Lepton Collider Probes for EWSB ≳

Precision Higgs Measurements @ e+e-

arXiv:1903.01629
1708.09079
1708.08912

ECFA Higgs @ FC
arXiv:1905.03974

Junping Tian (U' of Tokyo)

Workshop on "Opportunities at Future High Energy Colliders"
June 11 - July 5, 2019 @ IFT, Madrid

questions to address about Higgs physics @ e+e-

- what is the added value, w.r.t. LHC
- impact of $\sqrt{s}$, $\int L dt$
- role of beam polarization
- importance of EWPOs

outline — Higgs Physics at future e+e-

(i) motivation

(ii) key measurements

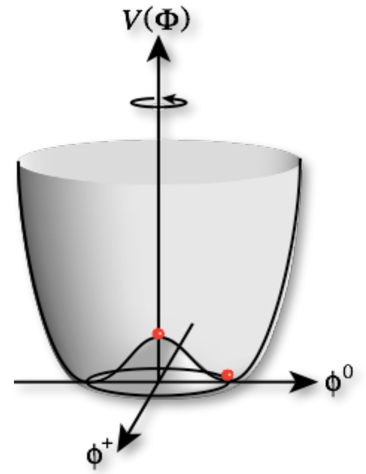
(iii) Higgs coupling determination

(iv) impact of $\sqrt{s}$, beam polarization, EWPOs

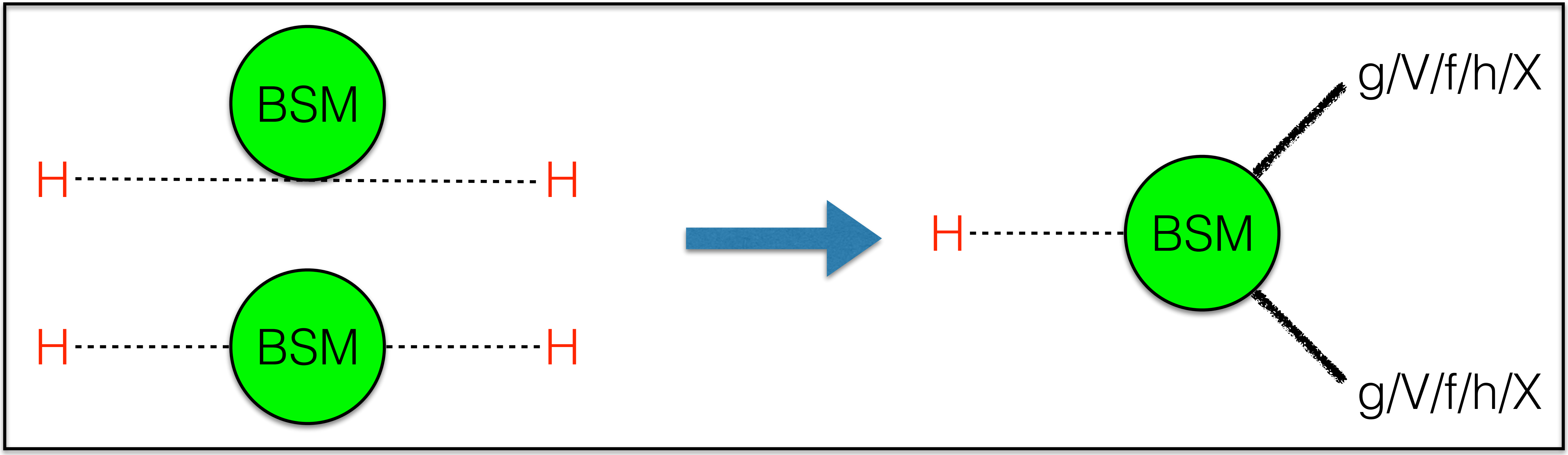
(v) Higgs self-coupling

mostly focus on experimental side, see theory talk by S.Kanemura next week

Higgs as a unique window for BSM



- What is the origin of EWSB?
- What protects m_H from quadratic divergence?
- Baryogenesis in EW phase transition? Portal to Dark Sector?



mysteries in the EW vacuum

can be revealed by looking in detail at Higgs properties

why haven't we seen yet at LHC

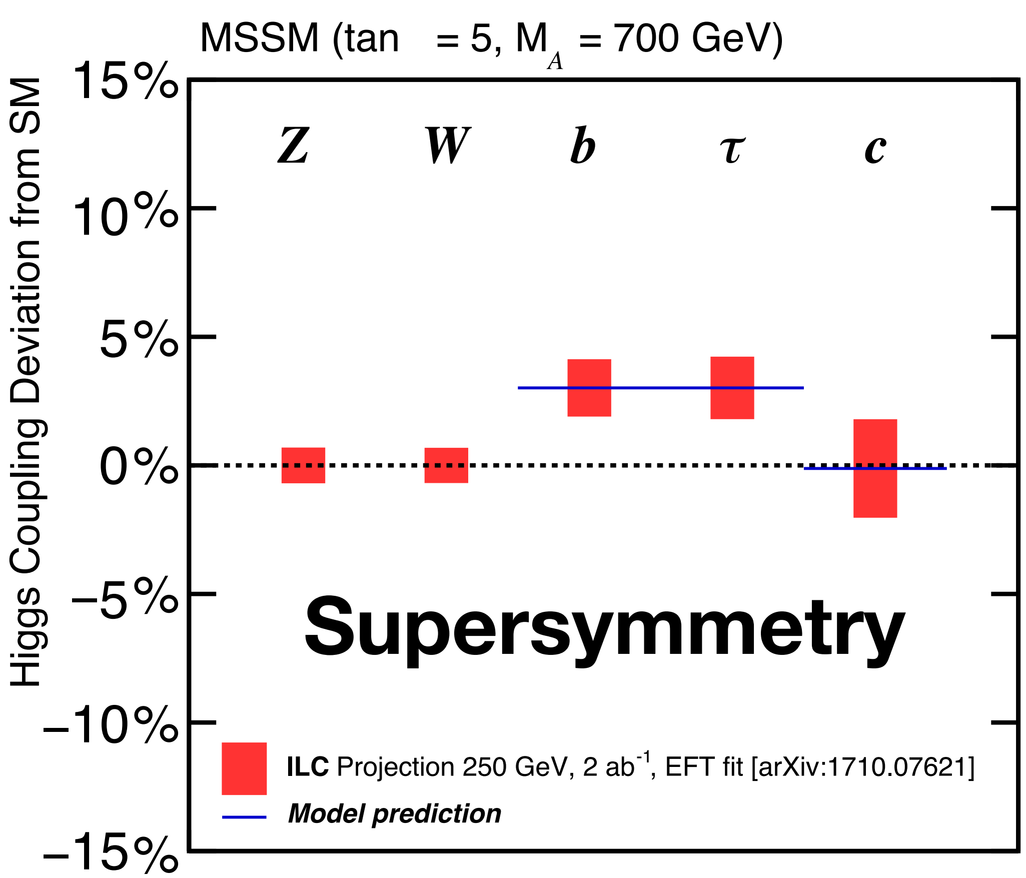
Sven's talk

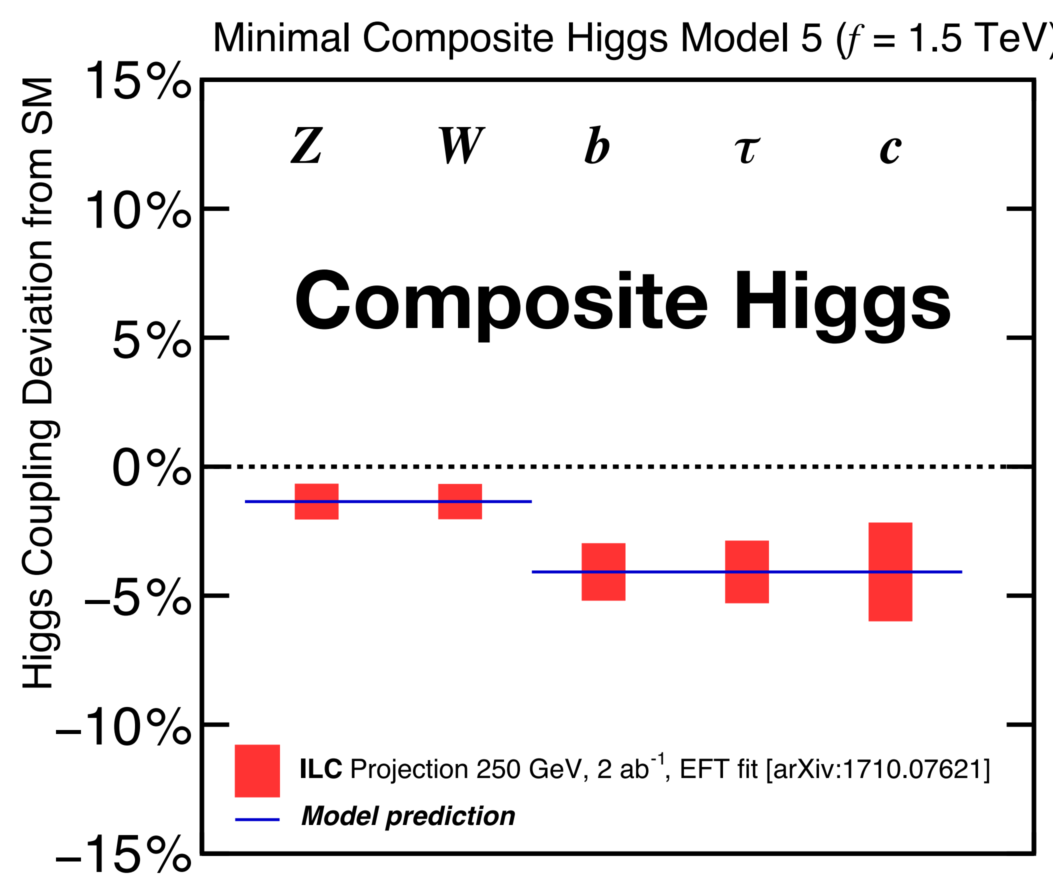
- deviation is small, typically 1-10% for m_{BSM}~1TeV

  —> need measurement with 1% or below

- deviation patterns are like fingerprints of BSM models

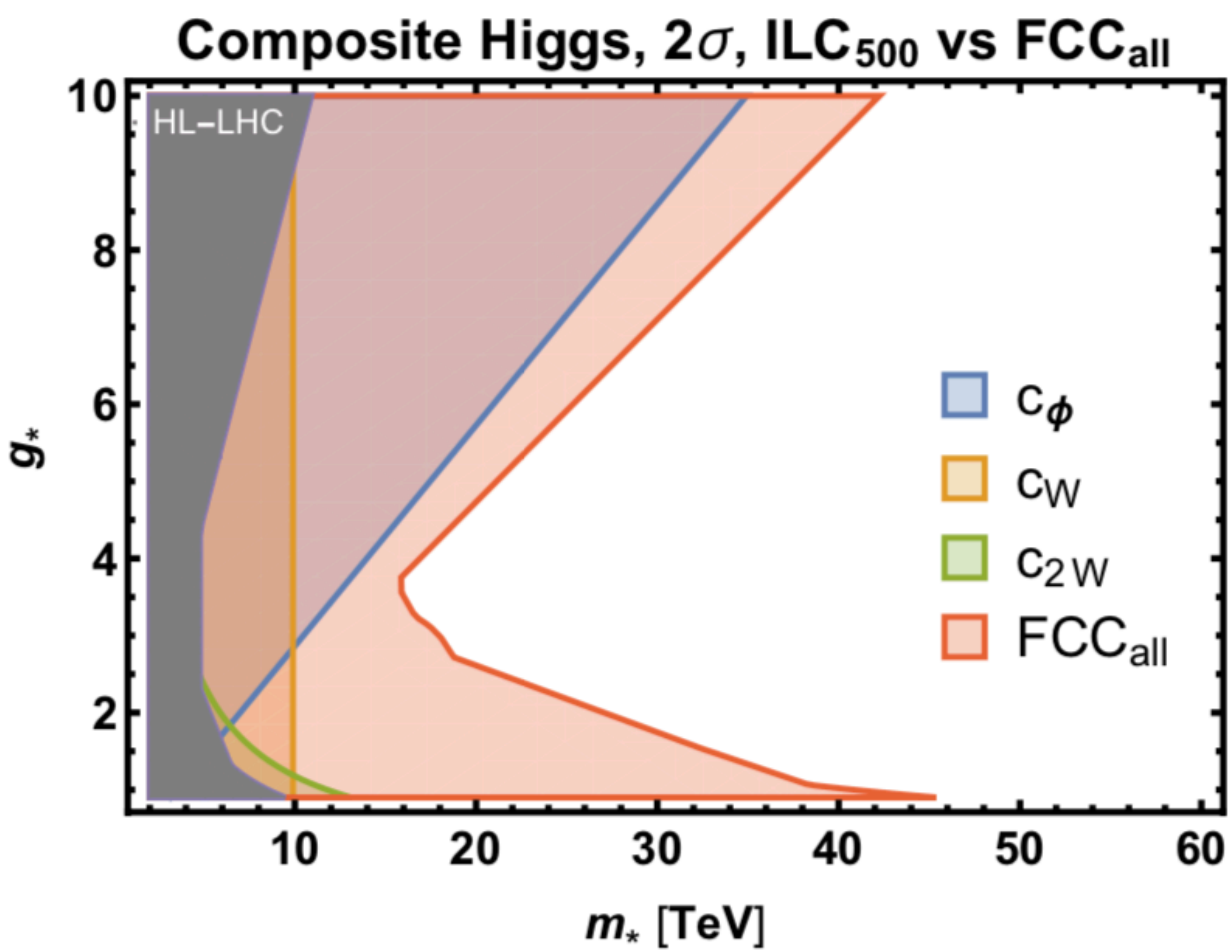
  —> need measure as many couplings as possible





direct and indirect discoveries

G.Giudice @ ESU Granada

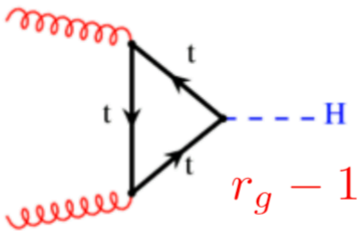


direct and indirect discoveries

- **What do we learn from indirect information?**

G.Giudice @ ESU Granada

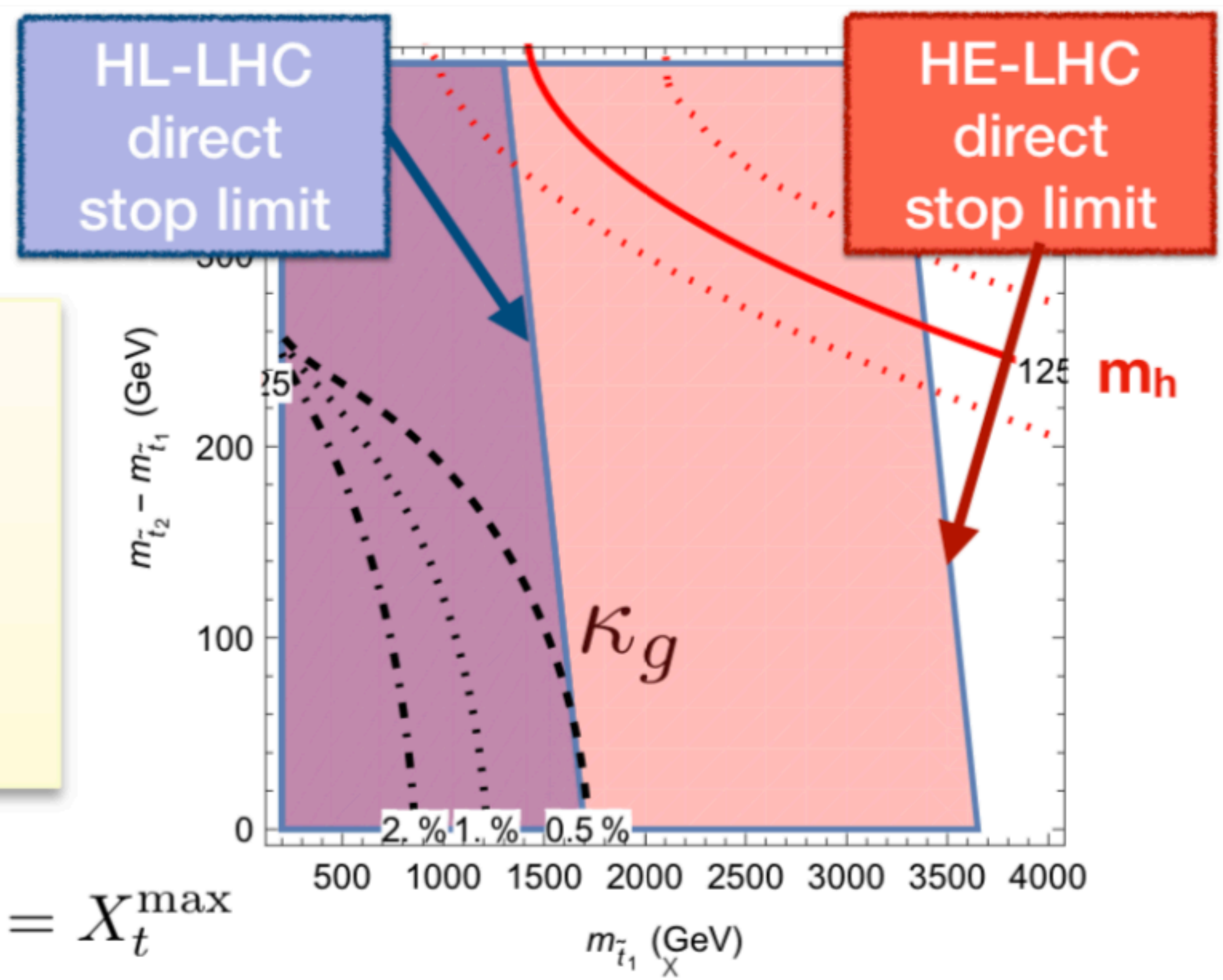
$$\frac{\delta\mathcal{O}_{\rm SUSY}}{\mathcal{O}_{SM}} \sim \frac{m^2_{\rm SM}}{m^2_{\rm SUSY}}$$



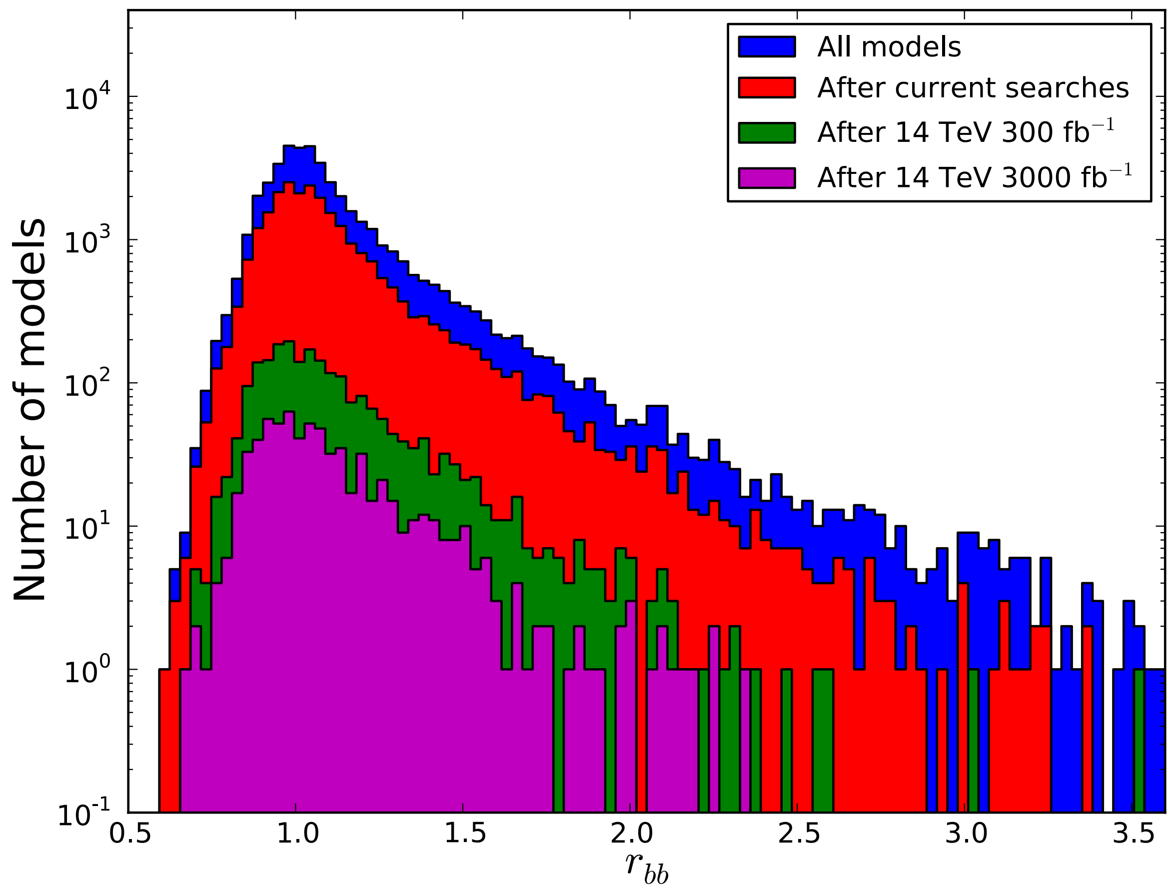
$$r_g - 1 \approx \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}_1}^2} \approx 0.7\% \left(\frac{1\,{\rm TeV}}{m_{\tilde{t}_1}^2}\right)^2$$

