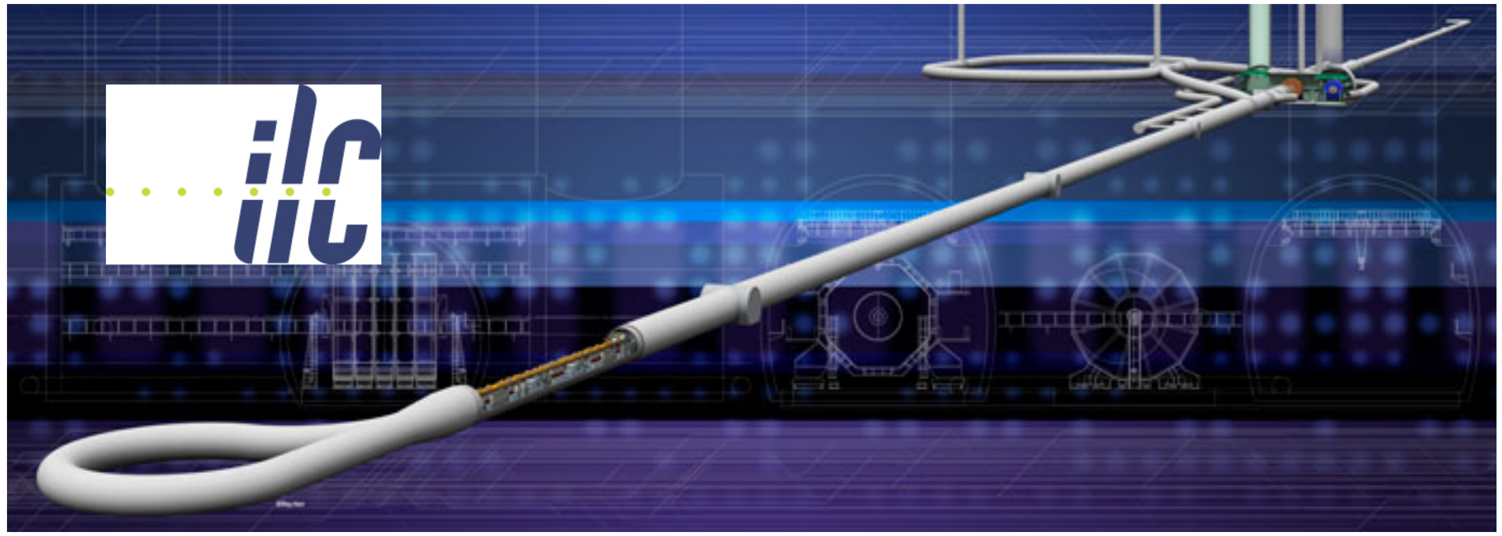
ILC Supporters



Precision Higgs Physics @ ILC

based on work with T.Barklow, M.Peskin, et al, arXiv:1903.01629
1708.09079
1708.08912

Junping Tian (U. of Tokyo)

Seminar @ SLAC, July 25, 2019

ICEPP
The University of Tokyo

outline — Higgs Physics at future e+e-

(i) introduction

(ii) key measurements

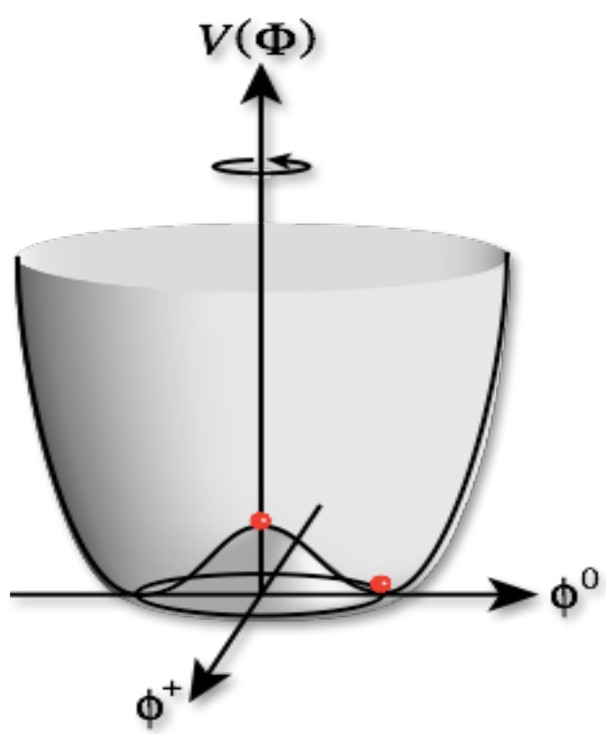
(iii) Higgs coupling determination

(iv) Higgs self-coupling

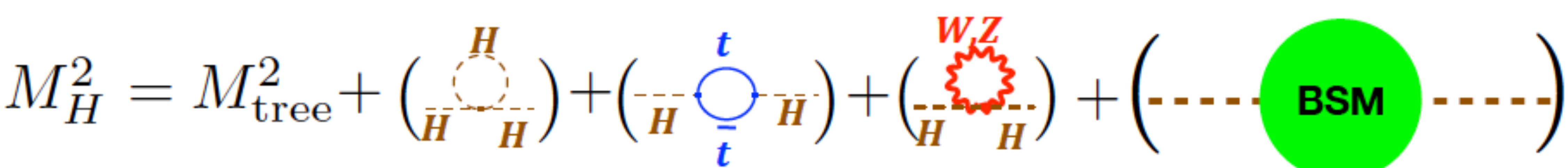
(v) ILC political status

mystery in Electroweak Symmetry Breaking

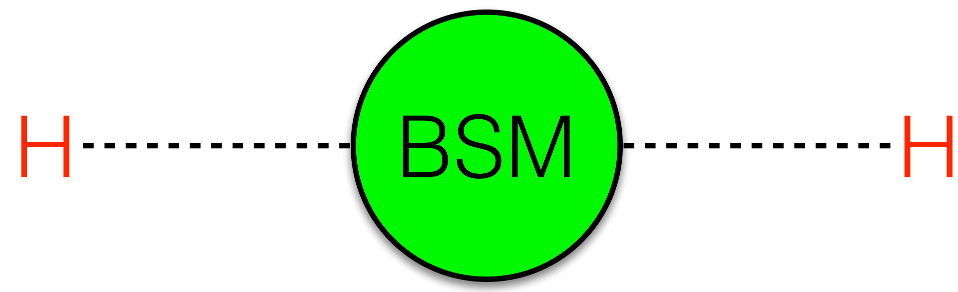
$$V(|\Phi|) = \mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$



- H(125) discovery
  - vacuum is EW charged; superconducting phase
- What is the origin of EWSB?
  - why $\mu^2<0$? BCS theory for Ginzburg-Landau?
- What BSM protects m_H?



golden time: BSM hunting



direct searches

ILC | **LHC**

$\tilde{t}, \tilde{g}, \tilde{\chi}, H^{\pm}, Z', \ldots$

indirect searches

LHC | **ILC, future e+e-**

precision Higgs couplings

☑ it must be there, let's just find it out

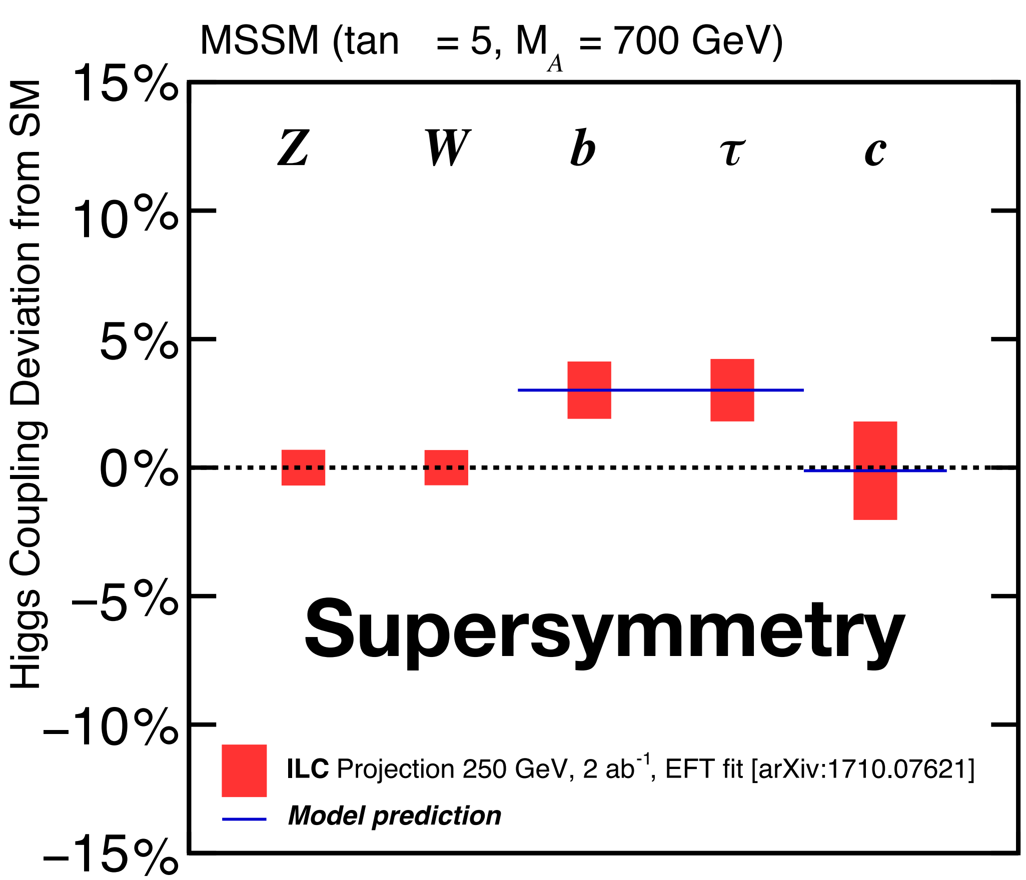
why haven't we seen yet at LHC

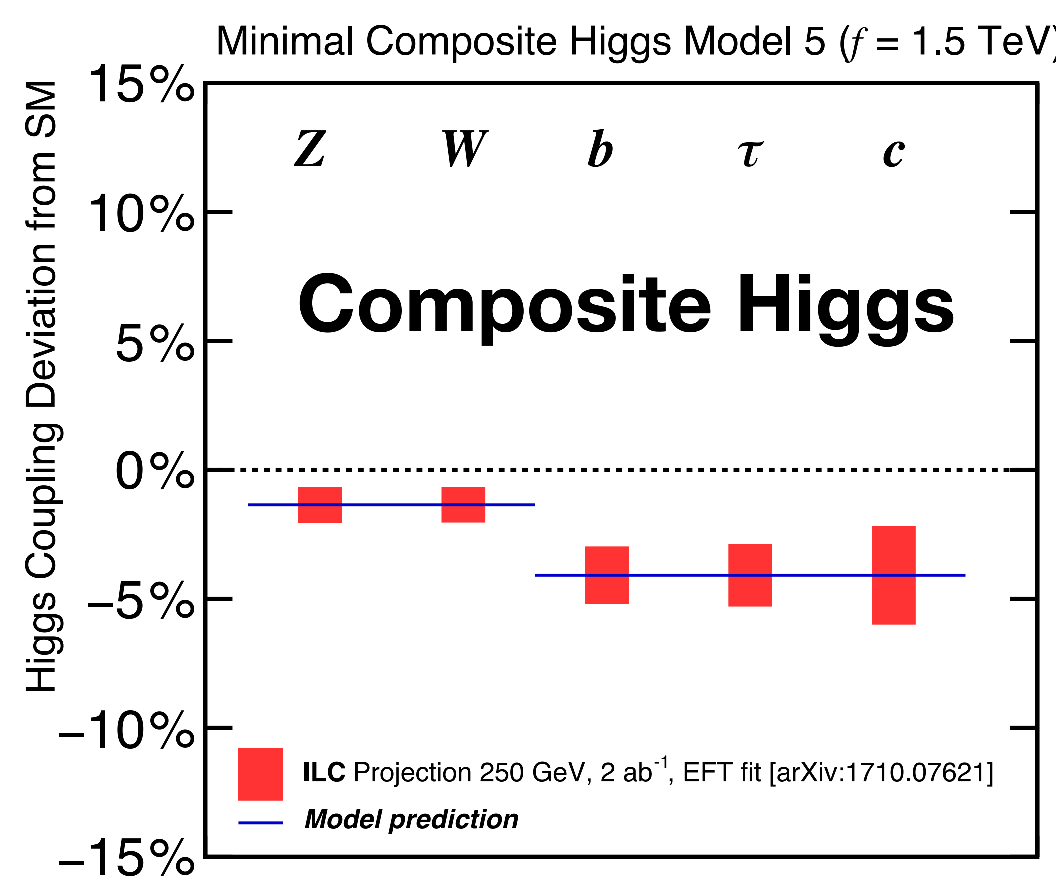
- deviation is small, typically 1-10% for m_{BSM}~1TeV

  —> need measurement with 1% or below

- deviation patterns are like fingerprints of BSM models

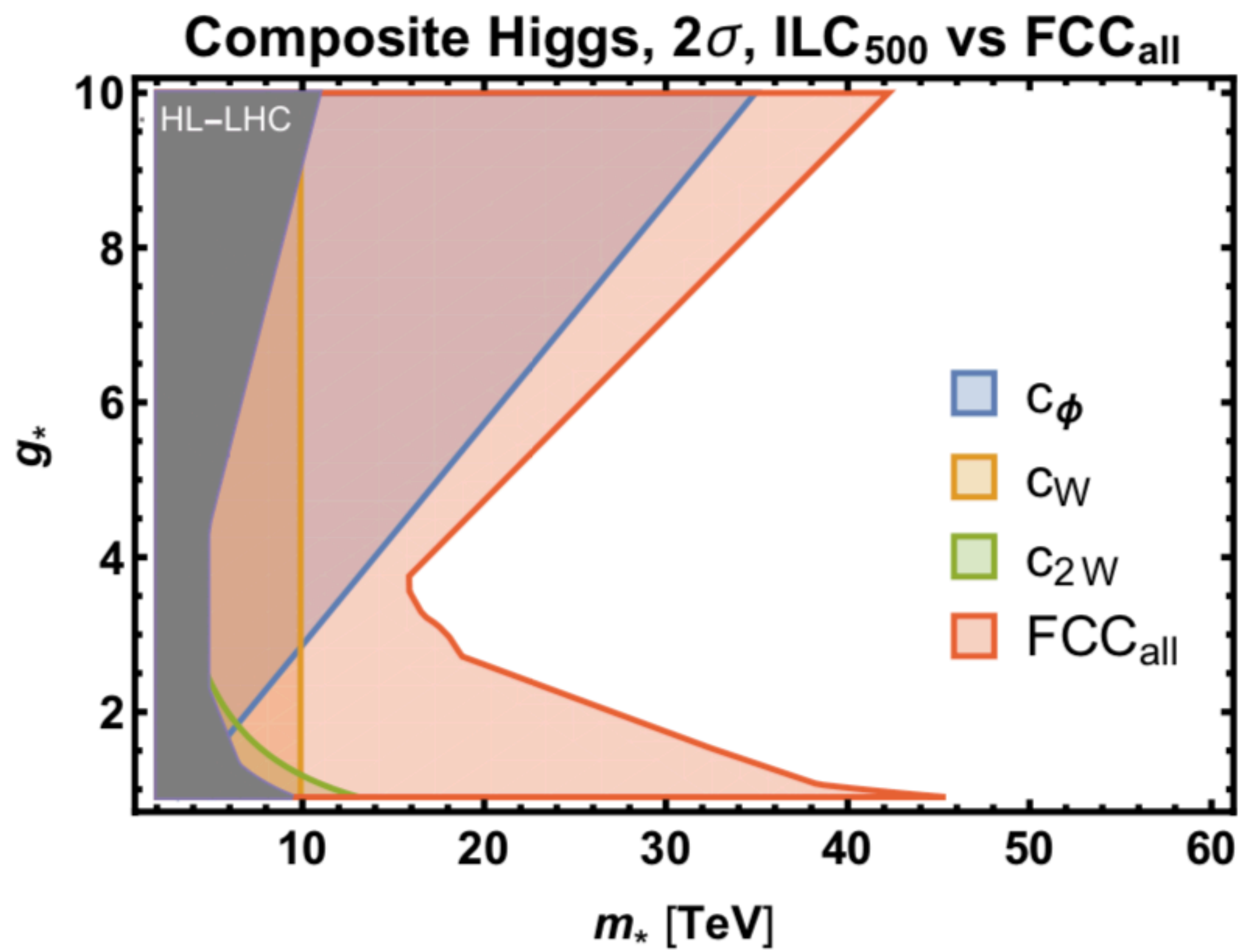
  —> need measure as many couplings as possible





Composite Higgs: direct and indirect search

G.Giudice @ ESU Granada

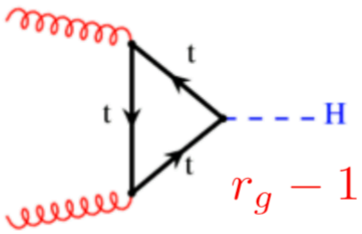


SUSY: direct and indirect search

G.Giudice @ ESU Granada

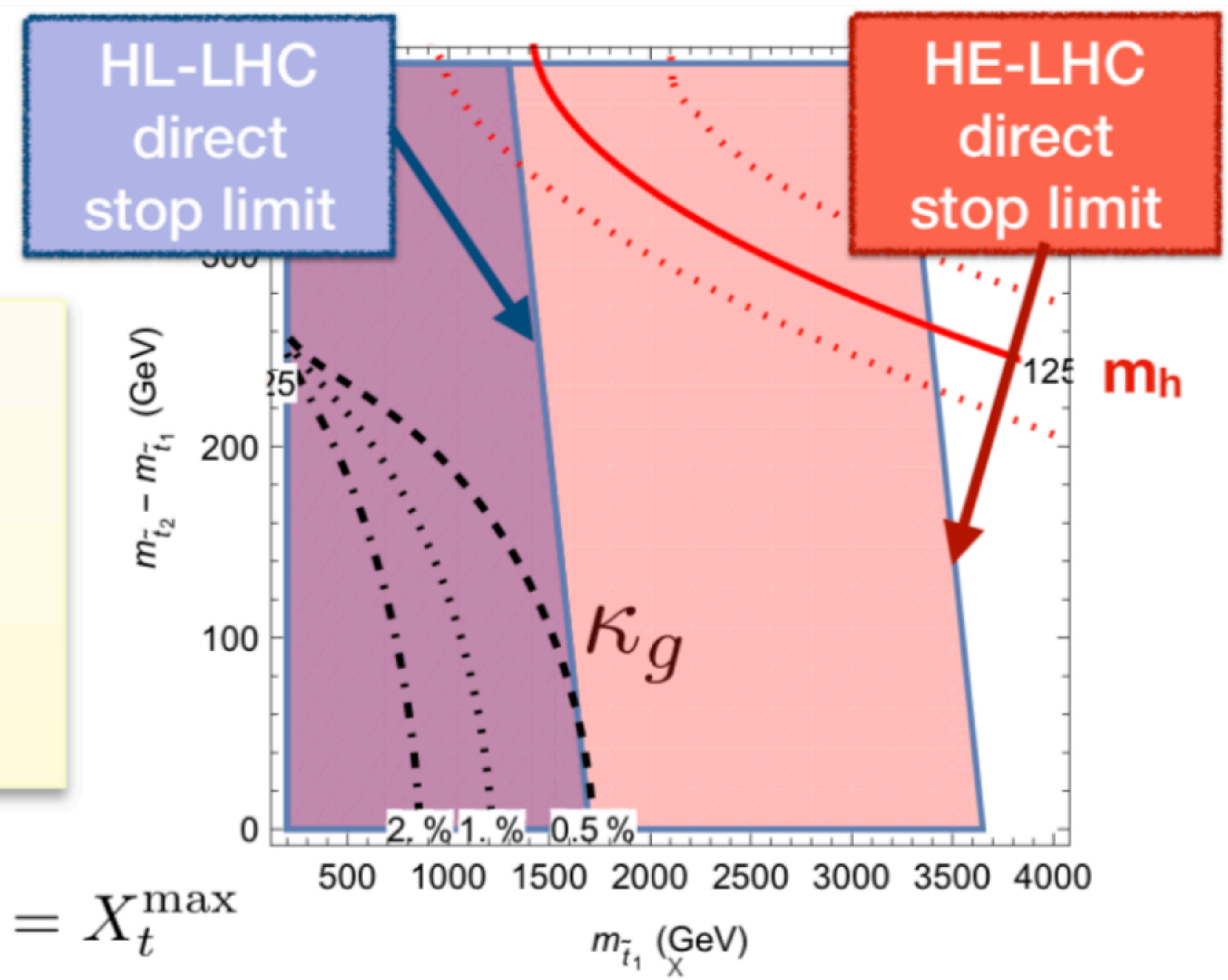
- **What do we learn from indirect information?**

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



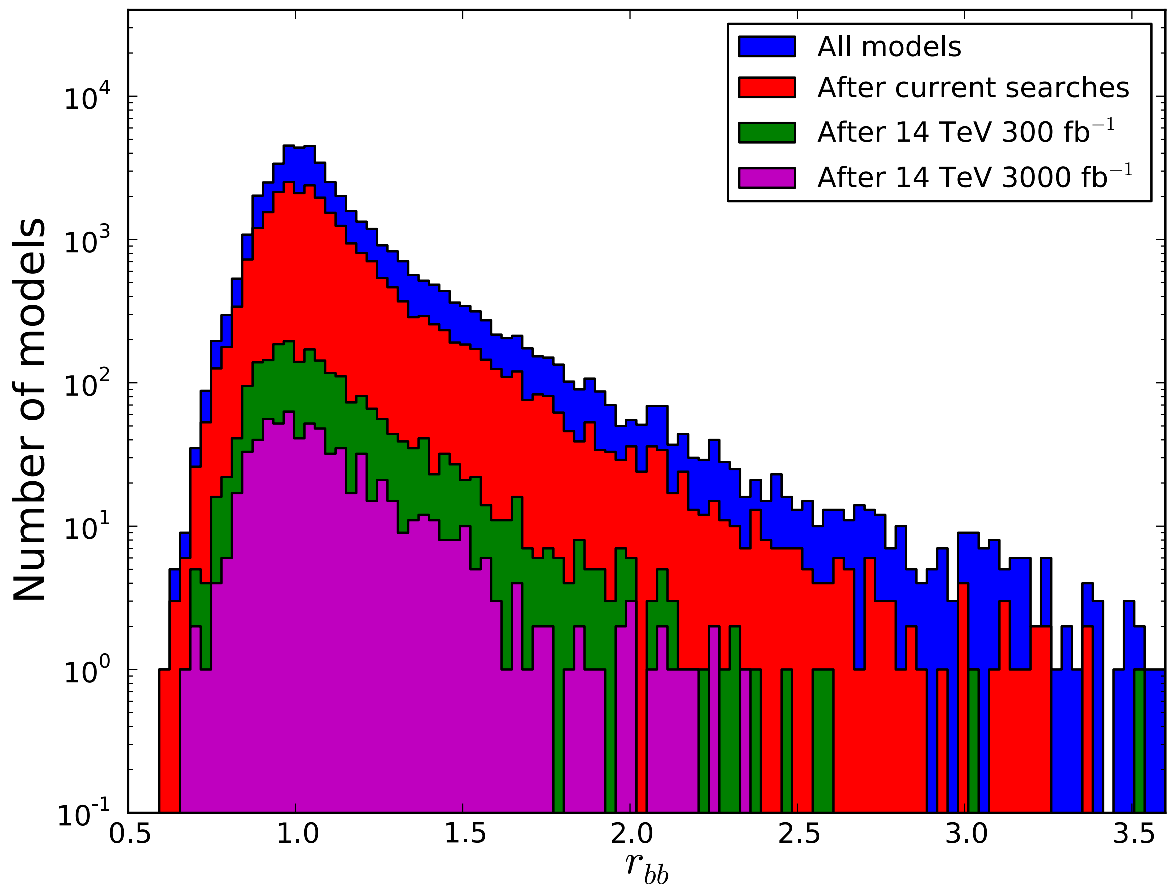
$$r_g - 1 \approx \frac{1}{4}\frac{m_t^2}{m_{\tilde{t}_1}^2} \approx 0.7\% \left(\frac{1\,\mathrm{TeV}}{m_{\tilde{t}_1}^2}\right)^2$$

