model-independent determination of Higgs (self-)couplings @ e+e- colliders

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CEPC Theory Group Workshop, July 11-14, 2017 @ IHEP

model independence in kappa framework (elementary school)

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

PoS EPS-HEP2013 (2013) 316

Nucl.Part.Phys.Proc. 273-275 (2016) 826-833

the key: inclusive σ_{Zh} (independent of h decay modes)

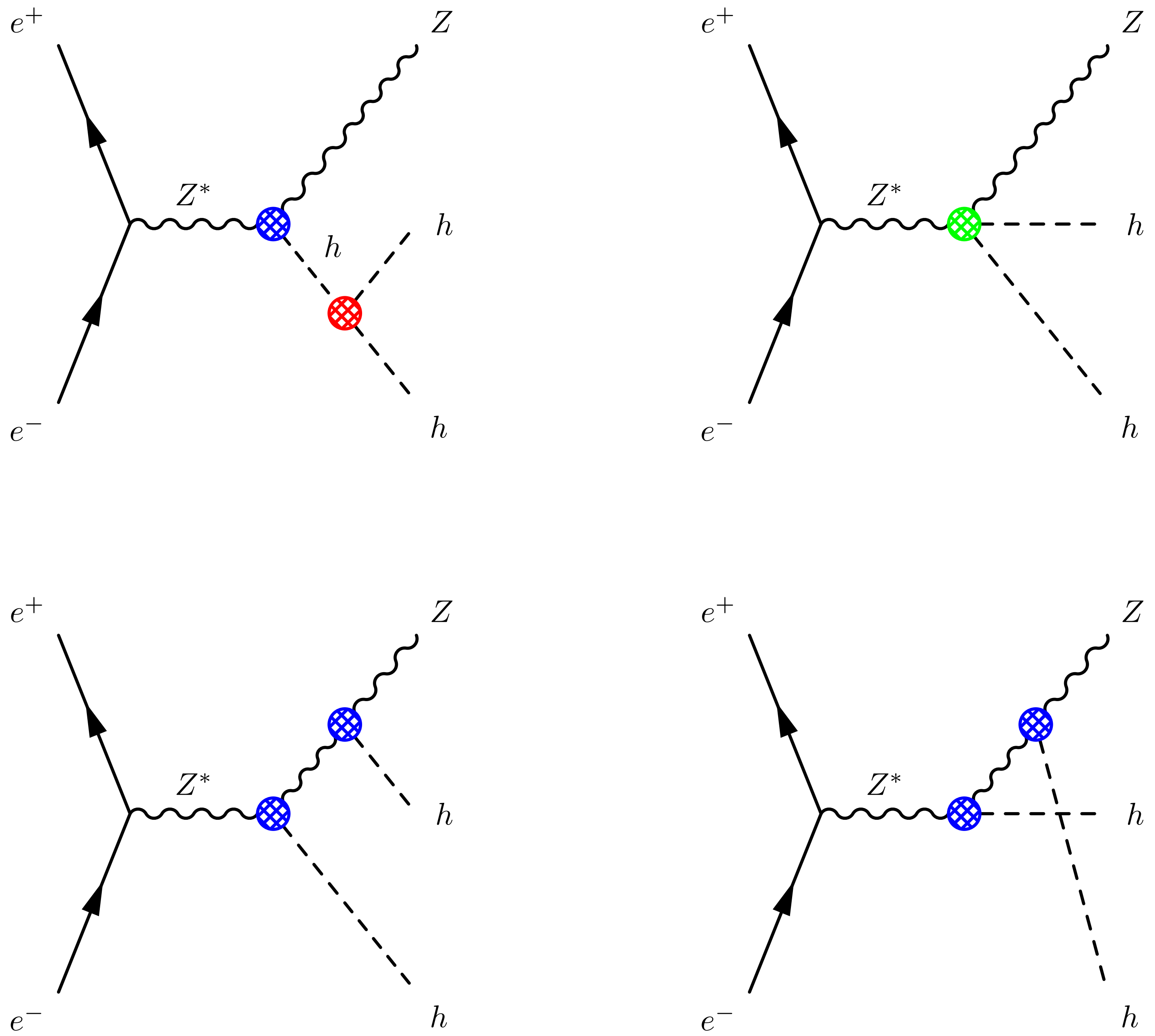
Yan, et al, Phys.Rev. D94 (2016) 113002;
Thomson, Eur.Phys.J. C76 (2016) 72

$H \to XX$	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%

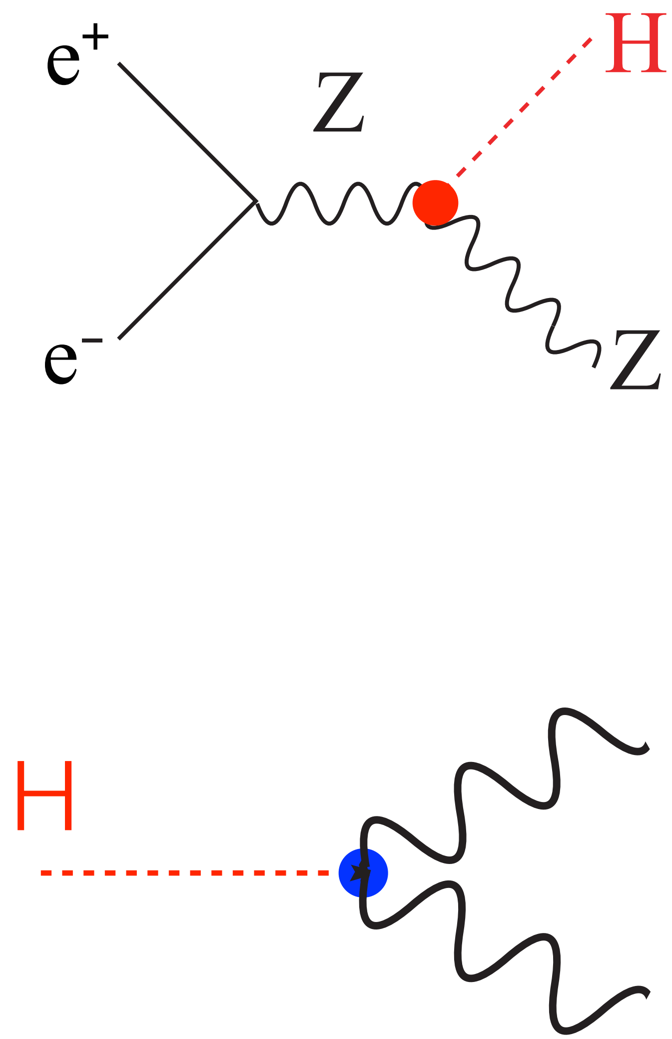
bias < 0.1 in leptonic recoil mode

still need effort to achieve bias in hadronic recoil mode < 1%

question 1: how can we determine λ_{hhh} if there are anomalous hhVV, hVV, hhh couplings?

