Introduction to Higgs physics at future e+e- — focused on single Higgs

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ICEPP
The University of Tokyo

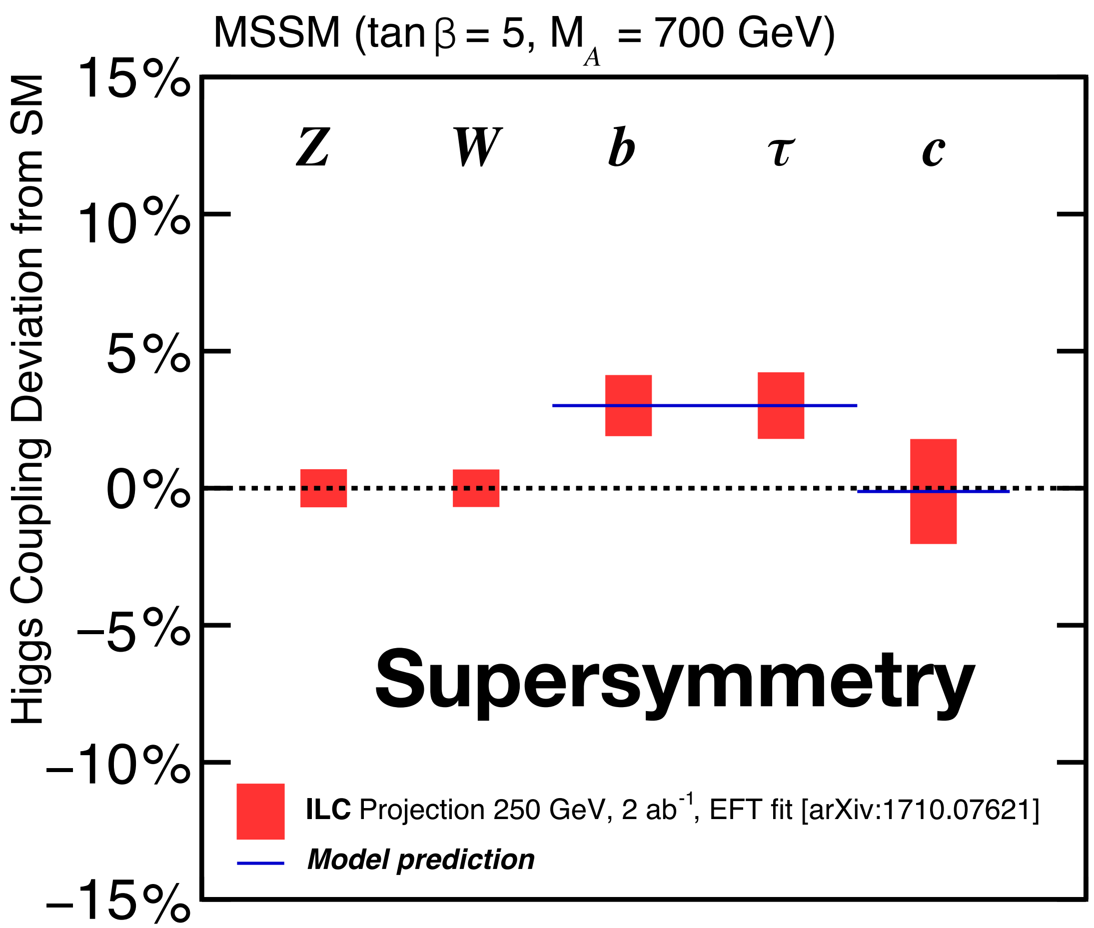
for comprehensive review, arXiv:1903.01629; 2203.07622

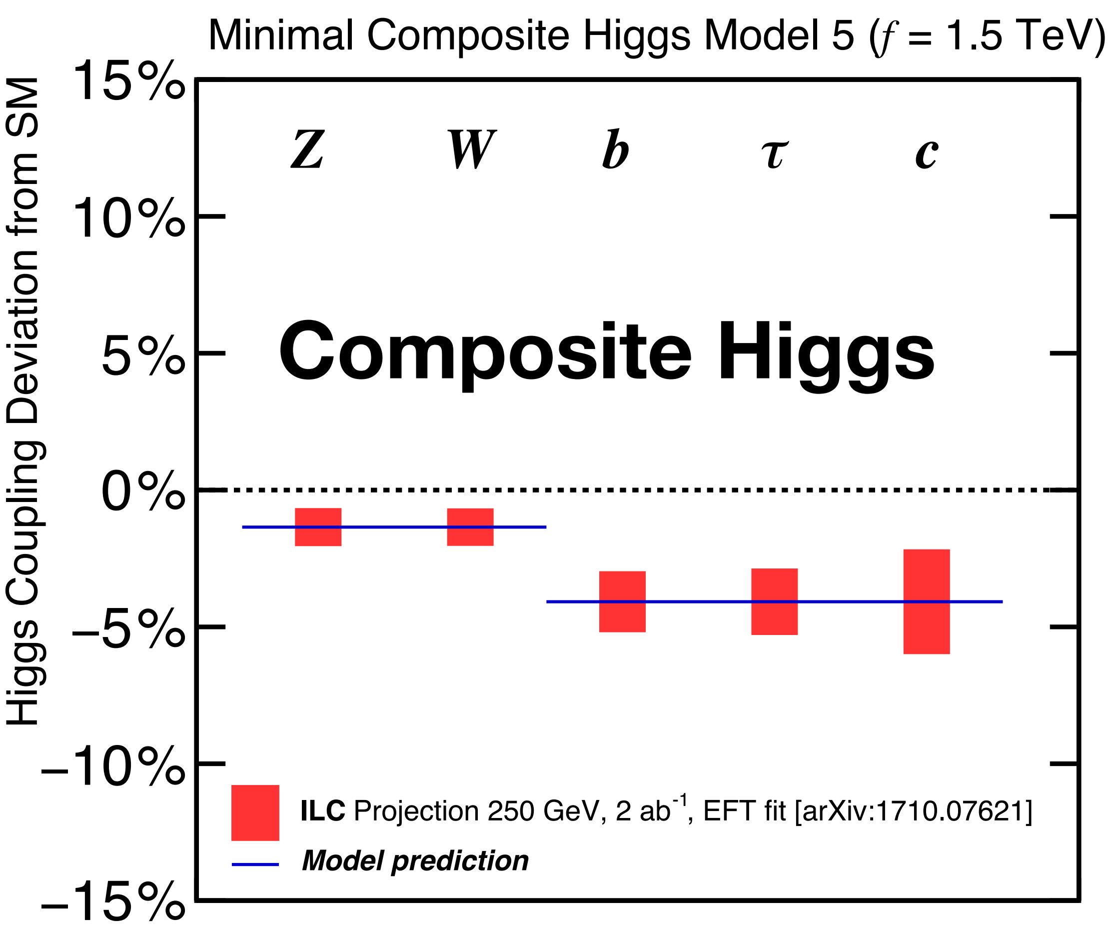
outline

- Introduction
- Single-Higgs cross section
- Differential cross section & CP
- Interplay between Higgs/EW/Top
- summary

opportunities from precision Higgs couplings

— another way towards discovery





arXiv: 1306.6352

- measuring deviation pattern of Higgs couplings will reveal the nature of BSM physics

general guidelines for Higgs coupling meas. @ future e+e-

—in light of what have been found at LHC

- new particles are heavy, deviation is small, 1-10% for m_{BSM}~1TeV: need measurement with 1% precision or below so that deviations with SM can be discovered
- measurement needs to be as model-independent as possible: so that the true BSM model can be discriminated from others, future HEP direction hence can be decided

proposals of future e+e- colliders

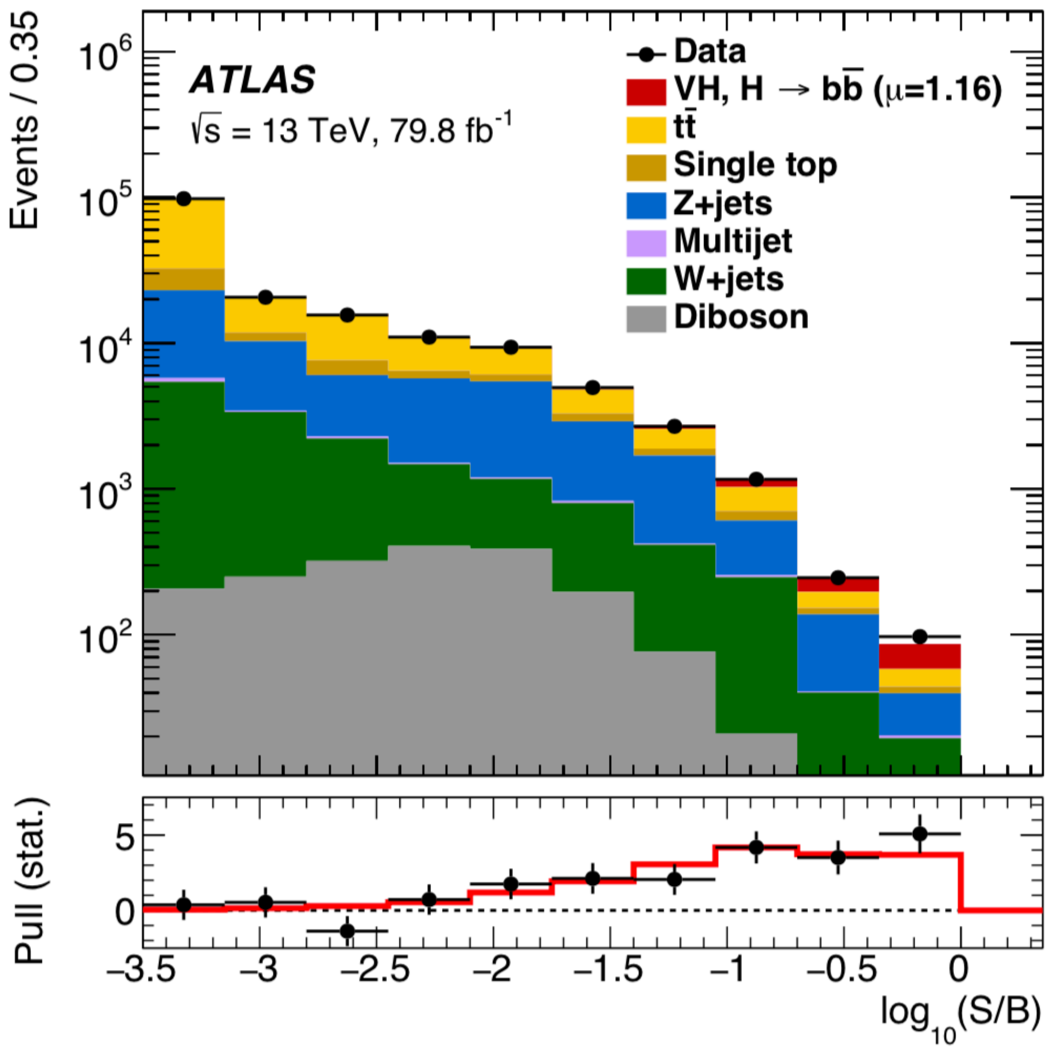
	$\sqrt{s}$	beam polarisation	$\int Ldt$ (baseline)	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2 ab^{-1} @ 250 GeV 0.2 ab^{-1} @ 350 GeV 4 ab-1 @ 500 GeV 8 ab-1 @ 1 TeV	TDR 2013
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	1 ab^{-1} @ 380 GeV 2.5 ab^{-1} @ 1.5 TeV 5 ab^{-1} @ 3 TeV	CDR 2012
CEPC	90 - 240 GeV	e-: 0% e+: 0%	20 ab^{-1} @ 240 GeV 100 ab^{-1} @ M_Z 6 ab^{-1} @ $2M_W$	TDR 2022
FCC-ee	90 - 350 GeV	e-: 0% e+: 0%	150 ab^{-1} @ M_Z 10 ab^{-1} @ $2M_W$ 5 ab^{-1} @ 240 GeV 1.7 ab^{-1} @ 365 GeV	CDR 2018

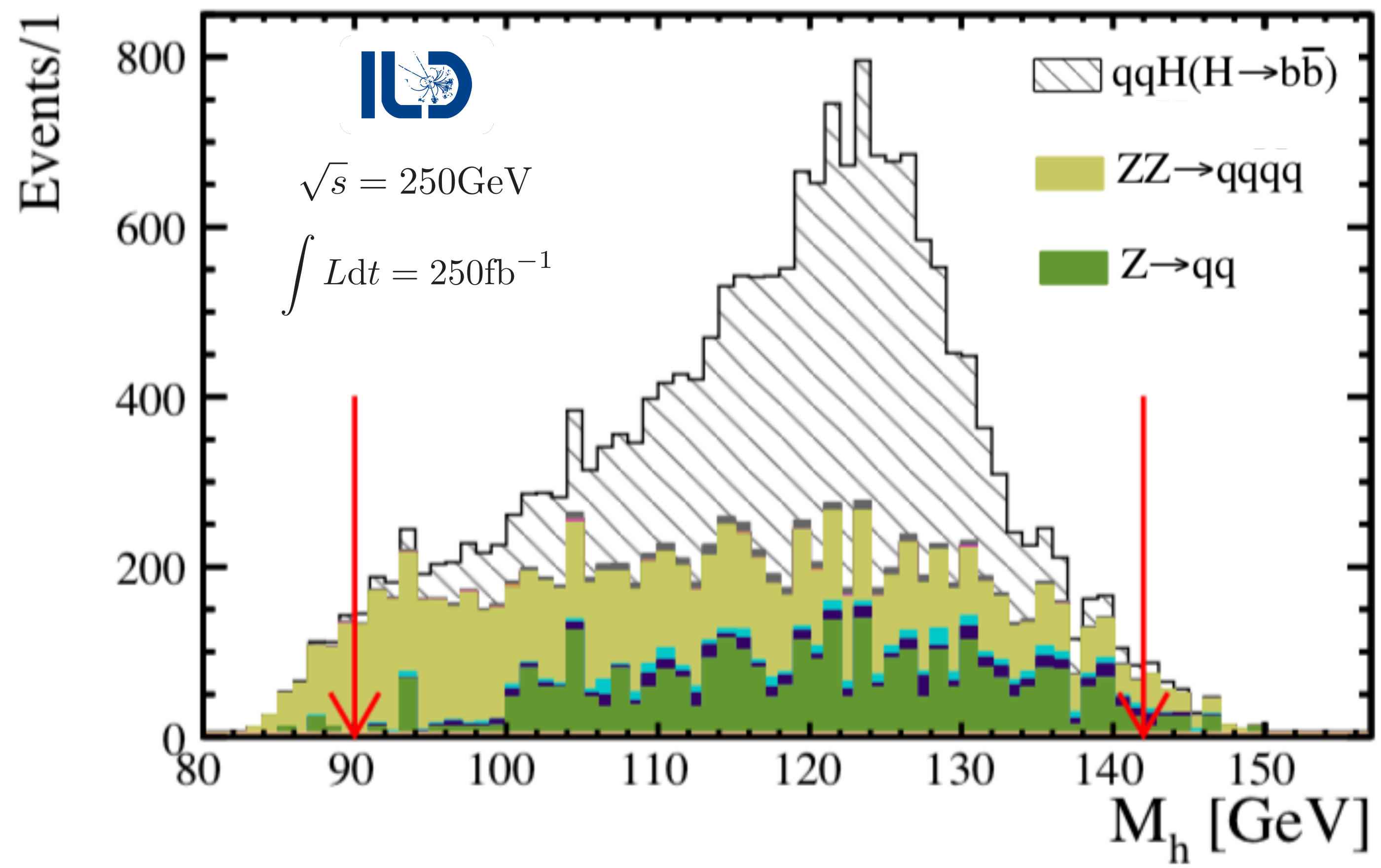
common: Higgs factory with $O(10^6)$ Higgs events

differ in energy reach, luminosity, polarization, project readiness

statistics vs S/B: example on H→bb discovery

LHC (super Higgs factory #10⁸) | e+e- (Higgs factory #10⁶)





full detector simulation

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

significance: 5.4σ | 5.2σ

[ATLAS, 1808.08238; CMS, 1808.08242]

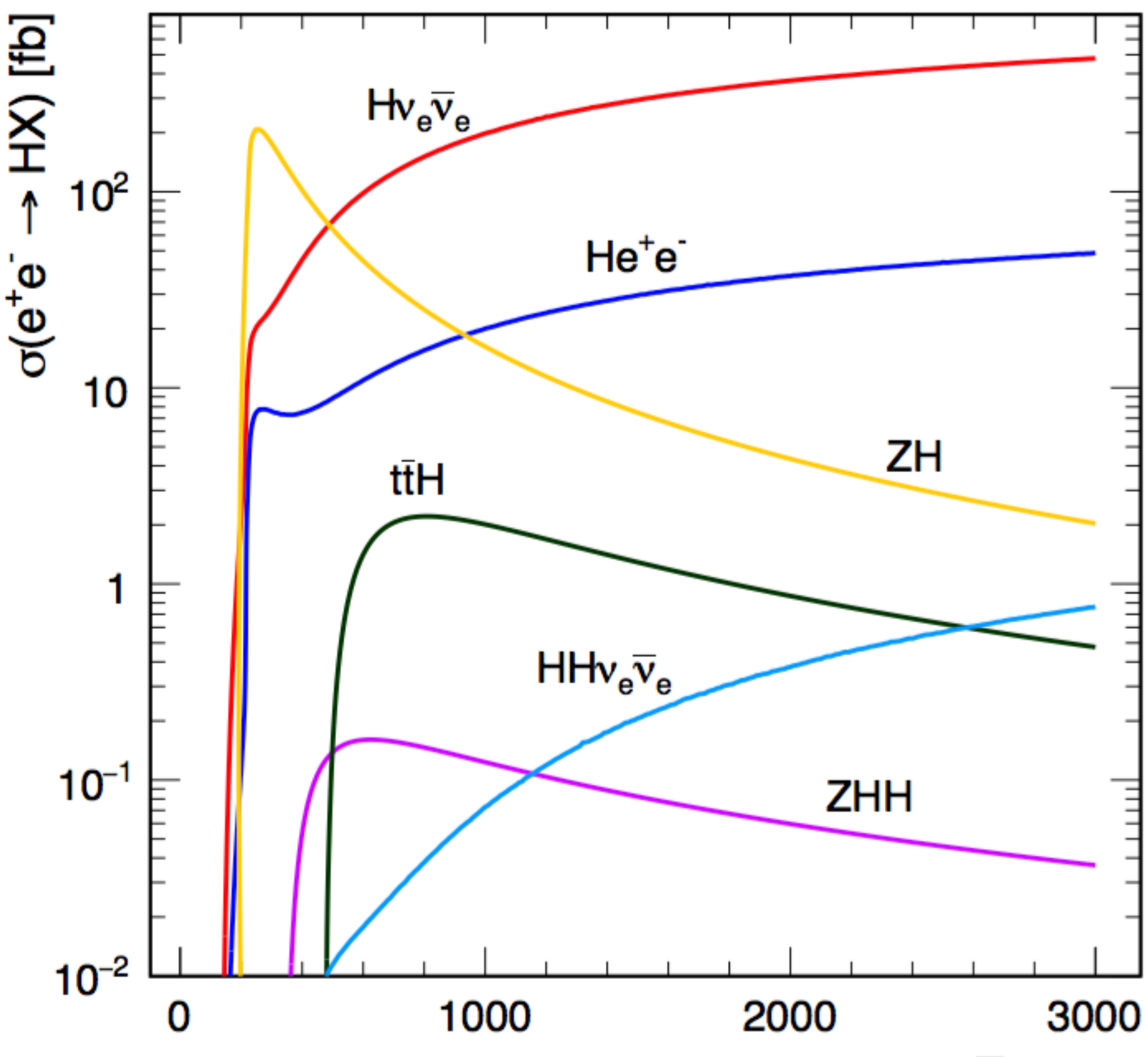
[Ogawa, PhD Thesis (Sokendai)]

(precision meas.)

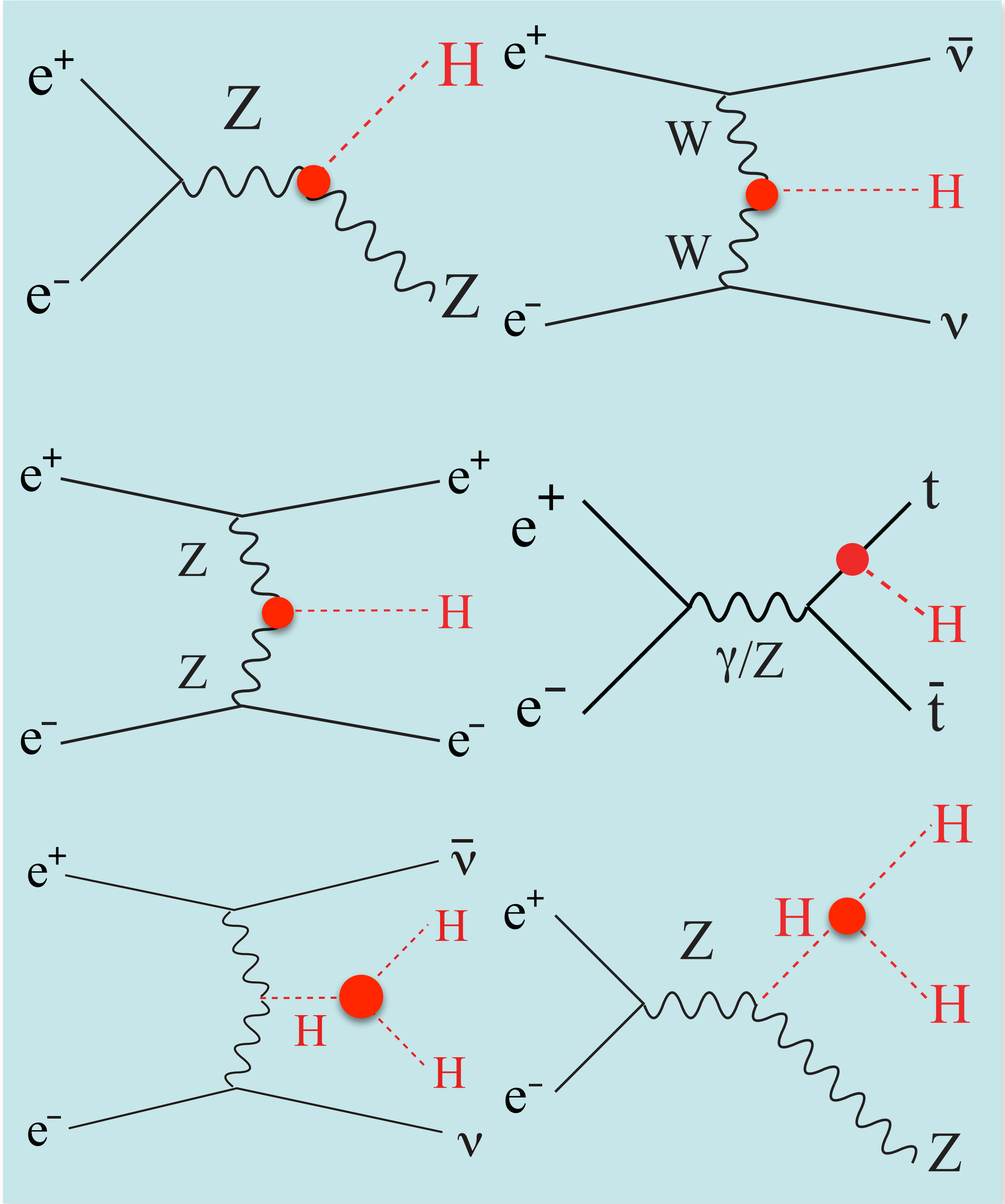
“that is much much easier, infinitely easier, on a e+e- machine than on a proton machine”

youtube: Burton Richter #mylinearcollider, 2015

(ii) Higgs productions at e+e-



(unpolarized case)



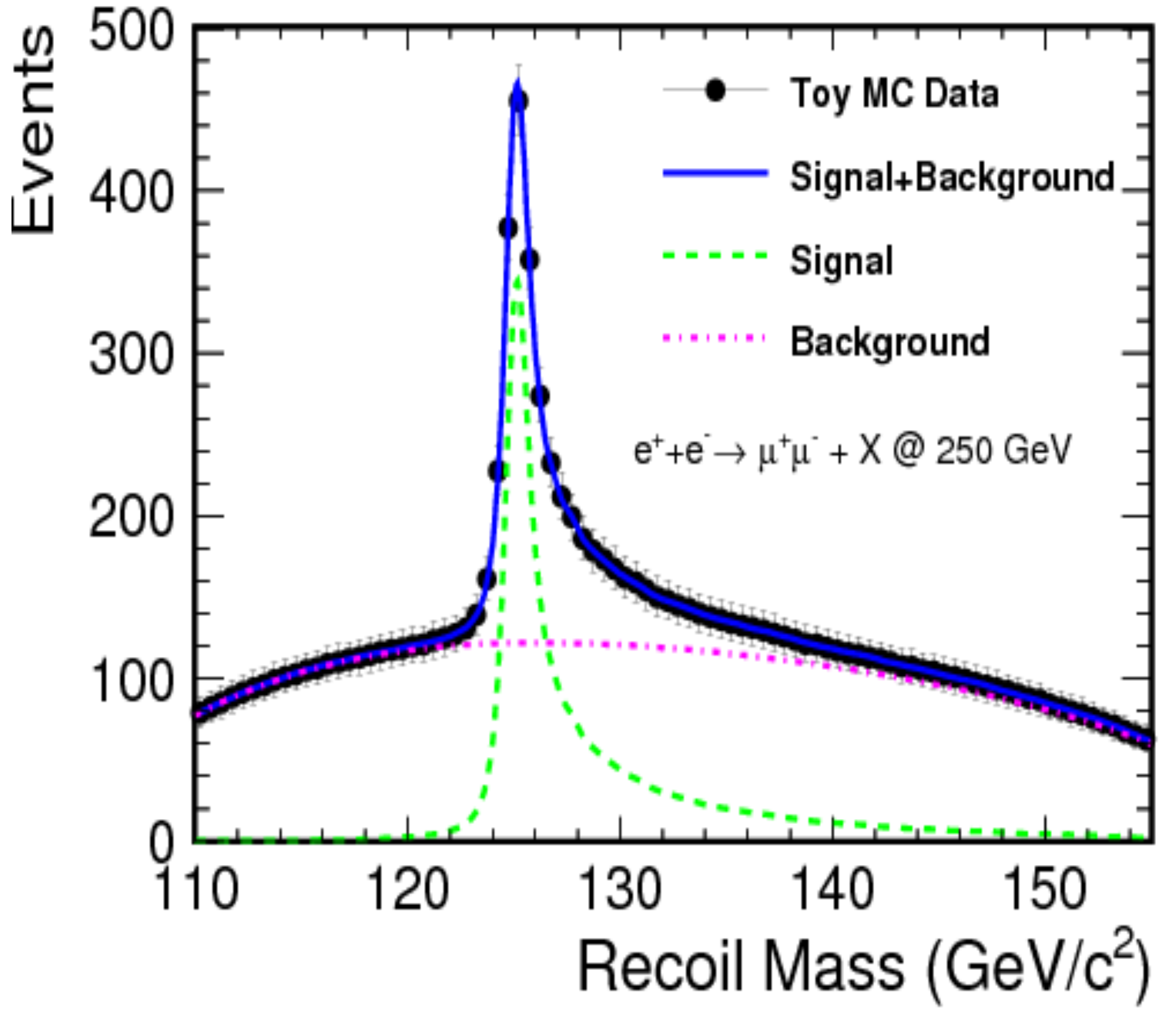
- two apparent important thresholds: √s ~ 250 GeV for ZH, ~500-600 GeV for ZHH and ttH
- + another threshold for t t-bar, important for Higgs physics as well

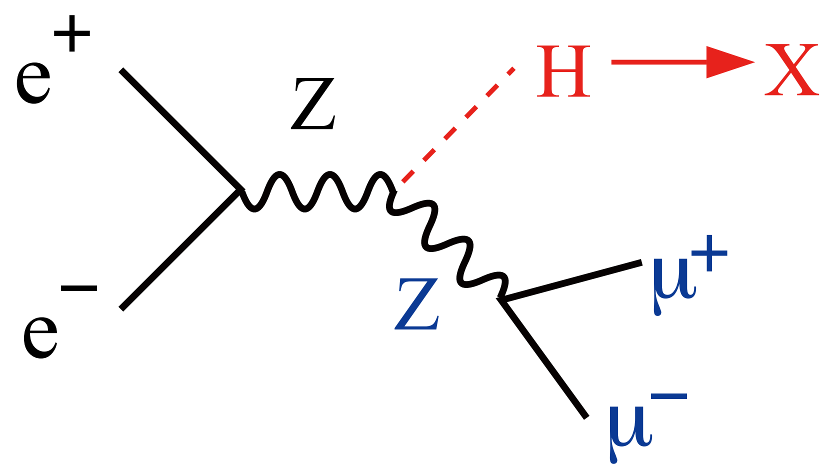
direct experimental observables: some are unique @ e+e-

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

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

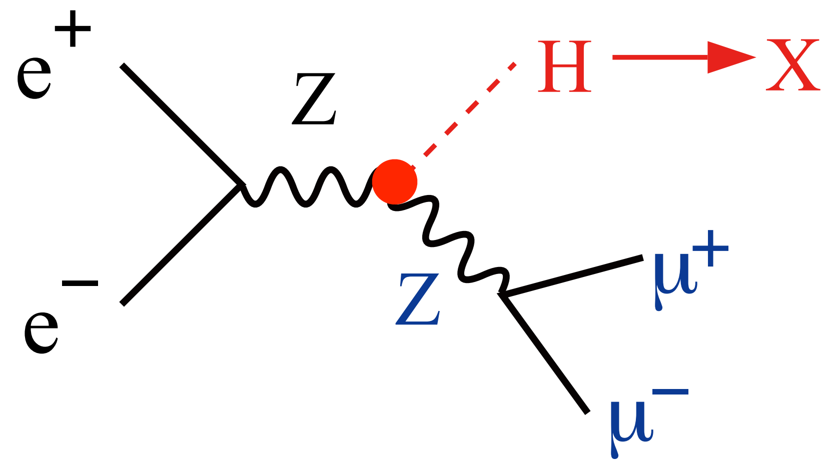
same technique can be used to search for H—>invisible / exotic decays

independent of H decay modes?