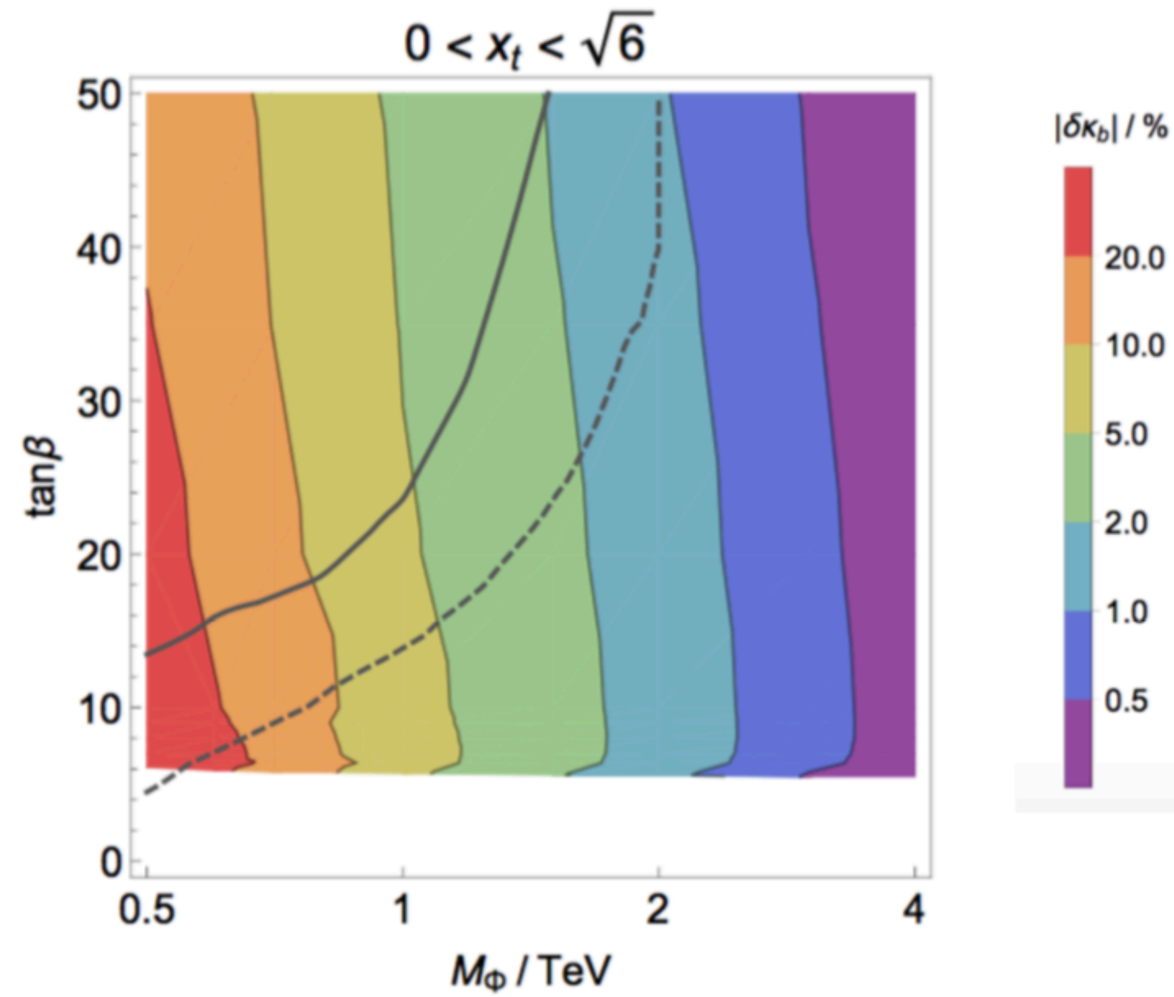
With HL-LHC stop limit: also for X_t=0



$X_t = X_t^{\rm max}$

direct and indirect discoveries: complementarity





Cahill-Rowley, et al, arXiv:1308.0297

Wells, Zhang, arXiv:1711.04774

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

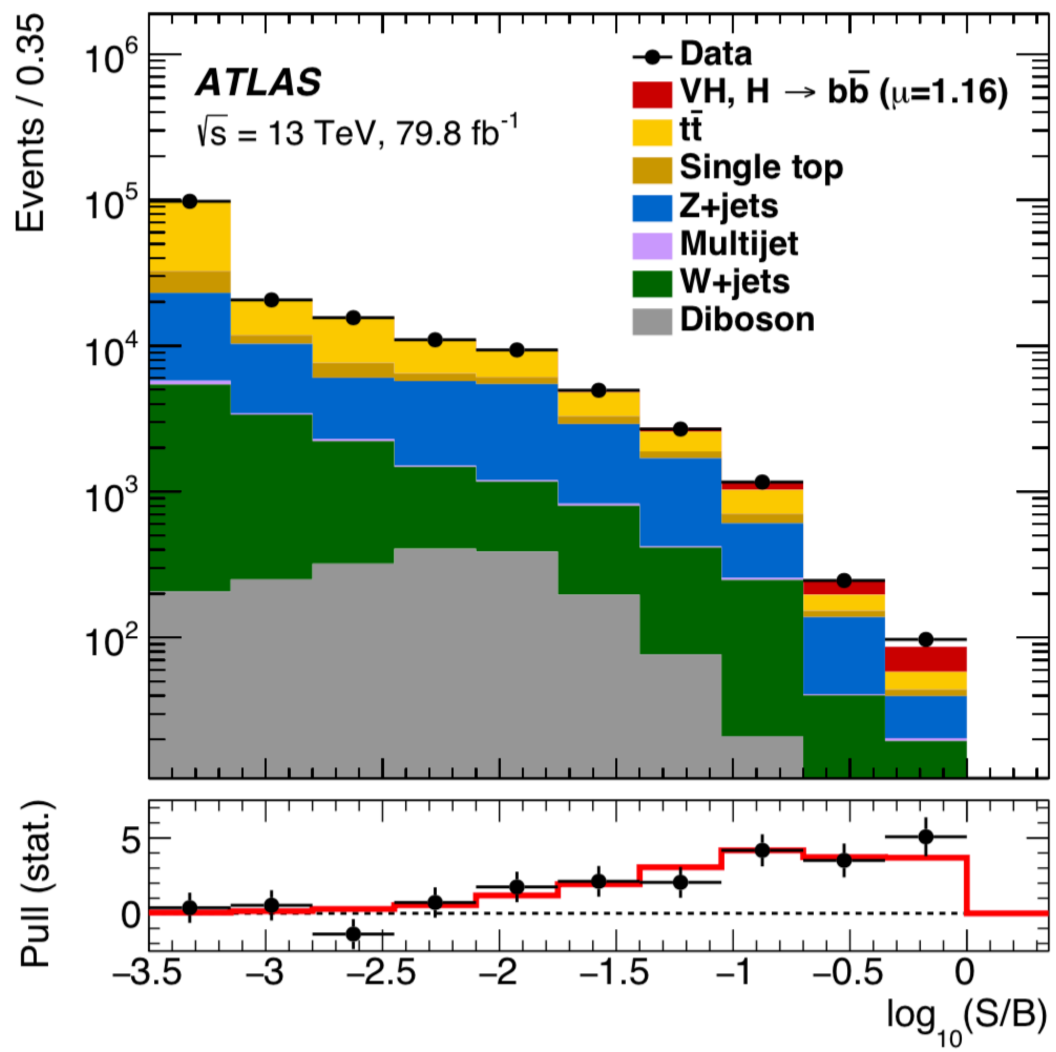
precision Higgs couplings

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

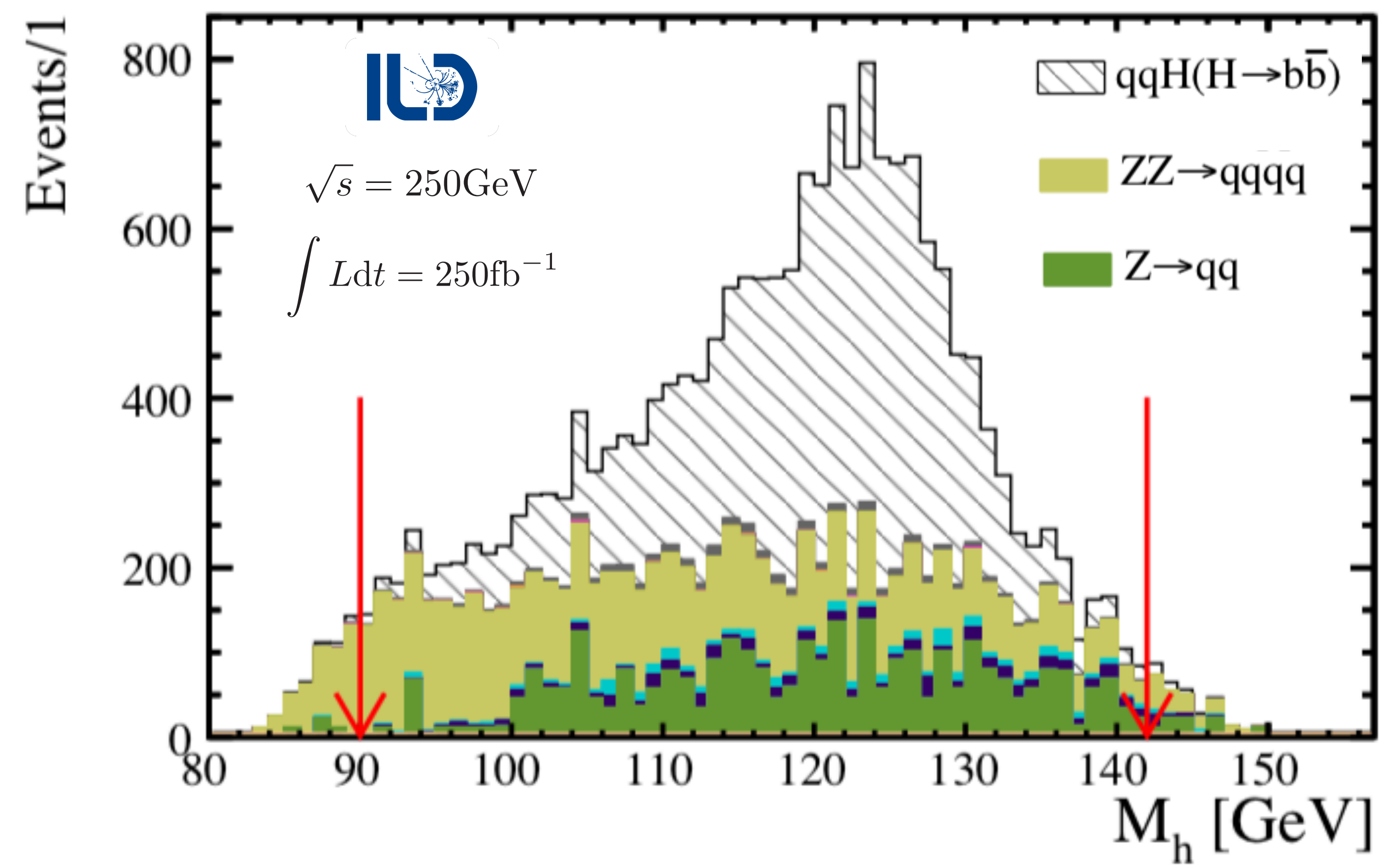
youtube: Burton Richter #mylinearcollider, 2015

for example: H->bb discovery

at LHC



at e+e-



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

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

significance: 5.4σ — 5.2σ

(ATLAS, 1808.08238; CMS, 1808.08242)

(Ogawa, PhD Thesis, ILD full simulation)

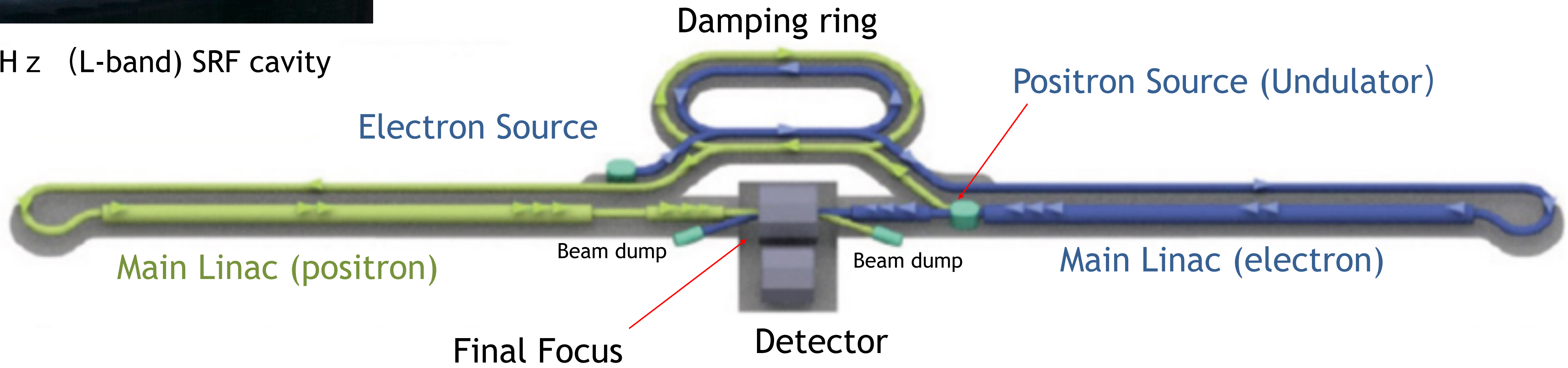
proposals of future lepton colliders

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

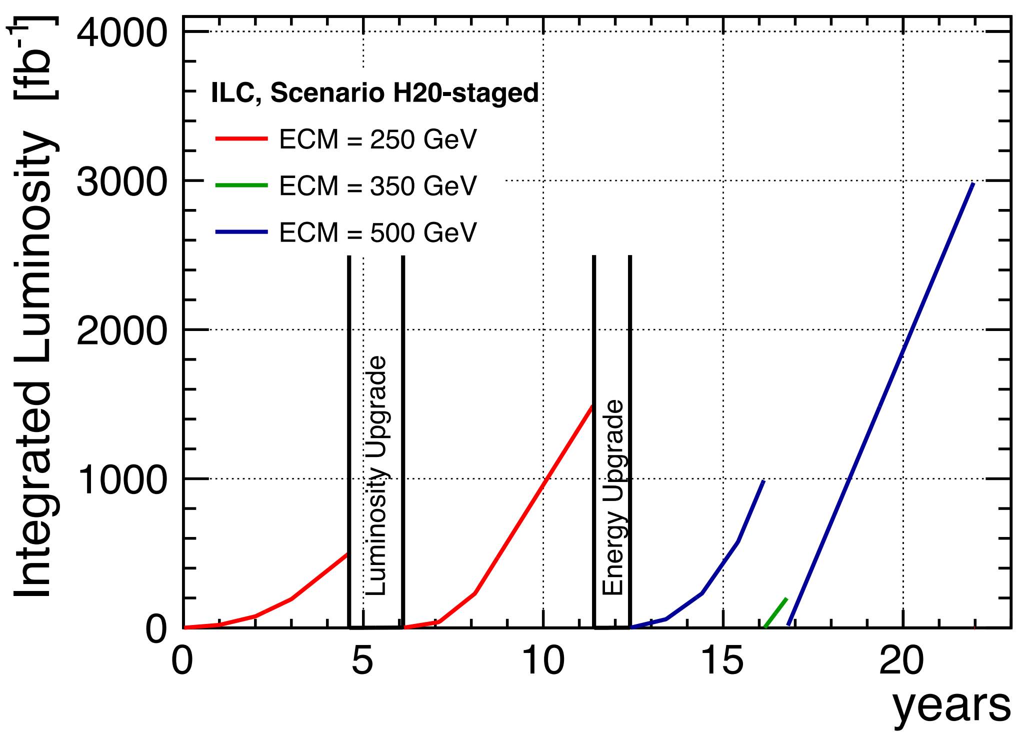
common: Higgs factory with $O(10^6)$ Higgs events

International Linear Collider

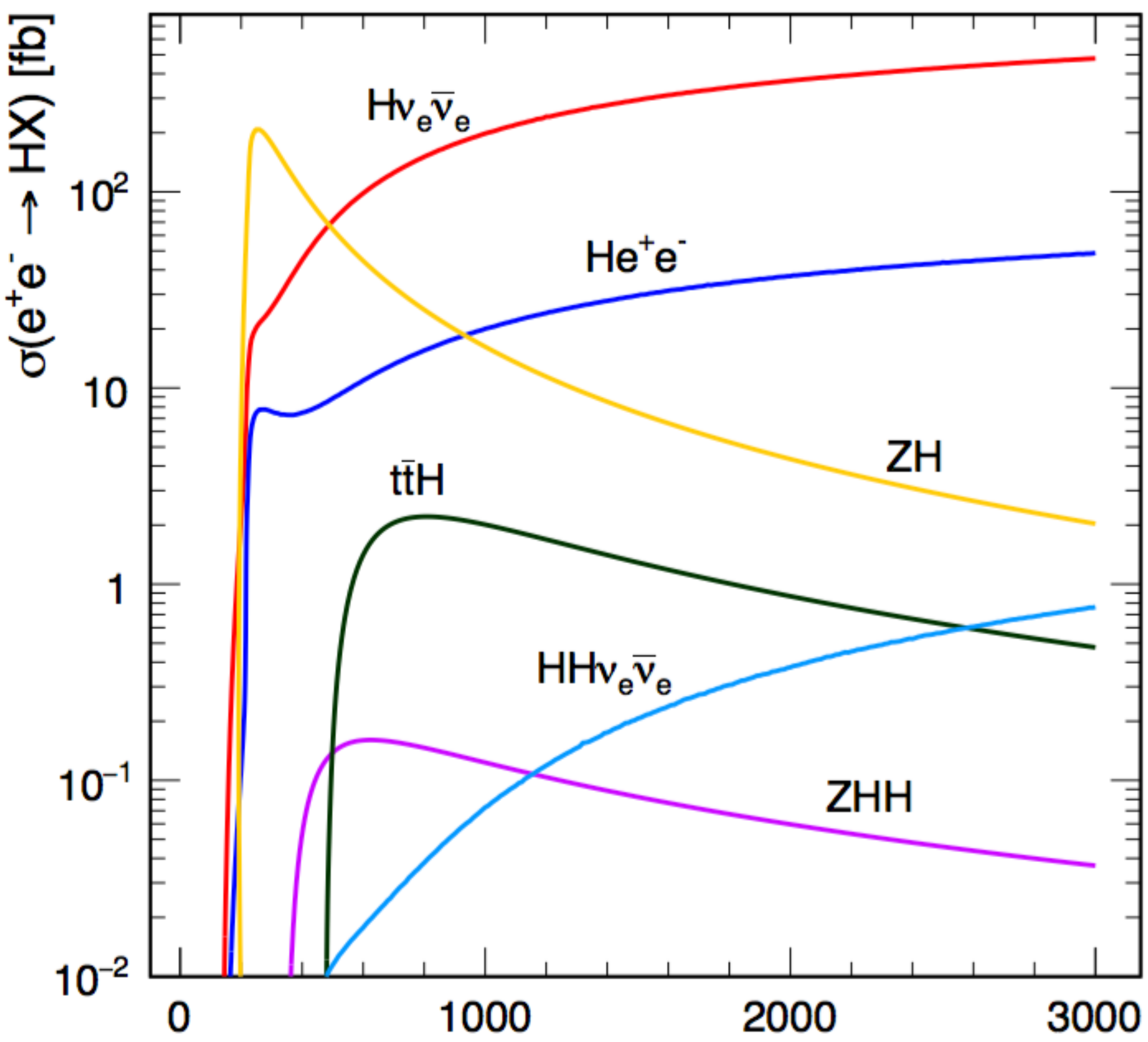
1.3GH z (L-band) SRF cavity



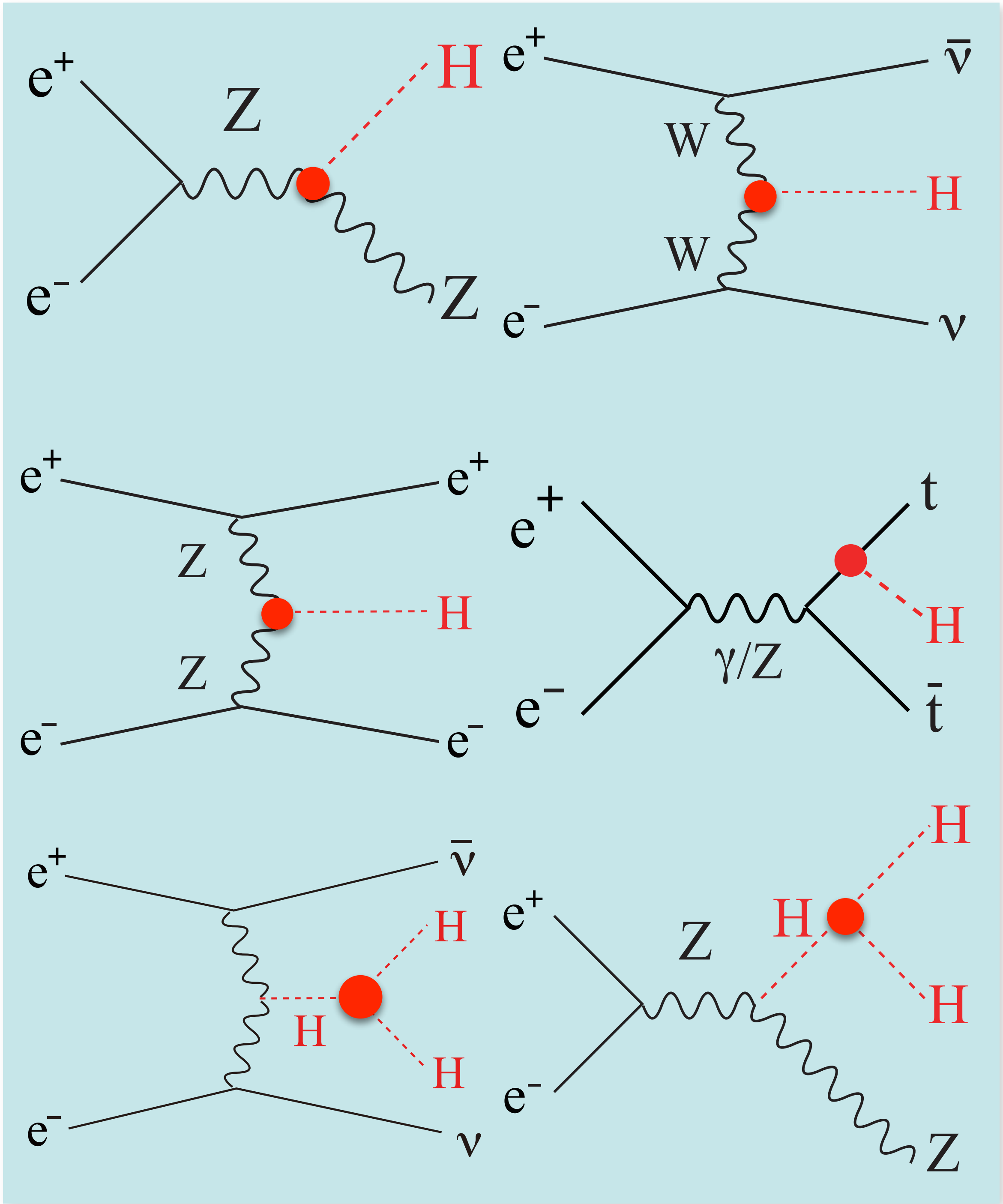
- TDR in 2013: 500 GeV e+e-, upgradable to 1 TeV
- for cost reduction -> 250 GeV at initial stage (ILC250)
- strong support: word-wide HEP; political, industrial, local in Japan
- waiting for a green light for realization



Higgs productions at e+e-



(unpolarized case)



