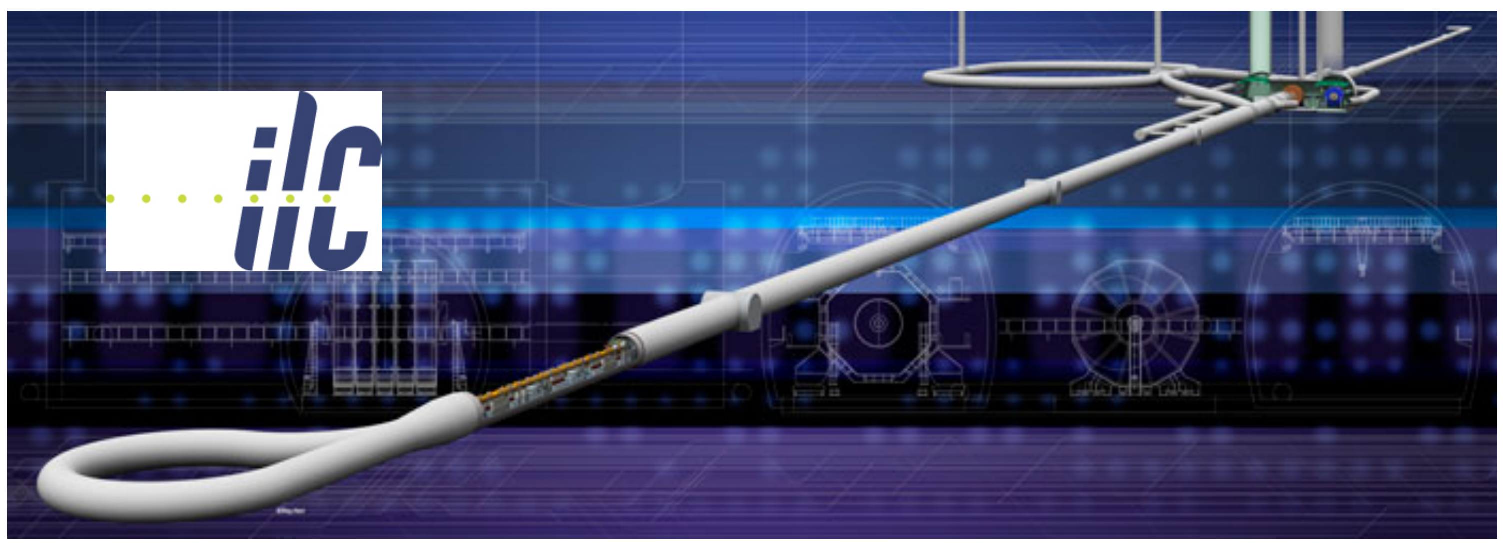
Higgs Precision Measurement at the ILC

ILC Supporters



ICEPP
The University of Tokyo

Junping Tian (U. Tokyo)

the 4th Kavli IPMU - Durham IPPP - KEK - KIAS Workshop
“Beyond the BSM”, October 1-4, 2018 @ Ikaho

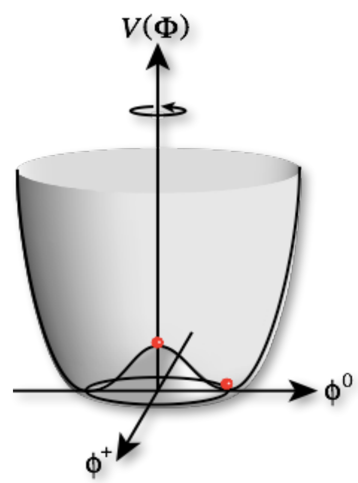
well documented Higgs physics at the ILC

- Report by the Committee on the Scientific Case of the ILC operating at 250 GeV as a Higgs Factory — Asai, et al, arXiv: 1710.08639
- Physics Case for the 250 GeV Stage of the ILC — Fujii, et al, arXiv: 1710.07621
- Physics Case for the International Linear Collider — Fujii, et al, arXiv: 1506.05992
- ILC TDR — Volume 2: Physics — Baer, et al, arXiv: 1306.6352
- ILC Higgs White Paper — Asner, et al, arXiv: 1310.0763

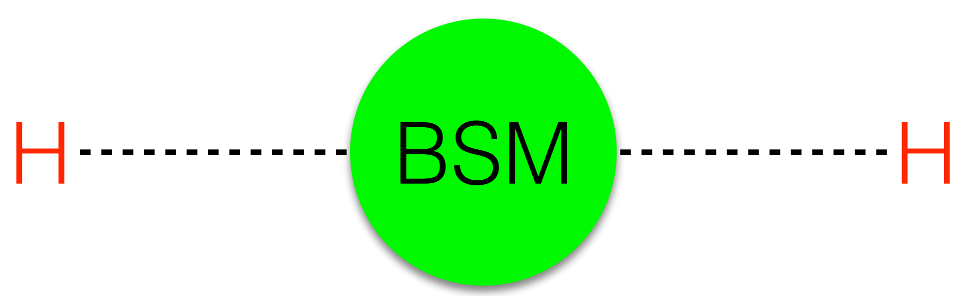
outline

- introduction: Higgs as a window for BSM
- Precision Higgs Physics at ILC250 (focus of this talk)
- Higgs Physics at ILC beyond 250 GeV
- ILC status

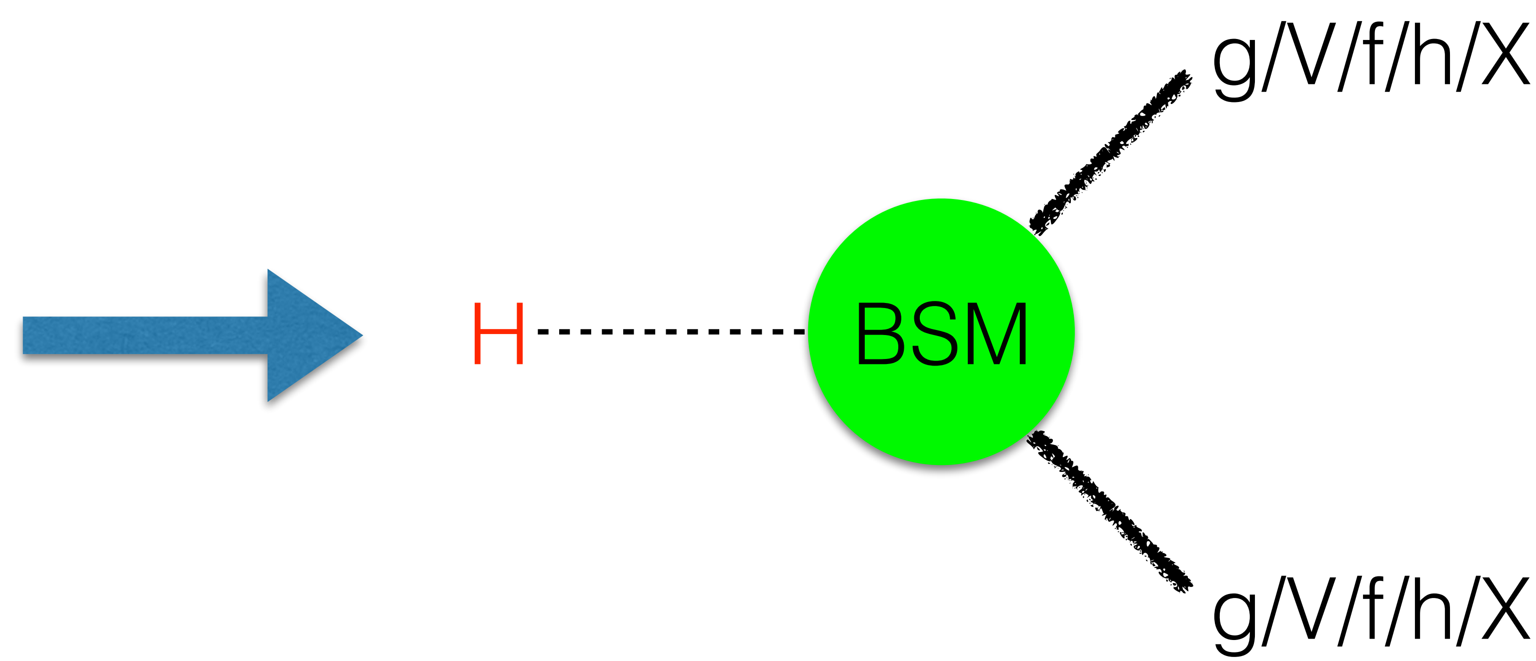
Higgs as a window for BSM



- What is the origin of EWSB?
- Naturalness of the light scalar mass?
- Connection to Dark Matter, BAU, inflation?



mysteries in the EW vacuum

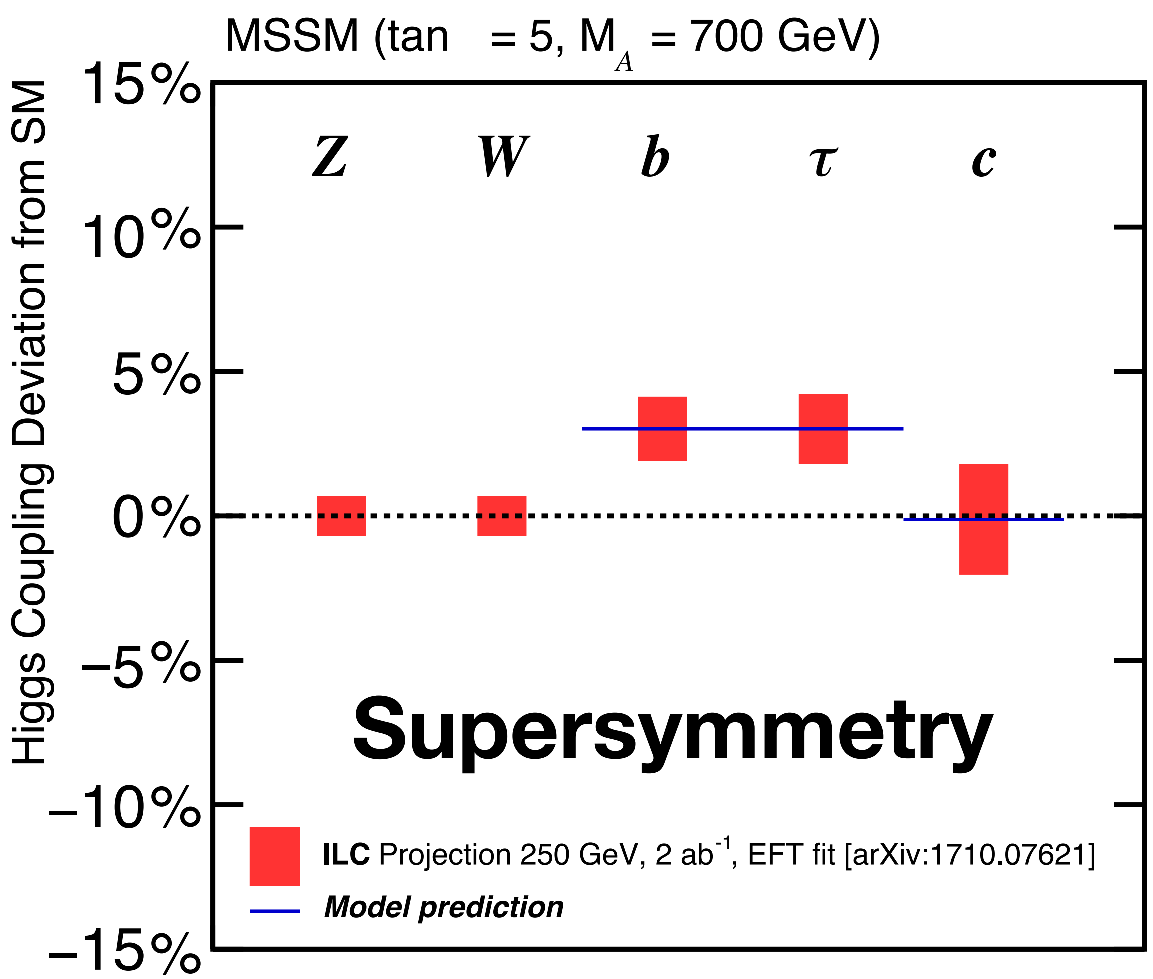


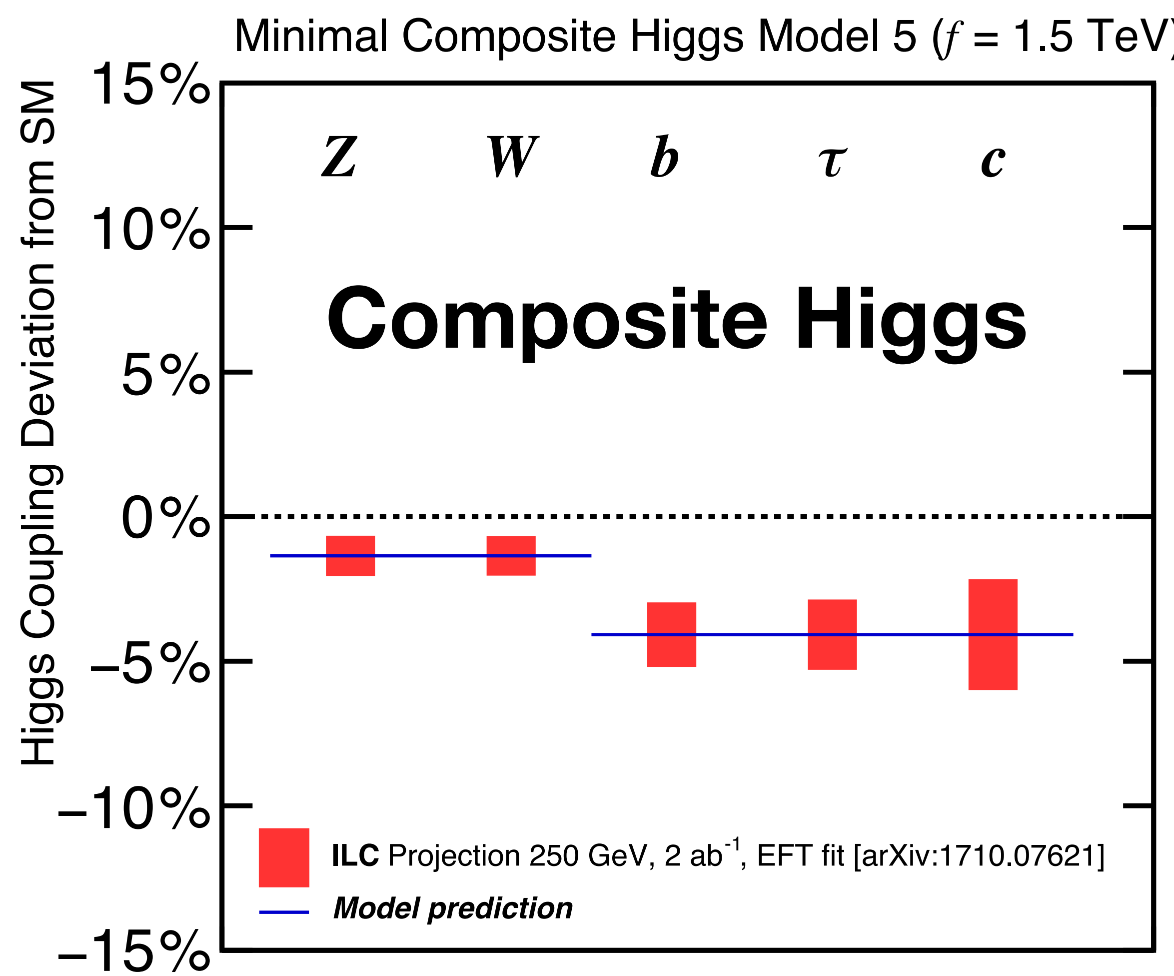
can be revealed by looking in detail at Higgs properties

