Higgs Precision (EFT) at the ILC

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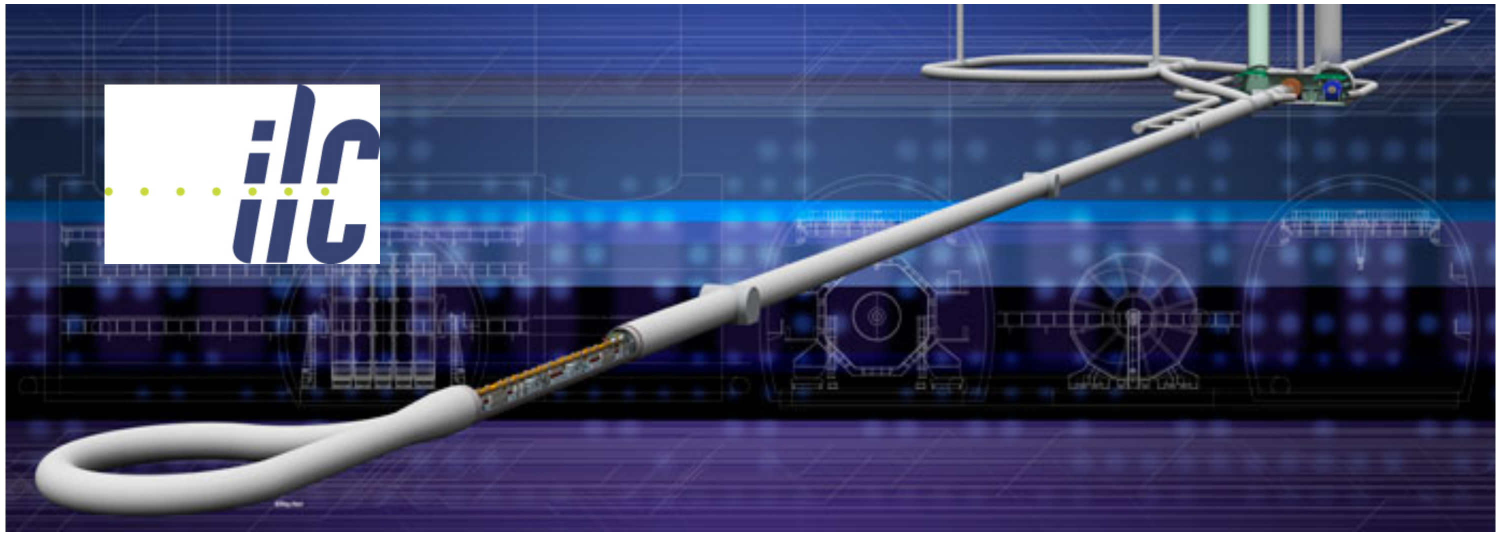
HPNP 2019, February 18-22, 2019 @ Osaka University

based on papers
Barklow, Fujii, Jung, Peskin, JT, 1708.09079;
Barklow, Fujii, Jung, Karl, List, Ogawa, Peskin, JT, 1708.08912



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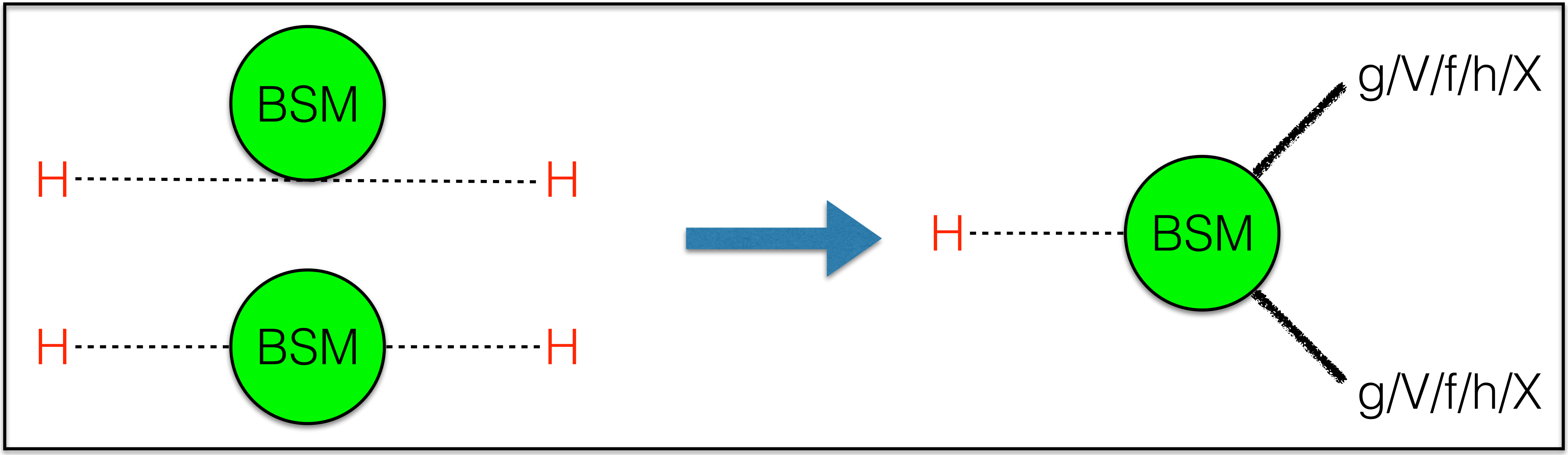
Higgs provides a unique window for BSM

- origin of EWSB? Naturalness? Baryogenesis? Dark Sector?



mysteries in the EW vacuum

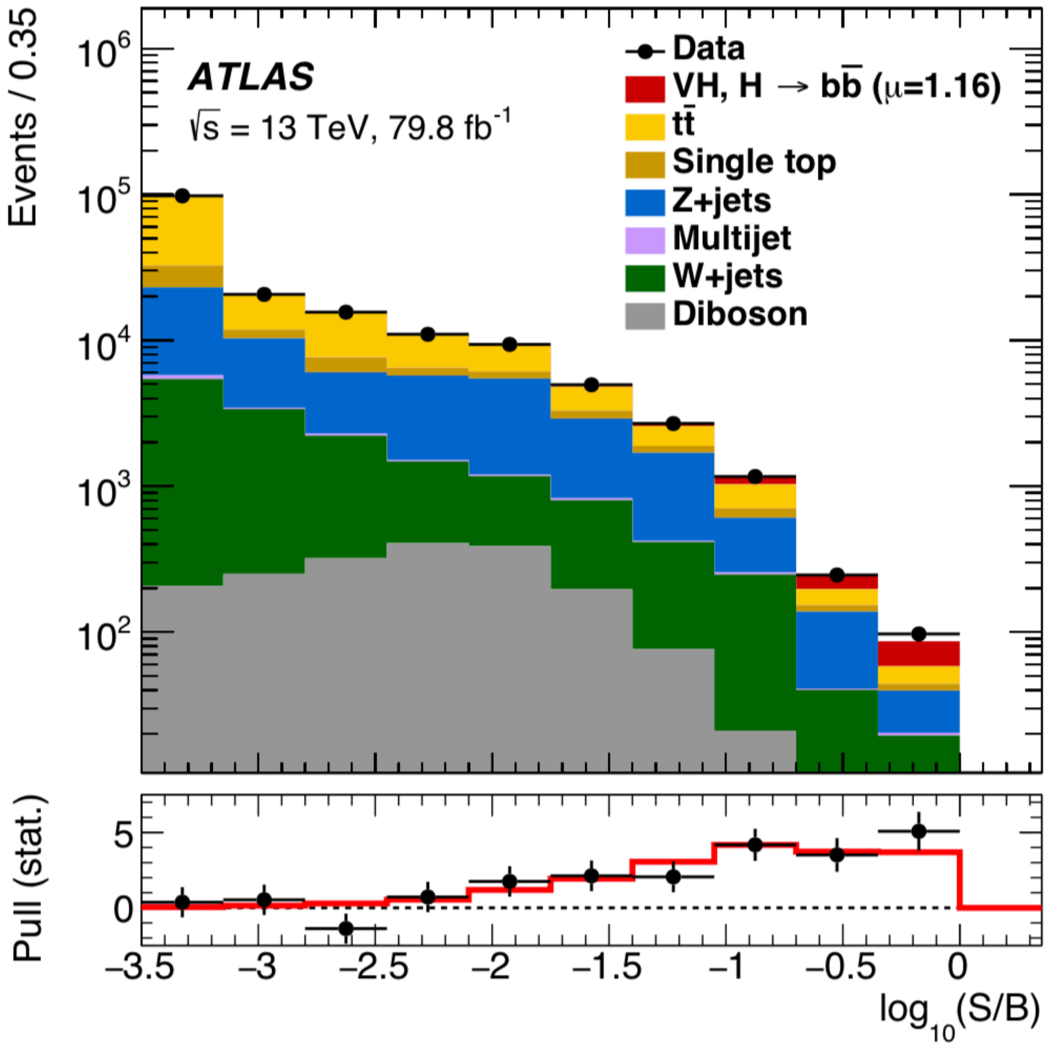
can be revealed by looking in detail at Higgs properties

“that is much much easier, infinitely easier,
on a e+e- machine than on a proton machine”

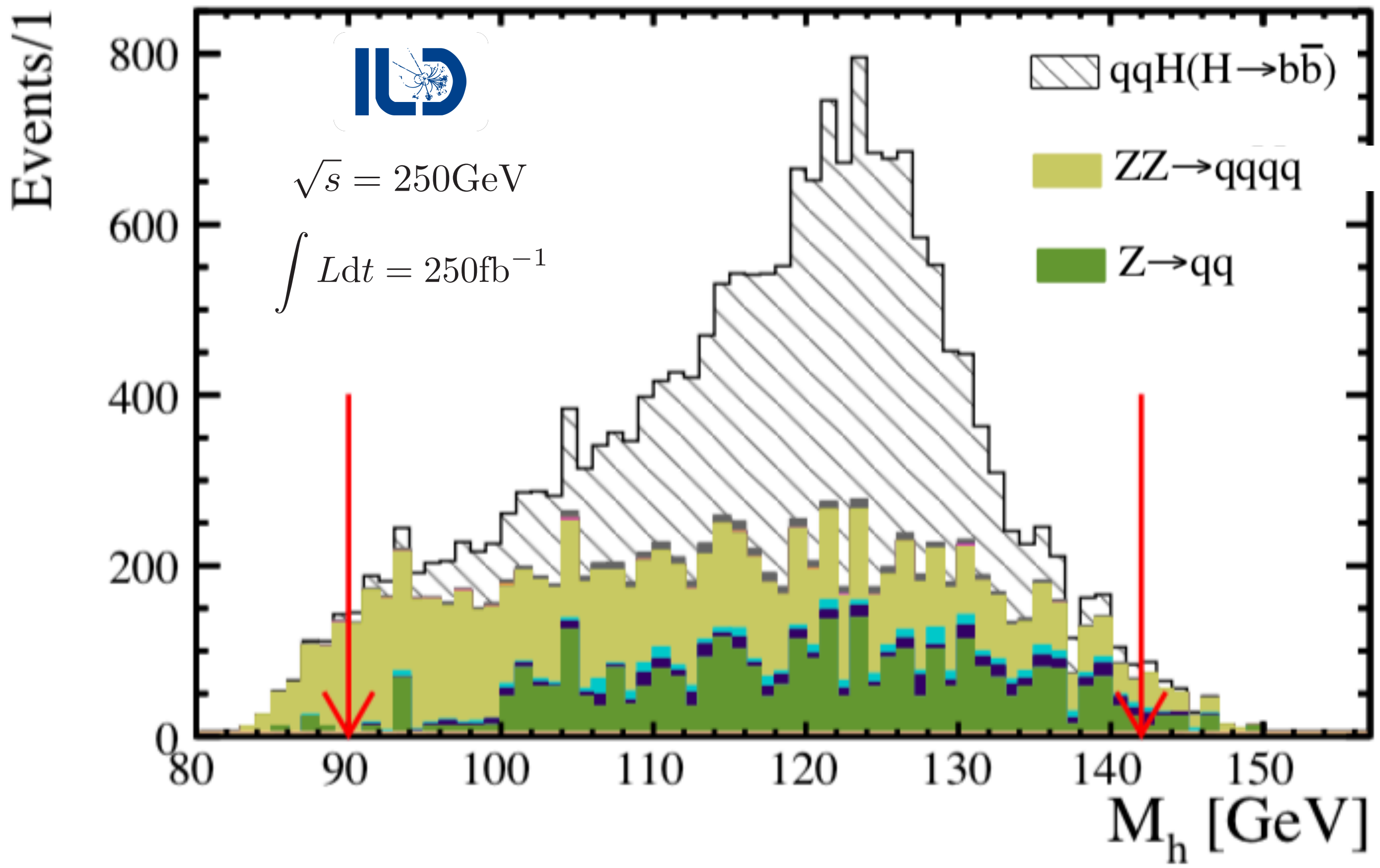
youtube: Burton Richter #mylinearcollider, 2015

for example: H->bb discovery

@ LHC



@ ILC



with 1.3 fb^{-1} data ~ 2 days running

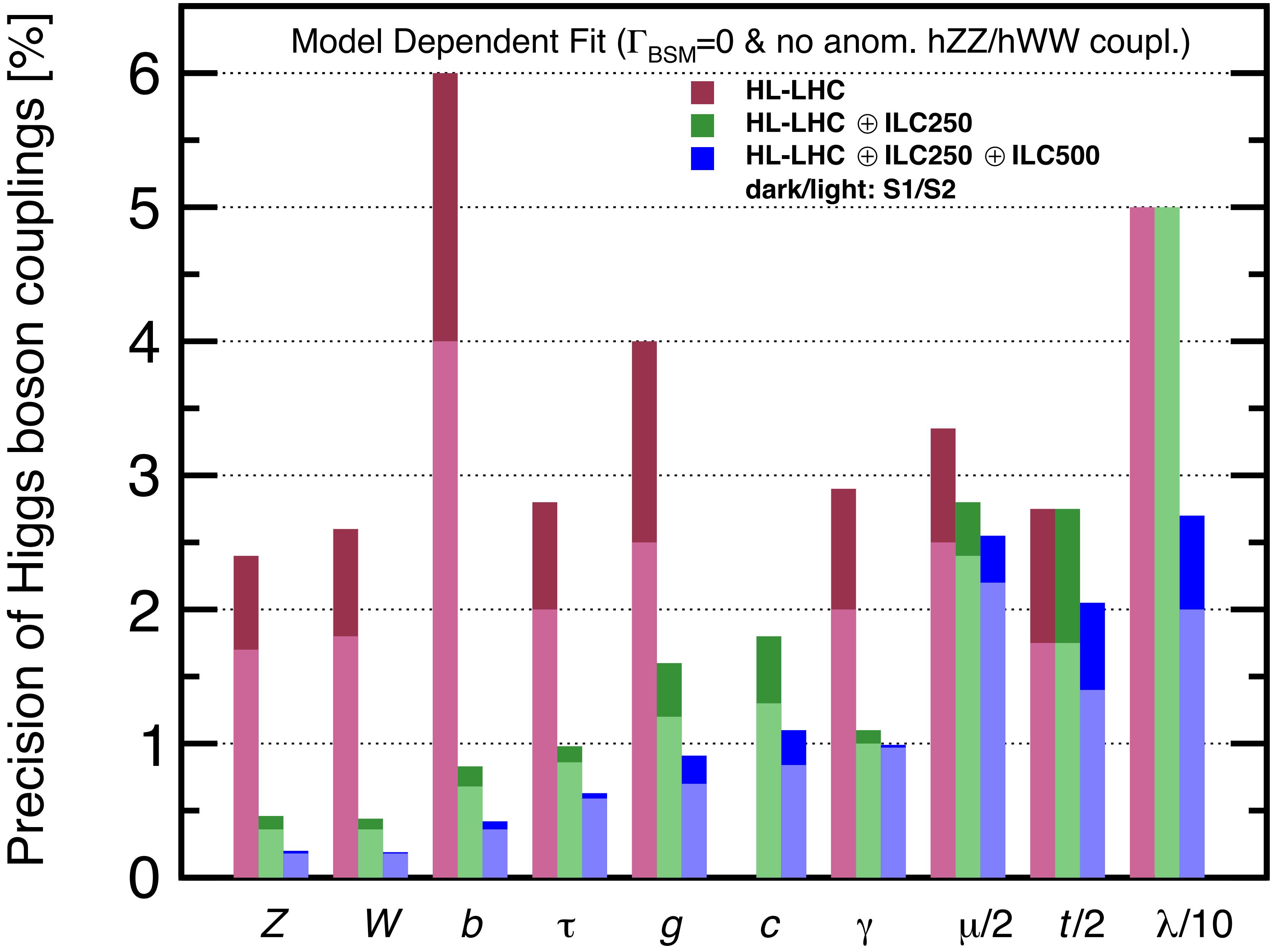
# of Higgs produced: ~4,000,000 ~400

significance: 5.4σ 5.2σ

(ATLAS, arXiv:1808.08238; CMS, arXiv:1808.08242)