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

- this question is almost equivalent to whether we can tag the Z decay products unambiguously
- might be easy in Z->ll, certainly not trivial in Z->qq
- even in Z->ll mode, we know there can be isolated leptons from Higgs decay, e.g. H->WW*/τ τ/ZZ, which get mis-identified as leptons from Z decay
- keep in mind we are targeting 0.1-1% precision measurement

independent of HZZ vertex?



- different HZZ vertex might change angular distributions of Z

- hence, this question is equivalent to whether the selections cuts are democratic for all production angles of Z

- open question, this is not sufficiently studied yet

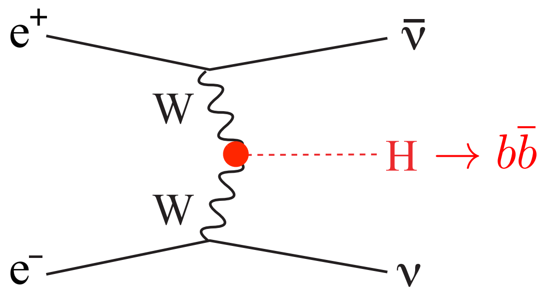
(ii-2) WW-fusion channel & Higgs total width Γ_H

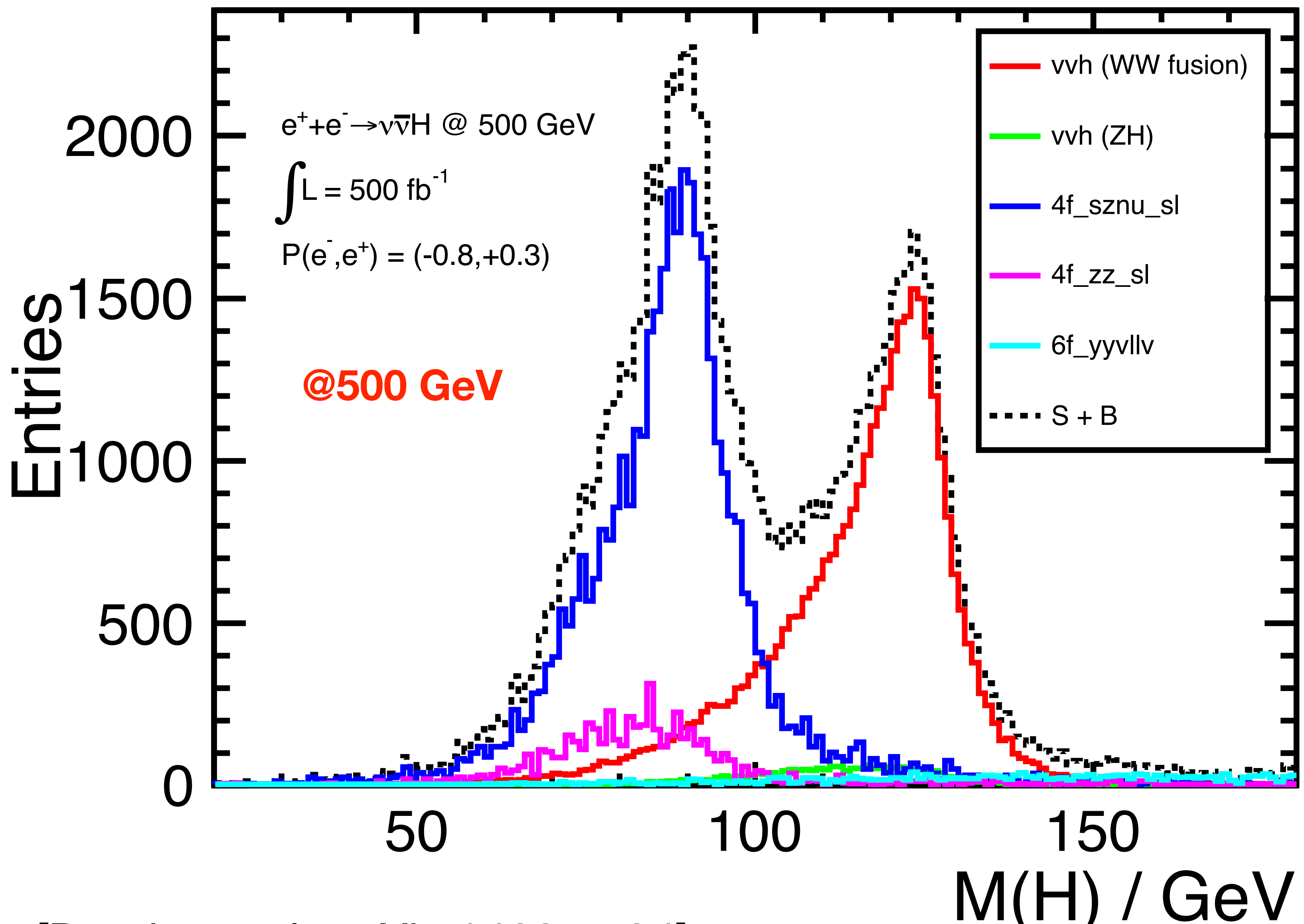
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

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

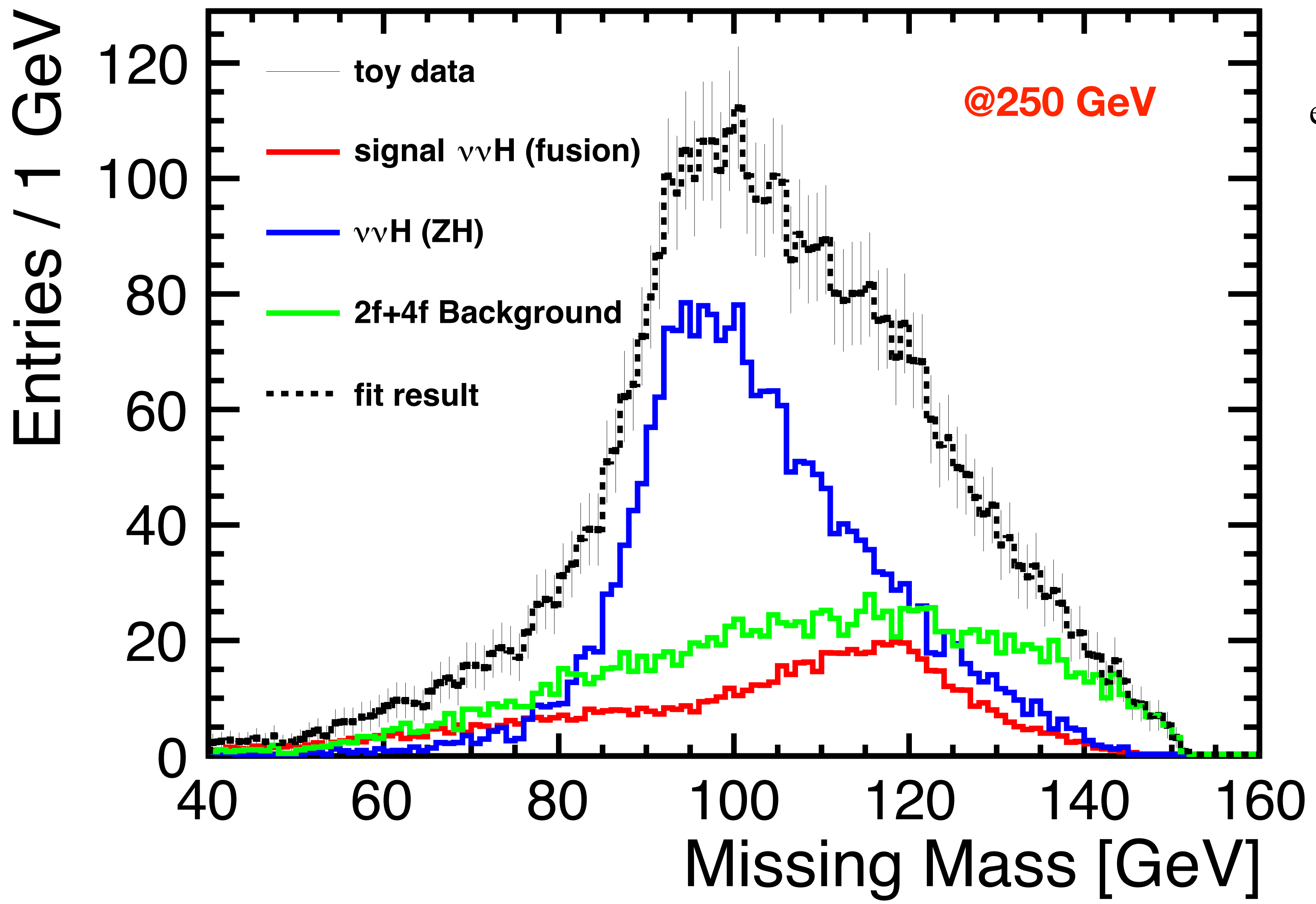
—> better option!

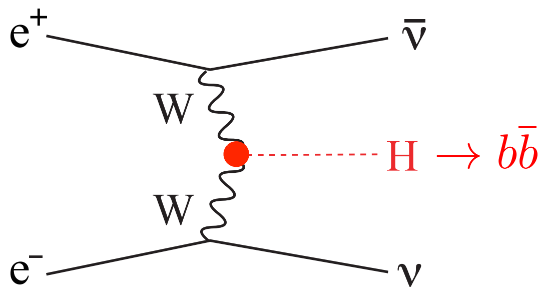




[Duerig, et al., arXiv:1403.7734]

very different at √s=250 GeV



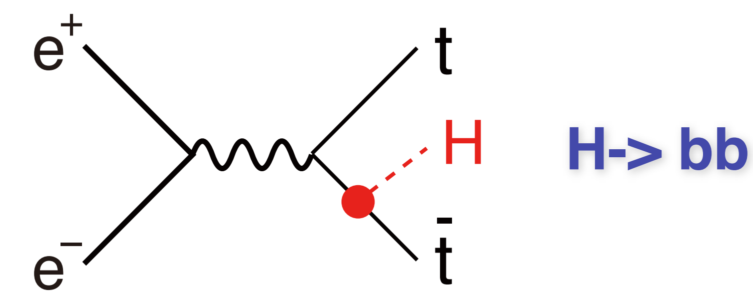


ρ = -34% correlation between

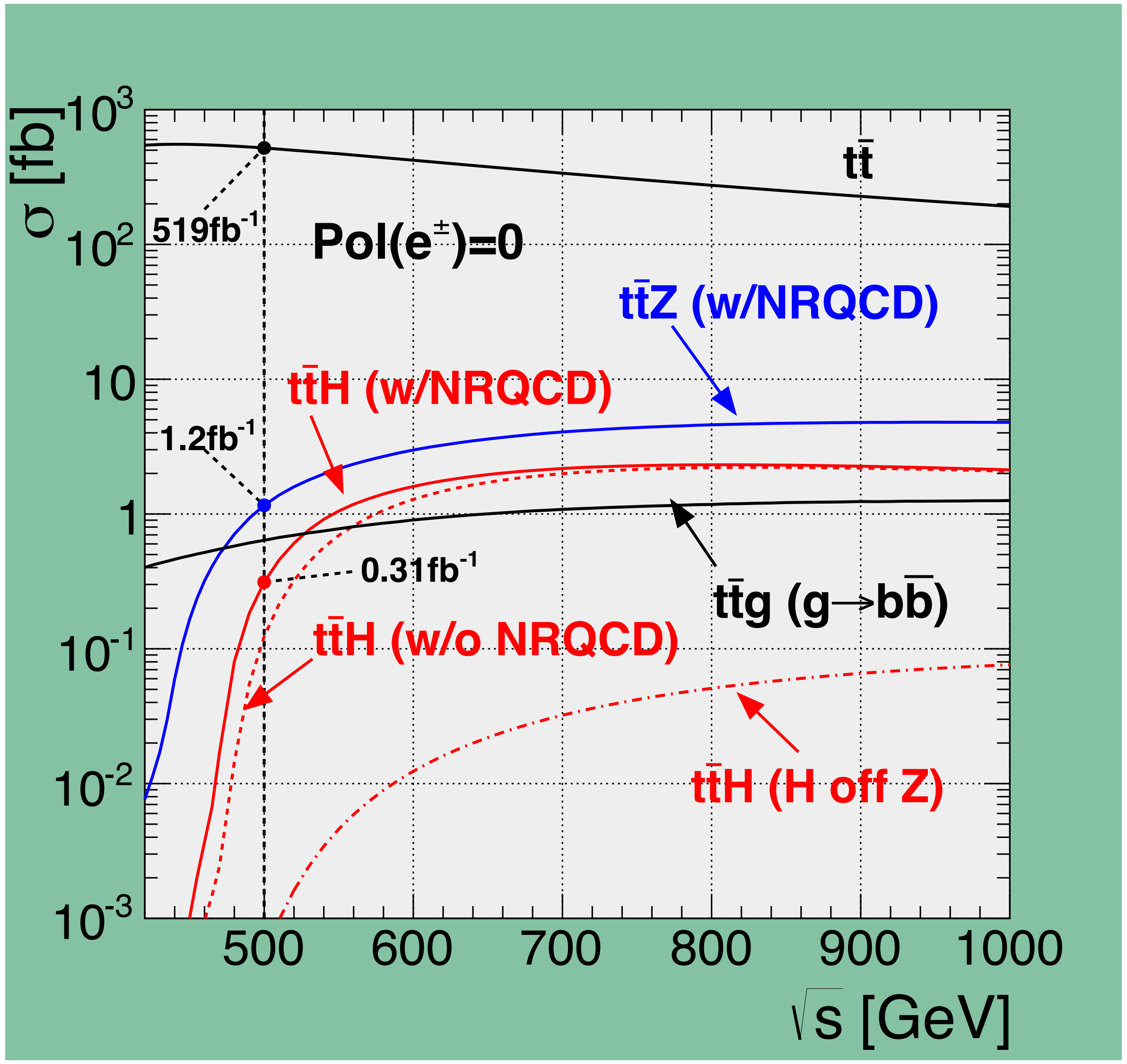
$\sigma_{\nu\nu H}$xBR(H—>bb) and σ_{ZH}xBR(H—>bb)

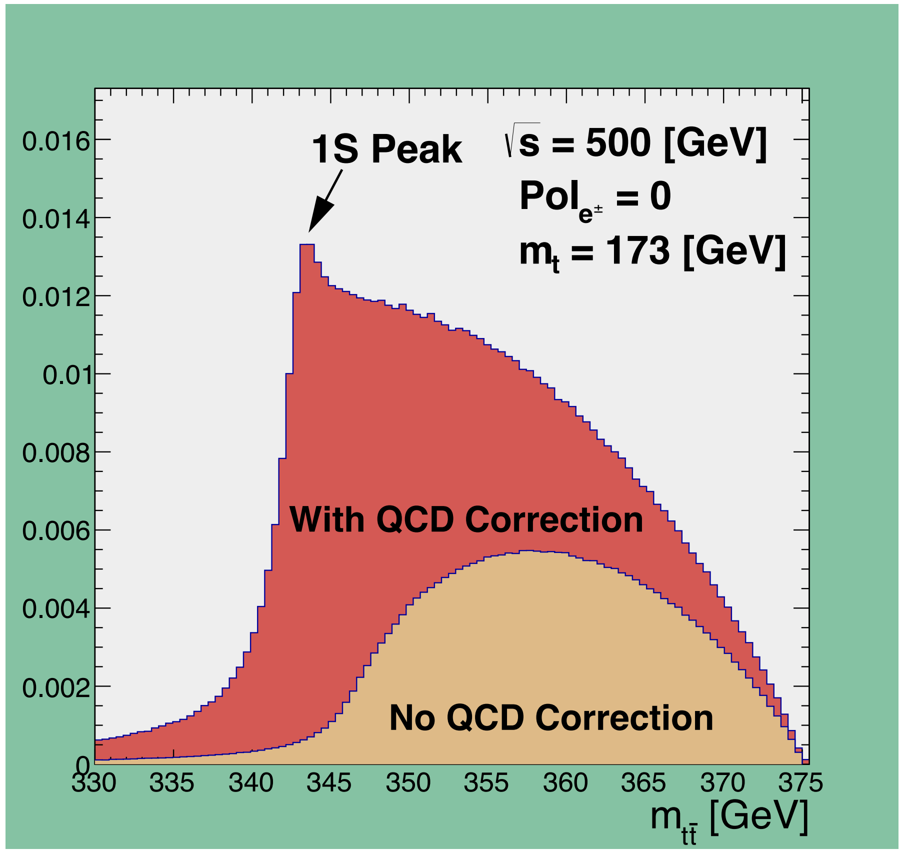
(ii-3) Top-Yukawa coupling

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



$\Delta g_{ttH} / g_{ttH}$	500 GeV	+ 1 TeV
ILC	6.3%	1.5%



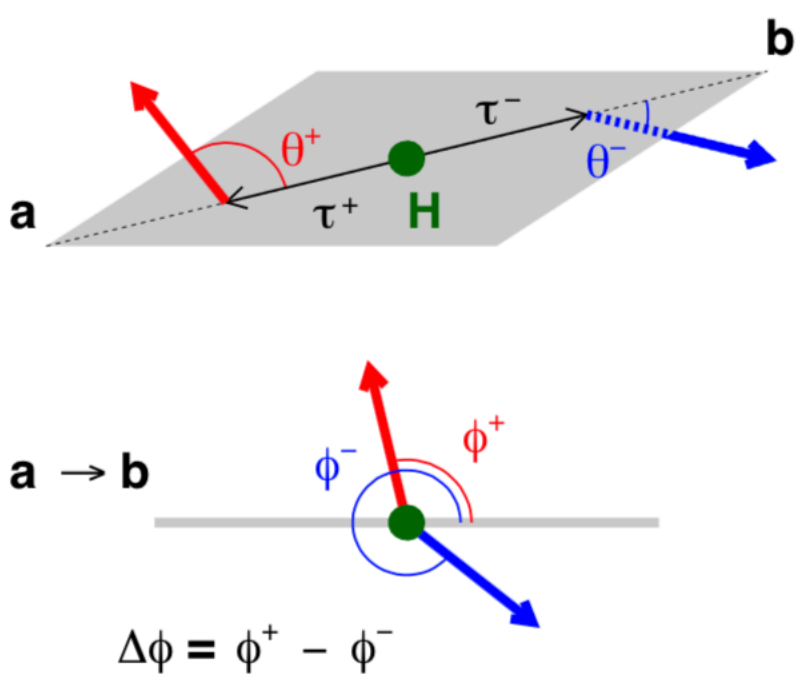


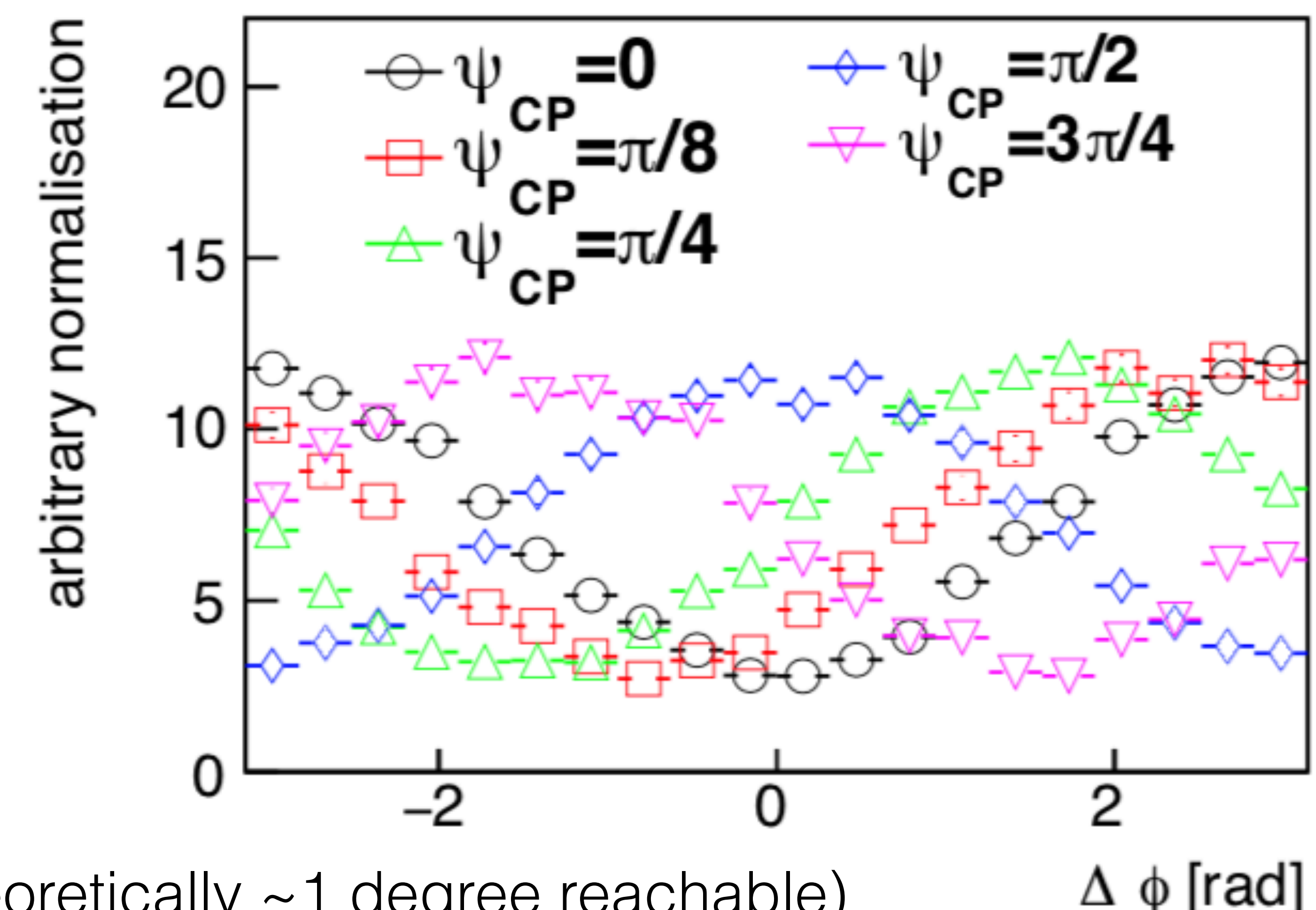
Yonamine, et al., PRD84, 014033;
Price, et al., Eur. Phys. J. C75 (2015) 309

(iii-1) Higgs CP in $H \to \tau^+\tau^-$

- CP is essential to understand structures of all Higgs couplings

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





$\Delta\Phi_{CP} \sim 4.3^\circ$ (theoretically ~1 degree reachable)