Higgs as a window for BSM

- fingerprint BSM by patterns of deviations

—> measure as many couplings as possible

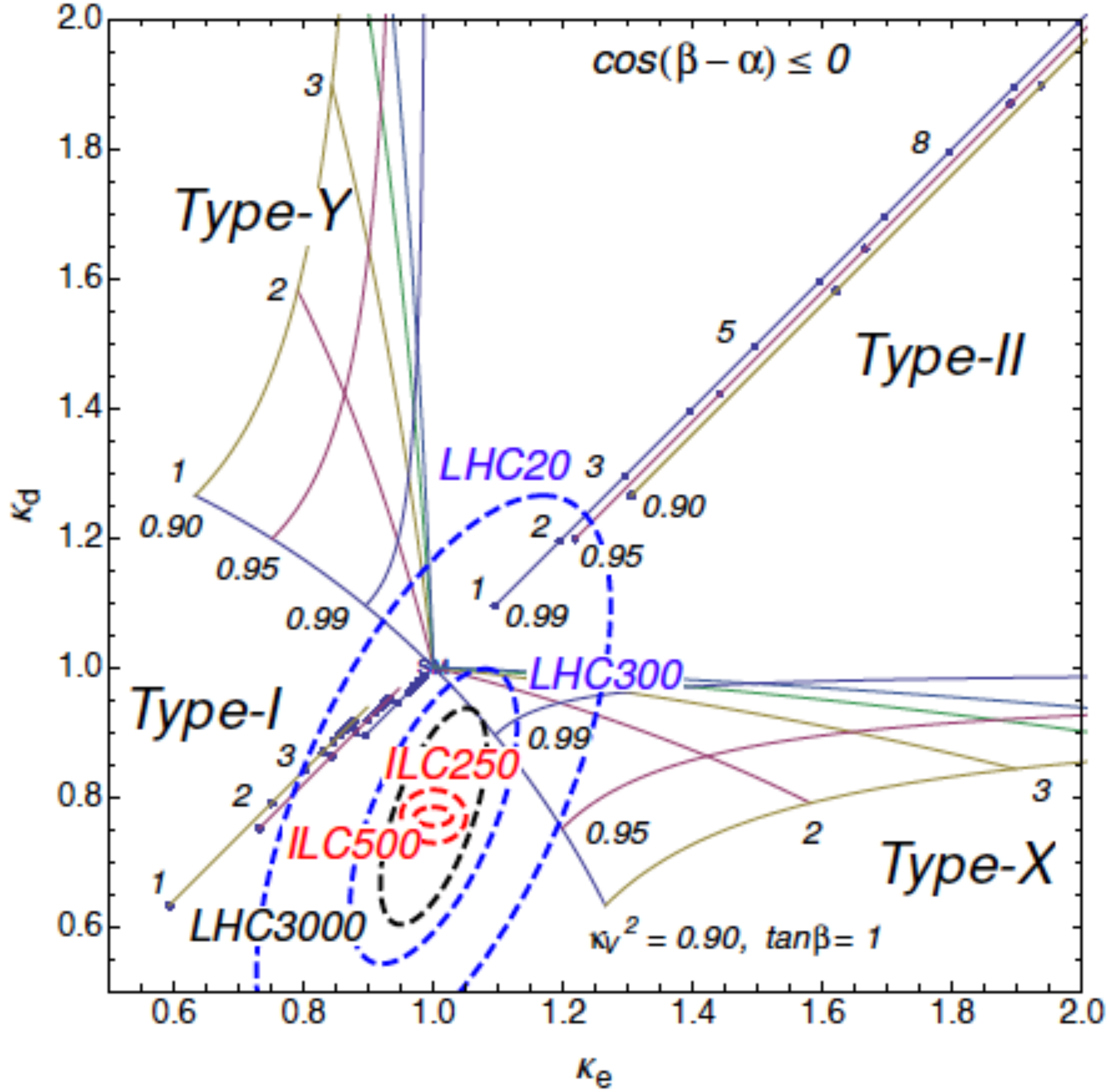




deviation is typically small, 1-10% for m_{BSM}~1TeV

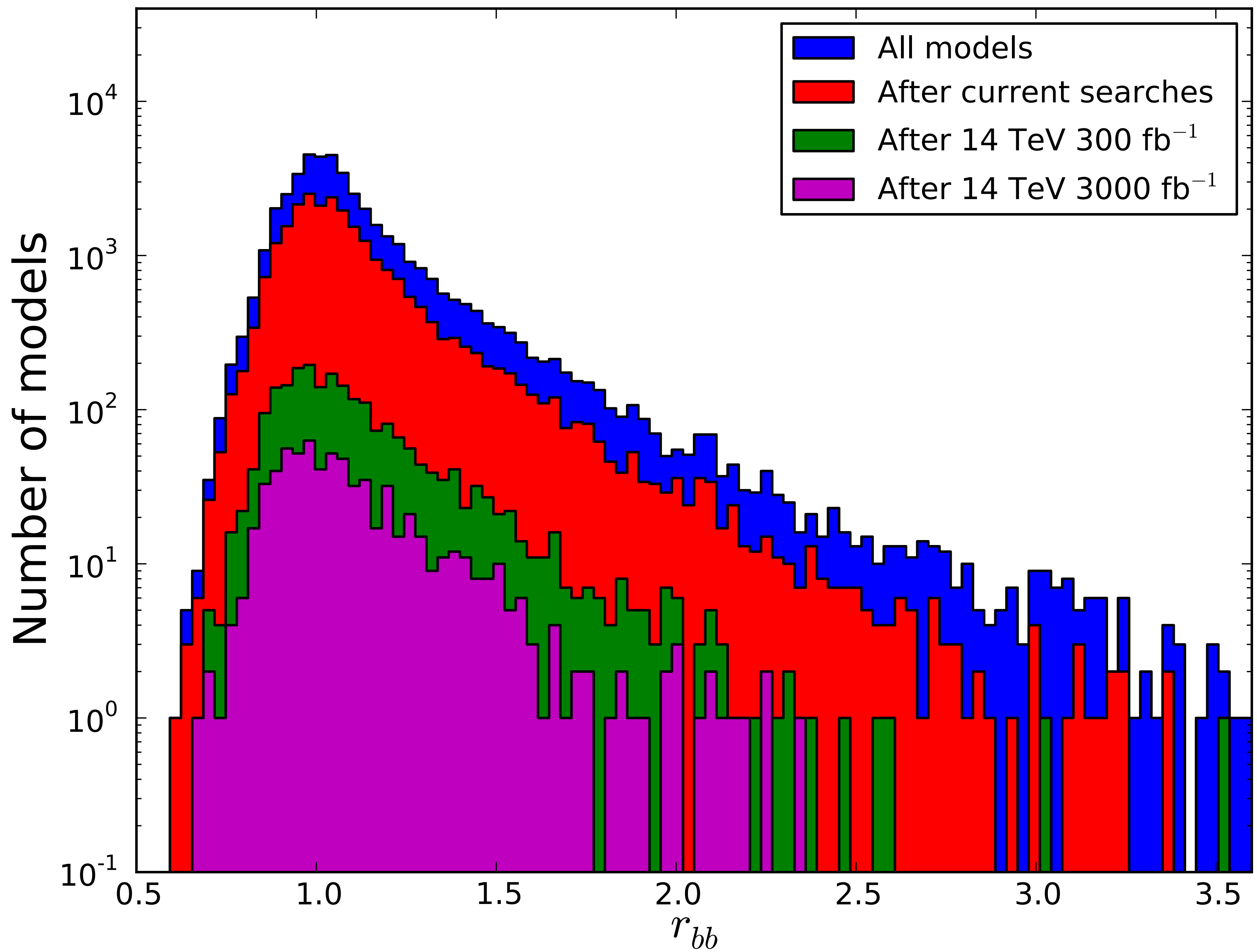
—> need 1% or below measurement

fingerprint 4 types of 2HDM: gHbb .vs. gHττ



Kanemura, et al, arXiv: 1406.3294

synergy with LHC: direct and indirect discoveries



Cahill-Rowley, et al, arXiv:1308.0297

Figure 8: Histograms of the ratio $r_{bb} = \Gamma(h \to \bar{b}b)/\Gamma(h \to \bar{b}b)_{\rm SM}$ within a scan of the approximately 250,000 supersymmetry parameter sets after various stages of the LHC, assuming the LHC does not find direct evidence for supersymmetry. The purple histogram shows parameter points that would not be discovered at future upgrades of the LHC (14 TeV and $3\,{\rm ab}^{-1}$ integrated luminosity). From [38].

ILC250: International Linear Collider at $\sqrt{s}$=250 GeV

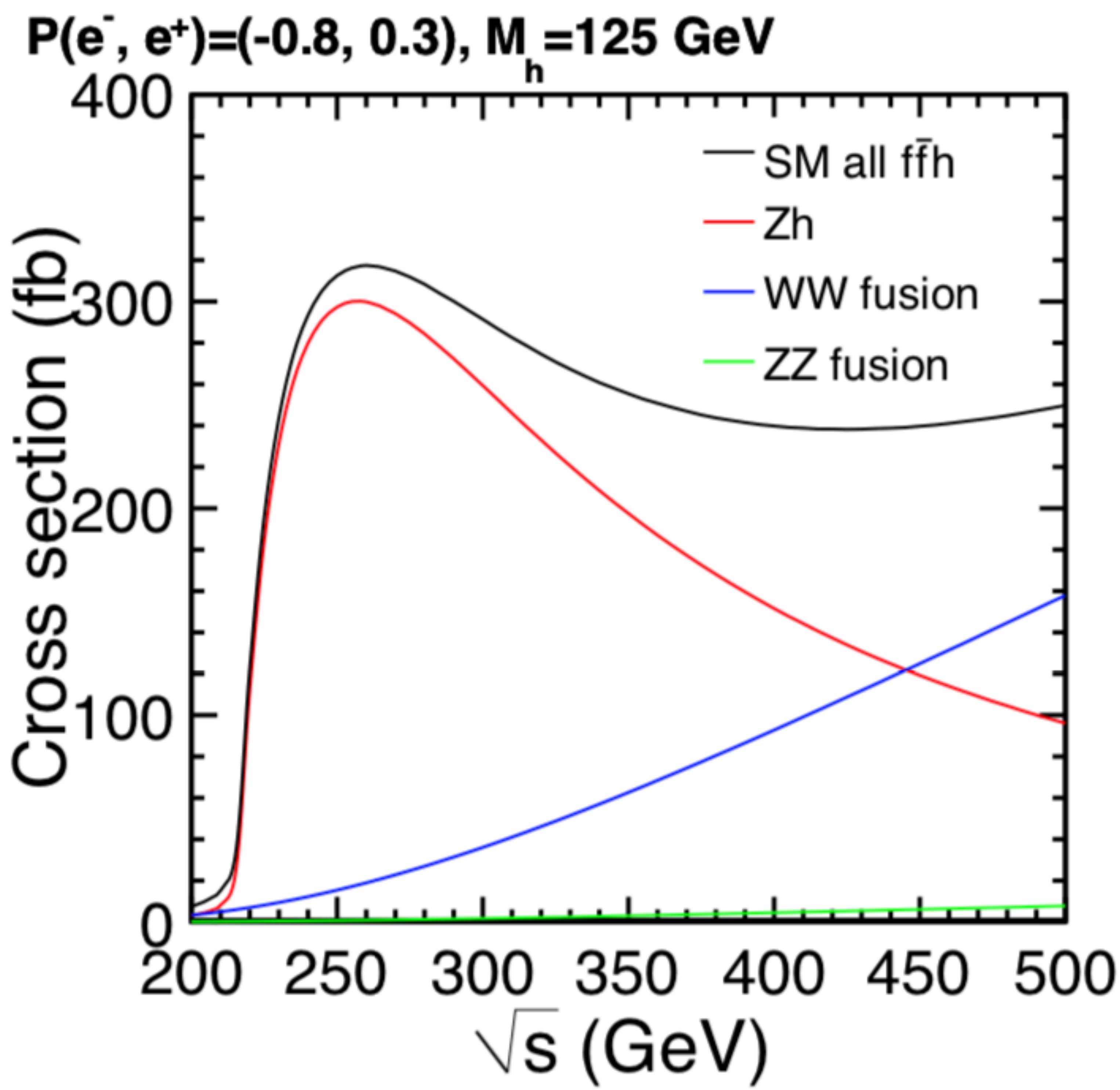
- ILC was proposed as a 500 GeV e+e- machine in TDR (2013)

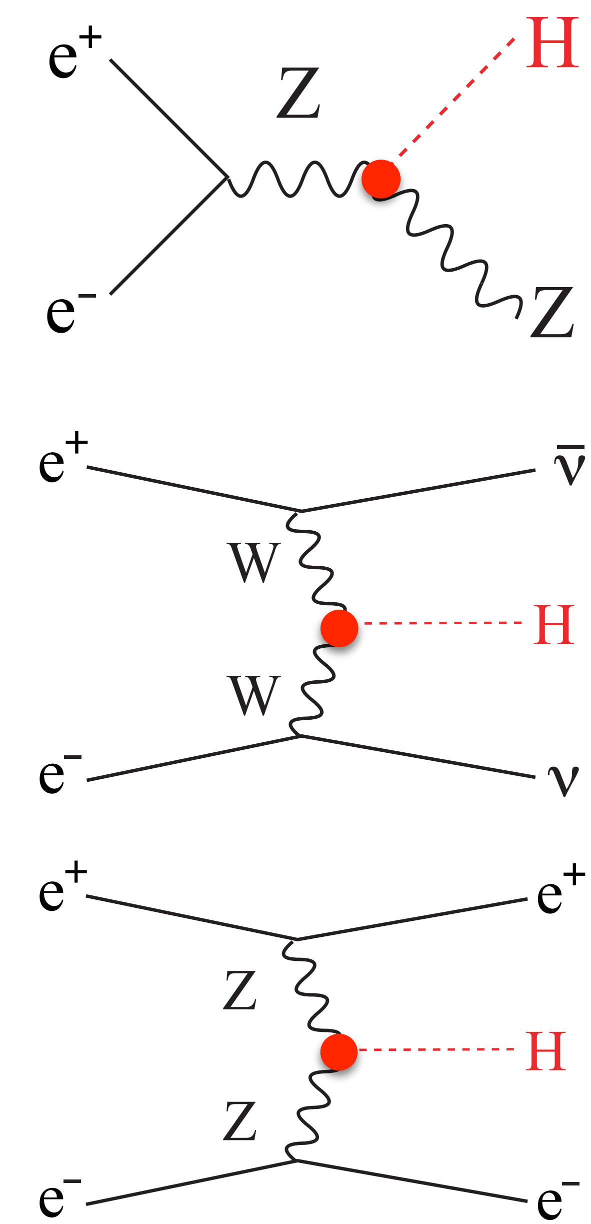
- in view of the new results by LHC Run 2 and the cost reduction issue, ILC is now proposed as a 250 GeV machine (ILC250 as a Higgs Factory) hopping for an early realization

