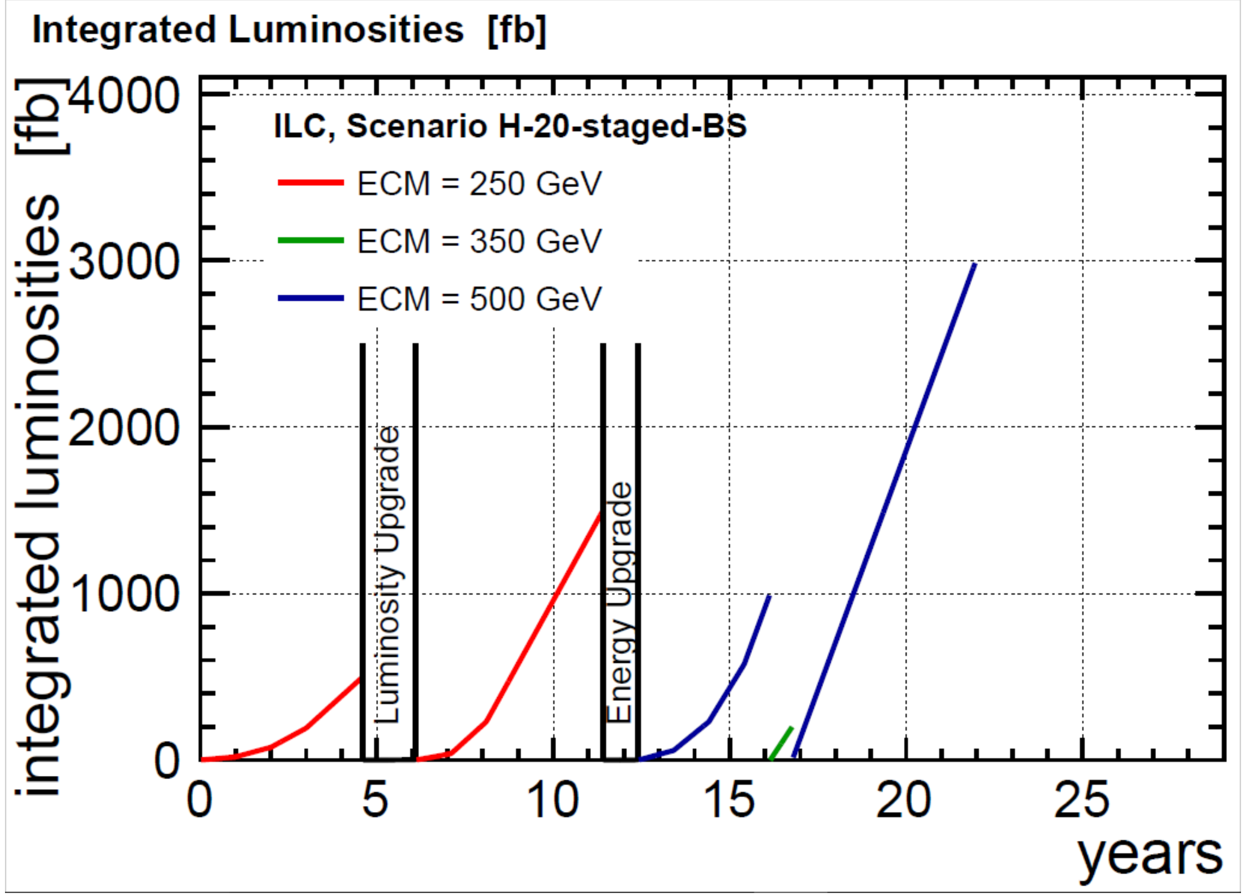




ILC Running Scenario

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

GigaZ – Basic facts

arXiv:1506.07830	$\mathrm{sgn}(P(e^-), P(e^+)) =$ (-,+)	(+,-)	(-,-)	(+,+)	sum
luminosity $[\mathrm{fb}^{-1}]$	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 → bb/cc/ττ)
  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu\mathrm{m}$

  ≈ CMS / 4

- **jet energy resolution** 3-4%
  (H → invisible)

