The global SMEFT fit at e+e- Higgs factories: what is the role of each measurement?

arXiv:1708.09079, 1708.08912;
+ paper in preparation

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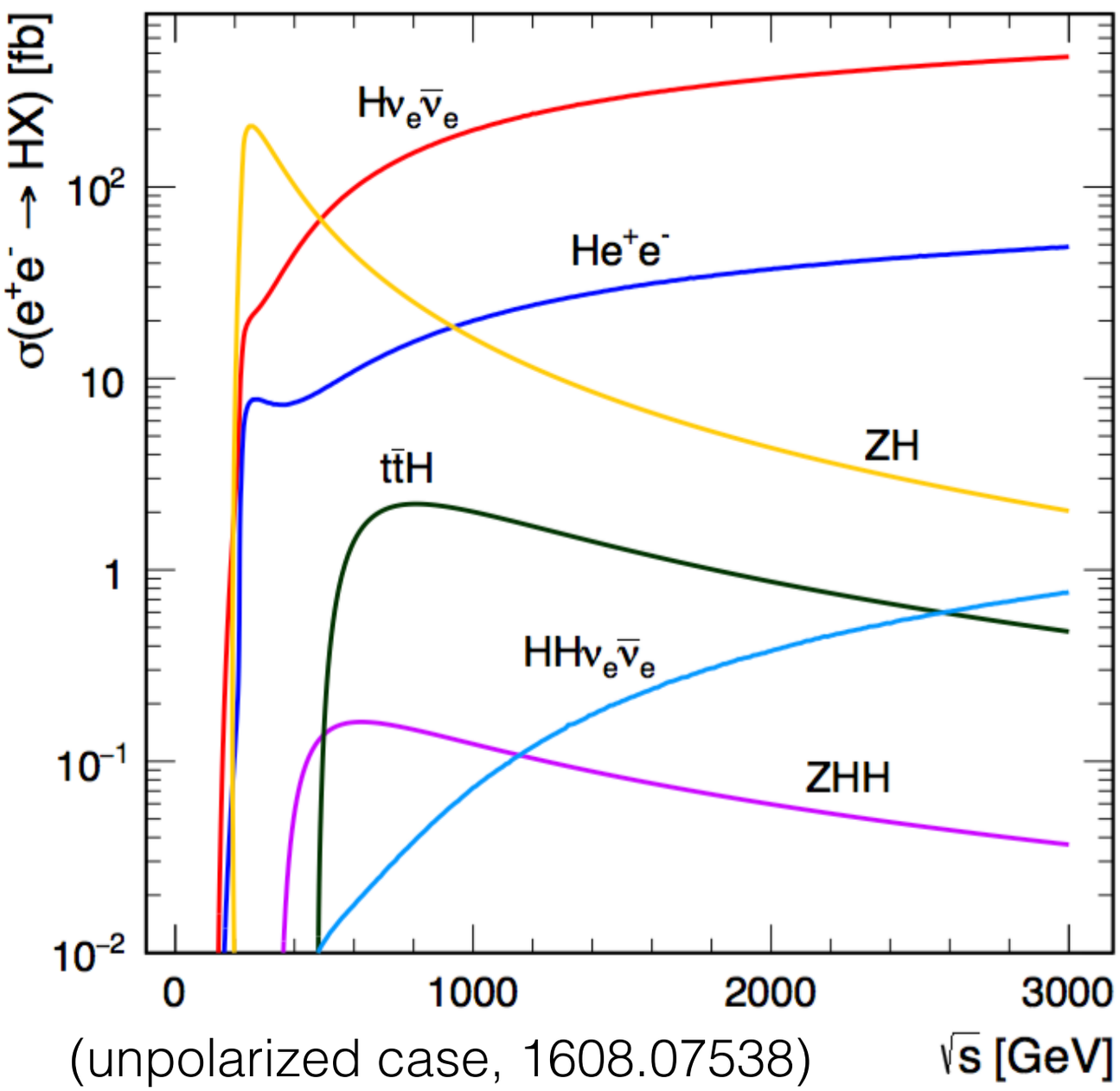
proposals of future lepton colliders

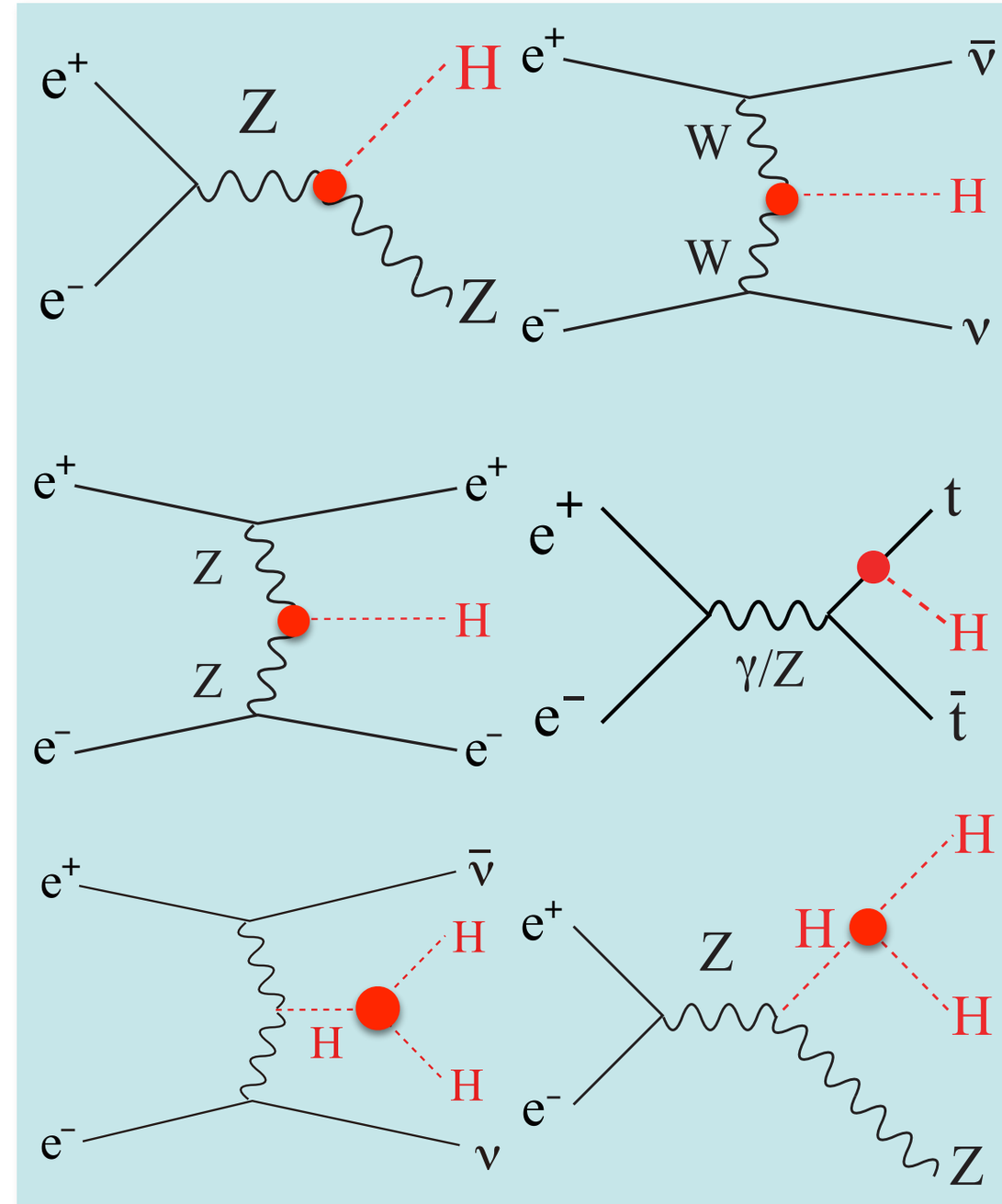
	$\sqrt{s}$	beam polarisation	$\int Ldt$ for Higgs	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2000 fb^{-1} @ 250 GeV 200 fb^{-1} @ 350 GeV 4000 fb-1 @ 500 GeV 8000 fb-1 @ 1 TeV	TDR
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	500 fb^{-1} @ 380 GeV 1500 fb^{-1} @ 1.4 TeV 2500 fb^{-1} @ 3 TeV	CDR
CEPC	90 - 240 GeV	e-: 0% e+: 0%	5600 fb^{-1} @ 240 GeV	CDR
FCC-ee	90 - 365 GeV	e-: 0% e+: 0%	5000 fb^{-1} @ 240 GeV 1500 fb^{-1} @ 365 GeV	CDR

common: Higgs factory with $O(10^6)$ Higgs events

Higgs productions at e+e-



(unpolarized case, 1608.07538)



- two apparent important thresholds: √s ~ **250** GeV for ZH, ~**500** GeV for ZHH and ttH
- + another threshold for t t-bar, important for vacuum stability

Higgs coupling determination — kappa formalism

1) recoil mass technique —> inclusive $\boldsymbol{\sigma_{Zh}}$

2) σ_{Zh} —> $\boldsymbol{\kappa_Z}$ —> $\Gamma(h\text{->}ZZ^*)$

3) W-fusion $\nu_e\nu_e h$ —> $\boldsymbol{\kappa_W}$ —> $\Gamma(h\text{->}WW^*)$

4) total width $\boldsymbol{\Gamma_h} = \Gamma(h\text{—>}ZZ^*)/BR(h\text{->}ZZ^*)$

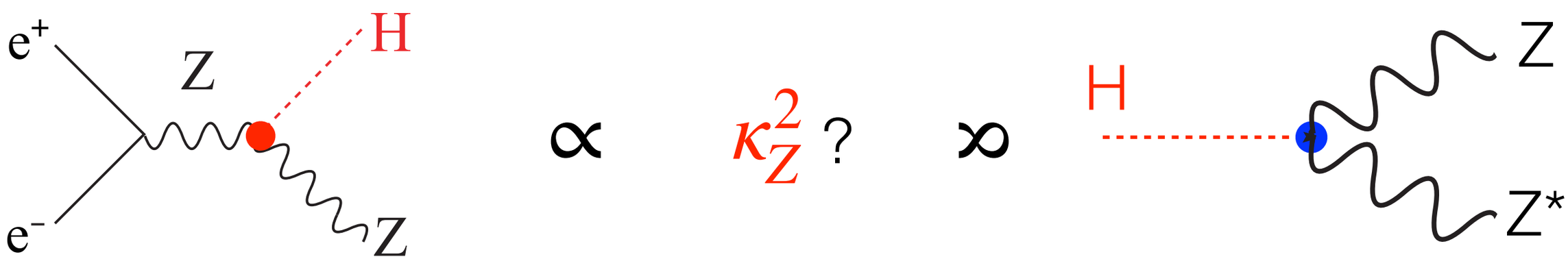
5) or $\boldsymbol{\Gamma_h} = \Gamma(h\text{—>}WW^*)/BR(h\text{->}WW^*)$

6) then all other couplings $BR(h\text{->}XX) * \Gamma_h$ -> $\boldsymbol{\kappa_X}$

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

one question in kappa formalism:

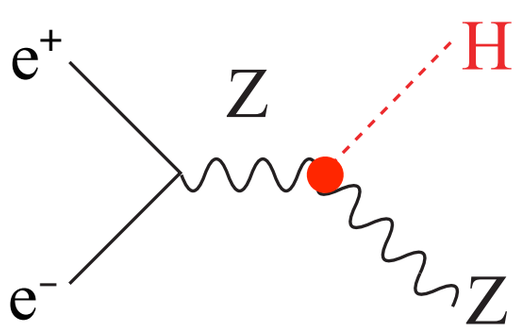
$$\frac{\sigma(e^+e^- \to Zh)}{SM} = \frac{\Gamma(h \to ZZ^*)}{SM} = \kappa_Z^2 \qquad ?$$

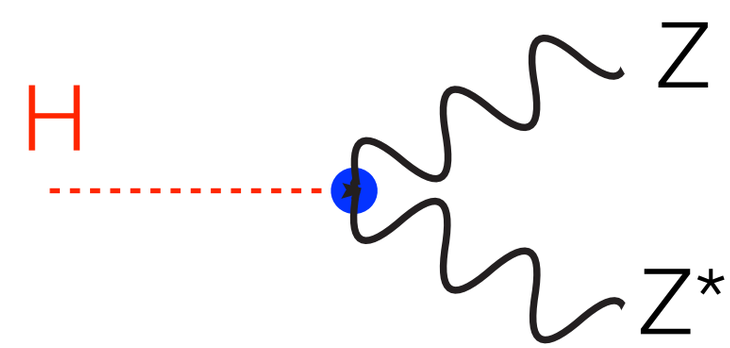


BSM territory: can deviations be represented by single κ_Z?

the answer is model dependent

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





$$\sigma(e^+e^- \to Zh) = (SM)\cdot$$

$$(1+2\eta_Z+(5.5)\zeta_Z)$$

$$\neq$$

$$\Gamma(h \to ZZ^*) = (SM)\cdot$$

$$(1+2\eta_Z-(0.50)\zeta_Z)$$

- BSM can induce new Lorentz structures in hZZ
- need a better, more theoretical sound framework

new 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
- most general effects from BSM represented
- respect SU(3)xSU(2)xU(1) gauge symmetries
- a consistent quantum field theory unifying BSM effects in Higgs, W/Z, top, 2-fermion physics

SM Effective Field Theory: some simplifications

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

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

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 B & L number conservation, there are ***59***

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

SM Effective Field Theory @ e+e-

(Barklow, Fujii, Jung, Peskin, JT, arXiv:1708.09079)