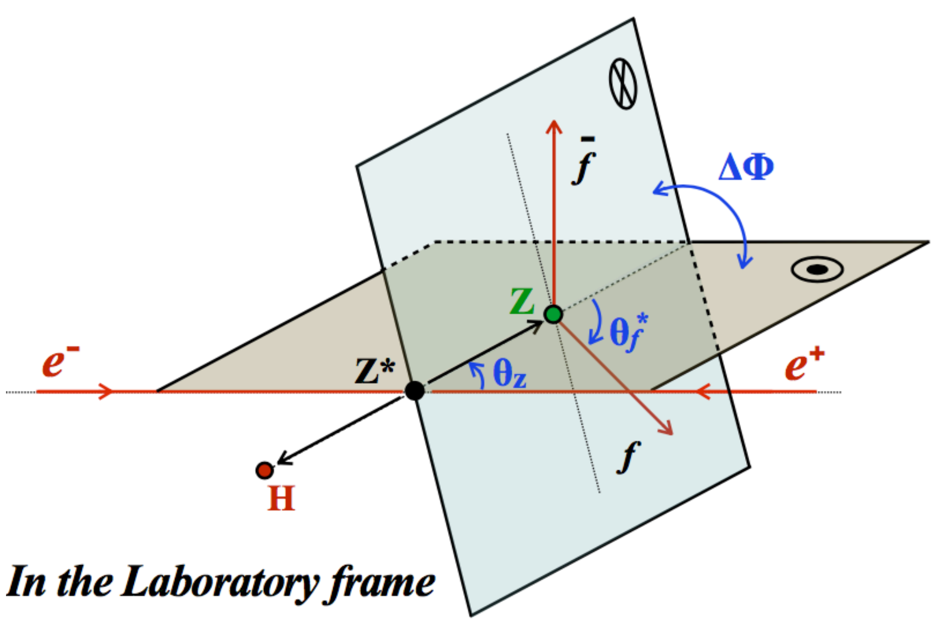
Jeans et al, arXiv:1804.01241

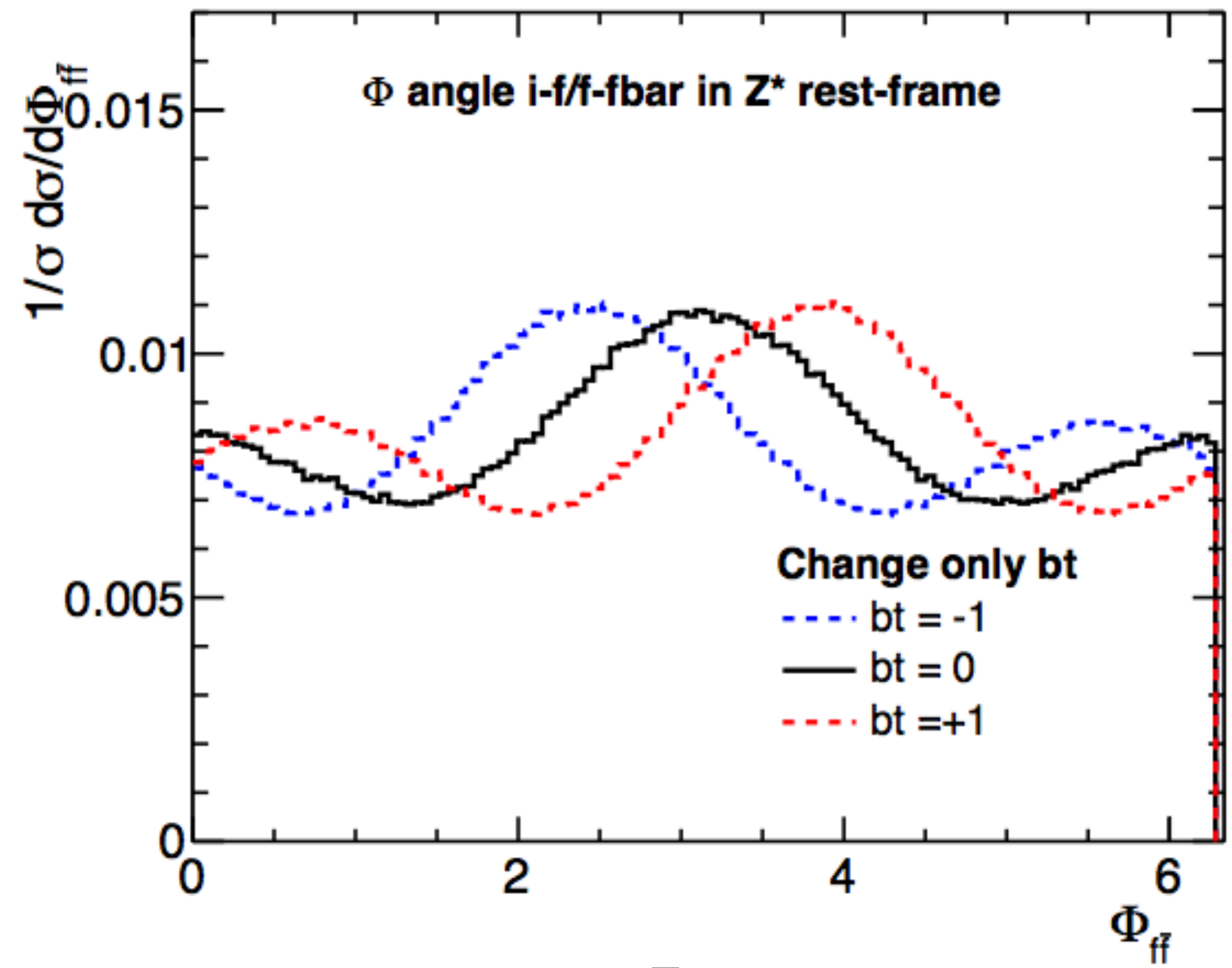
(iii-2) Higgs CP in HZZ coupling

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

(CP-even) (CP-odd)

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





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

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

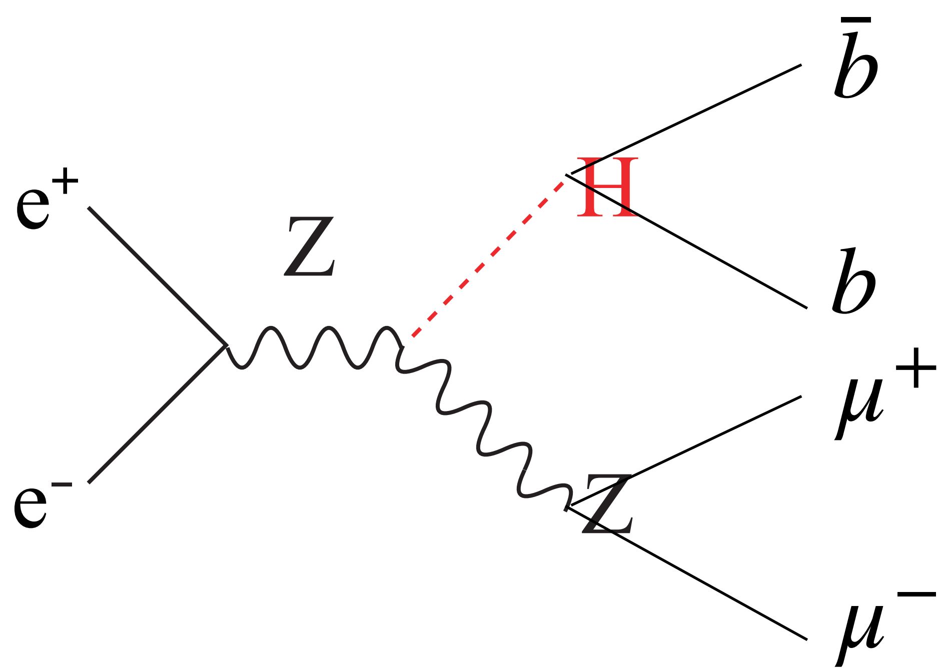
Ogawa et al, arXiv:1712.09772

(iv) Global interpretation: why do we need it?

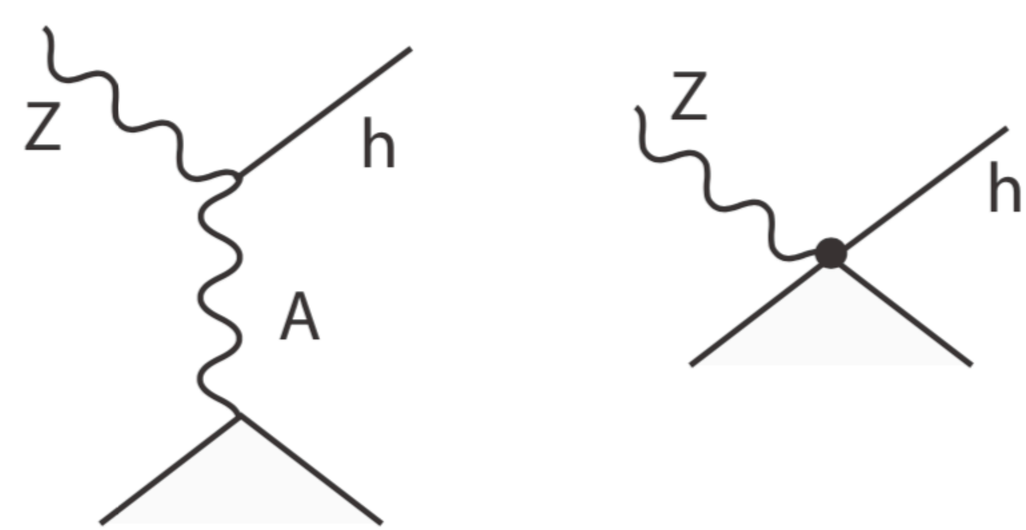
suppose we discover a deviation in, e.g. cross section of

$$e^+e^- \to ZH \to (\mu\mu)\,(bb)$$

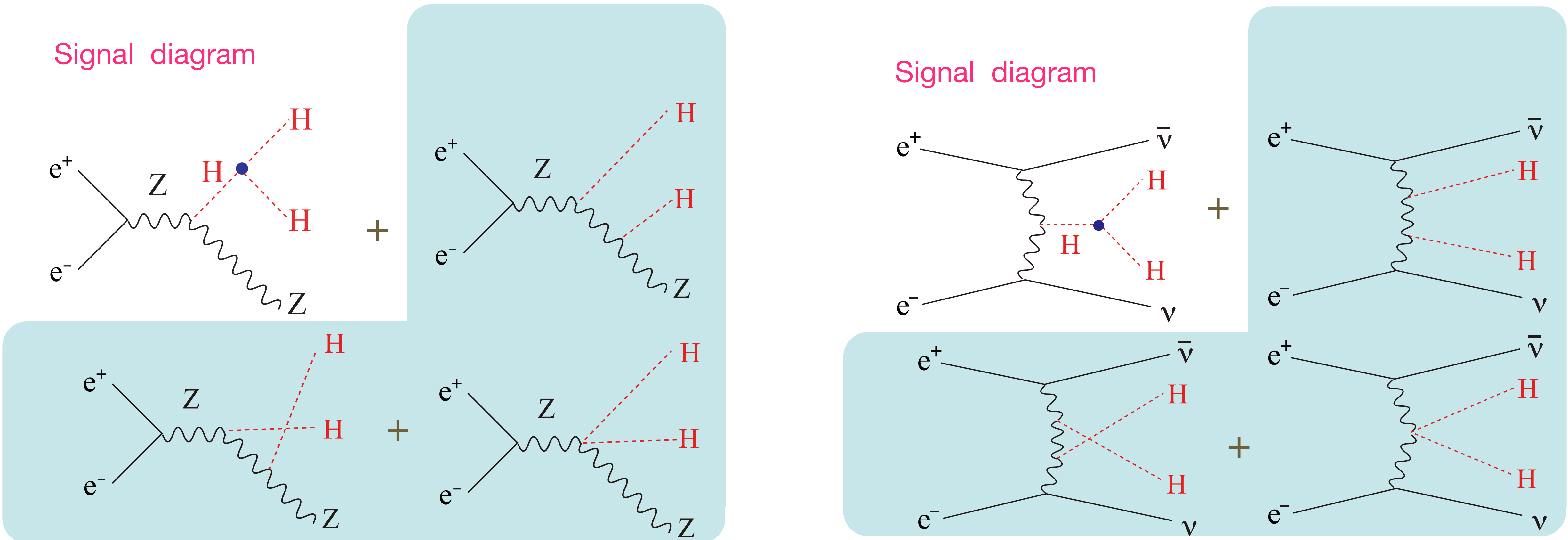
then we would like to know which coupling is deviated:



- hbb coupling?
- hZZ coupling?
- Zμμ coupling?
- Zee coupling?
- new diagrams?

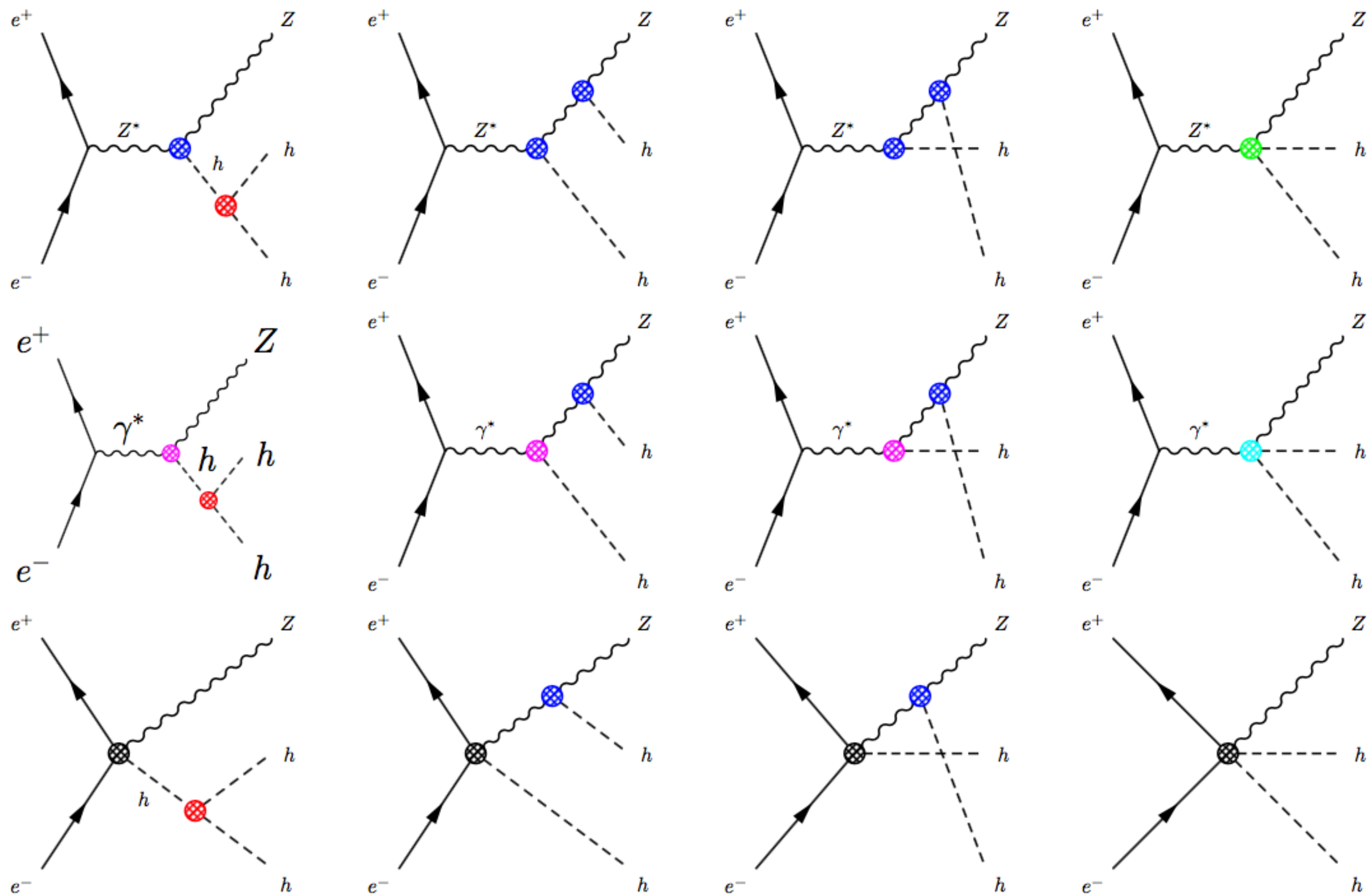


Higgs self-coupling determination in HH processes



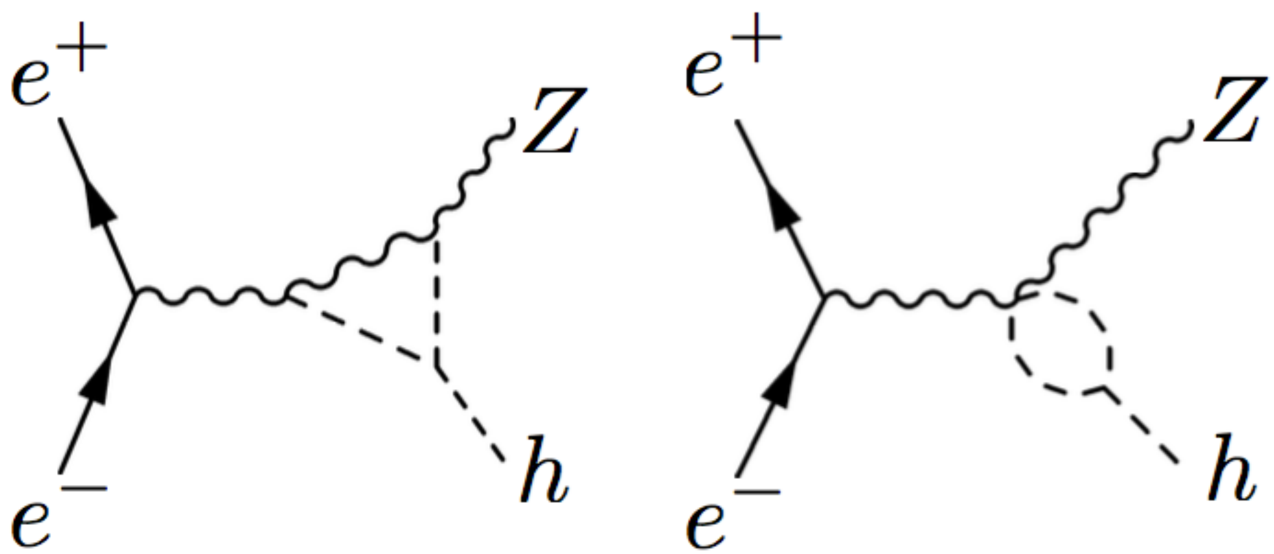
- classic studies always assume all the coupling except λ_{hhh} in these processes are fixed
- might be OK for many of the couplings, but definitely not obvious for ZZHH / WWHH couplings

more general interactions in HH processes



- what we are measuring if only σ_{ZHH} is determined?

λ_{hhh} determination in single-Higgs process



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; Jung, Peskin, JT, paper in preparation

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

From observables to couplings — Global Fit

$$\chi^2 = \sum_{i=1}^{n} (\frac{Y_i - Y_i'}{\Delta Y_i})^2$$

Yi: measured values by experiments

Yi': predicted values by underlying theory

ΔYi: measurement uncertainty

n: number of independent observables

- kappa formalism

$$Y_i' = F_i \cdot \frac{g^2_{HA_iA_i} \cdot g^2_{HB_iB_i}}{\Gamma_0} \qquad (A_i = Z, W, t) \quad (B_i = b, c, \tau, \mu, g, \gamma, Z, W : \text{decay})$$

$$g_{HXX} = \kappa_X \cdot g^{SM}_{HXX}$$

- SM Effective Field Theory formalism

Higgs coupling determination — kappa formalism

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

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

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

4) total width $\boldsymbol{\Gamma_h} = \Gamma(h \rightarrow ZZ^*)/BR(h \rightarrow ZZ^*)$

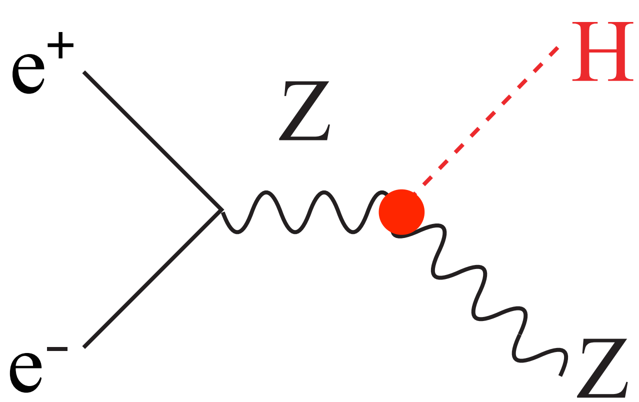
5) or $\boldsymbol{\Gamma_h} = \Gamma(h \rightarrow WW^*)/BR(h \rightarrow WW^*)$

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

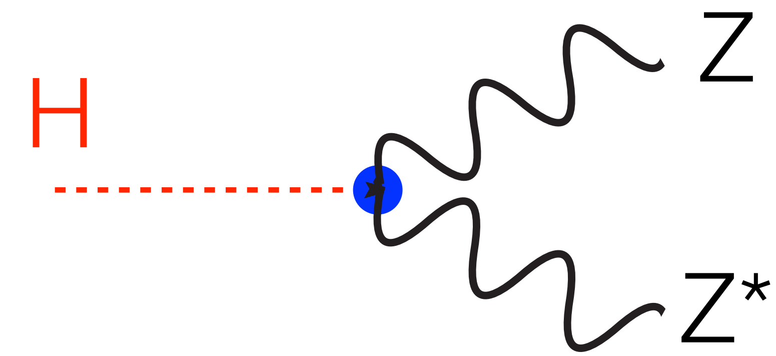
JT, et al, PoS EPS-HEP2013 (2013) 316 Nucl.Part.Phys.Proc. 273-275 (2016) 826-833

one question in kappa formalism:

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



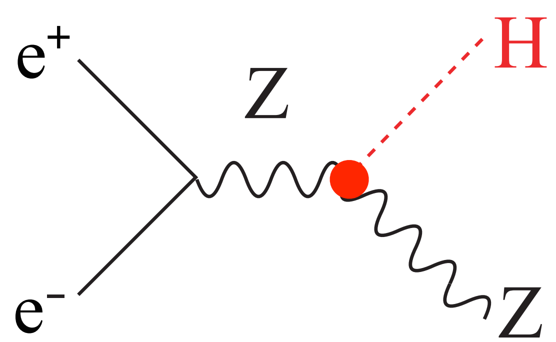
$\propto \quad \kappa_Z^2 \; ? \quad \propto$

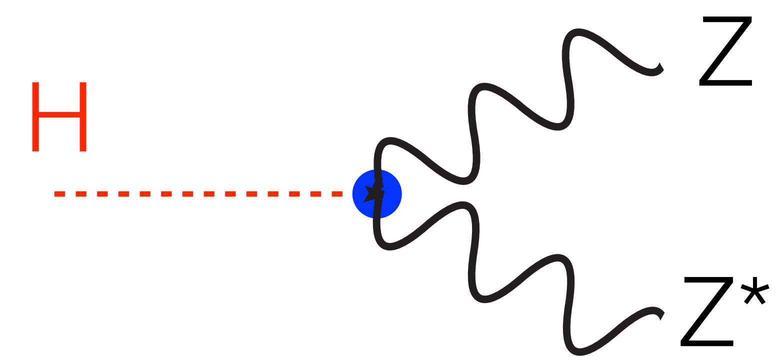


BSM territory: can deviations be represented by single κ_Z?

the answer is model dependent

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





$$\sigma(e^+e^- \to Zh) = (SM) \cdot (1 + 2\eta_Z + (5.5)\zeta_Z)$$

$$\neq$$

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

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

new strategy: SM Effective Field Theory

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

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

- most general BSM effects represented by $d_i > 4$ operators
  - more model-independent formalism
- well-defined quantum field theory respecting SM SU(3)xSU(2)xU(1) gauge symmetries
  - can include radiative corrections consistently
- unifying BSM effects in Higgs, W/Z, top, 2-fermion physics
  - global view in searching for BSM

global SMEFT fit @ e+e-

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

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

“Warsaw” basis,
Grzadkowski et al,
arXiv:1008.4884

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 backup slides)

next: highlight a few important implications

(iv-1) 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

(iv-1) Higgs couplings are related to themselves (synergy w/ LHC)

two measurements from LHC (model independent)

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

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

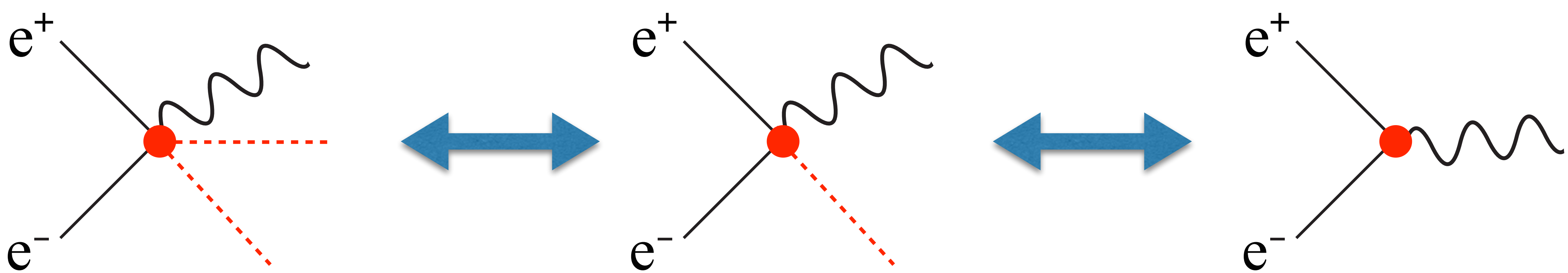
$$\delta\Gamma(h \to Z\gamma) = \mathbf{290}\,\delta Z_{AZ} - c_H \quad + \dots$$

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

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

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

$$i\frac{c_{HL}}{v^2}(\Phi^\dagger \overleftrightarrow{D}^{\mu}\Phi)(\overline{L}\gamma_\mu L) \qquad +(c'_{HL},\, c_{HE})$$

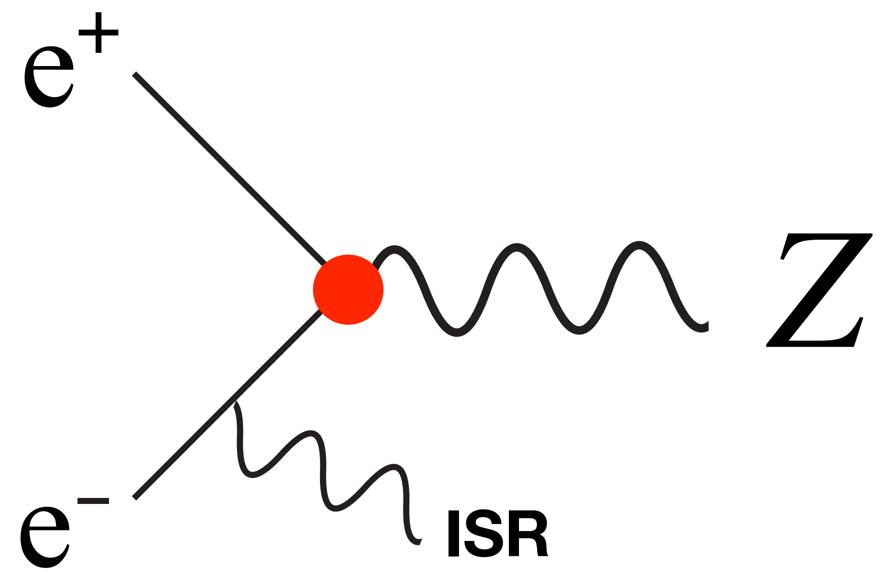


$e^+e^- \to Zh h$ | $e^+e^- \to Zh$ | Z-pole

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

new ideas: improving EWPOs @ ILC250

radiative return



[Mizuno, PhD thesis]

- a free gift by ISR: Higgs factory is meantime a Z factory
- **~10^8** Z events by ILC250, without any change of accelerator
- more over, **polarized beams**

