ILC Physics Overview & Staging Scenarios

ILC Physics Case	[arXiv:1506.05992]
ILC Operating Scenario	[arXiv:1506.07830]
ILC Discovery Potential	[arXiv:1702.05333]

Junping Tian (U' of Tokyo)
ILC Summer Camp, July 21-24, 2017 @ highland in Nagano Pref.

outline

(i) ILC physics overview

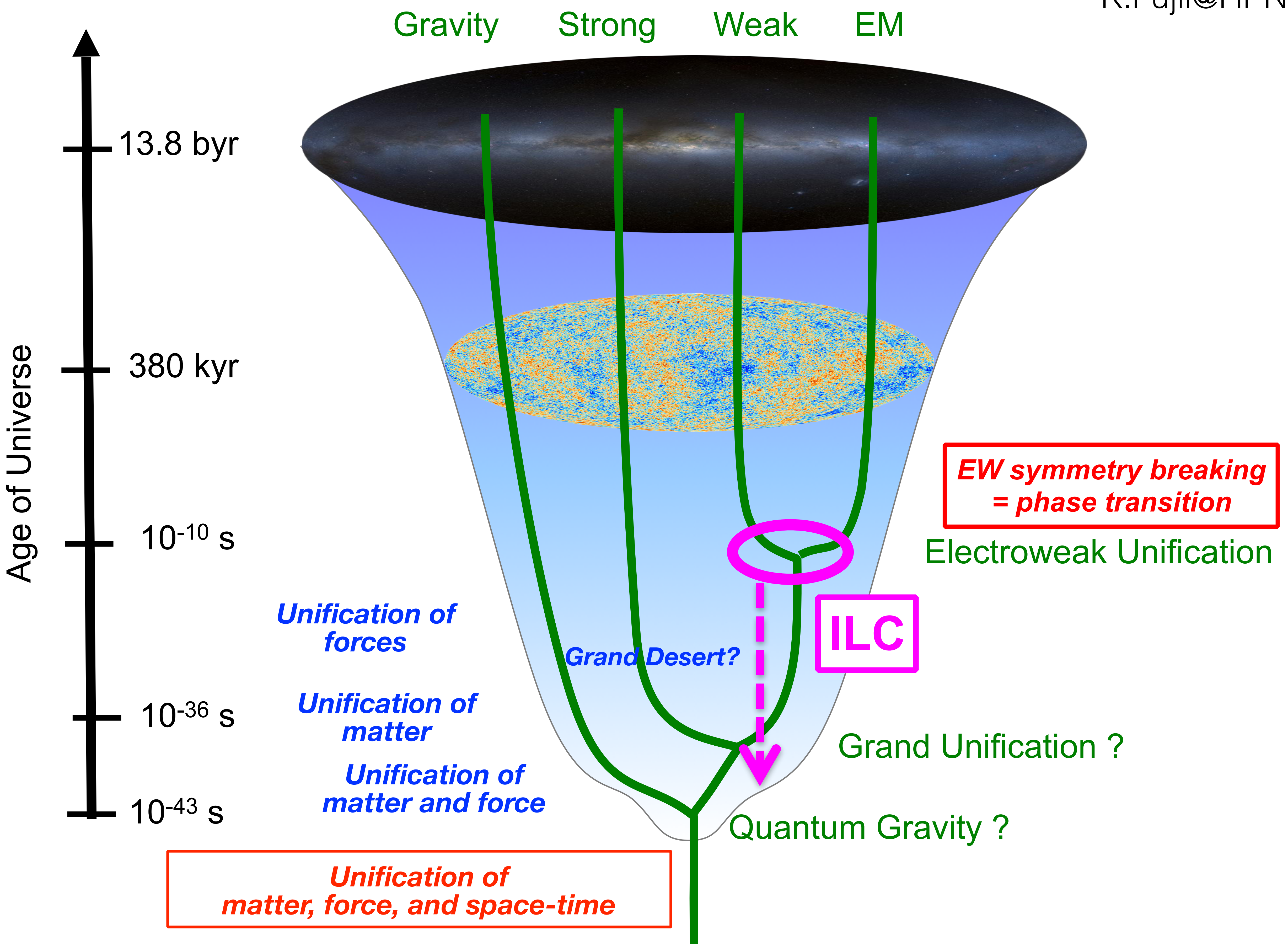
(ii) model independent determination of Higgs (self-)couplings at e+e-

➡ SM Effective Field Theory

(iii) recent ILC staging studies

towards ultimate unification

K.Fujii@HPNP2017

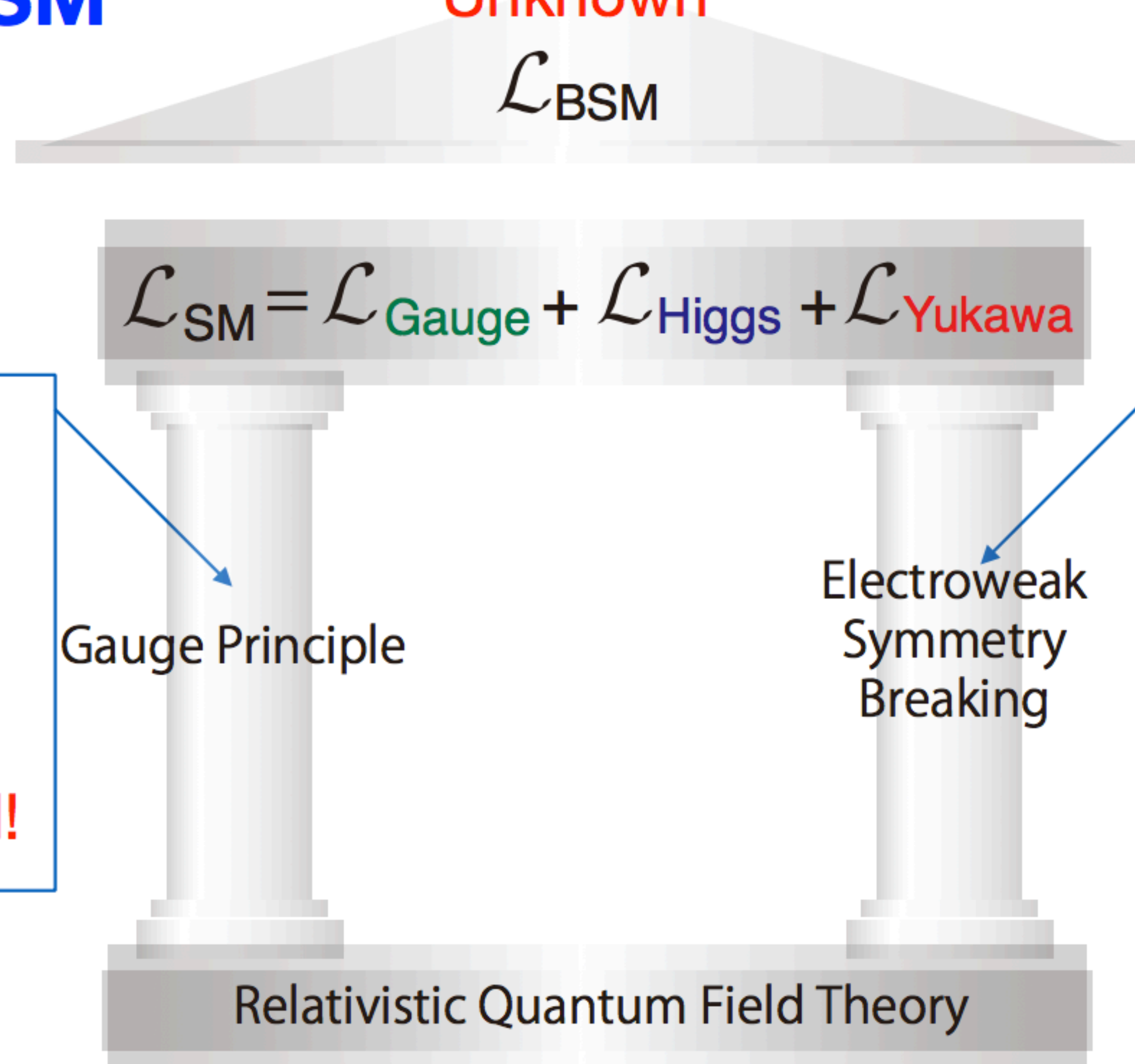


Why is the EW scale so important?

Mystery of something in the vacuum

K.Fujii@HPNP2017

2 Pillars of SM

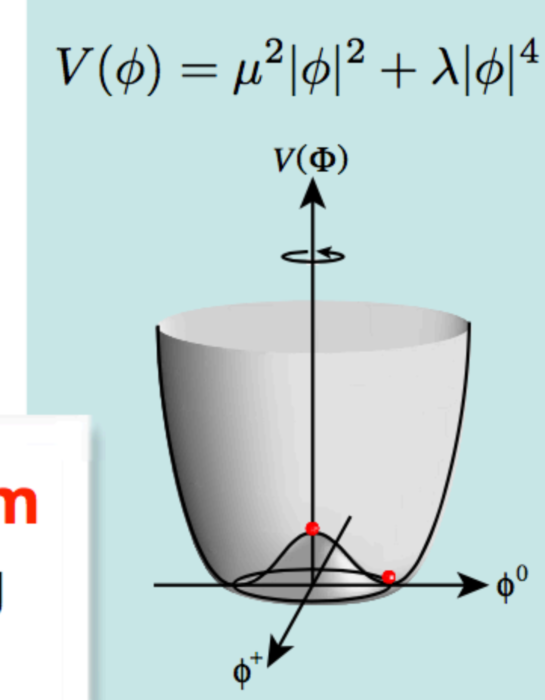


Success of SM
= success of
gauge theory
(left pillar)

Precisely tested!

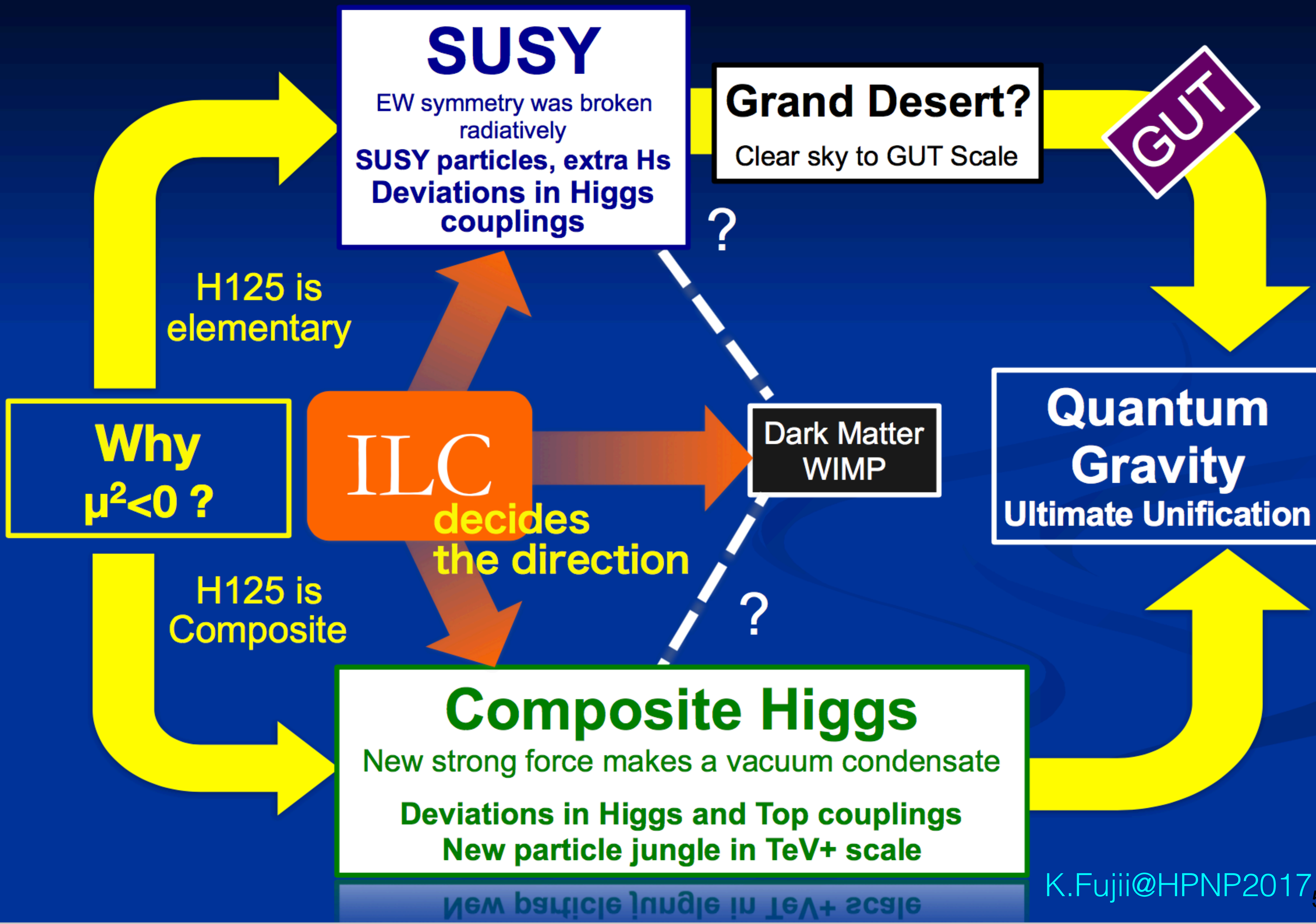
Vacuum filled with weak charge (evidence: H125)

The nature of the Higgs field - its multiplet structure & dynamics behind it - is all unknown!



The SM does not explain **why the Higgs field developed a vacuum expectation value** (***Why $\mu^2 < 0$?***)! **The answer forks depending on whether H125 is elementary or composite!**

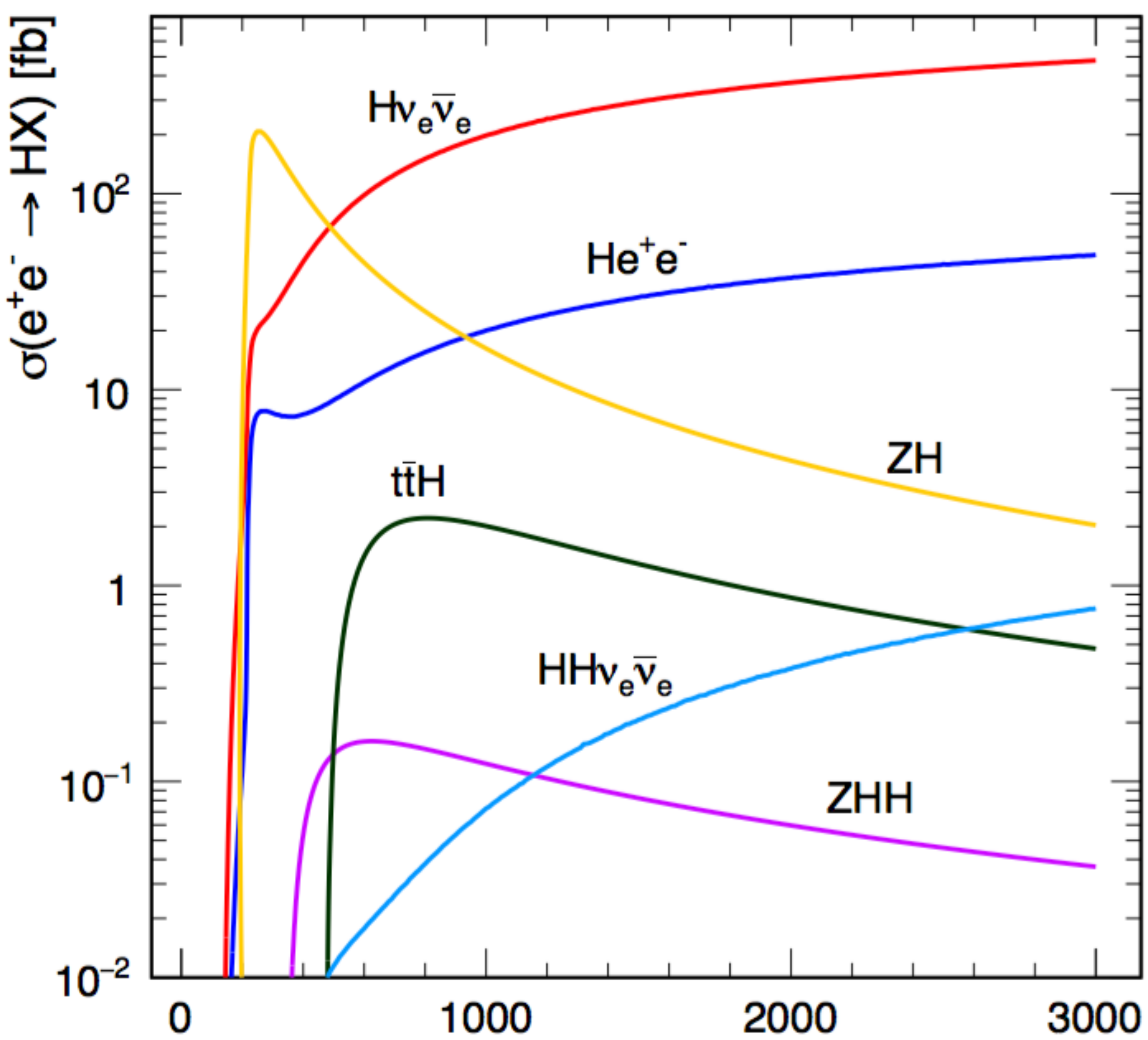
Big Branching Point at the EW Scale



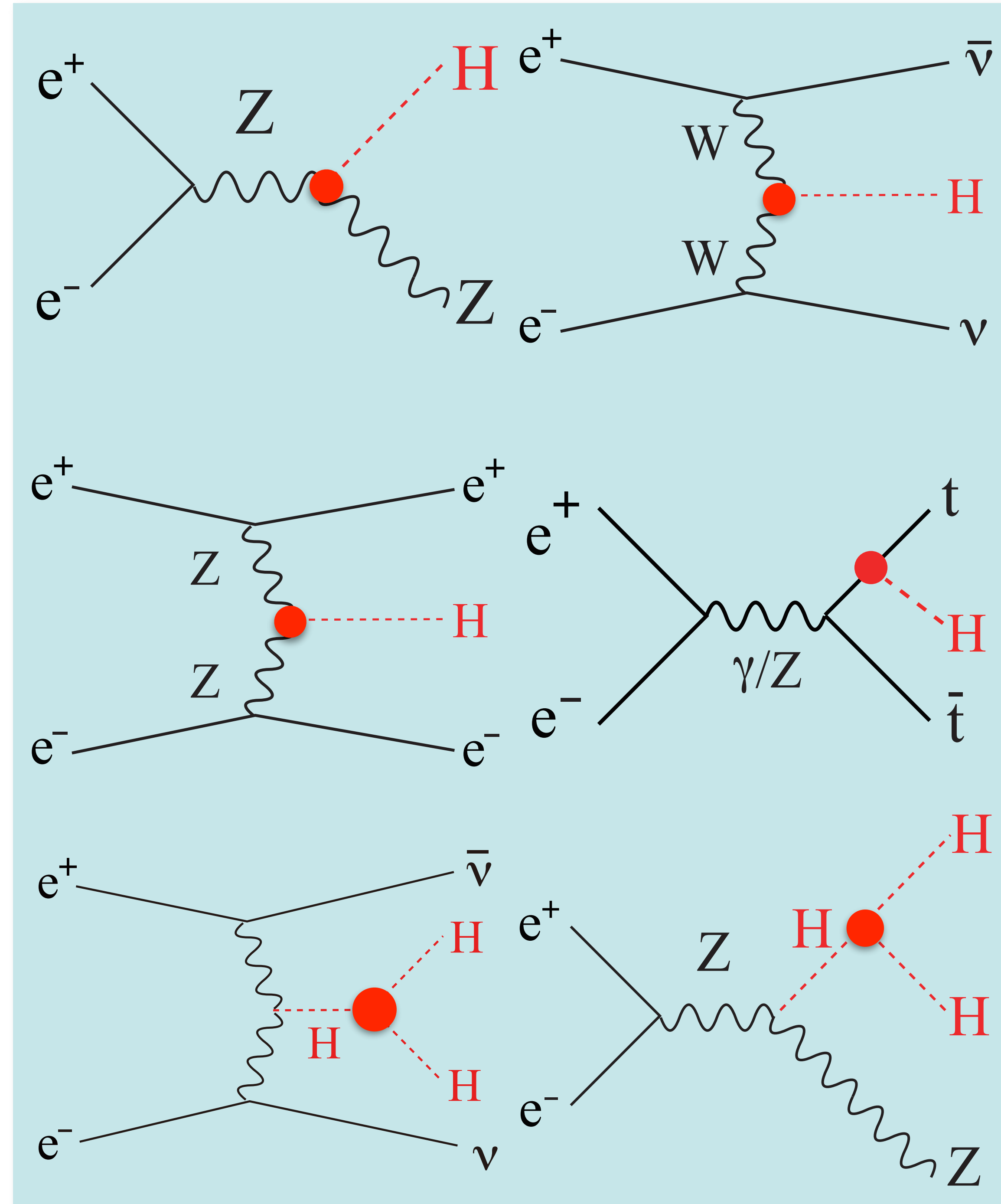
three major probes for BSM at e+e- colliders

- precision measurements of Higgs
- precision measurements of top
- direct search of new particles

Higgs productions at e+e-



(unpolarized case)



two important thresholds: $\sqrt{s}$ ~ 250 GeV for ZH,
~500 GeV for ZHH and ttH

nail down Higgs sector at future lepton colliders

bottom-up and model independent way

Mass & J^{CP}	$M_h \quad \Gamma_h \quad J^{\rm CP}$	new CP violating source?
$L_{\rm Higgs}$	$hhh: \; -6i\lambda v = -3i\frac{m_h^2}{v}, \quad hhhh: \; -6i\lambda = -3i\frac{m_h^2}{v^2}$	probe Higgs potential, EWBG?
$L_{\rm Gauge}$	$W^+_\mu W^-_\nu h: \; i\frac{g^2 v}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v} g_{\mu\nu}, \quad W^+_\mu W^-_\nu hh: \; i\frac{g^2}{2} g_{\mu\nu} = 2i\frac{M_W^2}{v^2} g_{\mu\nu},$ $Z_\mu Z_\nu h: \; i\frac{g^2+g'^2 v}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v} g_{\mu\nu}, \quad Z_\mu Z_\nu hh: \; i\frac{g^2+g'^2}{2} g_{\mu\nu} = 2i\frac{M_Z^2}{v^2} g_{\mu\nu}$	SU(2) nature? m_V from SSB?
$L_{\rm Yukawa}$	$h\bar{f}f: \; -i\frac{y^f}{\sqrt{2}} = -i\frac{m_f}{v}$	m_f from Yukawa coupling? 2HDM?
$L_{\rm Loop}$	$h\gamma\gamma \quad hgg \quad h\gamma Z$	new particles in the loop?

+ possible exotic interactions of Higgs, e.g. h—>dark matter?

The study of the deviations from these predictions is guided by the idea that each Higgs coupling has its own personality and is guided by different types of new physics. This is something of a caricature, but, still, a useful one.

M. Peskin @ HPNP2015

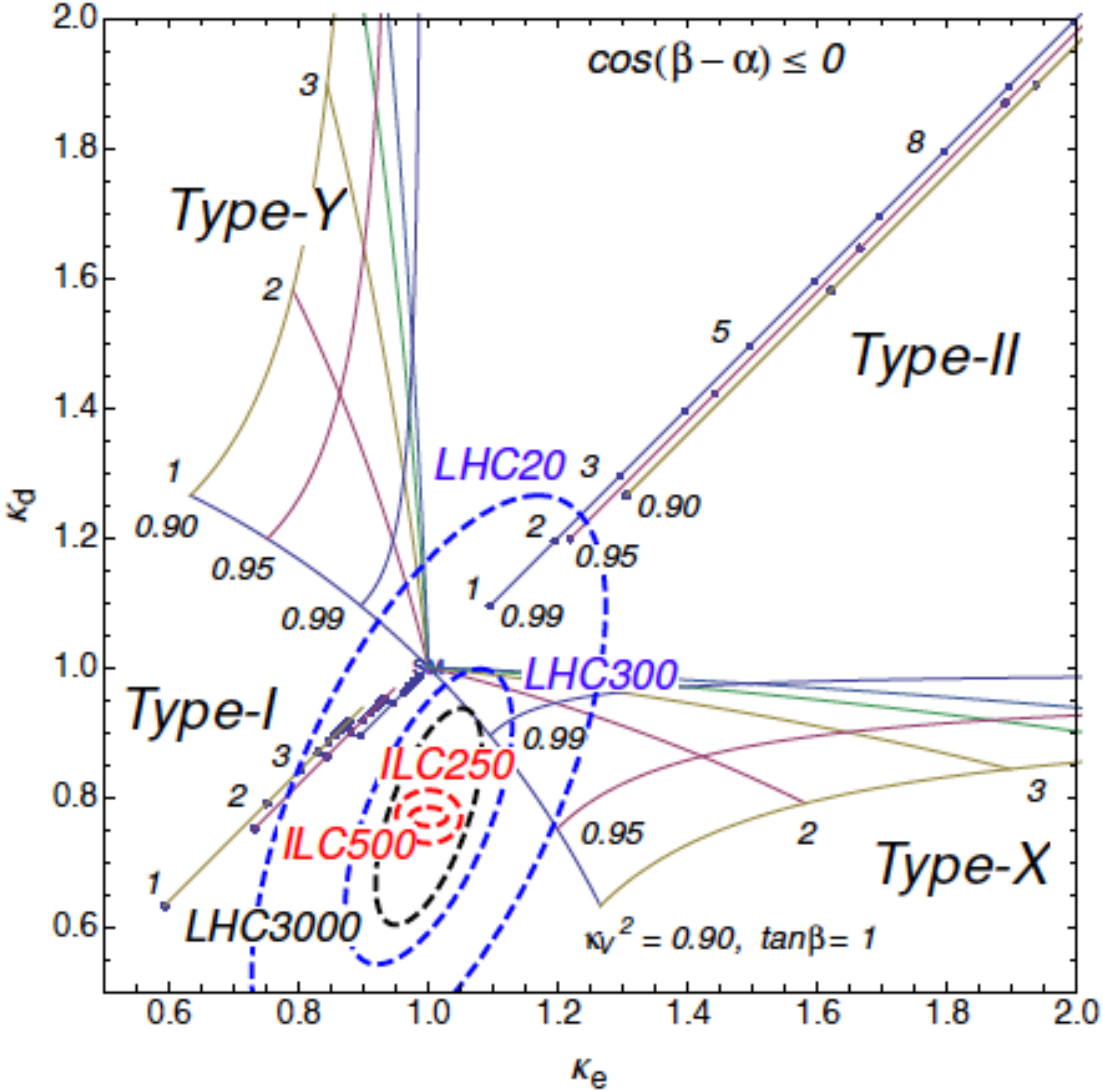
fermion couplings - multiple Higgs doublets

gauge boson couplings - Higgs singlets, composite Higgs

$\gamma\gamma$, gg couplings - heavy vectorlike particles

tt coupling - top compositeness

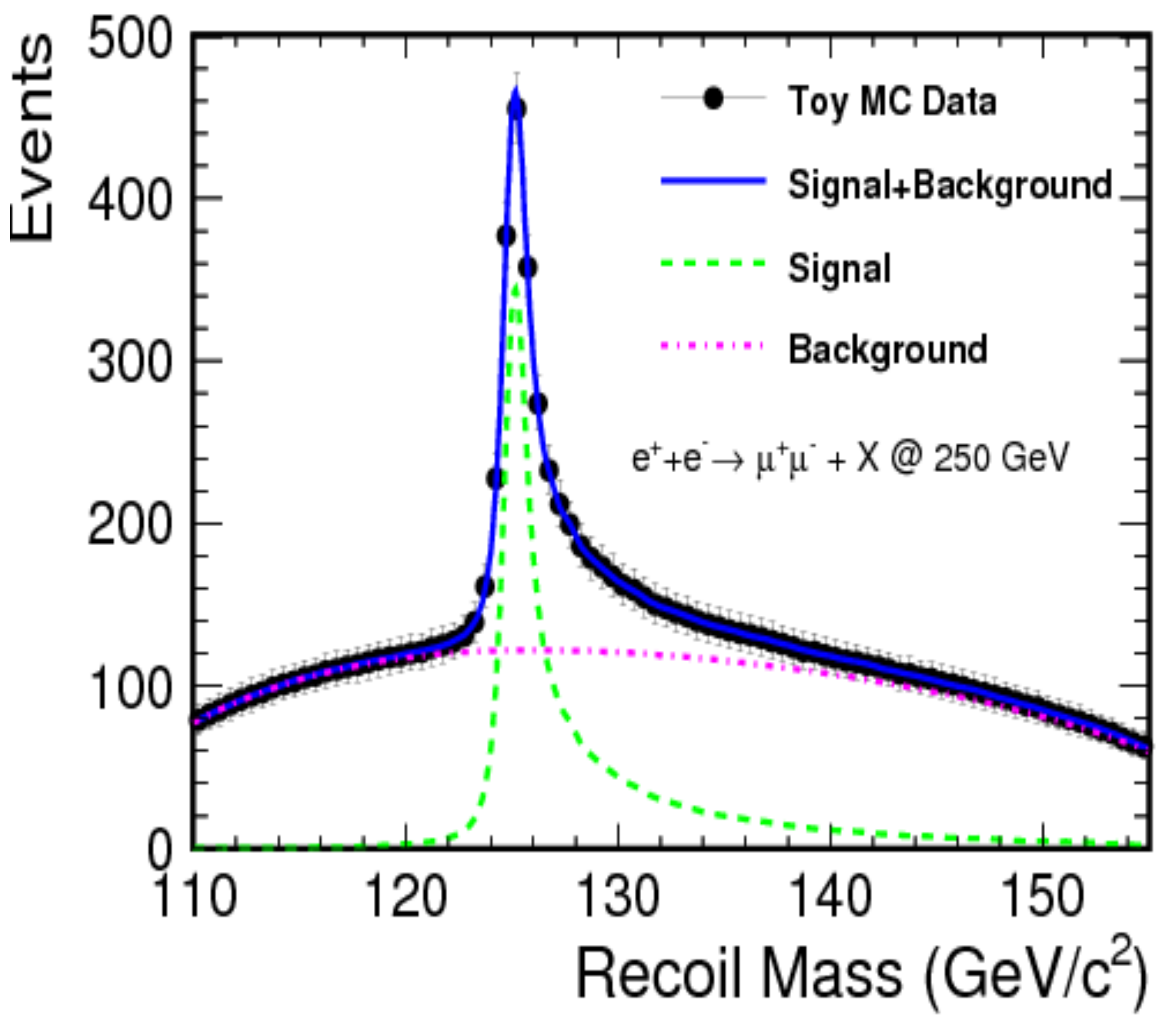
hhh coupling (large deviations) - baryogenesis

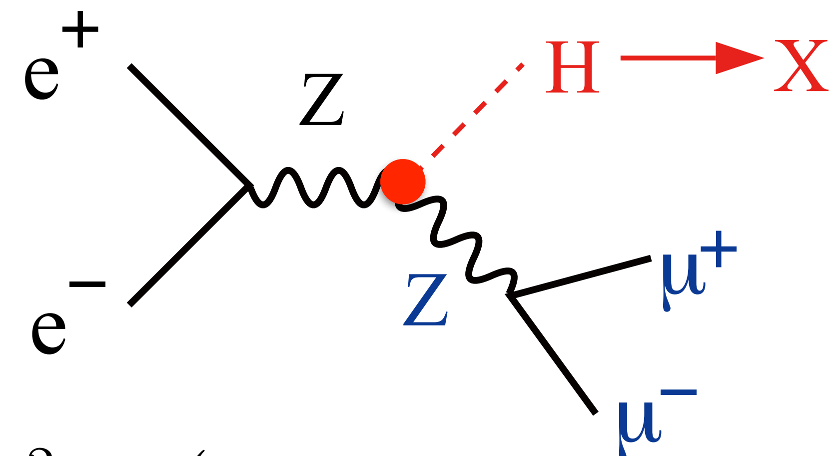


S.Kanemura, K.Yagyu, et al., arXiv: 1406.3294

the key of model independence: absolute σ_{ZH}

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





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

$$Y_1 = \sigma_{ZH} \propto g_{HZZ}^2$$
$$\delta g_{HZZ} \sim 0.38\%$$

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

importance of absolute coupling determination

- in some BSM, only Higgs wave function gets modified
- Higgs BR, and ratio of Higgs couplings could stay unchanged

$$\mathcal{O}_H = \frac{1}{2}\left(\partial_\mu |H|^2\right)^2$$

N. Craig @ LCWS16
arXiv: 1702.06079

Appears in Lagrangian as $\mathcal{L} \supset \frac{c_H}{\Lambda^2}\mathcal{O}_H$ and after EWSB $H \to v + \frac{1}{\sqrt{2}}h$

$$\frac{c_H}{\Lambda^2}\cdot\frac{1}{2}\left(\partial_\mu |H|^2\right)^2 \to \left(\frac{2c_H v^2}{\Lambda^2}\right)\cdot\frac{1}{2}(\partial_\mu h)^2$$

Correction to Higgs wavefunction in broken phase

Canonically normalizing $h \to \left(1 - c_H v^2/\Lambda^2\right) h$

shifts all Higgs couplings uniformly, e.g.

$$\frac{m_Z^2}{v} h Z_\mu Z^\mu \to \frac{m_Z^2}{v}\left(1 - c_H v^2/\Lambda^2\right) h Z_\mu Z^\mu$$

δg_{HZZ} ~ 0.38% —> Λ > 2.8 TeV

HWW coupling & Higgs total width Γ_H

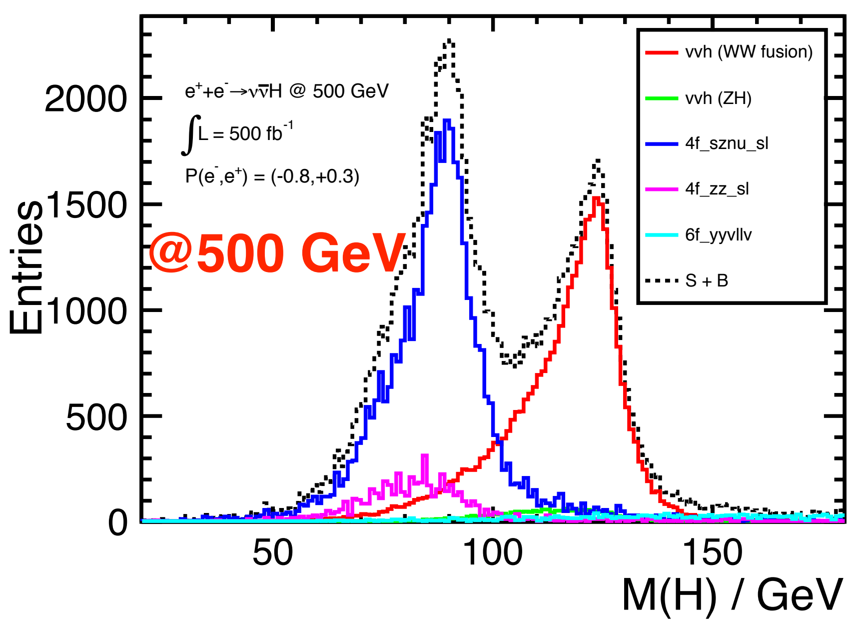
$$\Gamma_H = \frac{\Gamma_{HZZ}}{Br(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{Br(H \to ZZ^*)}$$

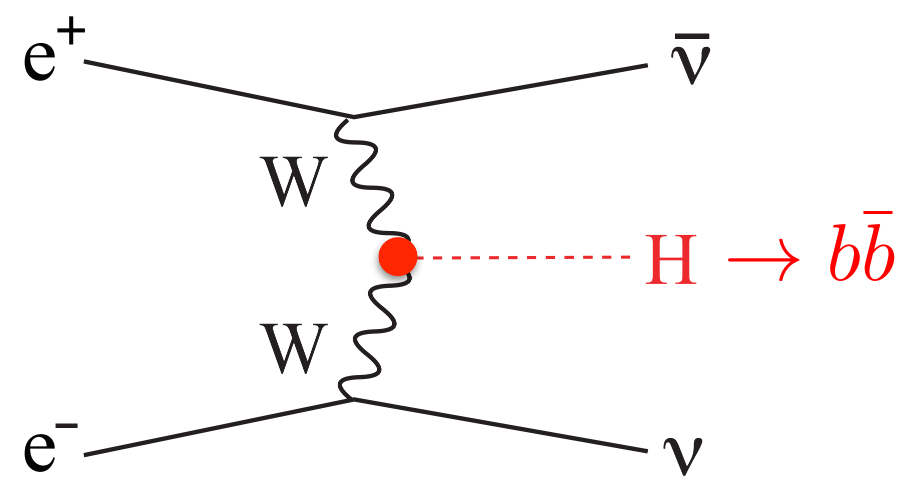
—>Br(H->ZZ*) very small

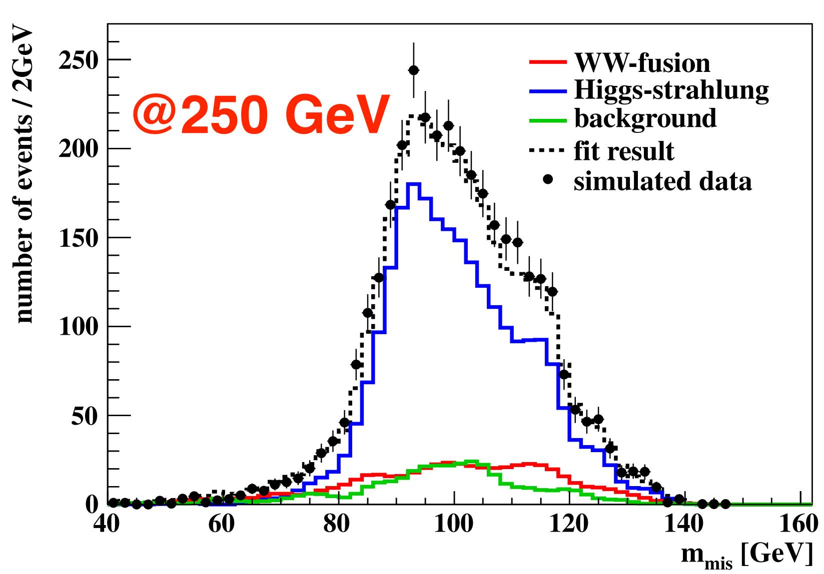
★ $$\Gamma_H = \frac{\Gamma_{HWW}}{Br(H \to WW^*)} \propto \frac{g^2_{HWW}}{Br(H \to WW^*)}$$

—> better option!

