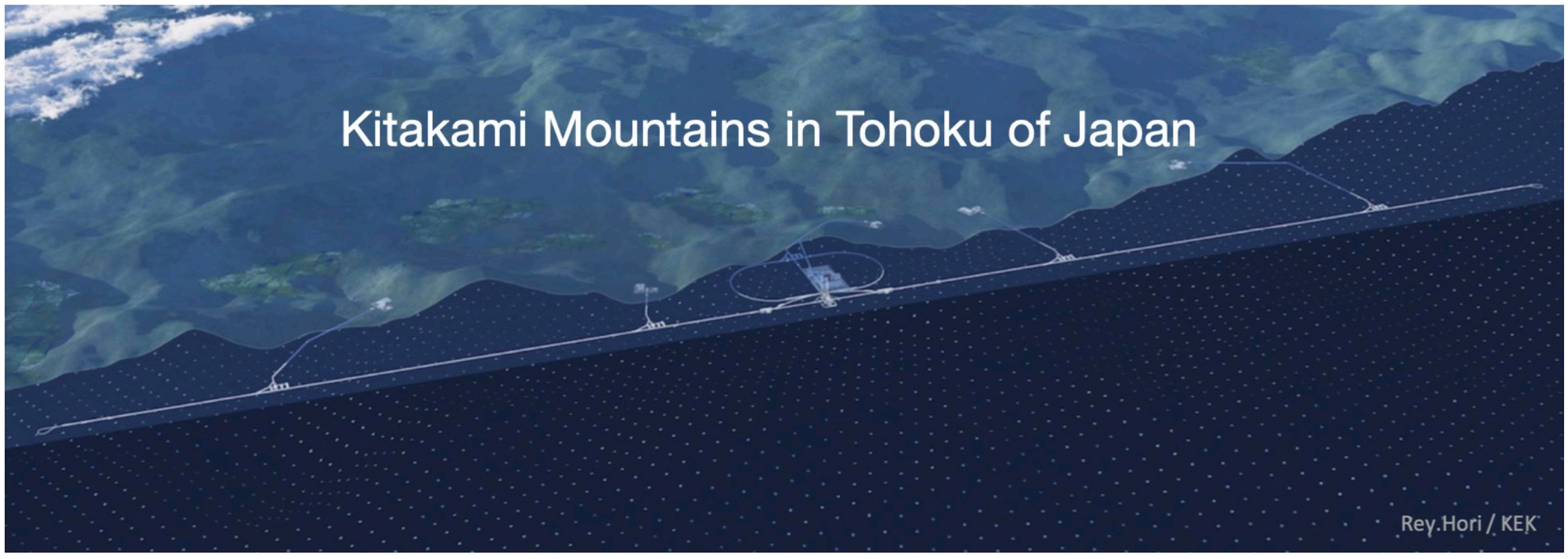
Higgs physics with ILC



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

HPNP 2023 @ Osaka U., June 5-9, 2023

ILC Supporters

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outline

- Introduction

  ILC & other Higgs Factories forge the path for discovery

- Highlight a few key measurements

  How ILC can advance our knowledges of Higgs

- A few open questions

  In particular those need help from theorists

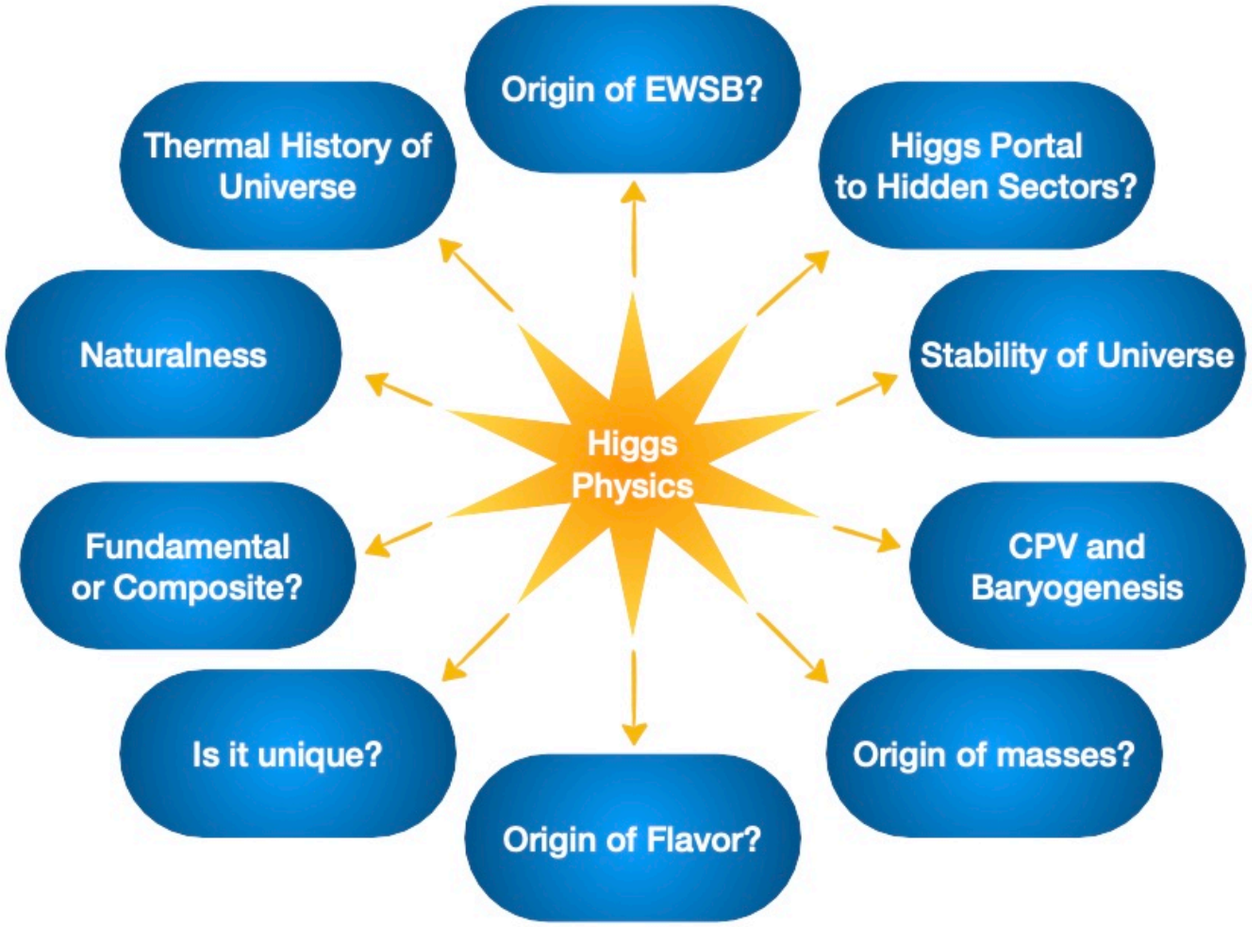
- Recent news of the ILC project

  Towards realization, please join the adventure

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

[ILC report to ESU 2020, arXiv:1903.01629]

Why the Higgs is the most important particle



[Snowmass EF01/02 report, arXiv: 2209.0710]

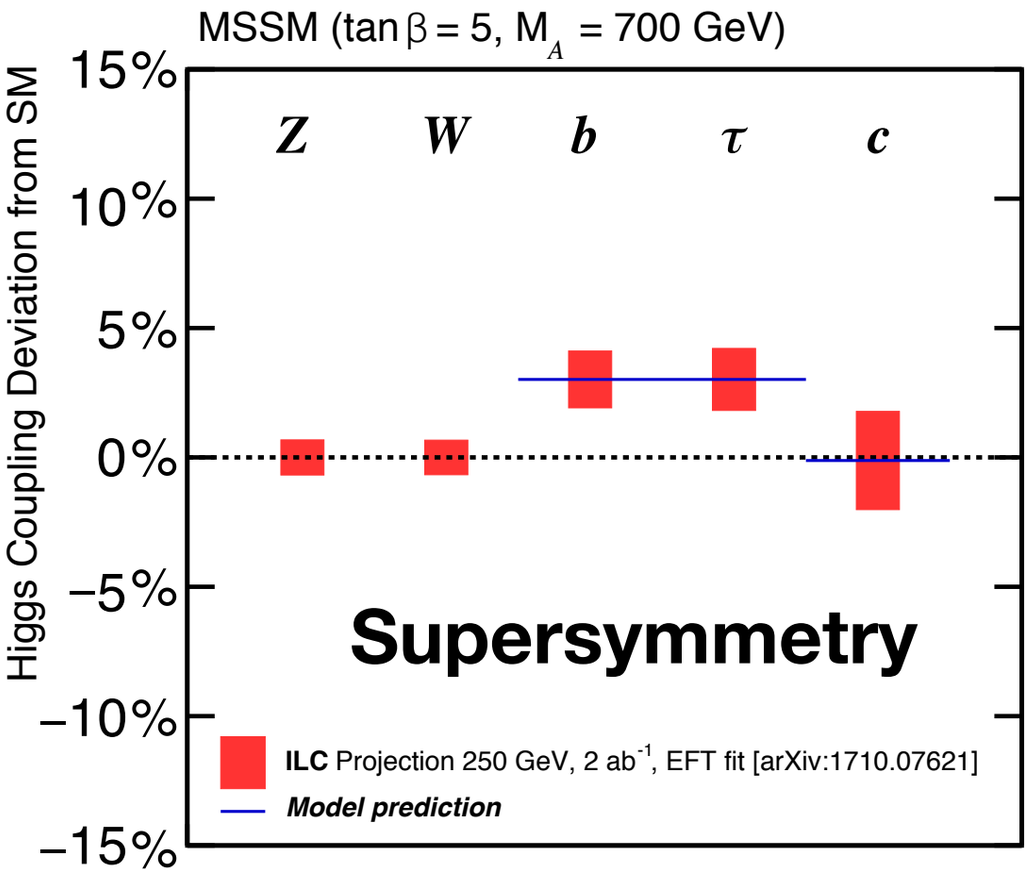
+

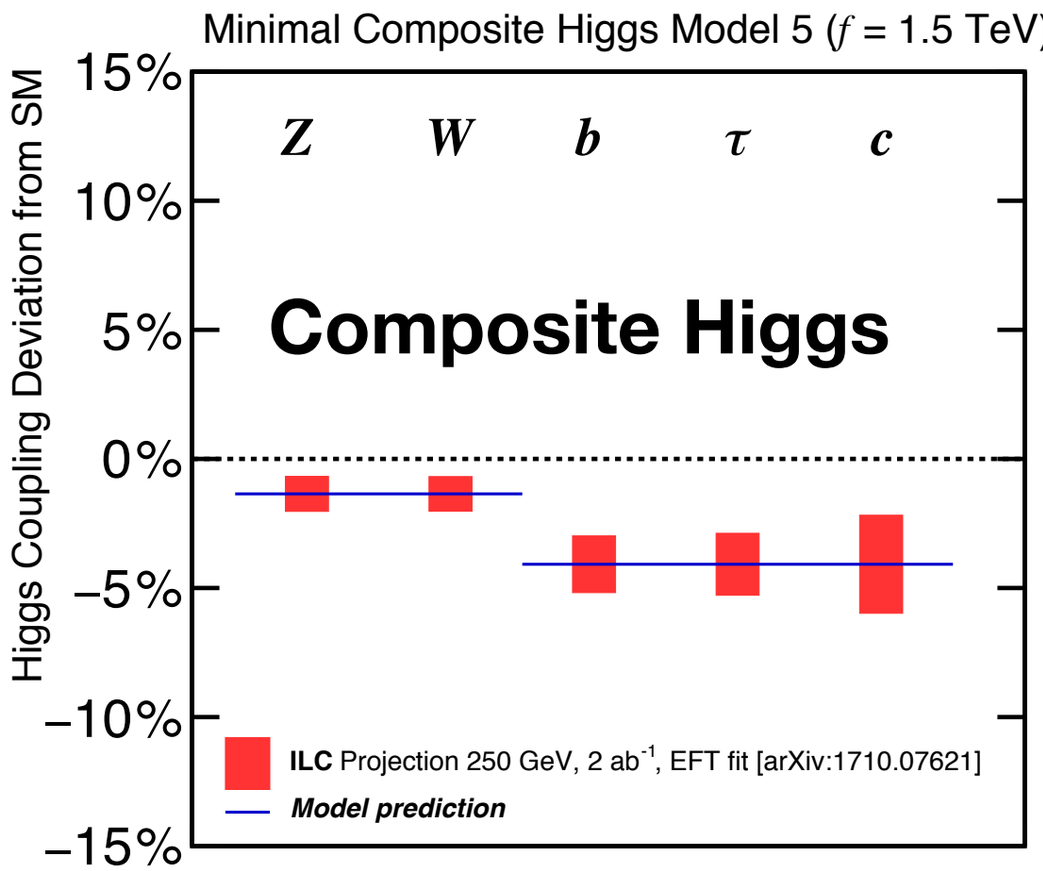
[all talks in this conference]