ILC250 = ILC250 + 100xLEP/SLC

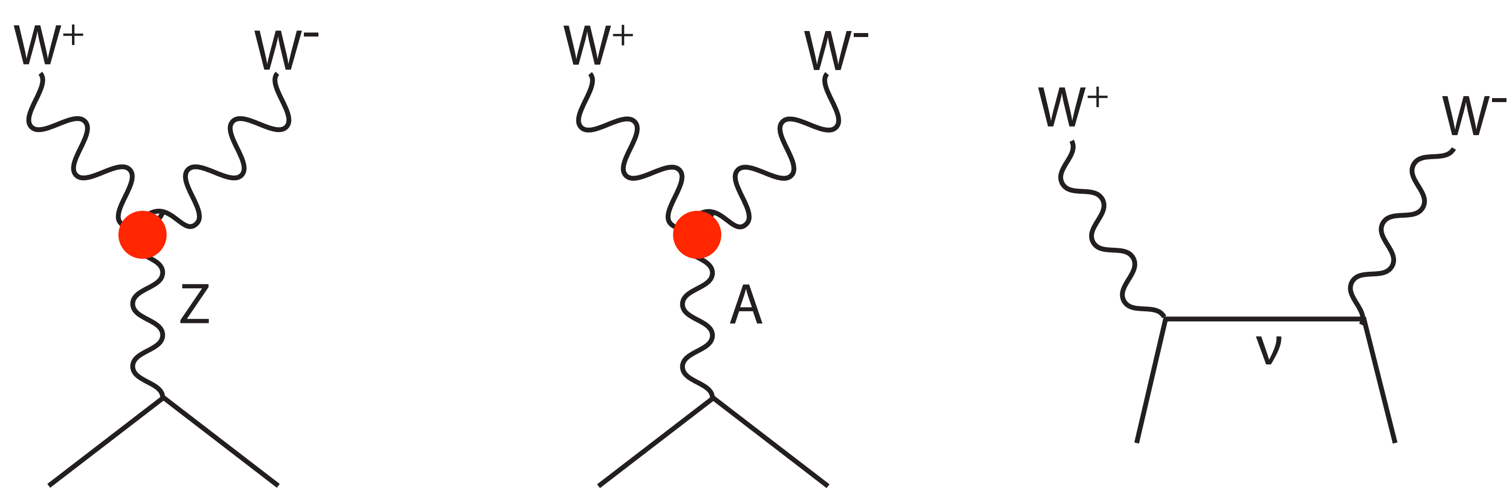
see more in arXiv:1908.11299

- expect a factor of 10 improvement on A_{LR}

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

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

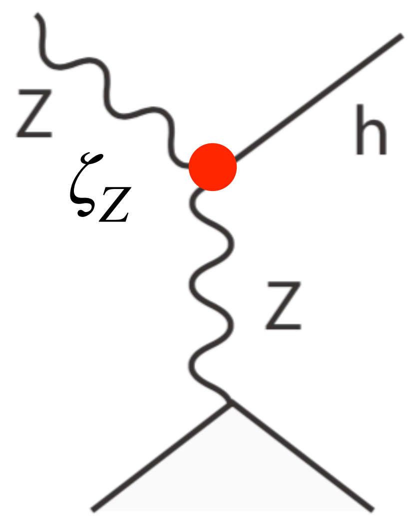
$e^+e^- \to WW$

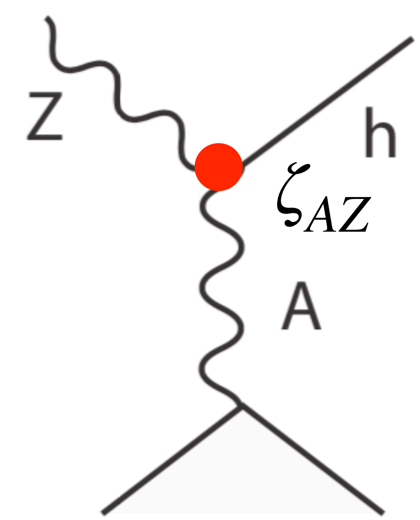


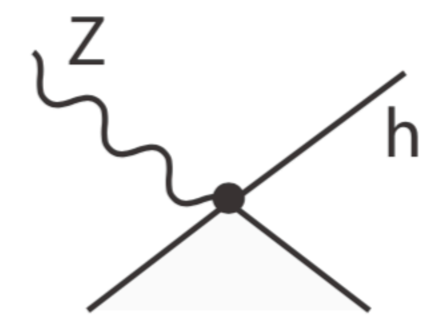
$h \to ZZ$ $\quad \zeta_Z \frac{h}{2v} Z_{\mu\nu} Z^{\mu\nu} \qquad \zeta_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB})$

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

(iv-3) role of beam polarizations (e+e- -> Zh)







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}

(iv-3) role of beam polarizations (e+e- -> Zh)

√s=250 GeV

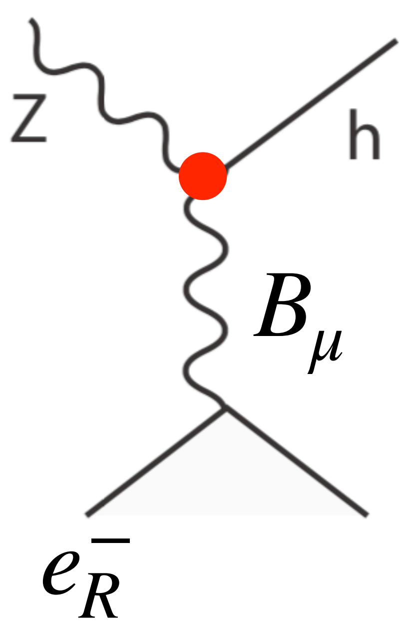
$$\delta\sigma_L = -c_H + 7.7(8c_{WW}) + \ldots$$

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

why?

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

(8cWW) ~ 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 $\frac{m_Z^2}{s}$

(iv-3) role of beam polarizations (overall effects)

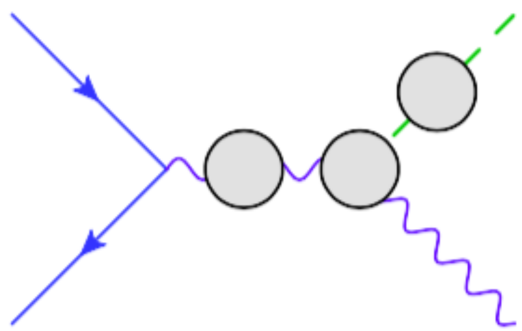
ILC250: 2 ab^{-1} **FCCee240: 5 ab^{-1}**

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

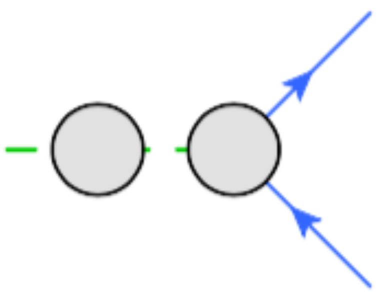
- 250 GeV e+e-: power of 2 ab^{-1} polarized ≈ 5 ab^{-1} unpolarized

(arXiv:1903.01629)

(iv-4) what happens at next leading order for SMEFT



WH,ZH



H→bb

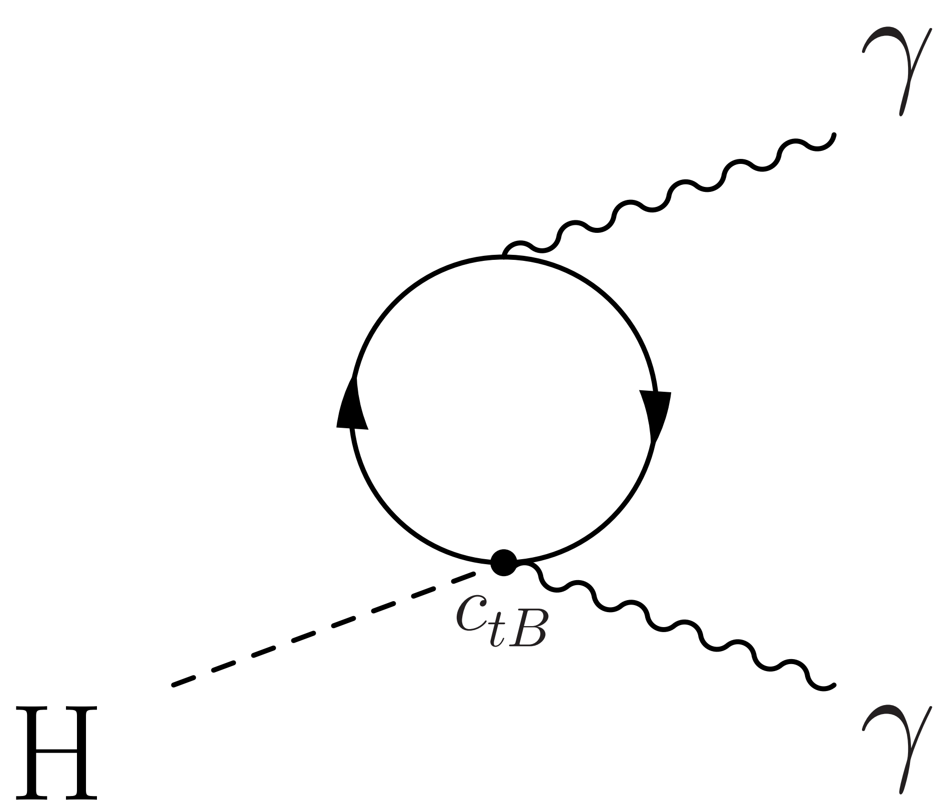
Zhang, et al, arXiv:1804.09766, 1807.02121

- 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

some detailed understandings

$$\delta\Gamma(h \to \gamma\gamma) : + = -0.56c_{tH} + 1.2c_{HQ}^{(3)} - 0.04c_{Htb} + 33c_{tW} + 61c_{tB}$$

HL-LHC~600%

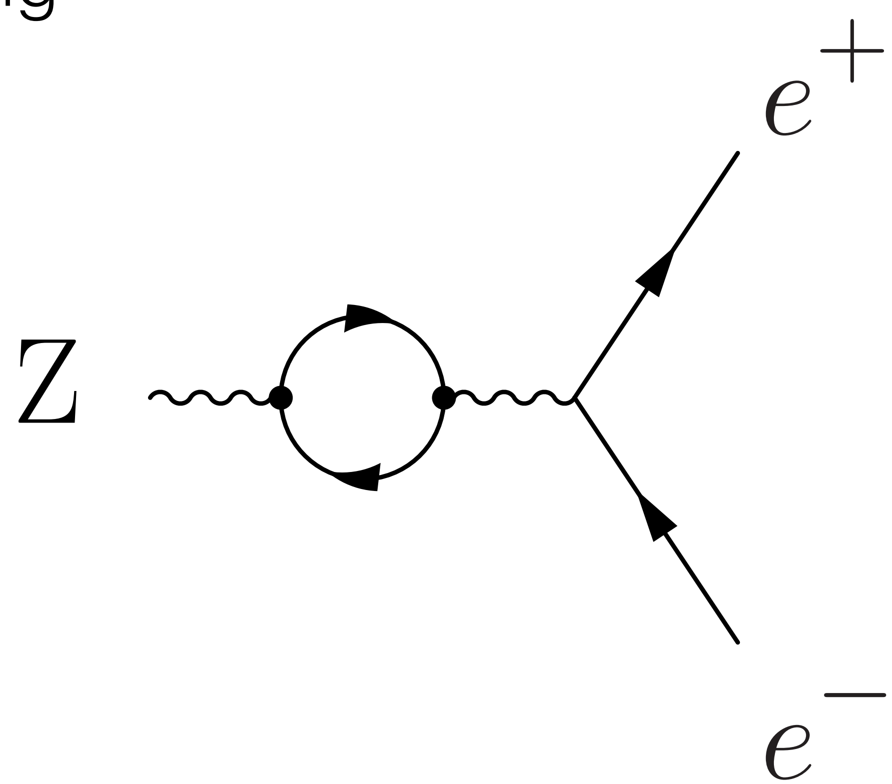


some detailed understandings

$$\delta A_l : + = 0.05 c_{HQ}^{(1)} - 0.2 c_{HQ}^{(3)} + 0.1 c_{Ht} + 1.8 c_{tW} - 0.3 c_{tB}$$

A_{LR}: left-right asymmetry in Z-e-e coupling

~1%



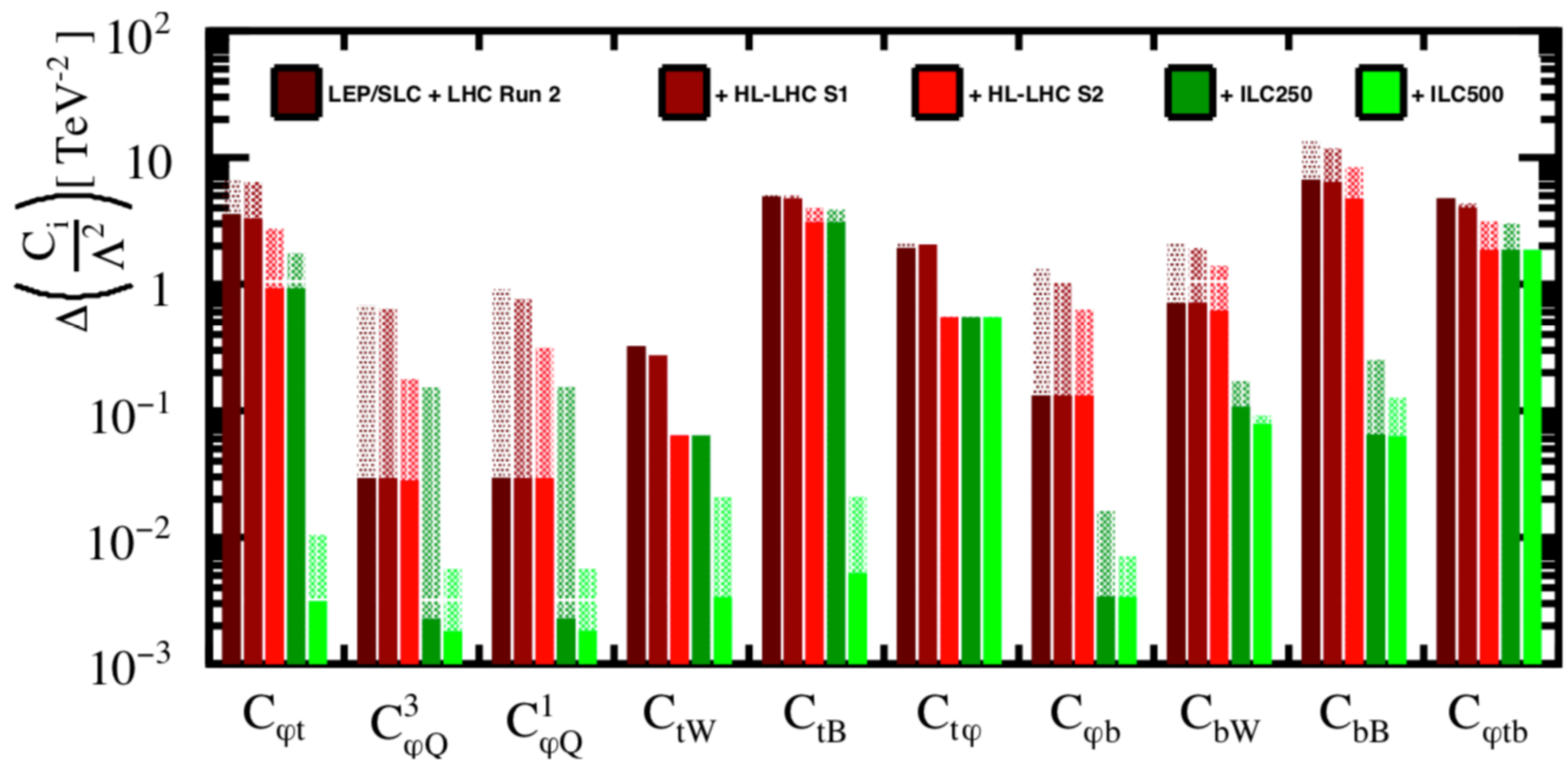
impact from top-EW operators: $\sqrt{s}$ = 250 GeV e+e-

- with the same set of observables (as previous global fit), at 250 GeV running only, the global fit will not converge at any of the Higgs factories
- e.g. Higgs couplings could not be determined unambiguously

impact from top-EW operators: ILC250 + LHC

- LHC will provide us valuable top data sets
- top operators will be constrained to some extent at (HL-)LHC

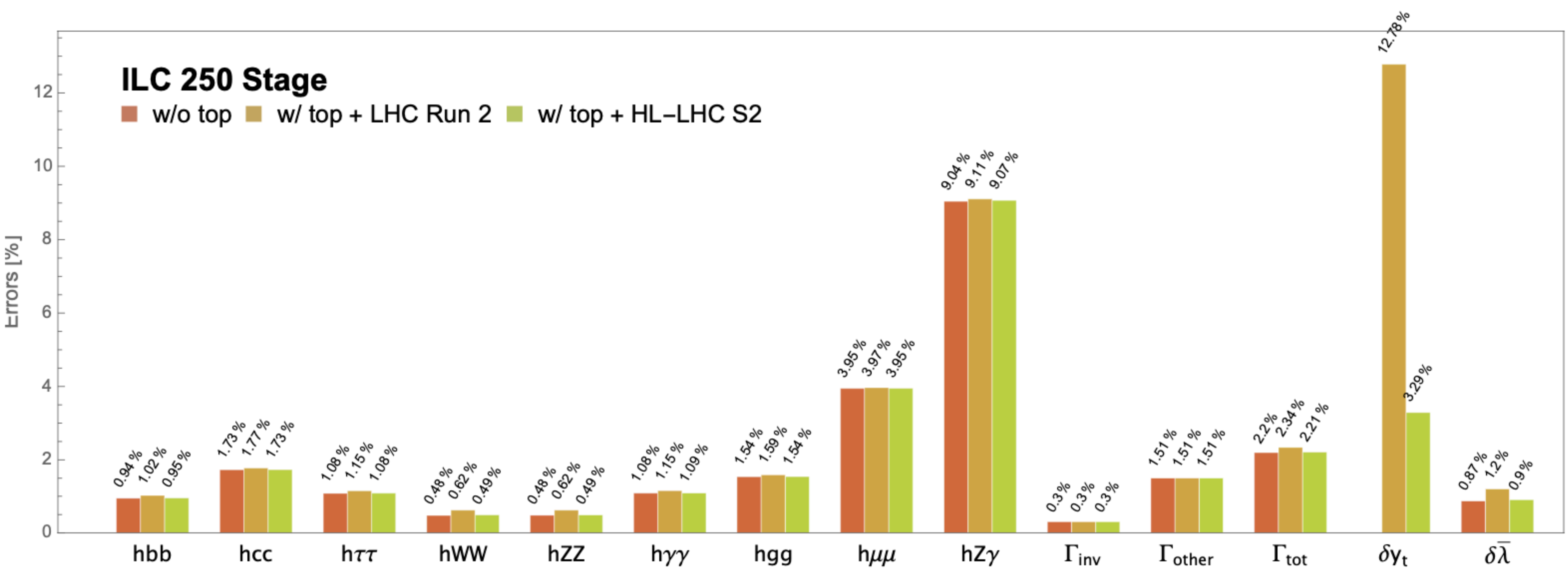
Process	observable
$pp \to t\bar{t}H$	cross section
$pp \to t\bar{t}Z/W$	cross section
$pp \to t\bar{t}\gamma$	fid. x-sec.
single-top (t-ch)	cross section
single-top (Wt)	cross section
single-top (tZq)	cross section
$t \to W^+ b$	$F_0,\ F_L$
$e^- e^+ \to b\bar{b}$	R_b , A_{FBLR}^{bb}



[Durieux, et al, arXiv:1907.10619]

impact from top-EW operators: ILC250 + LHC

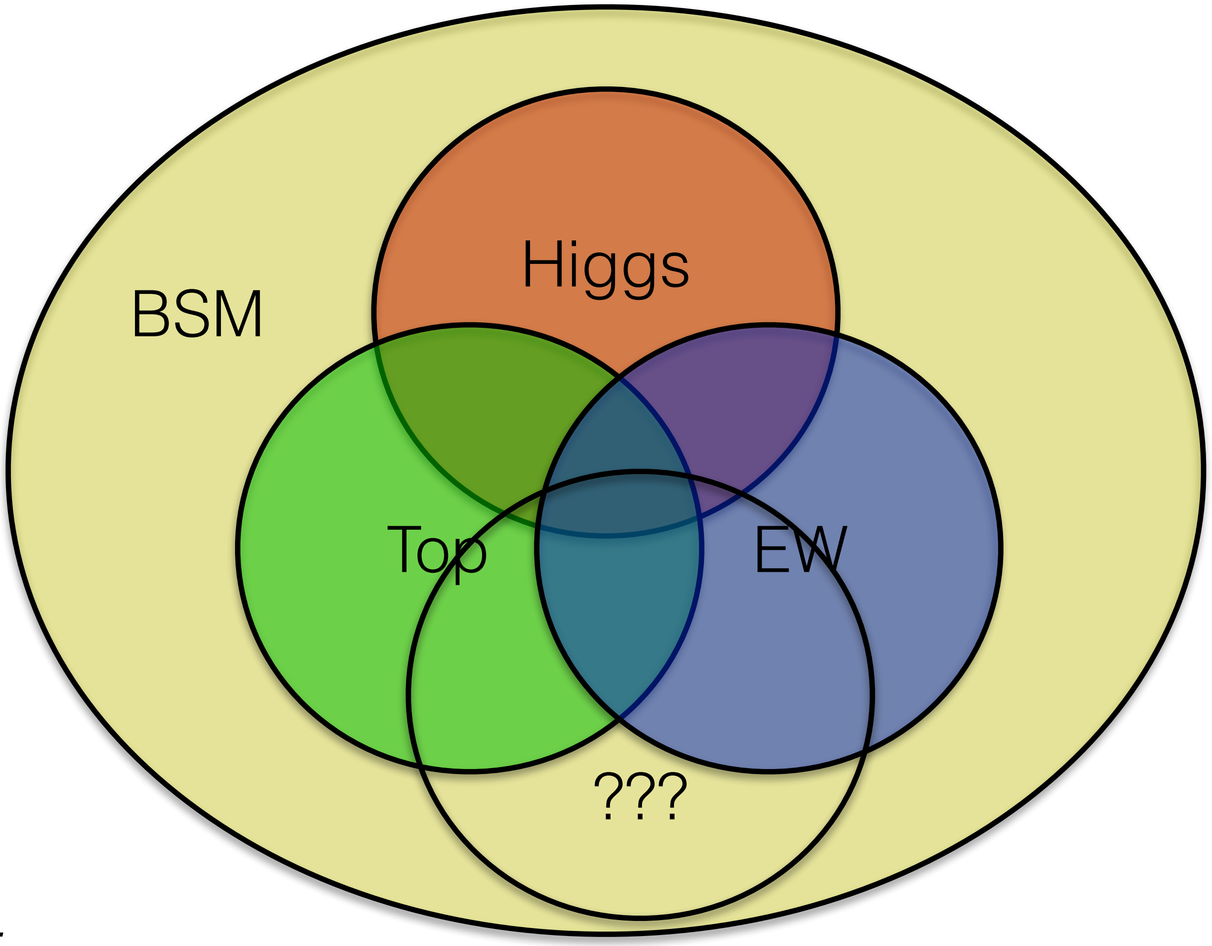
- with the help of LHC top data, Higgs coupling precisions @ ILC250 are almost restored
- note: top data from LHC Run 2 is not constraining enough



S.Jung, J.Lee, M.Perello, JT, M.Vos, arXiv:2006.14631

summary

- Higgs provides a unique window into BSM physics
- Many couplings can be measured to 1% or below using single-Higgs
- Differential cross section can be also measured precisely, important for CP, to be explored for self-coupling
- Room for new ideas & improvement



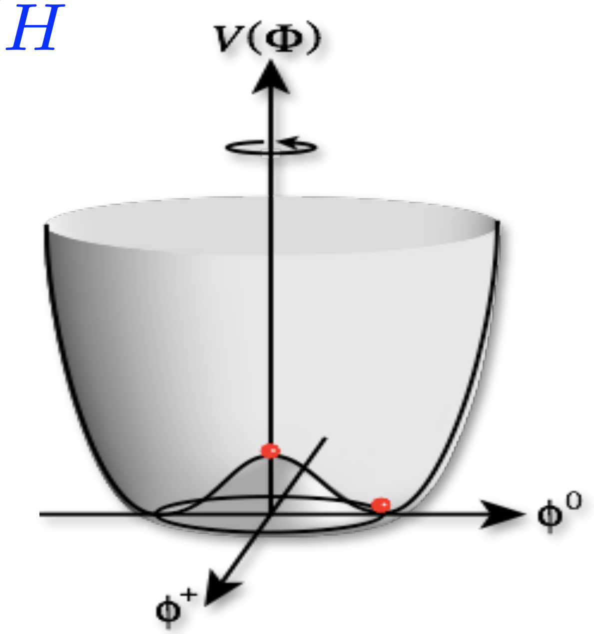
- Higgs is not alone in probing BSM, tightly connected with other EW and top-quark measurement & direct searches: global interpretation important

backup

(ii-3) Higgs self-coupling

$$V(\eta_H) = \frac{1}{2} m_H^2 \eta_H^2 + \lambda v \eta_H^3 + \frac{1}{4} \lambda \eta_H^4$$