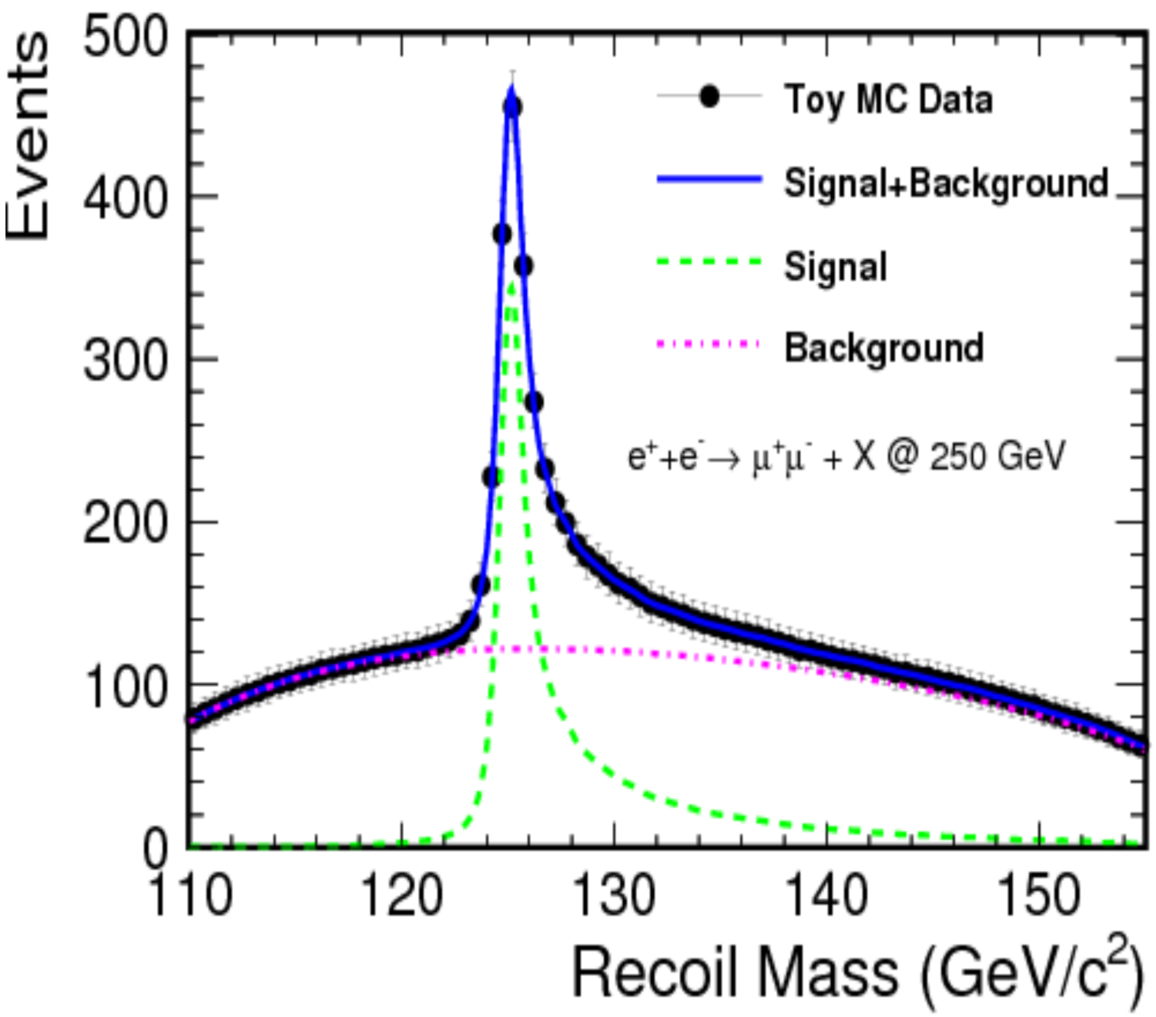
- two apparent important thresholds: $\sqrt{s}$ ~ 250 GeV for ZH, ~500 GeV for ZHH and ttH
- + another threshold for t t-bar, important for vacuum stability

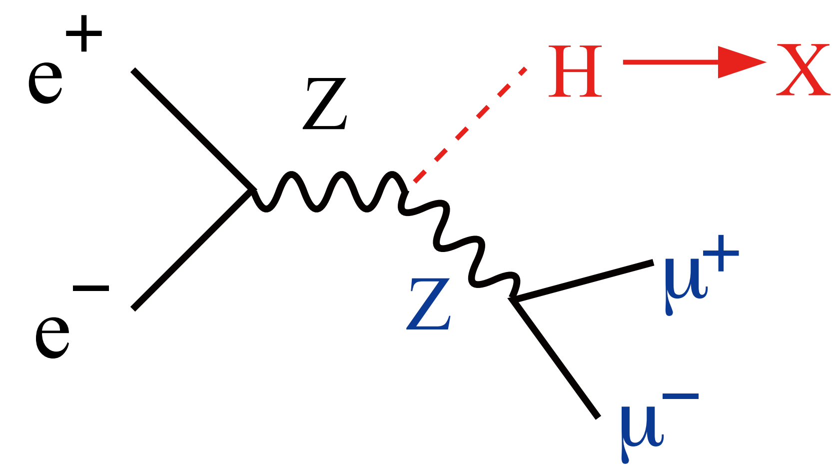
direct experimental observables: some are unique @ e+e-

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

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

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





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

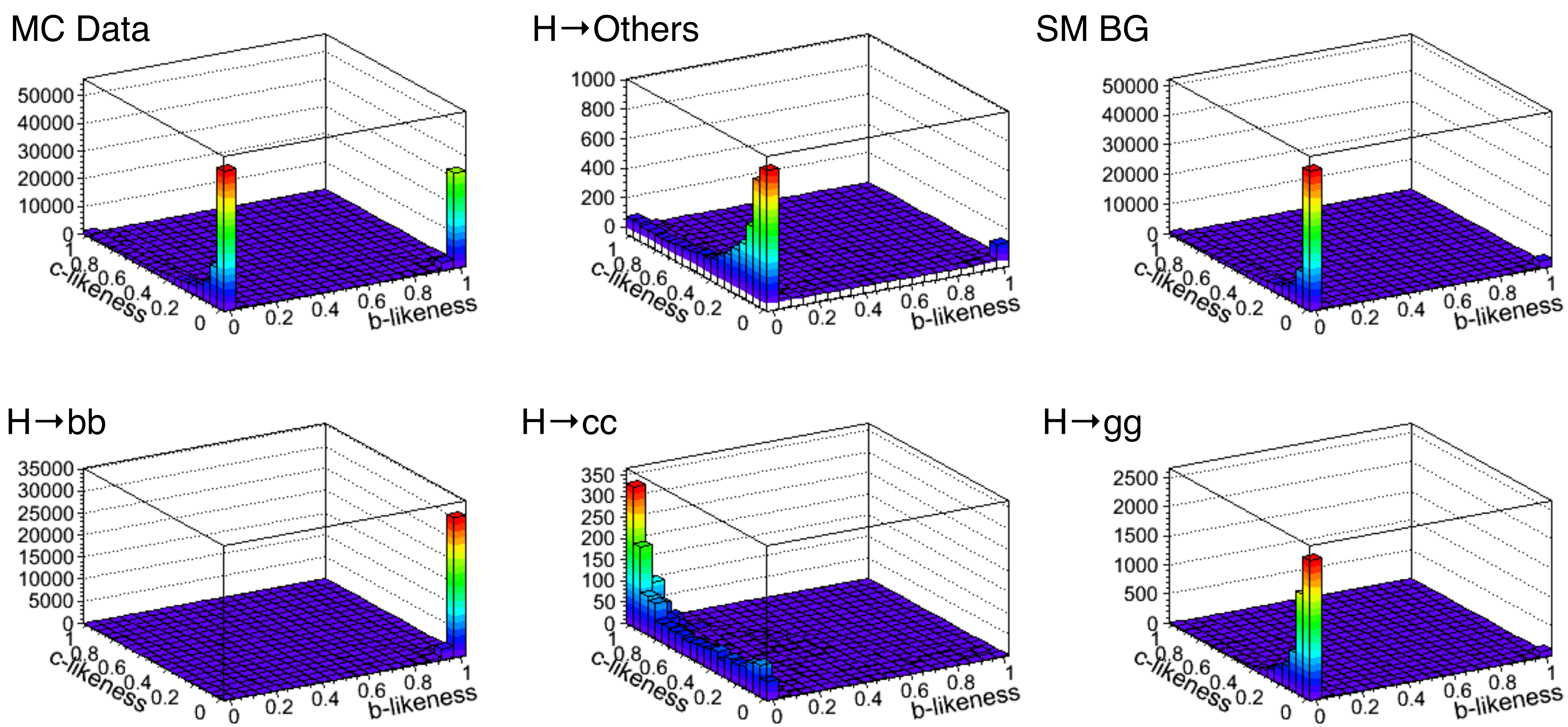
for Z->ll, Yan et al, arXiv:1604.07524;
for Z->qq, Thomson, arXiv:1509.02853

- 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

(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

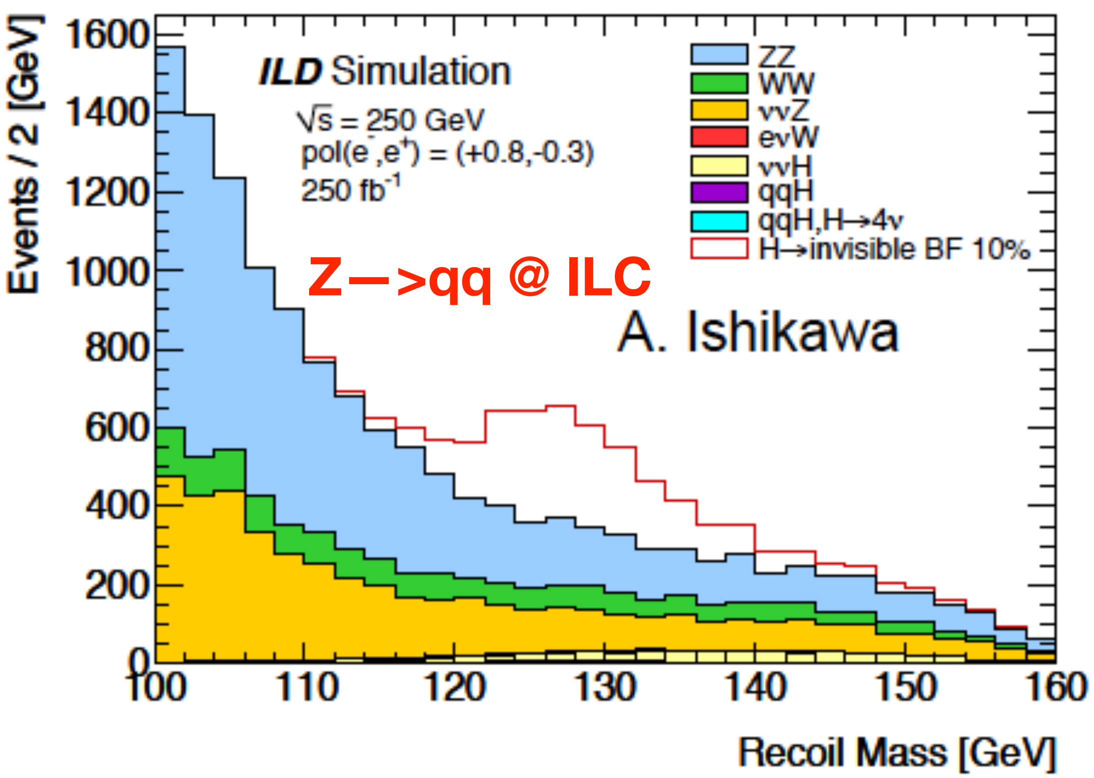


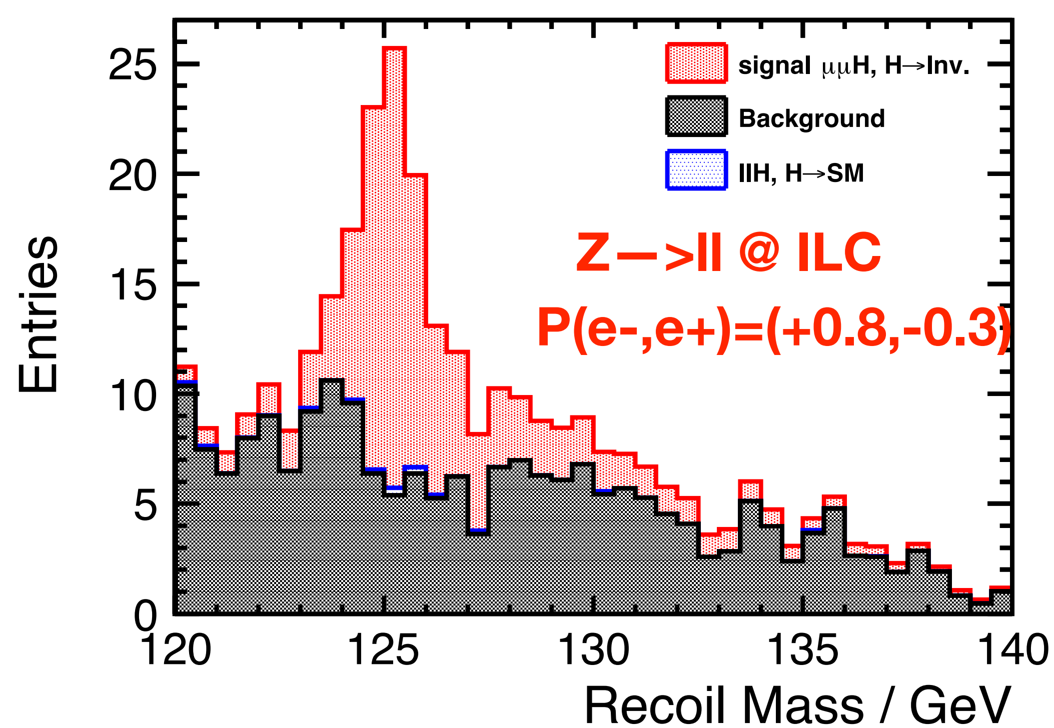
Ono, et. al, Euro. Phys. J. C73, 2343;   F.Mueller, PhD thesis (DESY)

(ii-3) search of Higgs to invisible

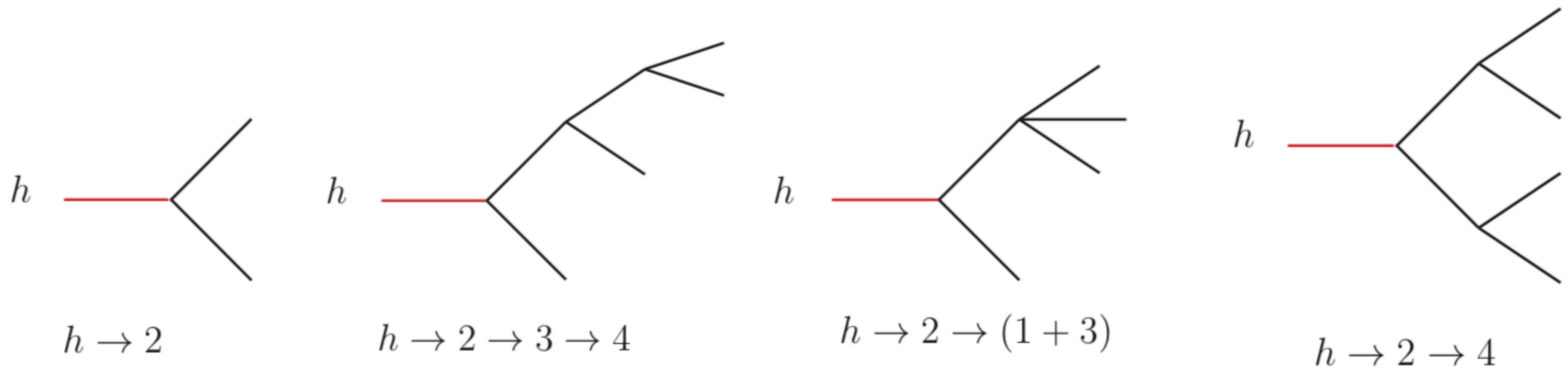
- BR(H—>inv.) < 0.3% (CL95%)
- Higgs portal dark mater search
- right-handed beam polarization: much lower background

$$e^+ + e^- \rightarrow ZH \rightarrow l^+l^-/q\bar{q} + \mathrm{Missing}$$

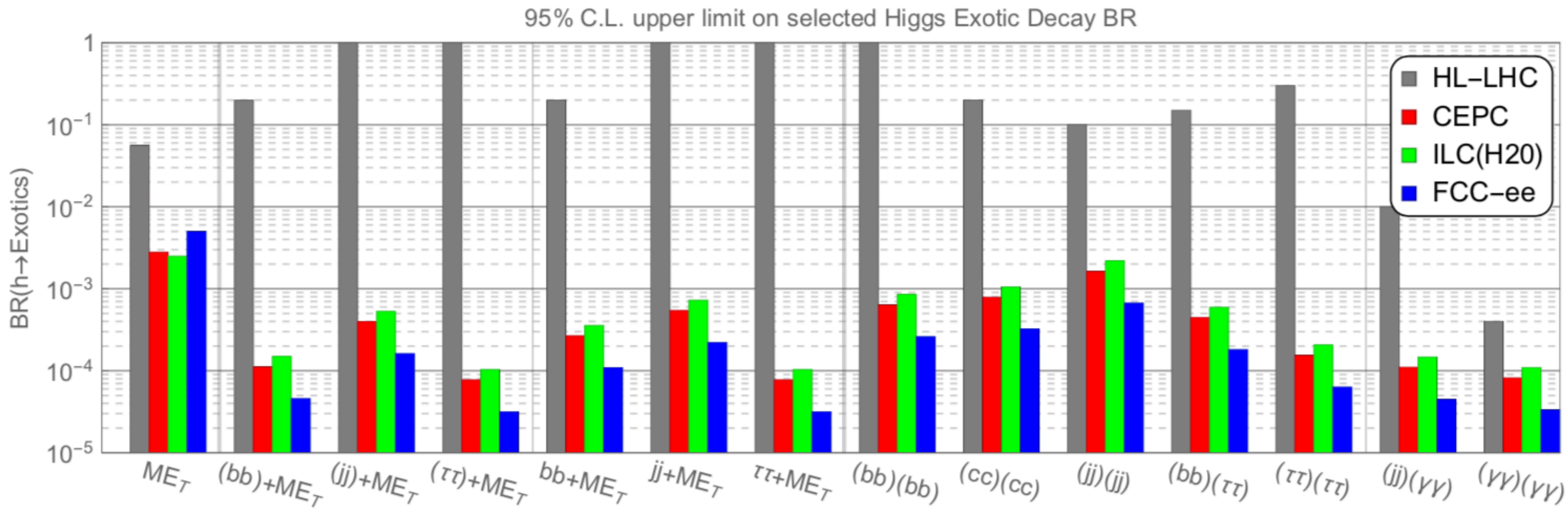




(ii-3) search of Higgs exotic decays



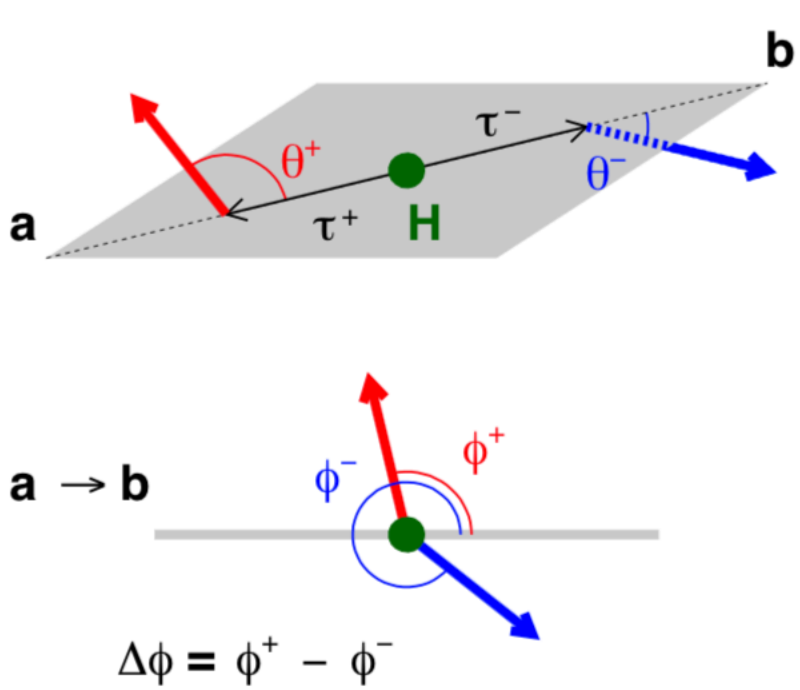
BR < 0.1-0.01% @ ILC, Liu et al, arXiv:1612.09284



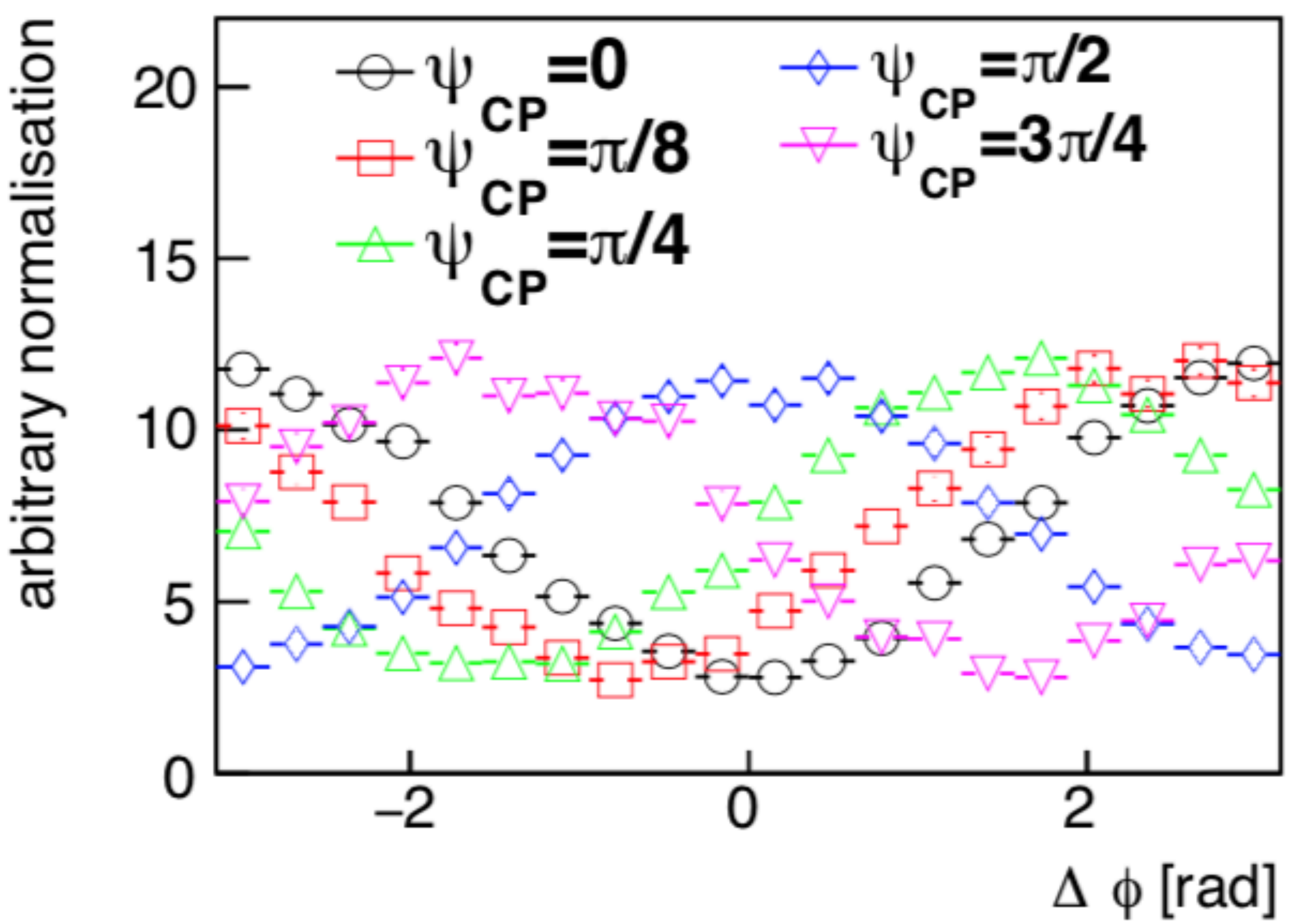
(ii-4) Higgs CP in H->$\tau^+\tau^-$

CP is essential to understand structures of all Higgs couplings

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



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



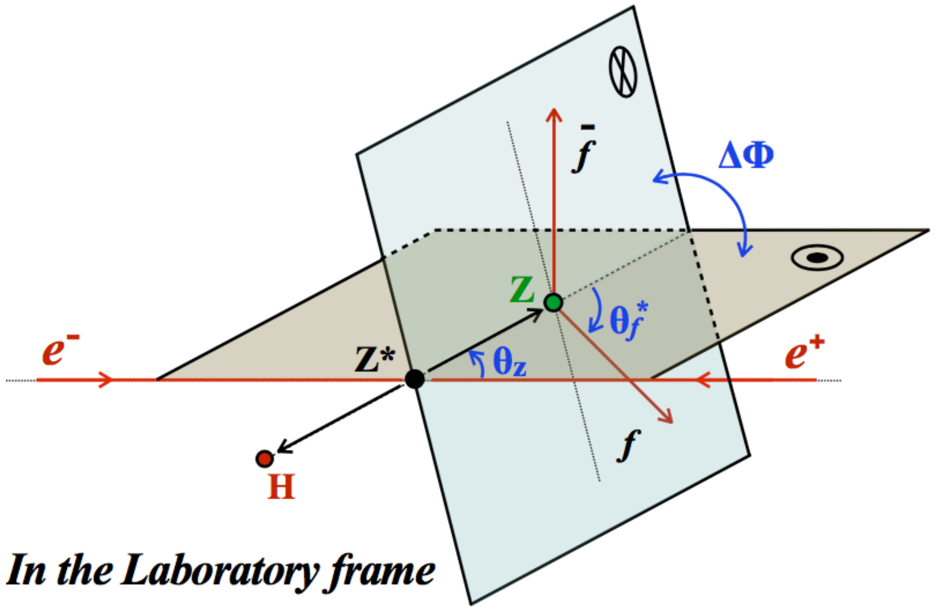
Jeans et al, arXiv:1804.01241

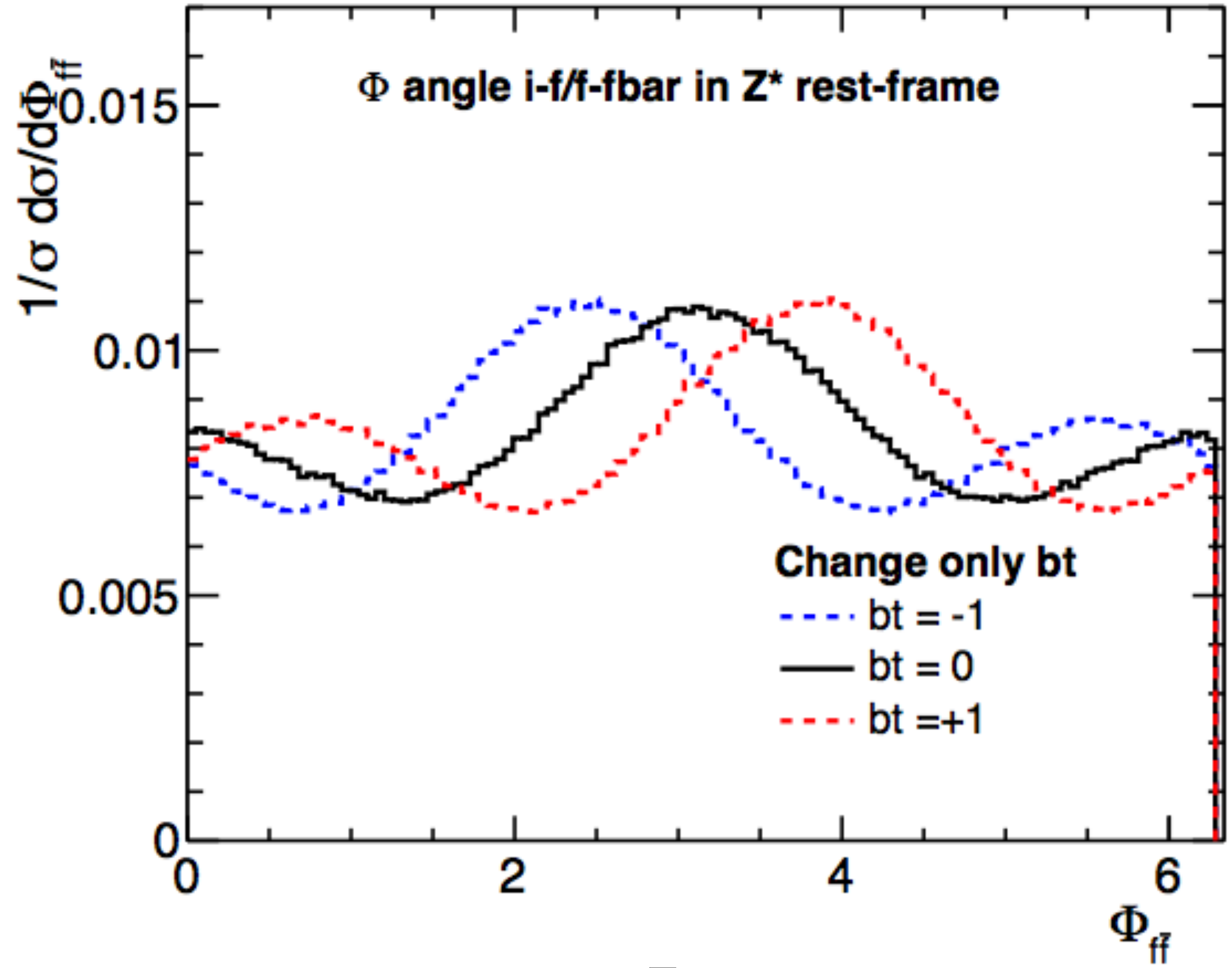
(ii-4) Higgs CP in HZZ coupling

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

(CP-odd)