With HL-LHC stop limit: also for X_t=0

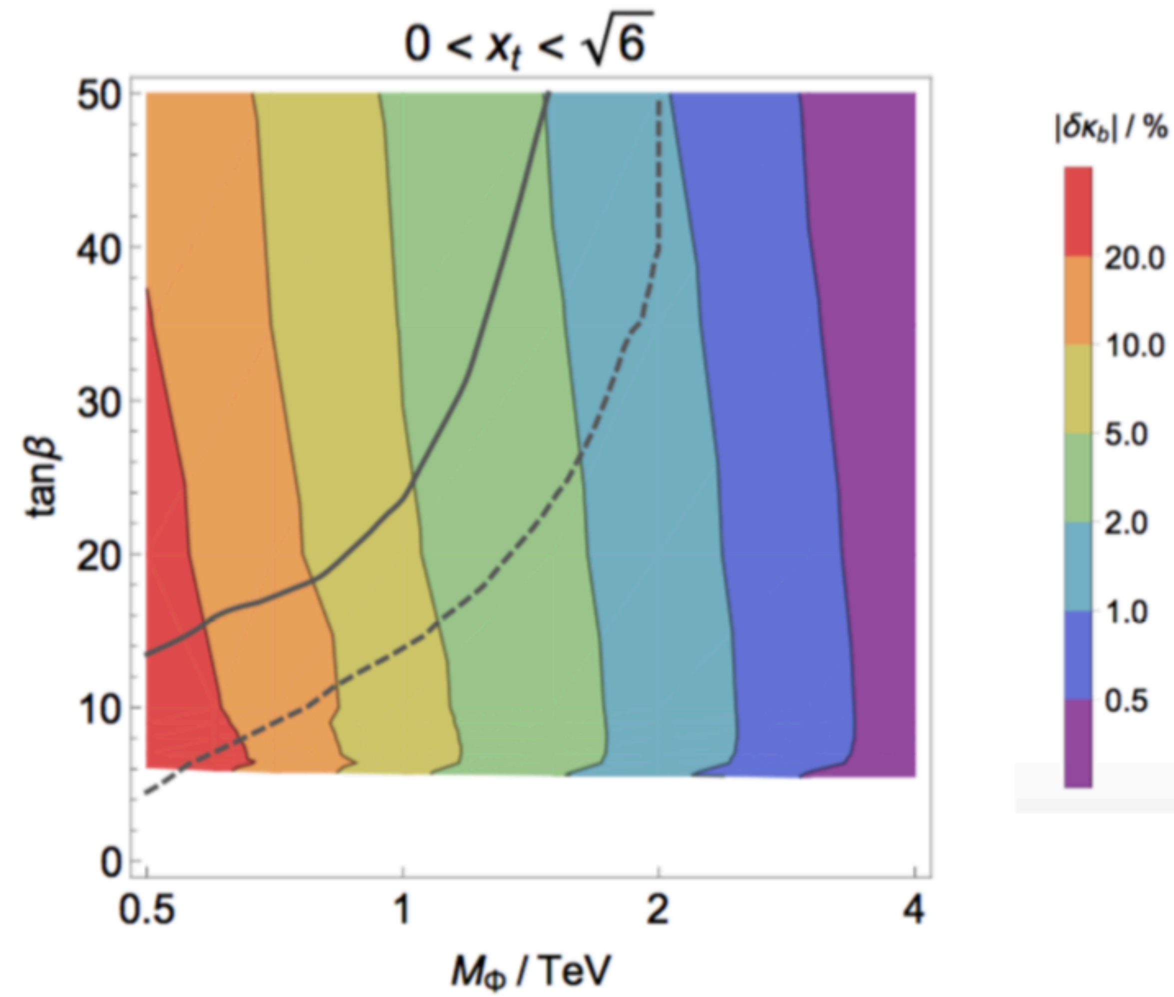
$$X_t = X_t^{\rm max}$$



direct and indirect discoveries: complementarity



Cahill-Rowley, et al, arXiv:1308.0297



Wells, Zhang, arXiv:1711.04774

an orthogonal way to discoveries w.r.t. direct search:

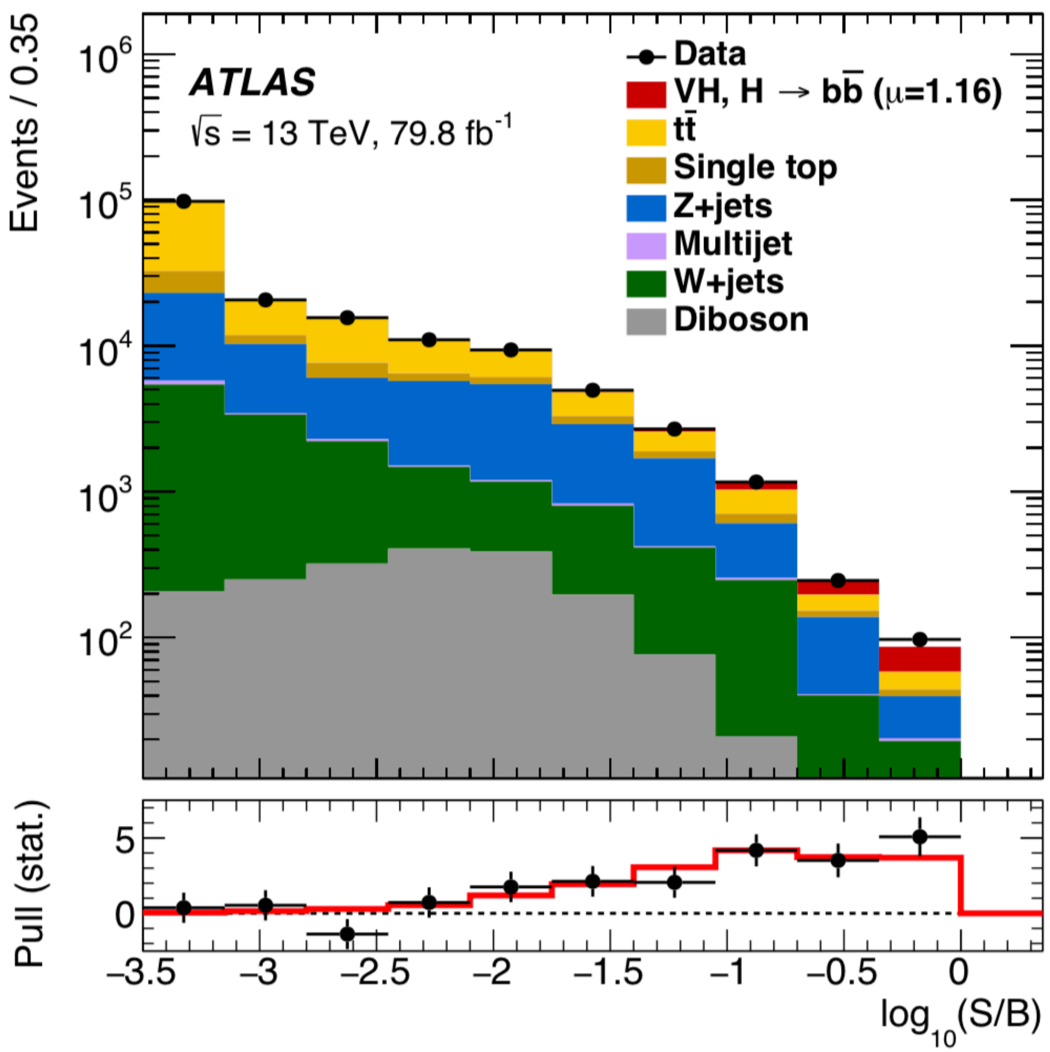
precision Higgs couplings

“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

at LHC

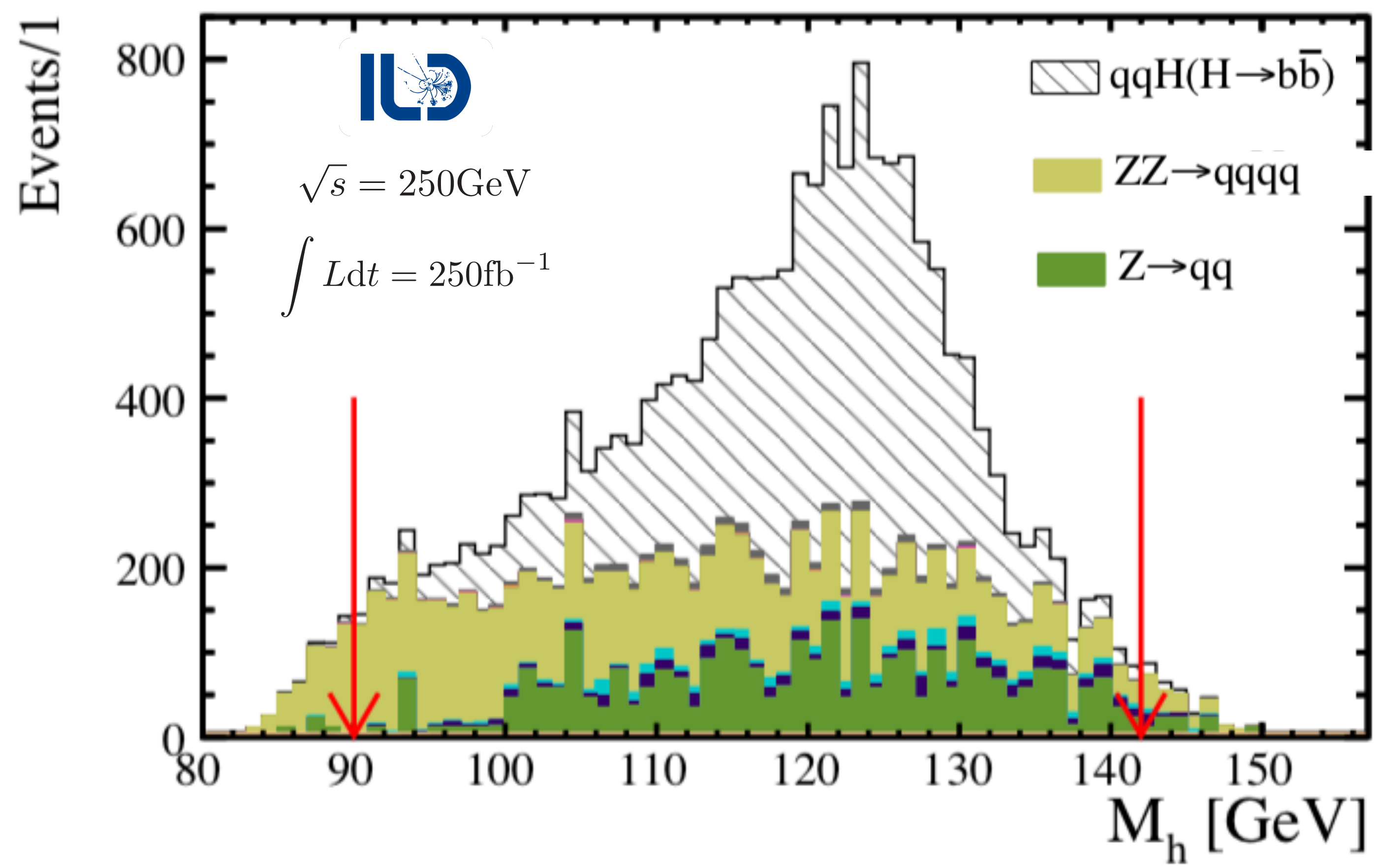


# of Higgs produced: ~4,000,000

significance: 5.4σ

(ATLAS, 1808.08238; CMS, 1808.08242)

at e+e-



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

~400

5.2σ

(Ogawa, PhD Thesis, ILD full simulation)

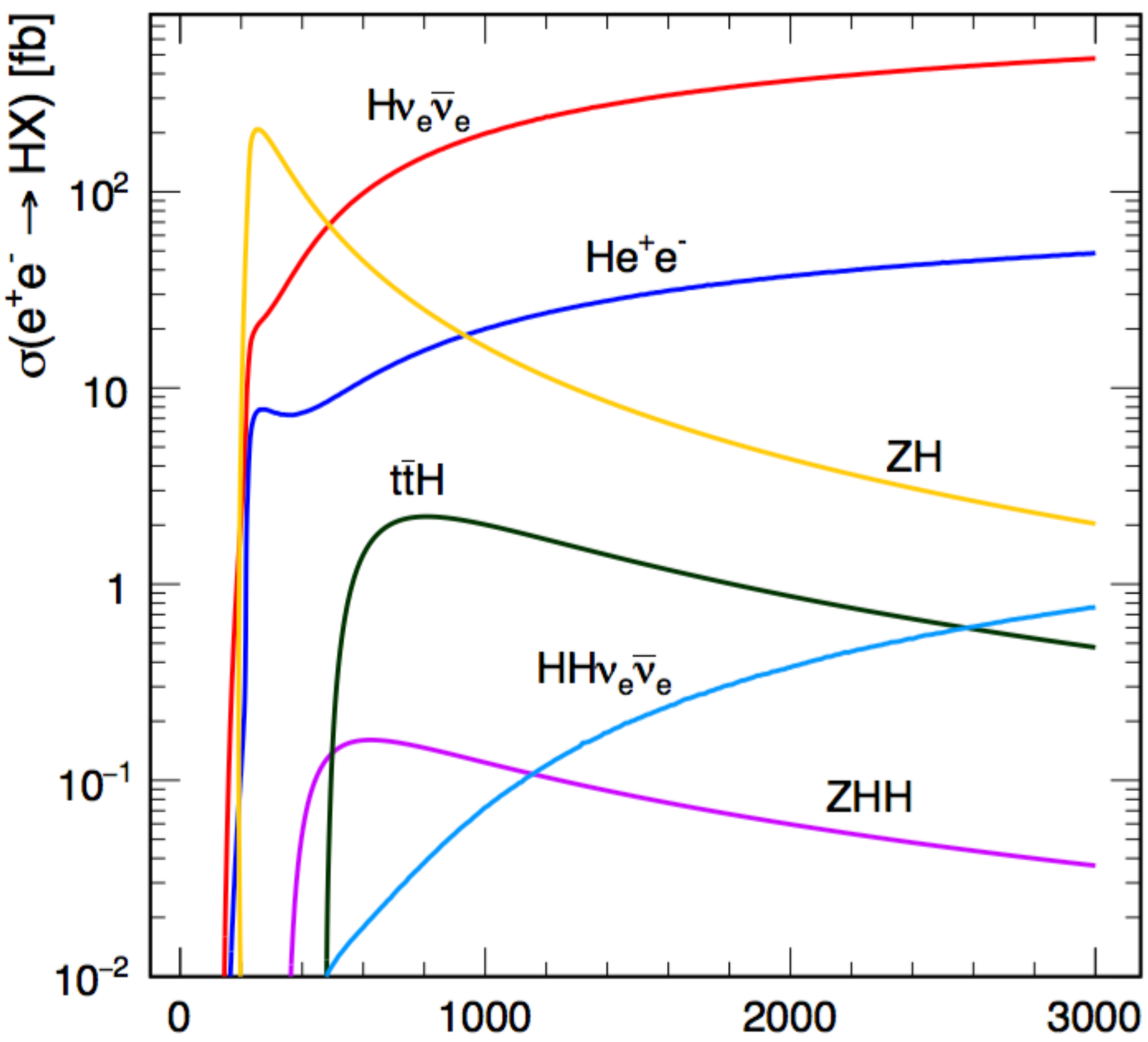
proposals of future lepton colliders

see more in next week's talks

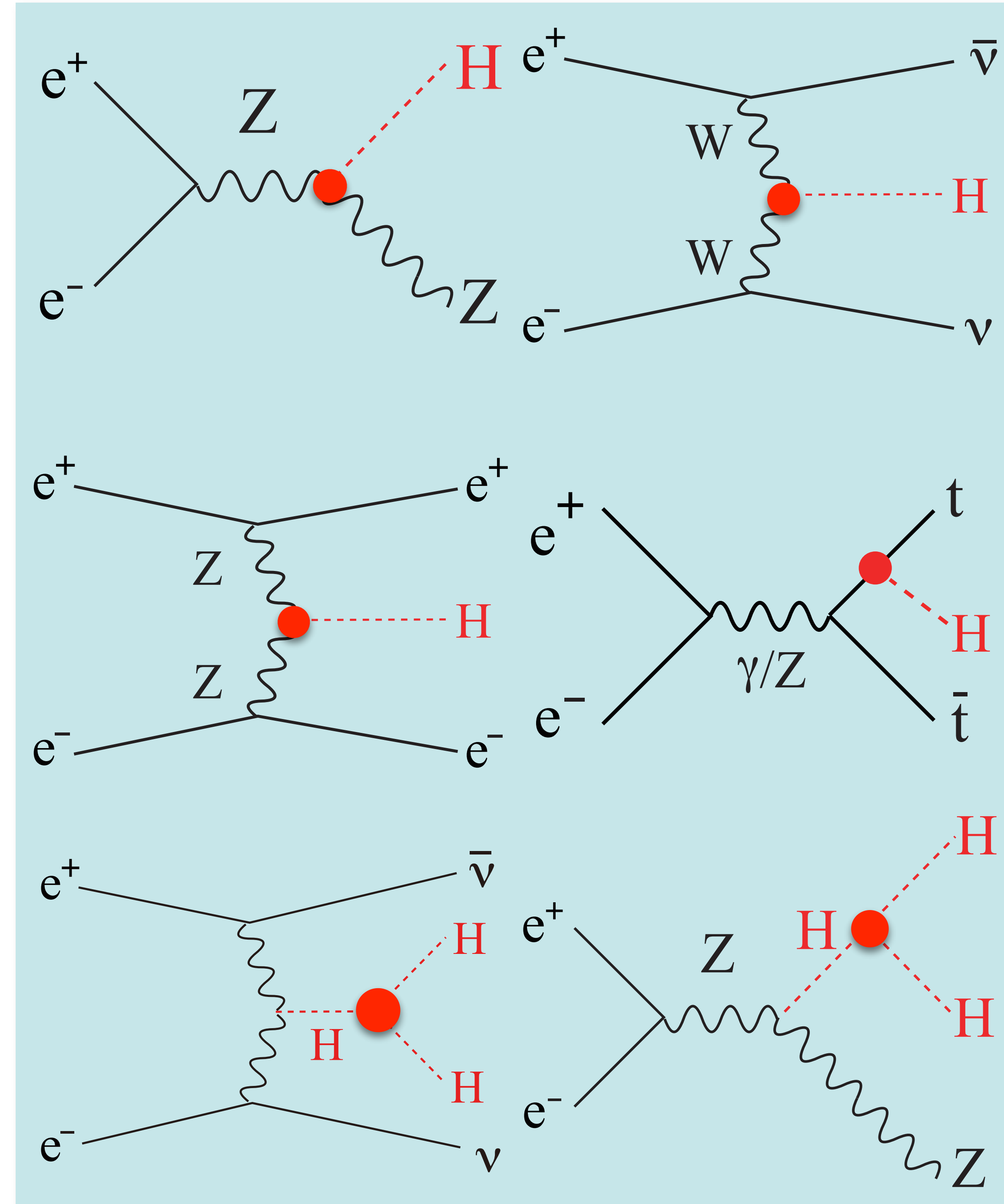
	$\sqrt{s}$	beam polarisation	$\int L dt$ for Higgs	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2000 fb^{-1} @ 250 GeV 200 fb^{-1} @ 350 GeV 4000 fb-1 @ 500 GeV 8000 fb-1 @ 1 TeV	TDR completed
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	500 fb^{-1} @ 380 GeV 1500 fb^{-1} @ 1.4 TeV 2500 fb^{-1} @ 3 TeV	CDR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

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

Higgs productions at e+e-



(unpolarized case)



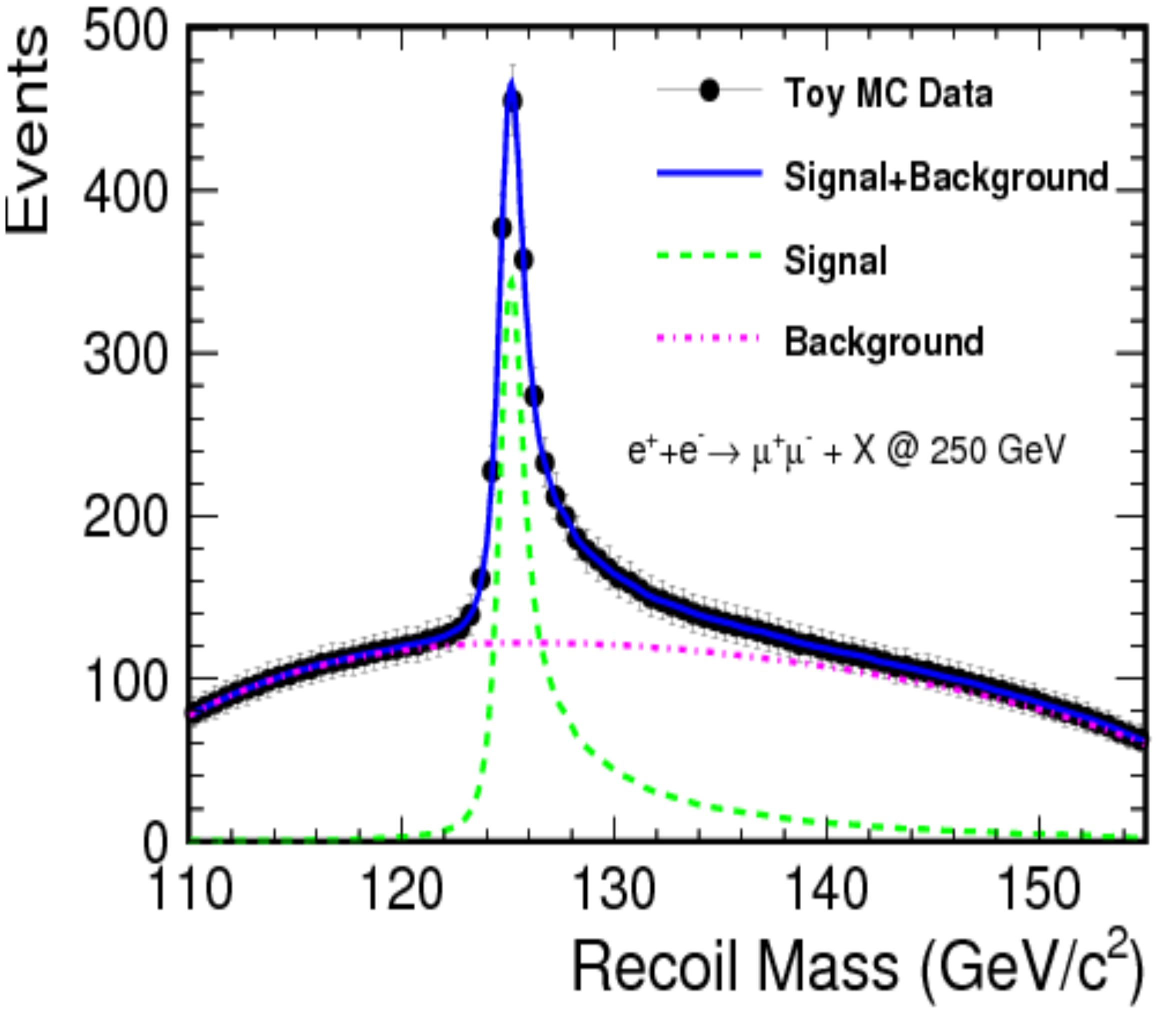
- two apparent important thresholds: √s ~ 250 GeV for ZH, ~500 GeV for ZHH and ttH
- + another threshold for t t-bar, important for Higgs sector as well