(Ogawa, PhD Thesis, ILD full simulation)

Higgs coupling precisions at ILC250



LCC Physics WG, arXiv: 1901.09829

#qualitative:

model independence;

hcc coupling

#quantitative (<~1%):

hZZ, hWW, hbb, h$\tau\tau$

h->invisible/exotic

#synergy:

h$\gamma\gamma$, hγZ, h$\mu\mu$,

htt, hgg

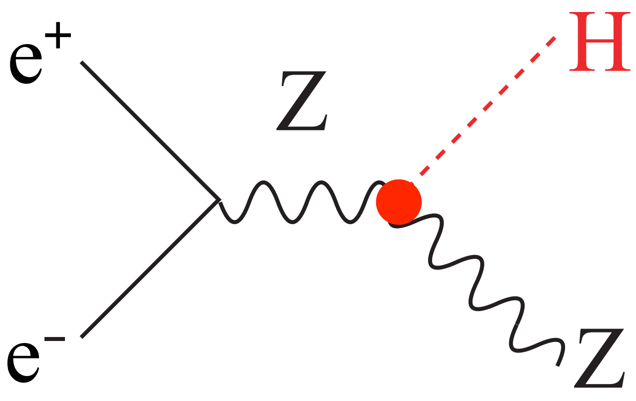
Higgs coupling determination — kappa formalism

1) recoil mass technique —> inclusive $\boldsymbol{\sigma_{Zh}}$
2) σ_{Zh} —> $\boldsymbol{\kappa_Z}$ —> Γ(h->ZZ*)
3) WW-fusion $\nu_e\nu_e h$ —> $\boldsymbol{\kappa_W}$ —> Γ(h->WW*)
4) total width $\boldsymbol{\Gamma_h}$ = Γ(h—>ZZ*)/BR(h->ZZ*)
5) or $\boldsymbol{\Gamma_h}$ = Γ(h—>WW*)/BR(h->WW*)
6) then all other couplings BR(h->XX) *Γ_h -> $\boldsymbol{\kappa_X}$

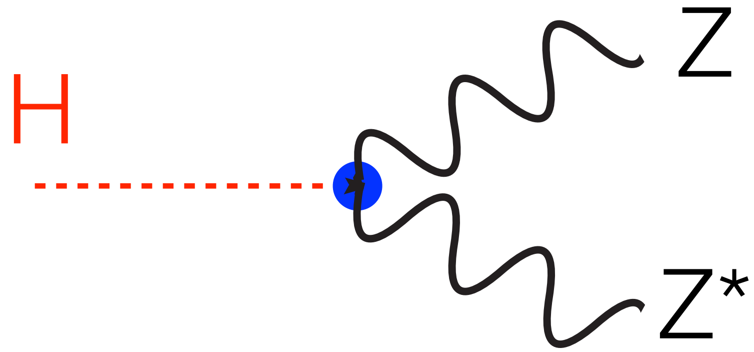
JT, et al, PoS EPS-HEP2013 (2013) 316 Nucl.Part.Phys.Proc. 273-275 (2016) 826-833

a key question in kappa formalism:

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



$\propto \quad \kappa_Z^2\ ? \quad \propto$

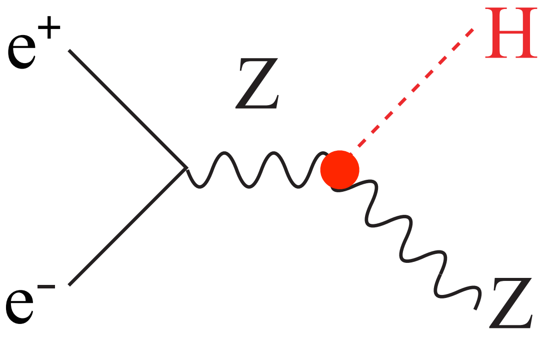


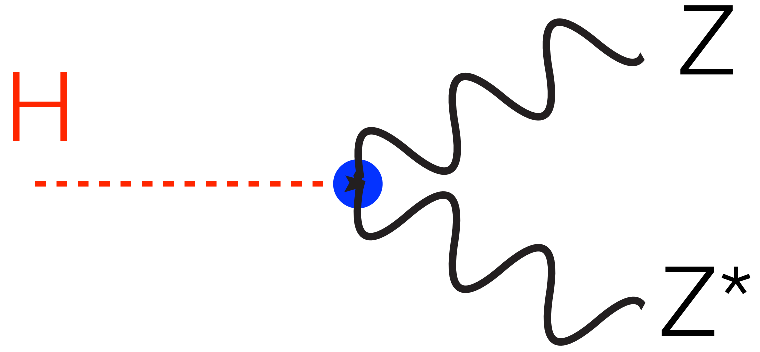
BSM territory -> can deviations be represented by single κ_Z?

the answer is model dependent

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

BSM can induce new Lorentz structures in hZZ





$$\sigma(e^+e^- \to Zh) = (SM)\cdot (1+2\eta_Z+(5.5)\zeta_Z) \neq \Gamma(h\to ZZ^*) = (SM)\cdot (1+2\eta_Z-(0.50)\zeta_Z)$$

- what would be a more model-independent formalism?

a strategy: SM Effective Field Theory

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

$$= \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^{d_i - 4}} O_i$$

- a more model independent formalism for Higgs coupling determination is based on *SMEFT*
- most general effects from BSM are represented by a set of higher dimension operators, respect SU(3)xSU(2)xU(1)
- the capabilities of a e+e- machine are best illustrated in SMEFT —> focus of following slides

SM Effective Field Theory: some simplifications

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

$$= \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i - 4}} O_i$$

the new particle searches at LHC Run 2 suggest ***Λ>500*** GeV

justify the analysis at dimension-6 operators

there are ***84*** of such operators for 1 fermion generation

assuming baryon number conservation, there are ***59***

- there exists a smaller but complete set relevant to physics at e+e-

SM Effective Field Theory: full formalism (23 pars.)

("Warsaw" basis by Grzadkowski et al)

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

10 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}

+ 4 SM parameters: g, g', v, λ

+ 5 operators modifying h couplings to b, c, τ, μ, g

+ 2 operators for contact interactions with quarks

+ 2 parameters for h->invisible and exotic

strategy to determine all the 23 parameters

Electroweak Precision Observables (9)

+

Triple Gauge boson Couplings (3)

+

Higgs observables at LHC & ILC (3+12x2)

↑ 2 beam polarizations

- at the ILC, all the 23 parameters can be measured ***simultaneously***

(focus on ILC250; details in backup)

recap 1: Higgs couplings are related to themselves (hVV)

$$\begin{aligned}\Delta\mathcal{L}_h =\ & \frac{1}{2}\partial_\mu h \partial^\mu h - \frac{1}{2}m_h^2 h^2 - (1+\eta_h)\bar{\lambda} v h^3 + \frac{\theta_h}{v} h\partial_\mu h \partial^\mu h \\ & +(1+\eta_W)\frac{2m_W^2}{v} W_\mu^+ W^{-\mu} h + (1+\eta_{WW})\frac{m_W^2}{v^2} W_\mu^+ W^{-\mu} h^2 \\ & +(1+\eta_Z)\frac{m_Z^2}{v} Z_\mu Z^\mu h + \frac{1}{2}(1+\eta_{ZZ})\frac{m_Z^2}{v^2} Z_\mu Z^\mu h^2 \\ & +\zeta_W \hat{W}_{\mu\nu}^+ \hat{W}^{-\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) + \frac{1}{2}\zeta_Z \hat{Z}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) \\ & +\frac{1}{2}\zeta_A \hat{A}_{\mu\nu}\hat{A}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right) + \zeta_{AZ}\hat{A}_{\mu\nu}\hat{Z}^{\mu\nu}\left(\frac{h}{v} + \frac{1}{2}\frac{h^2}{v^2}\right)\ .\end{aligned}$$

(SM structure: kappa like)

$$\eta_h = \delta\bar{\lambda} + \delta v - \frac{3}{2}c_H + c_6$$

$$\eta_W = 2\delta m_W - \delta v - \frac{1}{2}c_H$$

$$\eta_{WW} = 2\delta m_W - 2\delta v - c_H$$

$$\eta_Z = 2\delta m_Z - \delta v - \frac{1}{2}c_H - c_T$$

$$\eta_{ZZ} = 2\delta m_Z - 2\delta v - c_H - 5c_T$$

(Anomalous: new Lorentz structure)

$$\theta_h = c_H$$

$$\zeta_W = \delta Z_W \quad = (8c_{WW})$$

$$\zeta_Z = \delta Z_Z \quad = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB})$$

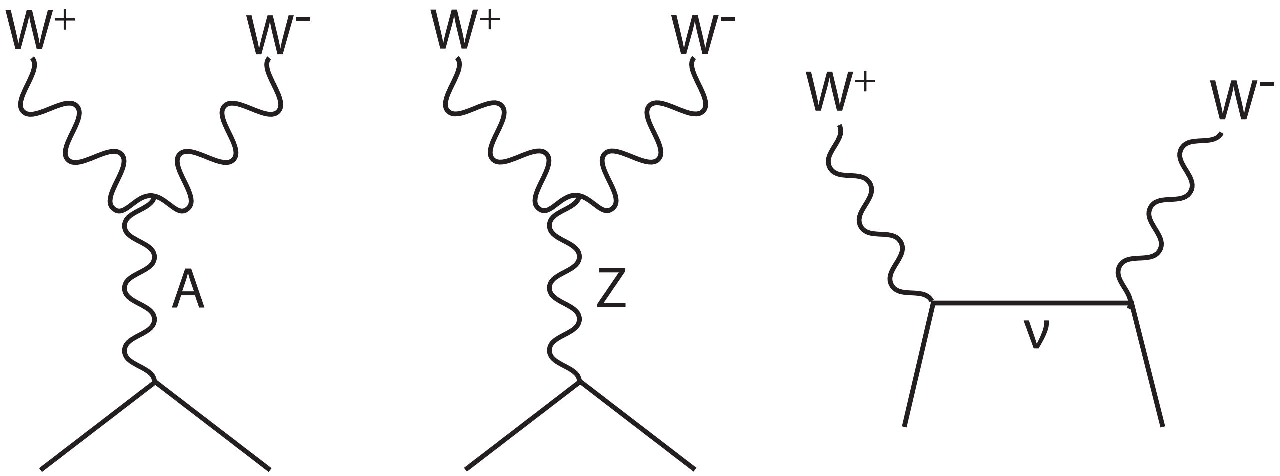
$$\zeta_A = \delta Z_A \quad = s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big)$$

$$\zeta_{AZ} = \delta Z_{AZ} \quad = s_w c_w\left((8c_{WW}) - (1-\frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\right)$$

- hZZ/hWW/hγZ/hγγ highly related: SU(2)xU(1) gauge symmetries

recap 2: Higgs couplings are related to W-/Z- couplings (TGCs)

$$\boxed{\frac{g^2 c_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}W^{a\mu\nu}}\qquad\boxed{\frac{4gg' c_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}B^{\mu\nu}}\qquad\boxed{\frac{g'^2 c_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu}}$$



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

$$g_Z = gc_w(1+\frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ}) \qquad \kappa_A = 1 + (8c_{WB}) \qquad \lambda_A = -6g^2 c_{3W}$$

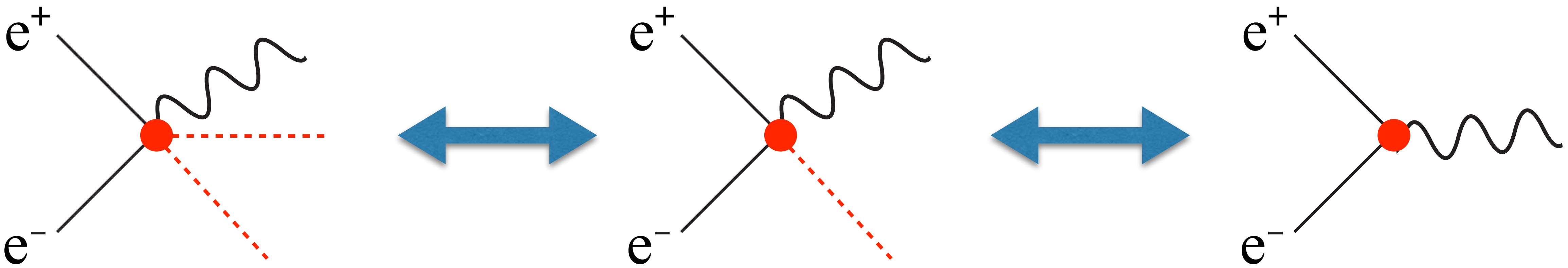
- longitudinal modes of W/Z are from Higgs fields
- c_{WB}, δZ_Z, δZ_{AZ} appear also in hZZ/hWW/hγγ/hγZ couplings

recap 3: Higgs couplings are related to W-/Z- couplings (contact interactions)

$$i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu L)$$

$$4i\frac{c'_{HL}}{v^2}(\Phi^\dagger t^a \overleftrightarrow{D}^\mu \Phi)(\overline{L}\gamma_\mu t^a L)$$

$$i\frac{c_{HE}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^\mu \Phi)(\overline{e}\gamma_\mu e)$$



e^+e^- ->Zhh

e^+e^- ->Zh

Z-pole

- contact interactions from $c_{HL}/c_{HL}'/c_{HE}$ in Higgs processes can be constrained by EWPOs at Z-pole

recap 4: absolute Higgs couplings (unique role of inclusive σ_{Zh})

$$\boxed{\frac{c_H}{2v^2}\partial^\mu(\Phi^\dagger\Phi)\partial_\mu(\Phi^\dagger\Phi)}$$