- the least understood sector of SM, theoretically or experimentally
- portal to many other big questions of our universe

not a question to audience today, but important to elaborate with colleagues in other fields

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”

	√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 - 350 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

H ⋯ H

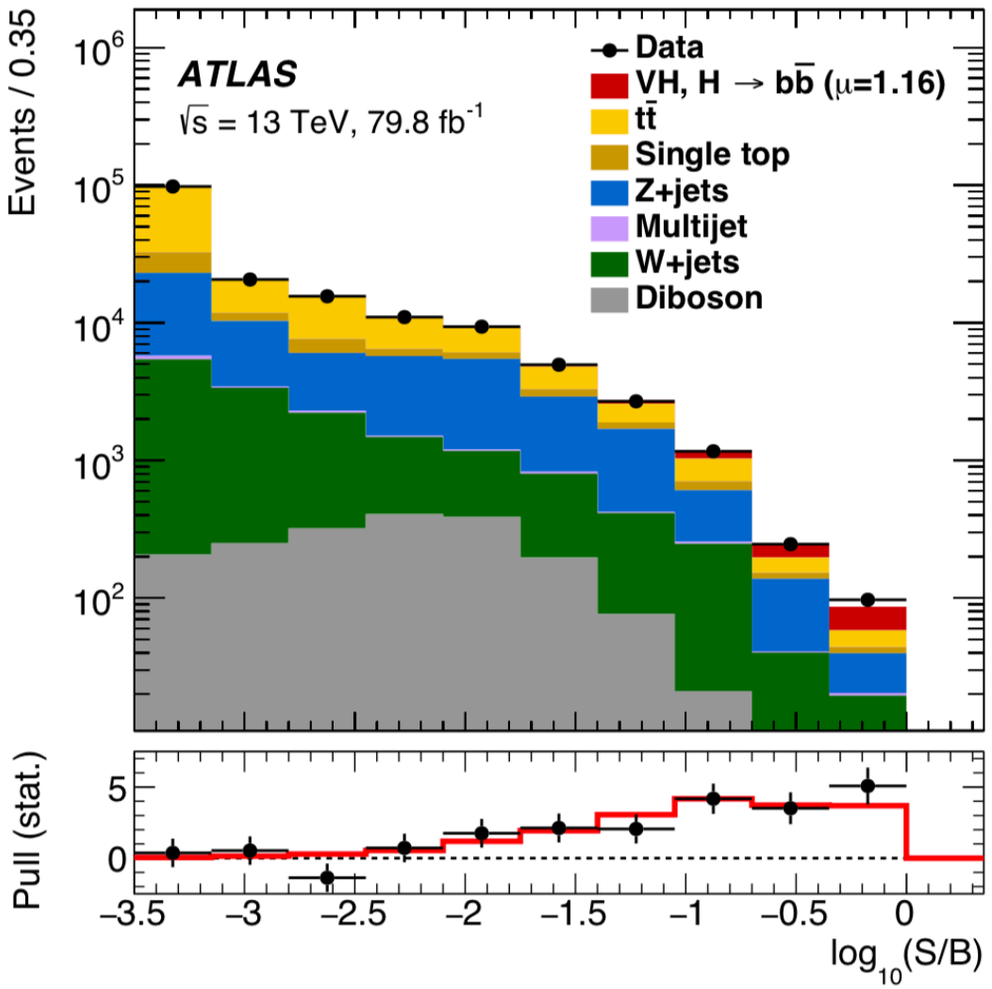
(+ emerging C^3, Muon Colliders, μTristen, etc)

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 $H \to bb$ discovery)

LHC (super Higgs factory #10^8)



# of Higgs produced: ~4,000,000

significance: 5.4σ

[ATLAS, 1808.08238; CMS, 1808.08242]

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

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

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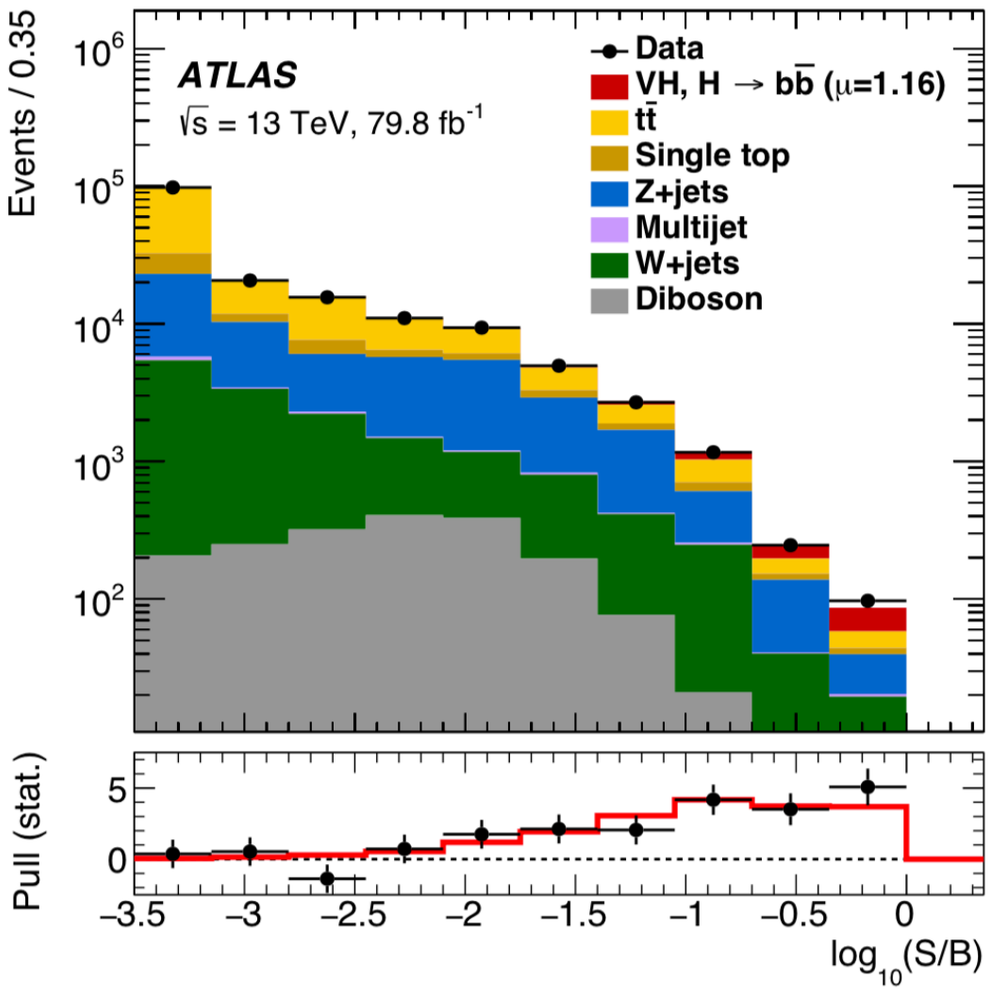

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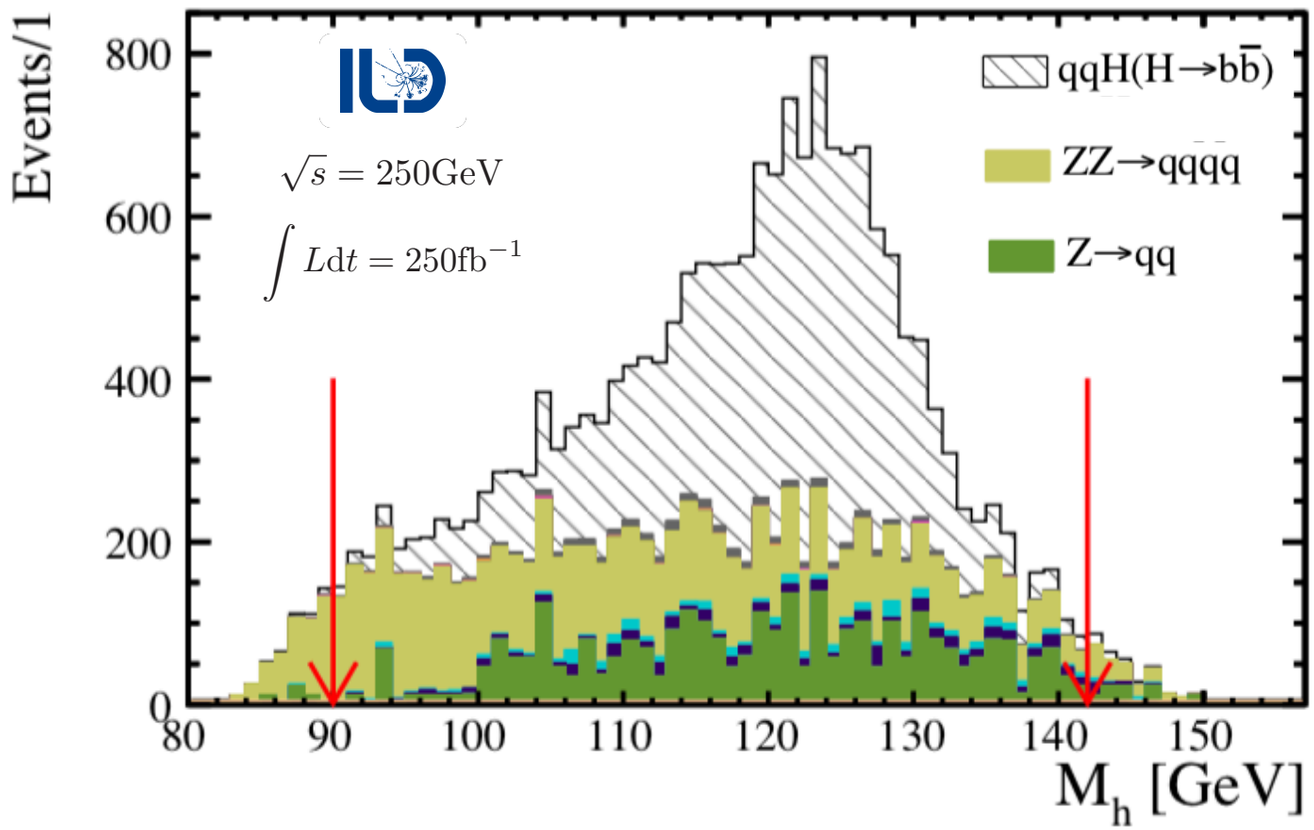


