Effective Field Theory in models with extended Higgs sector

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22nd Regular Meeting of the New Higgs Working Group,
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outline

(i) EFT formalism

reminder/recap

(ii) key measurements

(iii) EFT and BSM matching

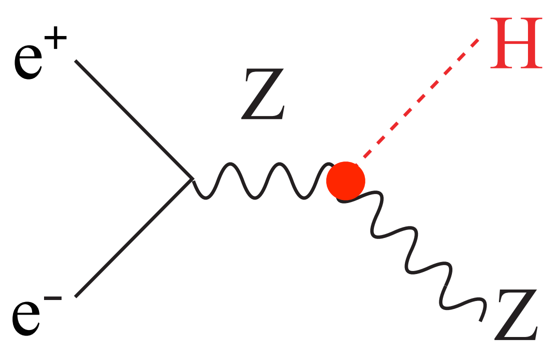
ongoing collaboration with K.Fujii, S.Kanemura, K.Mawatari effective field theory analysis at e+e-

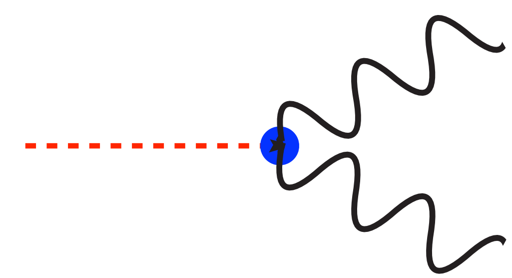
- we didn’t want to base on EFT from the very beginning
- it camp up as the BEST approach in terms of model independent determination of Higgs (self-)couplings

reminder 1: model dependence in kappa framework

- σ(e+e- ->Zh) ∝ κ^2_Z ∝ Γ(h->ZZ*) not any more: EFT is more general than kappa-framework

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





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

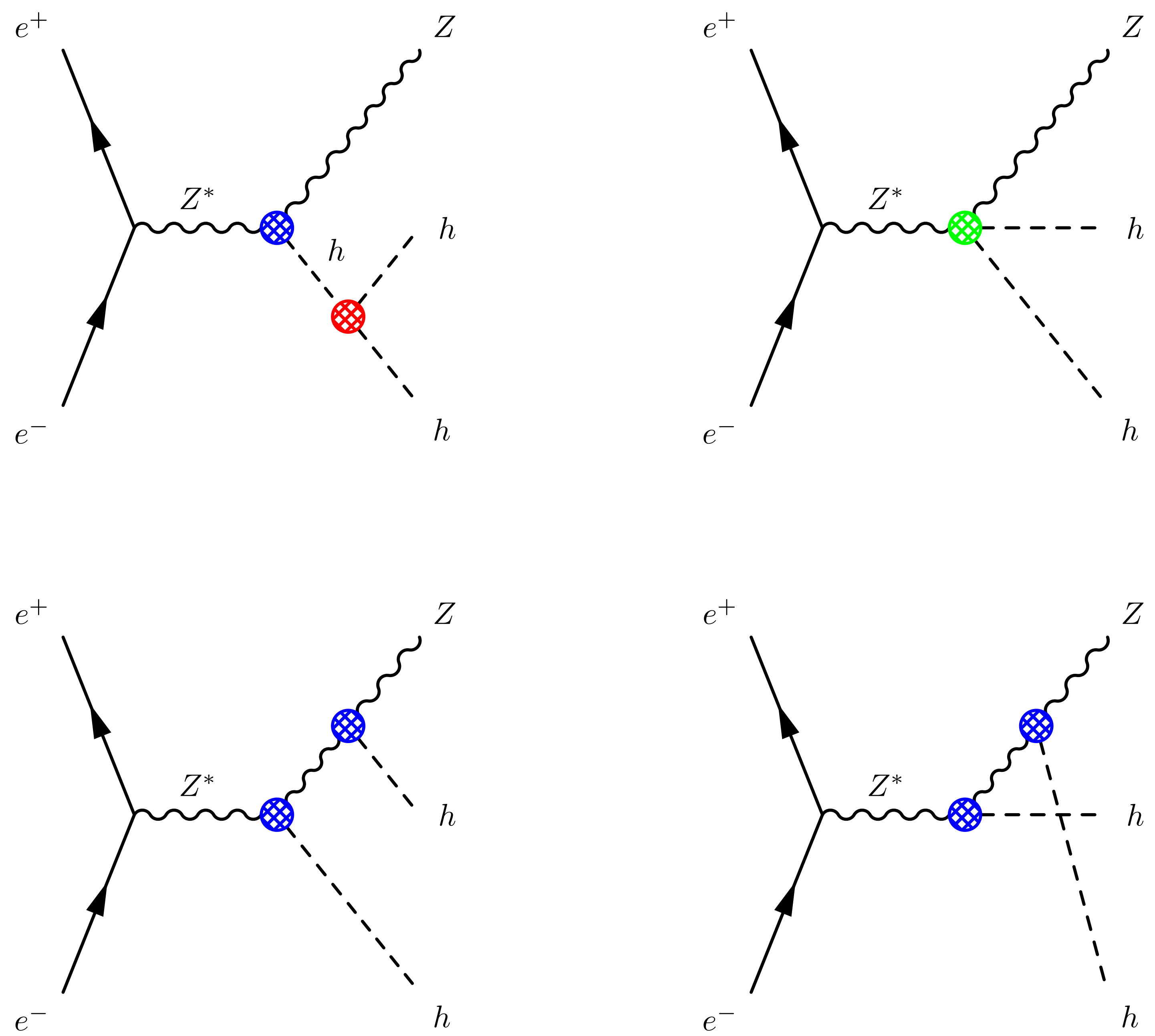
$$(1 + 2\eta_Z + (5.5)\zeta_Z)$$

$\neq$

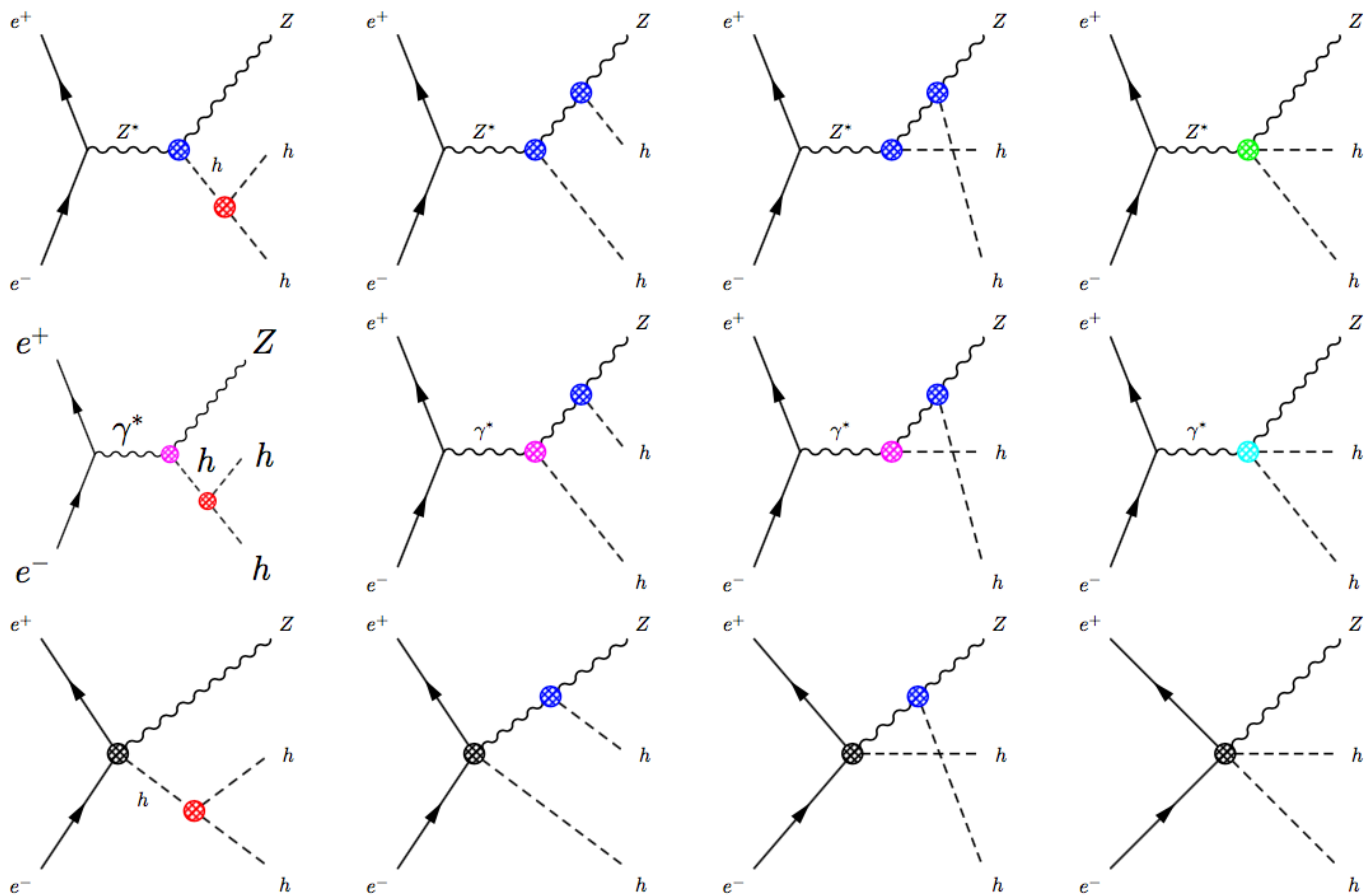
$$\Gamma(h \to ZZ^*) = (SM)\cdot$$

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

reminder 2: how can we determine λ_{hhh} if there are anomalous hhVV, hVV, hhh couplings?



reminder 2: determine λ_{hhh} in EFT



reminder 2: determine λ_{hhh} in EFT

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

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

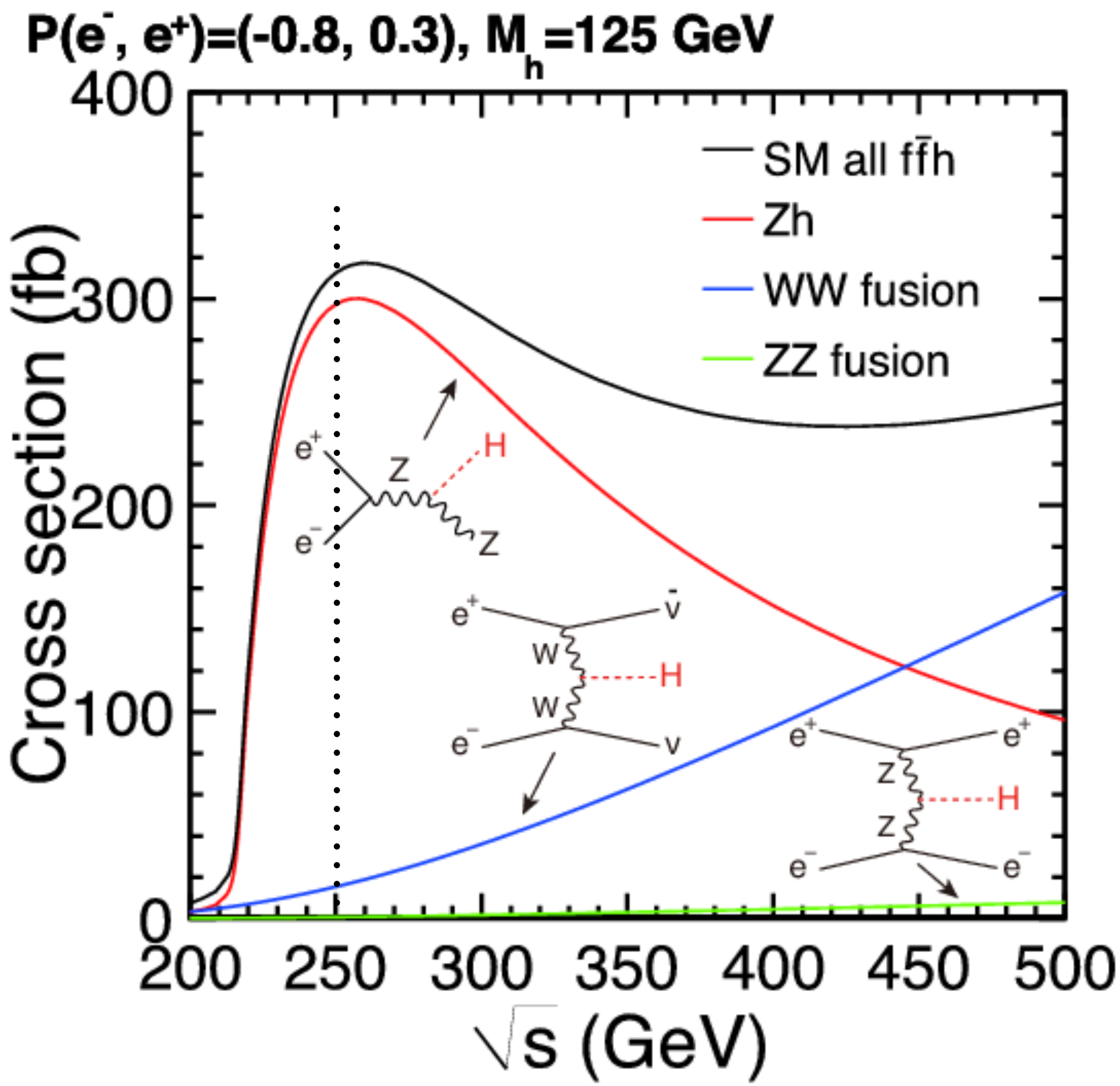
$$\Delta c_6 = \frac{1}{0.565}\left[\left(\frac{\Delta\sigma_{Zhh}}{\sigma_{SM}}\right)^2 + \sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}}$$

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)

reminder 3: can we do precision Higgs physics at $\sqrt{s}$ = 250 GeV?