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

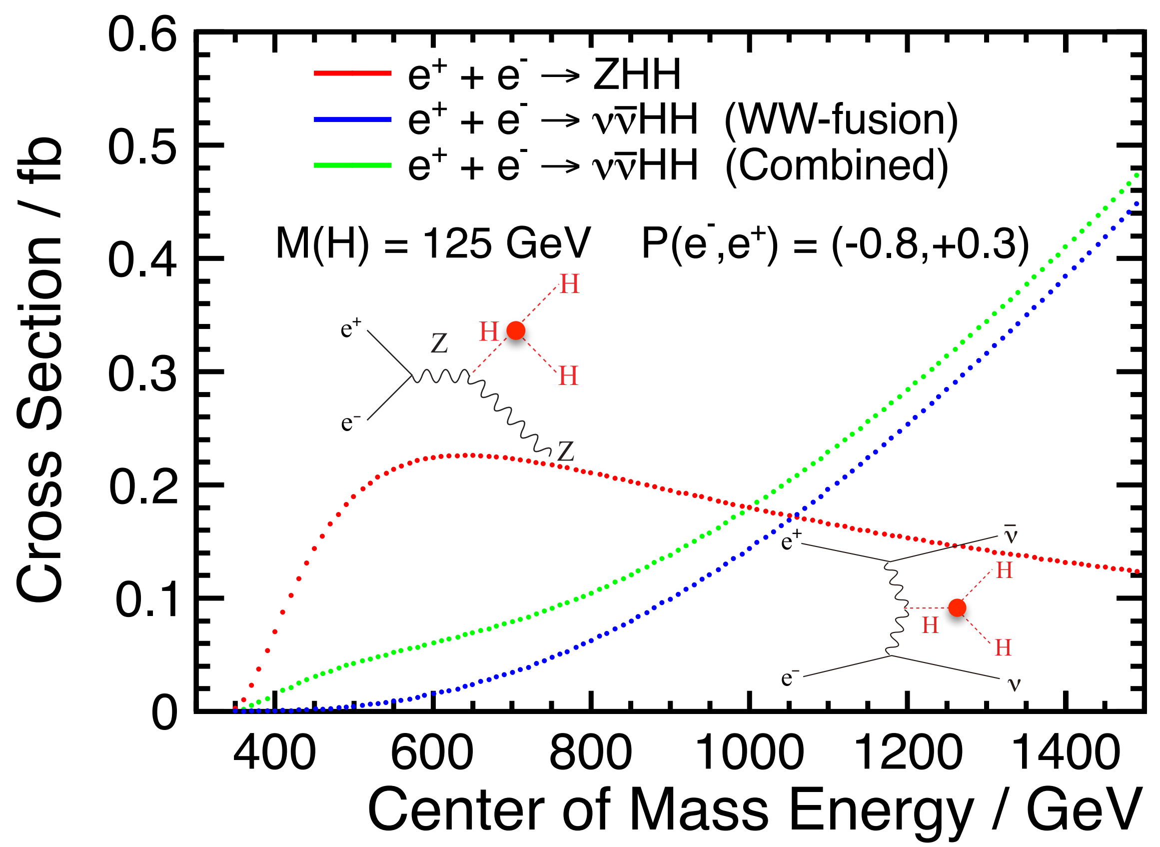


ILC

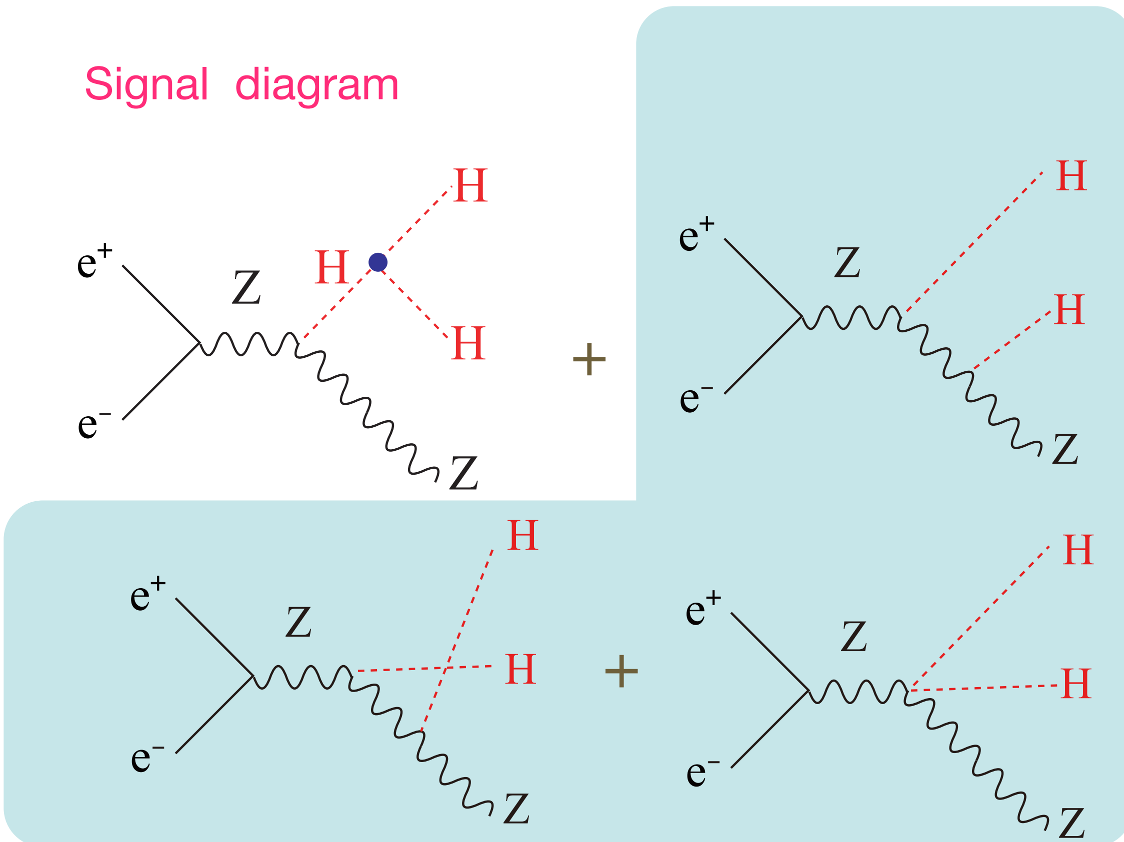
$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
H20	27%	10%

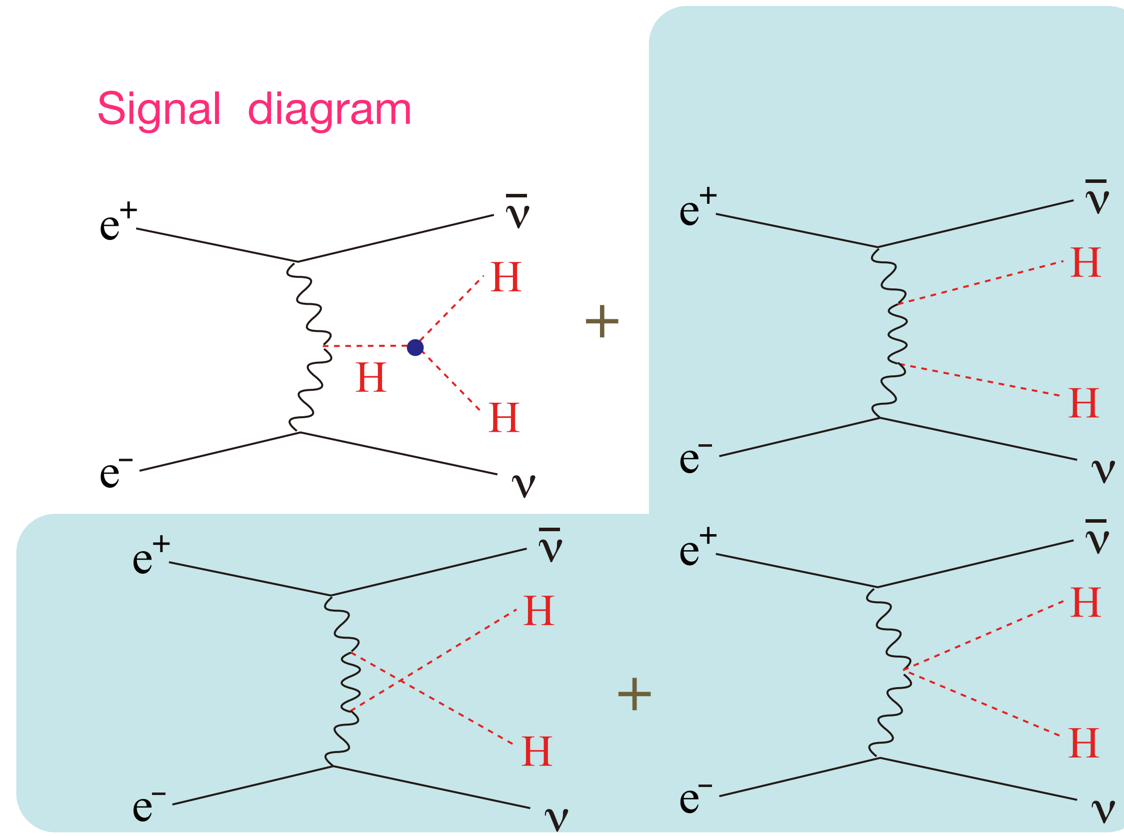
CLIC

1.5 TeV	+3 TeV
36%	10%



physics issues: diagrams for double Higgs production





$$\sigma = S\lambda^2 + I\lambda + B$$

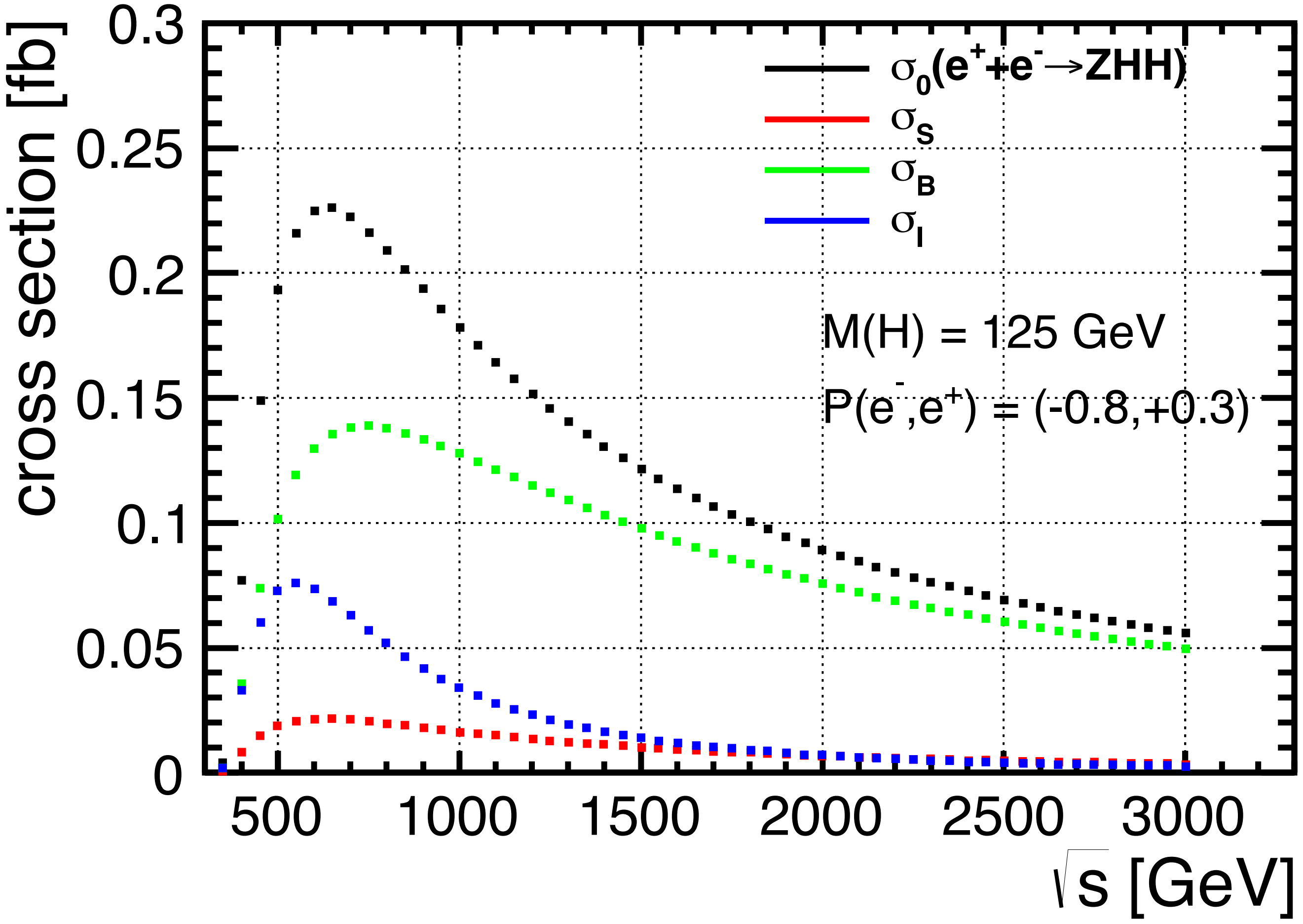
(signal diagram) (interference) (background diagram)

- the sensitivity of λ is determined not just by the apparent total cross section, in fact is determined by S and I term;
- if B term dominates, measurement would be very difficult

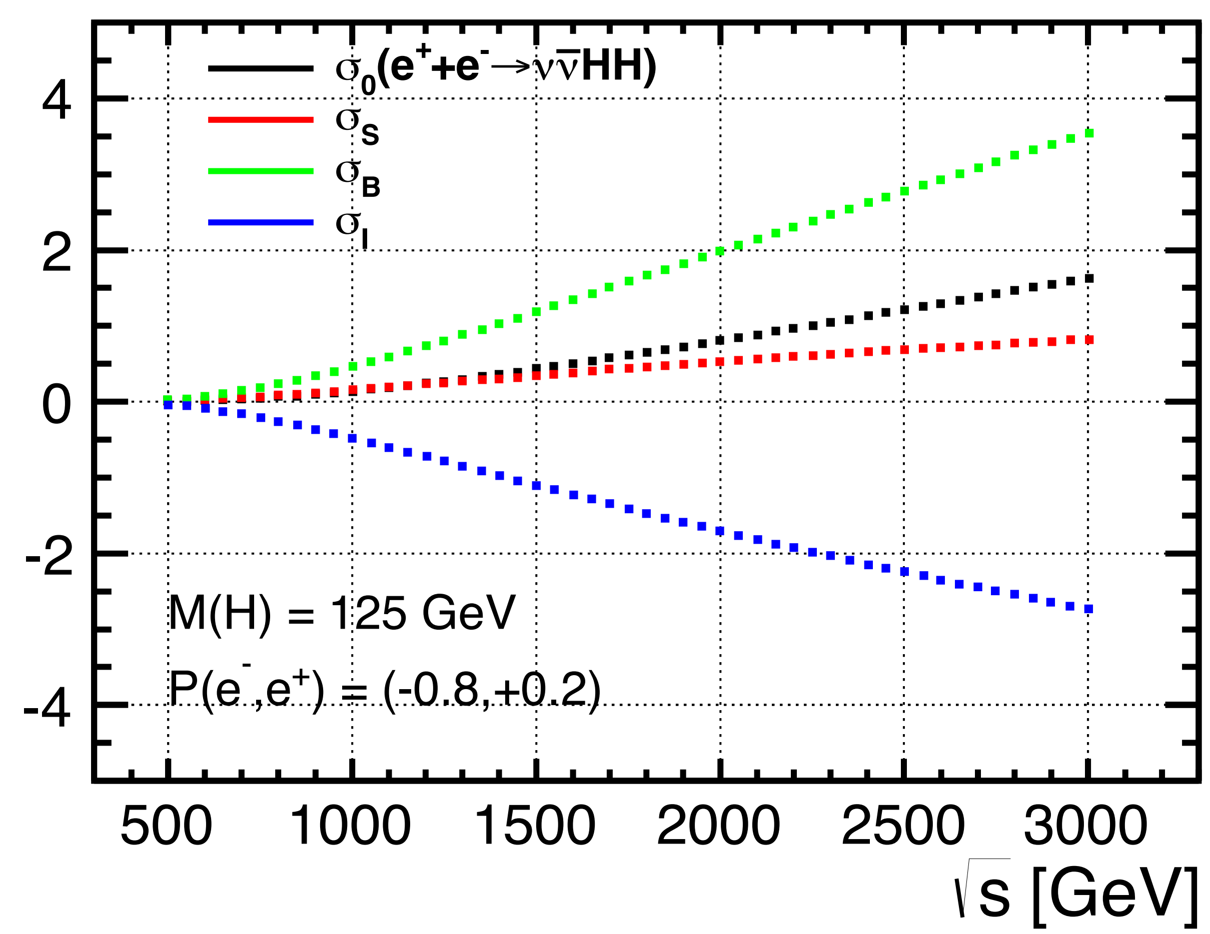
double Higgs x-section: breakdown for each diagram

$$\sigma = S\lambda^2 + I\lambda + B$$

ZHH



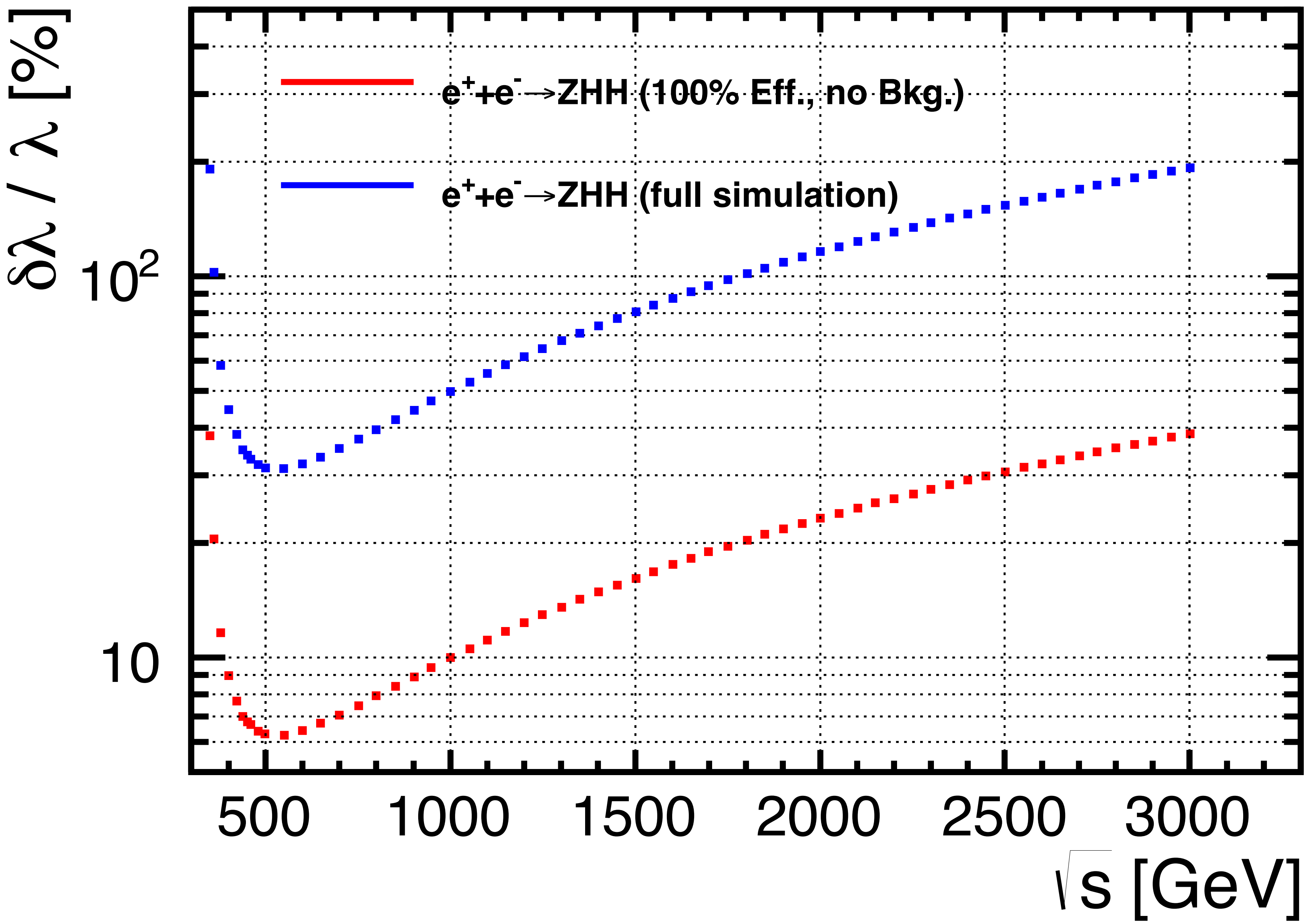
ννHH



- very useful to understand the impact of ECM (more in backup)

expected precision of λ: impact from analysis & √s

ZHH



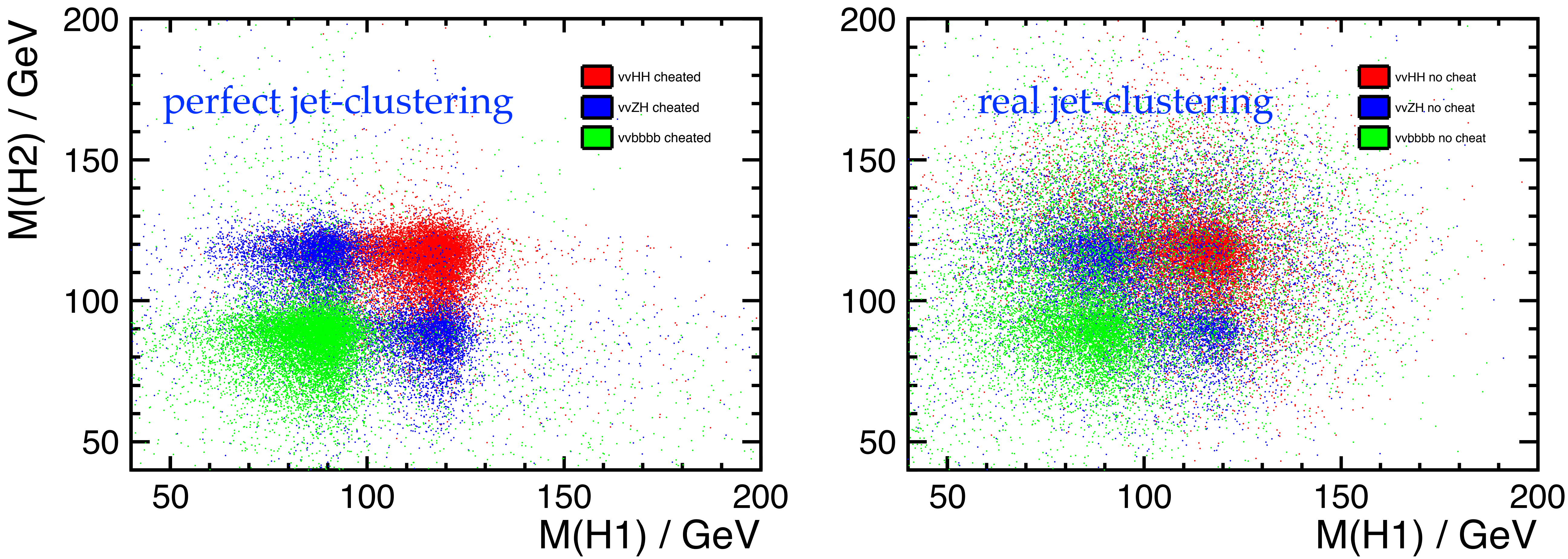
- huge gap of these two expectations —> room of improvement
- for ZHH: optimal at 500-600 GeV; significantly worse at higher √s

Di Micco et al, arXiv:1910.00012

one limiting factor: jet-clustering algorithm

ZHH->ννbbbb (BG: ZZH and ZZZ)

scatter plot of two Higgs masses



- the mis-clustering of particles degrades significantly the separation between signal and BG.
- it is studied that using perfect color-singlet-jet-clustering can improve $\delta\lambda/\lambda$ by 40%!

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

simplify the analysis up to dimension-**6** operators

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

assuming B / L conservation & CP even, there are ***59***

- there exists a smaller but complete set relevant to Higgs coupling determination 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}

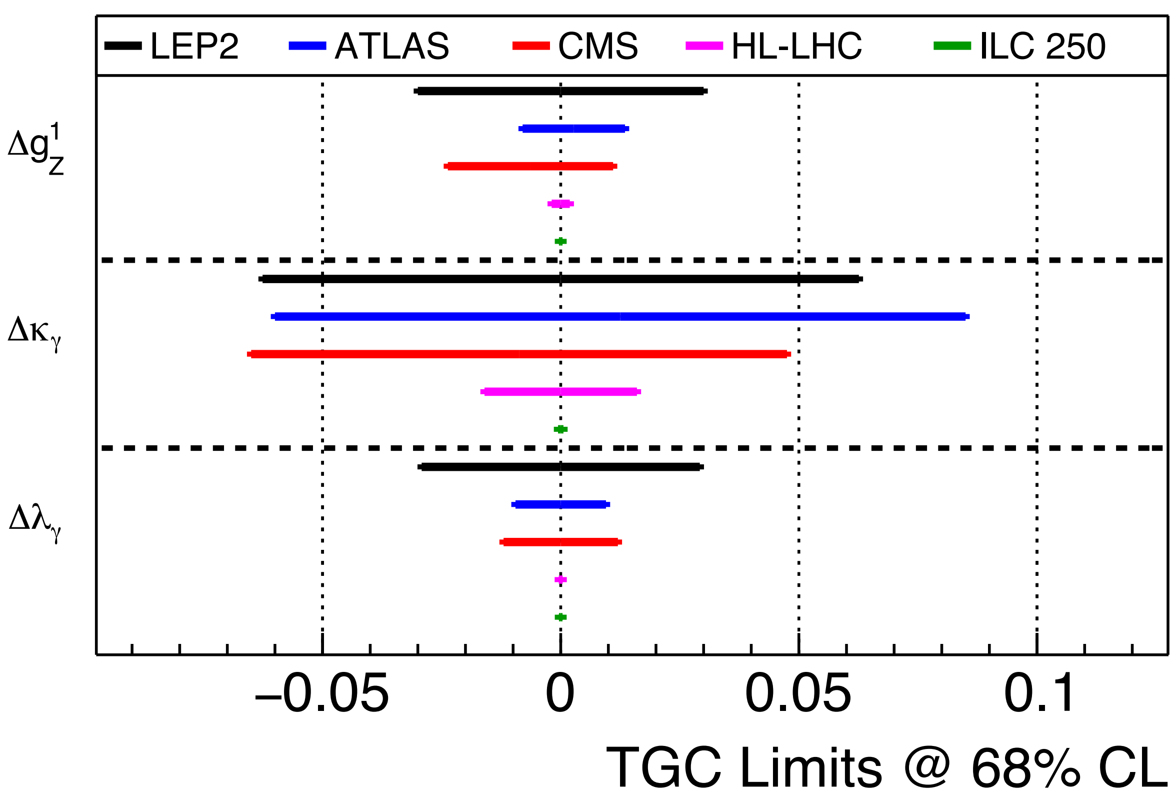
+ 4 SM parameters: g, g', v, λ
+ 5 operators modifying h couplings to b, c, τ, μ, g
+ 2 operators for contact interactions with quarks
+ 2 parameters for h->invisible and exotic

expected improvement on TGCs at ILC250

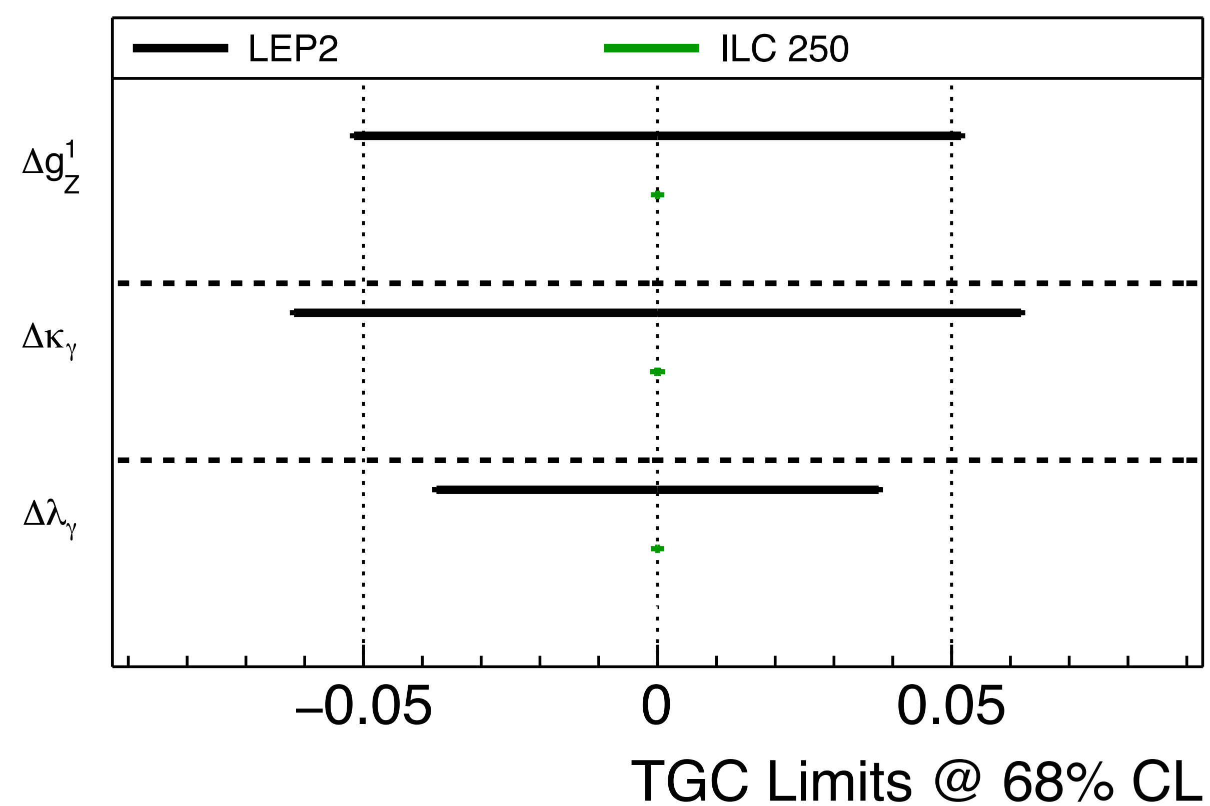
arXiv:1908.11299

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

1-par sensitivity



3-par sensitivity



- statistically x2000 more WW events w.r.t. LEP2

(iii-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

(iv-1) absolute Higgs couplings (unique role of inclusive σ_{Zh})