  $\int L dt = 2\ ab^{-1}$, ~0.5M Higgs, $P(e^-,e^+)=(80\%,30\%)$

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

How Higgs is produced at e+e-





- at √s ~ 250 GeV e+e- -> ZH attains its cross section maximum

what are the direct Higgs observables at ILC250

- ☑ σ_{ZH}
- ☑ $\sigma_{ZH}\times Br(H\text{—>}bb)$, $\sigma_{\nu\nu H}\times Br(H\text{—>}bb)$
- ☑ $\sigma_{ZH}\times Br(H\text{—>}cc)$
- ☑ $\sigma_{ZH}\times Br(H\text{—>}gg)$
- ☑ $\sigma_{ZH}\times Br(H\text{—>}WW^*)$
- ☑ $\sigma_{ZH}\times Br(H\text{—>}ZZ^*)$
- ☑ $\sigma_{ZH}\times Br(H\text{—>}\tau\tau)$
- ☑ $\sigma_{ZH}\times Br(H\text{—>}\gamma\gamma)$
- ☑ $\sigma_{ZH}\times Br(H\text{—>}\mu\mu)$
- ☑ $\sigma_{ZH}\times Br(H\text{—>}Invisible)$

+ $d\sigma/d\Omega$

what are the direct Higgs observables at ILC250

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

+ $d\sigma/d\Omega$

note the important complementarity with LHC

expected accuracies of Higgs observables at ILC250

(based on full detector simulations for ILD and SiD)

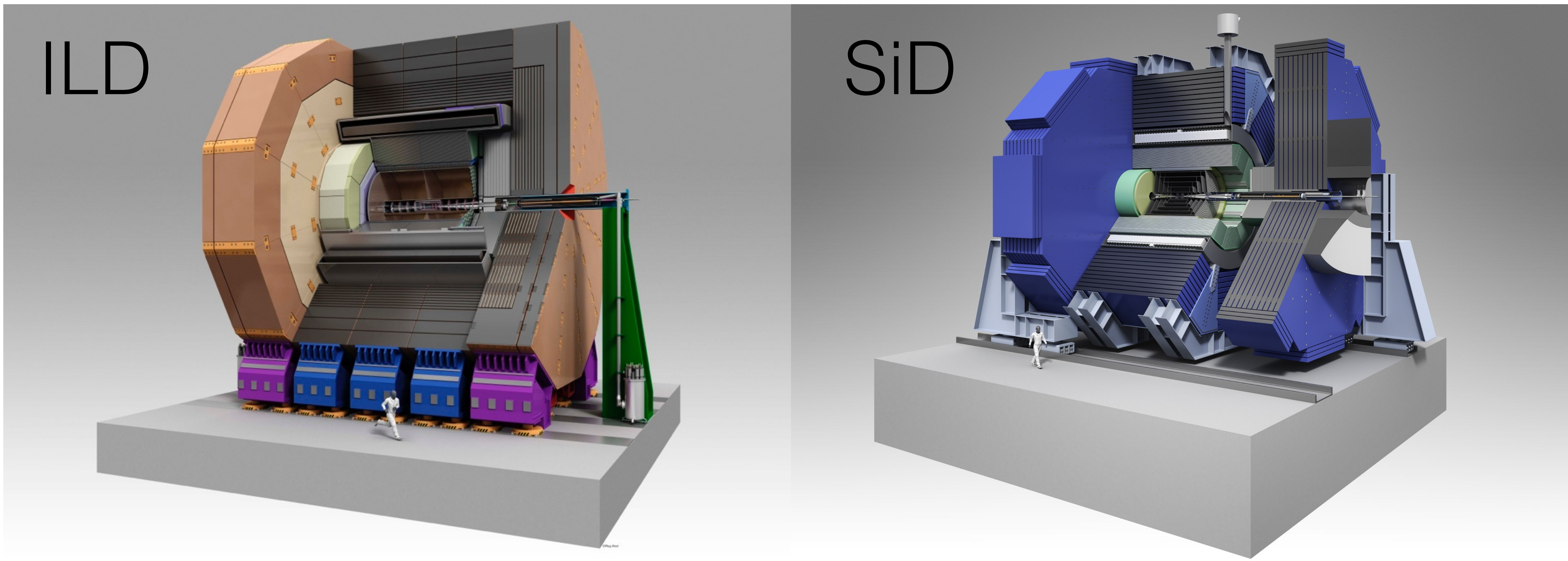
-80% e^-, +30% e^+ polarization:

	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})

expected accuracies of Higgs observables at ILC250

(based on full detector simulations for ILD and SiD)

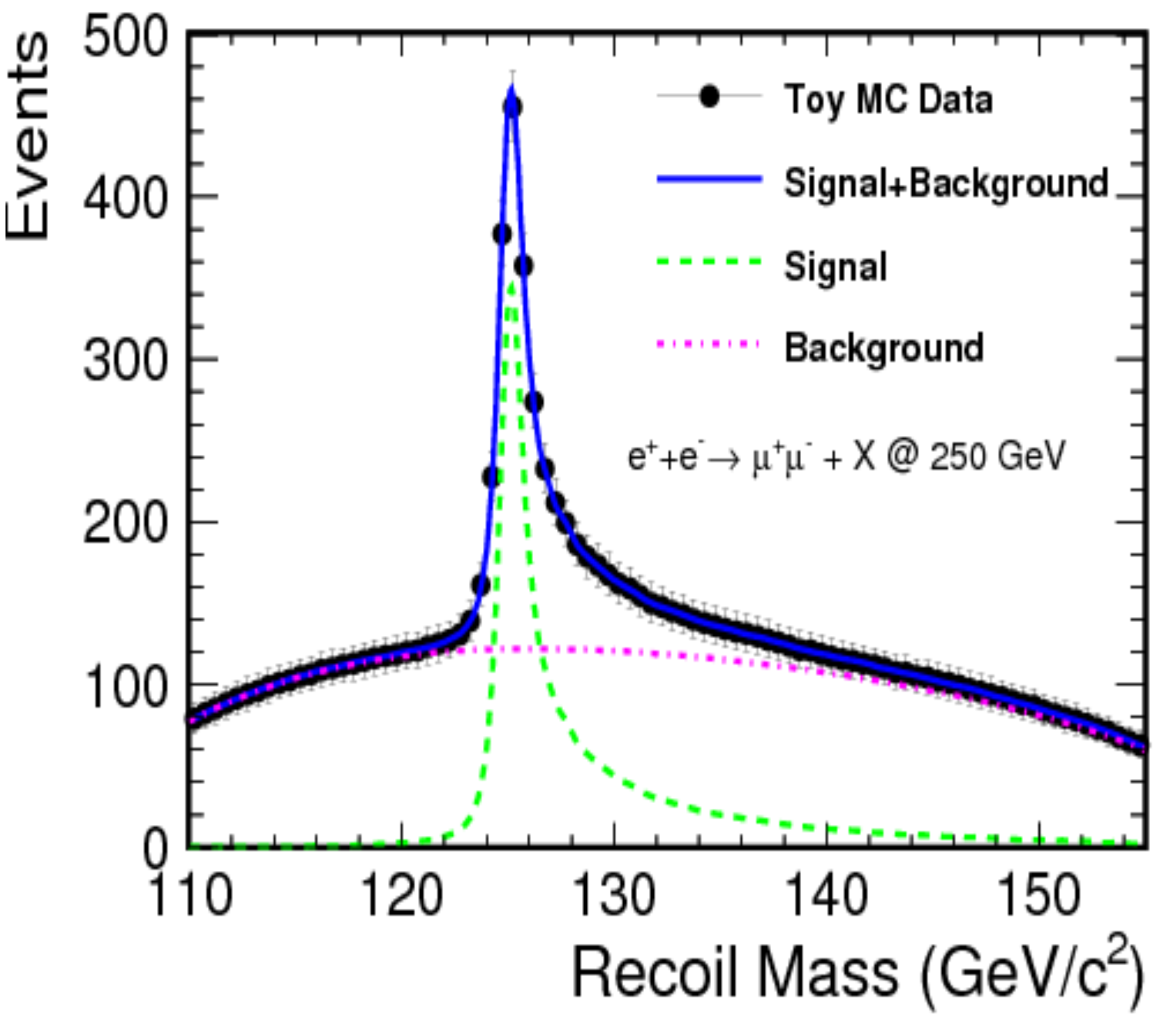


a [illegible]	[illegible]	[illegible]	[illegible]
b	2.7	0.69 *	0.70
$\rho(a,b)$	-99.17	-95.6 *	-84.8

(arXiv: 1708.08912; numbers are in %, for nominal $\int Ldt$ = 250 fb^{-1})

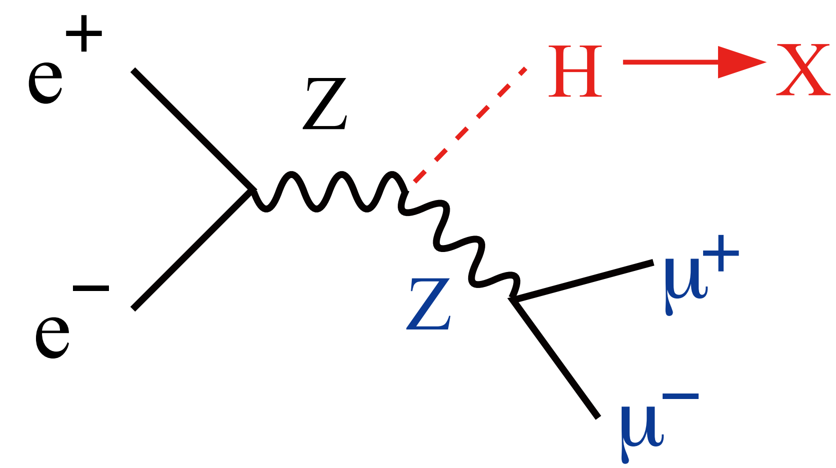
- Precision Higgs Physics at ILC250
  - some key experimental observables
  - from observable to couplings: kappa & EFT
  - BSM models discrimination & next energy scale
  - Higgs CP, Higgs exotic decays

inclusive σ_{ZH}: the key of model independence



$\Delta m_H = 14\text{MeV}$ $\delta g_{HZZ} \sim 0.38\%$

$Y_1 = \sigma_{ZH} \propto g^2_{HZZ}$

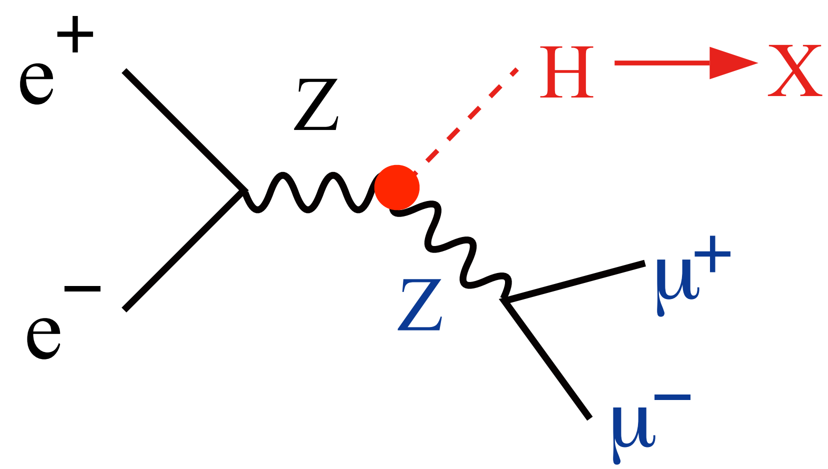


$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

- 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

for Z->ll (leptonic recoil), Yan et al, arXiv:1604.07524;
for Z->qq (hadronic recoil), Thomson, arXiv:1509.02853

what does model independence mean?



