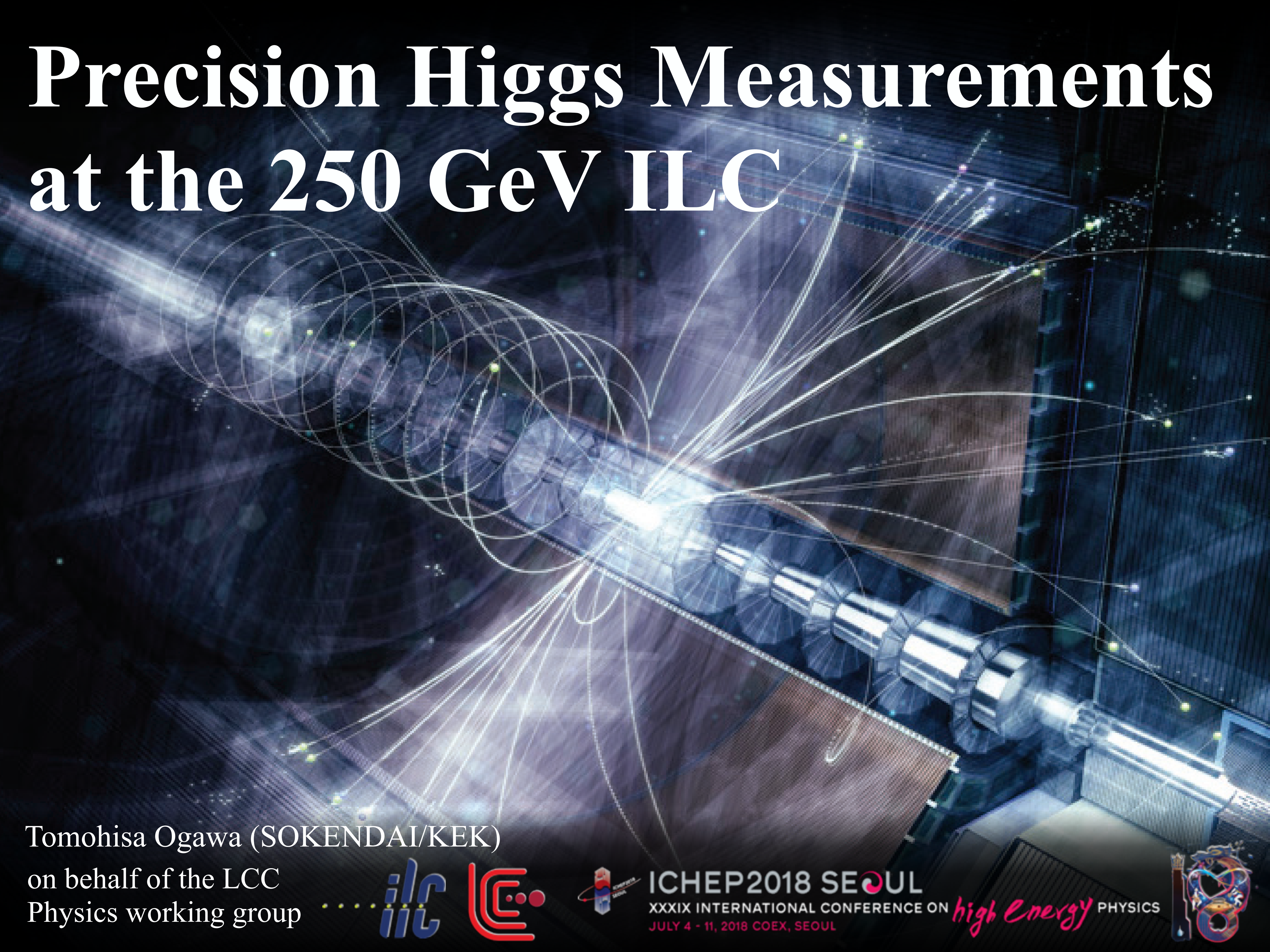


Precision Higgs Measurements at the 250 GeV ILC

Tomohisa Ogawa (SOKENDAI/KEK)
on behalf of the LCC Physics working group

ICHEP2018 SEOUL
XXXIX INTERNATIONAL CONFERENCE ON high Energy PHYSICS
JULY 4 - 11, 2018 COEX, SEOUL

After the Discovery of the Higgs Boson

○ **A major theme in particle physics** is to discover **new phenomena or principles** which can explain

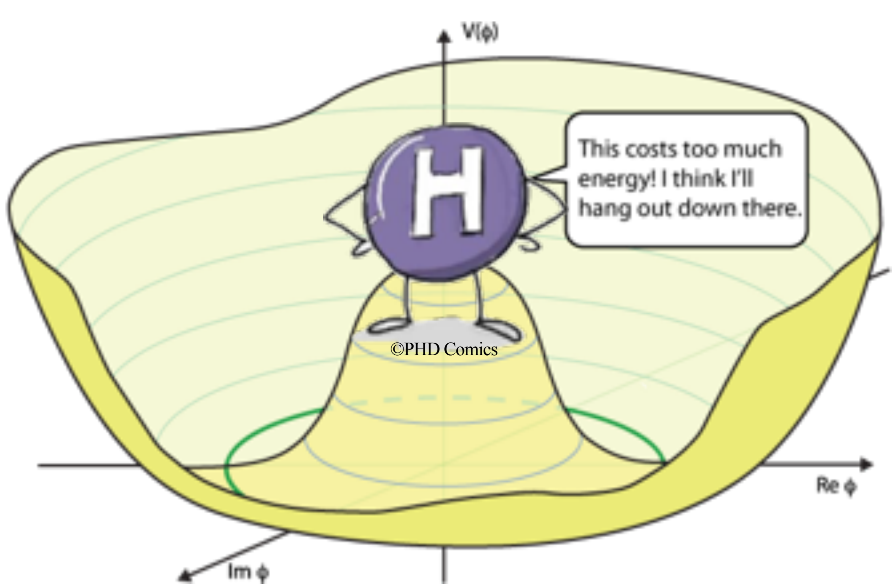
1). EWSB filling the Higgs field in the vacuum,

2). A dark matter candidate

3). matter-antimatter asymmetry

… neutrino mass … fine tuning

Standard Model can not explain these facts.



https://www.symmetrymagazine.org/article/december-2013/four-things-you-might-not-know-about-dark-matter

The Higgs boson is **a window to new physics beyond the SM.**

Required Higgs Precision

ILC-Technical Design Repor
arXiv1306.6352 [hep-ex]

○ Expected deviations for typical BSM scenarios.

Super Symmetry:

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

m_A : CP-odd Higgs A^0

Composite Higgs:

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 3\%(1\ \text{TeV}/f)^2$$

$$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \text{TeV}/f)^2 & \text{(MCHM4)} \\ 1 - 9\%(1\ \text{TeV}/f)^2 & \text{(MCHM5)} \end{cases}$$

f : a compositeness scale

Mixing with a singlet scalar:

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = \frac{g_{hff}}{g_{h_{\rm SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

$h = h_{\rm SM}\cos\theta + S\sin\theta$

○ Predicted deviations are small, **a few % ~ 10 % level.**

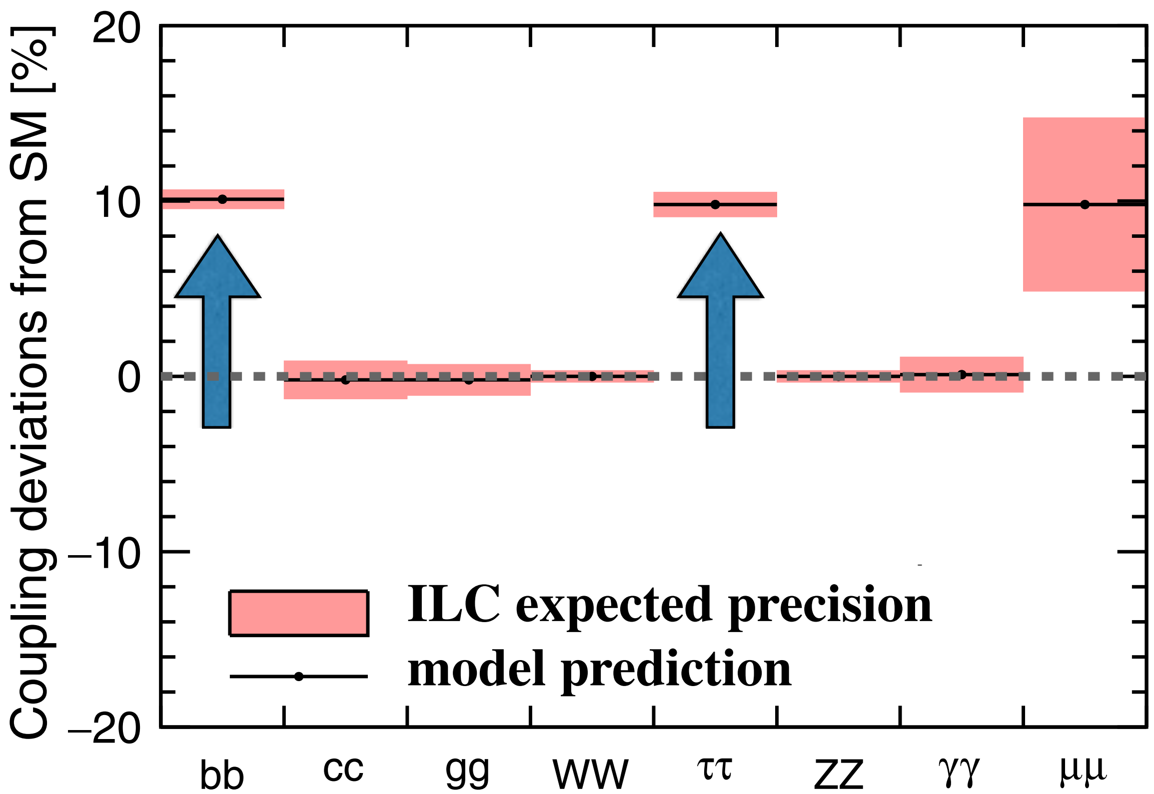
O(1%) precision (model independent) is needed to see the deviations.

Fingerprinting BSM models

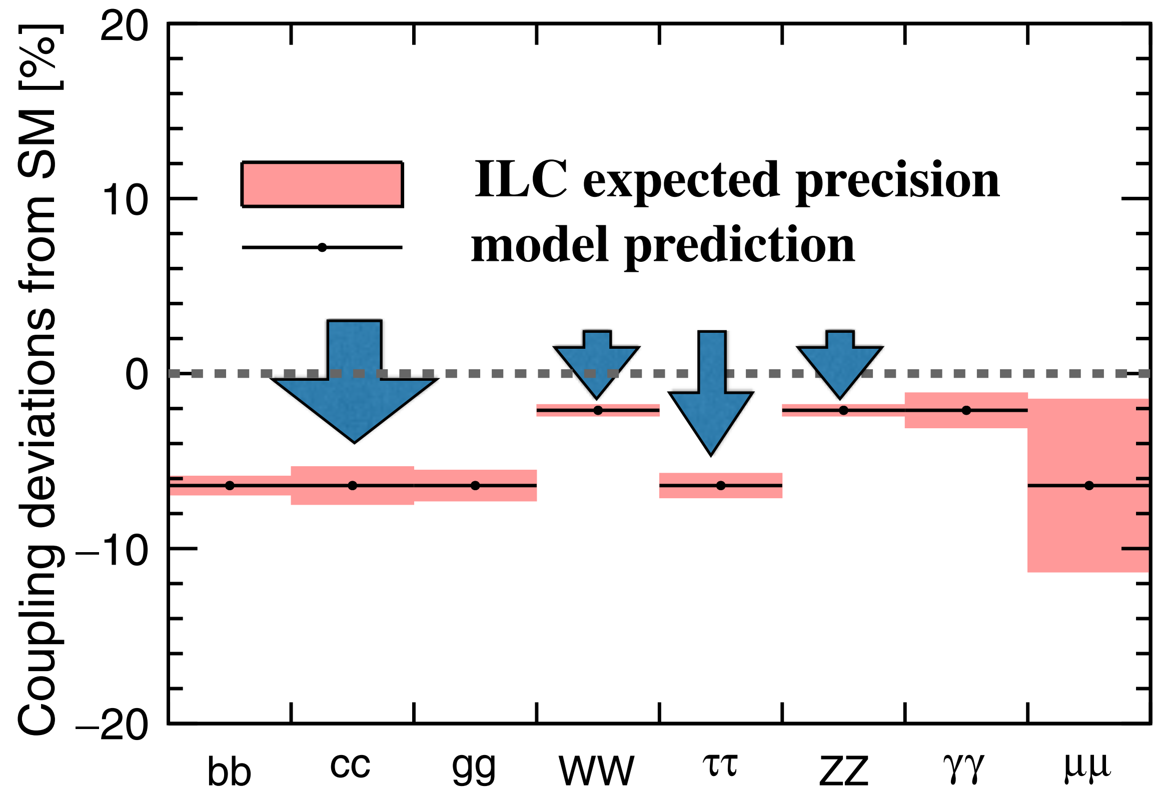
Phys. Rev. D 97, 053003 (2018)

○ **Different BSM models** **predict different deviation patterns.**

2HDM model (m_A=600 GeV, tanβ=7)