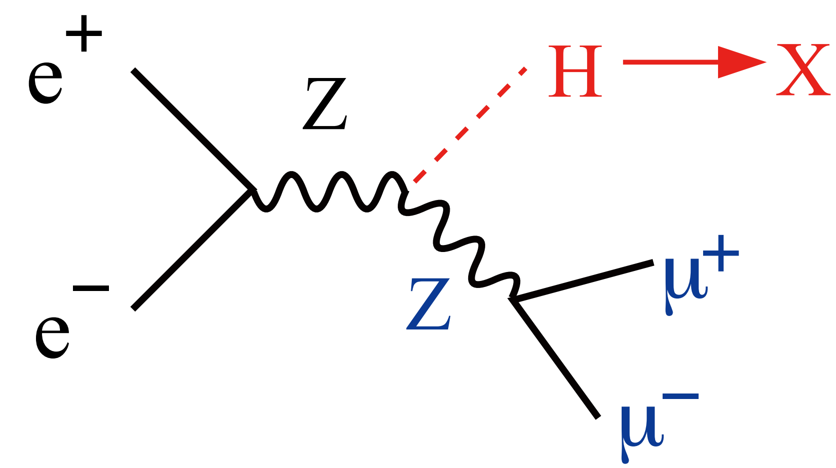
direct experimental observables: some are unique @ e+e-

- ☑ σ_{ZH}
- ☑ $\sigma_{ZH}\times Br(H\to bb)$, $\sigma_{\nu\nu H}\times Br(H\to bb)$
- ☑ $\sigma_{ZH}\times Br(H\to cc)$, $\sigma_{\nu\nu H}\times Br(H\to cc)$
- ☑ $\sigma_{ZH}\times Br(H\to gg)$, $\sigma_{\nu\nu H}\times Br(H\to gg)$
- ☑ $\sigma_{ZH}\times Br(H\to WW^*)$, $\sigma_{\nu\nu H}\times Br(H\to WW^*)$
- ☑ $\sigma_{ZH}\times Br(H\to ZZ^*)$, $\sigma_{\nu\nu H}\times Br(H\to ZZ^*)$
- ☑ $\sigma_{ZH}\times Br(H\to \tau\tau)$, $\sigma_{\nu\nu H}\times Br(H\to \tau\tau)$
- ☑ $\sigma_{ZH}\times Br(H\to \gamma\gamma)$, $\sigma_{\nu\nu H}\times Br(H\to \gamma\gamma)$
- ☑ $\sigma_{ZH}\times Br(H\to \mu\mu)$, $\sigma_{\nu\nu H}\times Br(H\to \mu\mu)$
- ☑ $\sigma_{ZH}\times Br(H\to Invisible)$
- ☑ $\sigma_{ttH}\times Br(H\to bb)$
- ☑ $\sigma_{ZHH}\times Br^2(H\to bb)$, $\sigma_{\nu\nu HH}\times Br^2(H\to bb)$

note the important synergy with LHC: H->γγ/γZ/μμ

(ii-1) inclusive σ_{ZH}: the key for model independence



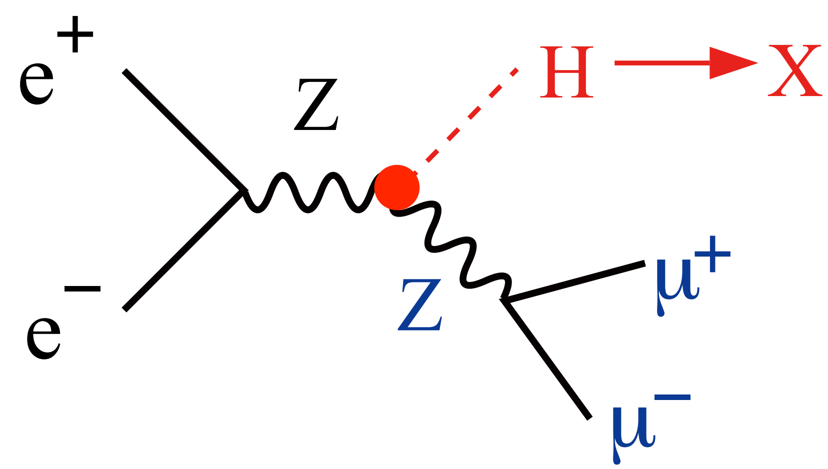


$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

for Z->ll, Yan et al, arXiv:1604.07524;
for Z->qq, Thomson, arXiv:1509.02853

- well defined initial states at e+e-
- recoil mass technique —> tag Z only
- Higgs is tagged without looking into H decay
- absolute cross section of e^+e^- —> ZH

what does model independence mean?



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

- meas. of σ_{ZH} doesn't depend on how Higgs decays
- meas. of σ_{ZH} doesn't depend on underlying HZZ vertex

is it really possible?

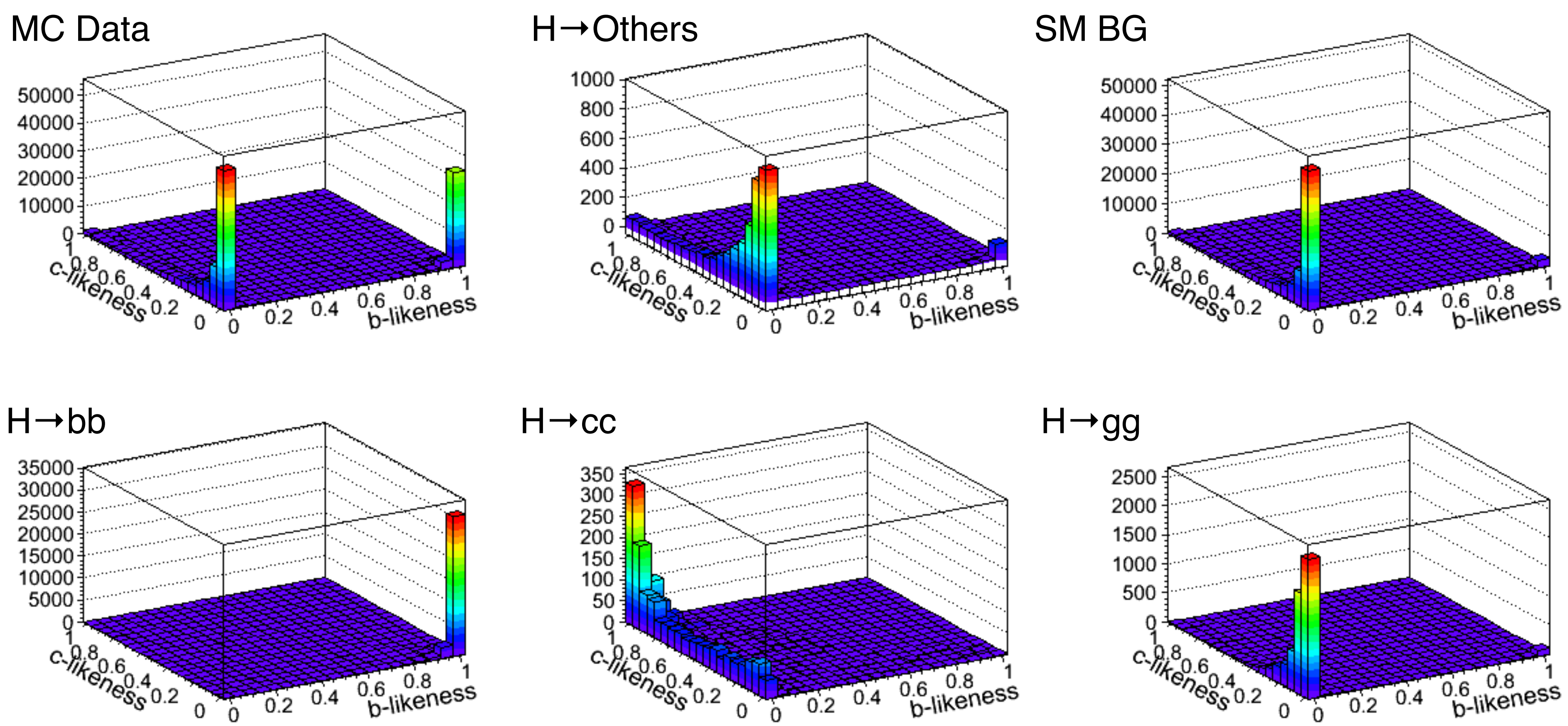
efficiencies for each decay mode (leptonic recoil)

$H \to XX$	bb	cc	gg	$\tau\tau$	WW^*	ZZ^*	$\gamma\gamma$	γZ
BR (SM)	57.8%	2.7%	8.6%	6.4%	21.6%	2.7%	0.23%	0.16%
Lepton Finder	93.70%	93.69%	93.40%	94.02%	94.04%	94.36%	93.75%	94.08%
Lepton ID+Precut	93.68%	93.66%	93.37%	93.93%	93.94%	93.71%	93.63%	93.22%
$M_{l^+l^-} \in [73, 120]$ GeV	89.94%	91.74%	91.40%	91.90%	91.82%	91.81%	91.73%	91.47%
$p_T^{l^+l^-} \in [10, 70]$ GeV	89.94%	90.08%	89.68%	90.18%	90.04%	90.16%	89.99%	89.71%
$\lvert\cos\theta_{miss}\rvert < 0.98$	89.94%	90.08%	89.68%	90.16%	90.04%	90.16%	89.91%	89.41%
BDT > - 0.25	88.90%	89.04%	88.63%	89.12%	88.96%	89.11%	88.91%	88.28%
$M_{rec} \in [110, 155]$ GeV	88.25%	88.35%	87.98%	88.43%	88.33%	88.52%	88.21%	87.64%

(ii-2) Higgs direct couplings to bb, cc and gg

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

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



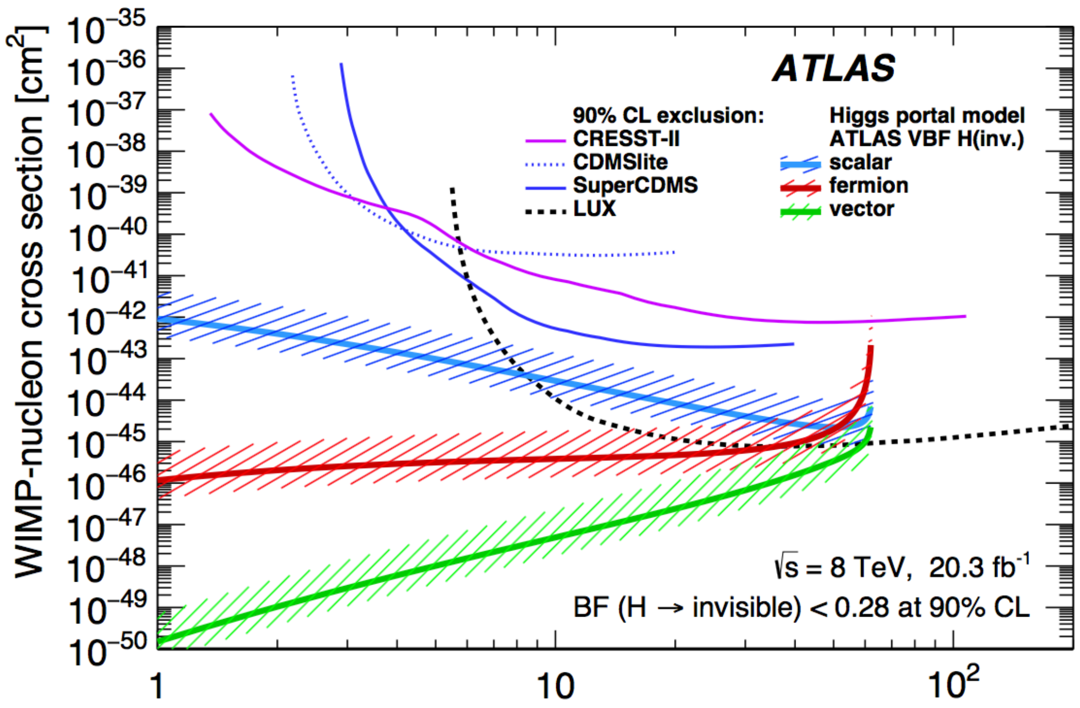
Ono, et. al, Euro. Phys. J. C73, 2343; F.Mueller, PhD thesis (DESY)

(ii-3) search of Higgs to invisible

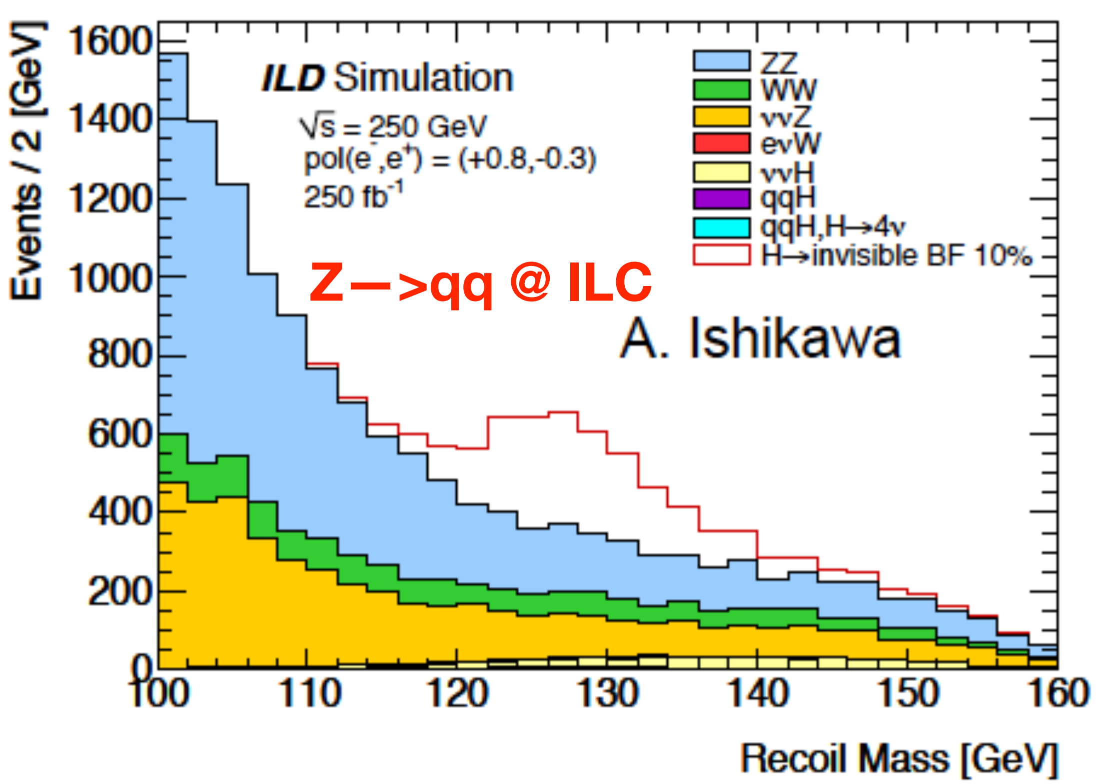
see H.Yamamoto's talk

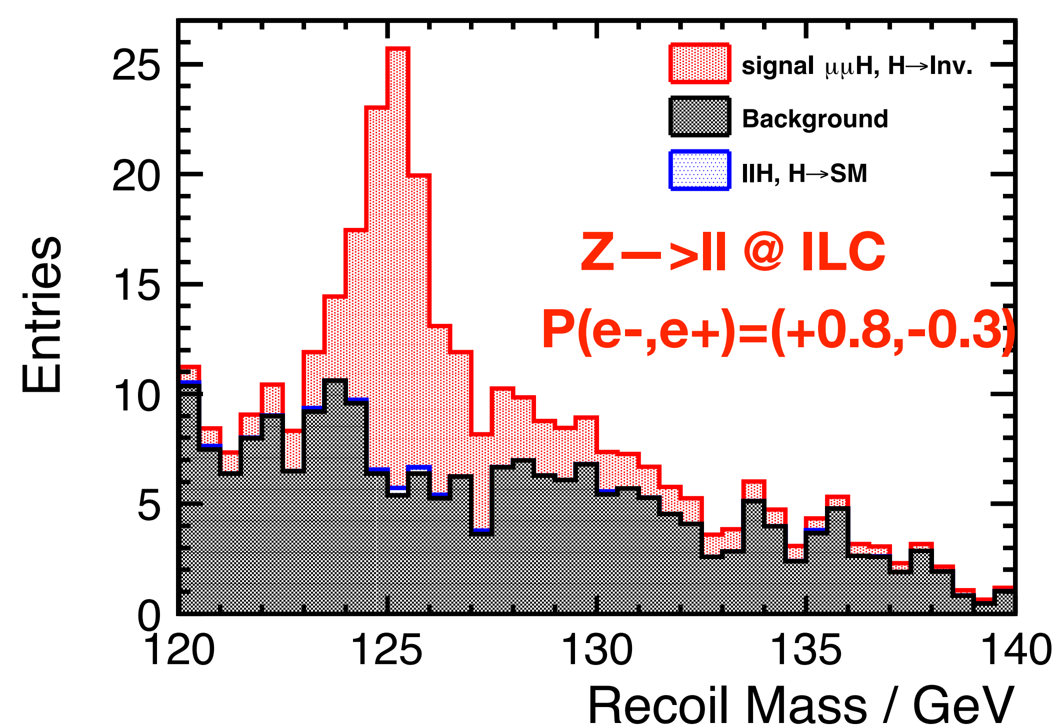
$$e^+ + e^- \to ZH \to l^+l^-/q\bar{q} + \text{Missing}$$

- BR(H—>inv.) < 0.3% (CL95%)
- a sensitive test for Higgs portal dark mater model —> complementary for low mass
- right-handed beam polarization: much lower background



JHEP 1601 (2016) 172





(ii-4) determine Higgs CP (admixture)

- find CP-violating source in Higgs sector —> EW baryongenesis
- essential to understand structures of all Higgs couplings

through H—>$\tau^+\tau^-$
(or ttH)

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

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

Jeans et al, 1804.01241

through HZZ/HWW

$$L_{HVV} = 2C_V M_V^2 (\frac{1}{v} + \frac{a}{\Lambda}) H V_\mu V^\mu + C_V \frac{b}{\Lambda} H V_{\mu\nu} V^{\mu\nu} + C_V \frac{\tilde{b}}{\Lambda} H V_{\mu\nu} \tilde{V}_{\mu\nu}$$

(CP-odd)

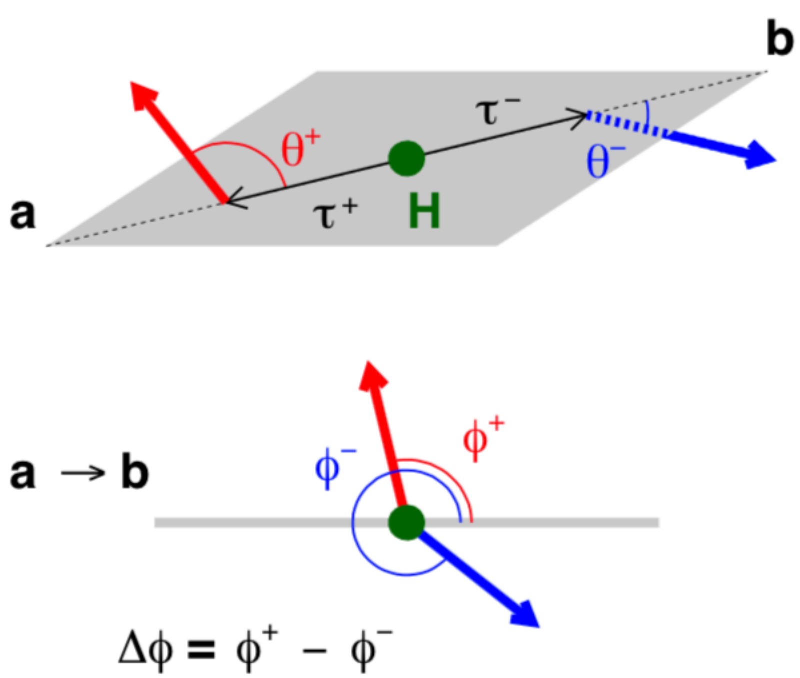
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