$\frac{c_H}{2}\partial^\mu h \partial_\mu h$ $\longrightarrow$ renormalize kinetic term of SM Higgs field

$h \longrightarrow (1-c_H/2)h$

$\longrightarrow$ **shift all SM Higgs couplings by $-c_H/2$**

- c_H can not be determined by any BR or ratio of couplings

- c_H has to rely on inclusive cross section of $e^+e^- \to Zh$, enabled by recoil mass technique at e+e-

recap 5: hWW is determined as precisely as hZZ @ √s = 250 GeV

$$\Gamma(h \to ZZ^*) = (SM) \cdot (1 + 2\eta_Z - (0.50)\zeta_Z) \ ,$$

$$\Gamma(h \to WW^*) = (SM) \cdot (1 + 2\eta_W - (0.78)\zeta_W)$$

SM-like hVV

$$\eta_W = -\frac{1}{2}c_H$$

$$\eta_Z = -\frac{1}{2}c_H - c_T$$

custodial symmetry is broken by cT -> constrained by EWPOs

$c_i \sim O(10^{-4}\text{-}10^{-3})$

anomalous hVV

$$\zeta_W = (8c_{WW})$$

$$\zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + (s_w^4/c_w^2)(8c_{BB})$$

- hWW/hZZ ratio can be determined to <0.1%: highly constrained by SU(2) x U(1) gauge theory

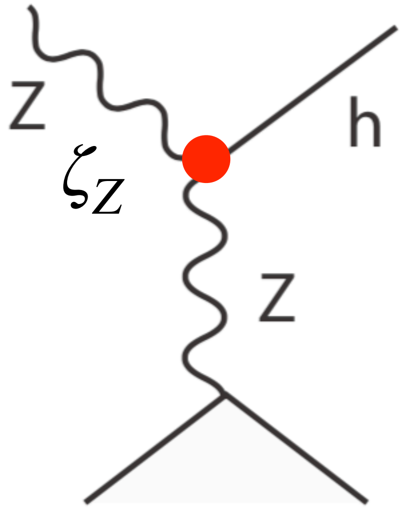
typical precisions by EFT: combined EWPO+TGC+Higgs fit

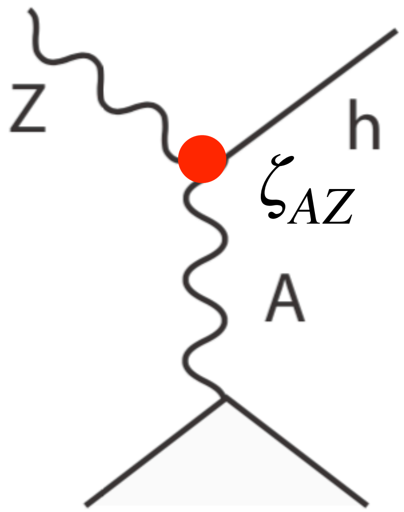
ILC250: $\int L dt = 2\ \mathrm{ab}^{-1}$ @ 250 GeV

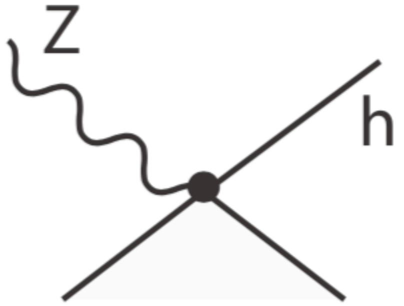
coupling $\Delta g/g$	kappa-fit	EFT-fit
hZZ	0.38%	0.68%
hWW	1.8%	0.67%
hbb	1.8%	1.1%
Γ_h	3.9%	2.5%

(for hZZ and hWW couplings: 1/2 of partial width precision)

recap 6: power of beam polarizations at the ILC





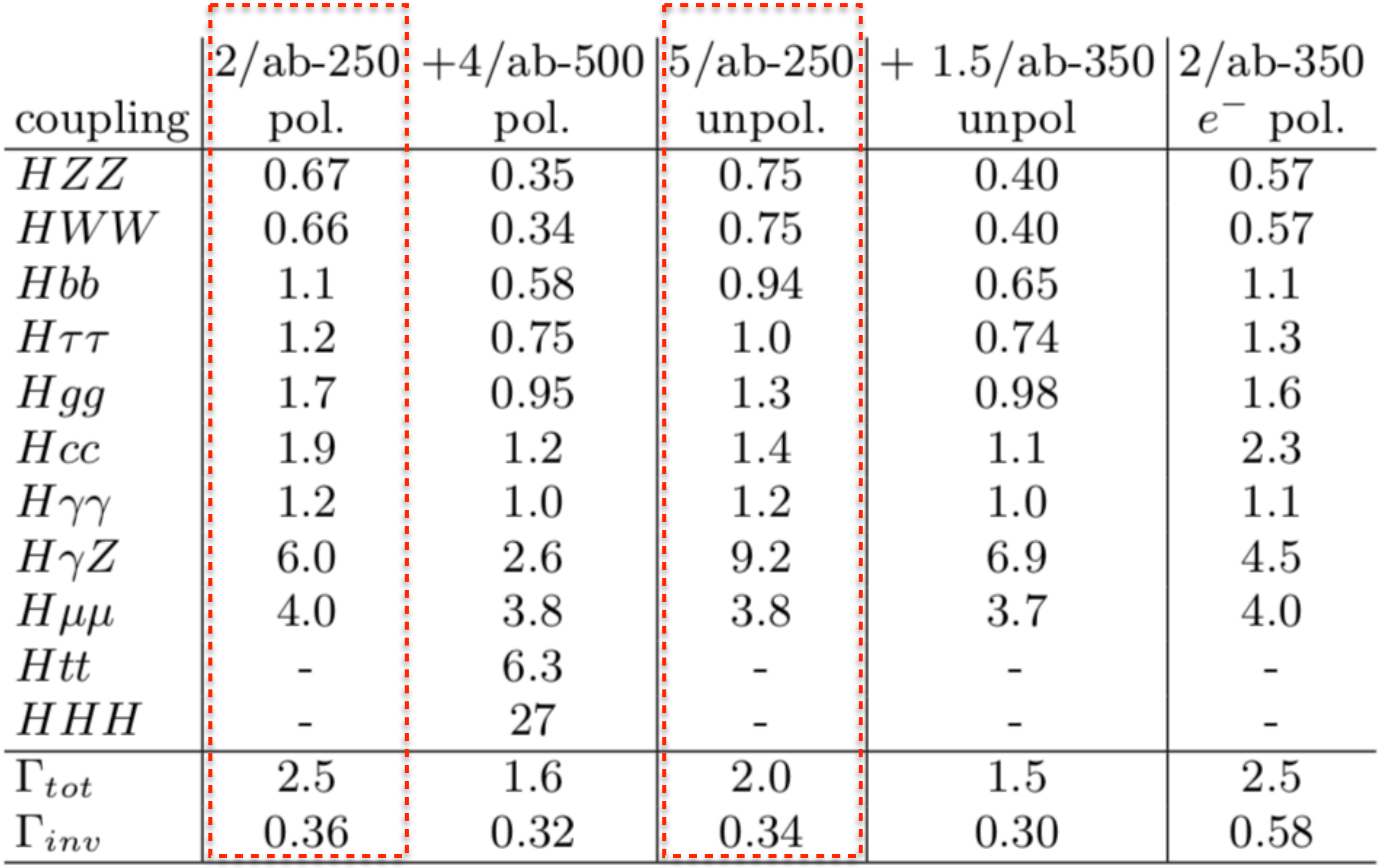


P(e⁻,e⁺)			
(-1,+1)	$\frac{g}{\cos\theta_w}(\frac{1}{2} - \sin\theta_w^2)$	$g\sin\theta_w$	$\frac{g}{\cos\theta_w}(c_{HL} + c'_{HL})$
(+1,-1)	$\frac{g}{\cos\theta_w}(-\sin\theta_w^2)$	$g\sin\theta_w$	$\frac{g}{\cos\theta_w}(c_{HE})$

- large cancellation in (+1,-1) -> a strong constraint on c_{WW} provided by left-right asymmetry for σ_{Zh}

- separation between contact interactions from $c_{HL}+c_{HL}'$ and c_{HE} which grows as ~ s/m_Z^2

recap 6: power of beam polarizations at the ILC



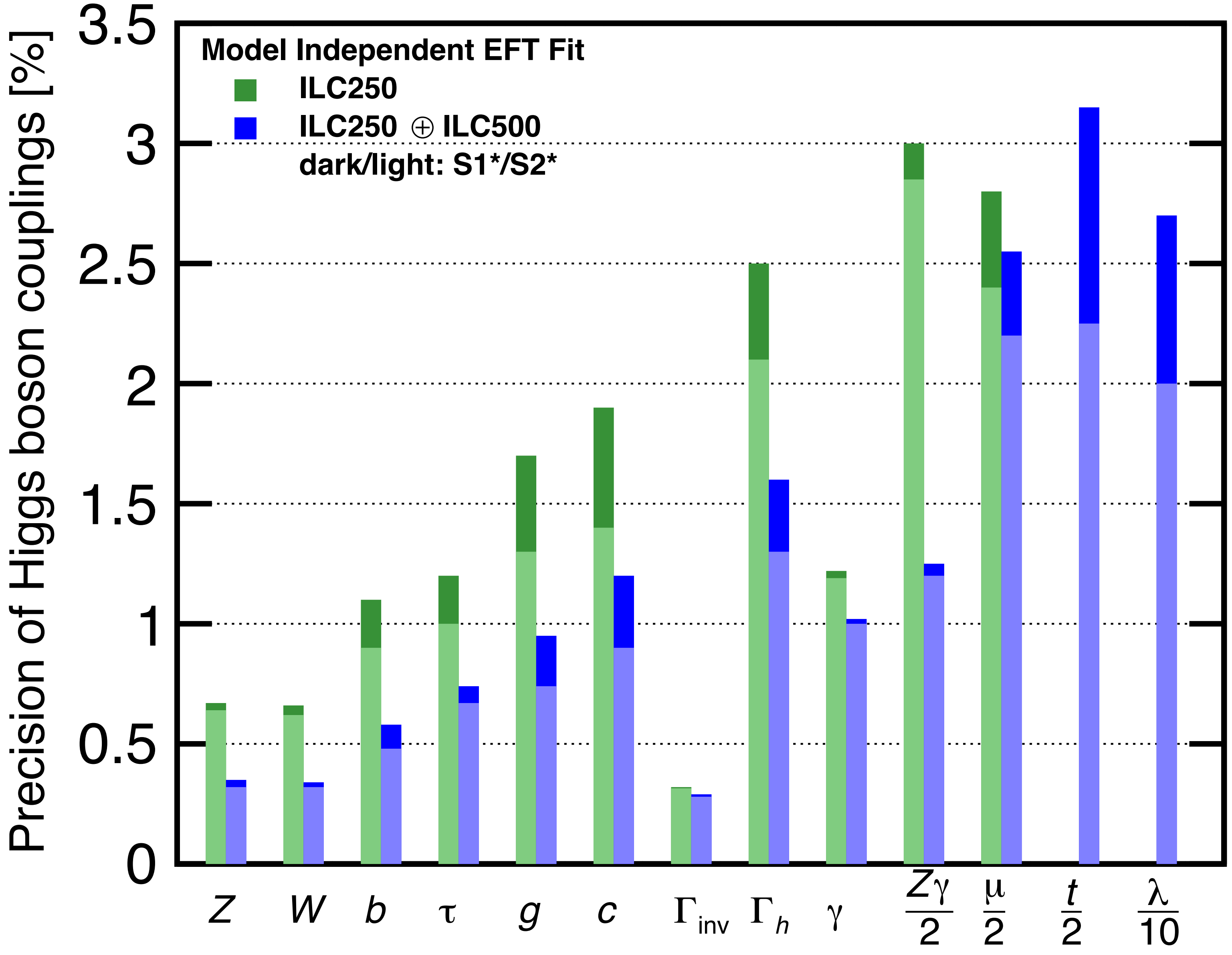
coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol	2/ab-350 e^- pol.
HZZ	0.67	0.35	0.75	0.40	0.57
HWW	0.66	0.34	0.75	0.40	0.57
Hbb	1.1	0.58	0.94	0.65	1.1
$H\tau\tau$	1.2	0.75	1.0	0.74	1.3
Hgg	1.7	0.95	1.3	0.98	1.6
Hcc	1.9	1.2	1.4	1.1	2.3
$H\gamma\gamma$	1.2	1.0	1.2	1.0	1.1
$H\gamma Z$	6.0	2.6	9.2	6.9	4.5
$H\mu\mu$	4.0	3.8	3.8	3.7	4.0
Htt	-	6.3	-	-	-
HHH	-	27	-	-	-
Γ_{tot}	2.5	1.6	2.0	1.5	2.5
Γ_{inv}	0.36	0.32	0.34	0.30	0.58

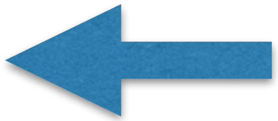
(ILC Supporting Document for European Strategy Update; to be published soon)