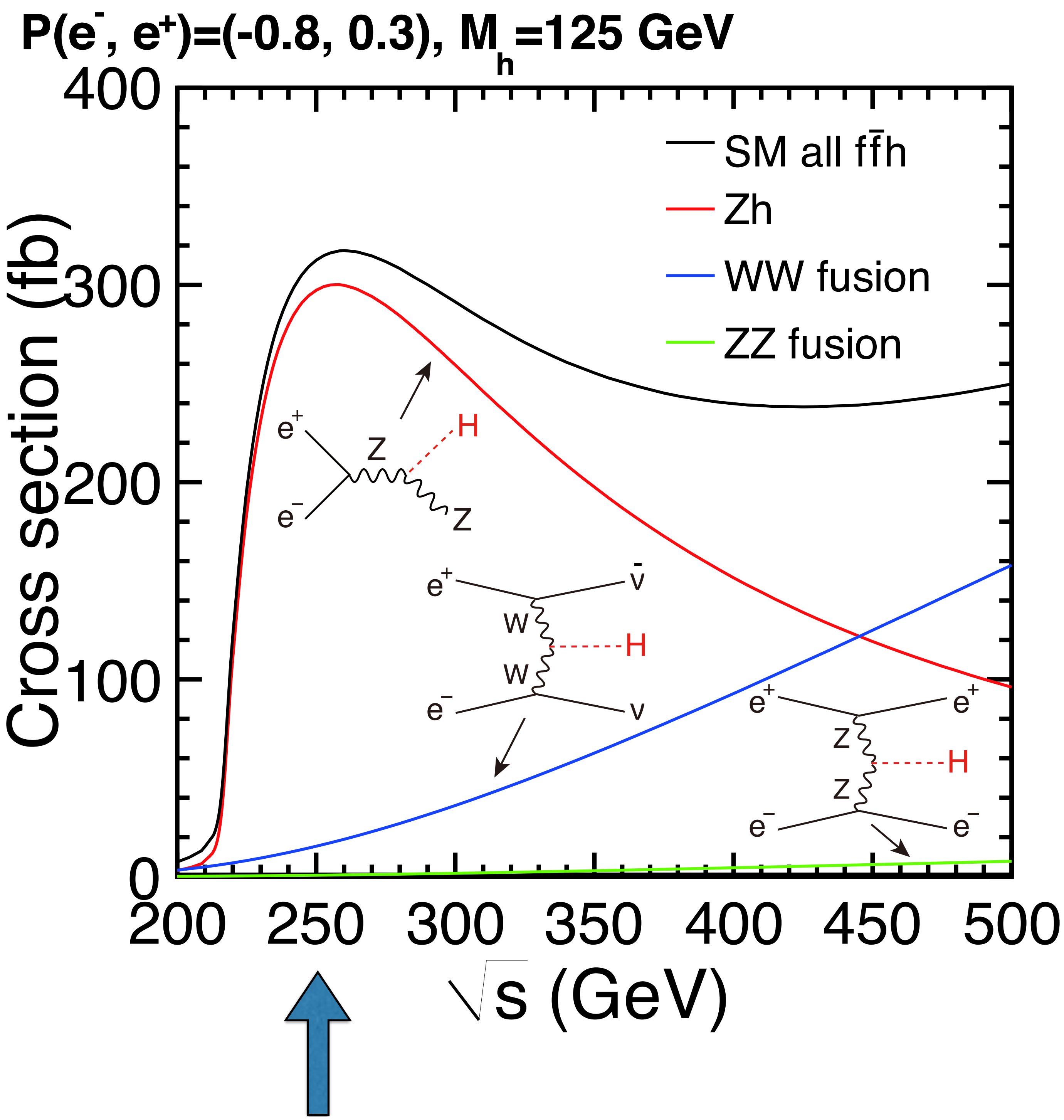
Composite Higgs (f =1.2 TeV)



The ILC250 has the capability to tell the nature of the BSM from its deviation patterns !

The ILC250 Higgs production

ILC-Technical Design Repor
arXiv1306.6352 [hep-ex]



○ **The Higgs-strahlung production**
is maximum at $\sqrt{s}$ = 250 GeV.

○ **Beam Polarization is available.**

Pol(e-,e+)=(-80%,+30%) & (+80%,-30%)

○ Accumulate data for 10 years, 2000 fb^{-1}.

Zh : ~ 500 K Higgs boson.
WW-f : ~ 15 K Higgs boson.

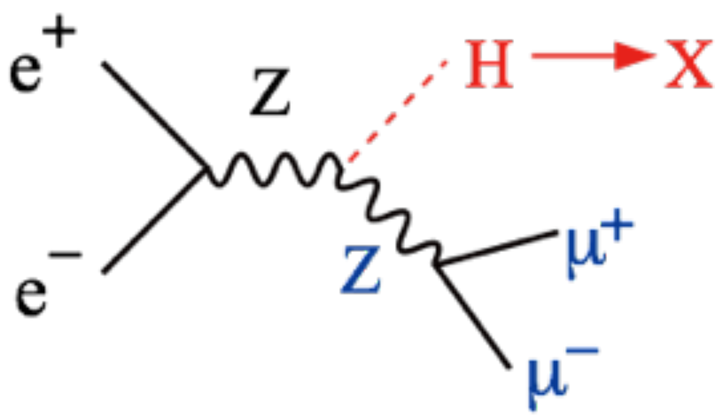
The ILC250 key measurement σ_{zh}

Phys. Rev. D 94, 113002 (2016)
Eur. Phys. J. C (2016) 76:72

○ **Unique measurement at lepton colliders is absolute σ_{zh}.**

→ A key for determining Higgs couplings model independently.

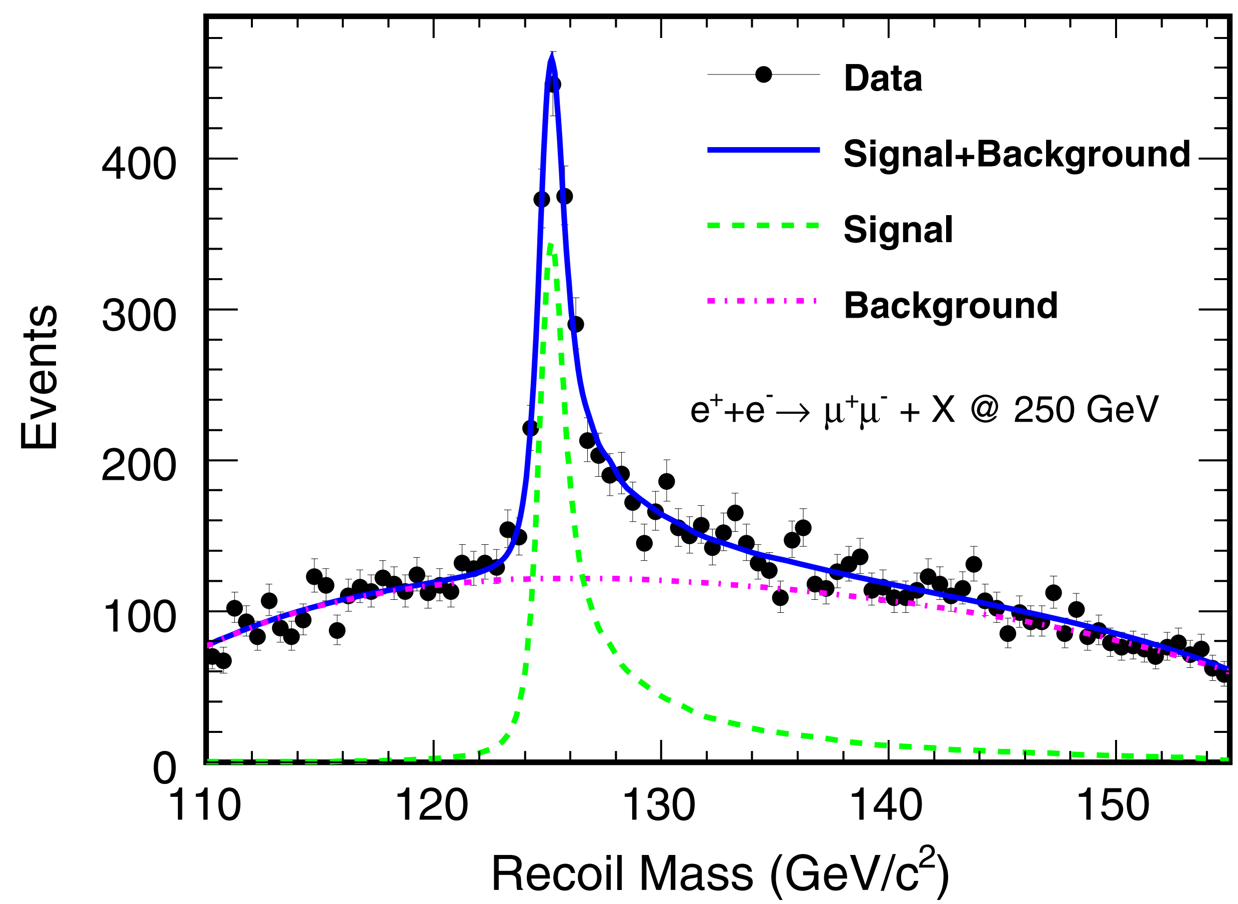
Recoil mass method



leptonic & hadronic

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

- without looking at Higgs
- detectable for invisible decay



ILC250 with 2000fb-1

$\Delta m_h =$ **14MeV** , $\dfrac{\Delta\sigma_{Zh}}{\sigma_{Zh}} =$ **0.7%**

Other direct Higgs Observables at the ILC250

$\sigma_{ZH}\times Br(H \rightarrow bb)$, $\sigma_{\nu\nu H}\times Br(H \rightarrow bb)$

$\sigma_{ZH}\times Br(H \rightarrow cc)$

$\sigma_{ZH}\times Br(H \rightarrow gg)$

$\sigma_{ZH}\times Br(H \rightarrow WW^*)$

$\sigma_{ZH}\times Br(H \rightarrow ZZ^*)$

$\sigma_{ZH}\times Br(H \rightarrow \tau\tau)$

$\sigma_{ZH}\times Br(H \rightarrow \gamma\gamma)$

$\sigma_{ZH}\times Br(H \rightarrow \mu\mu)$

$\sigma_{ZH}\times Br(H \rightarrow Invisible)$ (H—>exotic)

[red box] **: Observation is difficult at LHC**

+ Differential cross-section

*all the observables are estimated based on full detector simulation of ILD & SiD

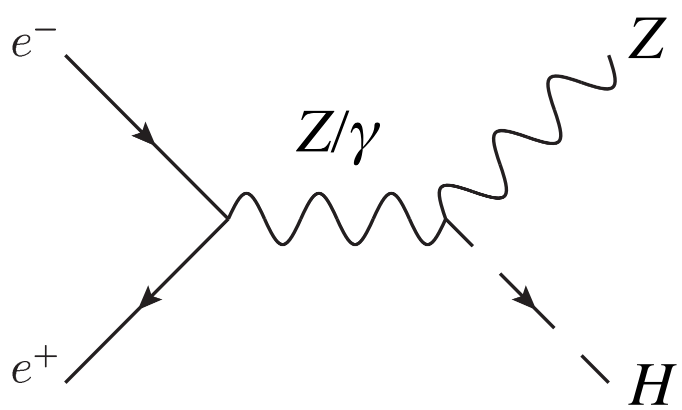
Higgs couplings in κ-formalism at the ILC250

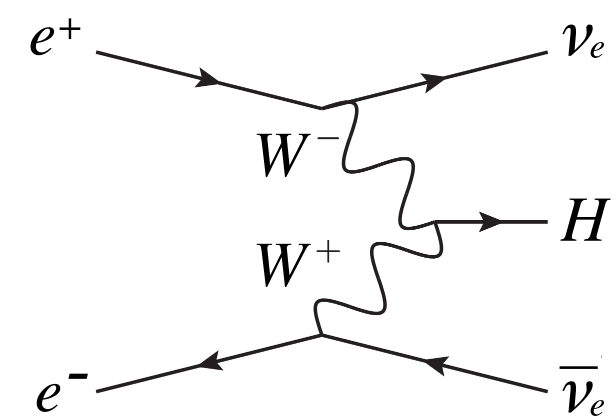
○ **Total width necessary to extract Higgs couplings from *BR*s**

$$\Gamma_h \cdot BR(h \to XX) = \Gamma(h \to XX) \propto g^2_{hXX}$$

○ **Determination of total width:** $\Gamma_h = \frac{\Gamma_{ZZ}}{BR_{ZZ}} \left(= \frac{\Gamma_{WW}}{BR_{WW}} \right)$

ZZ and WW **are independent**





BR(h→ ZZ)=O(1%) gives
statistical limit for δBR_{ZZ}

Small $\sigma_{\nu\nu h}$ @ 250GeV gives
statistical limit for δΓh

κ-formalism

→ SM values are put with a scaling factor "κ".

e.g. **hZZ** :

$$\frac{\sigma(e^+e^- \to Zh)}{SM} = \frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2$$

κ-formalism to EFT-formalism

Phys. Rev. D 97, 053004 (2018)

○ **A problem of the κ-formalism**

Higher dimensional operators (gauge invariant) are possible to induce new structures in hZZ.

