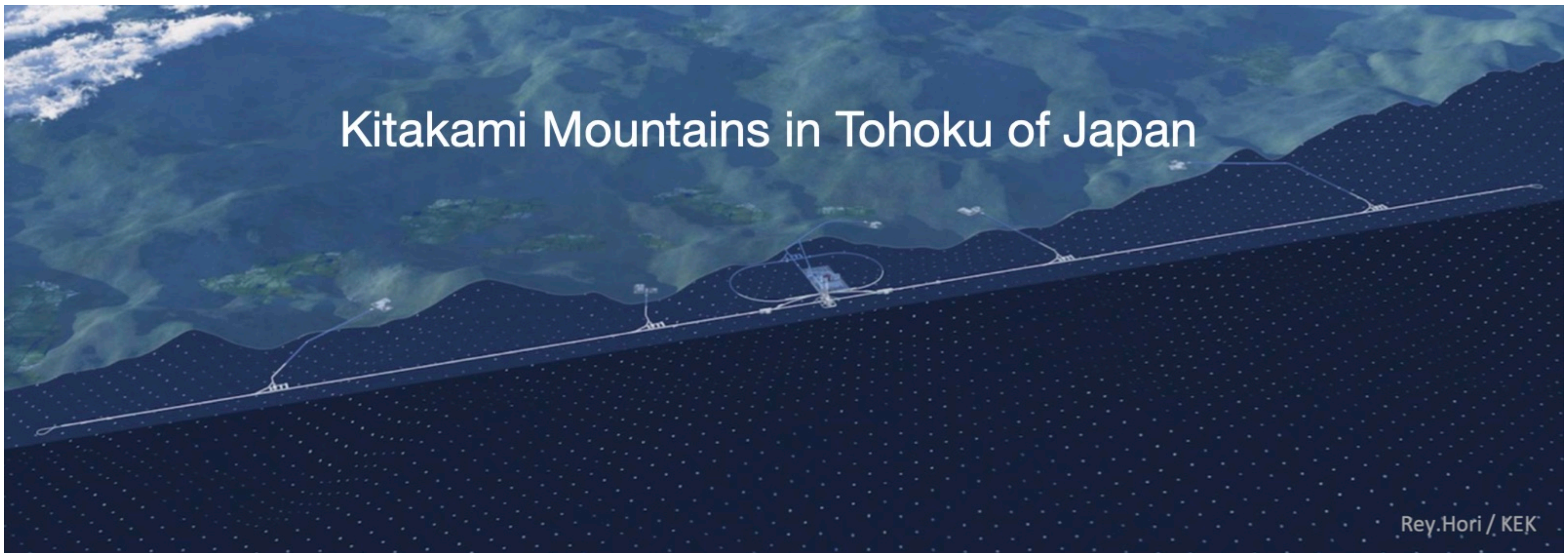
Higgs physics with ILC



Junping Tian (U. Tokyo) on behalf of ILC IDT-WG3

Higgs 2024 @ Uppsala U., Nov. 4-8, 2024

ILC Supporters

ICEPP
The University of Tokyo

outline

- Introduction

  Common goal of Higgs Factories

- Highlight a few key measurements

  How ILC can advance our knowledges of Higgs

- A few open questions

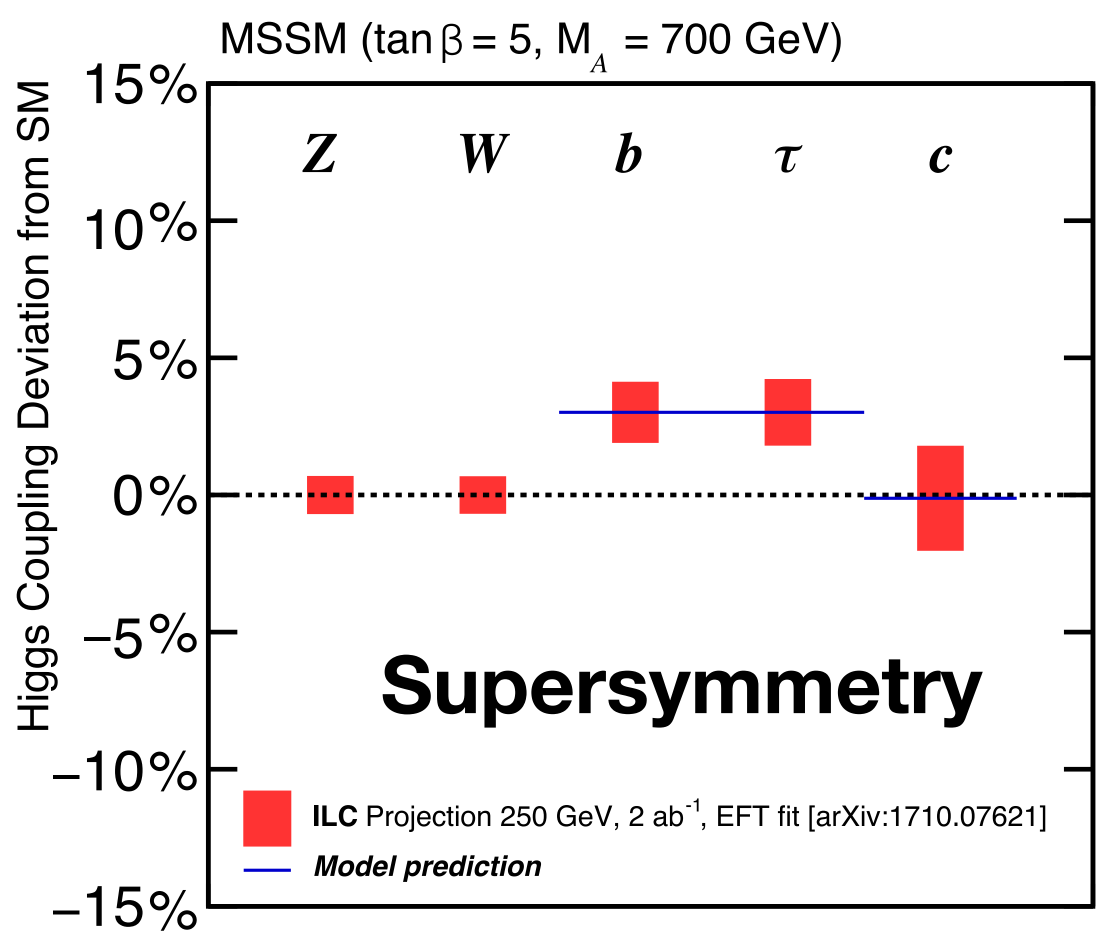
  In particular those need help from theorists

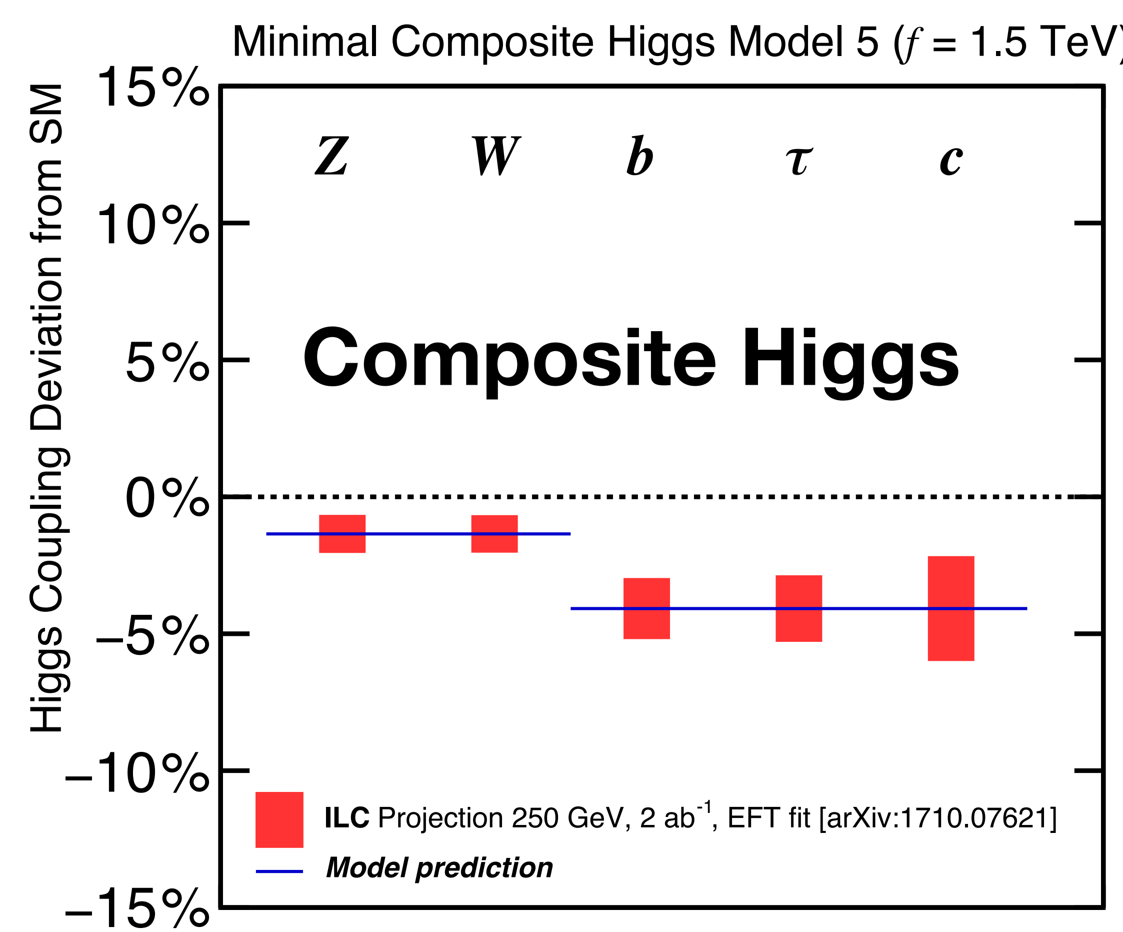
- Summary

[see comprehensive document, ILC report to Snowmass 2021, arXiv:2203.07622]

[ILC report to ESU 2020, arXiv:1903.01629]

Example: opportunities from precision Higgs couplings





[ILC TDR, arXiv: 1306.6352]

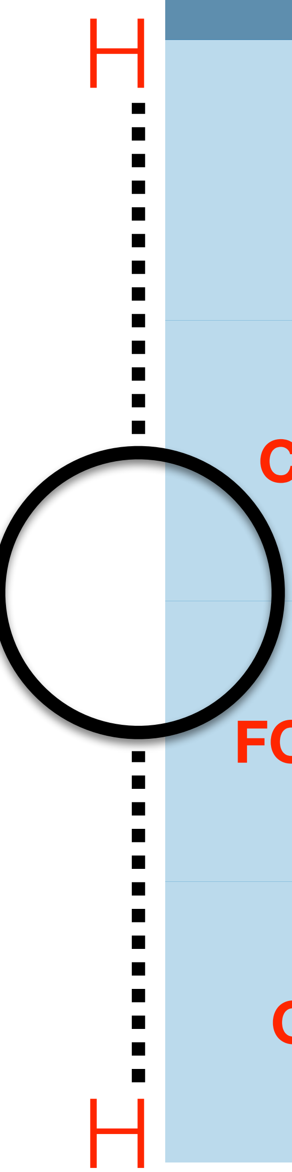
- can not only *discover* BSM physics, but also identify the *nature of BSM* by *precisely* measuring the *deviation pattern*

general guidelines for Higgs coupling meas. @ future e+e-

—in light of what have been found at LHC

- new particles are heavy, deviation is small, 1-10% for m_{BSM}~1TeV: need measurement with *1% precision* or below so that deviations from SM can be discovered
- measurement better to be as *model-independent* as possible: so that the true BSM model can be discriminated from others, future HEP direction hence can be decided

proposals of future "Higgs Factories"



	$\sqrt{s}$	beam polarisation	∫Ldt (baseline)	R&D phase
ILC	0.1 - 1 TeV	e-: 80% e+: 30% (20%)	2 ab^{-1} @ 250 GeV 0.2 ab^{-1} @ 350 GeV 4 ab-1 @ 500 GeV 8 ab-1 @ 1 TeV	TDR 2013
CEPC	90 - 240 GeV	e-: 0% e+: 0%	100 ab^{-1} @ M_Z 6 ab^{-1} @ $2M_W$ 20 ab^{-1} @ 240 GeV	TDR 2022
FCC-ee	90 - 365 GeV	e-: 0% e+: 0%	150 ab^{-1} @ M_Z 10 ab^{-1} @ $2M_W$ 5 ab^{-1} @ 240 GeV 1.7 ab^{-1} @ 365 GeV	CDR 2018
CLIC	0.35 - 3 TeV	e-: (80%) e+: 0%	1 ab^{-1} @ 380 GeV 2.5 ab^{-1} @ 1.5 TeV 5 ab^{-1} @ 3 TeV	CDR 2012

(+ emerging C^3, Muon Colliders, μTristen, etc)

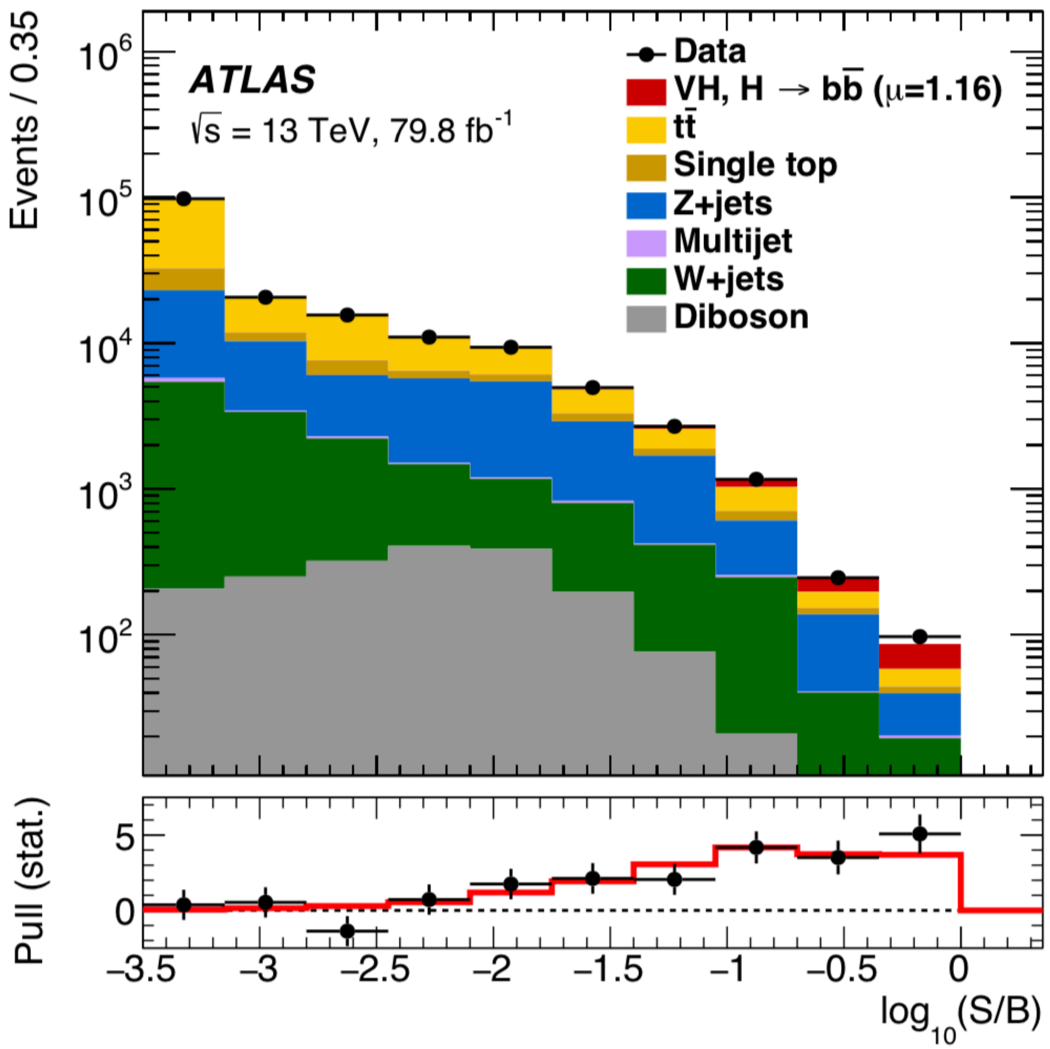
common: Higgs factory with $O(10^6)$ Higgs events

differ in energy reach, luminosity, polarization, project readiness

statistics isn't the only player: S/B, systematics, etc
(example on *H→bb* discovery)

LHC (super Higgs factory #10^8)

e+e- (Higgs factory #10^6)



\# of Higgs produced: ~4,000,000

significance: 5.4σ

[ATLAS, 1808.08238; CMS, 1808.08242]

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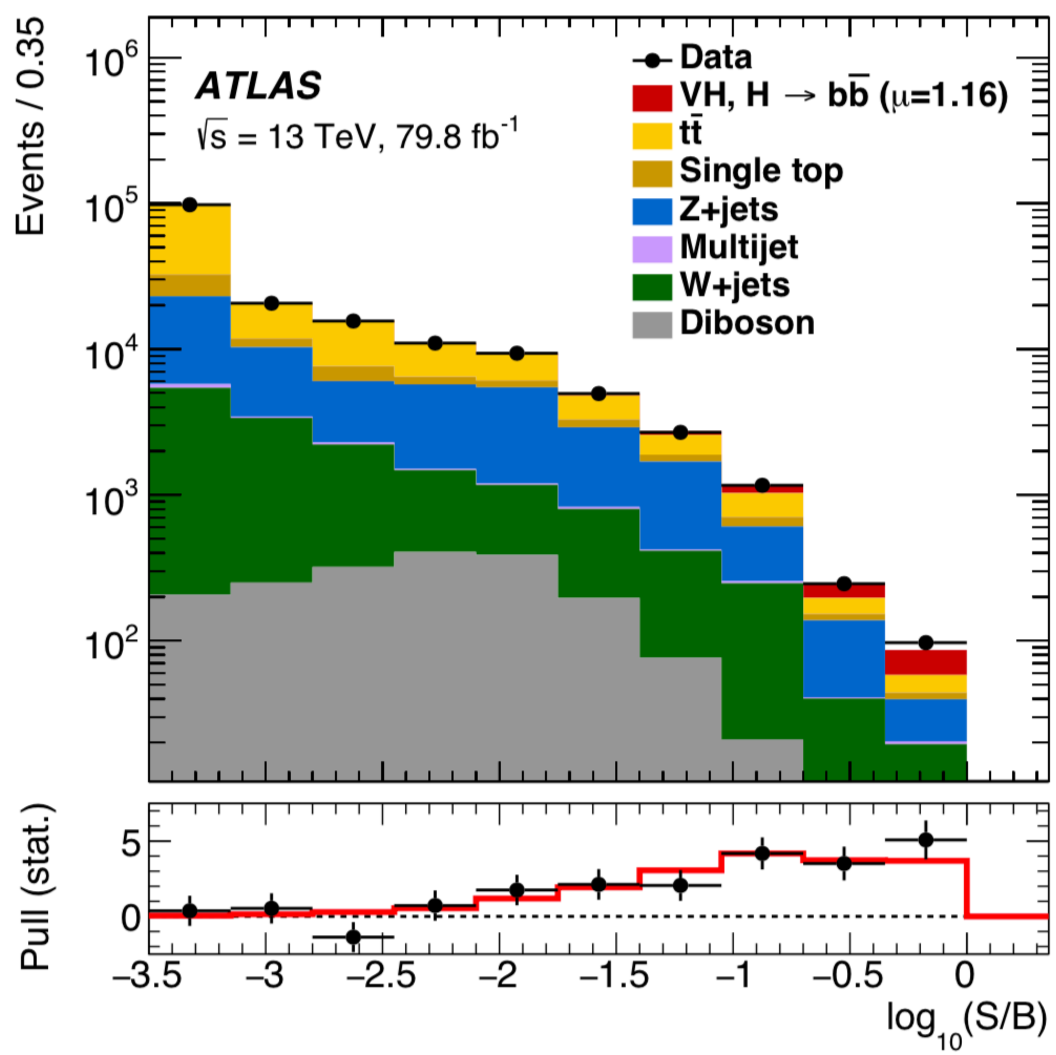
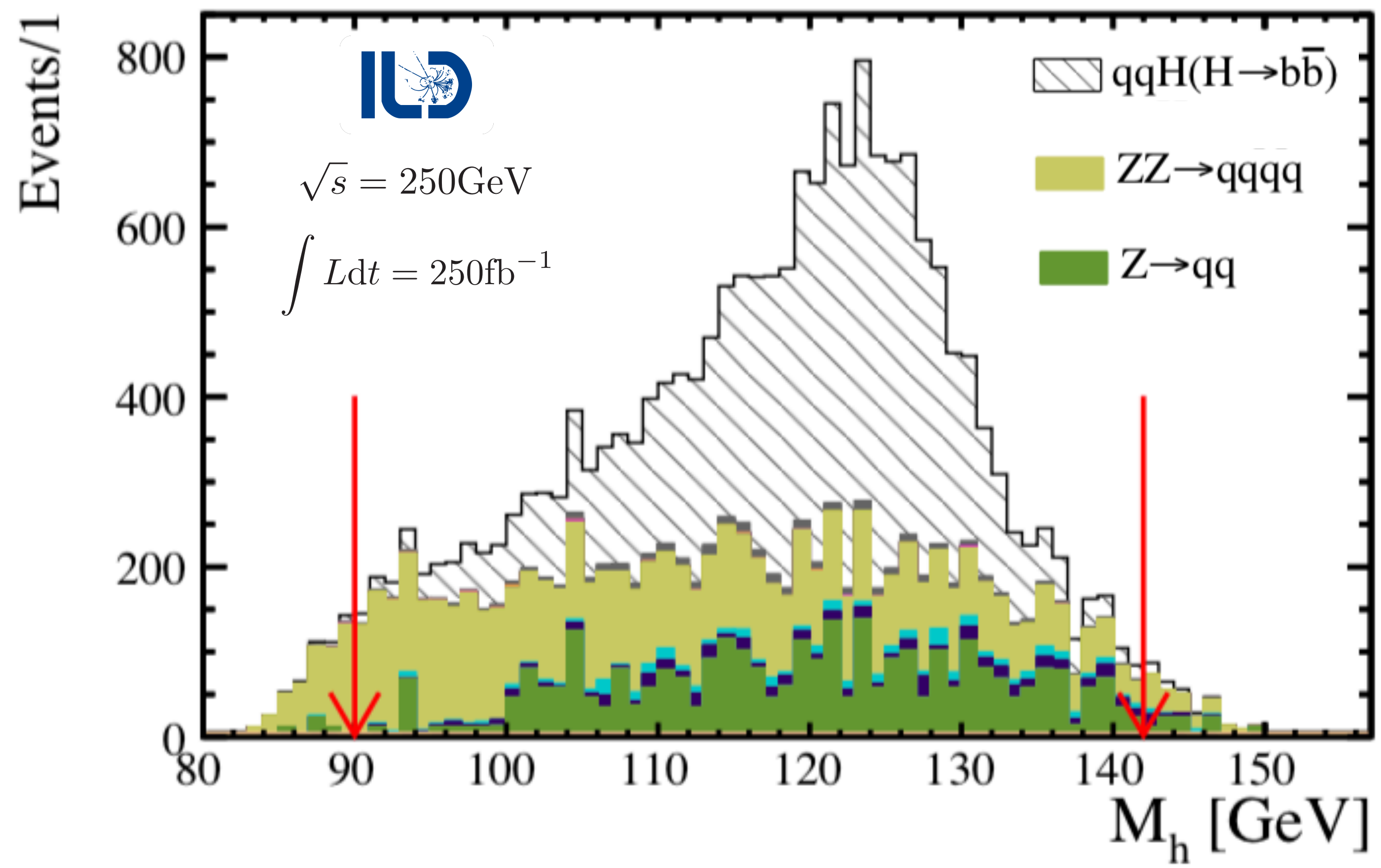