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

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

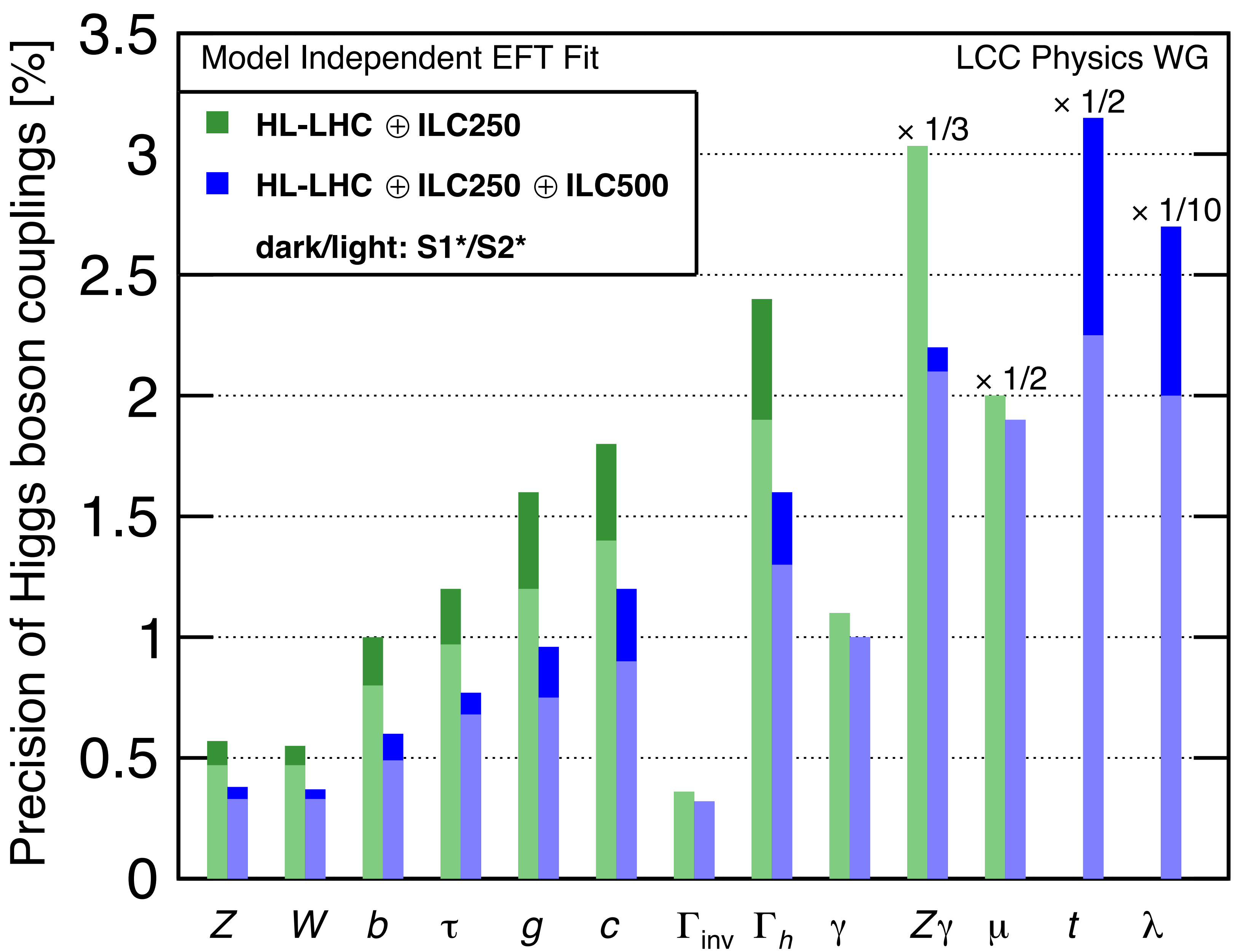
h ⟶ $(1-c_H/2)h$

⟶ **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 $e^+e^- \rightarrow Zh$, enabled by recoil mass technique at e+e-

precisions at Higgs factories: complementarity with LHC



(arXiv:1903.01629)

#qualitative:

model independence, hcc coupling

#quantitative (<~1%):

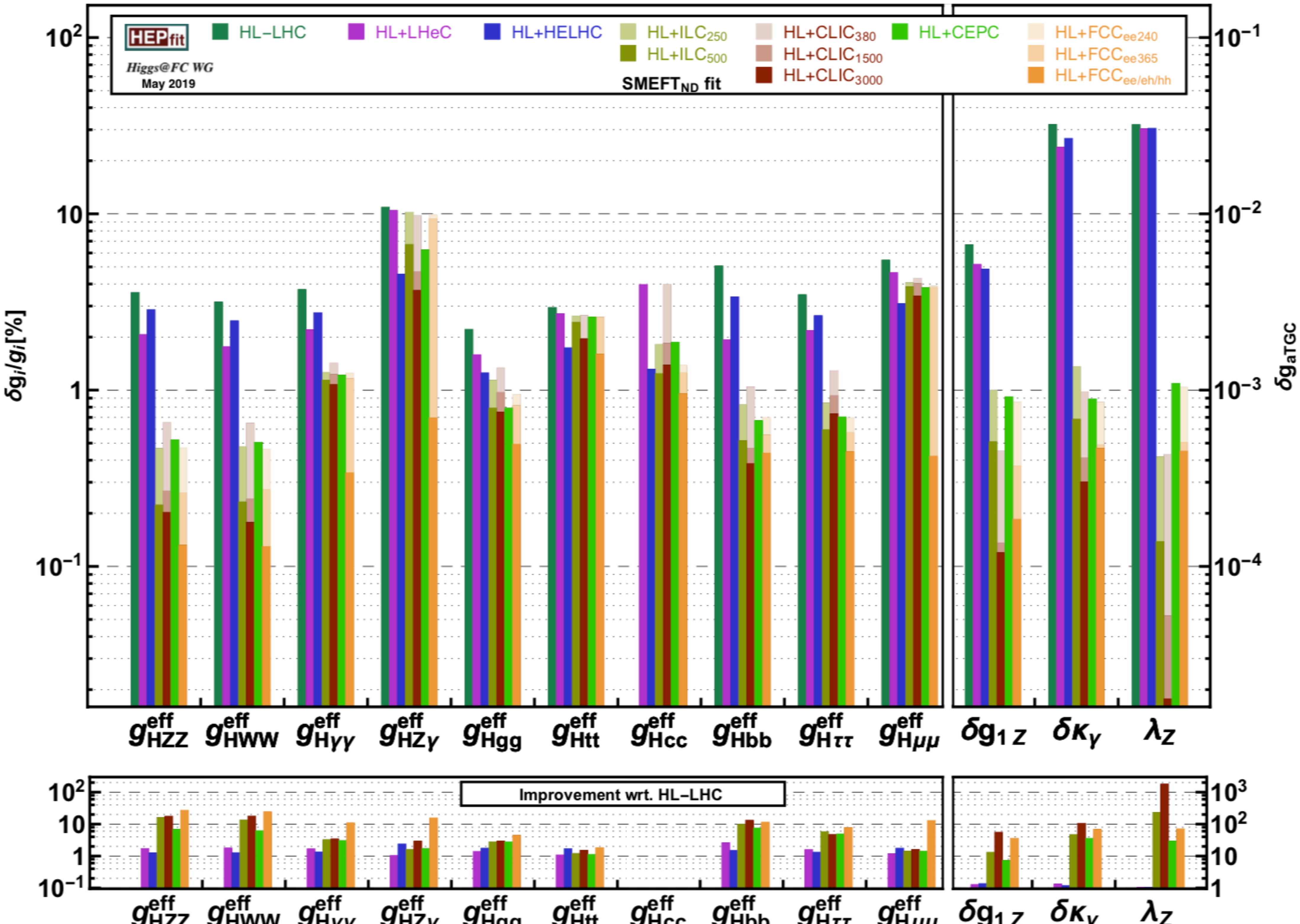
hZZ, hWW, hbb, $h\tau\tau$

h->invisible/exotic

#synergy:

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

precision at Higgs factories: European Strategy Update



(Physics Briefing Book, arXiv:1910.11775)

top-quark operators (added to previous SMEFT fit)

(no 4-fermion operators considered)

$$\mathcal{O}_{tH} = (\Phi^\dagger\Phi)(\bar{Q}t\tilde{\Phi}), \qquad \mathcal{O}_{Hq}^{(1)} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{Q}\gamma^\mu Q),$$

$$\mathcal{O}_{Hq}^{(3)} = (\Phi^\dagger i\overleftrightarrow{D}^a_\mu\Phi)(\bar{Q}\gamma^\mu\tau^a Q), \qquad \mathcal{O}_{Ht} = (\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{t}\gamma^\mu t),$$

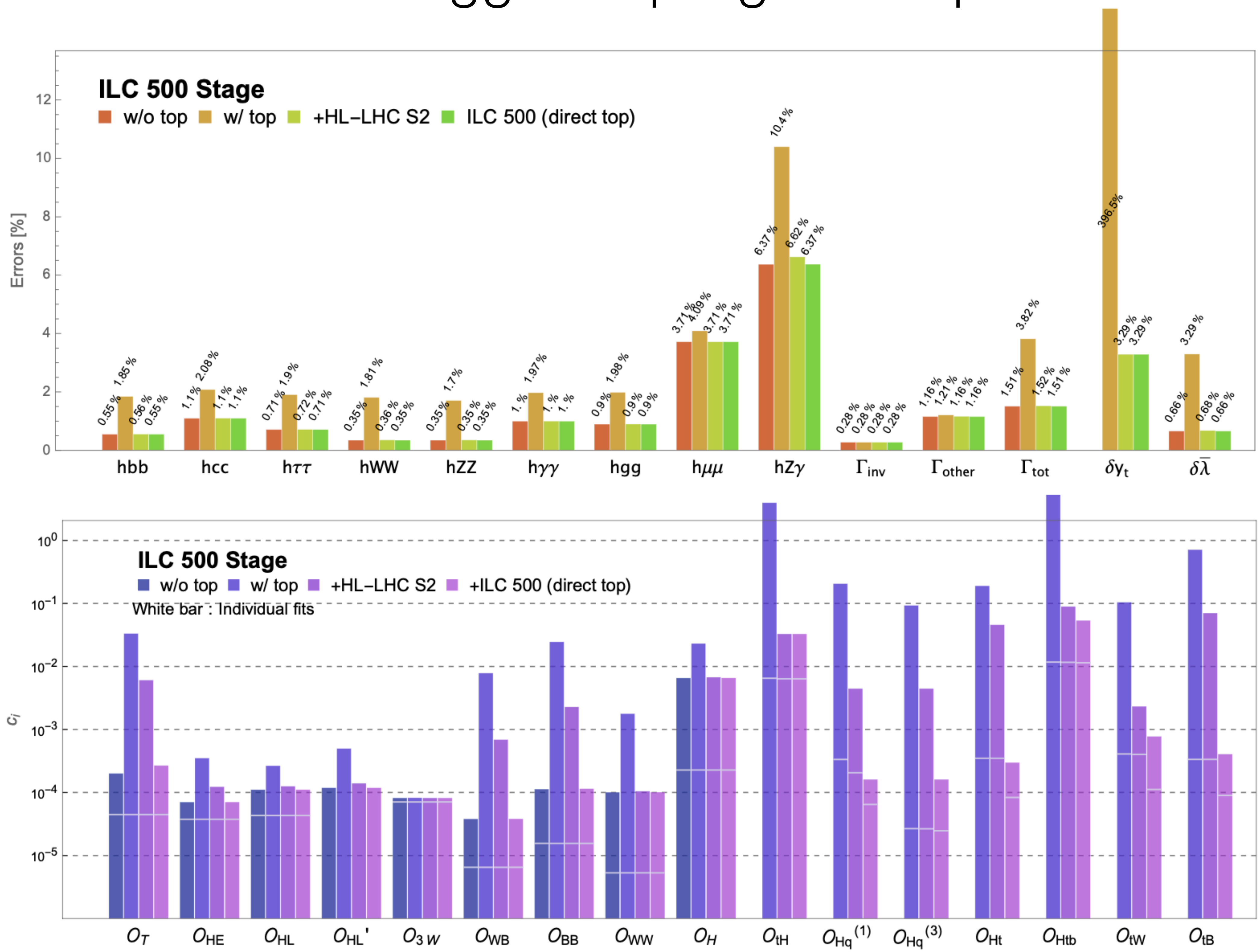
$$\mathcal{O}_{Htb} = i(\tilde{\Phi}^\dagger D_\mu\Phi)(\bar{t}\gamma^\mu b),$$

$$\mathcal{O}_{tW} = (\bar{Q}\sigma^{\mu\nu}t)\tau^a\tilde{\Phi}W^a_{\mu\nu}, \qquad \mathcal{O}_{tB} = (\bar{Q}\sigma^{\mu\nu}t)\tilde{\Phi}B_{\mu\nu},$$

$$\Delta\mathcal{L}_{\rm top} = y_t\frac{c_{tH}}{v^2}\mathcal{O}_{tH} + \frac{c_{Hq}^{(1)}}{v^2}\mathcal{O}_{Hq}^{(1)} + \frac{c_{Hq}^{(3)}}{v^2}\mathcal{O}_{Hq}^{(3)} + \frac{c_{Ht}}{v^2}\mathcal{O}_{Ht} + \frac{c_{Htb}}{v^2}\mathcal{O}_{Htb} + \frac{c_{tW}}{v^2}\mathcal{O}_{tW} + \frac{c_{tB}}{v^2}\mathcal{O}_{tB}$$

results (IV): ILC250+LHC+ILC500

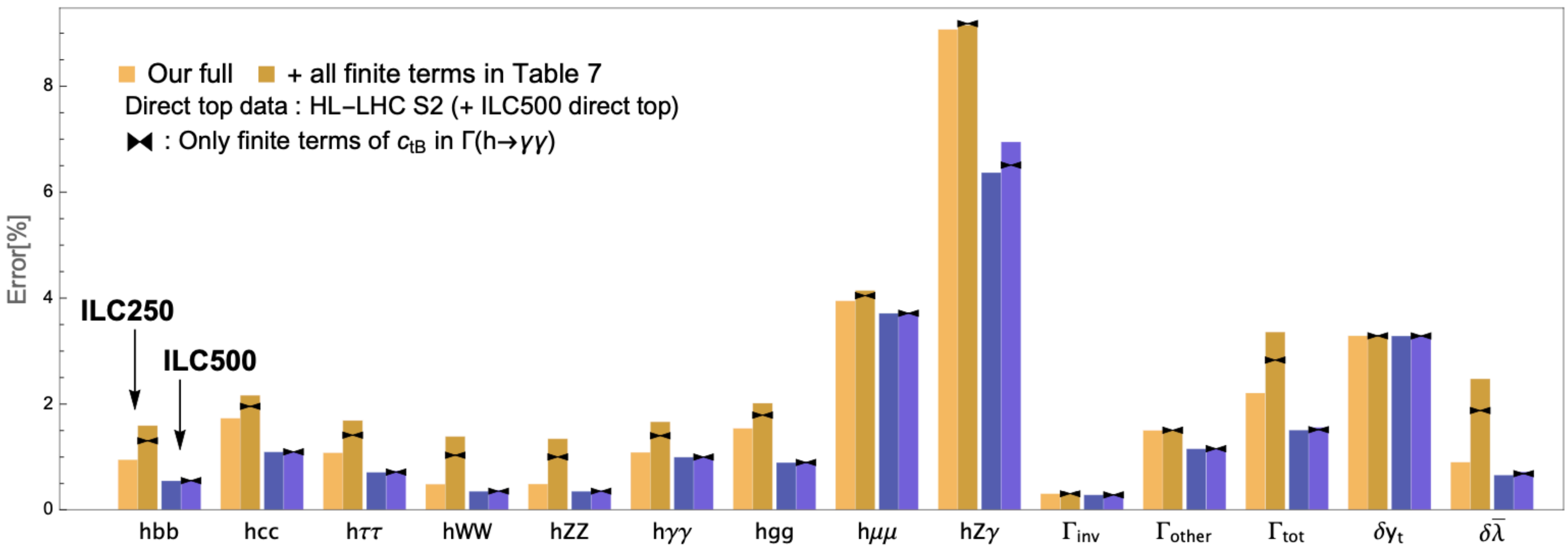
- precisions of both Higgs couplings and operators restored



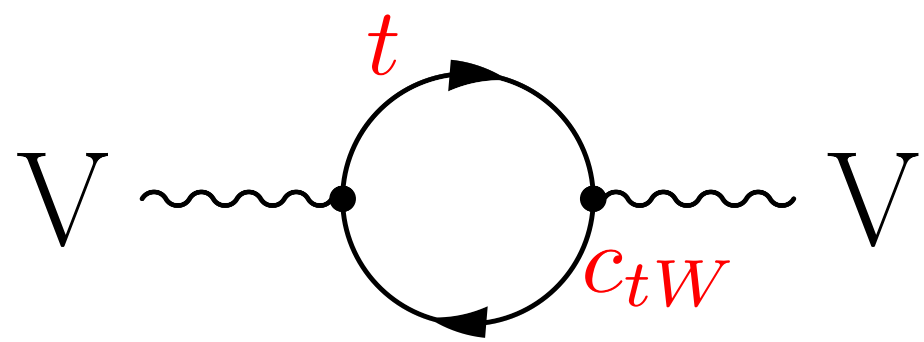
results (V): potential impact from finite one-loop effects

- could be significant @ 250 GeV, in particular for hZZ / hWW, x2-3 worse, though ~1-2% precision

- almost no difference once direct e+e- -> tt data is available



effect of top operators: example



log-dependence

higgs operator

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

top operator

$$\frac{c_{tW}}{v^2}(\bar{Q}\sigma^{\mu\nu}t)\tau^a\tilde{\Phi}W^a_{\mu\nu}$$

$$\dot{c}_{WW} = \frac{1}{4}(-2gy_tN_c\underline{c_{tW}})$$

more detailed power-counting rule

	Higgs loop production/decay	other observables	top production
SM	finite 1-loop	tree-level	tree-level
Higgs operator	tree-level from $c_{WW,WB,BB}$ finite 1-loop from other operators	tree-level	none
top operator	log 1-loop via $\dot{c}_{WW,WB,BB}$ log 2-loop via other $\dot{c}$ finite 1-loop via tree-shift of y_t, g_{Ztt}	log 1-loop via $\dot{c}$	tree-level

key: include leading contributions from top-quark operators

our approach to include NLO top effects

S.Jung, J.Lee, M.Perello, JT, M.Vos, arXiv:2006.14631

- we didn't try to include full NLO effects for all observables
- mainly include effects that have log-dependence on Q-scale
- captured by Renormalization Group Evolution (mixing)

$$\dot{c}_i \equiv 16\pi^2 \frac{\mathrm{d}c_i}{\mathrm{d}\ln\mu} = \gamma_{ij} c_j$$

[Alonso, Jekins, Manohar, Trott, 2013]

c_i: Higgs operators; ***c_j***: Top operators; ***γ_{ij}***: anomalous dimensions

- convenient to include such top-quark effects in all Higgs/EWPO/ WW observables that have been considered previously

λ_{hhh} model-independent determination in SMEFT (c_6)

(arXiv:1708.09079)

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

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

(statistical error) (systematic error)

16.8% >> 2.0%

- interesting to prove this in e+e- → ννHH as well: still open
- another crucial question: can we do the same analysis to HH processes at hadron collider? can we still measure λ_{hhh} to 5% at FCC-hh?

SMEFT fit: typical difference with kappa 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%

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

global SMEFT fit: 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)

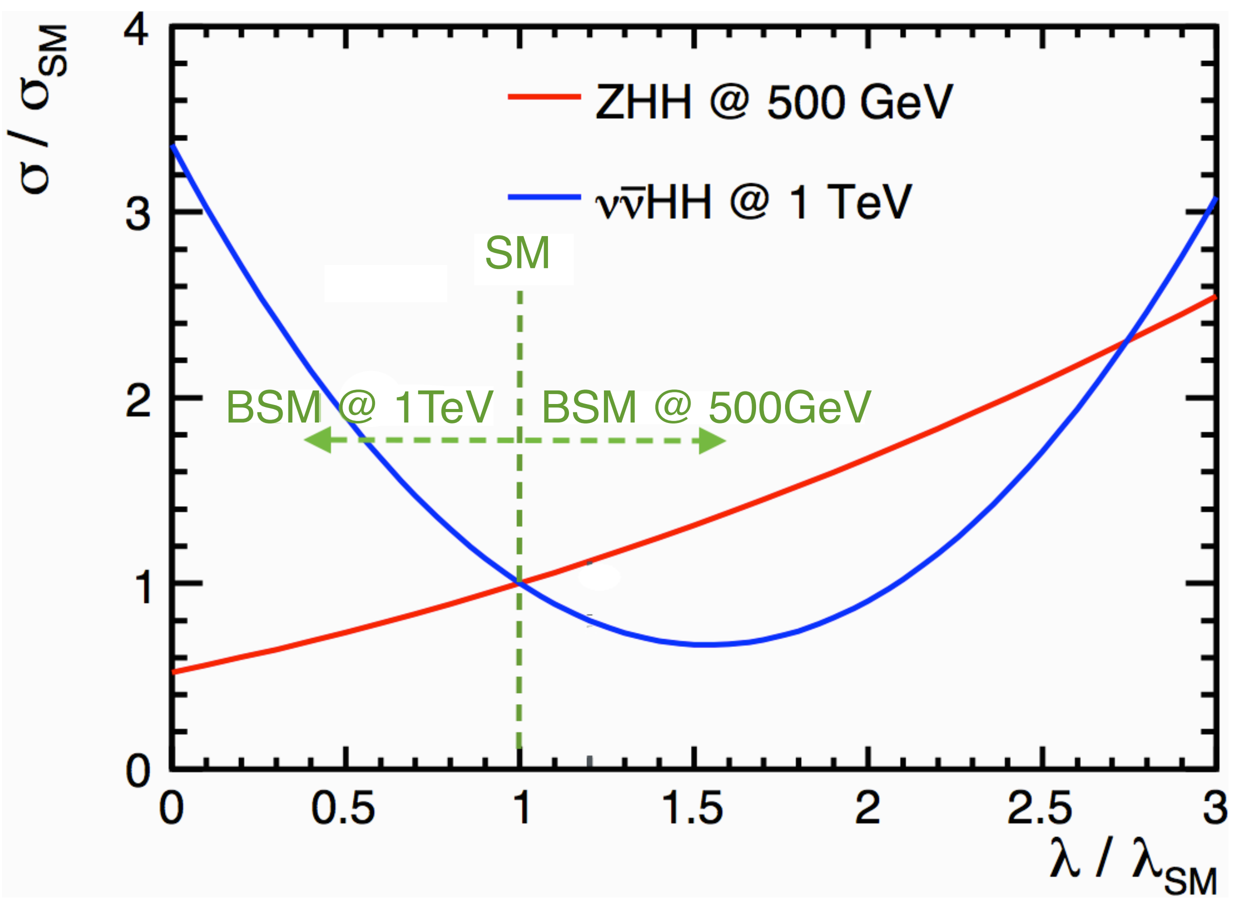
↑ 2 for polarized

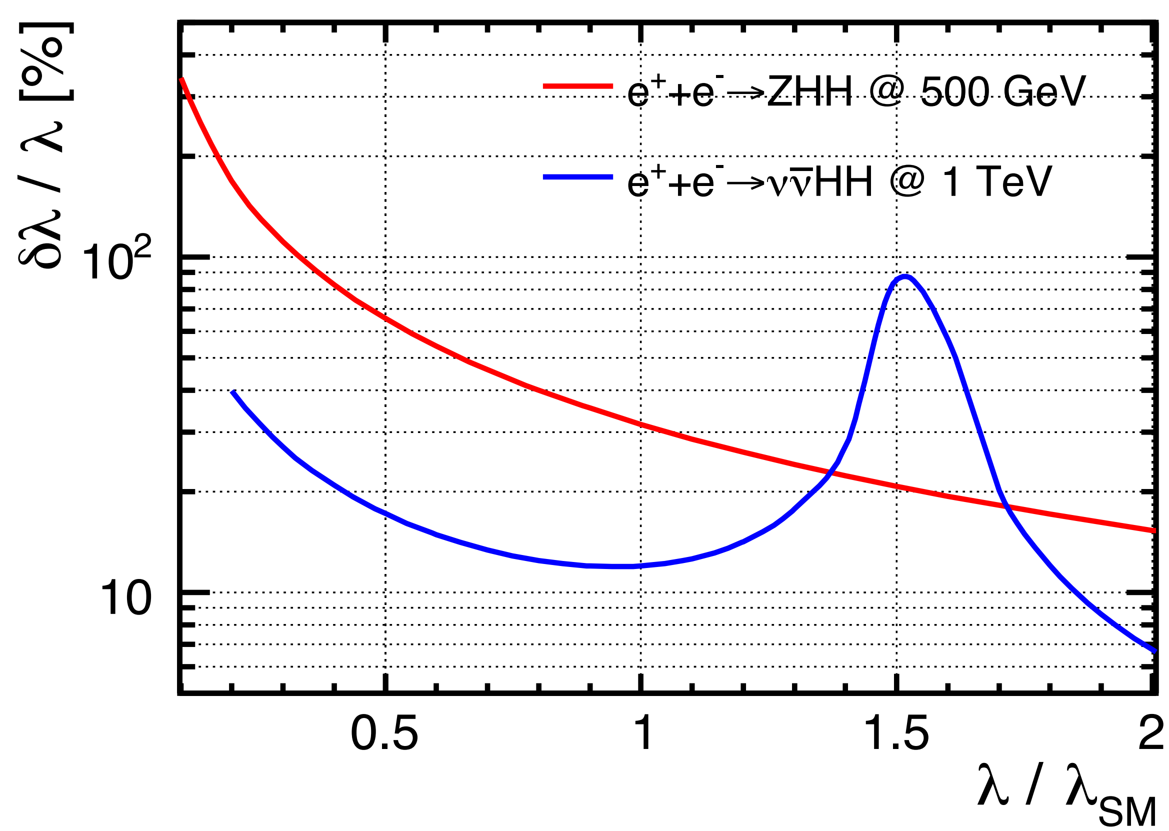
- all the 23 parameters can be determined ***simultaneously***

(details in backup)