SM structure | New structure

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

Under the κ-formalism → ζ_Z is assumed to be 0 → **model dependent !**

κ-formalism to EFT-formalism

Phys. Rev. D 97, 053004 (2018)

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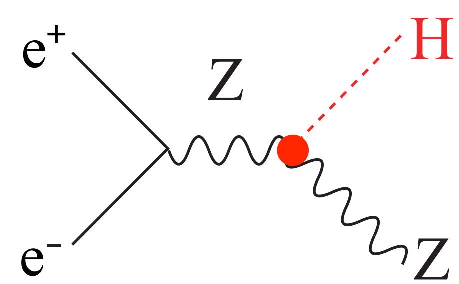
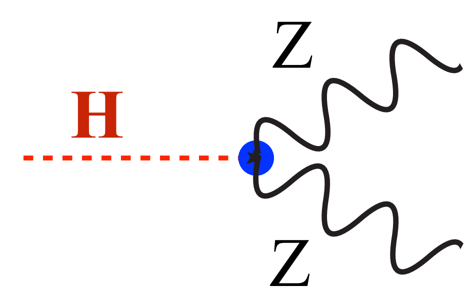
Under the κ-formalism → ζ_Z is assumed to be 0 → **model dependent !**

Consider the 2nd term → ζ_Z term is composed field strength tensors:

$\sqrt{s}$ = 250 GeV





$$\frac{\sigma(e^+e^- \to Zh)}{SM} = 1 + 2\eta_Z + 5.7\zeta_Z \neq \frac{\Gamma(h \to ZZ^*)}{SM} = 1 + 2\eta_Z - 0.5\zeta_Z$$

→ κ-formalism does not satisfy the model independence

κ-formalism to EFT-formalism

Phys. Rev. D 97, 053004 (2018)

○ Dim-6 Effective Field Lagrangian at the ILC

General $SU(2) \times U(1)$ gauge invariant Lagrangian
with dimension-6 operators in addition to the SM.

A dedicated talk on EFT
by Sunghoon Jung on 6/July

$\mathcal{L}_{SM} + \mathcal{L}_{eff}^{dim6}$

- **10 EFT coefficients** (h,W,Z,γ): C_H, C_T, C_6, C_{WW}, C_{WB}, C_{BB}, C_{3W}, C_{HL}, C'_{HL}, C_{HE}
- **2 EFT coefficients** for contact interaction with quarks
- 5 EFT coefficients for couplings to b, c, τ, μ, g
- 4 SM parameters: g, g', v, λ
- 2 parameters for h→invisible and exotic

○ Retain model independence

○ Make Z, W and γ relate → Improve precision of Higgs couplings

○ Treatable 23 parameters → The LHC situation has > 50 EFT coefficients,
it is not easy to determine them simultaneously.

Observables in EFT-formalism

Phys. Rev. D 97, 053004 (2018)

○ **ILC250 provides sufficient observables.**

23 parameters can be determined simultaneously

1) Higgs-related observables

→ σ and σ×BR …

[Higgs-leptons and its CP]
by Daniel Jeans on 7/July

2) Observables from angular distributions

→ Test new Lorentz structures…

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

4) Electroweak precision observables

[EW couplings]
by Sviatoslav Bilokin on 5/July

→ Constrain SM parameters …

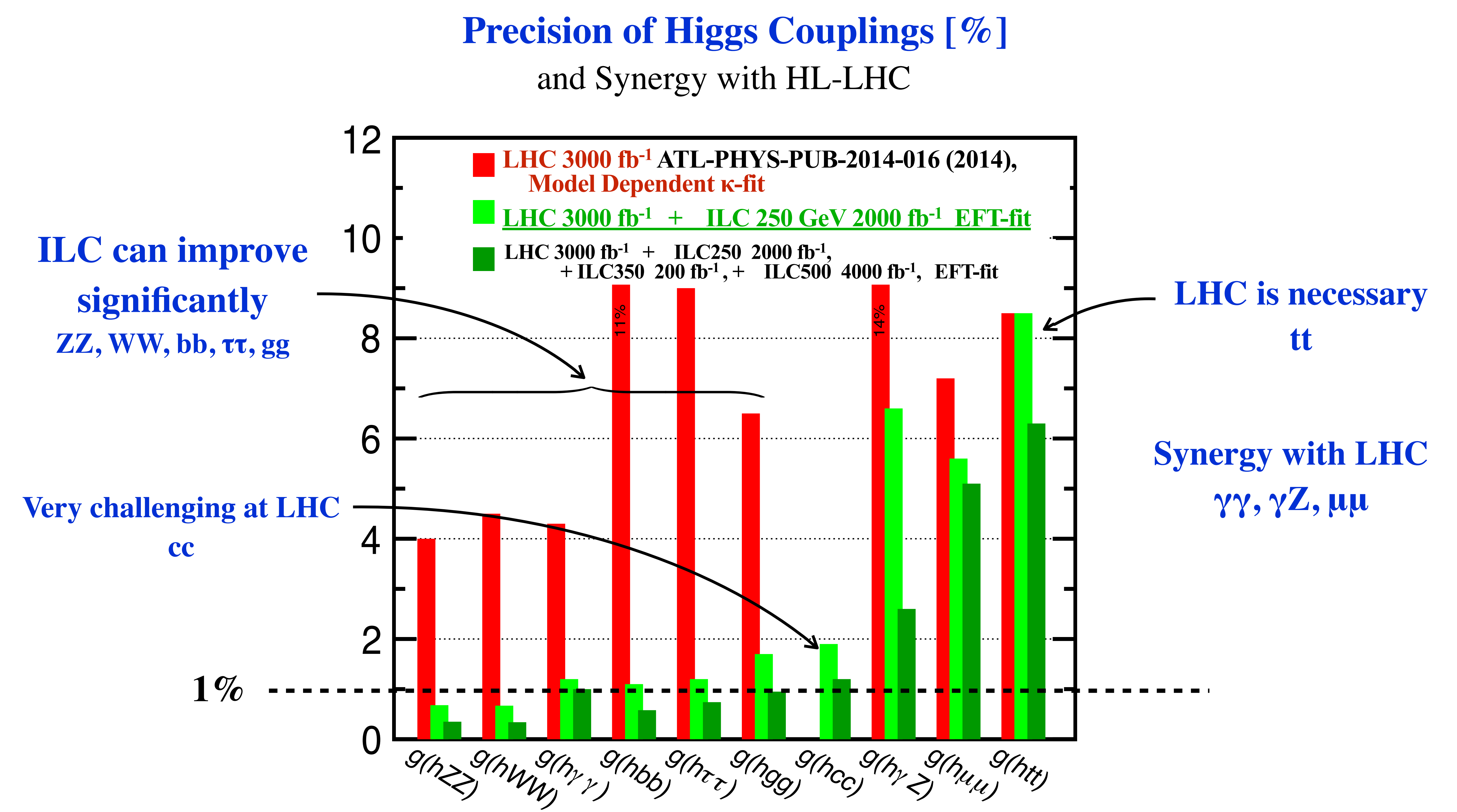
5) Beam polarizations double the number of observables

6) HL-LHC Higgs observables, BR(h→γγ, γZ)

[Positron Polarization]
by Jürgen Reuter on 5/July

Precision in EFT-formalism at the ILC

arXiv:1710.07621 [hep-ex]



ILC250 provides O(1%) precisions and that model-independently !

Discrimination of BSM models

Phys. Rev. D 97, 053003 (2018)

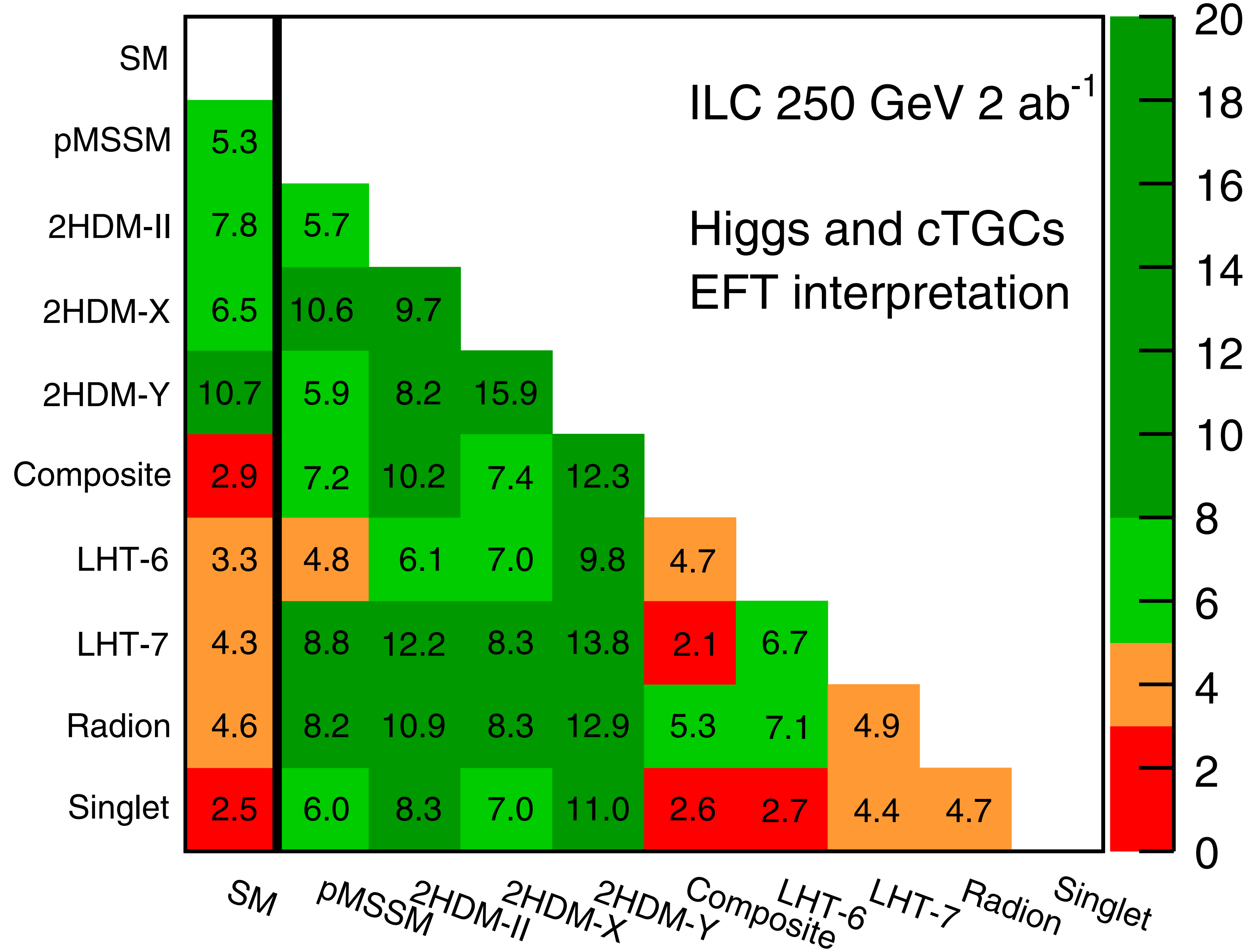
○ **Significance for benchmark points in typical BSM models :**

(escape HL-LHC direct search)

SUSY, Two-Higgs Doublet, Little Higgs, Composite Higgs,

With 2000 fb^{-1} from 10 years of **ILC250 operation**

Model discrimination in σ



Most benchmark models are distinguishable by more than 3 sigmas.

Discrimination of BSM models

Phys. Rev. D 97, 053003 (2018)

○ **Significance for benchmark points in typical BSM models :**

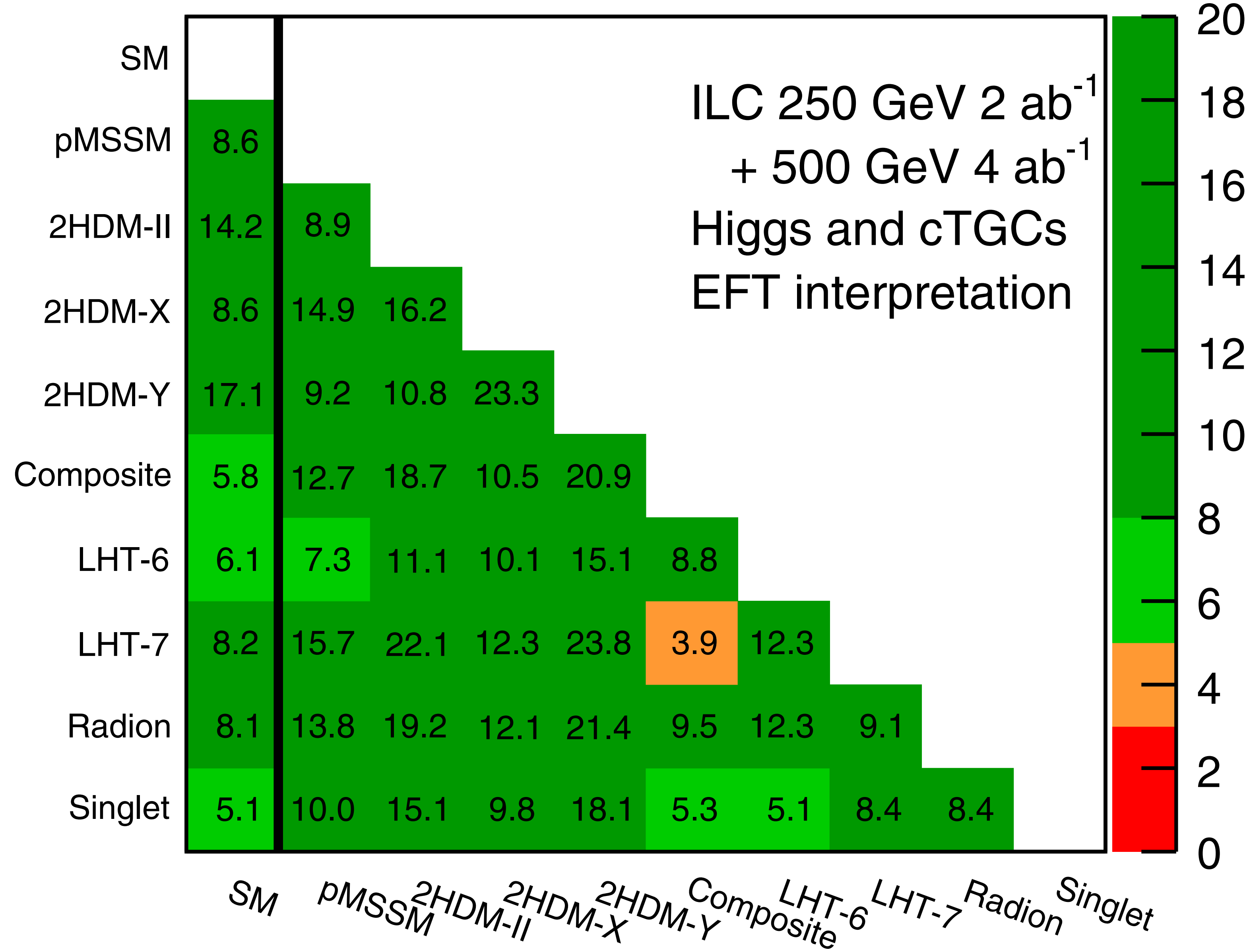
(escape HL-LHC direct search)

SUSY, Two-Higgs Doublet, Little Higgs, Composite Higgs,

With 2000 fb^{-1} from 10 years of **ILC250 operation**

\+ With 4000 fb^{-1} from additional 10 years running of **ILC500 operation**

Model discrimination in σ



Almost all benchmark models are distinguishable by more than 5 sigmas.