WW-fusion is smaller by x10 than 500 GeV

a strategy: SM Effective Field Theory

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

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

O_i: dimension d_i operators, respect SU(3)xSU(2)xU(1) of L_{SM}
c_i: Wilson coefficients
Λ: EFT cutoff scale

ΔL represent the most general effects of BSM physics

2, 84, 30, 993, 560, 15456, 11962, 261485,...: Higher dimension operators in the SM EFT

(arXiv:1512.03433)

comprehensive review, arXiv:1610.0792

a strategy: SM Effective Field Theory

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

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

the new particle searches at LHC suggest Λ>500 GeV

justify the analysis at dimension-6 operators

there are 84 of such operators for 1 fermion generation

if baryon number and CP conservation, there are 59

luckily, there exists a smaller set relevant to physics at e+e-

arXiv:1708.09079
arXiv:1708.08912

SM Effective Field Theory

("Warsaw" basis, JHEP 1010 (2010) 085)

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

Φ: Higgs field; D_μ: gauge-covariant derivative
$W^a_{\mu\nu}$, $B_{\mu\nu}$: Yang-Mills field strength tensor for SU(2) and U(1)
L: left-handed lepton field; e: right-handed lepton field
g, g': gauge couplings for SU(2) and U(1); $t^a=\sigma^\alpha/2$
v: vacuum expectation value; λ: quartic Higgs self-coupling

$$\Phi^\dagger \overleftrightarrow{D}_\mu \Phi = \Phi^\dagger D_\mu\Phi - D_\mu\Phi^\dagger\Phi$$

one example for illustrating the physics effect

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

after EWSB:

(1) $\frac{c_H}{2}\partial^\mu h \partial_\mu h$ → renormalize kinetic term of SM Higgs field $\frac{1}{2}\partial^\mu h \partial_\mu h$

h → $(1-c_H/2)h$

→ shift all SM Higgs couplings by $-c_H/2$

(2) $\frac{c_H}{v} h\partial^\mu h \partial_\mu h$ → anomalous triple Higgs coupling

(3) $\frac{c_H}{2v^2} hh\partial^\mu h \partial_\mu h$ → anomalous quartic Higgs coupling

full formalism
23 parameters

SM Effective Field Theory

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

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 parameters for h->invisible and exotic

+ 2 for contact interaction with quarks

strategy to determine all the 23 parameters

Electroweak Precision Observables

+

Triple Gauge boson Couplings

+

Higgs observables at LHC & 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 reminder 3: hWW is determined as precisely as hZZ @ √s = 250 GeV

- hWW/hZZ ratio can be determined to <0.1%: feature of a general SU(2) x U(1) gauge theory

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

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

SM-like hVV

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

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

custodial symmetry

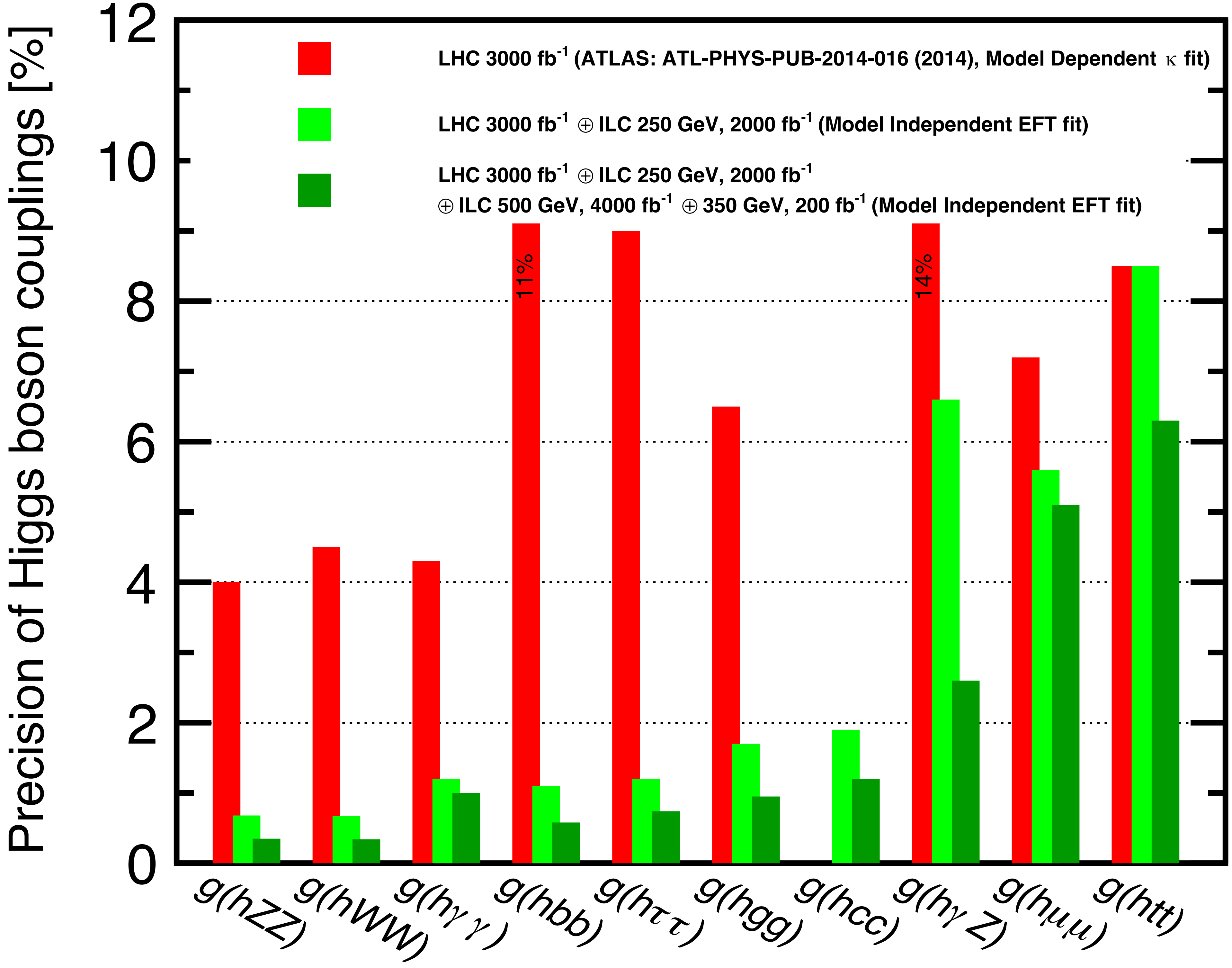
$c_i \sim O(10^{-4}\text{-}10^{-3})$

anomalous hVV

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

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

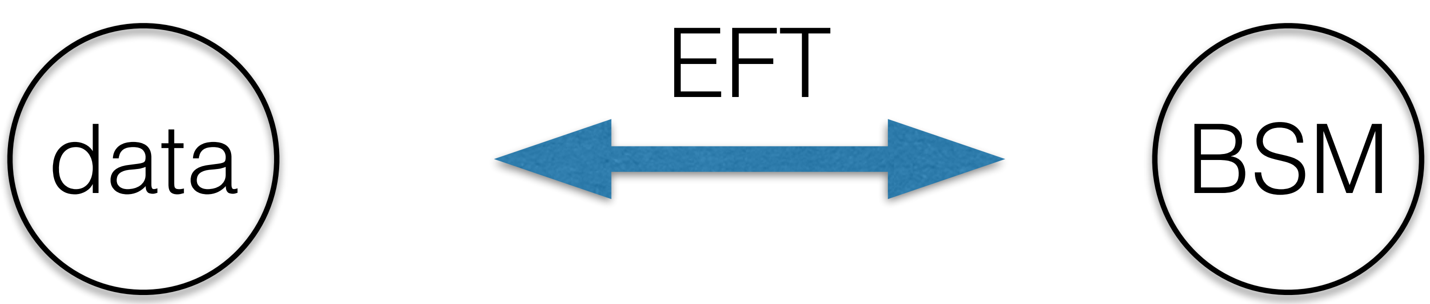
what a 250 GeV ILC would deliver



note the synergy: HL-LHC input is always included

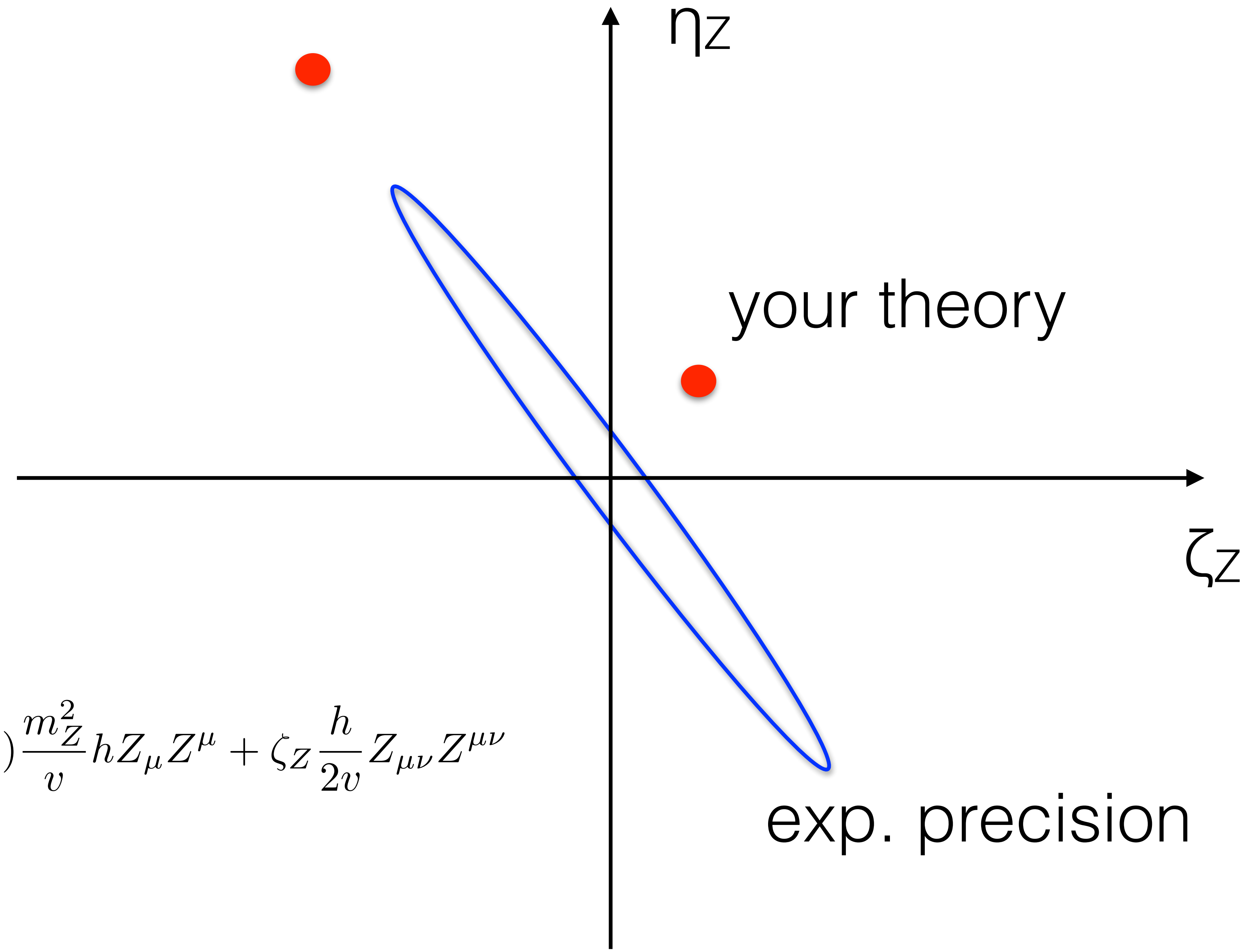
what's next?