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

Φ: higgs field
W, B: SU(2), U(1) gauge
L, e: left/right electron

- 10 operators modifying couplings for h/Z/W/γ
- in total, 23 parameters (see later slides)

next: highlight a few important implications

recap 1: 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

$$h \longrightarrow (1\text{-}c_H/2)h$$

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

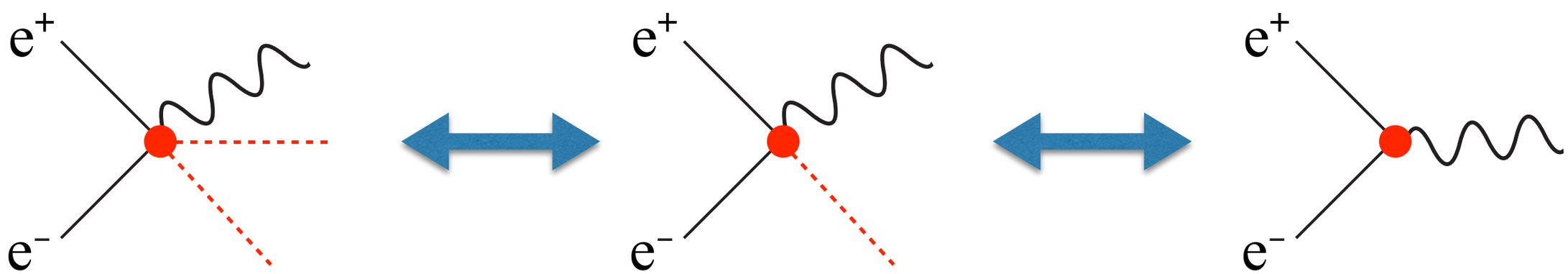
- c_H can not be determined by any BR or ratio of couplings

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

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

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

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

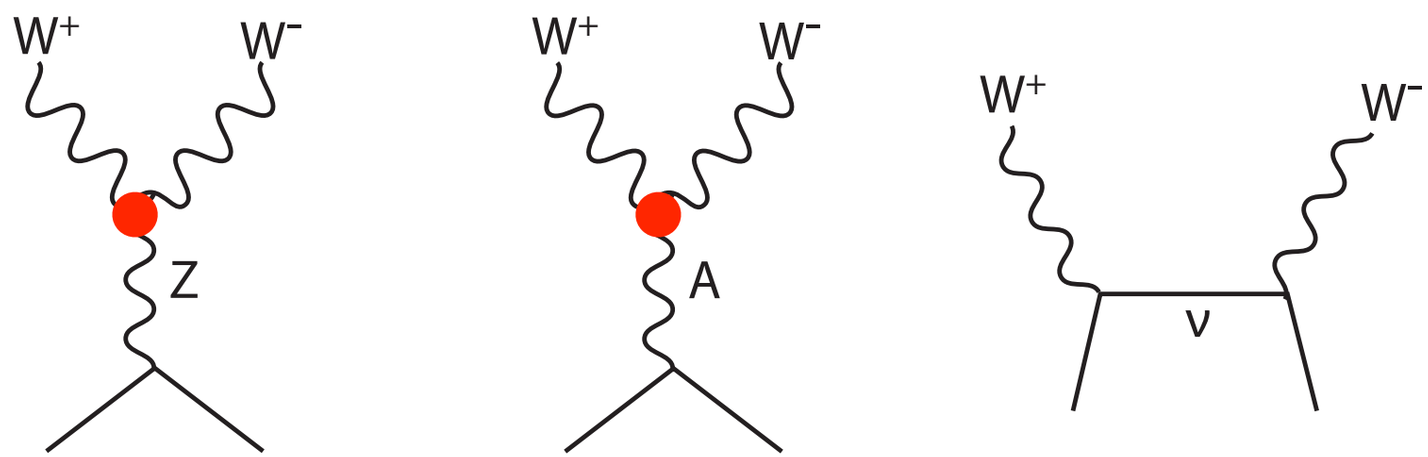


e^+e^- ->Zhh e^+e^- ->Zh Z-pole

- Higgs coupling helped by EWPOs at Z-pole: $\boldsymbol{A_{LR}}$, $\boldsymbol{\Gamma_l}$
- Z coupling helped by Higgs meas. at high $\sqrt{s}$: $\boldsymbol{\delta\sigma \sim s/m^2_Z}$

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

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



- longitudinal modes of W/Z are from Higgs fields
- higgs coupling helped by meas. of TGCs in e+e- -> WW

recap 3: Higgs couplings are related to themselves

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

(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 3: Higgs couplings are related to themselves (synergy w/ LHC)

two measurements from LHC (model independent)

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

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

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

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

- loop induced h->γγ/γZ depend strongly on $c_{WW}/c_{WB}/c_{BB}$
- h->γγ/γZ at LHC can nicely help higgs couplings at e+e-

recap 3: Higgs couplings are related to themselves (hWW/hZZ)

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

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

SM-like hVV

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

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

custodial symmetry is broken by c_T -> 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%

- very important for physics case of any 250 GeV e+e-
- hWW can be determined as precisely as hZZ at 250 GeV; hence precision total width & other couplings

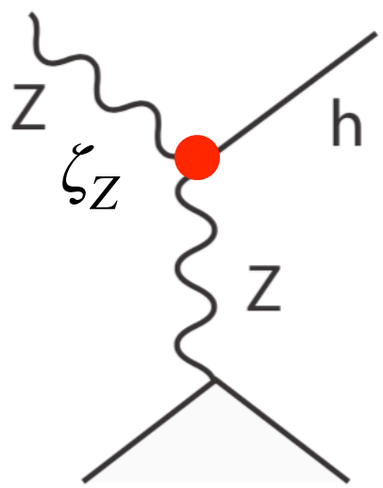
SMEFT fit: typical difference with kappa fit

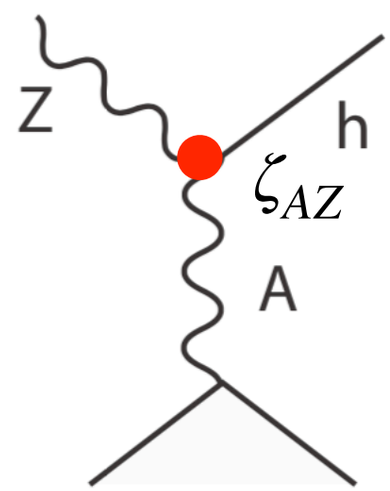
ILC250: $\int Ldt = 2\ ab^{-1}$ @ 250 GeV

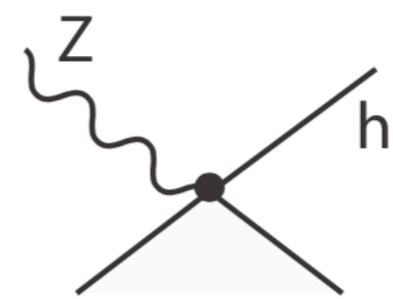
coupling $\Delta g/g$	kappa-fit	EFT-fit
hZZ	0.38%	0.50%
hWW	1.8%	0.50%
hbb	1.8%	0.99%
Γ_h	3.9%	2.3%

(definition for higgs coupling precision: 1/2 of partial width precision)

recap 4: role of beam polarizations







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

- sensitive to different couplings -> lift degeneracy
- A_{LR} in σ_{ZH} -> improve c_{WW}, c_{HL}+c_{HL}' and c_{HE}
- large cancellation in **(+1,-1)** -> weaker dependence on c_{WW}

recap 4: role of beam polarizations (e+e- -> Zh)

$\sqrt{s}$=250 GeV

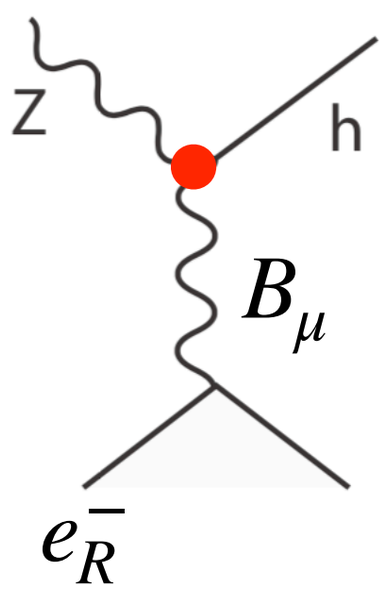
$$\delta\sigma_L = -c_H + 7.7(8c_{WW}) + \ldots$$

$$\delta\sigma_R = -c_H + 0.6(8c_{WW}) + \ldots$$

$$\delta\sigma_0 = -c_H + 4.6(8c_{WW}) + \ldots$$

why?

($8c_{WW}$) ~ 0.16% from other meas.



contribution from

almost cancels out

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

up to a difference in Z/γ propagator suppressed by $\frac{m_Z^2}{s}$

recap 4: role of beam polarizations (overall effects)

ILC250: 2 ab^{-1} FCCee240: 5 ab^{-1}

coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
Htt	-	6.3	-	-
HHH	-	27	-	-
Γ_{tot}	2.3	1.6	1.6	1.4
Γ_{inv}	0.36	0.32	0.34	0.30
Γ_{other}	1.6	1.2	1.1	0.94

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

(arXiv:1903.01629)

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

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

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 at e+e-

Electroweak Precision Observables (9)

+

Triple Gauge boson Couplings (3)

+

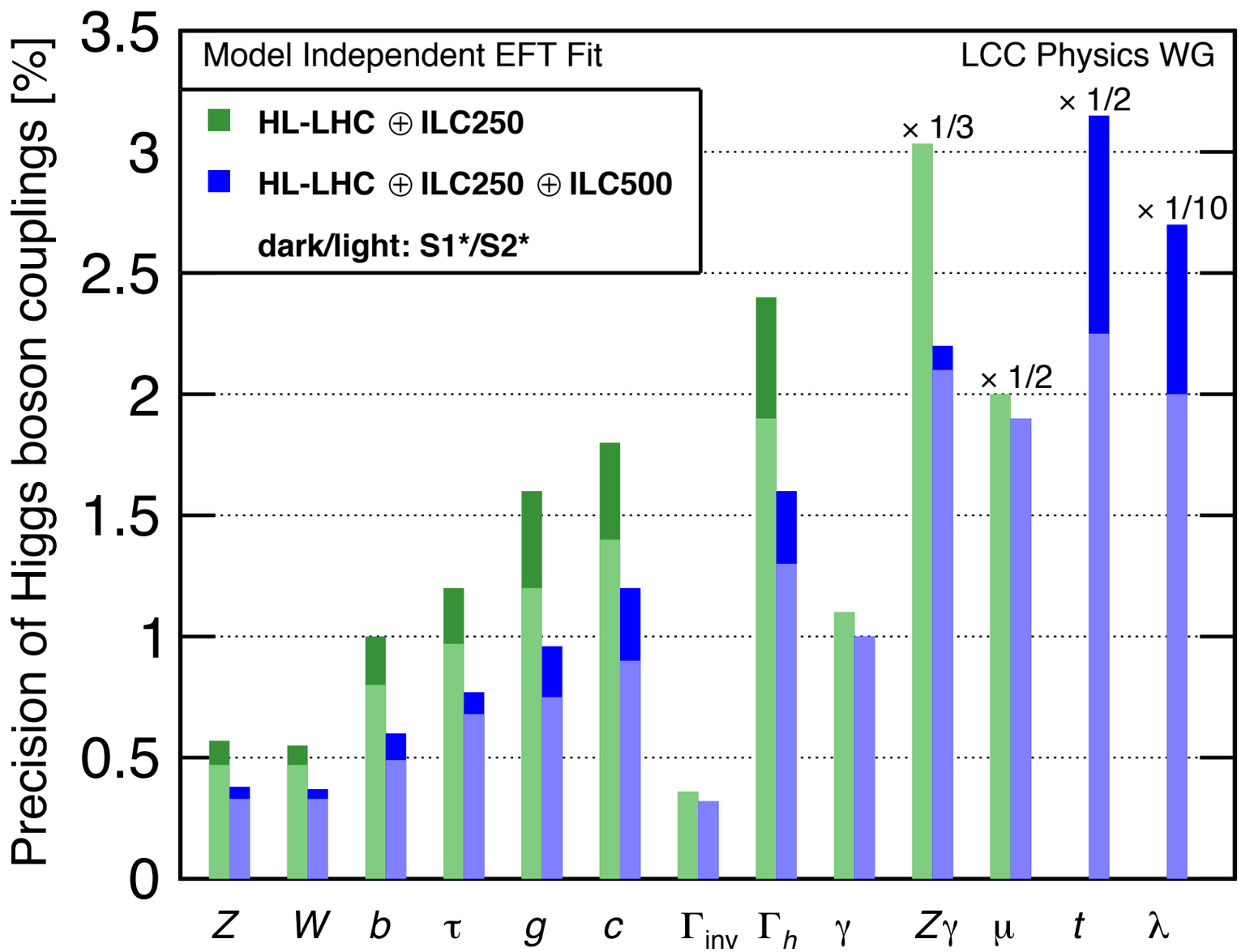
Higgs observables at LHC & e+e- (3+12x2)

2 for polarized

- at e+e-, all the 23 parameters can be determined ***simultaneously***

(details in backup)

precisions at Higgs factories: complementarity with LHC



(arXiv:1903.01629)

#qualitative:

model independence,
hcc coupling

#quantitative (<~1%):