full detector simulation

# of Higgs produced: ~4,000,000

significance: 5.4σ

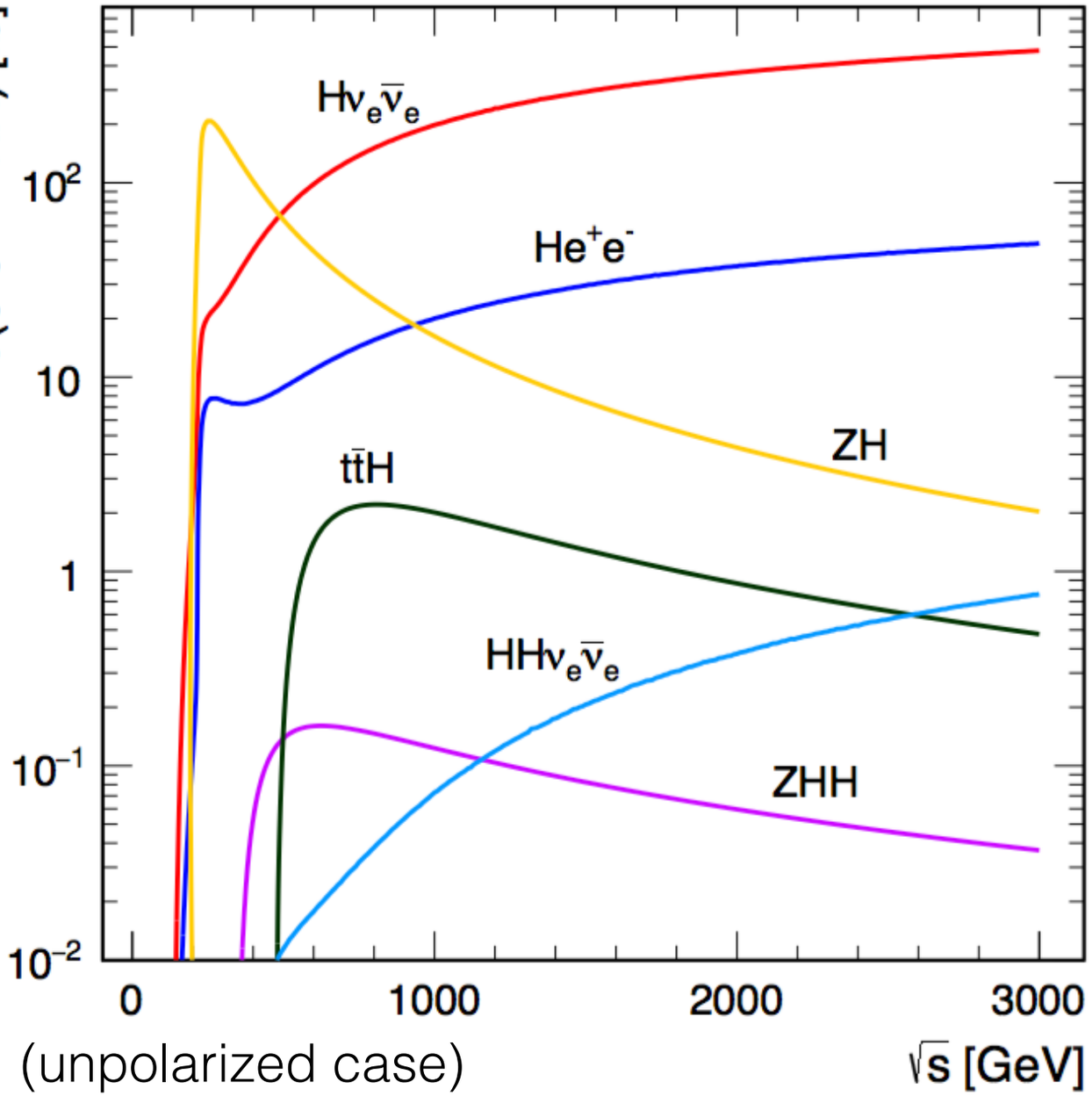
[ATLAS, 1808.08238; CMS, 1808.08242]

~400

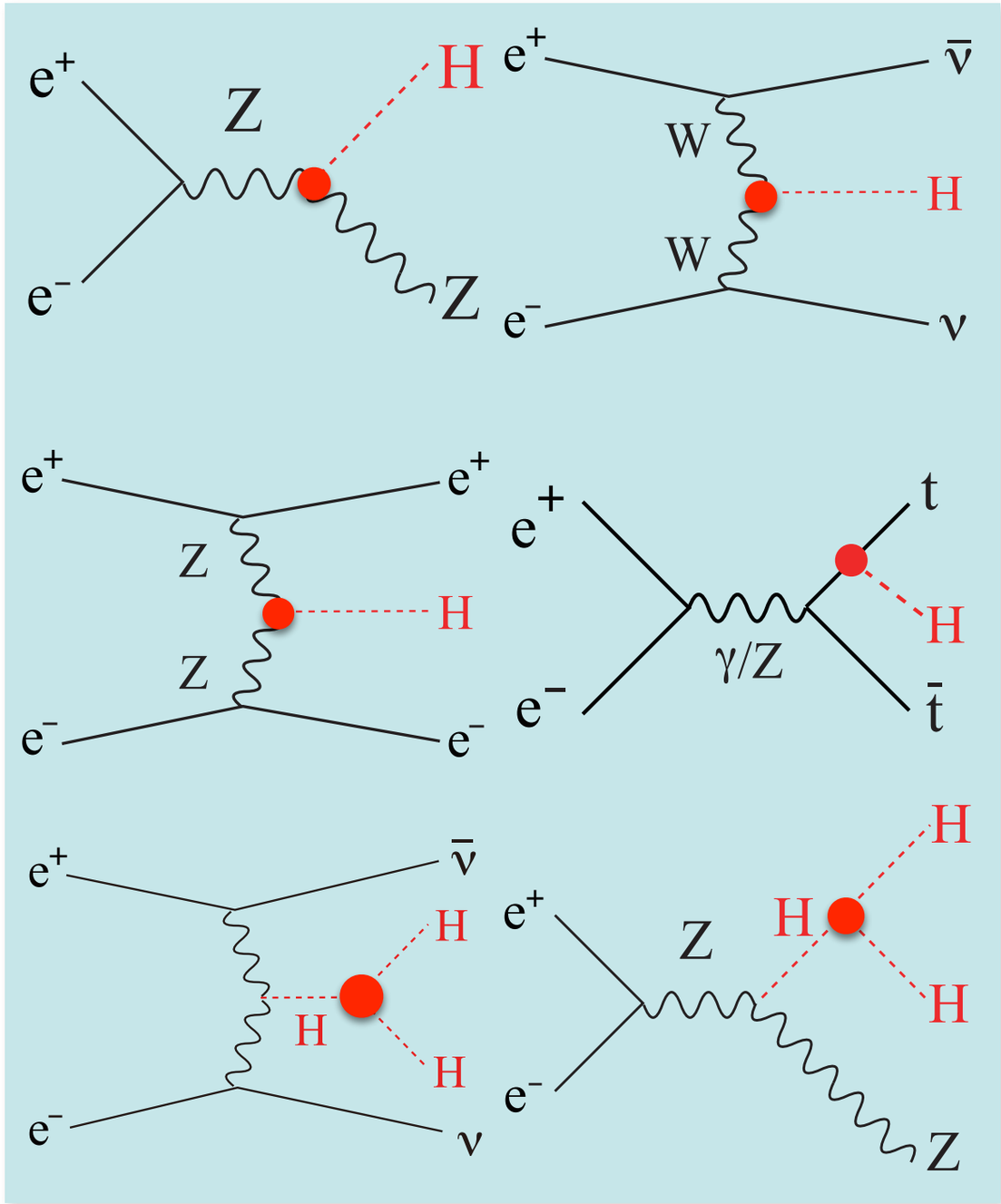
5.2σ

[Ogawa, PhD Thesis (Sokendai '18)]

Higgs productions at e+e-

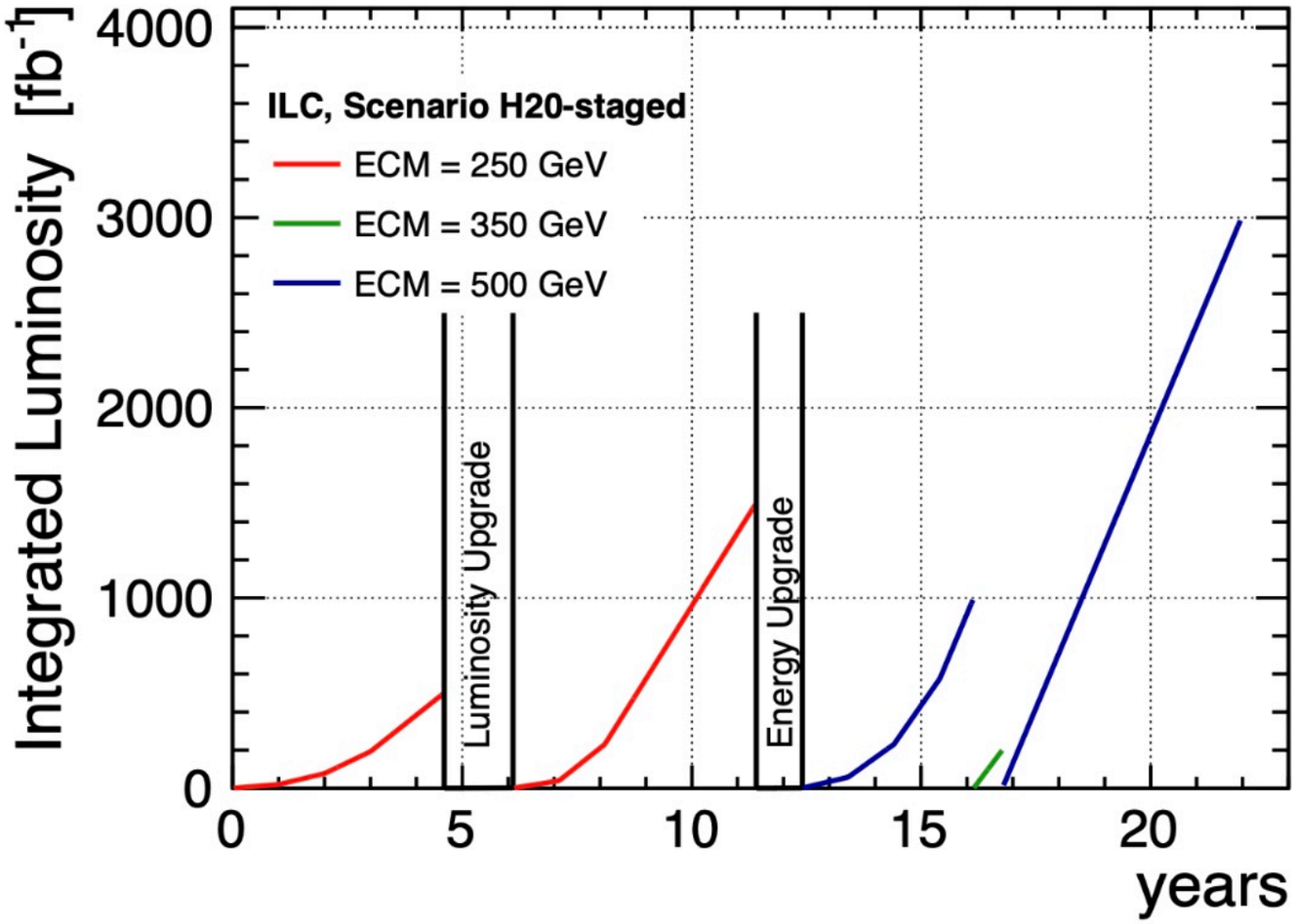


(unpolarized case)