- 250 GeV e+e-: power of 2 ab^{-1} polarized ≈ 5 ab^{-1} unpolarized

- redundancy is important for testing internal consistency

SMEFT: model independent determination of Higgs couplings





- 1% or below precisions will be reached at ILC250
- discrimination between BSM models (next by Kei, Eibun)
- -> future direction of HEP (talked by Keisuke)

summary

- the capabilities of a e+e- are best represented in SMEFT formalism
- Higgs couplings are related to EWPOs, W-/Z- couplings
- beam polarizations play an extremely important role
- ILC250 will reach 1% or better precision for Higgs couplings
- ILC500 will further improve precisions by a factor of ~2; provide direct meas. of triple Higgs self-coupling (backup)

backup

simplifications of our analysis

- at tree level, and to linear order in D-6 coefficients
- ignore some possible D-6 corrections involving light leptons, e.g. 4-fermion operators
- avoid using observables that involve contact interactions that include quark currents (see more later)
- ignore the effects of CP-violating operators

$$\begin{aligned}\Delta\mathcal{L}_{CP} = &+\frac{g^2\tilde{c}_{WW}}{m_W^2}\Phi^\dagger\Phi W^a_{\mu\nu}\widetilde{W}^{a\mu\nu} + \frac{4gg'\tilde{c}_{WB}}{m_W^2}\Phi^\dagger t^a\Phi W^a_{\mu\nu}\widetilde{B}^{\mu\nu} \\ &+\frac{g'^2\tilde{c}_{BB}}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}\widetilde{B}^{\mu\nu} + \frac{g^3\tilde{c}_{3W}}{m_W^2}\epsilon_{abc}W^a_{\mu\nu}W^{b\nu}{}_{\rho}\widetilde{W}^{c\rho\mu}\end{aligned}$$

on-shell renormalization

- D-6 operators modify the SM expressions for precision electroweak observables, thus shift the appropriate values for the SM couplings —> g, g’, v, λ free parameters
- D-6 operators also renormalize the kinetic terms of the SM fields —> rescale the boson fields

$$\begin{aligned}\mathcal{L} = &-\frac{1}{2}W^{+}_{\mu\nu}W^{-\mu\nu}\cdot(1-\delta Z_W) - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu}\cdot(1-\delta Z_Z)\\ &-\frac{1}{4}A_{\mu\nu}A^{\mu\nu}\cdot(1-\delta Z_A) + \frac{1}{2}(\partial_\mu h)(\partial^\mu h)\cdot(1-\delta Z_h)\ ,\end{aligned}$$

with

$$\begin{aligned}\delta Z_W &= (8c_{WW})\\ \delta Z_Z &= c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB})\\ \delta Z_A &= s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big)\\ \delta Z_h &= -c_H\quad .\end{aligned}$$

$$\Delta\mathcal{L} = \frac{1}{2}\,\delta Z_{AZ}\,A_{\mu\nu}Z^{\mu\nu}\ ,\qquad \delta Z_{AZ} = s_w c_w\Big((8c_{WW}) - (1-\frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\Big)$$

recap 7: (synergy with LHC) input observables from HL-LHC

$$\frac{\mathrm{BR}(h \to \gamma\gamma)}{\mathrm{BR}(h \to ZZ^*)} \qquad \frac{\mathrm{BR}(h \to \gamma Z)}{\mathrm{BR}(h \to ZZ^*)}$$

turn out to be very useful for constraining c_{WW}, c_{WB}, c_{BB}

$$\boxed{\frac{g^2 c_{WW}}{m_W^2} \Phi^\dagger \Phi W^a_{\mu\nu} W^{a\mu\nu}}$$

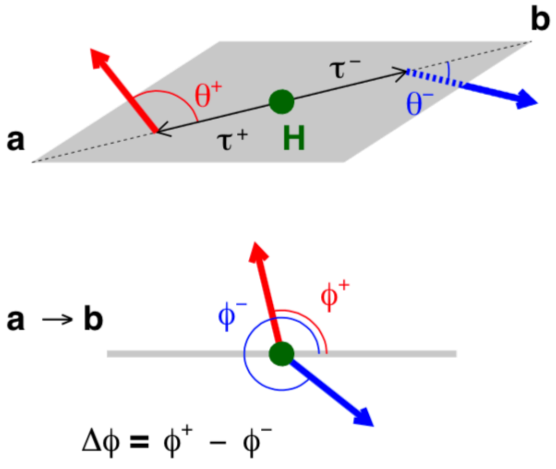
$$\boxed{\frac{4 g g' c_{WB}}{m_W^2} \Phi^\dagger t^a \Phi W^a_{\mu\nu} B^{\mu\nu}}$$

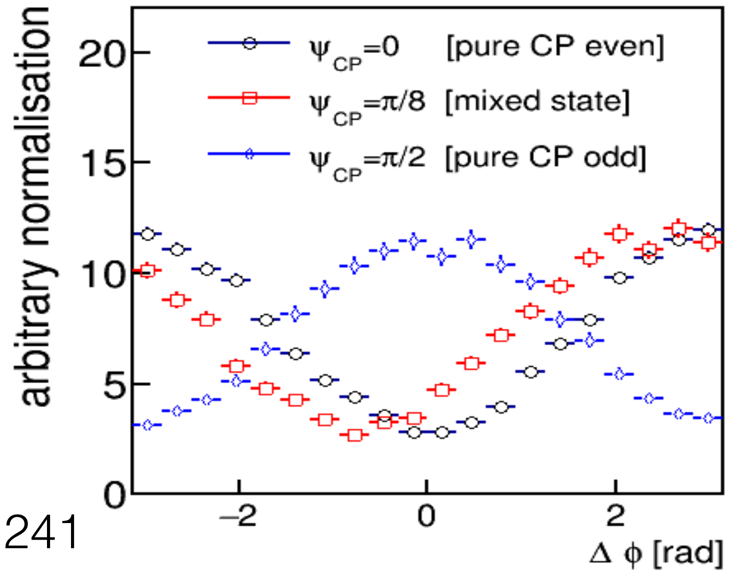
$$\boxed{\frac{g'^2 c_{BB}}{m_W^2} \Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu}}$$

expand the formalism: example adding CP-odd operators

$$L_{Hff} = -\frac{m_f}{v} H \bar{f} (\cos\Phi_{CP} + \underline{i\gamma^5 \sin\Phi_{CP}}) f$$

$$\Delta\Phi_{CP} \sim 4.3^\circ$$



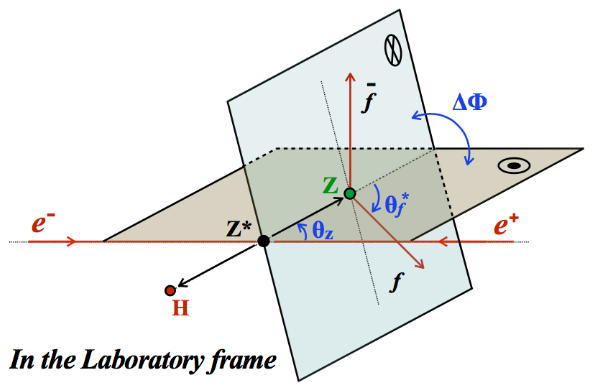


Jeans et al, 1804.01241

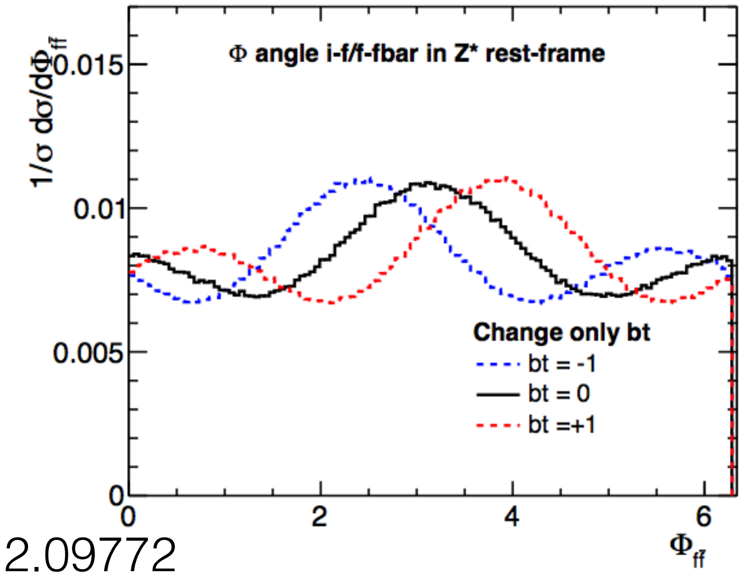
$$L_{hZZ} = M_Z^2 (\frac{1}{v} + \frac{a}{\Lambda}) h Z_\mu Z^\mu + \frac{b}{2\Lambda} h Z_{\mu\nu} Z^{\mu\nu} + \underline{\frac{\tilde{b}}{2\Lambda} h Z_{\mu\nu} \tilde{Z}_{\mu\nu}}$$

$$\Delta\tilde{b} \sim 0.016$$

(Λ=1TeV)



$$e^+ + e^- \to Zh \to f\bar{f}h$$



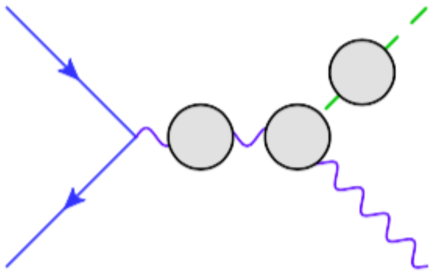
Ogawa, Fujii, JT, 1712.09772

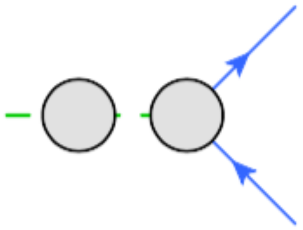
CP-even and CP-odd operators can be separated by $d\sigma/dX$

what happens at next leading order for SMEFT

- at e+e-, NLO ~ O(α), 1% level
- for NLO from W/Z/γ/H, operators constrained to ~<0.01, overall effect will be < 0.1%

- for NLO from top, operators would be much less constrained, currently ~ O(1) -> overall effect 1% -> potential impact in global fit on Higgs coupling precision


WH,ZH


H→bb

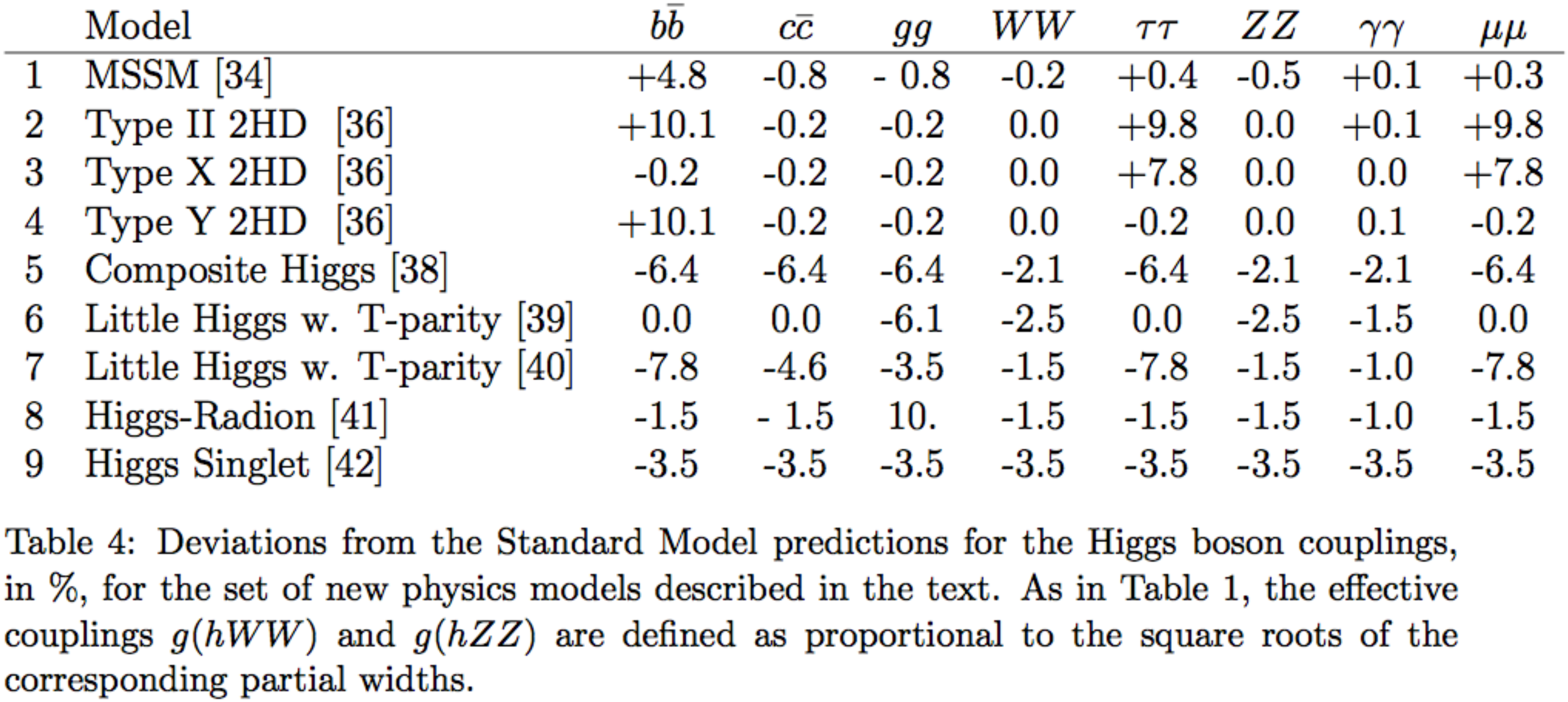
Zhang, et al, arXiv:1804.09766, 1807.02121

Jung, Vos, JT, et al, work in progress -> talk by M.Vos on Thursday

Higgs physics at √s>250 GeV

- vacuum stability: Δm_t=50MeV by top-pair threshold scan at √s~350GeV (with Δm_H=14MeV)
- top-Yukawa coupling: e+e- -> ttH -> δy_t=6-3% at √s~500-550GeV
- vvH production via WW-fusion becomes very powerful
- TGC sensitivities by e+e- -> WW significantly higher: ~ s/m2W
- more sensitive to anomalous HZZ coupling in e+e- -> ZH
- **triple Higgs self-coupling measurement at √s>=500GeV**

benchmark BSM models



	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [34]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [36]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [36]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [36]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [38]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [39]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [40]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [41]	-1.5	- 1.5	10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [42]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