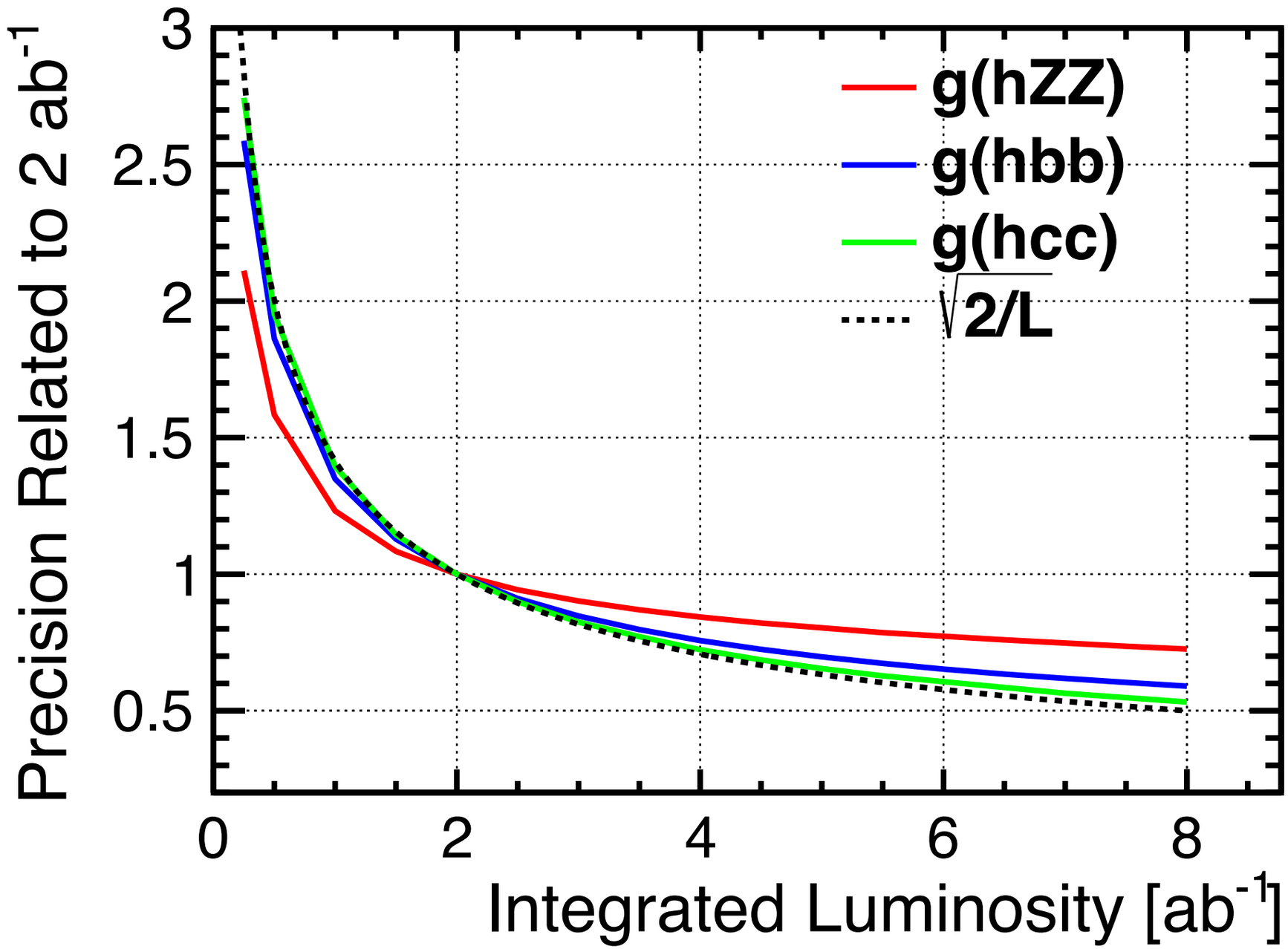
hZZ, hWW, hbb, h$\tau\tau$
h->invisible/exotic

#synergy:

h$\gamma\gamma$, hγZ, h$\mu\mu$, htt, λ

role of each measurement: more transparent understanding

(Peskin, JT, paper in preparation)



why not following 1/√L? why so different for hZZ/hbb/hcc?

role of each measurement: more transparent understanding

(Peskin, JT, paper in preparation)

to a very good approximation, every EFT coefficient and Higgs coupling can be expressed directly by a set of input observables

for example: unpolarized e+e- at 250 GeV

$$\delta g_{hZZ} = \frac{1}{2}\delta\sigma_{Zh} + 6.4\delta\Gamma_l + 5.3\delta g_{Z,eff} - 0.015\delta R_{\gamma Z} - 2.4\delta\kappa_{A,eff} + 8.9\delta m_h + 0.098\delta A_l + \cdots$$

$$\delta X = \frac{\Delta X}{X}$$

σ_{Zh}	:	cross section of e+e- -> Zh
A_l, Γ_l	:	A_{LR} and Γ(Z->ll) at Z-pole
g_{Zeff}, κ_{Aeff}	:	Triple Gauge Couplings
$R_{\gamma Z}$	:	BR(h->γZ) / BR(h->ZZ*)
m_h	:	Higgs mass

role of each measurement: more transparent understanding

(Peskin, JT, paper in preparation)

for example: unpolarized e+e- at 250 GeV

plug in measurement precisions for current EWPOs + 2 ab-1

$$\delta g_{hZZ} = \frac{1}{2}\delta\sigma_{Zh} + 6.4\delta\Gamma_l + 5.3\delta g_{Z,eff} - 0.015\delta R_{\gamma Z} - 2.4\delta\kappa_{A,eff} + 8.9\delta m_h + 0.098\delta A_l + \cdots$$

$$= 41 \oplus 66 \oplus 30 \oplus 23 \oplus 14 \oplus 11 \oplus 8.7 \oplus \cdots \times 10^{-4}$$

σ_{Zh} — **EWPOs** — **TGCs** — **BR(h->γZ)** — **Higgs mass**

importance hierarchy

role of each measurement: more transparent understanding

(Peskin, JT, paper in preparation)

for example: unpolarized e+e- at 250 GeV

plug in measurement precisions for current EWPOs + 2 ab-1

$$\delta g_{hbb} = \frac{1}{2}\delta B_{bb} - \frac{1}{2}\delta B_{WW} + \frac{1}{2}\delta\sigma_{Zh} - 5.79\delta\Gamma_l - 0.016\delta\Gamma_{\gamma Z} + \cdots$$

$$= 28 \oplus 91 \oplus 41 \oplus 59 \oplus 32 \oplus \cdots \times 10^{-4}$$

BR(h->WW)

σ_{Zh}

EWPOs

BR(h->bb)

BR(h->γZ)

role of each measurement: more transparent understanding

(Peskin, JT, paper in preparation)

for example: unpolarized e+e- at 250 GeV

plug in measurement precisions for current EWPOs + 2 ab-1

$$\delta g_{hcc} = \frac{1}{2}\delta B_{cc} - \frac{1}{2}\delta B_{WW} + \frac{1}{2}\delta\sigma_{Zh} - 5.79\delta\Gamma_l - 0.016\delta\Gamma_{\gamma Z} + \cdots$$

$$= 160 \oplus 91 \oplus 41 \oplus 59 \oplus 32 \oplus \cdots \times 10^{-4}$$

BR(h->cc)

BR(h->WW)

σ_{Zh}

EWPOs

BR(h->γZ)

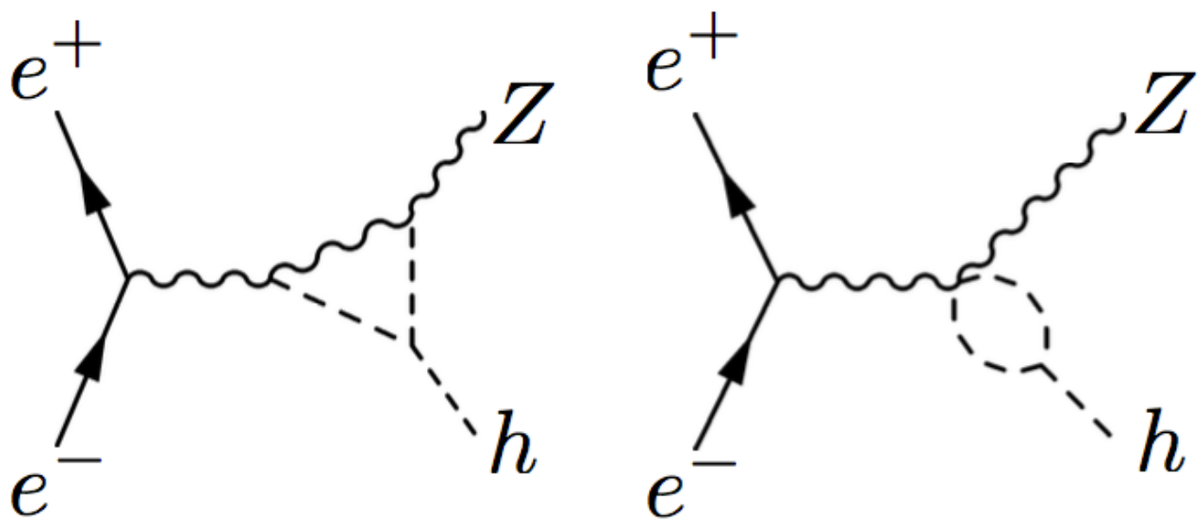
stay tuned

summary

- the capabilities of a e+e- are best represented in SMEFT formalism
- EWPOs and TGCs are related to Higgs couplings, hence important
- Higgs measurements from (HL-)LHC are helpful for e+e-
- beam polarizations play an important role
- all proposed Higgs factories can deliver 1% or below precision for many Higgs couplings already at $\sqrt{s} = 250$ GeV
- let's go for at least one of them

backup

Higgs self-coupling: indirect determination



McCullough, arXiv:1312.3322

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

- δσ could receive contributions from many other sources

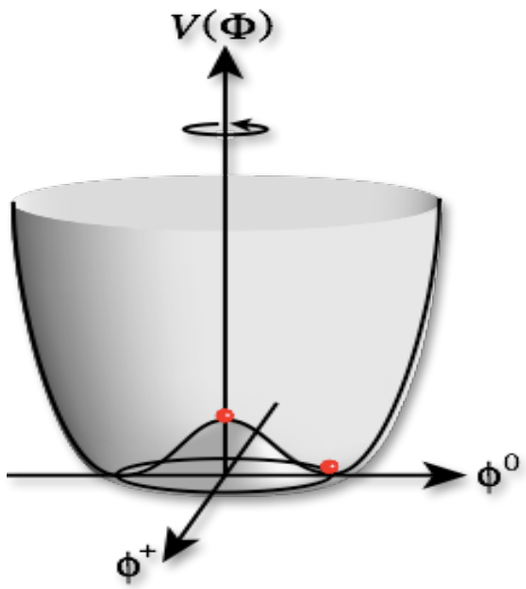
  —> **δh ~ 500%** at 250GeV only; Gu, et al, arXiv:1711.03978

  —> **δh ~ 50%** + 350/500GeV; Peskin, JT, paper in preparation

- open: what if we include other NLO effects as well?

(vi) Higgs self-coupling

- direct probe of the Higgs potential
- large deviation (> 20%) motivated by electroweak baryongenesis, could be ~100%
- √s>=500 GeV, e+e- —> ZHH
- √s>=1 TeV, e+e- —> ννHH (WW-fusion)