$\delta\Gamma_H$=1.8%







Duerig, et al., arXiv:1403.7734

$$Y_2 = \sigma_{\nu\bar{\nu}H} \cdot Br(H \to b\bar{b}) \propto g^2_{HWW} \cdot Br(H \to b\bar{b})$$

$$Y_3 = \sigma_{ZH} \cdot Br(H \to b\bar{b}) \propto g^2_{HZZ} \cdot Br(H \to b\bar{b})$$

$$g_{HWW} \propto \sqrt{\frac{Y_2}{Y_3}} \cdot g_{HZZ} \propto \sqrt{\frac{Y_1 Y_2}{Y_3}}$$

—>0.4%

- δg_{HWW} is a limiting factor for Γ_H & all other couplings (other than g_{HZZ})
- higher $\sqrt{s}$, much larger $\sigma_{\nu\nu H}$

determine Higgs CP admixture

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

through H—>$\tau^+\tau^-$

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

$$\Delta\Phi_{CP} \sim 3.8^\circ$$

D.Jeans @ LCWS16

through HZZ/HWW

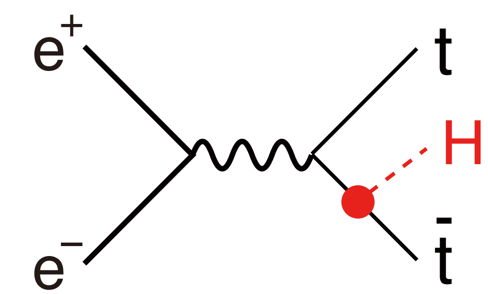
$$L_{HVV} = 2C_V M_V^2 (\frac{1}{v} + \frac{a}{\Lambda}) H V_\mu V^\mu + C_V \frac{b}{\Lambda} H V_{\mu\nu} V^{\mu\nu} + \underline{C_V \frac{\tilde{b}}{\Lambda} H V_{\mu\nu} \tilde{V}_{\mu\nu}}$$

(CP-odd)

$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV) T.Ogawa @ LCWS16

Top-Yukawa coupling

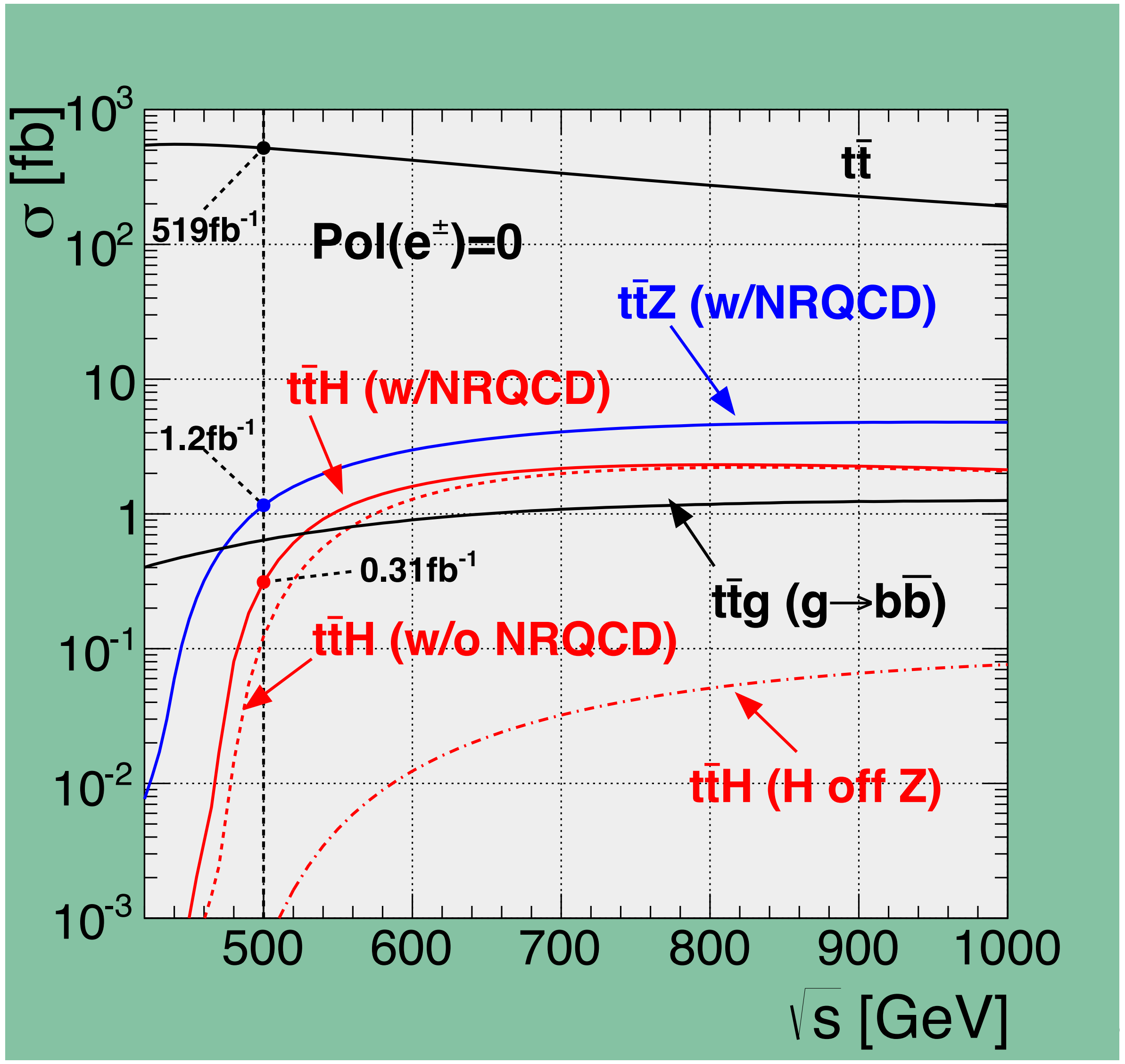
- largest Yukawa coupling; crucial role in theory
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- cross section increases by ~4 if √s goes from 500 to 550 GeV
- Higgs CP measurement

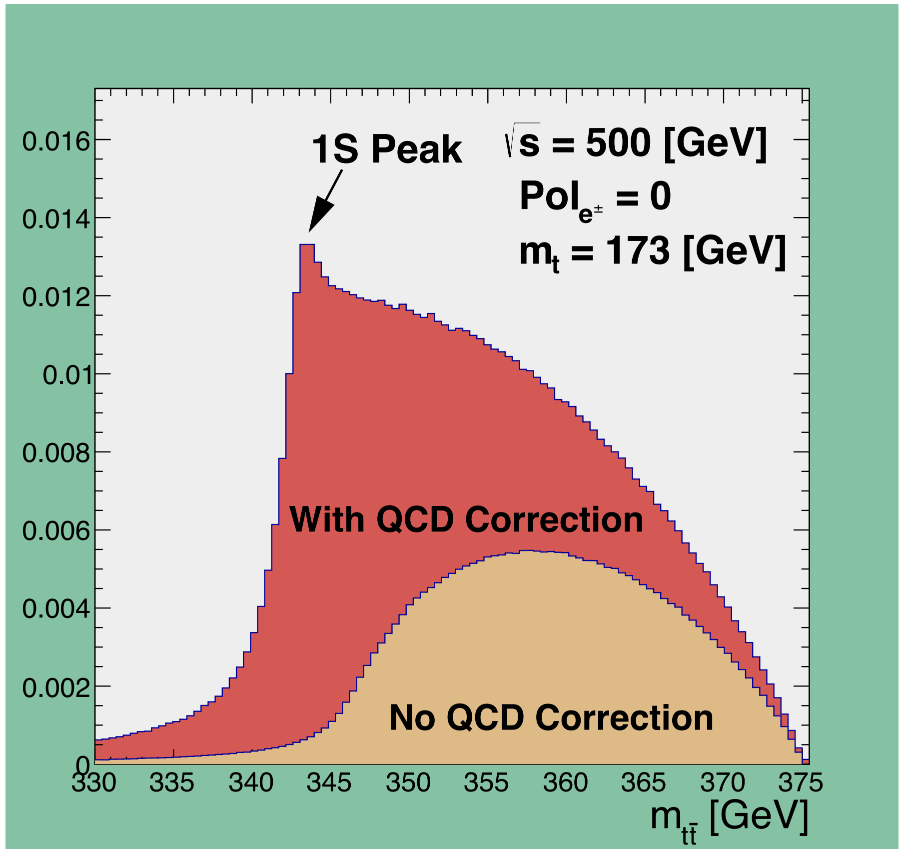


H-> bb

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

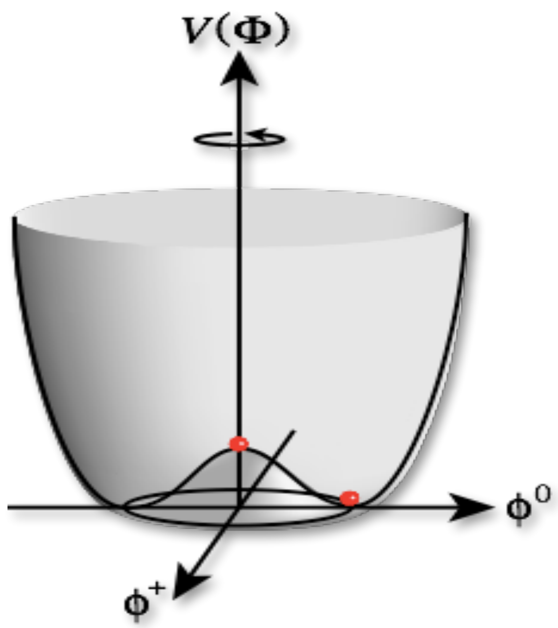
Yonamine, et al., PRD84, 014033;
Price, et al., Eur. Phys. J. C75 (2015) 309





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)

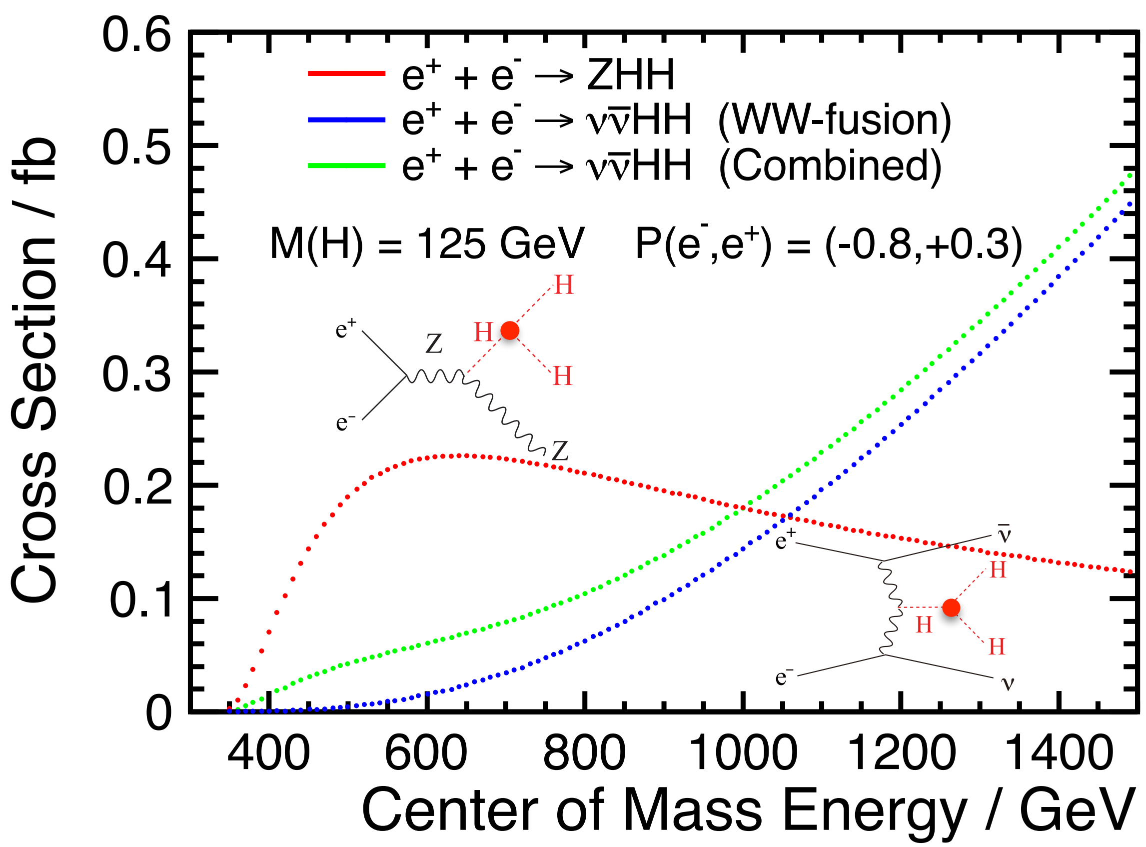


ILC

$\Delta\lambda_{HHH}/\lambda_{HHH}$	500 GeV	+ 1 TeV
Snowmass	46%	13%
H20	27%	10%

CLIC

1.4 TeV	+3 TeV
24%	11%



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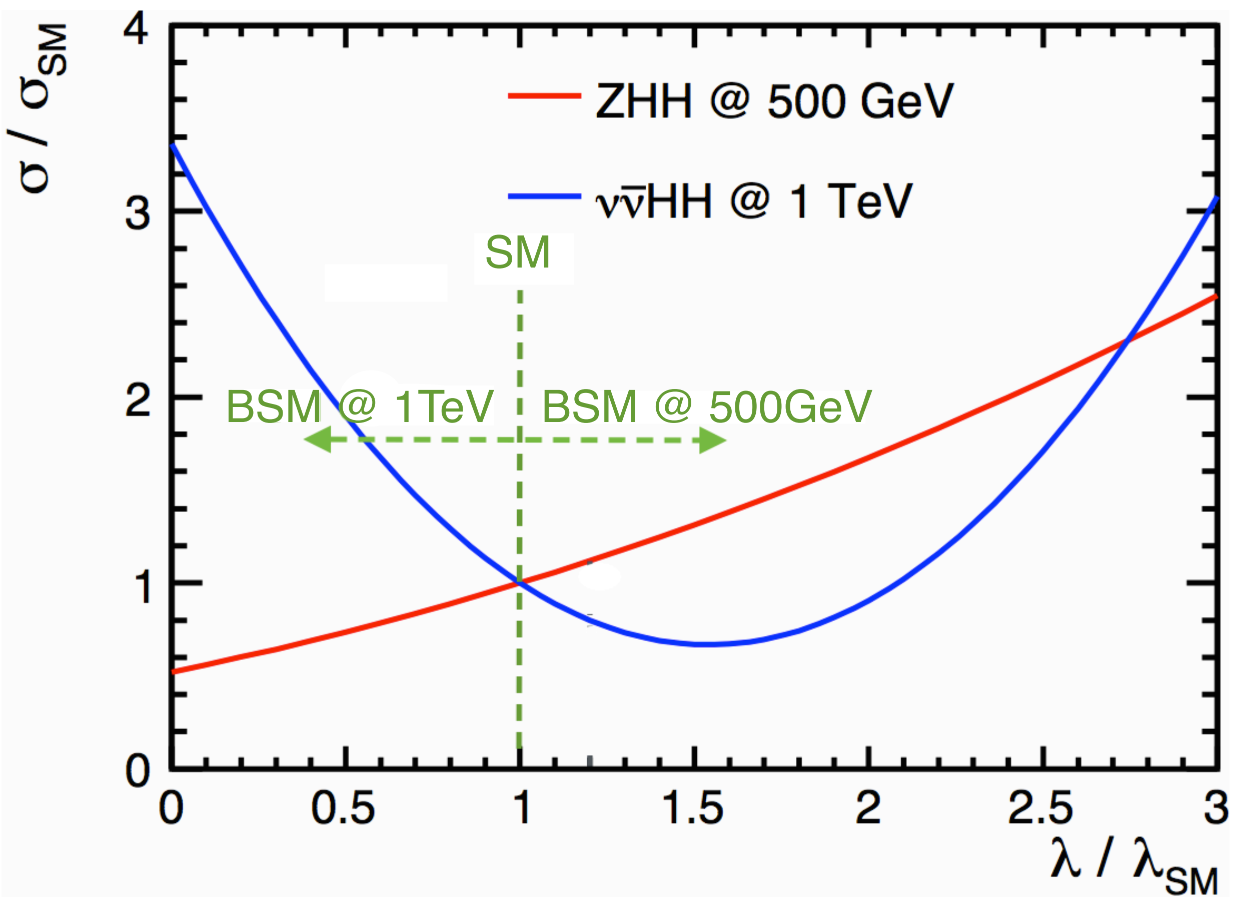
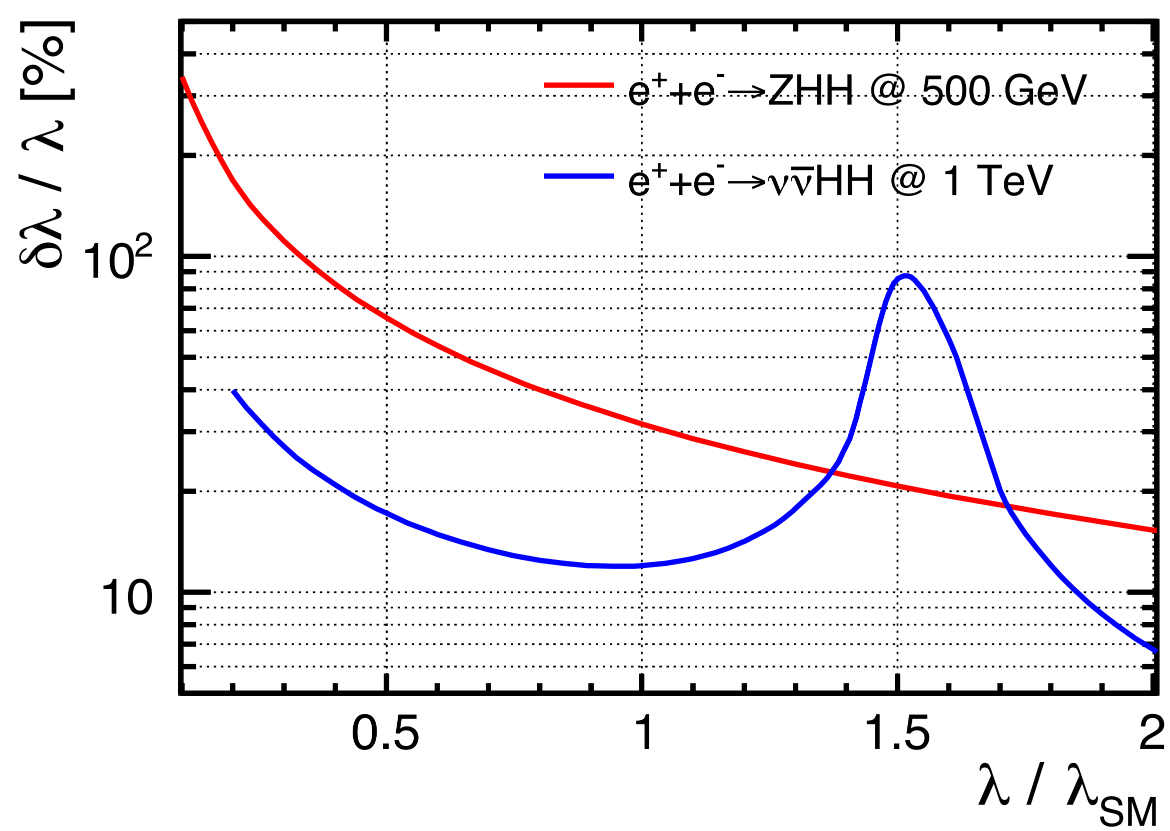
Higgs self-coupling: when $\lambda_{HHH} \neq \lambda_{SM}$?

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

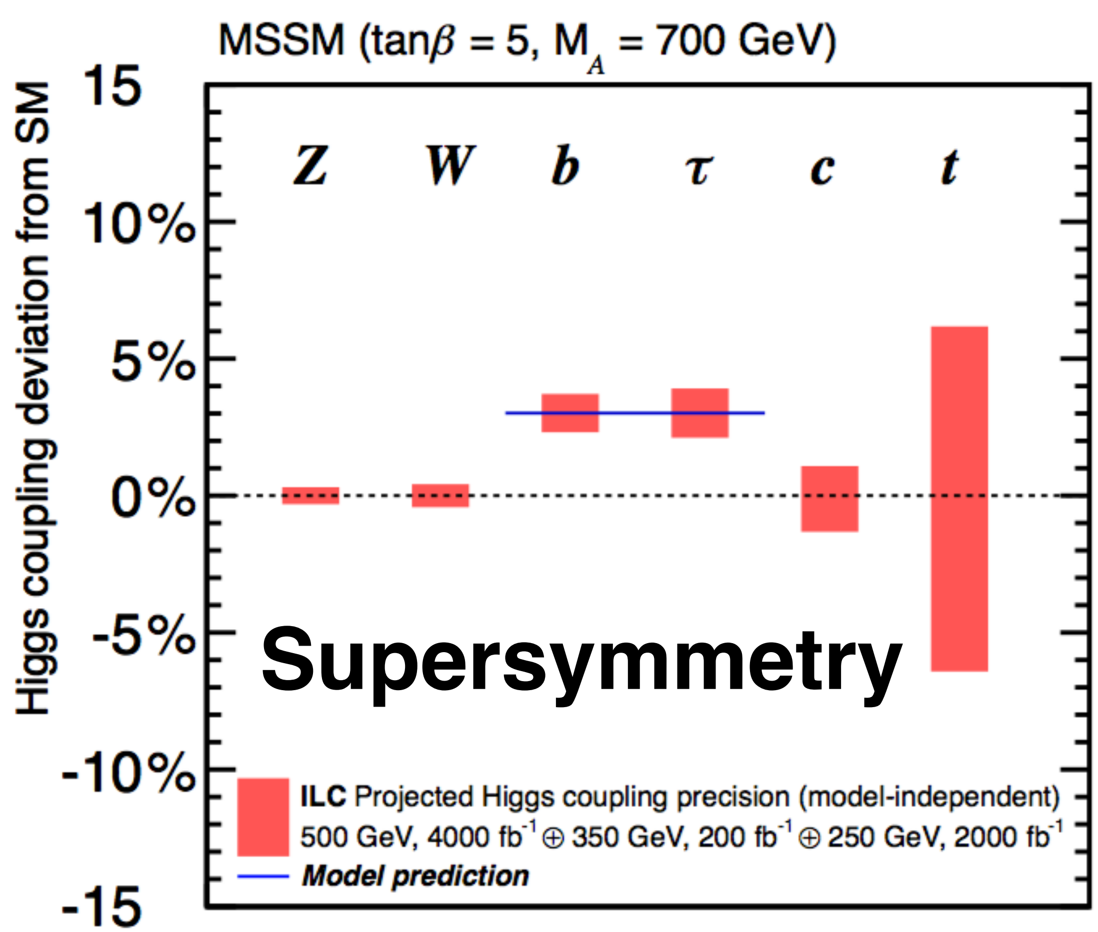
Duerig, Tian, et al, paper in preparation

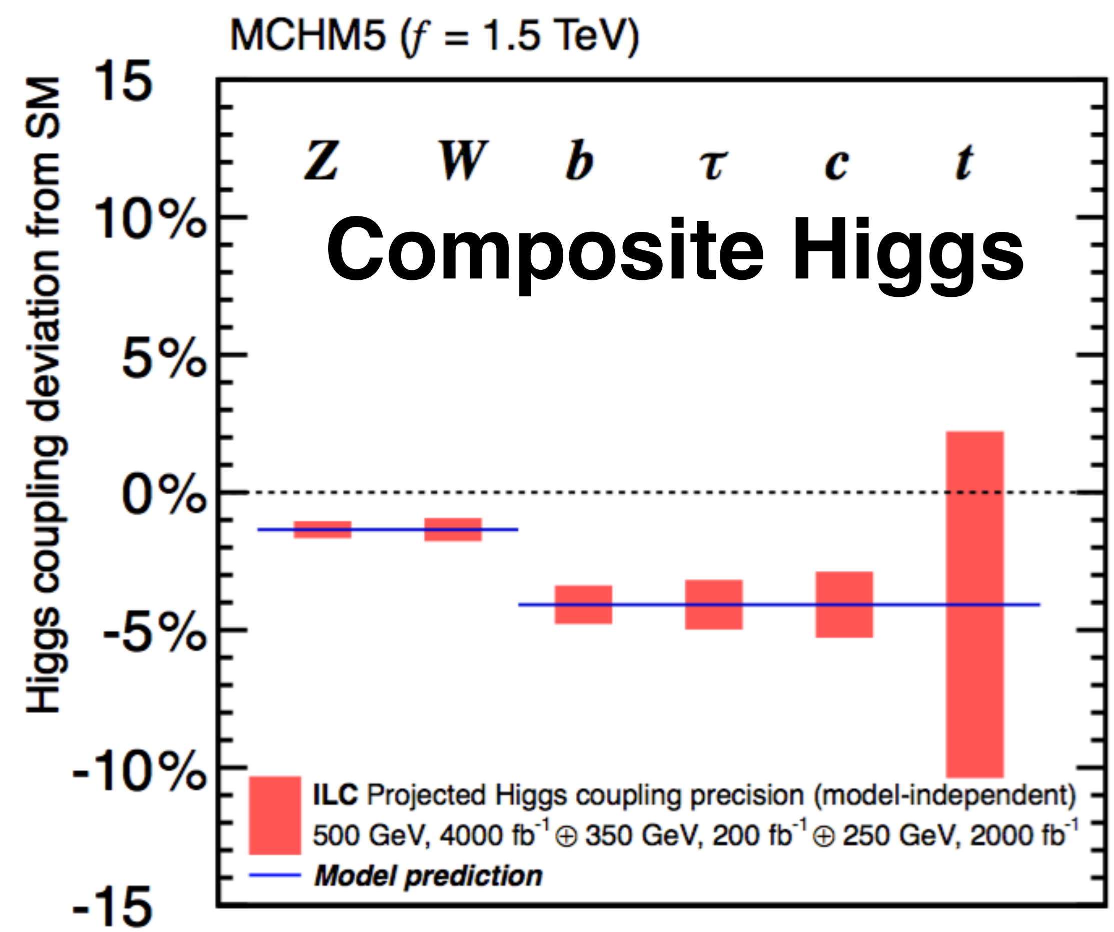




references for large deviations e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

precision Higgs couplings: probe/fingerprint BSM





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

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

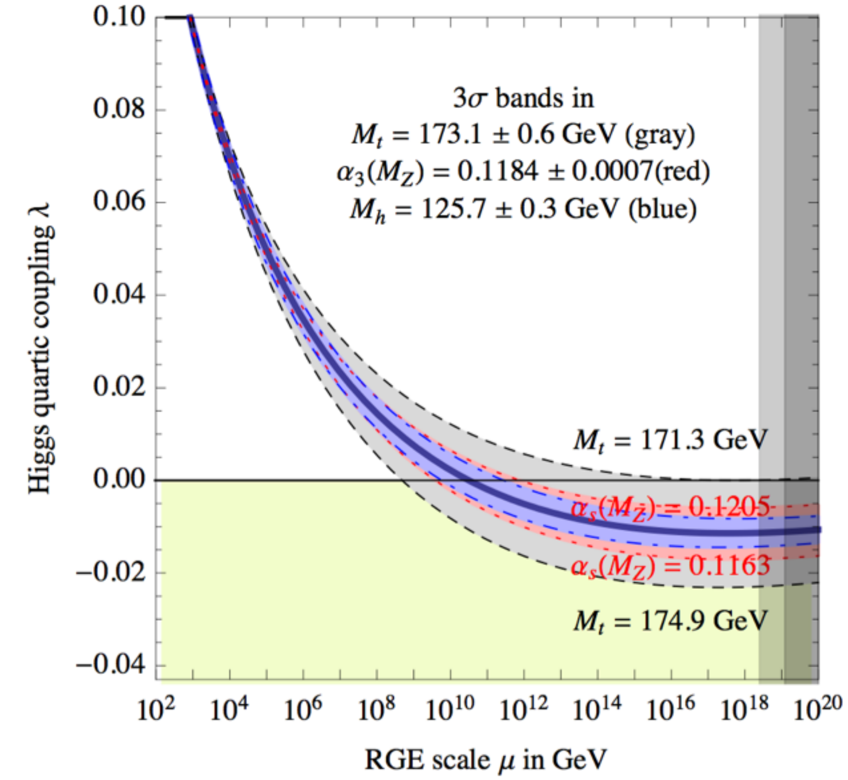
$$\frac{g_{hff}}{g_{h_{\rm SM}ff}} \simeq \begin{cases} 1 - 3\%(1\ \text{TeV}/f)^2 & (\text{MCHM4}) \\ 1 - 9\%(1\ \text{TeV}/f)^2 & (\text{MCHM5}). \end{cases}$$

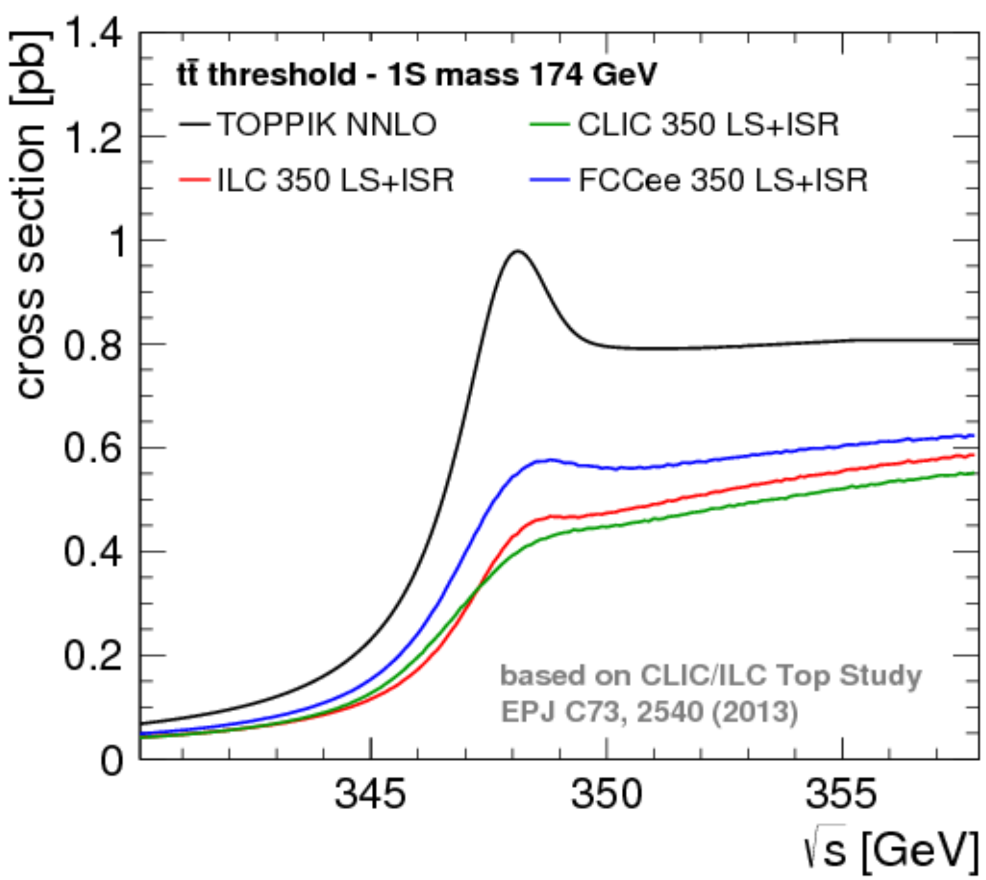
three major probes for BSM at e+e- colliders

- precision measurements of Higgs
- precision measurements of top
- direct search of new particles