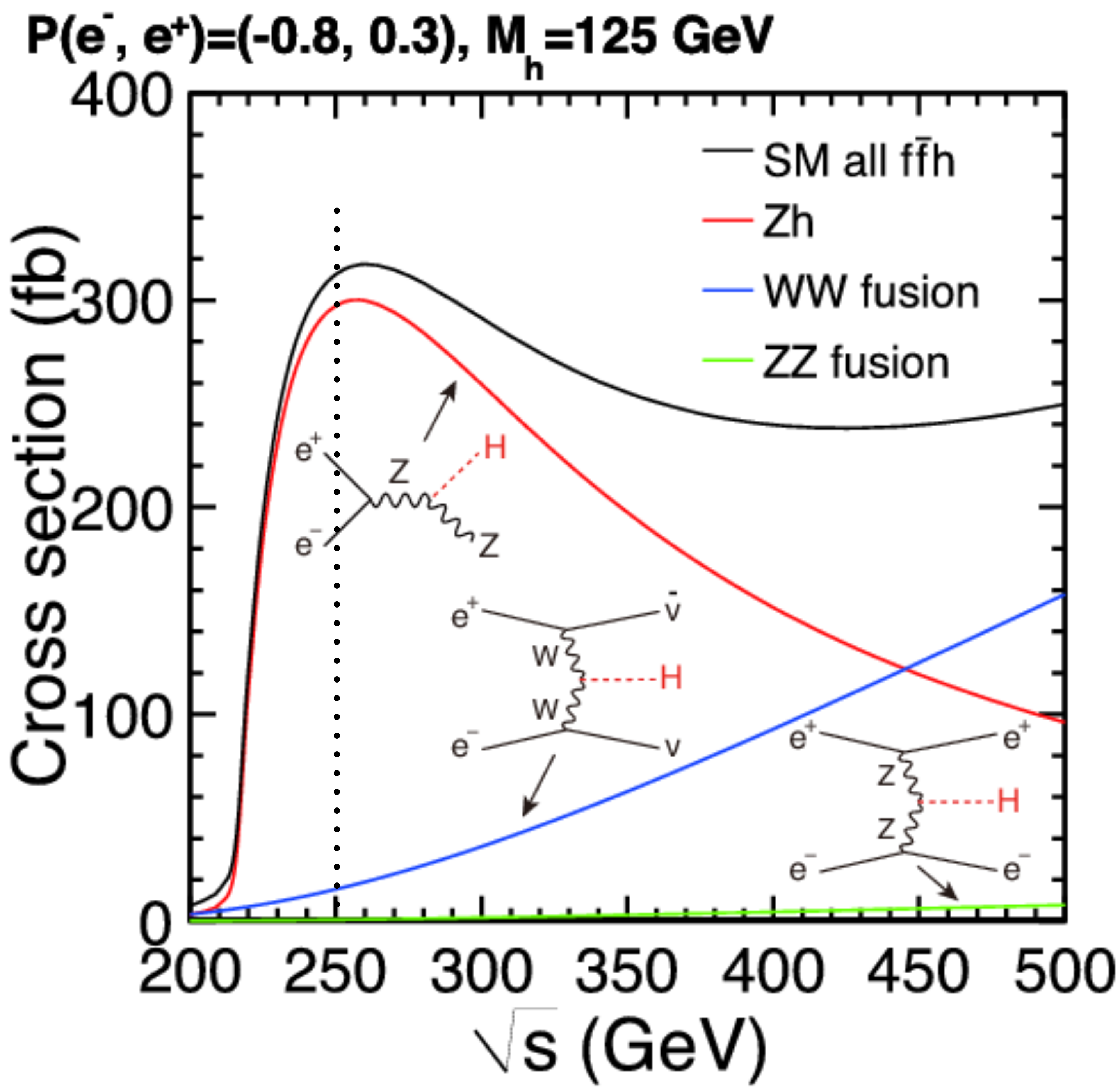


question 2: can we assume σ(e+e- ->Zh) ∝ Γ(h->ZZ*)?



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

question 3: can we determine hWW precisely at $\sqrt{s}$ = 250 GeV?



some quick answers

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

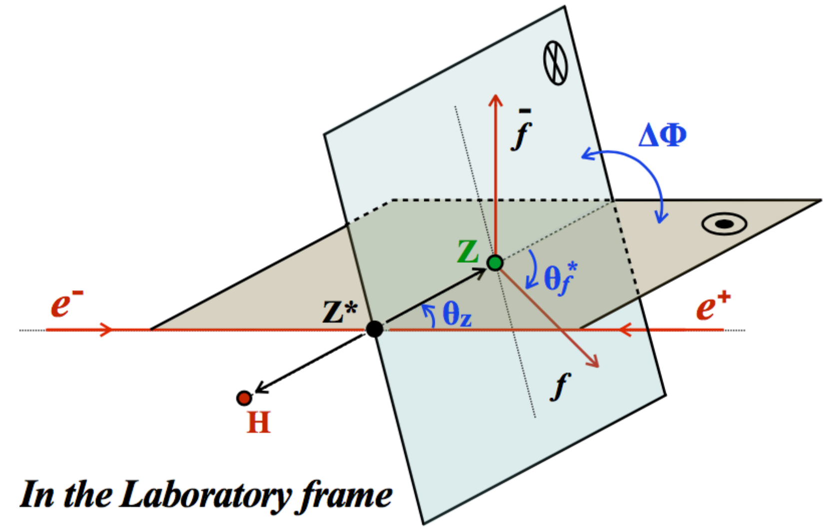
$$L_{hZZ} = M_Z^2(\frac{1}{v} + \frac{a}{\Lambda})hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}$$

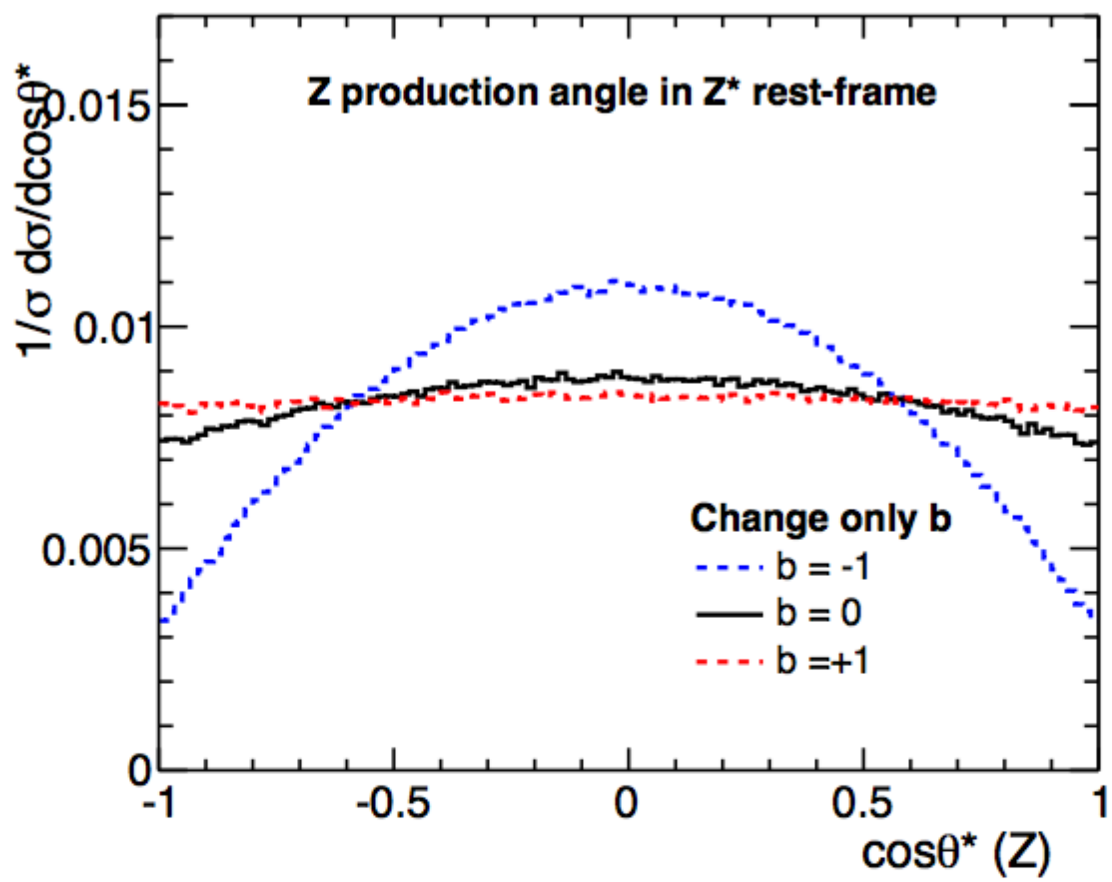
(SM-like) (CP-even) (CP-odd)