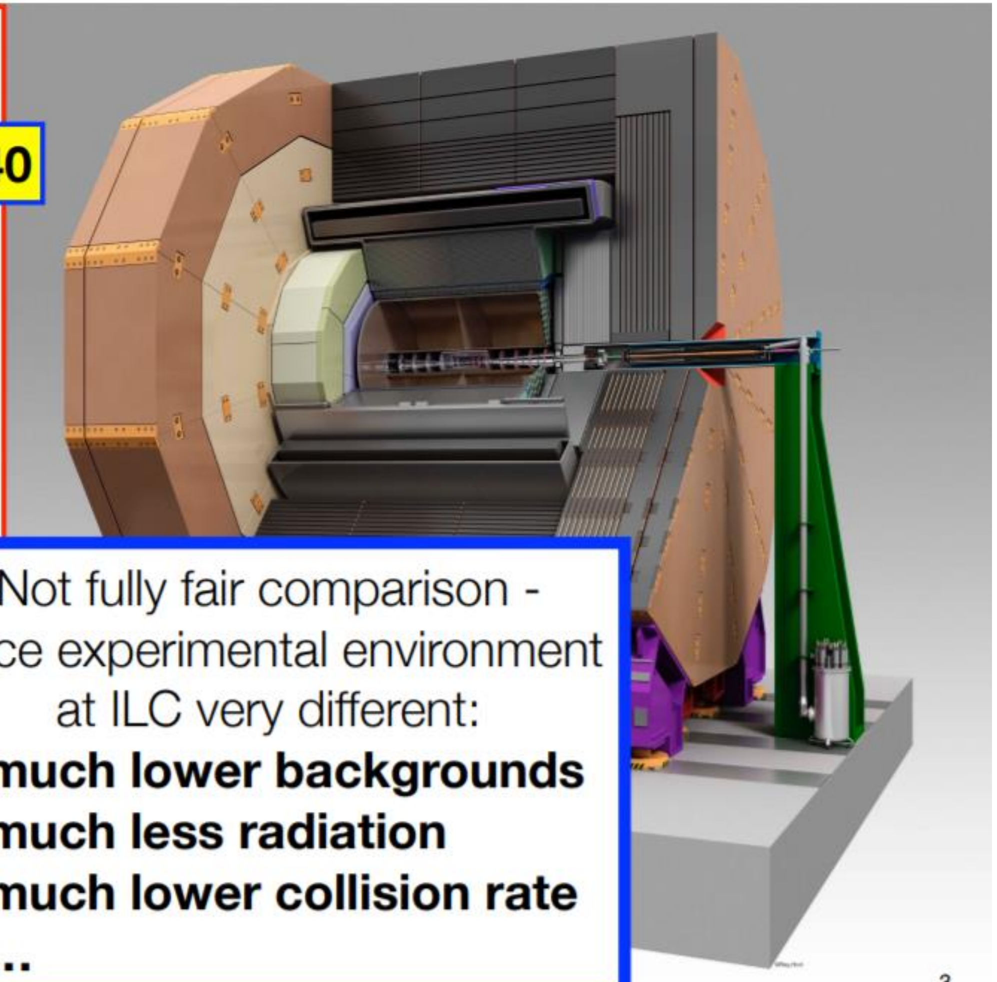
  ≈ ATLAS / 2

- **hermeticity** θ_{min} = 5 mrad
  (H → invis, BSM)