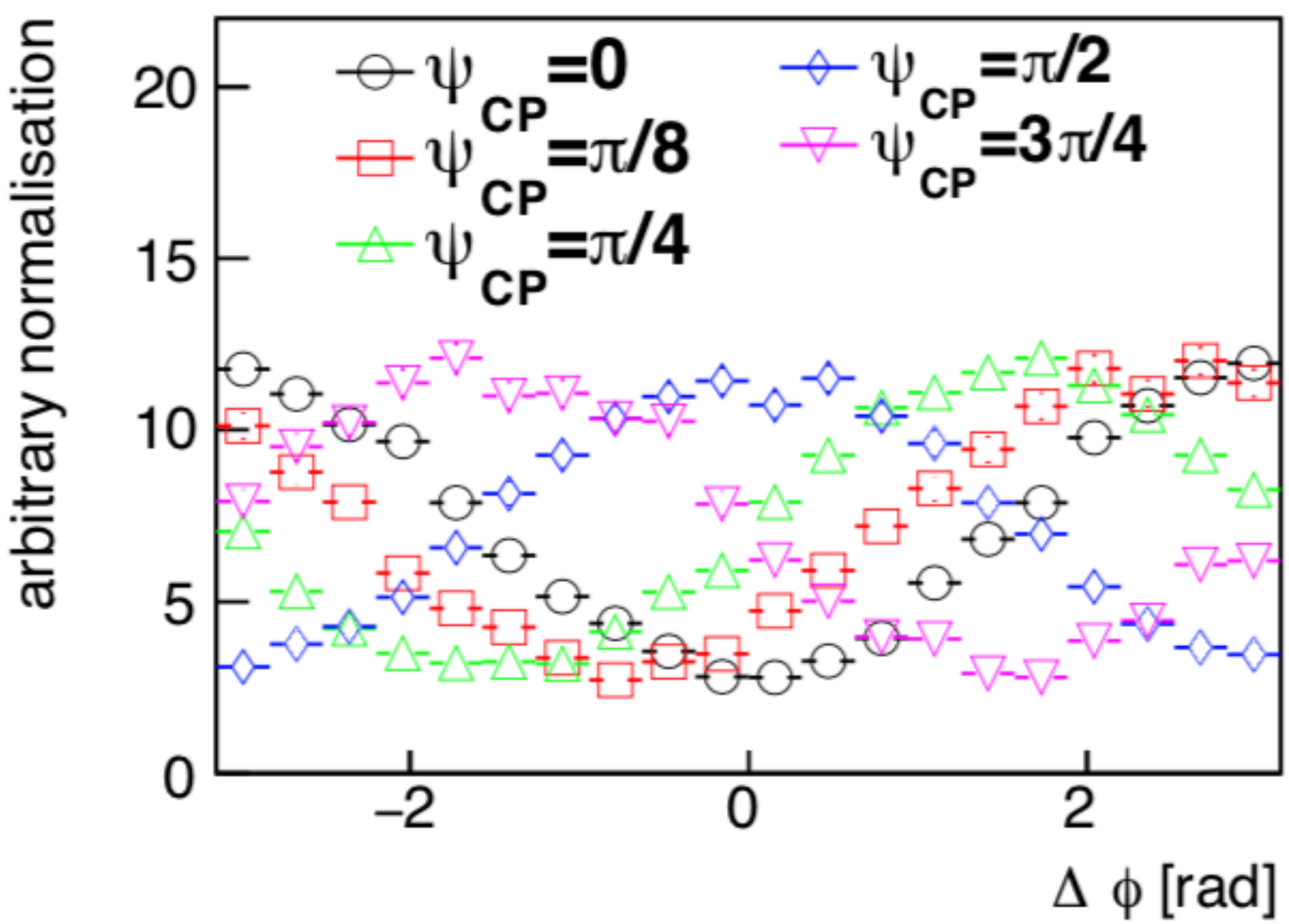
Ogawa, 1712.09772

for BR(H—>τ+τ-): Kawada, et. al, Eur.Phys.J. C75 (2015), 617

CP sensitive observable in $H \to \tau^+\tau^-$

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



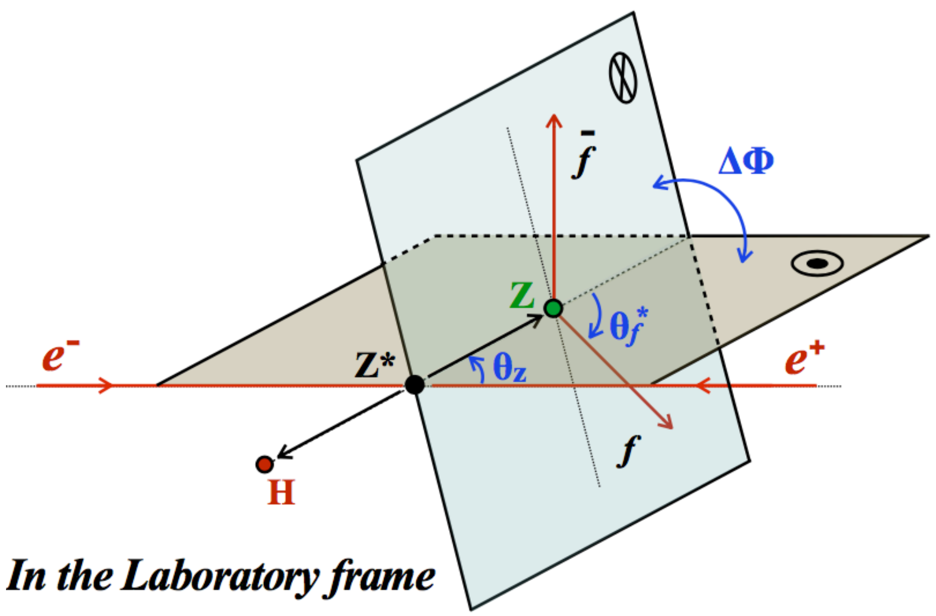


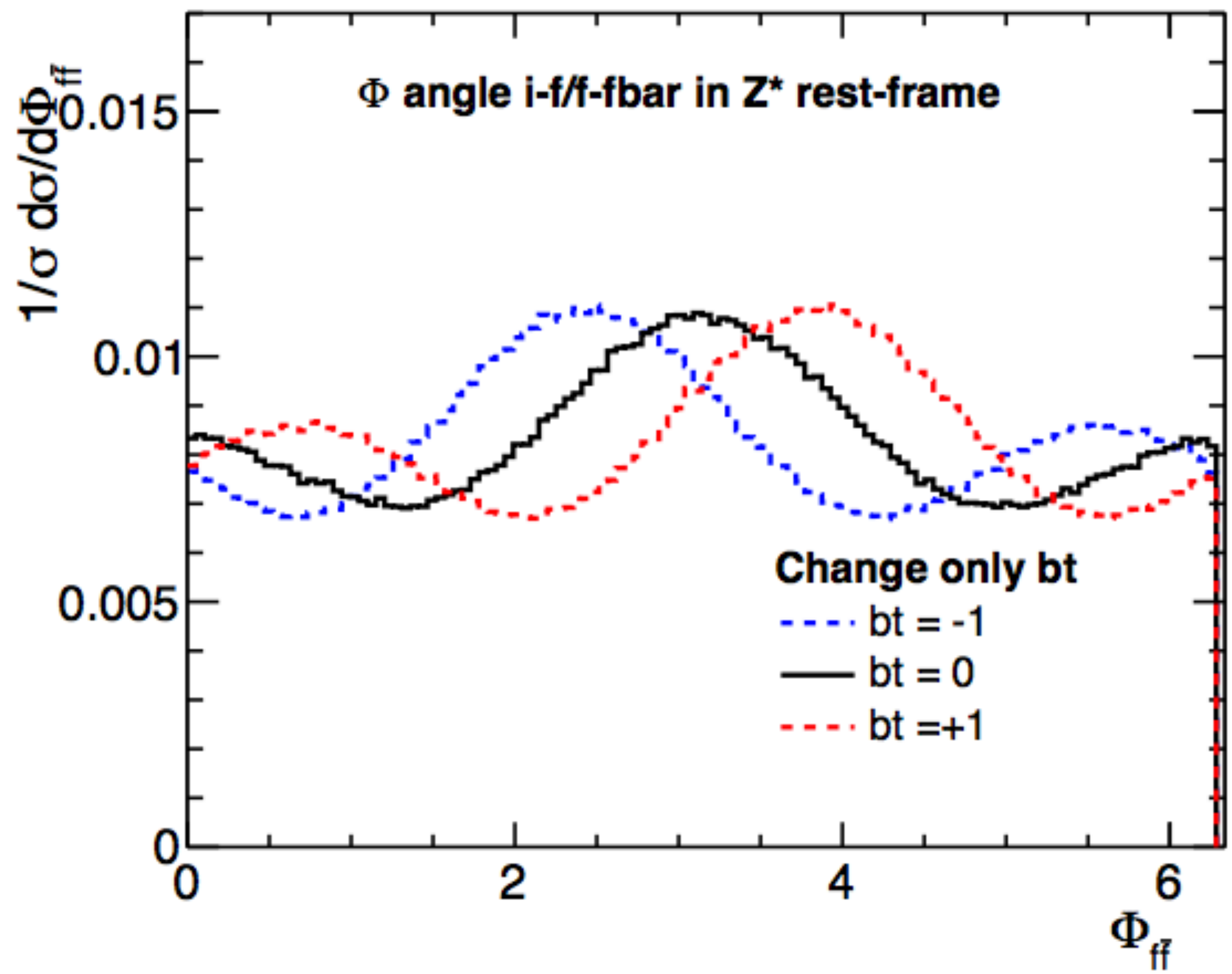
CP sensitive observable in HZZ coupling

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

(CP-odd)

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





$@\ \sqrt{s} = 250\text{GeV}$

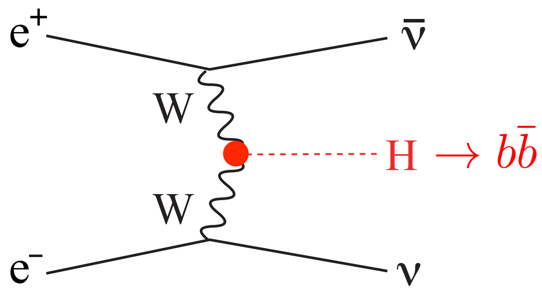
(ii-5) WW-fusion channel & Higgs total width Γ_H

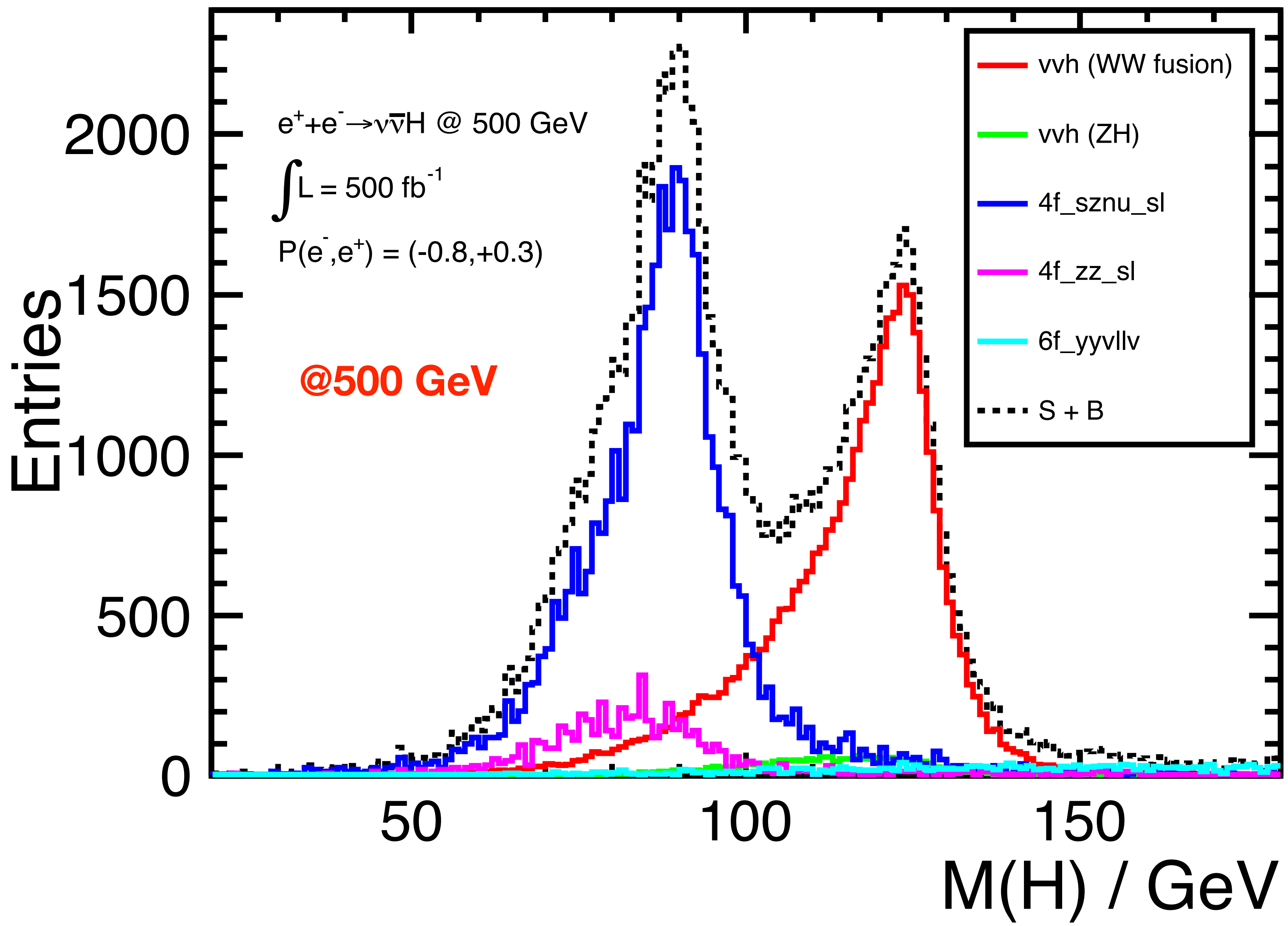
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

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

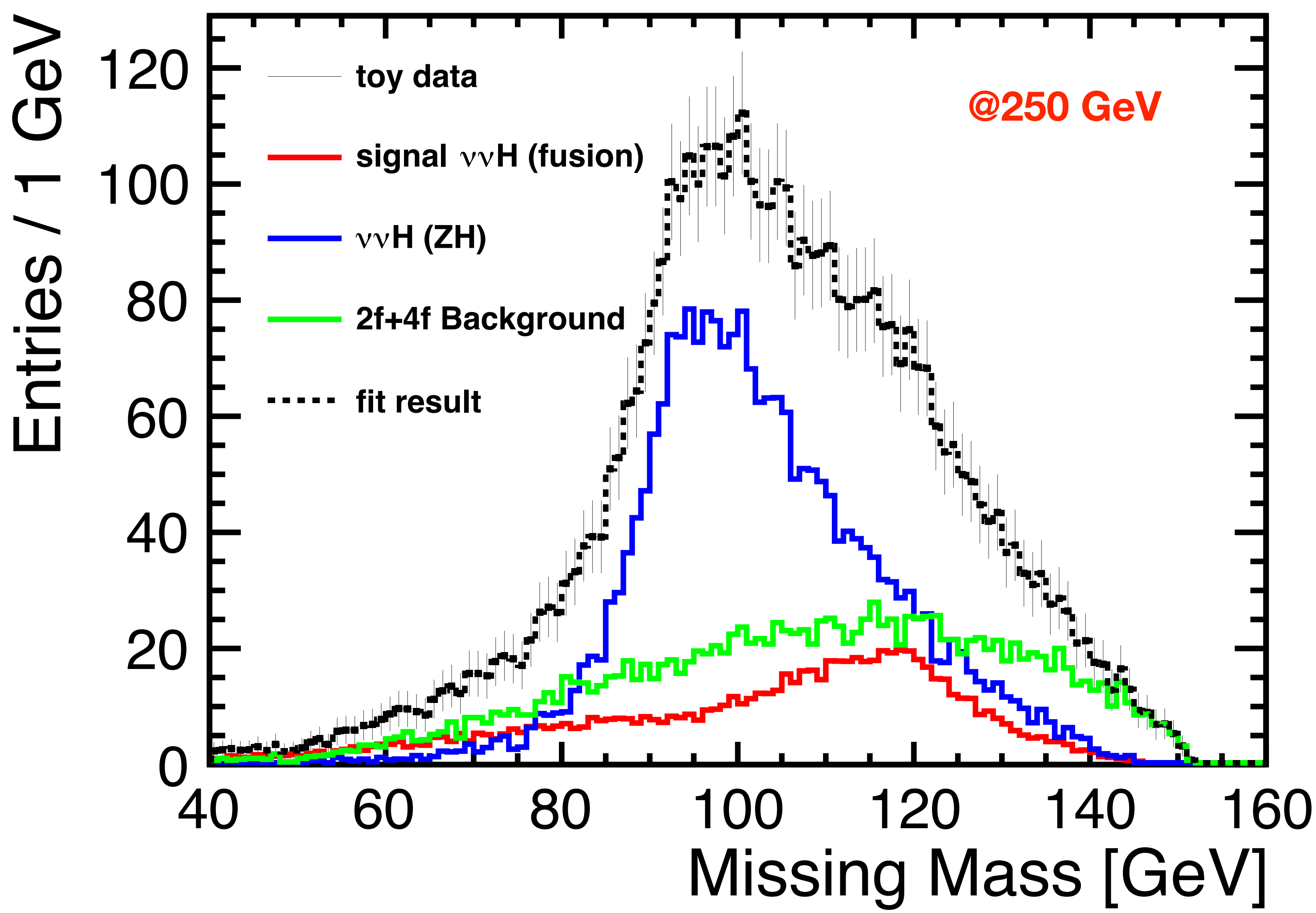
—> better option!

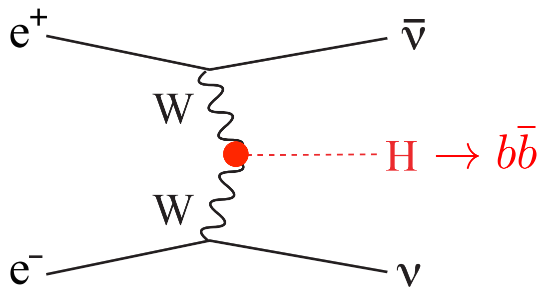




Duerig, et al., arXiv:1403.7734

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)

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

(iii) Higgs coupling determination

— model independent way

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*)

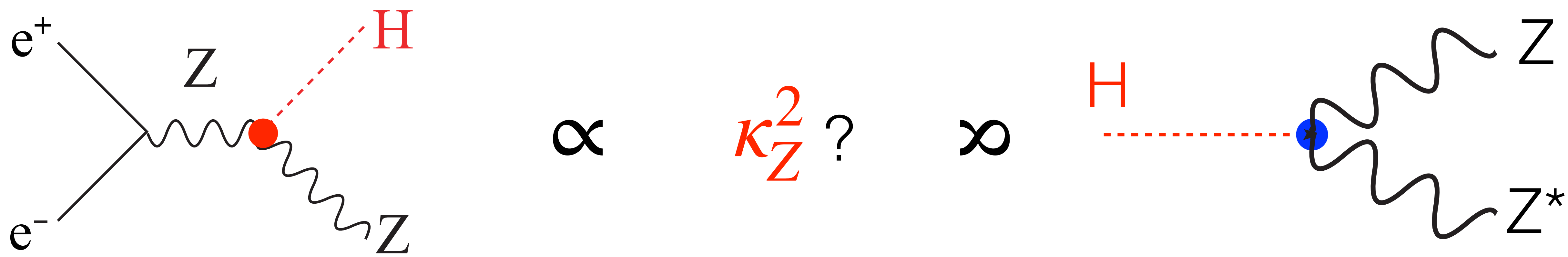
5) or $\boldsymbol{\Gamma_h}$ = Γ(h—>WW*)/BR(h->WW*)

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

one question in kappa formalism:

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

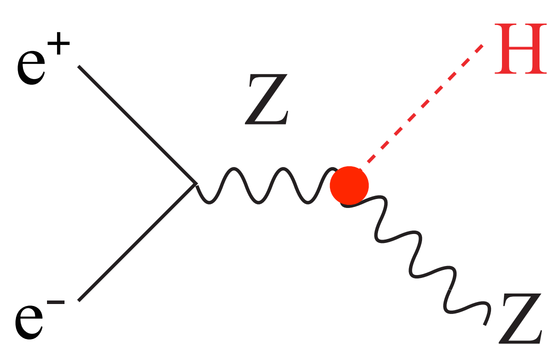


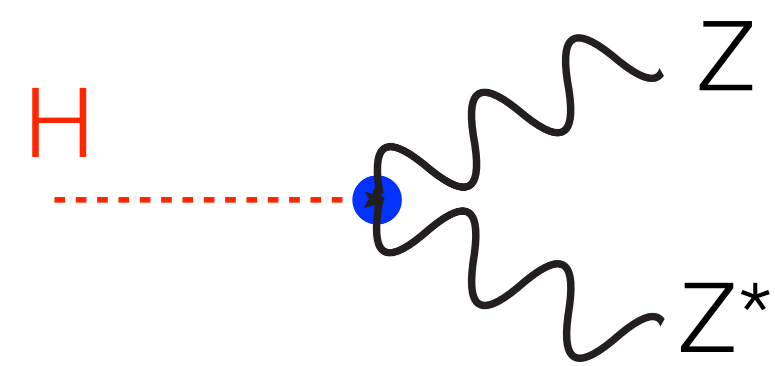
BSM territory -> can deviations be represented by single κ_Z?

the answer is model dependent

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

BSM can induce new Lorentz structures in hZZ





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

- there is a better, theoretical sound framework

a strategy: SM Effective Field Theory

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

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

- 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

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

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

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 Higgs physics at e+e-

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

("Warsaw" basis by Grzadkowski et al)

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

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

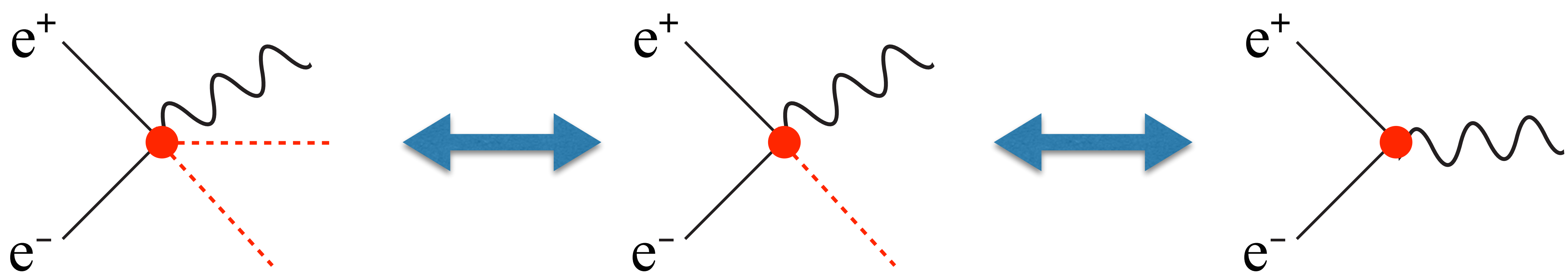
+ 2 parameters for h->invisible and exotic

recap 1: Higgs couplings are related to W-/Z- couplings (EWPOs)