- EFT provides a precise/model independent formalism to describe/combine the experimental data
- in the end of the world, we would like to know what the new physics is



proposals (NHWG20, Aug. 18-19, 2017)

- can you calculate (all) the EFT coefficients in your preferred BSM models? ($c_i/v^2 \sim g/\Lambda^2$)



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

the answer was remarkably fast (Oct. 2017)

arXiv:1710.04603

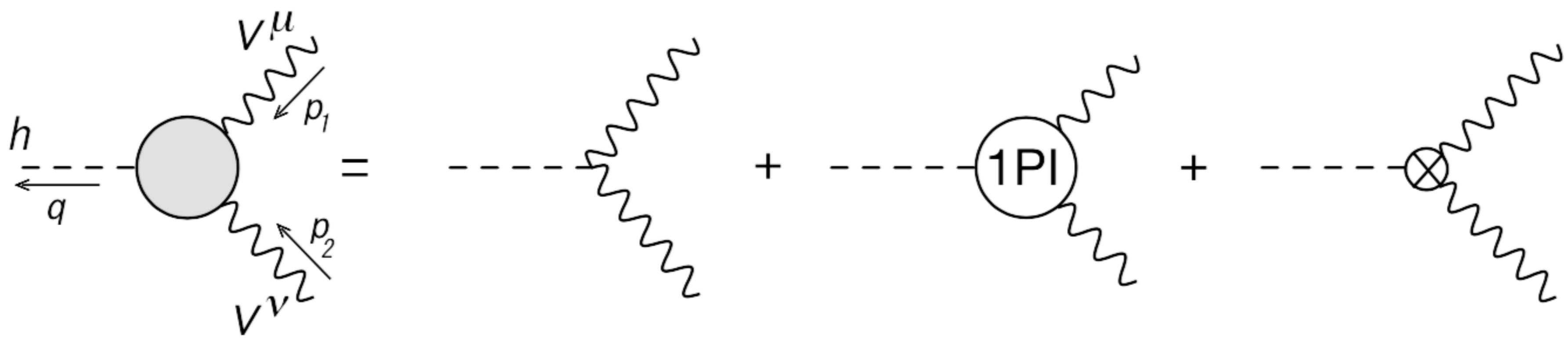
H-COUP:

a program for one-loop corrected Higgs boson couplings in non-minimal Higgs sectors

Shinya Kanemura,[1,*] Mariko Kikuchi,[2,†] Kodai Sakurai,[3,‡] and Kei Yagyu[4,§]

a first step

look at effective hZZ coupling in models: SM, HSM, 2HDM



renormalized hZZ vertex can be decomposed into 3 form factors

$$\hat{\Gamma}^{\mu\nu}_{hVV}(p_1^2, p_2^2, q^2) = g^{\mu\nu}\hat{\Gamma}^1_{hVV} + \frac{p_1^\mu p_2^\nu}{m_V^2}\hat{\Gamma}^2_{hVV} + i\epsilon^{\mu\nu\rho\sigma}\frac{p_{1\rho}p_{2\sigma}}{m_V^2}\hat{\Gamma}^3_{hVV}$$

the three Γs, which are usually functions of (p_i^2,q^2), can be calculated numerically by H-Coup (arXiv:1710.04603)

a first step

if we start from EFT Lagrangian for hZZ coupling

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

$$Z_{\mu\nu} = \partial_\mu Z_\nu - \partial_\nu Z_\mu$$

$$\tilde{Z}_{\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\rho\sigma} Z^{\rho\sigma}$$

let's focus on CP-even terms for now

vertex from a-term: $g^{\mu\nu}\frac{2m_Z^2}{v}(1+a)$

vertex from b-term: $(g^{\mu\nu} p_1 \cdot p_2 - p_1^\mu p_2^\nu)\frac{2b}{v}$

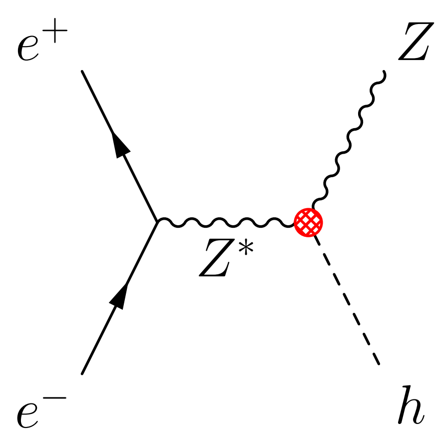
a first step

by comparing the vertices in two approaches:

$$\hat{\Gamma}^1_{hZZ} = \frac{2m_Z^2}{v}(1+a) + p_1 \cdot p_2 \frac{2b}{v}$$

$$\hat{\Gamma}^2_{hZZ} = -\frac{2m_Z^2}{v} b$$

in case of



$$p_1 = (\sqrt{s}, \mathbf{0})$$

$$p_2 = (E_Z, \mathbf{p}_Z)$$

$$a = \frac{v}{2m_Z^2}\hat{\Gamma}^1 + \frac{\sqrt{s}E_Z v}{2m_Z^4}\hat{\Gamma}^2 - 1$$

$$b = -\frac{v}{2m_Z^2}\hat{\Gamma}^2$$

(first EFT BSM matching?…)

numerical results by H-COUP

$$\hat{\Gamma}^{\mu\nu}_{hVV}(p_1^2, p_2^2, q^2) = g^{\mu\nu}\hat{\Gamma}^1_{hVV} + \frac{p_1^\mu p_2^\nu}{m_V^2}\hat{\Gamma}^2_{hVV} + i\epsilon^{\mu\nu\rho\sigma}\frac{p_{1\rho}p_{2\sigma}}{m_V^2}\hat{\Gamma}^3_{hVV}$$

Re[rGam_hZZ(1)]:	6.63606456E+01	Im[rGam_hZZ(1)]:	-1.55052694E+00
Re[rGam_hZZ(2)]:	-1.13818683E-01	Im[rGam_hZZ(2)]:	-9.24725320E-01
Re[rGam_hZZ(3)]:	4.43306800E-03	Im[rGam_hZZ(3)]:	-2.48999837E-06
Re[rGam_hWW(1)]:	5.31463661E+01	Im[rGam_hWW(1)]:	-1.41296896E+00
Re[rGam_hWW(2)]:	-9.76599594E-02	Im[rGam_hWW(2)]:	-9.09232189E-01
Re[rGam_hWW(3)]:	1.45357025E-03	Im[rGam_hWW(3)]:	-4.38354919E-02
Re[rGam_htt(S)]:	-7.26874884E-01	Im[rGam_htt(S)]:	-1.08793467E-03
Re[rGam_hbb(S)]:	-1.88039217E-02	Im[rGam_hbb(S)]:	7.78472272E-05
Re[rGam_hcc(S)]:	-5.13690642E-03	Im[rGam_hcc(S)]:	-3.68162893E-05
Re[rGam_hll(S)]:	-6.98376220E-03	Im[rGam_hll(S)]:	-1.90054055E-04
Re[rGam_hhh]:	-1.84513810E+02	Im[rGam_hhh]:	1.67554069E+00
Gam(h->gamgam):	9.07406501E-06		
Gam(h->Zgam):	6.30760961E-06		
Gam(h->gg):	1.90735956E-04		

arXiv:1710.04603

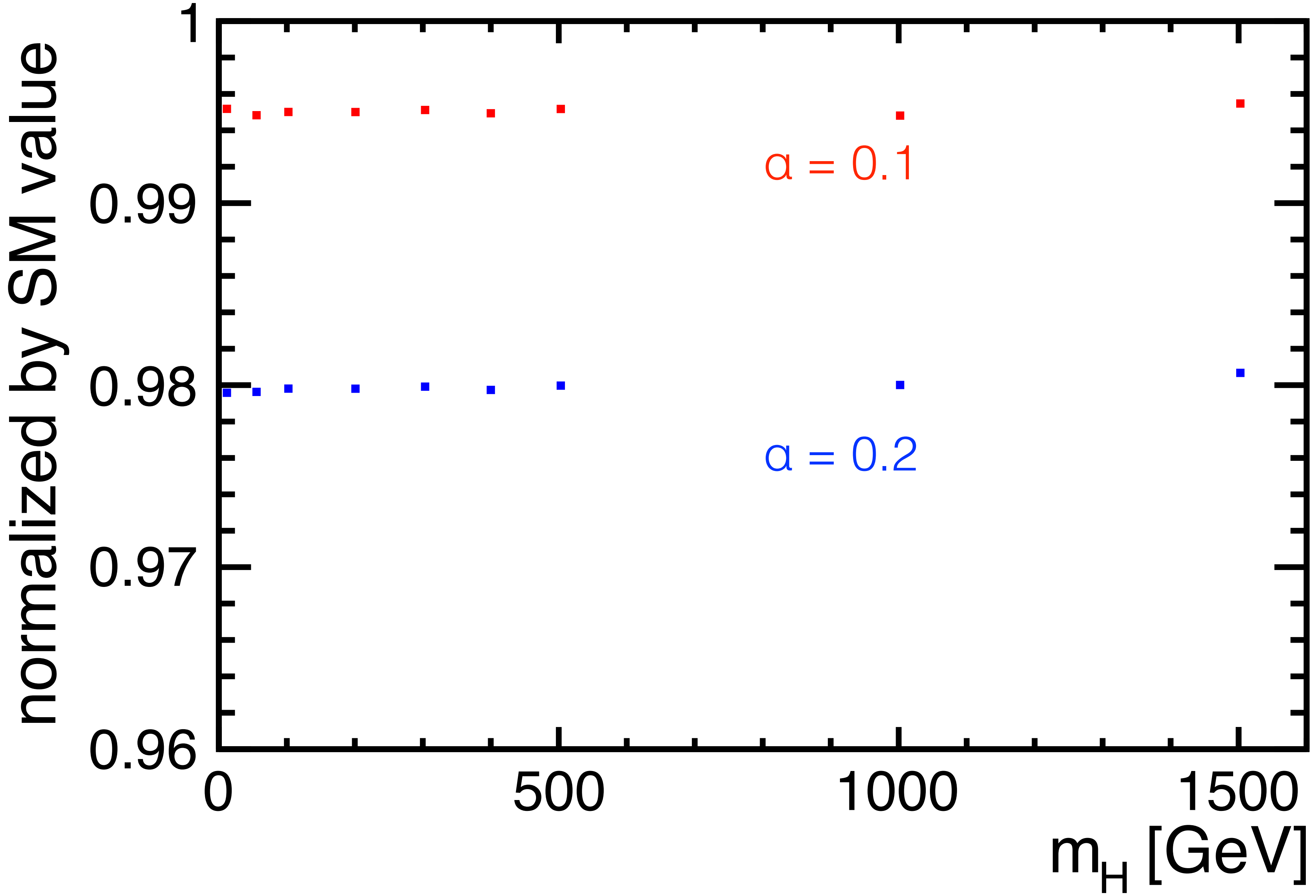
FIG. 3: Example of the output file (out_hsm.txt).