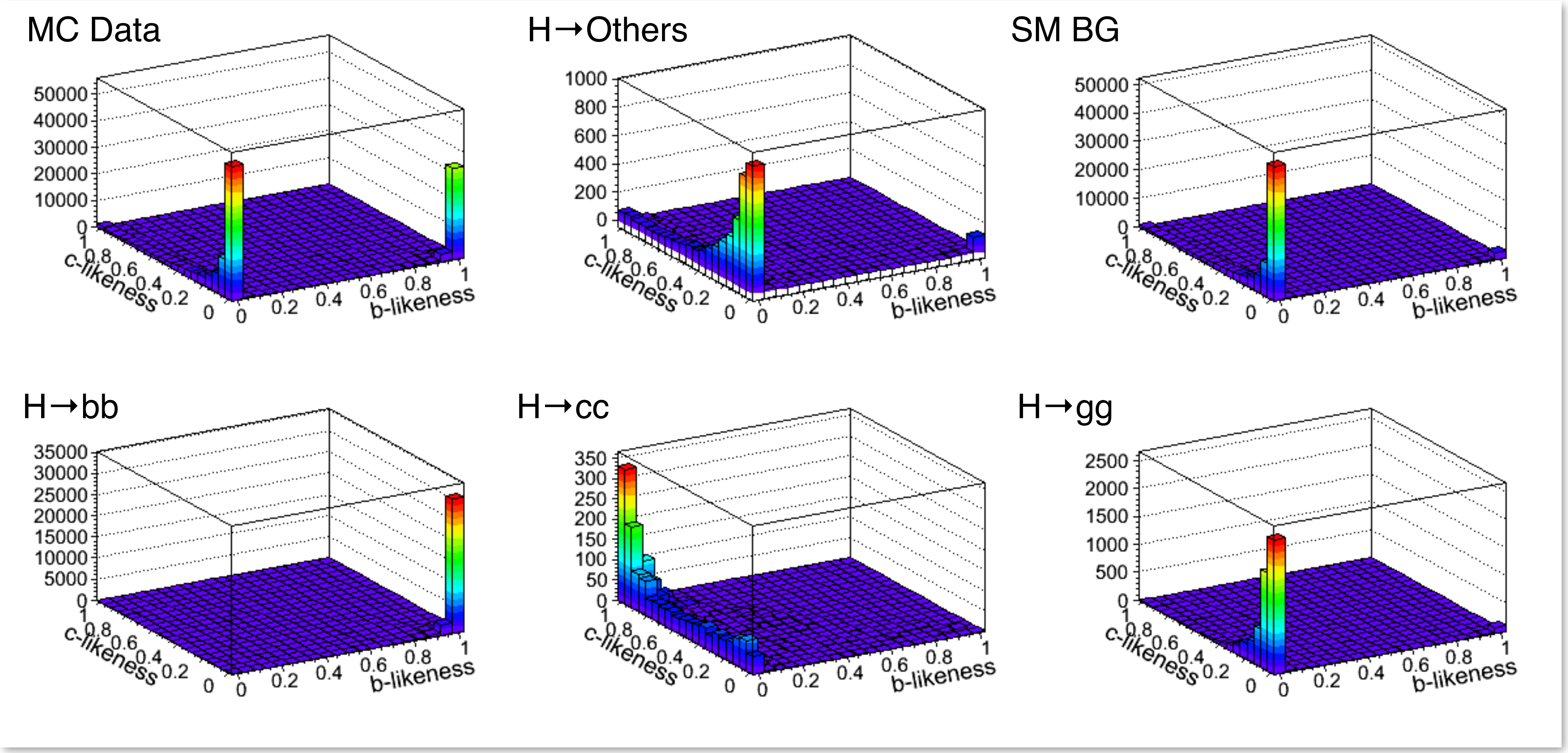
$$M_X^2 = \left(p_{CM} - (p_{\mu^+} + p_{\mu^-})\right)^2$$

- 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? (Yes, but not trivial at all, see backup slides)

Higgs direct couplings to cc and gg at ILC250

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



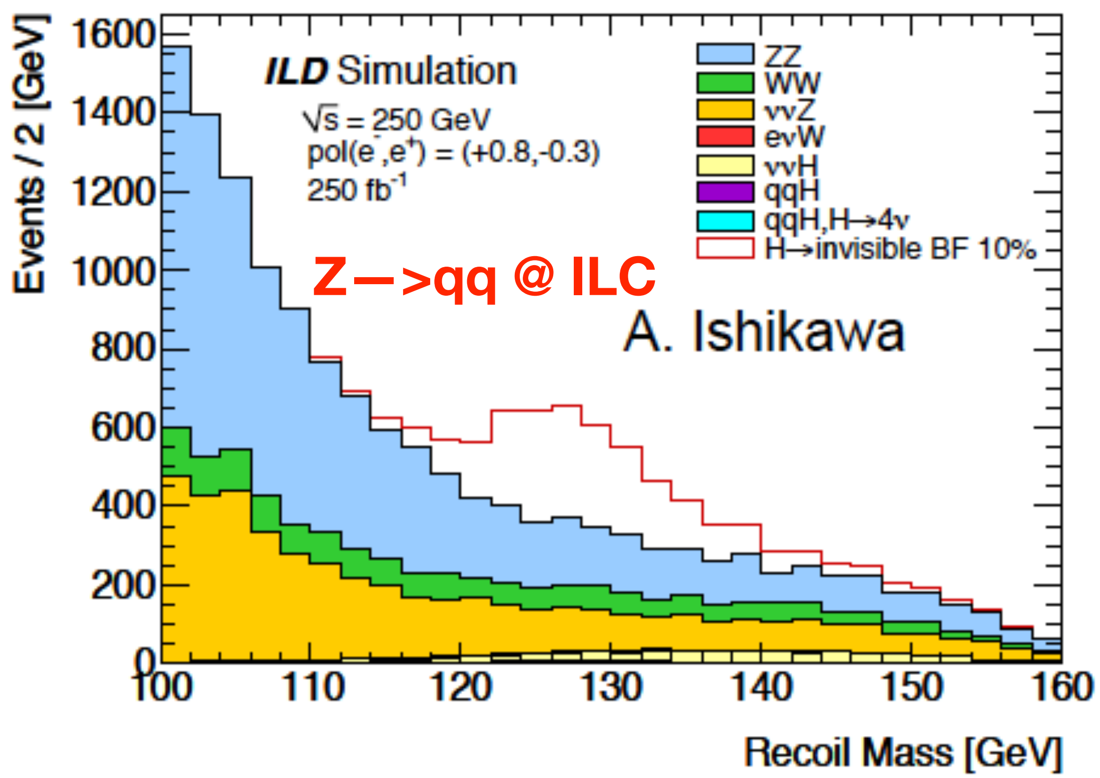
- clean environment at e+e-; excellent b- and c-tagging performance
- bb/cc/gg modes can be separated simultaneously by template fitting

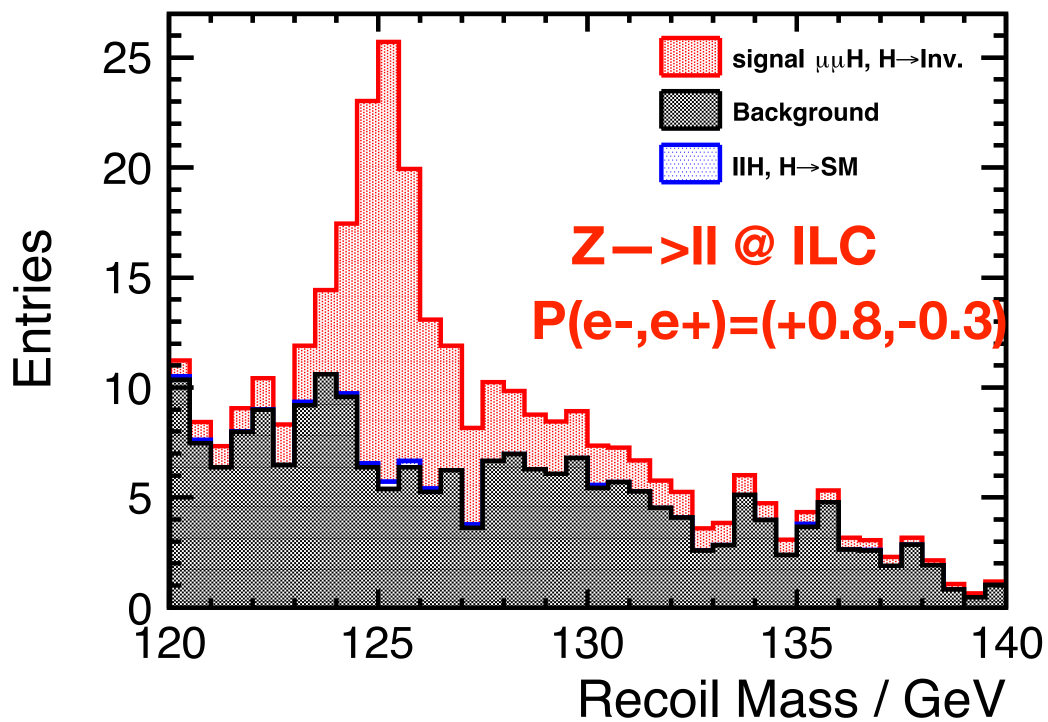
Ono, et. al, Euro. Phys. J. C73, 2343; F.Mueller, PhD thesis (DESY)

Higgs —> invisible at ILC250

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

Ishikawa, Kato, JT, et al





- recoil technique: Higgs mass fully reconstructed even it decays invisibly
- right-handed beam polarization helps: much lower background
- BR(H—>inv.) < 0.3% (CL95%)

From observables to couplings — Global Fit

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

Yi: measured values by experiments

Yi’: predicted values by underlying theory

ΔYi: measurement uncertainty

n: number of independent observables

- kappa formalism

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

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

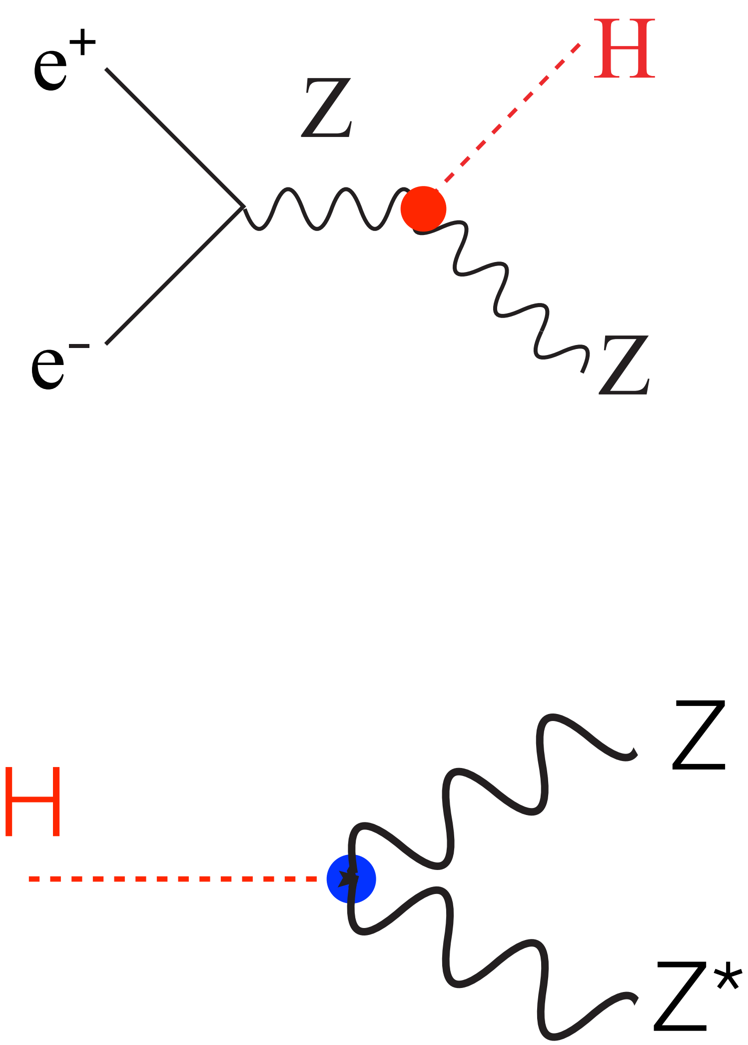
- effective field theory formalism

From observables to couplings — kappa formalism

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

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

Q1: can we assume $\sigma(e+e- \to Zh) \propto \Gamma(h \to ZZ^*)$?

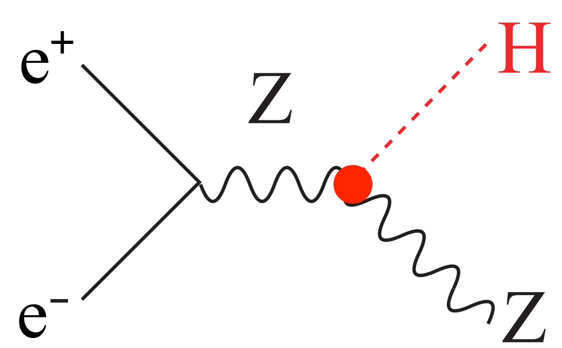


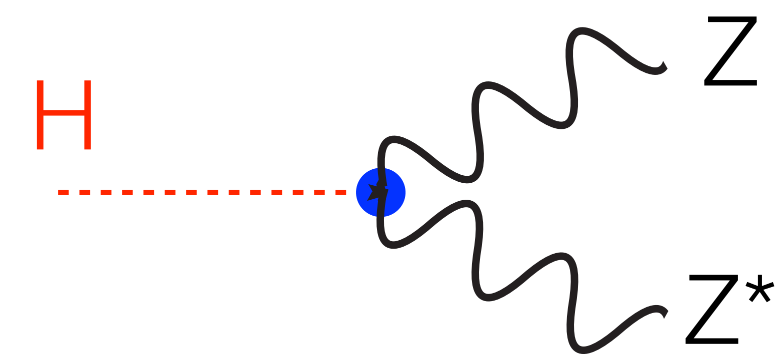
$$\propto ? \; \kappa_Z^2$$

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

the answer is: No, if there is anomalous hZZ coupling

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





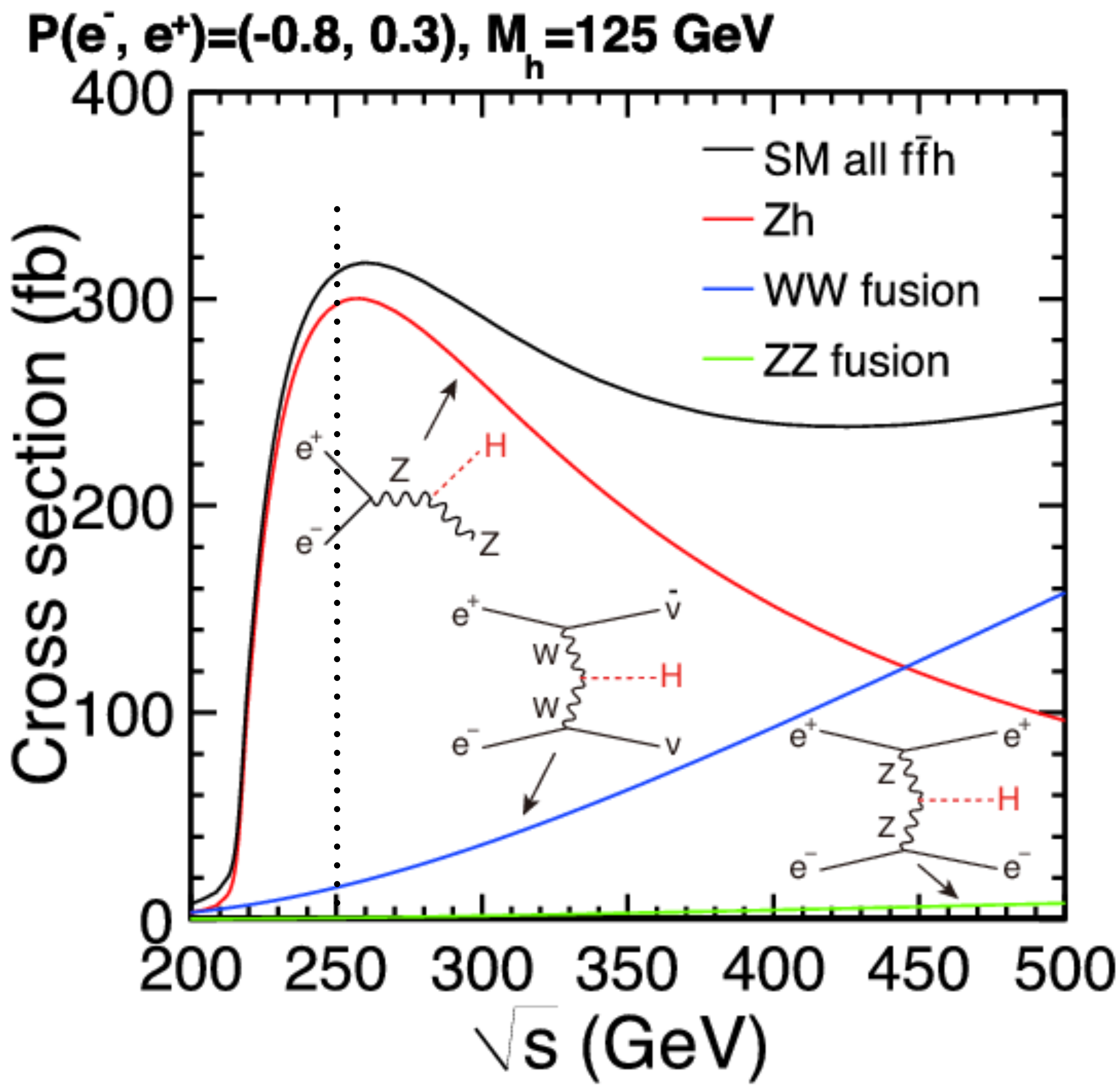
$$\sigma(e^+e^- \to Zh) = (SM)\cdot (1+2\eta_Z+(5.5)\zeta_Z)$$

$$\neq$$

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

- σ(e+e- ->Zh) ∝ κ^2_Z ∝ Γ(h->ZZ*) not any more:
  what would be a more model-independent formalism?