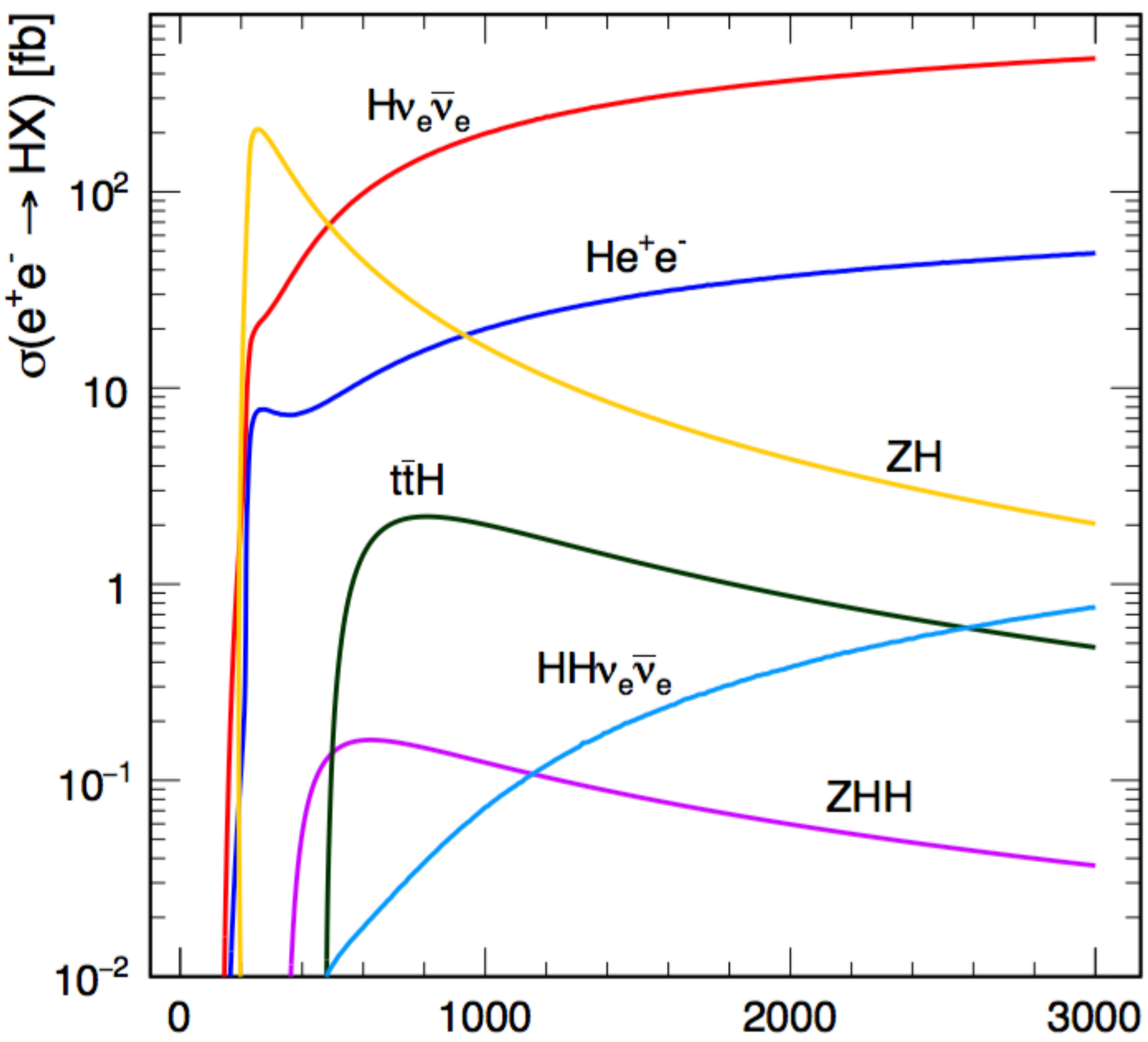
full detector simulation

	LHC	e+e-
# of Higgs produced:	~4,000,000	~400
significance:	5.4σ	5.2σ

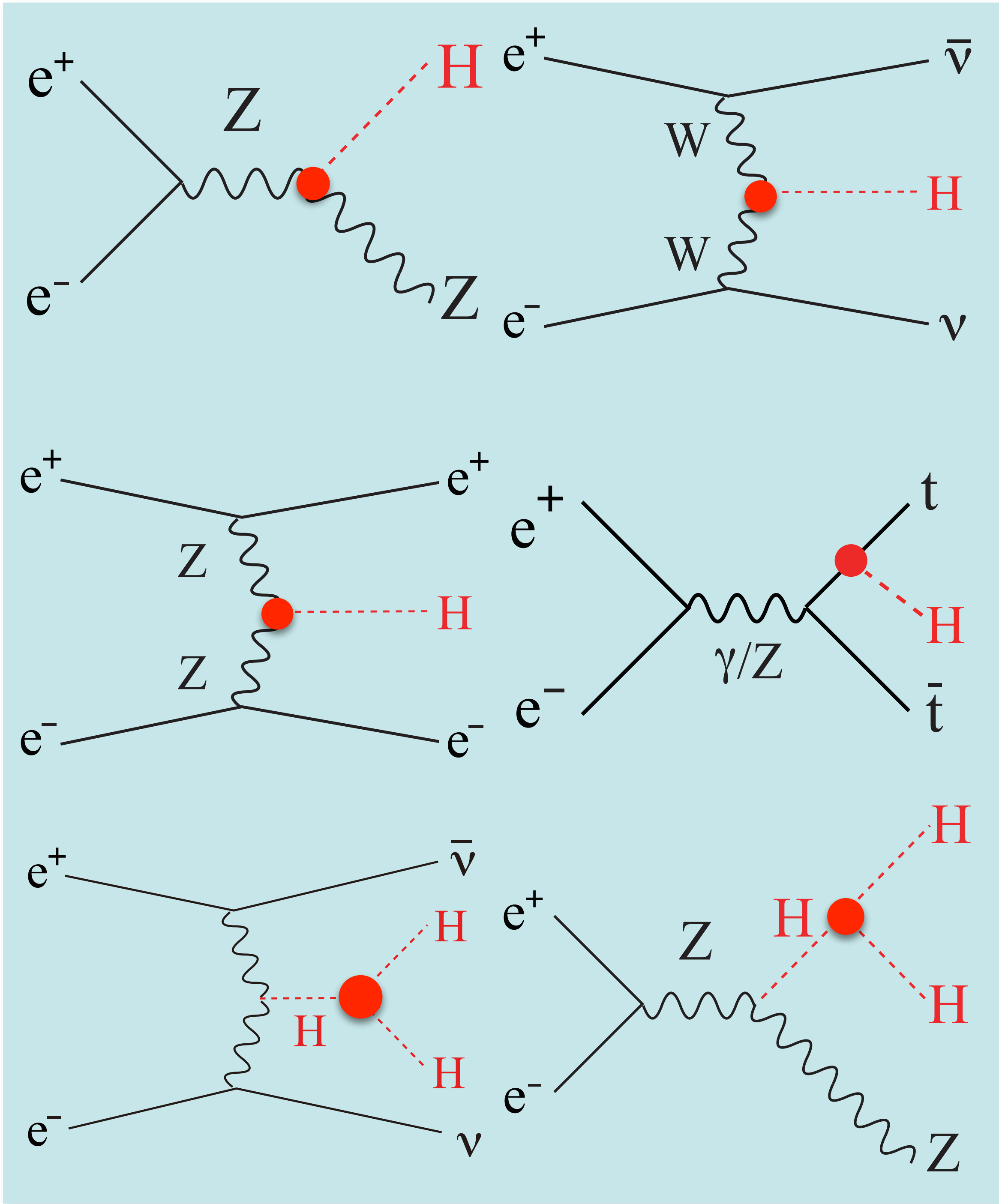
[ATLAS, 1808.08238; CMS, 1808.08242]

[Ogawa, PhD Thesis (Sokendai '18)]

Higgs productions at e+e-

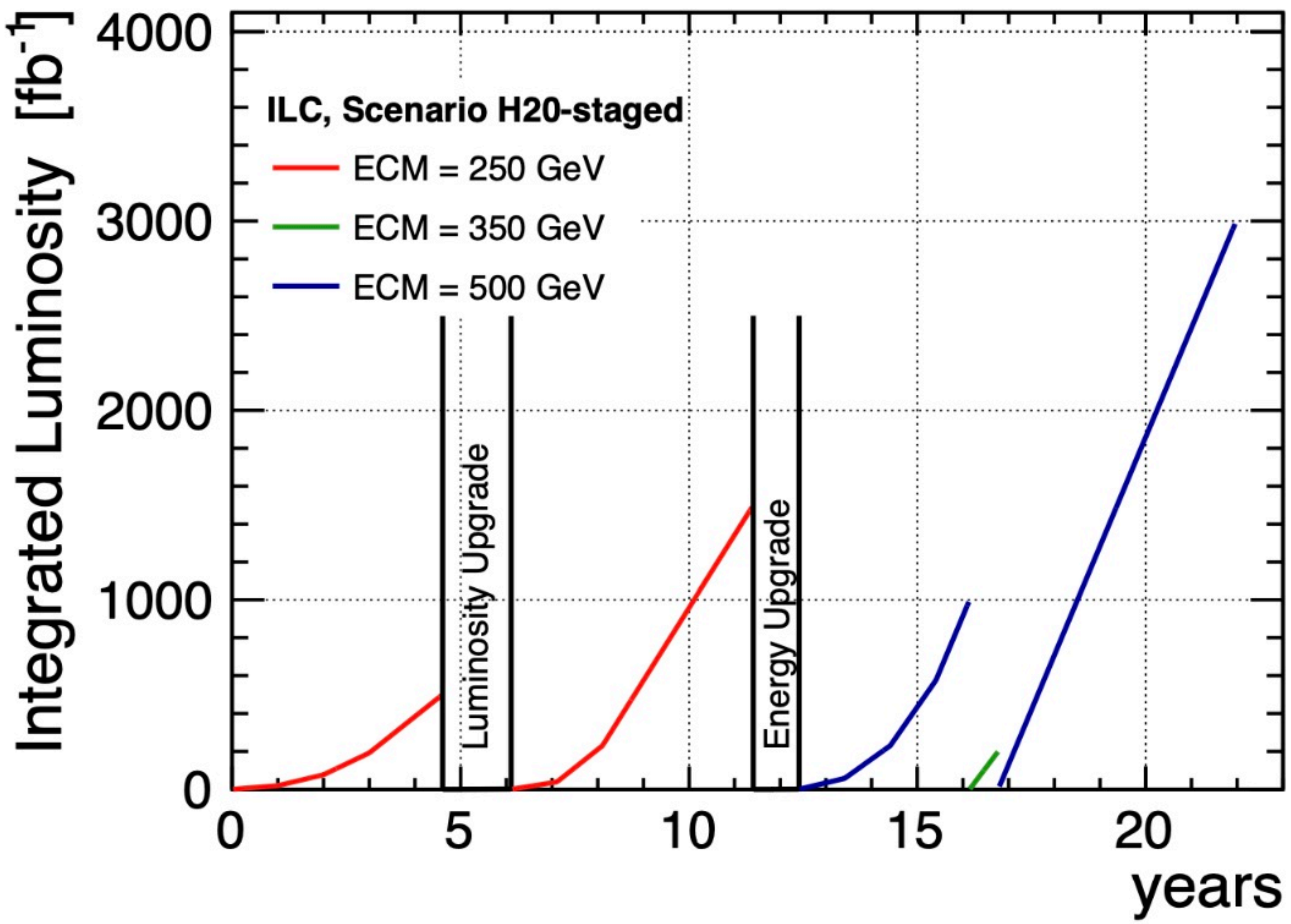


(unpolarized case)



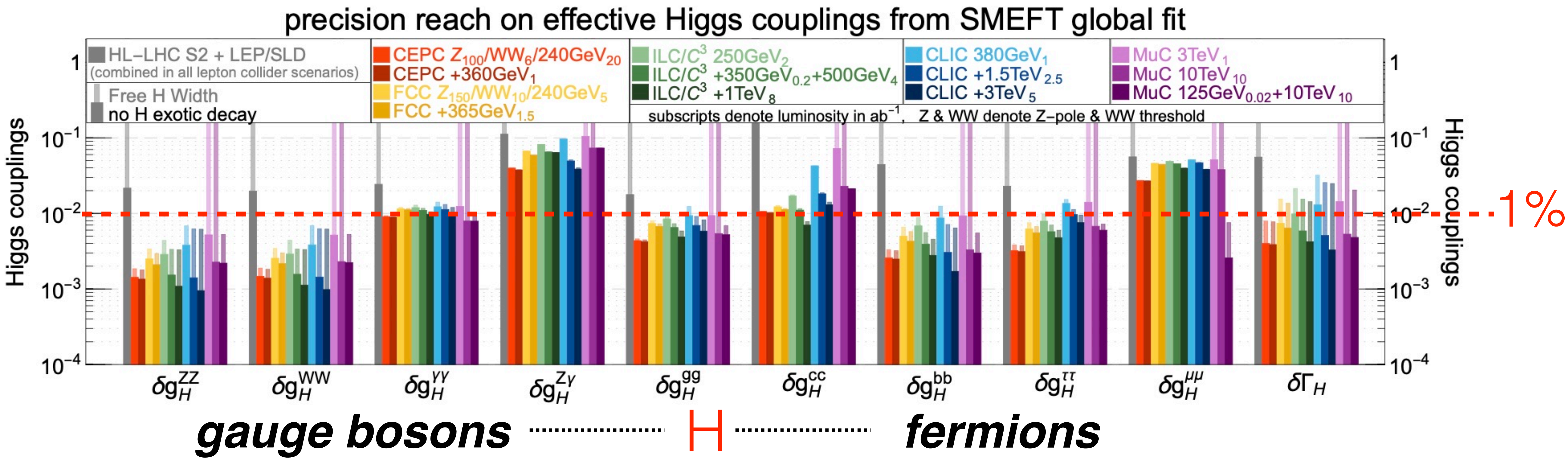
- two apparent important thresholds: √s ~ 250 GeV for ZH, ~500-600 GeV for ZHH and ttH
- + another threshold for t t-bar, important for Higgs physics as well

ILC running scenario for benchmark study



	91 GeV	250 GeV	350 GeV	500 GeV	1000 GeV
$\int \mathcal{L}$ (ab^{-1})	0.1	2	0.2	4	8
duration (yr)	1.5	11	0.75	9	10
beam polarization (e^-/e^+; %)	80/30	80/30	80/30	80/30	80/20
(LL, LR, RL, RR) (%)	(10,40,40,10)	(5,45,45,5)	(5,68,22,5)	(10,40,40,10)	(10,40,40,10)
δ_{ISR} (%)	10.8	11.7	12.0	12.4	13.0
δ_{BS} (%)	0.16	2.6	1.9	4.5	10.5

Projections of Higgs coupling precisions



[Snowmass White Paper on Global SMEFT Fits, arXiv:2206.08326]

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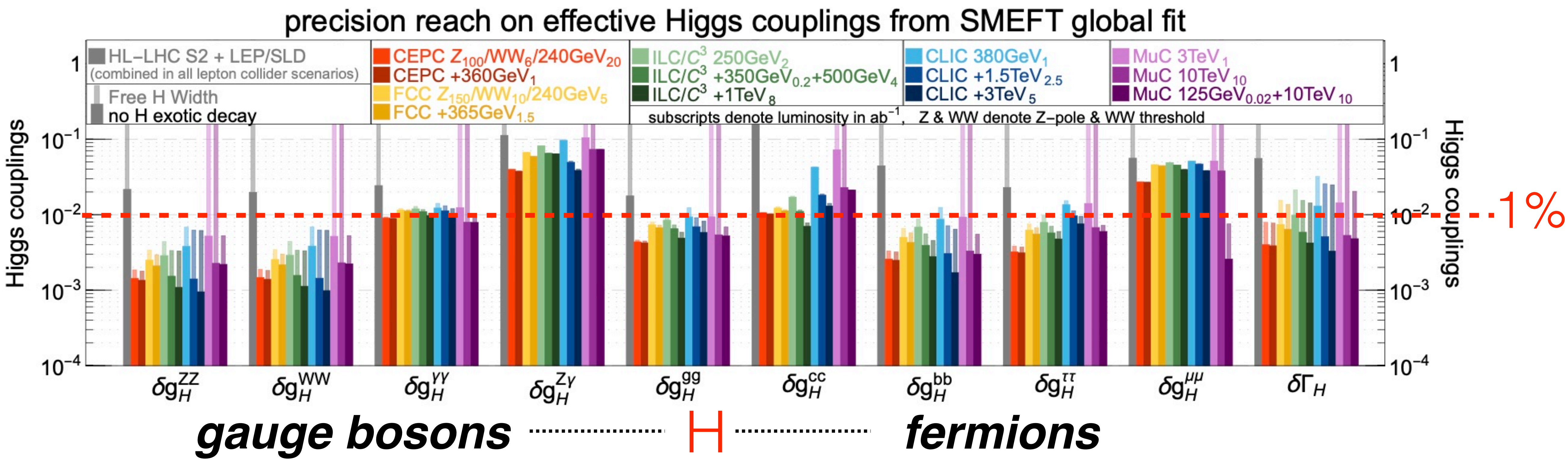
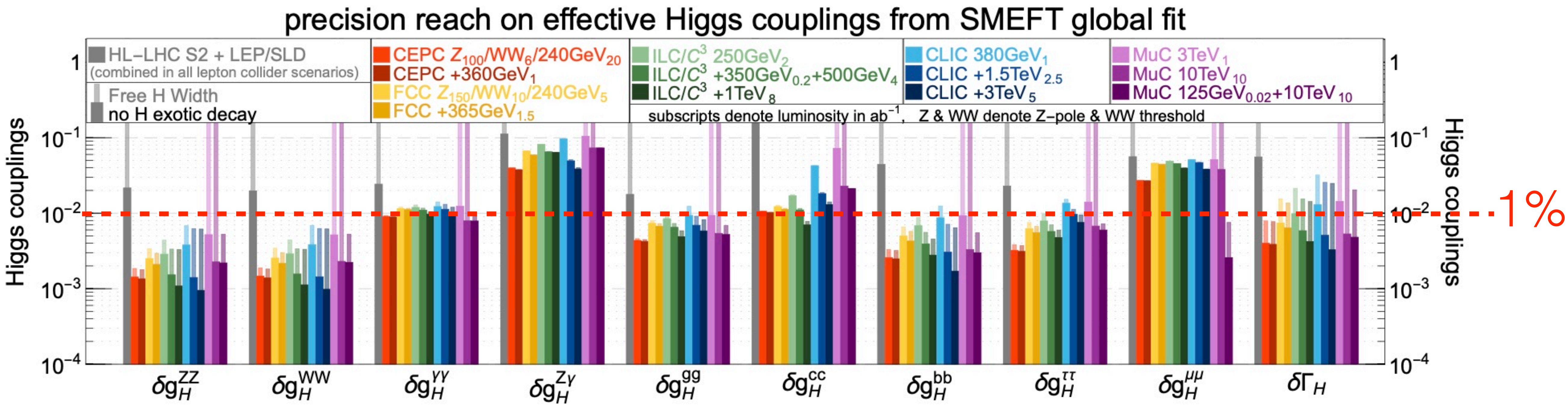


[Snowmass White Paper on Global SMEFT Fits, arXiv:2206.08326]

- 1% or below reachable by ILC as well as other Higgs factories
- no question on "which one *should* be realized", important is "which one *can*" given the preferred time and available resource

Projections of Higgs coupling precisions



gauge bosons ·················· H ·················· ***fermions***

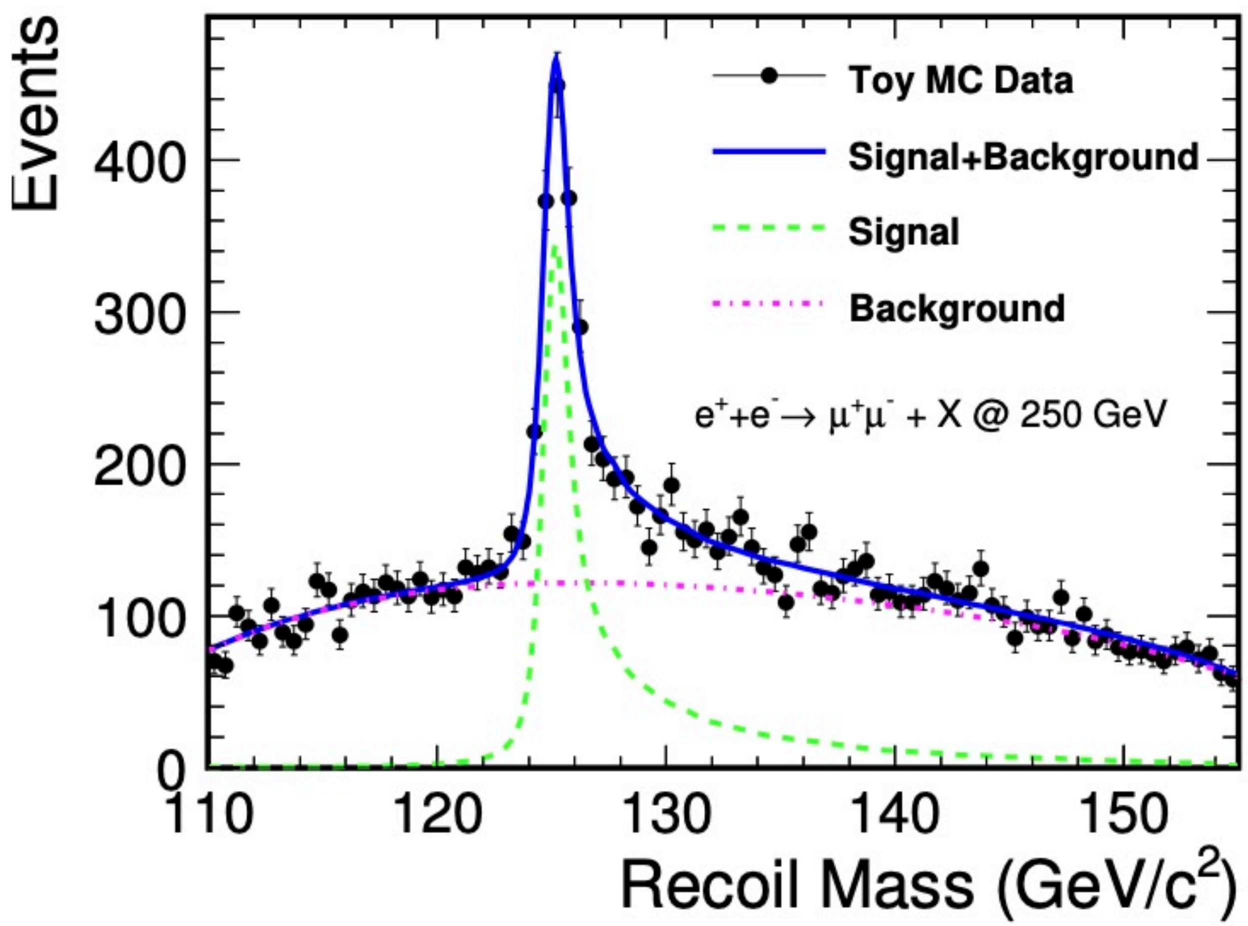
[Snowmass White Paper on Global SMEFT Fits, arXiv:2206.08326]

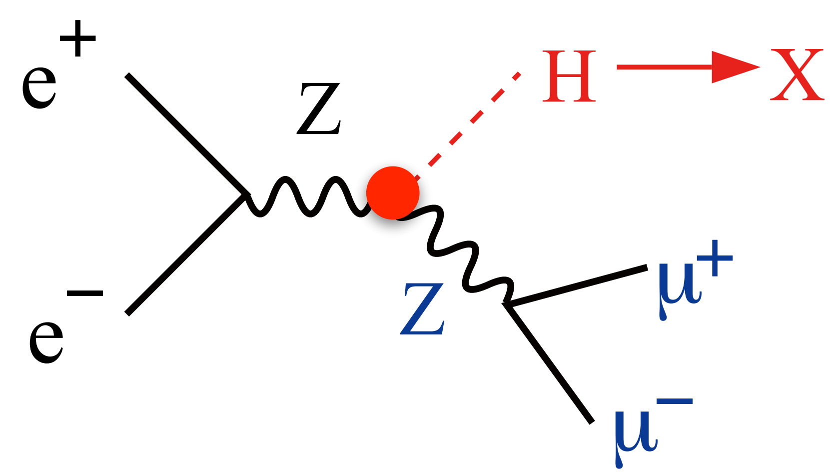
- 1% or below reachable by ILC as well as other Higgs factories
- no question on "which one *should* be realized", important is "which one *can*" given the preferred time and available resource

  - (ii) highlight a few key measurements, elaborate what understanding of Higgs properties is *qualitatively* advanced & how

(ii-1) σ_{ZH}: what is the normalization of Higgs couplings?