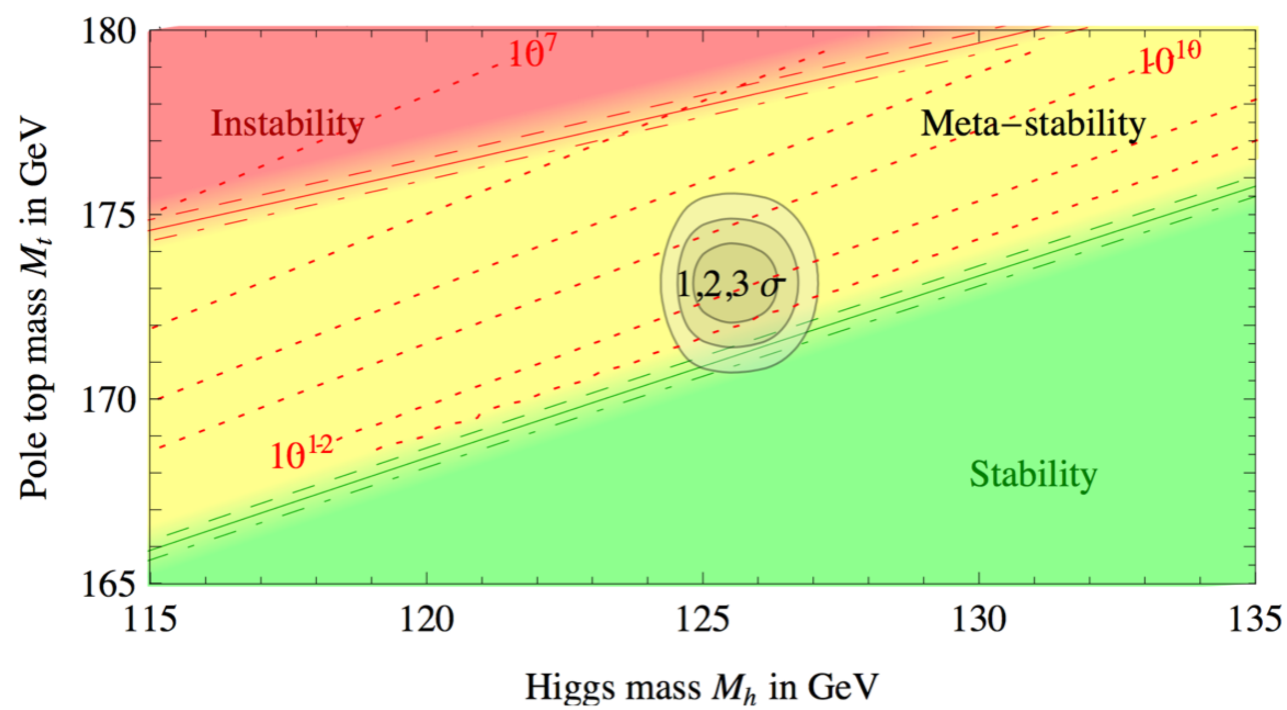
top mass: vacuum stability

- λ runs < 0? top mass precision crucial for vacuum stability
- at e+e-: top-pair threshold scan to measure m_t, much lower theory error
- Δm_t(MS-bar) < 100 MeV (Δm_H=14MeV)





Degrassi et al, JHEP 1208 (2012) 098



top mass at LCs: systematic errors

error source	Δm_t^{PS} [MeV]	references
stat. error (200 fb^{-1})	13	[63, 66]
theory (NNNLO scale variations, PS scheme)	40	[65, 66]
parametric (α_s, current WA)	35	[65]
non-resonant contributions (such as single top)	< 40	[67]
residual background / selection efficiency	$10 - 20$	[63]
luminosity spectrum uncertainty	< 10	[68]
beam energy uncertainty	< 17	[63]
combined theory & parametric	$30 - 50$	
combined experimental & backgrounds	25 - 50	
total (stat. + syst.)	$40 - 75$	

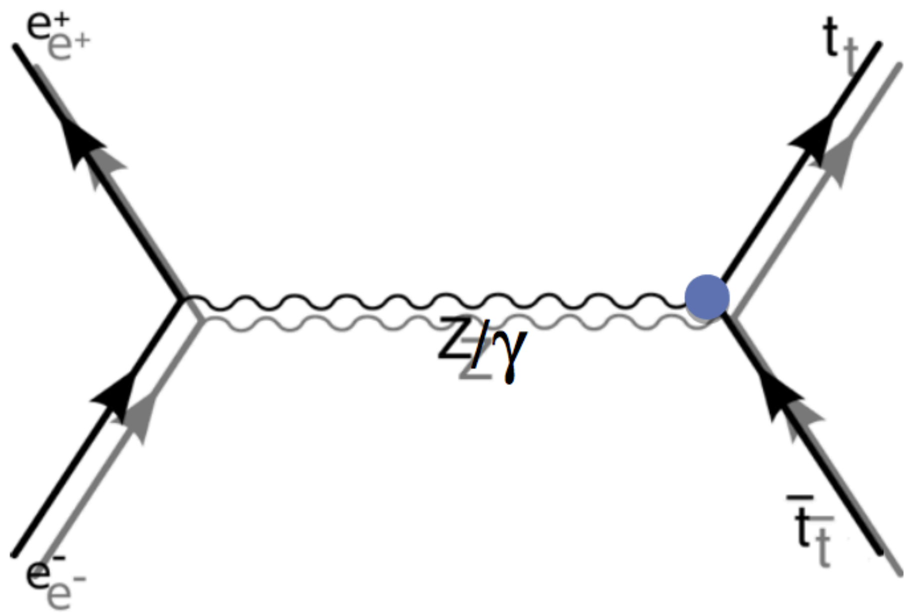
1702.05333

top EW chiral couplings

M.Vos @ LCWS16

Assume production is dominated by SM and NP scale is beyond direct reach.

$$\Gamma_\mu^{t\bar{t}X}(k^2, q, \bar{q}) = ie\left\{\gamma_\mu\left(\underline{F_{1V}^X}(k^2) + \gamma_5 \underline{F_{1A}^X}(k^2)\right) - \frac{\sigma_{\mu\nu}}{2m_t}(q+\bar{q})^\nu\left(i\underline{F_{2V}^X}(k^2) + \gamma_5 F_{2A}^X(k^2)\right)\right\}$$



Measure 2 observables for 2 beam polarizations at ILC500 and CLIC380 (full-simulation):

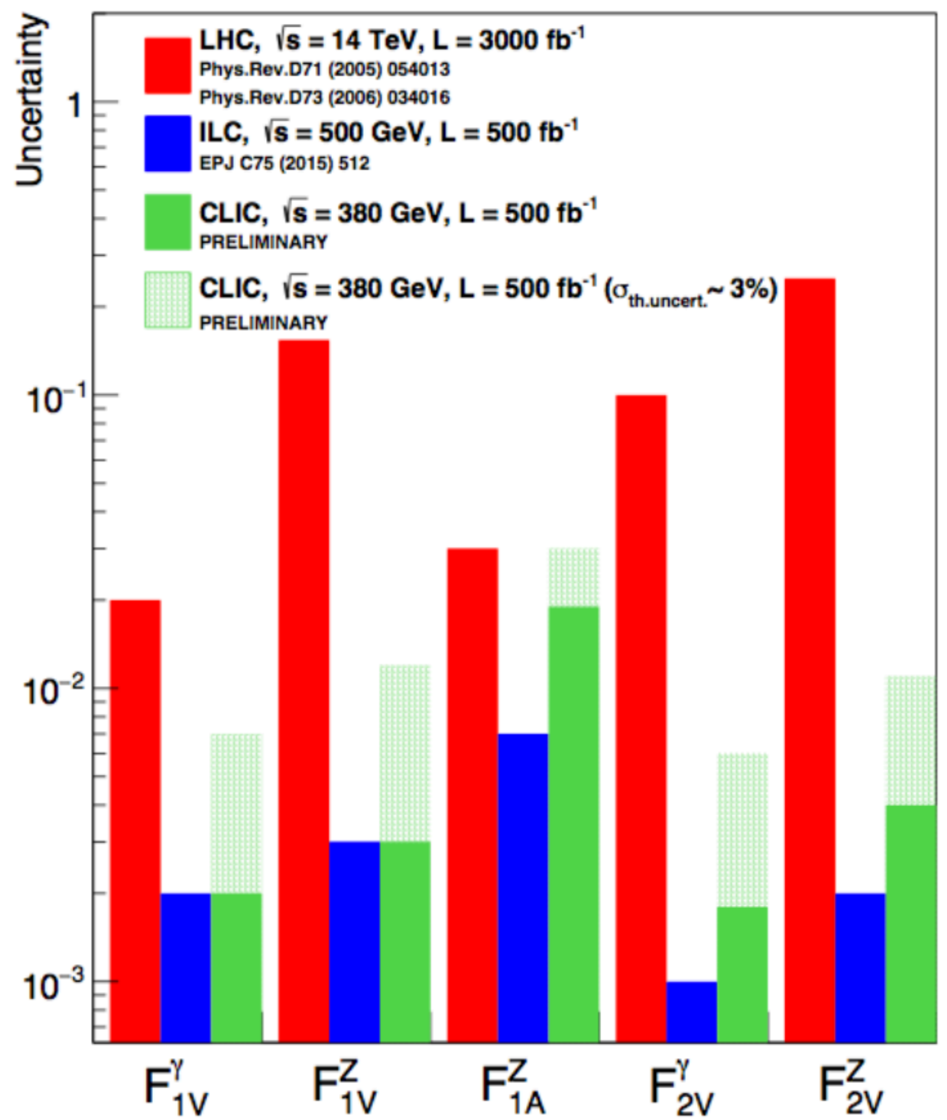
$F_{1A}^{\gamma,SM} = 0$ always because of the gauge invariance

$$\begin{matrix} \sigma(+) & A_{FB}(+) \\ \sigma(-) & A_{FB}(-) \end{matrix} \qquad \left.\begin{matrix}(+ = e_R^-) \\ (- = e_L^-)\end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F_{1V}^\gamma & * & F_{2V}^\gamma \\ F_{1V}^Z & F_{1A}^Z & F_{2V}^Z \end{matrix}\right\}$$

Measure **Extract**

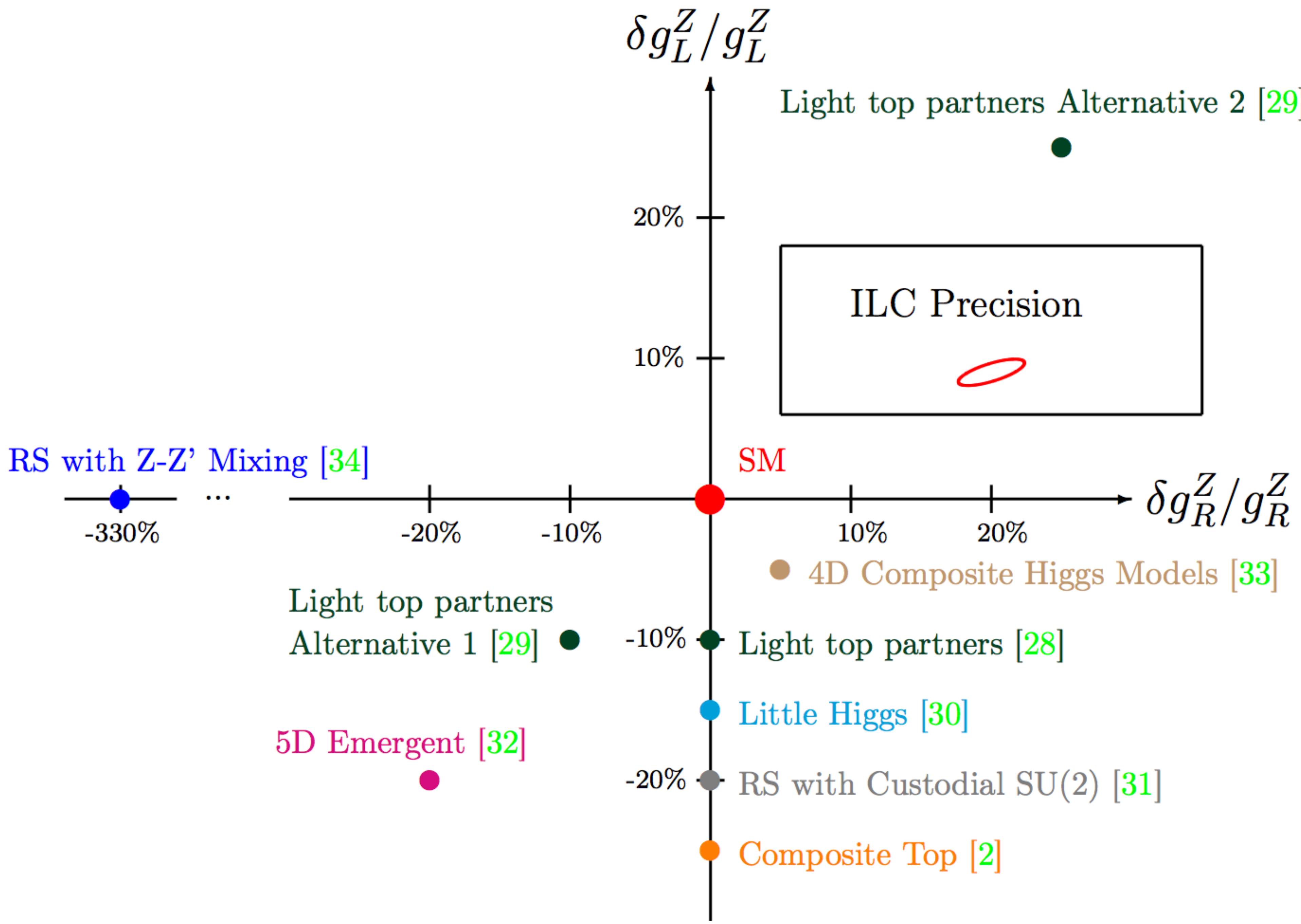
IFIC - LAL Collaboration

arXiv:1505.06020



top EW chiral couplings

Eur.Phys.J. C75 (2015) no.10, 512



great sensitivities to discover/distinguish various composite models

three major probes for BSM at e+e- colliders

- precision measurements of Higgs
- precision measurements of top
- direct search of new particles

Chargino search

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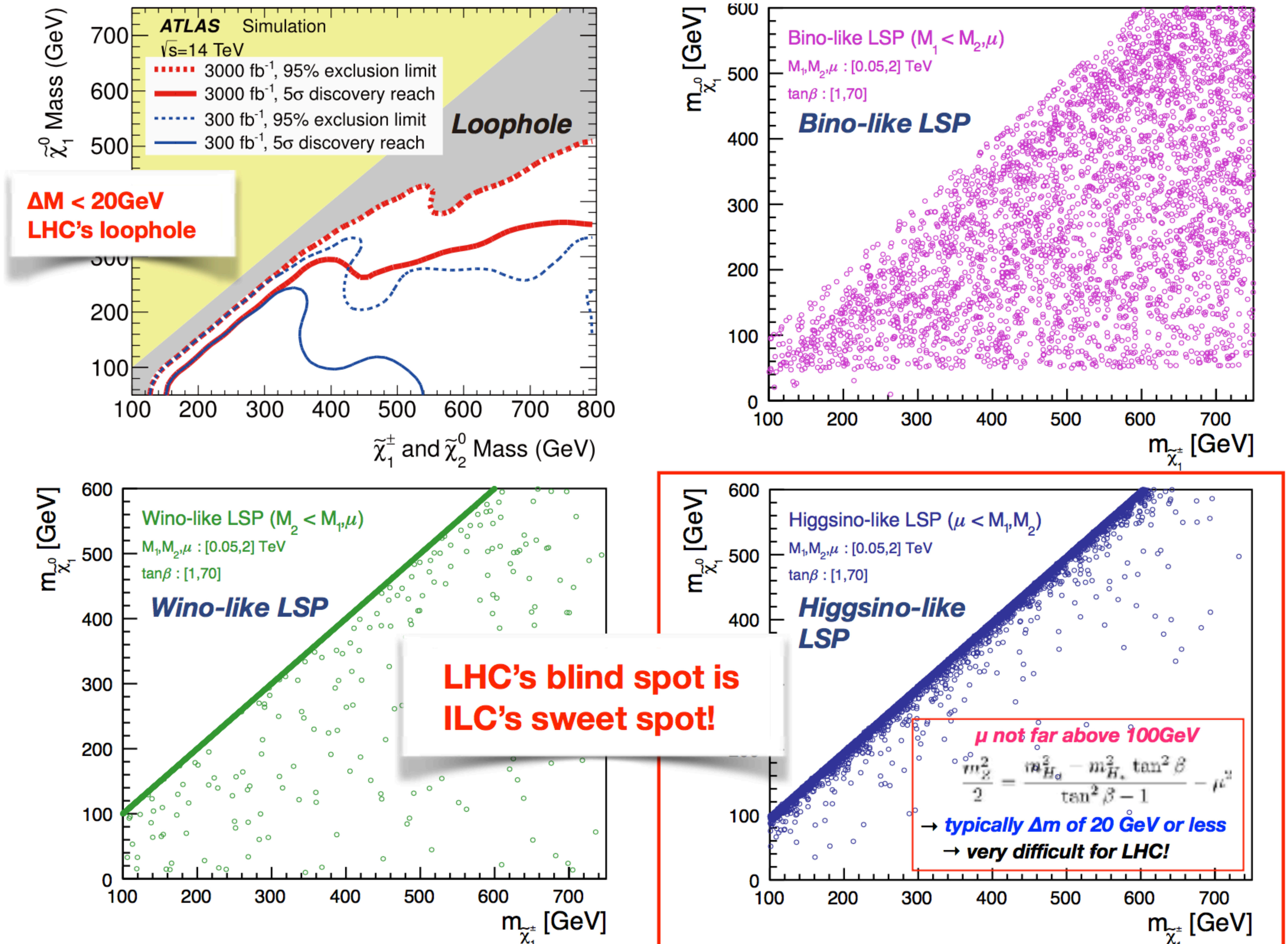
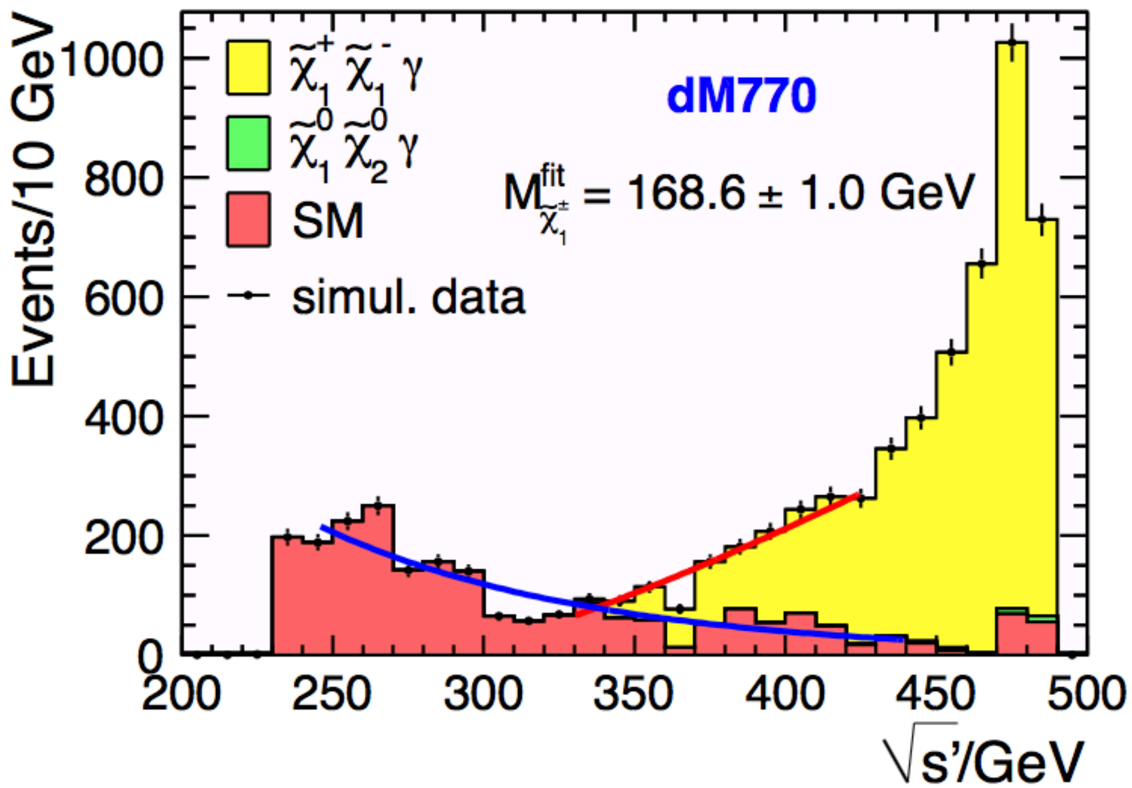
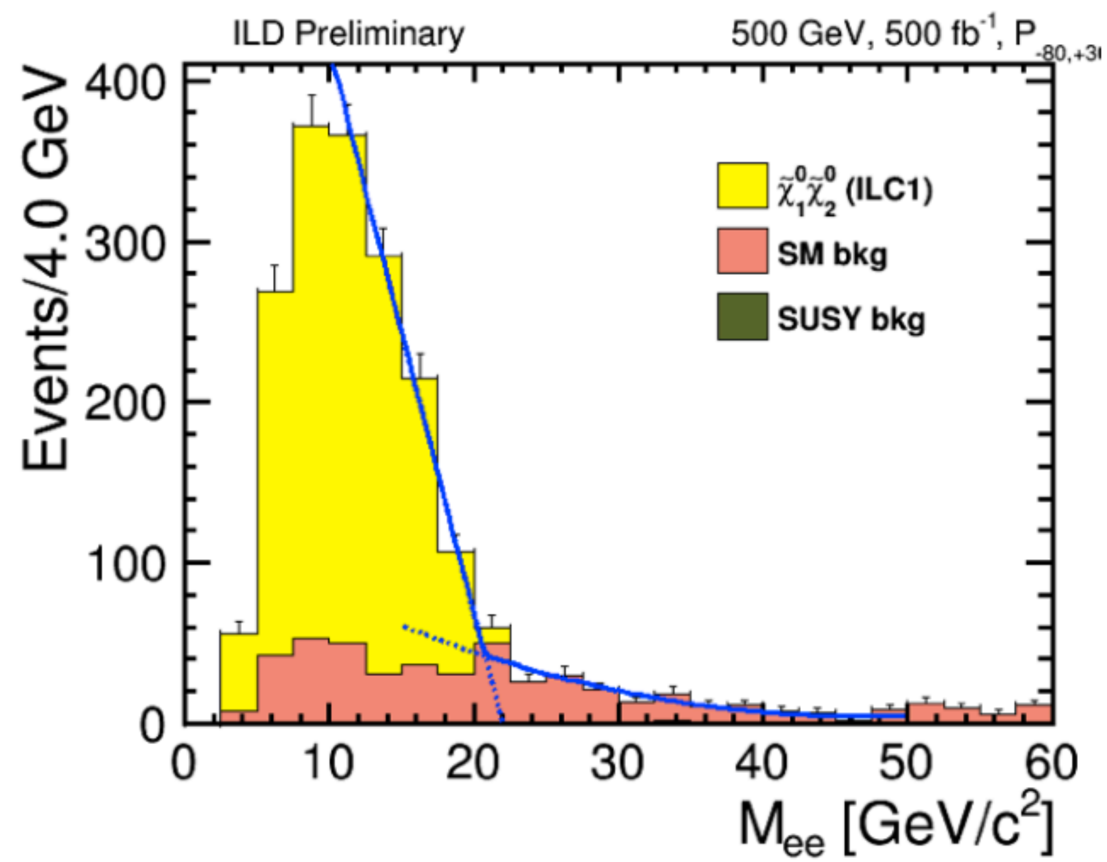


$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2$$

Natural SUSY: light Higgsinos

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \Sigma_u^u - \mu^2$$





$$M_{\widetilde{\chi_1}^{\pm}} - M_{\widetilde{\chi_1}^0} = 770\mathrm{MeV}$$

$$M_{\widetilde{\chi_2}^0} - M_{\widetilde{\chi_1}^0} = 20\mathrm{GeV}$$

arXiv:1307.3566

arXiv:1611.02846

WIMP Dark Matter search

K.Fujii@HPNP2017

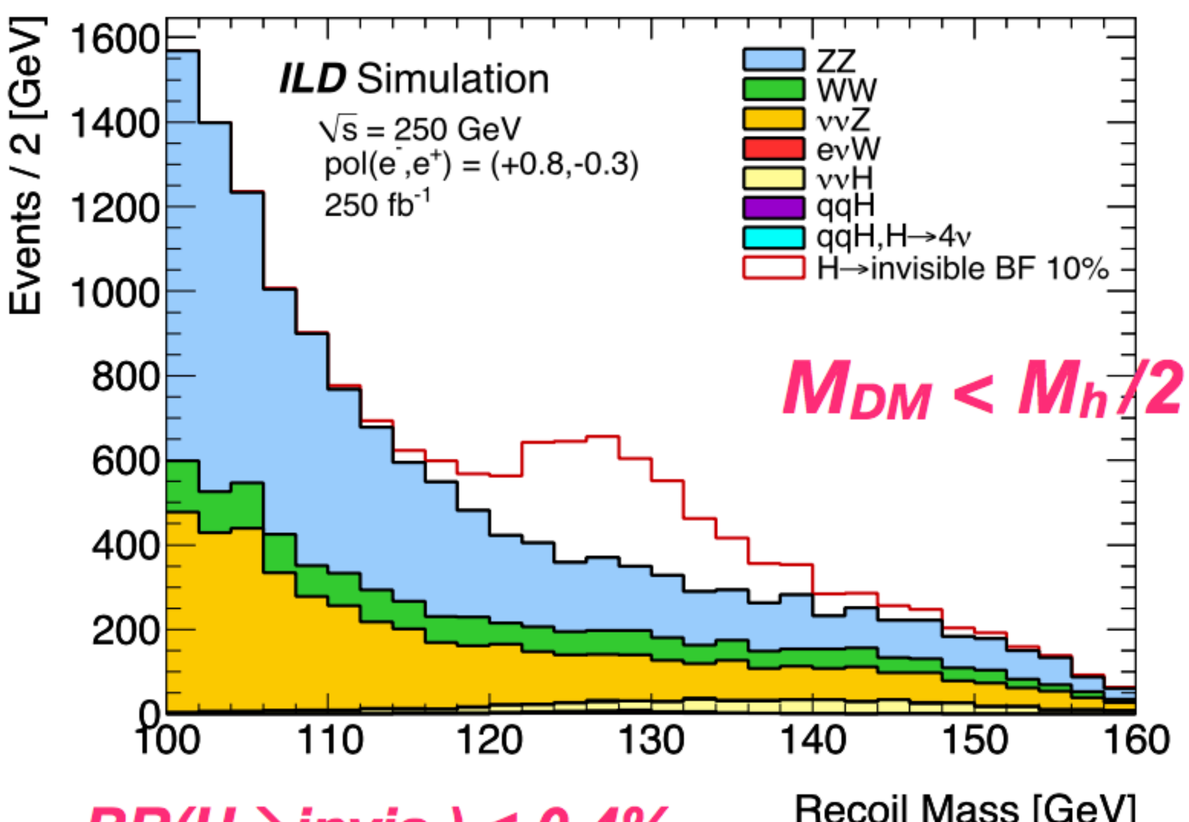
Decay of a new particle to Dark Matter (DM)

DM has a charged partner in many new physics models.

SUSY: The Lightest SUSY Particle (LSP) = DM → Its partner decays to a DM.

- Events with missing Pt (example: light chargino: see the previous page)

Higgs Invisible Decay

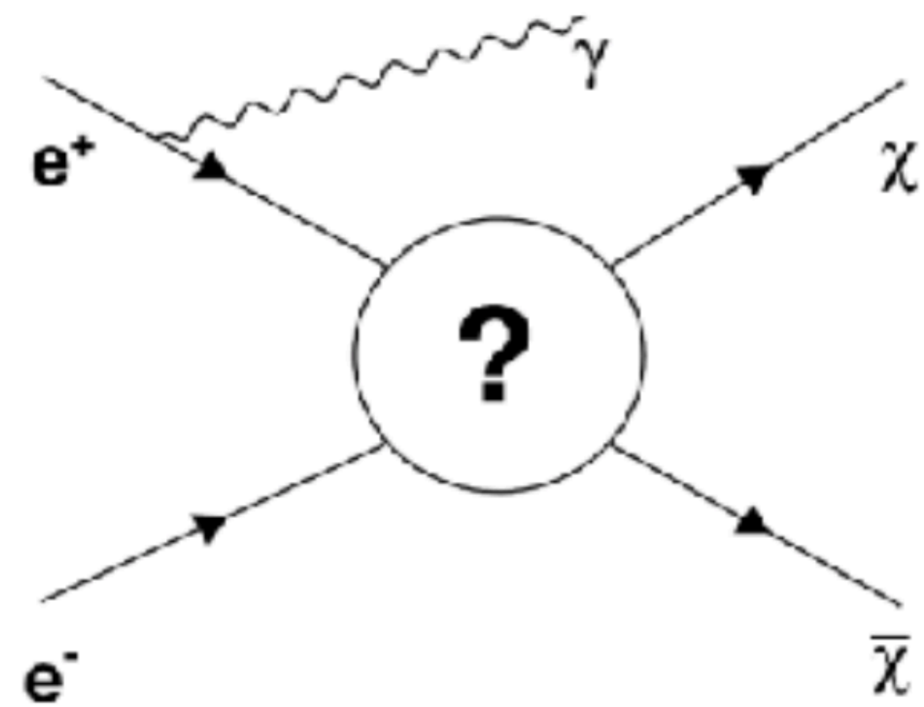


BR(H→invis.) < 0.4%

at 250 GeV, 1150 fb^{-1} ***(<0.3% at 95%CL: H20)***

Possible to access BR_{inv} to 0.4%!

Mono-photon Search



→ ***M_{DM} reach ~ $E_{cm}/2$***

Possible to access DM to ~$E_{cm}/2$!

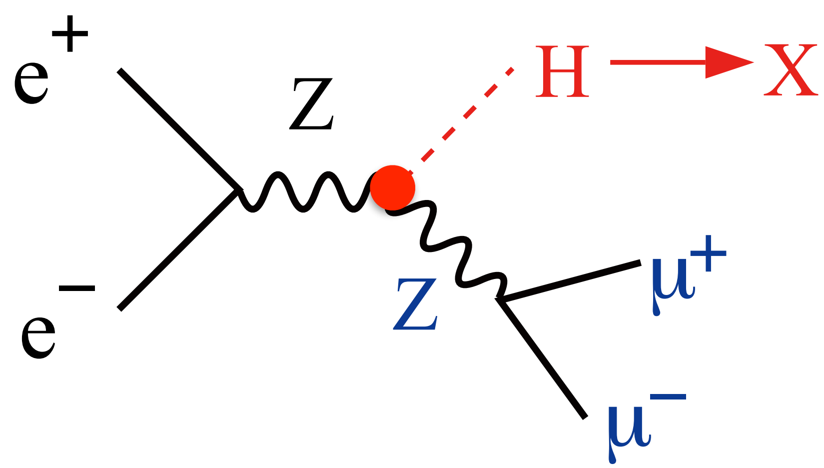
(ii) model independent determination of Higgs (self-)couplings model independence in kappa framework (elementary school)

- 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)



is it really easy?

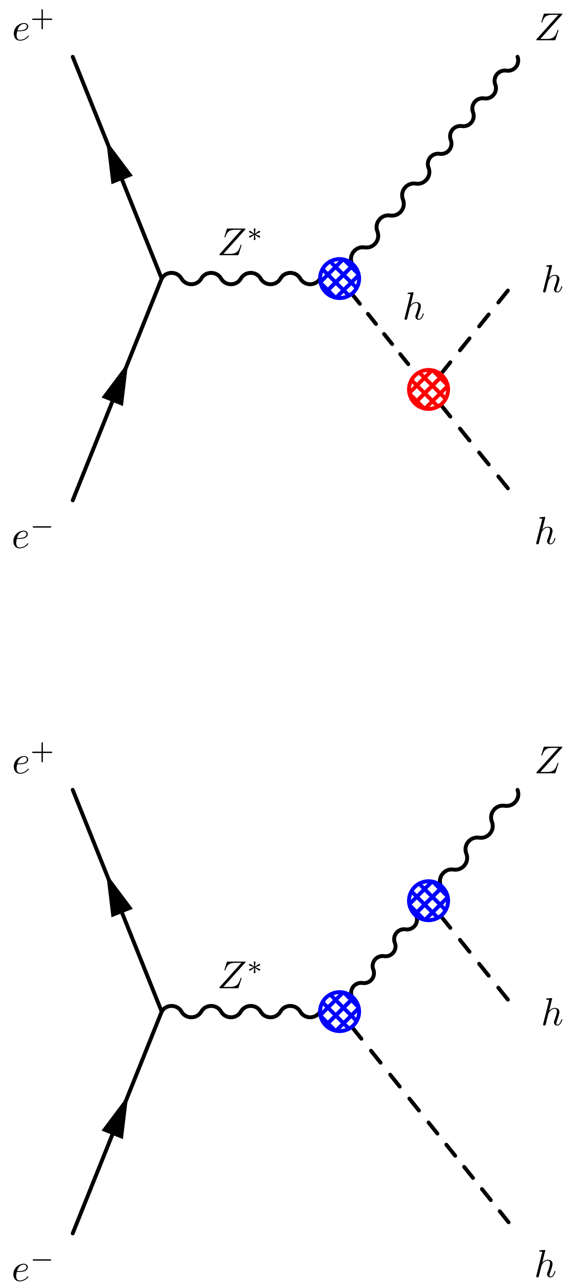
Yan, et al, Phys.Rev. D94 (2016) 113002;
Thomson, Eur.Phys.J. C76 (2016) 72

$H \to XX$	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

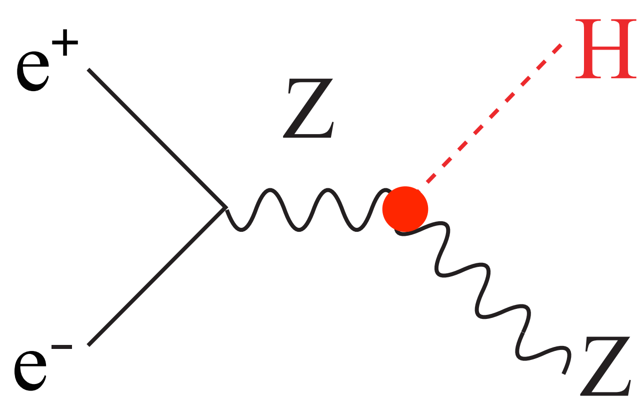
still need effort to achieve bias in hadronic recoil mode < 1%

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

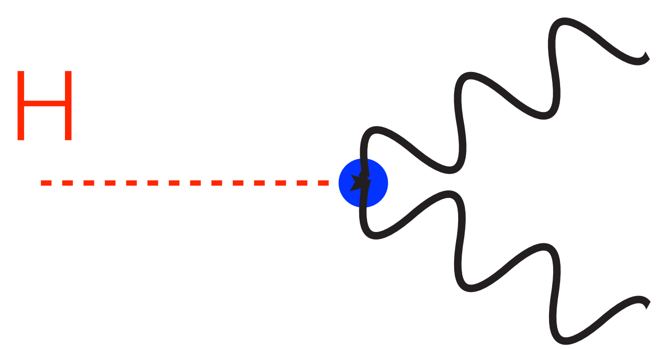


BSM territory -> if we measure a change in this cross section, what actually do we measure?