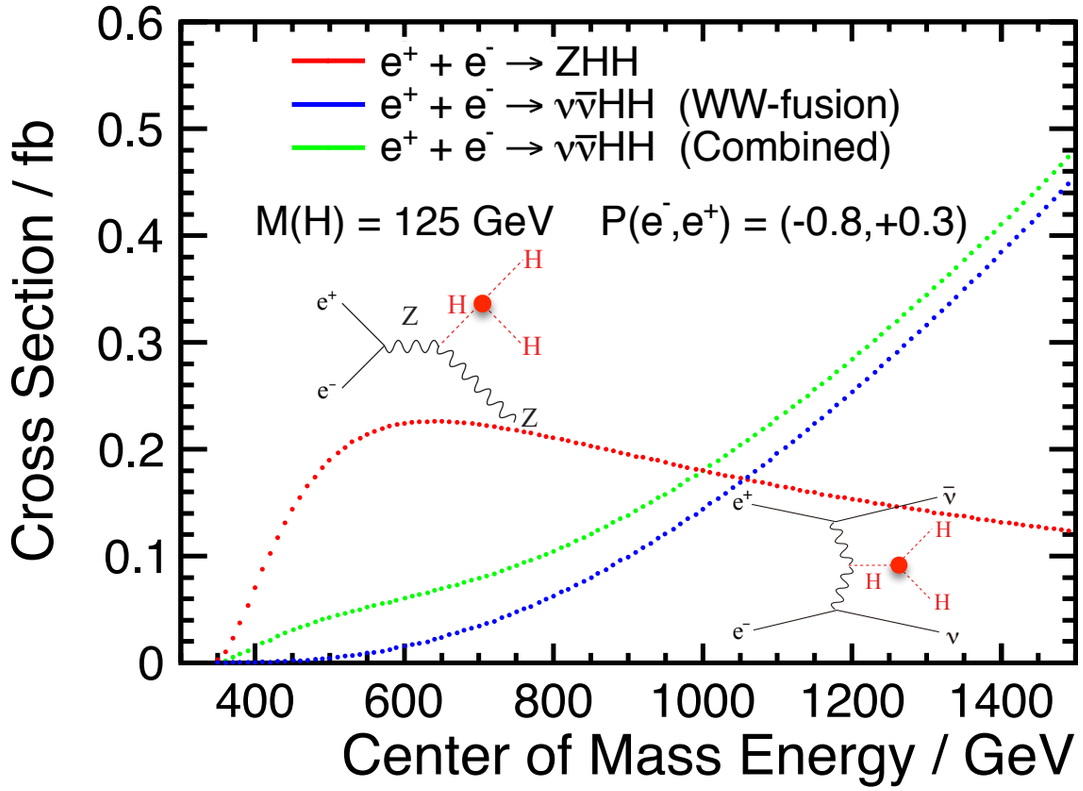


ILC

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
H20	27%	10%

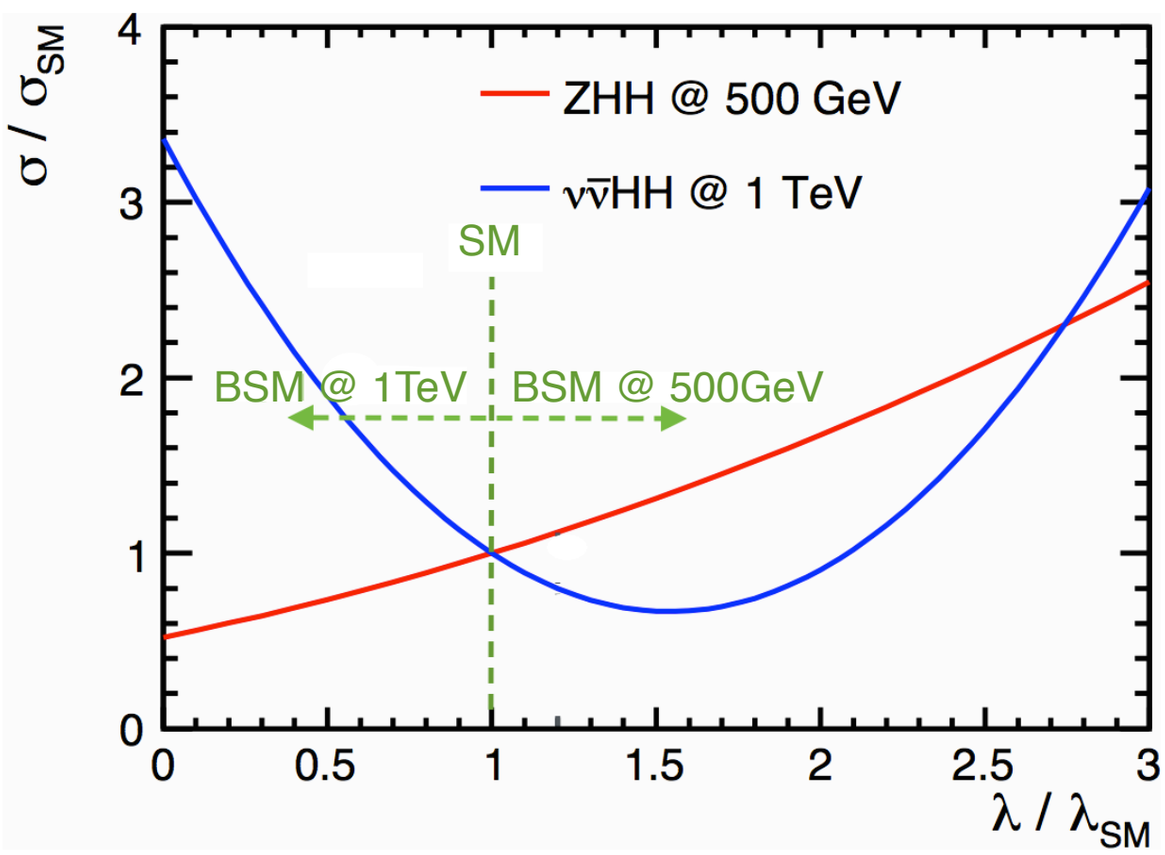
CLIC

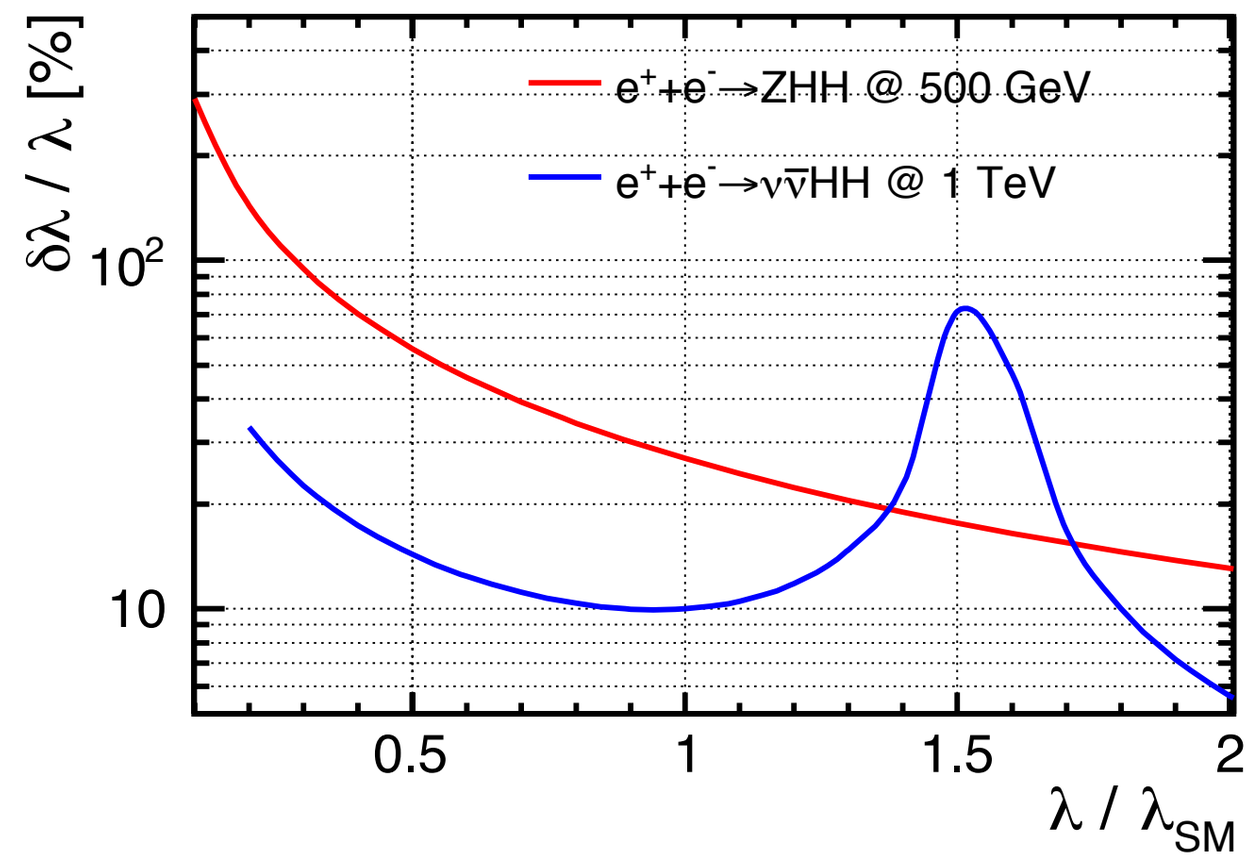
1.5 TeV	+3 TeV
36%	10%



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

- constructive interference in ZHH, while destructive in ννHH (& LHC) —> complementarity between ILC & LHC, between √s ~500 GeV and >1TeV
- if $\lambda_{HHH} / \lambda_{SM} = 2$, Higgs self-coupling can be measured to ~15% using ZHH at 500 GeV e+e-





Duerig, Tian, et al, paper in preparation

role of each measurement: more transparent understanding

(Peskin, JT, paper in preparation)

for example: **polarized** e+e- at 250 GeV

plug in measurement precisions for current EWPOs + 2 ab-1

$$\delta g_{hZZ} = \frac{1}{2}\delta\sigma^R_{Zh} + 0.35\delta A_l + 3.6\delta\kappa_{A,eff} - 4.0\delta g_{Z,eff} - 1.8\delta\Gamma_l + 8.9\delta m_h + \cdots$$

$$= 51 \oplus 31 \oplus 20 \oplus 17 \oplus 18 \oplus 11 \oplus \cdots \times 10^{-4}$$

σ_{Zh} | A_{LR} | TGCs | TGCs | Γ_l | Higgs mass

importance hierarchy

strategy to determine all the 23 parameters

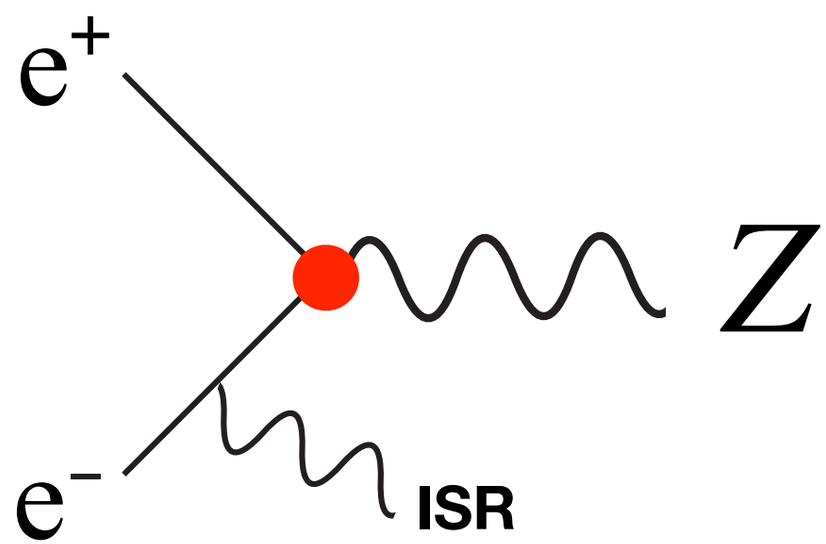
- m_W and $\alpha(m_Z)$ -> g, g';
- G_F -> v; m_h -> λ; m_Z -> c_T;
- A_l and Γ_l -> $c_{HL}+c_{HL}'$, c_{HE};
- Γ_W and Γ_Z -> c_W, c_Z;

- g_{1Z} -> c_{HL}'; κ_γ -> c_{WB}; κ_λ -> c_{3W};

- $BR(h\to\gamma\gamma)$ and $BR(h\to\gamma Z)$ -> c_{BB}, c_{WW};
- σ_{ZH} -> c_H; σ_{ZHH} -> c_6;
- $BR(h\to bb/cc/gg/\mu\mu/\tau\tau)$ -> y_b, y_c, c_g, y_μ, y_τ;
- $BR(h\to invisible)$ and $BR(h\to other)$;
- c_{WW} is helped by A_{LR} in σ_{ZH}, angular meas., W-fusion;
- $c_{HL}/c_{HL}'/c_{HE}$ are helped by A_{LR} in σ_{ZH}

recap 4: role of beam polarizations (improving EWPOs)

radiative return



- a Higgs factory is meantime a Z factory
- ~10^8 Z produced @ ILC250 + beam polarizations
- improve $\boldsymbol{A_l}$ by a factor of 10

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

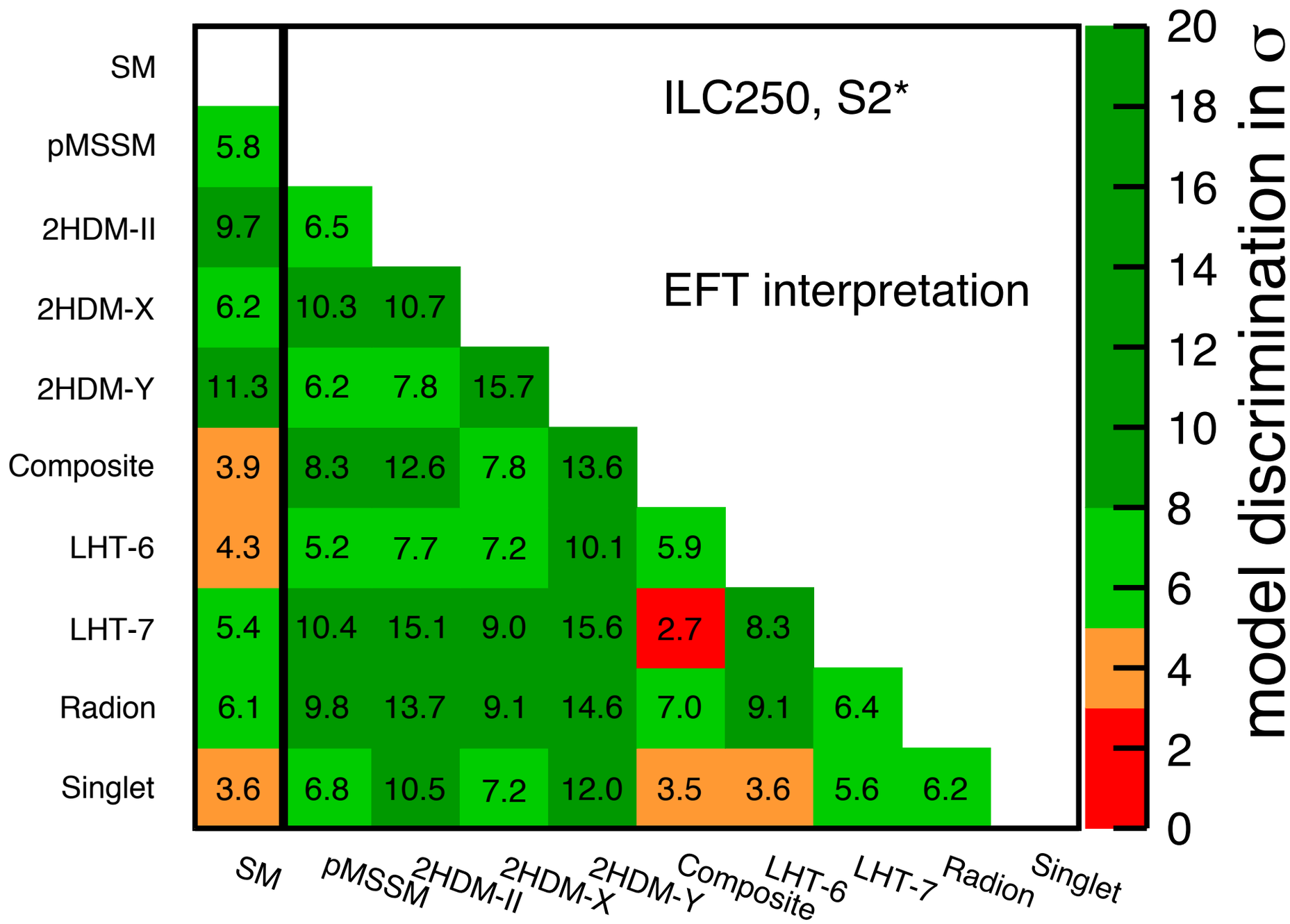
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> quantitative assessment for models discrimination