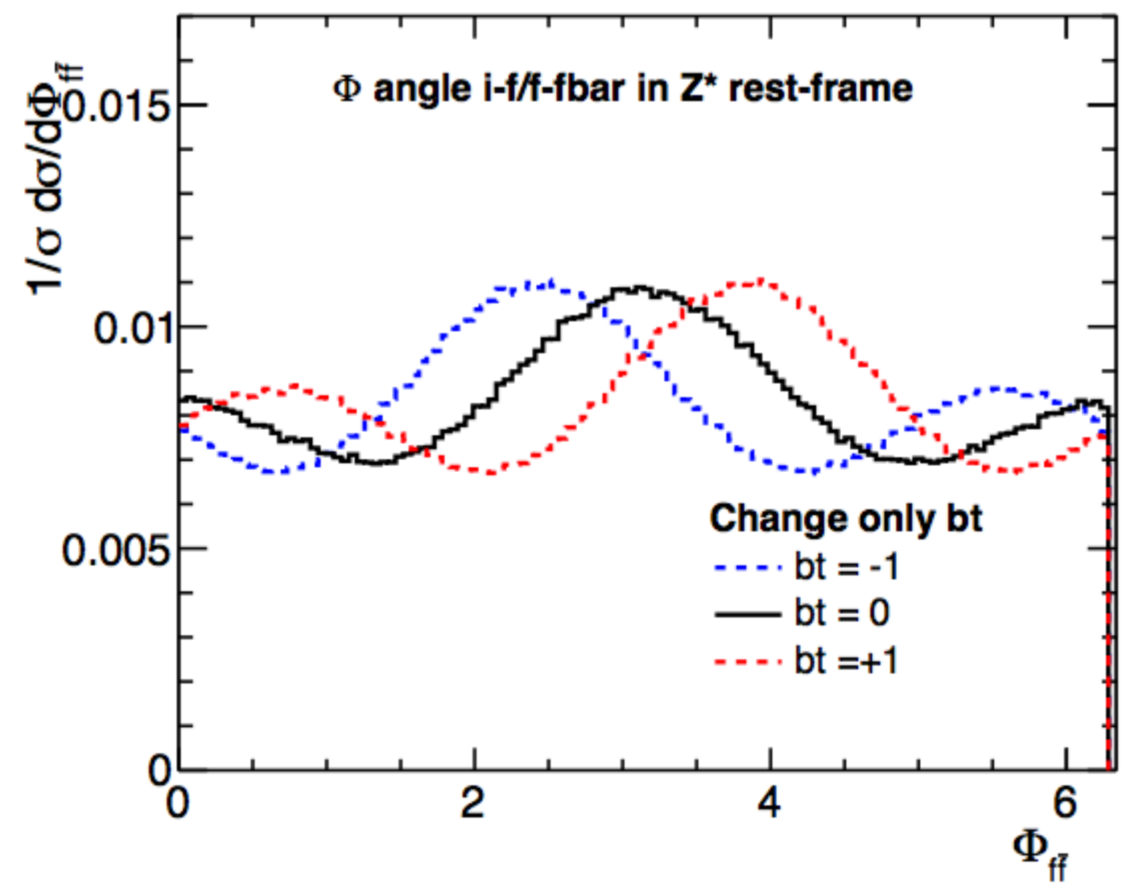
Ogawa, Fujii, Tian, EPS-HEP 2017

- 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

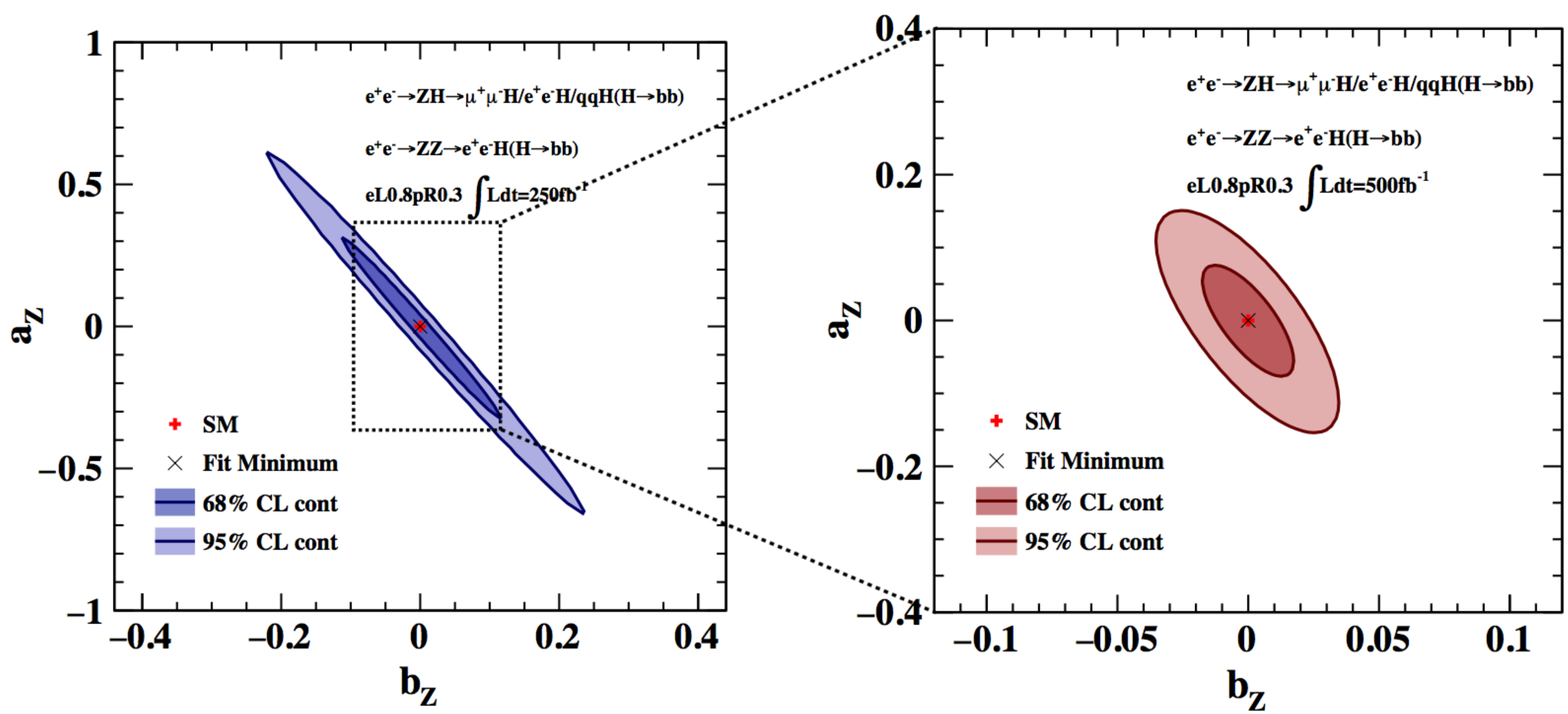
determine tensor structure of hVV couplings (full simulation)

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

$\Lambda = 1$ TeV

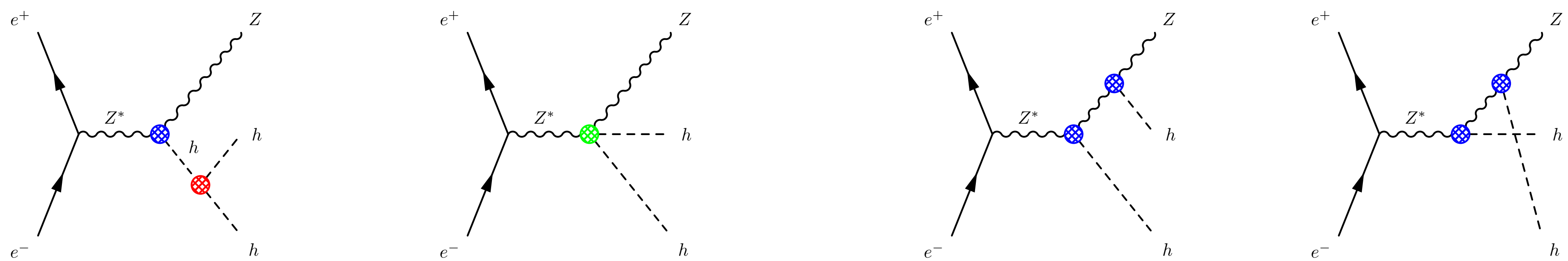
√s=250GeV and ∫Ldt=250fb-1

√s=500GeV and ∫Ldt=500fb-1



for 2 ab-1 @ 250 GeV —> κ_Z ~ 3%

hhVV, hVV and λ_{hhh} in e+e- —> Zhh



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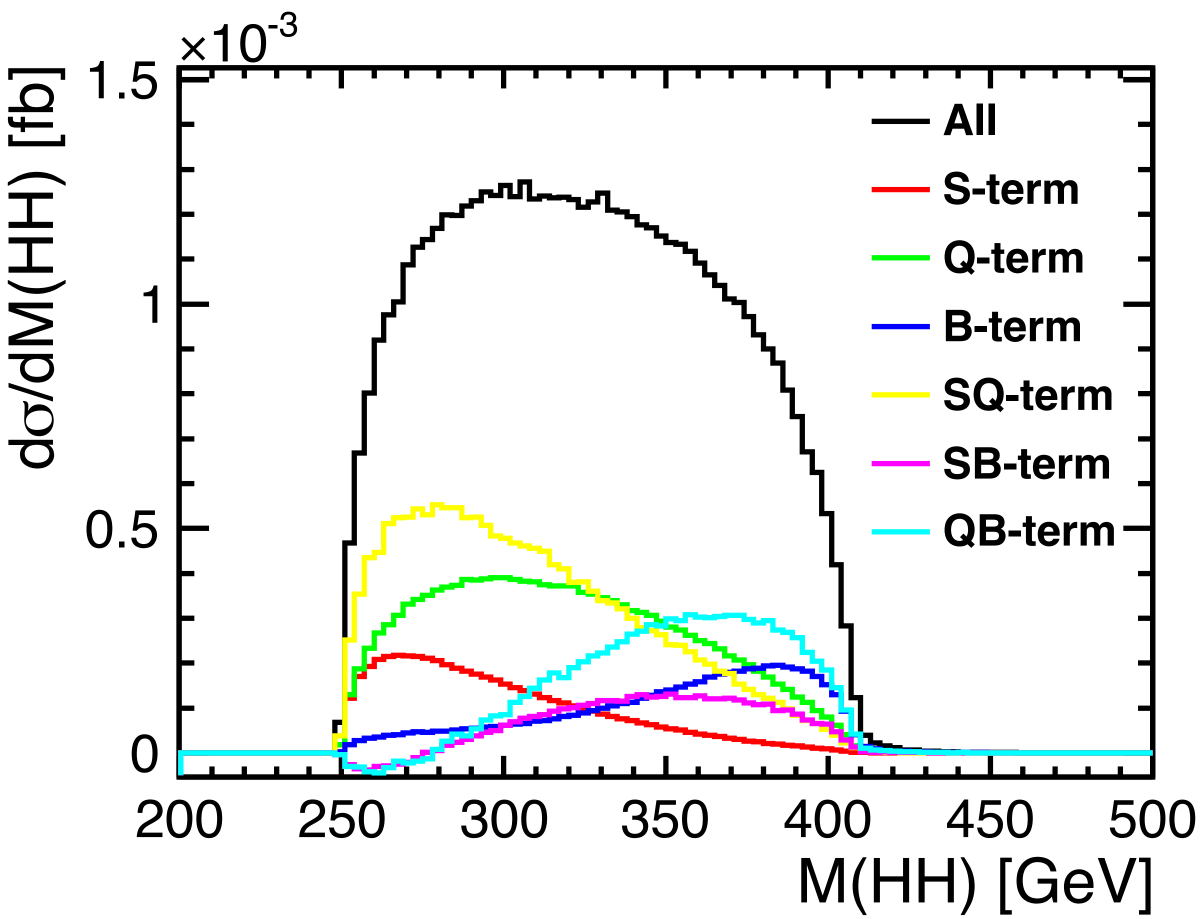