Q2: if WW-fusion is so important, can we do precision Higgs physics at √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

Henning, et al, 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

assuming baryon number 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: full formalism (23 pars.)

("Warsaw" basis)

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

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 operators for contact interactions with quarks

strategy to determine all the 23 parameters simultaneously

Electroweak Precision Observables (9)

+

Triple Gauge boson Couplings (3)

+

Higgs observables at LHC & ILC (3+12x2)

↑ 2 beam polarizations

arXiv:1708.09079; arXiv:1708.08912

(see papers the details of input observables and dependence on EFT operators)

recap 1: (synergy with LHC) two input observables from HL-LHC

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

turn out to be very useful for constraining c_{WW}, c_{WB}, c_{BB}

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

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

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

recap 2: hWW is determined as precisely 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

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

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

recap 3: σ_{ZH}, σ_{ZHH} & beam polarizations

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

$$\frac{c_6\lambda}{v^2}(\Phi^\dagger\Phi)^3$$

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

  unique role of recoil mass analysis remains same

- c_6 has to be determined by double Higgs measurement

  c6 is decoupled with single Higgs process (tree level), large deviation is allowed

- beam polarizations very powerful in EFT, separating hγZ and hZZ couplings: improved precisions and provide means to test EFT validity

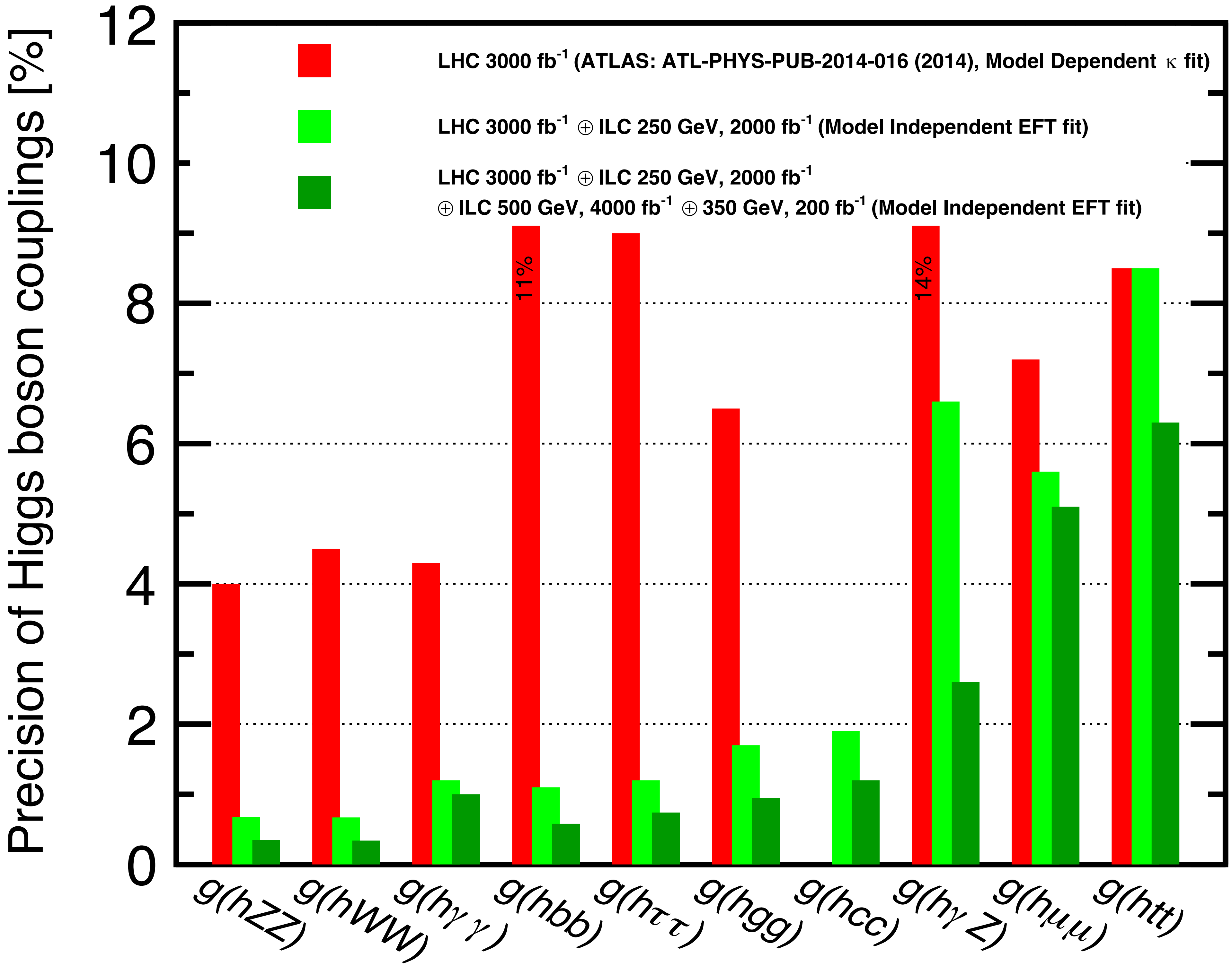
typical precisions by EFT: combined EWPO+TGC+Higgs fit

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

coupling $\Delta g/g$	kappa-fit	EFT-fit
hZZ	0.38%	0.68%
hWW	1.8%	0.67%
hbb	1.8%	1.1%
Γ_h	3.9%	2.5%

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

Higgs coupling precisions at ILC250



note the synergy: HL-LHC input is always included

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

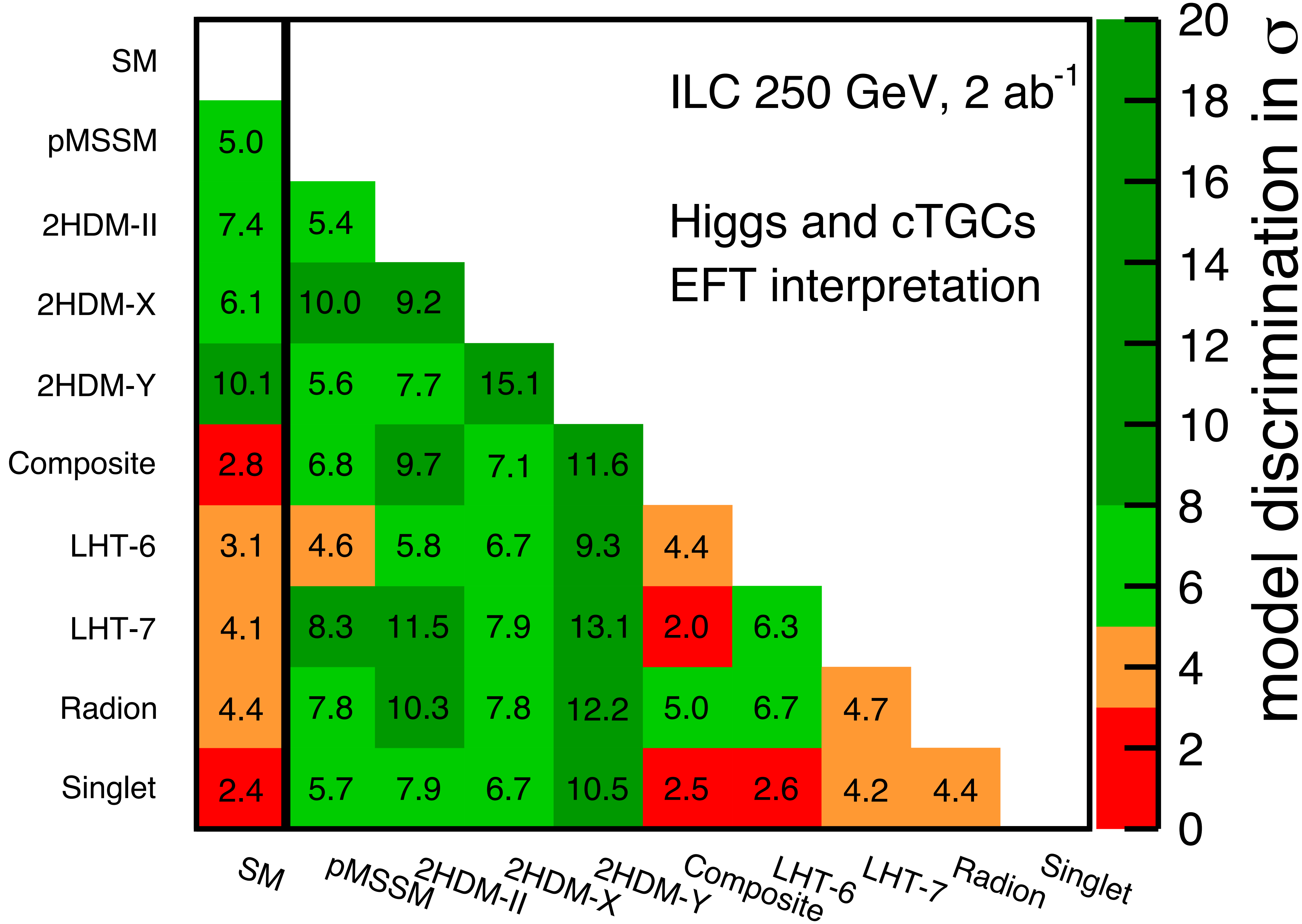
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> 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 $m_A = 600\ \mathrm{GeV}, \tan\beta = 7$
- a Type X 2 Higgs doublet model with $m_A = 450\ \mathrm{GeV}, \tan\beta = 6$
- a Type Y 2 Higgs doublet model with $m_A = 600\ \mathrm{GeV}, \tan\beta = 7$
- a composite Higgs model MCHM5 with $f = 1.2\ \mathrm{TeV}, m_T = 1.7\ \mathrm{TeV}$
- a Little Higgs model with T-parity with $f = 785\ \mathrm{GeV}, m_T = 2\ \mathrm{TeV}$
- A Little Higgs model with couplings to 1st and 2nd generation with $f = 1.2\ \mathrm{TeV}, m_T = 1.7\ \mathrm{TeV}$
- A Higgs-radion mixing model with $m_r = 500\ \mathrm{GeV}$
- a model with a Higgs singlet at $2.8\ \mathrm{TeV}$ creating a Higgs portal to dark matter and large λ for electroweak baryogenesis

BSM model discrimination at ILC250



once find deviation against SM —> can tell which BSM

then the next energy scales would be known: reachable 2~3 TeV

In MSSM, NMSSM [hbb/hWW ~ 0.64%] 1.6 TeV

In general two Higgs doublet models (unitarity bound)
[hZZ~0.38%] 1 TeV
[hbb/hWW~0.64%] 2HDM Type II, Y 3 TeV
[hττ/hWW~0.84%] 2HDM Type II, X 2.7 TeV

In the Higgs doublet and singlet model (unitarity bound)
[hZZ~0.38%] 5 TeV

In Minimal Composite Higgs Model ($\xi=\sin^2(v/f)$)
[hZZ~0.38%] MCHM4 2.8 TeV
[hbb/hWW~0.64%] MCHM5, MCHM10 3.8 TeV

Calculation done using the results from arXiv:1705.05399.

Endo, Kanemura, et al

determine Higgs CP (admixture)

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

through H—>$\tau^+\tau^-$

(or ttH)

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

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

Jeans et al, 1804.01241

through HZZ/HWW

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

(CP-odd)

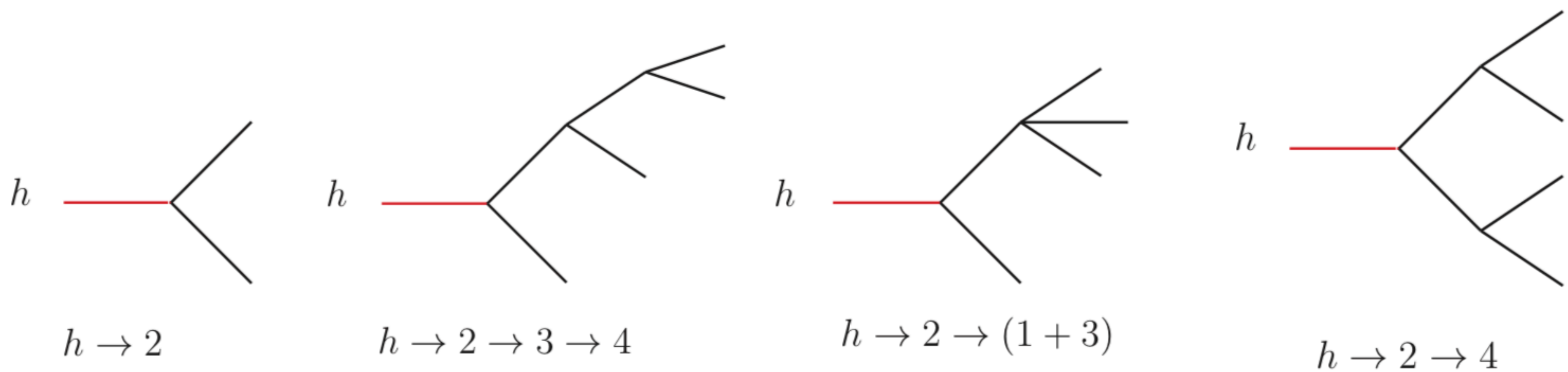
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