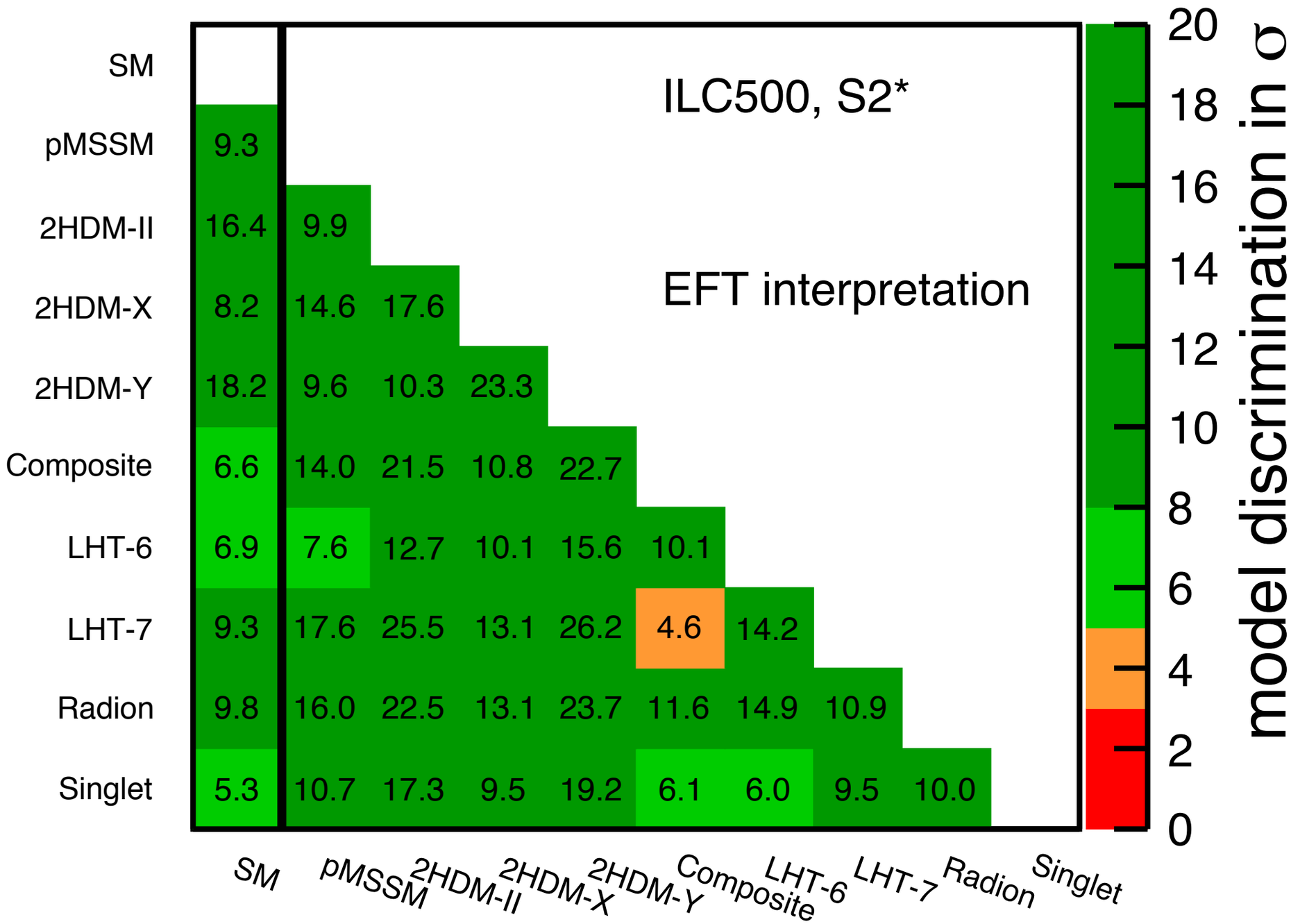
model parameters (chosen as escaping direct search at HL-LHC)

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

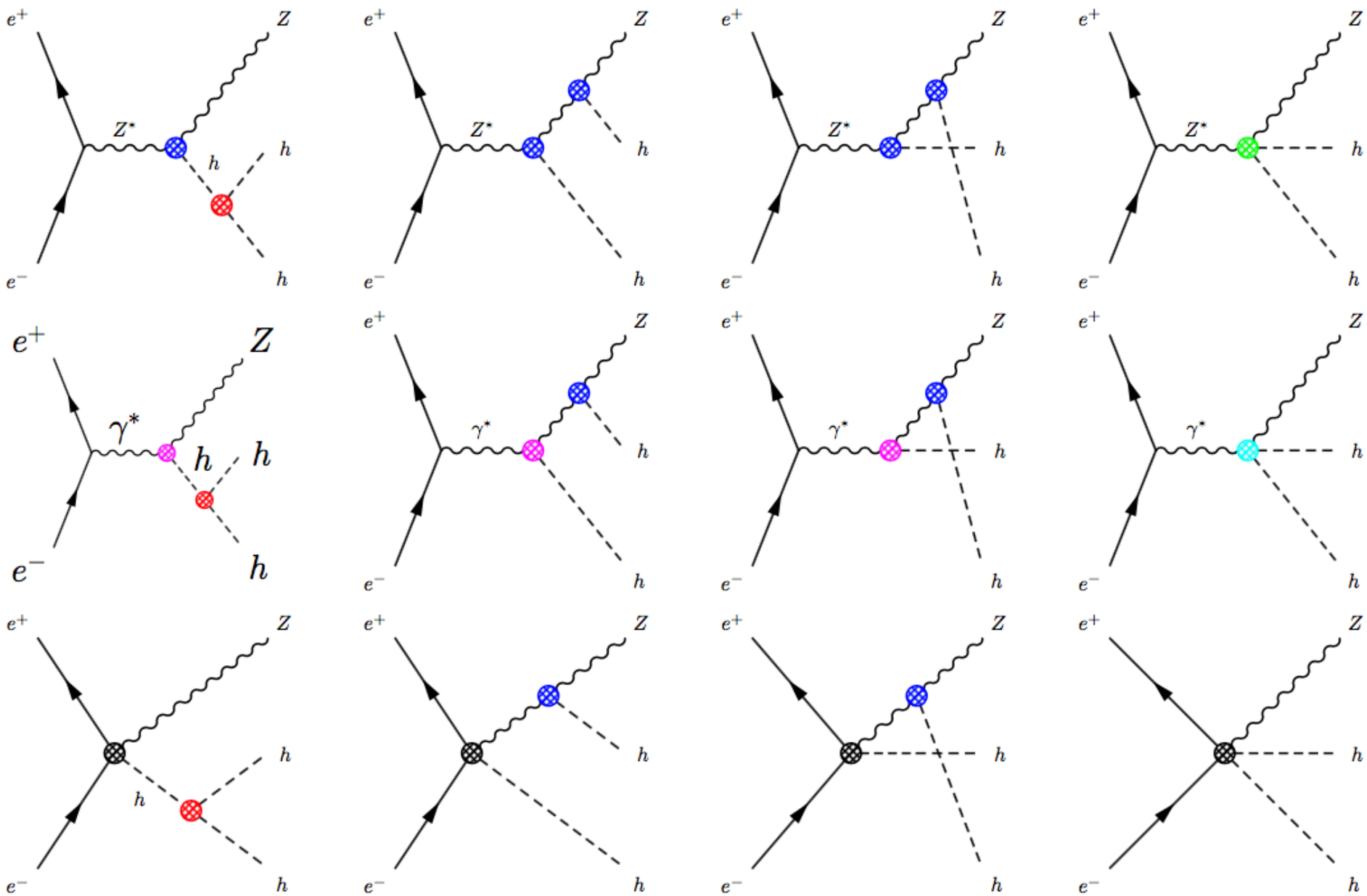
BSM benchmark models discrimination at ILC250



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



λ_{hhh} determination in SMEFT



λ_{hhh} determination in SMEFT

(Barklow, Fujii, Jung, Peskin, JT, arXiv:1708.09079)

$$\frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 = 0.565c_6 - 3.58c_H + 16.0(8c_{WW}) + 8.40(8c_{WB}) + 1.26(8c_{BB})$$
$$-6.48c_T - 65.1c'_{HL} + 61.1c_{HL} + 52.6c_{HE},$$

$$c_6 = \frac{1}{0.565}\left[\frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 - \sum_i a_i c_i\right]$$

$$\Delta c_6 = \frac{1}{0.565}\left[(\frac{\Delta\sigma_{Zhh}}{\sigma_{SM}})^2 + \sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}}$$

Given the full ILC program of 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV

$$\left[\sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}} = 0.04 \quad \ll \quad \frac{\Delta\sigma_{Zhh}}{\sigma_{SM}} = 0.168$$

(systematic error) (statistical error)

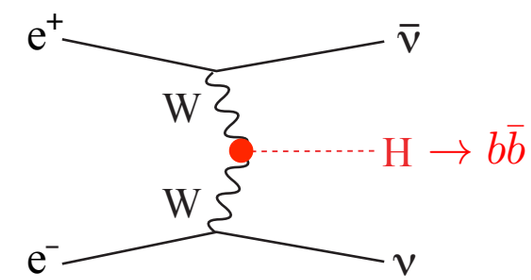
(ii-5) WW-fusion channel & Higgs total width Γ_H

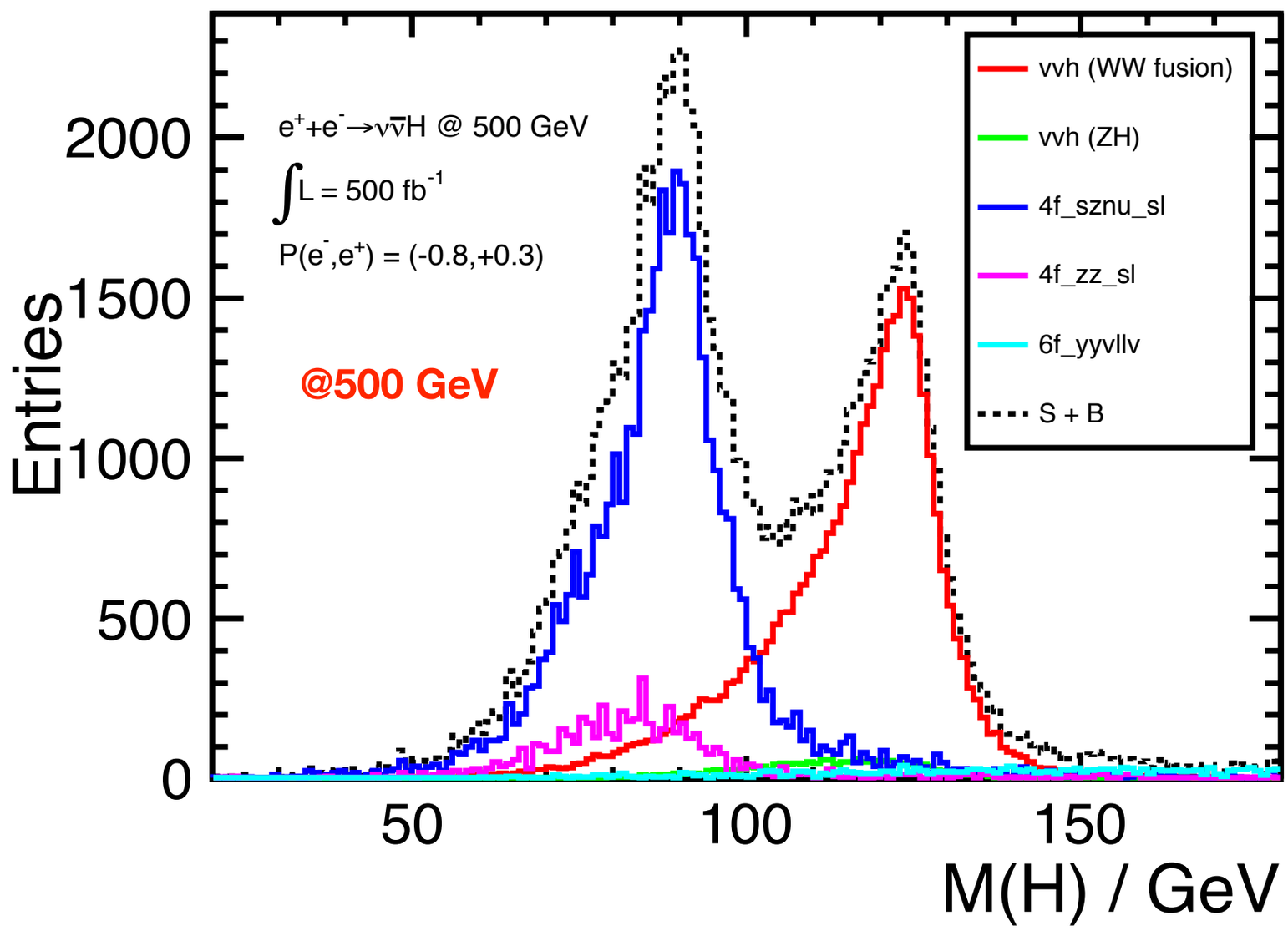
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