Summary

1) **The Higgs boson is a window to new physics.**

The precision study of the Higgs couplings is the indispensable probe for BSM physics.

2) **The ILC250 as a Higgs factory.**

The ILC250 has capability to achieve O(1%) Higgs precision model-independently, and perform exploration and verification of BSMs.

3) **The ILC for future collider experiments.**

The ILC is upgradable to new physics scale suggested by its own physics outcomes.

Main References

1). arXiv:1710.07621v3 [hep-ex] 23 Jan 2018
Physics Case for the 250 GeV Stage of the International Linear Collider
Keisuke Fujii et al.

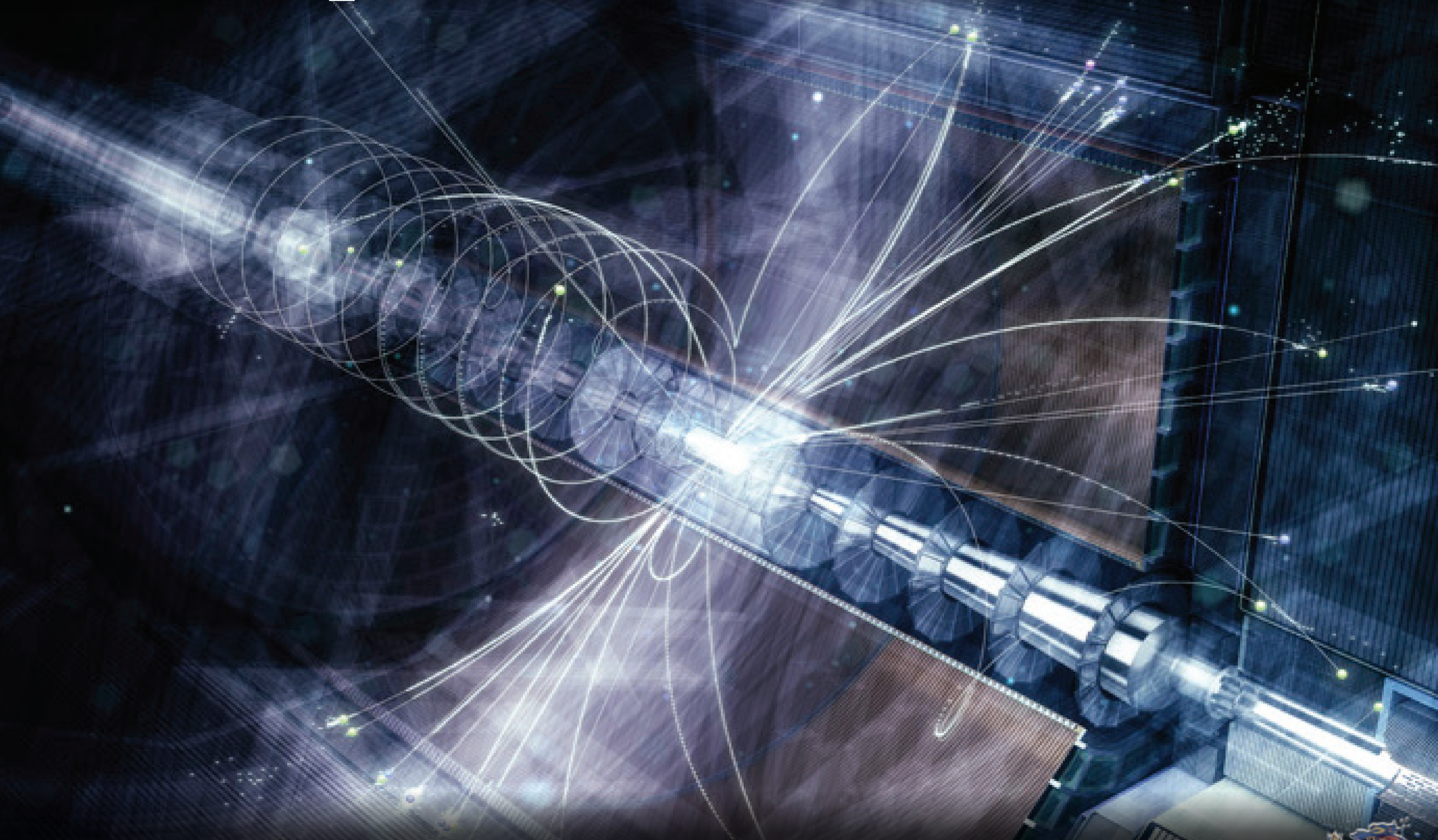
2). Model-independent determination of the triple Higgs coupling at e^+e^- colliders
Tim Barklow, Keisuke Fujii, Sunghoon Jung, Michael E. Peskin, and Junping Tian
PHYSICAL REVIEW D 97, 053004 (2018)

3). Improved formalism for precision Higgs coupling fits
Tim Barklow et al,
PHYSICAL REVIEW D 97, 053003 (2018)

4). Japan-MEXT Commission report on scientific significance of ILC250 etc.
Shoji Asai et al.
http://www.mext.go.jp/b_menu/shingi/chousa/shinkou/038/index.htm

5). Physics and Status of ILC250
Junping Tian
Joint Kavli IPMU - ICEPP Workshop on New Directions for LHC: Run 2 and Beyond
https://indico.cern.ch/event/714089/

Back up



ICHEP2018 SEOUL

Contribution ID : **755**

Type : **Parallel**

Precision Higgs Measurements at the 250 GeV ILC

Saturday, 7 July 2018 17:00 (15)

The plan for the International Linear Collider is now being prepared as a staged design, with the first stage at 250 GeV and later stages achieving the full project specifications with 4 ab-1 at 500 GeV. This talk will present the capabilities for precision Higgs boson measurements at 250 GeV and their relation to the full ILC program. It will show that the 250 GeV stage of ILC will already provide many compelling results in Higgs physics, with new measurements not available at LHC, model-independent determinations of key parameters, and tests for and possible discrimination of a variety of scenarios for new physics.

Higgs Properties at the ILC250

○ **Dark matter**: **“Hidden sector with Higgs portal model”**

Higgs full width Γh and BR_invisible

○ **Origin of asymmetry on matter and antimatter**:

“Baryongenesis & Leptogenesis”

Higgs CP-admixture in an extended Higgs sector

Precision on WIMP in a Hidden-sector

○ **DM theories constructed with a Hidden sector** (particles are SM singlets).

Interactions through gravity ?

→ Several models as a portal

Neutrino Portal $HL\psi$: sterile neutrino

⋮

Higgs Portal $|H|^2 S^2$: Higgs invisible decay

S: a dark matter field

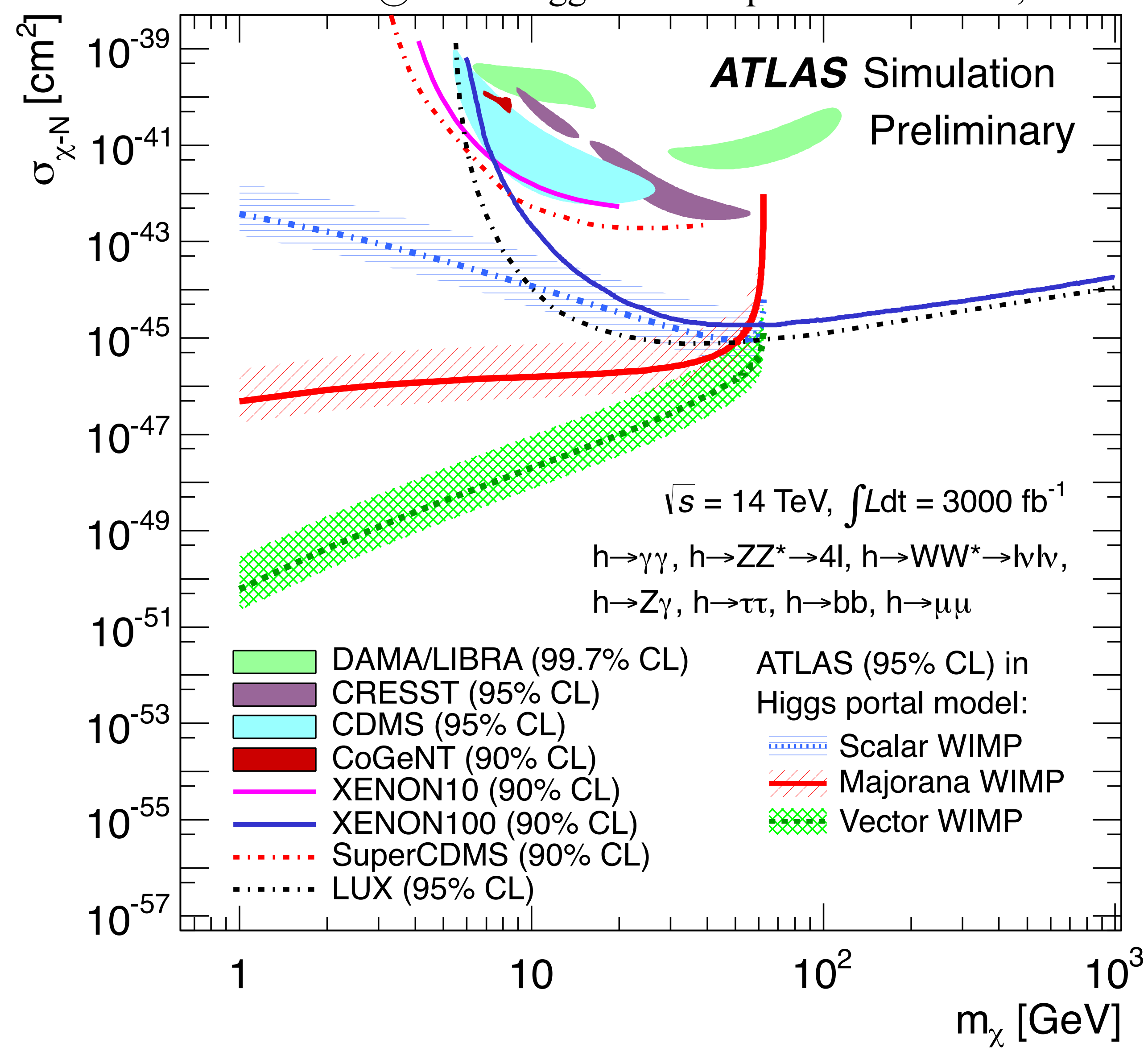
$$|H|^2\phi^2,\quad |H|^2\bar{\chi}\chi,\quad |H|^2 V_\mu V^\mu$$

scalar, Majonara, vector WIMP.

Higgs invisible decay BR with 3000 fb^{-1}		
ATLAS:	BR_{inv}	< 10% ~ 14%
CMS:	BR_{inv}	< 7% ~ 11%

ATLAS & CMS, Eric Feng (Argonne)
@ BSM Higgs Workshop Fermilab Nov 3, 2014

ATLAS & CMS, Eric Feng (Argonne)
@ BSM Higgs Workshop Fermilab Nov 3, 2014



Direct exploration of singlet dark matter is possible up to 2/Mh GeV .

Precision on WIMP in a Hidden-sector

○ **DM theories constructed with a Hidden sector** (particles are SM singlets).