☆ measure absolute *σ*, instead of *σ•BR*





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

[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

same technique searching for extra Higgs bosons

$\delta g^{HZZ} \sim 0.3\%$

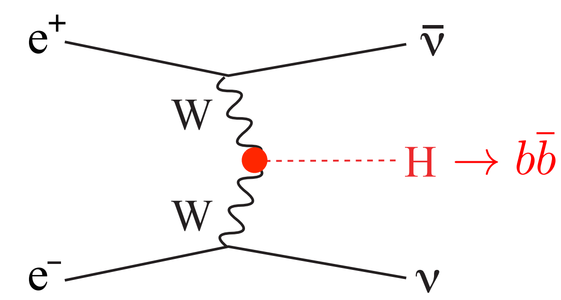
(ii-2) H total width: model-independent determination?

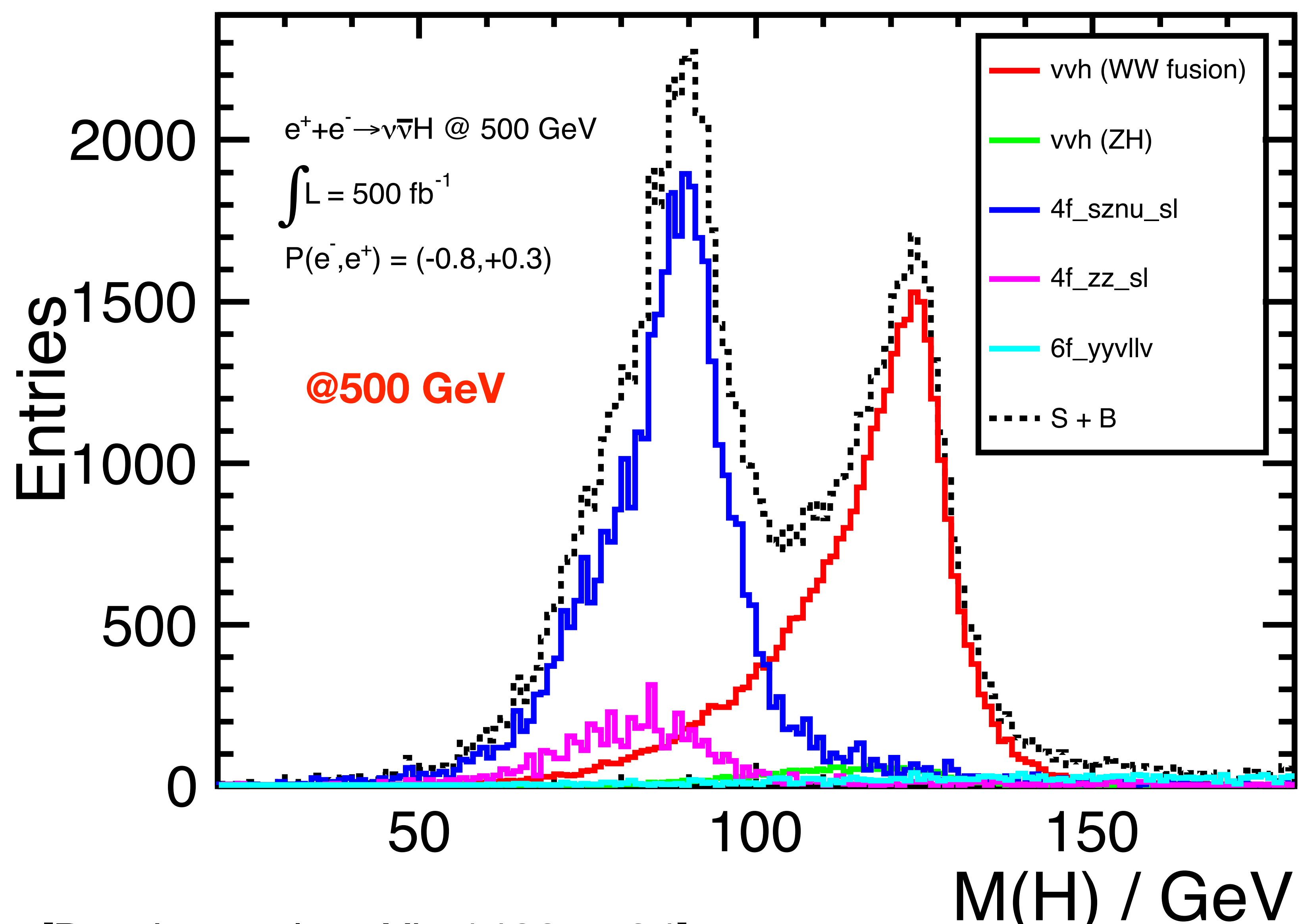
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>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



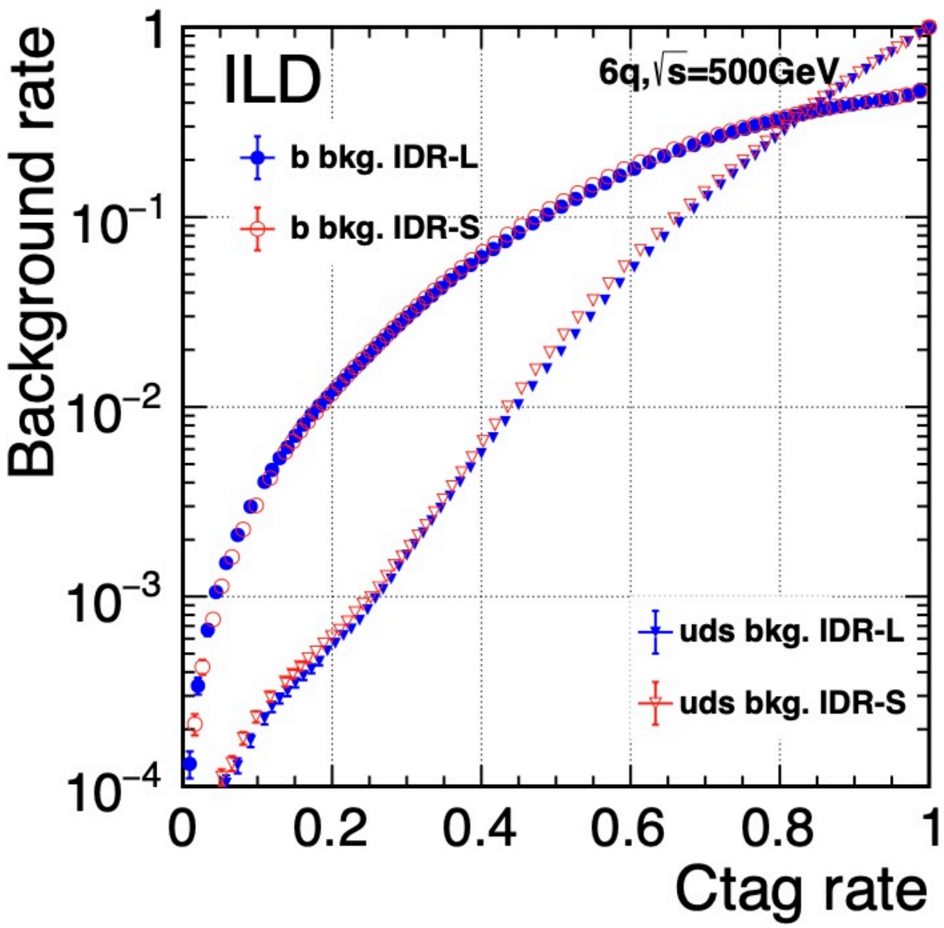


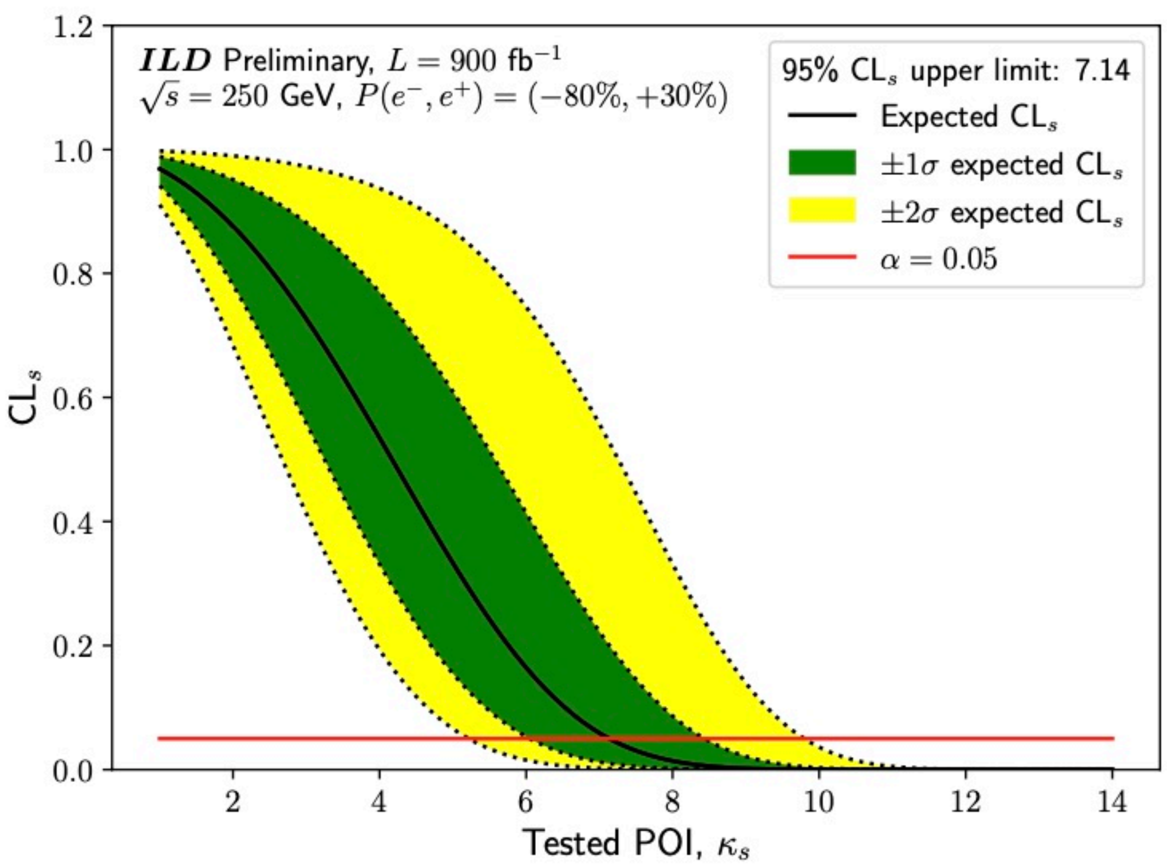
$\delta\Gamma_H \sim 1\%$

[Duerig, et al., arXiv:1403.7734]

(ii-3) H—>cc/ss: discover Yukawa coupling with 2nd gen. quarks?

- clean environment at e+e- offers lower QCD bkg, allows
- excellent favor tagging performance for b- and c-quark
- s-quark tagging is now also being pursued





c-Yukawa ~ 1%

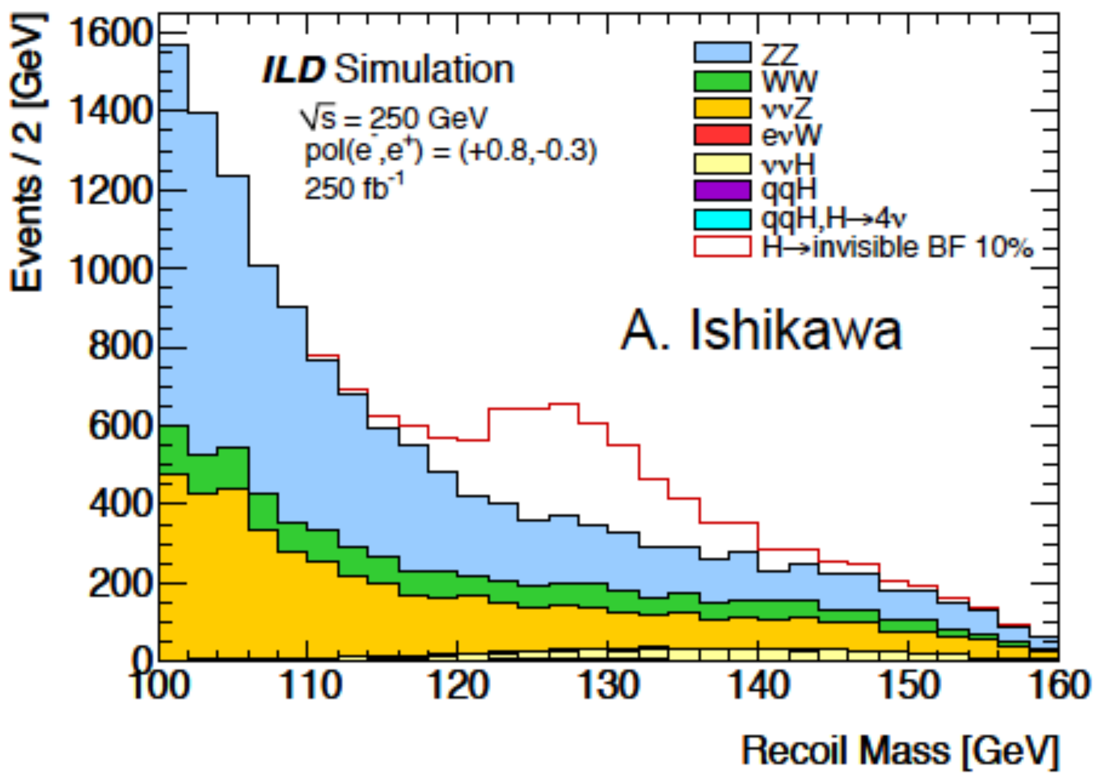
s-Yukawa < 7xSM reachable at ILC250

[Ono, et. al, Euro. Phys. J. C73, 2343; F.Mueller, PhD thesis (DESY); M.Basso, 2203.07535]

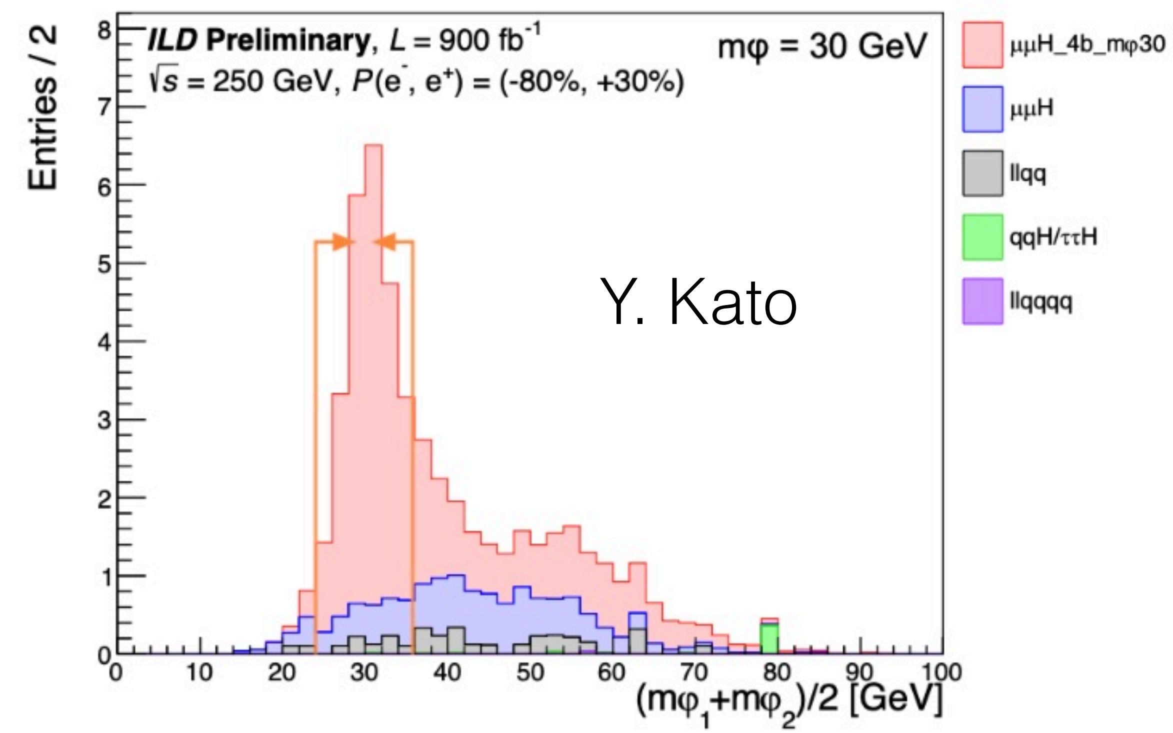
getting outdated quickly with the ML

(ii-4) exotic decays: access the hidden sectors?