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



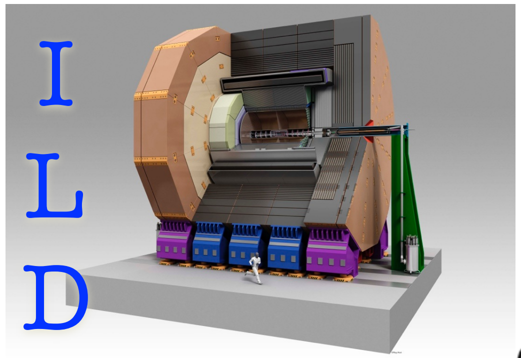


@ $\sqrt{s} = 250\text{GeV}$

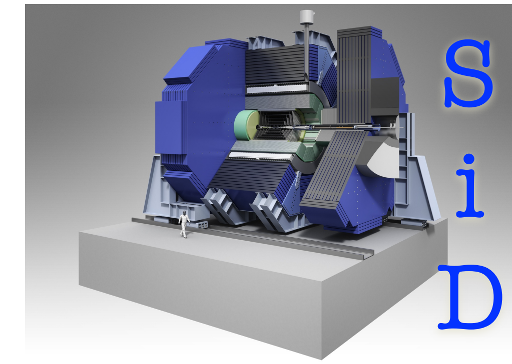
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

Ogawa et al, arXiv:1712.09772

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})

(iii) Higgs coupling determination

— model independent way

Higgs coupling determination — kappa formalism

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

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

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

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

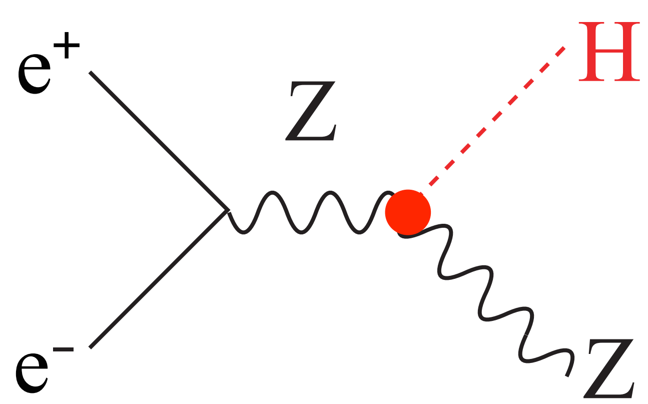
5) or $\boldsymbol{\Gamma_h} = \Gamma(h\text{—>}WW^*)/BR(h\text{->}WW^*)$

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

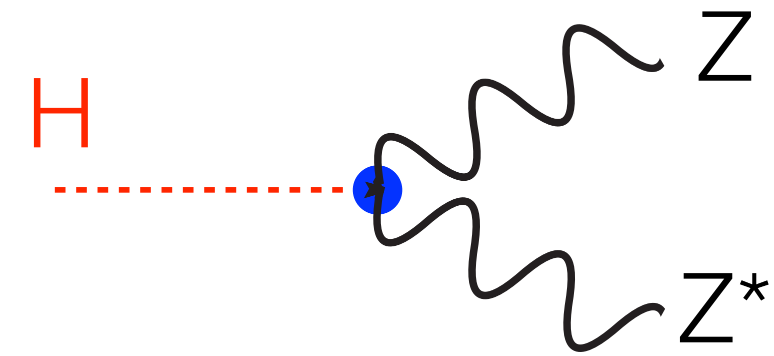
JT, et al, PoS EPS-HEP2013 (2013) 316 Nucl.Part.Phys.Proc. 273-275 (2016) 826-833

one question in kappa formalism:

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



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

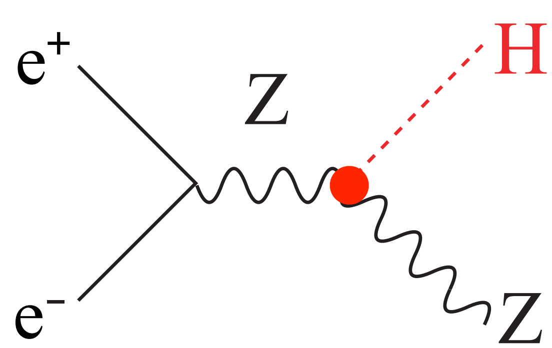


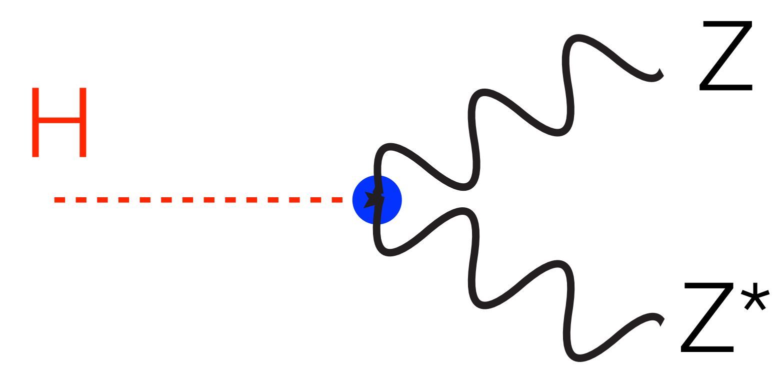
BSM territory -> can deviations be represented by single κ_Z?

the answer is model dependent

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

BSM can induce new Lorentz structures in hZZ





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

$$\neq$$

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

- there is a better, theoretical sound framework

new strategy: SM Effective Field Theory

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

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

- a more model independent formalism
- most general effects from BSM; respect SU(3)xSU(2)xU(1)
- a consistent quantum field theory unifying BSM effects in Higgs, W/Z, top, 2-fermion physics

SM Effective Field Theory: some simplifications

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

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

the new particle searches at LHC Run 2 suggest ***Λ>500*** GeV

justify the analysis at dimension-6 operators

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

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

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

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

(Barklow et al, arXiv:1708.08912)

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

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

Electroweak Precision Observables	(9)
+	
Triple Gauge boson Couplings	(3)
+	
Higgs observables at LHC & ILC	(3+12x2)
	↑ 2 beam polarizations

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

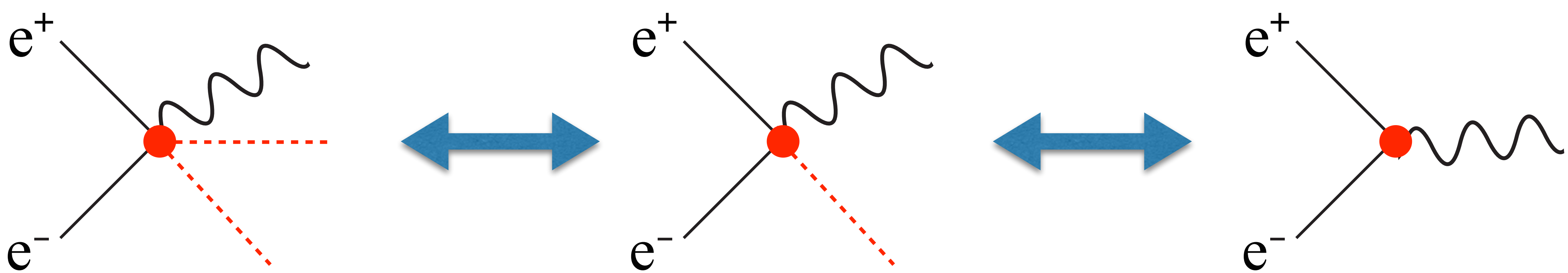
(details in backup)

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

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

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

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



$e^+e^- \to Zhh$ $e^+e^- \to Zh$ Z-pole

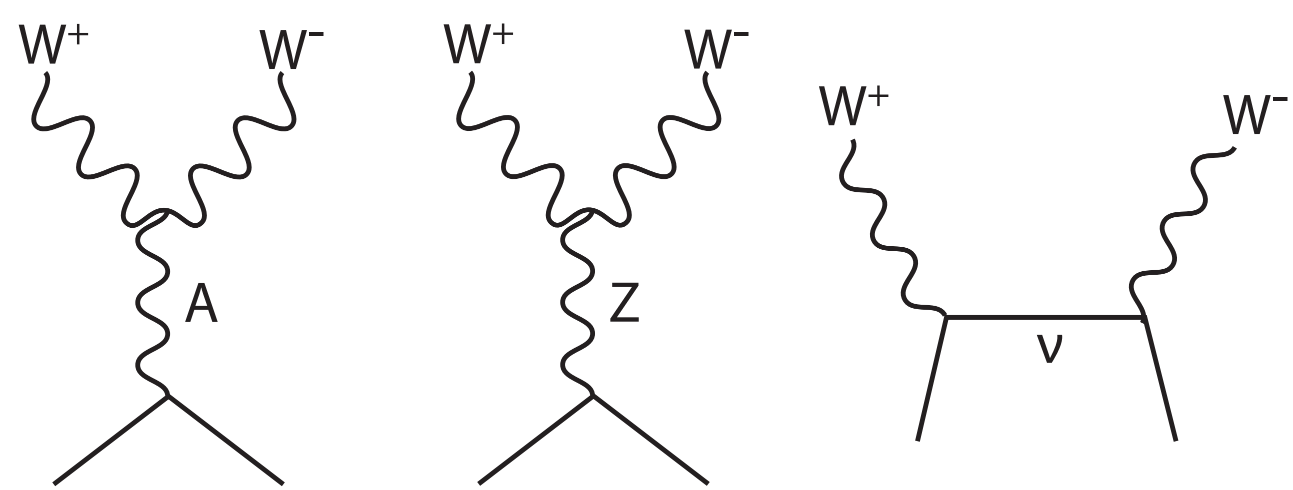
- Higgs coupling helped by EWPOs at Z-pole: $\boldsymbol{A_{LR}}$, $\boldsymbol{\Gamma_l}$
- Z coupling helped by Higgs obs at high $\sqrt{s}$: $\boldsymbol{\delta\sigma \sim s/m^2_Z}$

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

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

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

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



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

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

- longitudinal modes of W/Z are from Higgs fields
- higgs coupling helped by TGCs

recap 2: 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)

$$\theta_h = c_H$$
$$\zeta_W = \delta Z_W = (8c_{WW})$$
$$\zeta_Z = \delta Z_Z = c_w^2(8c_{WW}) + 2s_w^2(8c_{WB}) + s_w^4/c_w^2(8c_{BB})$$
$$\zeta_A = \delta Z_A = s_w^2\Big((8c_{WW}) - 2(8c_{WB}) + (8c_{BB})\Big)$$
$$\zeta_{AZ} = \delta Z_{AZ} = s_w c_w\left((8c_{WW}) - (1-\frac{s_w^2}{c_w^2})(8c_{WB}) - \frac{s_w^2}{c_w^2}(8c_{BB})\right)$$

- hZZ/hWW/hγZ/hγγ highly related: SU(2)xU(1) gauge symmetries

recap 2: Higgs couplings are related to themselves (synergy w/ LHC)

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

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

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

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

- loop induced h->γγ/γZ provide two very strong constraints
- a significant help from LHC

recap 2: 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 ~ $O(10^{-4}$-$10^{-3})$

anomalous hVV

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

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

- hWW/hZZ ratio can be determined to <0.1%

- very important for physics case of a 250 GeV e+e-
- no need to heavily rely on W-fusion @ higher √s

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

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

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

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

recap 3: 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

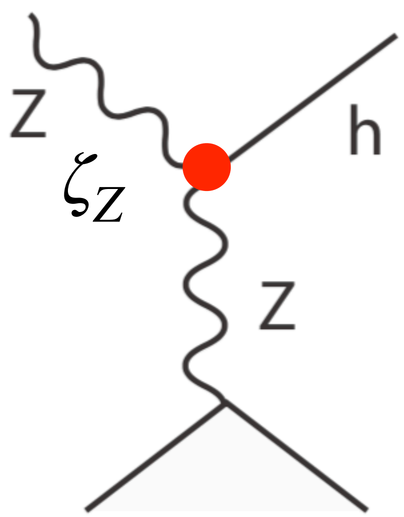
h ⟶ $(1-c_H/2)h$

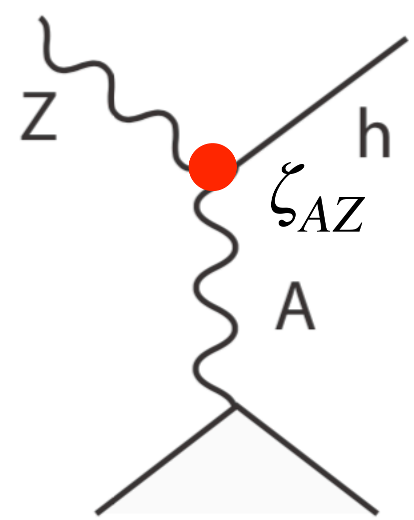
⟶ **shift all SM Higgs couplings by $-c_H/2$**

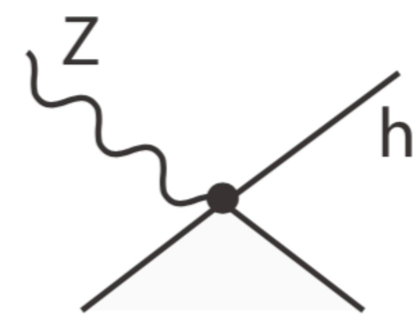
- c_H can not be determined by any BR or ratio of couplings

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

recap 4: role of beam polarizations







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

- A_{LR} in σ_{ZH} -> improve c_{WW}, c_{HL}+c_{HL}’ and c_{HE}

- large cancellation in (+1,-1) -> weaker dependence on c_{WW}

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

√s=250 GeV

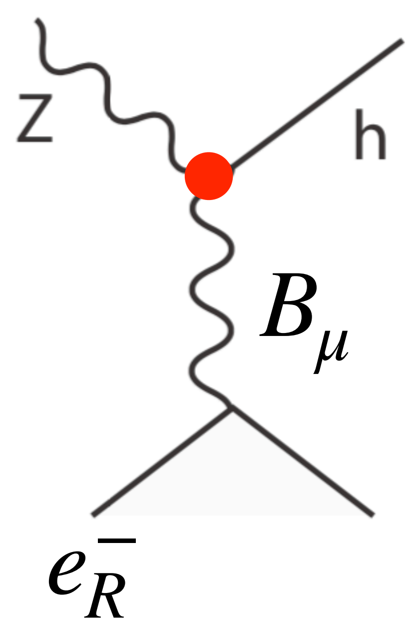
$$\delta\sigma_L = -c_H + 7.7(8c_{WW}) + \ldots$$

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

why?

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

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



contribution from

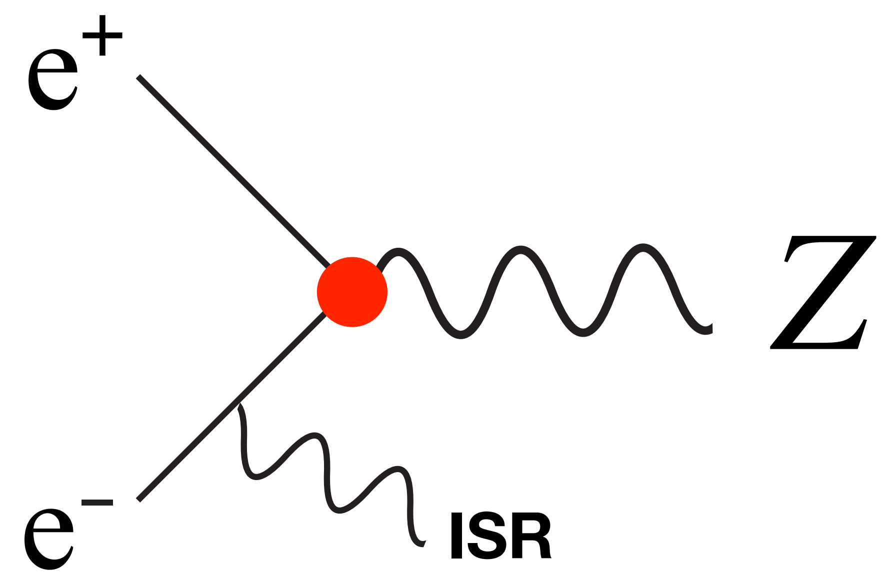
almost cancels out

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

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

recap 4: role of beam polarizations (improving EWPOs)

radiative return



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

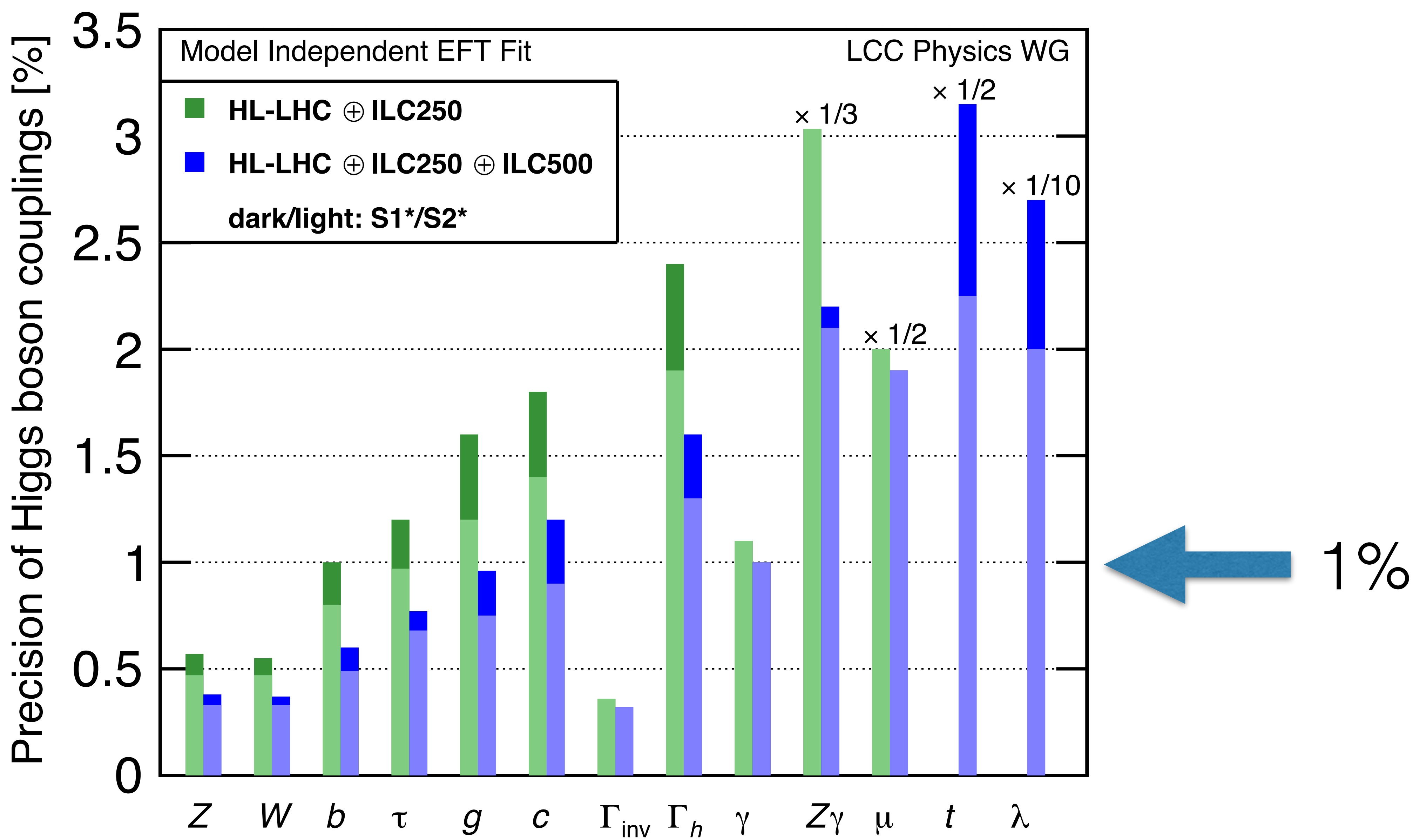
recap 4: role of beam polarizations

ILC250: 2 ab^{-1} **FCCee: 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

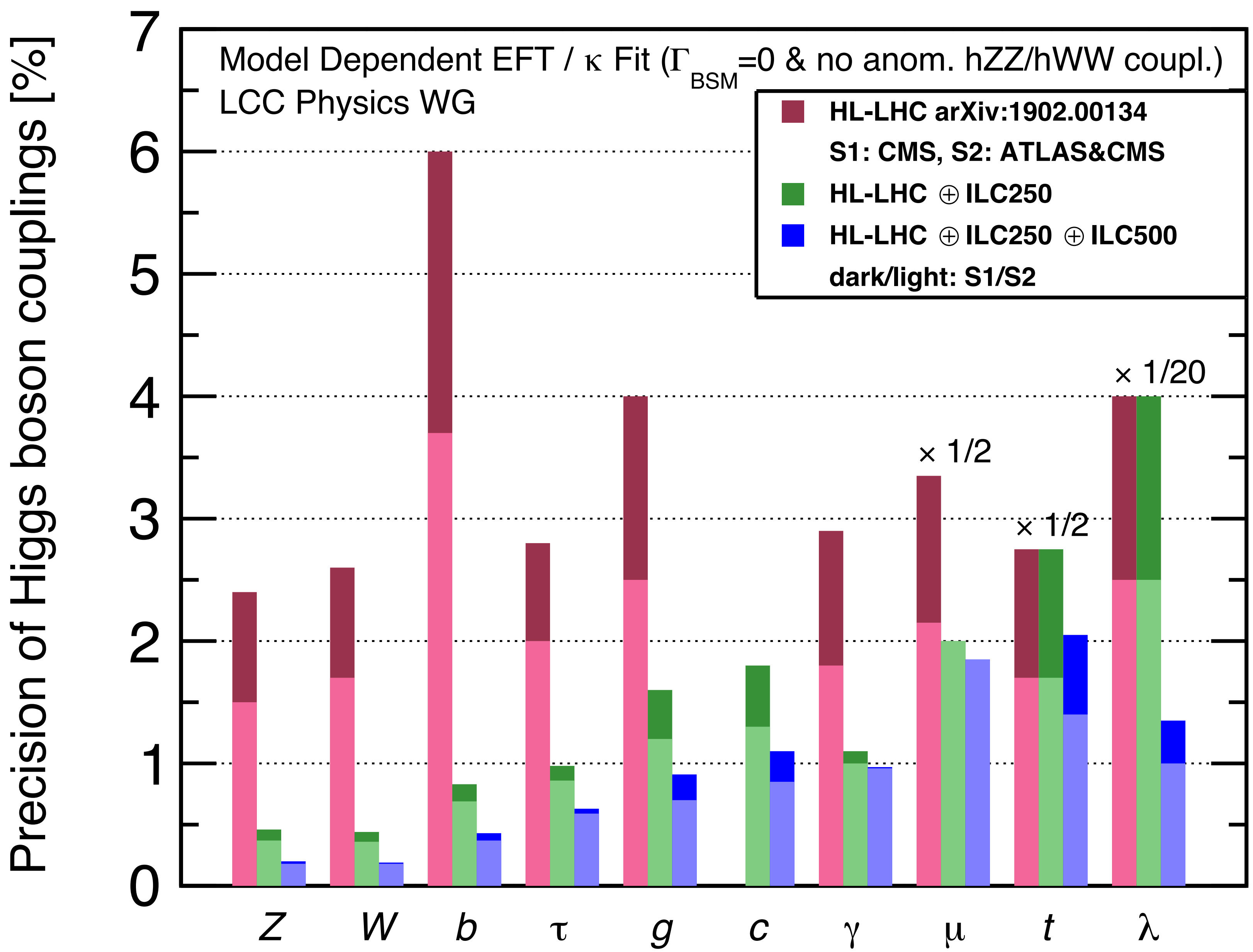
- power of 2 ab^{-1} polarized ≈ 5 ab^{-1} unpolarized