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⋮

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S: a dark matter field

$$|H|^2\phi^2,\ \ |H|^2\bar{\chi}\chi,\ \ |H|^2 V_\mu V^\mu$$

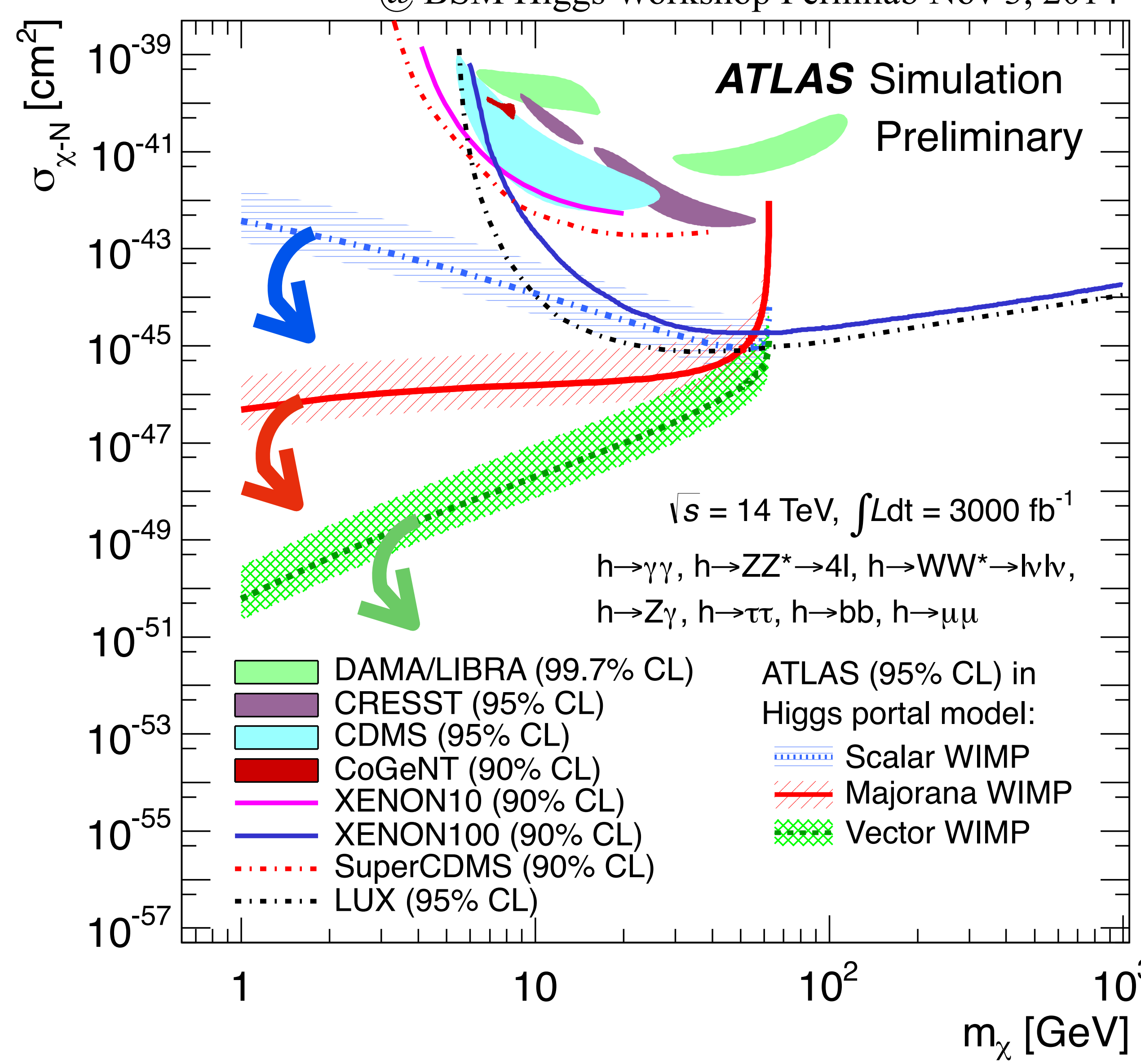
scalar, Majonara, vector WIMP.

ILC250 2000 fb^{-1}

Γ_h	2.5	
$BR(h \to inv)$	0.32	[%]
$BR(h \to other)$	1.6	[%]

→ ~ two orders of magnitude higher !

ATLAS & CMS, Eric Feng (Argonne)
@ BSM Higgs Workshop Fermilab Nov 3, 2014



Direct exploration of singlet dark matter is possible up to 2/Mh GeV .
with high sensitivity !

arXiv:1710.07621
Keisuke Fujii et al.

Higgs CP-admixture in $h\tau\tau$

Eibun Senaha ***et al,***
Phys. Lett. B 762, 315 (2016)
modified parameters

○ SUSY: Type3 - 2HDM
(fermion couples to both Higgs doublets
with Higgs-mediated FC processes at tree level)

several values on EDM
Current value $|d_e|$< **8.7 ×10^-29^ e cm**

○ Higgs CP admixture

$$\Delta\mathcal{L}_{h\tau\tau} = -\frac{\kappa_\tau y_\tau}{\sqrt{2}} h\tau^+(\cos\phi + i\sin\phi\gamma_5)\tau^-$$

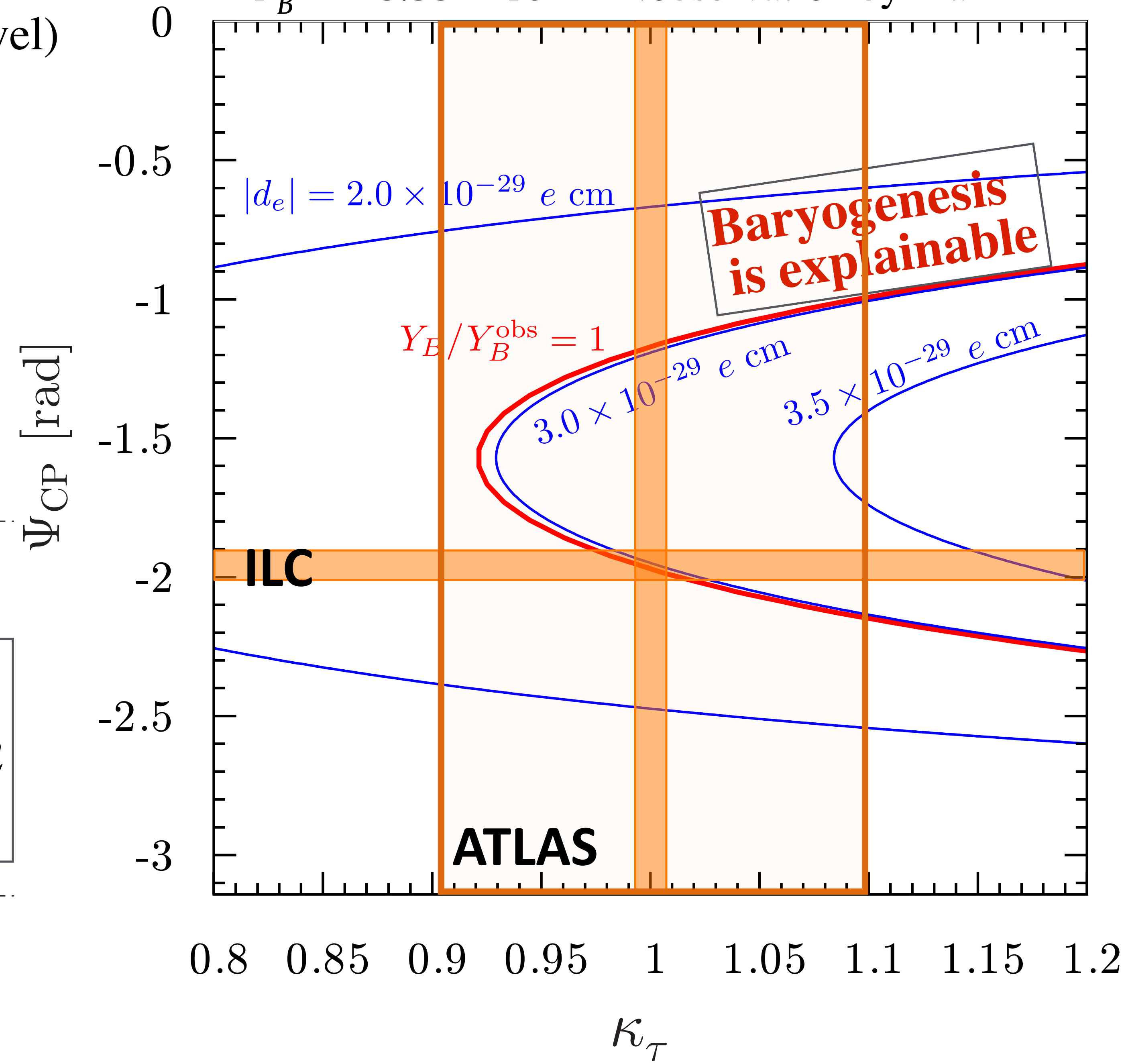
ATLAS : κτ ~ 10% , CMS: κτ ~ 4%

hττ CP-pahse φ with 3000 fb^{-1}
√S = 13 TeV: **120 mrad** arXiv:1708.02882
√S = 14 TeV: **90 mrad** arXiv:1408.0798

ILC250 2000 fb^{-1}

CP-pahse φ: 75mrad
precision on κ_τ ~ 1.9%

$Y_B \equiv n_B/s$: s is a 2HDM parameter
$Y_B^{obs} = 8.59 \times 10^{-11}$:observation by Plank



Precise verification on Baryongenesis models by **measuring κτ and CP-pahse mixture,** and also **future EDM measurement**

D. Jeans et al,
Phys. Rev. D 13 June (2018)

Higgs CP-admixture in hVV

arXiv:1710.07621
Keisuke Fujii et al.

○ CP-odd Higgs induced by **Diemnntion-6 operators**

$$\Delta\mathcal{L}_{hZZ} = \frac{1}{2}\frac{\tilde{b}}{v} h Z_{\mu\nu}\tilde{Z}^{\mu\nu}$$

ILC250 2000 fb^{-1}

Exploiting Angular asymmetry

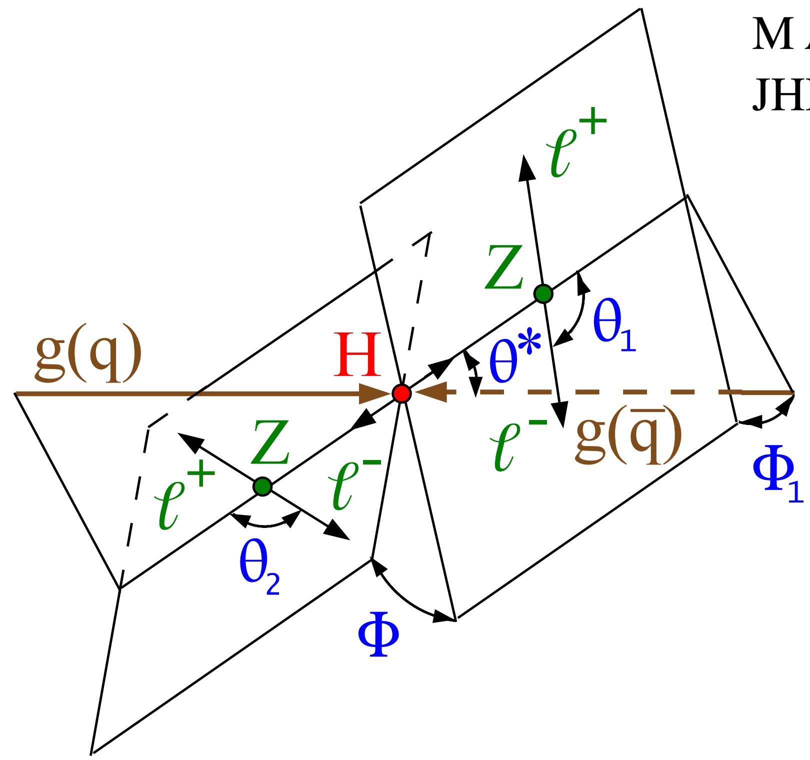
hZZ : **bt_z ~ 0.5%**

(hWW : bt_w ~ 11%)

○ **LHC ATLAS : EFT analysis**

M Aaboud et, al
JHEP 03 (2018) 095

$$\begin{aligned}\mathcal{L}_0^V = \Bigg\{ & \kappa_{\rm SM}\left[\frac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu}\right] \\ & - \frac{1}{4}\left[\kappa_{Hgg} g_{Hgg} G^a_{\mu\nu} G^{a,\mu\nu} + \tan\alpha\, \kappa_{Agg} g_{Agg} G^a_{\mu\nu}\tilde{G}^{a,\mu\nu}\right] \\ & - \frac{1}{4}\frac{1}{\Lambda}\left[\kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + \tan\alpha\, \kappa_{AZZ} Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] \\ & - \frac{1}{2}\frac{1}{\Lambda}\left[\kappa_{HWW} W^+_{\mu\nu} W^{-\mu\nu} + \tan\alpha\, \kappa_{AWW} W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right] \Bigg\} X_0 .\end{aligned}$$



Expected and observed confidence intervals at 95% CL with 36.1 fb^{-1} of data at $\sqrt{s}$ = 13 TeV.