Ogawa, 1712.09772

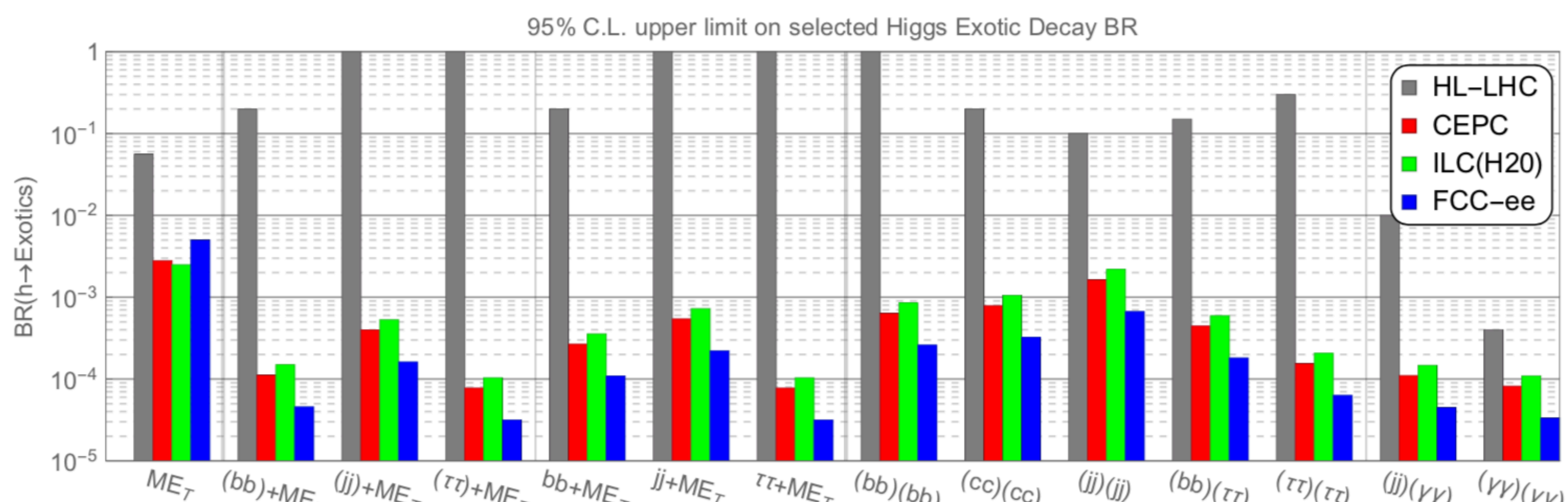
probing Hidden Sector: h->invisible / exotic decay

$$\epsilon\, B_{\mu\nu}\hat{F}^{\mu\nu}\ , \qquad \epsilon\,|\varphi|^2|\hat{S}|^2\ , \qquad \epsilon\, L^\dagger\cdot\varphi\hat{N}\ ,$$

gauge portal — Higgs portal — neutrino portal



Liu, et al,
arXiv:1612.09284



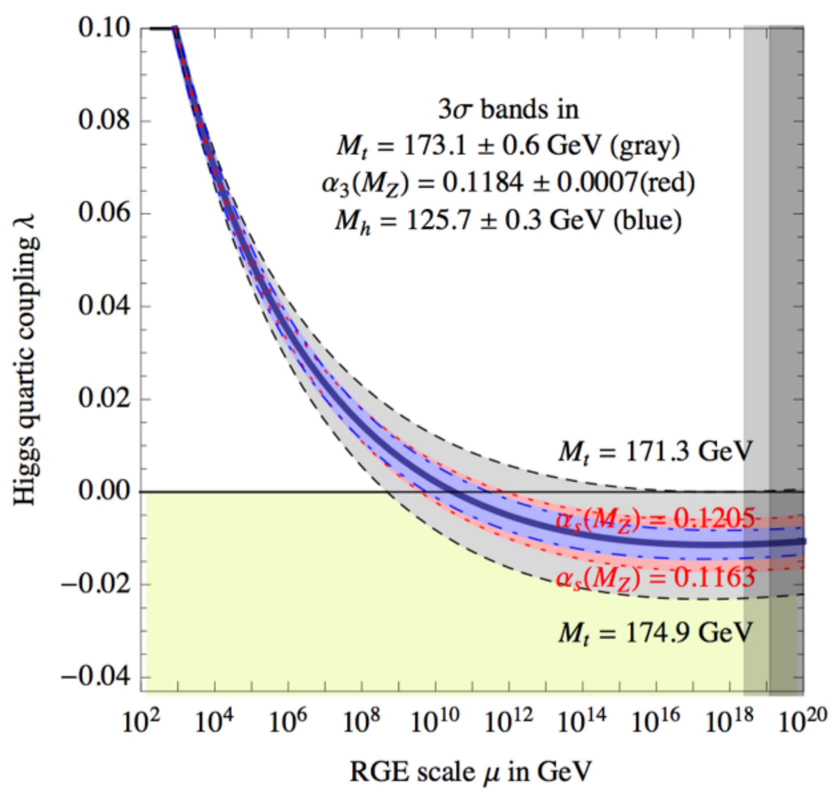
Higgs Physics beyond 250 GeV

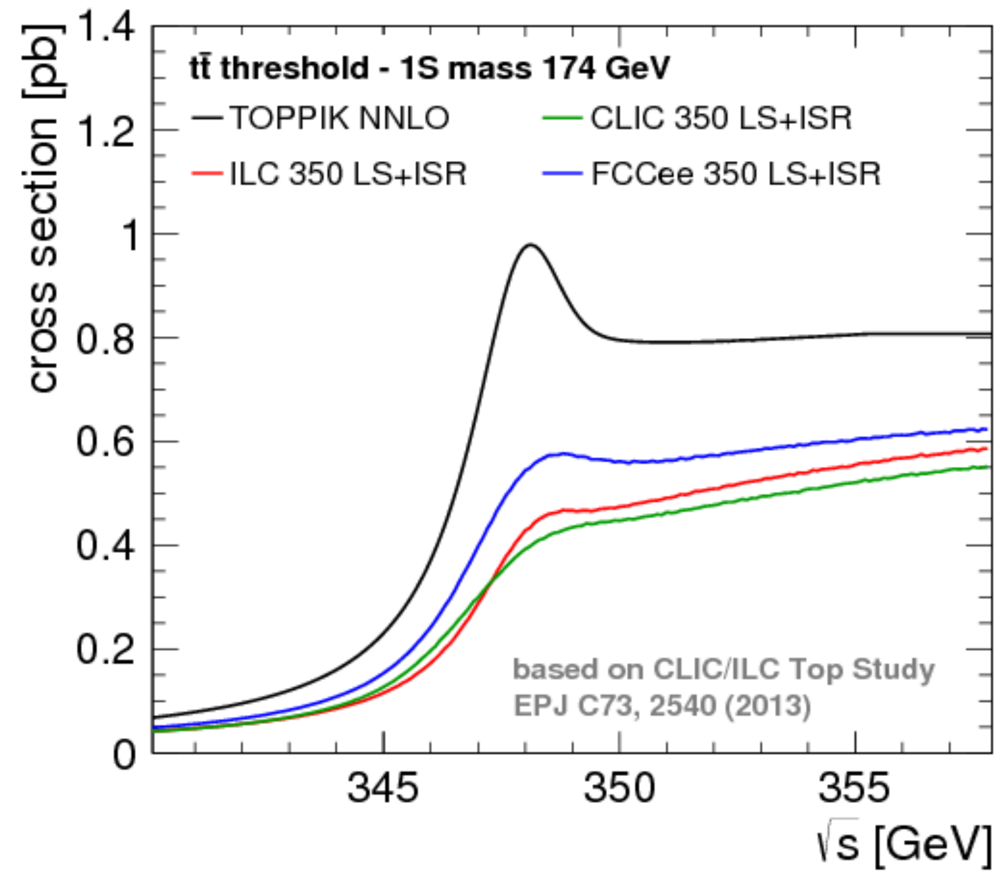
the intrinsic advantage of a linear collider is
its energy extendability

top mass measurement at ~350 GeV: 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)