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

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

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



e^+e^- ->Zhh

e^+e^- ->Zh

Z-pole

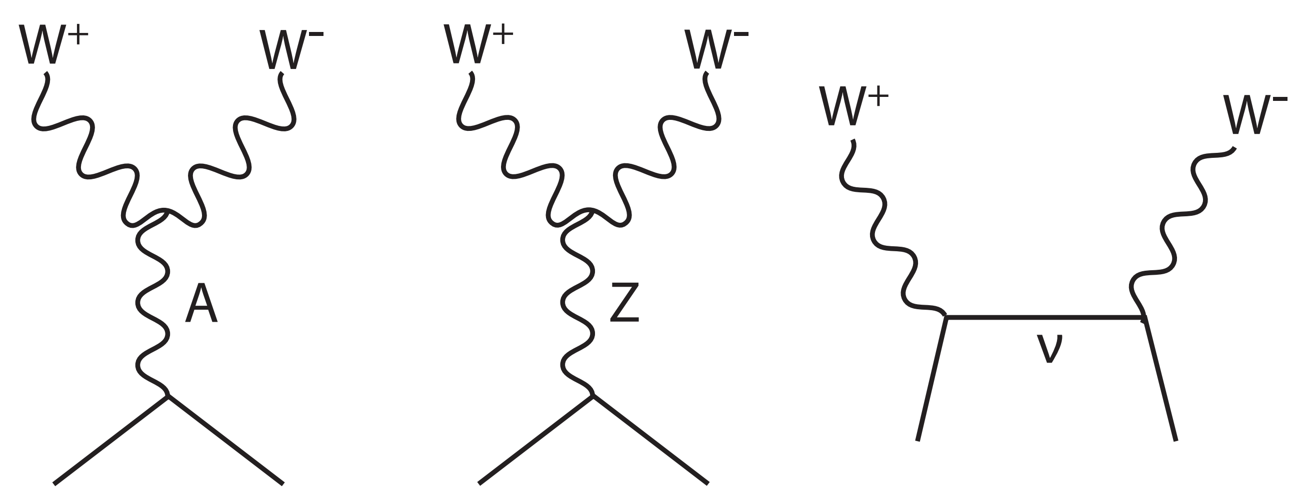
- contact interactions from $c_{HL}/c_{HL}'/c_{HE}$ in Higgs processes can be constrained by EWPOs at Z-pole: $\boldsymbol{A_{LR}}$, $\boldsymbol{\Gamma_l}$

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

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

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

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



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

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

- longitudinal modes of W/Z are from Higgs fields
- $c_{WW}/c_{WB}/c_{BB}$ appear also in higgs couplings

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

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

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

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

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

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

recap 5: 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^- -> Zh, enabled by recoil mass technique at e+e-

recap 6: hWW is determined as precisely as hZZ @ $\sqrt{s}$ = 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 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%: highly constrained by SU(2) x U(1) gauge theory

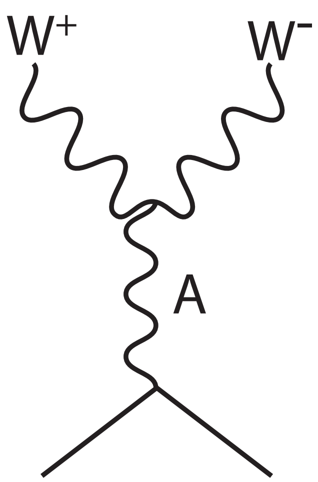
typical precisions by EFT: combined EWPO+TGC+Higgs fit

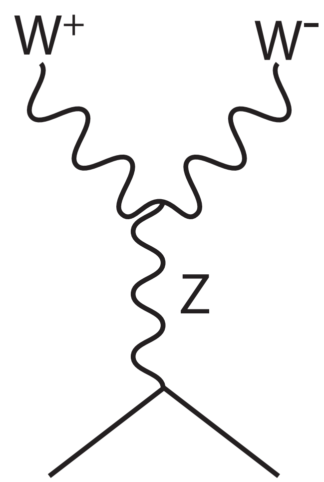
ILC250: $\int L dt$ = 2 ab^{-1} @ 250 GeV

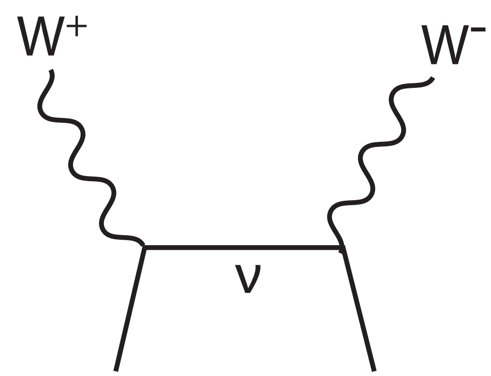
coupling $\Delta g/g$	kappa-fit	EFT-fit
hZZ	0.38%	0.50%
hWW	1.8%	0.50%
hbb	1.8%	0.99%
Γ_h	3.9%	2.3%

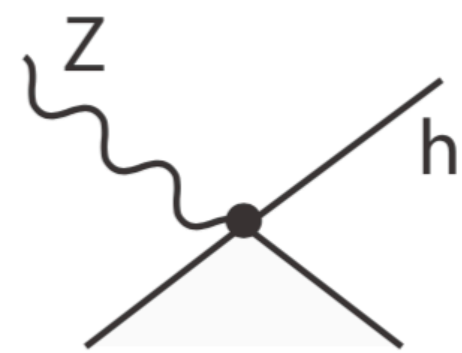
(for hZZ and hWW couplings: 1/2 of partial width precision)

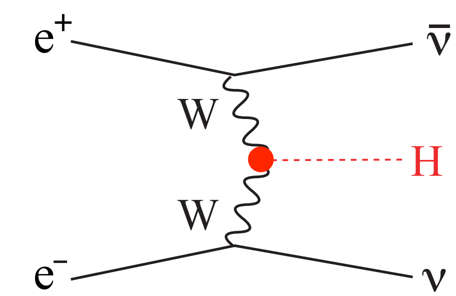
impact of √s in SMEFT











- dependences on aTGC and contact interactions grow as s/m_Z^2

- W-fusion process becomes very useful at √s>= 500 GeV

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

("Warsaw" basis by Grzadkowski et al)

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

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

Electroweak Precision Observables	(9)
+	
Triple Gauge boson Couplings	(3)
+	
Higgs observables at LHC & ILC	(3+12x2)

↑ 2 beam polarizations

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

(details in backup)

strategy to determine all the 23 parameters

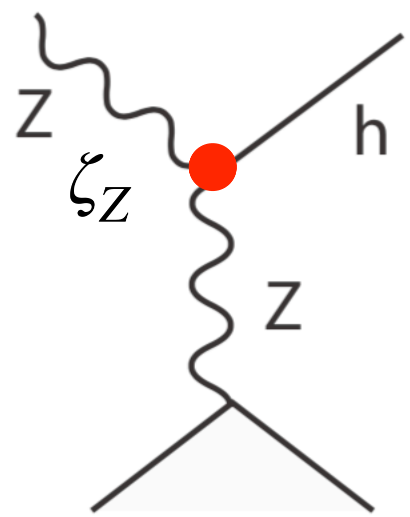
- m_W and $\alpha(m_Z)$ -> g, g';
- G_F -> v; m_h -> λ; m_Z -> c_T;
- A_l and Γ_l -> $c_{HL}+c_{HL}'$, c_{HE};
- Γ_W and Γ_Z -> c_W, c_Z;

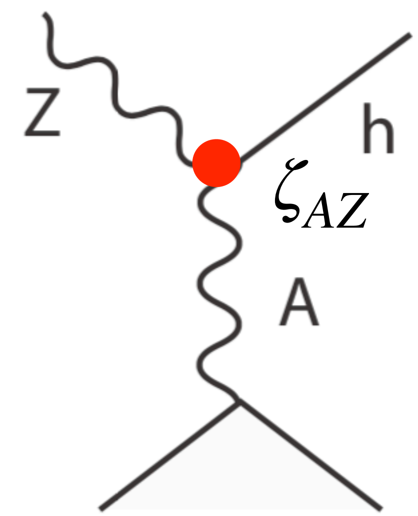
- g_{1Z} -> c_{HL}'; κ_γ -> c_{WB}; κ_λ -> c_{3W};

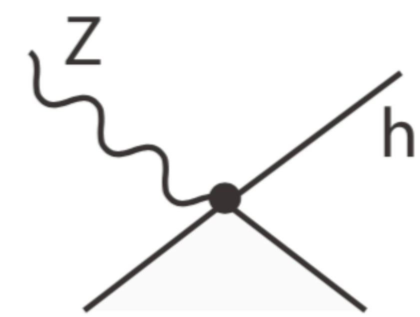
- $BR(h\to\gamma\gamma)$ and $BR(h\to\gamma Z)$ -> c_{BB}, c_{WW};
- σ_{ZH} -> c_H; σ_{ZHH} -> c_6;
- $BR(h\to bb/cc/gg/\mu\mu/\tau\tau)$ -> y_b, y_c, c_g, y_μ, y_τ;
- *BR(h->invisible)* and *BR(h->other)*;
- c_{WW} is helped by A_{LR} in σ_{ZH}, angular meas., W-fusion;
- $c_{HL}/c_{HL}'/c_{HE}$ are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

(details in backup)

recap 7: role of beam polarizations (e.g. at ILC/CLIC)







$P(e^-,e^+)$	ζ_Z	ζ_{AZ}	
(-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)	$\frac{g}{\cos\theta_w}(-\sin^2\theta_w)$	$g\sin\theta_w$	$\frac{g}{\cos\theta_w}(c_{HE})$

- large cancellation in (+1,-1) -> weaker dependence on c_{WW}
- A_{LR} in σ_{ZH} -> improve c_{WW}, $c_{HL}+c_{HL}'$ and c_{HE}

recap 7: role of beam polarizations (e+e- -> Zh)

√s=250 GeV

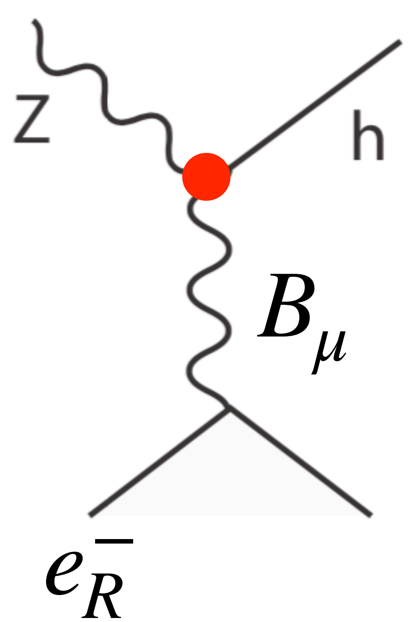
$$\delta\sigma_L = -c_H + 7.7(8c_{WW}) + \ldots$$

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

why?

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

$(8c_{WW}) \sim 0.16\%$

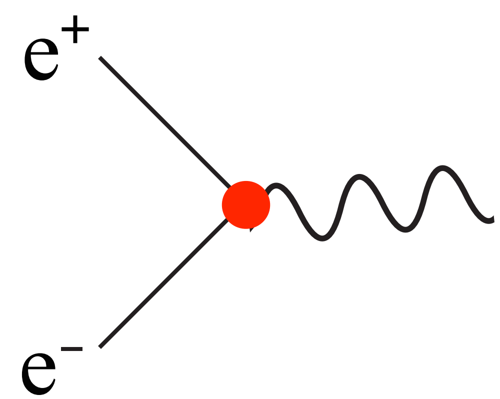


no direct contribution from

except via γ-Z mixing

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

recap 7: role of beam polarizations (EWPOs)



- improve $\boldsymbol{A_l}$ by a factor of 10 using radiative return

- or even more running at GigaZ

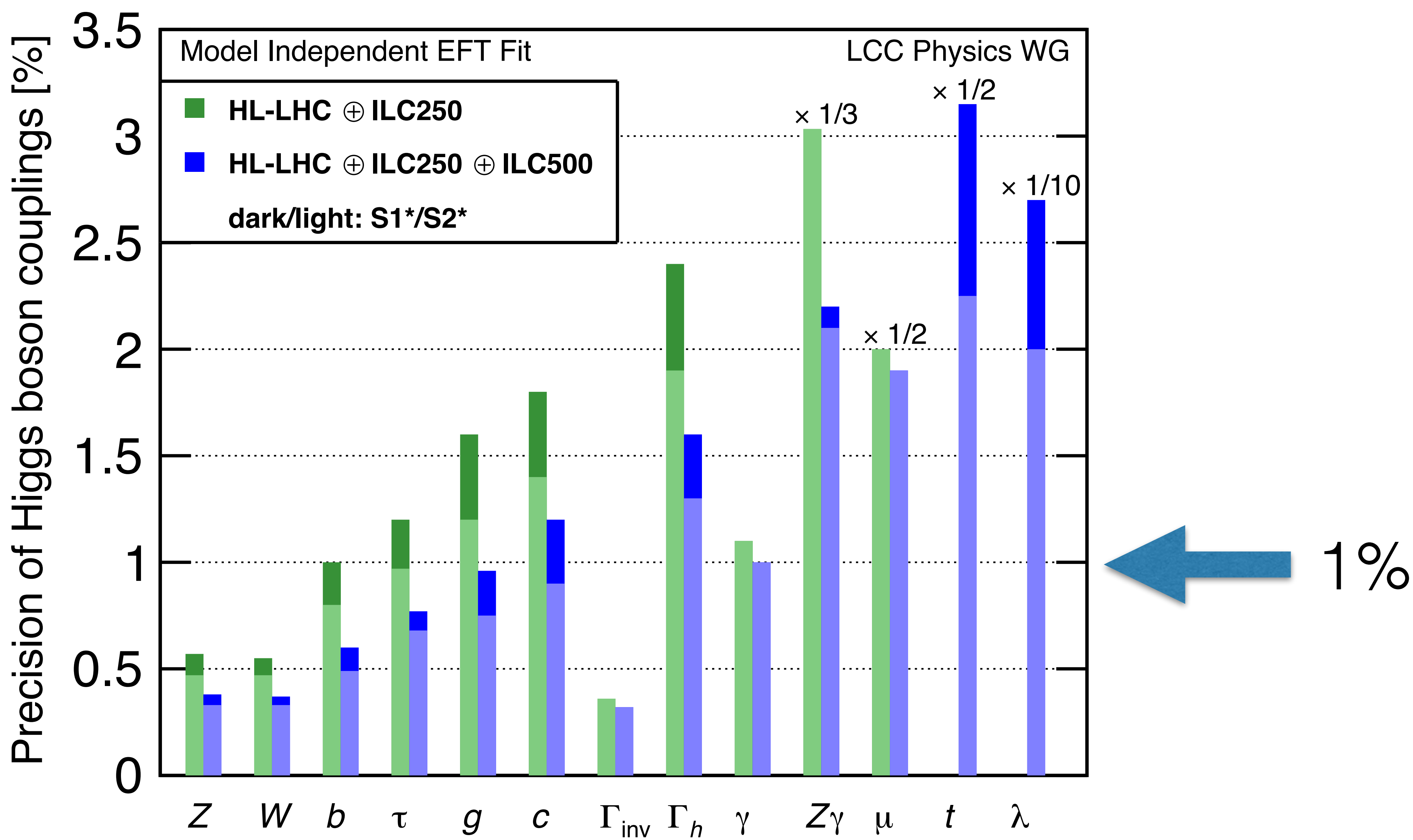
- $\Delta\sin^2\theta_W$ at polarized GigaZ is as good as unpolarized TeraZ: differ only by a factor of 3

recap 7: role of beam polarizations

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

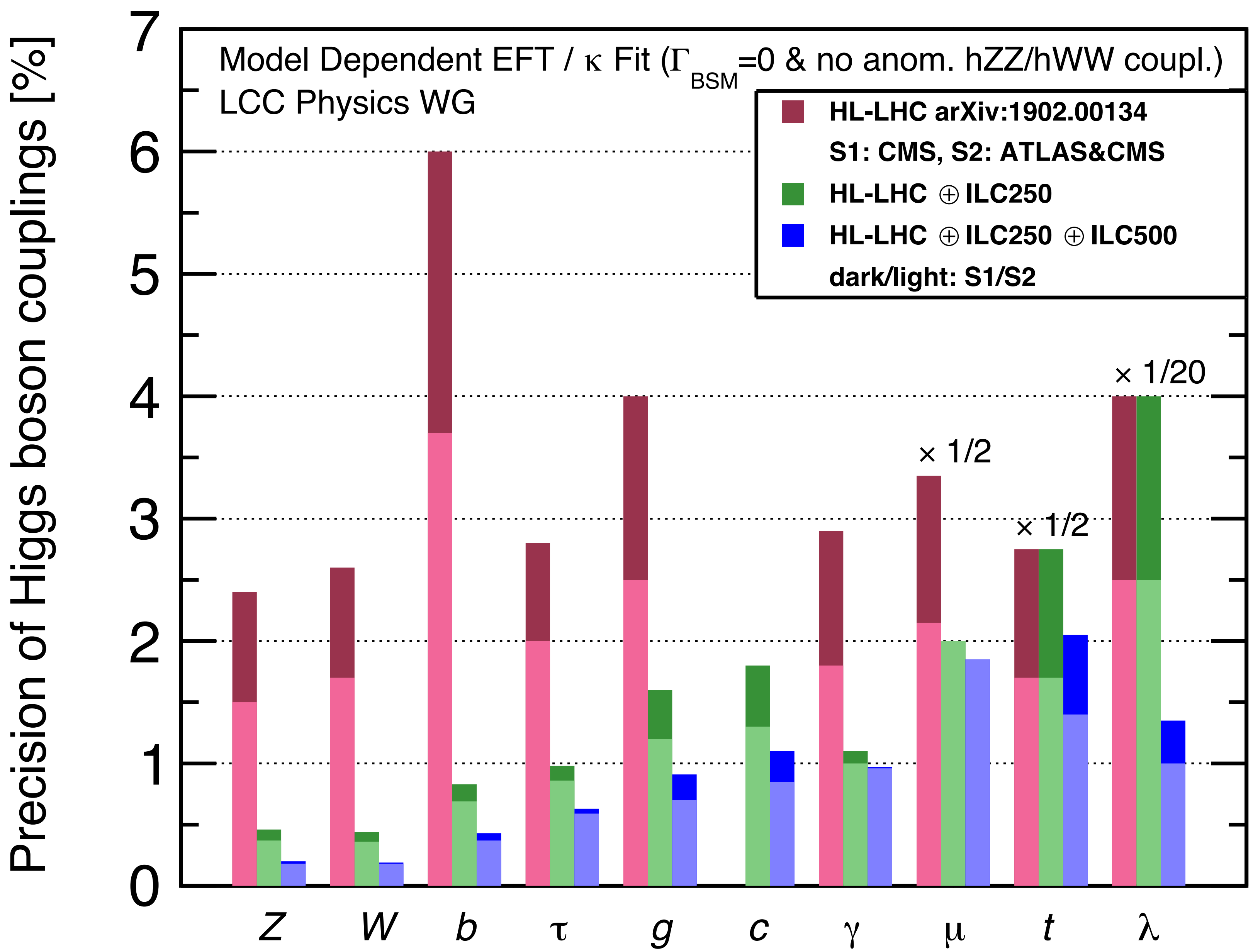
- 250 GeV e+e-: power of 2 ab^{-1} polarized ≈ 5 ab^{-1} unpolarized
- redundancy is important for testing internal consistency

SMEFT: model independent determination of Higgs couplings



- 1% or below precisions will be reached at a 250 e+e-
- discrimination between BSM models (see backup)
- -> future direction of HEP

Higgs precisions: complementarity with LHC



#qualitative:

model independence,

hcc coupling

#quantitative (<~1%):

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

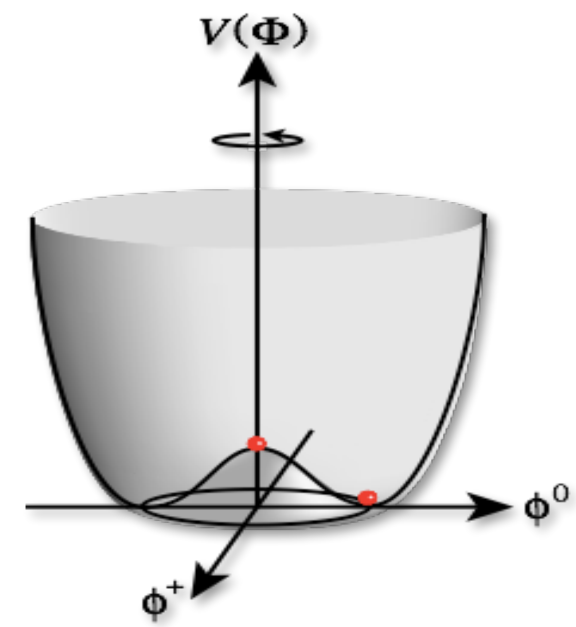
h->invisible/exotic

#synergy:

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

(v) 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- —> vvHH (WW-fusion)