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

- λ_{HHH} can be enhanced significantly in BSM
- complementarity between ZHH & ννHH (& LHC): interference nature
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be measured to ~13% using ZHH at 500 GeV e+e-





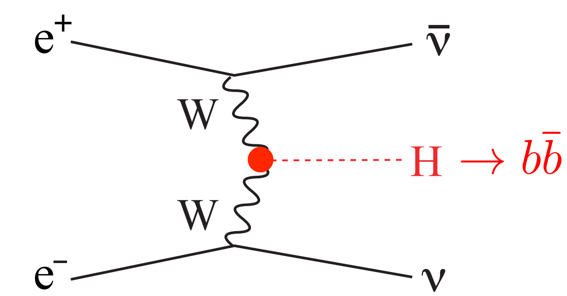
direct meas. of hWW coupling & impact of √s

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

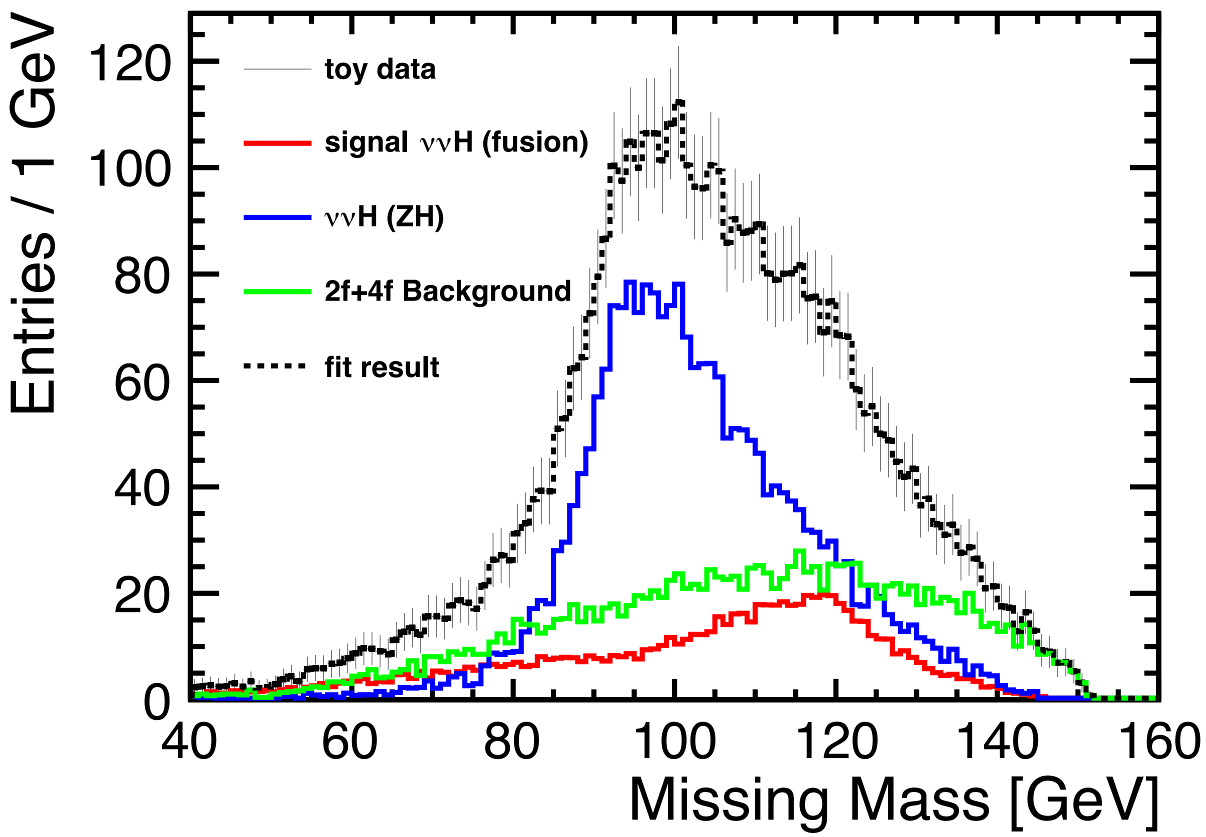
—>Br(H->ZZ*) very small

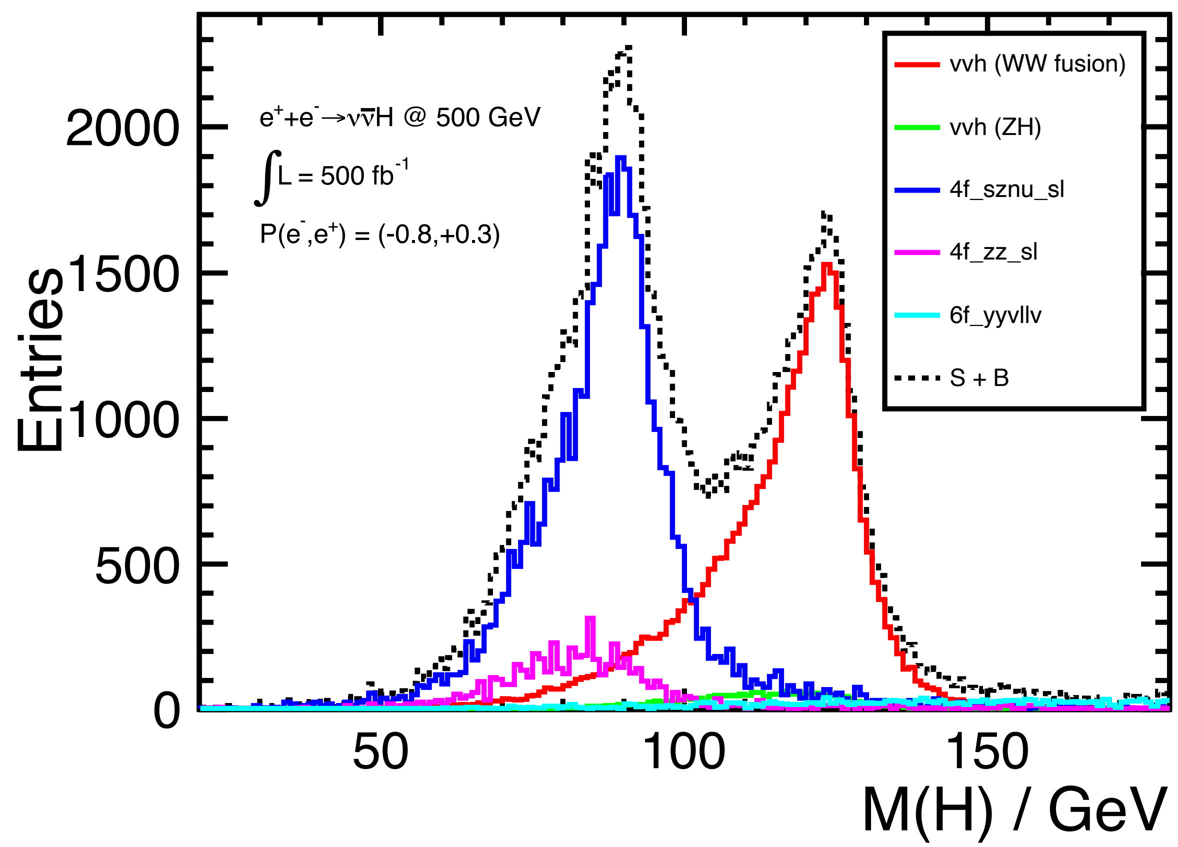
★ $$\Gamma_H = \frac{\Gamma_{HWW}}{\mathrm{Br}(H \to WW^*)} \propto \frac{g^2_{HWW}}{\mathrm{Br}(H \to WW^*)}$$

—> better option!



@250 GeV Duerig, et al., arXiv:1403.7734 **@500 GeV**





- we used to think W-fusion production is crucial…

From observables to couplings — Global Fit

in case there are correlated observables

$$\chi^2 = \sum_{i=1}^{n} (\frac{Y_i - Y_i'}{\Delta Y_i})^2 + (Y_j - Y_j')^T C_j^{-1} (Y_j - Y_j')$$

Yj: column vector of correlated observables

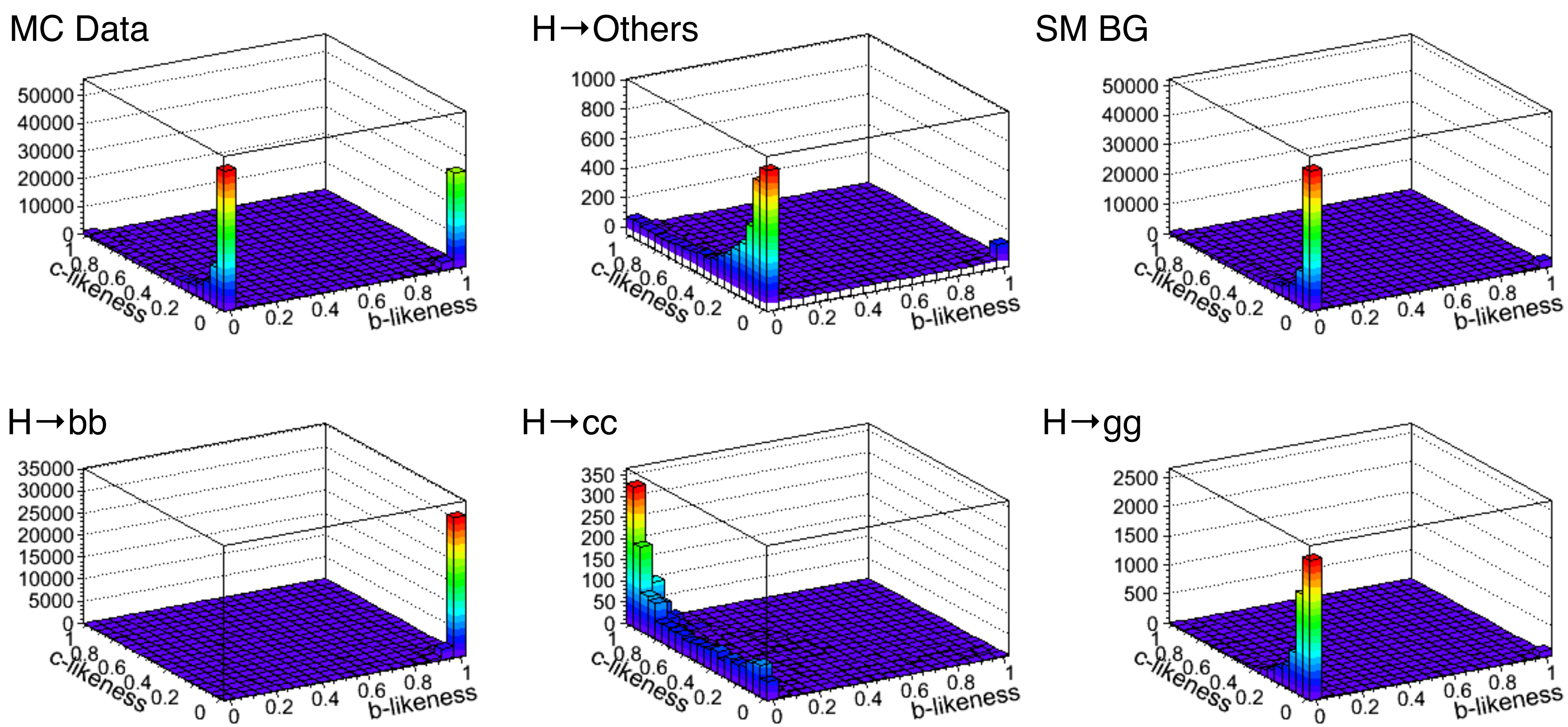
Cj: covariance matrix for those observables

one example: TGCs in SMEFT fit

(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

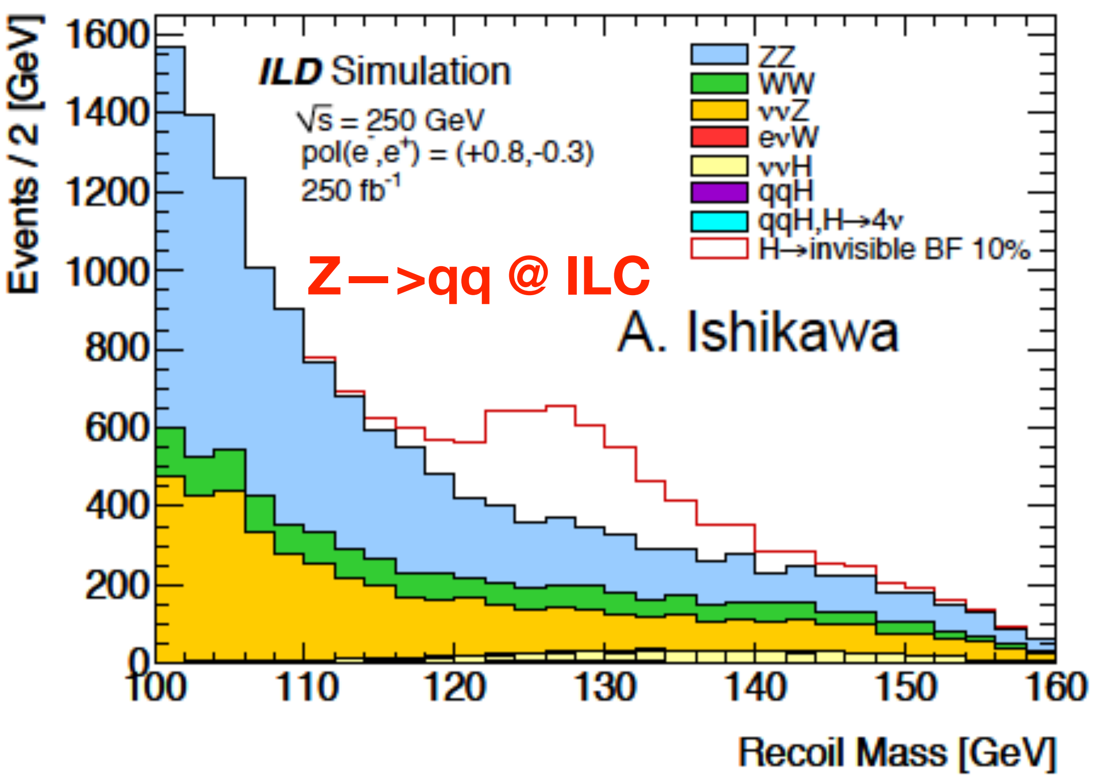


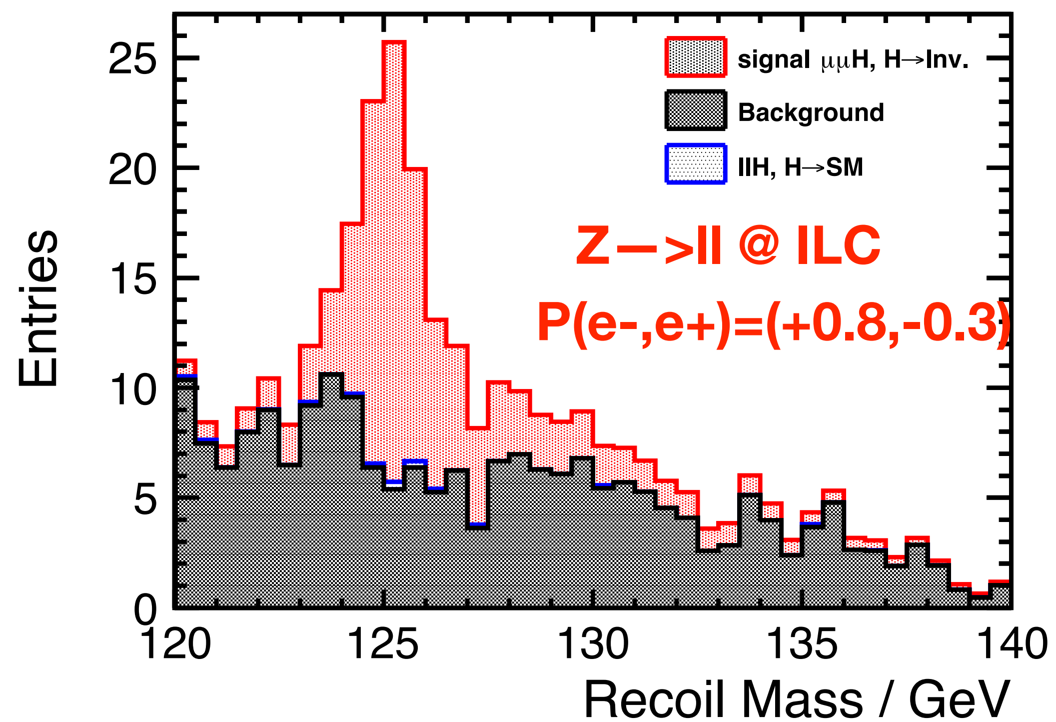
Ono, et. al, Euro. Phys. J. C73, 2343;   F.Mueller, PhD thesis (DESY)

(ii-3) search of Higgs to invisible

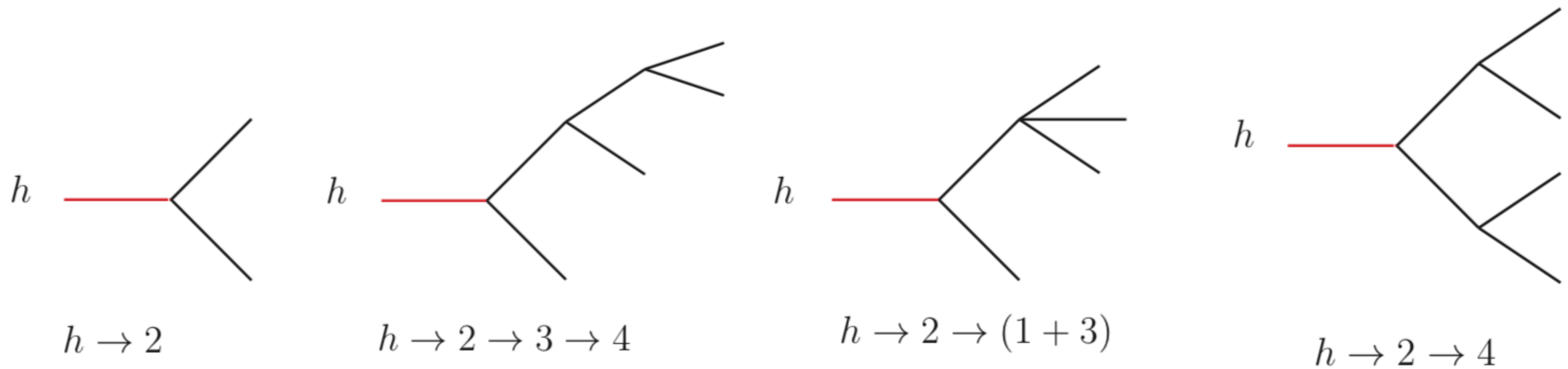
- BR(H—>inv.) < 0.3% (CL95%)
- Higgs portal dark mater search
- right-handed beam polarization: much lower background

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

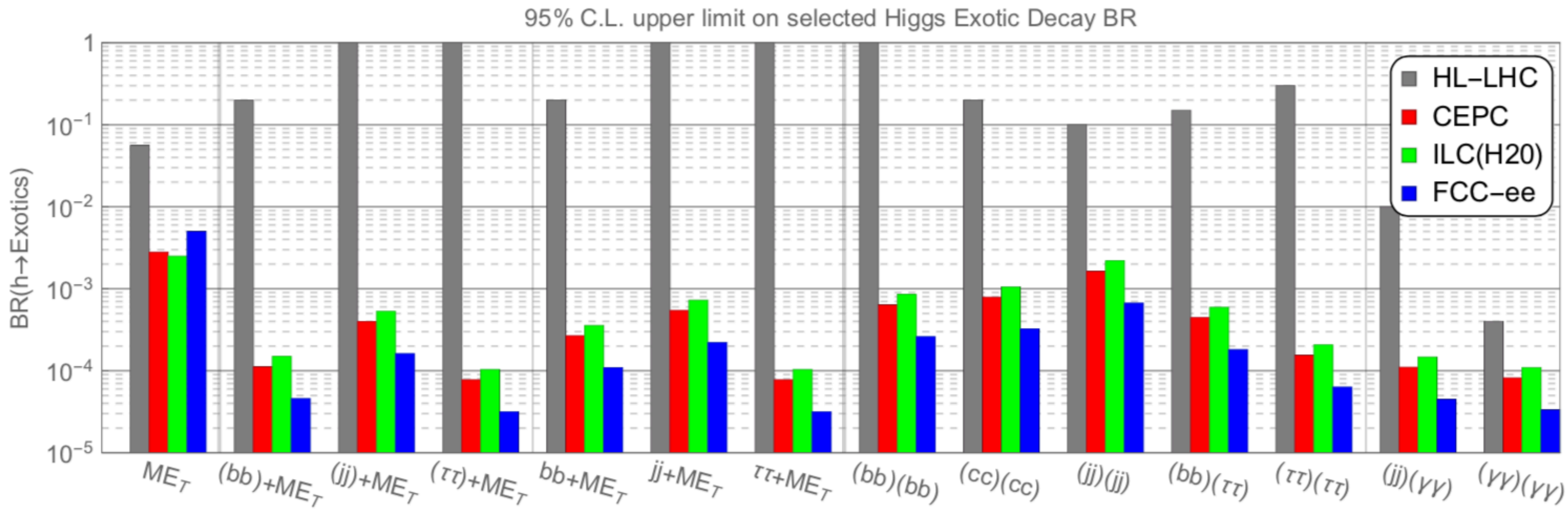




(ii-3) search of Higgs exotic decays



BR < 0.1-0.01% @ ILC, Liu et al, arXiv:1612.09284



efficiencies breakdown (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%

- every cut is applied very carefully to avoid large bias, still ~1%
- nevertheless, it becomes almost a paradox:
  - no cut, no bias; looser cuts, less bias
  - extremely tighter cuts, less bias;
  - too loose or too tight cuts -> remain too much background or too little signal -> bad precision measurement

efficiencies breakdown (hadronic recoil)

Decay mode	$\varepsilon^{\text{vis.}}_{\mathscr{L}>0.65}$	$\varepsilon^{\text{invis.}}_{\mathscr{L}>0.60}$	$\varepsilon^{\text{vis.}} + \varepsilon^{\text{invis.}}$
$H \to$ invis.	<0.1 %	23.5 %	23.5 %
$H \to q\bar{q}/gg$	22.6 %	<0.1 %	22.6 %
$H \to WW^*$	22.1 %	0.1 %	22.2 %
$H \to ZZ^*$	20.6 %	1.1 %	21.7 %
$H \to \tau^+\tau^-$	25.3 %	0.2 %	25.5 %
$H \to \gamma\gamma$	25.7 %	<0.1 %	25.7 %
$H \to Z\gamma$	18.6 %	0.3 %	18.9 %
$H \to WW^* \to q\bar{q}q\bar{q}$	20.8 %	<0.1 %	20.8 %
$H \to WW^* \to q\bar{q}\ell\nu$	23.3 %	<0.1 %	23.3 %
$H \to WW^* \to q\bar{q}\tau\nu$	23.1 %	<0.1 %	23.1 %
$H \to WW^* \to \ell\nu\ell\nu$	26.5 %	0.1 %	26.5 %
$H \to WW^* \to \ell\nu\tau\nu$	21.1 %	0.5 %	21.6 %
$H \to WW^* \to \tau\nu\tau\nu$	16.3 %	2.3 %	18.7 %

- relative bias can be as large as ~15%

a nice trick: categorization

$$\sigma_{ZH} = \sigma^{cat1} + \sigma^{cat2} + \sigma^{cat3} + \sigma^{cat4} + \cdots$$

- if we have a complete list of categories
- then we only need to keep all selection cuts independent of decay mode in each category;
- selections cuts among categories can be very different

for example

$$\sigma_{ZH} = \sigma^{H\to\text{invisible}} + \sigma^{H\to\text{visible}}$$

a realistic solution: make use of individual BR measurement

$$\sigma_{ZH} = \frac{N_S}{R_f L \bar{\epsilon}} \qquad \bar{\epsilon} \equiv \sum_i B_i \epsilon_i$$

N_S: # of signal
R_f: BR of Z->ff
L: int. luminosity
Bi: BR of H decay mode i
εi: efficiency of mode i

- if every ε_i is same -> $\Sigma B_i = 1$; no need for any knowledge about B_i
- nevertheless, we can measure many of the $\sigma \times B_i$; assume i=1..n is known with ΔBi; i=n+1,… is unknown, sum up to Bx;

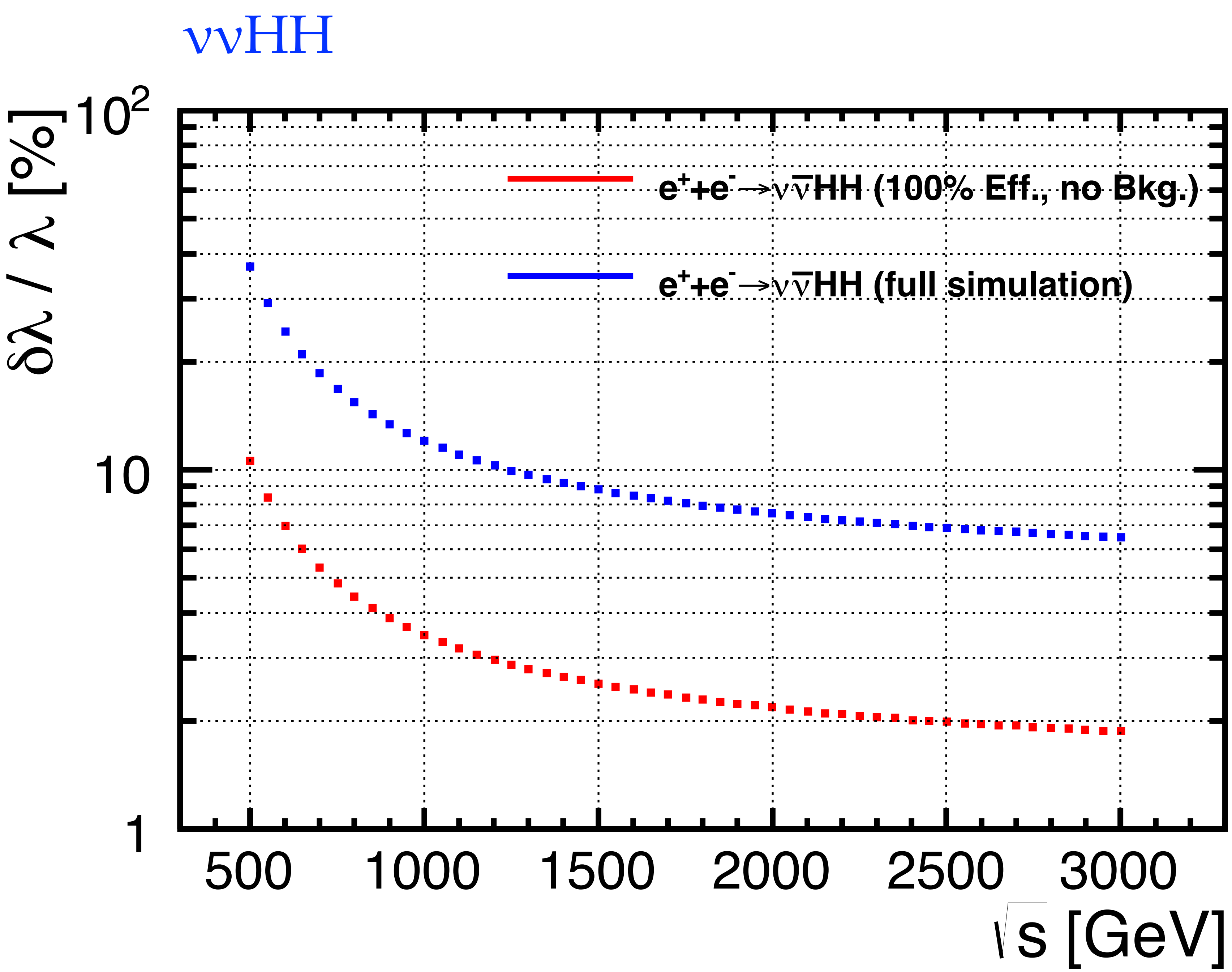
known modes — systematic error to σ_{ZH} — unknown modes

$$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}} = \frac{\Delta\bar{\varepsilon}}{\bar{\epsilon}} = \sqrt{\sum_{i=1}^{n} \Delta B_i^2 \left(\frac{\varepsilon_i}{\varepsilon_0} - 1\right)^2}$$

$$\frac{\Delta\sigma_{ZH}}{\sigma_{ZH}} = \frac{\Delta\bar{\varepsilon}}{\bar{\epsilon}} < \sum_{i=n+1} B_i \frac{\delta\varepsilon_{max}}{\varepsilon_0} = B_x \frac{\delta\varepsilon_{max}}{\varepsilon_0}$$