SMEFT: model independent determination of Higgs couplings



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

Higgs precisions: complementarity with LHC



#qualitative:

model independence,

hcc coupling

#quantitative (<~1%):

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

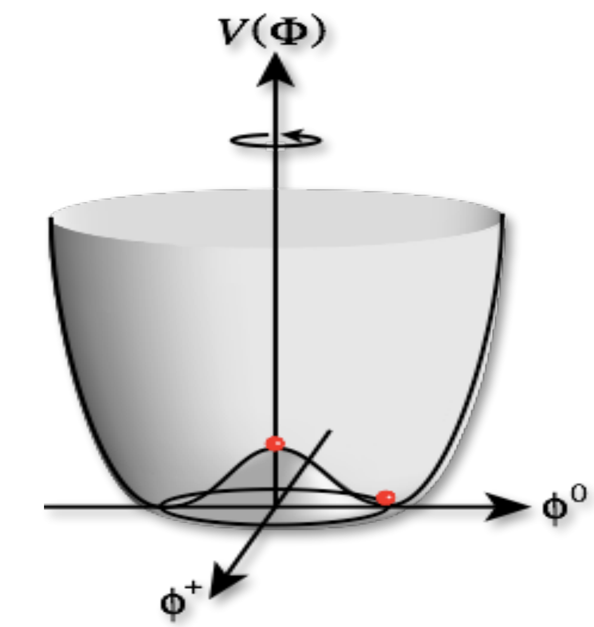
h->invisible/exotic

#synergy:

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

(vi) Higgs self-coupling

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

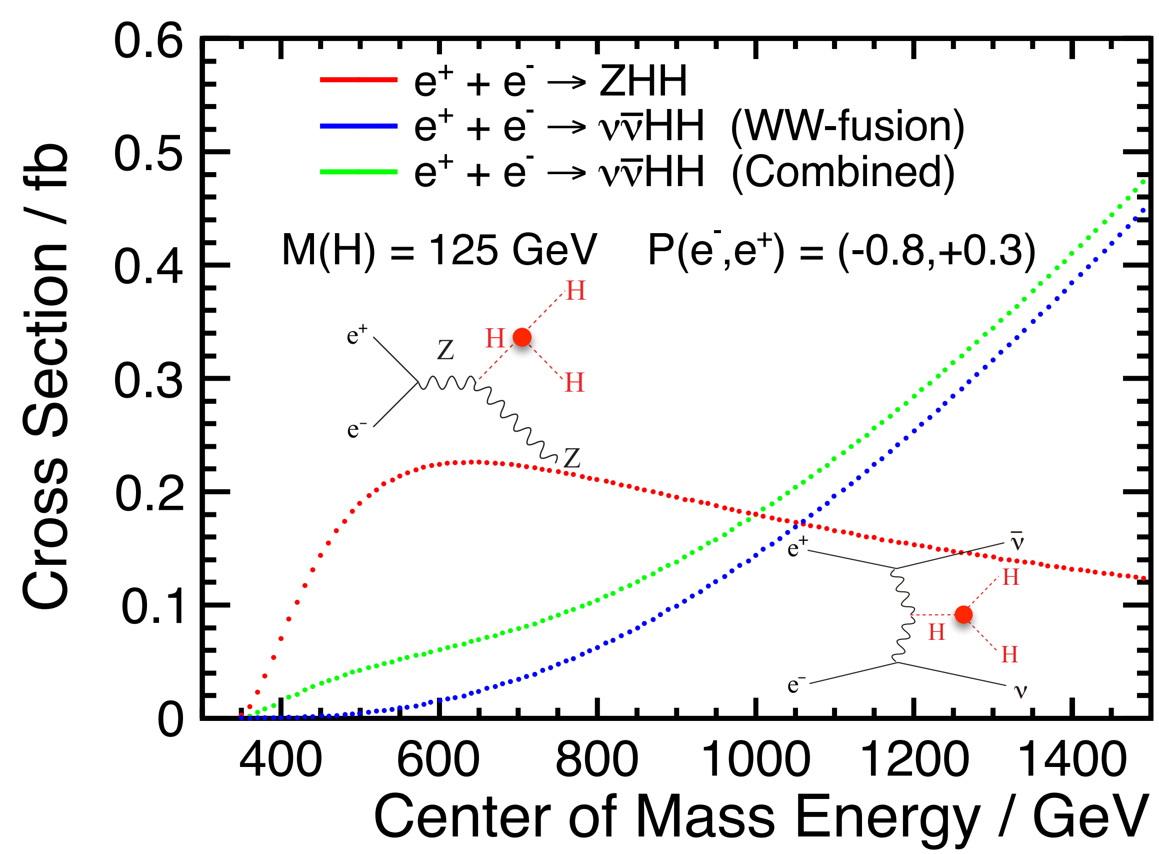


ILC

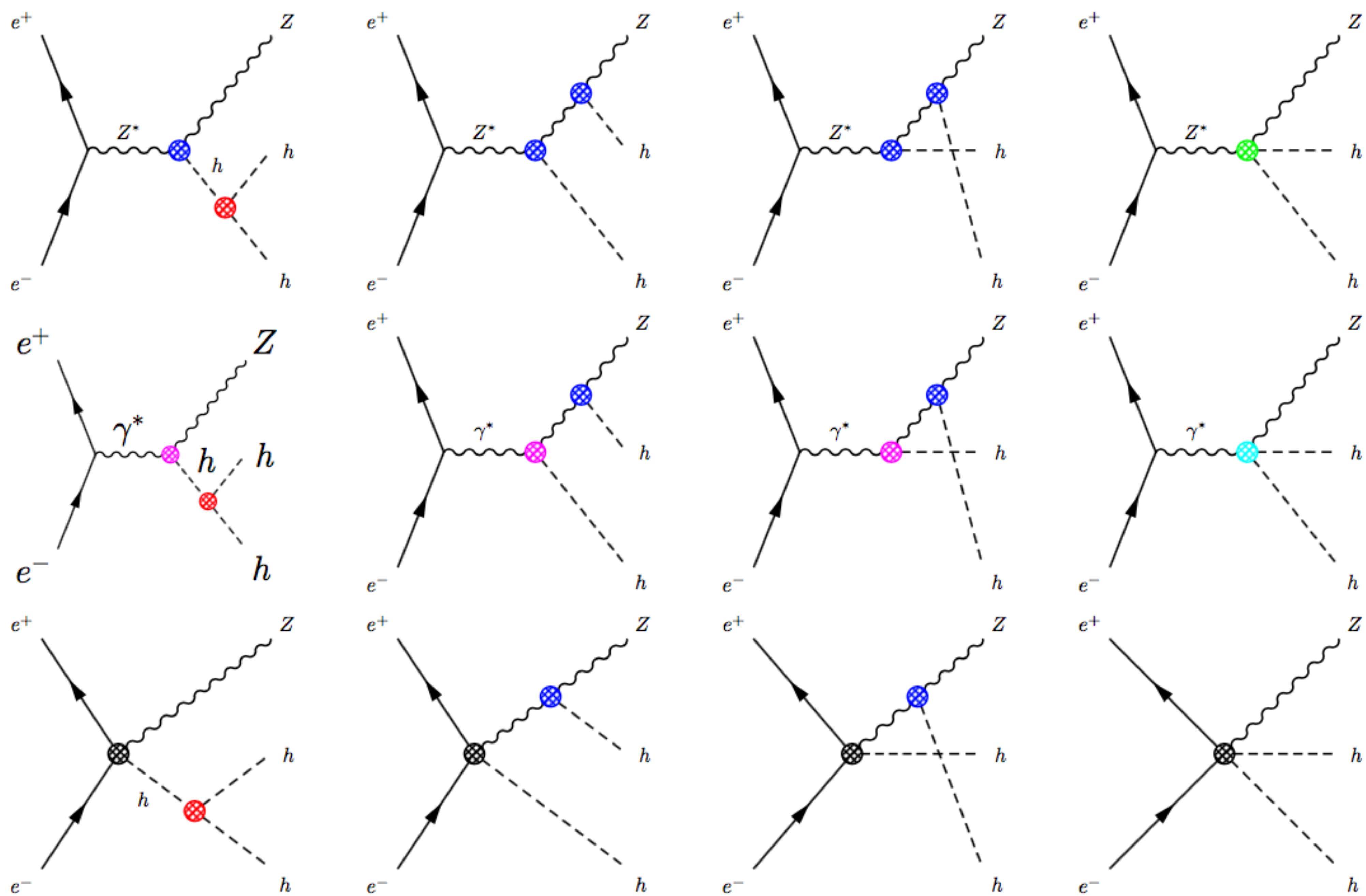
$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
H20	27%	10%

CLIC

1.5 TeV	+3 TeV
36%	10%



λ_{hhh} determination in SMEFT



λ_{hhh} determination in SMEFT

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

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

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

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

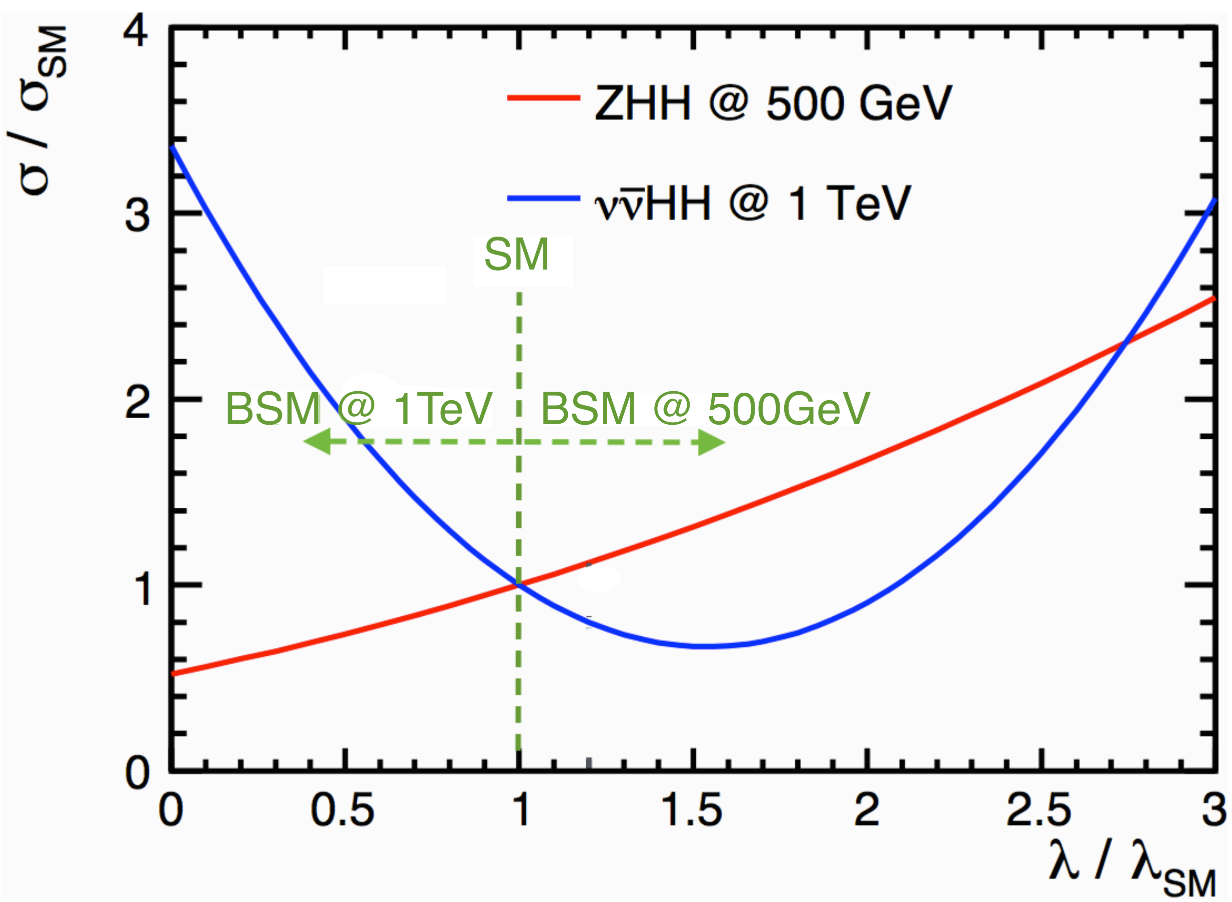
Given the full ILC program of 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV

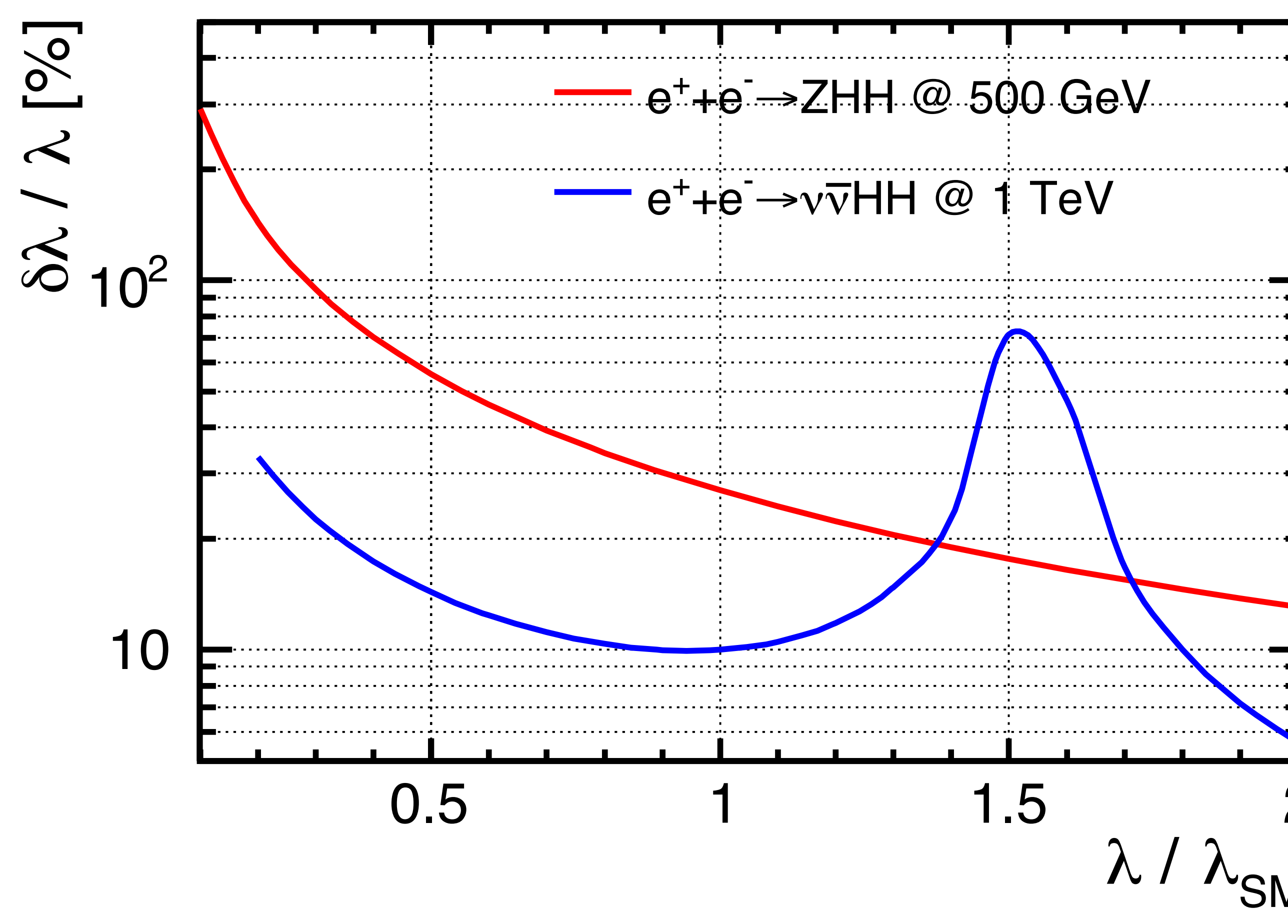
$$\left[\sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}} = 0.04 \quad \ll \quad \frac{\Delta\sigma_{Zhh}}{\sigma_{SM}} = 0.168$$

(systematic error) (statistical error)

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

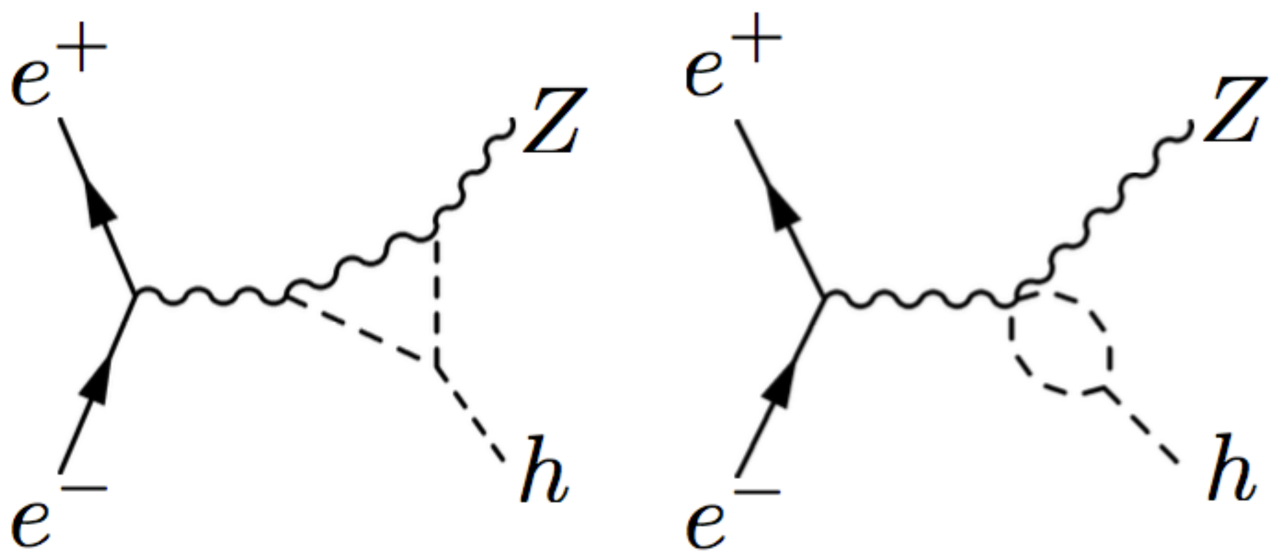
- constructive interference in ZHH, while destructive in ννHH (& LHC) —> complementarity between ILC & LHC, between √s ~500 GeV and >1TeV
- if $\lambda_{HHH} / \lambda_{SM} = 2$, Higgs self-coupling can be measured to ~15% using ZHH at 500 GeV e+e-





Duerig, Tian, et al, paper in preparation

Higgs self-coupling: indirect determination



McCullough, arXiv:1312.3322

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

- δσ could receive contributions from many other sources

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

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

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

ILC Political Status: March 7, 2019

- Following the opinion of the SCJ, **MEXT has not yet reached declaration for hosting the ILC in Japan at this moment.** The ILC project requires further discussion in formal academic decision-making processes such as the SCJ Master Plan, where it has to be clarified whether the ILC project can gain **understanding and support from the domestic academic community**.

- MEXT will pay close attention to the progress of the discussions at the European Strategy for Particle Physics Update.

- The ILC project has certain scientific significance in particle physics particularly in the precision measurements of the Higgs boson, and also has possibility in the technological advancement and in its effect on the local community, although the SCJ pointed out some concerns with the ILC project. Therefore, considering the above points, **MEXT will continue to discuss the ILC project with other governments having an interest in the ILC project.**

ILC Political Status after March 7: to be done by MEXT

Answers given by MEXT at the Diet session on March 13, 2019.

- In the future, while paying close attention to the progress of discussions on the European Elementary Particle Physics Strategy, we would like to **deepen discussions with France and Germany at the governmental level**, by proposing, for instance, to establish a standing discussion group similar to the one with the US. (Mr.Isogai)

- So, also for the ILC project, we expect there will be **a working group set up in the High Energy Accelerator Research Organization, so-called KEK, and at its initiative,** discussions within the community of domestic and foreign researchers will proceed regarding international cost sharing, etc. (Mr.Isogai)

- As I mentioned earlier, I am also aware that this is a project of great significance both from the academic research point of view and from the perspective of regional revitalization. Therefore, I would like to **continue our investigations, closely collaborating with related communities while keeping an eye on the international situation.** (Minister Shibayama)

International Working Group Established

- ***Model of international cost-sharing for construction and operation***
- ***Organization and governance of the ILC Laboratory***
- ***International sharing of the remaining technical preparation***

○Klaus Desch

○Andrew J. Lankford

○Kajari Mazumdar

○Patricia McBride

○Shinichiro Michizono

○Yasuhiro Okada

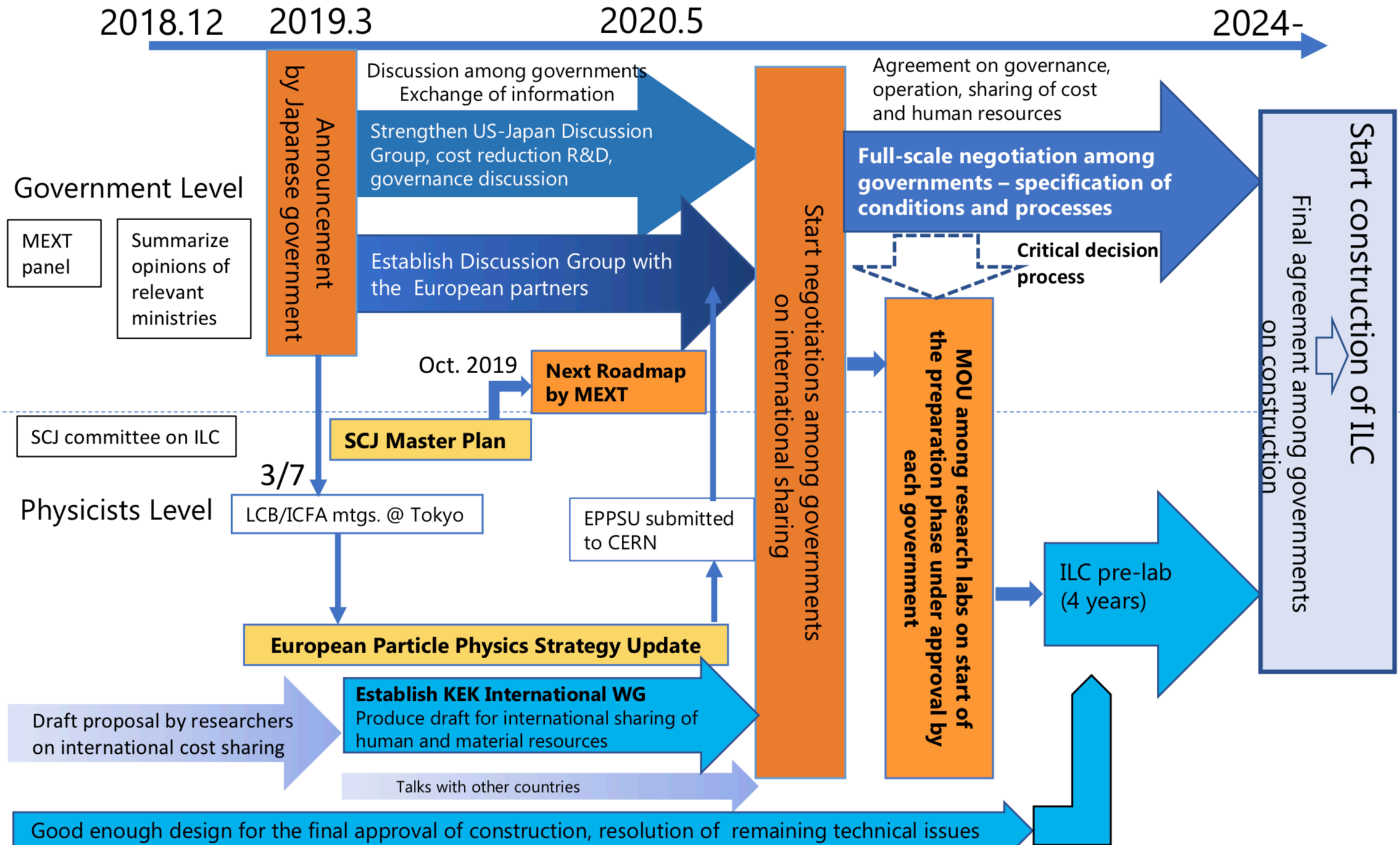
○Claude Vallée

1st meeting in May @ Granada; draft in LP2019 @ Toronto; complete in September

KEK news room, May 2019

Processes and Approximate Timelines Toward Realization of ILC (Physicists' view)

Restricted



* ICFA: international organization of researchers consisting of directors of world's major accelerator labs and representatives of researchers
* ILC pre-lab: International research organization for the preparation of ILC based on agreements among world's major accelerator labs such as KEK, CERN, FNAL, DESY etc.