BSM coupling $\kappa_{\rm BSM}$	Fit configuration	Expected conf. inter.	Observed conf. inter.
κ_{Agg}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ = 1)	[−0.47, 0.47]	[−0.68, 0.68]
κ_{HVV}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ = 1)	[−2.9, 3.2]	[0.8, 4.5]
κ_{HVV}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ free)	[−3.1, 4.0]	[−0.6, 4.2]
κ_{AVV}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ = 1)	[−3.5, 3.5]	[−5.2, 5.2]
κ_{AVV}	(κ_{Hgg} = 1, $\kappa_{\rm SM}$ free)	[−4.0, 4.0]	[−4.4, 4.4]

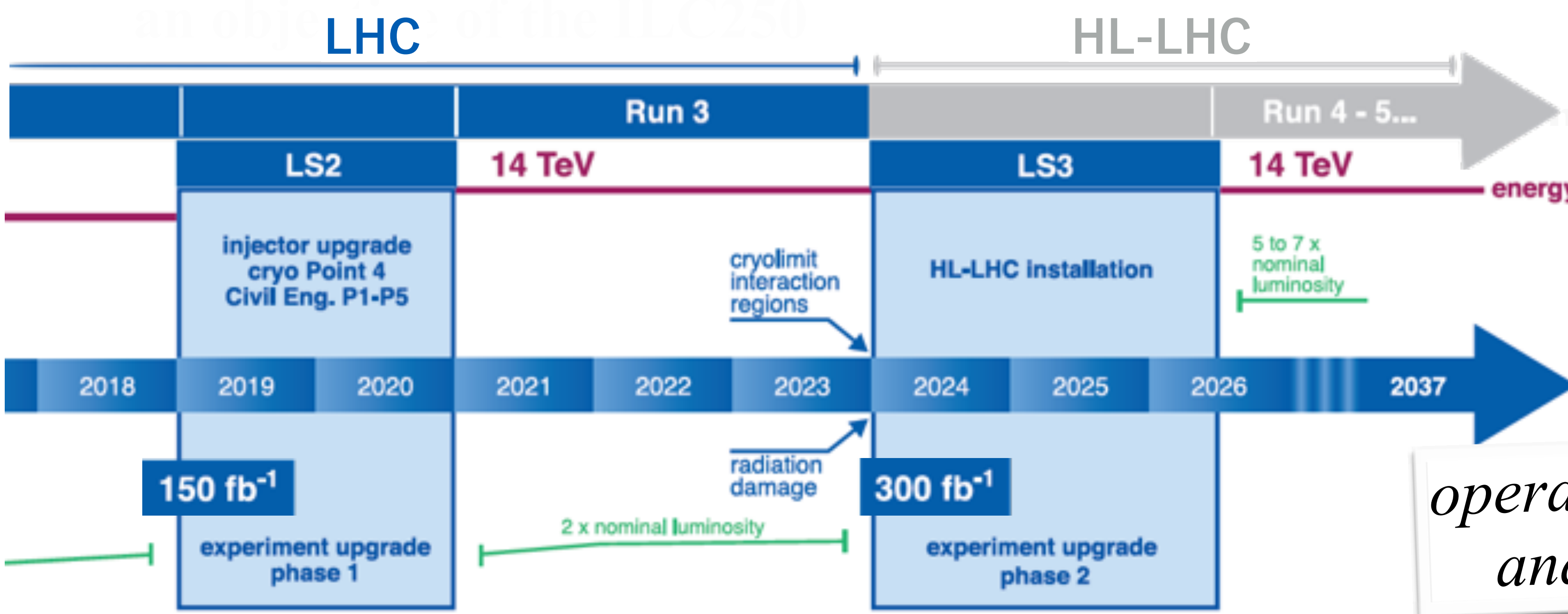
overall HVV precision (no individually) :

translate to the ILC condition

36fb-1 bt_v [-200%, 200%]

HL-LHC bt_v [-20%, 20%]

Synergy with the HL-LHC + other experiments



operation from later 2020
and accumulate 3000 fb^{-1}

→10 years 2000 fb^{-1}

- "SuperKEK-B" will give some conclusion on flavor physics,
- "LISA" project will give observation in later 2030s .

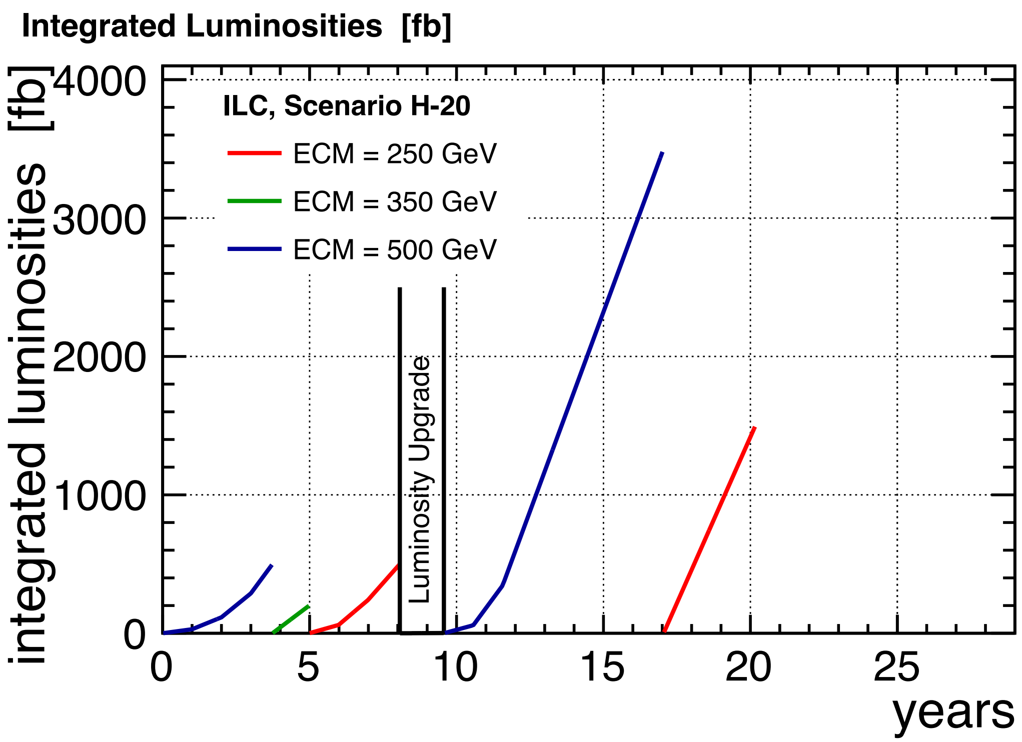
Higgs sector will be elucidated, and
a direction of new physics be uncovered

Bring Revolution
in 2030s !

ILC operation plan

arXiv:1506.05992v2 [hep-ex] 26 Jun 2015

Physics Case for the International Linear Collide



arXiv:1710.07621v2 [hep-ex] 3 Nov 2017

Physics Case for the 250 GeV Stage of the International Linear Collider

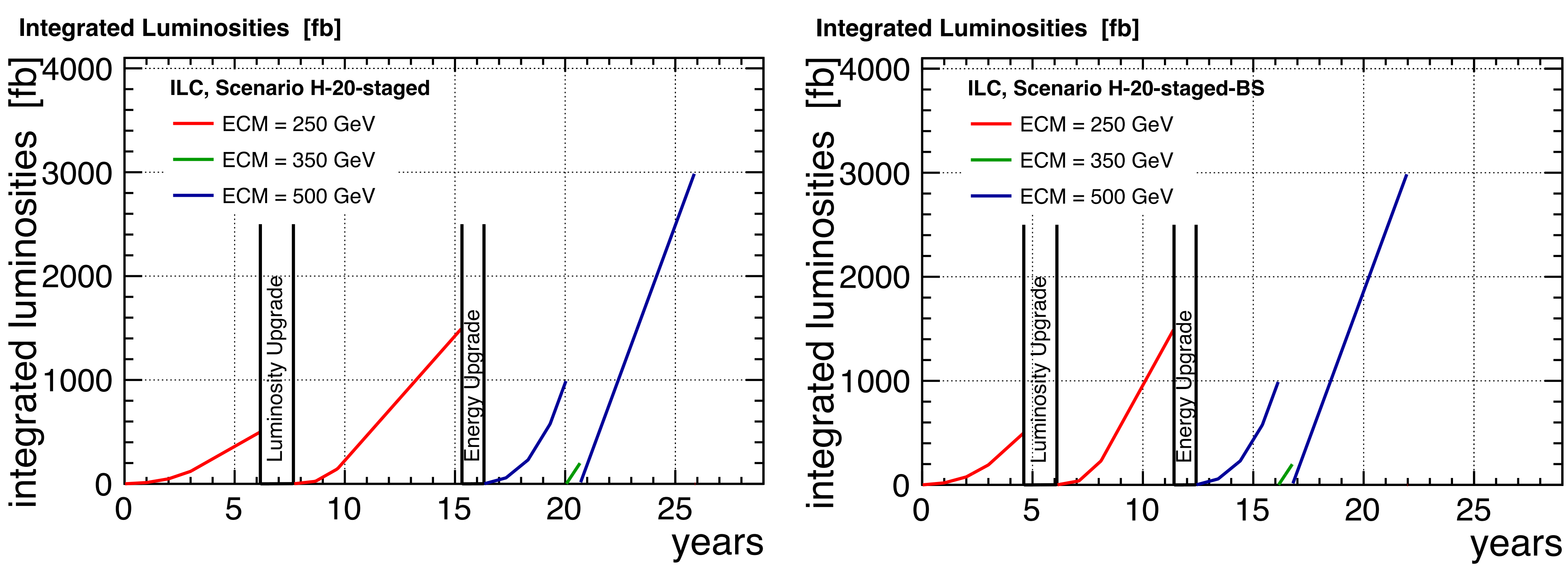


Figure 2: Run plan for the staged ILC starting with a 250-GeV machine under two different assumptions on the achievable instantaneous luminosity at 250 GeV. Both cases reach the same final integrated luminosities as in Fig. 1.

EWPOs

PHYS. REV. D 97, 053004 (2018)

7 observables

TABLE I. Values and uncertainties for precision electroweak observables used in this paper. The values are taken from Ref. [42], except for the averaged value of A_ℓ, which corresponds to the averaged value of $\sin^2\theta_{\rm eff}$ in Ref. [43]. The best -fit values are those of the fit in Ref. [42]. For the purpose of fitting Higgs boson couplings as described in Sec. VII, we use improvements in some of the errors expected from the LHC [44] and ILC [45]. The improved estimate of the W width is obtained from $\Gamma_W = \Gamma(W \to \ell\nu)/\mathrm{BR}(W \to \ell\nu)$.

Observable	Current value	Current σ	Future σ	SM best-fit value
$\alpha^{-1}(m_Z^2)$	128.9220	0.0178		(same)
G_F (10^{-10} GeV^{-2})	1166378.7	0.6		(same)
m_W (MeV)	80 385	15	5	80 361
m_Z (MeV)	91 187.6	2.1		91 188.0
m_h (MeV)	125 090	240	15	125 110
A_ℓ	0.14696	0.0013		0.147937
Γ_ℓ (MeV)	83.984	0.086		83.995
Γ_Z (MeV)	2495.2	2.3		2494.3
Γ_W (MeV)	2085	42	2	2088.8

EWPOs and Renormalization EFT

PHYS. REV. D 97, 053004 (2018)

7 observables

$\underline{\alpha(m_Z), G_F, m_W, m_Z, m_h,}\ A_{LR}(\ell), \Gamma(Z \to \ell^+\ell^-)$

$$\delta e = \delta(4\pi\alpha(m_Z^2))^{1/2} = s_w^2 \delta g + c_w^2 \delta g' + \frac{1}{2}\delta Z_A$$

$$\delta G_F = \ -2\delta v + 2c'_{HL}$$

$$\delta m_W = \delta g + \delta v + \frac{1}{2}\delta Z_W$$

$$\delta m_Z = c_w^2 \delta g + s_w^2 \delta g' + \delta v - \frac{1}{2}c_T + \frac{1}{2}\delta Z_Z$$

$$\delta m_h = \frac{1}{2}\delta\overline{\lambda} + \delta v + \frac{1}{2}\delta Z_h$$

→ δg, $\delta g'$, δv, $\delta\lambda$, c_T

($\delta X = \Delta X / X$)

$$\overline{\lambda} = \lambda(1 + \frac{3}{2}c_6)$$

$$s_w^2 = \sin^2\theta_w = \frac{g'^2}{g^2 + g'^2}$$

$$c_w^2 = \cos^2\theta_w = \frac{g^2}{g^2 + g'^2}$$

$\alpha(m_Z), G_F, m_W, m_Z, m_h,\ \underline{A_{LR}(\ell), \Gamma(Z \to \ell^+\ell^-)}$

$$\delta\Gamma_\ell = \delta m_Z + 2\frac{g_L^2\delta g_L + g_R^2 \delta g_R}{g_L^2 + g_R^2}$$

$$\delta A_\ell = \frac{4g_L^2 g_R^2(\delta g_L - \delta g_R)}{g_L^4 - g_R^4}$$

$$g_L = \frac{g}{c_w}\left[(-\frac{1}{2} + s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}(c_{HL} + c'_{HL}) - s_w c_w \delta Z_{AZ}\right]$$

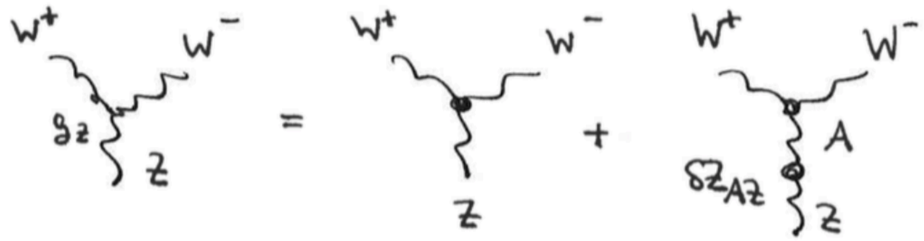
$$g_R = \frac{g}{c_w}\left[(+s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}c_{HE} - s_w c_w \delta Z_{AZ}\right]$$

→ $c_{HL} + c'_{HL}$, c_{HE}

TGC : 3 parameters

PHYS. REV. D 97, 053004 (2018)