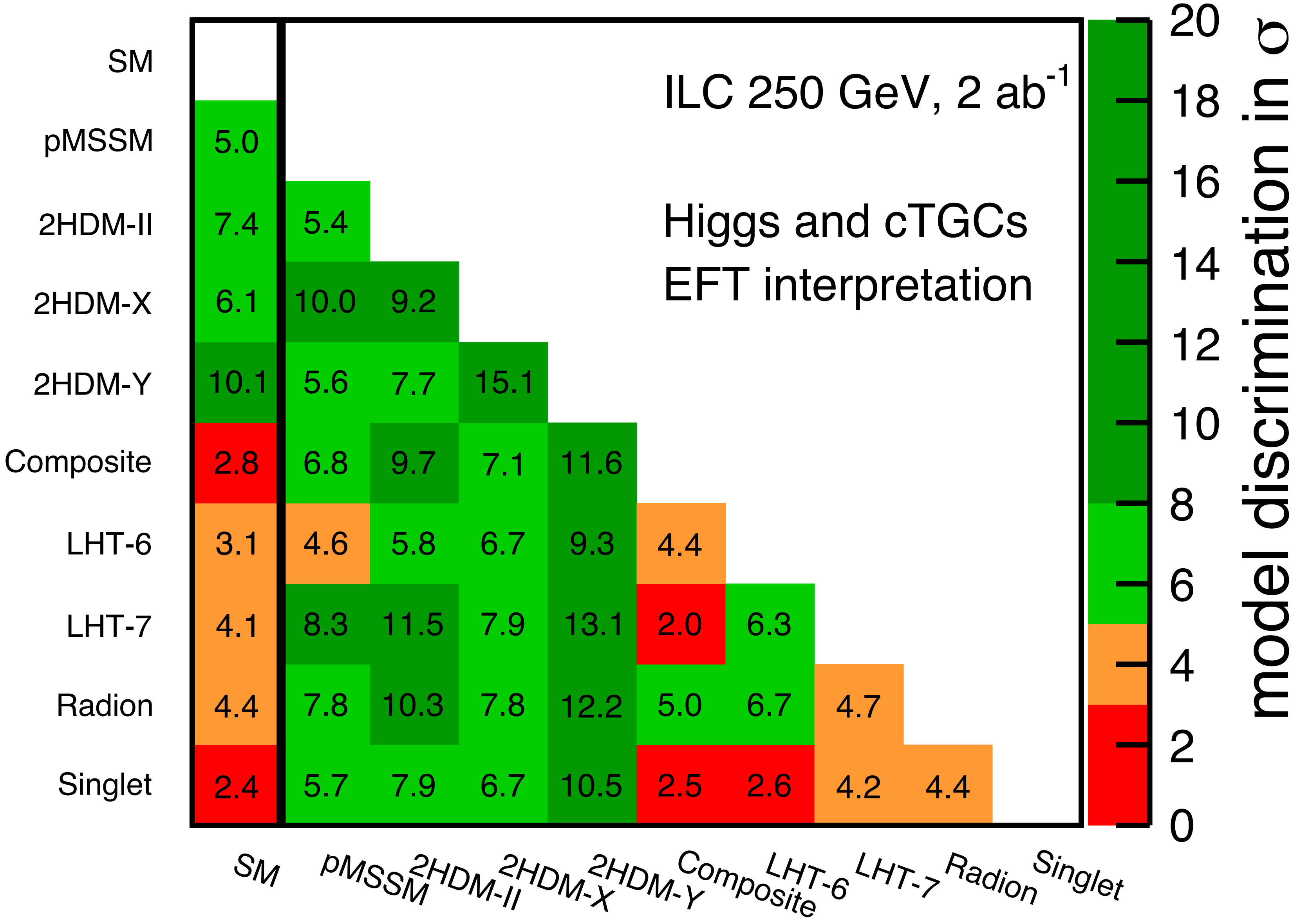
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> quantitative assessment for models discrimination

model parameters (chosen as escaping direct search at HL-LHC)

- a PMSSM model with b squarks at 3.4 TeV, gluino at 4 TeV
- a Type II 2 Higgs doublet model with $m_A = 600 \text{ GeV}, \tan\beta = 7$
- a Type X 2 Higgs doublet model with $m_A = 450 \text{ GeV}, \tan\beta = 6$
- a Type Y 2 Higgs doublet model with $m_A = 600 \text{ GeV}, \tan\beta = 7$
- a composite Higgs model MCHM5 with $f = 1.2 \text{ TeV}, m_T = 1.7 \text{ TeV}$
- a Little Higgs model with T-parity with $f = 785 \text{ GeV}, m_T = 2 \text{ TeV}$
- A Little Higgs model with couplings to 1st and 2nd generation with $f = 1.2 \text{ TeV}, m_T = 1.7 \text{ TeV}$
- A Higgs-radion mixing model with $m_r = 500 \text{ GeV}$
- a model with a Higgs singlet at 2.8 TeV creating a Higgs portal to dark matter and large λ for electroweak baryogenesis

BSM benchmark models discrimination at e+e- (ILC250)



ILC 250 GeV, 2 ab^{-1}

Higgs and cTGCs
EFT interpretation

	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.0									
2HDM-II	7.4	5.4								
2HDM-X	6.1	10.0	9.2							
2HDM-Y	10.1	5.6	7.7	15.1						
Composite	2.8	6.8	9.7	7.1	11.6					
LHT-6	3.1	4.6	5.8	6.7	9.3	4.4				
LHT-7	4.1	8.3	11.5	7.9	13.1	2.0	6.3			
Radion	4.4	7.8	10.3	7.8	12.2	5.0	6.7	4.7		
Singlet	2.4	5.7	7.9	6.7	10.5	2.5	2.6	4.2	4.4	

measure deviations

↓

identify the BSM model

↓

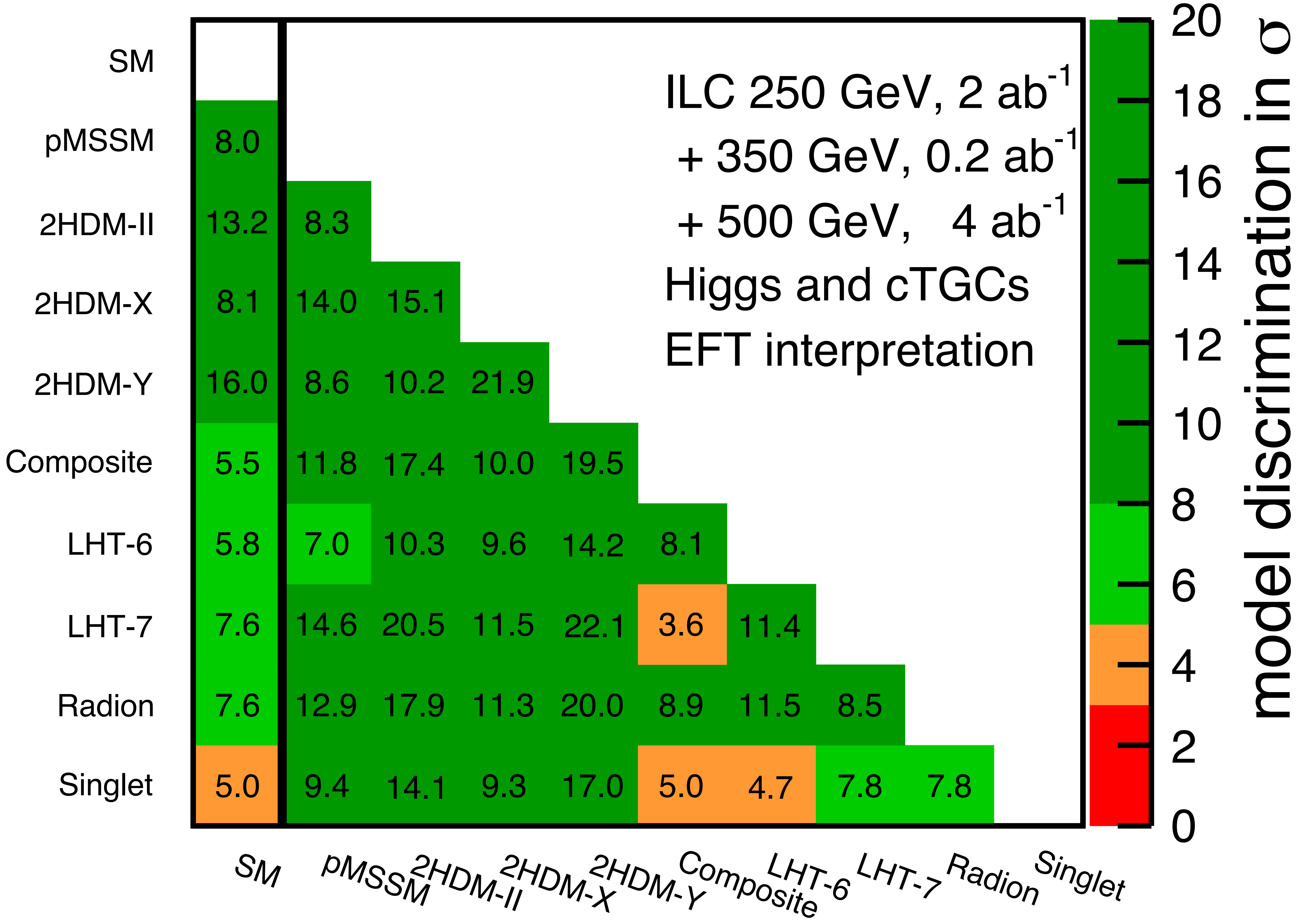
tell the next energy scale

↓

future direction

LCC Physics WG, arXiv: 1710.07621

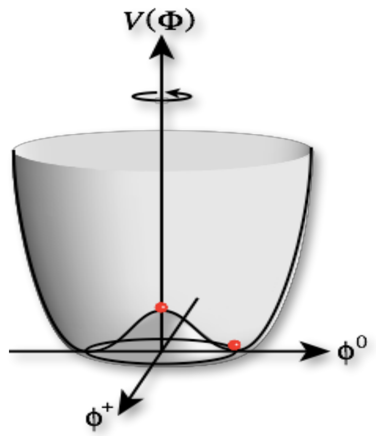
effect of improvement from TGC, ννH, ZH at 500GeV



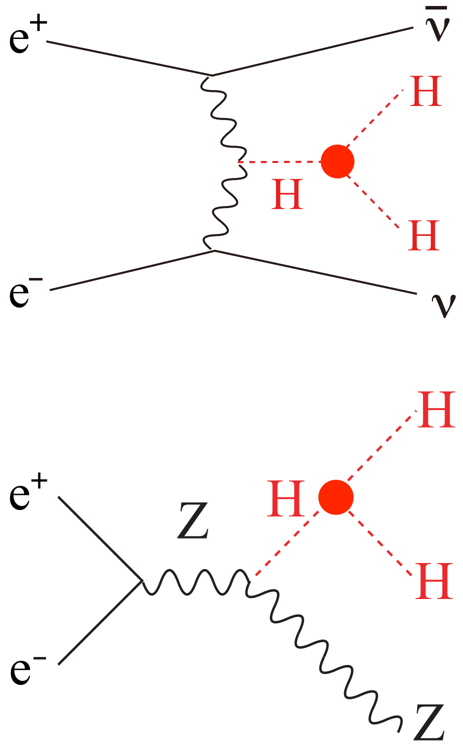
ILC 250 GeV, 2 ab^{-1}
+ 350 GeV, 0.2 ab^{-1}
+ 500 GeV, 4 ab^{-1}
Higgs and cTGCs
EFT interpretation

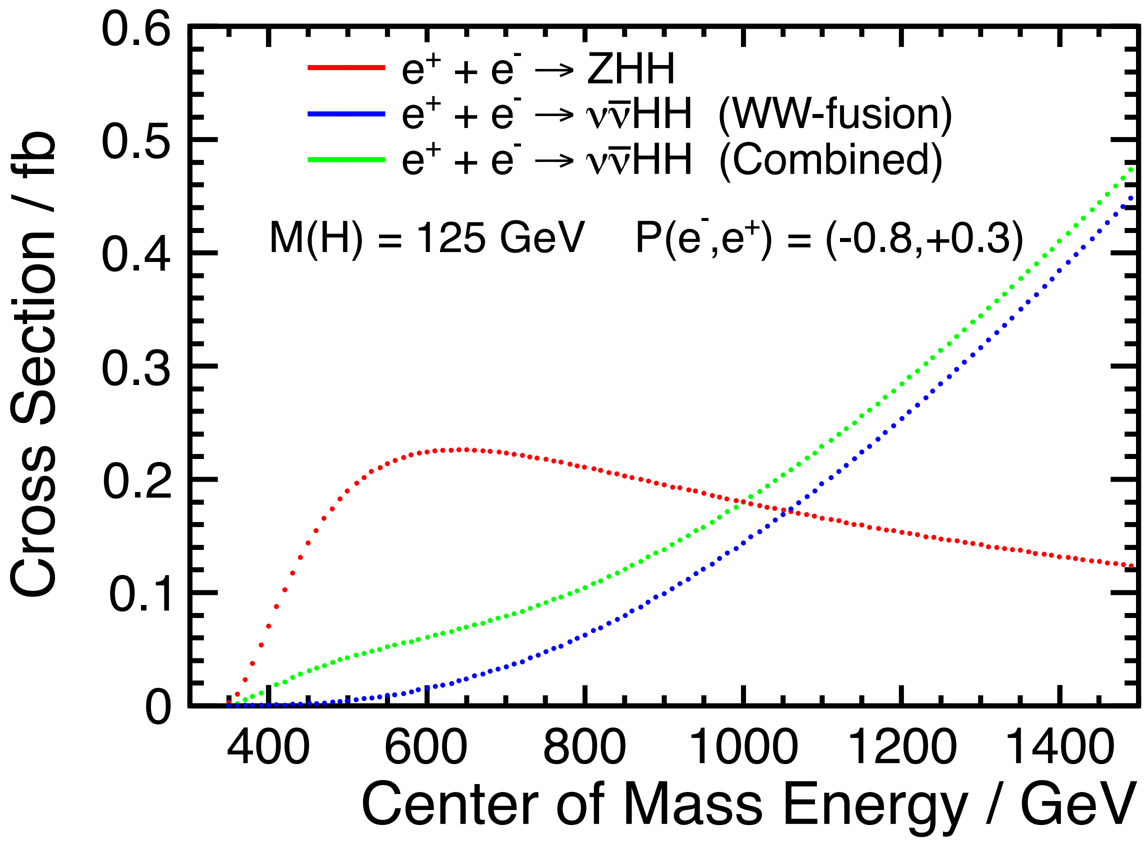
	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	8.0									
2HDM-II	13.2	8.3								
2HDM-X	8.1	14.0	15.1							
2HDM-Y	16.0	8.6	10.2	21.9						
Composite	5.5	11.8	17.4	10.0	19.5					
LHT-6	5.8	7.0	10.3	9.6	14.2	8.1				
LHT-7	7.6	14.6	20.5	11.5	22.1	3.6	11.4			
Radion	7.6	12.9	17.9	11.3	20.0	8.9	11.5	8.5		
Singlet	5.0	9.4	14.1	9.3	17.0	5.0	4.7	7.8	7.8	