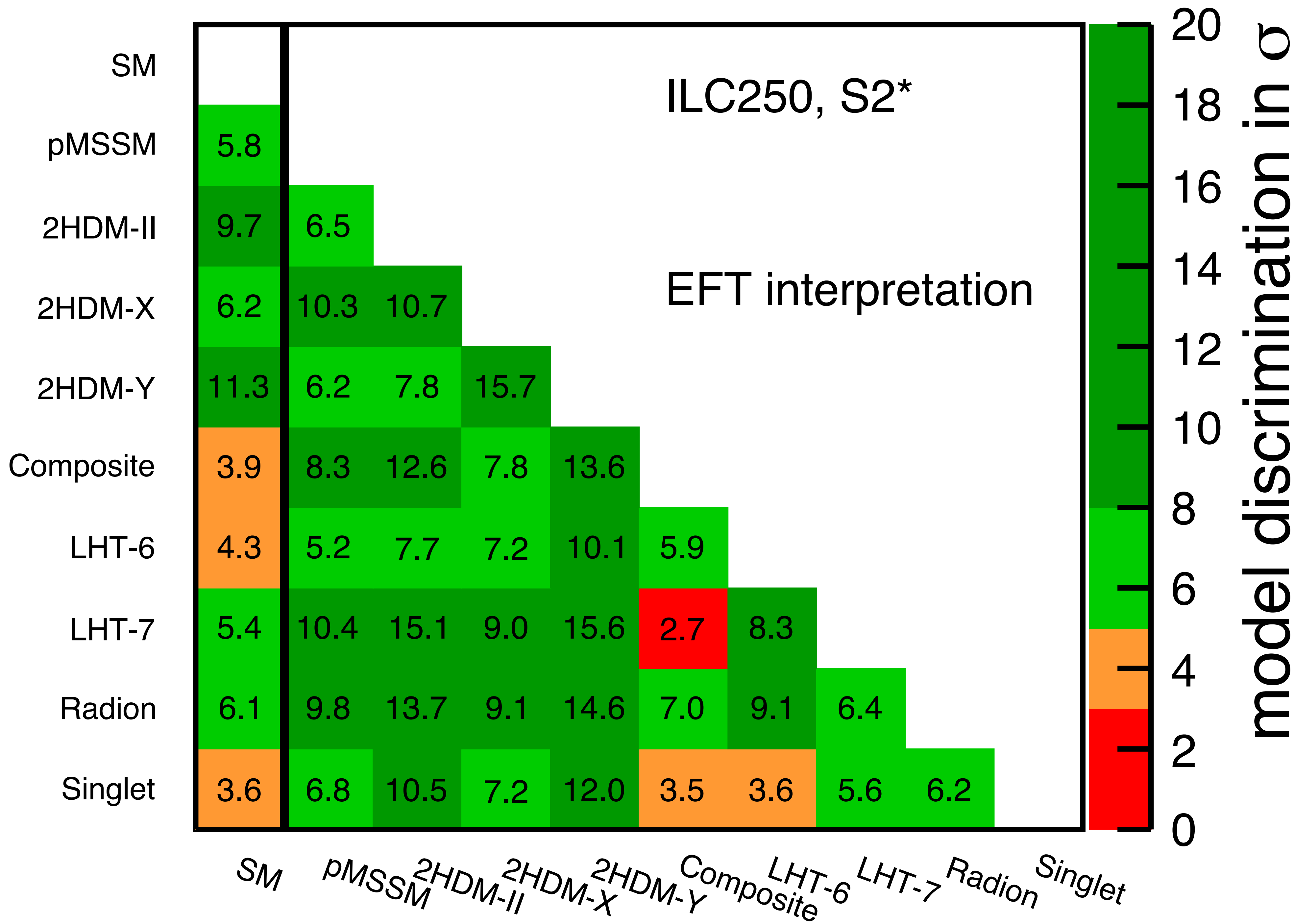
M.Yamauchi @ Lausanne, April 2019

summary

- precision Higgs will help to reveal mystery of EWSB, and identify the BSM models
- ILC250 can deliver precision Higgs, complementary to LHC
- the capabilities of a e+e- are best represented in SMEFT formalism
- beam polarizations play an important role
- ILC is in full swing towards realization

ILC Supporters

BSM benchmark models discrimination at ILC250



backup

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

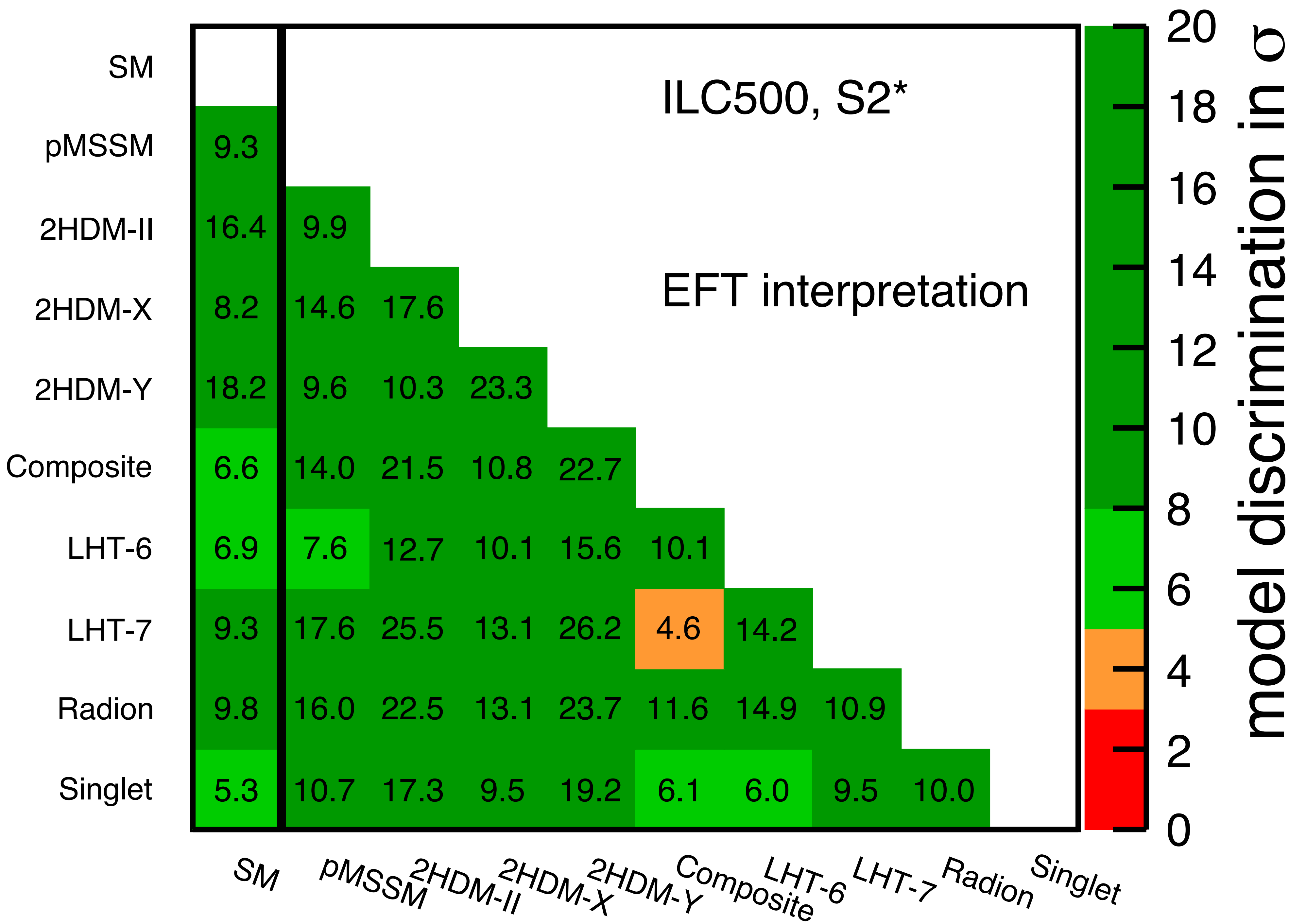
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> quantitative assessment for models discrimination

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

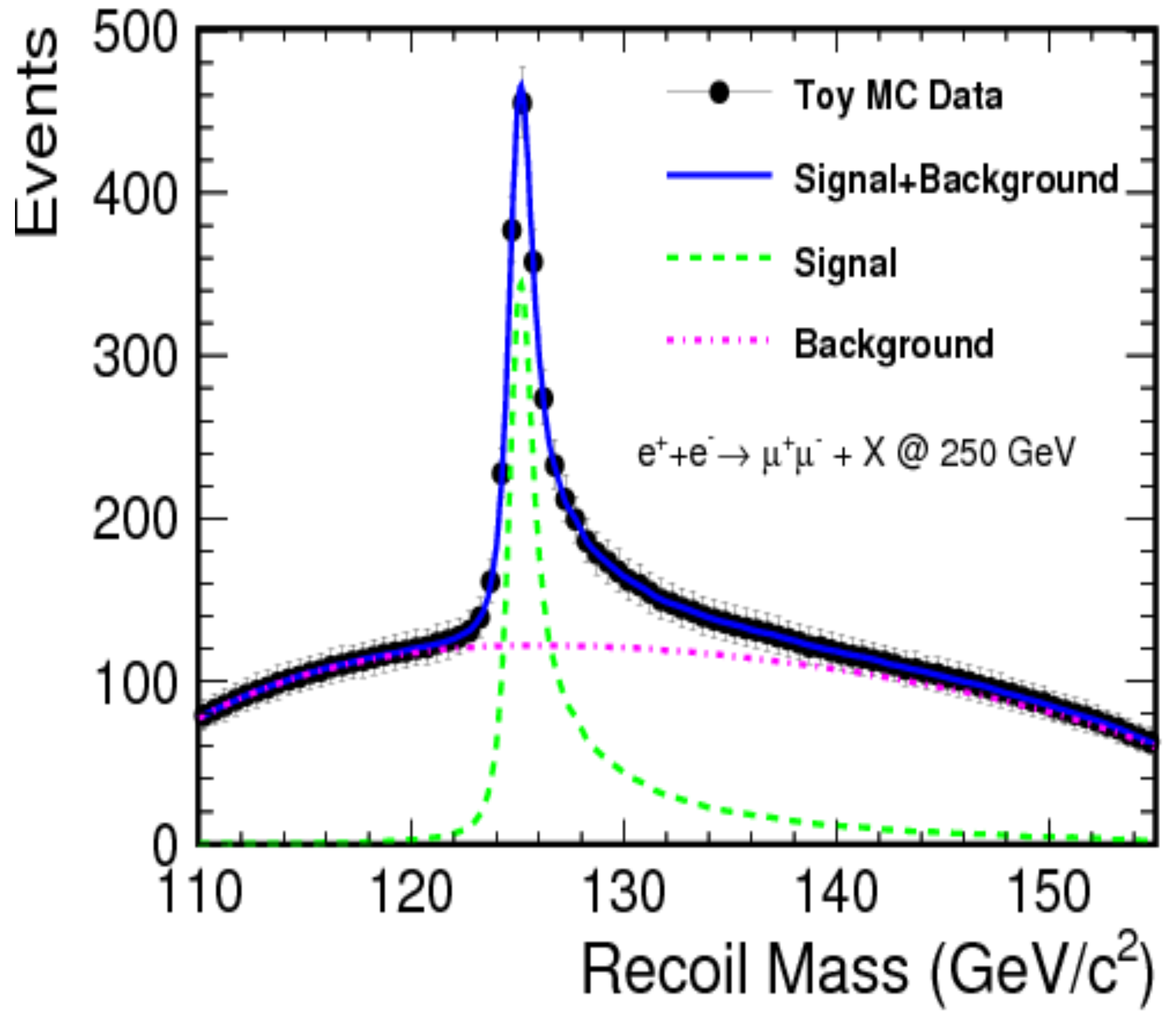
- a PMSSM model with b squarks at 3.4 TeV, gluino at 4 TeV
- a Type II 2 Higgs doublet model with $m_A = 600\ \text{GeV}, \tan\beta = 7$
- a Type X 2 Higgs doublet model with $m_A = 450\ \text{GeV}, \tan\beta = 6$
- a Type Y 2 Higgs doublet model with $m_A = 600\ \text{GeV}, \tan\beta = 7$
- a composite 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 $2.8\ \text{TeV}$ creating a Higgs portal to dark matter and large λ for electroweak baryogenesis

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

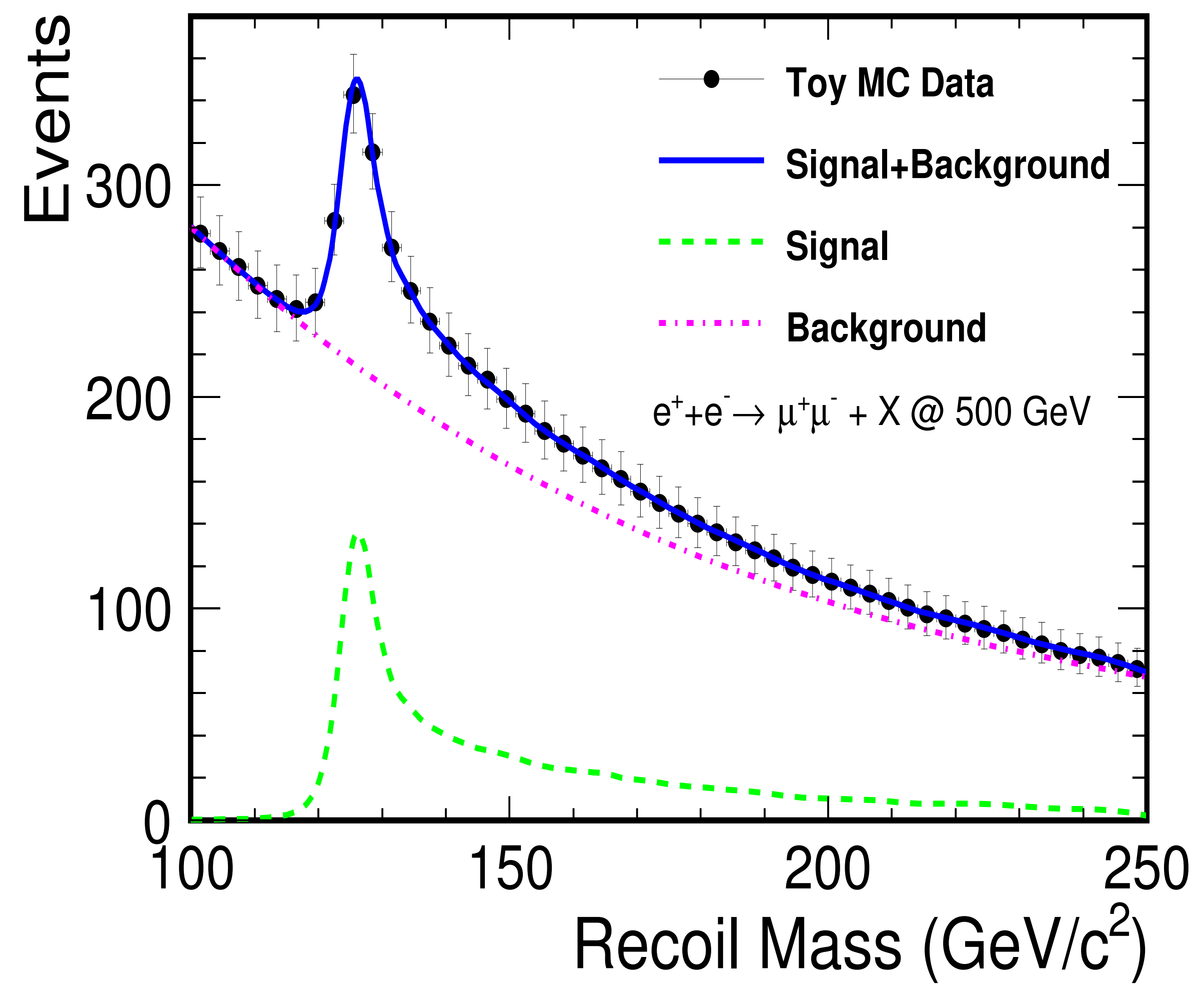


(ii-1) inclusive σ_{ZH}: impact of ECM

$\sqrt{s} = 250$ GeV

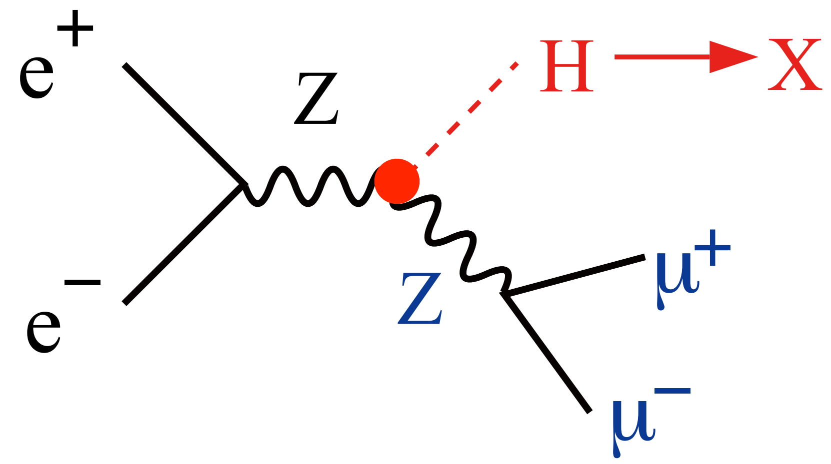


$\sqrt{s} = 500$ GeV



Yan et al, arXiv:1604.07524

what does model independence mean?



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

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

is it really possible?

efficiencies for each decay mode (leptonic recoil)

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

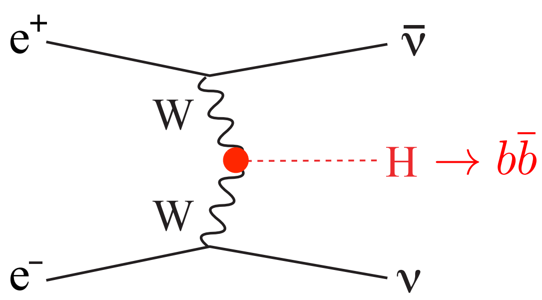
(ii-5) WW-fusion channel & Higgs total width Γ_H

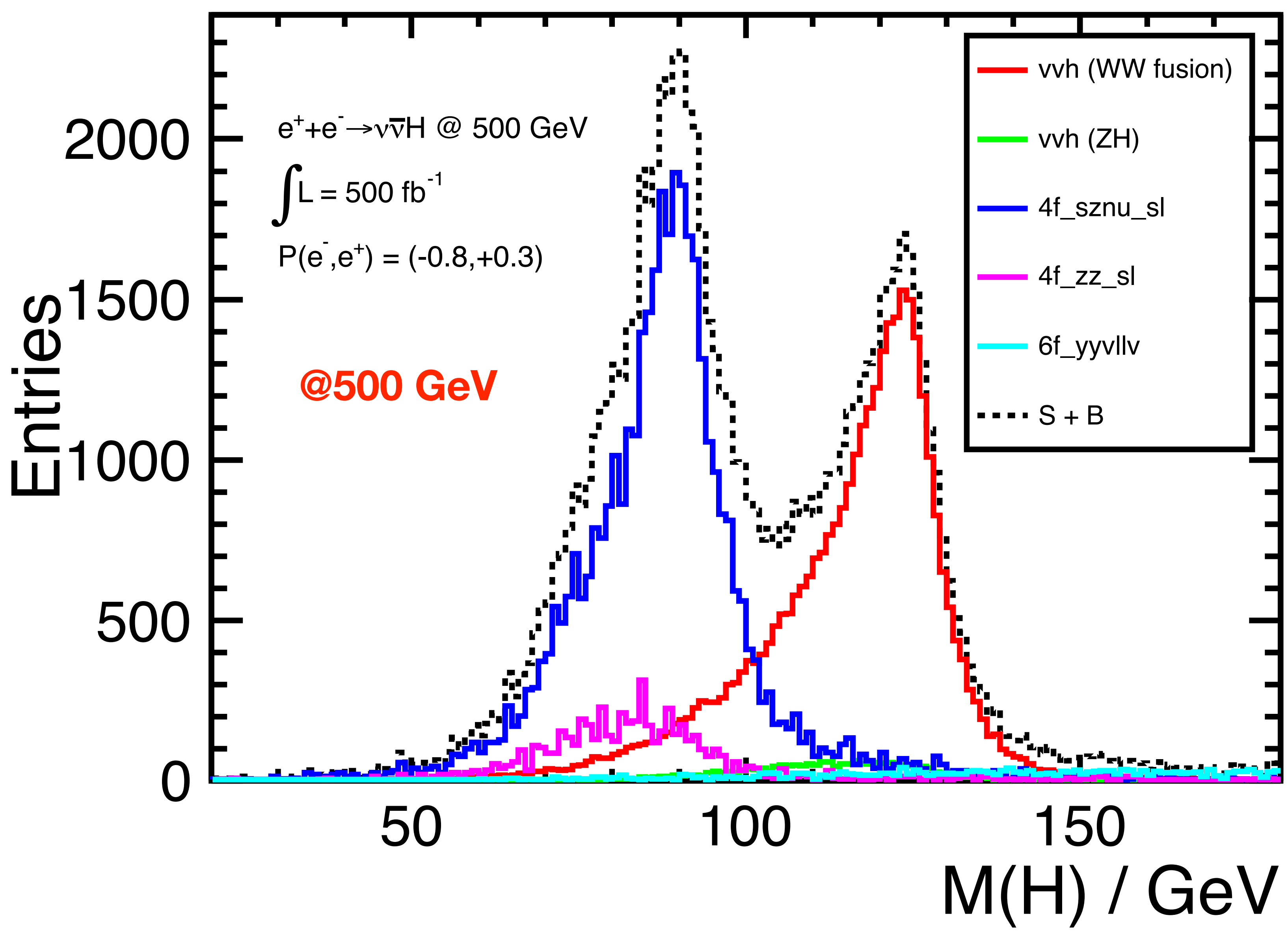
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>Br(H->ZZ*) very small

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

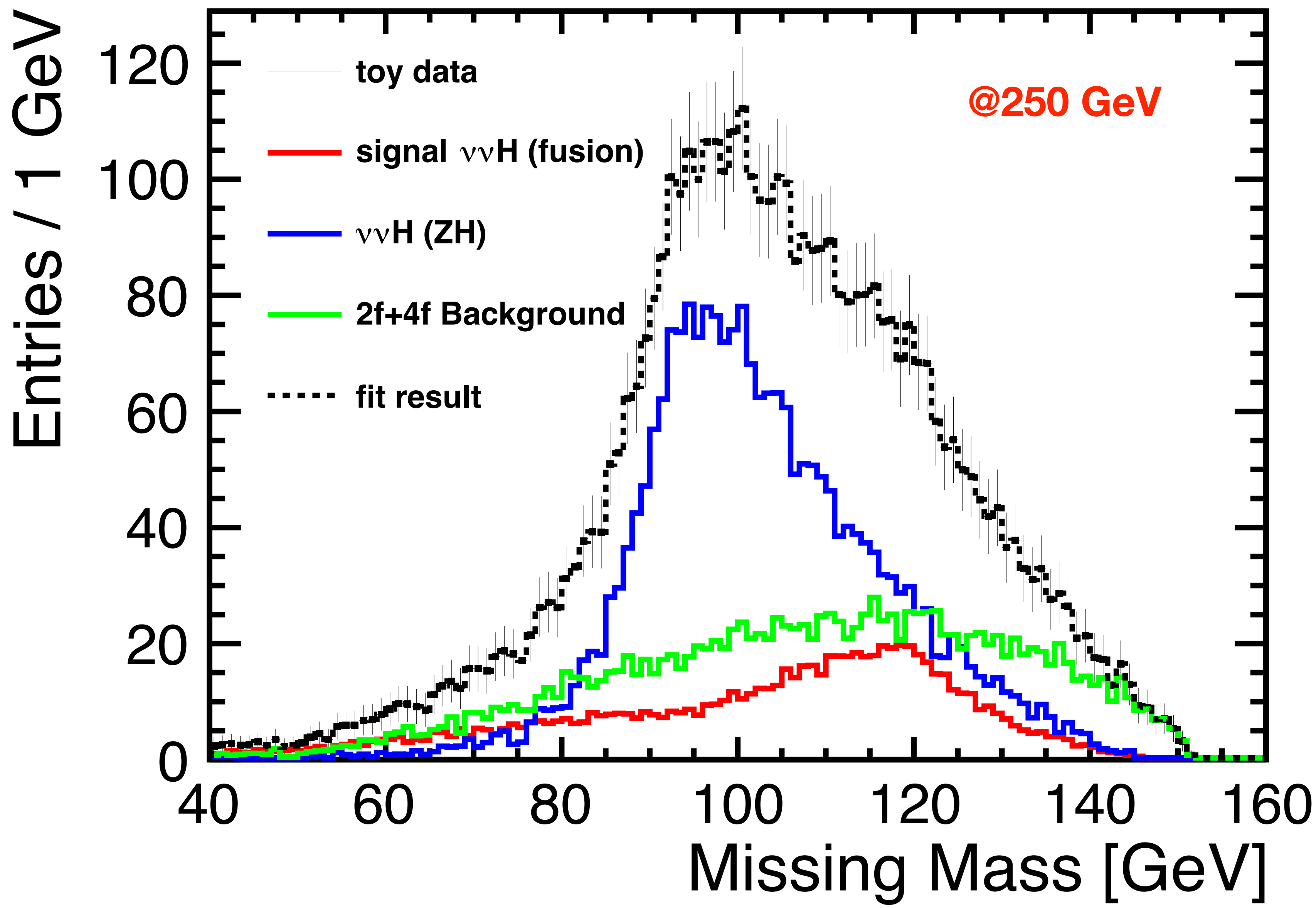
—> better option!