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

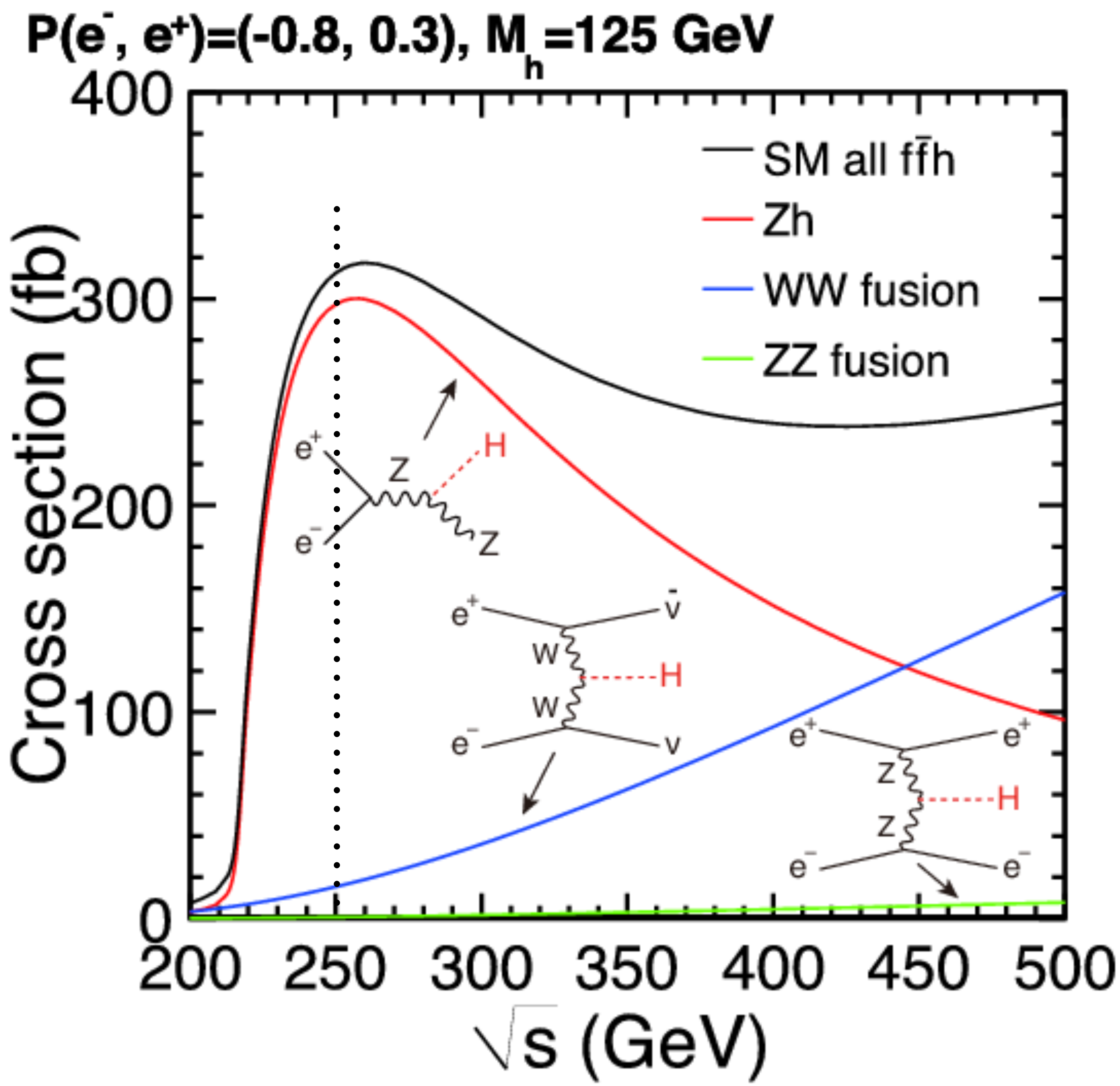


$\propto ?\ \kappa_Z^2$



BSM territory -> are we measuring the right coupling?

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



WW-fusion is smaller by x10 than 500 GeV

some quick answers

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

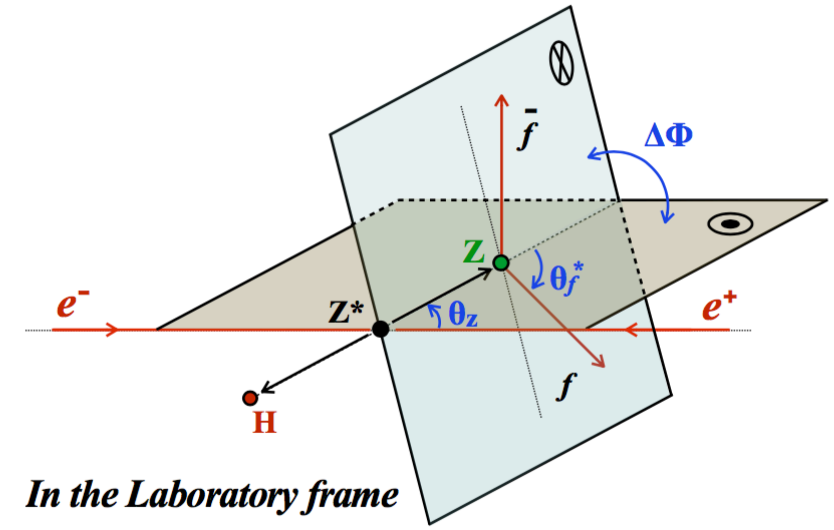
$$L_{hZZ} = M_Z^2(\frac{1}{v} + \frac{a}{\Lambda})hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}$$

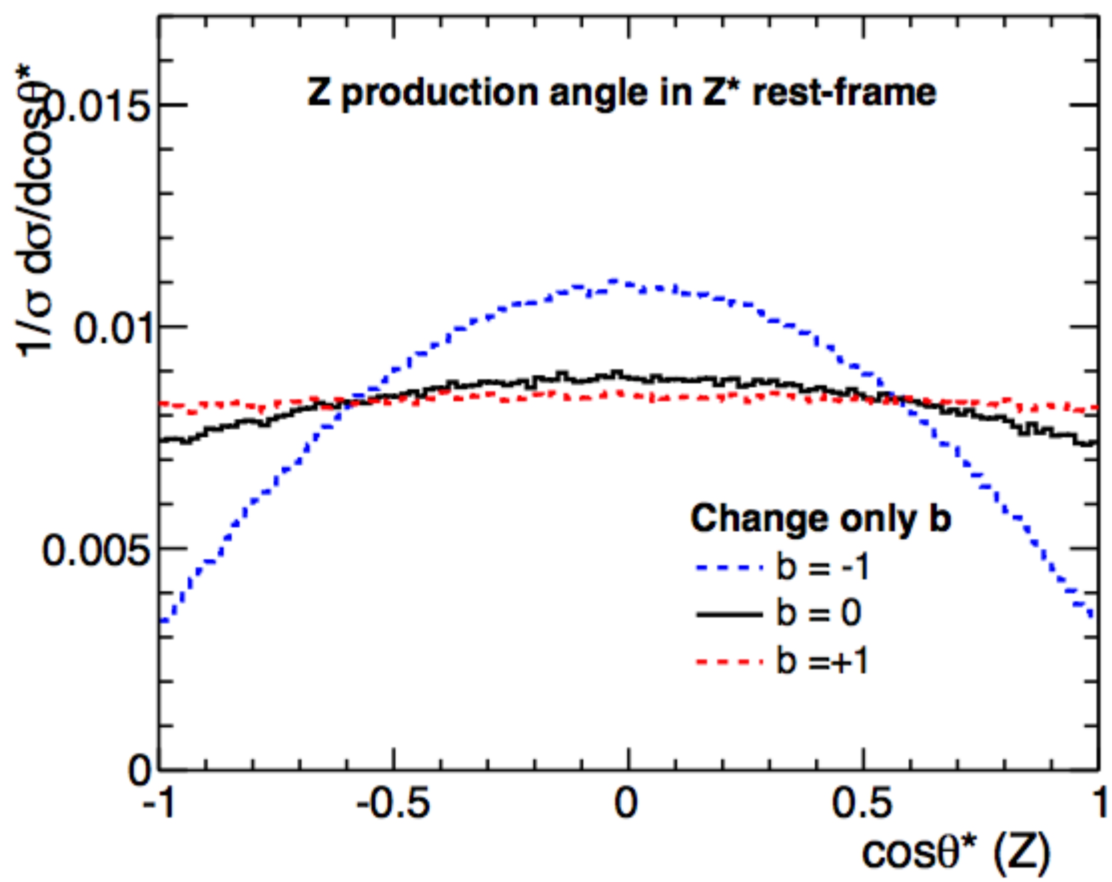
(SM-like) (CP-even) (CP-odd)

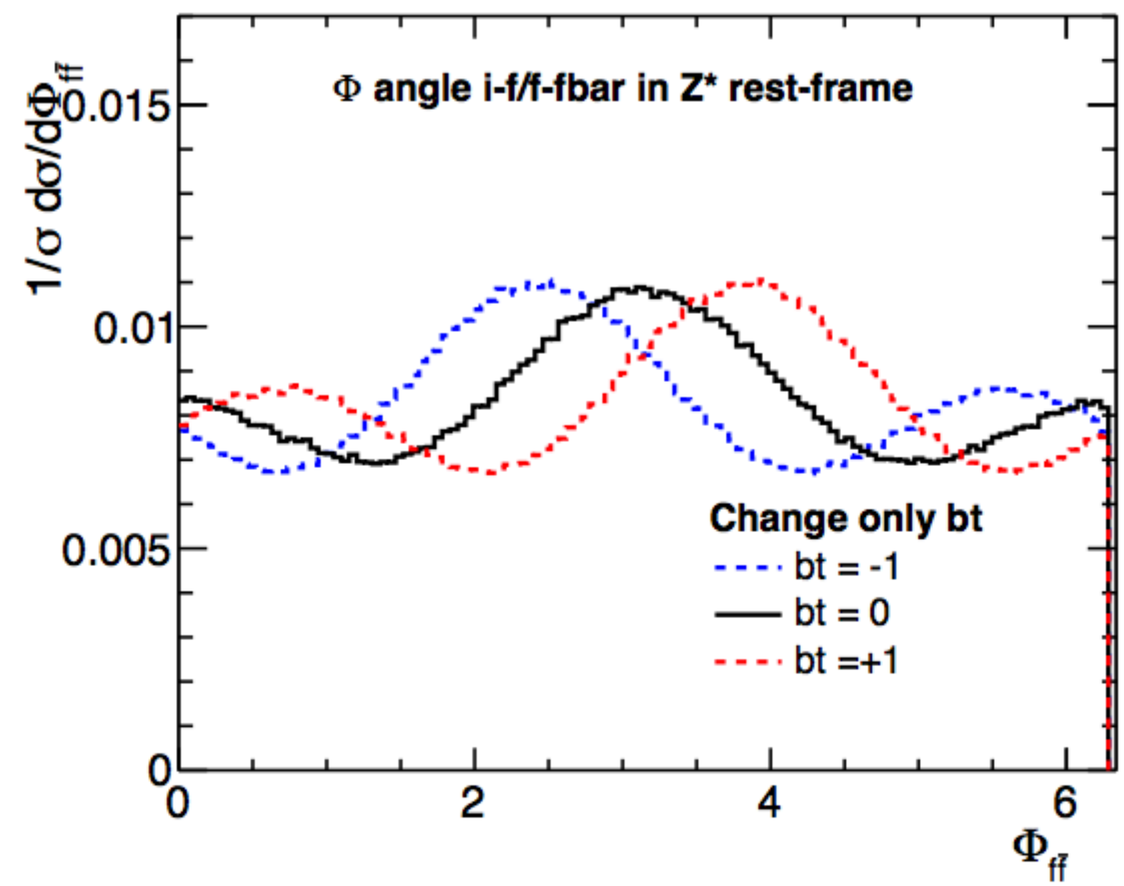
Ogawa, Fujii, Tian, EPS-HEP 2017

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

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







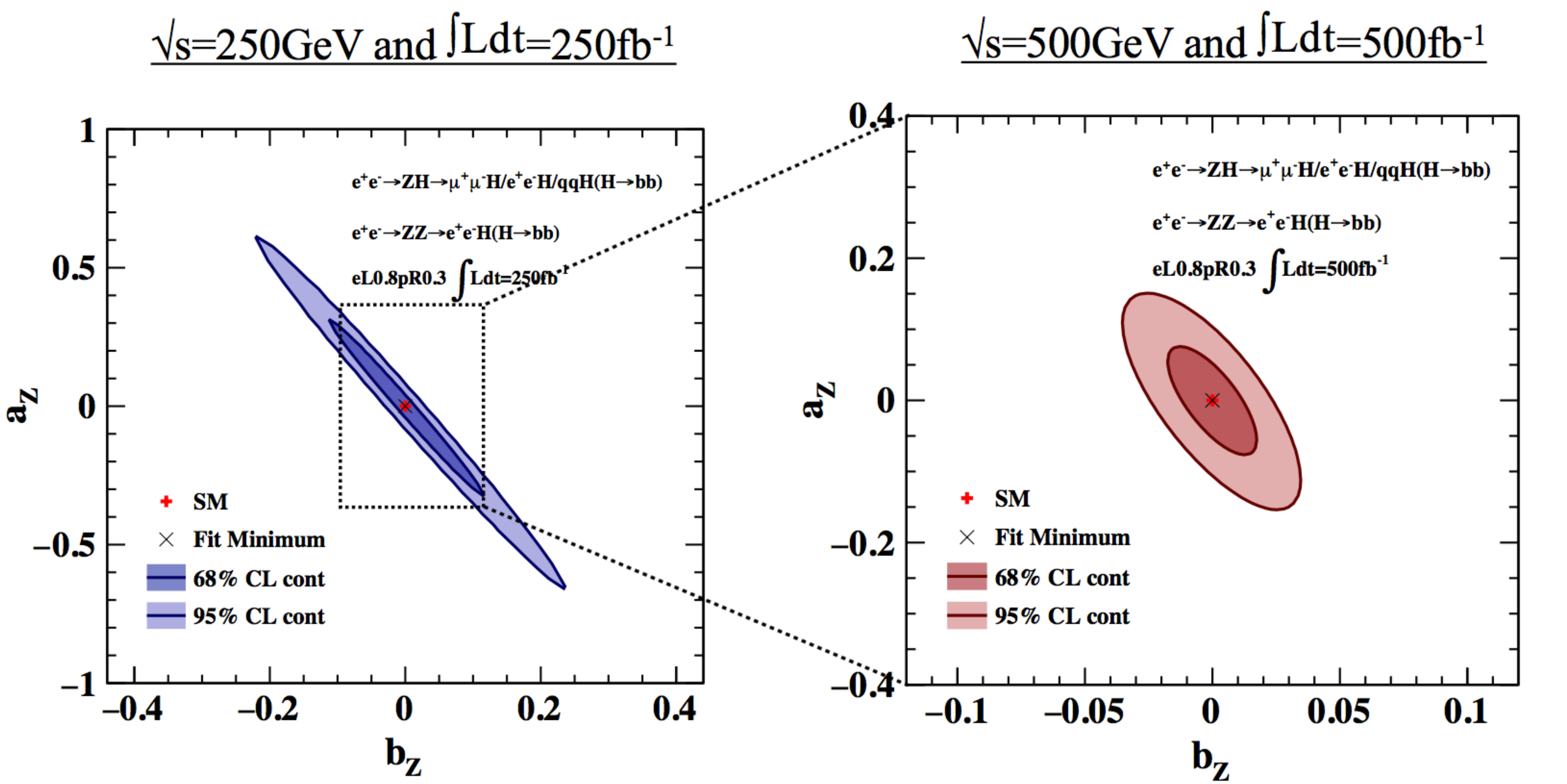
@ $\sqrt{s} = 250\text{GeV}$

example: how b/b~ changes dσ/dX

determine tensor structure of hVV couplings (full simulation)

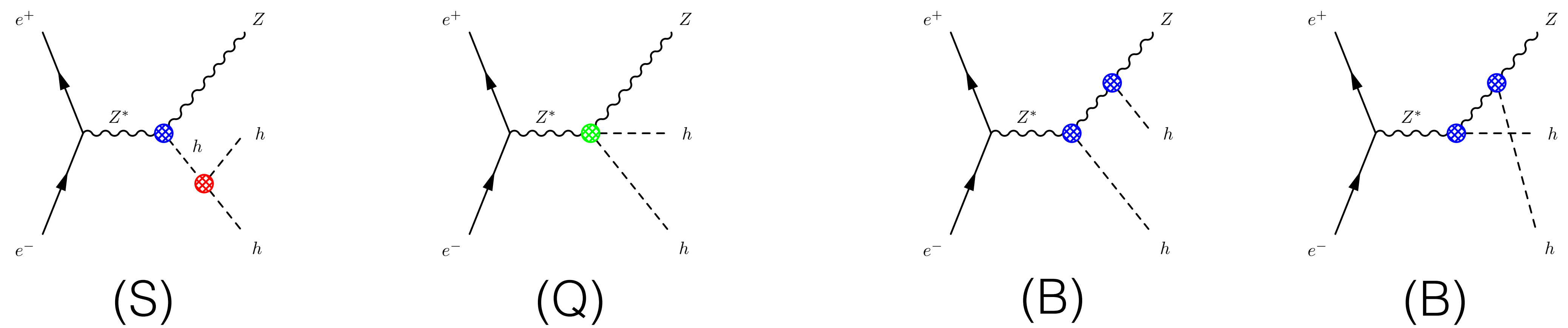
$$L_{hZZ} = M_Z^2(\frac{1}{v} + \frac{a}{\Lambda})hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}$$

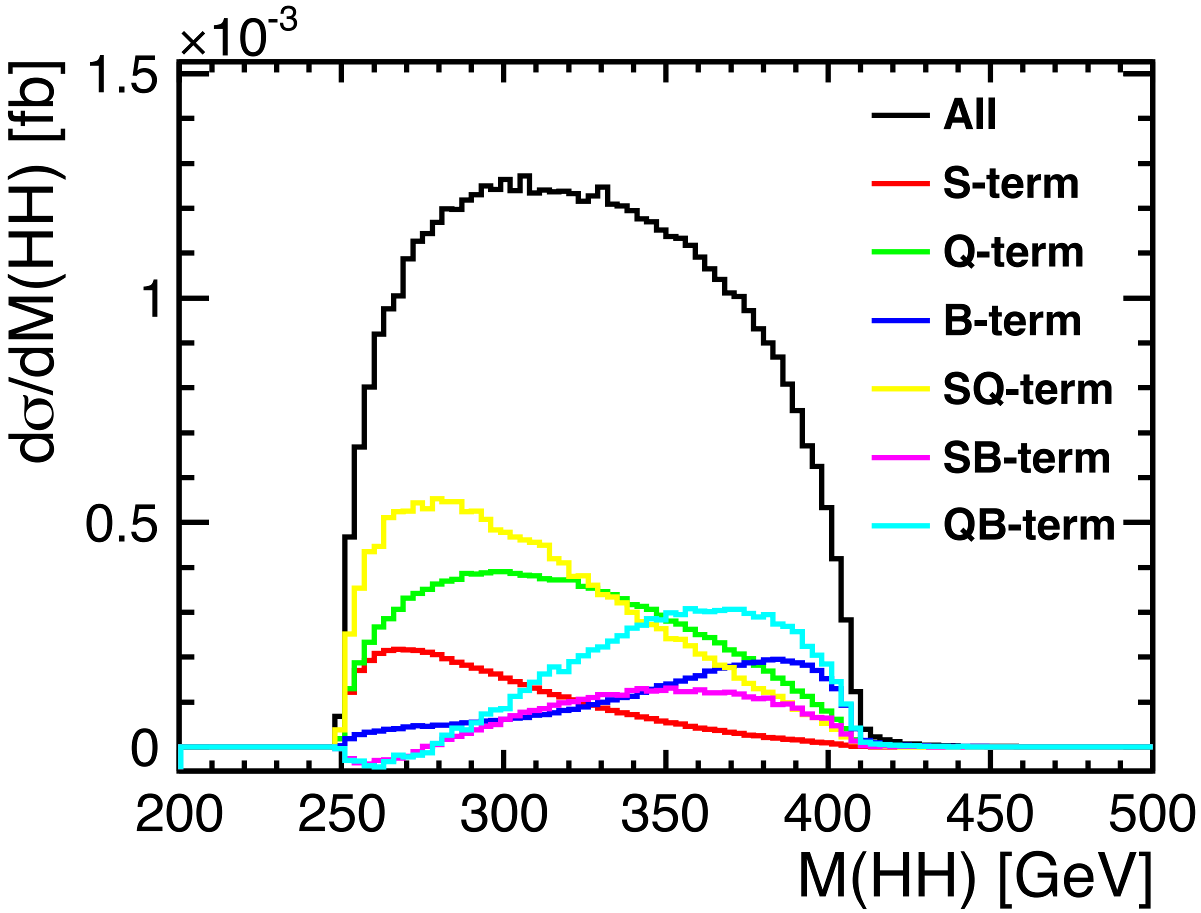
$\Lambda = 1$ TeV

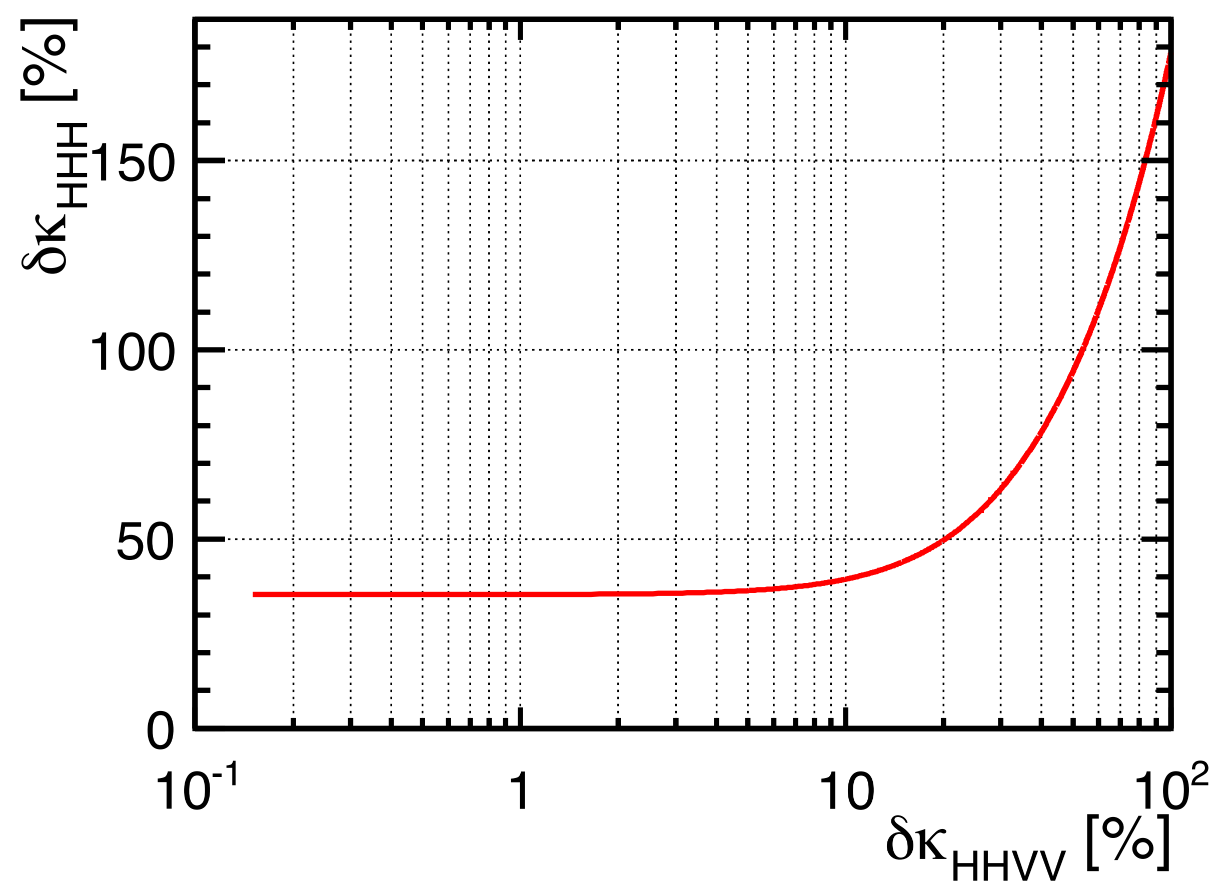


for 2 ab-1 @ 250 GeV —> κ_Z (a) ~ 3% >> 0.38%

hhVV, hVV and λ_{hhh} in e+e- —> Zhh







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

long answer: SM Effective Field Theory

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

Tim Barklow[a1], Keisuke Fujii[b], Sunghoon Jung[a1],
Michael E. Peskin[a1], and Junping Tian[c]

Improved Formalism for Precision Higgs Coupling Fits

Tim Barklow[a], Gauthier Durieux[b], Keisuke Fujii[c],
Christophe Grojean[b,d], Jiayin Gu[b,e], Sunghoon Jung[f], Robert Karl[b],
Jenny List[b], Tomohisa Ogawa[c], Michael E. Peskin[a], Junping Tian[g],
and Kechen Wang[b,e]

"The leptonic future of the Higgs", Durieux, et al, 1704.02333

SM Effective Field Theory

("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

EFT input: EWPOs (7)

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

$$\begin{aligned}
4\pi\alpha(m_Z) &= g_0^2 s_0^2 \Big(1 + 2s_0^2\delta g + 2c_0^2 \delta g' \\
&\quad + s_0^2(8c_{WW}) - 2s_0^2(8c_{WB}) + s_0^2(8c_{BB}) \Big) \\
\frac{G_F}{\sqrt{2}} &= \frac{1}{2v_0^2}\Big(1 - 2\delta v + 2c'_{HL}\Big) \\
m_W &= \frac{g_0 v_0}{2}\Big(1 + \delta g + \delta v + \frac{1}{2}(8c_{WW})\Big) \\
m_Z &= \frac{(g_0^2 + g_0'^2)^{1/2} v_0}{2}\Big(1 + c_0^2\delta g + s_0^2 \delta g' + \delta v - \frac{1}{2}c_T \\
&\quad + \frac{1}{2}c_0^2(8c_{WW}) + s_0^2(8c_{WB}) + \frac{1}{2}(s_0^4/c_0^2)(8c_{BB})\Big) \\
m_h &= \sqrt{2\lambda_0}\; v_0 \Big(1 + \delta v + \frac{1}{2}\delta\lambda - \frac{1}{2}c_H + \frac{3}{4}c_6\Big)
\end{aligned}$$

$$\begin{aligned}
A_\ell &= \frac{(1-4s_0^2)}{(1-4s_0^2+8s_0^4)} + \frac{32c_0^2 s_0^4(1-2s_0^2)}{D^2}\delta g - \frac{32c_0^2 s_0^4(1-2s_0^2)}{D^2}\delta g' \\
&\quad + \frac{16s_0^4(1-2s_0^2)}{D^2}(c_{HL} + c'_{HL}) + \frac{8s_0^2(1-2s_0^2)^2}{D^2}c_{HE} \\
&\quad + \frac{16c_0^2 s_0^4(1-2s_0^2)}{D^2}(8c_{WW}) - \frac{16s_0^4(1-2s_0^2)^2}{D^2}(8c_{WB}) - \frac{16s_0^6(1-2s_0^2)}{D^2}(8c_{BB}) \\
\Gamma_\ell &= \Gamma_{\ell 0}\Big(1 + \frac{2c_0^2(1-8s_0^2)}{D}\delta g - \frac{2s_0^2(3-16s_0^2+8s_0^4)}{D}\delta g' + \frac{2(1-2s_0^2)}{D}(c_{HL} + c'_{HL}) - \frac{4s_0^2}{D}c_{HE} \\
&\quad + \frac{c_0^2(1-8s_0^2)}{D}(8c_{WW}) - \frac{2s_0^2(1-8s_0^2+8s_0^4)}{D}(8c_{WB}) - \frac{s_0^4(3-16s_0^2+8s_0^4)}{c_0^2 D}(8c_{BB})\Big)
\end{aligned}$$

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

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

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

$$\Delta \lambda_\gamma = 3.8 \times 10^{-4} \qquad \rho(\kappa_\gamma, \lambda_\gamma) = 38.5\%$$

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

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

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

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

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

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

EFT input: σ(e+e- —>Zh), σ(e+e- —> Zhh)

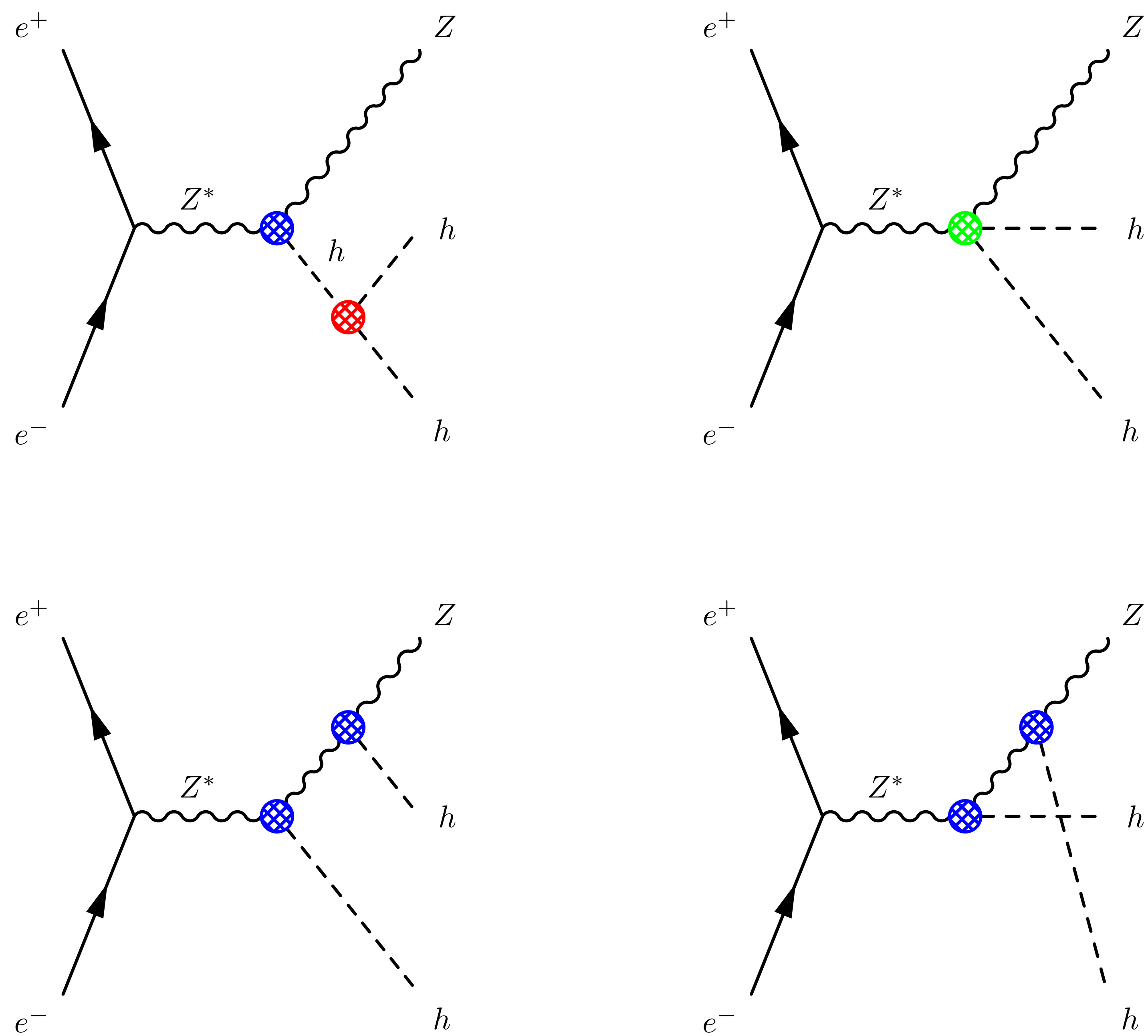
- c_H has to be determined by inclusive σ_{Zh} measurement

- c_6 has to be determined by double Higgs measurement

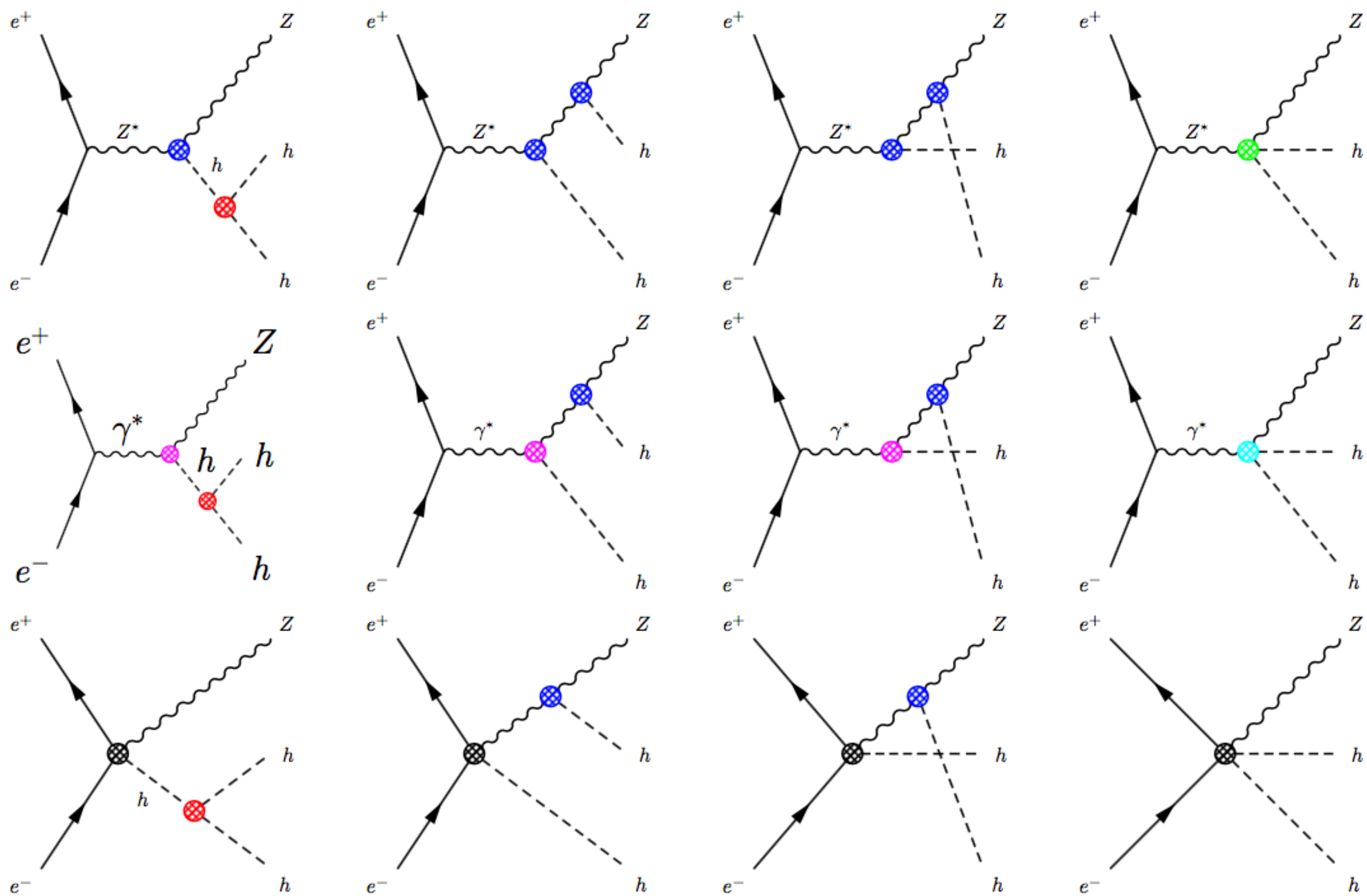
EFT input: BR(h—>XX)