Higgs self-coupling



a direct probe of the Higgs potential





ILC: 4 ab^{-1} @ 500 GeV —> 27%

C.Duerig, DESY-Thesis-2016-027

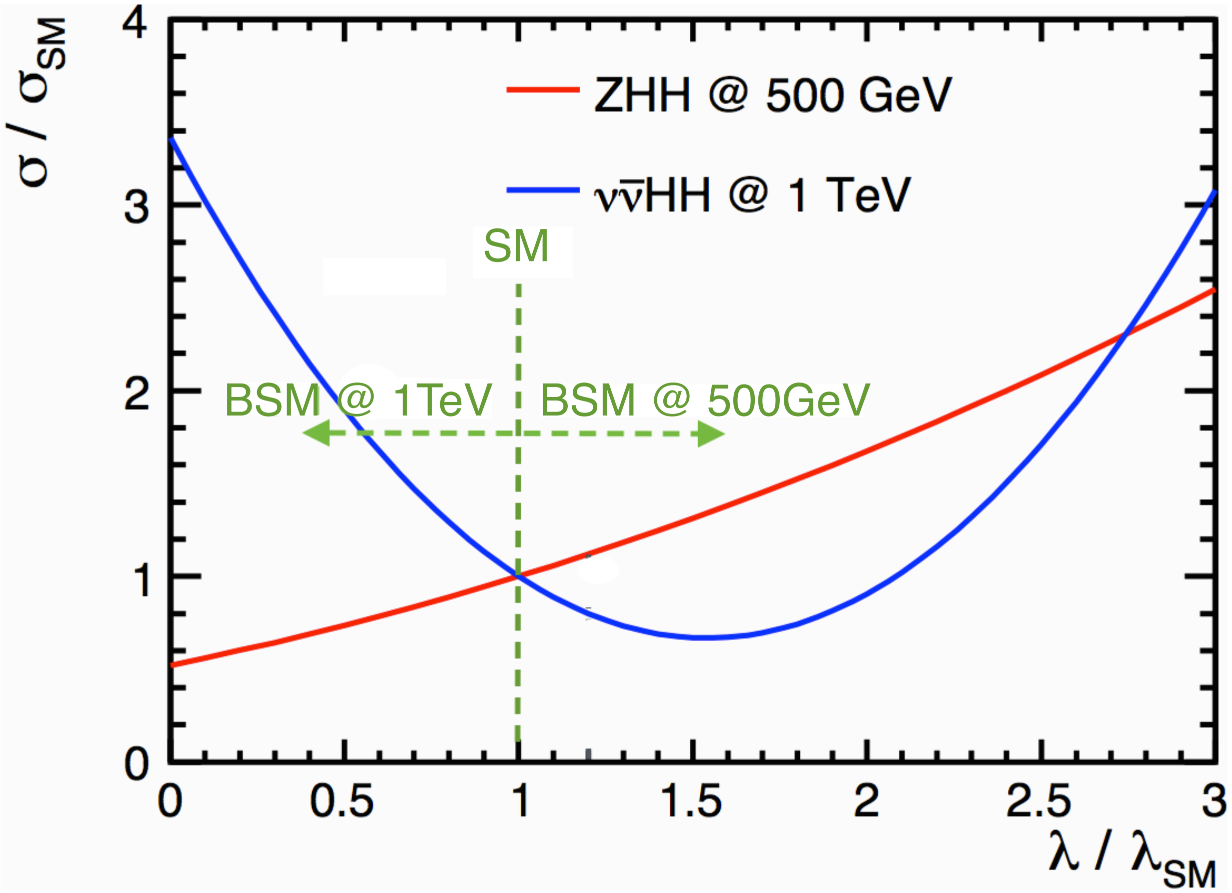
CLIC: 2.5 ab^{-1} @ 1.4TeV + 5 ab^{-1}@ 3TeV —> 13%

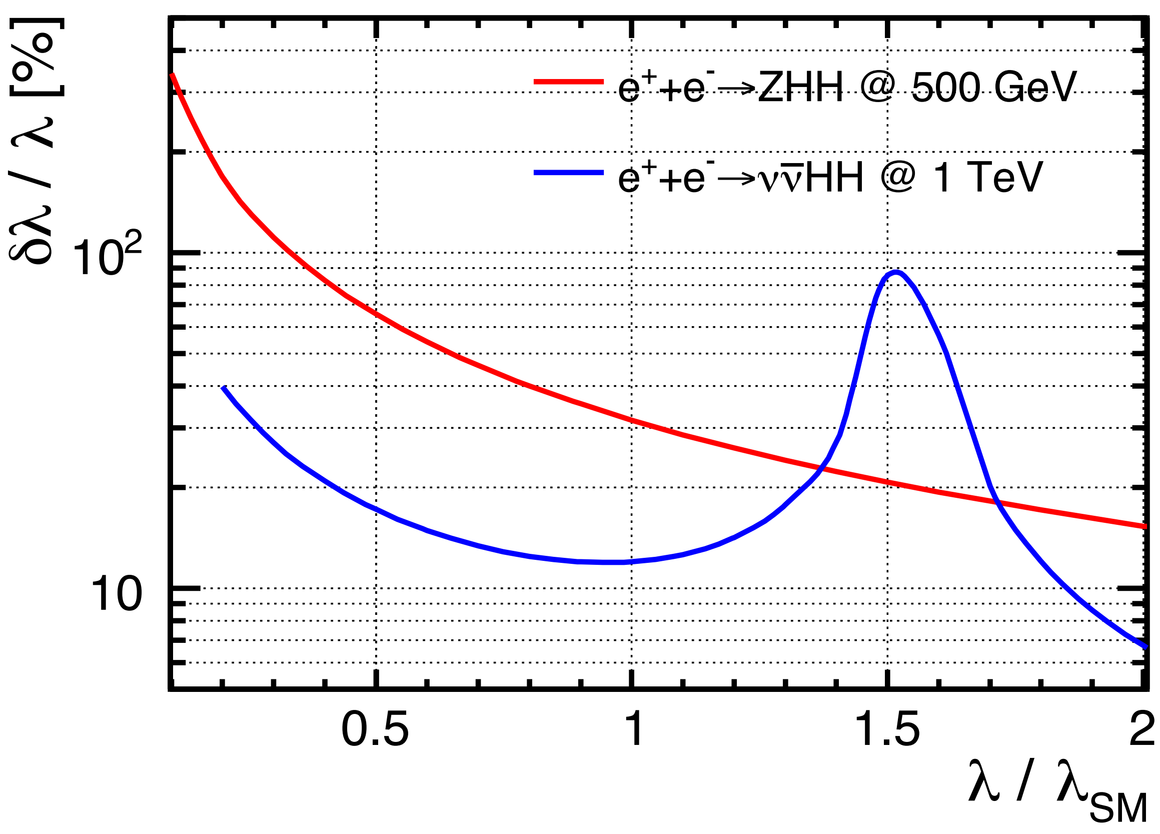
P.Roroff @ HH Workshop, 2018

Higgs self-coupling: when $\lambda_{HHH} \neq \lambda_{SM}$?

- λ_{HHH} can be enhanced significantly in BSM
- complementarity between ZHH & vvHH (& LHC): interferences different
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be measured to ~15% using ZHH at 500 GeV e+e-

Duerig, JT, et al, paper in preparation

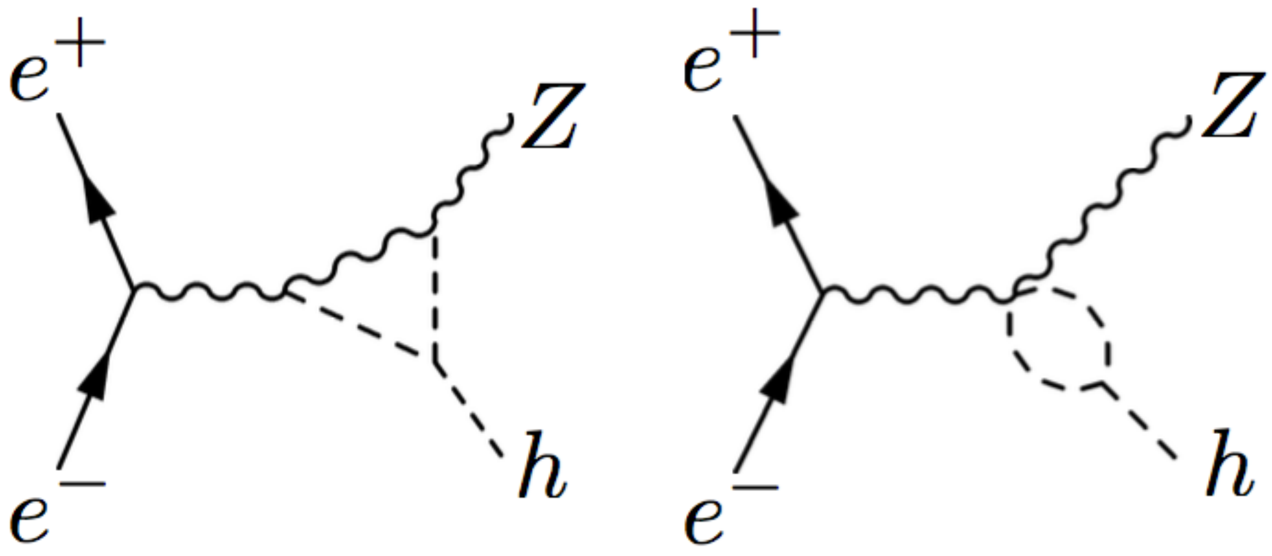




references for large deviations

e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

Higgs self-coupling: indirect determination

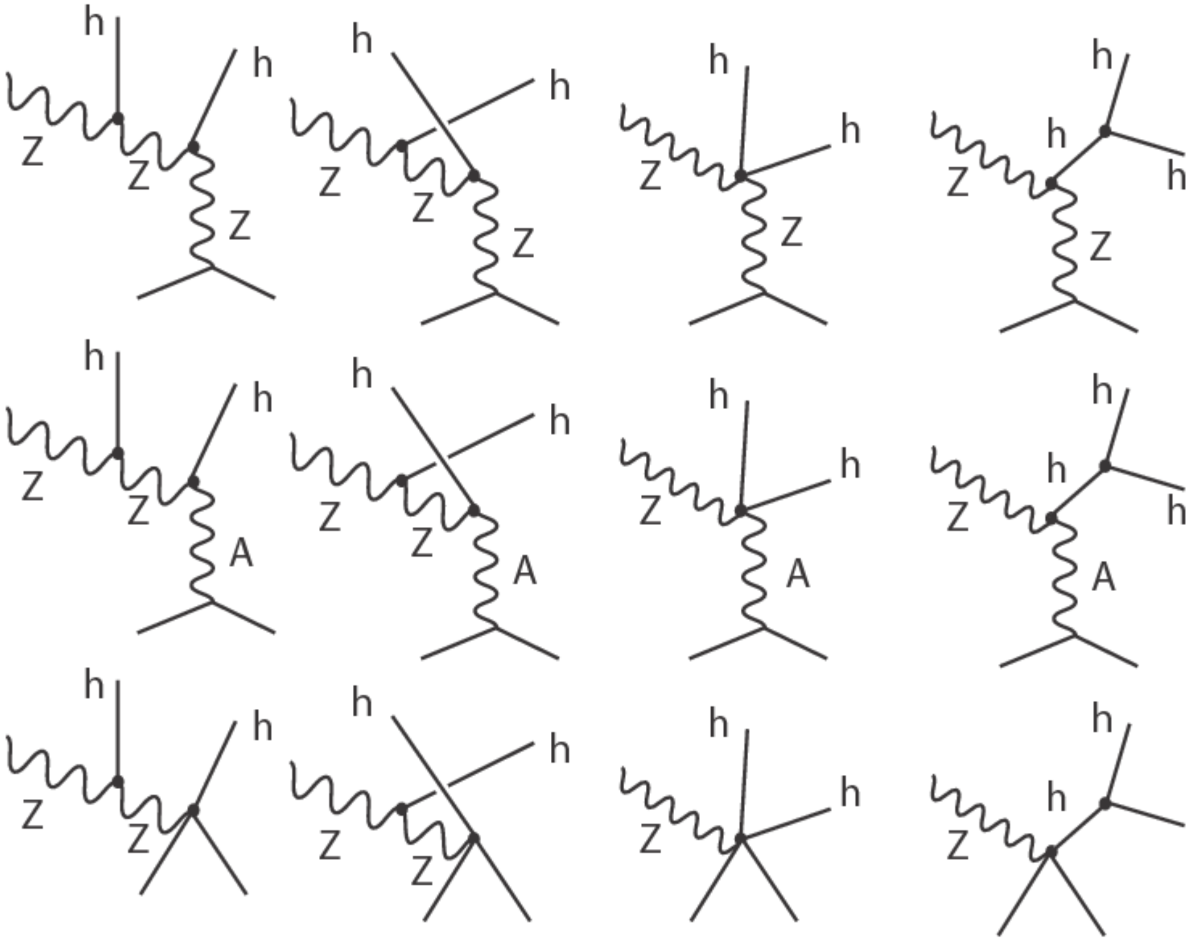


McCullough, arXiv:1312.3322

$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- if only δh is deviated —> δh ~ 28%
- if both δz and δh deviated —> δh ~ 90%
- δσ could receive contributions from many other sources
  - —> **δh ~ 500%** at 250GeV only; Gu, Liu, et al, arXiv:1711.03978
- what if we also include other NLO effects as well?

Higgs self-coupling: systematic errors

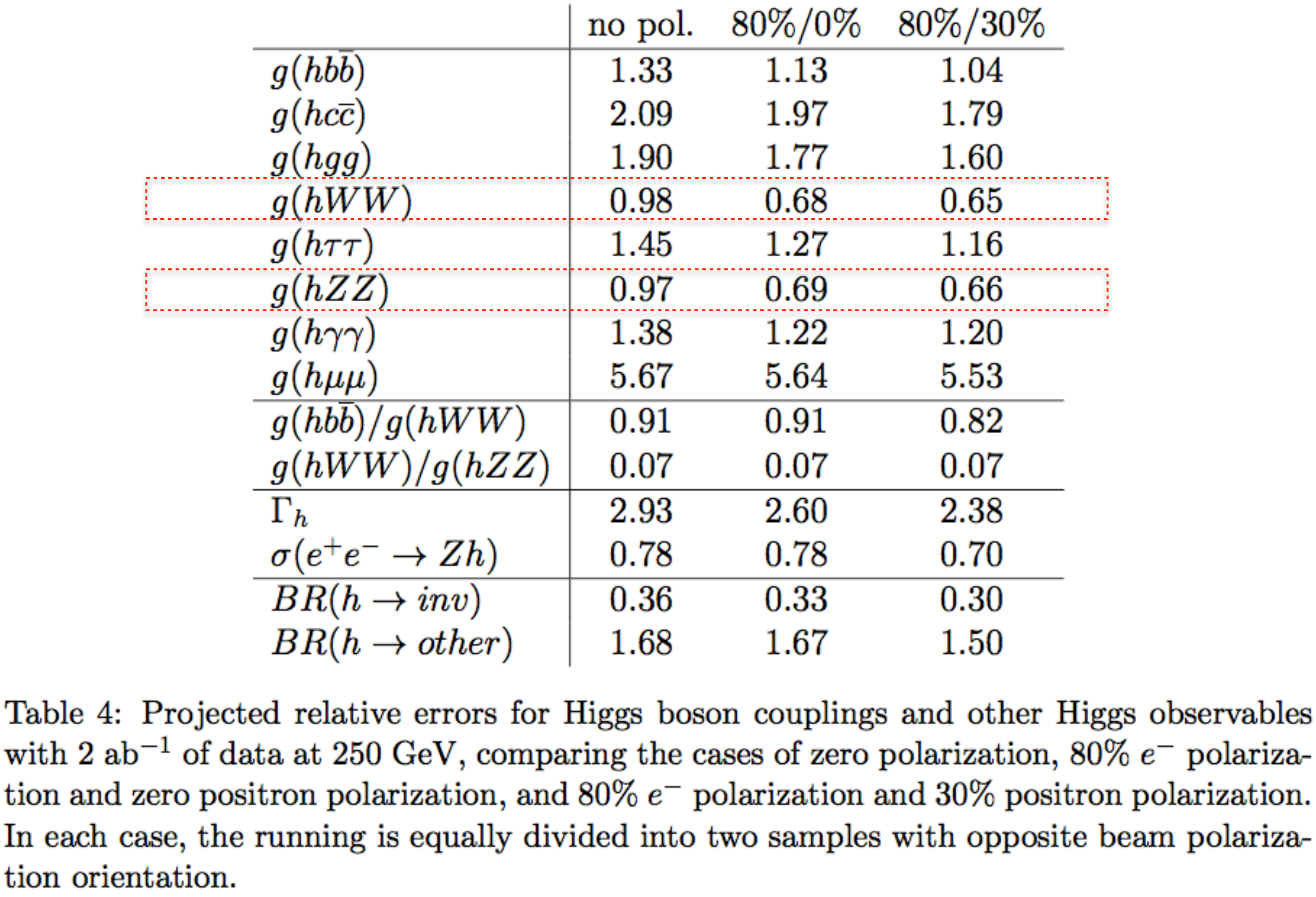


e+e- -> ZHH @ general models

Barklow, Fujii, Jung, Peskin, Tian
arXiv:1708.09079

- σ(HH+X) depends on many couplings other than λ_{HHH}
- σ(e+e- ->ZHH) receives 5% systematic error from uncertainties of other couplings, which are measured at e+e- at 1% level
- in the same spirit, are we sure about the prospect of 5% $\delta\lambda_{HHH}$ at 100 TeV pp collider?