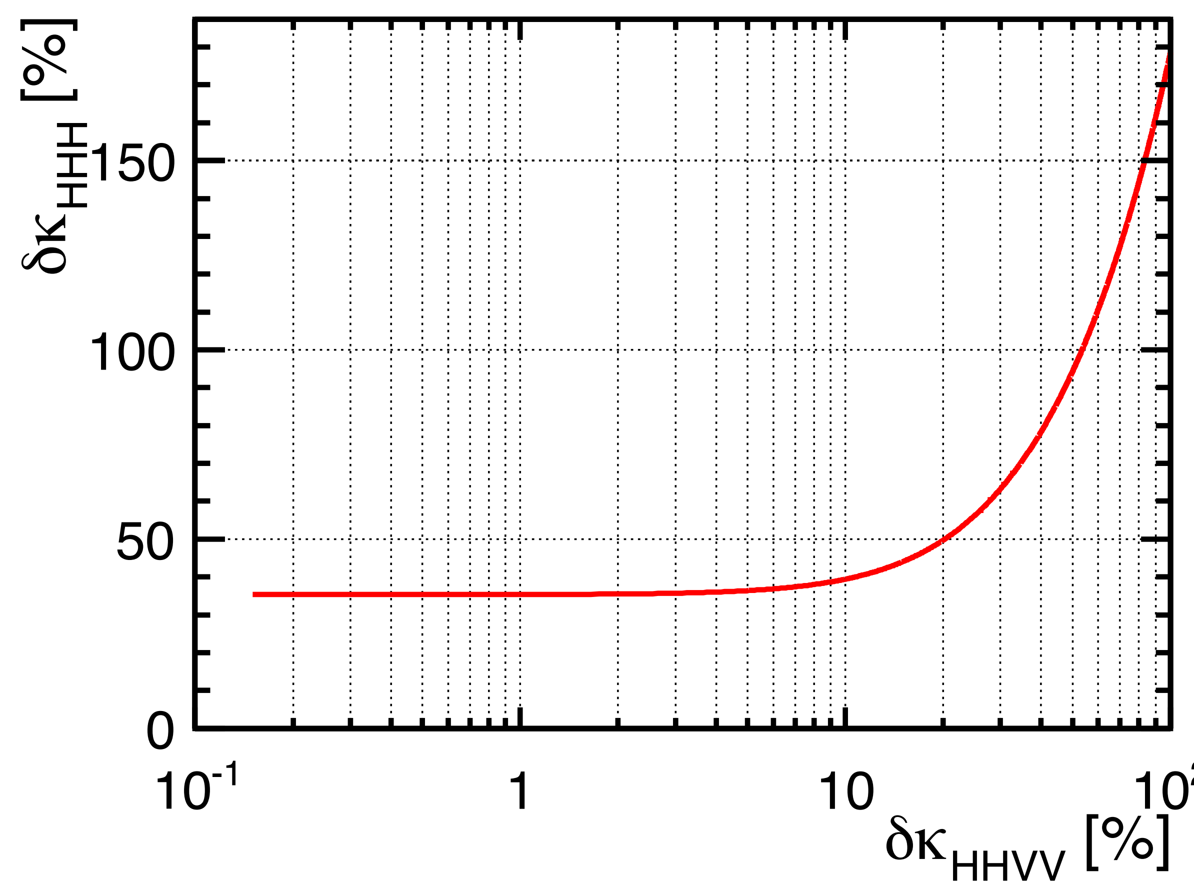

$\delta\kappa_{hhVV}$ < 5% would be needed

long answer: SM Effective Field Theory

Model-Independent Determination of the Triple Higgs Coupling at e^+e^- Colliders

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Improved Formalism for Precision Higgs Coupling Fits

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“The leptonic future of the Higgs”, Durieux, et al, 1704.02333

SM Effective Field Theory

("Warsaw" basis)

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

10 operators (h,W,Z,γ): c_H, c_T, c_6, c_{WW}, c_{WB}, c_{BB}, c_{3W}, c_{HL}, c'_{HL}, c_{HE}

+ 4 SM parameters: g, g', v, λ

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

+ 2 parameters for h->invisible and exotic

EFT input: EWPOs (7)

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

$$4\pi\alpha(m_Z) = g_0^2 s_0^2\Big(1 + 2s_0^2\delta g + 2c_0^2\delta g' + s_0^2(8c_{WW}) - 2s_0^2(8c_{WB}) + s_0^2(8c_{BB})\Big)$$

$$\frac{G_F}{\sqrt{2}} = \frac{1}{2v_0^2}\Big(1 - 2\delta v + 2c'_{HL}\Big)$$

$$m_W = \frac{g_0 v_0}{2}\Big(1 + \delta g + \delta v + \frac{1}{2}(8c_{WW})\Big)$$

$$m_Z = \frac{(g_0^2 + g_0'^2)^{1/2} v_0}{2}\Big(1 + c_0^2\delta g + s_0^2\delta g' + \delta v - \frac{1}{2}c_T + \frac{1}{2}c_0^2(8c_{WW}) + s_0^2(8c_{WB}) + \frac{1}{2}(s_0^4/c_0^2)(8c_{BB})\Big)$$

$$m_h = \sqrt{2\lambda_0}\, v_0\Big(1 + \delta v + \frac{1}{2}\delta\lambda - \frac{1}{2}c_H + \frac{3}{4}c_6\Big)$$

$$A_\ell = \frac{(1-4s_0^2)}{(1-4s_0^2+8s_0^4)} + \frac{32c_0^2 s_0^4(1-2s_0^2)}{D^2}\delta g - \frac{32c_0^2 s_0^4(1-2s_0^2)}{D^2}\delta g' + \frac{16s_0^4(1-2s_0^2)}{D^2}(c_{HL} + c'_{HL}) + \frac{8s_0^2(1-2s_0^2)^2}{D^2}c_{HE} + \frac{16c_0^2 s_0^4(1-2s_0^2)}{D^2}(8c_{WW}) - \frac{16s_0^4(1-2s_0^2)^2}{D^2}(8c_{WB}) - \frac{16s_0^6(1-2s_0^2)}{D^2}(8c_{BB})$$

$$\Gamma_\ell = \Gamma_{\ell 0}\Big(1 + \frac{2c_0^2(1-8s_0^2)}{D}\delta g - \frac{2s_0^2(3-16s_0^2+8s_0^4)}{D}\delta g' + \frac{2(1-2s_0^2)}{D}(c_{HL} + c'_{HL}) - \frac{4s_0^2}{D}c_{HE} + \frac{c_0^2(1-8s_0^2)}{D}(8c_{WW}) - \frac{2s_0^2(1-8s_0^2+8s_0^4)}{D}(8c_{WB}) - \frac{s_0^4(3-16s_0^2+8s_0^4)}{c_0^2 D}(8c_{BB})\Big)$$

EFT input: TGC (3)

$$g_{1Z} = 1 + (1 + s_0^2)\delta g - s_0^2 \delta g' + \frac{1}{2}(1 + s_0^2)(8c_{WW}) + \frac{s_0^4}{c_0^2}(8c_{WB}) - \frac{1}{2}\frac{s_0^4}{c_0^2}(8c_{BB})$$