  ≈ ATLAS / 3

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



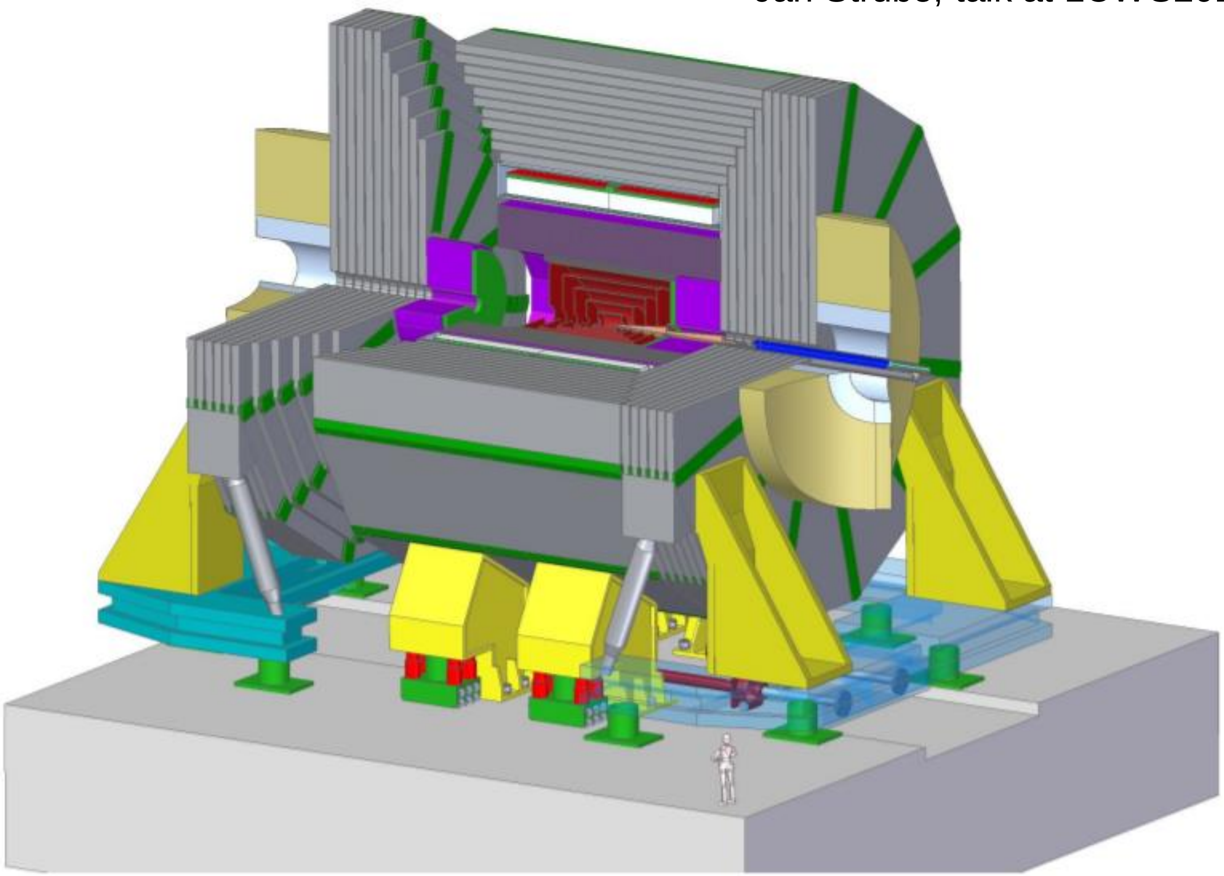
Not fully fair comparison - since experimental environment at ILC very different:

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

3

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)

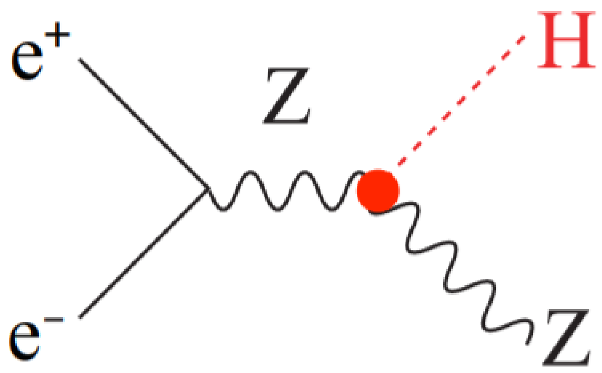
(1) recoil mass technique ---> σ_{Zh}
(2) σ_{Zh} ---> κ_Z ---> $\Gamma(h \to ZZ^*)$
(3) WW-fusion measurement ---> κ_W ---> $\Gamma(h \to WW^*)$
(4) total width $\Gamma_h = \frac{\Gamma(h \to ZZ^*)}{\mathrm{BR}(h \to ZZ^*)}$, or $\Gamma_h = \frac{\Gamma(h \to WW^*)}{\mathrm{BR}(h \to WW^*)}$
(5) then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

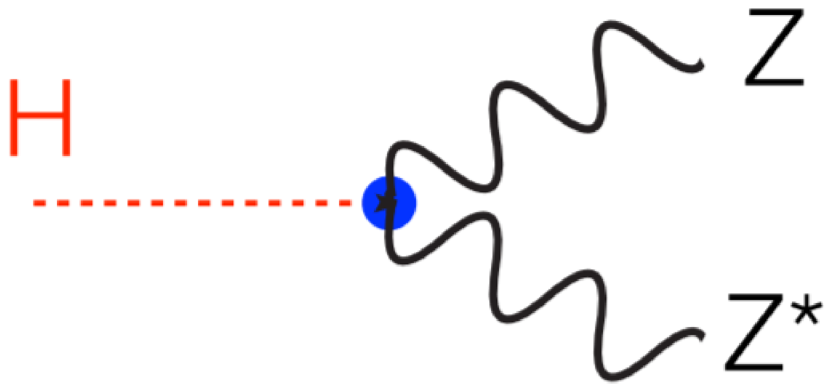
Simple, but **model-dependent**
anomalous coupling is not considered