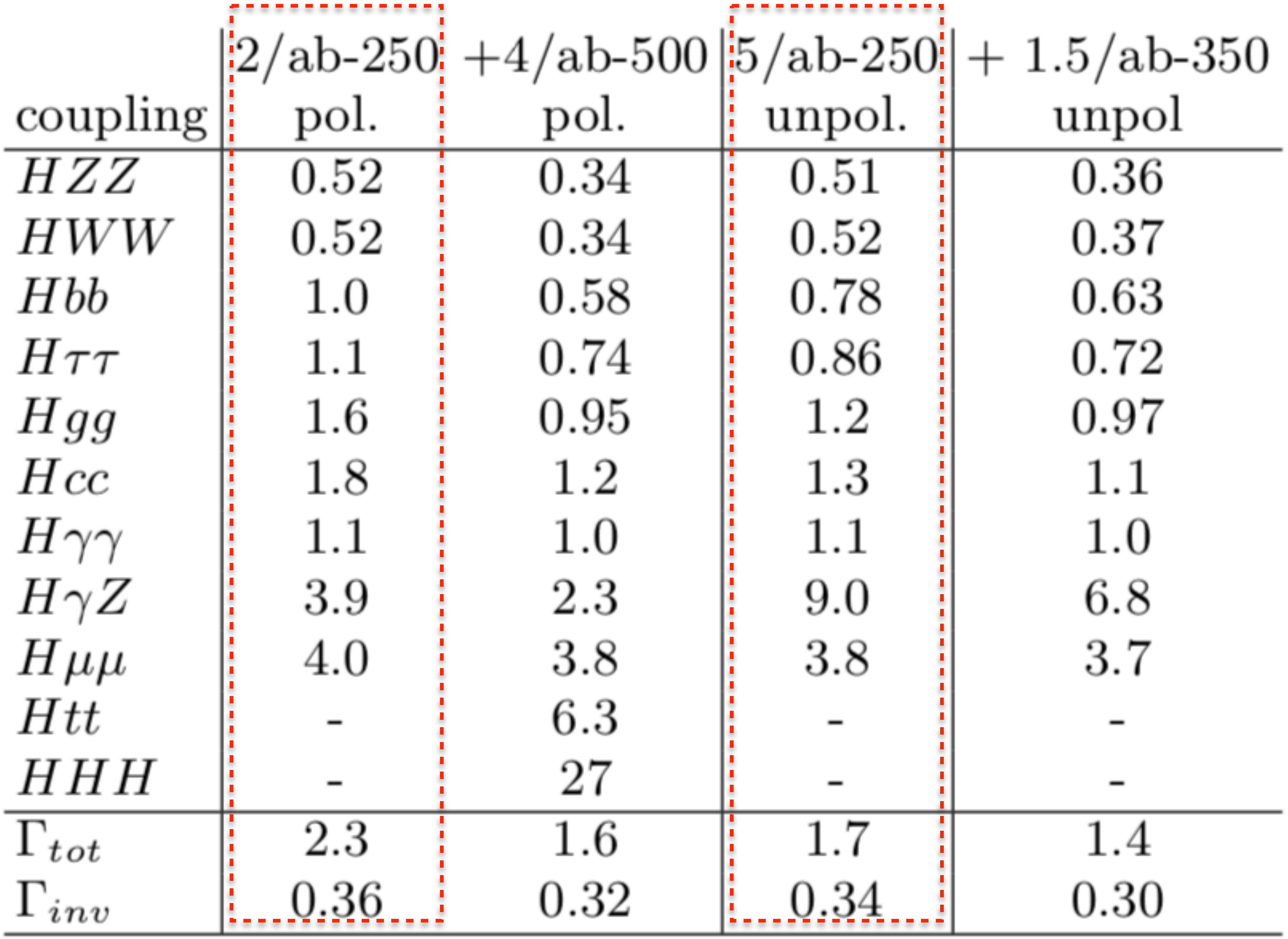
comments on beam polarizations



	no pol.	80%/0%	80%/30%
$g(hb\bar{b})$	1.33	1.13	1.04
$g(hc\bar{c})$	2.09	1.97	1.79
$g(hgg)$	1.90	1.77	1.60
$g(hWW)$	0.98	0.68	0.65
$g(h\tau\tau)$	1.45	1.27	1.16
$g(hZZ)$	0.97	0.69	0.66
$g(h\gamma\gamma)$	1.38	1.22	1.20
$g(h\mu\mu)$	5.67	5.64	5.53
$g(hb\bar{b})/g(hWW)$	0.91	0.91	0.82
$g(hWW)/g(hZZ)$	0.07	0.07	0.07
Γ_h	2.93	2.60	2.38
$\sigma(e^+e^- \to Zh)$	0.78	0.78	0.70
$BR(h \to inv)$	0.36	0.33	0.30
$BR(h \to other)$	1.68	1.67	1.50

Table 4: Projected relative errors for Higgs boson couplings and other Higgs observables with 2 ab^{-1} of data at 250 GeV, comparing the cases of zero polarization, 80% e^- polarization and zero positron polarization, and 80% e^- polarization and 30% positron polarization. In each case, the running is equally divided into two samples with opposite beam polarization orientation.

recap 6: power of beam polarizations at the ILC

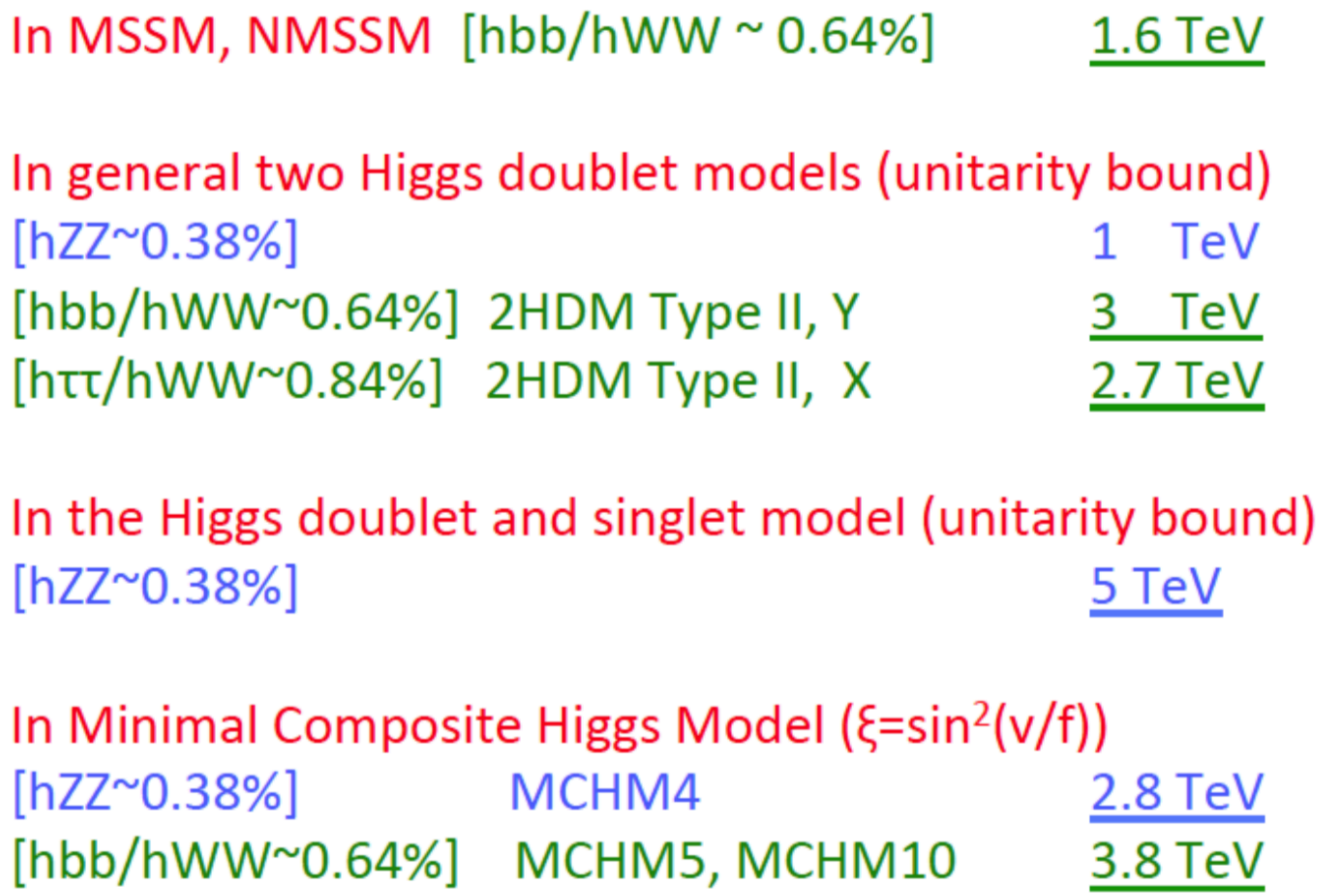


coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.52	0.34	0.51	0.36
HWW	0.52	0.34	0.52	0.37
Hbb	1.0	0.58	0.78	0.63
$H\tau\tau$	1.1	0.74	0.86	0.72
Hgg	1.6	0.95	1.2	0.97
Hcc	1.8	1.2	1.3	1.1
$H\gamma\gamma$	1.1	1.0	1.1	1.0
$H\gamma Z$	3.9	2.3	9.0	6.8
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.7	1.4
Γ_{inv}	0.36	0.32	0.34	0.30

(ILC Supporting Document for European Strategy Update; to be published soon)

- with improved EWPOs at Z-pole

then the next energy scales would be known: reachable 2~3 TeV



In MSSM, NMSSM [hbb/hWW ~ 0.64%] 1.6 TeV

In general two Higgs doublet models (unitarity bound)
[hZZ~0.38%] 1 TeV
[hbb/hWW~0.64%] 2HDM Type II, Y 3 TeV
[hττ/hWW~0.84%] 2HDM Type II, X 2.7 TeV

In the Higgs doublet and singlet model (unitarity bound)
[hZZ~0.38%] 5 TeV

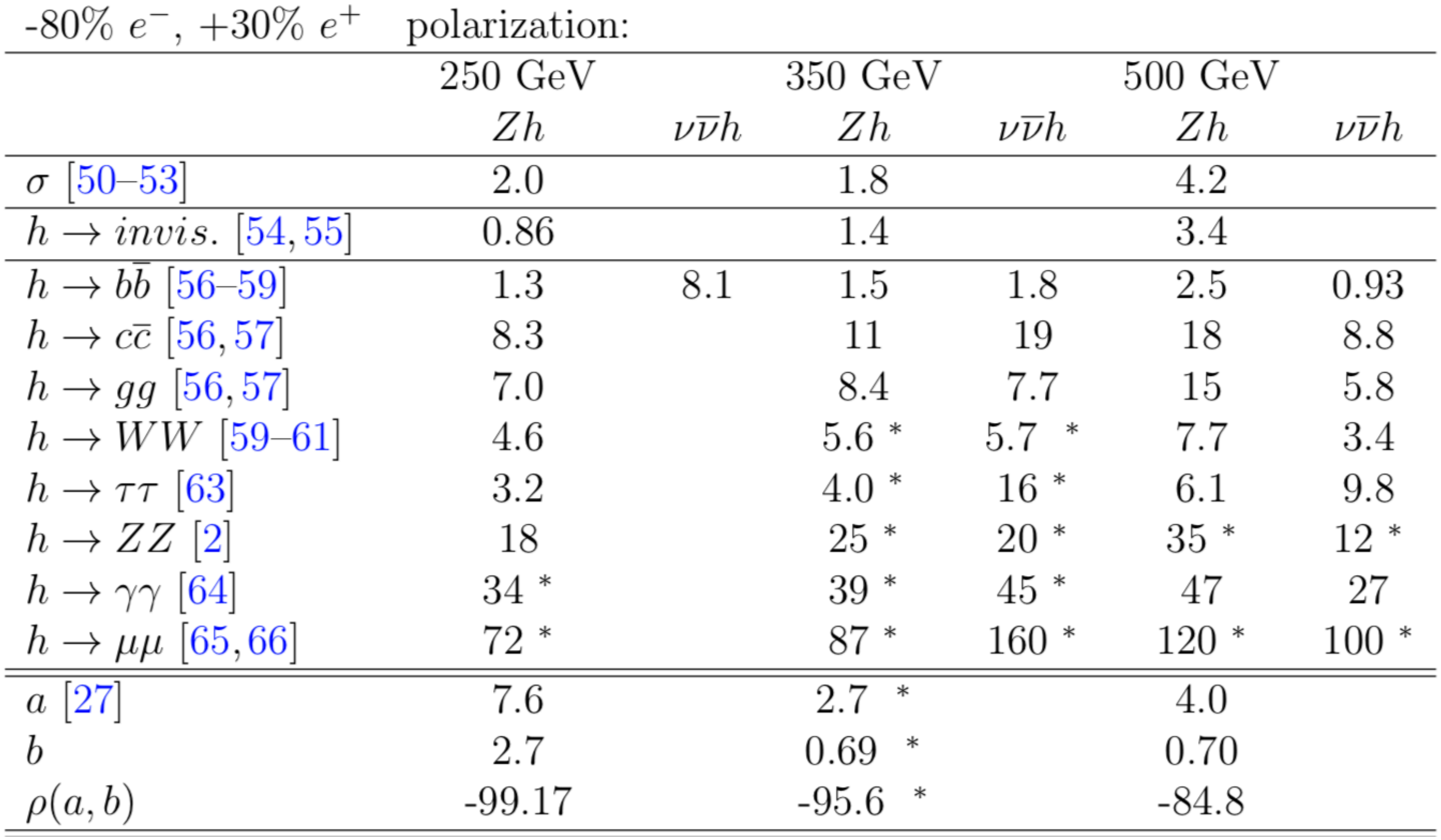
In Minimal Composite Higgs Model ($\xi=\sin^2(v/f)$)
[hZZ~0.38%] MCHM4 2.8 TeV
[hbb/hWW~0.64%] MCHM5, MCHM10 3.8 TeV

Calculation done using the results from arXiv:1705.05399.