★ $$\Gamma_H = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HWW}}{\mathrm{Br}(H \to WW^*)}$$

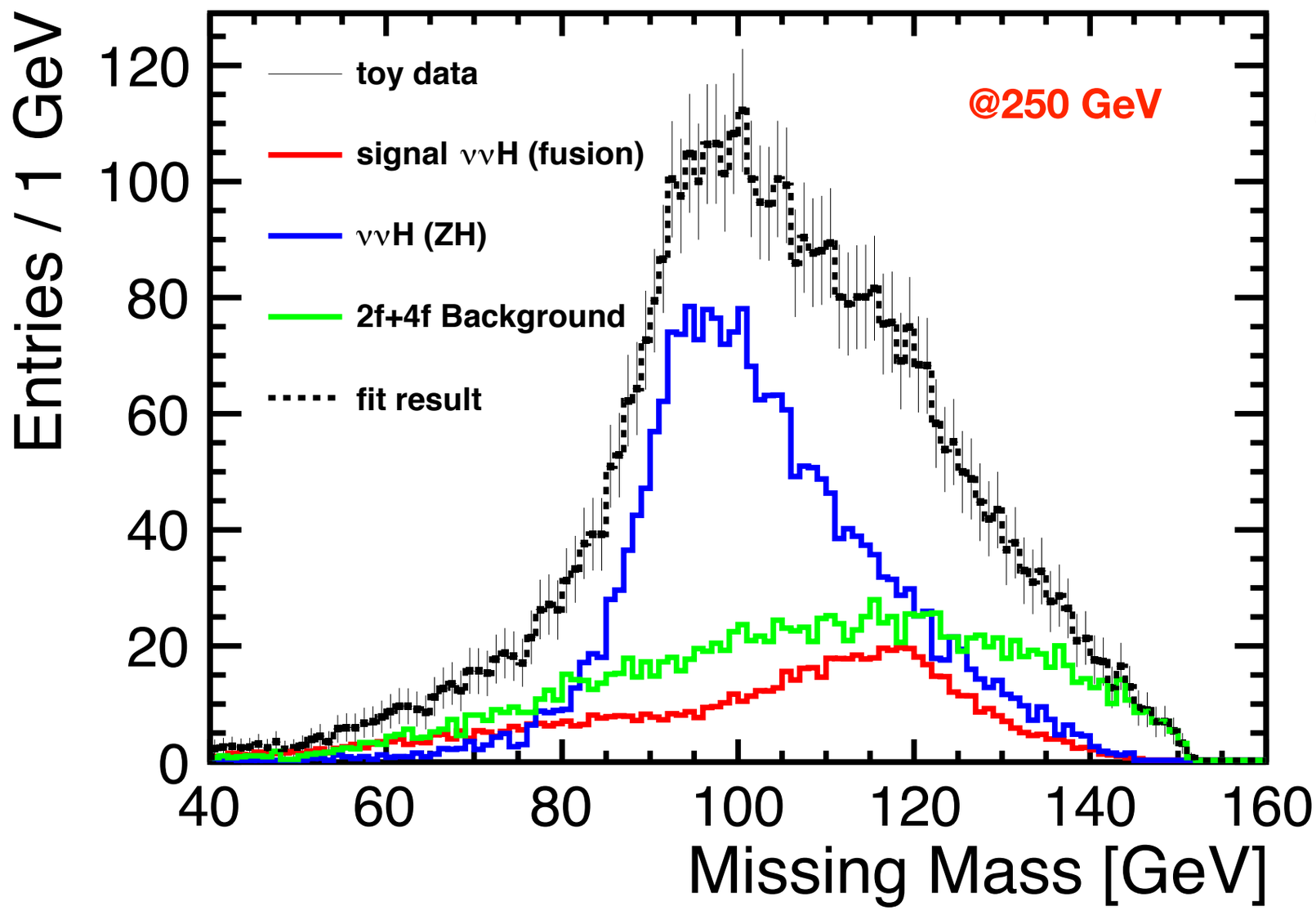
—> better option!

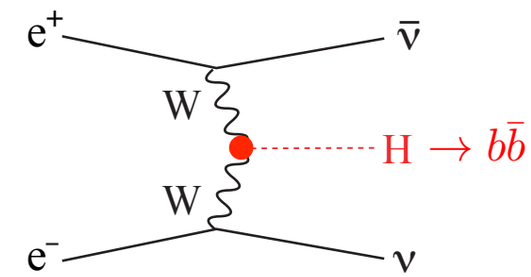




Duerig, et al., arXiv:1403.7734

very different at Ecm=250 GeV





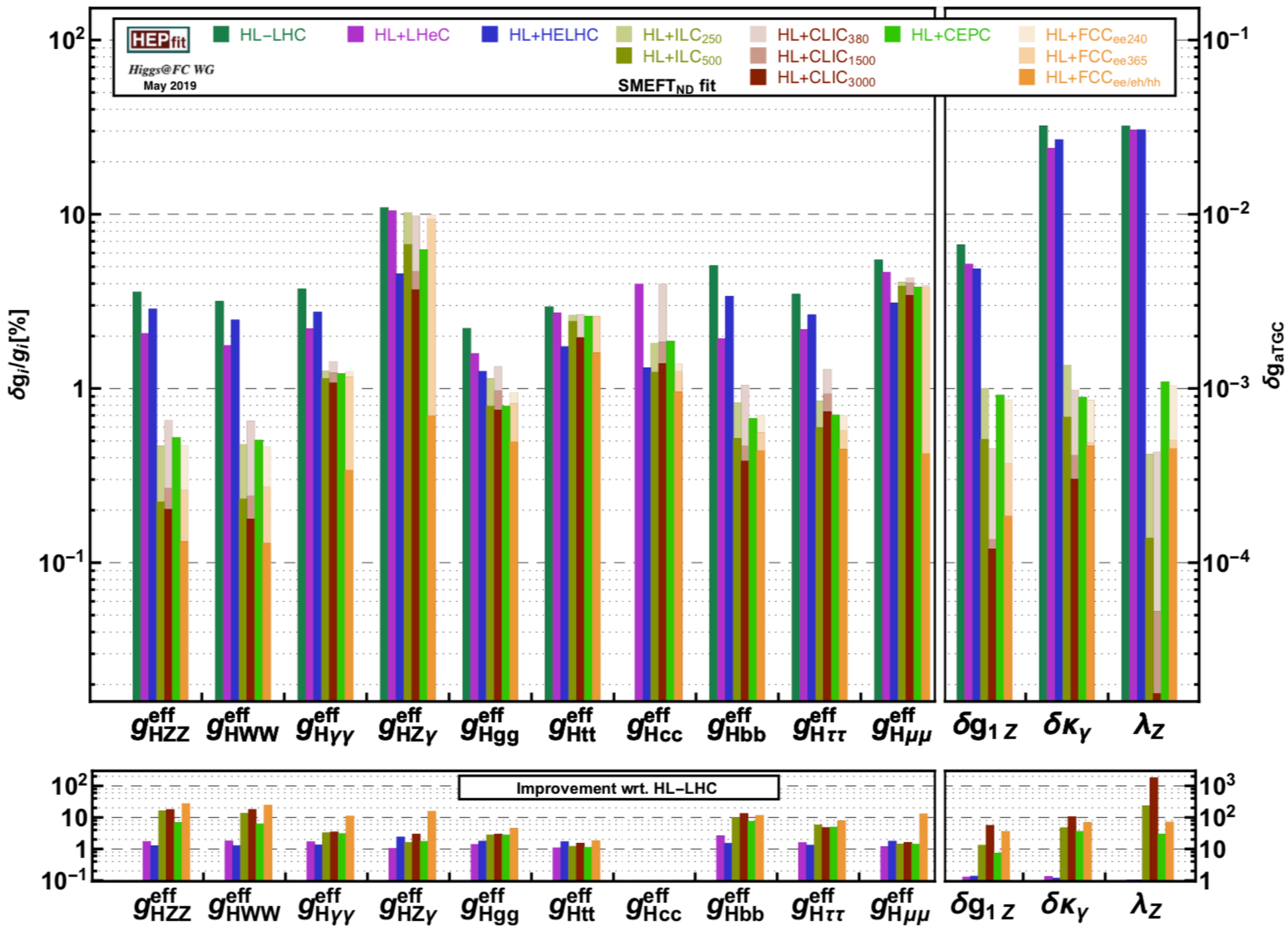
ρ = -34% correlation (larger if unpolarized)

between $\sigma_{\nu\nu H}$xBR(H->bb) and σ_{ZH}xBR(H->bb)