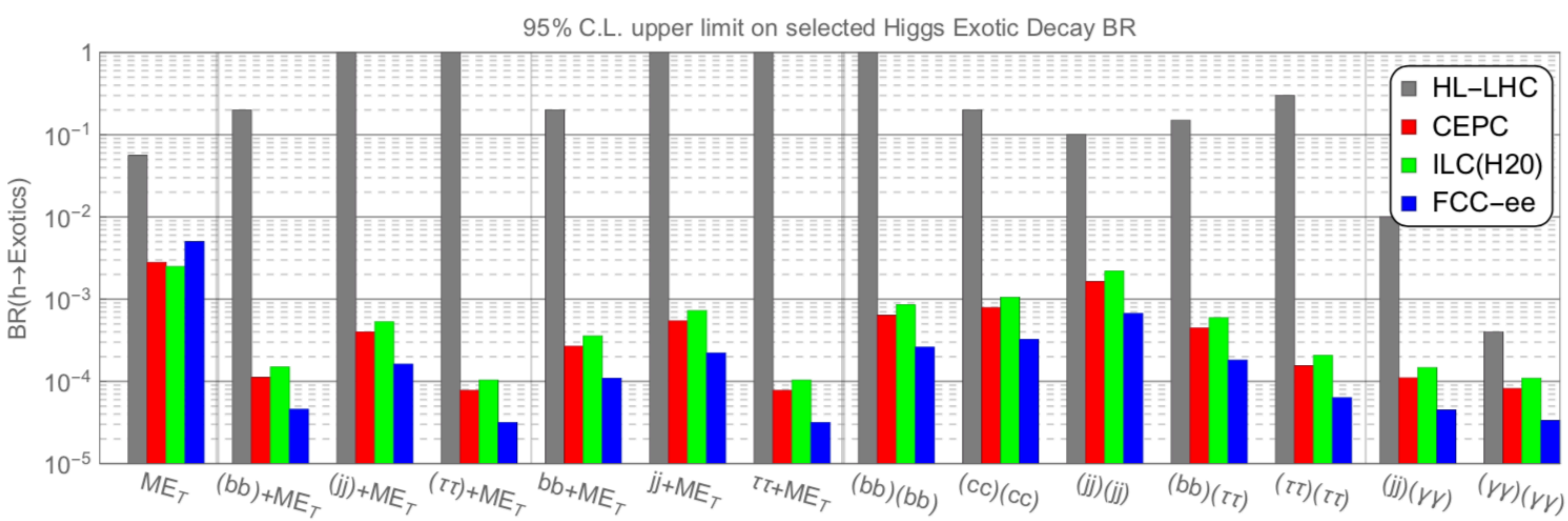
H—>Invisible



H—>ϕϕ—>4-b



a few exotic decays of BR~0.1% confirmed by full simulation

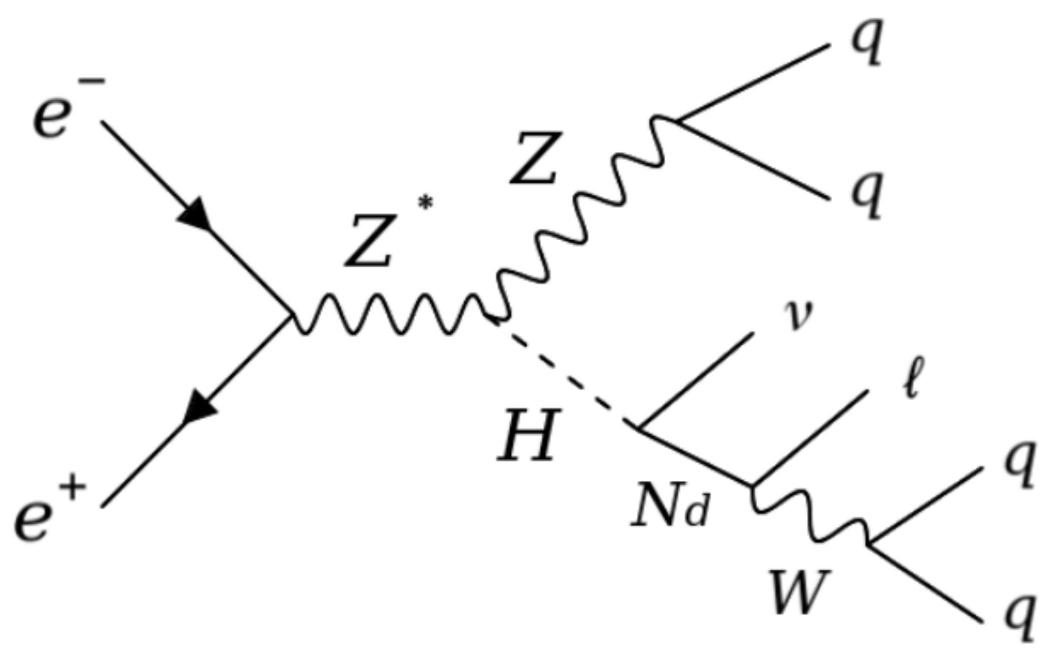


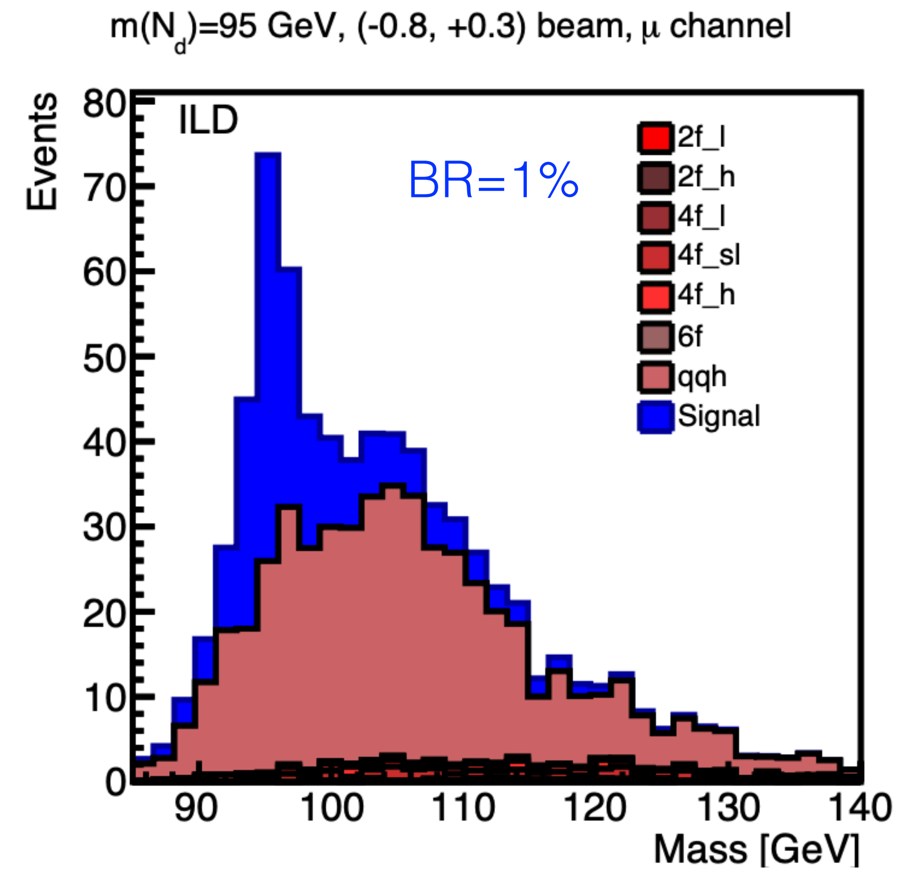
[Liu, Wang, Zhang, arXiv:1612.09284]

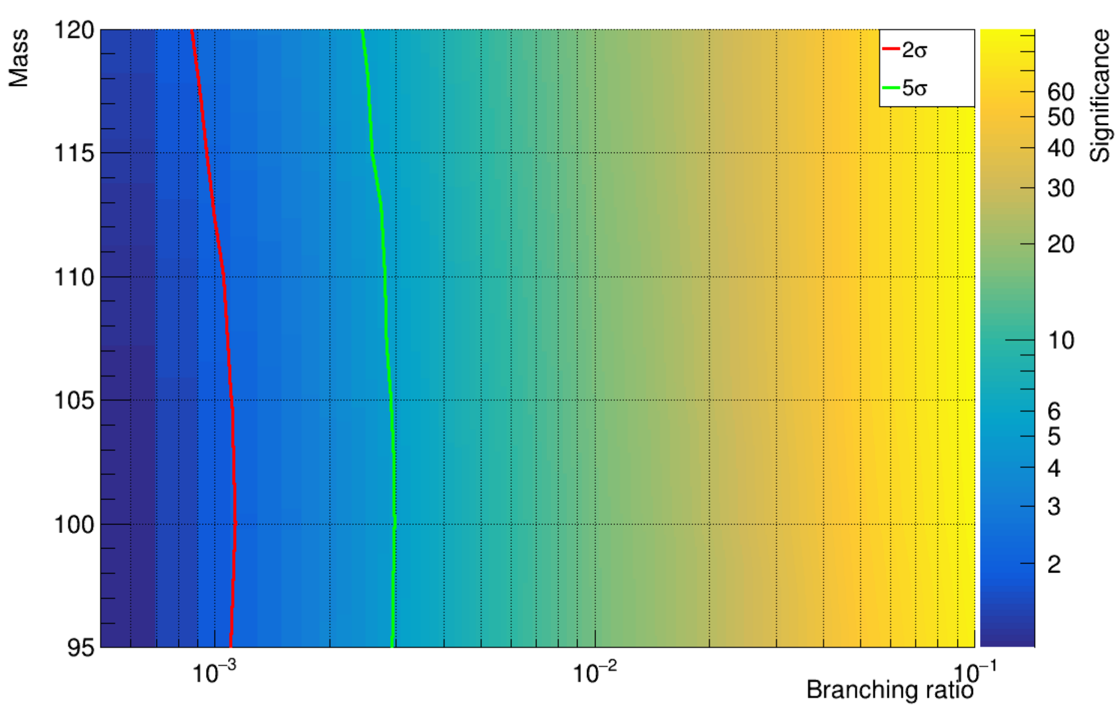
(ii-4) exotic decays to Heavy Neutral Leptons

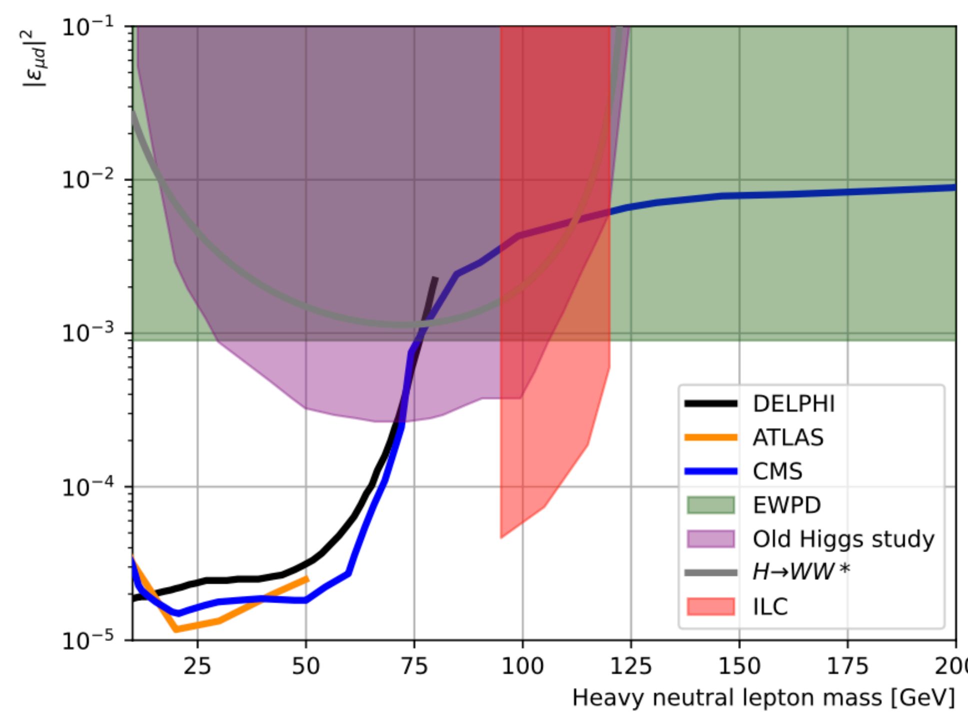
New analysis focused on H—>HNL with mass [m_Z, m_H]

[Thor, et al., arXiv:2309.11254]



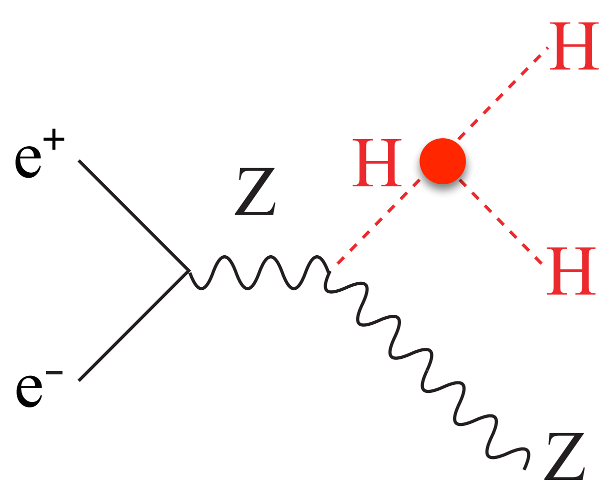


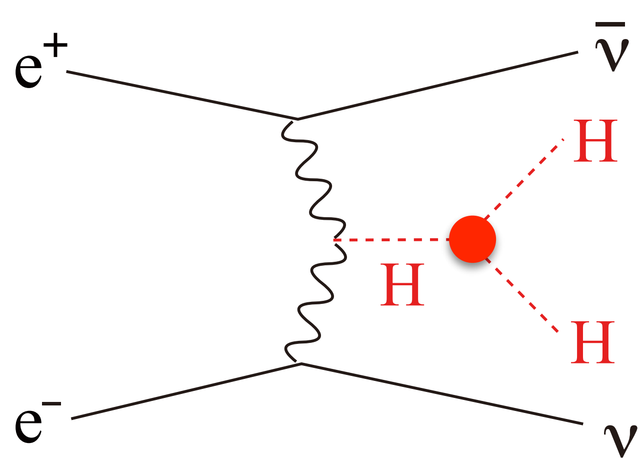




(ii-5) λ_{HHH}: discover the Higgs self-coupling?

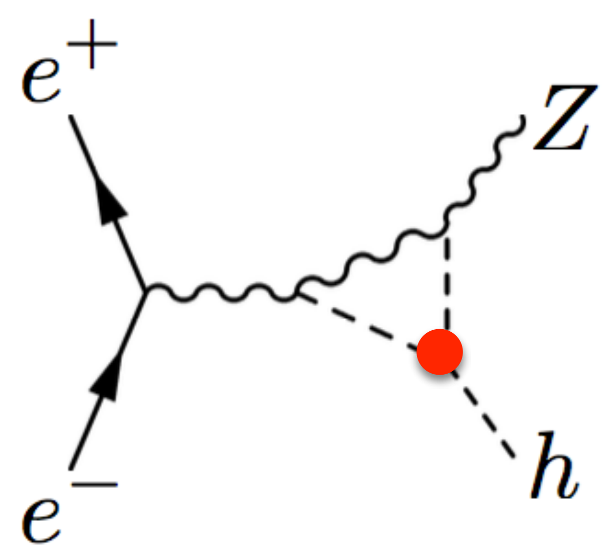
$\sqrt{s} \gtrsim 500$ GeV

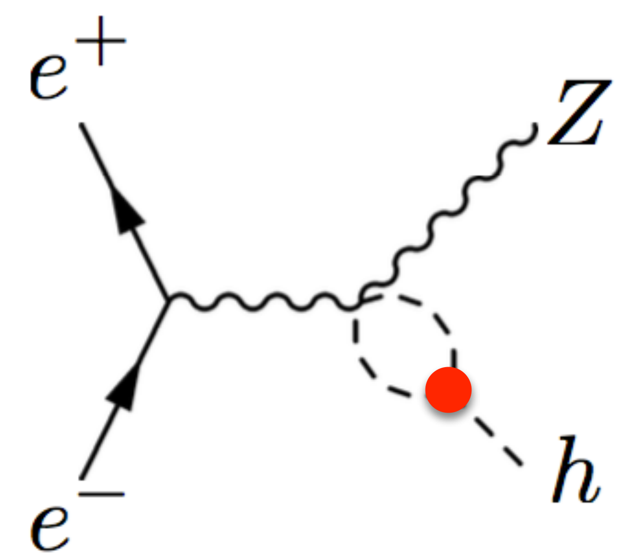




$\sigma_{HH} \sim O(0.1)$ fb

$\sqrt{s} \gtrsim 240\text{–}250$ GeV

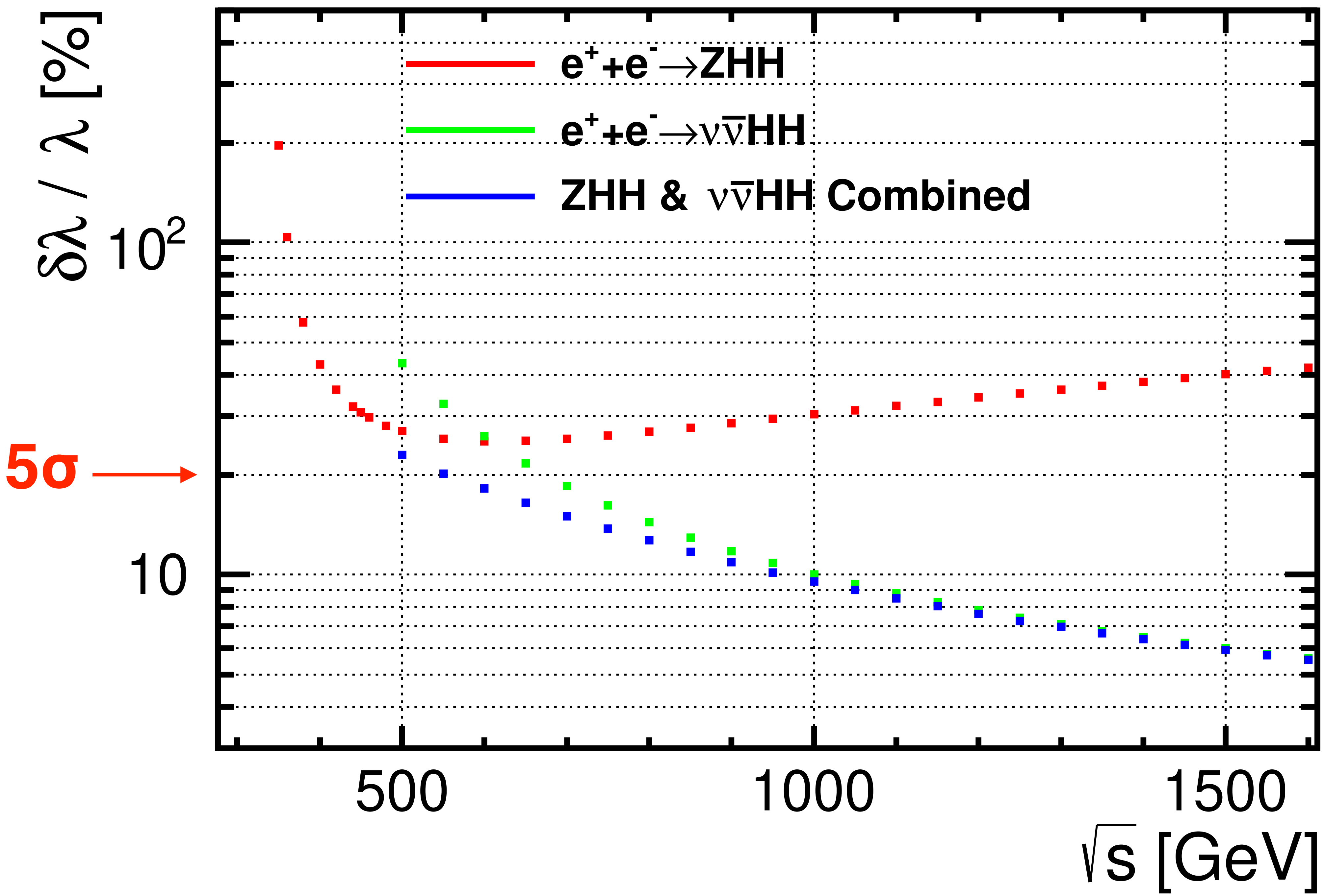




$\delta\sigma_{ZH} \sim O(1\%)$

(ii-5) λ_{HHH}: discover the Higgs self-coupling?

[preview; more details in my talk tomorrow]