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

$$\lambda_A = -6g_0^2 c_{3W}$$

2000 fb-1 @ 250 GeV, simultaneous fit

$\Delta g_{1Z} = 3.8 \times 10^{-4}$	$\rho(g_{1Z}, \kappa_\gamma) = 70.1\%$
$\Delta \kappa_\gamma = 4.5 \times 10^{-4}$	$\rho(g_{1Z}, \lambda_\gamma) = 41.0\%$
$\Delta \lambda_\gamma = 3.8 \times 10^{-4}$	$\rho(\kappa_\gamma, \lambda_\gamma) = 38.5\%$

Barklow, Karl, List,
preliminary results, extrapolated from 500 GeV (1TeV) full simulation studies;

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

(2: HL-LHC)

$$\Gamma(h \to \gamma\gamma) = \Gamma(h \to \gamma\gamma)_0 \cdot \Big(1 + (1 + 2s_w^2)\delta g + 2c_w^2 \delta g' - \delta v - c_H$$
$$+526.1\ s_w^2((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})]\Big)$$

$$\Gamma(h \to Z\gamma) = \Gamma(h \to Z\gamma)_0 \cdot \Big(1 + [0 \text{ for the moment}] - \delta v - c_H$$
$$+289.7\ s_w c_w((8c_{WW}) - (1 - \frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})]\Big)$$

$$\Gamma(h \to ZZ^*) = \Gamma(h \to ZZ^*)_0 \cdot (1 - \delta v - c_H - (0.50)[c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + \frac{s_w^4}{c_w^2}(8c_{BB})]\Big)$$

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

$$\Delta\mathcal{L}_{Zhh} = -\eta_h\lambda_0 v_0 h^3 + \eta_Z\frac{m_Z^2}{v_0}Z_\mu Z^\mu h + \frac{1}{2}\eta_{2Z}\frac{m_Z^2}{v_0^2}Z_\mu Z^\mu h^2$$
$$+\frac{\theta_h}{v_0}h\partial_\mu h\partial^\mu h + \frac{\zeta_Z}{2v_0}Z_{\mu\nu}Z^{\mu\nu}h + \frac{\zeta_{2Z}}{4v_0^2}Z_{\mu\nu}Z^{\mu\nu}h^2$$
$$+\frac{\zeta_{AZ}}{v_0}A_{\mu\nu}Z^{\mu\nu}h + \frac{\zeta_{2AZ}}{2v_0^2}A_{\mu\nu}Z^{\mu\nu}h^2$$
$$+g_{LZh}(\bar{e}_L\gamma_\mu e_L)Z^\mu(\frac{h}{v_0}+\frac{1}{2}\frac{h^2}{v_0^2}) + g_{RZh}(\bar{e}_R\gamma_\mu e_R)Z^\mu(\frac{h}{v_0}+\frac{1}{2}\frac{h^2}{v_0^2})$$

$$\eta_h = (1 - c'_{HL} - \frac{1}{2}c_H + c_6)$$
$$\theta_h = c_H$$

$$g_{LZh} = -\frac{e_0}{c_0 s_0}(c_{HL} + c'_{HL})$$
$$g_{RZh} = -\frac{e_0}{c_0 s_0}(c_{HE})$$

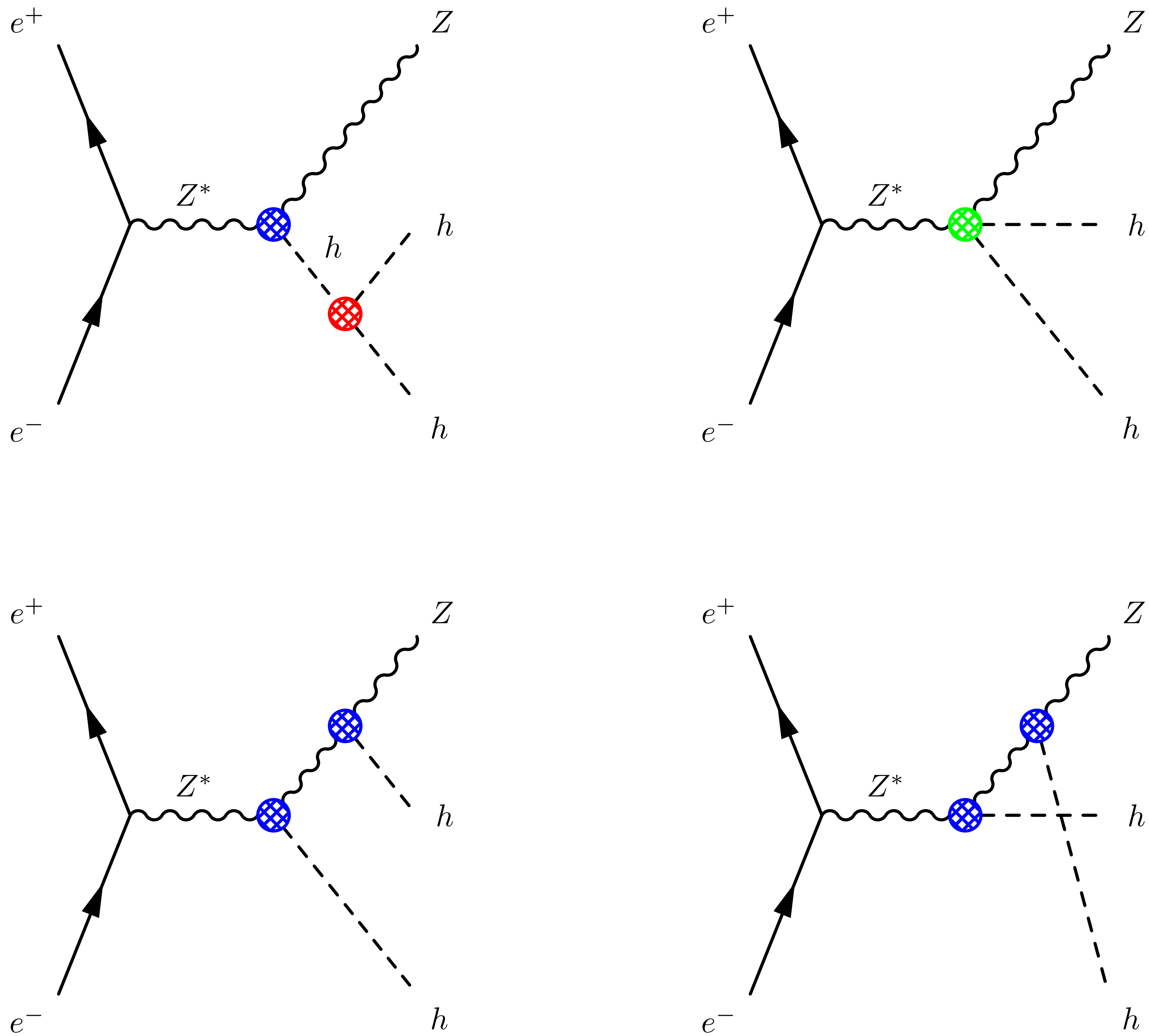
$$\eta_Z = (1 - c_T - \frac{1}{2}c_H - c'_{HL})$$
$$\eta_{2Z} = (1 - 5c_T - c_H - 2c'_{HL})$$
$$\eta_W = (1 - \frac{1}{2}c_H - c'_{HL})$$
$$\eta_{2W} = (1 - c_H - c'_{HL})\ .$$

$$\zeta_W = \zeta_{2W} = 8(c_{WW})$$
$$\zeta_Z = \zeta_{2Z} = 8(c_0^2 c_{WW} + 2s_0^2 c_{WB} + \frac{s_0^4}{c_0^2}c_{BB})$$
$$\zeta_{AZ} = \zeta_{2AZ} = 8(s_0 c_0 c_{WW} - s_0 c_0(1 - \frac{s_0^2}{c_0^2})c_{WB} - \frac{s_0^3}{c_0}c_{BB})$$
$$\zeta_A = \zeta_{2A} = 8s_0^2(c_{WW} - 2c_{WB} + c_{BB})\ .$$