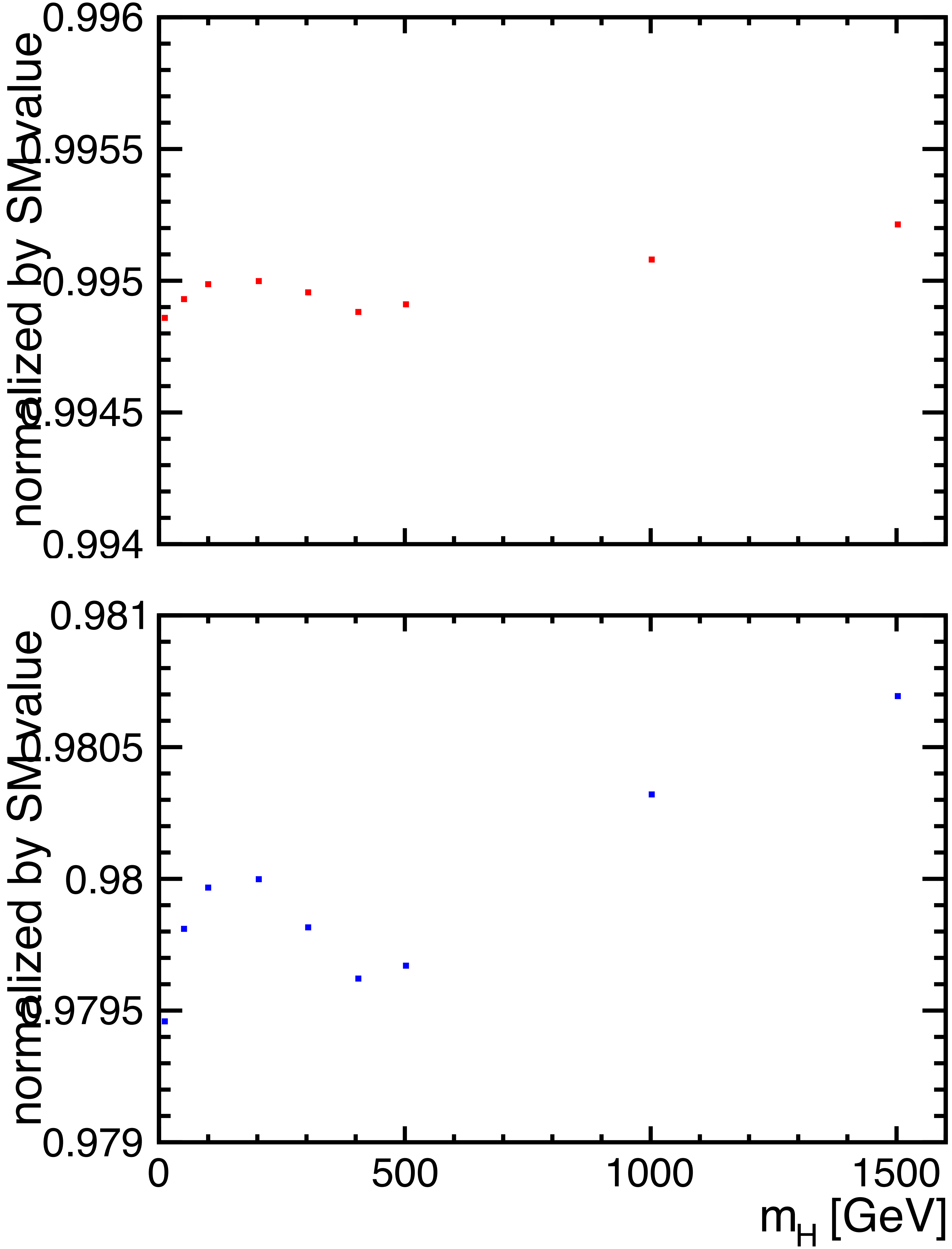
some preliminary results: HSM

$$\frac{\hat{\Gamma}^1}{\hat{\Gamma}^1_{\rm SM}}$$

(real part)

α: mixing angle





0.996
0.9955
0.995
0.9945
0.994
normalized by SM value
0.981
0.9805
0.98
0.9795
0.979
normalized by SM value
0
500
1000
1500
m_H [GeV]

arXiv:1705.05399

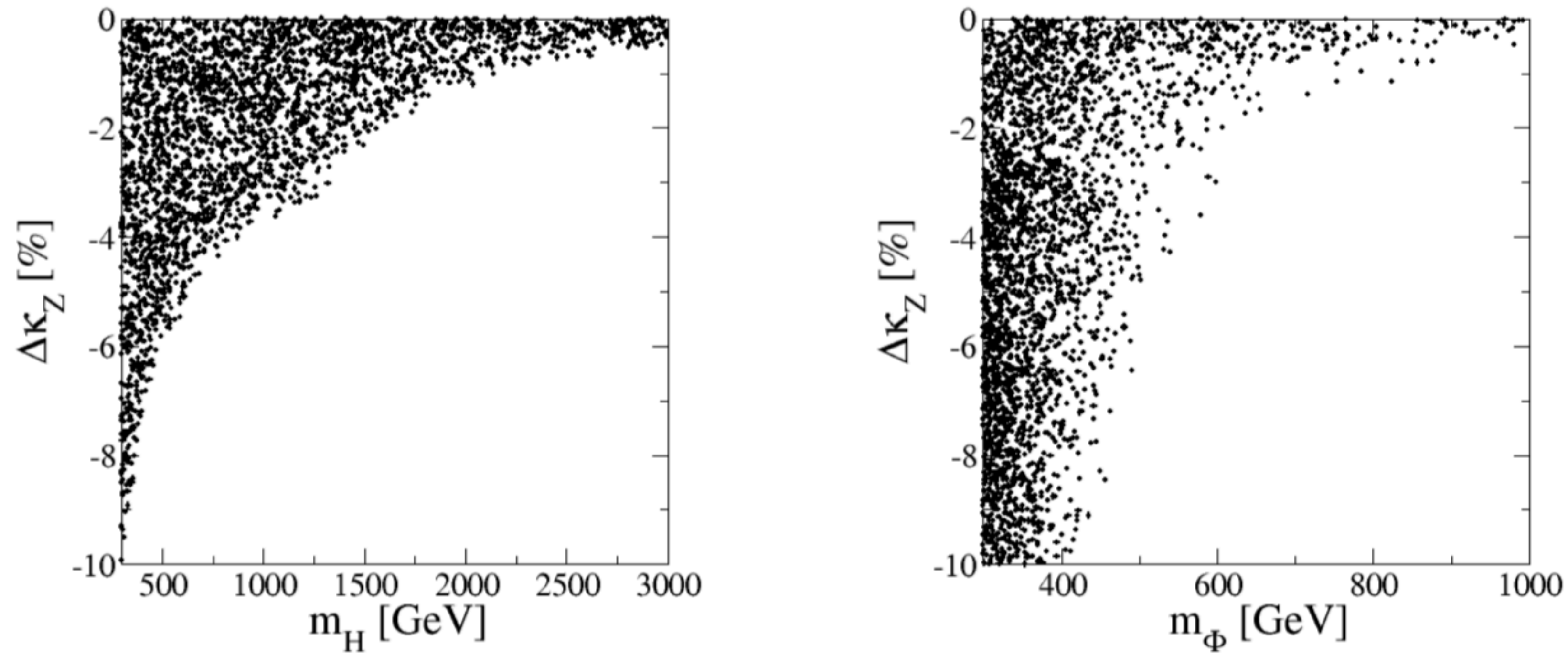


FIG. 14: Allowed parameter region under the constraints from the perturbative unitarity, the vacuum stability, the triviality and the S, T parameters on the $\Delta\kappa_Z$–m_H plane and the $\Delta\kappa_Z$–m_Φ plane in the HSM (left) and in the THDM (right), respectively.

some preliminary findings & next

1. attention to pay for parameters in non-minimal Higgs sectors
    - unitarity violation
    - vacuum instability
    - false vacuum

2. in addition to Γ^1, which was usually used to test the deviation, at the ILC we expect good sensitivity to Γ^2 or Γ^3 as well

3. next is to get correct dependence on mass by proper scan, for both Γ^1 and Γ^2, first for HZZ coupling, then for HWW, $H\gamma\gamma$, $H\gamma Z$… (meeting with collaborators tomorrow 7:30am…)

backup

summary

- advantage of e+e- (e.g. ILC): model-independent determination of all Higgs couplings (and precisely)
    - ➡ kappa formalism turns out not general enough to accommodate all BSM effects
    - ➡ EFT formalism (combined EWPOs+TGCs+Higgs) is more suitable, and a realistic fit based on this formalism is proved to work very well

- one important conclusion based on the EFT formalism: hWW coupling can be determined precisely at $\sqrt{s}$ = 250 GeV without relying on WW-fusion process —> go ahead ILC250 (or any other affordable Higgs factory)

- beam polarization shows additional importance in EFT formalism

- EFT opens up new (better) way for BSM model discrimination

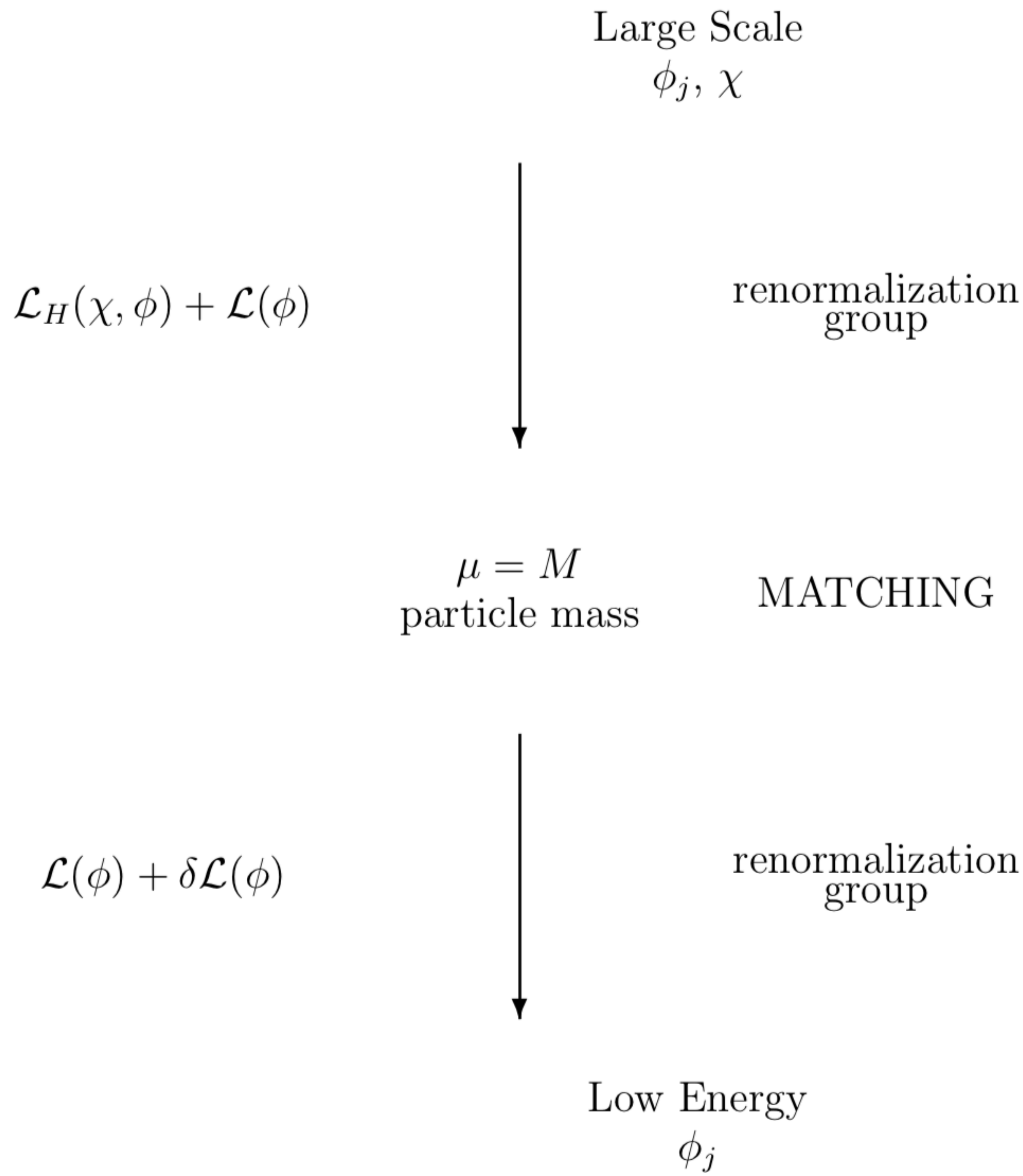


Figure 4: The general form of a matching calculation.