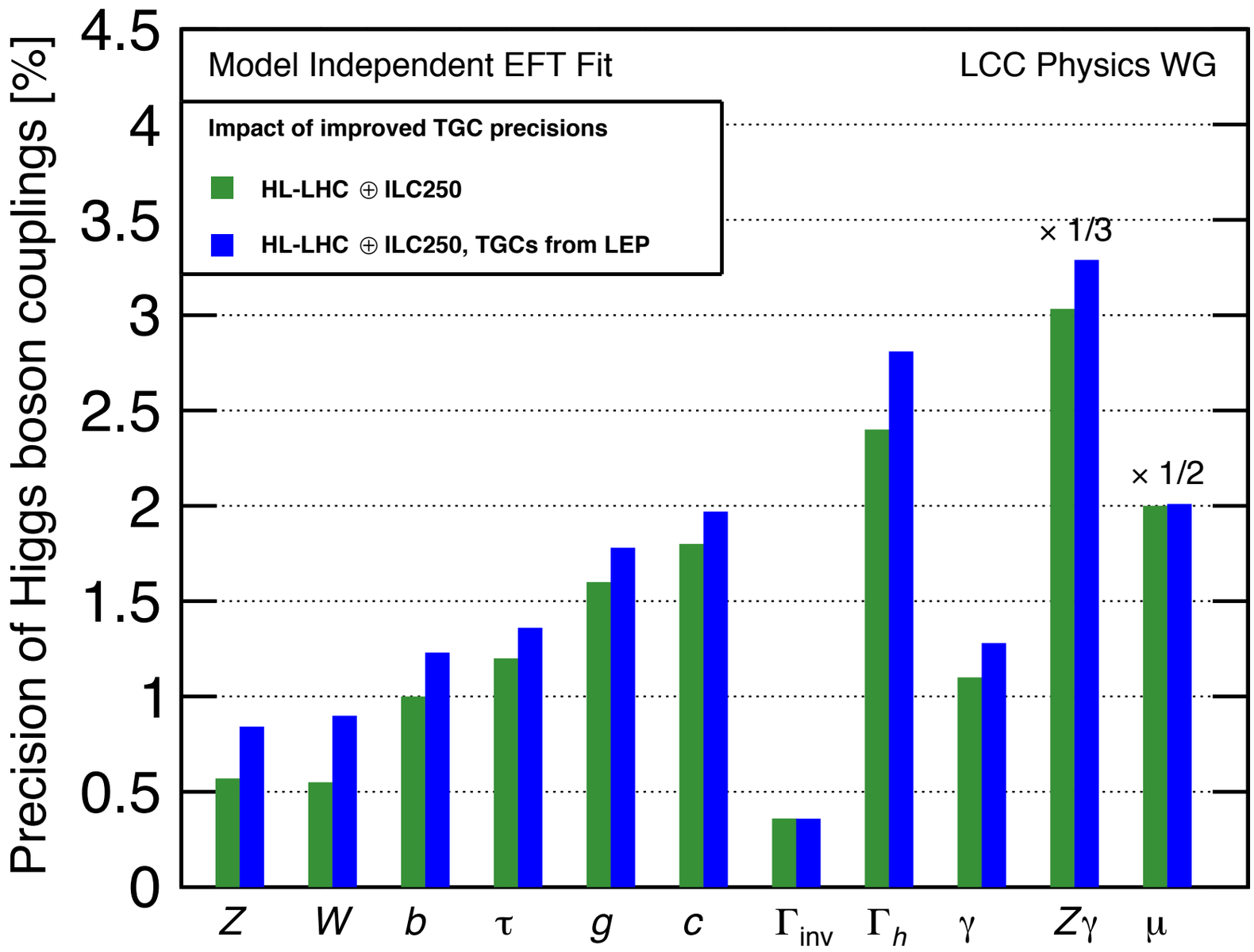
ECFA Higgs @ FC WG

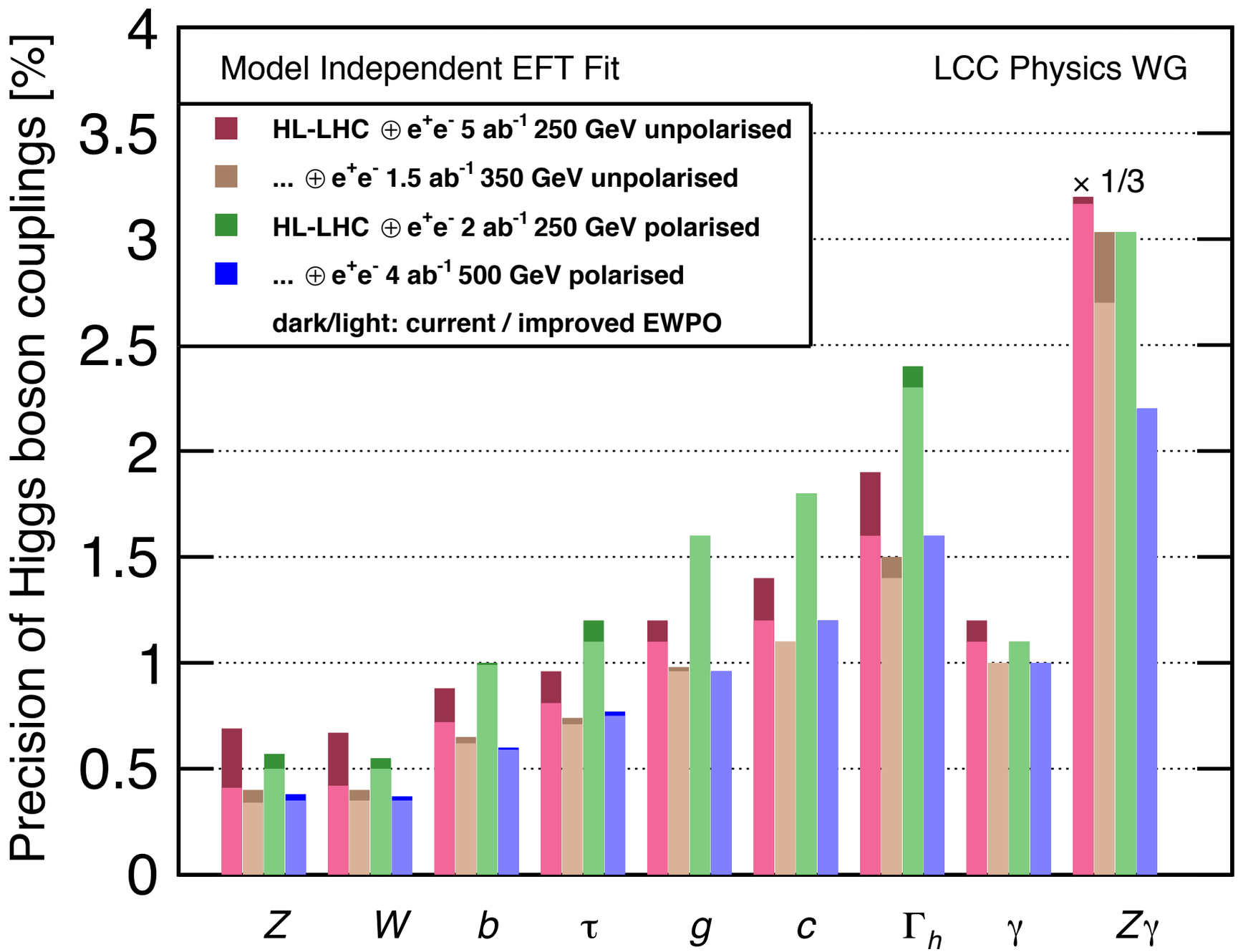
collider	(1) di-H excl.	(2.a) di-H glob.	(3) single-H excl.	(4) single-H glob.
HL-LHC	$^{+60}_{-50}$% (50%)	52%	46%	50%
HE-LHC	10-20% (n.a.)	n.a.	41%	50%
ILC_{250}	–	–	28%	49%
ILC_{350}	–	–	28%	47%
ILC_{500}	27% (27%)	27%	26%	37%
$CLIC_{380}$	–	–	45%	50%
$CLIC_{1500}$	36% (36%)	36%	40%	49%
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)	n.a.	35%	49%
FCC-ee_{240}	–	–	19%	48%
FCC-ee_{365}	–	–	19%	34%
FCC-ee/eh/hh	5% (5%)	6%	18%	25%
CEPC	–	–	17%	49%

ECFA Higgs @ FC WG



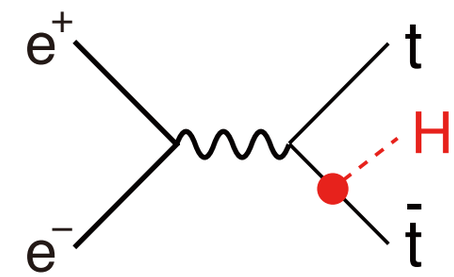
impact of TGCs




Model Independent EFT Fit
LCC Physics WG
HL-LHC ⊕ e+e- 5 ab-1 250 GeV unpolarised
... ⊕ e+e- 1.5 ab-1 350 GeV unpolarised
HL-LHC ⊕ e+e- 2 ab-1 250 GeV polarised
... ⊕ e+e- 4 ab-1 500 GeV polarised
dark/light: current / improved EWPO
× 1/3
Precision of Higgs boson couplings [%]
0
0.5
1
1.5
2
2.5
3
3.5
4
Z
W
b
τ
g
c
Γh
γ
Zγ

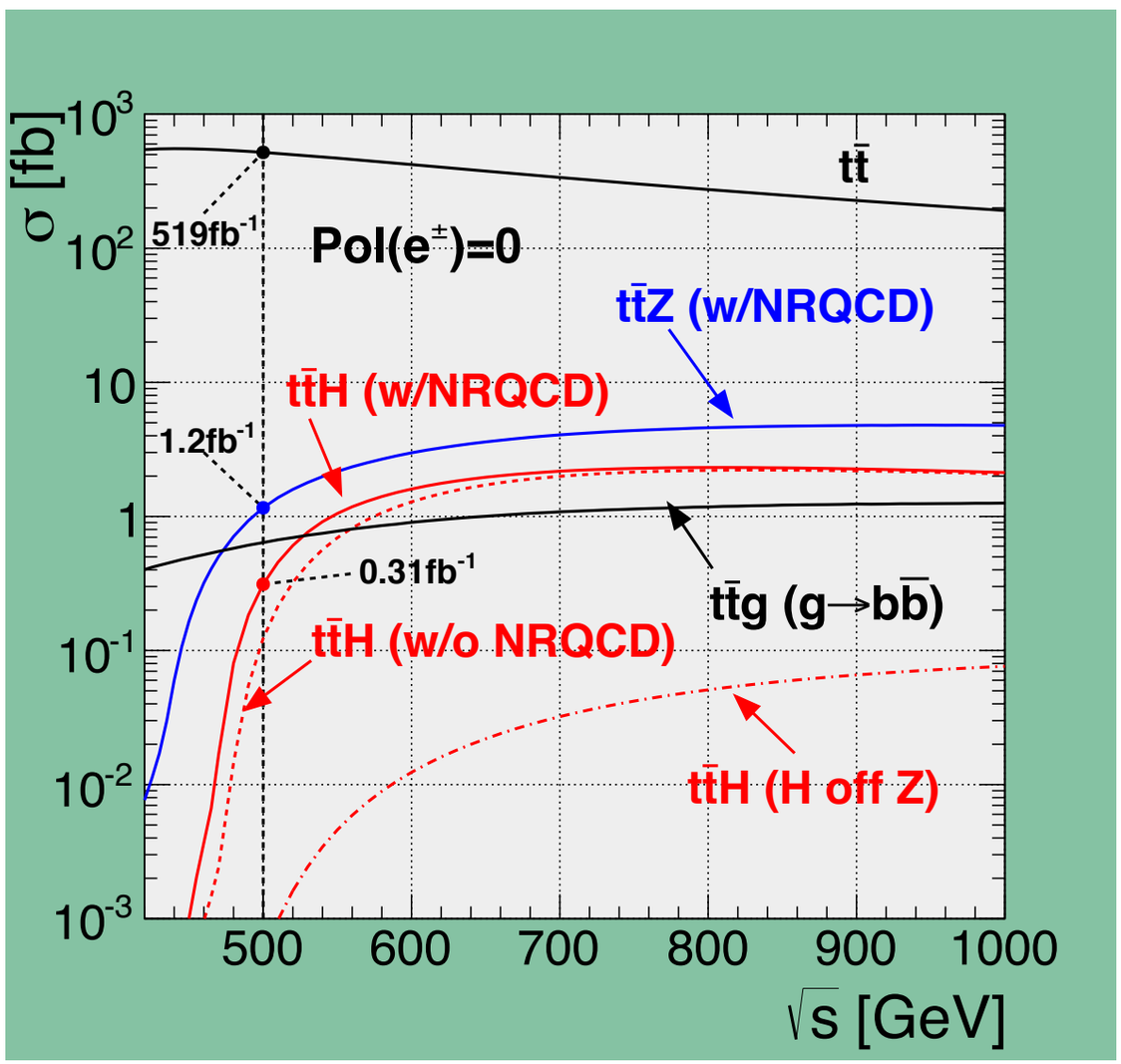
(ii-5) Top-Yukawa coupling

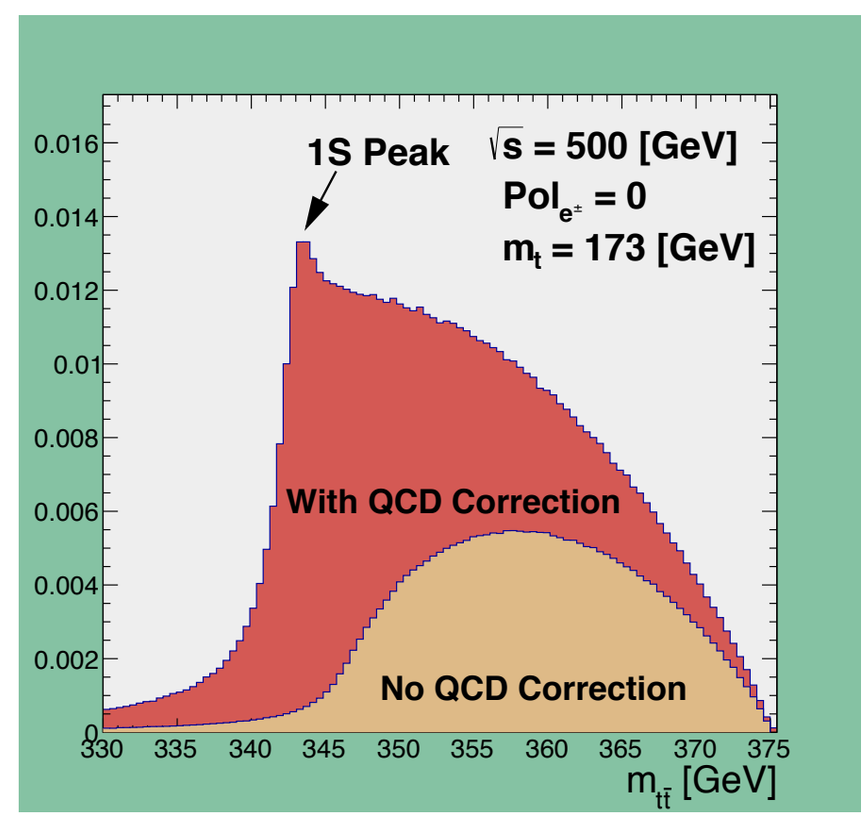
- largest Yukawa coupling; crucial role in theory
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



H-> bb

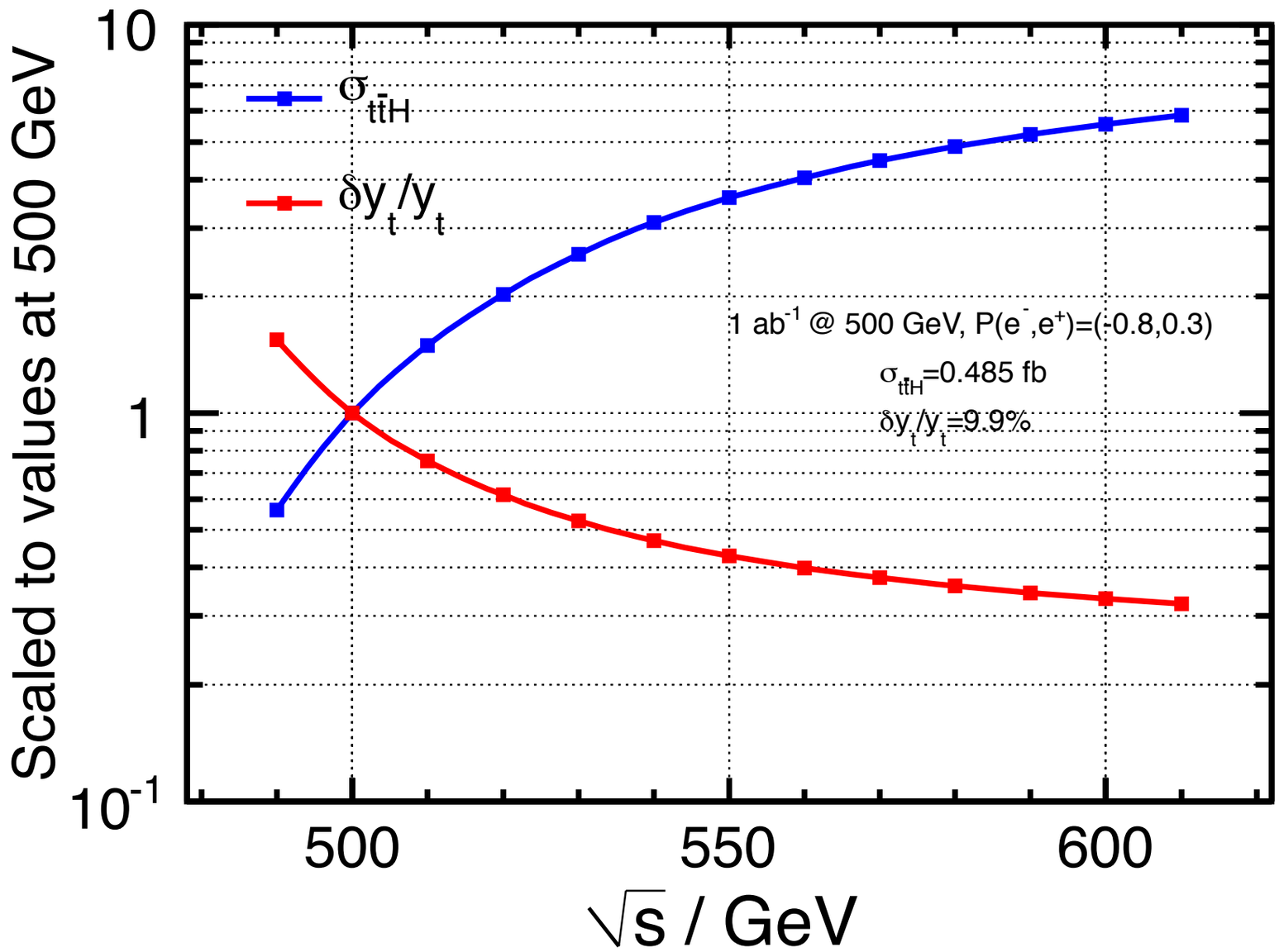
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
Snowmass	7.8%	2.0%
H20	6.3%	1.5%