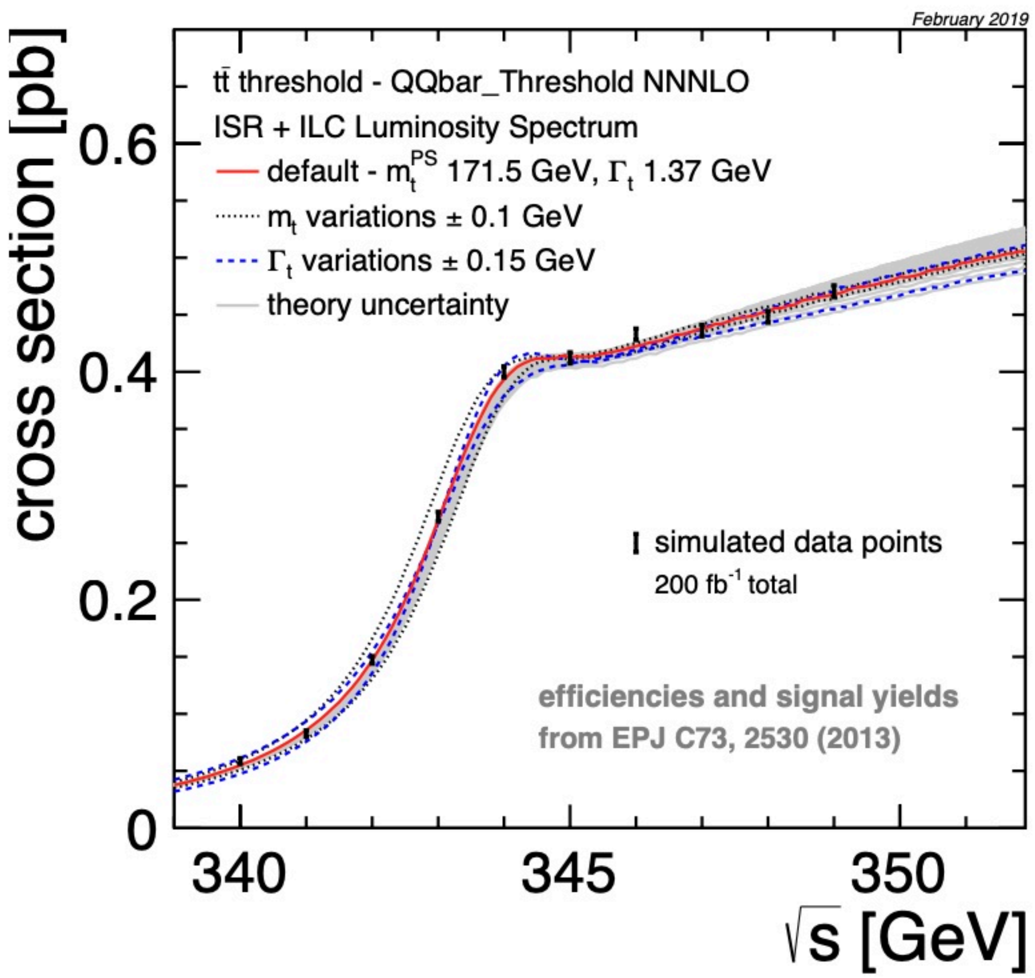
Discovery can be guaranteed

ILC500: 23%

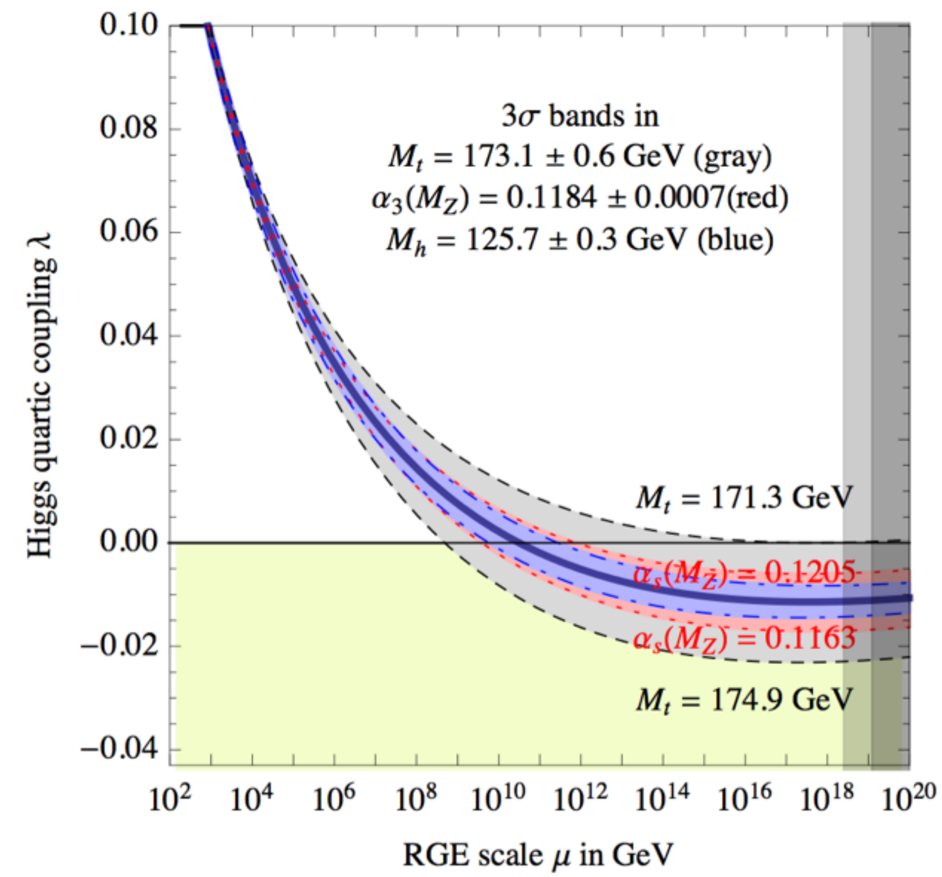
ILC550: 20%

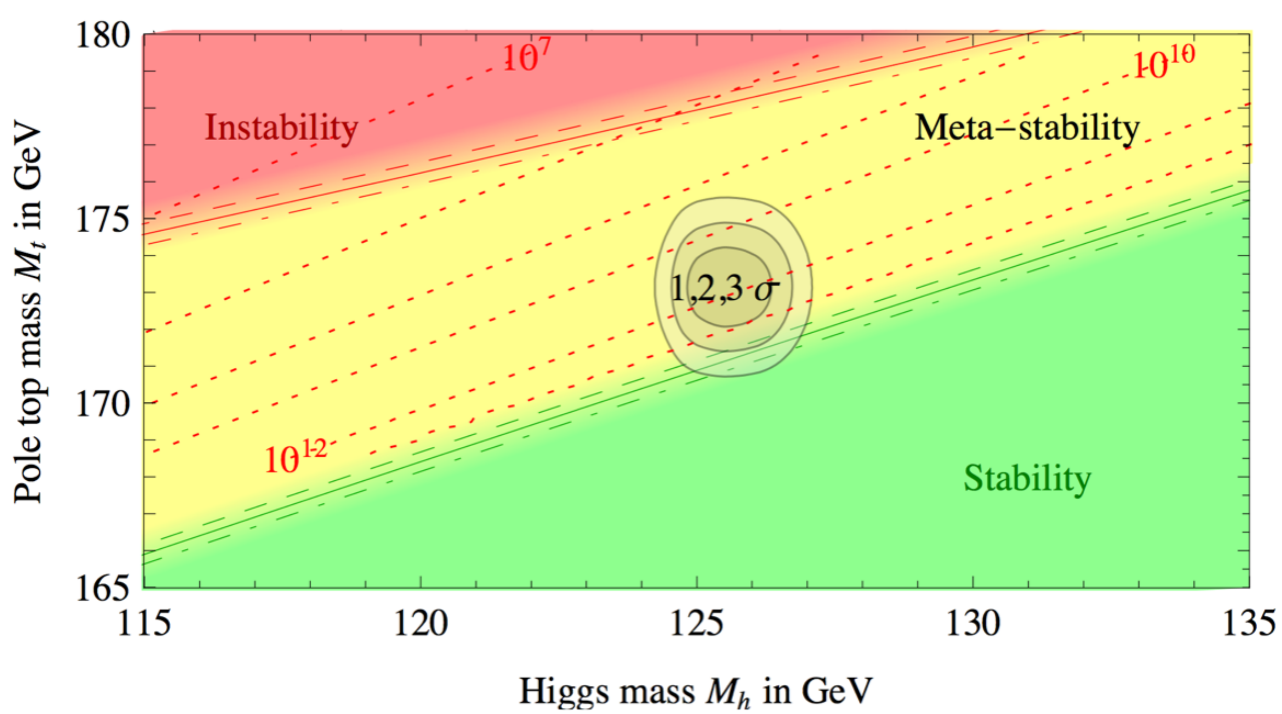
ILC600: 18%

(ii-6) m_t: which vacuum are living in?



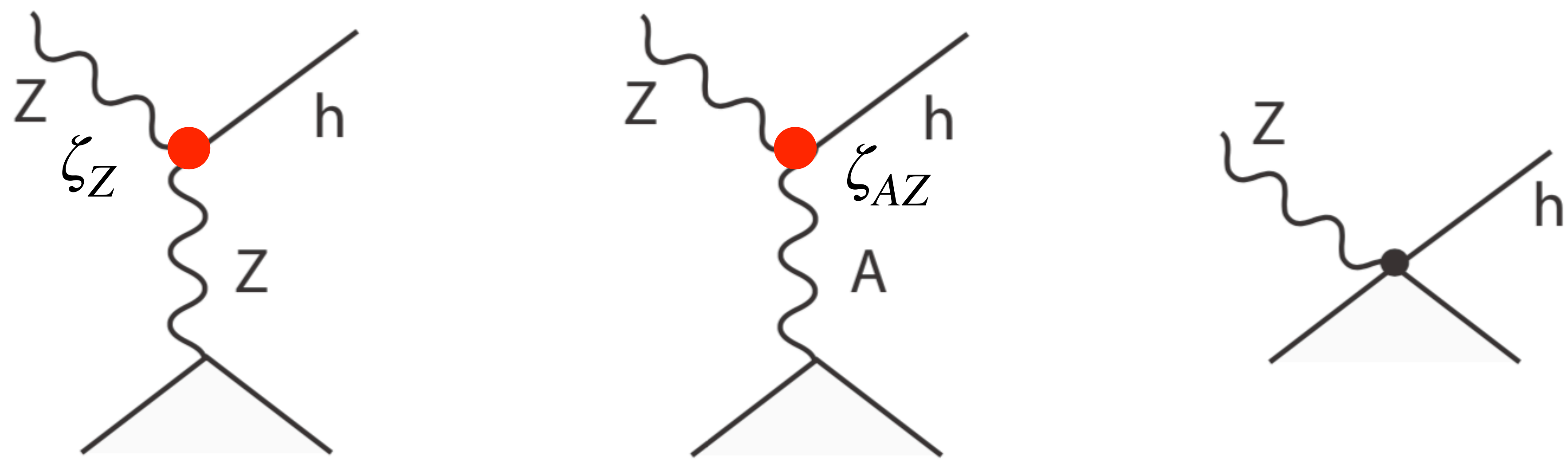
Degrassi et al, JHEP 1208 (2012) 098





- e^+e^-: top-pair threshold scan, much lower theory error
- Δm_t(MS-bar) ~ 50 MeV (Δm_H=14MeV)

(ii-7) role of beam polarizations (e+e- -> Zh)



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)	$\frac{g}{\cos\theta_w}(-\sin^2\theta_w)$	$g\sin\theta_w$	$\frac{g}{\cos\theta_w}(c_{HE})$

- σ_{ZH} (for L or R) are qualitatively different observables
- sensitive to different couplings -> lift degeneracy

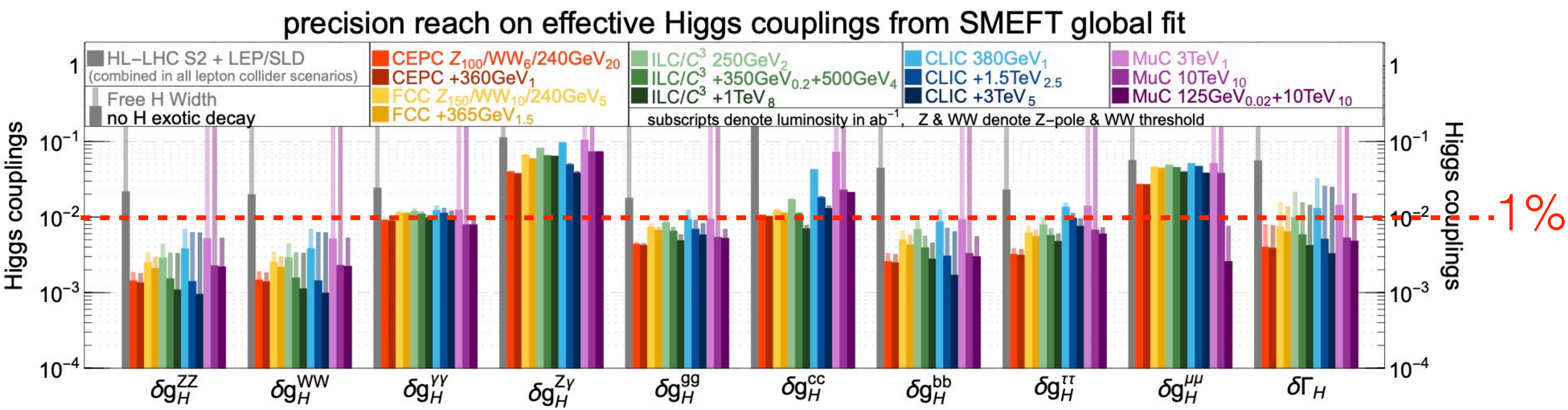
(iii) open questions

[welcome to check out 18 pages of questions… ILC input to Snowmass 2021, arXiv:2007.03650]

- By the end of ILC, what if we find everything is “aligned”? Would you consider it as the most striking discovery?

theory uncertainties

- Improving intrinsic theory uncertainties is crucial for precision physics at future e+e-



[arXiv:2206.08326]

theory uncertainties

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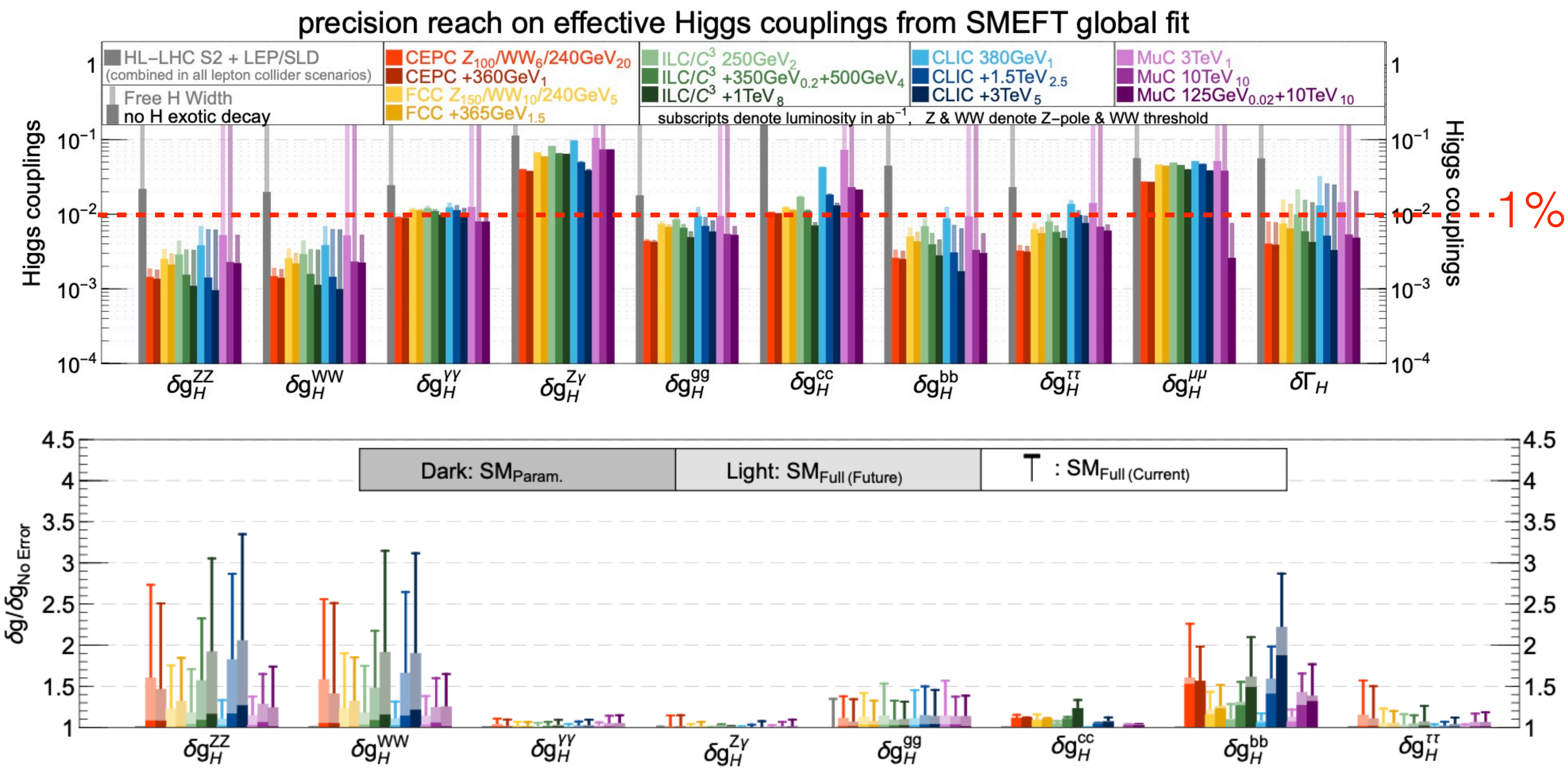
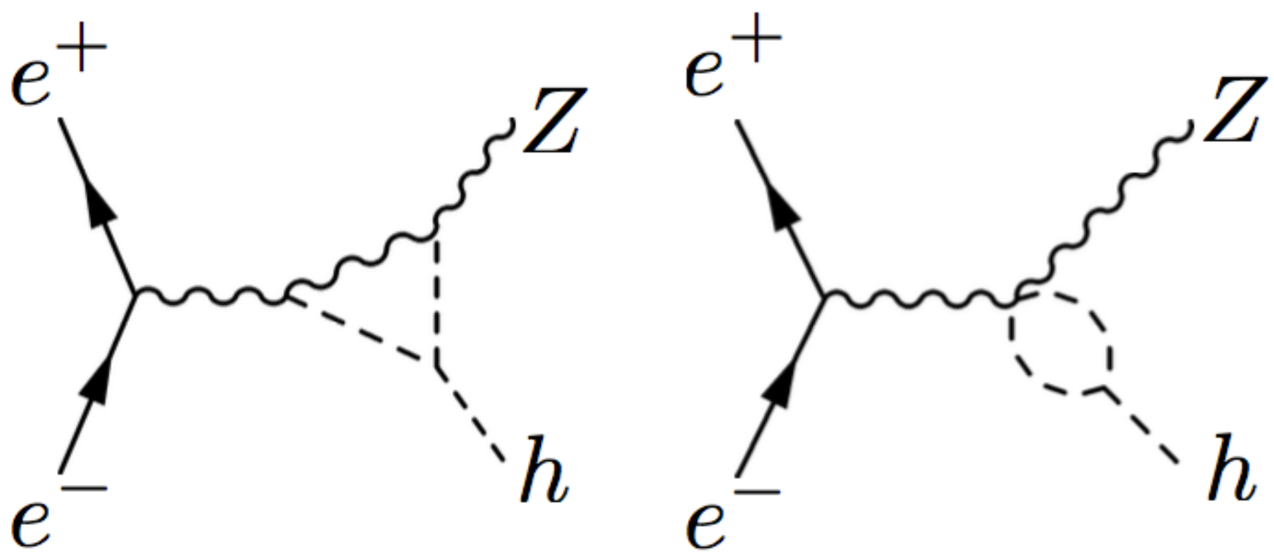


[arXiv:2206.08326]

λ_{HHH} by single-Higgs process: just a test?



McCullough, arXiv:1312.3322

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

- if only δh is deviated —> δh ~ 28%
- if both δz and δh deviated —> δh ~ 90%
- δσ could receive contributions from many other sources

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

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

- **what if we include other NLO effects as well, e.g. top?**

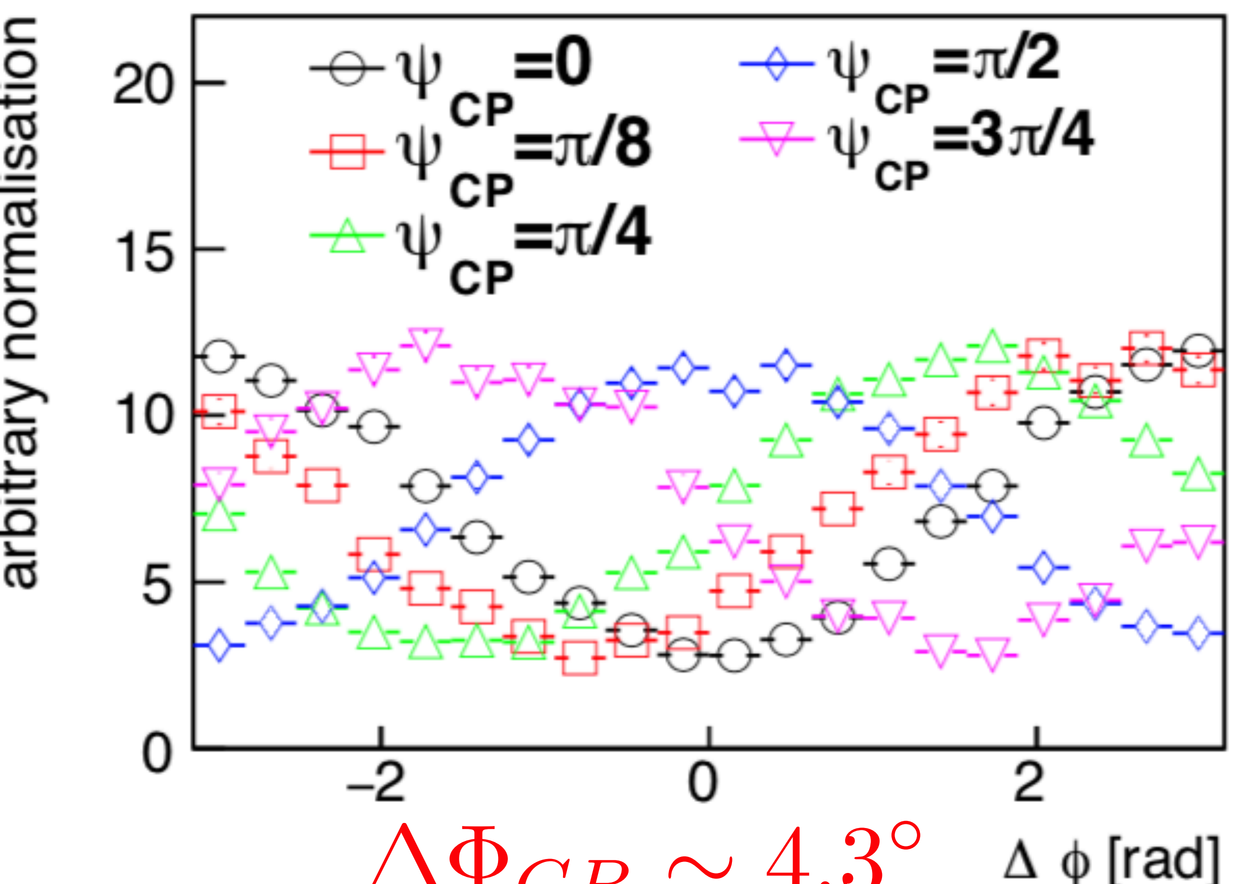
Higgs CP: synergy between Hff & HVV?

[talk by N. Vukasinovic]

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

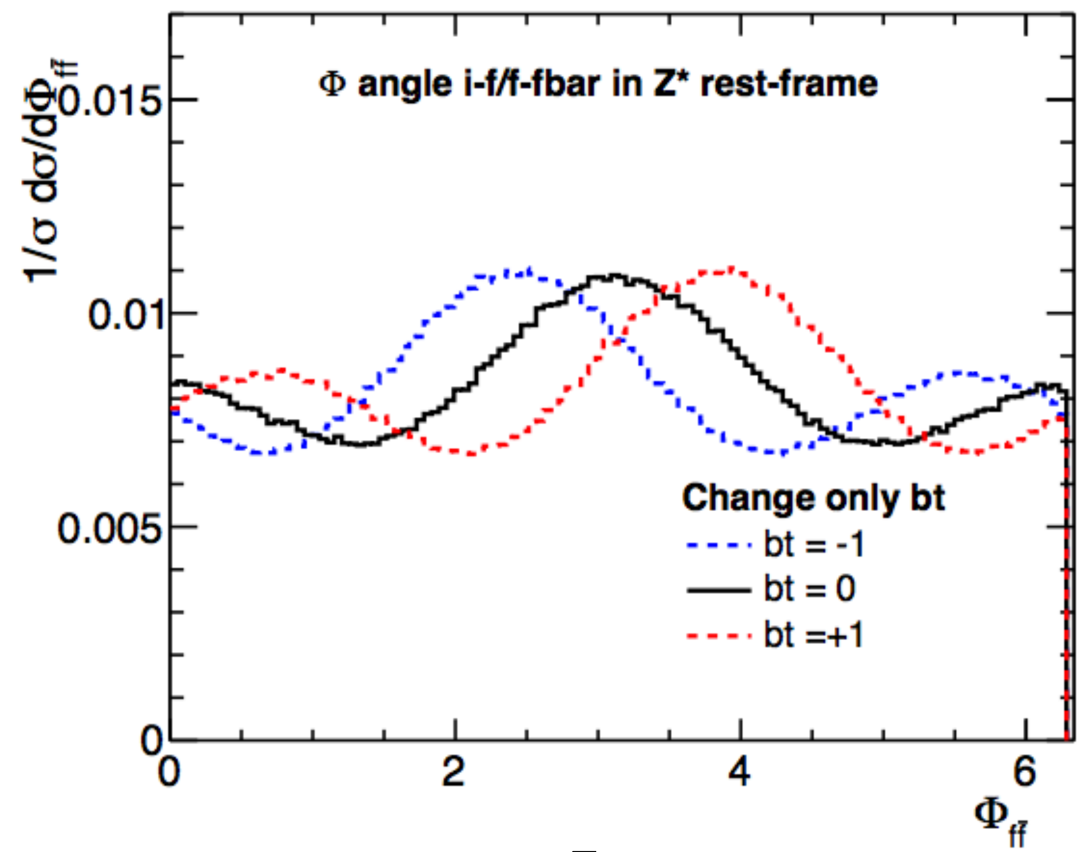
$$L_{hZZ} = M_Z^2(\frac{1}{v} + \frac{a}{\Lambda}) h Z_\mu Z^\mu + \frac{b}{2\Lambda} h Z_{\mu\nu} Z^{\mu\nu} + \frac{\tilde{b}}{2\Lambda} h Z_{\mu\nu} \tilde{Z}_{\mu\nu}$$

(CP-odd)



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

[Jeans et al, arXiv:1804.01241]



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

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

[Ogawa et al, arXiv:1712.09772]