- h couplings to b, c, τ, μ, g
- Γ(h->invisible), total decay width

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



answer to Q1: determine λ_{hhh} in EFT



answer to Q1: determine λ_{hhh} in EFT

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

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

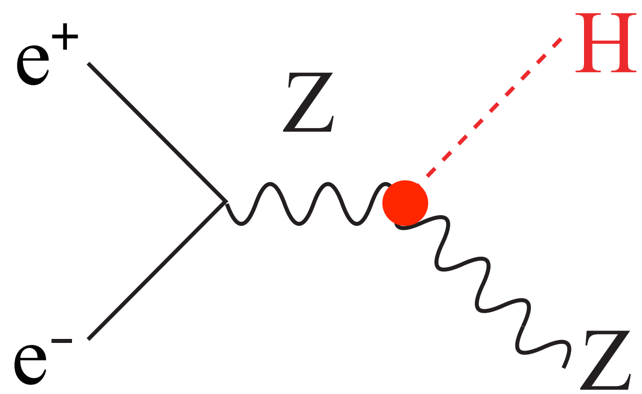
$$\Delta c_6 = \frac{1}{0.565}\left[\left(\frac{\Delta\sigma_{Zhh}}{\sigma_{SM}}\right)^2 + \sum_{i,j} a_i a_j (V_c)_{ij}\right]^{\frac{1}{2}}$$

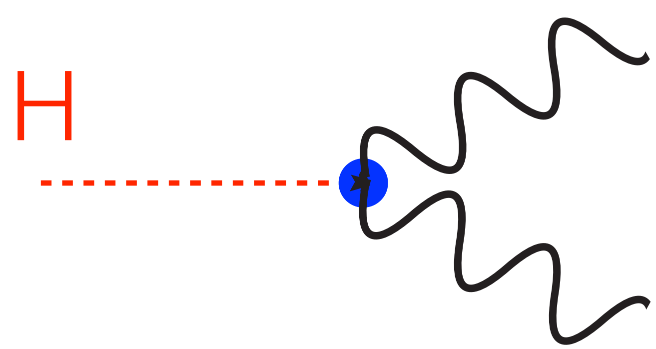
Given the full ILC program of 2 ab^{-1} at 250 GeV and 4 ab^{-1} at 500 GeV

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

T.Barlow @ EPS-HEP 2017

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



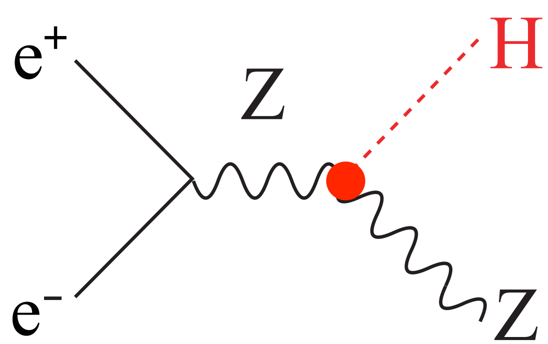


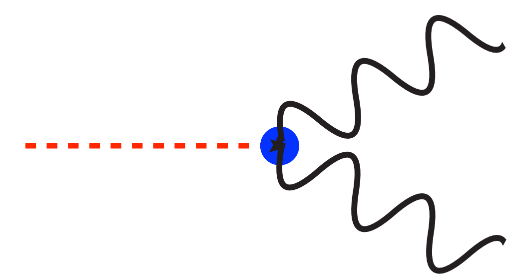
$$\propto ?\ \kappa_Z^2$$

answer to Q2:

- σ(e+e- ->Zh) ∝ κ²(hZZ) ∝ Γ(h->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

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

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

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

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

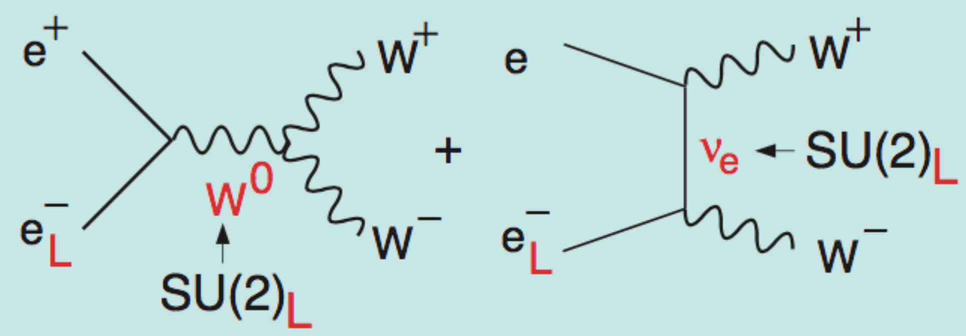
coupling $\Delta g/g$	kappa-fit	EFT-fit
hZZ	0.38%	0.63%
hWW	1.9%	0.63%
hbb	2.0%	0.89%
Γ_h	4.2%	2.1%

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

Power of Beam Polarization

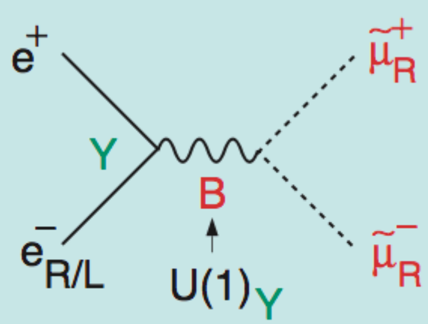
BG Suppression

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



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

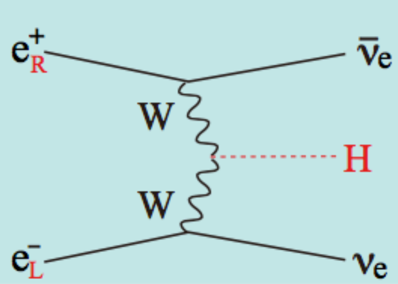
Slepton Pair



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

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

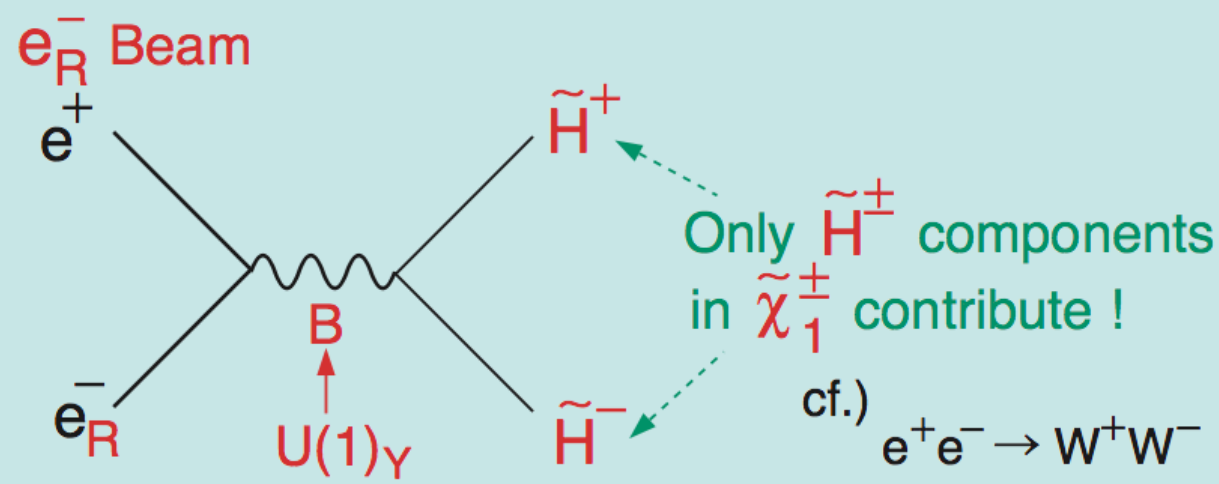
WW-fusion Higgs Prod.



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

Signal Enhancement

Chargino Pair



$$\tilde{\chi}^\pm_1 = \bigcirc \cdot \tilde{W}^\pm + \bullet \cdot \tilde{H}^\pm$$

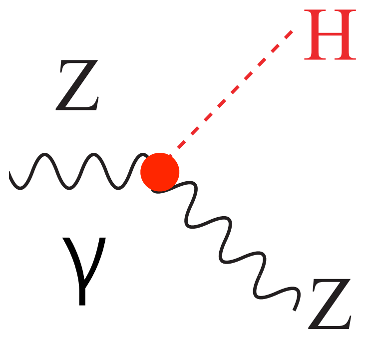
$$\bullet = \langle \tilde{H}^\pm | \tilde{\chi}^\pm_1 \rangle$$

Decomposition

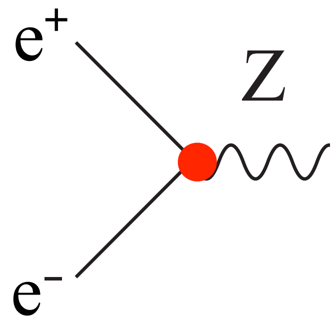
comments on beam polarizations

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

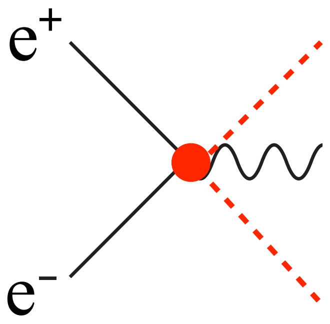
-> separate hZZ and hγZ couplings



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

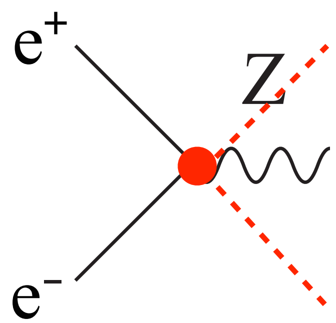


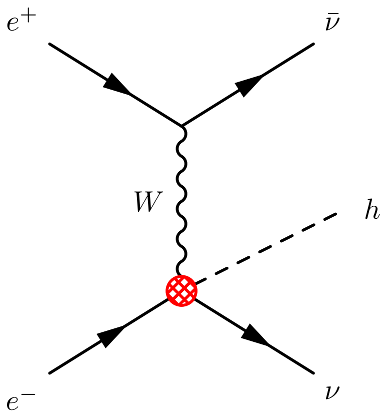
important to constrain contact interaction



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

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





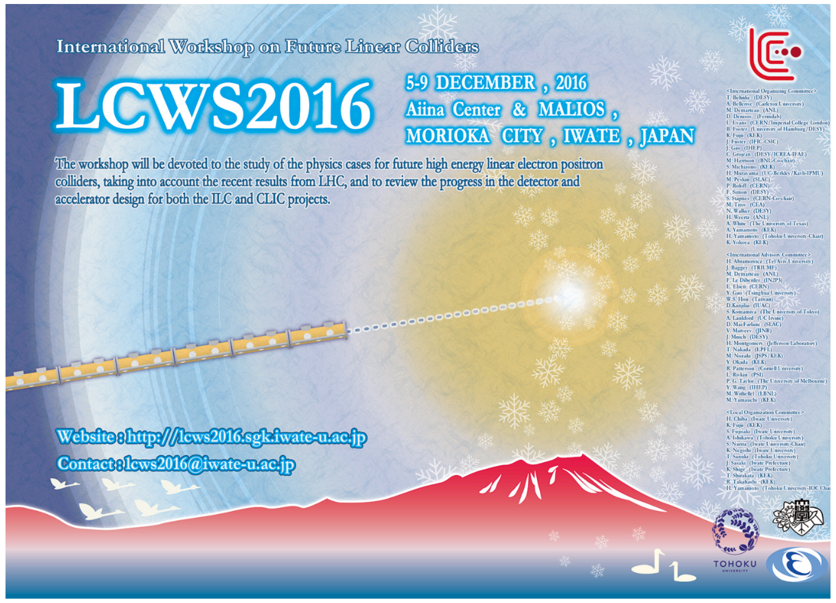
summary (i & ii)

- goal of ILC —> understand mystery of electroweak symmetry breaking (decide which path to BSM)
    - ➡ precision Higgs
    - ➡ precision Top
    - ➡ new particles
- advantage of ILC: model-independent determination of all Higgs couplings (and precisely)
    - ➡ kappa formalism
    - ➡ EFT formalism (combined EWPOs+TGCs+Higgs)

(iii) recent ILC staging studies

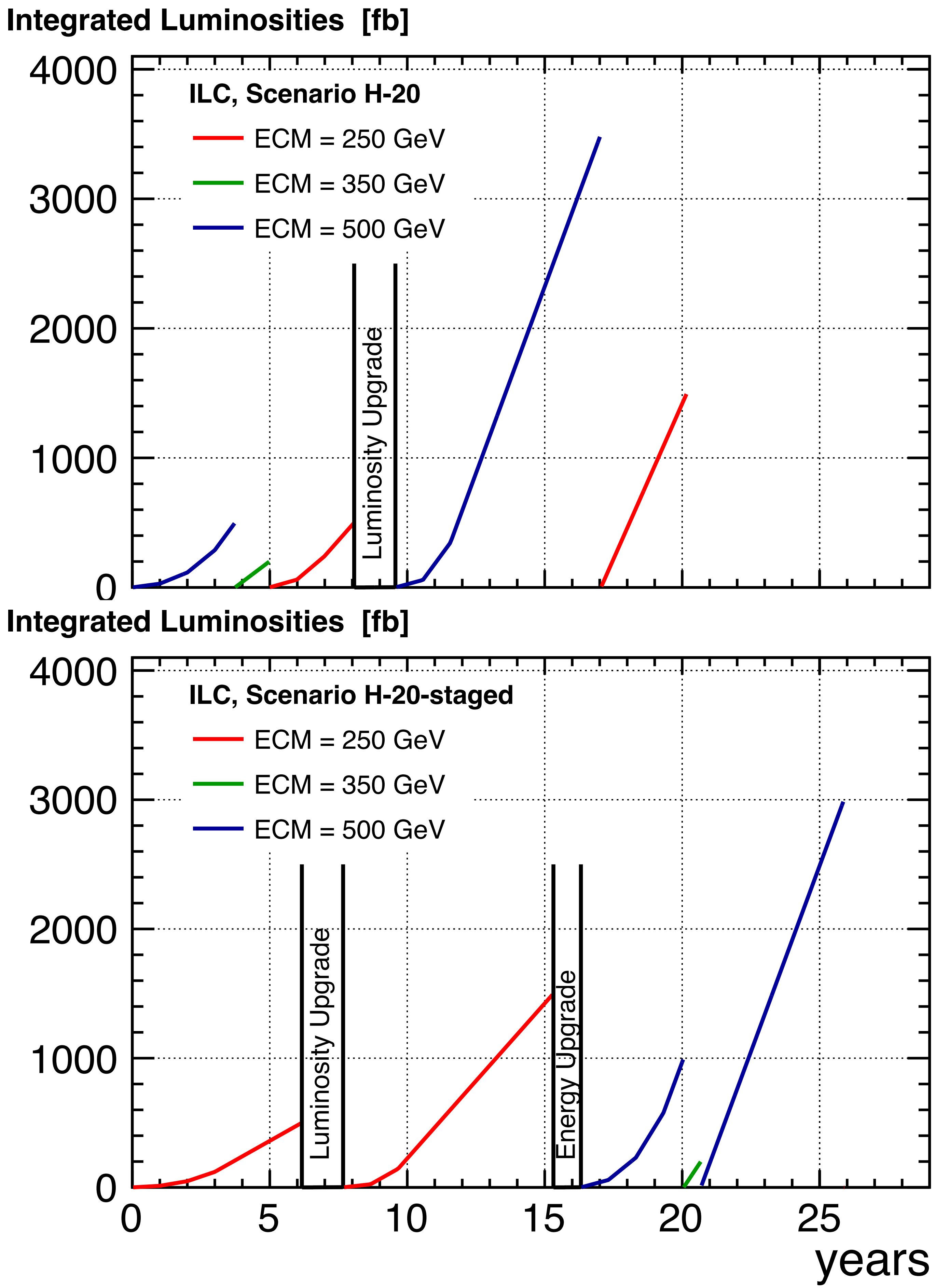
background of new staging

- learned from LCWS16:
  - ★ “science first” with ILC
  - ★ cost reduction is important



- reduce initial $\sqrt{s}$=500 to 250 GeV would be most effective in cost reduction
- no NP discovered yet at LHC Run 2 —> weight of a “Higgs factory” gets higher
- that’s why ILC Parameters WG is investigating new staging scenarios which start from 250 GeV

scenario:
example



ILC500
H20

ILC250
H20 staged

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

new development: higher luminosity at 250 GeV

K.Yokoya @ AWLC2017

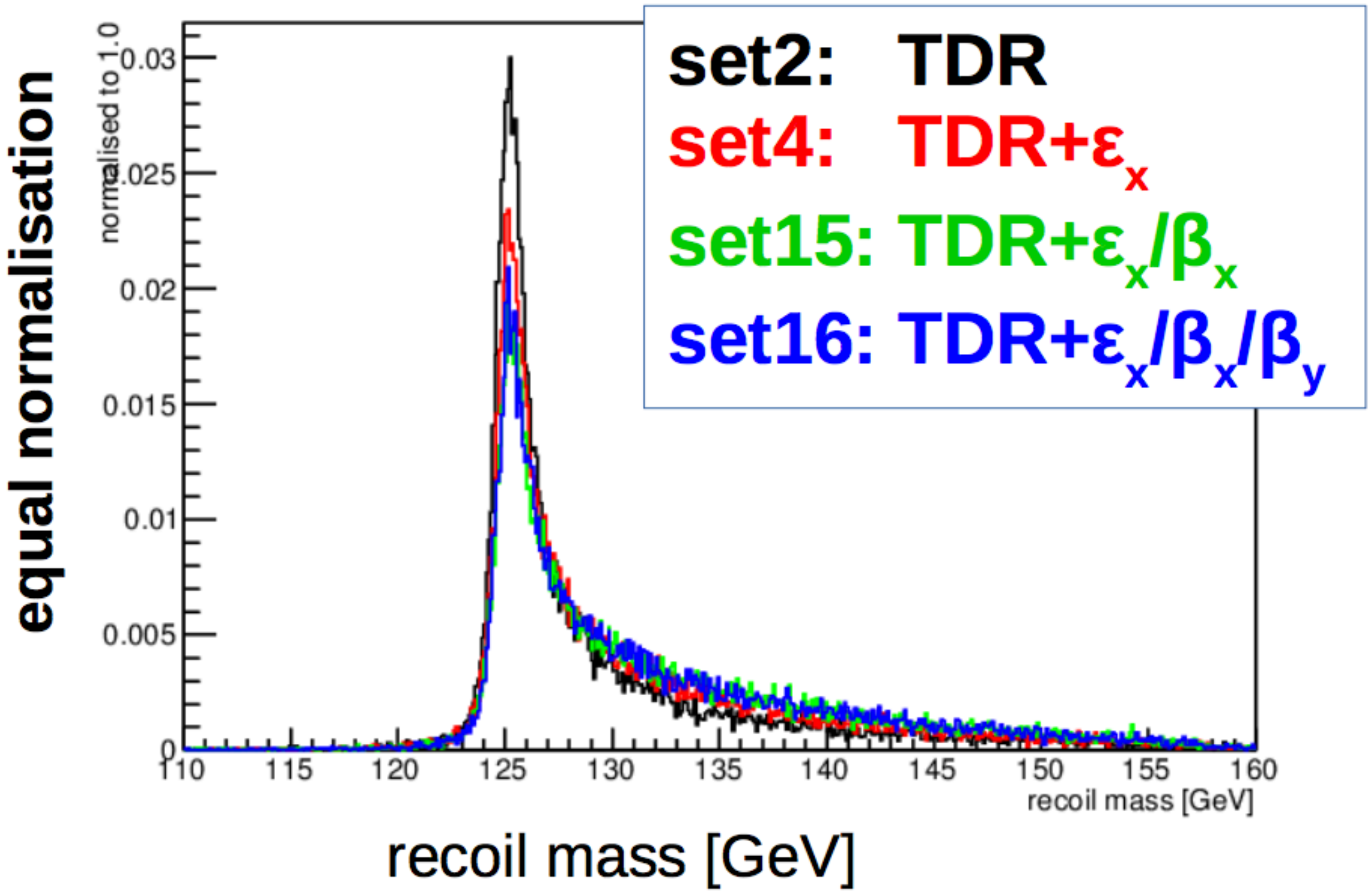
$$\mathcal{L} \approx C \frac{P_B}{E} \sqrt{\frac{\delta_{BS}}{\epsilon_{y,n}}} \min\left(1, \sqrt{\sigma_z/\beta_y}\right)$$

$$\delta_{BS} = \left\langle -\frac{\Delta E}{E} \right\rangle \approx 0.836 \frac{N^2 r_e^3 \gamma}{\sigma_z \sigma_x^2}, \qquad \sigma_x = \sqrt{\frac{\epsilon_{x,n} \beta_x^*}{\gamma}}$$

- luminosity can be increased by higher δ_{BS} (beamstrahlung energy loss, which is 1% at TDR)
- higher δ_{BS} can be achieved by smaller $\varepsilon_{x,n}$ or β_x^*
- set of new beam parameters with smaller $\varepsilon_{x,n}$ is being tried —> x1.6 higher luminosity is promising
- if works —> can further try smaller β_x^*

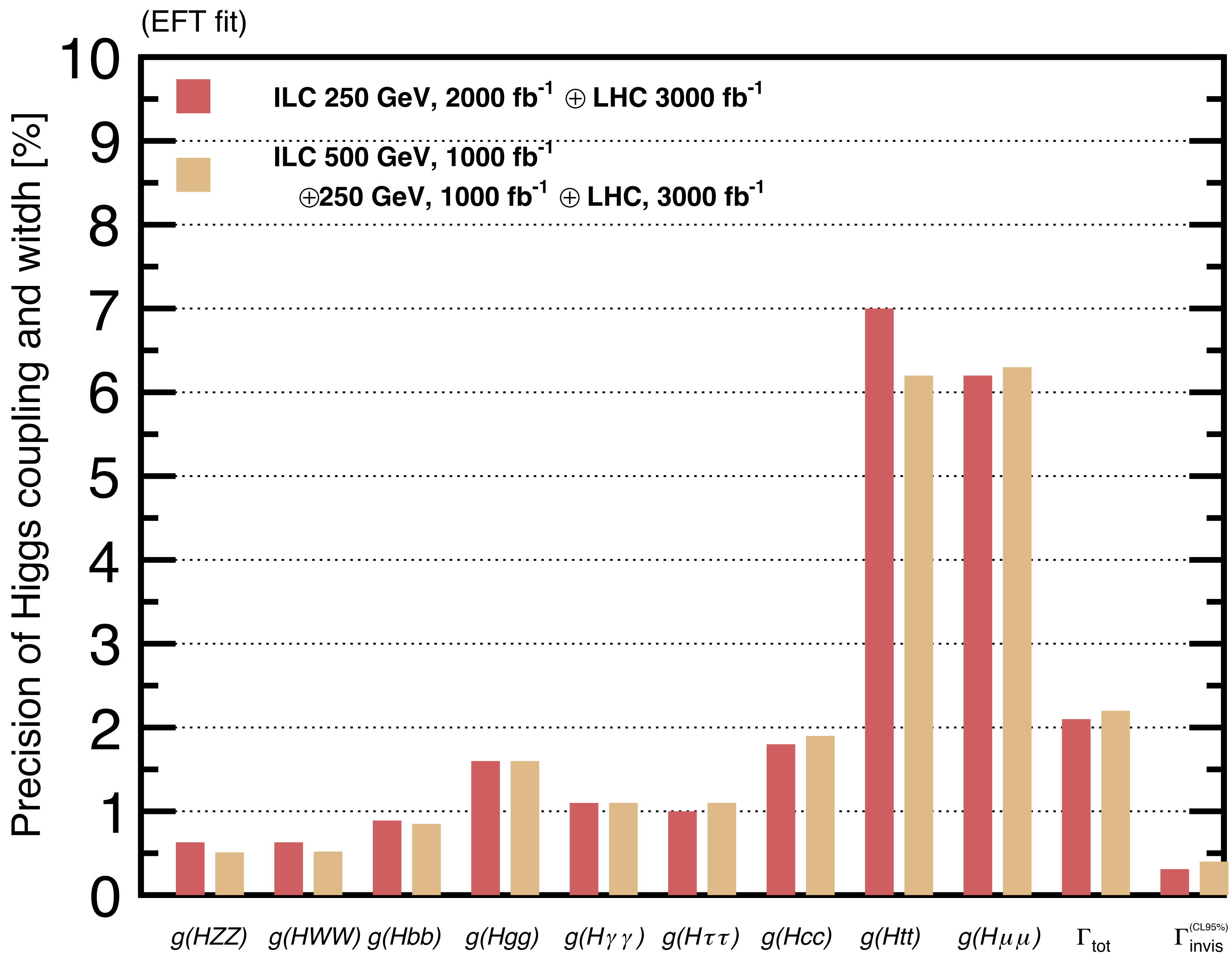
new development: impact of higher beamstrahlung

talk by D.Jeans



- at 250 GeV, even the most sensitive one, recoil mass, is not much affected, recoil mass shape is more dominated by ISR
- there is complementary method to measure Higgs mass, using h —>bb, without using z-momentum balance (J.Tian @ LCWS16)
- simulation inputs used in later slides are based on TDR beam

new development: EFT analysis



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

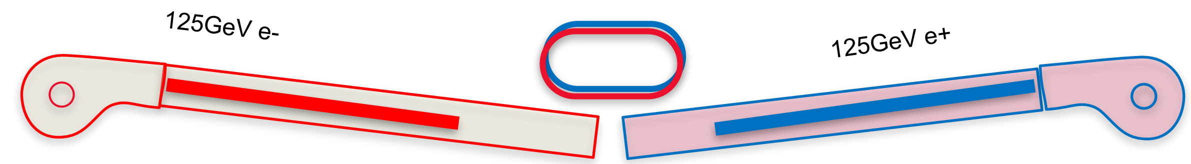
new scenarios: assumptions

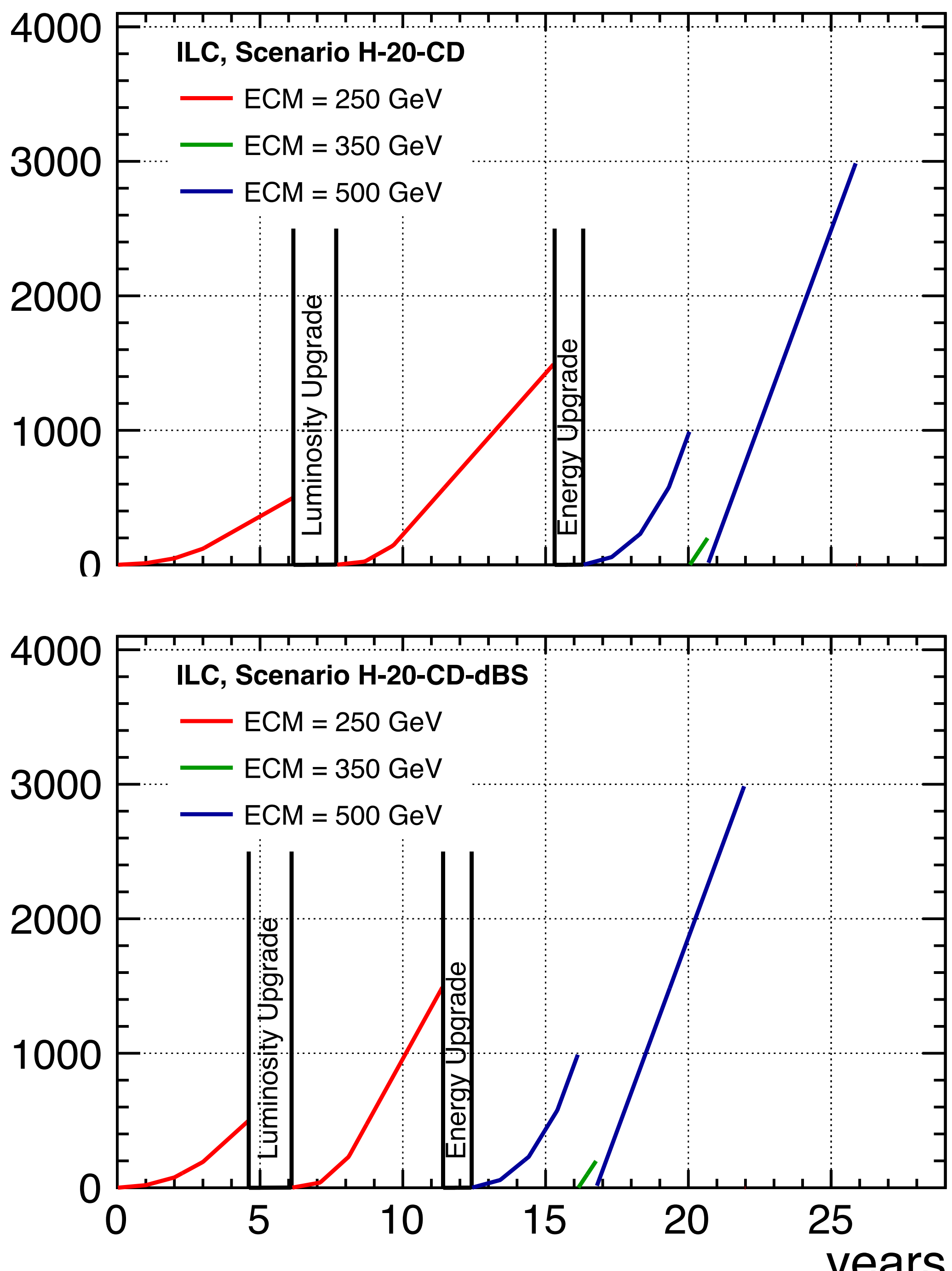
- all start with $\sqrt{s}$ = 250 GeV
- corresponding to different options of machine staged design: C,D,E,F (B.List, S.Michizono @ AWLC2017)
- with or without x1.6 higher luminosity assumed (only for 250 GeV running, beamstrahlung would be too high for other $\sqrt{s}$)
- total $\int L dt$, share of left- and right-handed running for each $\sqrt{s}$ are as same as H20
- luminosity ramp up after year-0 is as same as H20

new scenarios: H-20-CD (-δ_{BS})

Option C:

(same scenario for option D)





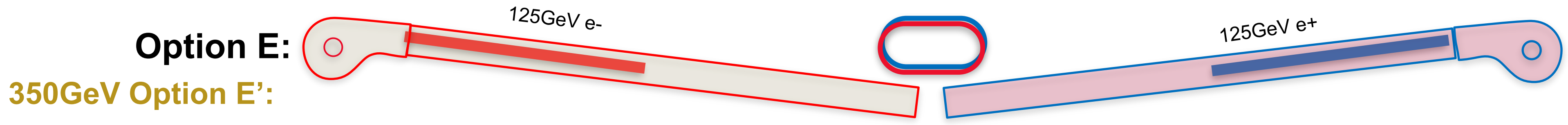
lumi upgrade after $\int Ldt \sim 500\ fb^{-1}$ (double bunches)

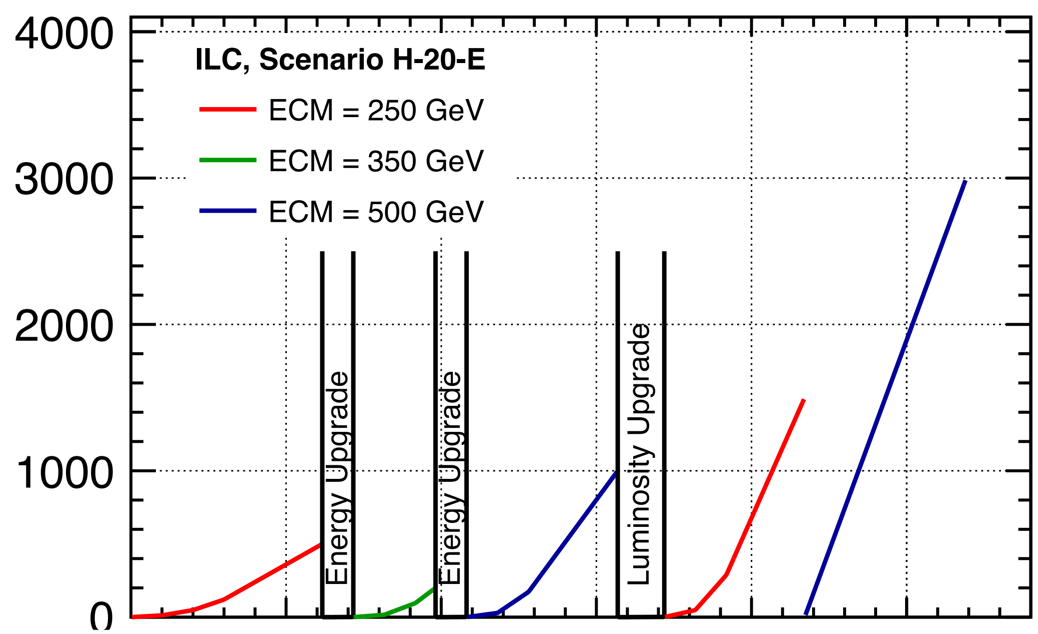
energy upgrade after $\int Ldt \sim 2\ ab^{-1}$ at 250 GeV in ~15 (11)y

ILC500 starts with x2 bunches directly

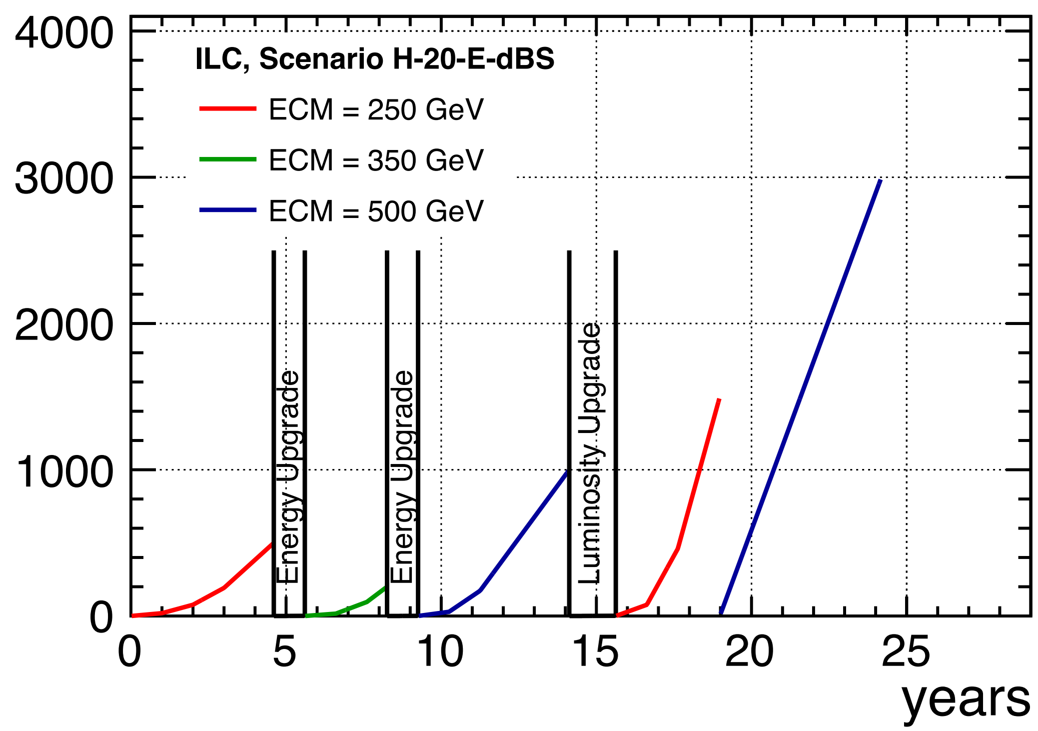
save ~4y with δ_{BS}

new scenarios: H-20-E (-δ_{BS})