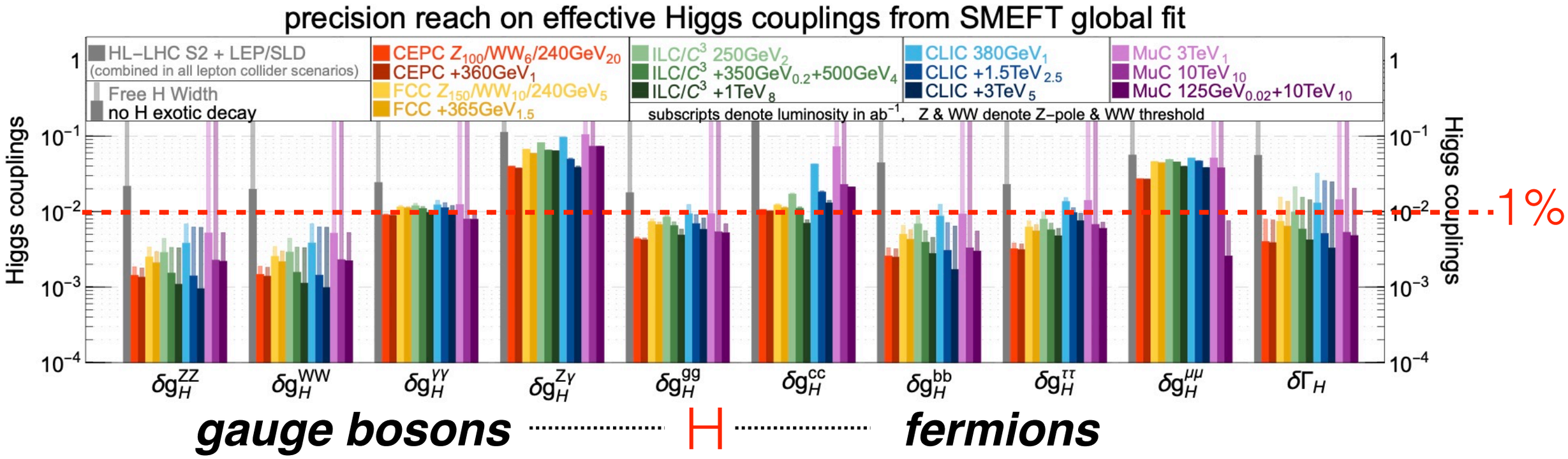
- two apparent important thresholds: √s ~ 250 GeV for ZH, ~500-600 GeV for ZHH and ttH
- + another threshold for t t-bar, important for Higgs physics as well

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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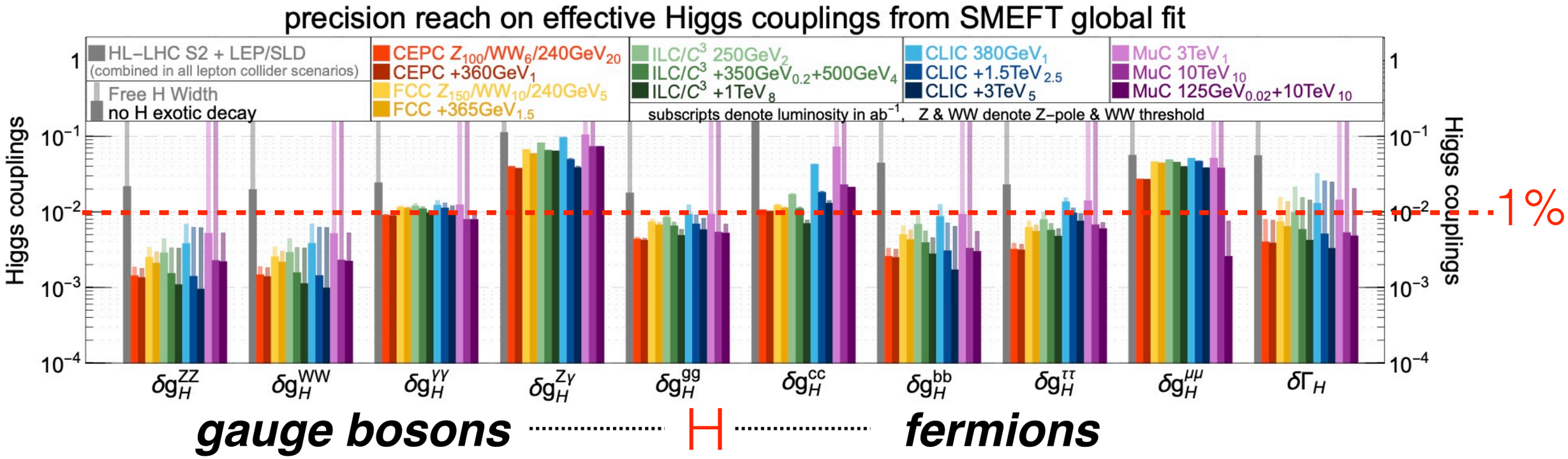
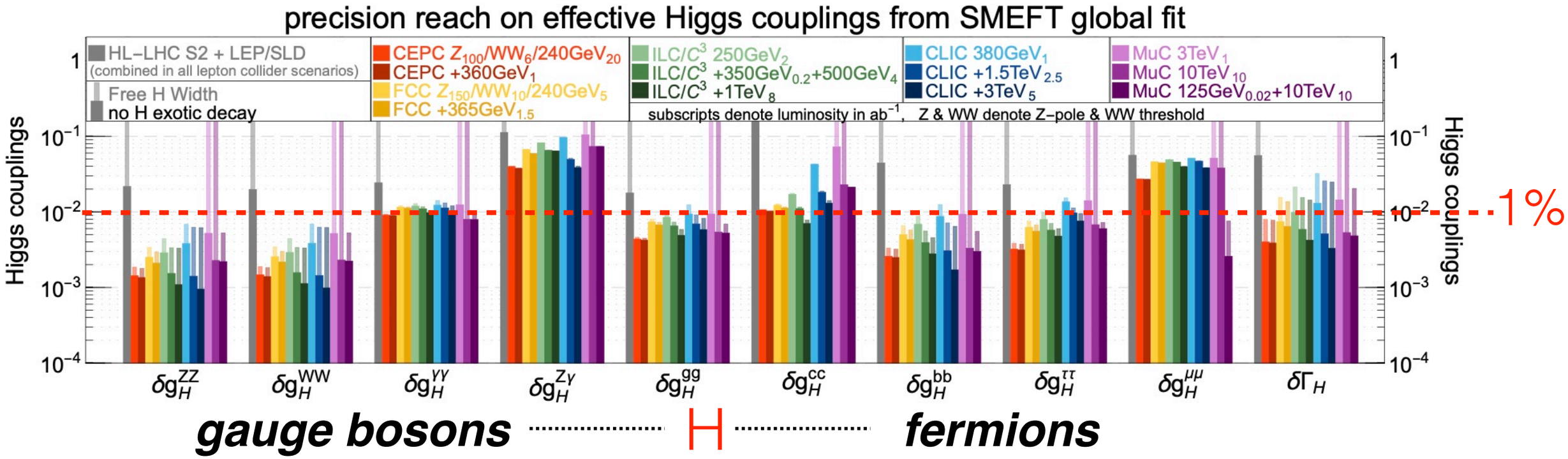


[Snowmass White Paper on Global SMEFT Fits, arXiv:2206.08326]

- 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



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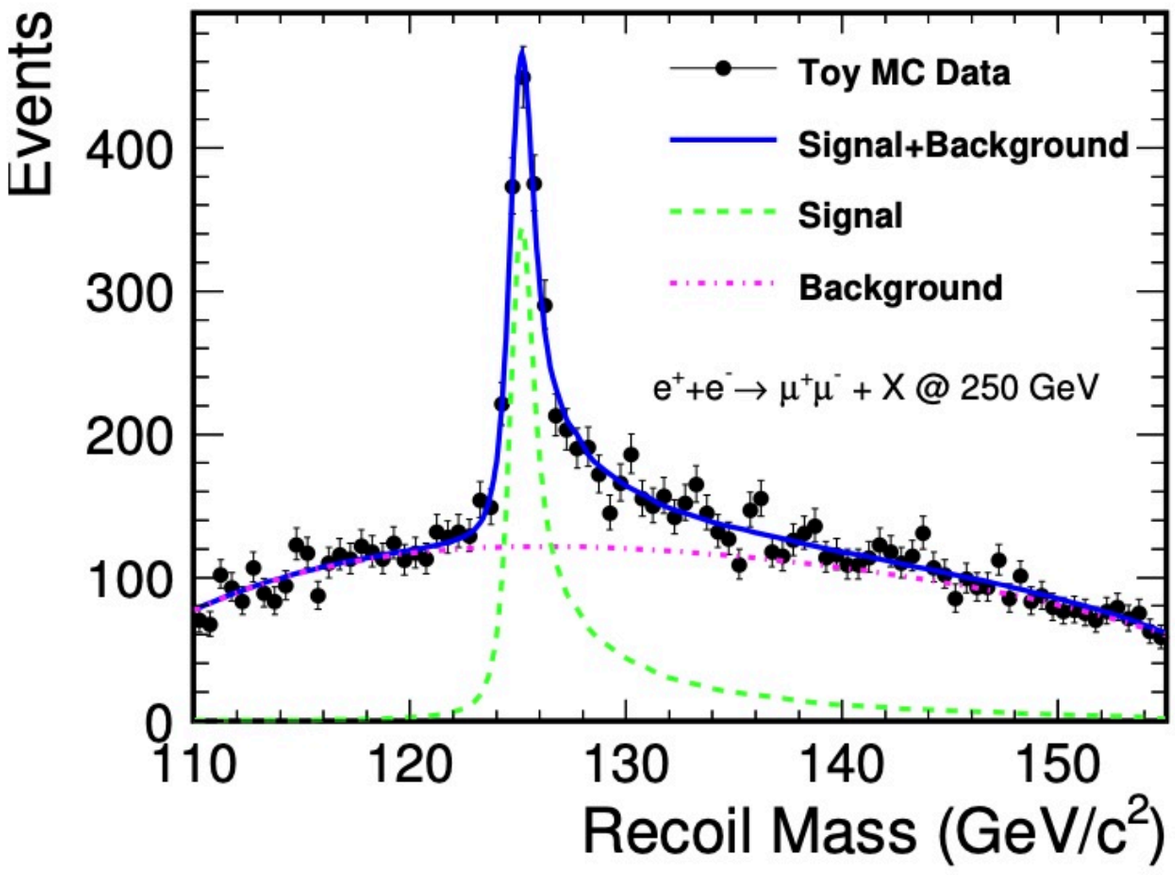
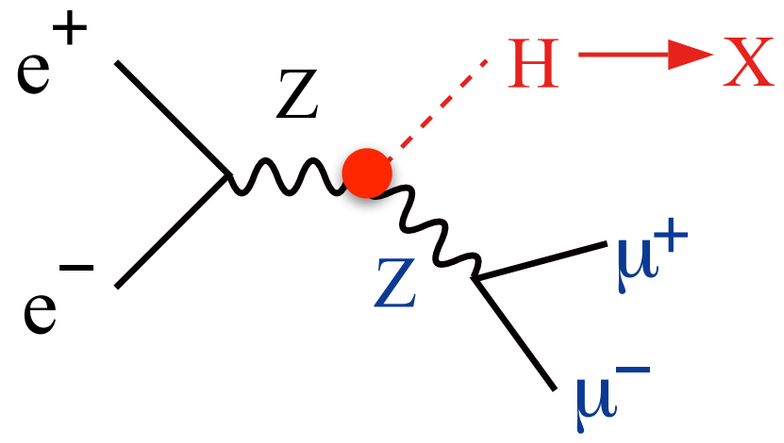
- 1% or below reachable by ILC as well as other Higgs factories
- no question on "which one *should* be realized", important is "which one *can*" given the preferred time and available resource
  - (ii) highlight a few key measurements, elaborate what understanding of Higgs properties is *qualitatively* advanced & how

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

☆ measure absolute σ, instead of $\sigma \cdot BR$



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



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

- 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

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

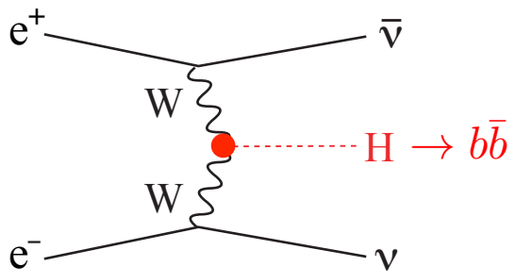
(ii-2) H total width: model-independent determination?