- leptonic recoil, demonstrated possible $\delta\sigma_{ZH}$~0.1% for Bx<10%
- hadronic recoil, still need more work for $\delta\sigma_{ZH}$ <1% for Bx<10%

expected precision of λ: impact from analysis & √s



- for ννHH: significantly better from 500 GeV to 1 TeV, $\delta\lambda/\lambda$~10% achievable at >= 1TeV; not drastically better, from 1 TeV to 3 TeV, improved by 50%

strategy to determine all the 23 parameters

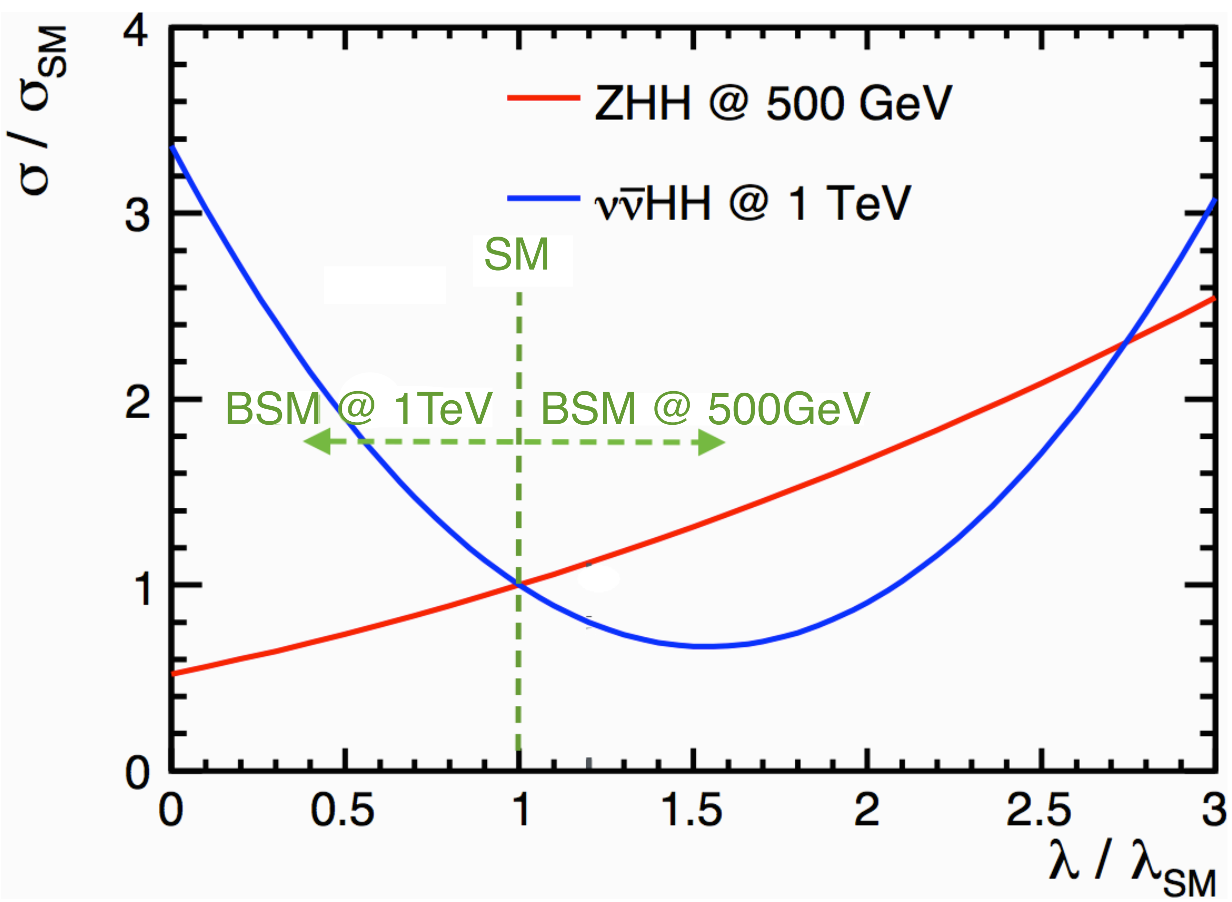
- m_W and $\alpha(m_Z)$ -> g, g';
- G_F -> v; m_h -> λ; m_Z -> c_T;
- A_l and Γ_l -> $c_{HL}+c_{HL}'$, c_{HE};
- Γ_W and Γ_Z -> c_W, c_Z;

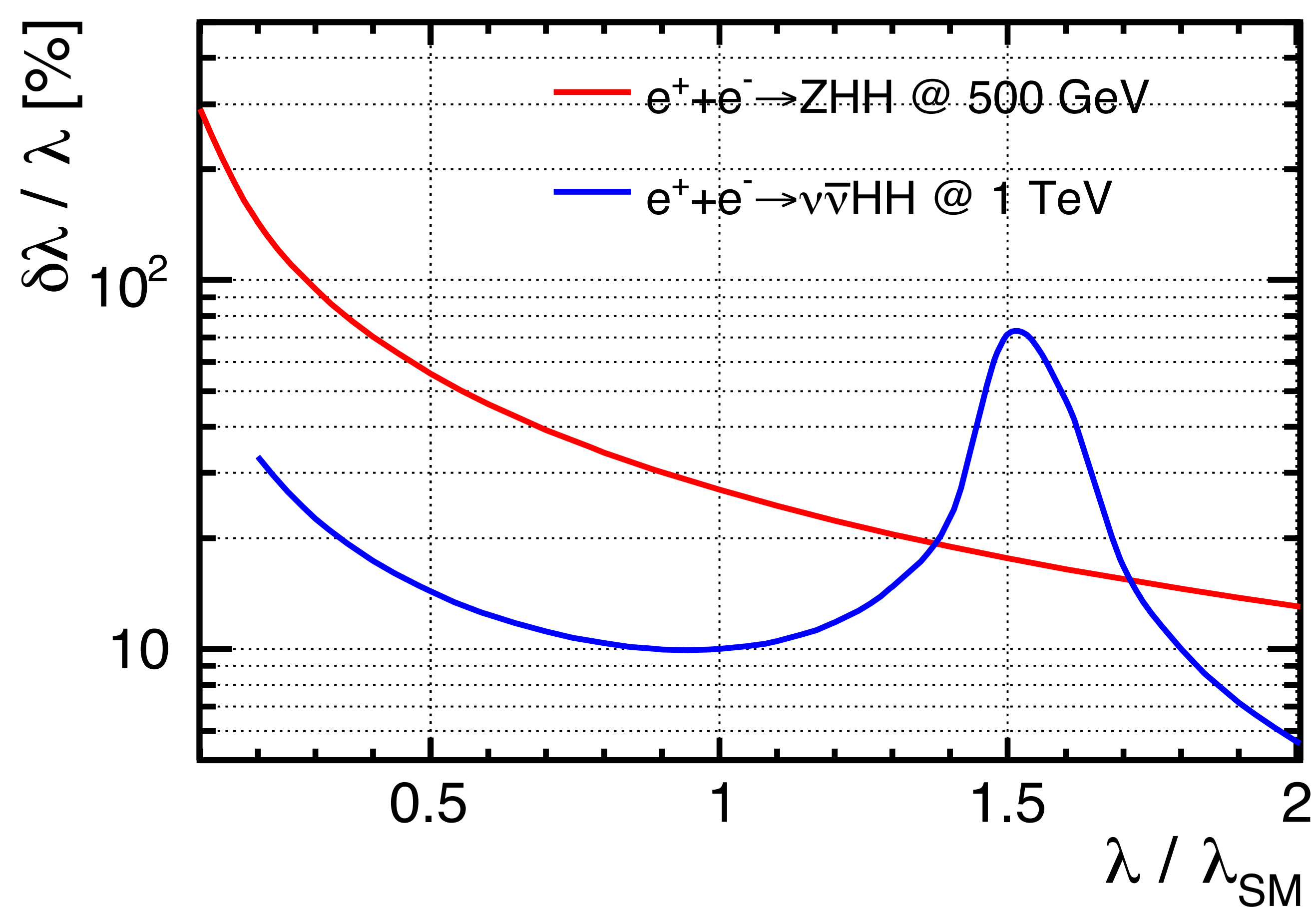
- g_{1Z} -> c_{HL}'; κ_γ -> c_{WB}; κ_λ -> c_{3W};

- $BR(h\text{->}\gamma\gamma)$ and $BR(h\text{->}\gamma Z)$ -> c_{BB}, c_{WW};
- σ_{ZH} -> c_H; σ_{ZHH} -> c_6;
- $BR(h\text{->}bb/cc/gg/\mu\mu/\tau\tau)$ -> 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}

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

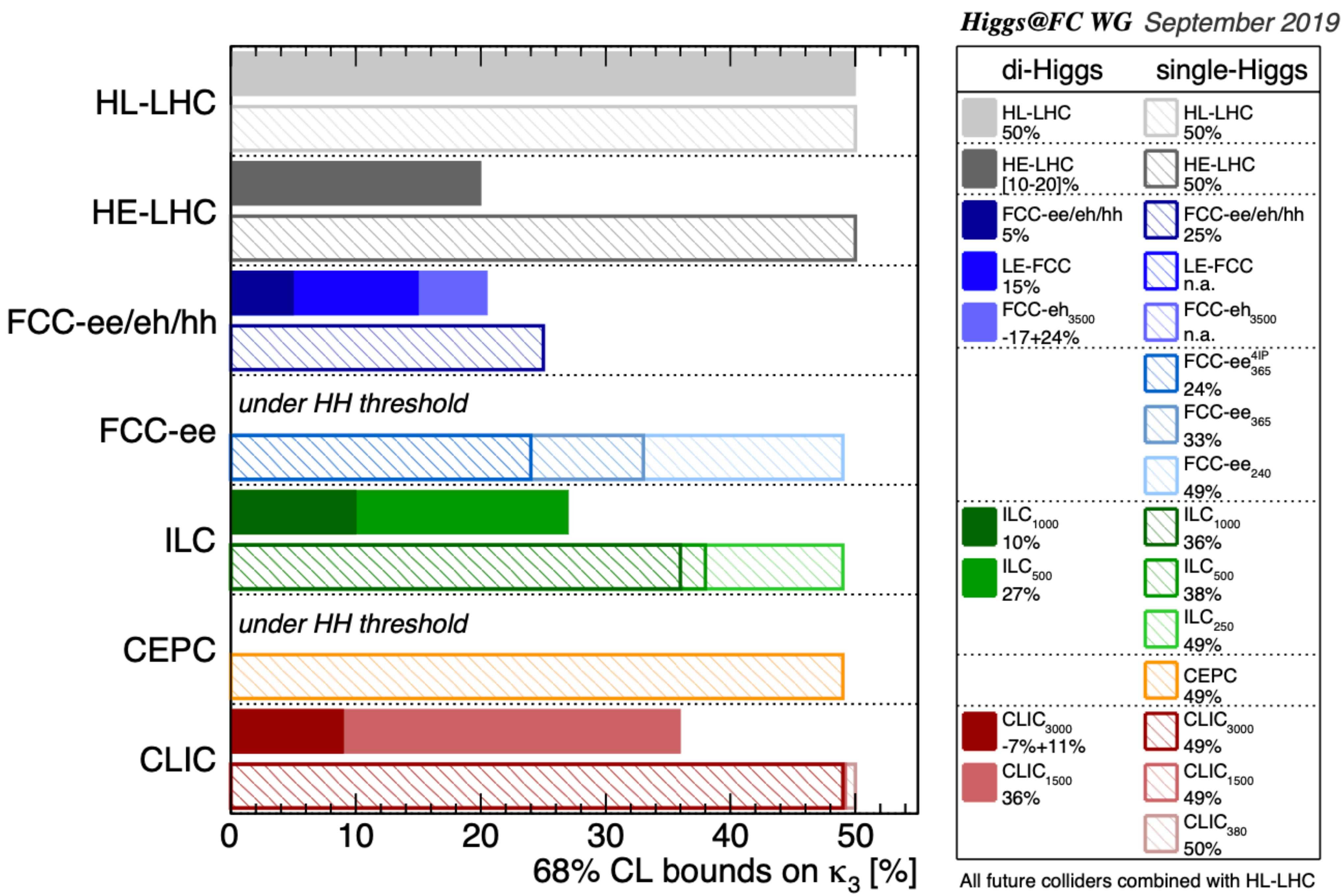
- constructive interference in ZHH, while destructive in vvHH (& LHC) —> complementarity between ILC & LHC, between √s ~500 GeV and >1TeV
- if $\lambda_{HHH} / \lambda_{SM} = 2$, Higgs self-coupling can be measured to ~15% using ZHH at 500 GeV e+e-





Duerig, Tian, et al, paper in preparation

λ_{hhh} by double / single Higgs processes



(Physics Briefing Book, arXiv:1910.11775)

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

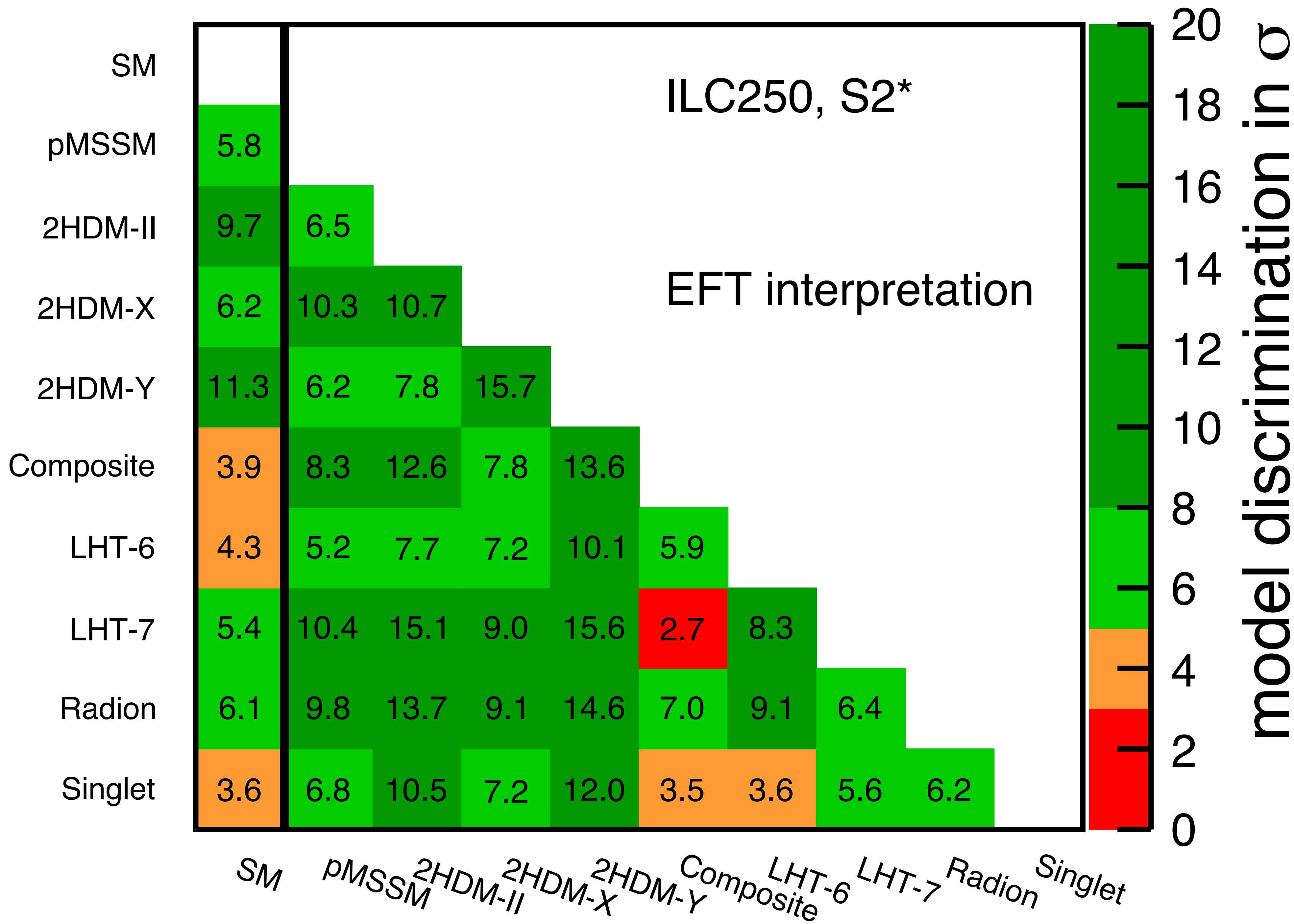
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> quantitative assessment for models discrimination

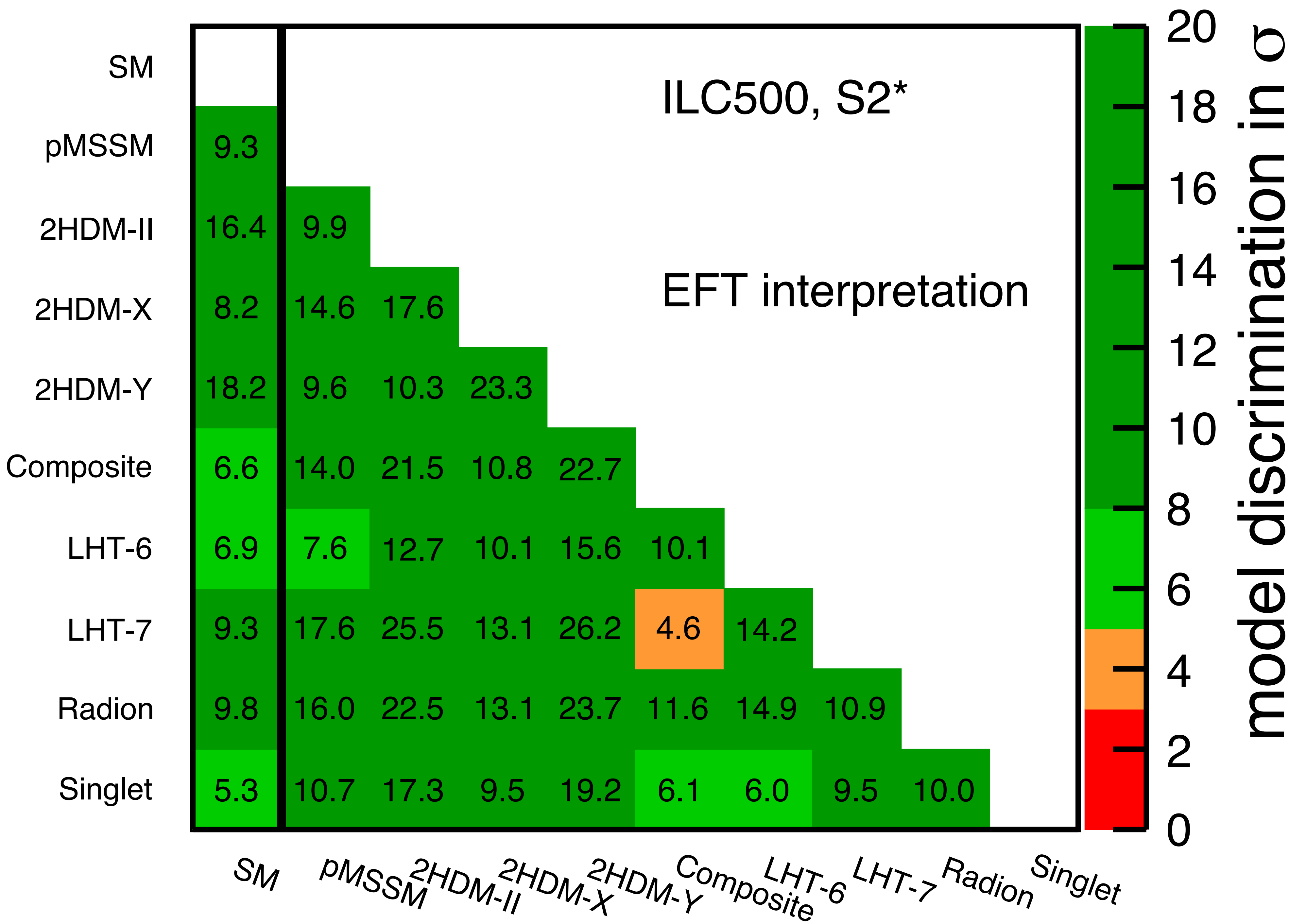
model parameters (chosen as escaping direct search at HL-LHC)

- 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 ILC250



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



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

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

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

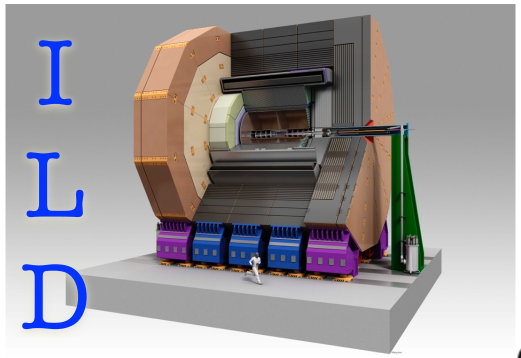
systematic errors included in the global fit

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

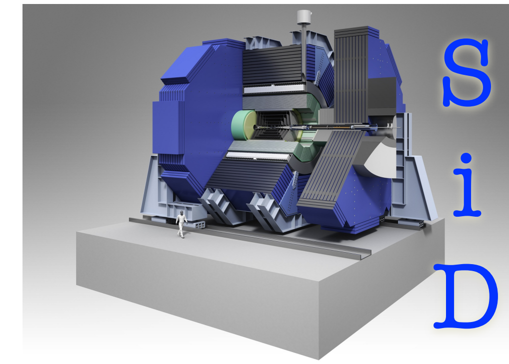
improvement factors in S2

- 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 $\int L dt$ = 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)

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

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

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

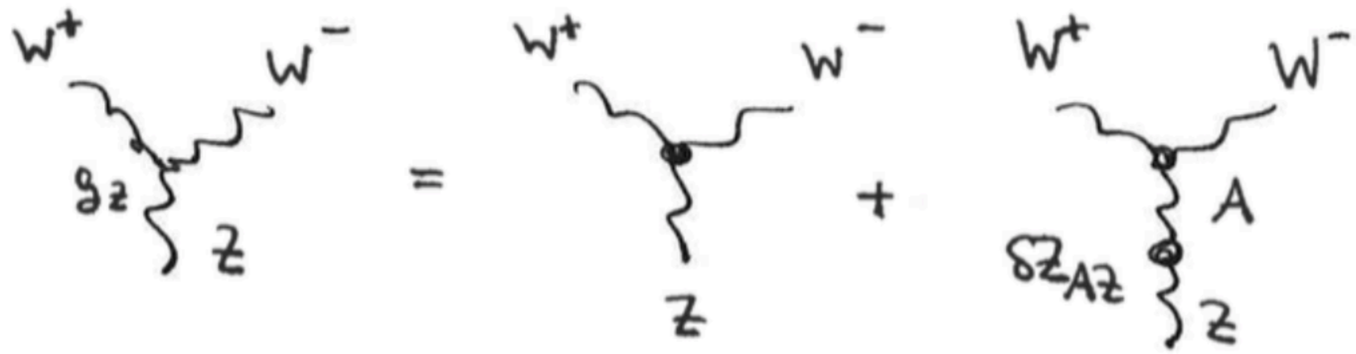
$$g_L = \frac{g}{c_w}\left[(-\frac{1}{2} + s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}(c_{HL} + c'_{HL}) - s_w c_w \delta Z_{AZ}\right]$$

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

→ $c_{HL} + c'_{HL}$, c_{HE}

EFT input: TGC (3)

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

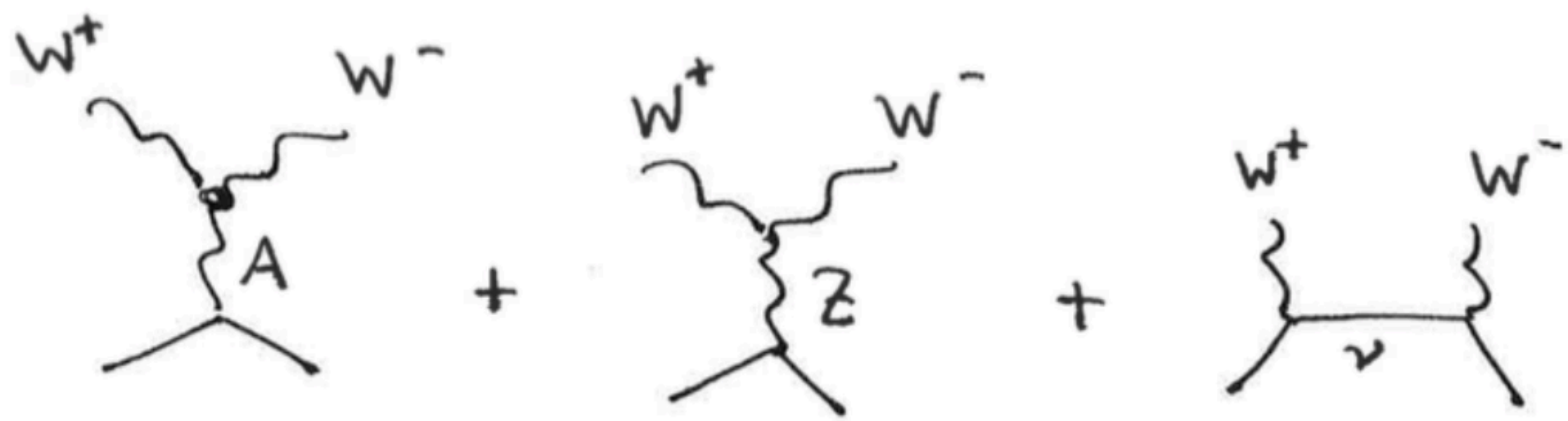


$$g_Z = gc_w(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ})$$

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

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

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*)

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

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

(c'_X: contact interactions)

EFT input:

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

(similar for Z)