reminder: model independence in kappa framework

- recoil mass technique —> inclusive σ_{Zh}
- σ_{Zh} —> κ_Z —> $\Gamma(h\text{->}ZZ^*)$
- WW-fusion $\nu_e\nu_e h$ —> κ_W —> $\Gamma(h\text{->}WW^*)$
- total width $\Gamma_h = \Gamma(h\text{—>}ZZ^*)/BR(h\text{->}ZZ^*)$
- or $\Gamma_h = \Gamma(h\text{—>}WW^*)/BR(h\text{->}WW^*)$
- then all other couplings

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an interesting comment about EFT and SU(2)xU(1)

H.Georgi, 1993

4.3 Above the Z

One of the most important applications of effective field theory technology today is to the issue $SU(2) \times U(1)$ breaking. The general question here is the following: **What does the physics we see at scales up to and just above the masses of the W and Z tell us about higher scales that we cannot see directly?** Even before the discovery of the W and Z, the observed properties of the weak interactions of quarks and leptons convinced almost all particle physicists that they must exist, as the massive gauge bosons of spontaneously broken $SU(2) \times U(1)$. Amazingly, this history seems to have been forgotten by some. One still occasionally sees papers in which the properties of the W and Z are discussed without proper regard to the constraints of $SU(2) \times U(1)$ symmetry. Thus it may be useful to recount the important issues.

Ann.Rev.Nucl.Part.Sci. 43 (1993) 209-252

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

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

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

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

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

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)

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

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

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

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

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

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

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

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

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

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

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

EFT input: EWPOs (7)

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

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

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

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

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

⟶ $c_{HL}+c'_{HL}$, c_{HE}

EFT input: TGC (3)

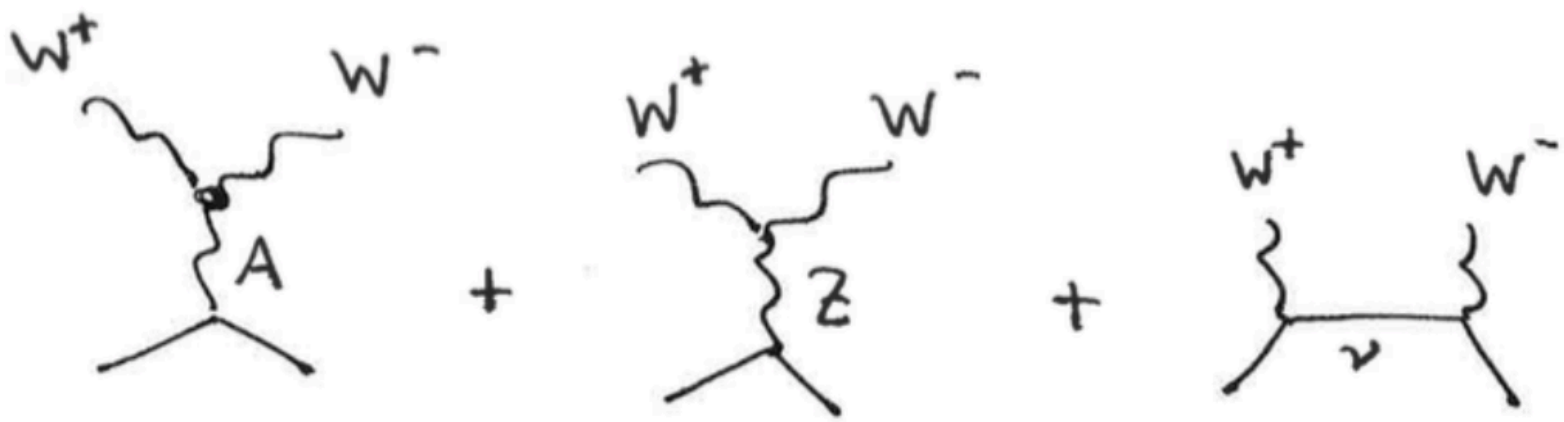
$$\Delta\mathcal{L}_{TGC} = ig_V\left\{V^\mu(\hat{W}^-_{\mu\nu}W^{+\nu} - \hat{W}^+_{\mu\nu}W^{-\nu}) + \kappa_V W^+_\mu W^-_\nu \hat{V}^{\mu\nu} + \frac{\lambda_V}{m_W^2}\hat{W}^{-\rho}_\mu \hat{W}^+_{\rho\nu}\hat{V}^{\mu\nu}\right\}$$

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

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

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

EFT input: TGC (3)



$$\delta g_{Z,eff} = \delta g_Z + \frac{1}{c_w^2}((c_w^2 - s_w^2)\delta g_L + s_w^2 \delta g_R - 2\delta g_W)$$
$$\delta \kappa_{A,eff} = (c_w^2 - s_w^2)(\delta g_L - \delta g_R) + 2(\delta e - \delta g_W) + (8 c_{WB})$$
$$\delta \lambda_{A,eff} = -6 g^2 c_{3W}$$

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

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-

Higgs couplings in EFT

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

$$\eta_h = \delta\overline{\lambda} + \delta v - \frac{3}{2}c_H + c_6$$
$$\eta_W = 2\delta m_W - \delta v - \frac{1}{2}c_H$$
$$\eta_{WW} = 2\delta m_W - 2\delta v - c_H$$
$$\eta_Z = 2\delta m_Z - \delta v - \frac{1}{2}c_H - c_T$$
$$\eta_{ZZ} = 2\delta m_Z - 2\delta v - c_H - 5c_T$$

$$\theta_h = c_H$$
$$\zeta_W = \delta Z_W$$
$$\zeta_Z = \delta Z_Z$$
$$\zeta_A = \delta Z_A$$
$$\zeta_{AZ} = \delta Z_{AZ}$$

EFT input from Higgs observables at e+e-

-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})

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

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)

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

ILC H20: $\int L dt$ = 2 ab^{-1} @ 250 GeV

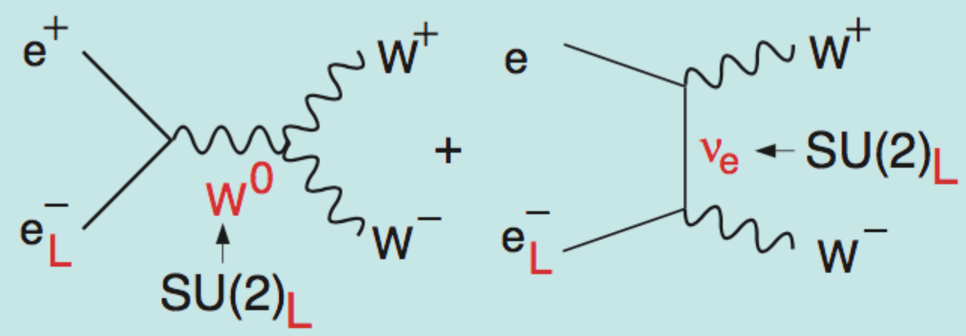
coupling $\Delta g/g$	kappa-fit	EFT-fit
hZZ	0.38%	0.63%
hWW	1.9%	0.63%
hbb	2.0%	0.89%
Γ_h	4.2%	2.1%

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

Power of Beam Polarization

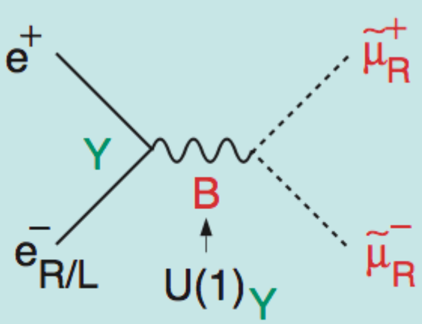
BG Suppression

W^+W^- *(Largest SM BG in SUSY searches)*



In the symmetry limit, $\sigma_{WW} \to 0$ for e^-_R !

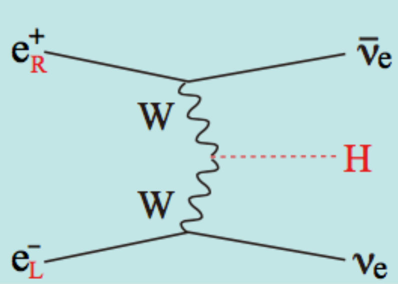
Slepton Pair



$$\begin{cases} Y_L = -1/2 : e^-_L \\ Y_R = -1 \quad : e^-_R \end{cases}$$

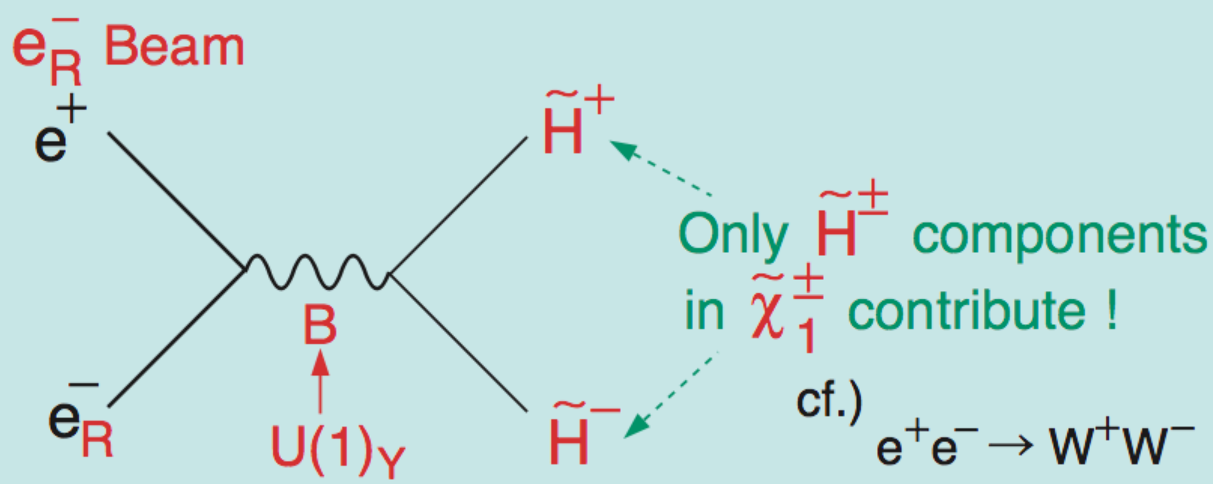
In the symmetry limit, $\sigma_R = 4\,\sigma_L$!

WW-fusion Higgs Prod.