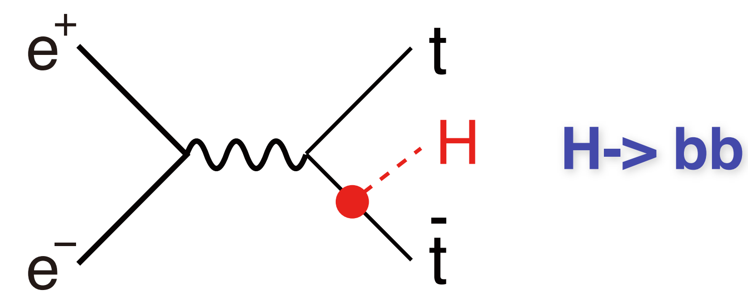
Degrassi et al, JHEP 1208 (2012) 098



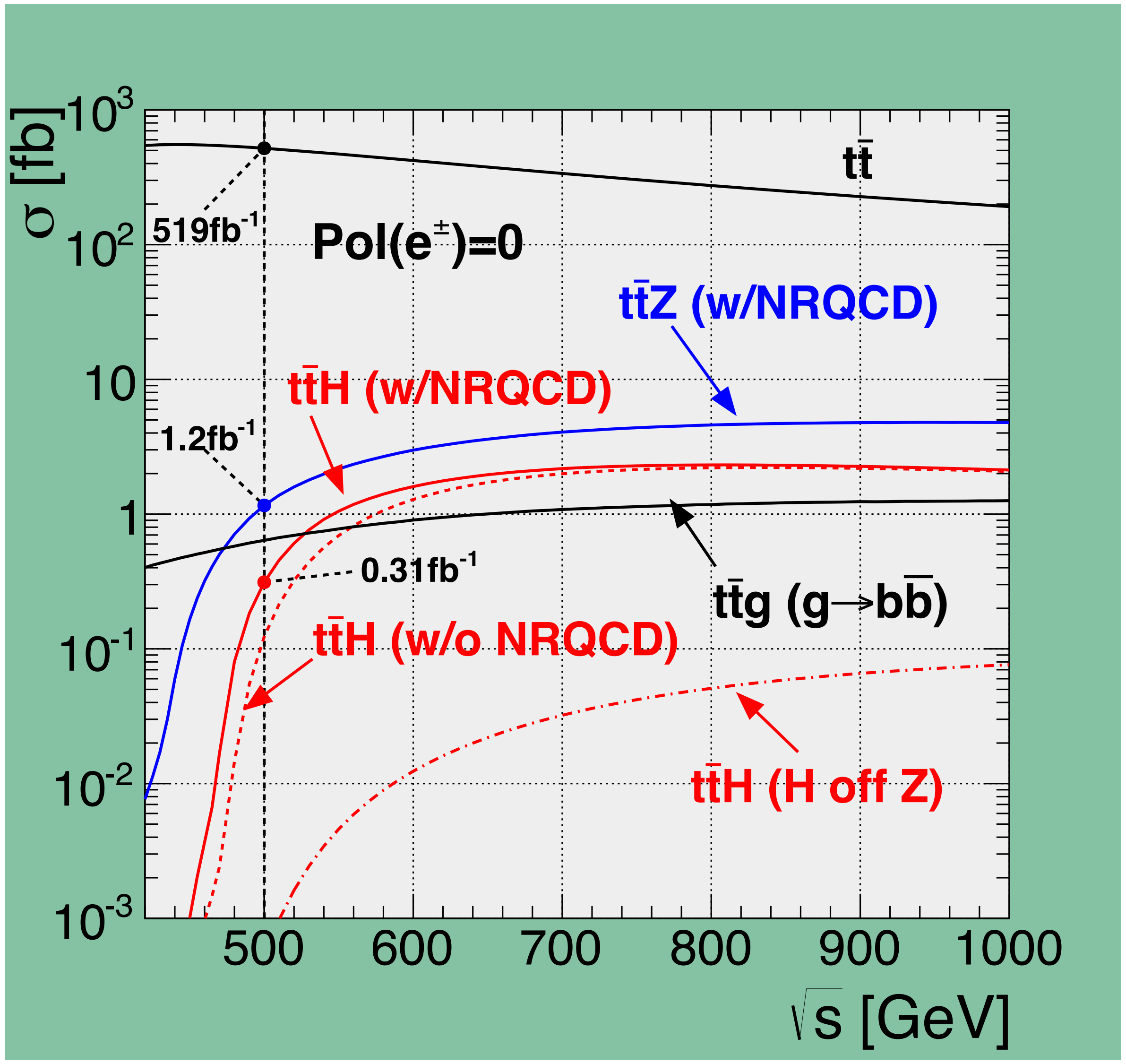


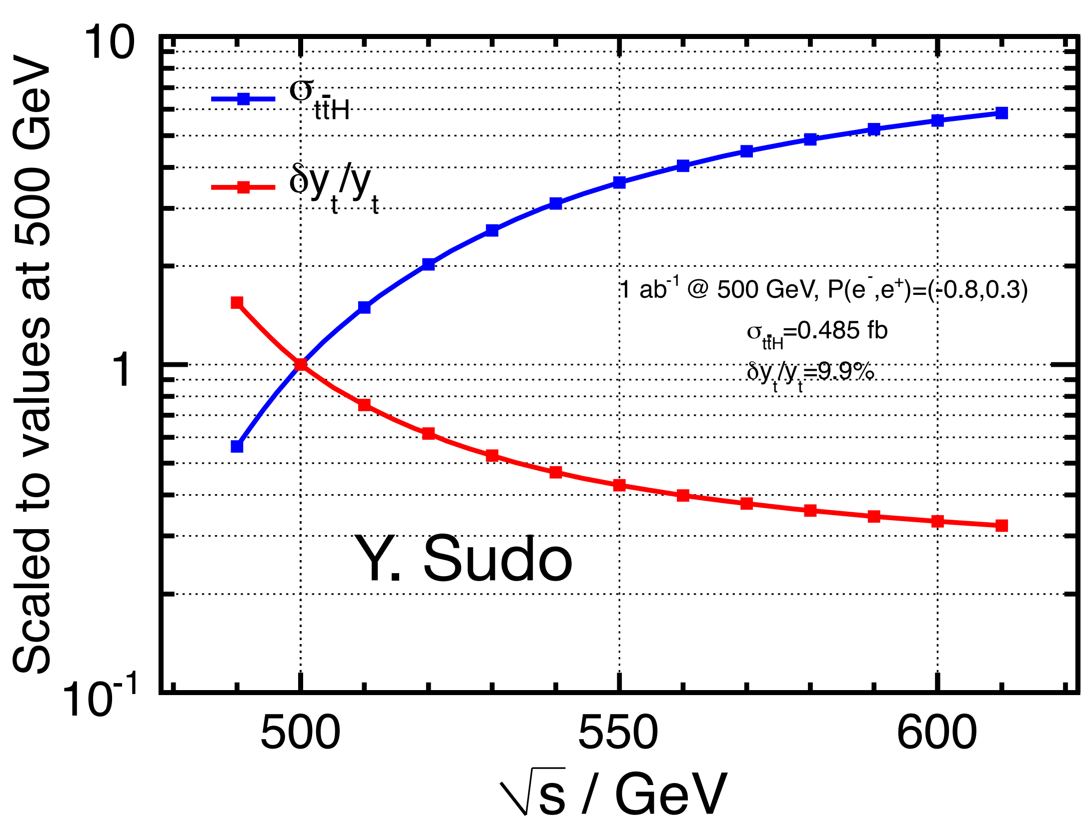
Top-Yukawa coupling

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



$\Delta g_{ttH}/g_{ttH}$	500 GeV	550 GeV	1 TeV
H20	6.3%	2.7%	1.5%

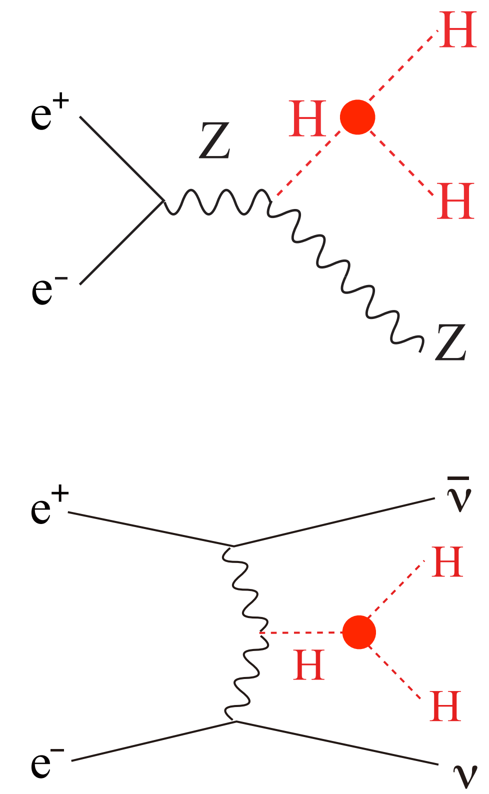


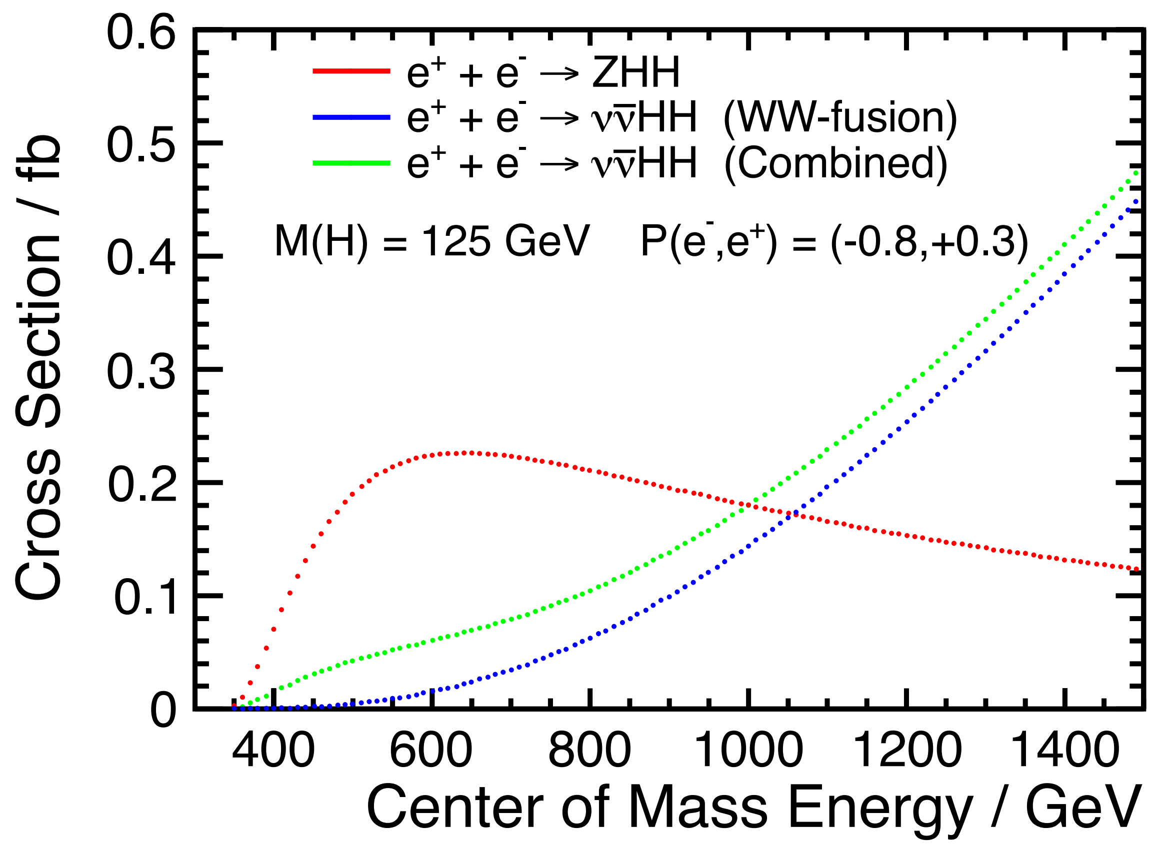


Yonamine, et al., PRD84, 014033;
Price, et al., Eur. Phys. J. C75 (2015) 309

Higgs self-coupling

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





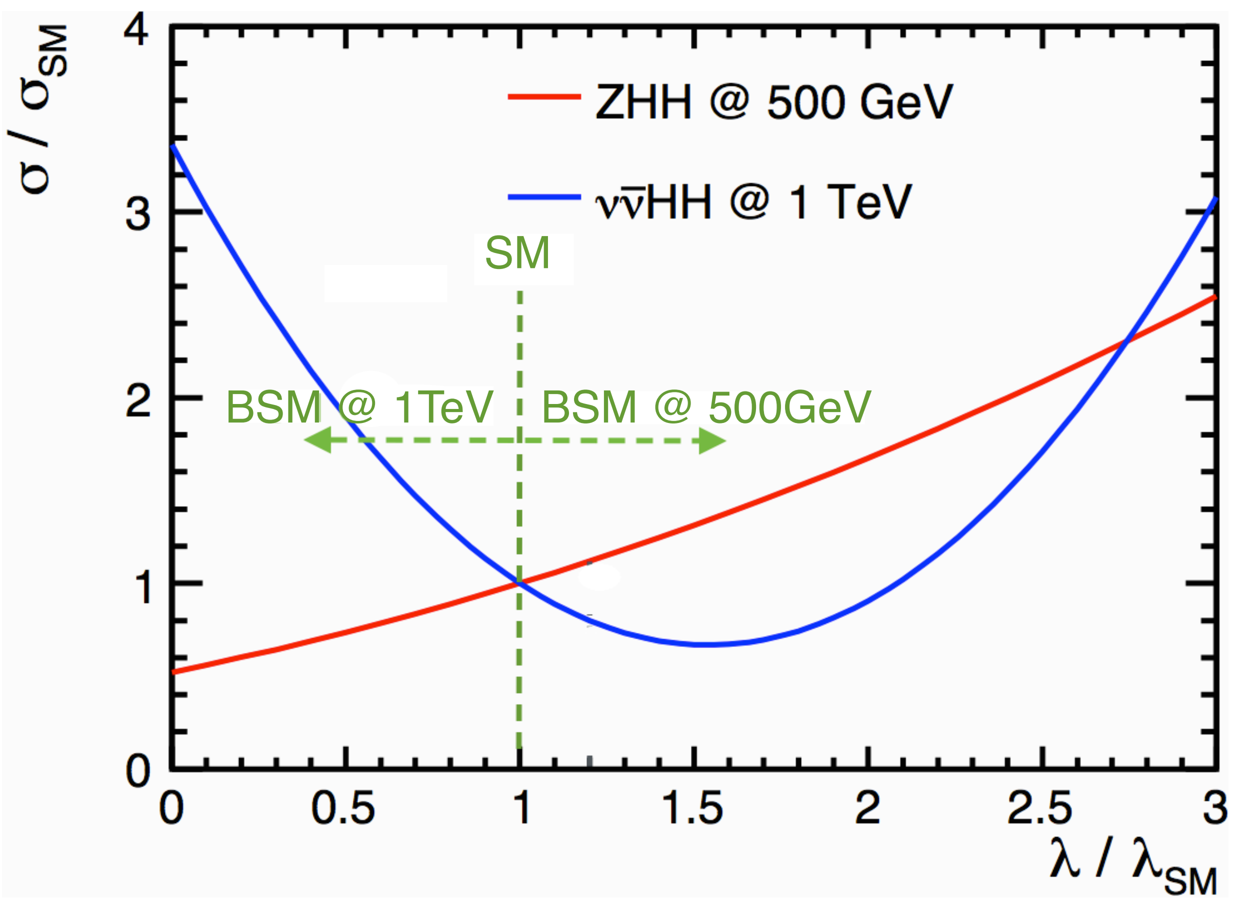
$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
H20	27%	10%