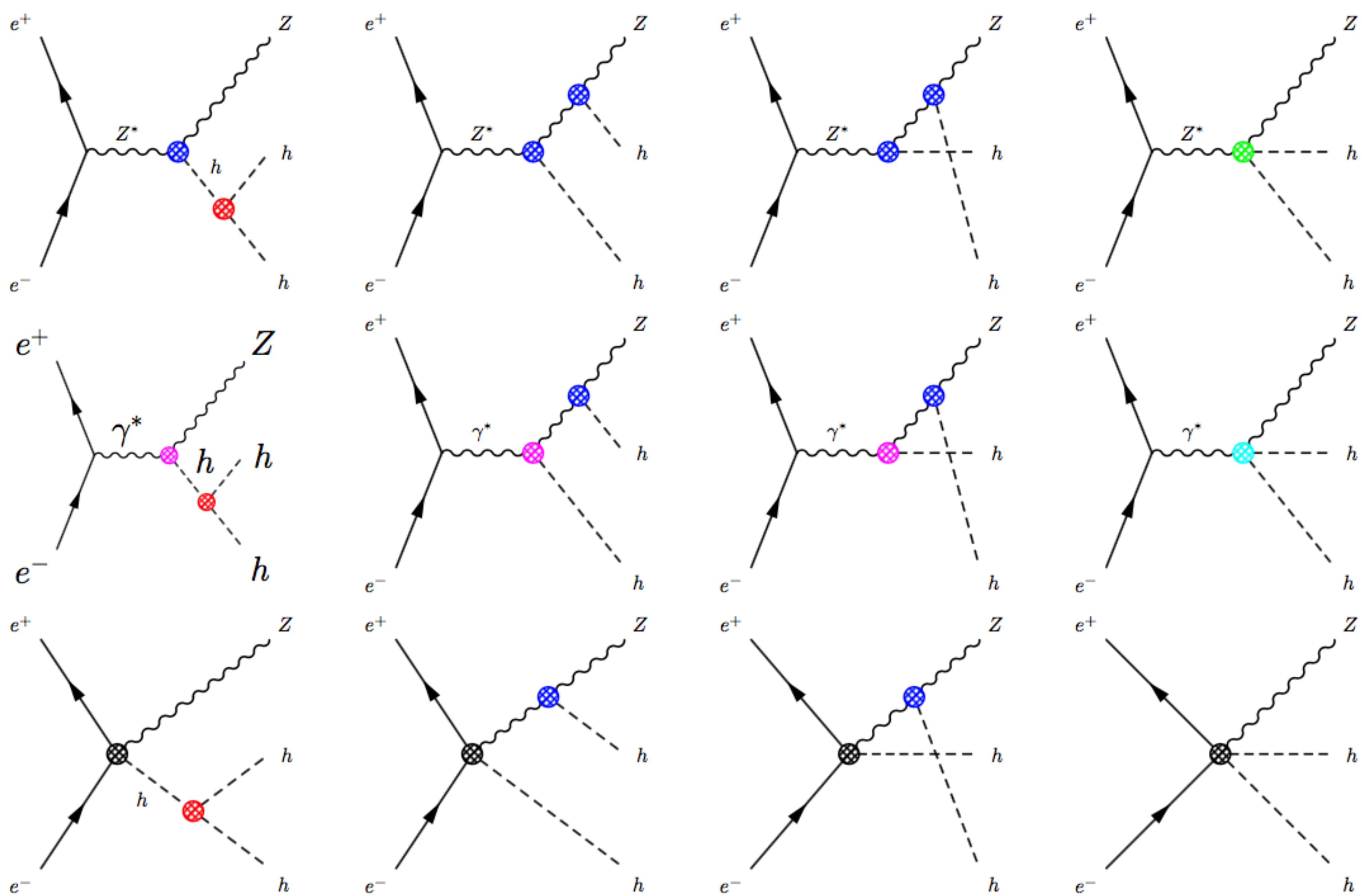
EFT input: $\sigma(e+e- \longrightarrow Zh)$, $\sigma(e+e- \longrightarrow Zhh)$

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

- c_6 has to be determined by double Higgs measurement question 1: how can we determine λ_{hhh} if there are anomalous hhVV, hVV, hhh couplings?

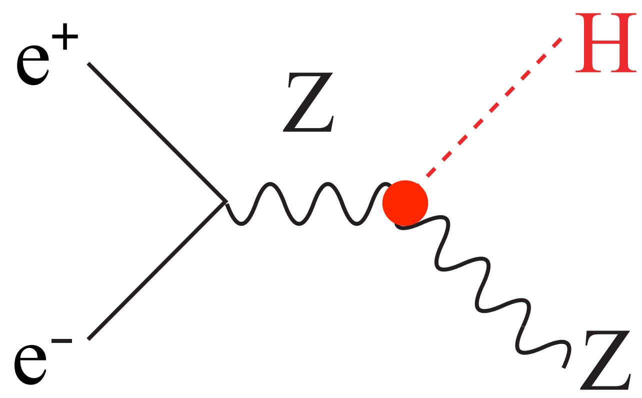


answer to Q1: determine λ_{hhh} in EFT

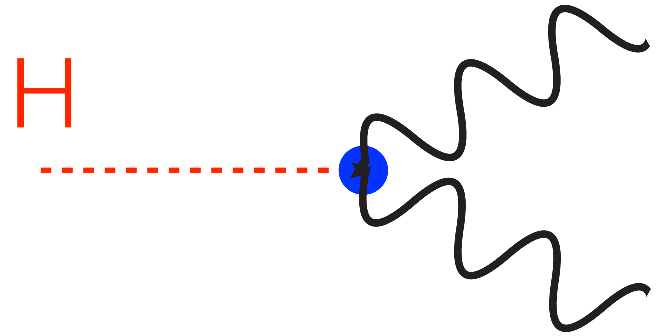


$$\frac{\sigma_{Zhh}}{\sigma_{SM}} - 1 = 0.565 c_6 - 3.58 c_H + 16.0(8c_{WW}) + 8.40(8c_{WB}) + 1.26(8c_{BB})$$
$$-6.48 c_T - 65.1 c'_{HL} + 61.1 c_{HL} + 52.6 c_{HE},$$

question 2: can we assume $\sigma(e^+e^- \to Zh) \propto \Gamma(h \to ZZ^*)$?



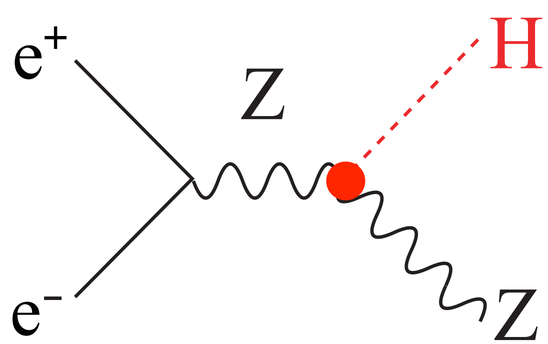
$$\propto ?\ \kappa_Z^2$$

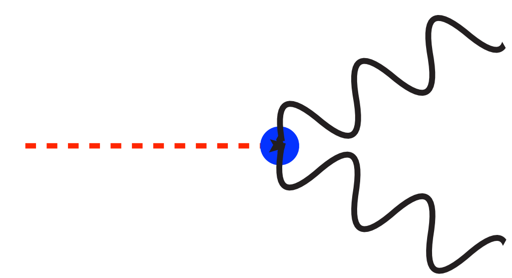


answer to Q2:

- $\sigma(e+e- \to Zh) \propto \kappa^2(hZZ) \propto \Gamma(h \to ZZ^*)$ not any more: EFT is more general than kappa-framework

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





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

$$\neq$$

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

answer to Q3: hWW coupling can be as precise as hZZ @ $\sqrt{s}$ = 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

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

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

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

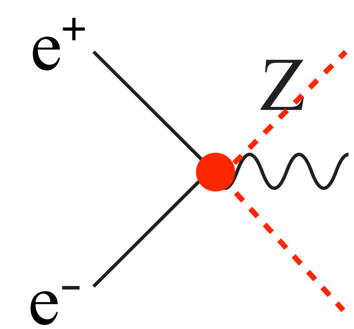
ILC H20: $\int L dt$ = 2 ab^{-1} @ 250 GeV

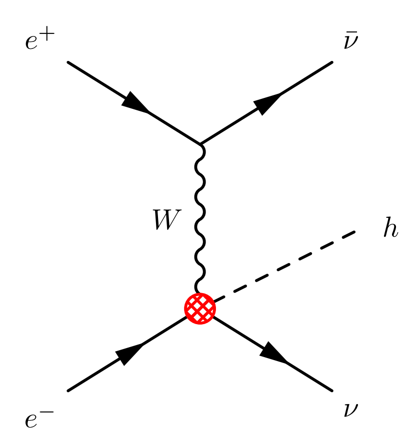
coupling $\Delta g/g$	kappa-fit	EFT-fit
hZZ	0.38%	0.63%
hWW	1.9%	0.63%
hbb	2.0%	0.89%
Γ_h	4.2%	2.1%

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

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 ALR (AFB)
  - improve Γ(Z->ee)
  - improve Γ(W->eν)





Higgs is a window to new physics

coupling deviation patter in BSM benchmark 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.