	ILC
Pol (e-)	-0.8
Pol (e+)	+0.3
$(\sigma/\sigma_0)_{\nu\nu H}$	1.8x1.3=2.34

Chargino Pair



$$\tilde{\chi}^{\pm}_1 = \bigcirc \cdot \tilde{W}^{\pm} + \bullet \cdot \tilde{H}^{\pm}$$

$$\bullet = \langle \tilde{H}^{\pm} | \tilde{\chi}^{\pm}_1 \rangle$$

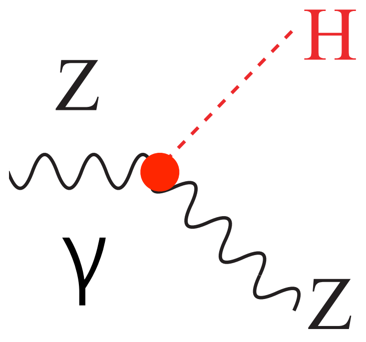
Decomposition

Signal Enhancement

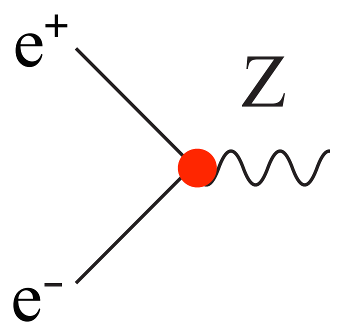
comments on beam polarizations

- not changed: important for systematics control, nature of new particle (once found), e.g. Higgsino, WIMPs
- new roles in EFT

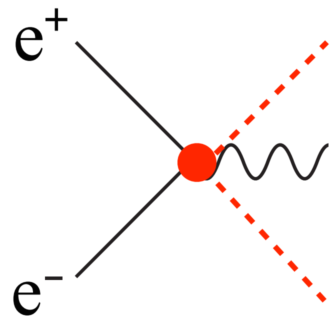
-> separate hZZ and hγZ couplings



-> improve A_{LR} in Z-e-e coupling

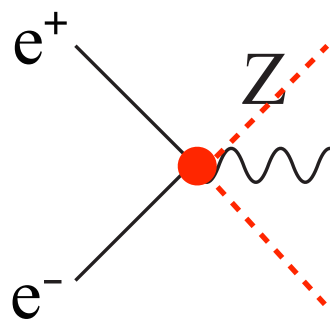


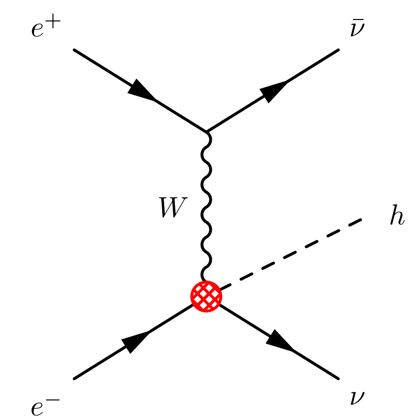
important to constrain contact interaction



homework from EFT (limiting factors other than usual Higgs observables)

- TGC: full simulation at 250 GeV
- improve hγZ couplings: using both h->γZ and e+e- ->γh
- better constrain contact interactions:
  - improve A_{LR}
  - improve Γ(Z->ee)
  - improve Γ(W->eν)





comments on validity of our EFT analysis

- though most of the coefficients are assumed to be small, it is not necessary for c6, which modifies triple higgs coupling only, would not affect the formalism of other part (tree level)
- thus it can be applied to the case where λ_{hhh} is significantly enhanced (e.g. EWBG, CSI)
- in general we assume the mass scales of new particles which contribute to the D-6 operators are heavy, but it is fine with light WIMP, if it is only relevant in h->invisible decay (decoupled with other observable)

new application: model discrimination by EFT

	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.

typical parameters of benchmark models

- 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

new development: model discrimination by EFT

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

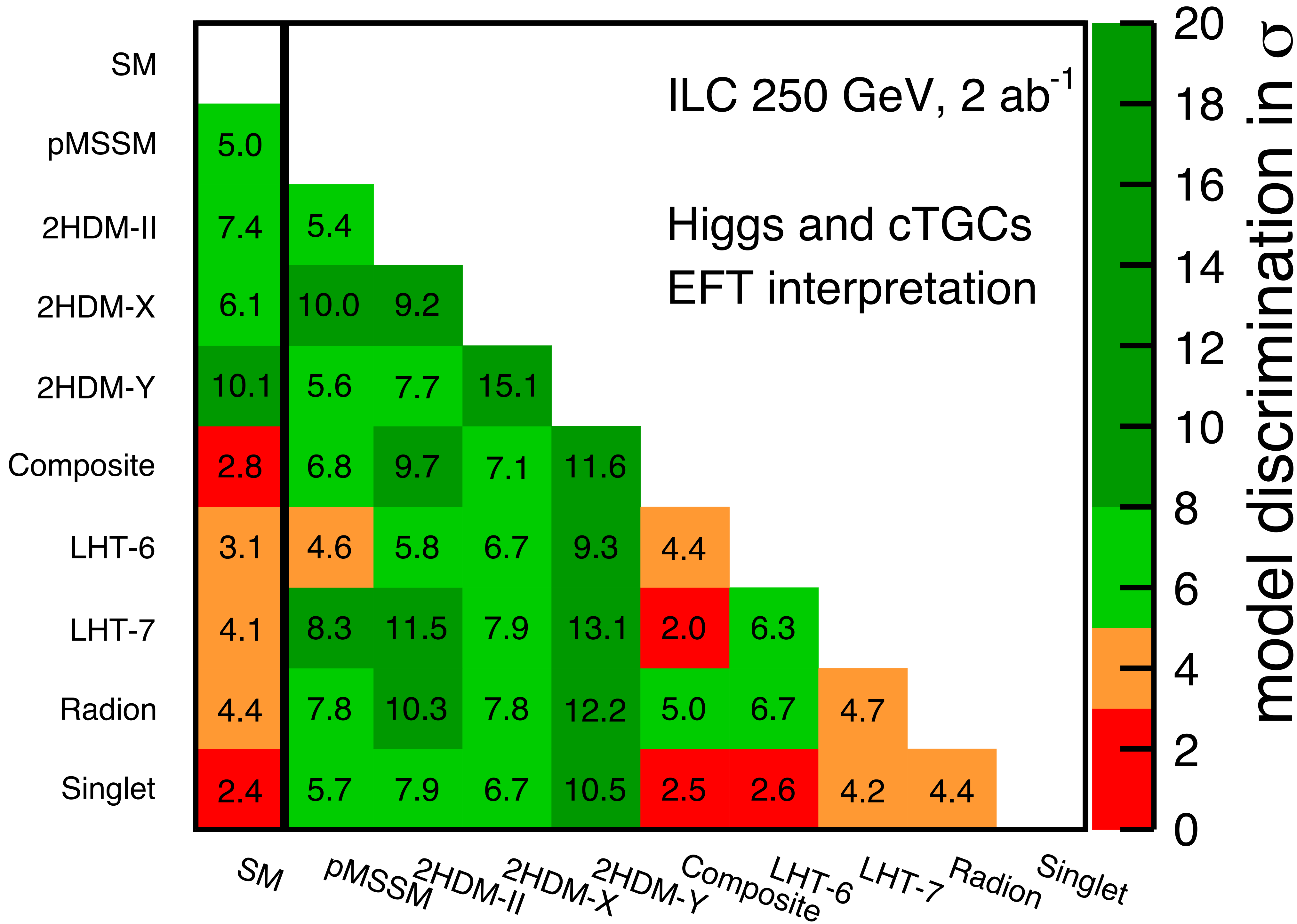
g_A, g_B: vector of couplings in Model A, B

V_{ij}: linear dependence of coupling g_i on EFT coefficient c_j

C: covariance matrix of EFT coeffs

- given the coupling deviations in two models, this χ^2 gives the most appropriate separation power, taking into account all correlations

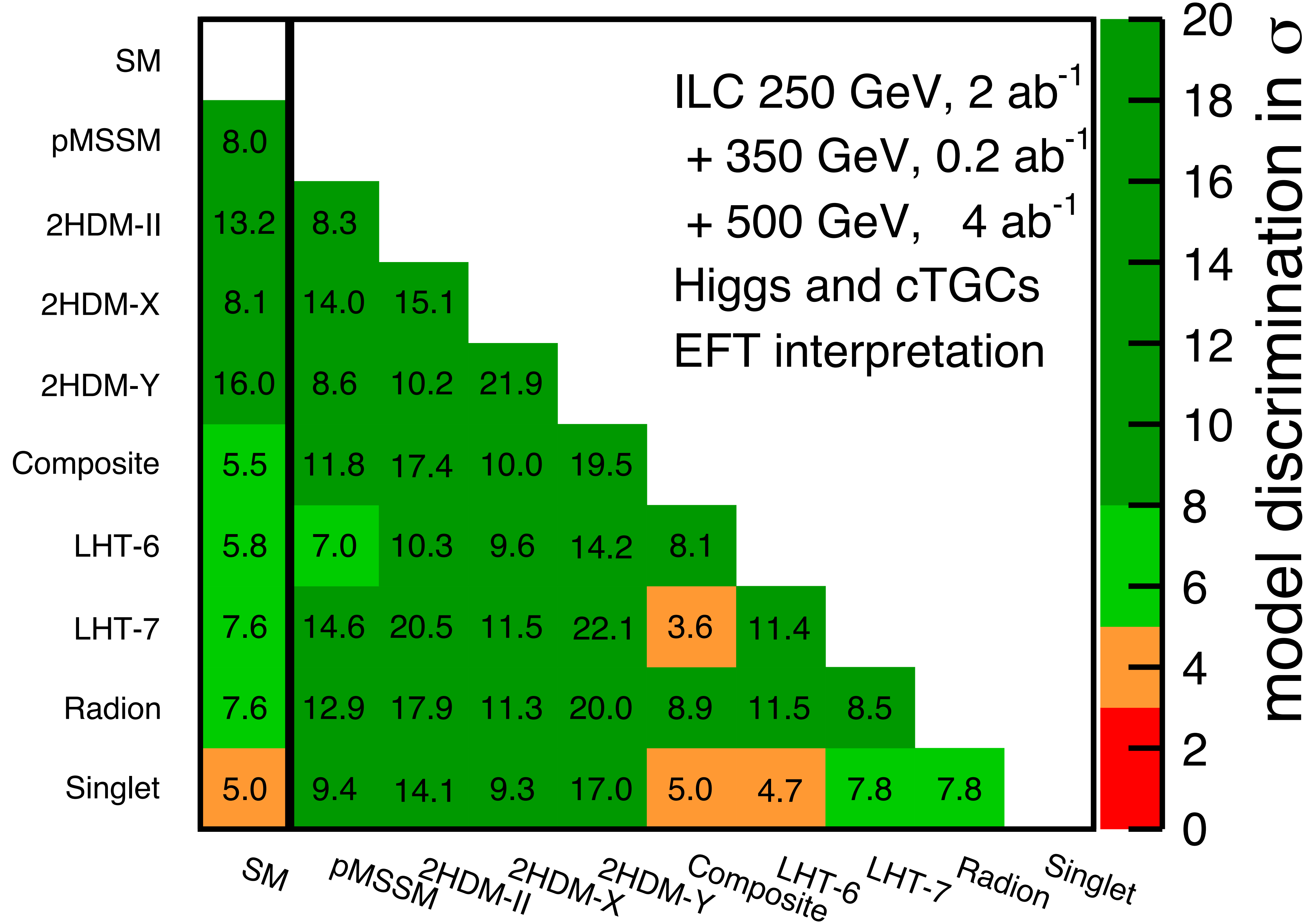
discrimination between BSM models (ILC250 stage)



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

once find deviation against SM —> can tell which BSM

discrimination between BSM models (ILC500 stage)



political change

- to meet required cost reduction, ILC is proposed as a 250 GeV machine in the initial stage —> hopefully for an early realization (check out recent JAHEP statement)