Endo, Kanemura, et al

EFT input from Higgs observables at ILC

(based on full detector simulations for ILD and SiD)



-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 [50–53]	2.0		1.8		4.2	
$h \to invis.$ [54, 55]	0.86		1.4		3.4	
$h \to b\bar{b}$ [56–59]	1.3	8.1	1.5	1.8	2.5	0.93
$h \to c\bar{c}$ [56, 57]	8.3		11	19	18	8.8
$h \to gg$ [56, 57]	7.0		8.4	7.7	15	5.8
$h \to WW$ [59–61]	4.6		5.6 *	5.7 *	7.7	3.4
$h \to \tau\tau$ [63]	3.2		4.0 *	16 *	6.1	9.8
$h \to ZZ$ [2]	18		25 *	20 *	35 *	12 *
$h \to \gamma\gamma$ [64]	34 *		39 *	45 *	47	27
$h \to \mu\mu$ [65, 66]	72 *		87 *	160 *	120 *	100 *
a [27]	7.6		2.7 *		4.0	
b	2.7		0.69 *		0.70	
$\rho(a, b)$	-99.17		-95.6 *		-84.8	

(arXiv: 1708.08912; numbers are in %, for nominal ∫Ldt = 250 fb^{-1})

+ another set for P(e-,e+)=(+80%,-30%)

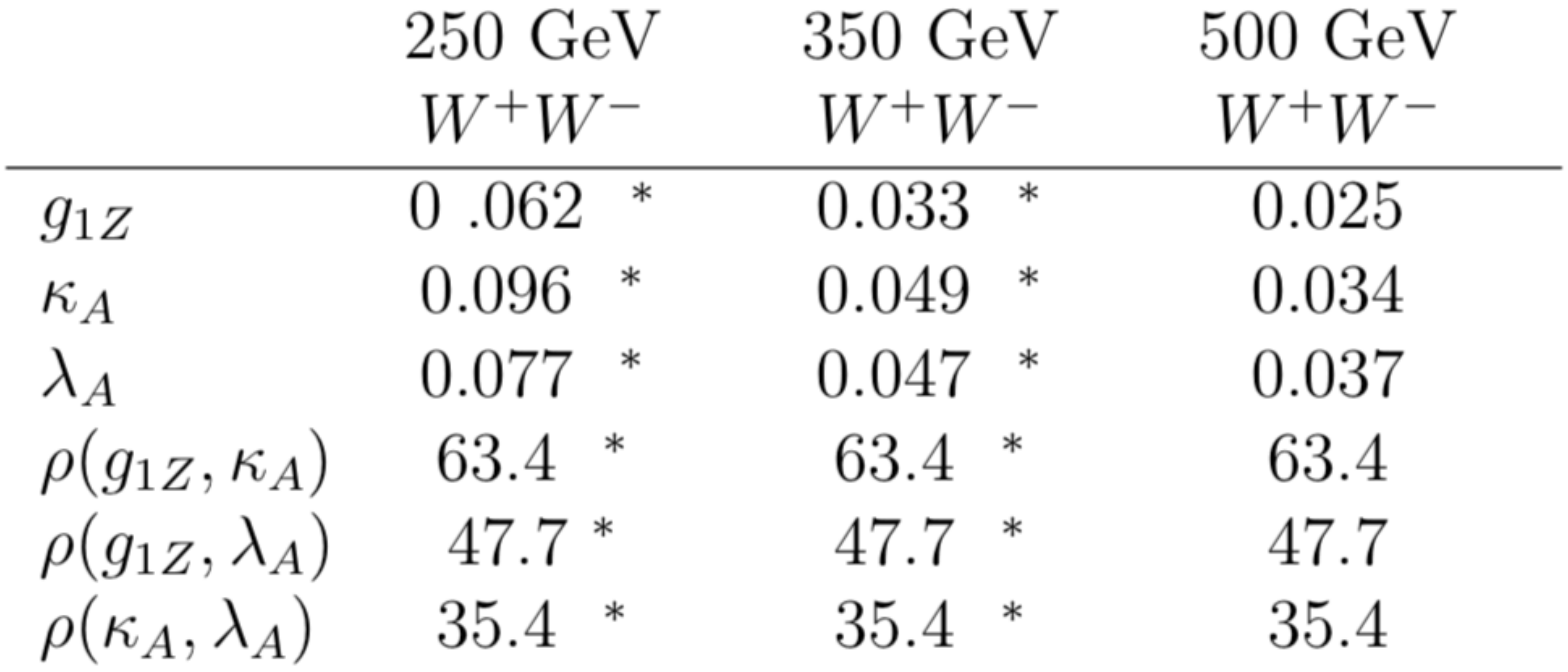
systematic errors included in the global fit

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

improvement factors in S2

- 10% from better jet-clustering algorithm
- 20% from better flavor-tagging algorithm
- 20% from including more signal channels in h->WW*
- x10 better for A_{LR} using e+e- -> γ Z at ILC250

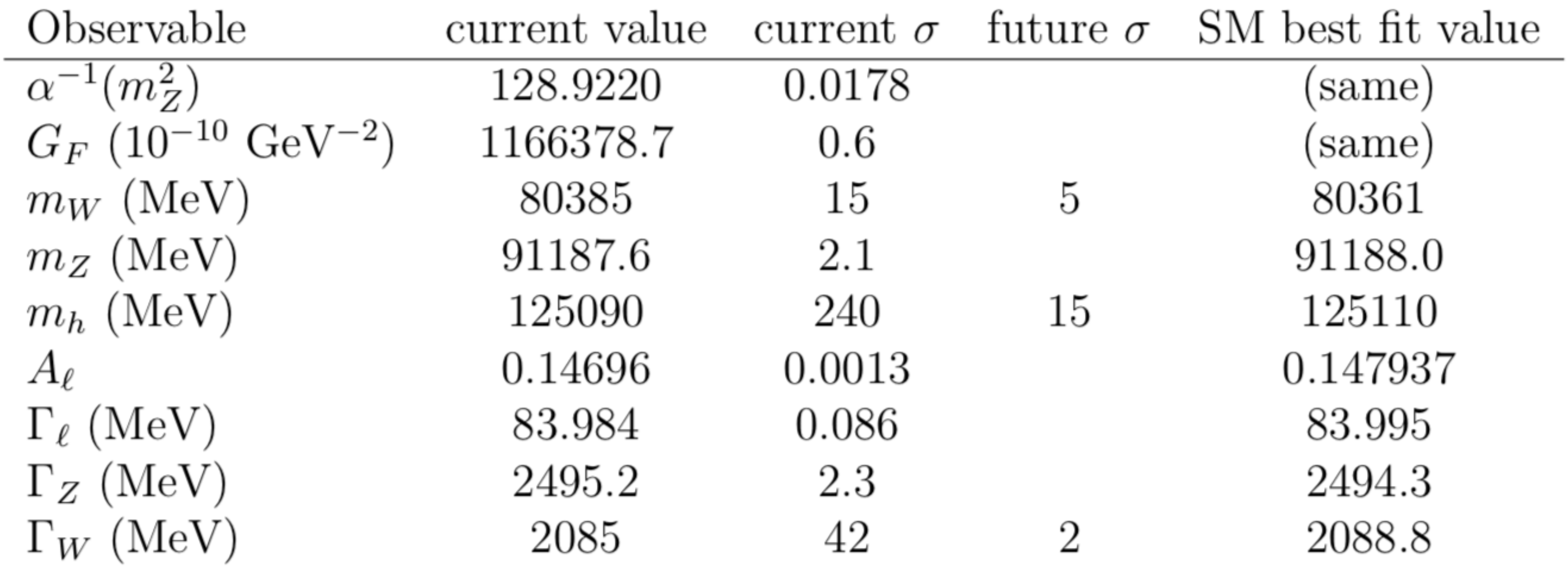
EFT input from TGCs in e+e- -> W^+W^-



	250 GeV W^+W^-	350 GeV W^+W^-	500 GeV W^+W^-
g_{1Z}	0 .062 *	0.033 *	0.025
κ_A	0.096 *	0.049 *	0.034
λ_A	0.077 *	0.047 *	0.037
$\rho(g_{1Z}, \kappa_A)$	63.4 *	63.4 *	63.4
$\rho(g_{1Z}, \lambda_A)$	47.7 *	47.7 *	47.7
$\rho(\kappa_A, \lambda_A)$	35.4 *	35.4 *	35.4

(arXiv: 1708.08912; numbers are in %, for nominal $\int$Ldt = 500 fb^{-1} shared equally by left-/right- polarized data)

EFT input: EWPOs



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)	80385	15	5	80361
m_Z (MeV)	91187.6	2.1		91188.0
m_h (MeV)	125090	240	15	125110
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

EFT input: EWPOs (7)

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

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

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

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

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

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

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

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

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

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

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

EFT input: EWPOs (7)

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

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

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

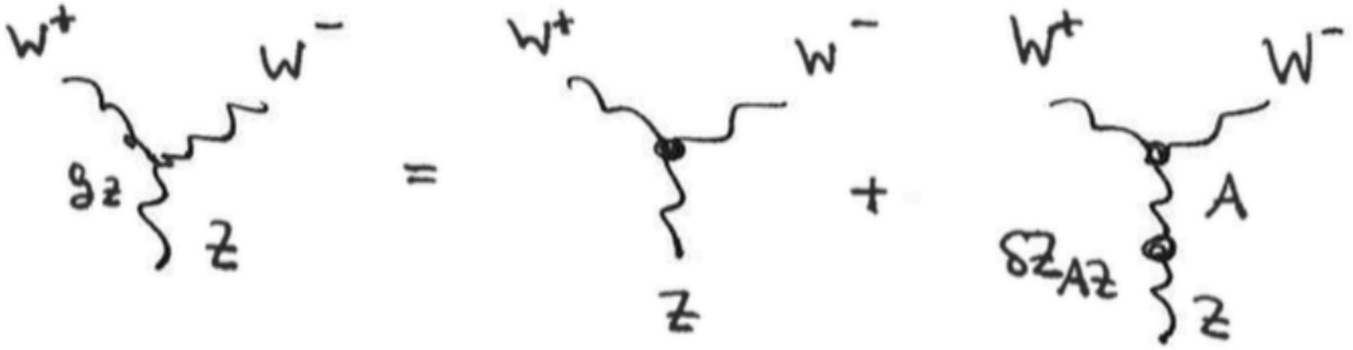
$$g_L = \frac{g}{c_w}\left[(-\frac{1}{2} + s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}(c_{HL} + c'_{HL}) - s_w c_w \delta Z_{AZ}\right]$$

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

$\longrightarrow$ $c_{HL}+c'_{HL}$, c_{HE}

EFT input: TGC (3)

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

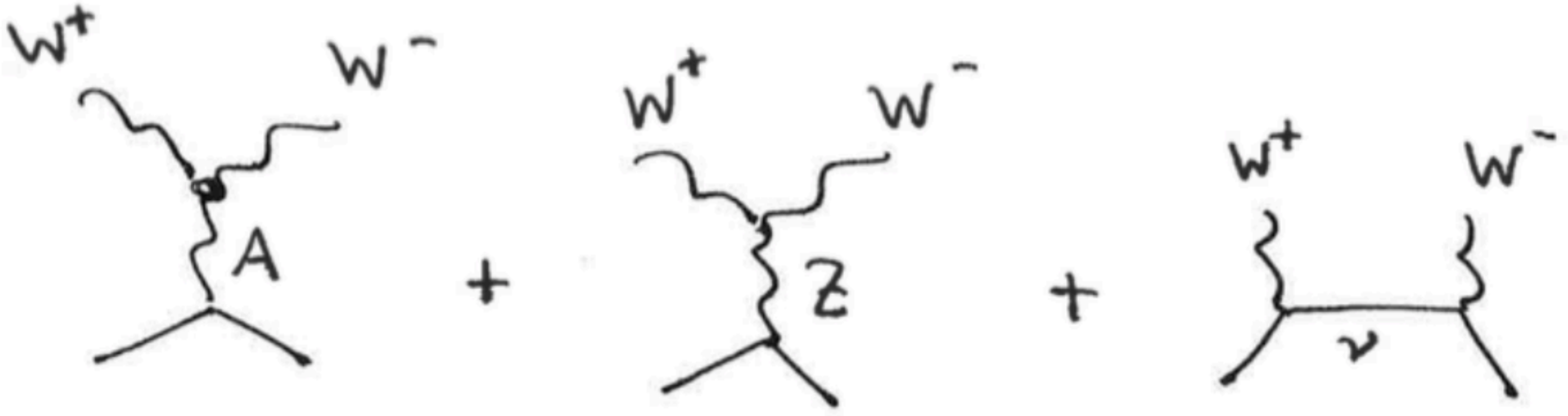


$$g_Z = g c_w \left(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ}\right)$$

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

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

EFT input: TGC (3)



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

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

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

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

EFT input: BR(h->γγ)/BR(h->ZZ*), BR(h->γZ)/BR(h->ZZ*)

(2: HL-LHC)

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

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

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

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

EFT coefficients

10: c_H, c_T, c_6, c_{WW}, c_{WB}, c_{BB}, c_{3W}, c_{HL}, c'_{HL}, c_{HE}

+ 4: g, g’, v, λ

can already be determined,
except c_6, c_H

—> Higgs observables @ e+e-

EFT input: σ(e+e- —>Zh), σ(e+e- —> Zhh)

- c_H has to be determined by inclusive σ_{Zh} measurement
- c_6 has to be determined by double Higgs measurement

EFT input: BR(h—>XX)

$$\Delta\mathcal{L} = -c_{\tau\Phi}\frac{y_\tau}{v^2}(\Phi^\dagger\Phi)\overline{L}_3\cdot\Phi\tau_R + h.c.$$

- h couplings to b, c, τ, μ, g

$$\delta\mathcal{L} = \mathcal{A}\frac{h}{v}G_{\mu\nu}G^{\mu\nu}$$

- Γ(h->invisible), total decay width

note: beam polarizations provide several independent (redundant) set of σ,σxBR input, which are powerful to test EFT validity

two more parameters: C_W, C_Z for $\Gamma(h\to WW^*)$ and $\Gamma(h\to ZZ^*)$

$$\Gamma/(SM) = 1 + 2\eta_W - 2\delta v - 11.7\delta m_W + 13.6\delta m_h$$
$$-0.75\zeta_W - 0.88 C_W + 1.06\delta\Gamma_W \ ,$$

$$C_W = \sum_X c'_X \mathcal{N}_X \ / \ \sum_X \mathcal{N}_X \ ,$$

(c'_X: contact interactions)

EFT input:

$$\Gamma_W = \frac{g^2 m_W}{48\pi}\left(\sum_X \mathcal{N}_X\right)\cdot(1 + 2\delta g + \delta m_W + \delta Z_W + 2C_W)$$

(similar for Z)