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

model discrimination by EFT

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

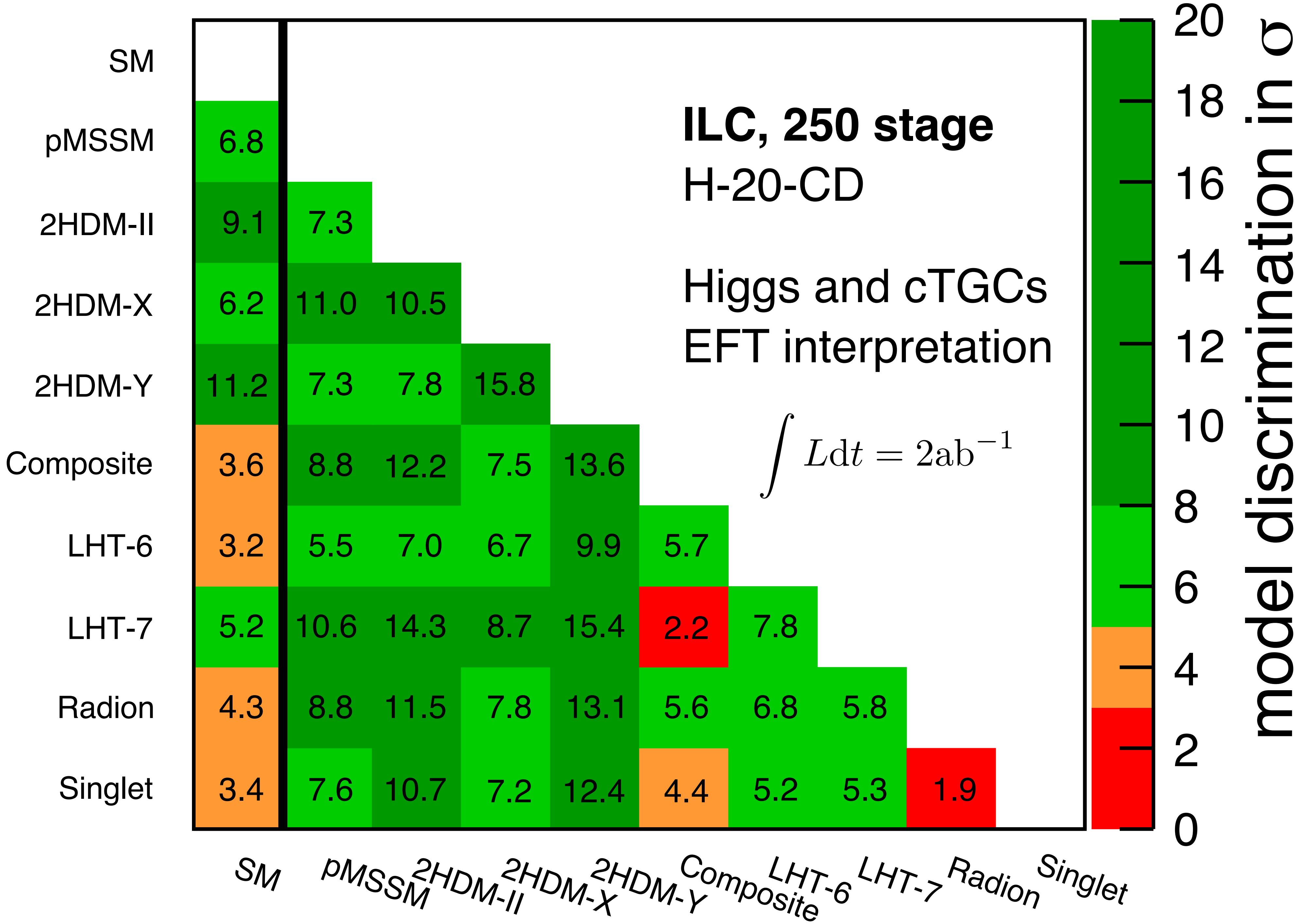
g_A, g_B: vector of couplings in Model A, B

Vij: linear dependence of coupling gi on EFT coefficient cj

C: covariance matrix of EFT coeffs

- given the coupling deviations in two models, this χ2 gives the most appropriate separation power, taking into account all correlations

discrimination between BSM models (ILC250 stage)



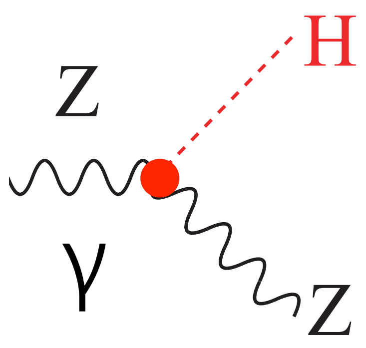
once find deviation against SM —> can tell which BSM