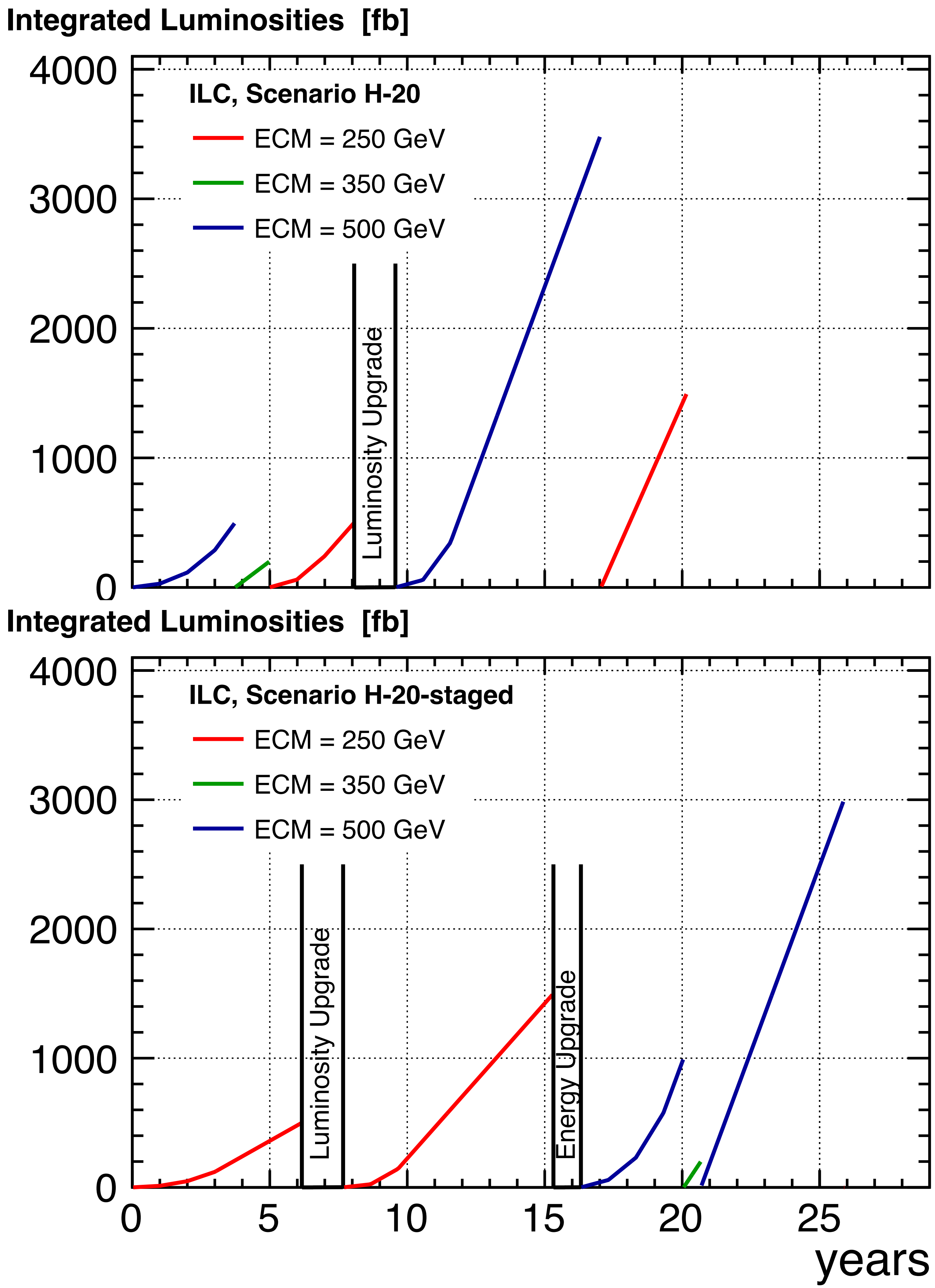
Japan Association of High Energy Physicists

Scientific Significance of ILC and Proposal of its Early Realization
in light of the Outcomes of LHC Run 2

scientific change

- Higgs couplings in effective theory formalism -> view of coupling measurement at 250 GeV is dramatically changed

scenario:
example



ILC500
H20

ILC250
H20 staged

top physics starts
after > 16y
in total ~ 6y longer

some quick answers

- measure directly hVV couplings (tensor structure) using σ, dσ/dX, in e+e- —> Zh process

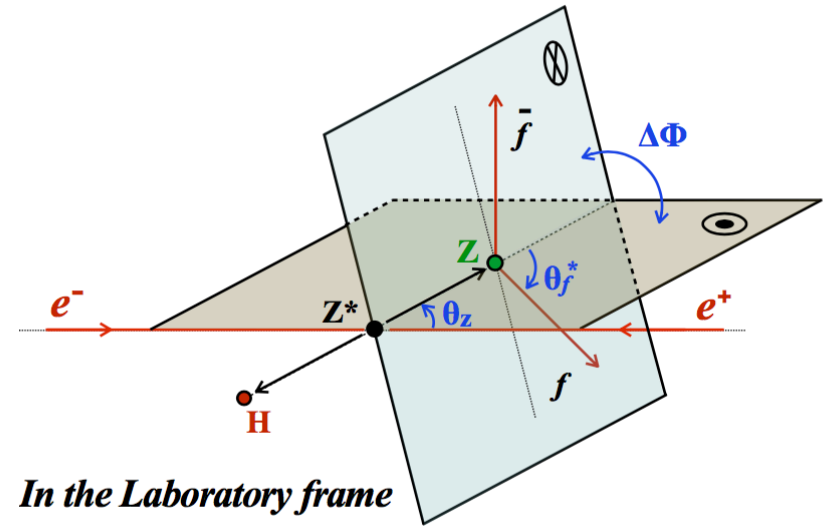
$$L_{hZZ} = M_Z^2\left(\frac{1}{v} + \frac{a}{\Lambda}\right)hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}$$

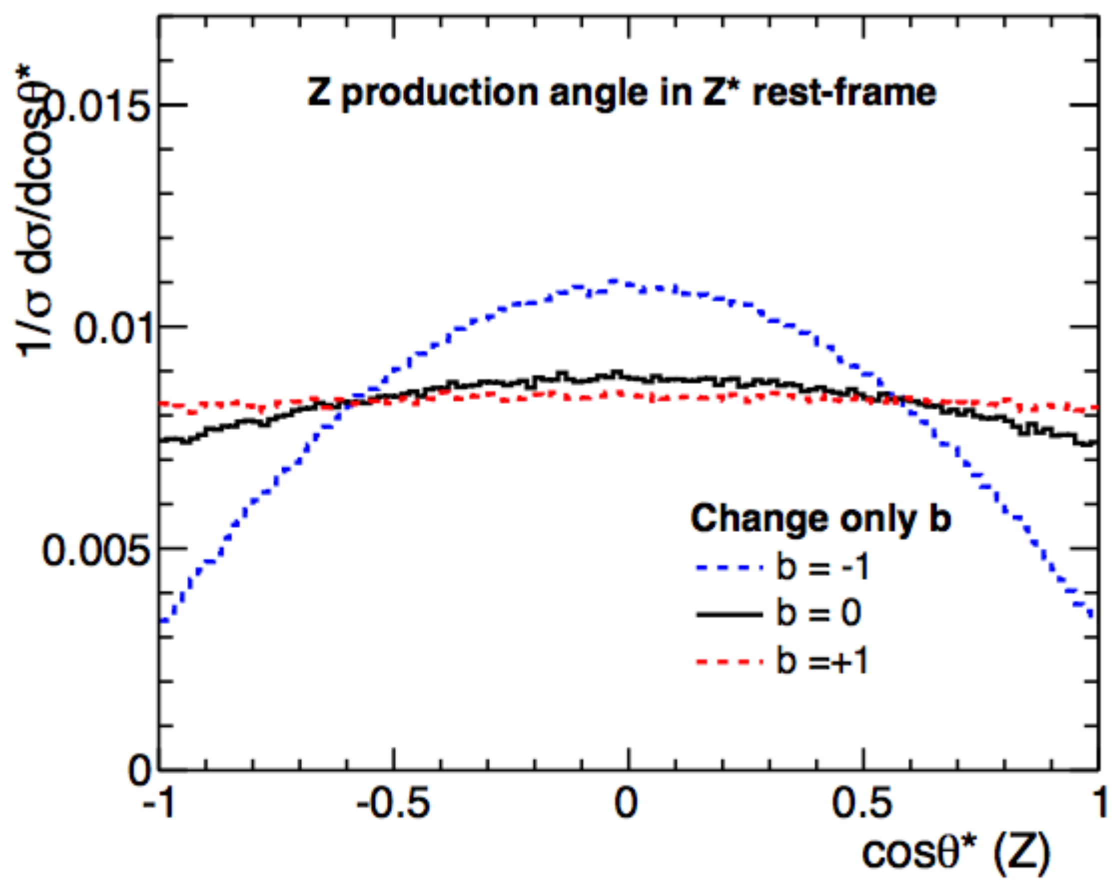
(SM-like) (CP-even) (CP-odd)

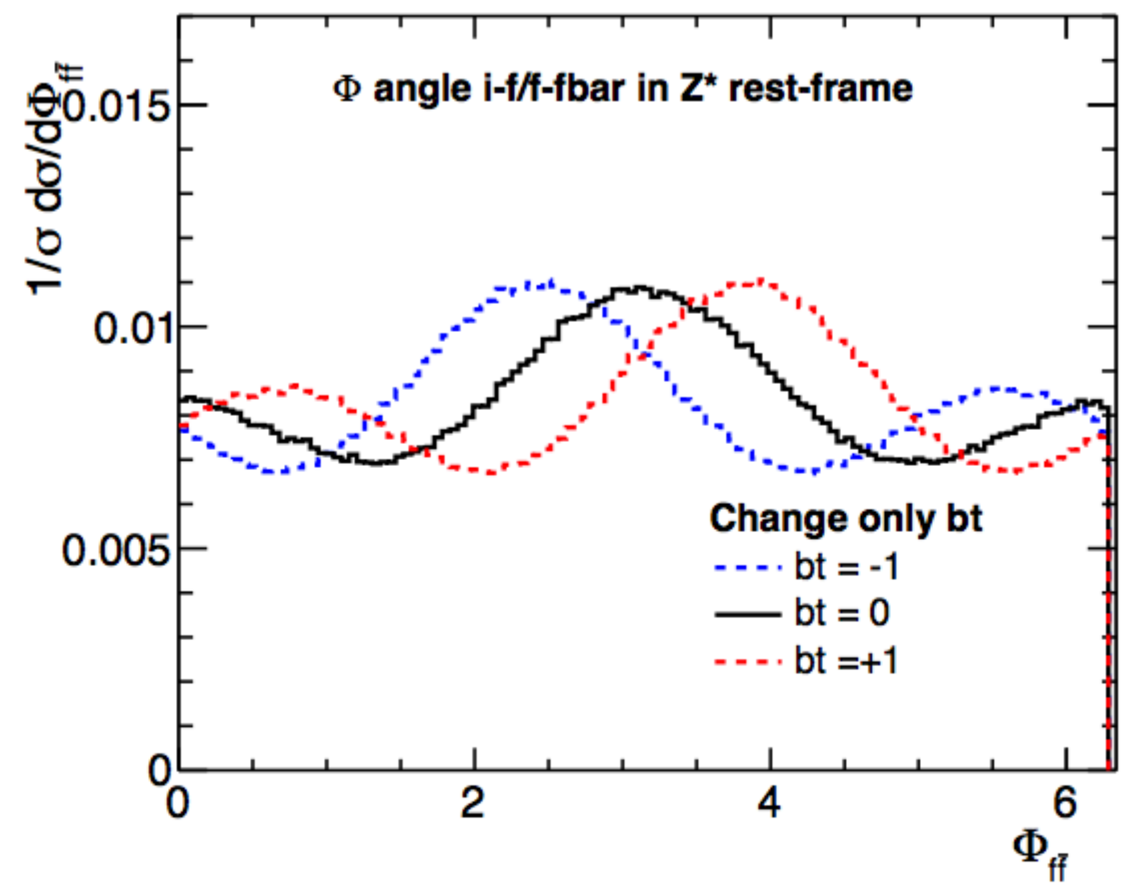
Ogawa et al, EPS-HEP 2017

- measure hhVV couplings and λ_{hhh} simultaneously using σ, dσ/dX, in e+e- —> Zhh process determine tensor structure of hVV couplings