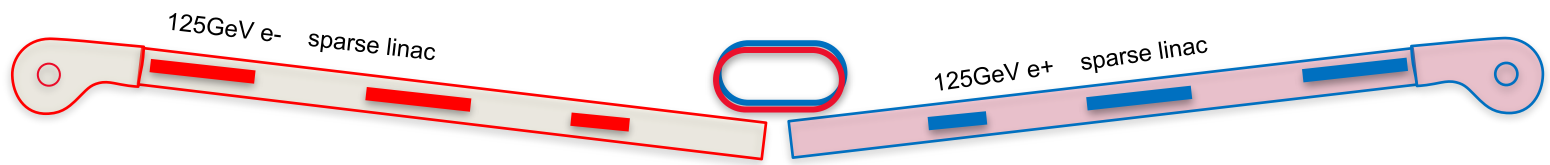


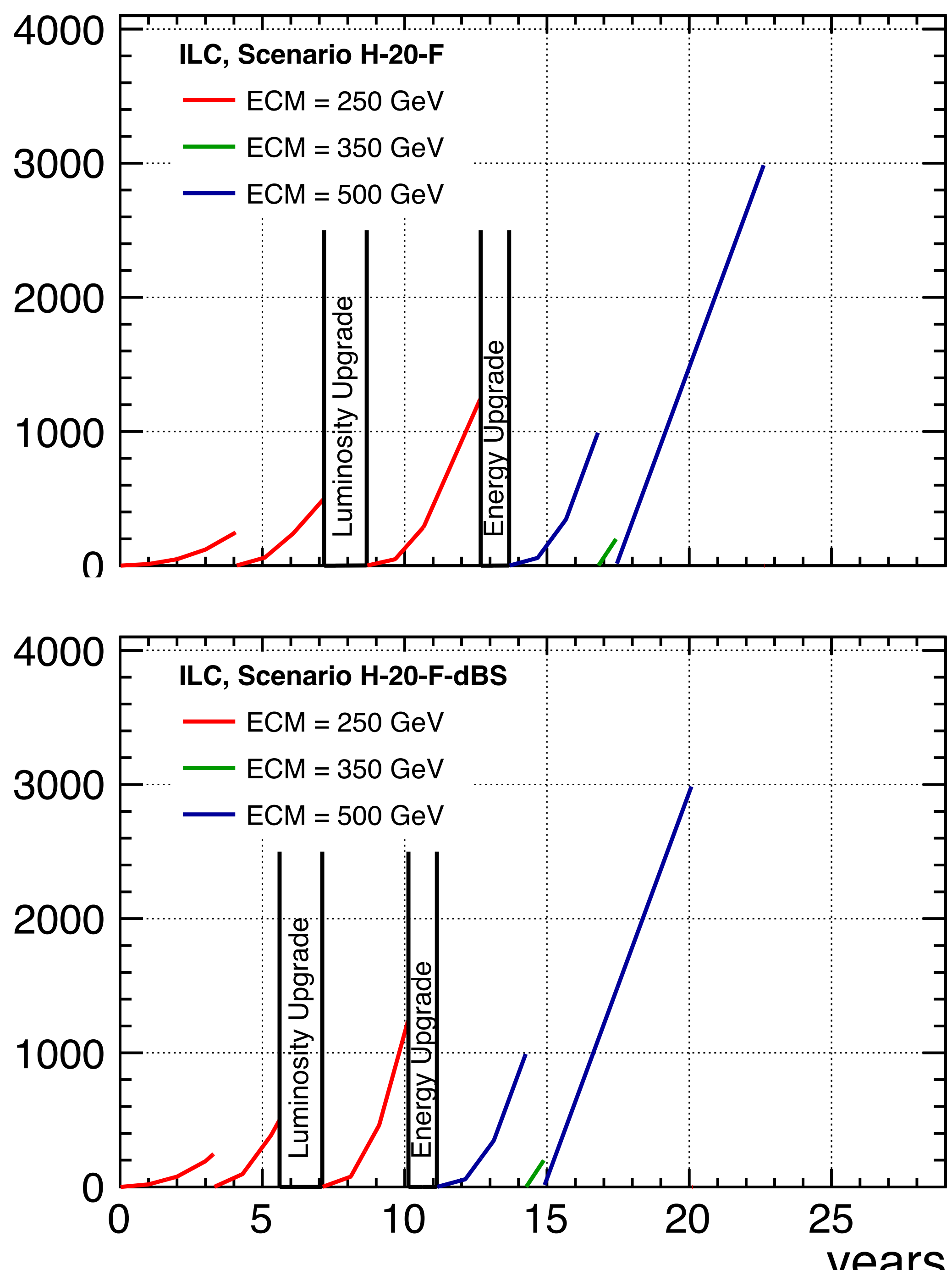
energy upgrade first
->350 GeV after ~6 (4.5)y
->500 GeV after ~10 (8)y



lumi upgrade after ~16 (14)y

new scenarios: H-20-F (-δ_{BS})





10Hz mode after ~4 (3)y

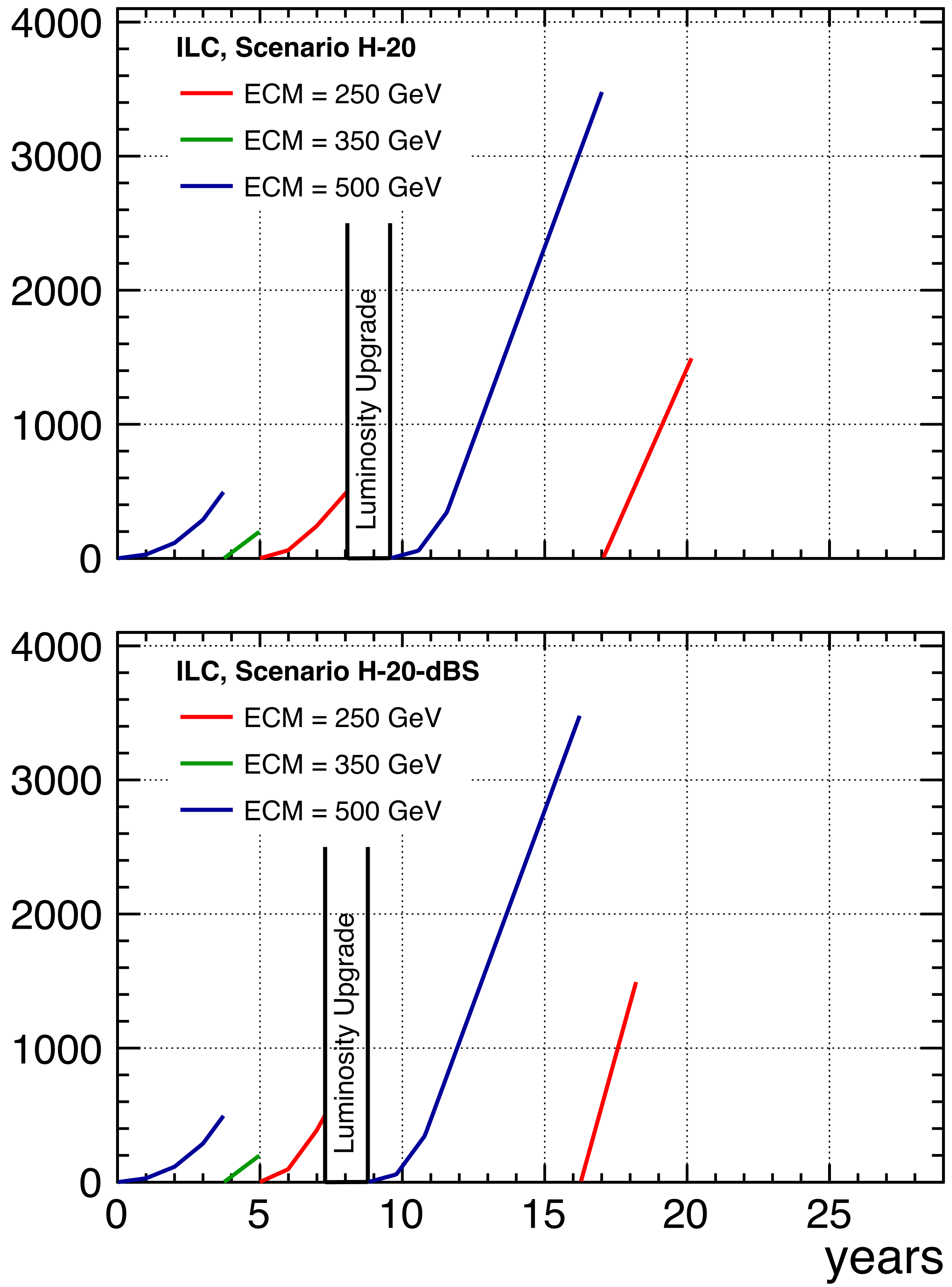
lumi upgrade after ~7 (6)y

energy upgrade after ~13 (10)y

quickest to reach full H20

most flexible choice: can do option C/D/E in F

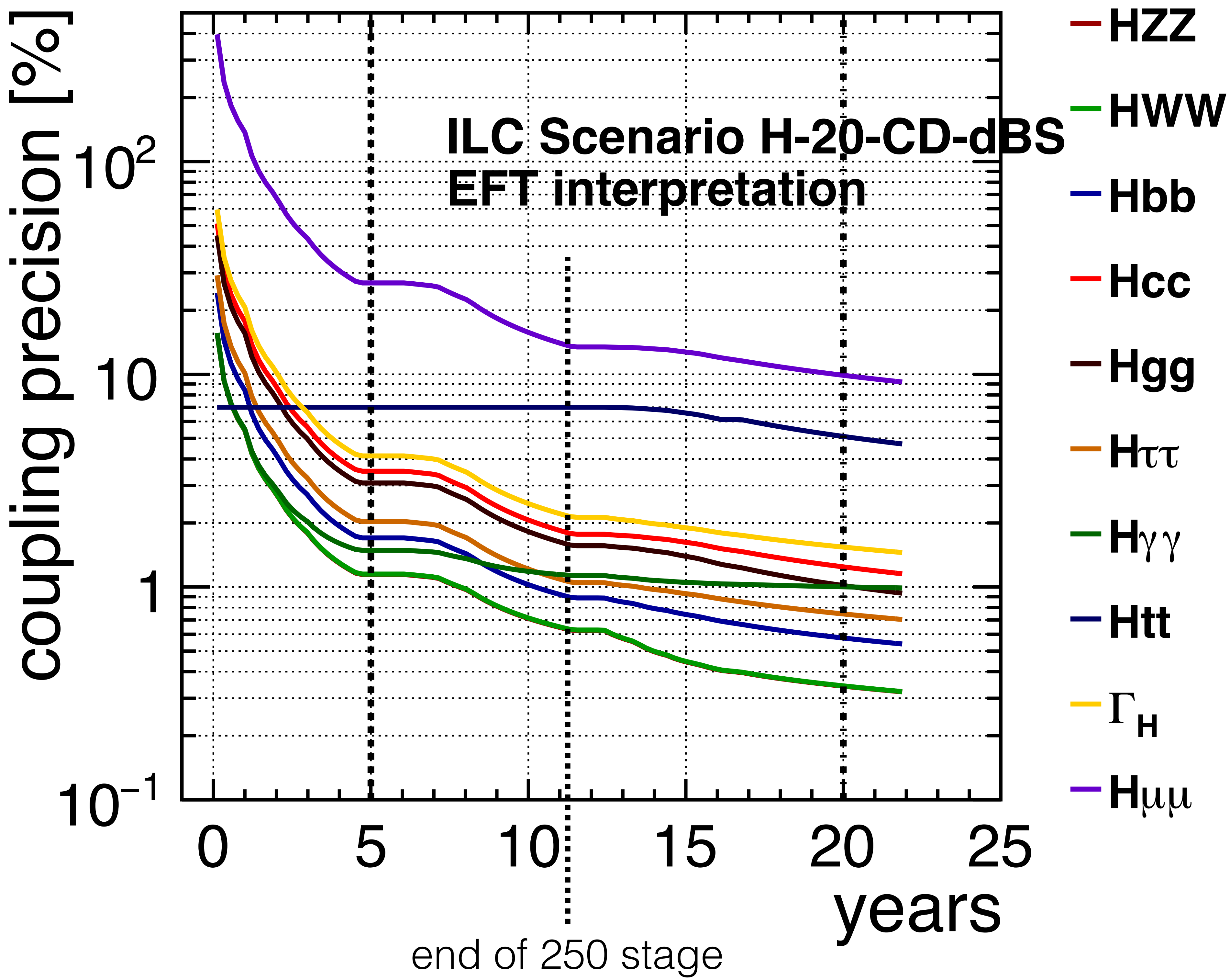
previous scenarios: H-20 (-δ_{BS})



2y shorter with δ_{BS}

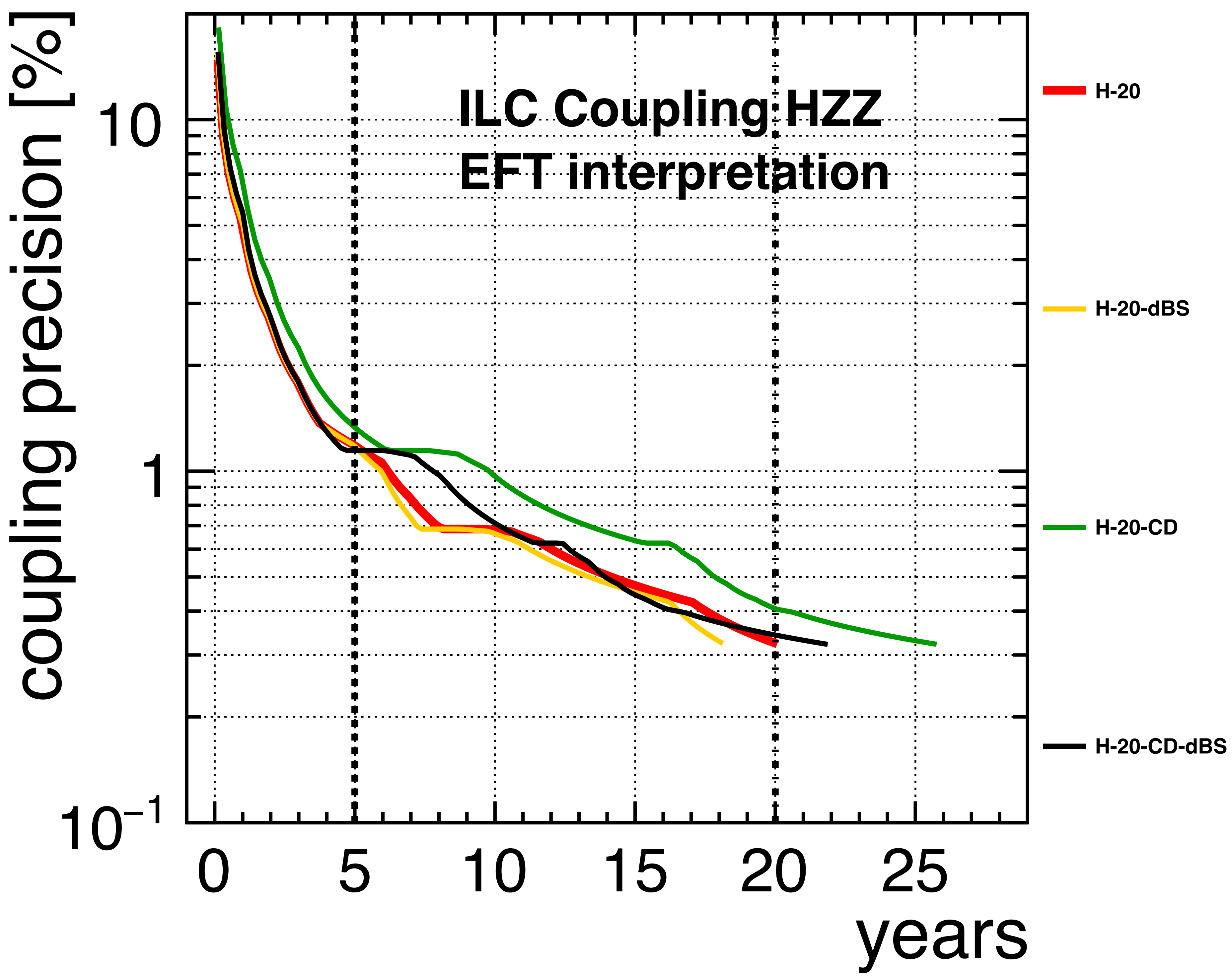
evolution of coupling precisions

(example for option C(D) with δ_{BS}, see backup more for other options)

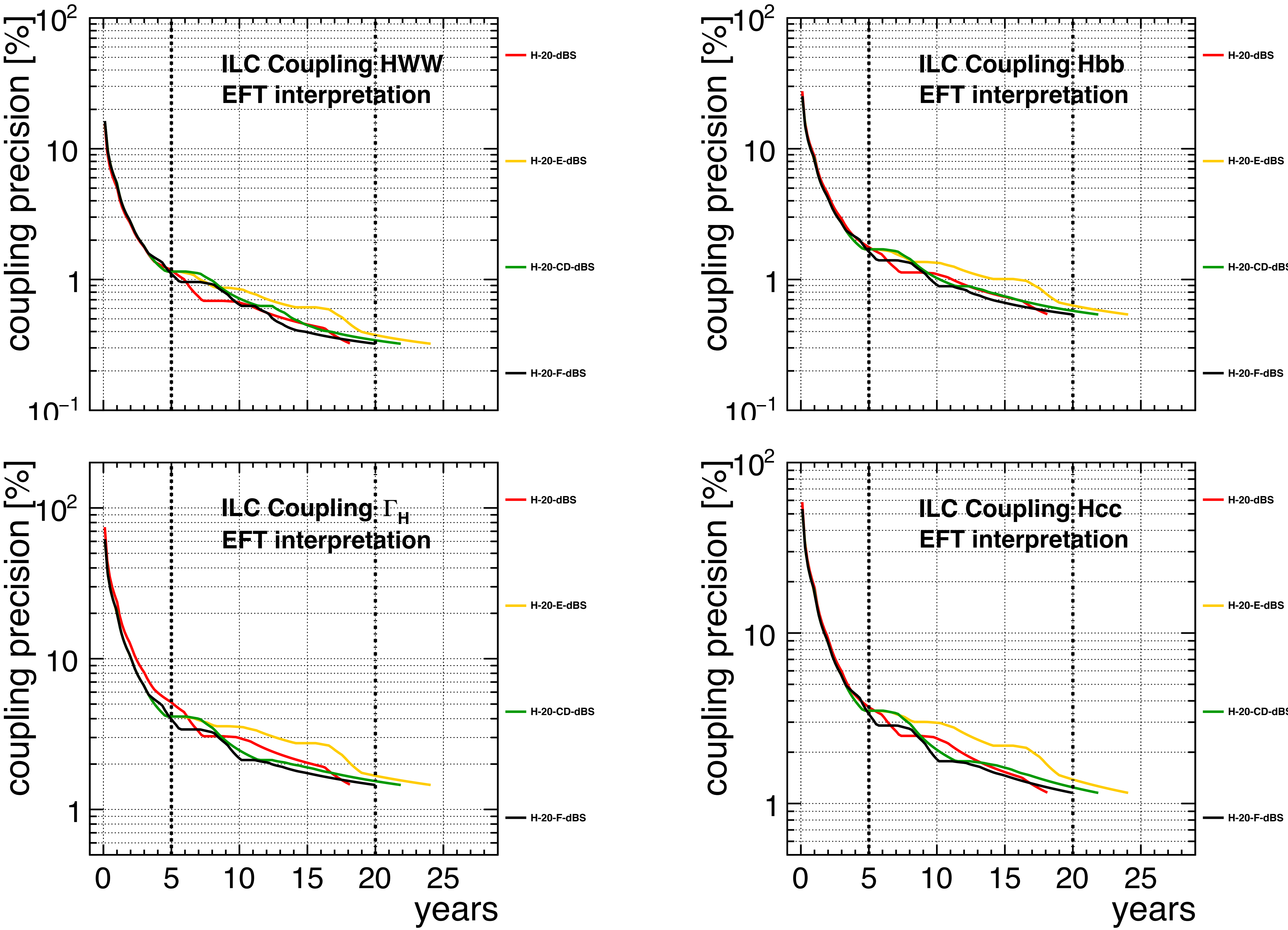


evolution of coupling precisions: hZZ

(difference between with and without δ_{BS})



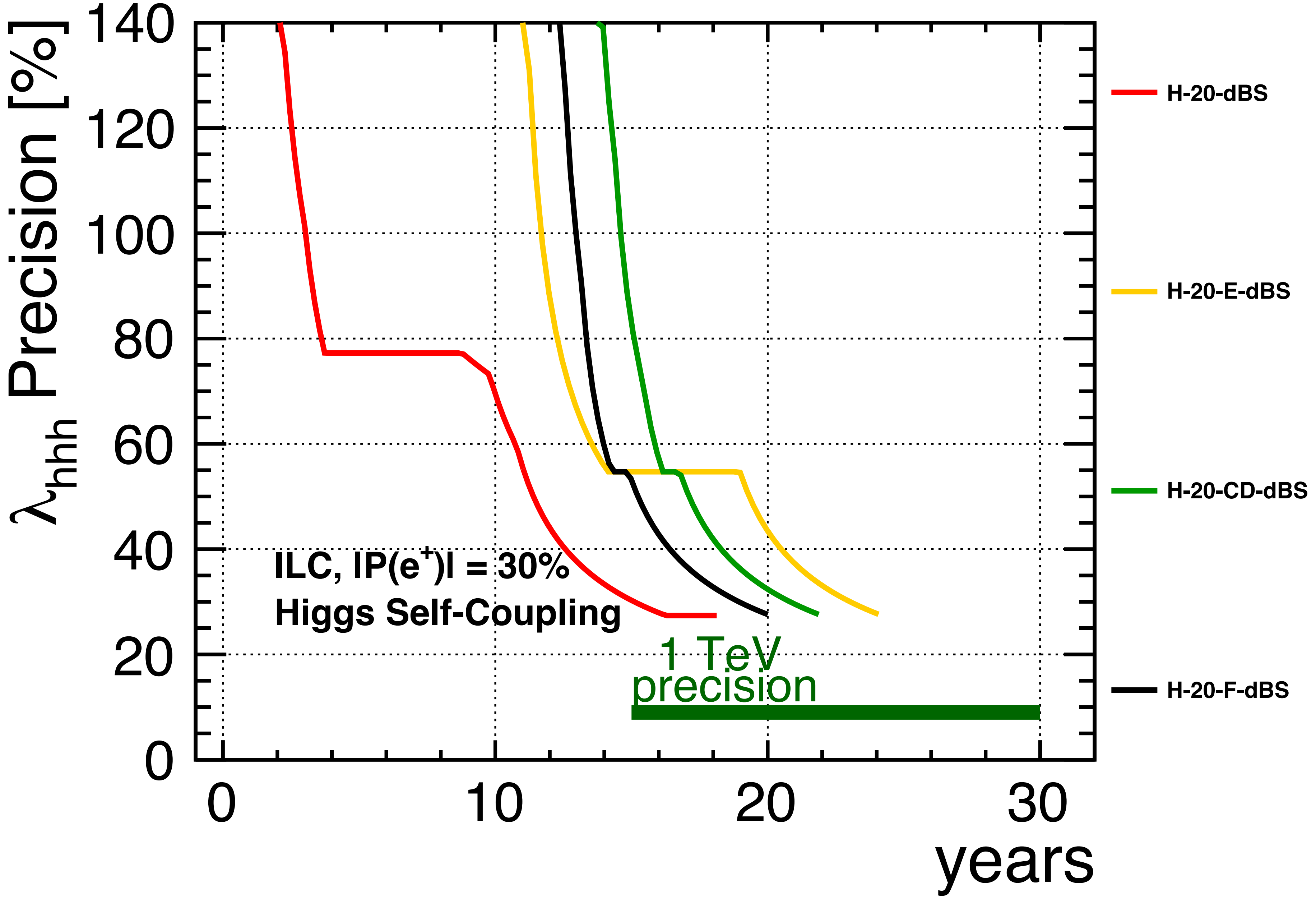
evolution of couplings (-δ_{BS}): hWW, hbb, hcc, Γ_H



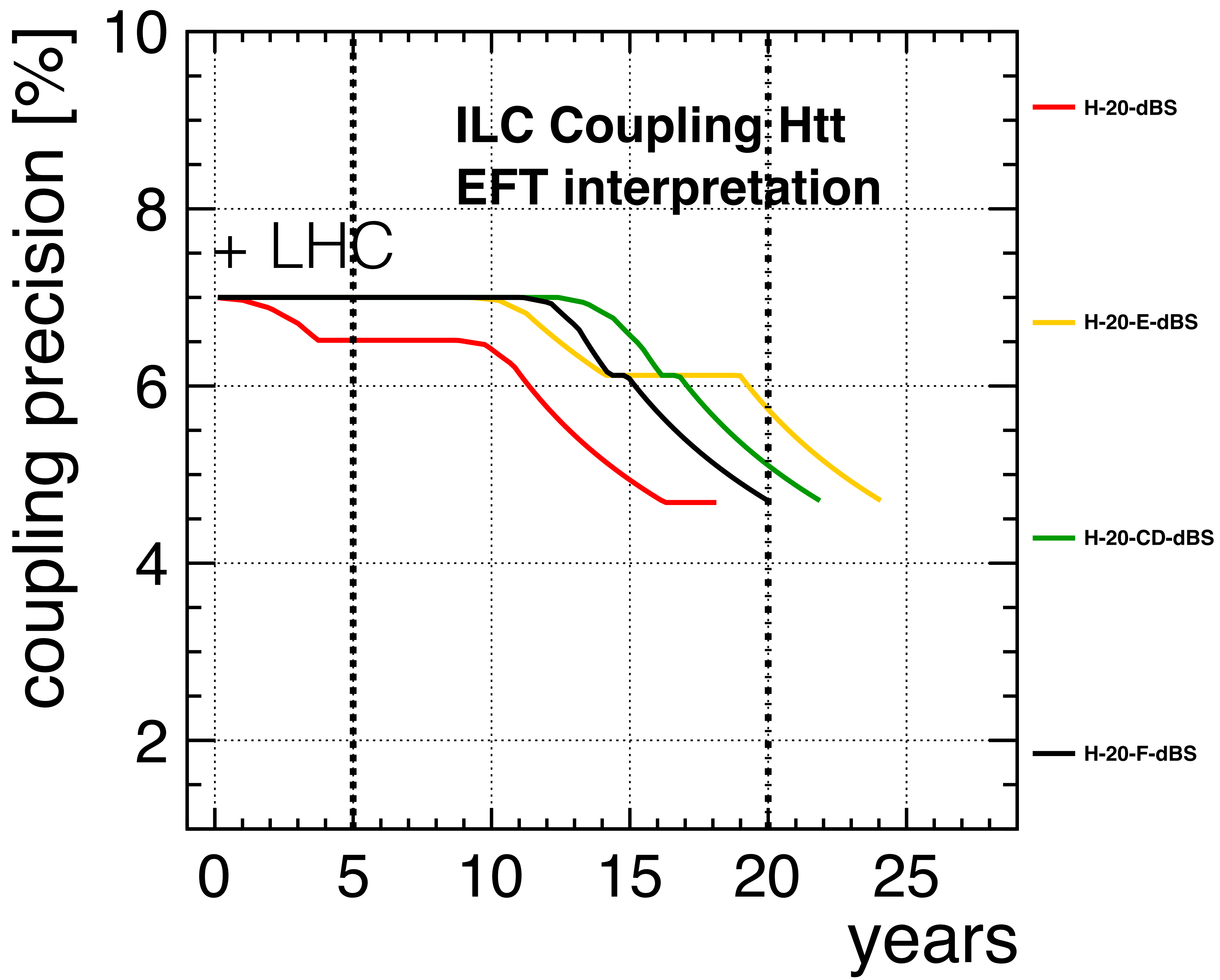
evolution of coupling precisions

- for couplings which can be accessed by ZH, difference is not large among all scenarios, at least in the first 10 years
- how about other couplings, new particles?

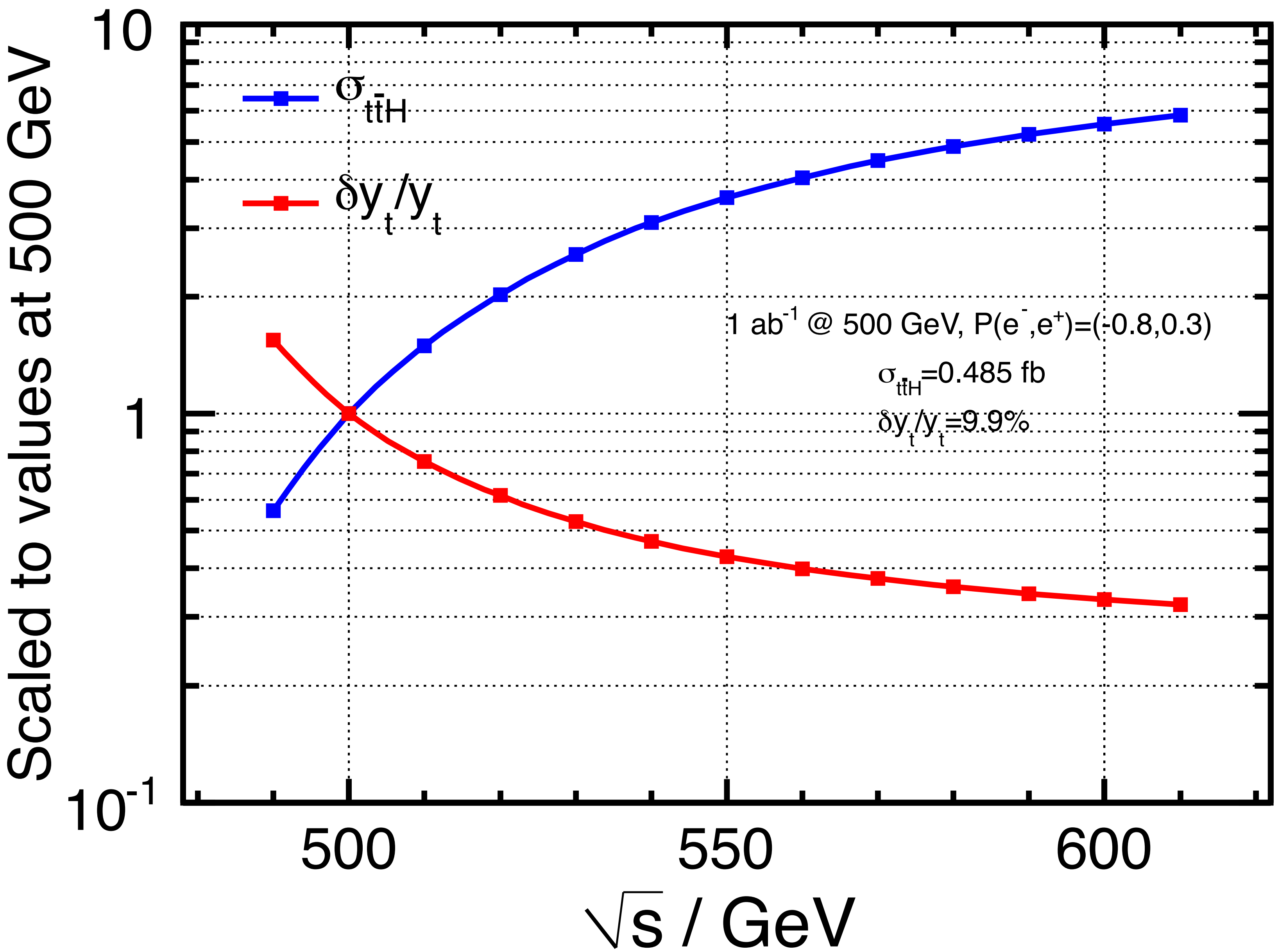
evolution of coupling precisions (-δ_{BS}): λ_{hhh}