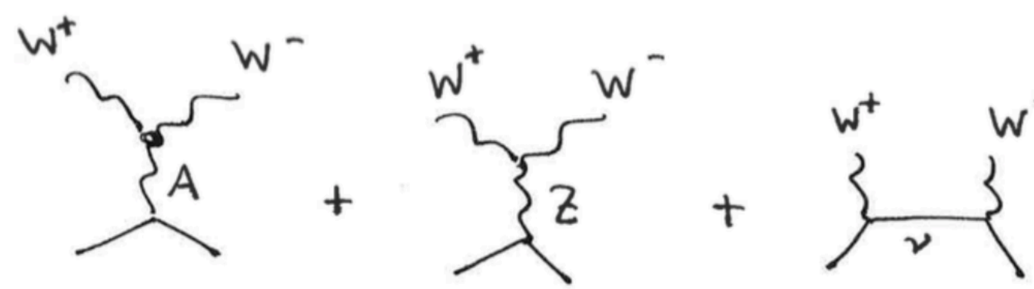
$$\Delta\mathcal{L}_{TGC} = ig_V\left\{V^\mu(\hat{W}^-_{\mu\nu}W^{+\nu} - \hat{W}^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu \hat{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2}\hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu}\hat{V}^{\mu\nu}\right\}$$



$$g_Z = gc_w(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ})$$

$$\kappa_A = 1 + (8c_{WB})$$

$$\lambda_A = -6g^2 c_{3W}$$



$$\delta g_{Z,eff} = \delta g_Z + \frac{1}{c_w^2}((c_w^2 - s_w^2)\delta g_L + s_w^2 \delta g_R - 2\delta g_W)$$

$$\delta\kappa_{A,eff} = (c_w^2 - s_w^2)(\delta g_L - \delta g_R) + 2(\delta e - \delta g_W) + (8c_{WB})$$

$$\delta\lambda_{A,eff} = -6g^2 c_{3W}$$

$$g_W = g\,(1 + c'_{HL} + \frac{1}{2}\delta Z_W)$$

Synergy with HL-LHC

PHYS. REV. D 97, 053004 (2018)

EFT input from HL-LHC: $\frac{\mathrm{BR}(h \to \gamma\gamma)}{\mathrm{BR}(h \to ZZ^*)}$ $\frac{\mathrm{BR}(h \to \gamma Z)}{\mathrm{BR}(h \to ZZ^*)}$

(synergy with HL-LHC)

$$\delta\Gamma(h \to \gamma\gamma) = 528\,\delta Z_A - c_H + 4\delta e + 4.2\,\delta m_h - 1.3\,\delta m_W - 2\delta v$$

$$\delta\Gamma(h \to Z\gamma) = 290\,\delta Z_{AZ} - c_H - 2(1 - 3s_W^2)\delta g + 6c_w^2\delta g' + \delta Z_A + \delta Z_Z$$
$$+9.6\,\delta m_h - 6.5\,\delta m_Z - 2\delta v$$

$$\delta\Gamma(h \to ZZ^*) = 2\eta_Z - 2\delta v - 13.8\delta m_Z + 15.6\delta m_h - 0.50\delta Z_Z - 1.02 C_Z + 1.18\delta\Gamma_Z$$

$$\delta Z_A = s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big) \qquad \delta Z_{AZ} = s_w c_w\Big((8c_{WW}) - (1 - \frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\Big)$$

60

Discrimination of BSM models

Phys. Rev. D 97, 053003 (2018)

	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion	-1.5	- 1.5	+10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

Discrimination of BSM models

Phys. Rev. D 97, 053003 (2018)

1 • a PMSSM model with b squarks at 3.4 TeV, gluino at 4 TeV

2 • a Type II 2 Higgs doublet model with $m_A = 600$ GeV, $\tan\beta = 7$

• a Type X 2 Higgs doublet model with $m_A = 450$ GeV, $\tan\beta = 6$

• a Type Y 2 Higgs doublet model with $m_A = 600$ GeV, $\tan\beta = 7$

• a composite Higgs model MCHM5 with $f = 1.2$ TeV, $m_T = 1.7$ TeV

• a Little Higgs model with T-parity with $f = 785$ GeV, $m_T = 2$ TeV

• A Little Higgs model with couplings to 1st and 2nd generation with $f = 1.2$ TeV, $m_T = 1.7$ TeV

• A Higgs-radion mixing model with $m_r = 500$ GeV

9 • a model with a Higgs singlet at 2.8 TeV creating a Higgs portal to dark matter and large λ for electroweak baryogenesis

Discrimination of BSM models

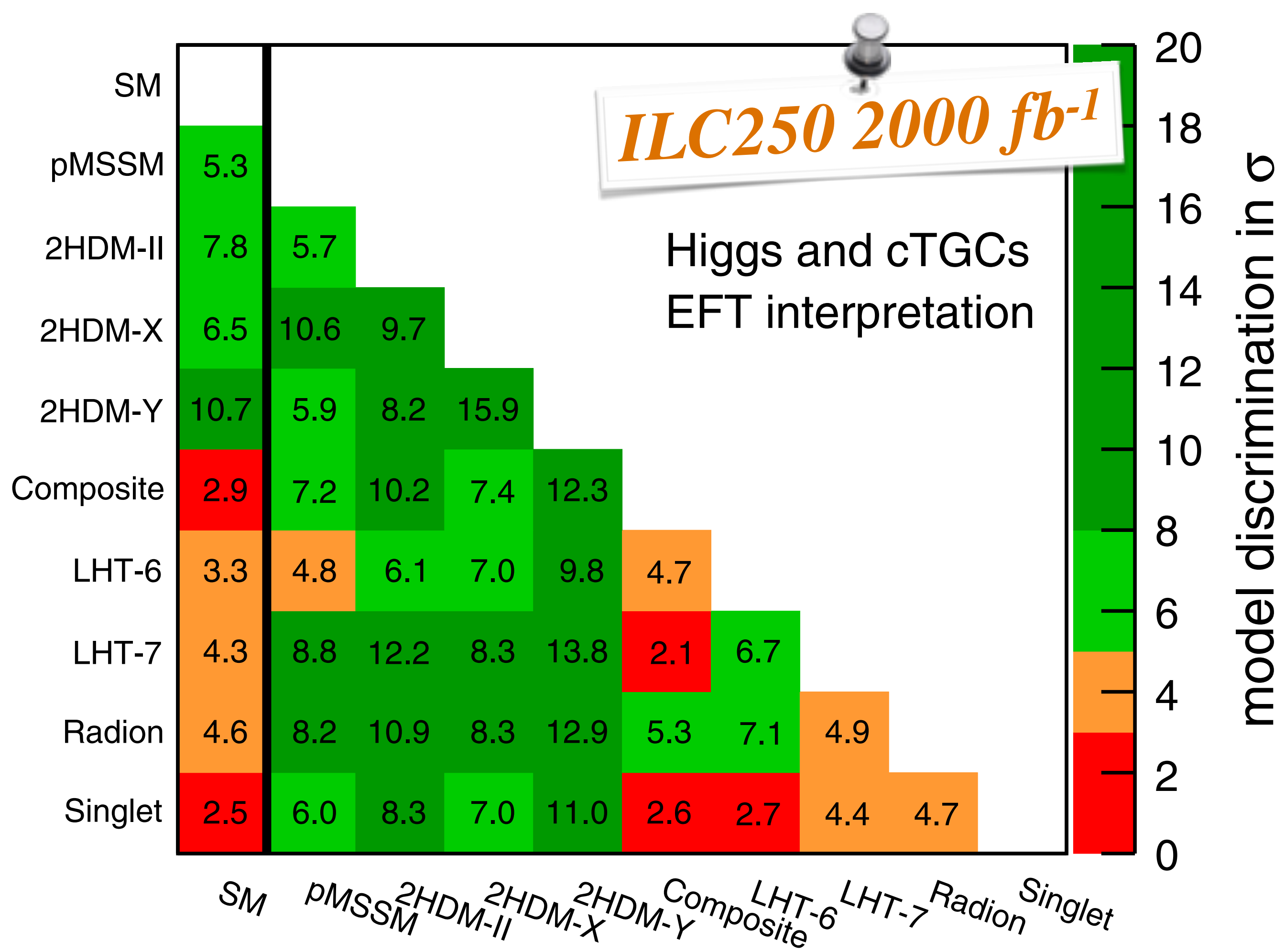
Phys. Rev. D 97, 053003 (2018)

○ chi2 discrimination test

$$(\chi^2)_{AB} = (g_A^T - g_B^T)[VCV^T]^{-1}(g_A - g_B)$$

Unit n [σ] $n = \sqrt{\chi^2}$

- gA, gB: vector of couplings in Model A, B
- C: covariance matrix of EFT coefficients
- Vij: linear dependence of coupling g_i on EFT coefficient c_j



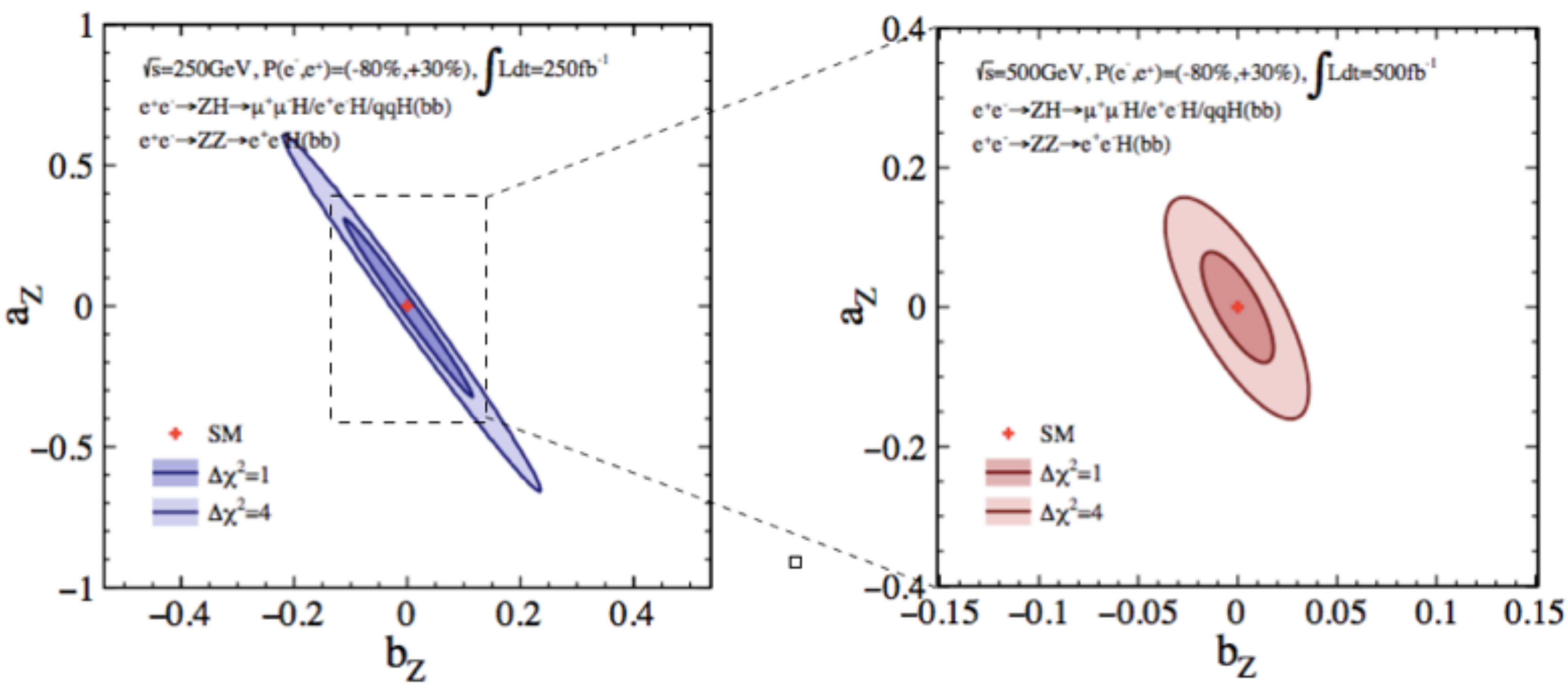
Distinguishable with more than 3σ for Most of the BSM models !