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







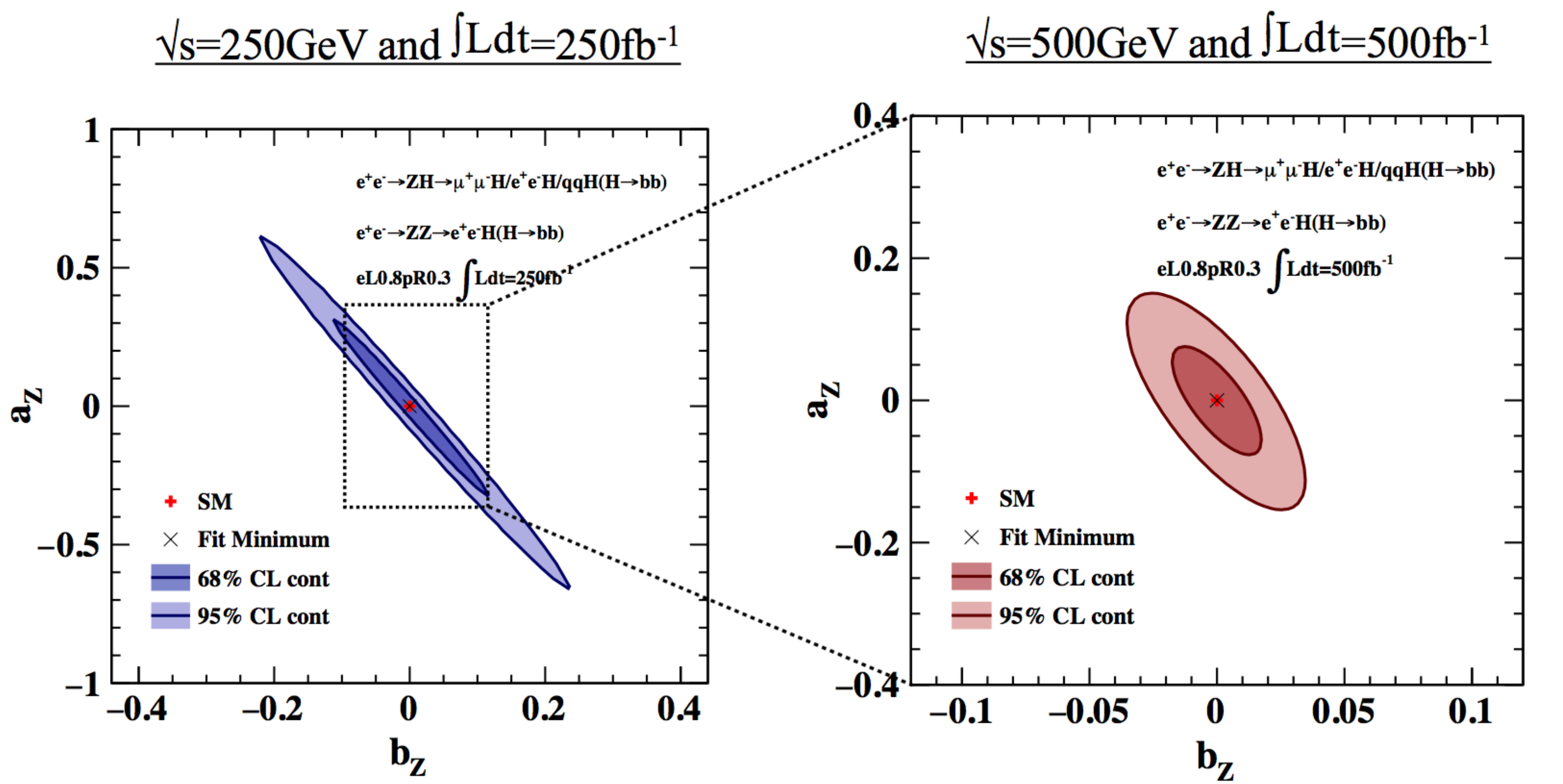
$$@ \sqrt{s} = 250\text{GeV}$$

example: how b/b~ changes dσ/dX

determine tensor structure of hVV couplings (full simulation)

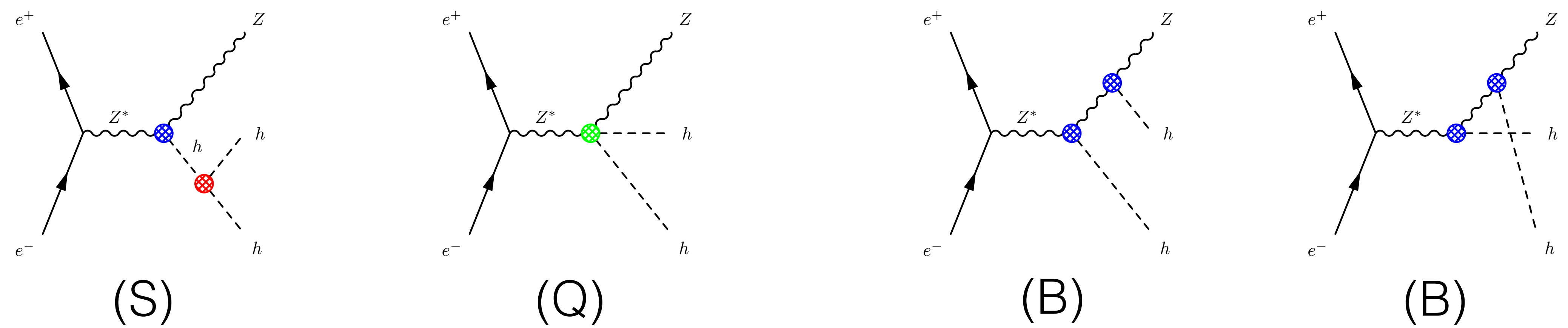
$$L_{hZZ} = M_Z^2(\frac{1}{v} + \frac{a}{\Lambda})hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}$$

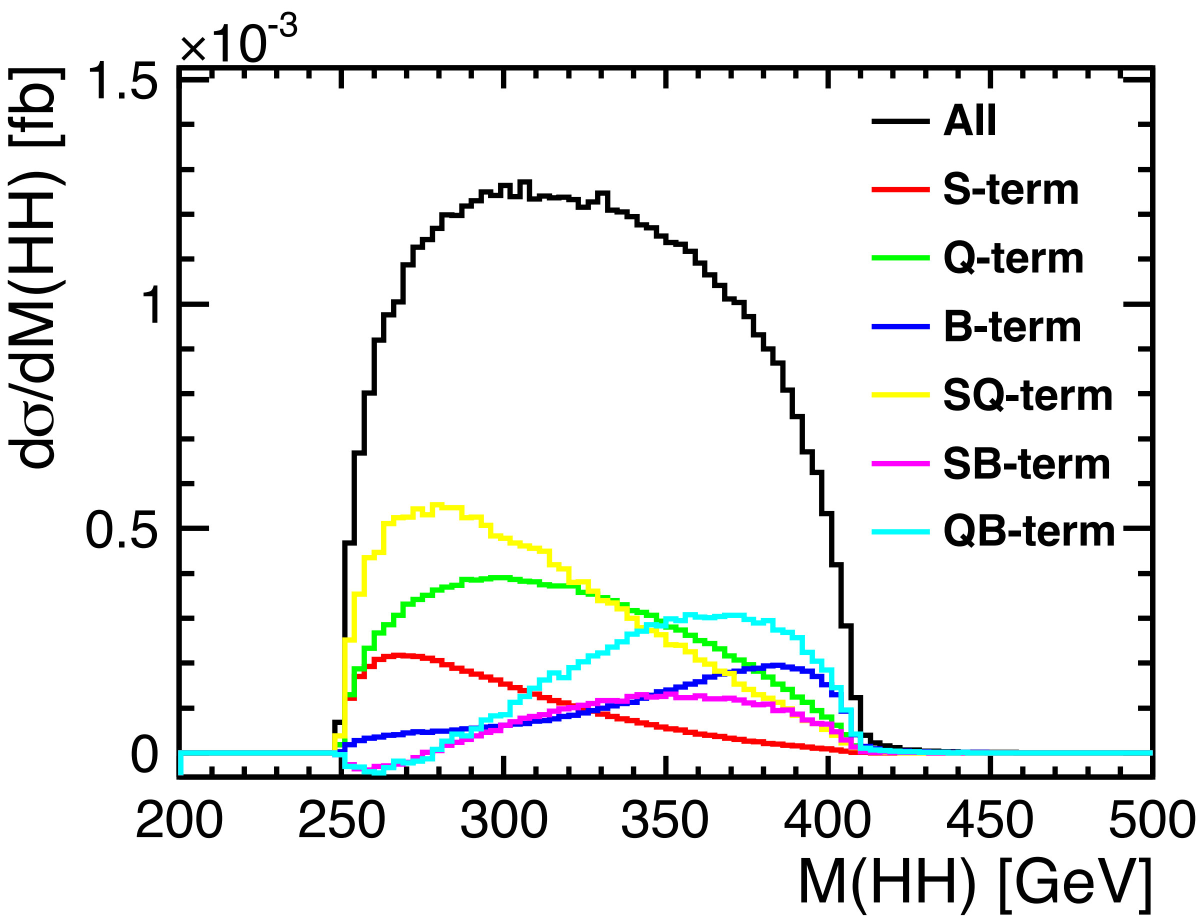
$\Lambda = 1$ TeV

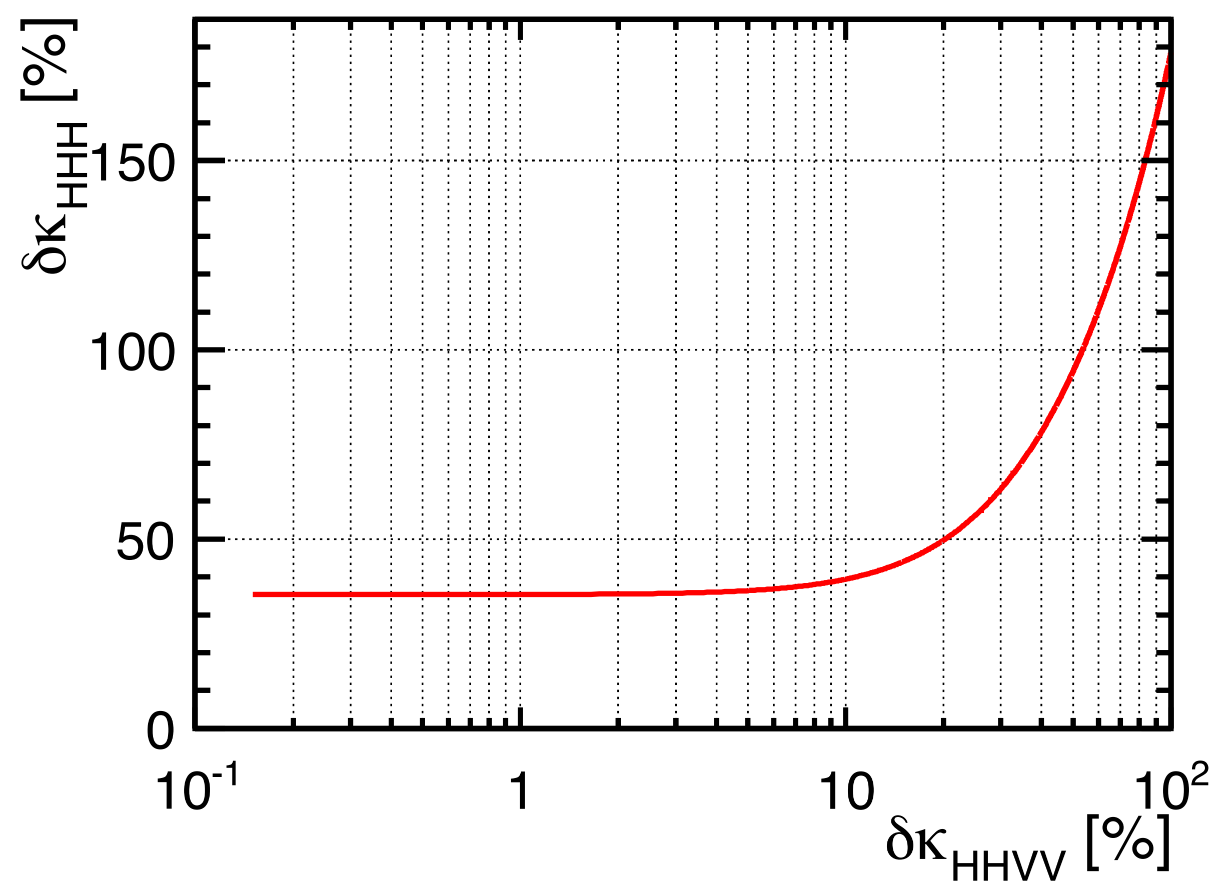


for 2 ab-1 @ 250 GeV —> κ_Z (a) ~ 3% >> 0.38%

hhVV, hVV and λ_{hhh} in e+e- —> Zhh







$\delta\kappa_{hhVV}$ < 5% would be needed —> challenging by shape