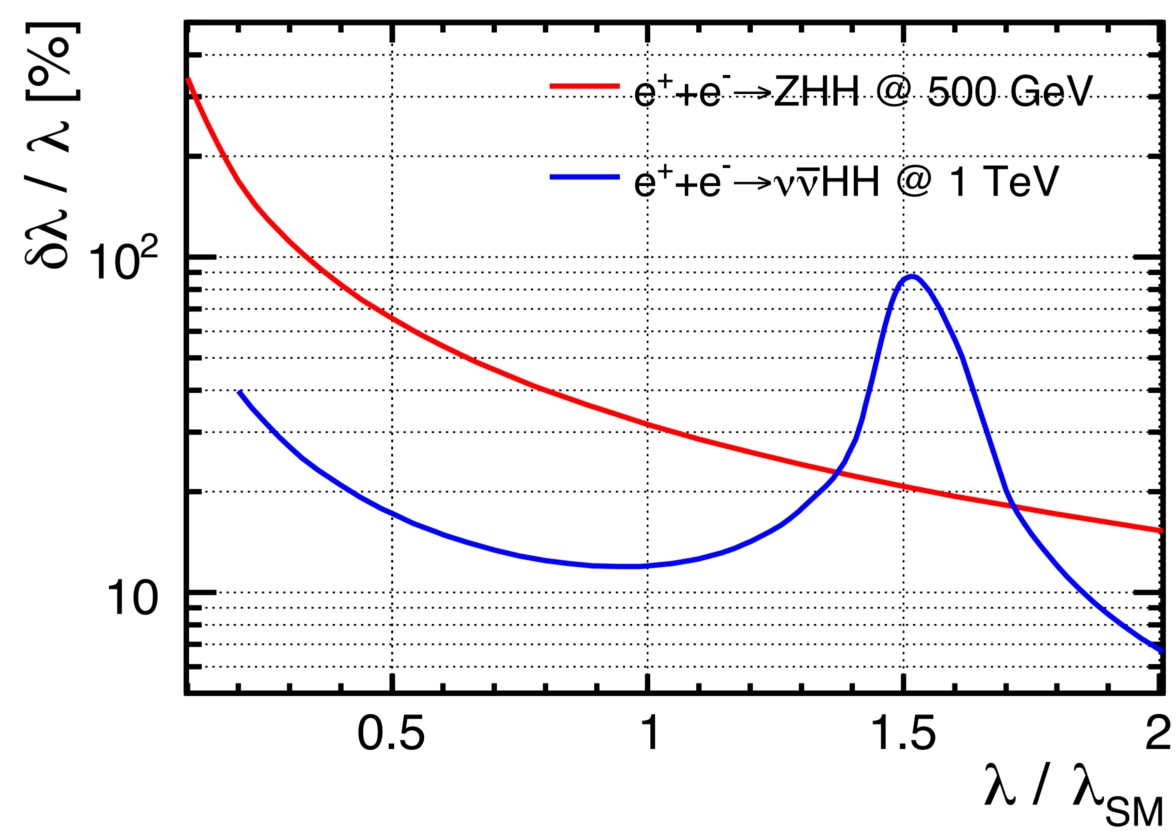
Duerig, JT, et al, paper in preparation

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

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

Duerig, JT, et al, paper in preparation





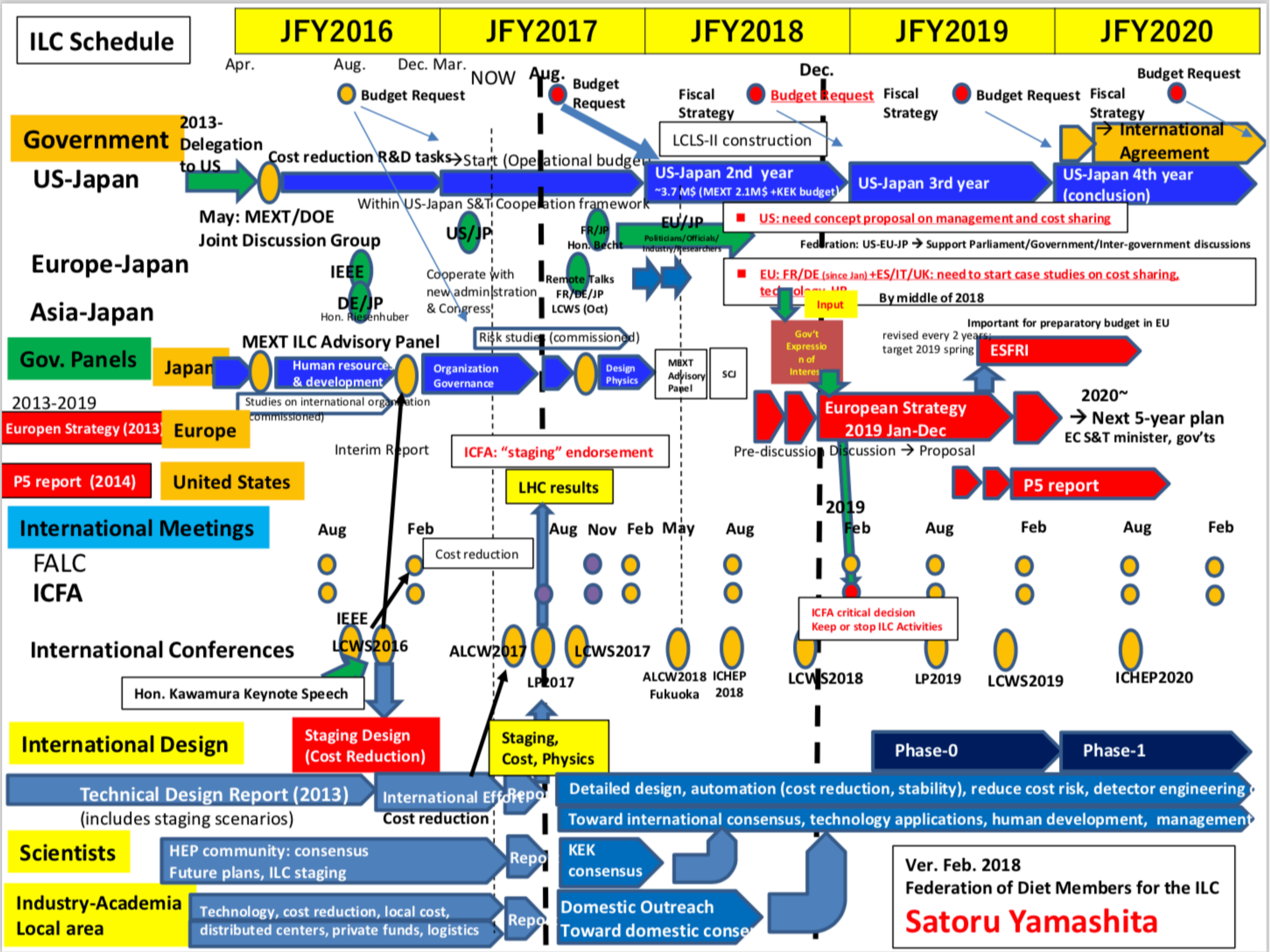
references for large deviations

e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

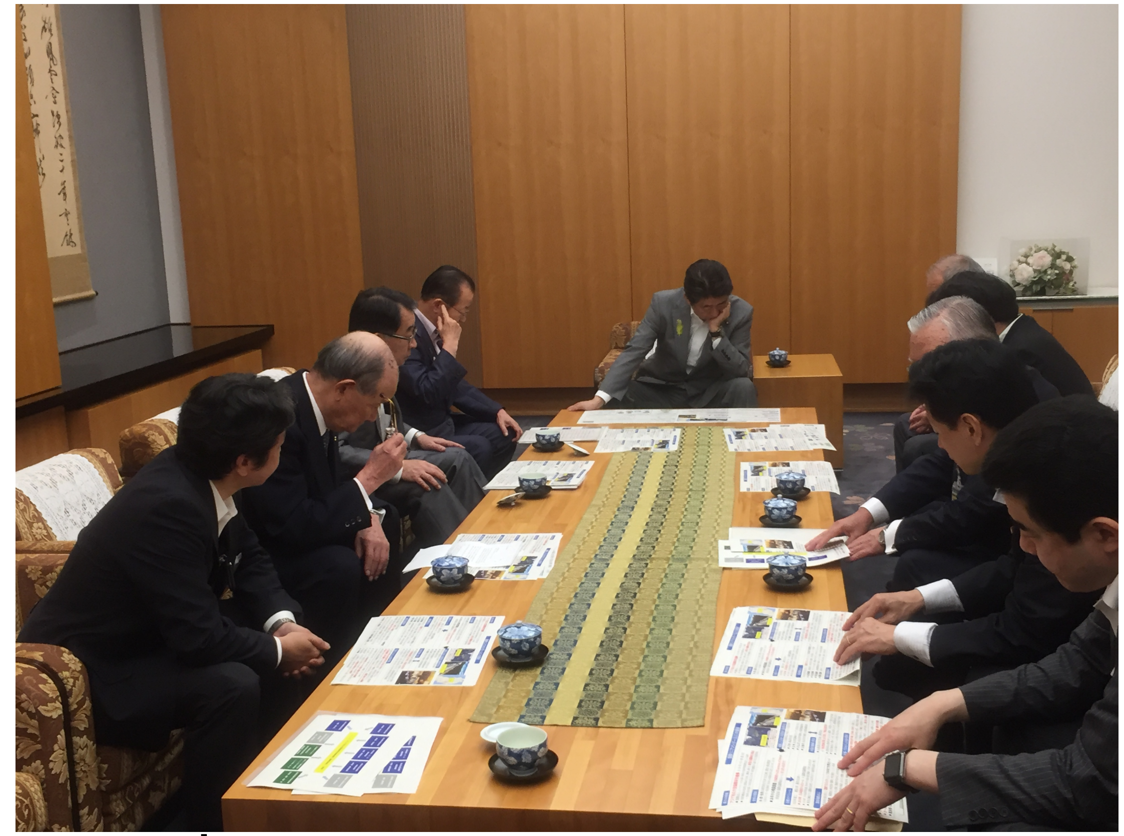
Status of ILC250

status of ILC250

- it’s been a really long journey (my former two bosses at KEK & U.Tokyo both have been working on linear colliders for 30 years)
- scientific case is very strong and well justified -> Snowmass 2013, European Strategy 2013, AsiaHEP, and see most recently endorsement by ICFA, JAHEP
- technologically, entered from “matured stage” to “robust stage” -> extensive SCRF developments especially at European XFEL and LCSL-II
- under serious consideration by Japanese government -> expect some decision in this year, hopefully a green light



ILC Schedule
JFY2016
JFY2017
JFY2018
JFY2019
JFY2020
Apr.
Aug.
Dec. Mar.
NOW
Aug.
Dec.
Budget Request
Budget Request
Fiscal Strategy
Budget Request
Fiscal Strategy
Budget Request
Fiscal Strategy
Budget Request
Government
2013- Delegation to US
US-Japan
Cost reduction R&D tasks→Start (Operational budget)
LCLS-II construction
→ International Agreement
US-Japan 2nd year
~3.7 M$ (MEXT 2.1M$ +KEK budget)
US-Japan 3rd year
US-Japan 4th year (conclusion)
Within US-Japan S&T Cooperation framework
May: MEXT/DOE Joint Discussion Group
US/JP
FR/JP Hon. Becht
EU/JP
Politicians/Officials/Industry/Researchers
US: need concept proposal on management and cost sharing
Federation: US-EU-JP → Support Parliament/Government/Inter-government discussions
Europe-Japan
IEEE
DE/JP
Hon. Riesenhuber
Cooperate with new administration & Congress
Remote Talks FR/DE/JP LCWS (Oct)
EU: FR/DE (since Jan) +ES/IT/UK: need to start case studies on cost sharing, technology, HR
By middle of 2018
Input
Asia-Japan
Gov. Panels
Japan
MEXT ILC Advisory Panel
Human resources & development
Organization Governance
Design Physics
Risk studies (commissioned)
MEXT Advisory Panel
SCJ
Gov't Expression of Interest
Important for preparatory budget in EU
revised every 2 years; target 2019 spring
ESFRI
2013-2019
Studies on international organization (commissioned)
Europen Strategy (2013)
Europe
European Strategy 2019 Jan-Dec
2020~
→ Next 5-year plan
EC S&T minister, gov'ts
Interim Report
ICFA: "staging" endorsement
Pre-discussion
Discussion → Proposal
P5 report (2014)
United States
LHC results
P5 report
International Meetings
Aug
Feb
Aug
Nov
Feb
May
Aug
2019
Feb
Aug
Feb
Aug
Feb
FALC
ICFA
Cost reduction
ICFA critical decision
Keep or stop ILC Activities
IEEE
International Conferences
LCWS2016
ALCW2017
LP2017
LCWS2017
ALCW2018 Fukuoka
ICHEP 2018
LCWS2018
LP2019
LCWS2019
ICHEP2020
Hon. Kawamura Keynote Speech
International Design
Staging Design (Cost Reduction)
Staging, Cost, Physics
Phase-0
Phase-1
Technical Design Report (2013)
(includes staging scenarios)
International Effort
Cost reduction
Report
Detailed design, automation (cost reduction, stability), reduce cost risk, detector engineering
Toward international consensus, technology applications, human development, management
Scientists
HEP community: consensus
Future plans, ILC staging
Report
KEK consensus
Industry-Academia Local area
Technology, cost reduction, local cost, distributed centers, private funds, logistics
Report
Domestic Outreach
Toward domestic conse
Ver. Feb. 2018
Federation of Diet Members for the ILC
Satoru Yamashita

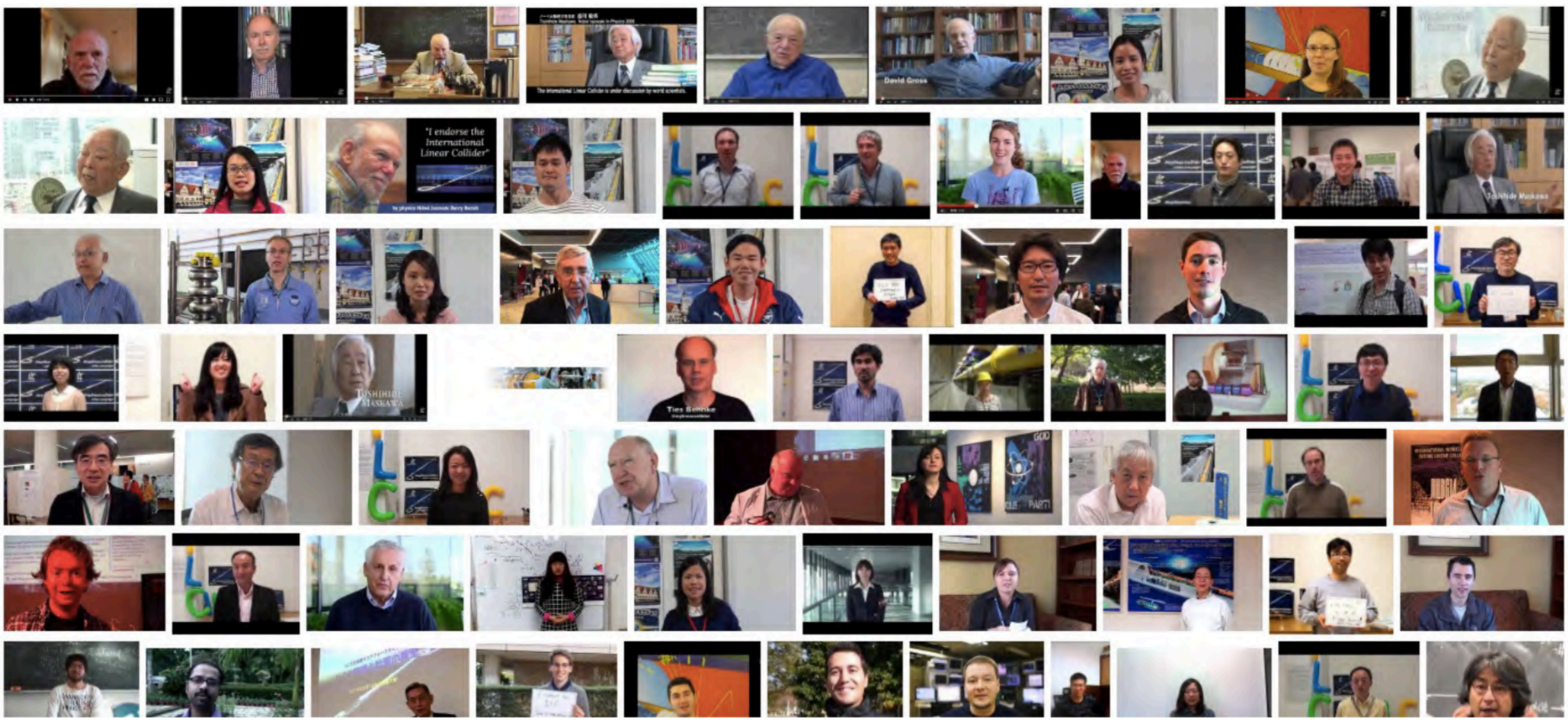


government

industry

public

#mylinearcollider youtube



Call for ILC supporters

ILC Supporters 募集

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ILC Supporters 発起人
押井 守 Mamoru Oshii

シンボルマーク作成
森本 晃司 Koji Morimoto

東京大学特任教授
山下 了 Satoru Yamashita

ゲームディレクター
鈴木 裕 Yu Suzuki

クリエイター・声優
木村 優 Yu Kimura

backup

typical Higgs coupling deviation in BSM

Mixing with singlet

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} = \frac{g_{hff}}{g_{h_{\rm SM}ff}} = \cos\theta \simeq 1 - \frac{\delta^2}{2}$$

Composite Higgs

$$\frac{g_{hVV}}{g_{h_{\rm SM}VV}} \simeq 1 - 3\%(1\ \mathrm{TeV}/f)^2$$

$$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM4}) \\ 1 - 9\%(1\ \mathrm{TeV}/f)^2 & (\mathrm{MCHM5}). \end{cases}$$

SUSY

$$\frac{g_{hbb}}{g_{h_{\rm SM}bb}} = \frac{g_{h\tau\tau}}{g_{h_{\rm SM}\tau\tau}} \simeq 1 + 1.7\% \left(\frac{1\ \mathrm{TeV}}{m_A}\right)^2$$

arXiv:1306.6352

Higgs couplings in EFT

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

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

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

comments on beam polarizations

	2 ab^{-1} w. pol.	2 ab^{-1} 350 GeV	5 ab^{-1} no pol.	+ 1.5 ab^{-1} at 350 GeV	full ILC 250+500 GeV
$g(hb\bar{b})$	1.04	1.08	0.98	0.66	0.55
$g(hc\bar{c})$	1.79	2.27	1.42	1.15	1.09
$g(hgg)$	1.60	1.65	1.31	0.99	0.89
$g(hWW)$	0.65	0.56	0.80	0.42	0.34
$g(h\tau\tau)$	1.16	1.35	1.06	0.75	0.71
$g(hZZ)$	0.66	0.57	0.80	0.42	0.34
$g(h\gamma\gamma)$	1.20	1.15	1.26	1.04	1.01
$g(h\mu\mu)$	5.53	5.71	5.10	4.87	4.95
$g(hbb)/g(hWW)$	0.82	0.90	0.58	0.51	0.43
$g(hWW)/g(hZZ)$	0.07	0.06	0.07	0.06	0.05
Γ_h	2.38	2.50	2.11	1.49	1.50
$\sigma(e^+e^- \to Zh)$	0.70	0.77	0.50	0.22	0.61
$BR(h \to inv)$	0.30	0.56	0.30	0.27	0.28
$BR(h \to other)$	1.50	1.63	1.09	0.94	1.15

comments on beam polarizations

	no pol.	80%/0%	80%/30%
$g(hb\bar{b})$	1.33	1.13	1.04
$g(hc\bar{c})$	2.09	1.97	1.79
$g(hgg)$	1.90	1.77	1.60
$g(hWW)$	0.98	0.68	0.65
$g(h\tau\tau)$	1.45	1.27	1.16
$g(hZZ)$	0.97	0.69	0.66
$g(h\gamma\gamma)$	1.38	1.22	1.20
$g(h\mu\mu)$	5.67	5.64	5.53
$g(hb\bar{b})/g(hWW)$	0.91	0.91	0.82
$g(hWW)/g(hZZ)$	0.07	0.07	0.07
Γ_h	2.93	2.60	2.38
$\sigma(e^+e^- \to Zh)$	0.78	0.78	0.70
$BR(h \to inv)$	0.36	0.33	0.30
$BR(h \to other)$	1.68	1.67	1.50

Table 4: Projected relative errors for Higgs boson couplings and other Higgs observables with 2 ab^{-1} of data at 250 GeV, comparing the cases of zero polarization, 80% e^- polarization and zero positron polarization, and 80% e^- polarization and 30% positron polarization. In each case, the running is equally divided into two samples with opposite beam polarization orientation.

discrimination between BSM models (ILC500 stage)