CP-violating ZZh Coupling at e^+e^- Linear Colliders

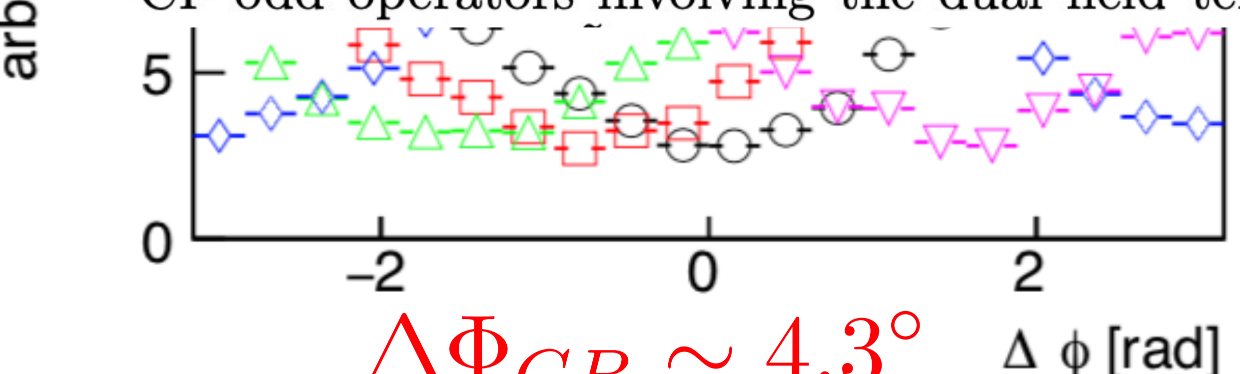
[Phys.Rev.D63:096007,2001]

[talk by N. Vukasinovic]

T. Han* and J. Jiang†

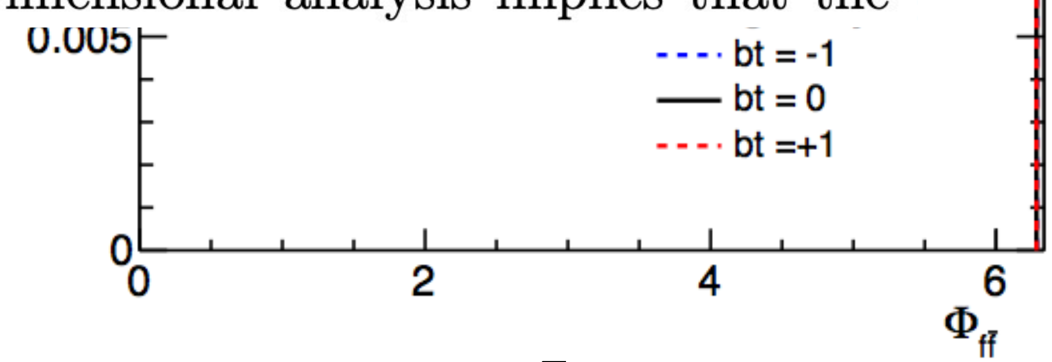
$$\Gamma^{\mu\nu}(k_1, k_2) = i\frac{2}{v}\, h\, [a\, M_Z^2 g^{\mu\nu} + b\,(k_1^\mu k_2^\nu - k_1 \cdot k_2 g^{\mu\nu}) + \tilde{b}\, \epsilon^{\mu\nu\rho\sigma} k_{1\rho} k_{2\sigma}], \quad (1)$$

where $v = (\sqrt{2}G_F)^{-1/2}$ is the vacuum expectation value of the Higgs field, and the Z boson four-momenta are both incoming, as depicted in Fig. [1]. The a and b terms are CP-even and the $\tilde{b}$ term is CP-odd. Thus, the simultaneous existence of terms a (or b) and $\tilde{b}$ would indicate CP violation for the ZZh coupling [1–3]. We note that in the SM at tree level, $a = 1$ and $b = \tilde{b} = 0$. In supersymmetric theories with CP-violating soft SUSY breaking terms [4], these CP-violating interactions may be generated by loop diagrams. More generally, the parameters can be momentum-dependent form factors and of complex values to account for the dispersive $[\mathcal{R}e(\tilde{b})]$ and absorptive $[\mathcal{I}m(\tilde{b})]$ effects from radiative corrections. Alternatively, in terms of an effective Lagrangian, the b term can be from gauge invariant dimension-6 operators [5], and the $\tilde{b}$ term can be constructed similarly with CP-odd operators involving the dual field tensors. Dimensional analysis implies that the



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

[Jeans et al, arXiv:1804.01241]



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

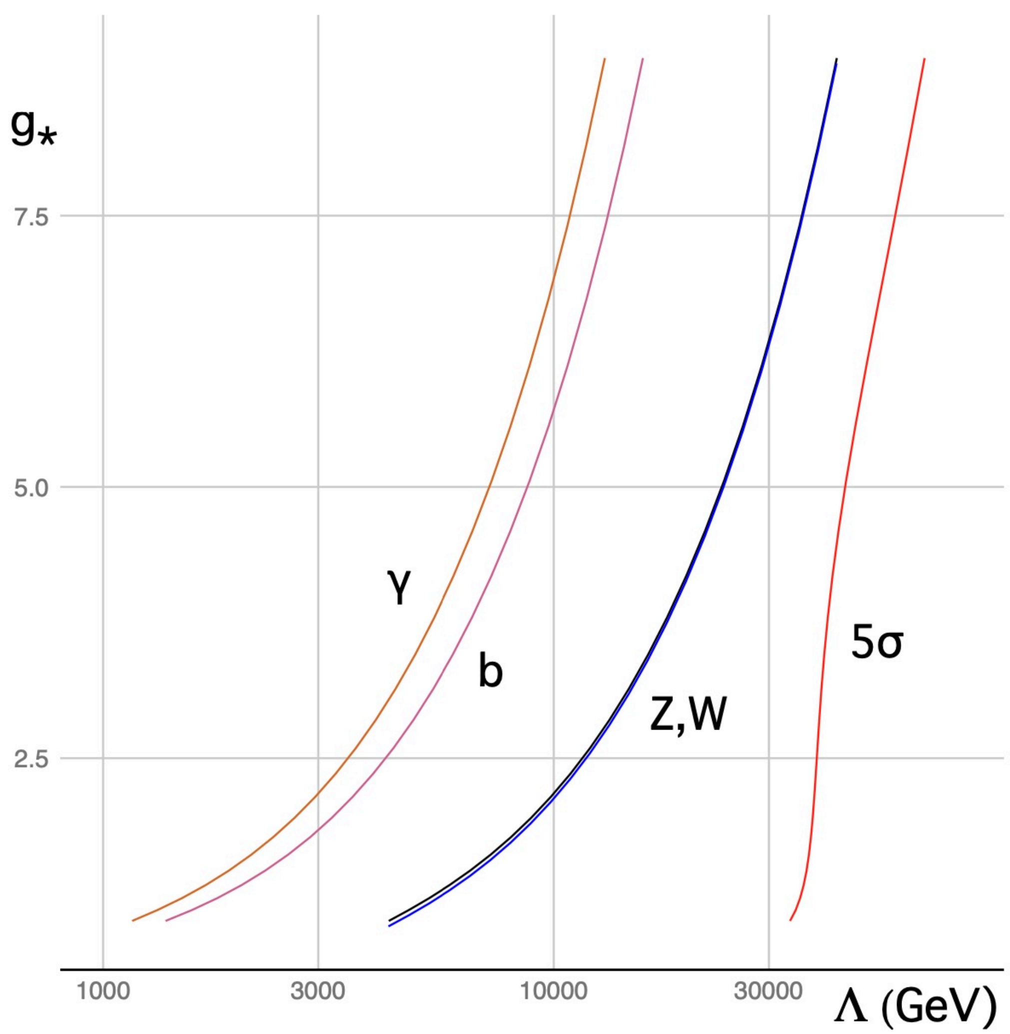
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

[Ogawa et al, arXiv:1712.09772]

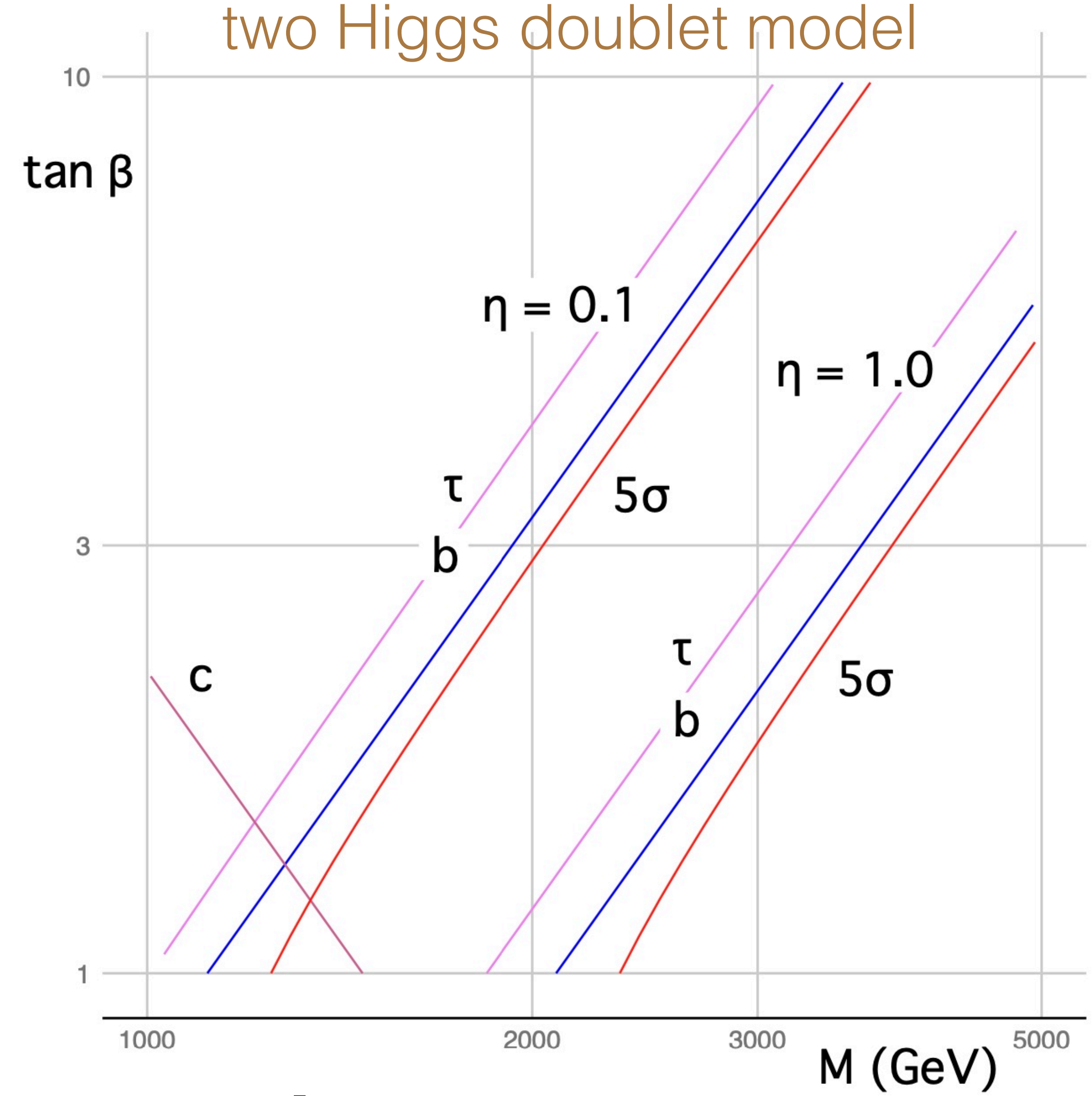
synergy between direct & indirect searches

- are the reach of scales by precision Higgs couplings already excluded by direct searches of new particles?

strongly interacting light Higgs



two Higgs doublet model

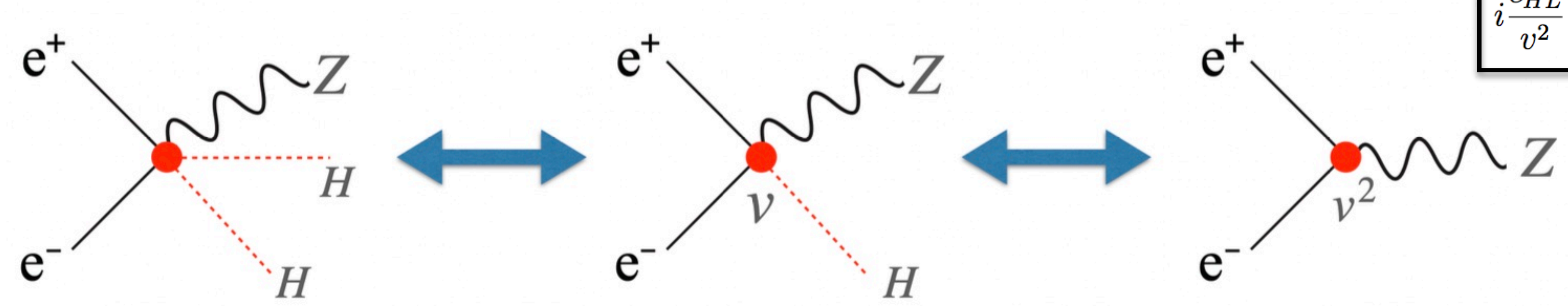


[Peskin, arXiv:2209.03303]

- continue exploring along this line is very important for realizing a Higgs factory

Global interpretation: Higgs is not alone

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



[Snowmass EF04 Report, arXiv:2209.08078]

- Have we explored all the important synergies between Higgs and EW/Top/2f, between e+e- and LHC/low-energy measurements, which are naturally established by SMEFT?
- SMEFT is now the standard framework for Higgs coupling determination, but we know its limitations, what would be the alternative strategy?

summary

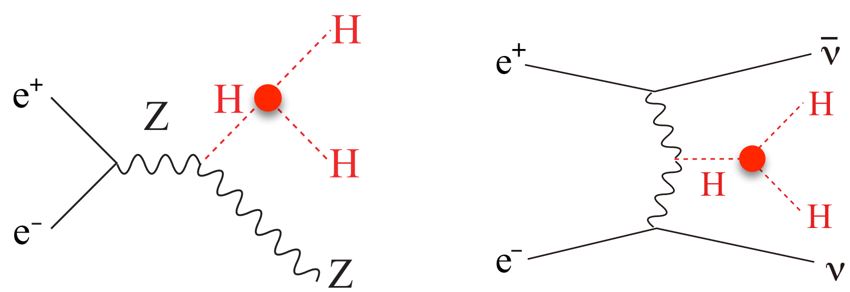
- ILC as a future Higgs factory can lead us to a new discovery path, advancing our understanding of the mysteries around the Higgs sector
- there are still a lot of open questions, please join and help

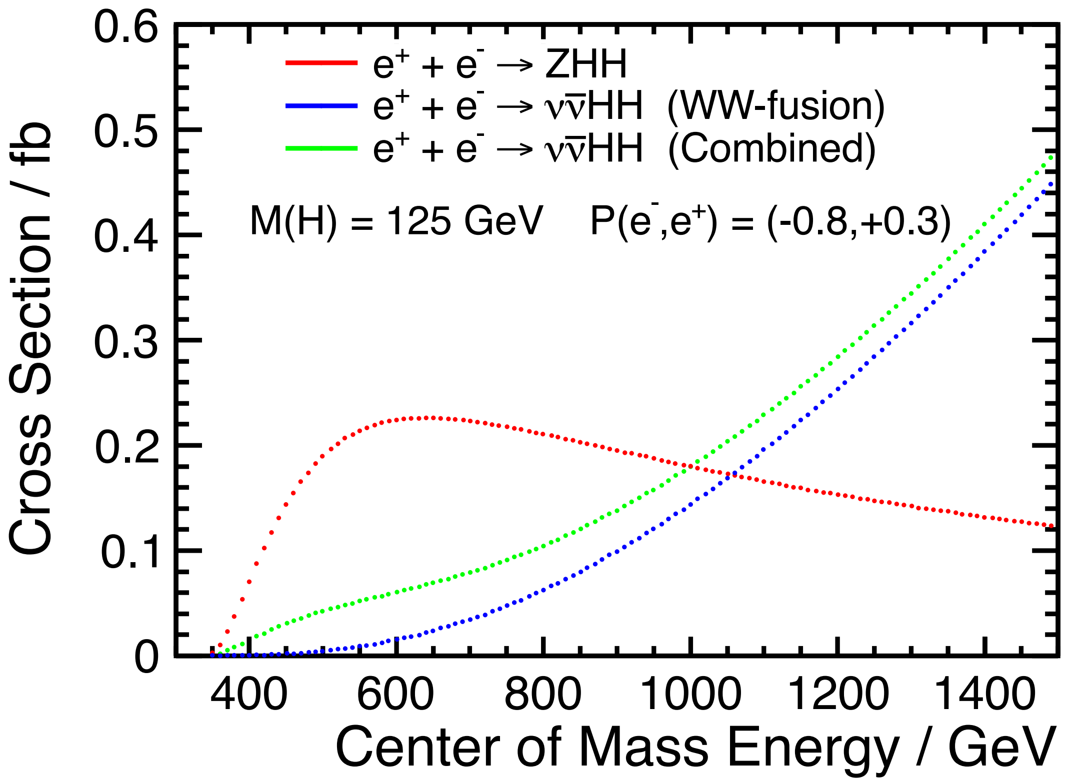
get engaged in ILC physics studies

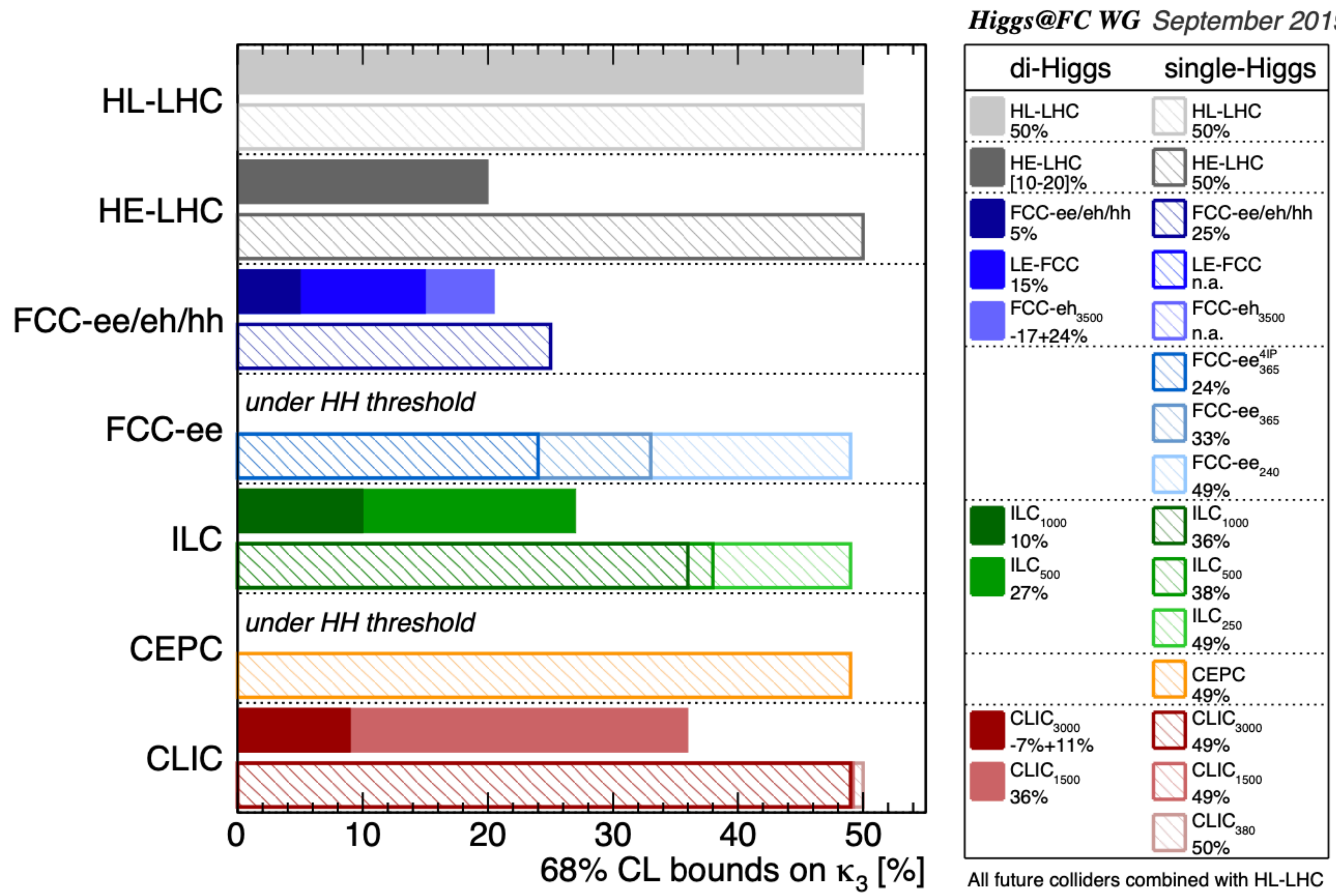
- IDT-WG3 Physics Group: monthly open meeting
- ILC-Japan Physics Group: general seminar / 2-3 months
- ECFA Study on Higgs / EW / Top factories

backup

(ii-5) λ_{HHH}: discover the Higgs self-coupling?