Observables To Couplings: κ-formalism (2)

assume ζ_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

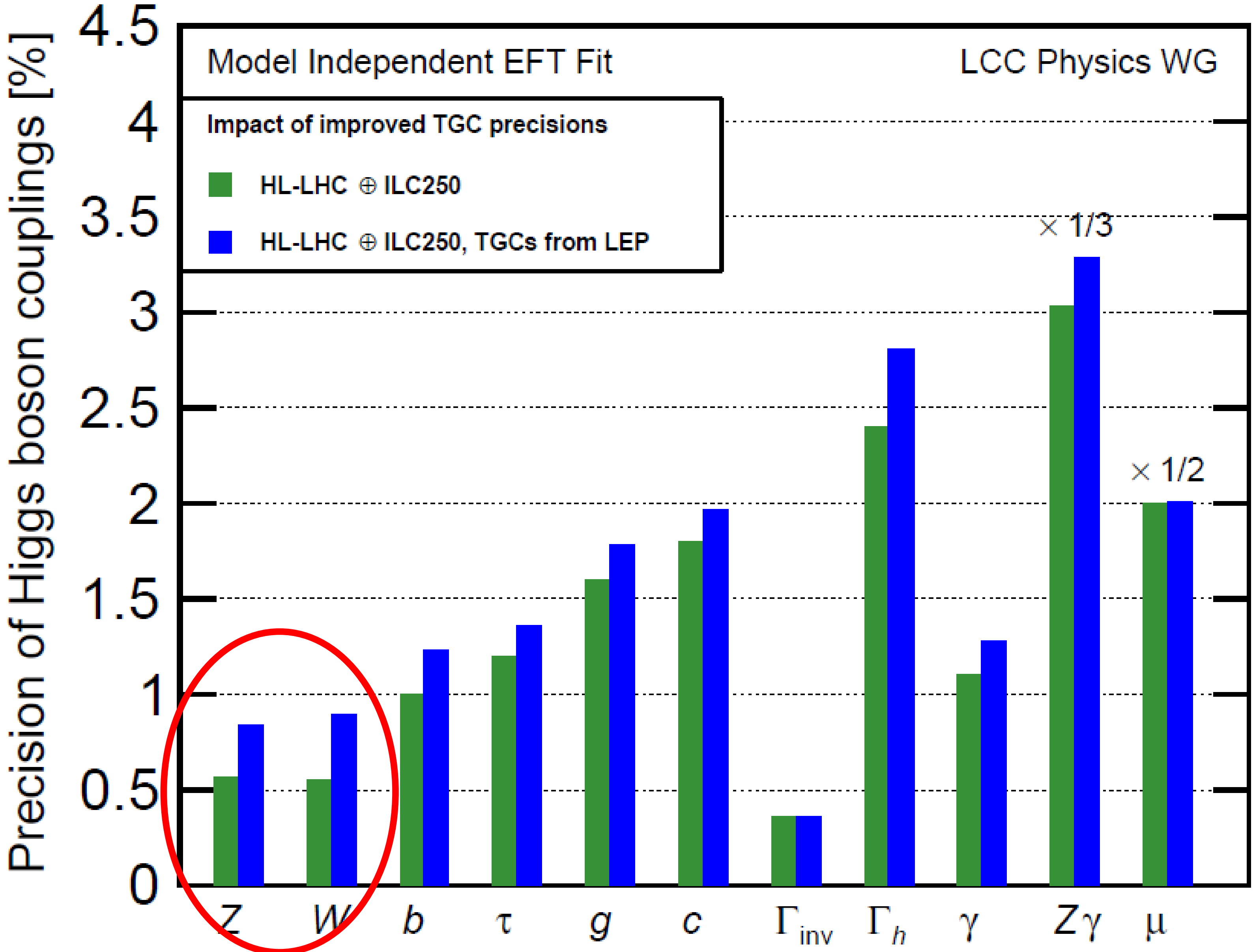
Systematic Errors

- 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
Γ_{inv}
Γ_h
γ
Zγ
μ