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

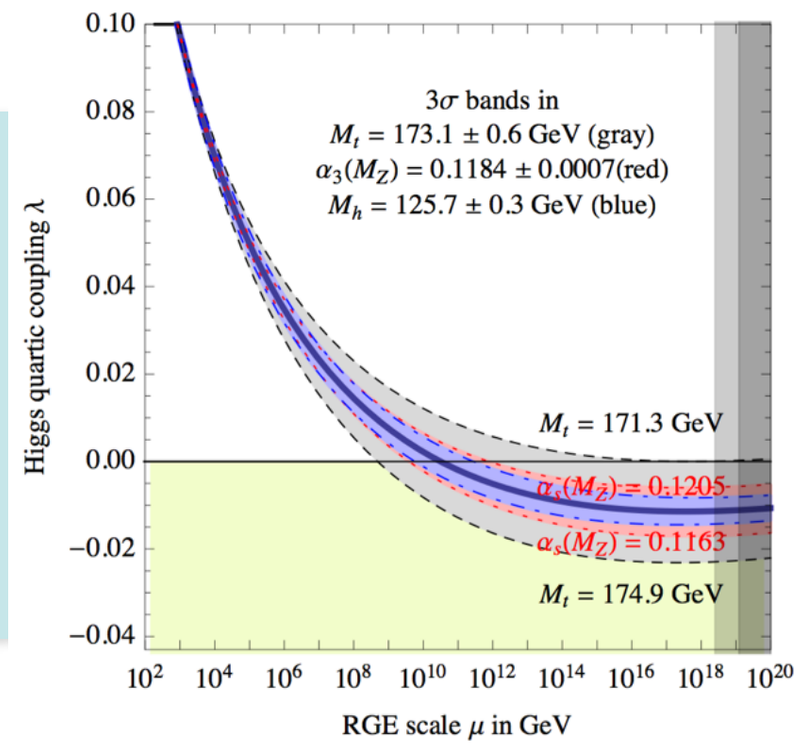
Top-Yukawa coupling

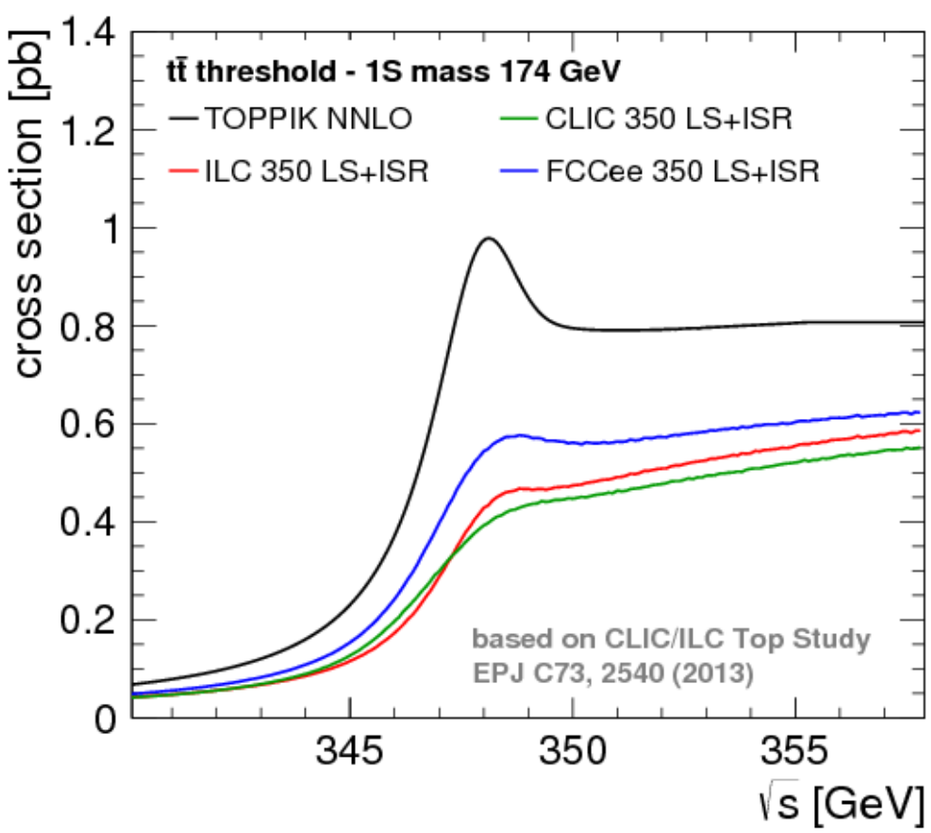


Y. Sudo

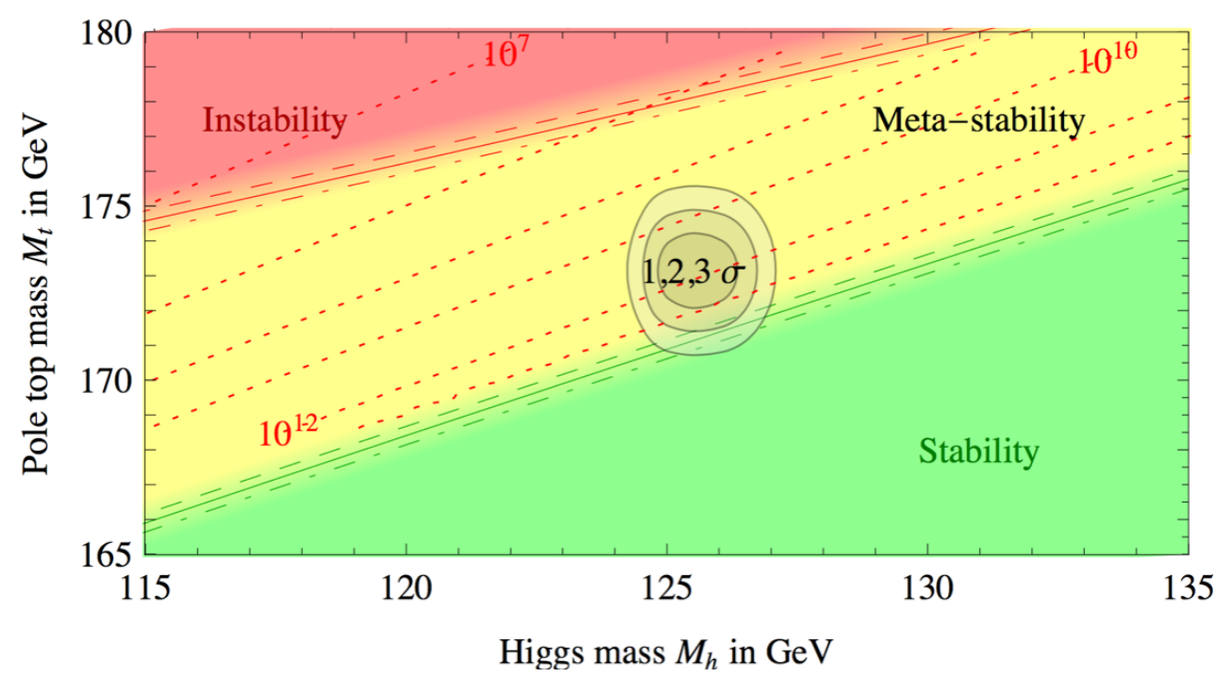
vacuum stability

- λ runs < 0? top mass precision crucial for vacuum stability
- at e+e-: top-pair threshold scan, much lower theory error
- Δm_t(MS-bar) ~ 50 MeV (Δm_H=14MeV)





Degrassi et al, JHEP 1208 (2012) 098



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

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

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

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

with

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

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

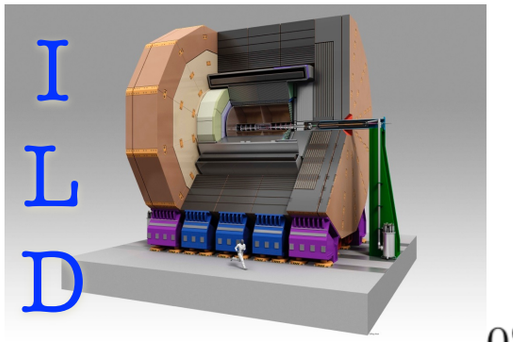
systematic errors included in the global fit

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

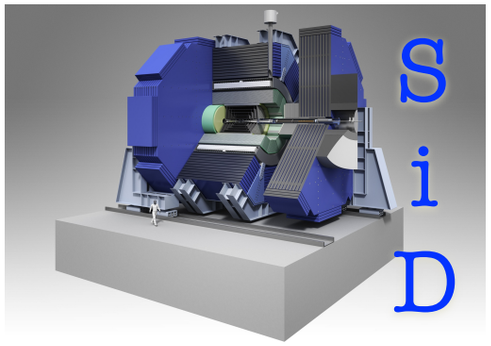
improvement factors in S2

- 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

expected meas. for direct observables



estimates at ILC by full simulation



-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 $\int Ldt$ = 250 fb^{-1})

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)

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

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

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

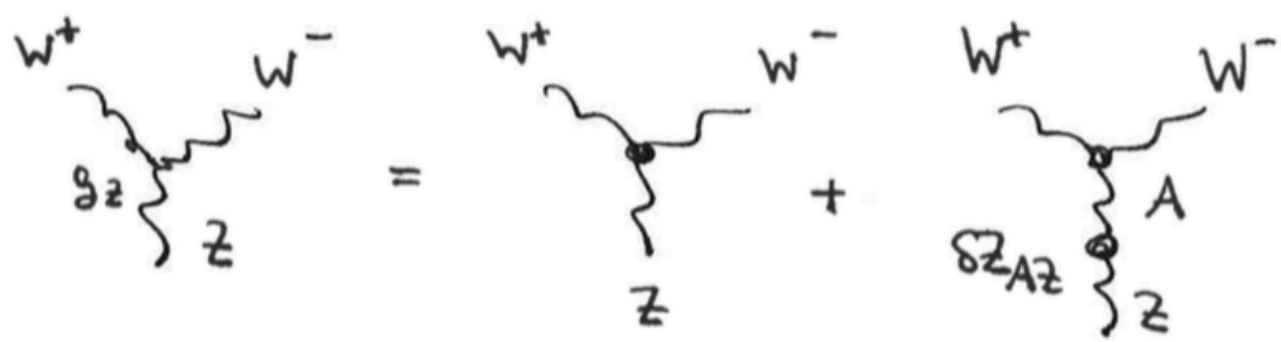
$$g_L = \frac{g}{c_w}\left[(-\frac{1}{2} + s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}(c_{HL} + c'_{HL}) - s_w c_w \delta Z_{AZ}\right]$$

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

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

EFT input: TGC (3)

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

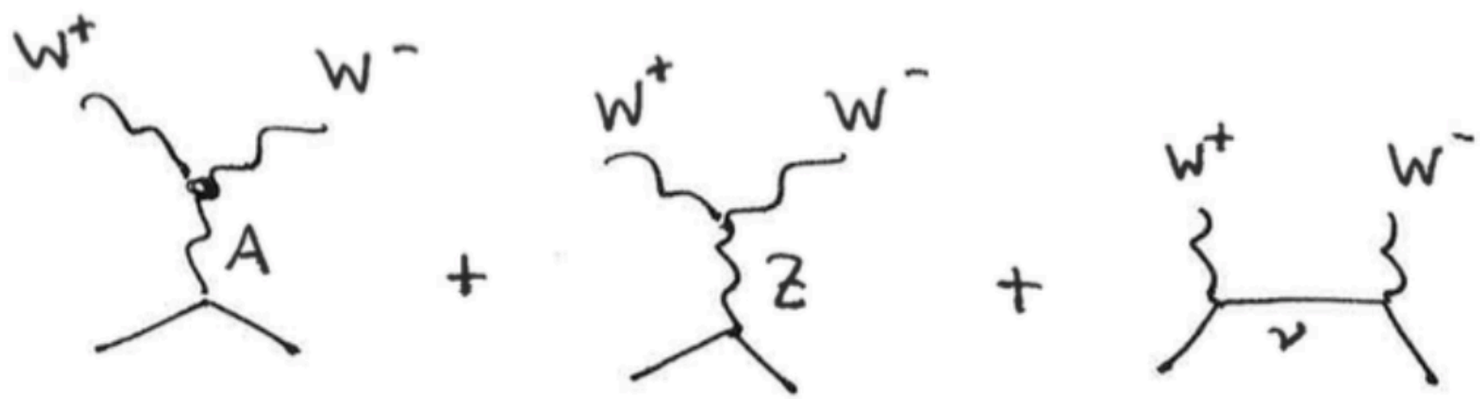


$$g_Z = gc_w(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ})$$

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

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

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)

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

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

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

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

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

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 Γ(h->WW*) and Γ(h->ZZ*)

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

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

(c'$_X$: contact interactions)

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

(similar for Z)