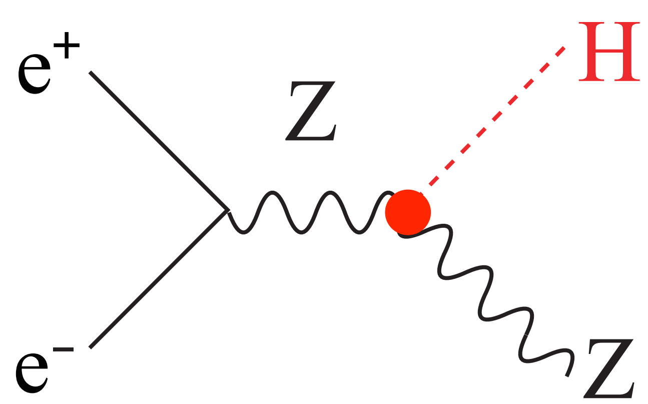




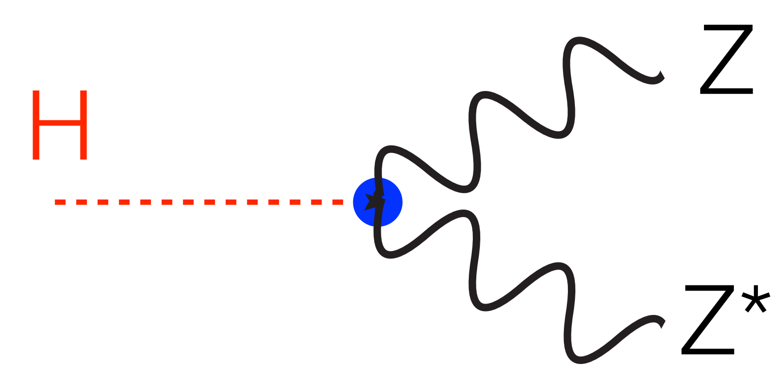
(ESU 2020 Physics Briefing Book, arXiv:1910.11775)

one question in kappa formalism:

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



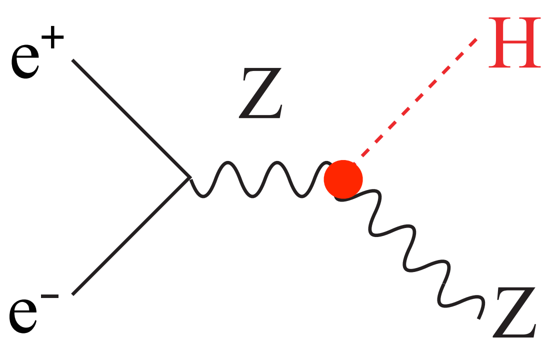
$\propto$ κ_Z^2 ? $\propto$

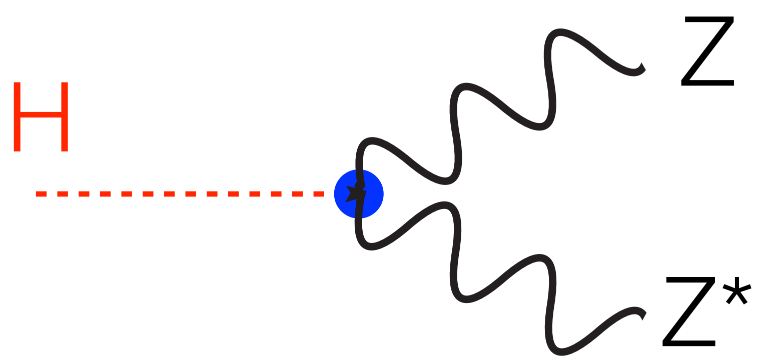


BSM territory: can deviations be represented by single κ_Z?

the answer is model dependent

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





$$\sigma(e^+e^- \to Zh) = (SM)\cdot (1+2\eta_Z+(5.5)\zeta_Z) \neq \Gamma(h\to ZZ^*) = (SM)\cdot (1+2\eta_Z-(0.50)\zeta_Z)$$

- BSM can induce new Lorentz structures in hZZ
- need a better, more theoretical sound framework

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

√s=250 GeV

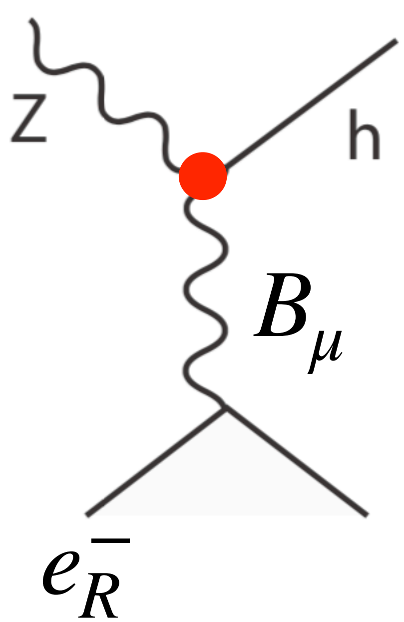
$$\delta\sigma_L = -c_H + 7.7(8c_{WW}) + \ldots$$

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

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 $\frac{m_Z^2}{s}$

(iii-4) role of beam polarizations (overall effects)

ILC250: 2 ab^{-1} FCCee240: 5 ab^{-1}

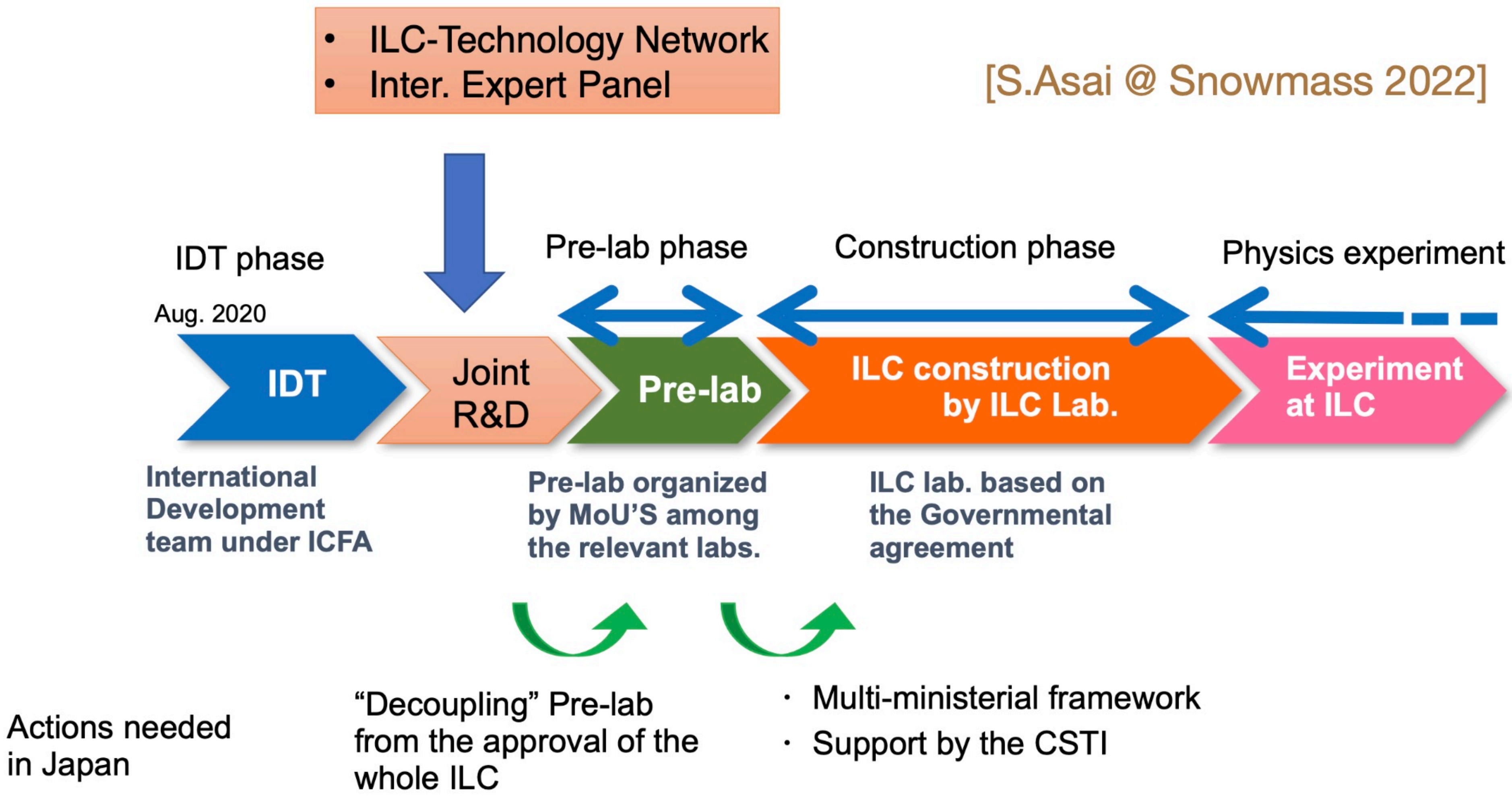
coupling	2/ab-250 pol.	+4/ab-500 pol.	5/ab-250 unpol.	+ 1.5/ab-350 unpol
HZZ	0.50	0.35	0.41	0.34
HWW	0.50	0.35	0.42	0.35
Hbb	0.99	0.59	0.72	0.62
$H\tau\tau$	1.1	0.75	0.81	0.71
Hgg	1.6	0.96	1.1	0.96
Hcc	1.8	1.2	1.2	1.1
$H\gamma\gamma$	1.1	1.0	1.0	1.0
$H\gamma Z$	9.1	6.6	9.5	8.1
$H\mu\mu$	4.0	3.8	3.8	3.7
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

- 250 GeV e+e-: power of 2 ab^{-1} polarized ≈ 5 ab^{-1} unpolarized

(arXiv:1903.01629)

ILC Project News

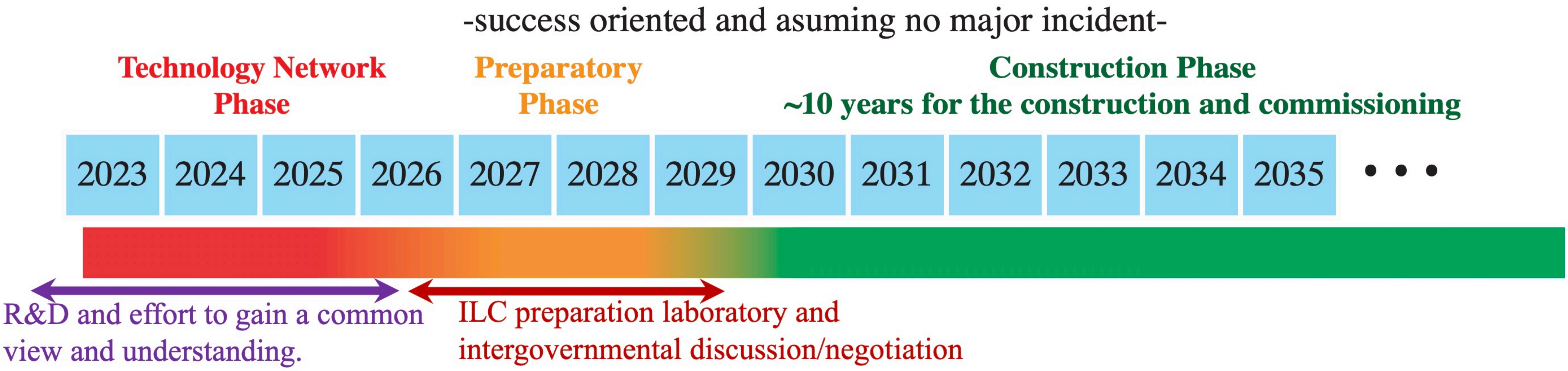
current plan



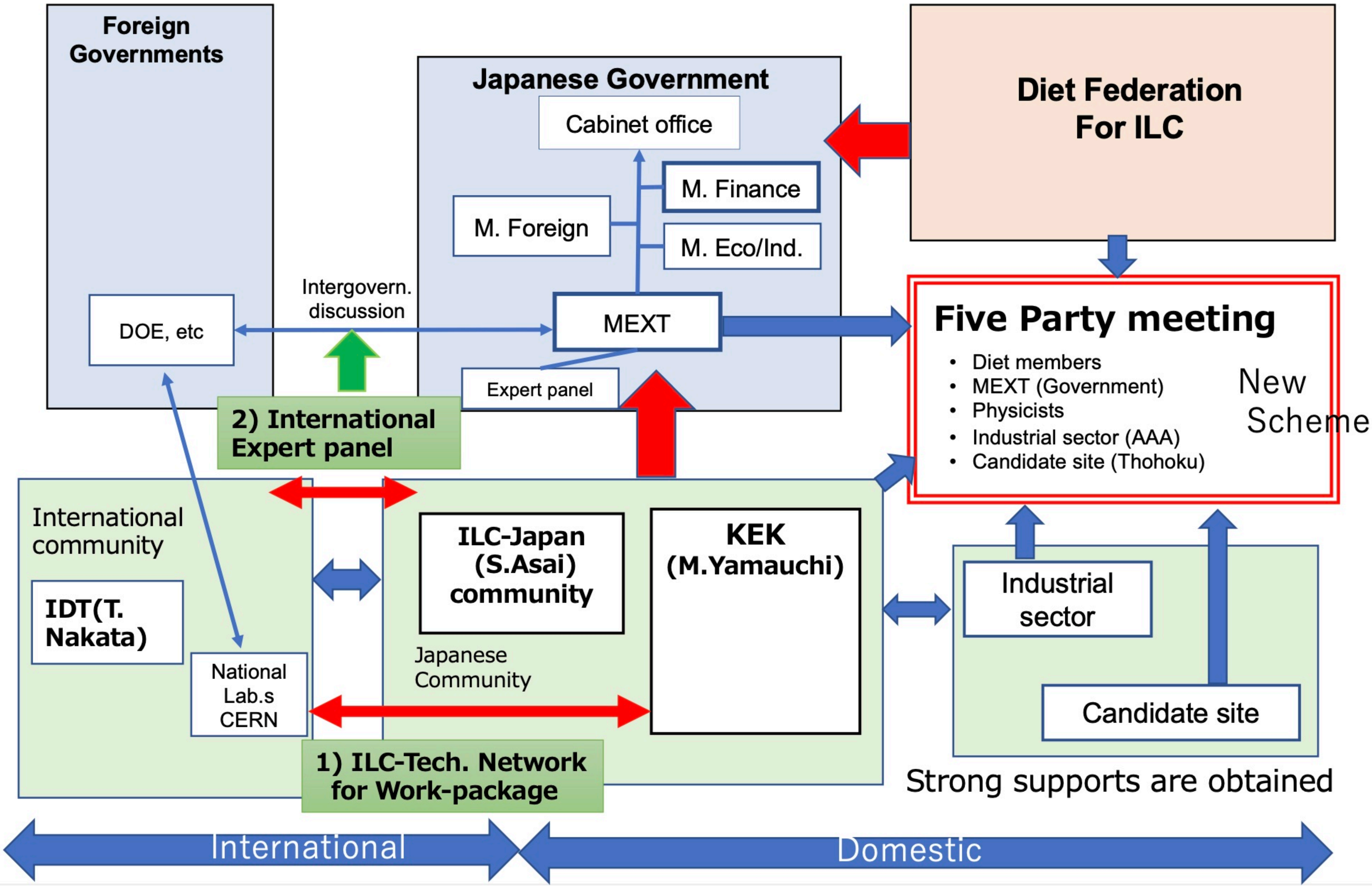
(iv) ILC project status

[T.Nakada & S. Asai's LCWS 2023 talks]

- New scheme: "International" —> "Global" project
- Led by ILC International Development Team (IDT)
- ILC-Japan represents our community (JAHEP) for promotion
- **Recently: MEXT doubled the ILC R&D budget (~9.7 hundred million yen from 2023)**
- The next step: ILC Technological Network (ITN) & International Expert Panel (IEP)

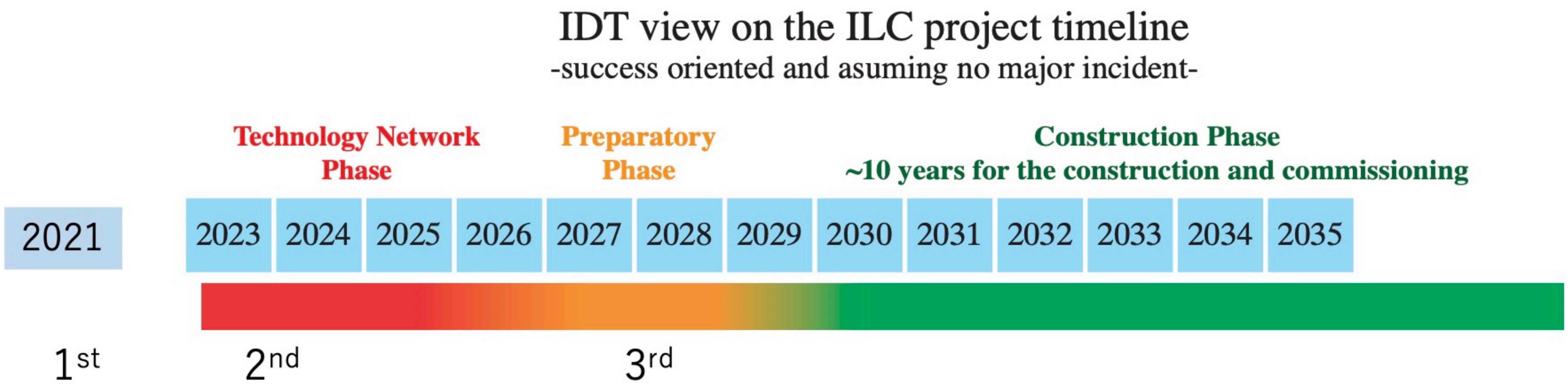


Promotion scheme of ILC / relation of Stakeholder



7. Timeline / Step-by-Step ILC promotion

This Timeline is considered,
Discussed in IDT/ICFA/Diet Federation.
not Government approved.



1st stage Prepare ILCTN
International expert panel makes global script.

Condition

- Budget is ready
- Various National Labs join ILCTN

2nd Stage ILC TN develops TC-WP

Community cultivates environment for international discussion (both @ scientist community and government level)

Japan takes role / initiative in ILCTN (we are asking to JG)

Condition

- FCC-ee FS final report
- recognize ILC as the most realistic, cost-friendly, carbon-friendly project
- Understand of Governments/Communities ILC is global project
- Better International situation(Pandemic, global economy, tension)

3rd Stage Governments discuss cost sharing/responsibility of ILC (as Global project)

Condition

- Fix final cost including civil engineering
- Cost sharing / responsibilities are agreed @ Governments

Start construction.

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

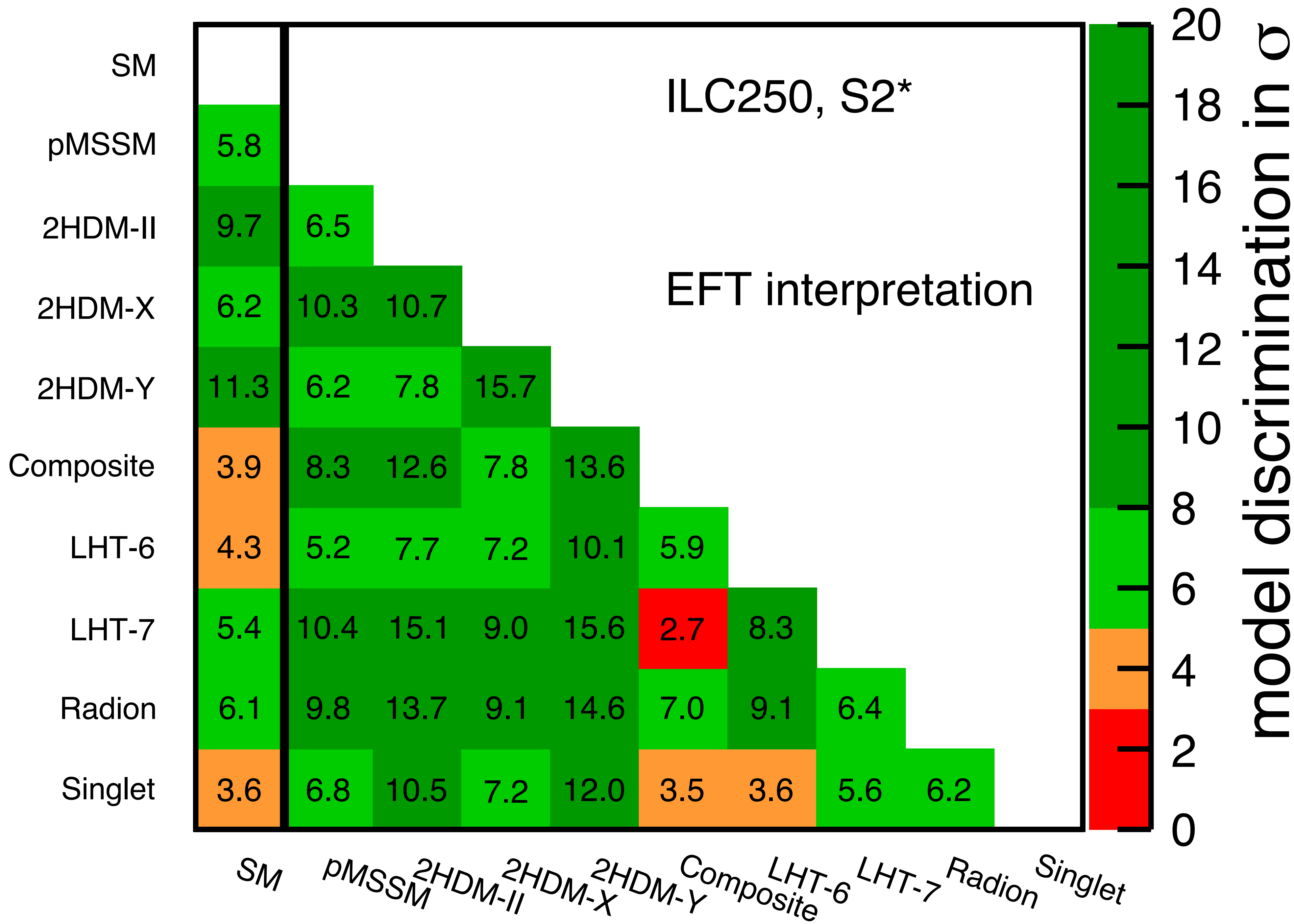
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> quantitative assessment for models discrimination

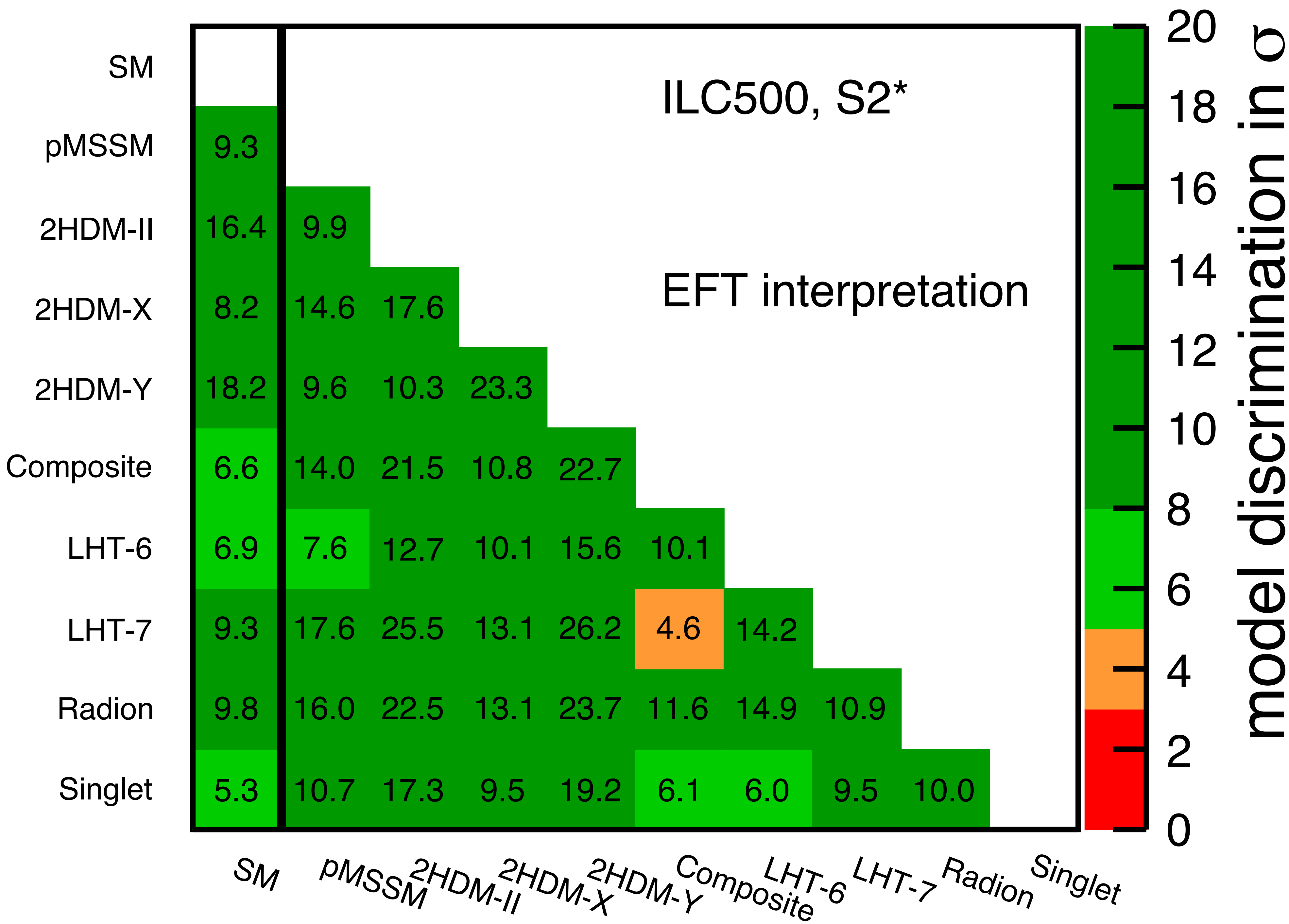
model parameters (chosen as escaping direct search at HL-LHC)