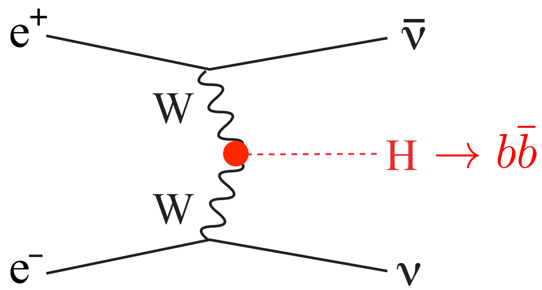




Duerig, et al., arXiv:1403.7734

very different at Ecm=250 GeV





ρ = -34% correlation (larger if unpolarized)

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

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};

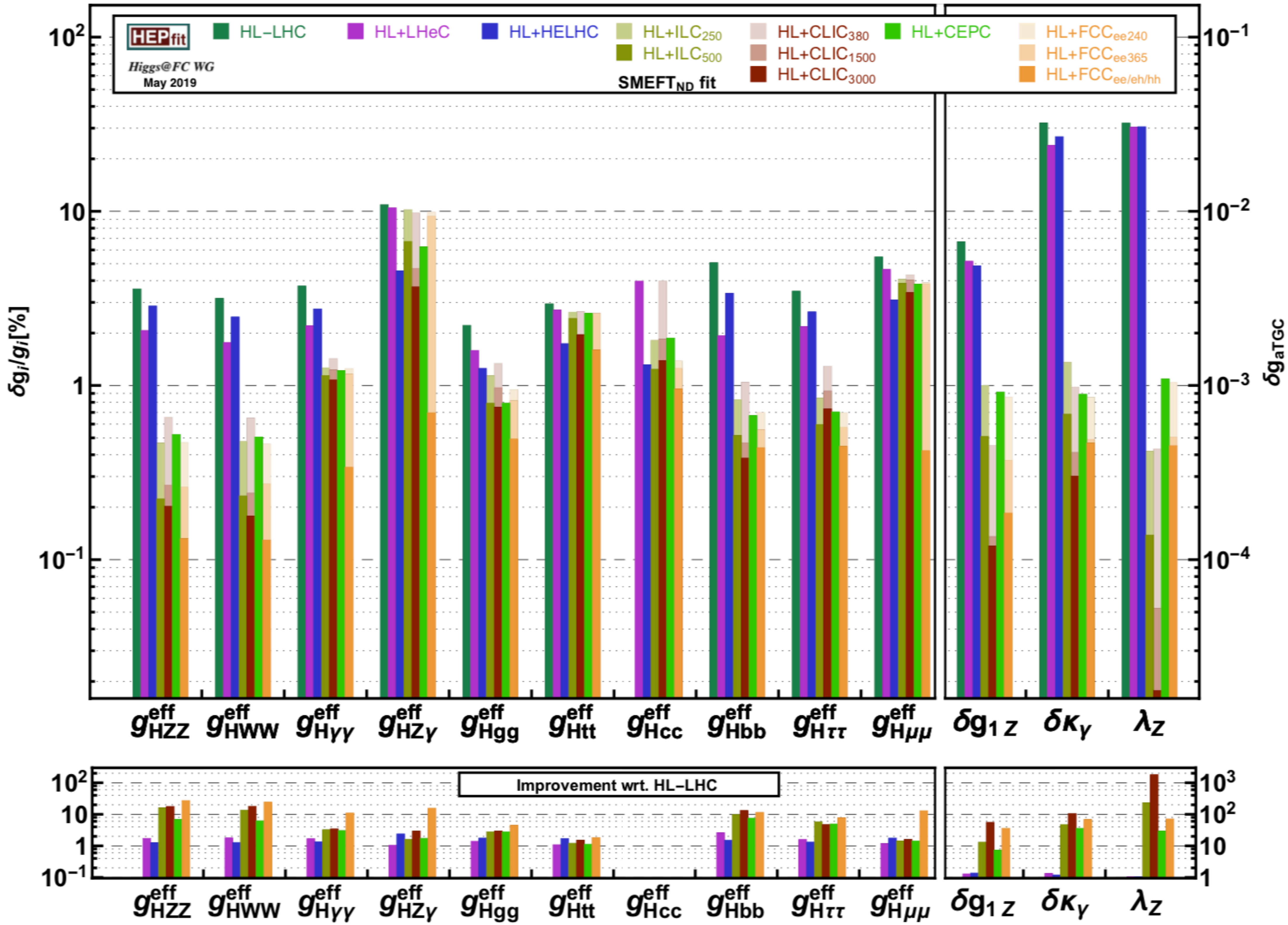
- *BR(h->γγ)* and *BR(h->γZ)* -> c_{BB}, c_{WW};
- σ_{ZH} -> c_H; σ_{ZHH} -> c_6;
- *BR(h->bb/cc/gg/μμ/ττ)* -> y_b, y_c, c_g, y_μ, y_τ;
- *BR(h->invisible)* and *BR(h->other)*;
- c_{WW} is helped by A_{LR} in σ_{ZH}, angular meas., W-fusion;
- c_{HL}/c_{HL}'/c_{HE} are helped by A_{LR} in σ_{ZH}

(details in backup)

ECFA Higgs @ FC WG

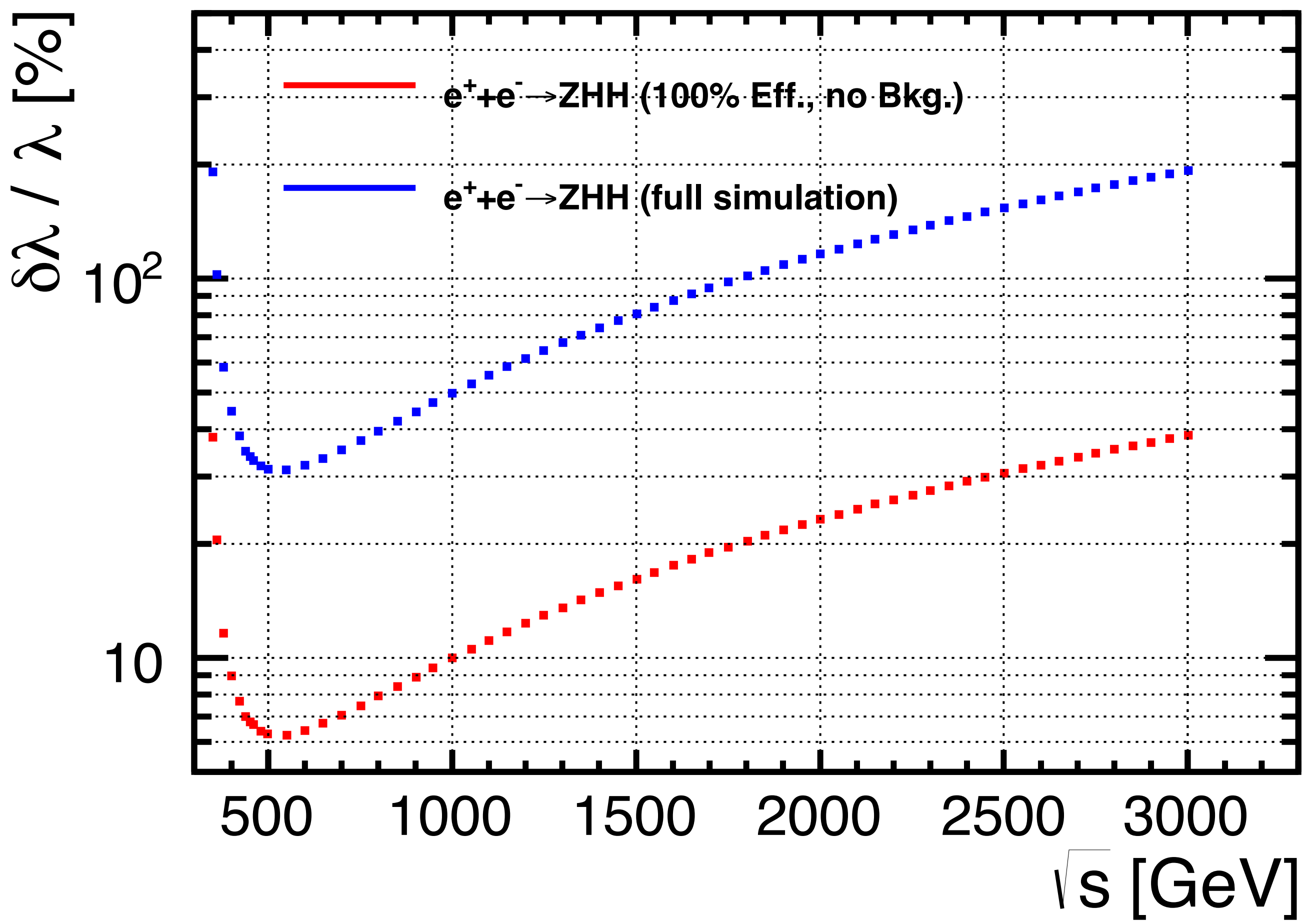
collider	(1) di-H excl.	(2.a) di-H glob.	(3) single-H excl.	(4) single-H glob.
HL-LHC	$^{+60}_{-50}$% (50%)	52%	46%	50%
HE-LHC	10-20% (n.a.)	n.a.	41%	50%
ILC_{250}	–	–	28%	49%
ILC_{350}	–	–	28%	47%
ILC_{500}	27% (27%)	27%	26%	37%
$CLIC_{380}$	–	–	45%	50%
$CLIC_{1500}$	36% (36%)	36%	40%	49%
$CLIC_{3000}$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

ECFA Higgs @ FC WG

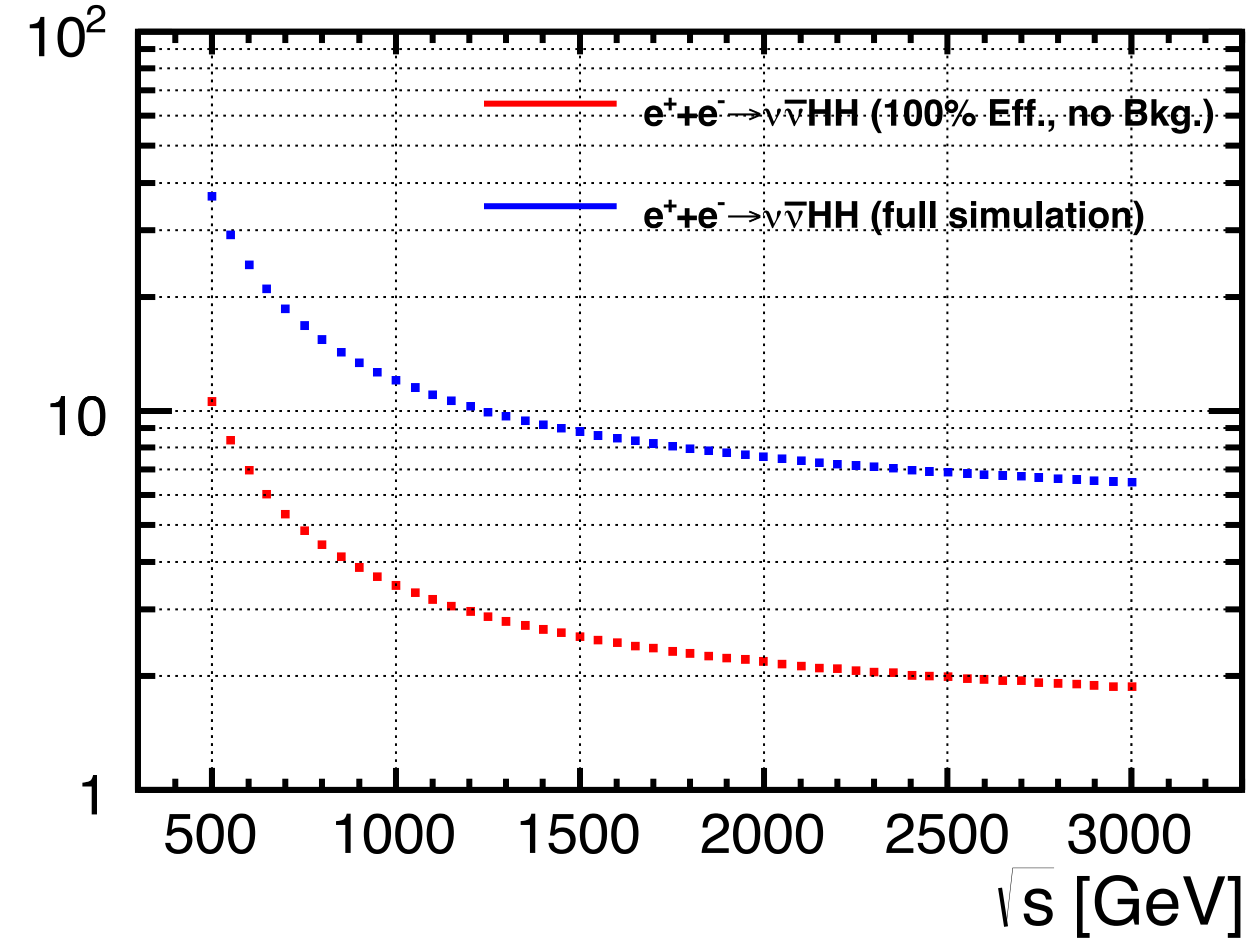


expected precision of λ: impact of Ecm

ZHH

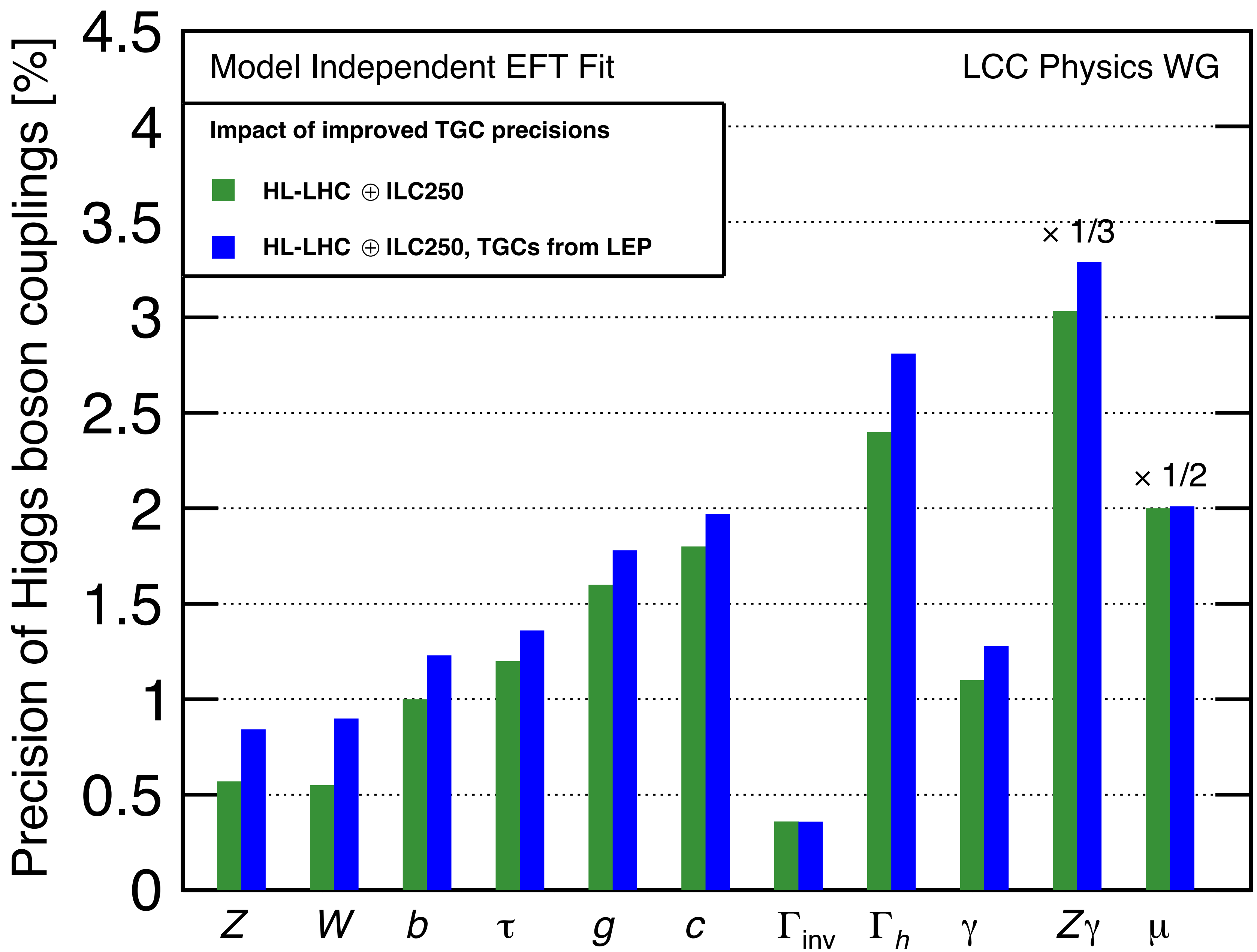


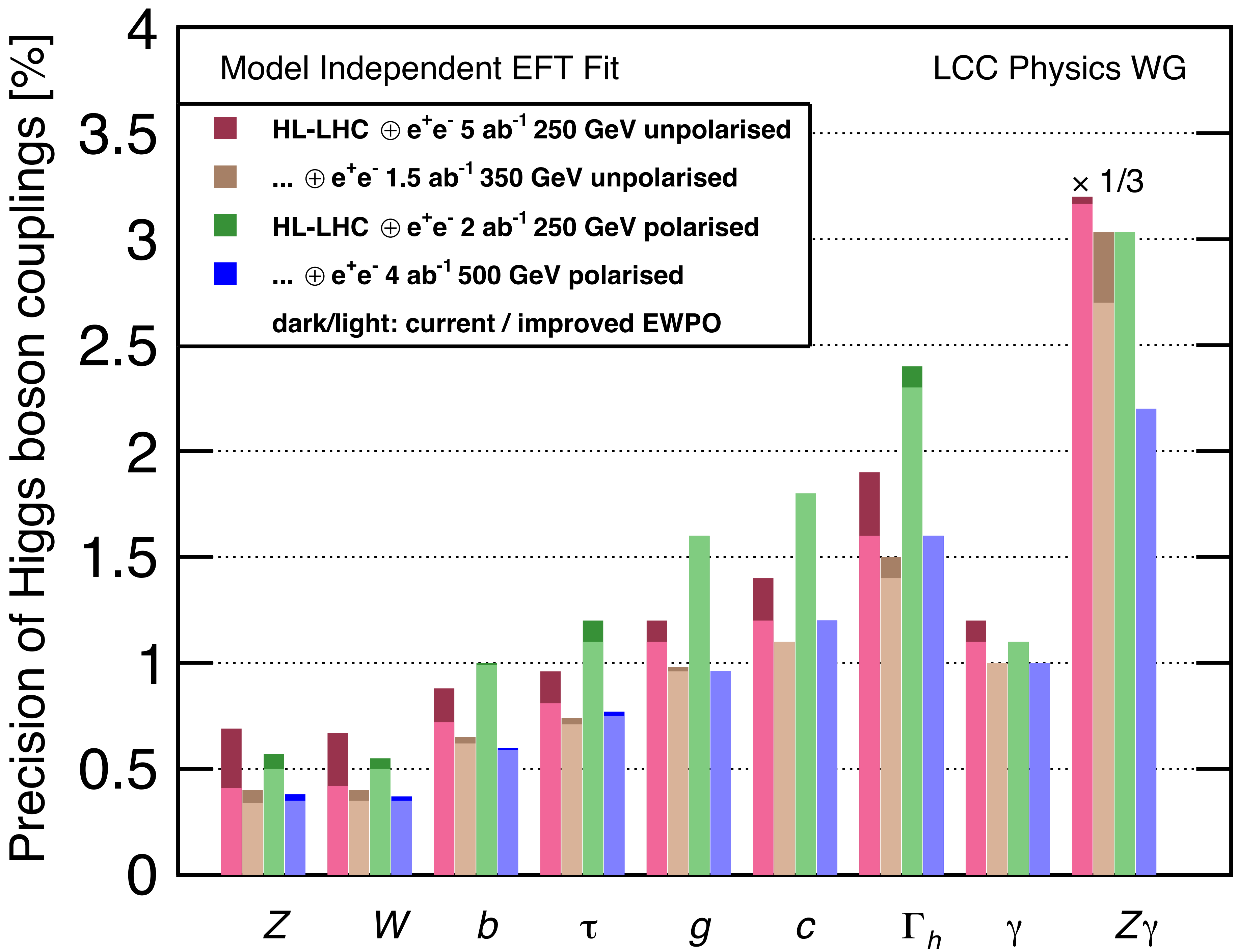
ννHH



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

impact of TGCs

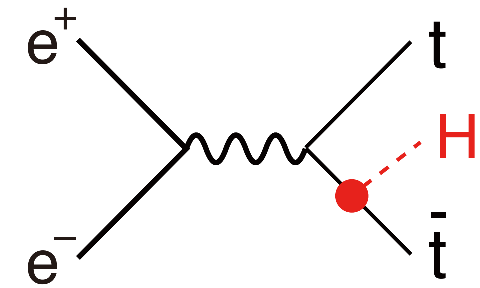




Model Independent EFT Fit
LCC Physics WG
HL-LHC ⊕ e+e- 5 ab-1 250 GeV unpolarised
... ⊕ e+e- 1.5 ab-1 350 GeV unpolarised
HL-LHC ⊕ e+e- 2 ab-1 250 GeV polarised
... ⊕ e+e- 4 ab-1 500 GeV polarised
dark/light: current / improved EWPO
× 1/3
Precision of Higgs boson couplings [%]
0
0.5
1
1.5
2
2.5
3
3.5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