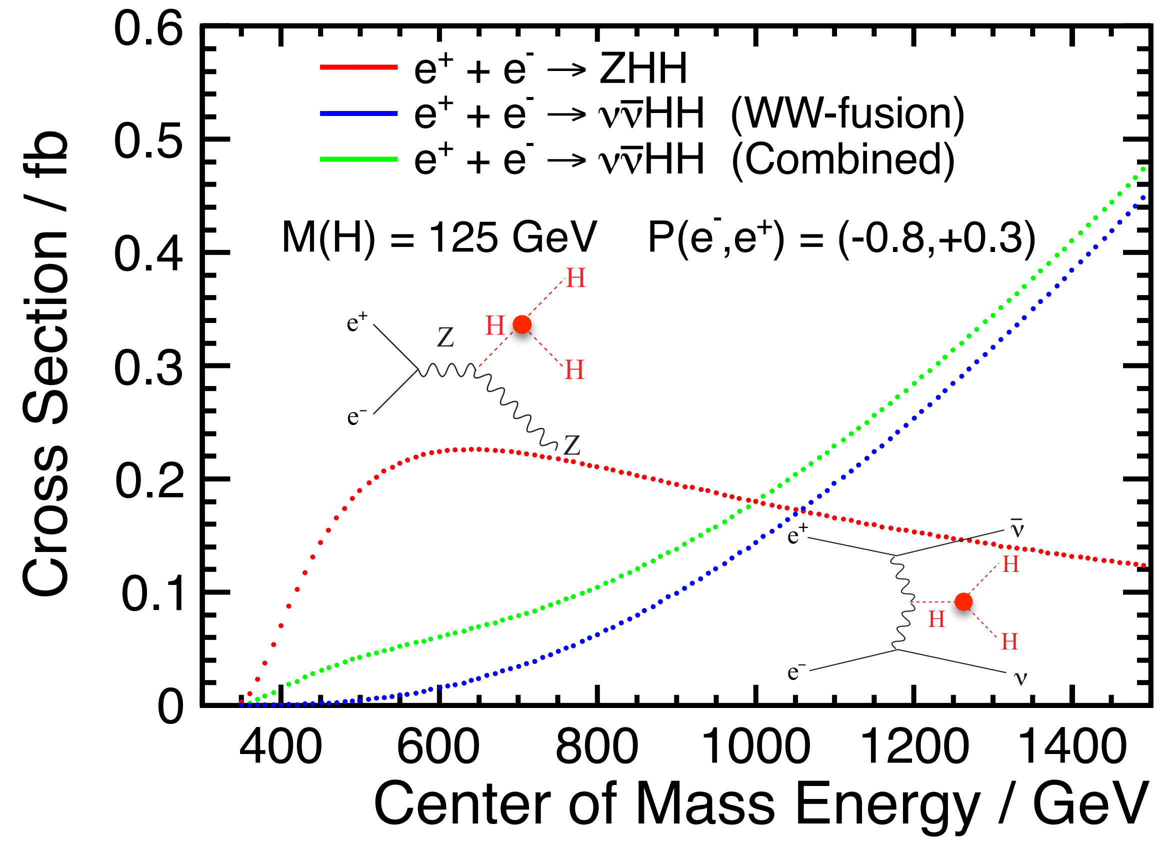


ILC

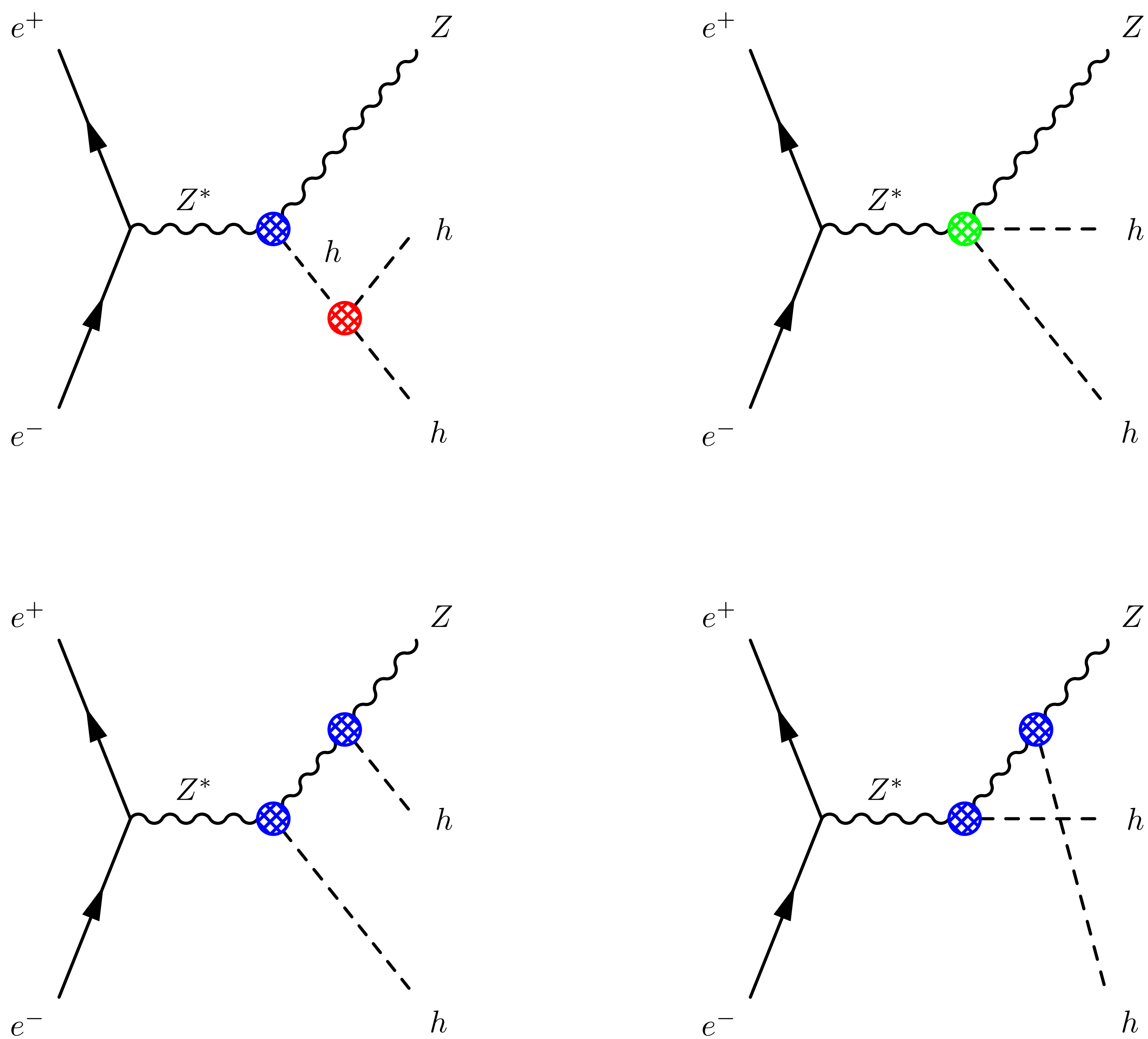
$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
H20	27%	10%

CLIC

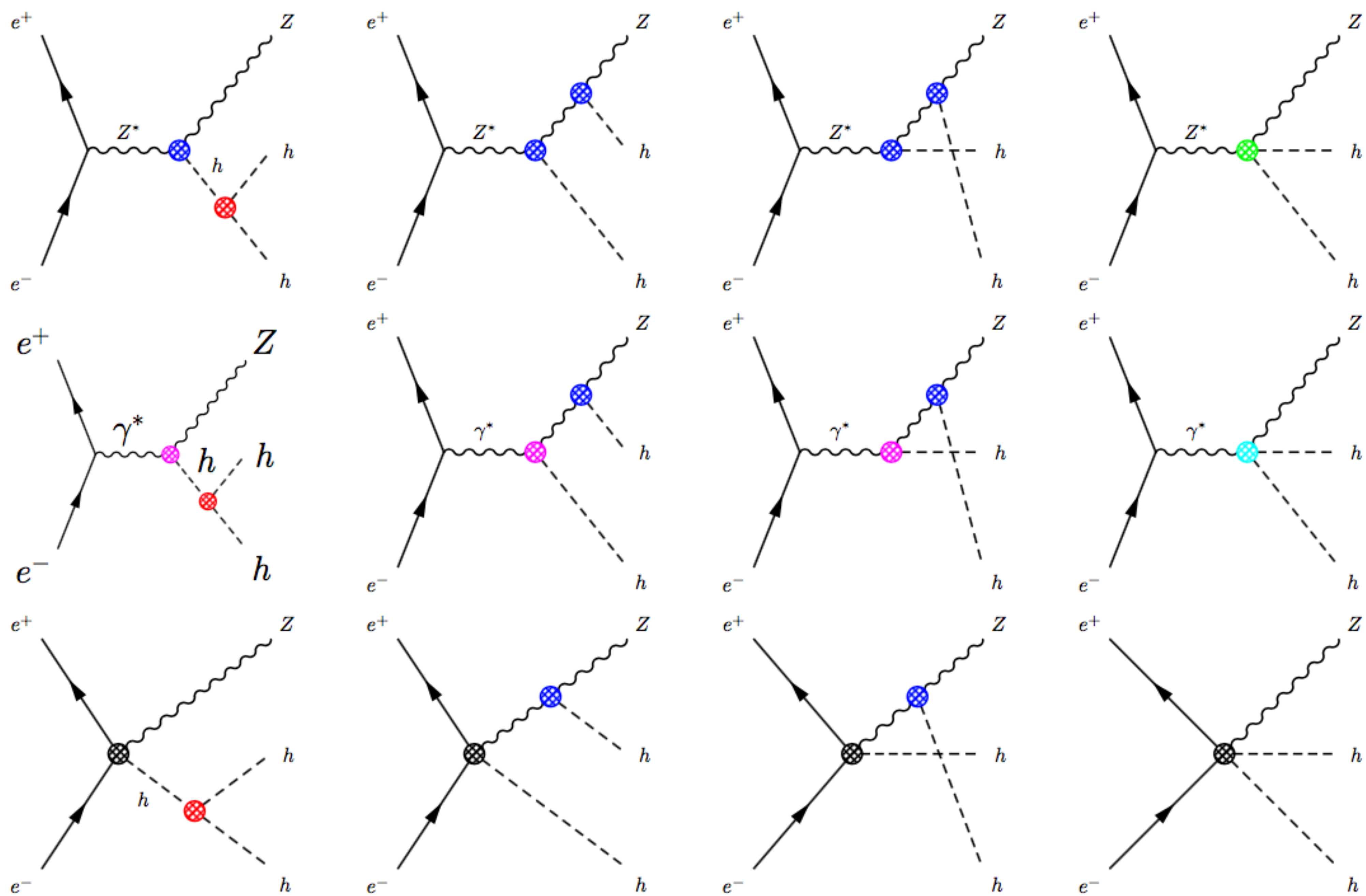
1.5 TeV	+3 TeV
36%	10%



can we really determine λ_{hhh}? (e.g. if hhZZ coupling unknown)



λ_{hhh} determination in SMEFT



λ_{hhh} determination in SMEFT

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

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

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

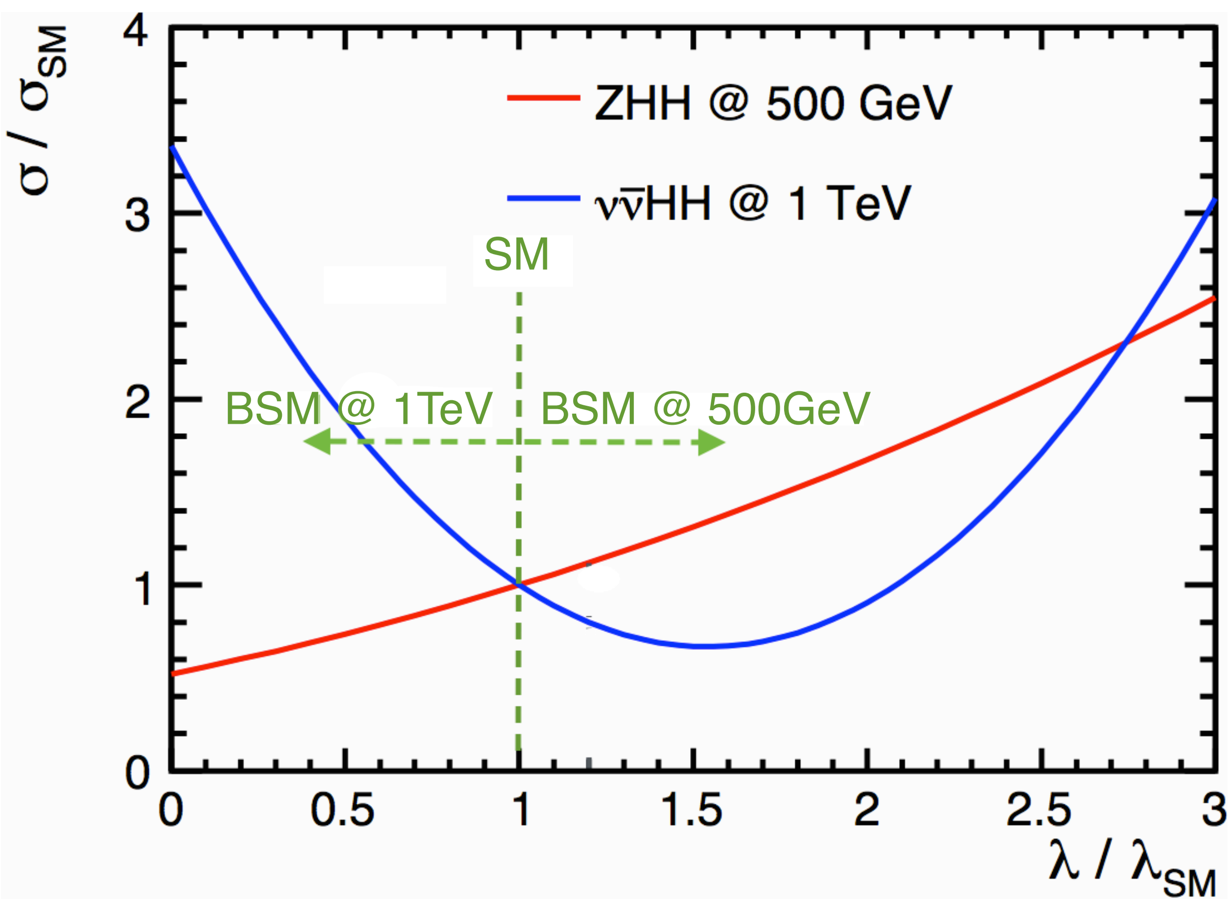
Given the full ILC program of 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV

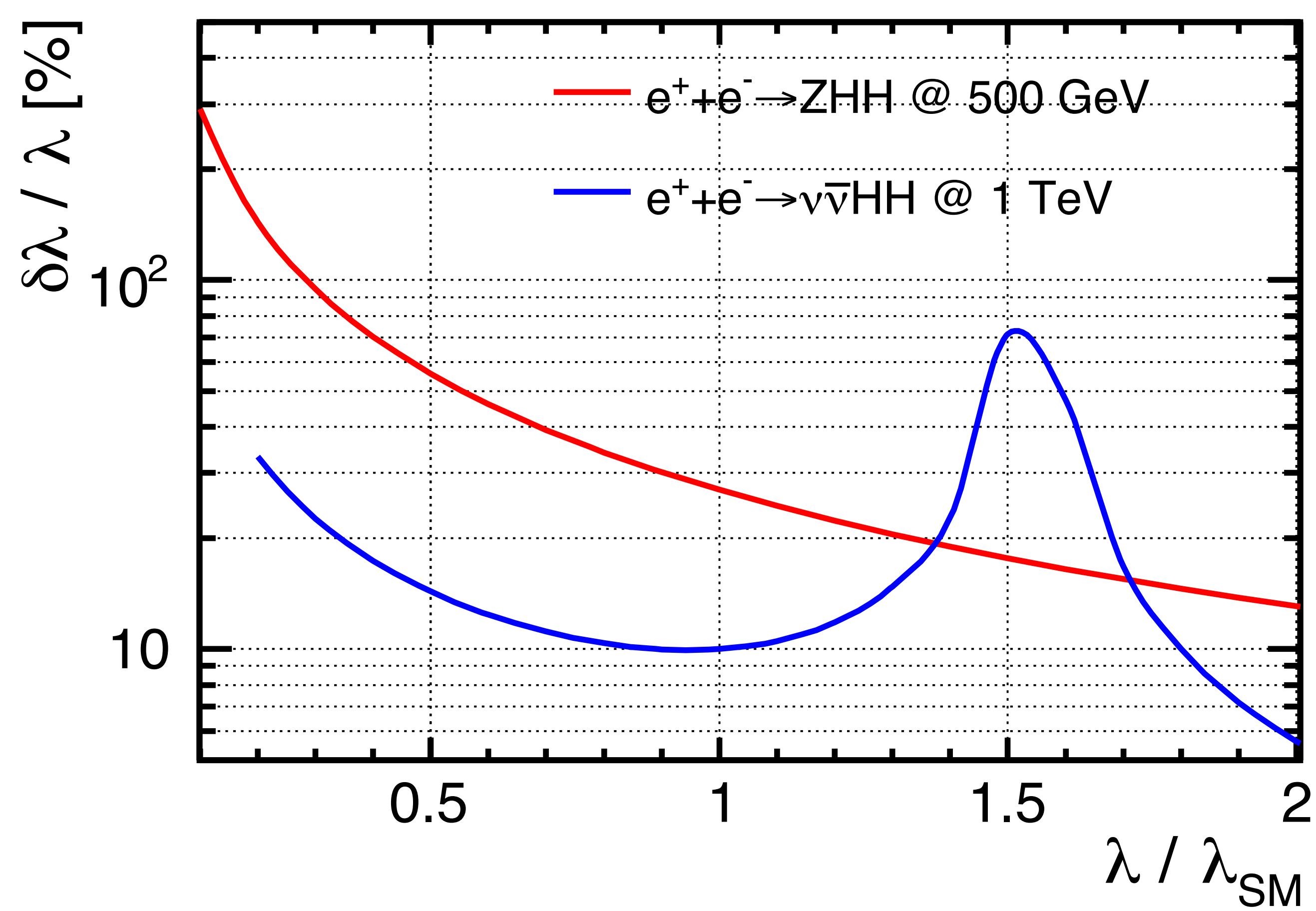
$$\left[\sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}} = 0.04 \quad \ll \quad \frac{\Delta\sigma_{Zhh}}{\sigma_{SM}} = 0.168$$

(systematic error) (statistical error)

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

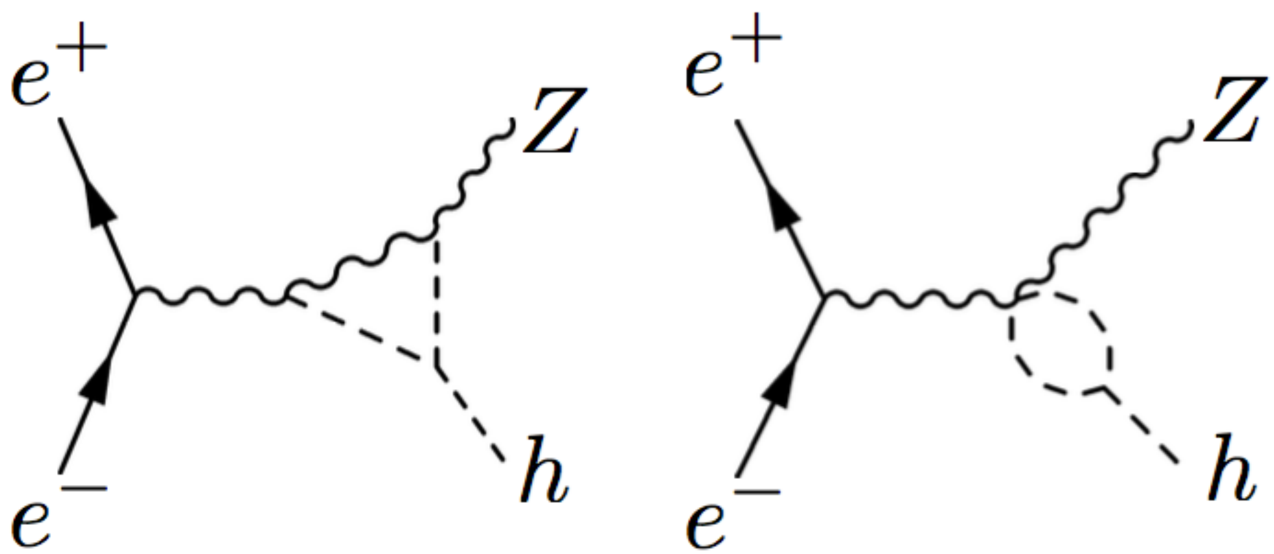
- constructive interference in ZHH, while destructive in ννHH (& LHC) —> complementarity between ILC & LHC, between √s ~500 GeV and >1TeV
- if $\lambda_{HHH} / \lambda_{SM} = 2$, Higgs self-coupling can be measured to ~15% using ZHH at 500 GeV e+e-





Duerig, Tian, et al, paper in preparation

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

  —> **δh ~ 50%** + 350/500GeV

- what if we also include other NLO effects as well?