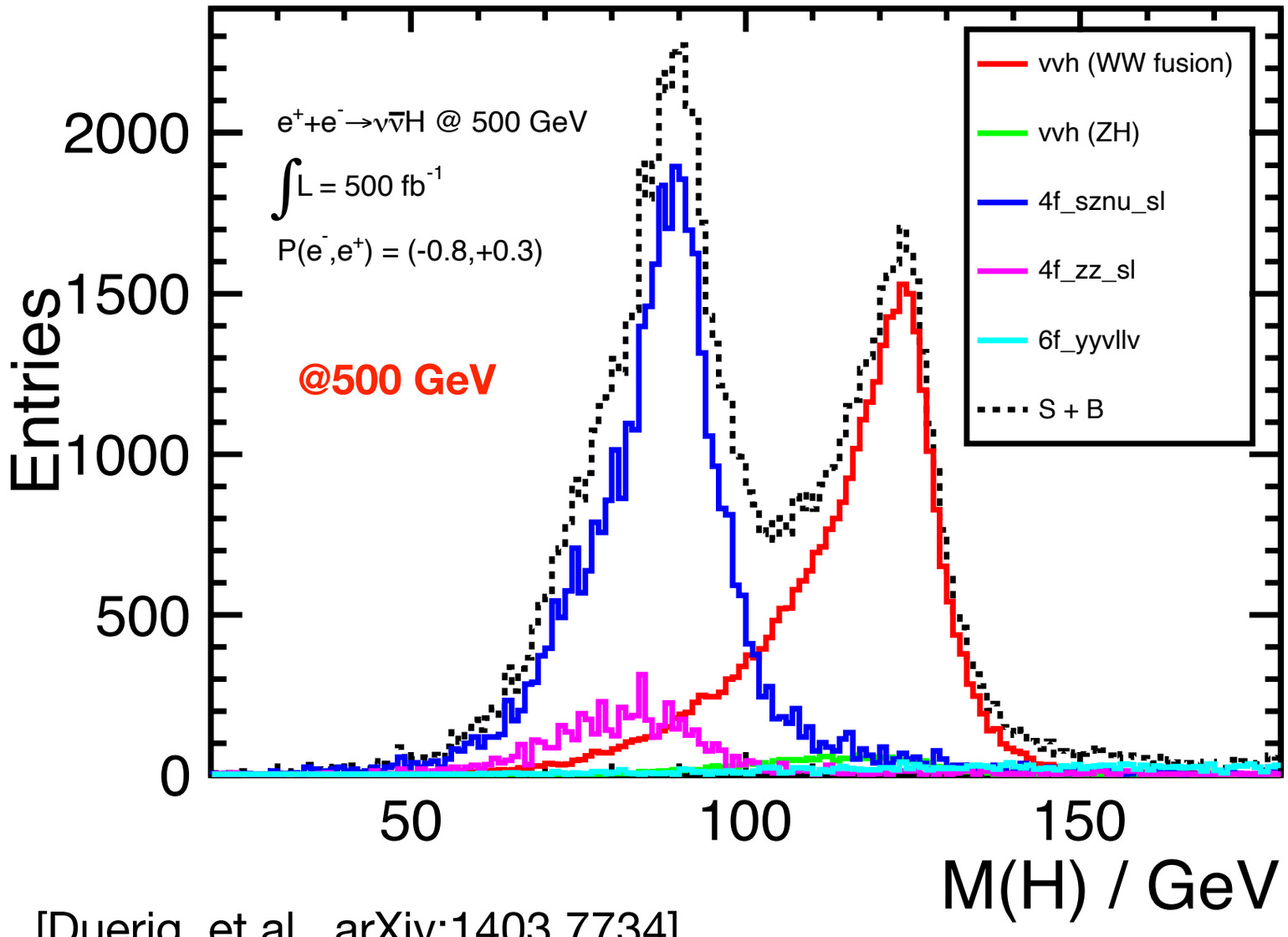
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>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



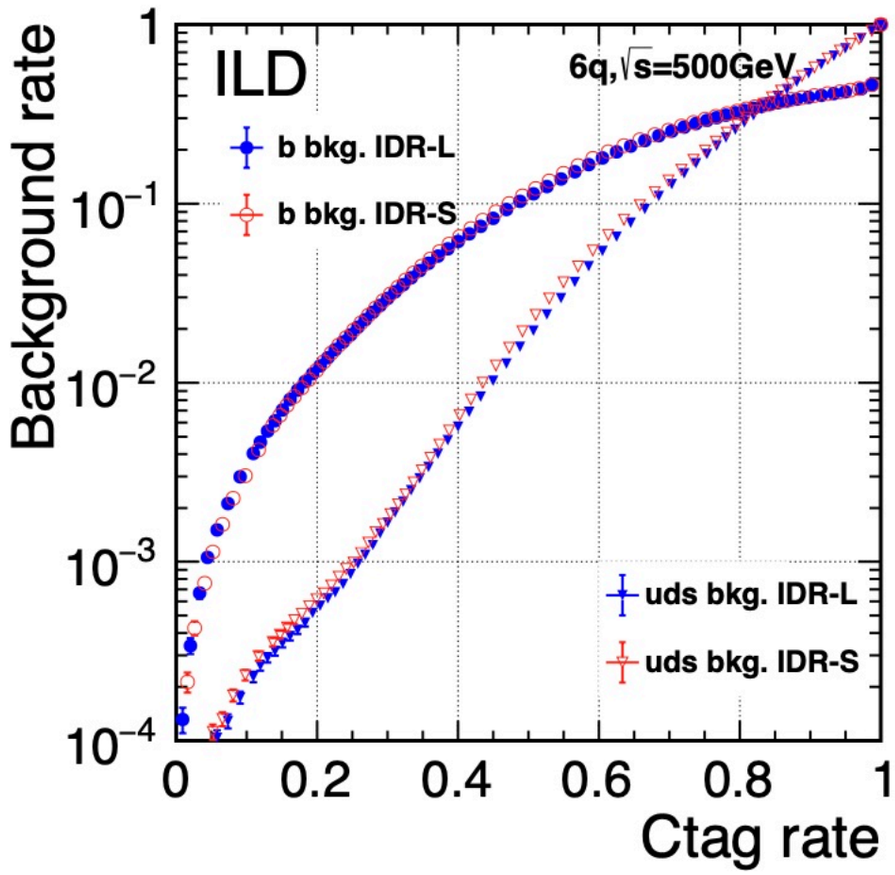


[Duerig, et al., arXiv:1403.7734]