Anomalous ZZH

$$\mathcal{L}_{ZZH} \;=\; M_Z^2\left(\frac{1}{\mathrm{v}}+\frac{a_Z}{\Lambda}\right)Z_\mu Z^\mu H+\frac{b_Z}{2\Lambda}\hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}H+\frac{\tilde{b}_Z}{2\Lambda}\hat{Z}_{\mu\nu}\tilde{\hat{Z}}^{\mu\nu}H$$

(Λ=1TeV)

250GeV 500GeV



Higgs couplings precision

arXiv:1506.05992v2 [hep-ex] 26 Jun 2015

Physics Case for the International Linear Collider

Topic	Parameter	Initial Phase	Full Data Set	units	ref.
Higgs	m_h	25	15	MeV	[15]
	$g(hZZ)$	0.58	0.31	%	[2]
	$g(hWW)$	0.81	0.42	%	[2]
	$g(hb\bar{b})$	1.5	0.7	%	[2]
	$g(hgg)$	2.3	1.0	%	[2]
	$g(h\gamma\gamma)$	7.8	3.4	%	[2]
		1.2	1.0	%, w. LHC results	[17]
	$g(h\tau\tau)$	1.9	0.9	%	[2]
	$g(hc\bar{c})$	2.7	1.2	%	[2]
	$g(ht\bar{t})$	18	6.3	%, direct	[2]
		20	20	%, $t\bar{t}$ threshold	[34]
	$g(h\mu\mu)$	20	9.2	%	[2]
	$g(hhh)$	77	27	%	[2]
	Γ_{tot}	3.8	1.8	%	[2]
	Γ_{invis}	0.54	0.29	%, 95% conf. limit	[2]
Top	m_t	50	50	MeV (m_t(1S))	[33]
	Γ_t	60	60	MeV	[34]
	g_L^γ	0.8	0.6	%	[42]
	g_R^γ	0.8	0.6	%	[42]
	g_L^Z	1.0	0.6	%	[42]
	g_R^Z	2.5	1.0	%	[42]
	F_2^γ	0.001	0.001	absolute	[42]
	F_2^Z	0.002	0.002	absolute	[42]
W	m_W	2.8	2.4	MeV	[62]
	g_1^Z	8.5×10^{-4}	6×10^{-4}	absolute	[63]
	κ_γ	9.2×10^{-4}	7×10^{-4}	absolute	[63]
	λ_γ	7×10^{-4}	2.5×10^{-4}	absolute	[63]
Dark Matter	EFT Λ: D5	2.3	3.0	TeV, 90% conf. limit	[61]
	EFT Λ: D8	2.2	2.8	TeV, 90% conf. limit	[61]

Table 1: Projected accuracies of measurements of Standard Model parameters at the two stages of the ILC program proposed in the report of the ILC Parameters Joint Working Group [7]. This program has an initial phase with 500 fb^{-1} at 500 GeV, 200 fb^{-1} at 350 GeV, and 500 fb^{-1} at 250 GeV, and a luminosity-upgraded phase with an additional 3500 fb^{-1} at 500 GeV and 1500 fb^{-1} at 250 GeV. Initial state polarizations are taken according to the prescriptions of [7]. Uncertainties are listed as 1σ errors (except where indicated), computed cumulatively at each stage of the program. These estimated errors include both statistical uncertainties and theoretical and experimental systematic uncertainties. Except where indicated, errors in percent (%) are fractional uncertainties relative to the Standard Model values. More specific information for the sets of measurements is given in the text. For each measurement, a reference describing the technique is given.

arXiv:1710.07621v2 [hep-ex] 3 Nov 2017

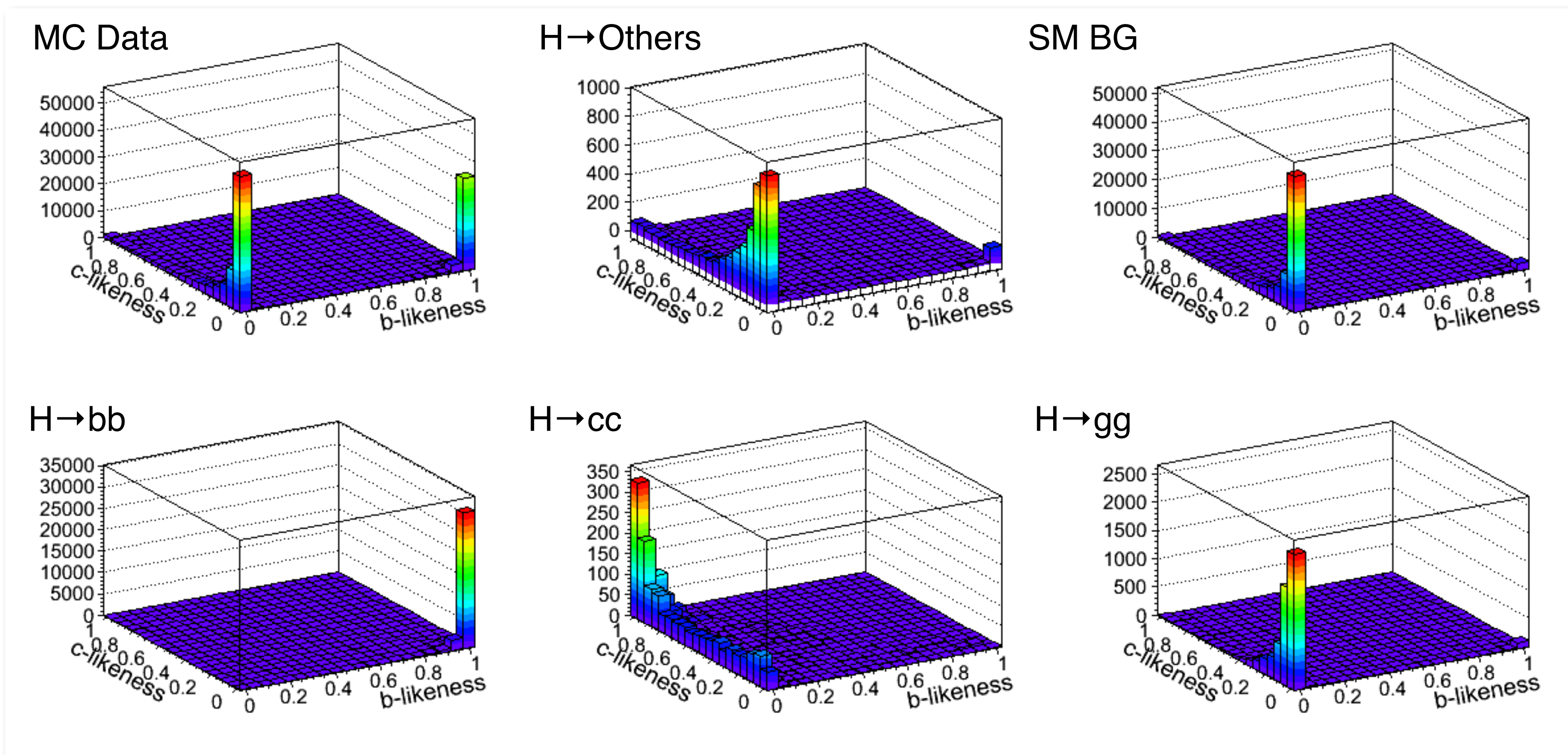
Physics Case for the 250 GeV Stage of the International Linear Collider

	ILC250		+ILC500	
	κ fit	EFT fit	κ fit	EFT fit
$g(hbb)$	1.8	1.1	0.60	0.58
$g(hcc)$	2.4	1.9	1.2	1.2
$g(hgg)$	2.2	1.7	0.97	0.95
$g(hWW)$	1.8	0.67	0.40	0.34
$g(h\tau\tau)$	1.9	1.2	0.80	0.74
$g(hZZ)$	0.38	0.68	0.30	0.35
$g(h\gamma\gamma)$	1.1	1.2	1.0	1.0
$g(h\mu\mu)$	5.6	5.6	5.1	5.1
$g(h\gamma Z)$	16	6.6	16	2.6
$g(hbb)/g(hWW)$	0.88	0.86	0.47	0.46
$g(h\tau\tau)/g(hWW)$	1.0	1.0	0.65	0.65
$g(hWW)/g(hZZ)$	1.7	0.07	0.26	0.05
Γ_h	3.9	2.5	1.7	1.6
$BR(h \to inv)$	0.32	0.32	0.29	0.29
$BR(h \to other)$	1.6	1.6	1.3	1.2

Table 1: Projected relative errors for Higgs boson couplings and other Higgs observables, in %, for fits in the κ and EFT formalisms. The ILC250 columns assume a total integrated luminosity of 2 ab^{-1} at $\sqrt{s} = 250$ GeV, shared by $(-+, +-, --, ++) = (45\%, 45\%, 5\%, 5\%)$ as described in Section 2. The ILC500 columns assume, in addition, a total integrated luminosity of 200 fb^{-1} at $\sqrt{s} = 350$ GeV, shared as $(45\%, 45\%, 5\%, 5\%)$, and a total integrated luminosity of 4 ab^{-1} at $\sqrt{s} = 500$ GeV, shared as $(40\%, 40\%, 10\%, 10\%)$. Three observables at the HL-LHC, $BR_{\gamma\gamma}/BR_{ZZ}$, $BR_{\gamma Z}/BR_{\gamma\gamma}$ and $BR_{\mu\mu}/BR_{\gamma\gamma}$, are included in all of the fits. The effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square root of the corresponding partial widths. The last two lines give 95% confidence upper limits on the exotic branching ratios. The detailed formulae used in the EFT fit, and the resulting covariance matrix, can be found in [15].

Higgs direct couplings to cc and gg at ILC250

e+e- —> ZH —> ff(jj): b-likeness .vs. c-likeness

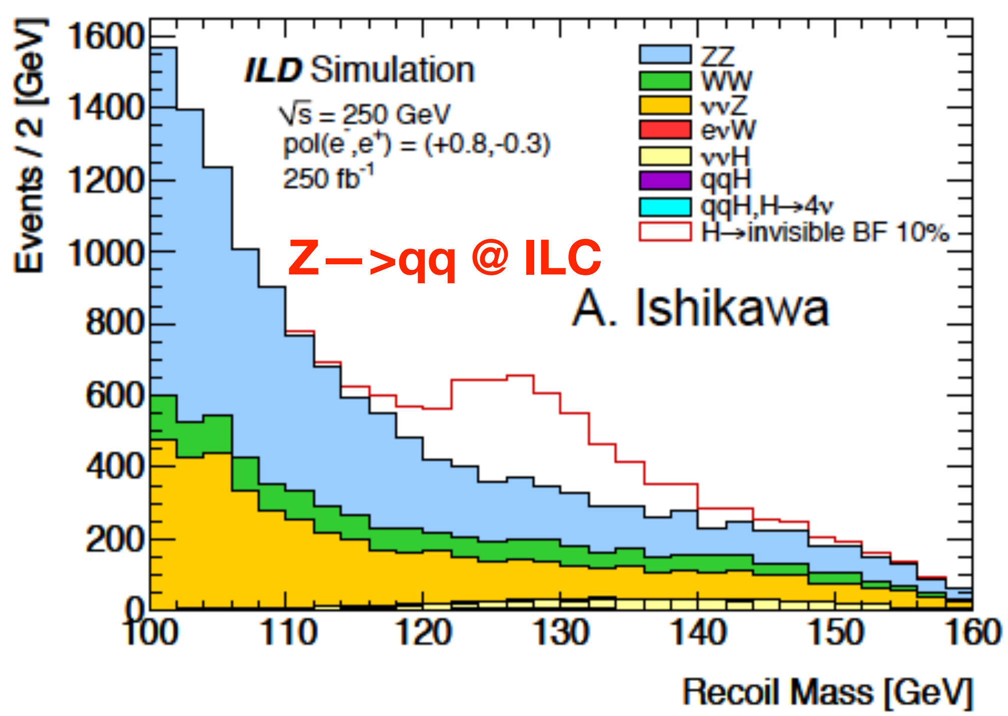


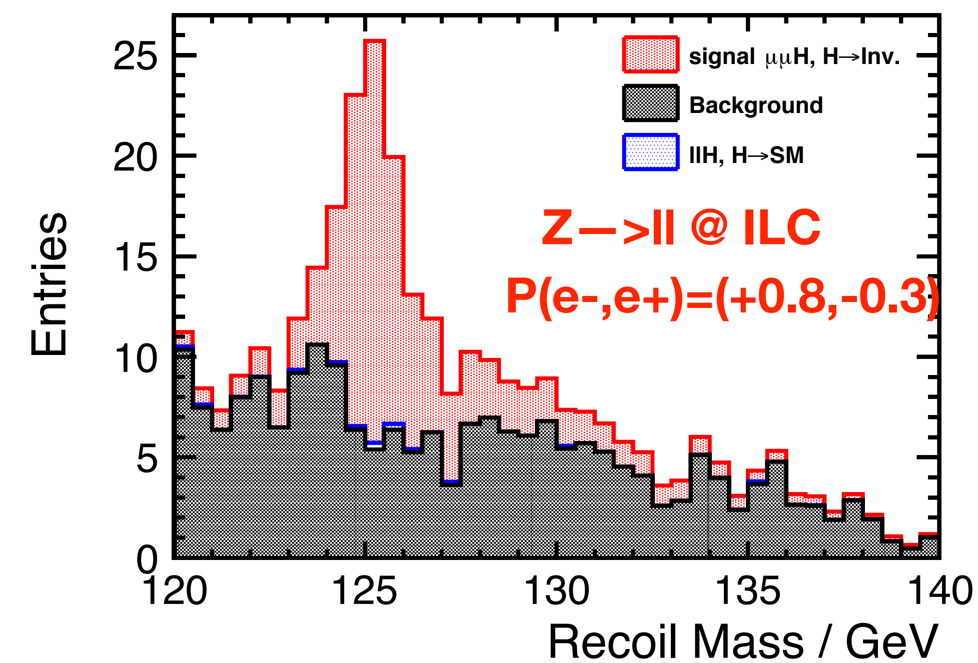
- clean environment at e+e-; excellent b- and c-tagging performance
- bb/cc/gg modes can be separated simultaneously by template fitting

Ono, et. al, Euro. Phys. J. C73, 2343; F.Mueller, PhD thesis (DESY)

Higgs —> invisible at ILC250

$$e^+ + e^- \to ZH \to l^+l^-/q\bar{q} + \text{Missing}$$





- recoil technique: Higgs mass fully reconstructed even it decays invisibly
- right-handed beam polarization helps: much lower background
- BR(H—>inv.) < 0.3% (CL95%)

ILC site in North Japan