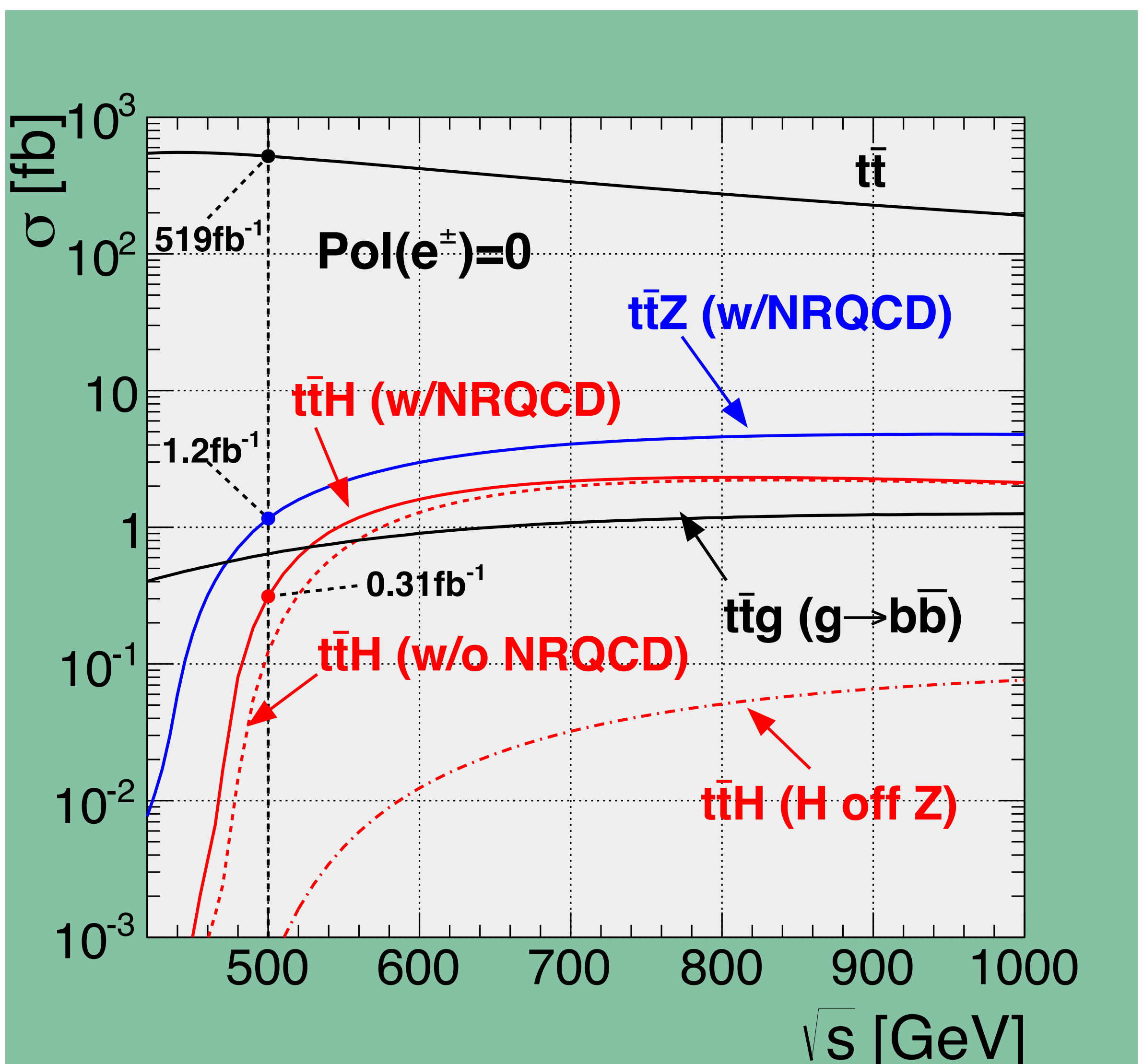
(ii-5) Top-Yukawa coupling

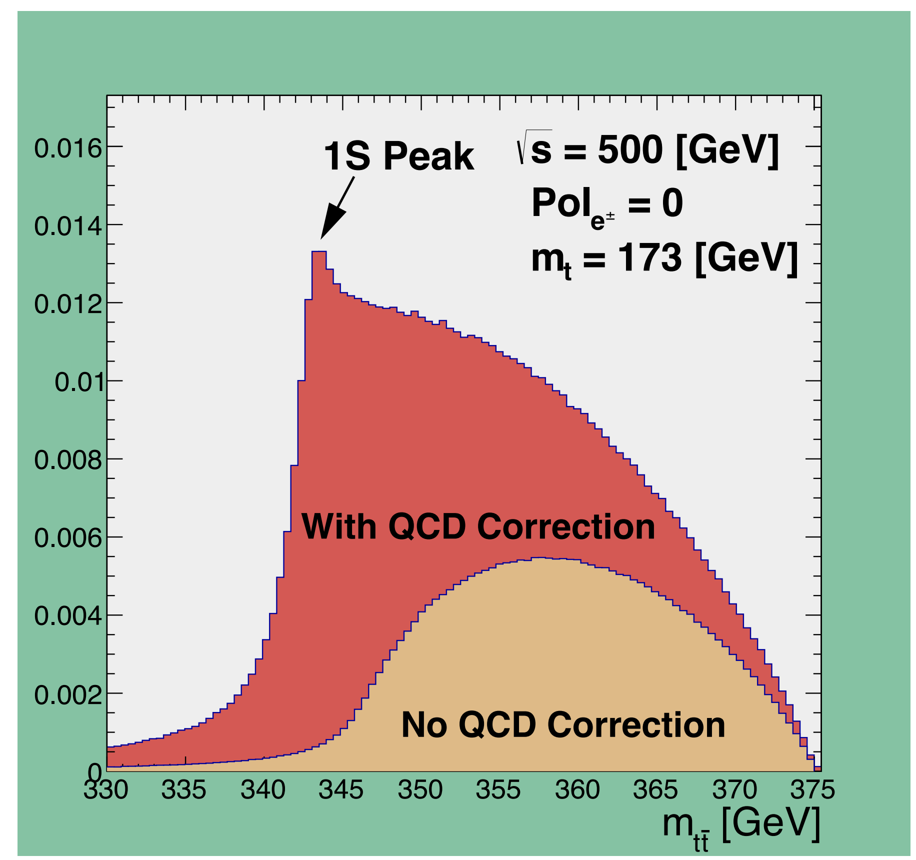
- largest Yukawa coupling; crucial role in theory
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



H-> bb

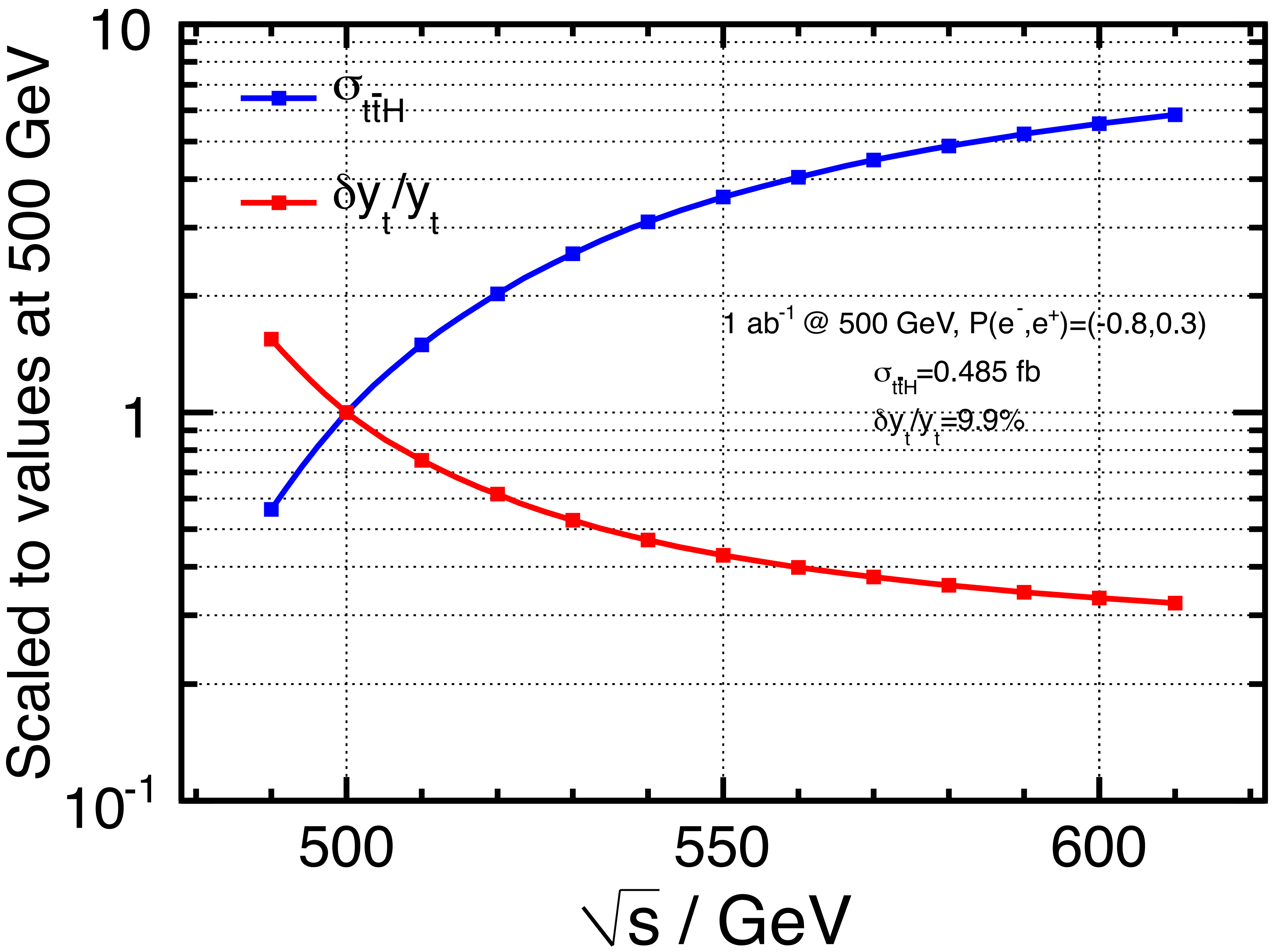
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
Snowmass	7.8%	2.0%
H20	6.3%	1.5%





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

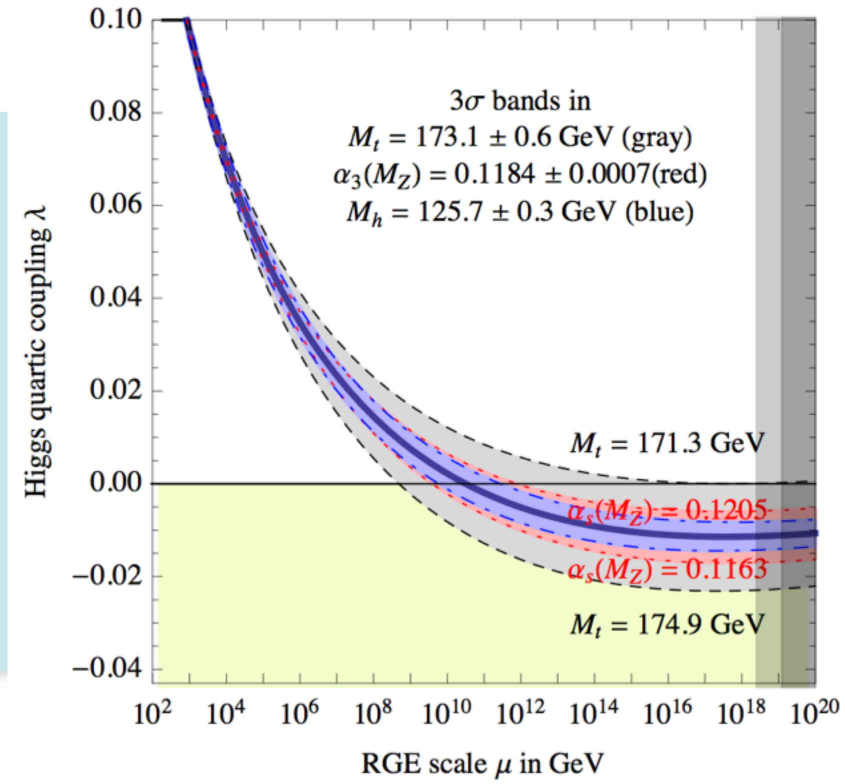
Top-Yukawa coupling

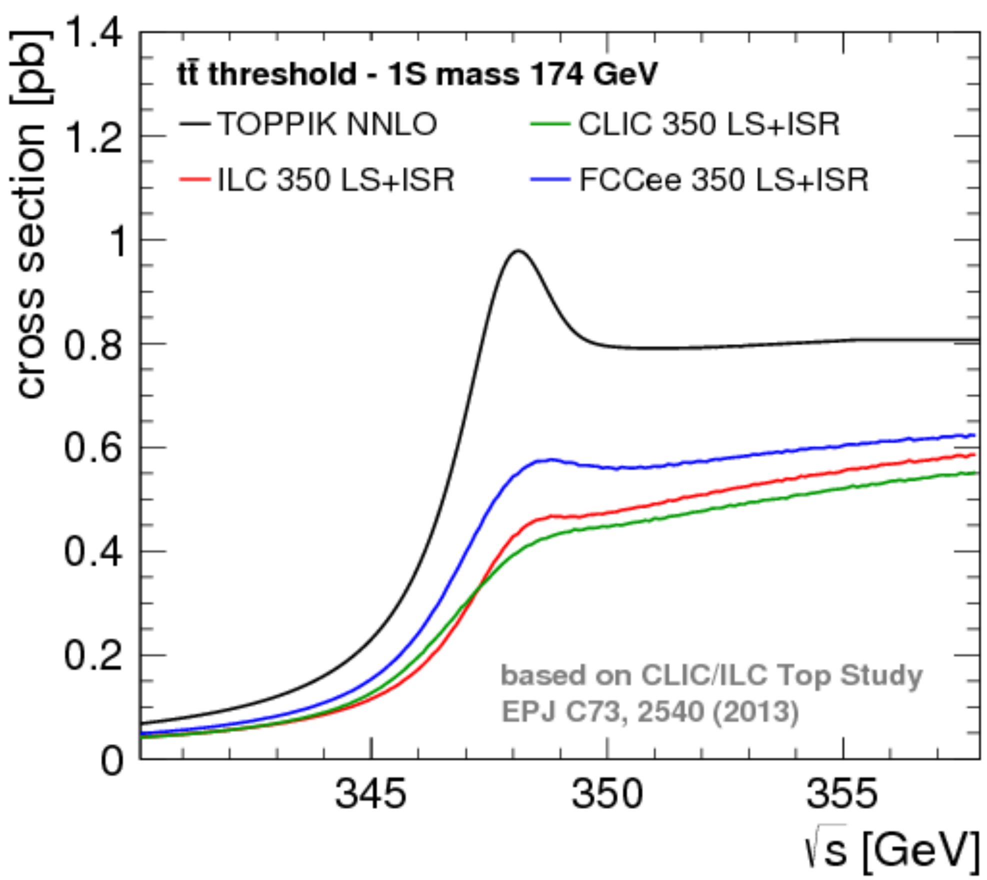


Y. Sudo

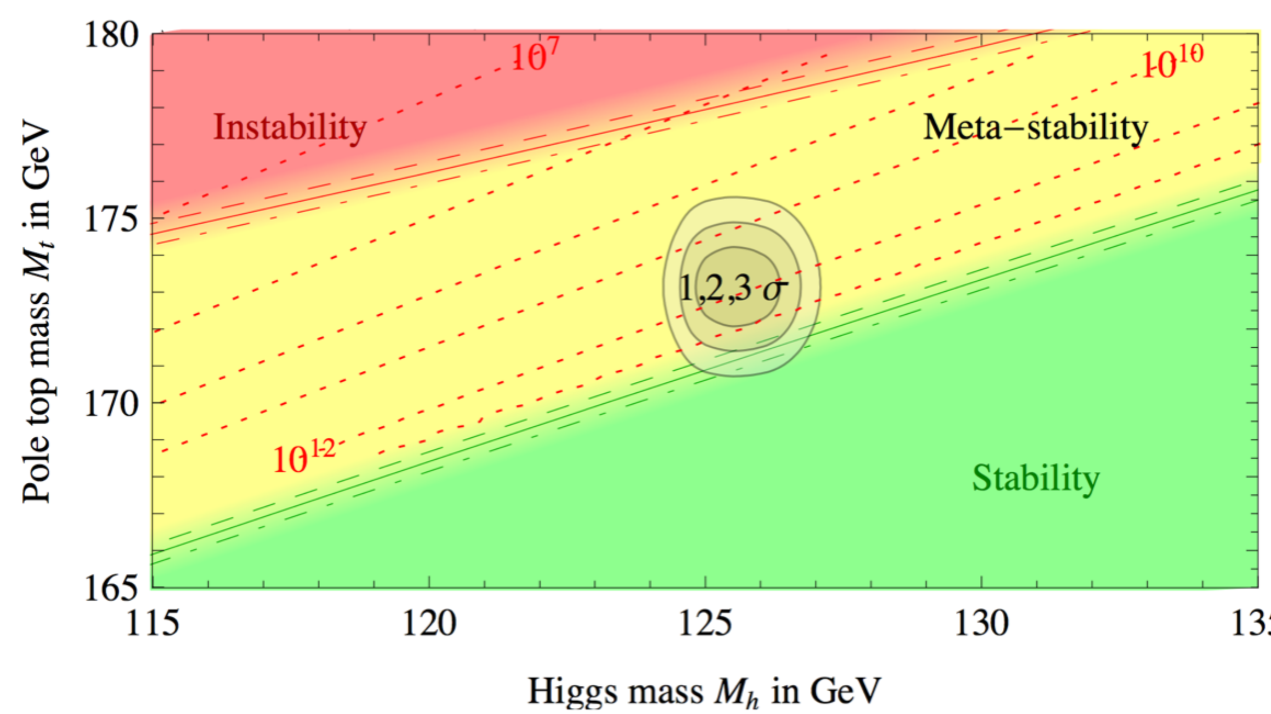
vacuum stability

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





Degrassi et al, JHEP 1208 (2012) 098



simplifications of our analysis

- at tree level, and to linear order in D-6 coefficients
- ignore some possible D-6 corrections involving light leptons, e.g. 4-fermion operators
- avoid using observables that involve contact interactions that include quark currents (see more later)
- ignore the effects of CP-violating operators

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

on-shell renormalization

- D-6 operators modify the SM expressions for precision electroweak observables, thus shift the appropriate values for the SM couplings —> g, g', v, λ free parameters
- D-6 operators also renormalize the kinetic terms of the SM fields —> rescale the boson fields

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

with

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

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

systematic errors included in the global fit

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

improvement factors in S2

- 10% from better jet-clustering algorithm
- 20% from better flavor-tagging algorithm
- 20% from including more signal channels in h->WW*
- x10 better for A_{LR} using e+e- -> γ Z at ILC250

EFT input from TGCs in e+e- -> W^+W^-

	250 GeV W^+W^-	350 GeV W^+W^-	500 GeV W^+W^-
g_{1Z}	0 .062 *	0.033 *	0.025
κ_A	0.096 *	0.049 *	0.034
λ_A	0.077 *	0.047 *	0.037
$\rho(g_{1Z}, \kappa_A)$	63.4 *	63.4 *	63.4
$\rho(g_{1Z}, \lambda_A)$	47.7 *	47.7 *	47.7
$\rho(\kappa_A, \lambda_A)$	35.4 *	35.4 *	35.4

(arXiv: 1708.08912; numbers are in %, for nominal $\int Ldt = 500\ fb^{-1}$ shared equally by left-/right- polarized data)

EFT input: EWPOs

Observable	current value	current σ	future σ	SM best fit value
$\alpha^{-1}(m_Z^2)$	128.9220	0.0178		(same)
G_F (10^{-10} GeV^{-2})	1166378.7	0.6		(same)
m_W (MeV)	80385	15	5	80361
m_Z (MeV)	91187.6	2.1		91188.0
m_h (MeV)	125090	240	15	125110
A_ℓ	0.14696	0.0013		0.147937
Γ_ℓ (MeV)	83.984	0.086		83.995
Γ_Z (MeV)	2495.2	2.3		2494.3
Γ_W (MeV)	2085	42	2	2088.8

EFT input: EWPOs (7)

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

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

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

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

(δX=ΔX/X)

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

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

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

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

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

$\longrightarrow$ δg, δg', δv, δλ, c_T

EFT input: EWPOs (7)

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

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

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

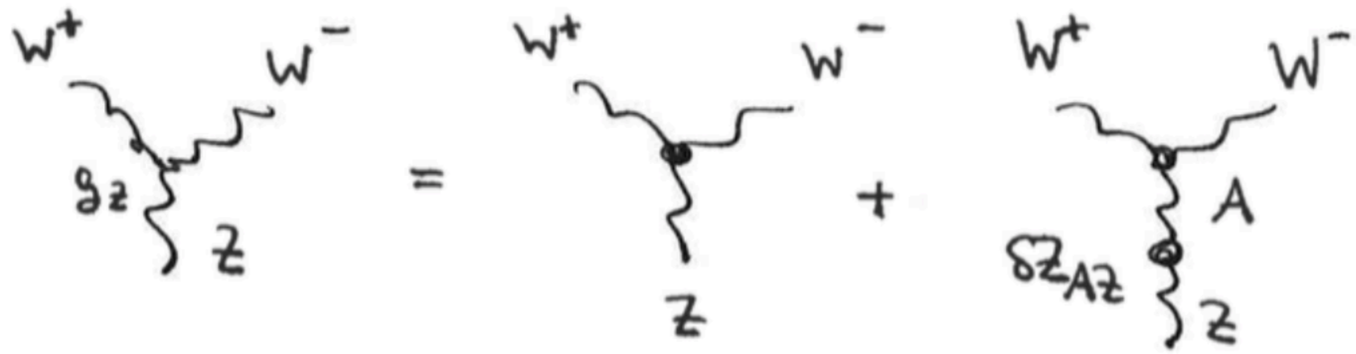
$$g_L = \frac{g}{c_w}\left[(-\frac{1}{2} + s_w^2)(1 + \frac{1}{2}\delta Z_Z) - \frac{1}{2}(c_{HL} + c'_{HL}) - s_w c_w \delta Z_{AZ}\right]$$

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

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

EFT input: TGC (3)

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

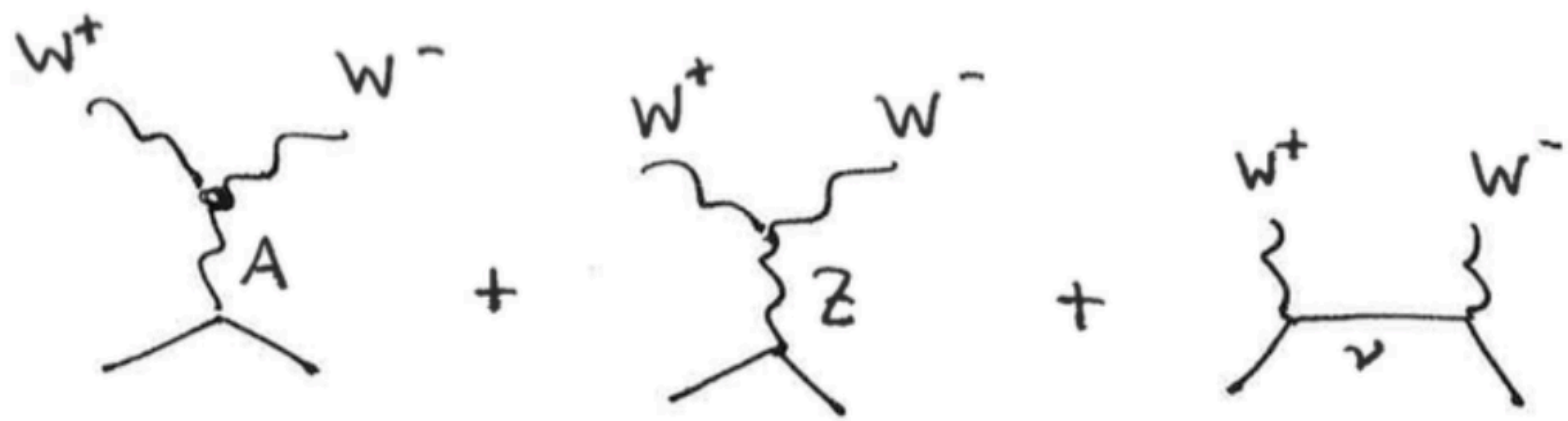


$$g_Z = gc_w(1 + \frac{1}{2}\delta Z_Z + \frac{s_w}{c_w}\delta Z_{AZ})$$

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

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

EFT input: TGC (3)



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

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

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-

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)