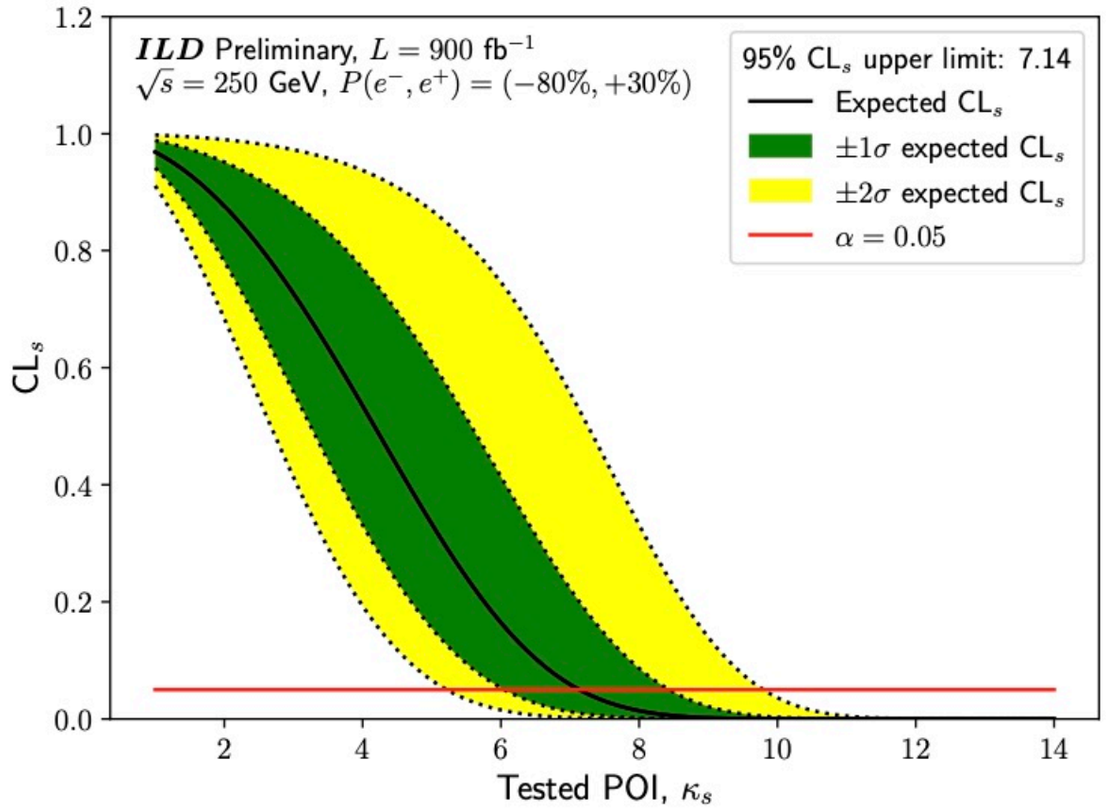
δΓ$_H$ ~ 1%

(ii-3) H—>cc/ss: direct 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%

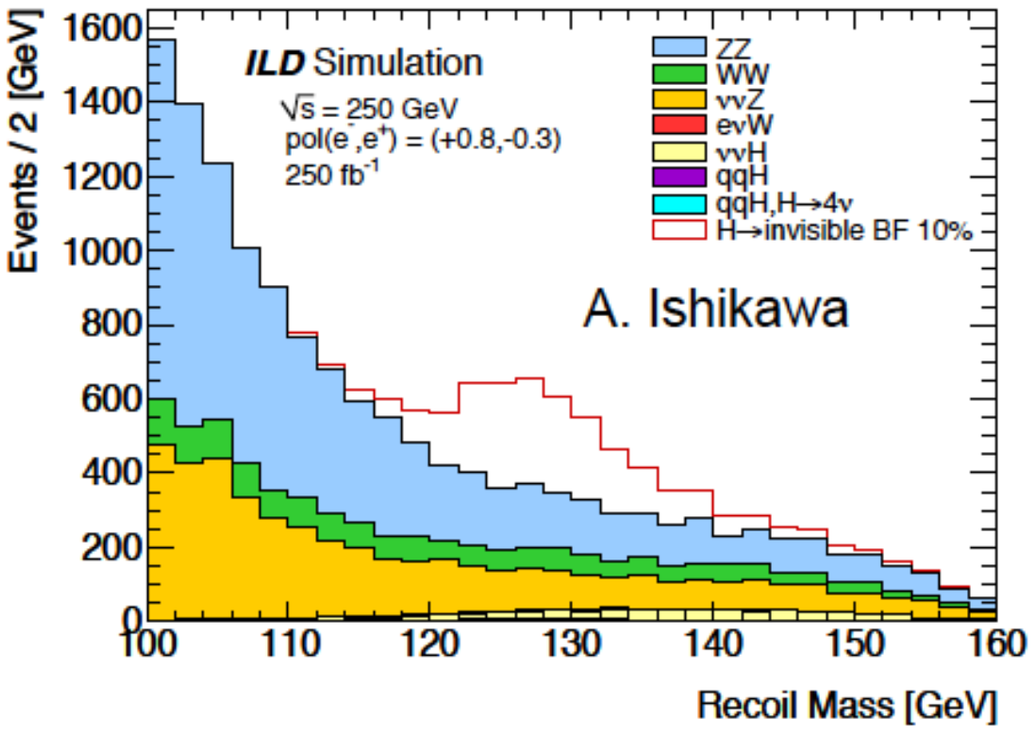


s-Yukawa < 7SM reachable at ILC250

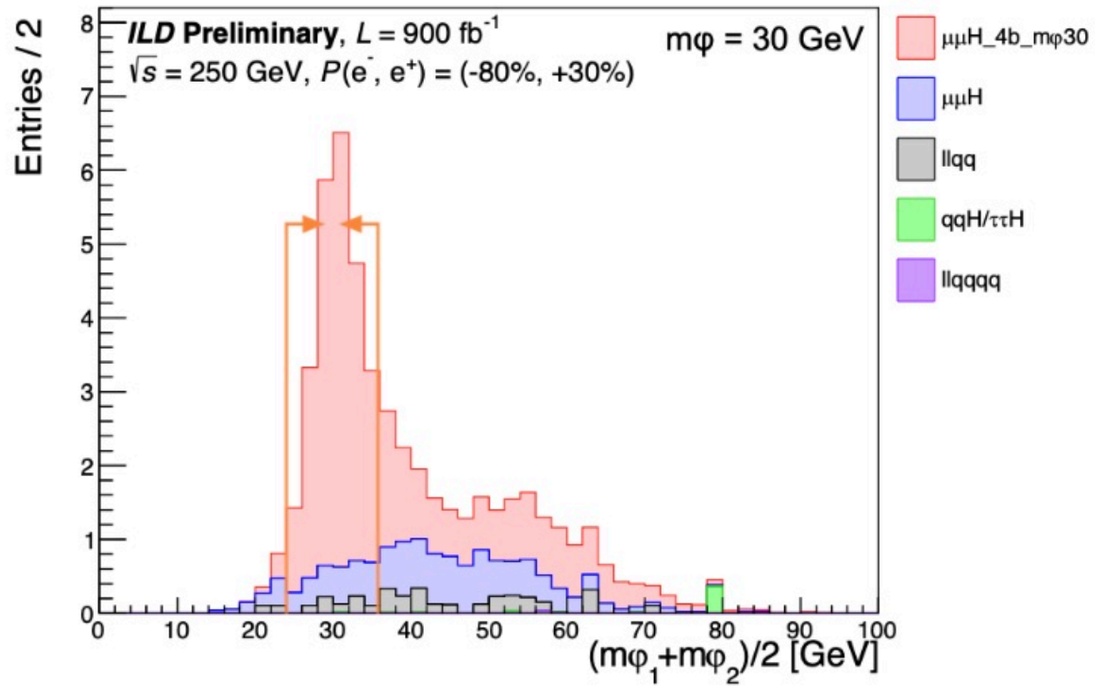
[Ono, et. al, Euro. Phys. J. C73, 2343; F.Mueller, PhD thesis (DESY); M.Basso, 2203.07535]

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

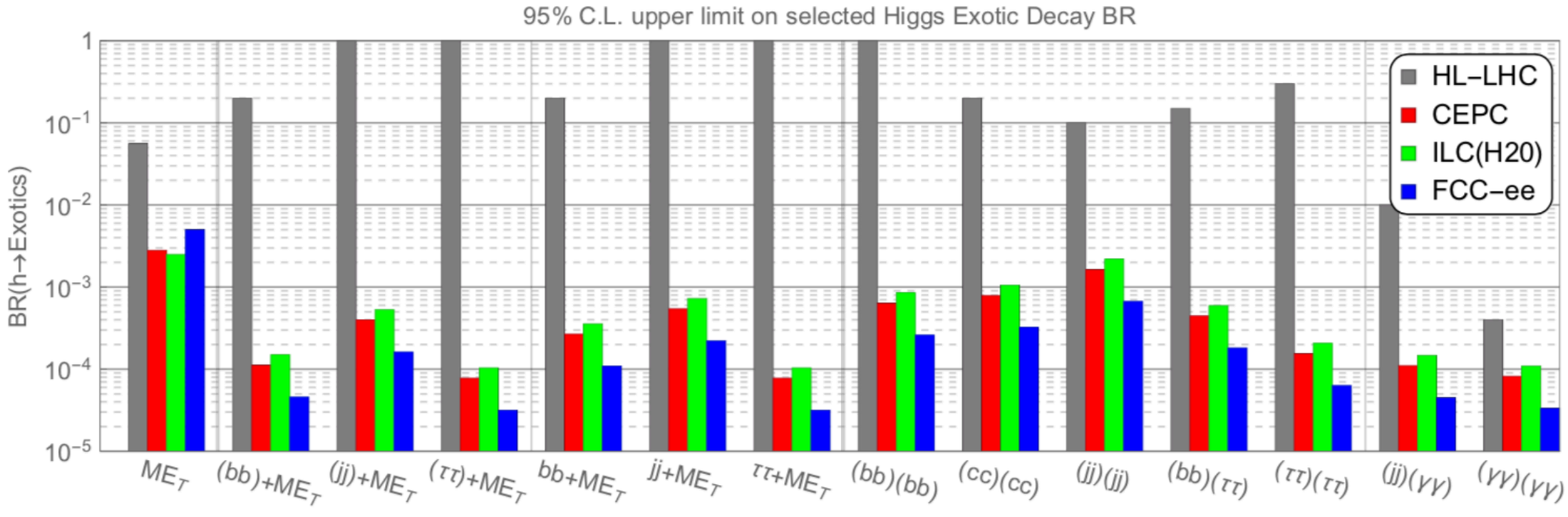
H—>Invisible



H—>ϕϕ—>4-b

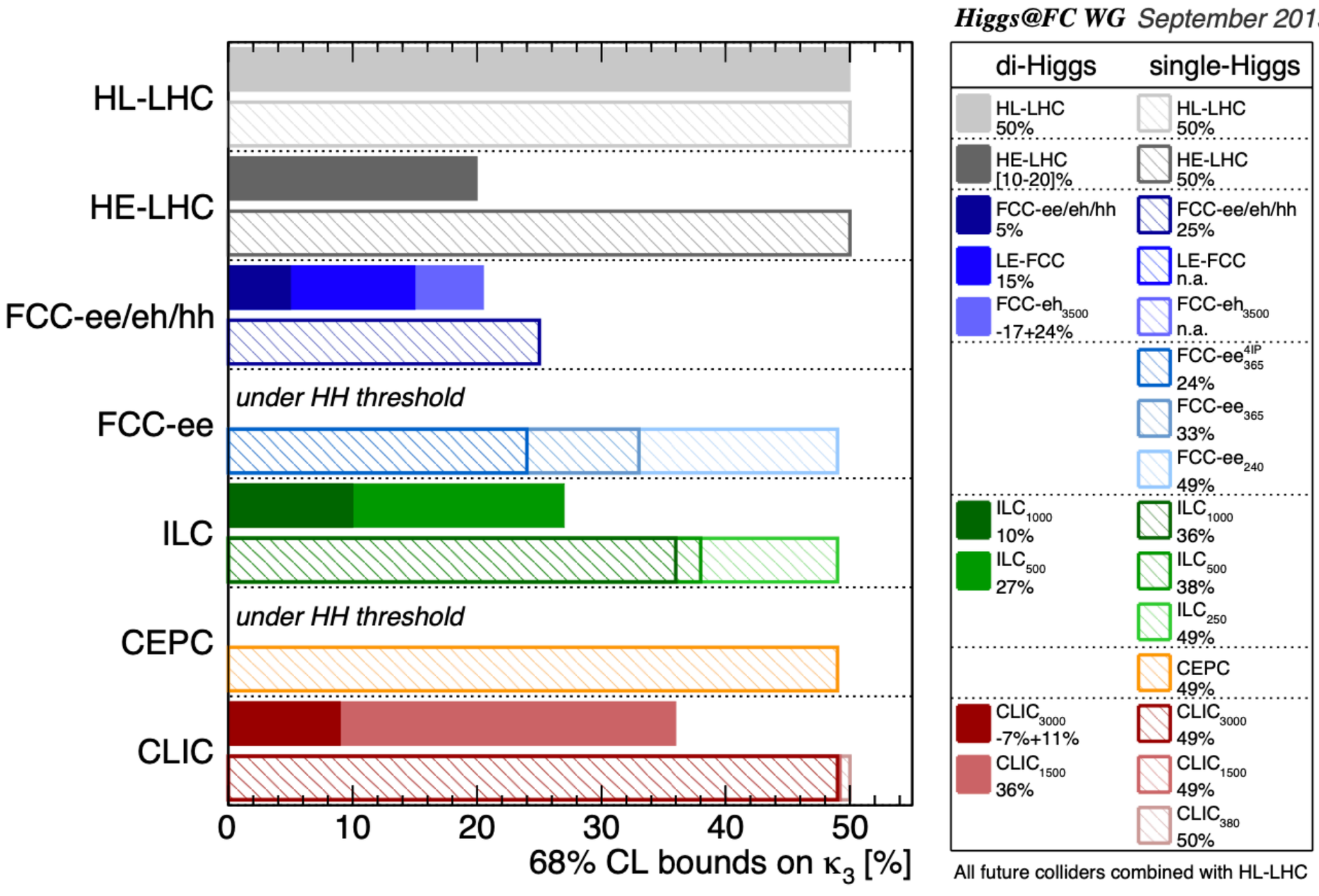


a few exotic decays of BR~0.1% confirmed by full simulation



[Liu, Wang, Zhang, arXiv:1612.09284

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



(ESU 2020 Physics Briefing Book, arXiv:1910.11775)