summary

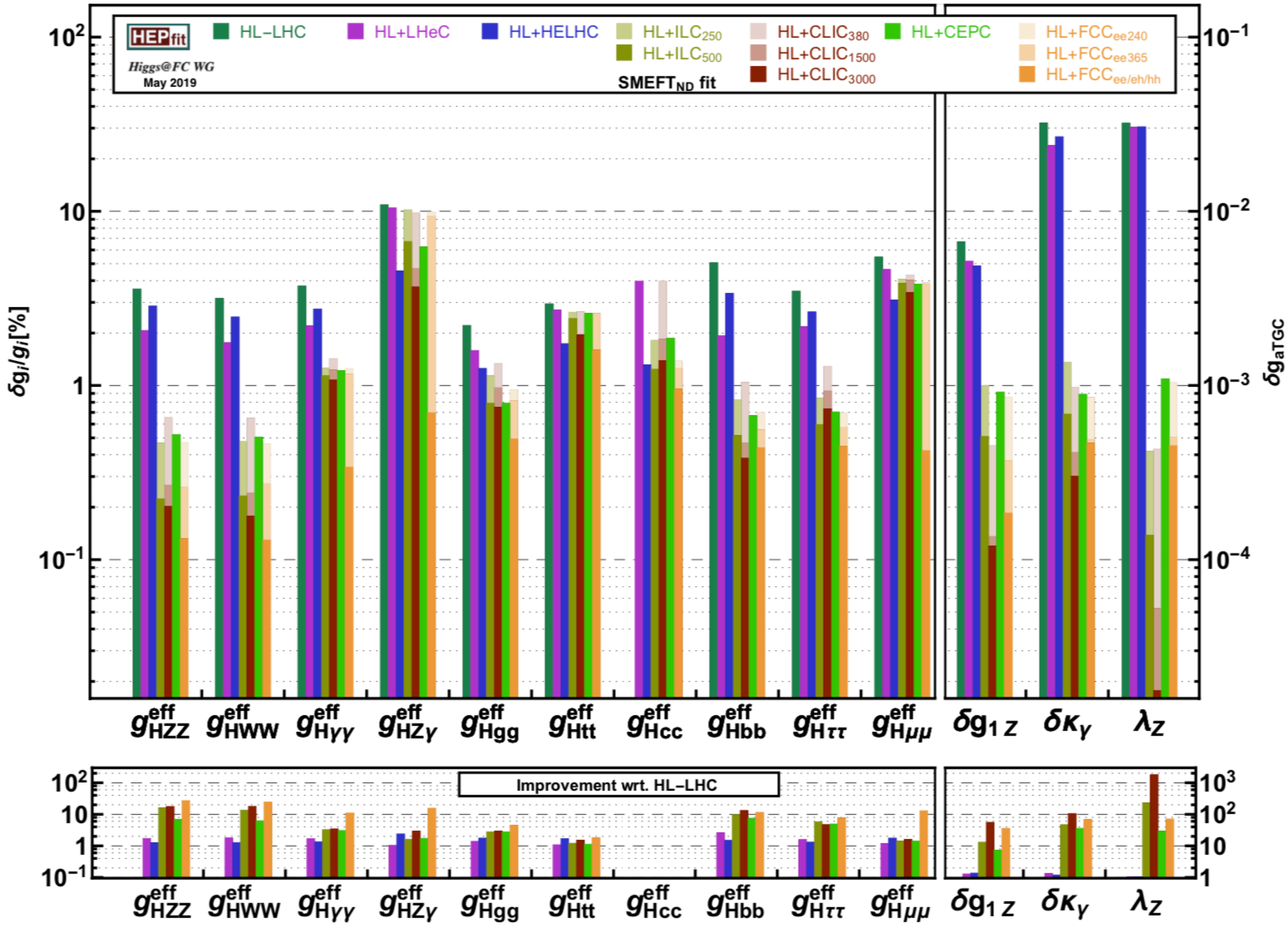
- precision Higgs meas. will help to reveal mystery of EWSB, and identify the BSM models
- a 250 GeV Higgs factory can do excellent Higgs physics, complementary to LHC
- the capabilities of a e+e- are best represented in SMEFT formalism
- Higgs couplings are related to EWPOs, W-/Z- couplings
- beam polarizations play an extremely important role
- need go to >=500 GeV for Higgs self-coupling

backup

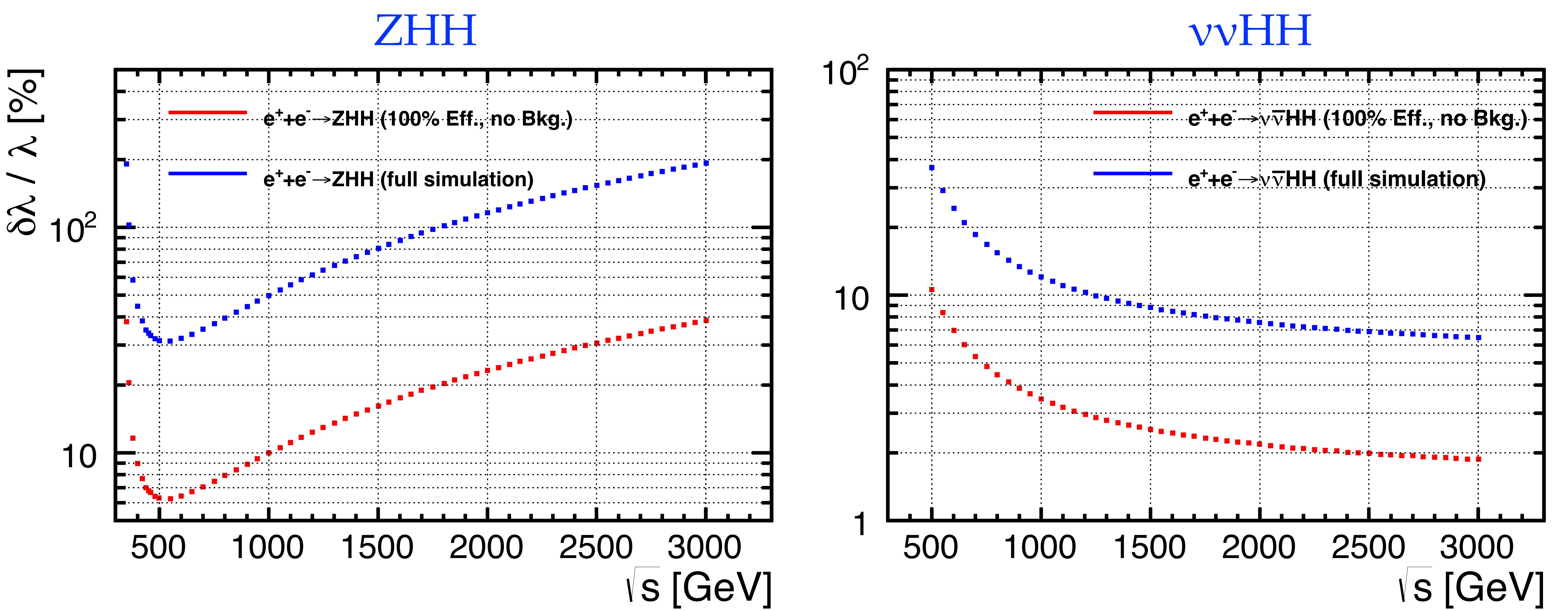
ECFA Higgs @ FC WG

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



expected precision of λ: impact of Ecm



- gap of these two expectations —> room of improvement
- for ZHH: 500 GeV is the optimal energy, $\delta\lambda/\lambda$ ~ 6% : 30%, but rather mild dependence between around 500-600 GeV, significantly worse if much lower or higher than that
- for ννHH: significantly better going from 500 GeV to 1 TeV, $\delta\lambda/\lambda$~10% achievable when ecm >= 1TeV; better precision at higher ecm, but not drastically, from 1 TeV to 3 TeV, improved by 50%

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

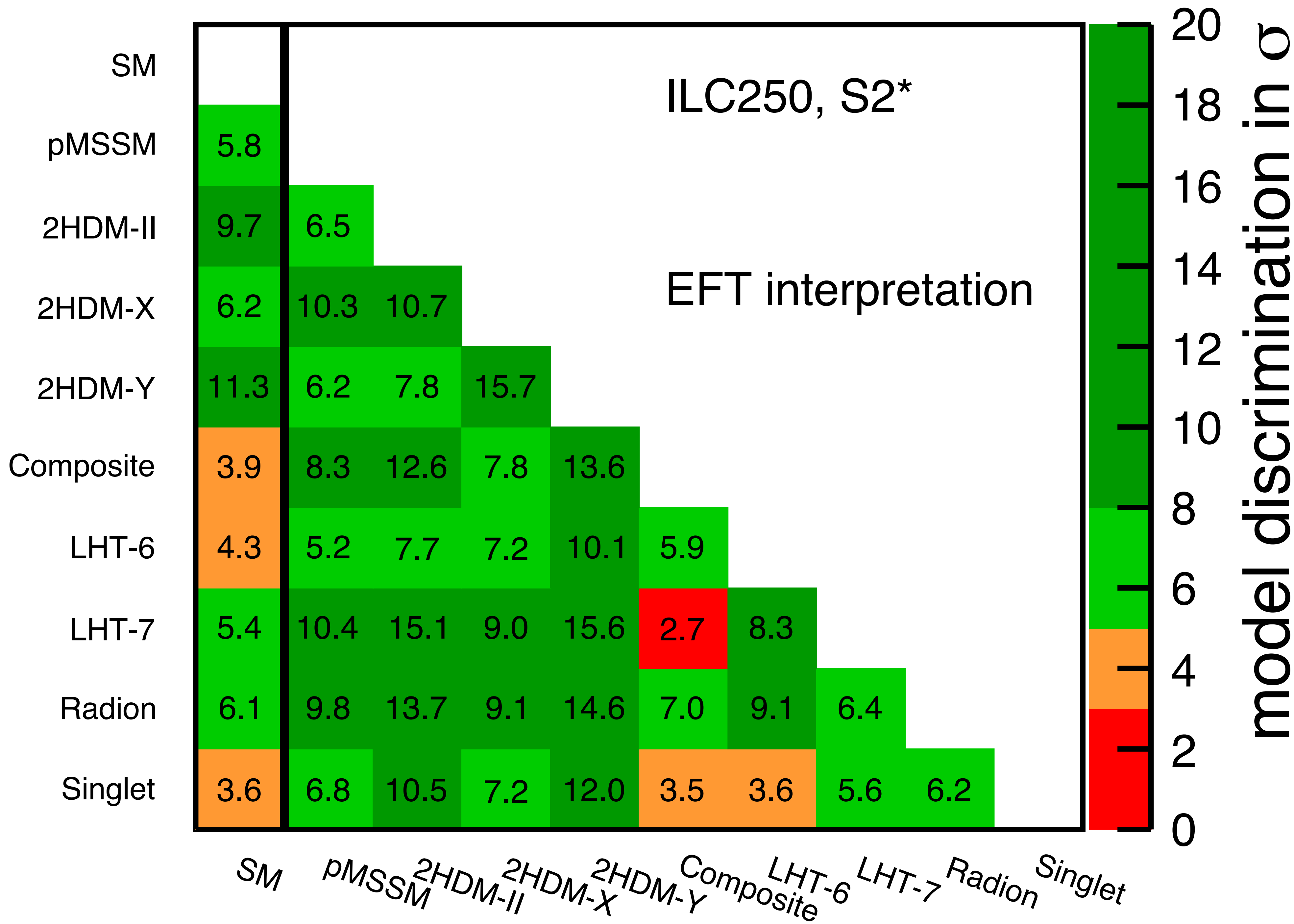
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> quantitative assessment for models discrimination

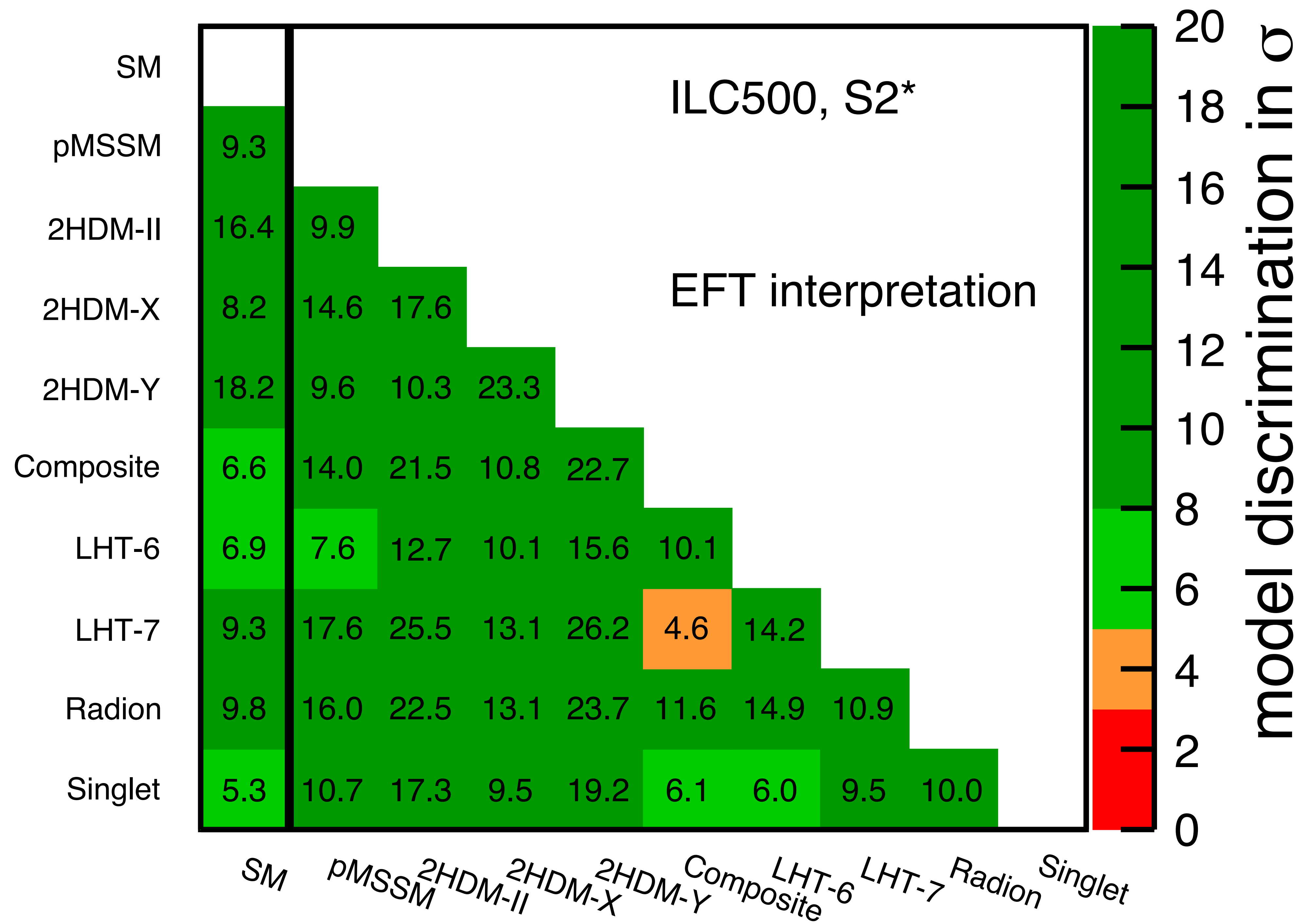
model parameters (chosen as escaping direct search at HL-LHC)

- 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

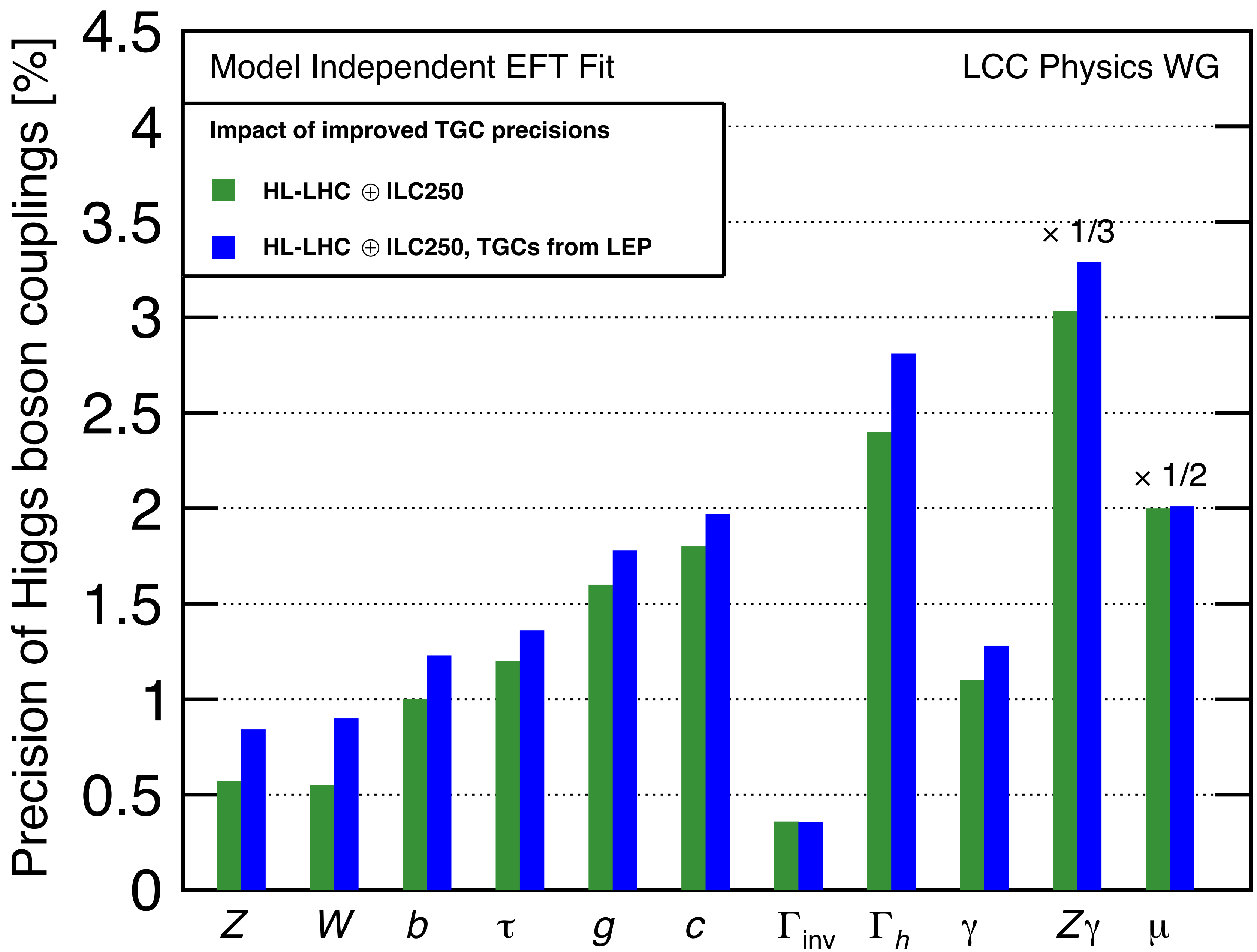
BSM benchmark models discrimination at e+e- (ILC250)

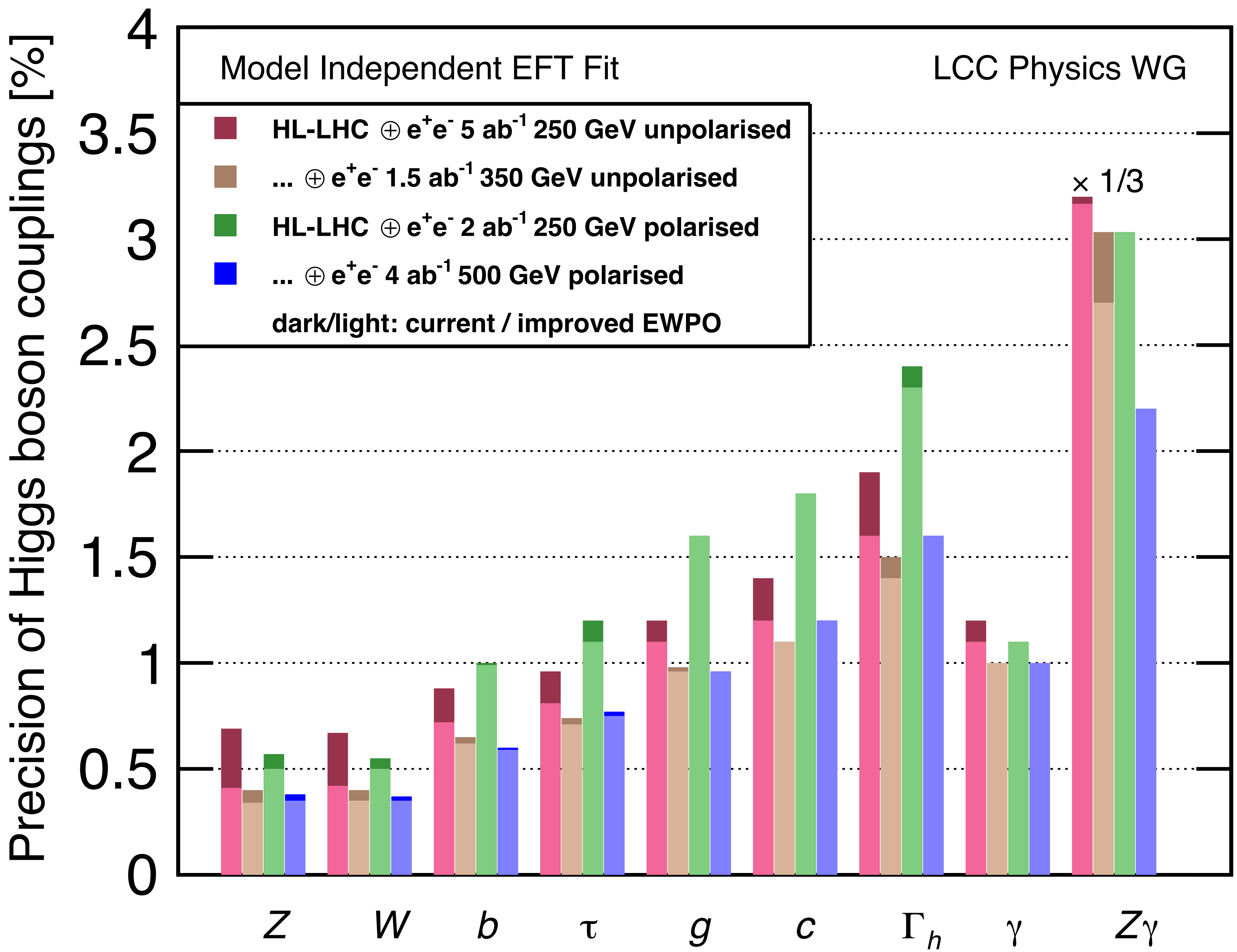


effect of improvement from TGC, ννH, ZH at 500GeV



impact of TGCs

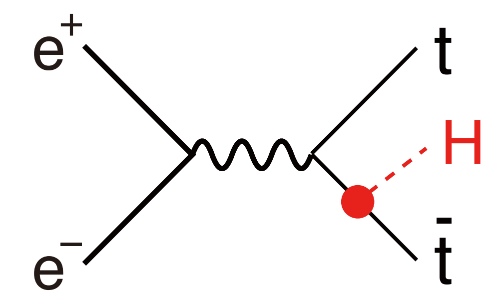




Model Independent EFT Fit
LCC Physics WG
HL-LHC ⊕ e+e- 5 ab-1 250 GeV unpolarised
... ⊕ e+e- 1.5 ab-1 350 GeV unpolarised
HL-LHC ⊕ e+e- 2 ab-1 250 GeV polarised
... ⊕ e+e- 4 ab-1 500 GeV polarised
dark/light: current / improved EWPO
× 1/3
Precision of Higgs boson couplings [%]
0
0.5
1
1.5
2
2.5
3
3.5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