evolution of coupling precisions ($-\delta_{BS}$): htt

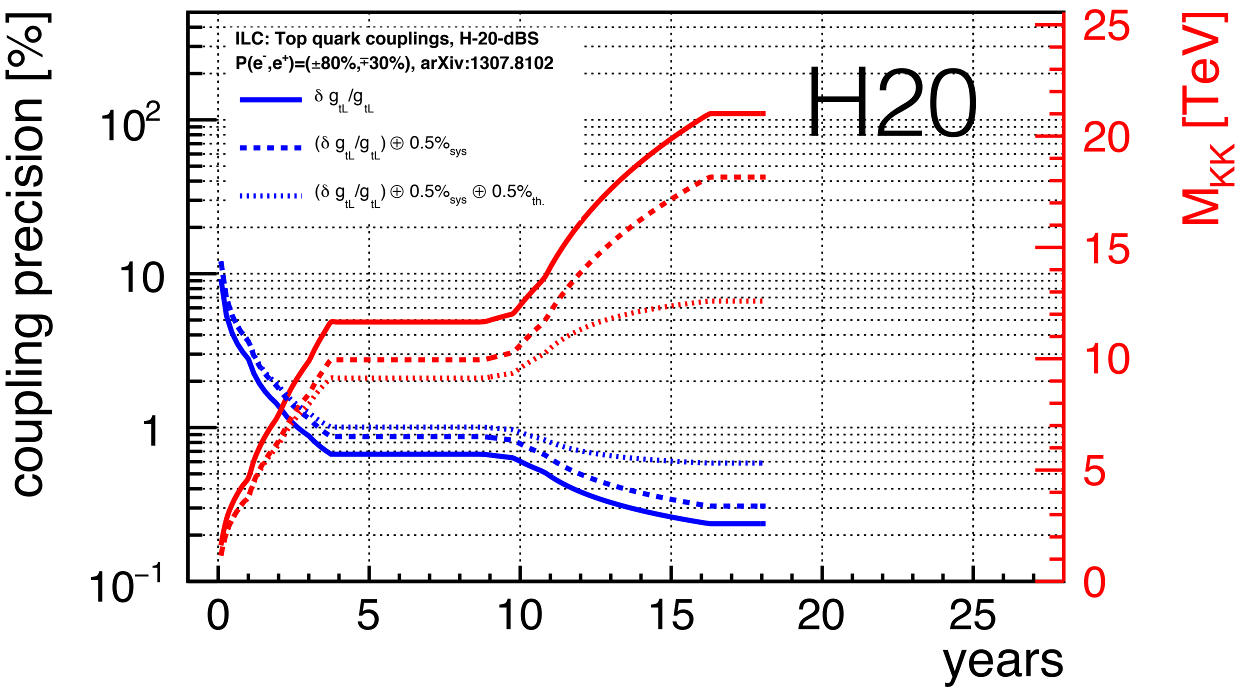


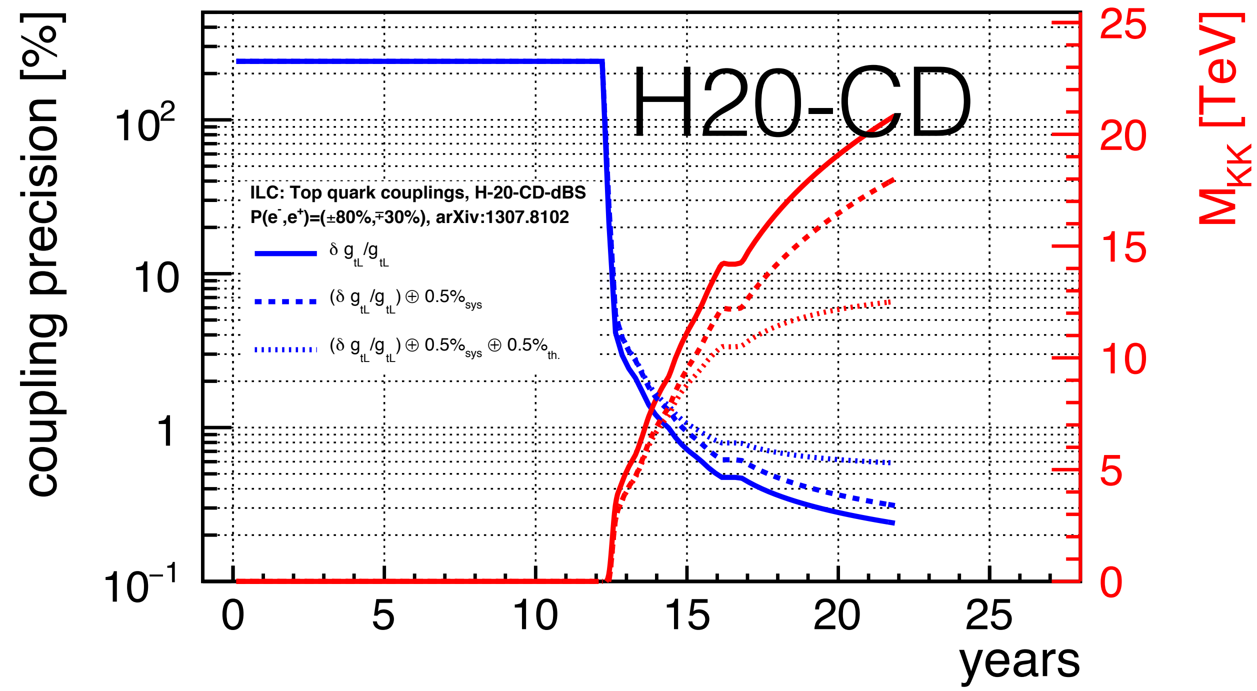
opportunity for top-Yukawa coupling

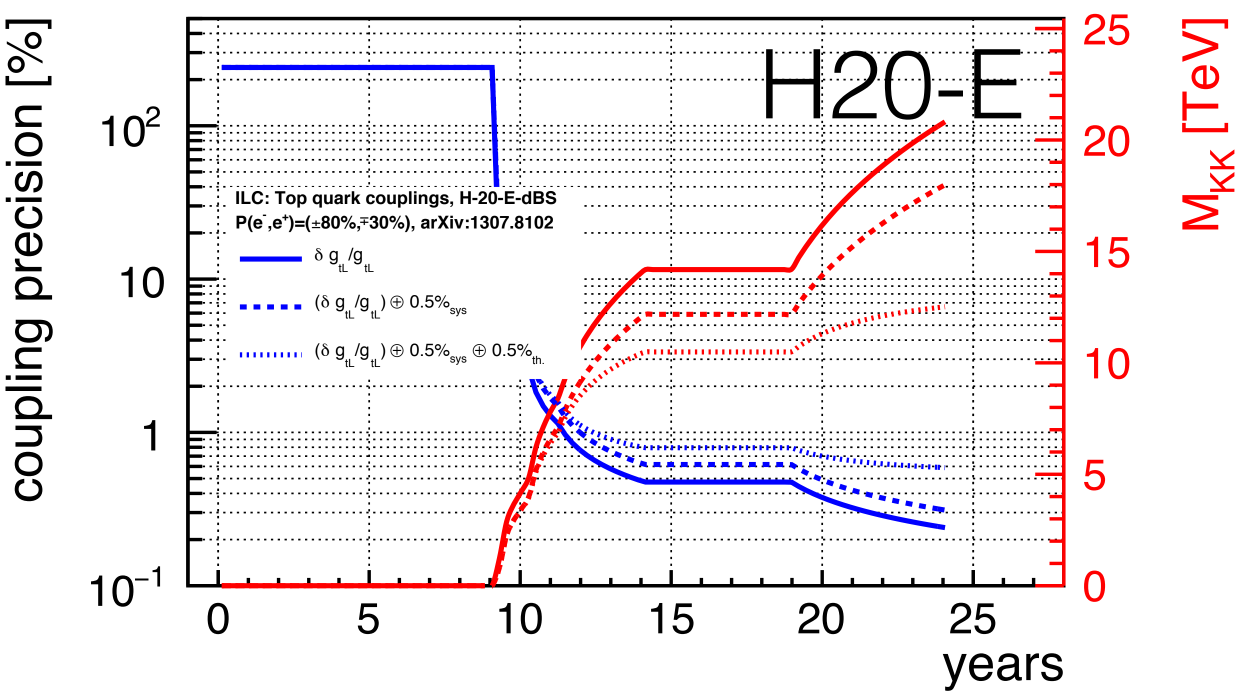


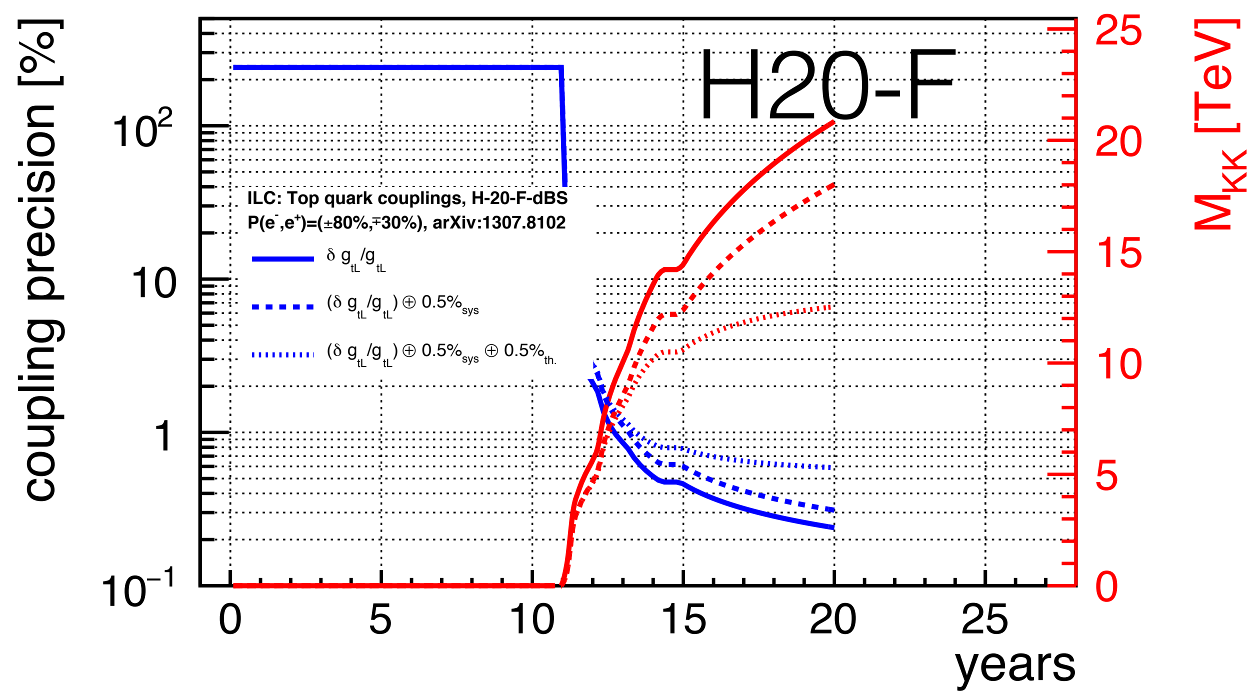
after 250 stage, taking advantage of possible technology improvement, we may afford 550-600 GeV, dreaming for ~2% htt precision

top EW couplings ($-\delta_{BS}$)

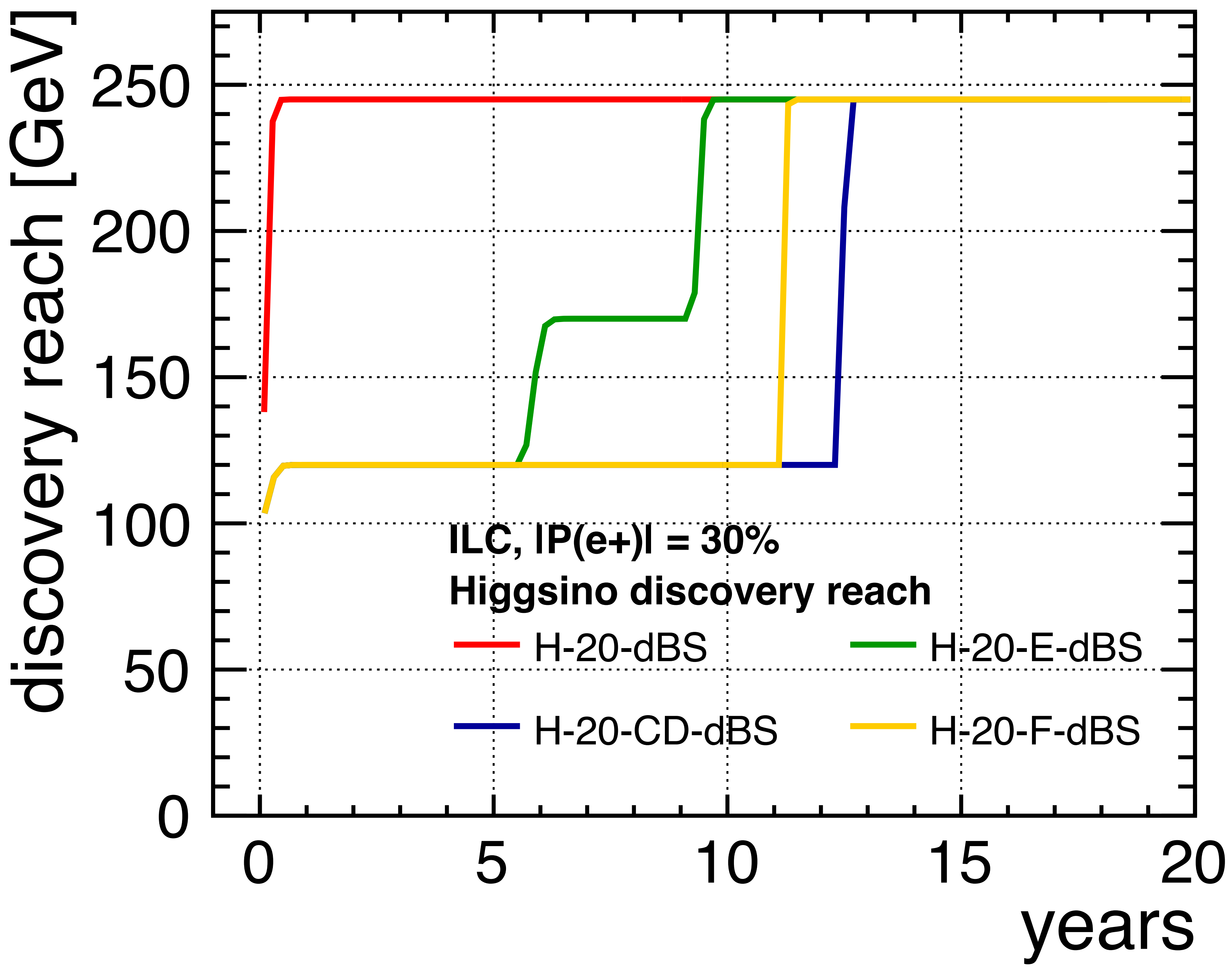




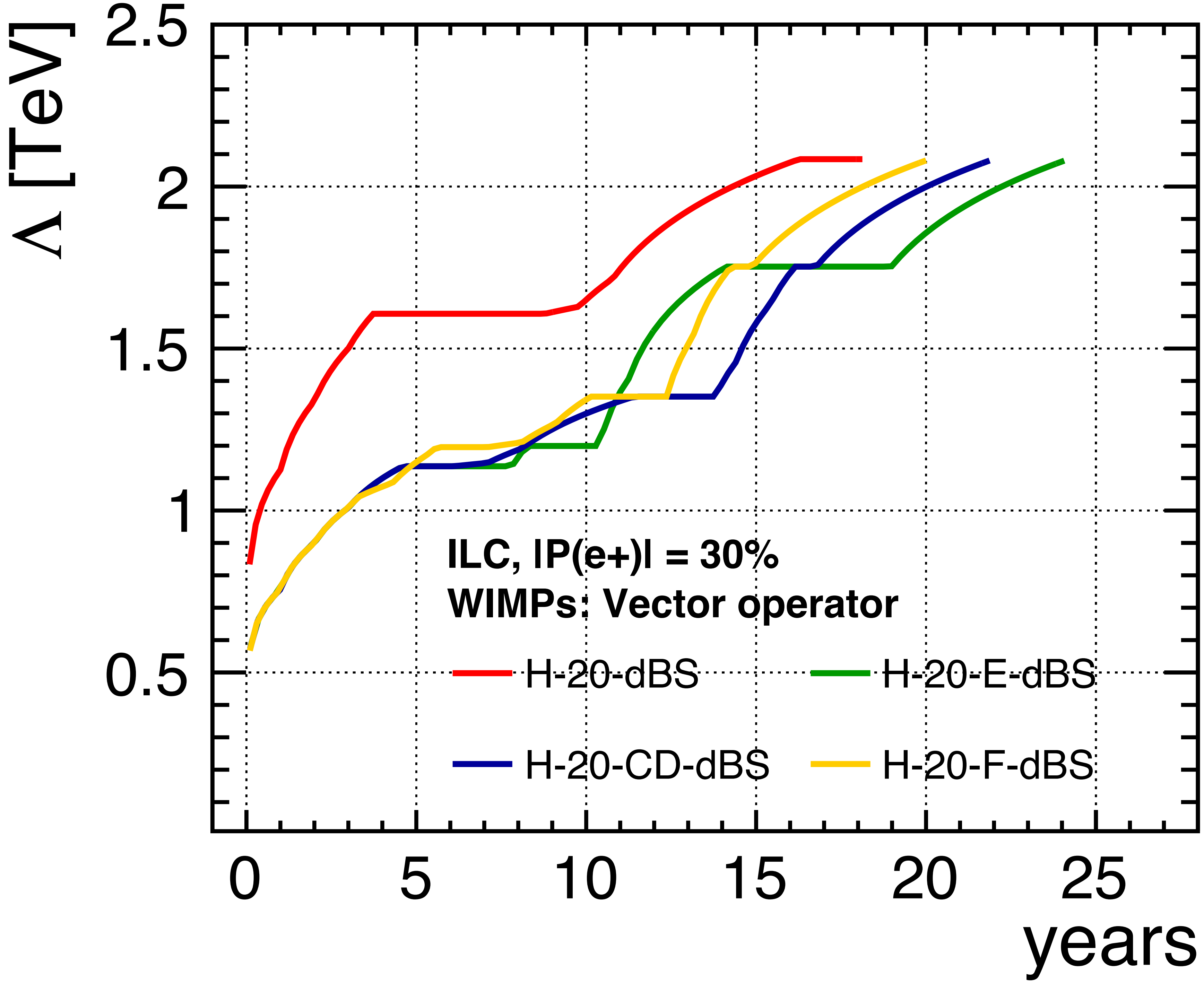




direct search ($-\delta_{BS}$): Higgsino



direct search ($-\delta_{BS}$): WIMPs



evolution of coupling precisions

- for Higgs self-coupling, top coupling, new particle search, clearly new scenarios are worse than H-20
- nevertheless, same precisions will be reached in the end by additional 4, 6, 2 years for option C/D, E, F

- what about the indirect discovery potential by Higgs precision couplings?

new development: model discrimination by EFT

talk by M.Peskin

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

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

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

C: covariance matrix of EFT coeffs

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

new development: model discrimination by EFT

talk by M.Peskin

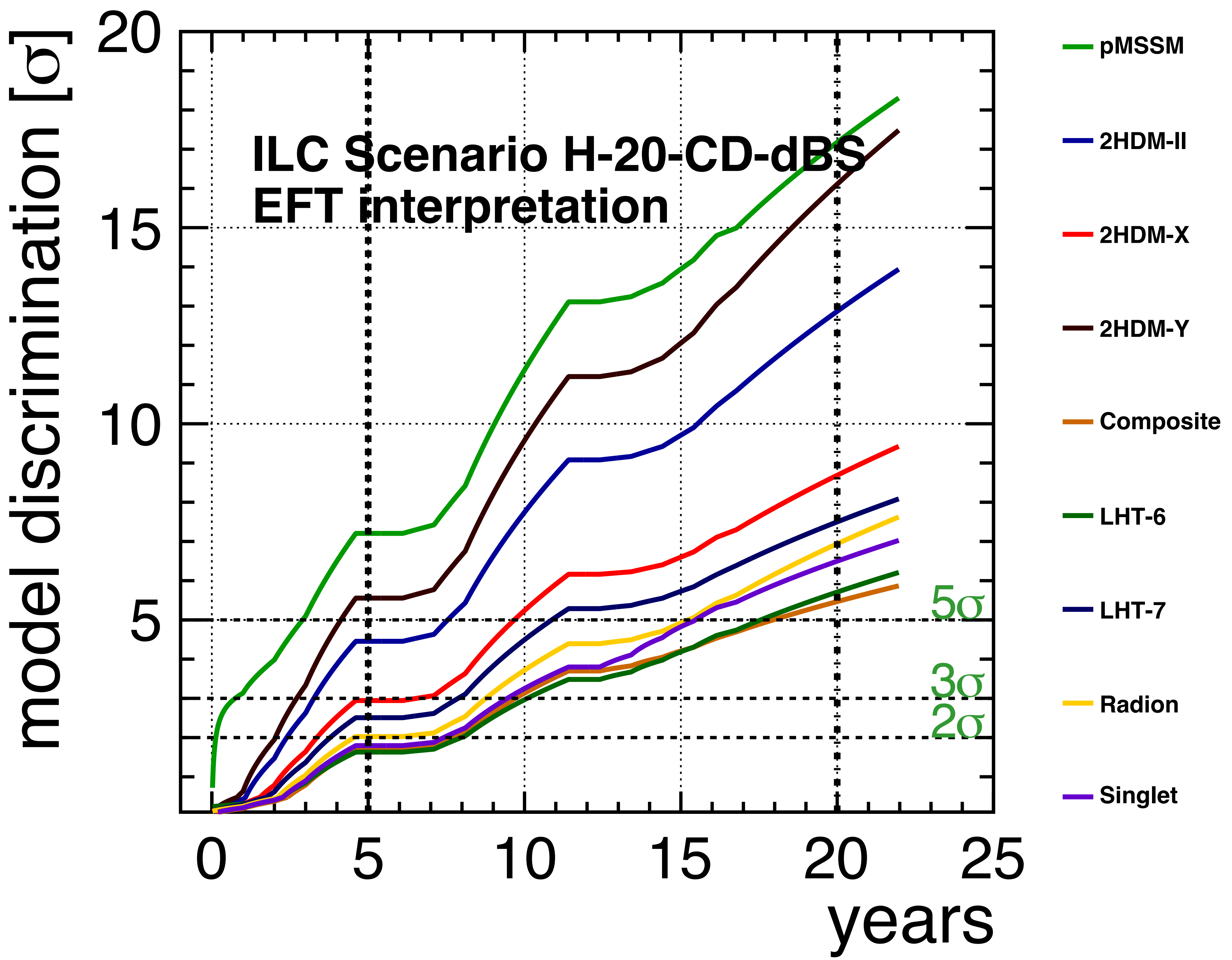
	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [34]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [36]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [36]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [36]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite 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 $m_A = 600\ \mathrm{GeV}, \tan\beta = 7$
- 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

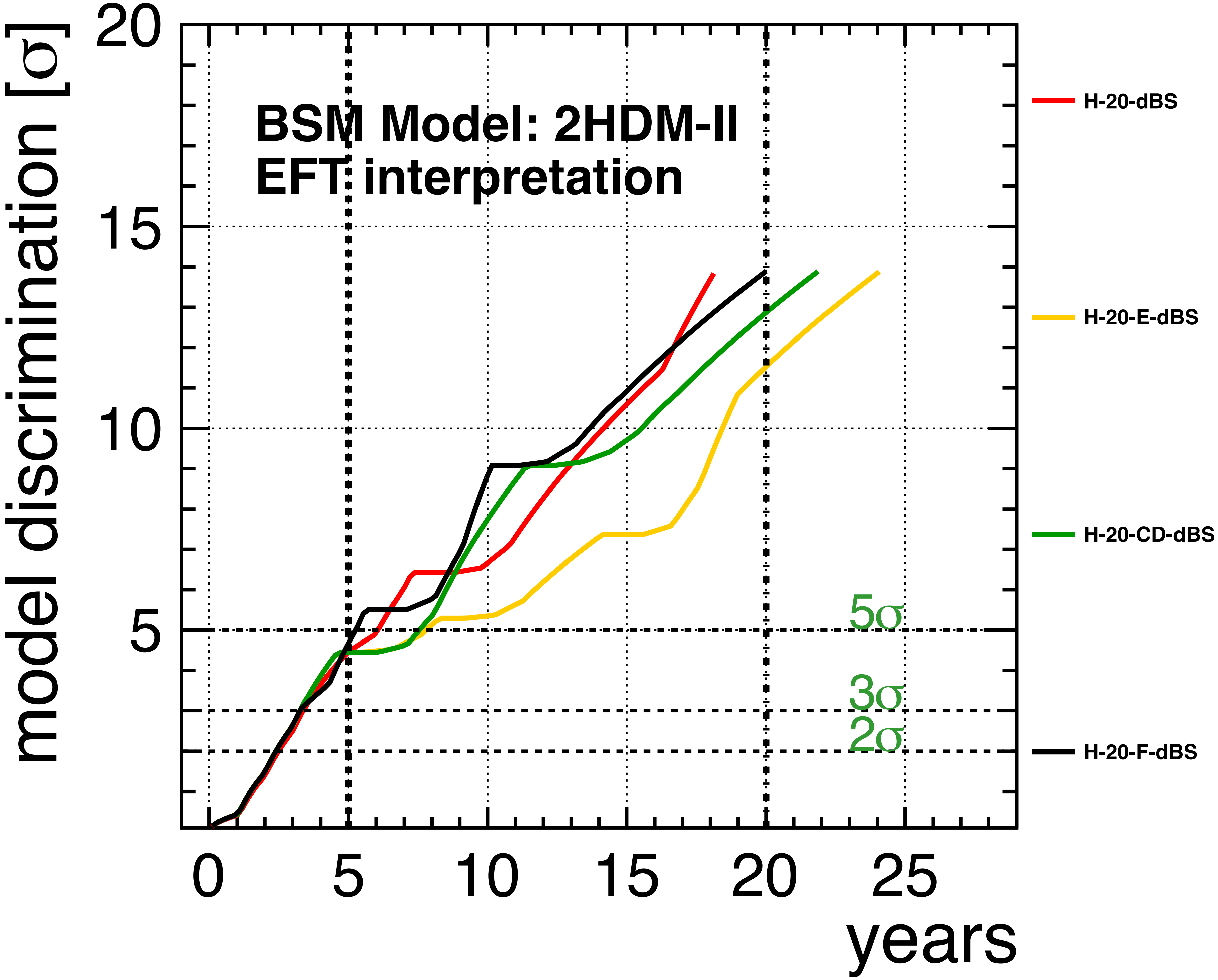
evolution of discovery potential (against SM)



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

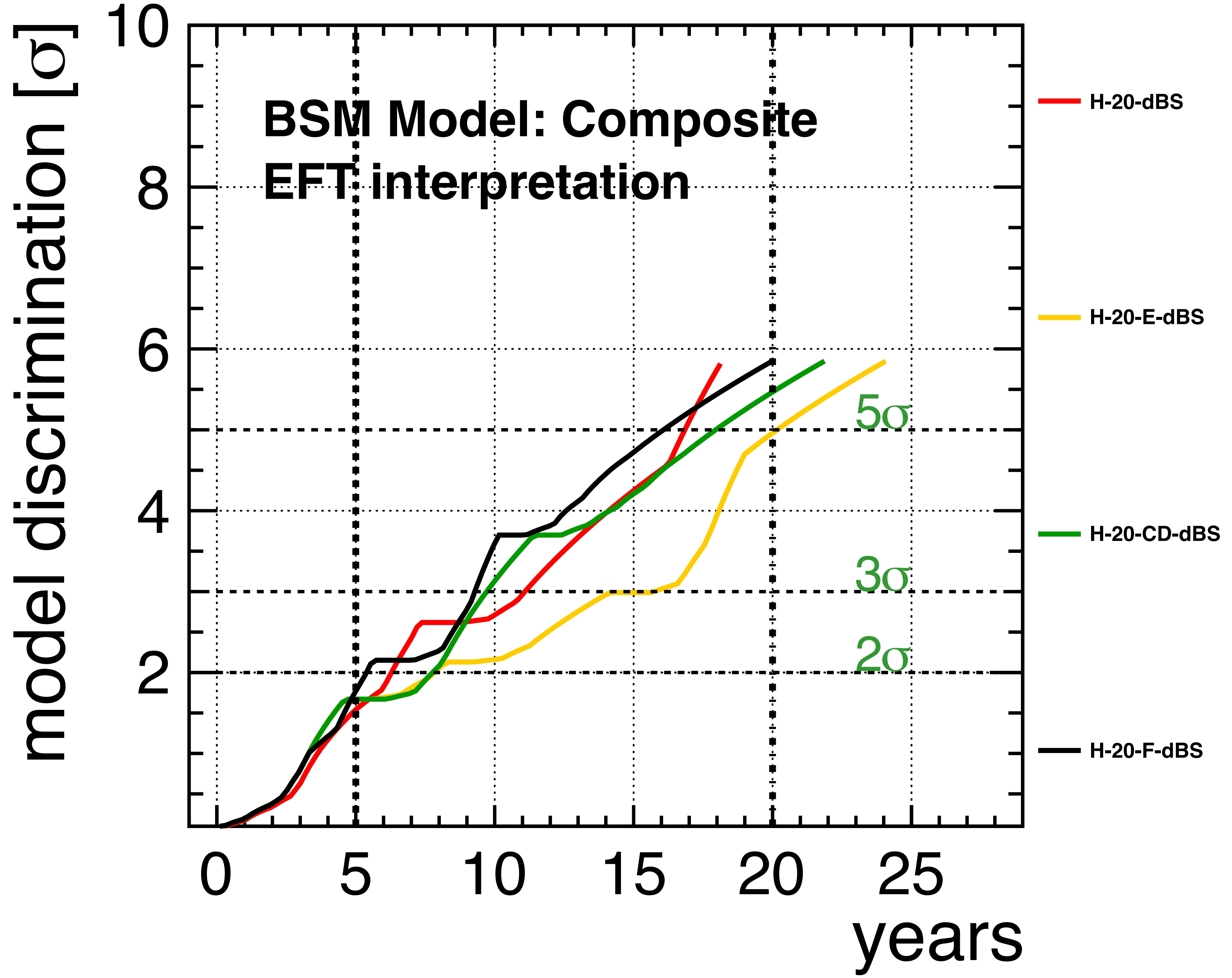
evolution of discovery potential ($-\delta_{BS}$): 2HDM-II

(m_A=600GeV; tanβ=7)

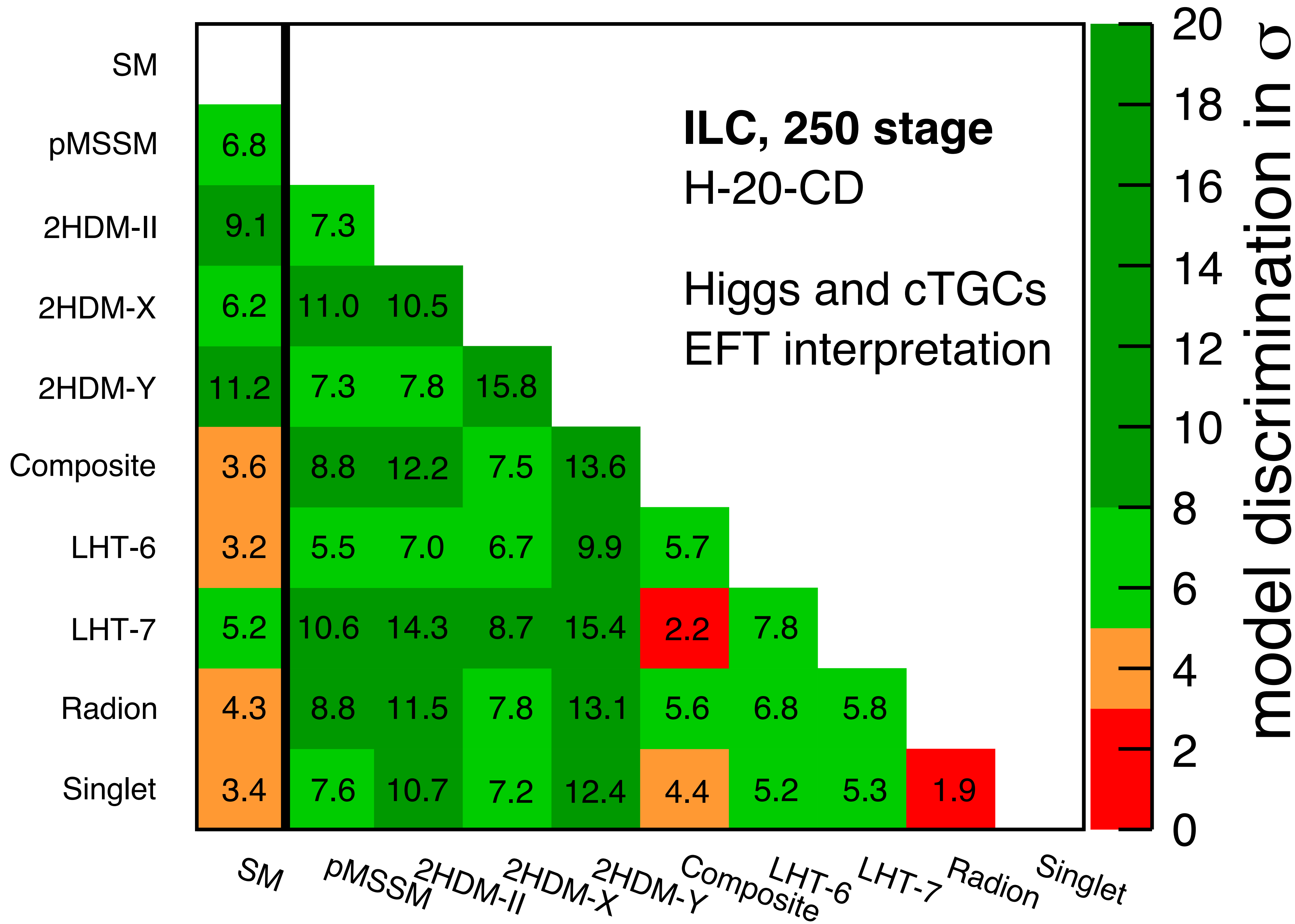


evolution of discovery potential ($-\delta_{BS}$): Composite

(f=1.2TeV; T=1.7TeV)

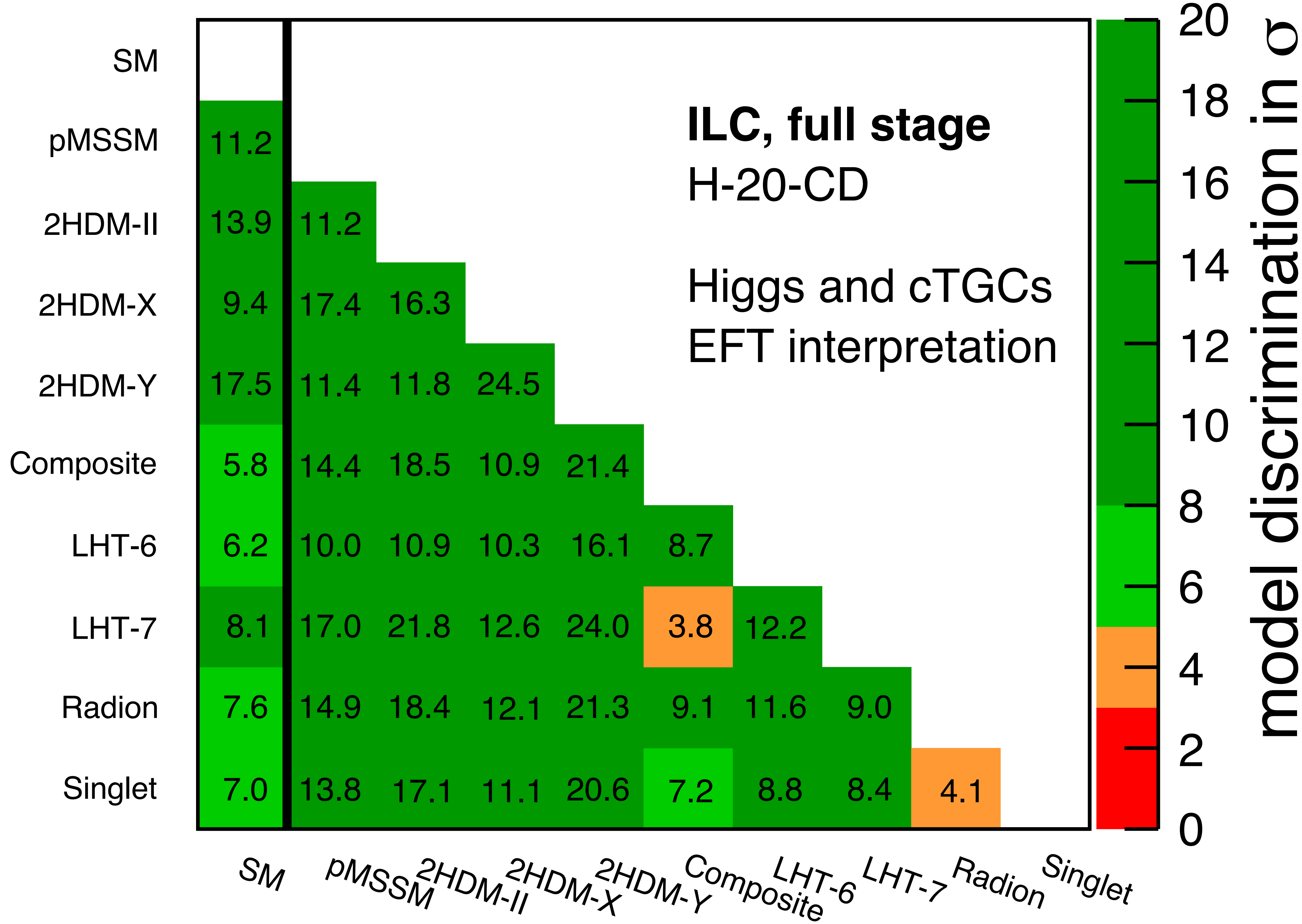


discrimination between BSM models (ILC250 stage)



once find deviation against SM —> can tell which BSM

discrimination between BSM models

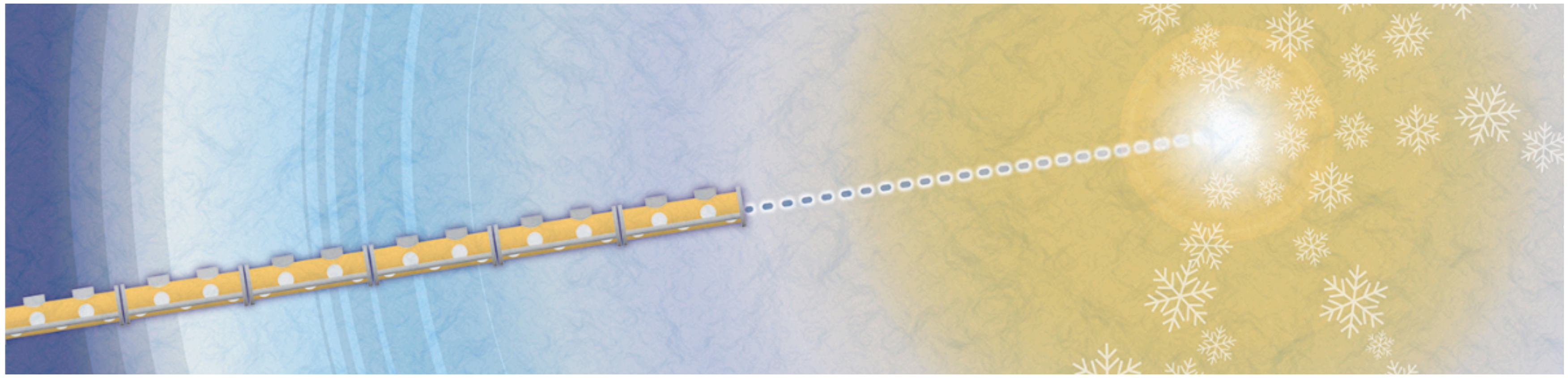


pin down the story after 250 + 500 full ILC

summary

- a few new staging scenarios are investigated, differences are manifest in the promise of energy upgrade
- new developments on both luminosity and physics study get the physics case at 250 GeV stronger
- initial 250 GeV stage can deliver great physics in terms of Higgs coupling precisions and BSM discovery potential (see more in Maxim’s talk)
- there is clear physics case beyond 250 GeV, and the greatest advantage of linear colliders is energy extendibility
- so if budget is allowed, it is highly preferable to integrate the upgrade path in the design of the initial stage