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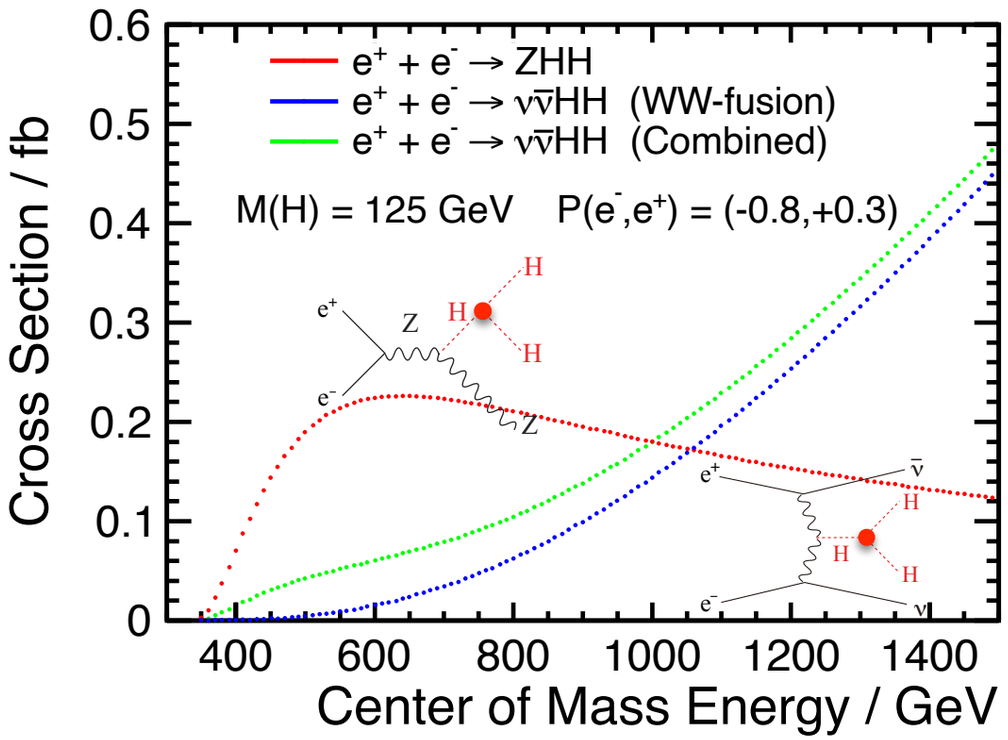
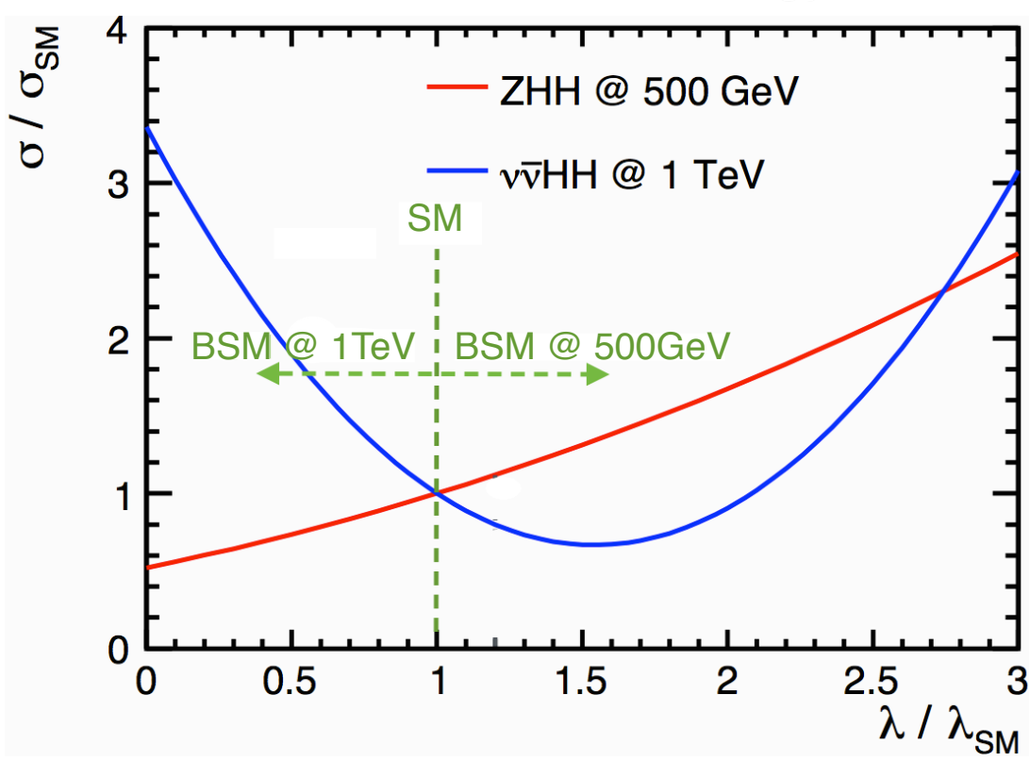
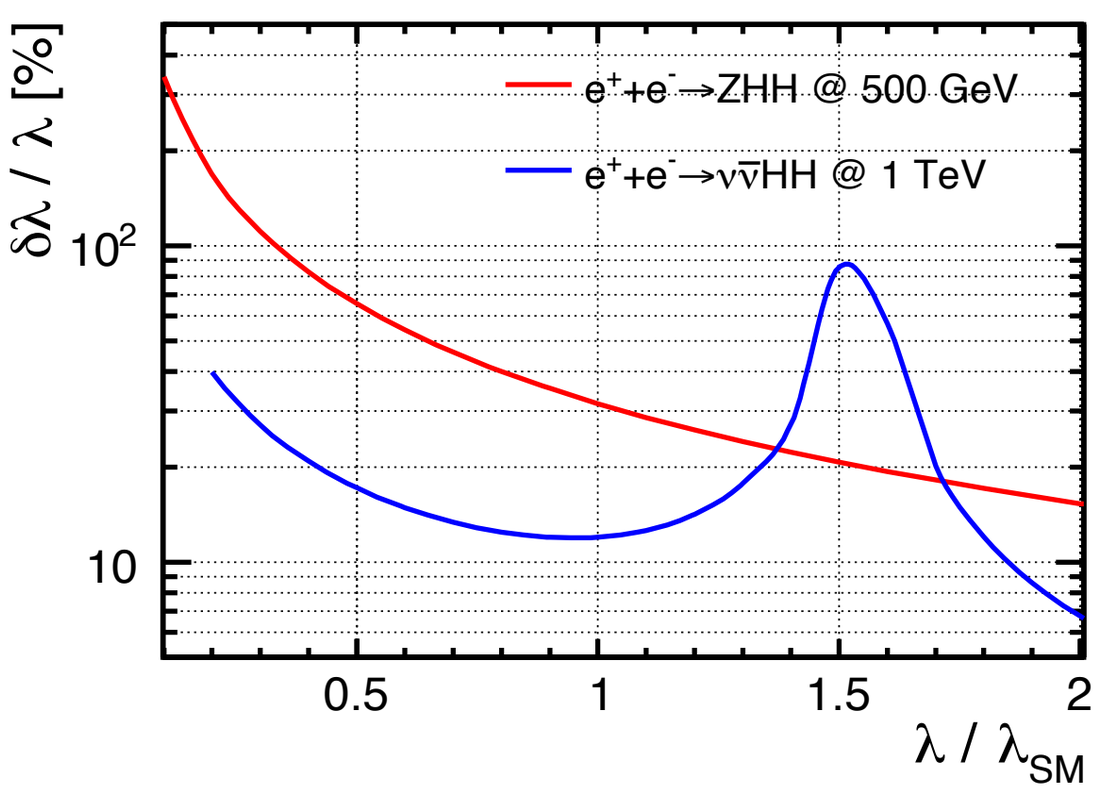


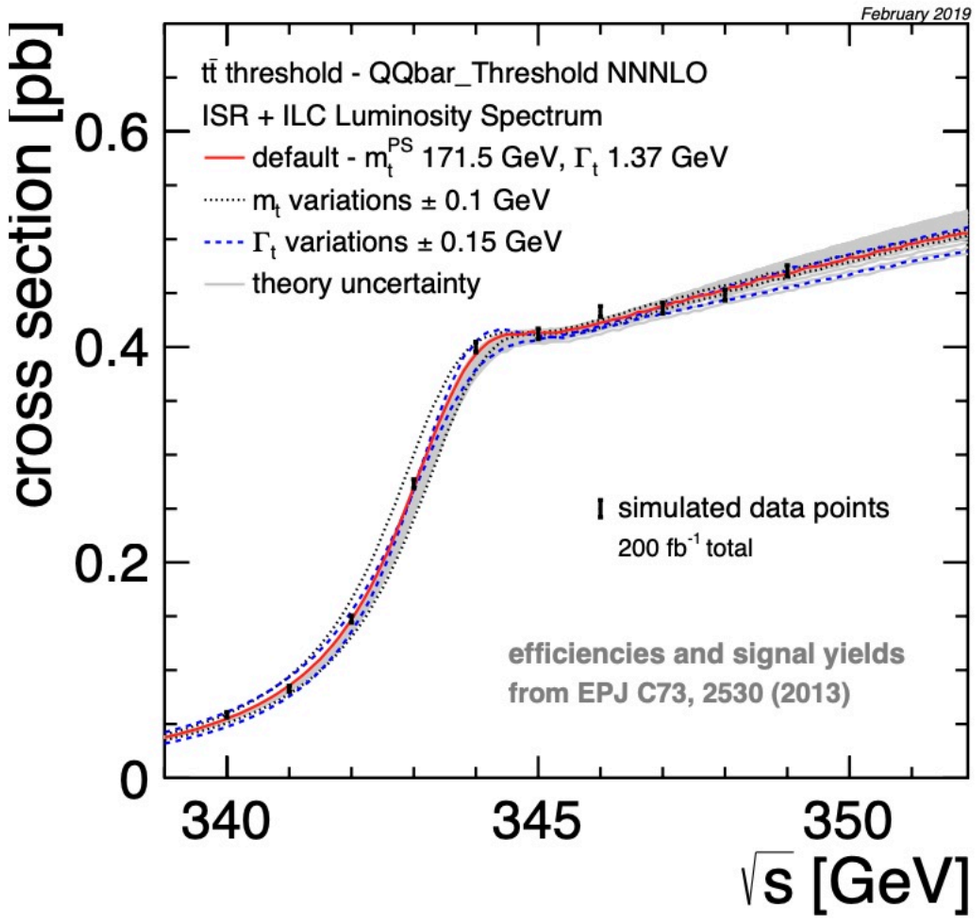
- complementarity between ZHH & vvHH (& LHC): interference nature
- λ_{HHH} : possibly large deviation in BSM
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be measured to ~13% using ZHH at 500 GeV e+e-





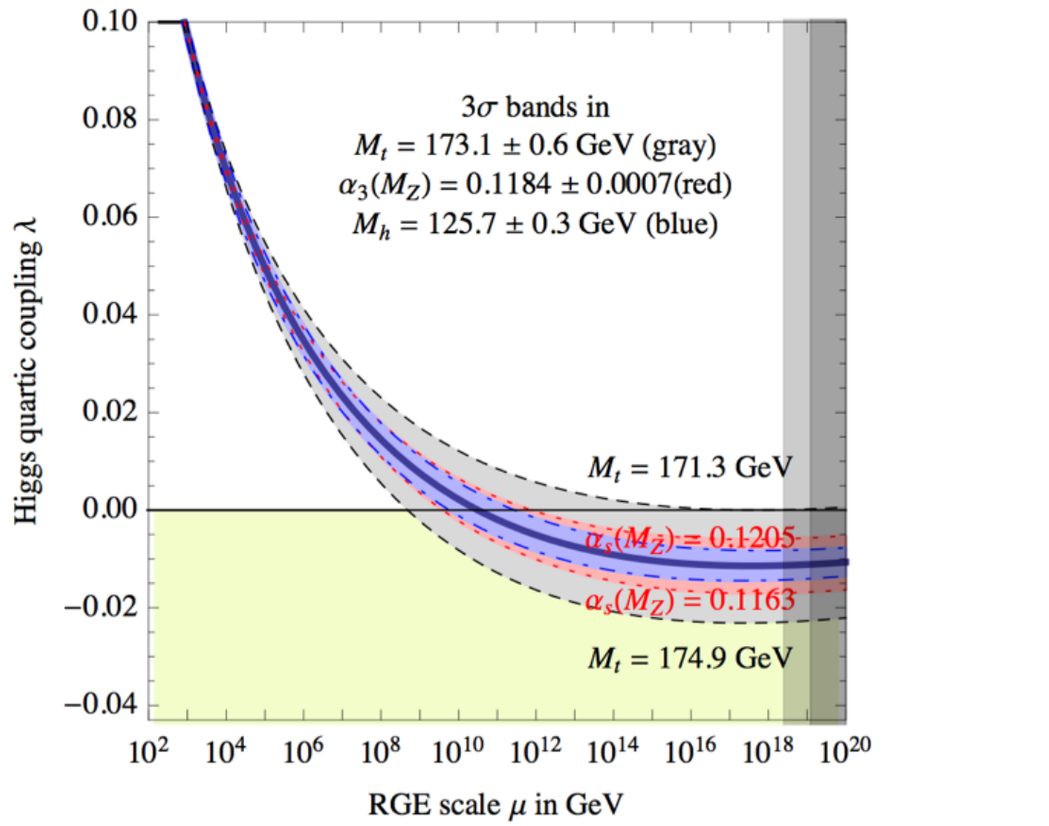
references for large deviations e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