- 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 benchmark models discrimination at ILC250

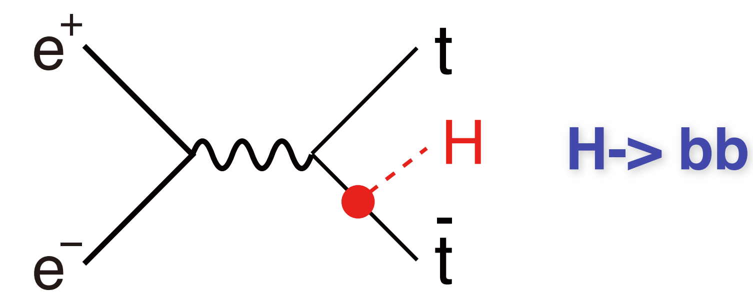


effect of improvement from TGC, vvH, ZH at 500GeV

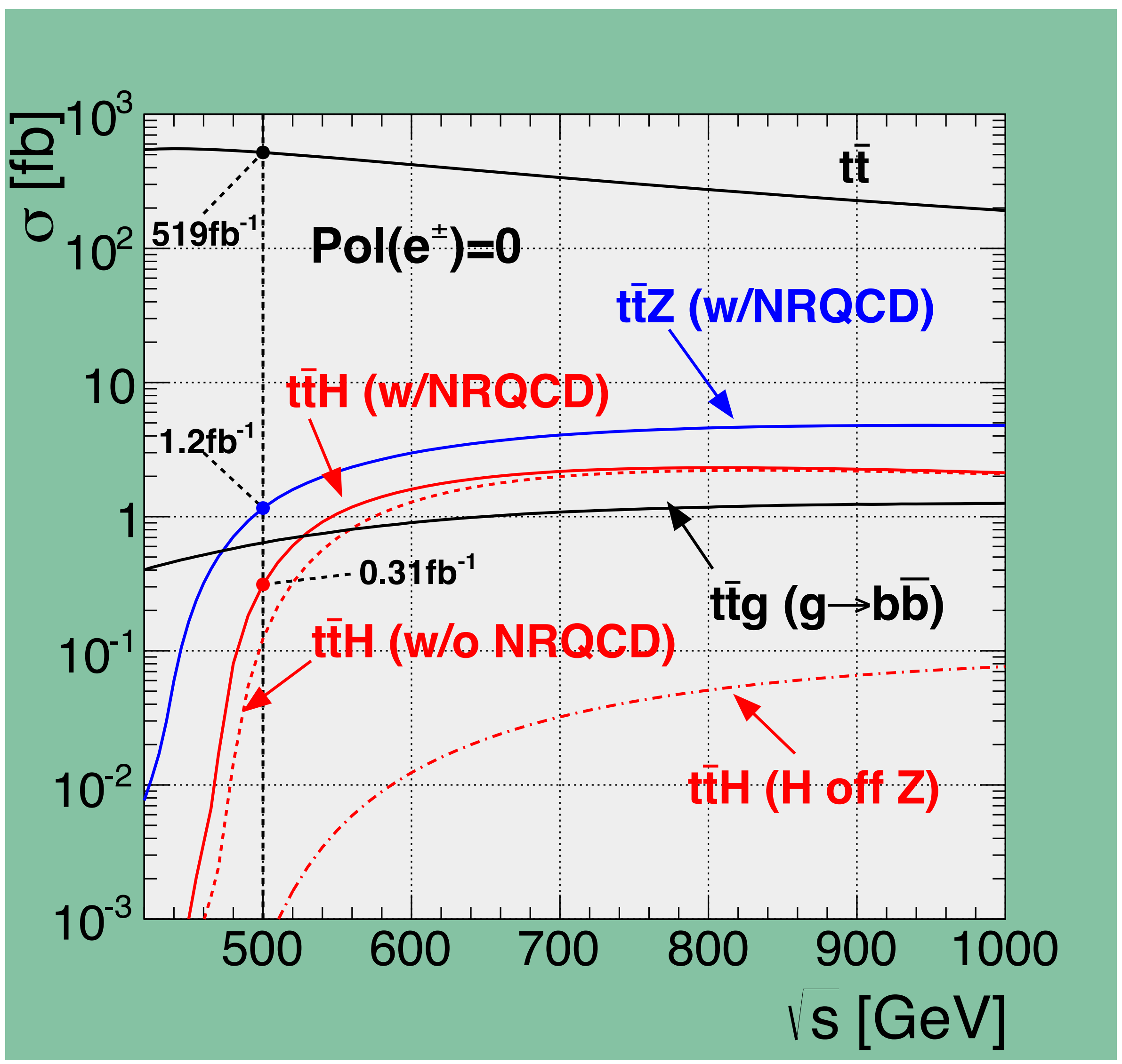


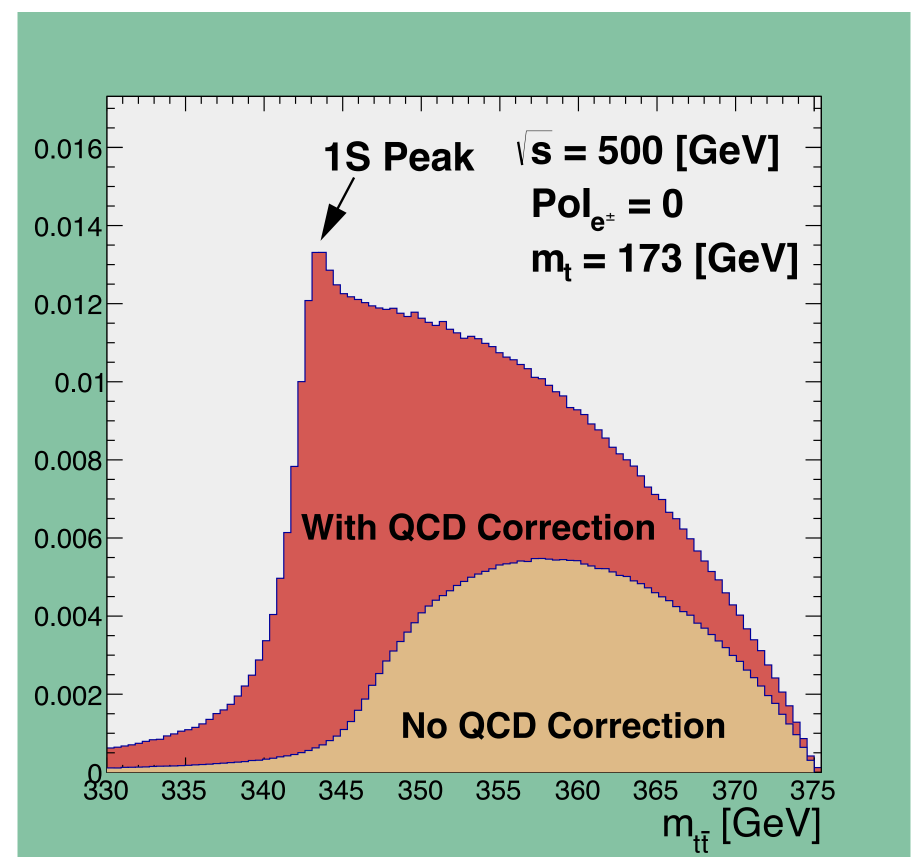
(ii-6) Top-Yukawa coupling

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



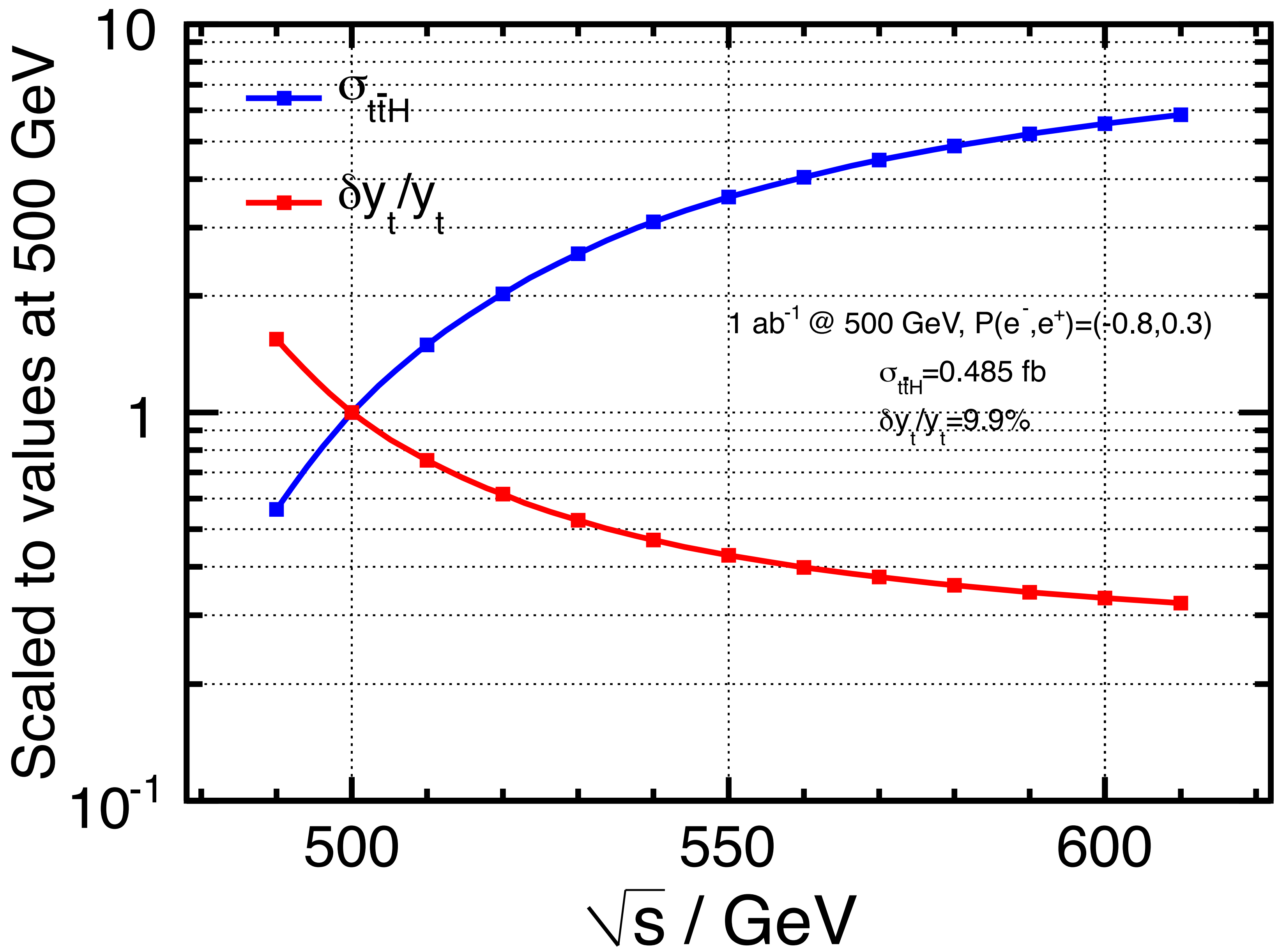
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
ILC	6.3%	1.5%





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

Top-Yukawa coupling: impact of √s



[Y. Sudo]

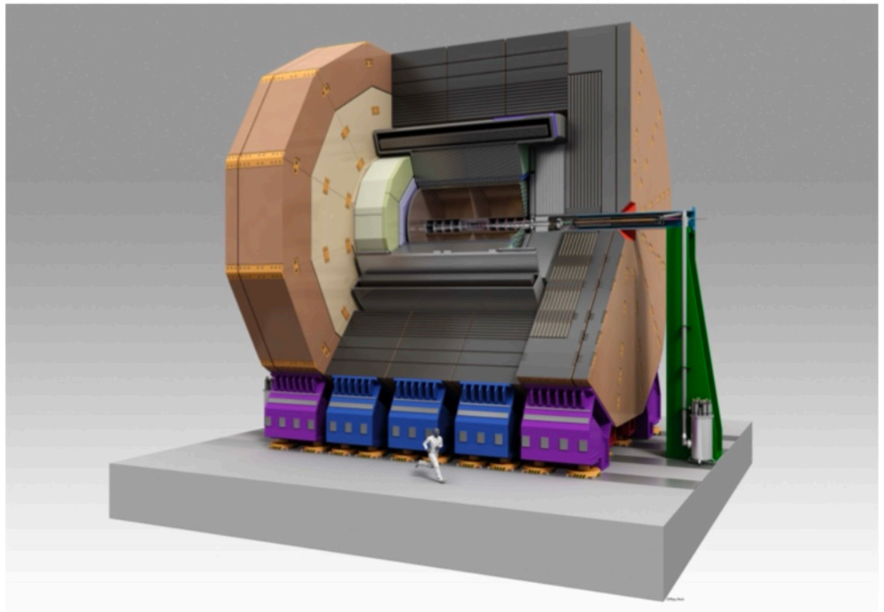
- increase √s slightly by 50GeV can improve δy_t by a factor of 2

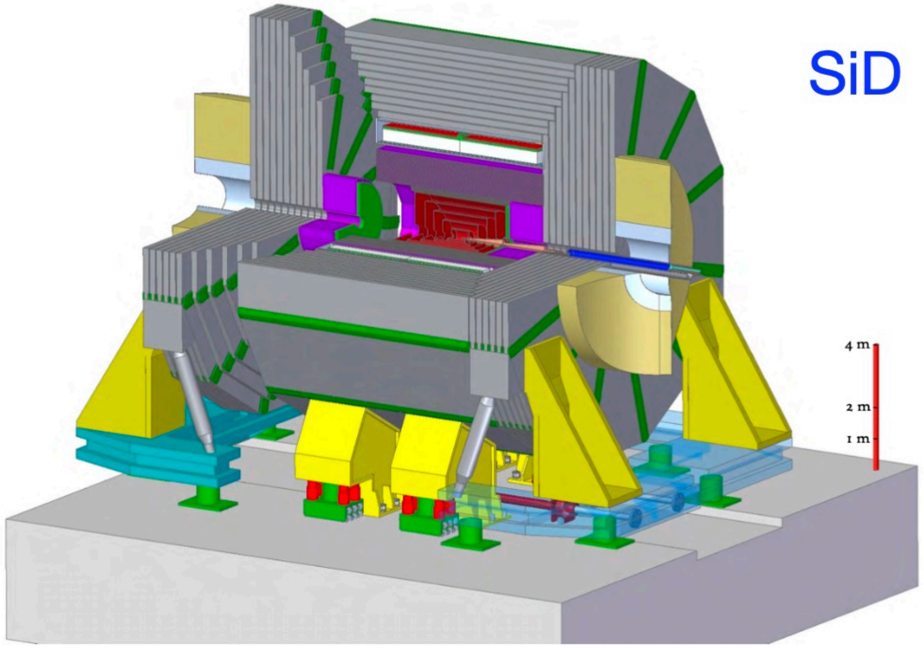
Detector for Linear Colliders

lineup

- Only one IP at linear colliders; two detector concepts proposed for ILC with "push-pull" scheme
- ILD and SiD concepts are very mature: Detailed Baseline Design (DBD) completed a decade ago; continuous prototyping and demonstrating by beam test; very close collaboration with CALICE, LCTPC, FCAL
- Current status are summarized in ILD interim design report and Updating the SiD concept
- [ILD2022] towards a strategy for ILD not only at ILC but also at other e+e-

ILD





SiD

similar performance; major difference in tracking volume, TPC vs Full Silicon;

Detector Concepts

driving factors

東京大学 THE UNIVERSITY OF TOKYO

- “Clean” environment at e+e- allows the design of detectors with very ambitious performance: event rate, event complexity, radiation level, all much lower comparing to that at hadron colliders
- Performance requirement driven by physics program from Z-pole to TeV

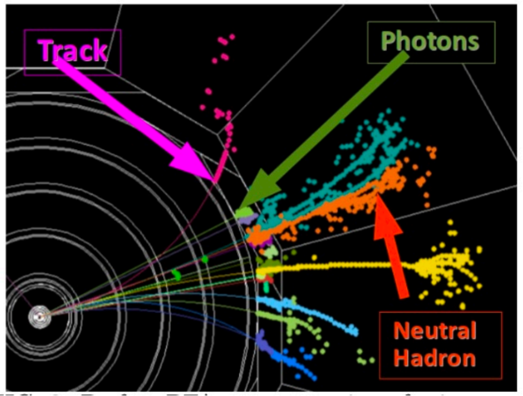
detector performance		physics performance
Impact Parameter resolution	$5\ \mu\mathrm{m} \oplus \frac{10\ \mu\mathrm{m\ GeV}/c}{p\ \sin^{3/2}\theta}$	flavor tagging, e.g. hadronic Higgs BR meas. for bb/cc/gg
Momentum resolution	$\Delta(1/p) = 2\times10^{-5}\ (\mathrm{GeV/c})^{-1}$	leptonic recoil mass meas.
Jet Energy Resolution	ΔE/E = 3-4%	hadronic decays of W/Z
Triggerless readout		
Power pulsing		

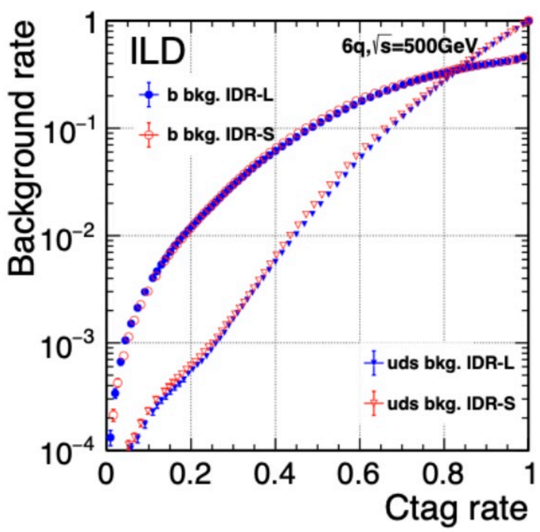
(asymptotic resolution)

Detector Concepts

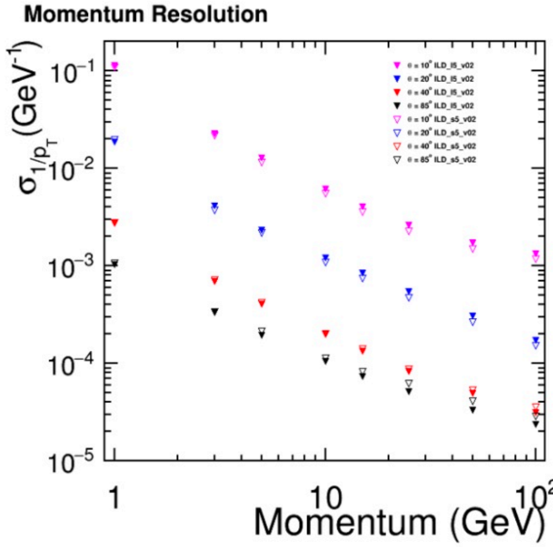
meet the requirements

- Key criteria: Particle Flow Algorithm (PFA), allowing a complete event reconstruction
- High granular calorimeters in both electromagnetic and hadronic sections
- Very low material budget in the vertexing and tracking volumes

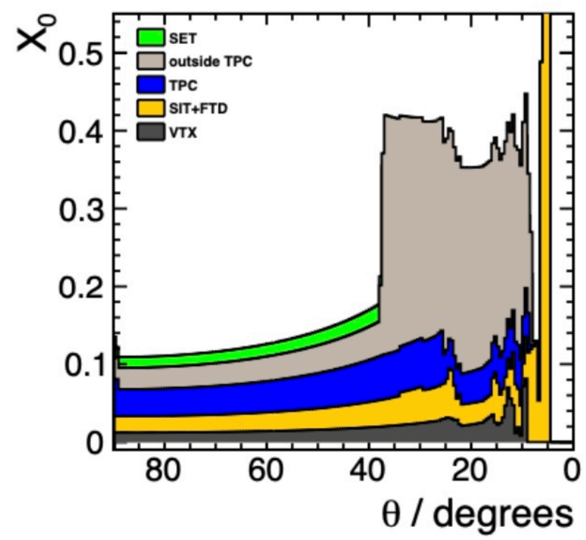




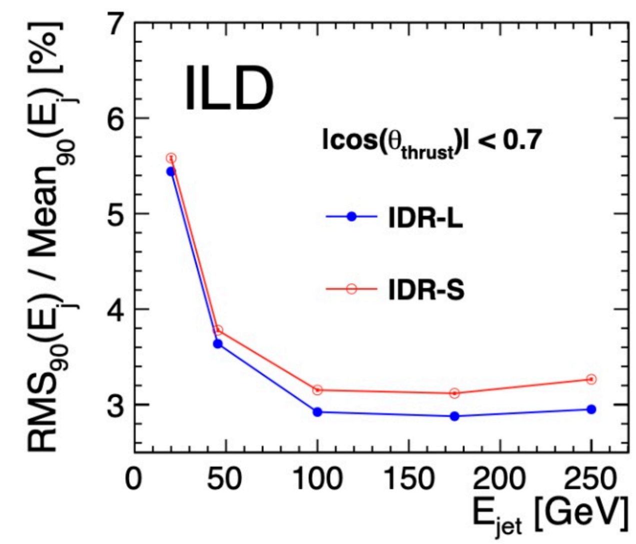
charm tagging



momentum resolution



material budget



jet energy resolution

[see details in many talks / posters in this workshop]