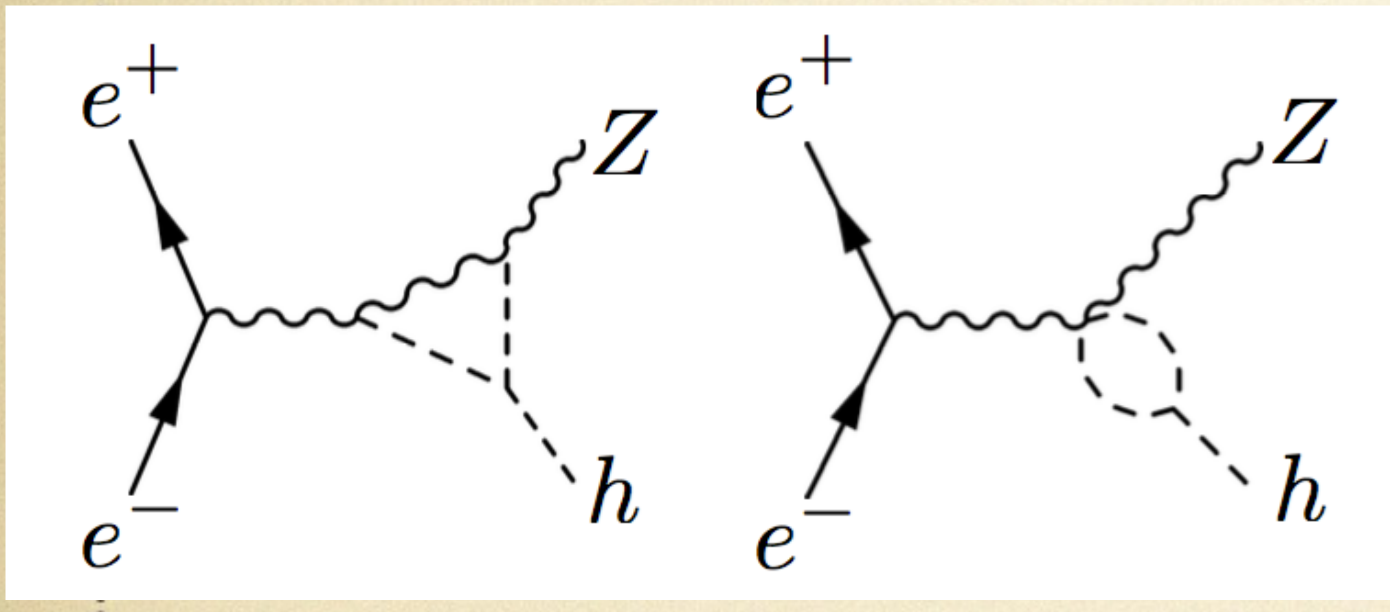
summary (personal)



- learned from LCWS17 (by above time machine):
  - ★ “science first” with ILC250
  - ★ cost reduction is just more than enough
  - ★ physics at ILC250 is great
  - ★ go ahead, ILC250 (from LCWS18)

backup

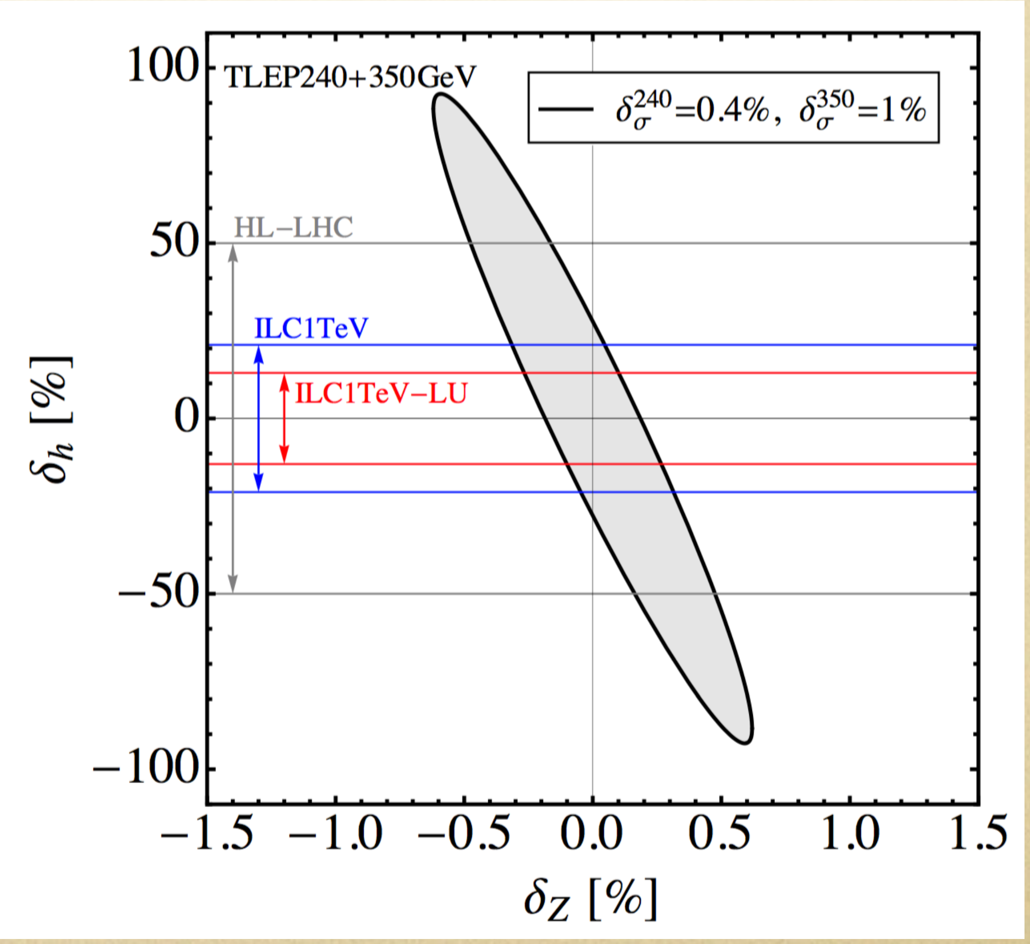
indirect model dependent probe of λ_{HHH}: $\sqrt{s} \sim 250$ GeV



McCullough, 1312.3322

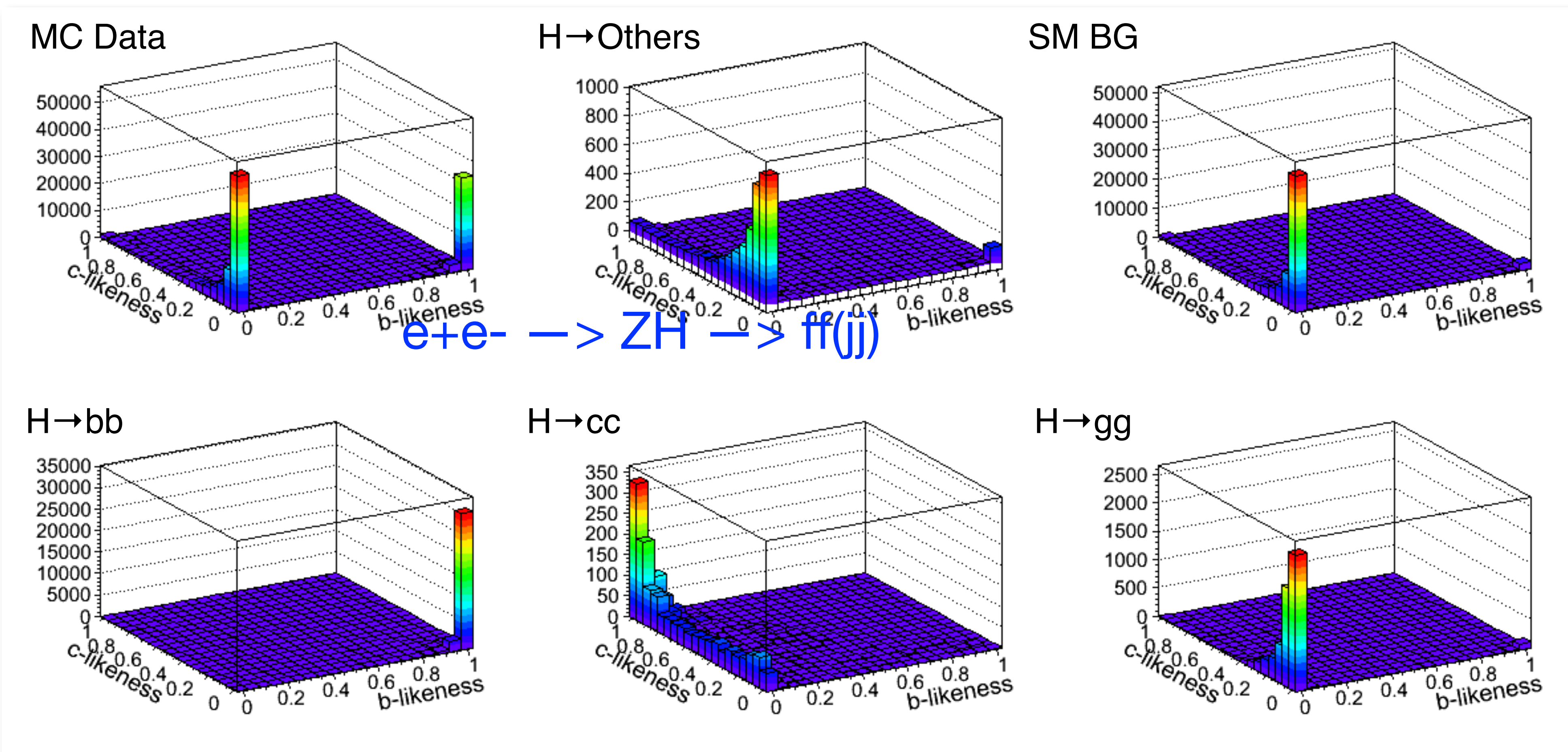
$$\delta_\sigma^{240} = 100\,(2\delta_Z + 0.014\delta_h)\,\%$$

- if only δ_h is deviated —> $\delta_h \sim 28\%$
- if both δ_Z and δ_h deviated —> $\delta h \sim 90\%$
- δ_σ could receive contributions from many other sources
- can be considered as a useful consistency test of SM



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



directly measured

$$\sigma_{ZH} \cdot \mathrm{Br}(H \to b\bar{b}) \propto g_{HZZ}^2 g_{Hbb}^2 / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to c\bar{c}) \propto g_{HZZ}^2 g_{Hcc}^2 / \Gamma_H$$
$$\sigma_{ZH} \cdot \mathrm{Br}(H \to gg) \propto g_{HZZ}^2 g_{Hgg}^2 / \Gamma_H$$

with Γ_H

g_{HZZ}

g_{Hbb}

g_{Hcc}

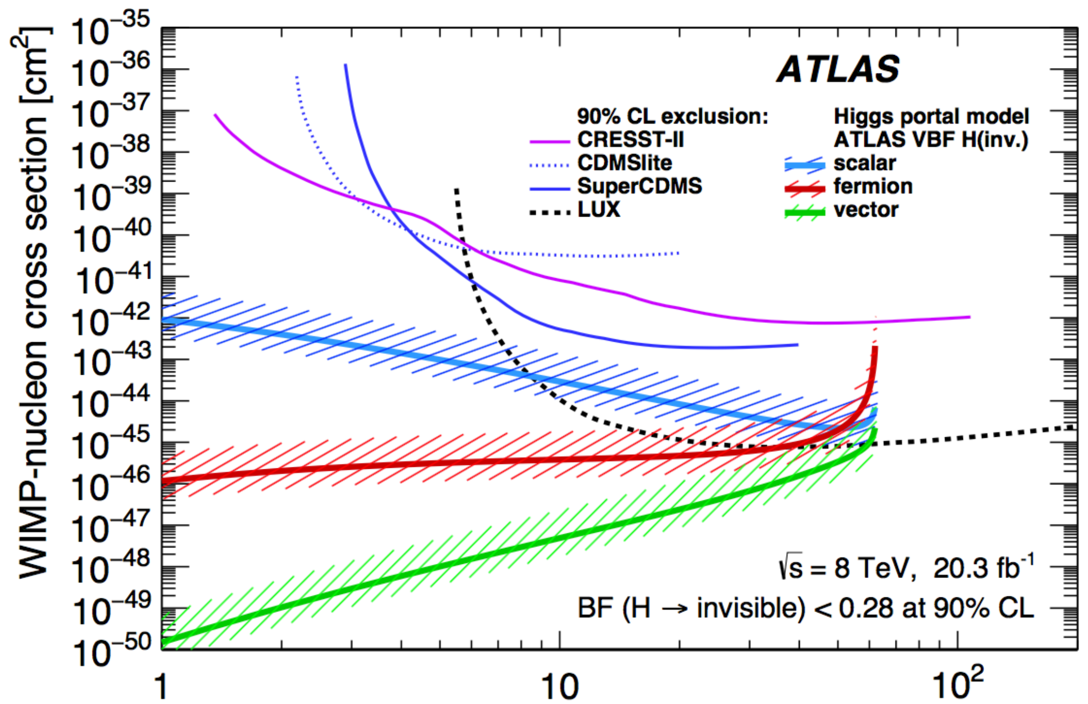
g_{Hgg}

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

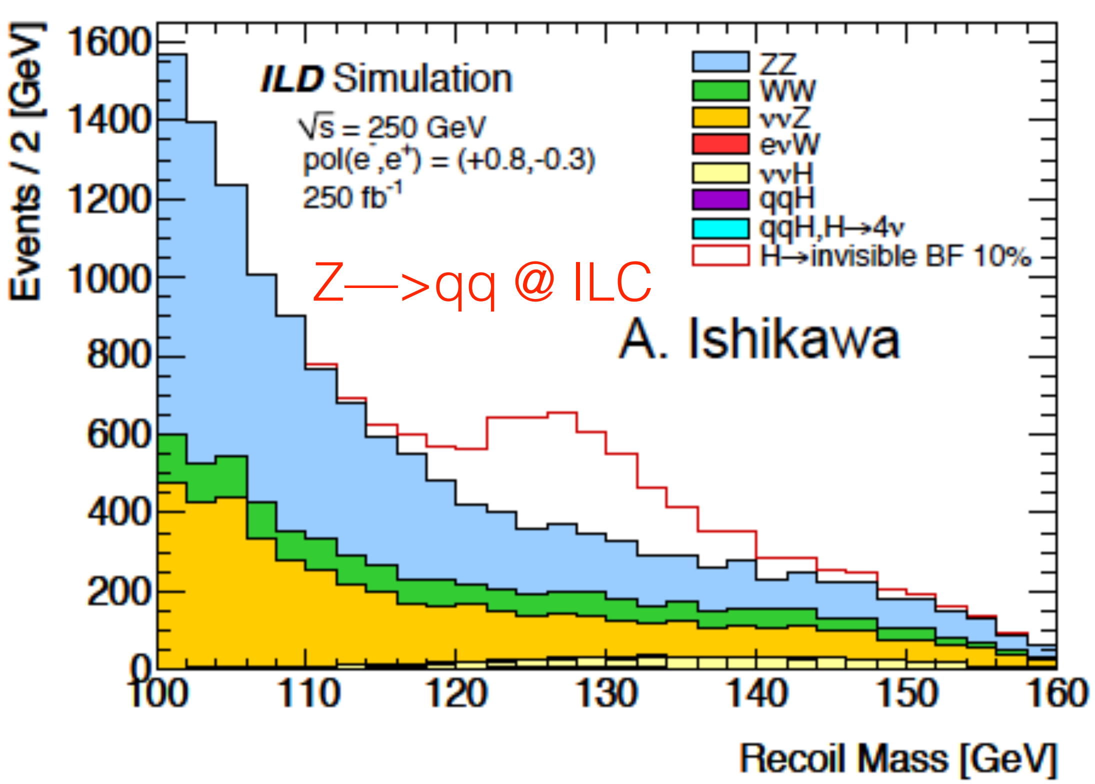
exotic decay: search of Higgs to invisible

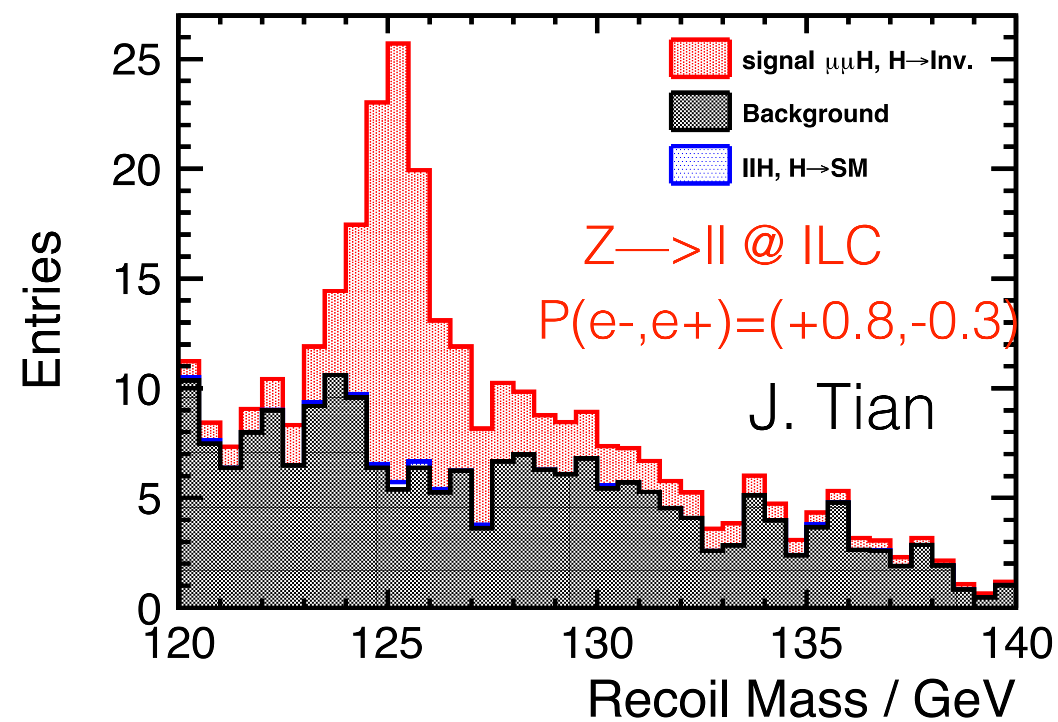
$$e^+ + e^- \rightarrow ZH \rightarrow l^+l^-/q\bar{q} + \text{Missing}$$

- BR(H—>inv.) < 0.3% (CL[95%])
- a sensitive test for Higgs portal dark mater model —> complementary for low mass
- beam polarisation does help

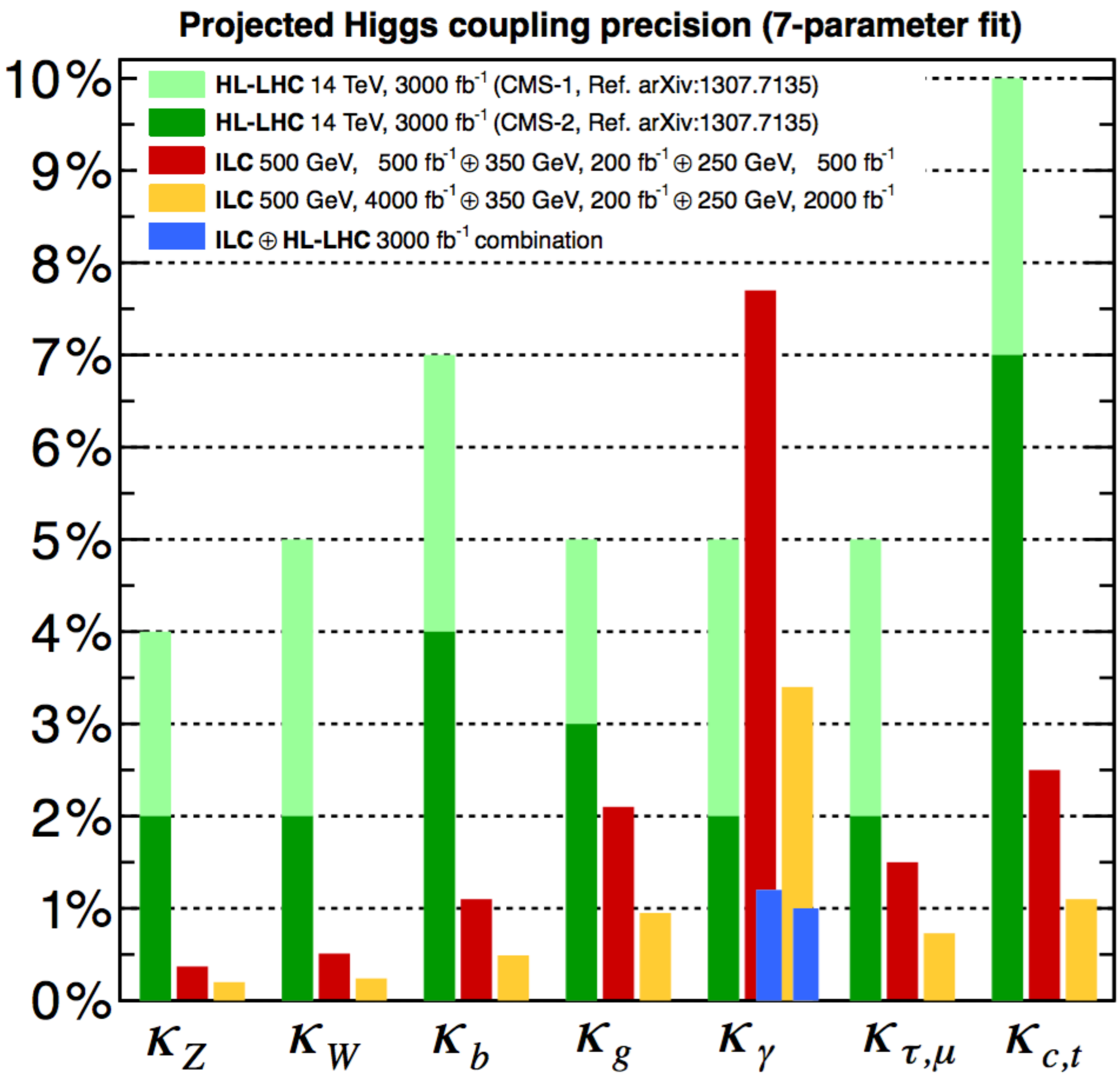


JHEP 1601 (2016) 172





expected precisions of Higgs couplings



Two-Fermion Processes

Z’ Search / Study

arXiv:0912.2806 [hep-ph]

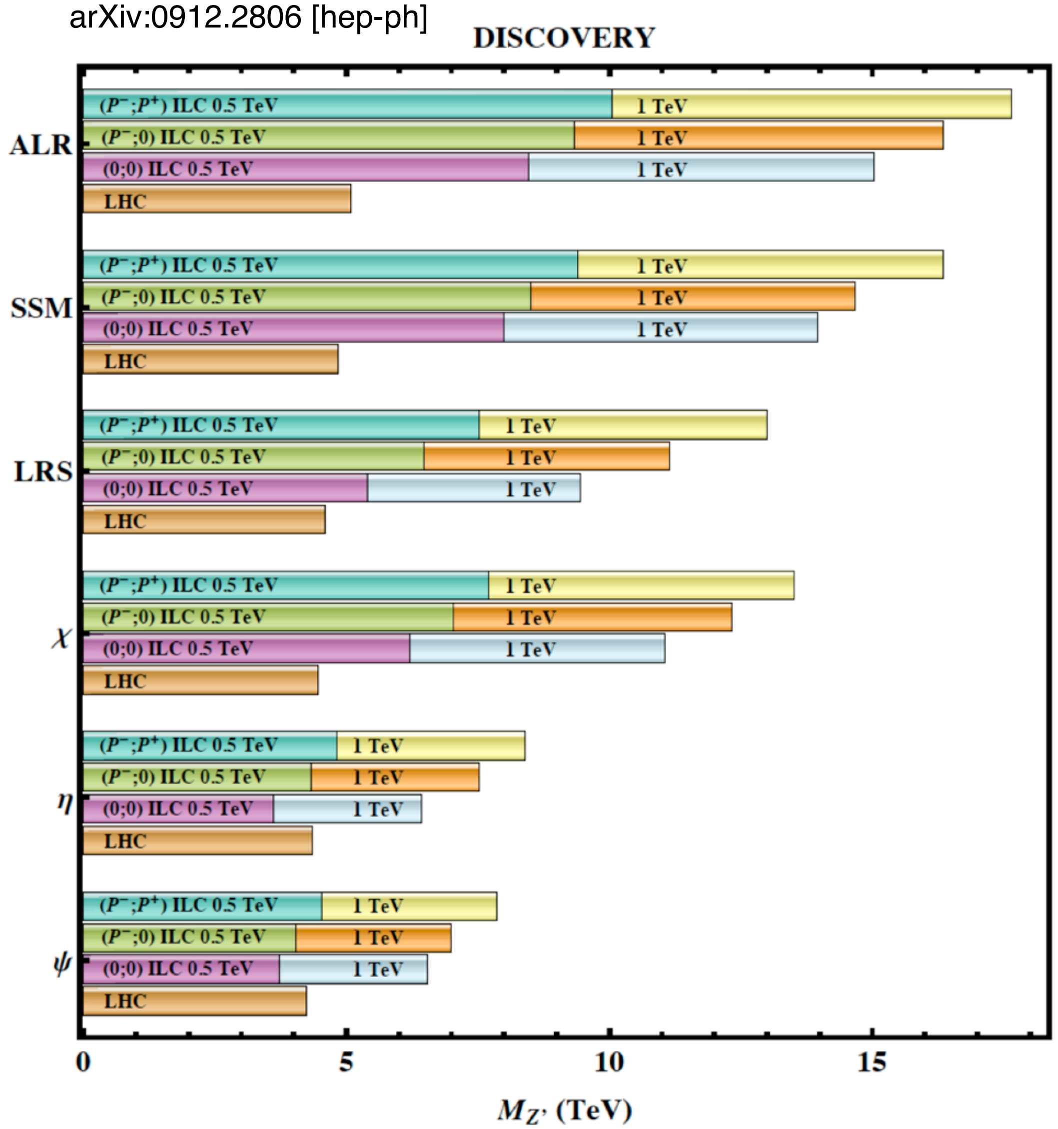
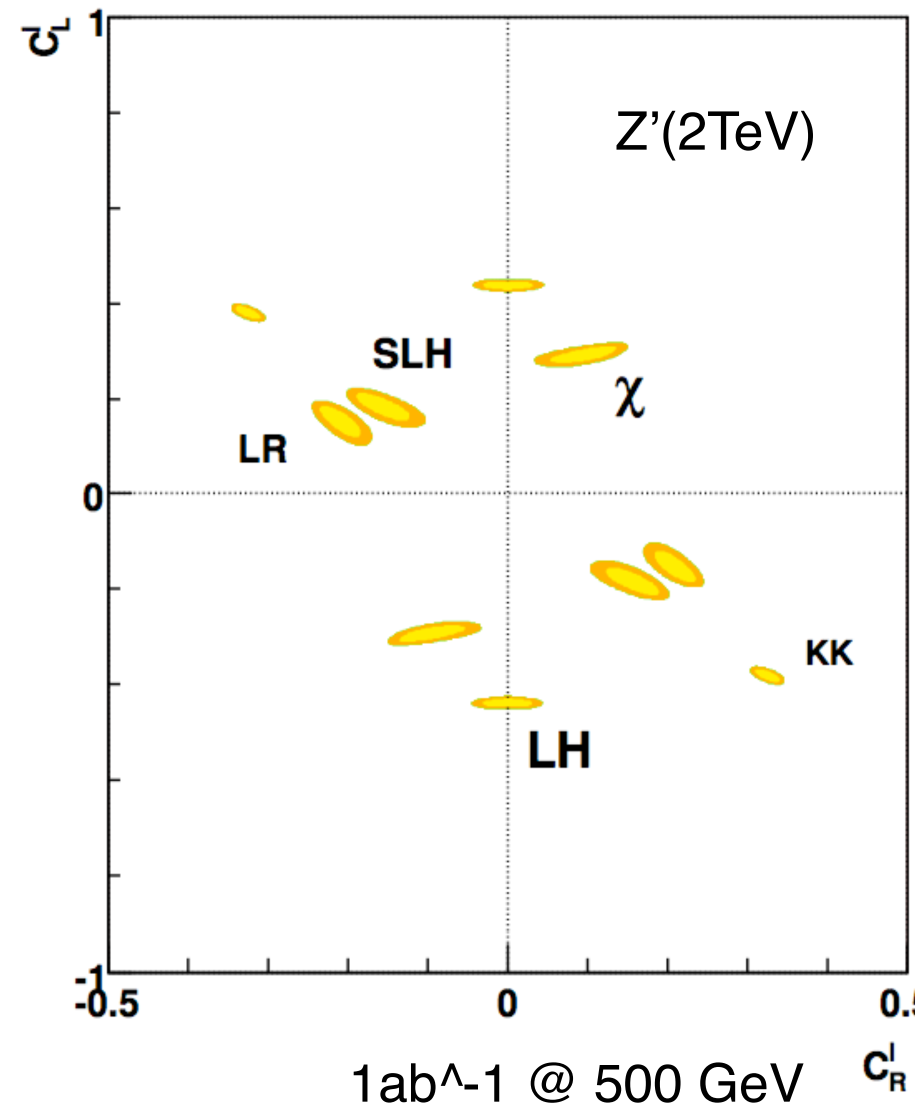


Figure 23: Sensitivity of the ILC to various candidate Z' bosons, quoted at 95% conf., with $\sqrt{s} = 0.5$ (1.0) TeV and $\mathcal{L}_{\rm int} = 500$ (1000) fb^{-1}. The sensitivity of the LHC-14 via Drell-Yan process $pp \to \ell^+\ell^- + X$ with 100 fb^{-1} of data are shown for comparison. For details, see [14].

hep-ph/0511335

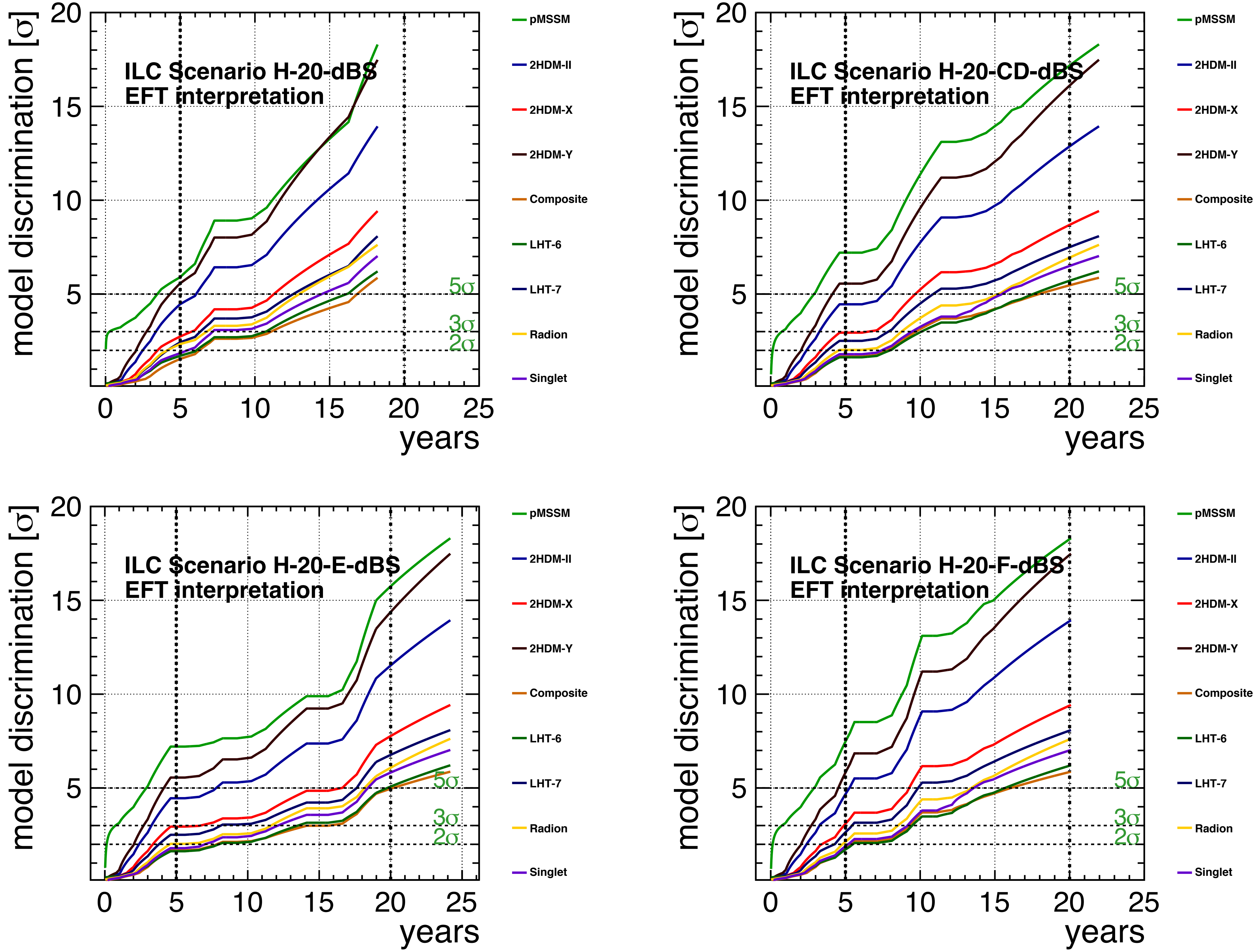


1ab^-1 @ 500 GeV

ILC’s Model ID capability is expected to exceed that of LHC even if we cannot hit the Z’ pole.

Beam polarization is essential to sort out various possibilities.

evolution of discovery potential (against SM)



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