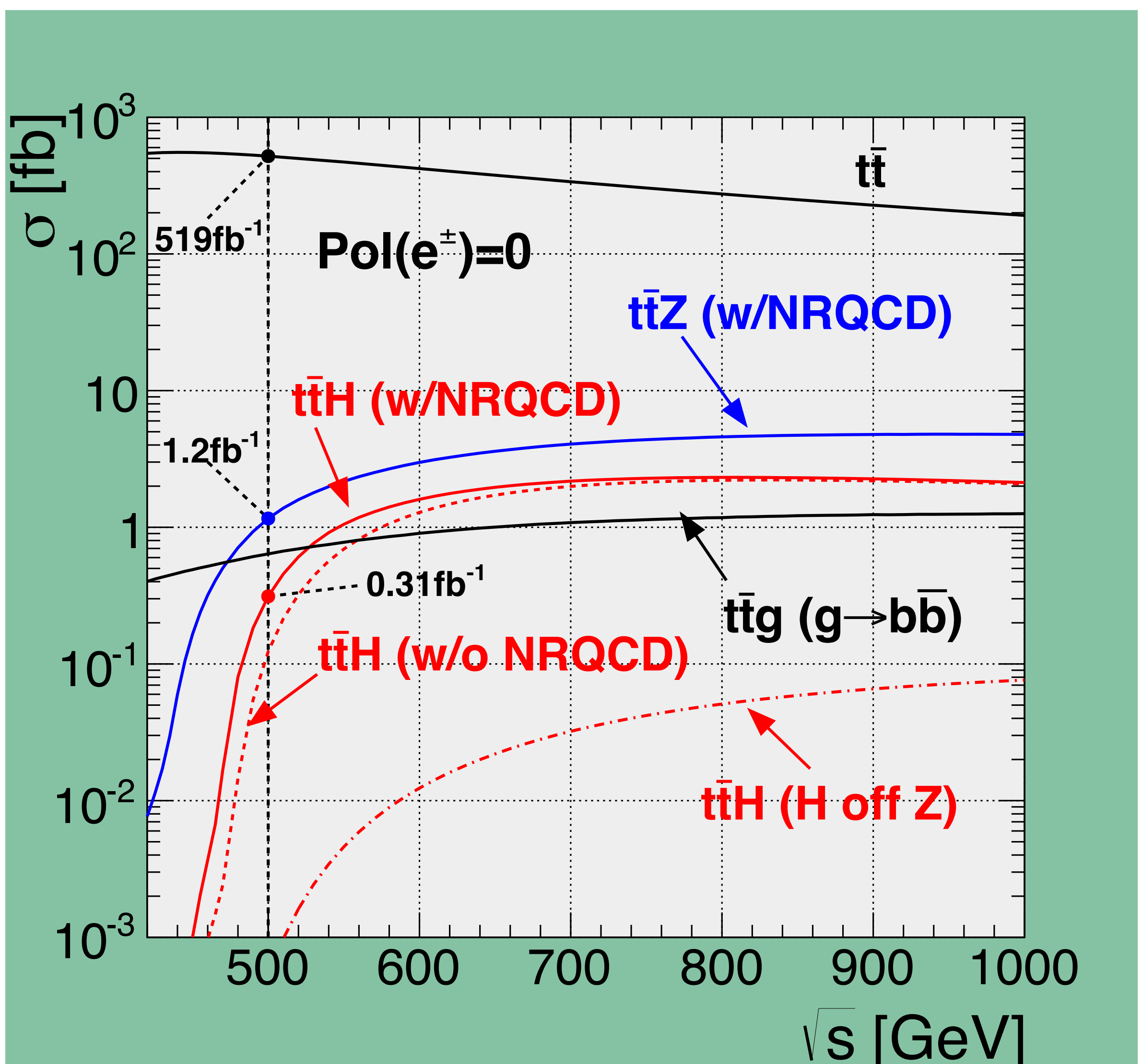
(ii-5) Top-Yukawa coupling

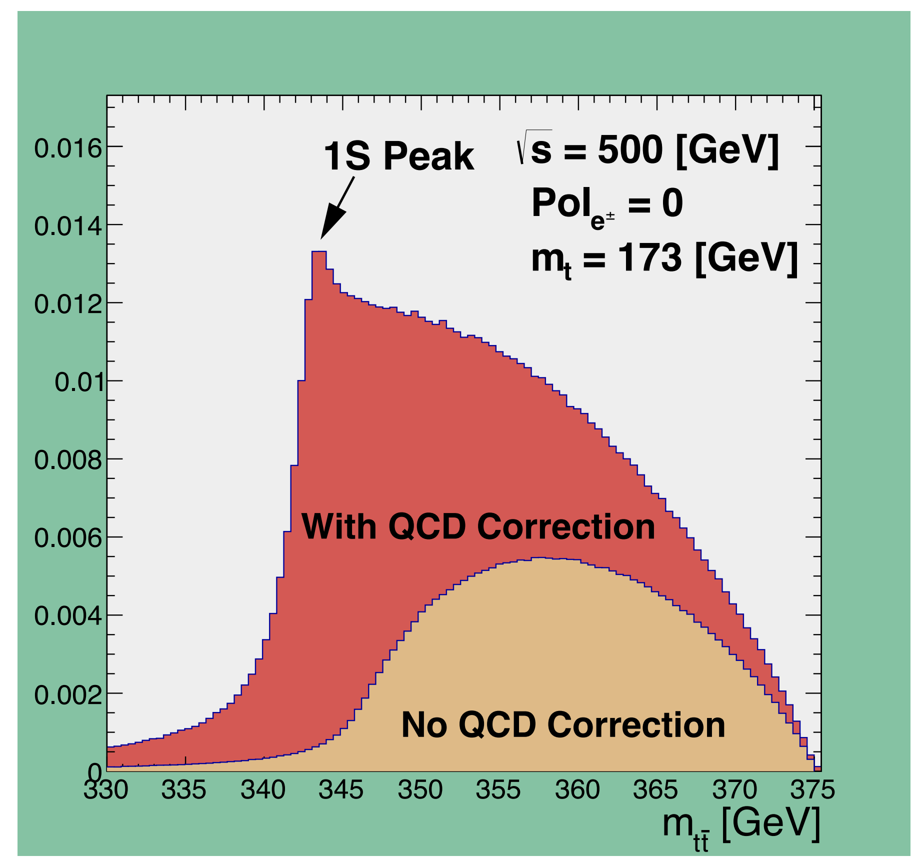
- largest Yukawa coupling; crucial role in theory
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



H-> bb

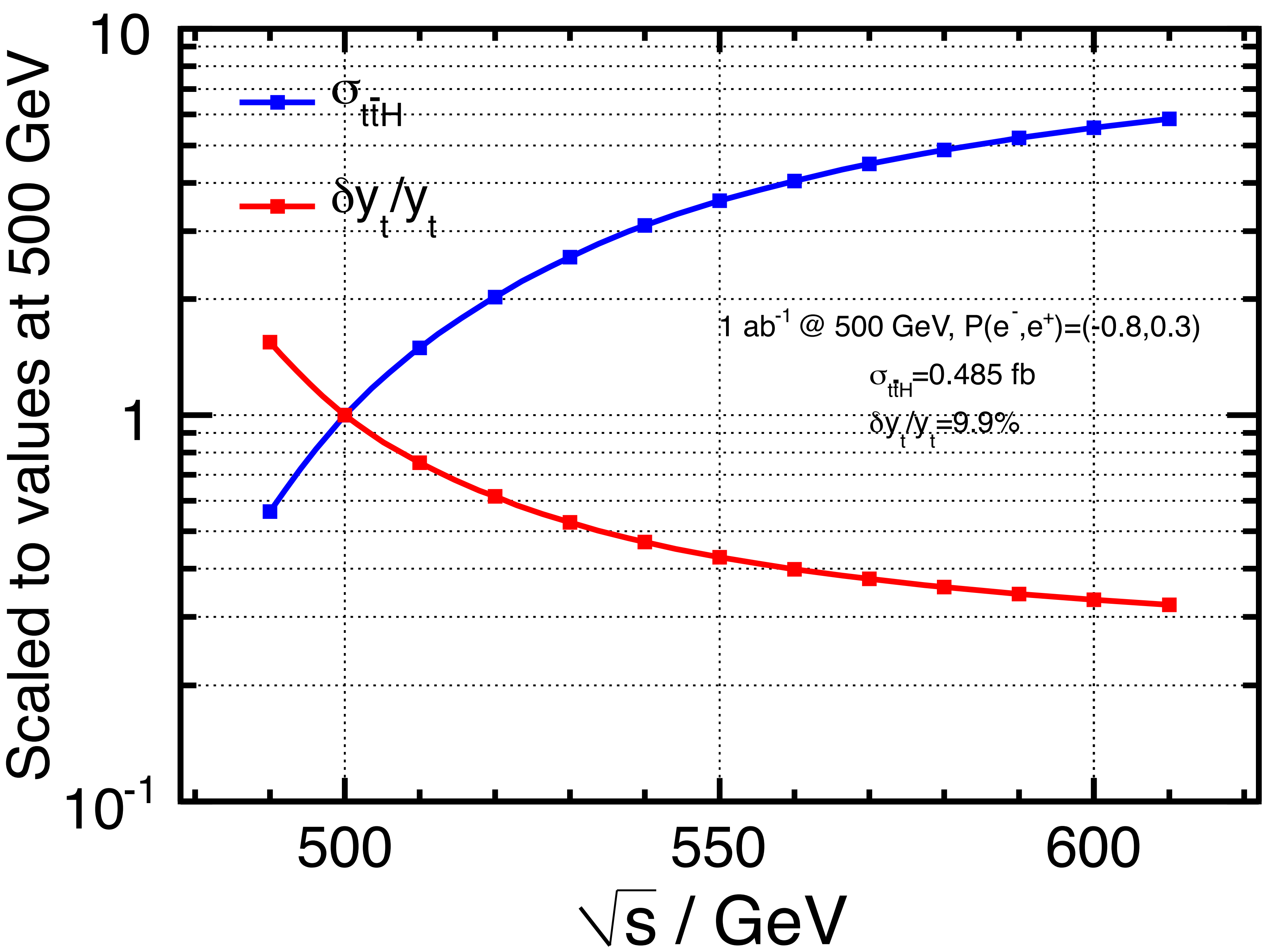
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
Snowmass	7.8%	2.0%
H20	6.3%	1.5%





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

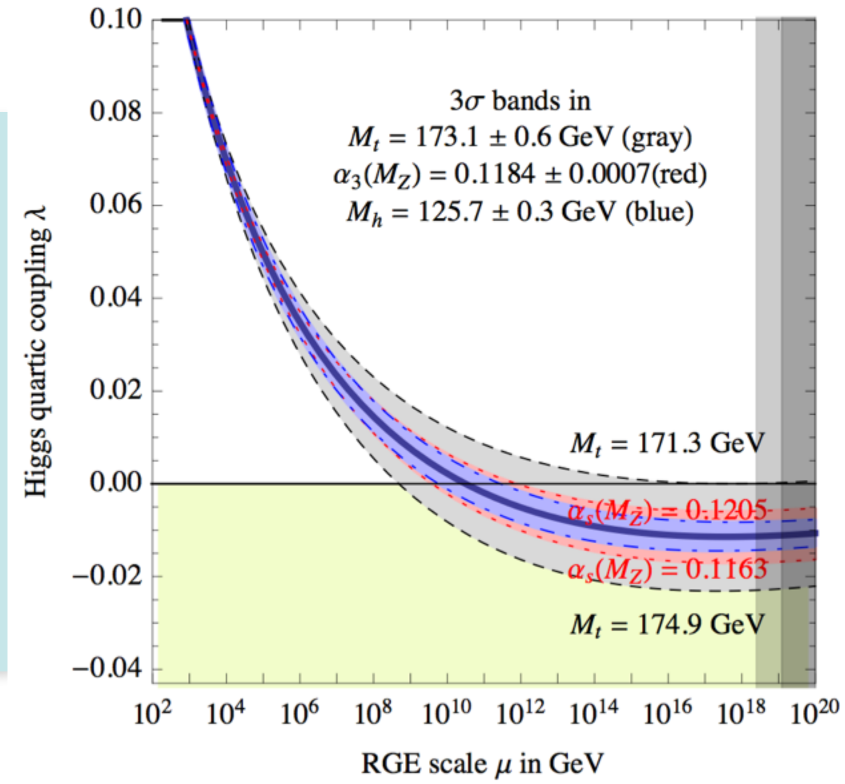
Top-Yukawa coupling



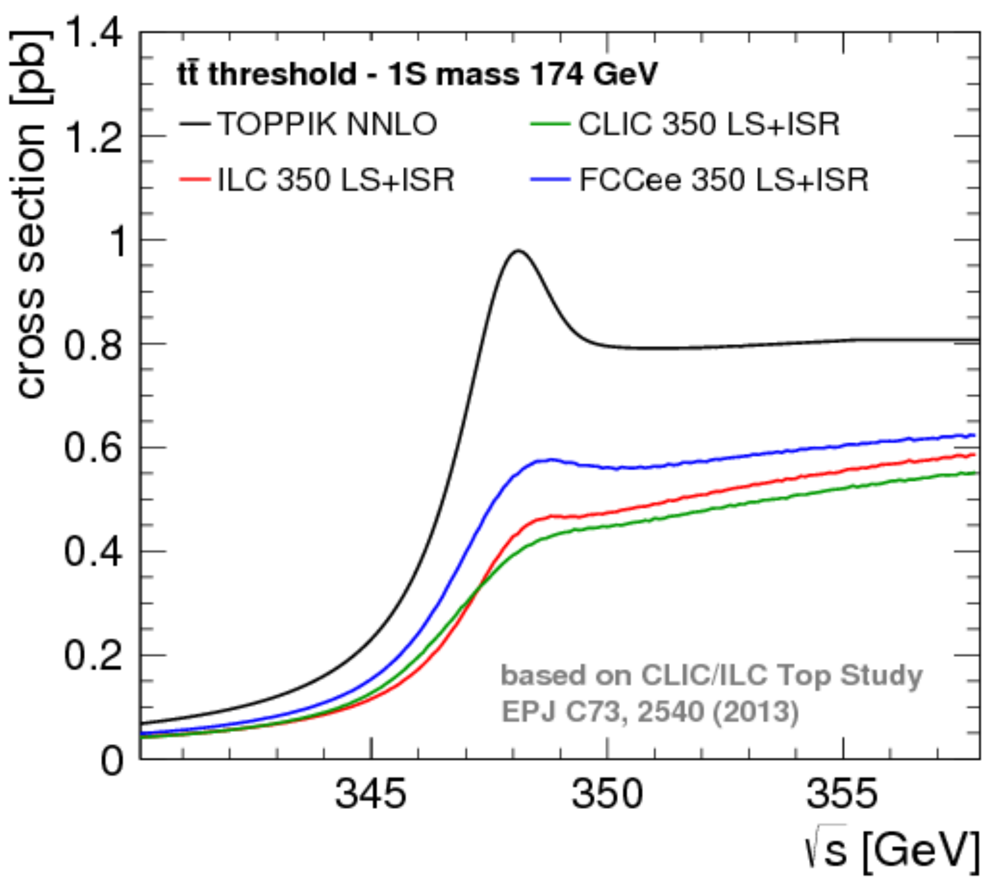
Y. Sudo

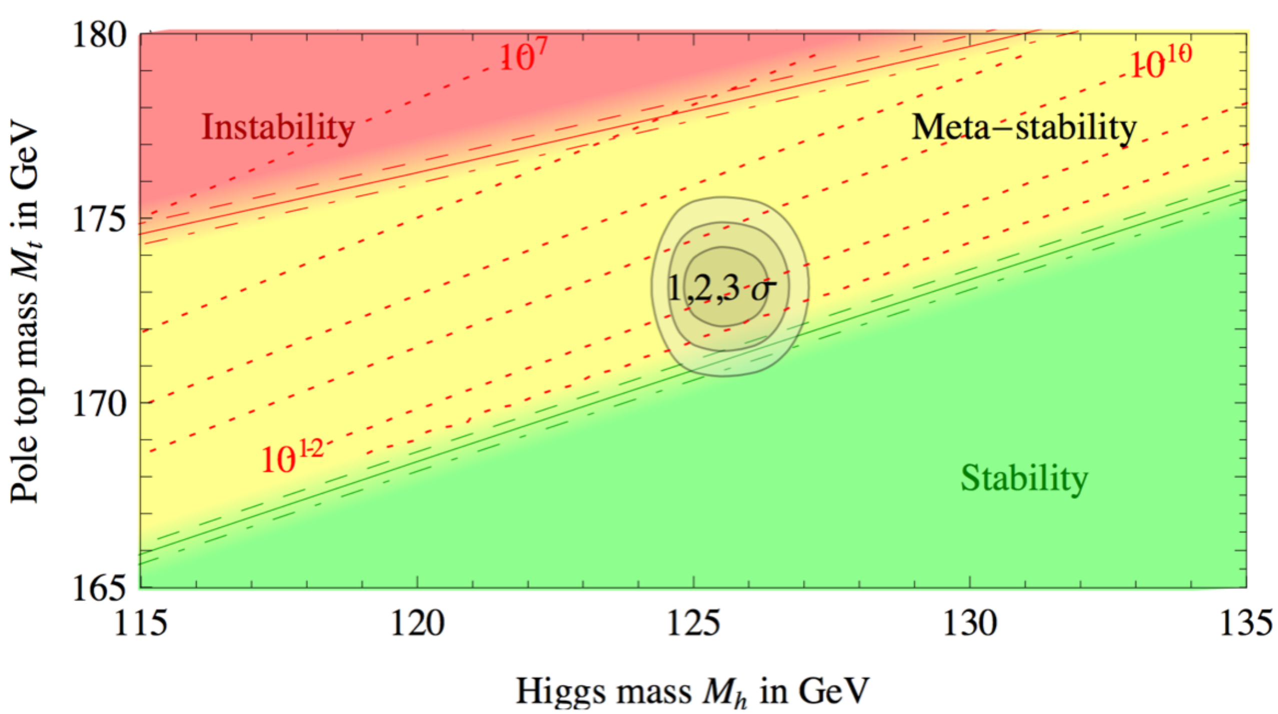
vacuum stability

- 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

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)

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

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

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

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

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

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

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

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

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

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

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

EFT input: EWPOs (7)

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

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

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

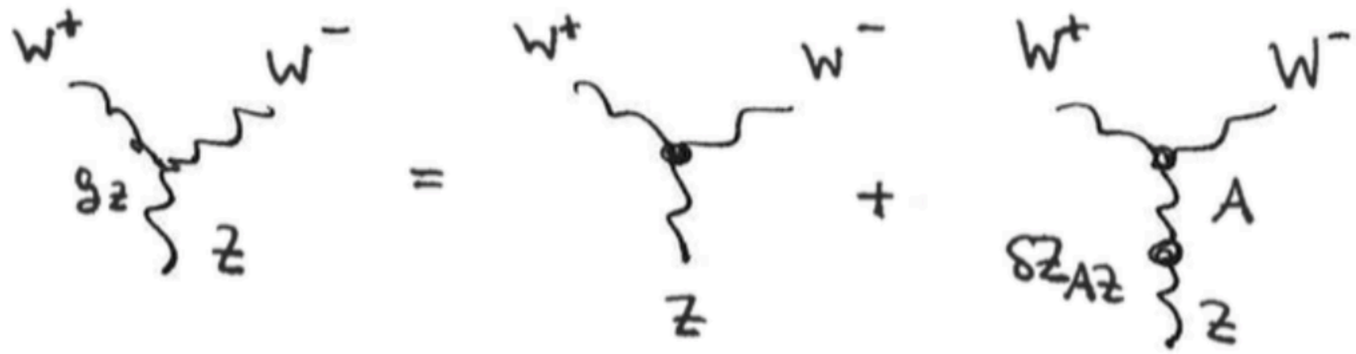
$$g_L = \frac{g}{c_w}\left[(-\frac{1}{2} + s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}(c_{HL} + c'_{HL}) - s_w c_w \delta Z_{AZ}\right]$$

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

⟶ $c_{HL}+c'_{HL}$, c_{HE}

EFT input: TGC (3)

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

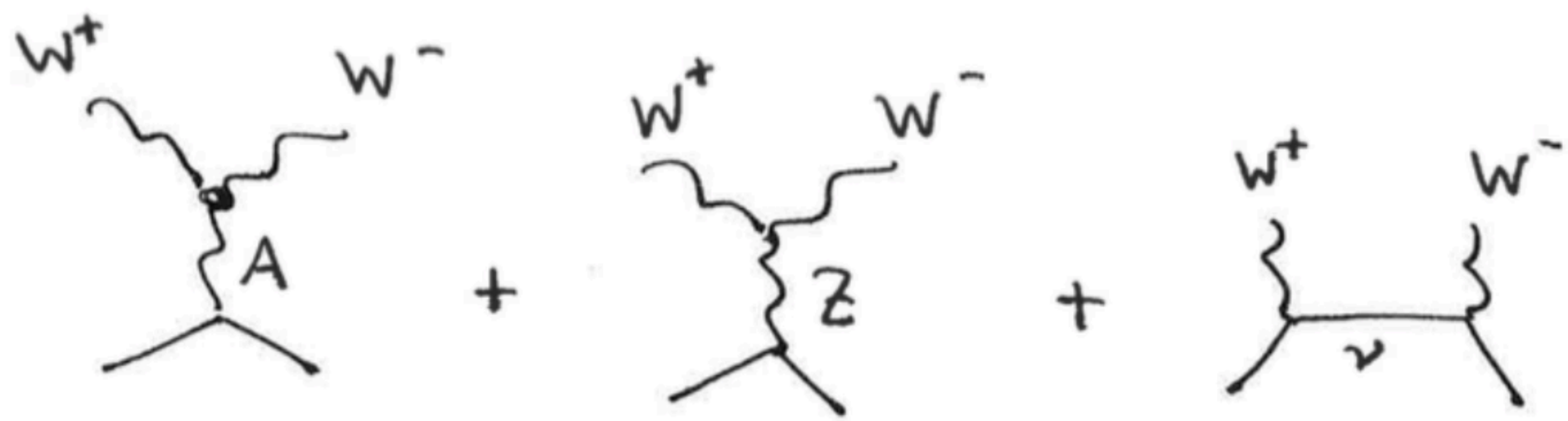


$$g_Z = gc_w(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ})$$

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

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

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)

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

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

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

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

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)