backup

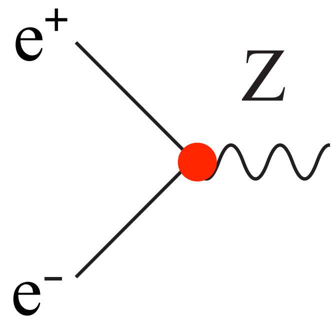
comments on beam polarizations

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

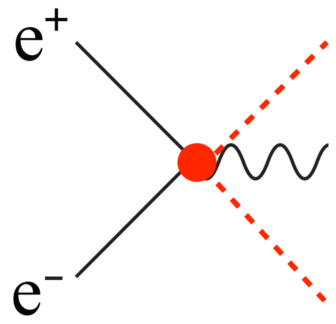
-> separate hZZ and hγZ couplings



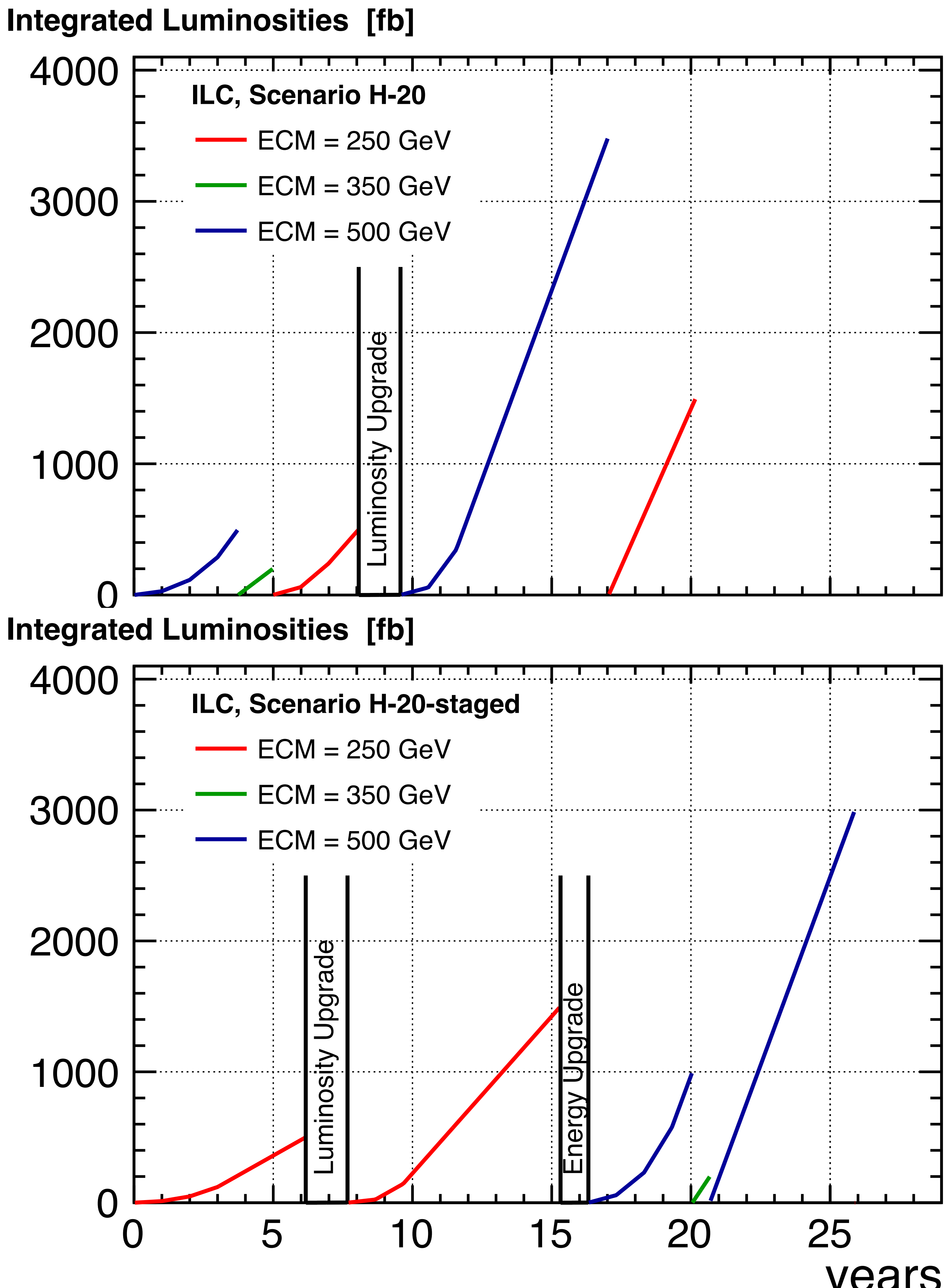
-> improve A_{LR} in Z-e-e coupling



important to constrain contact interaction



scenario:
example

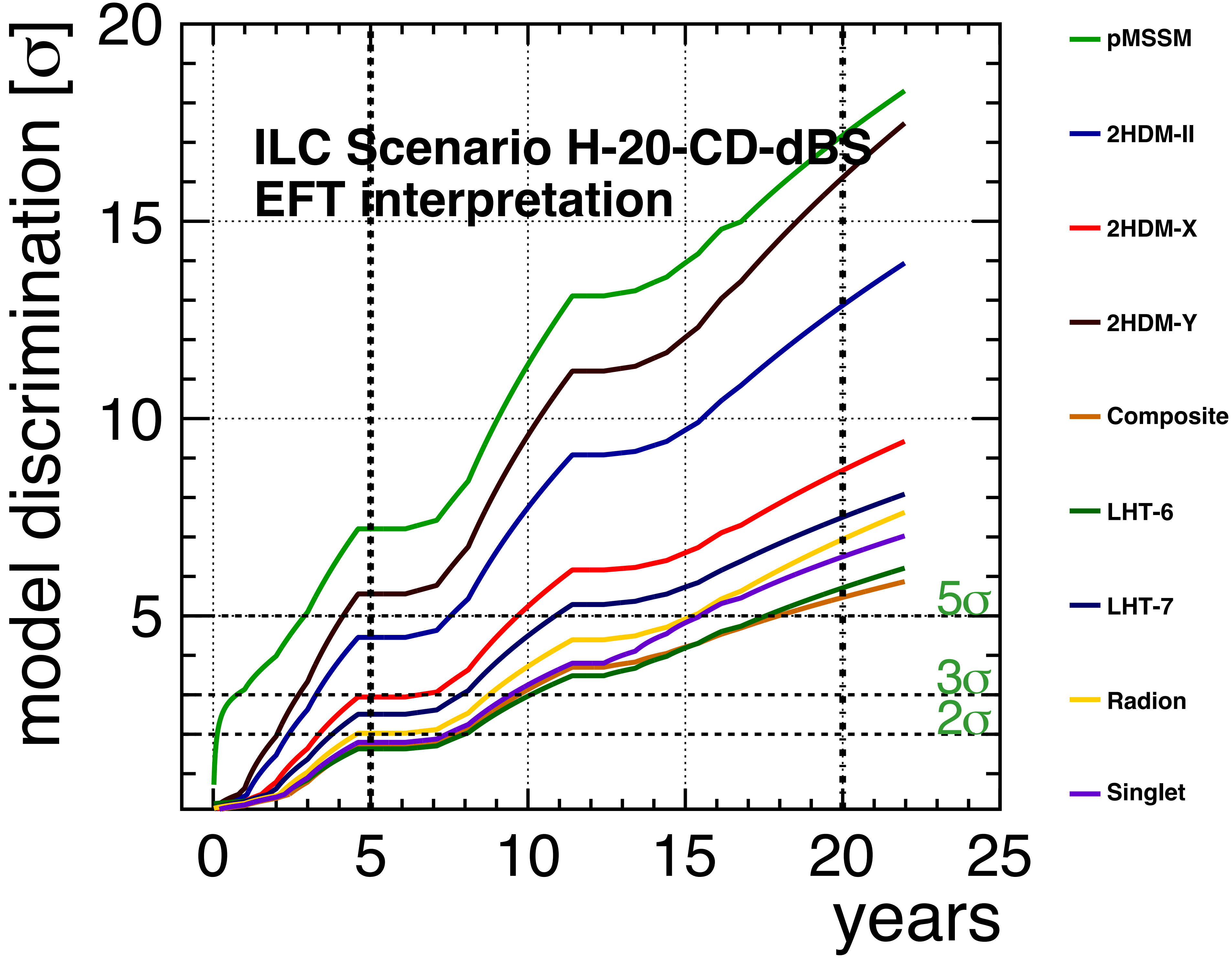


ILC500
H20

ILC250
H20 staged

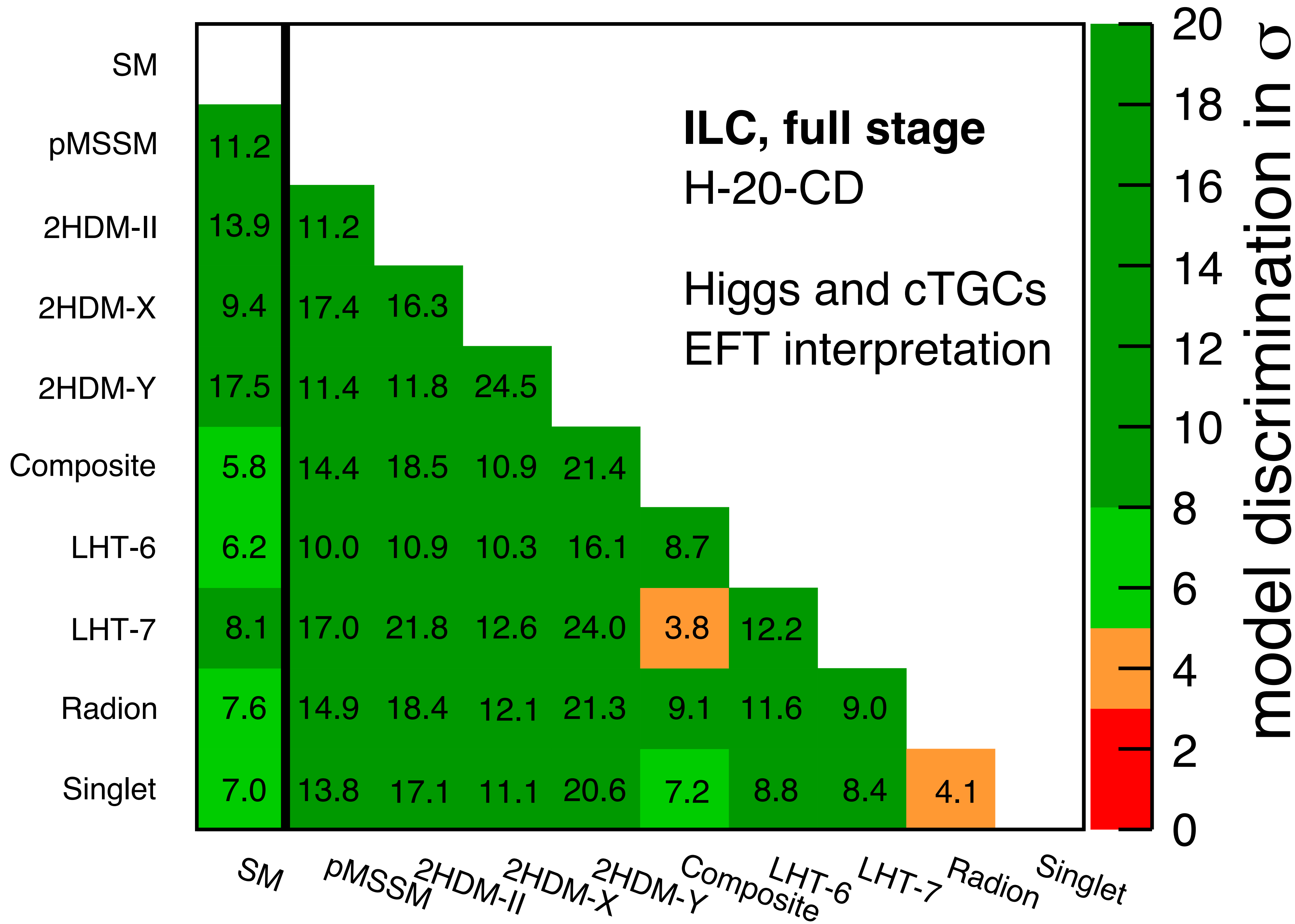
top physics starts
after > 16y
in total ~ 6y longer

evolution of discovery potential (against SM)



after the 250 GeV stage (~11y): >3σ for all models
after ~18y): >5σ for all models

discrimination between BSM models



pin down the story after 250 + 500 full ILC

evolution of coupling precisions: H-20 (-CD/E/F)