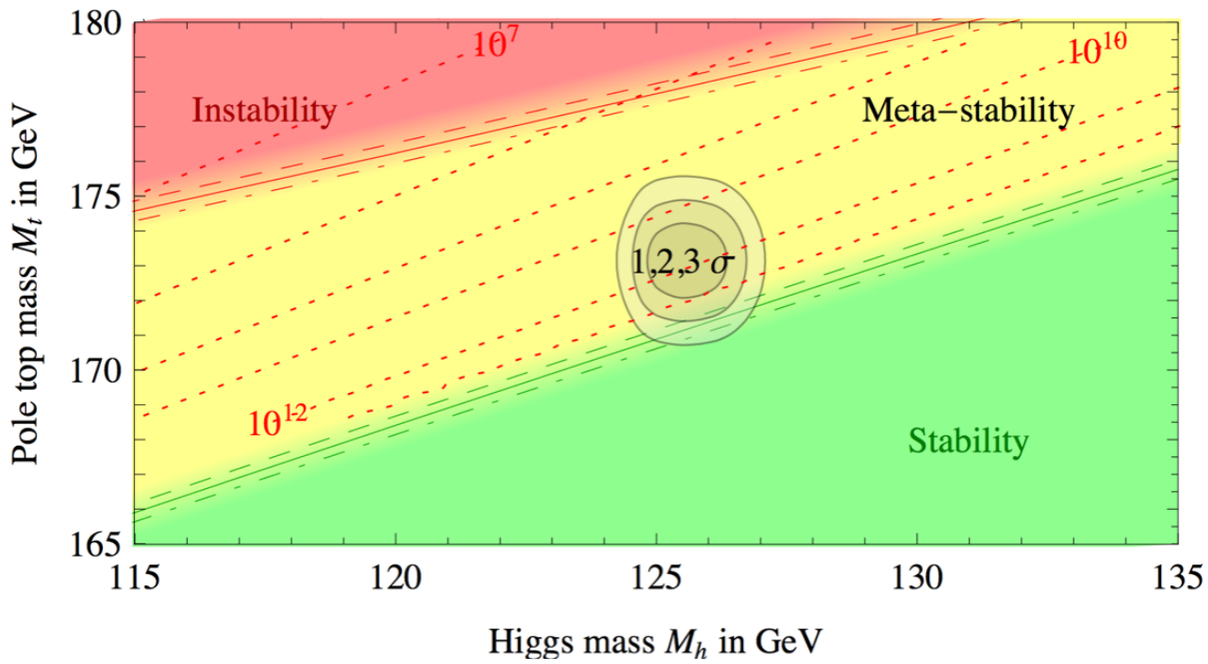
(ii-6) m_t: which vacuum are living in?



- 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



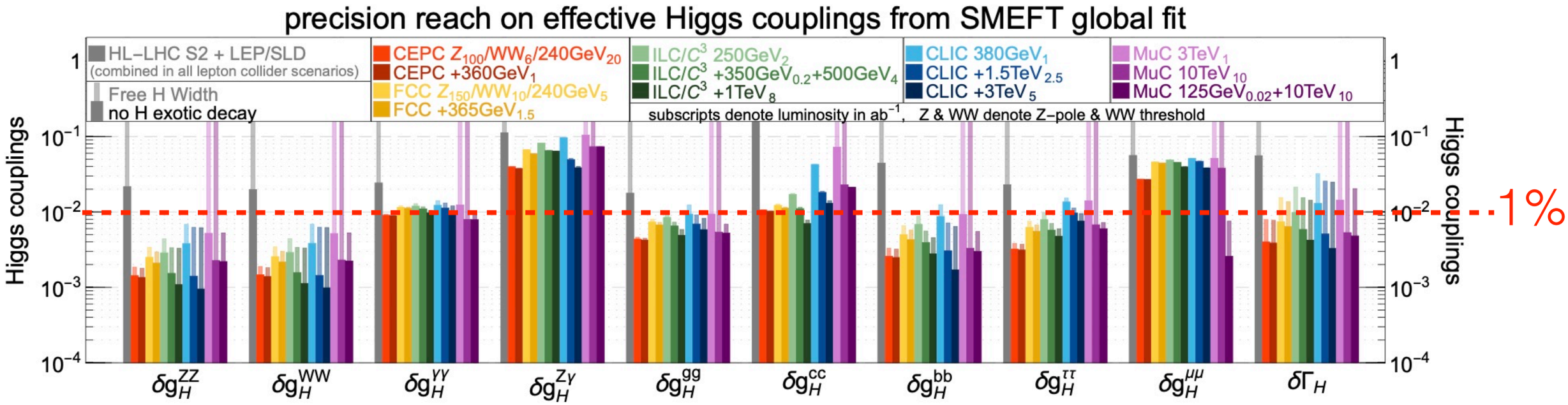


(iii) open questions

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

theory uncertainties

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



[arXiv:2206.08326]

theory uncertainties

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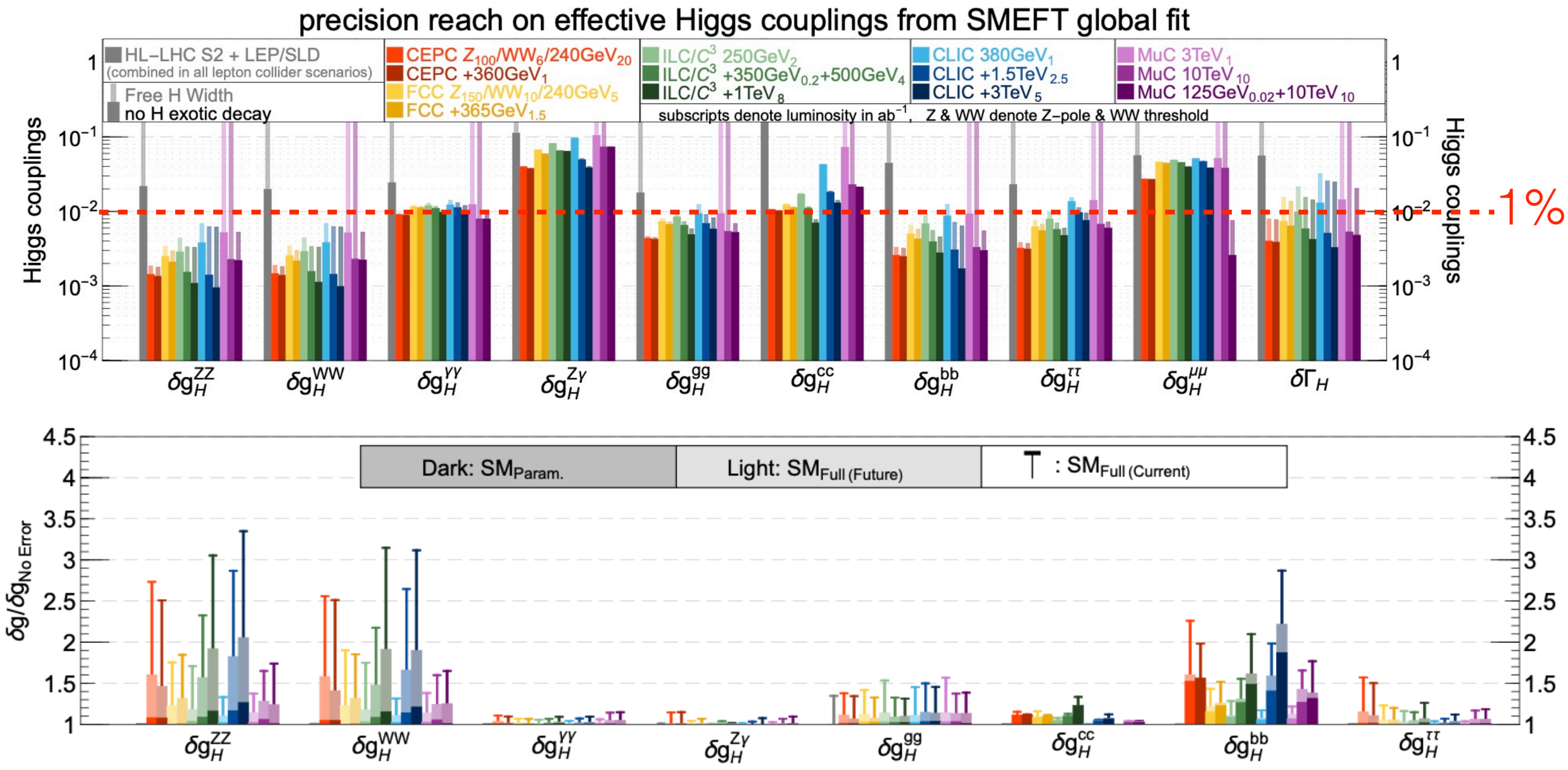
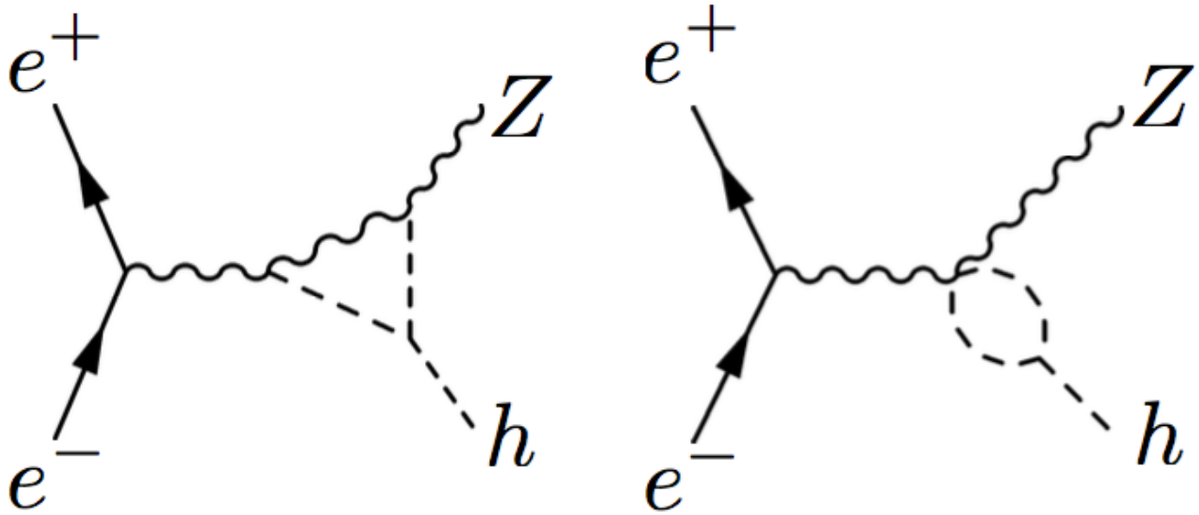


[arXiv:2206.08326]

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; Jung, Peskin, JT, paper in preparation

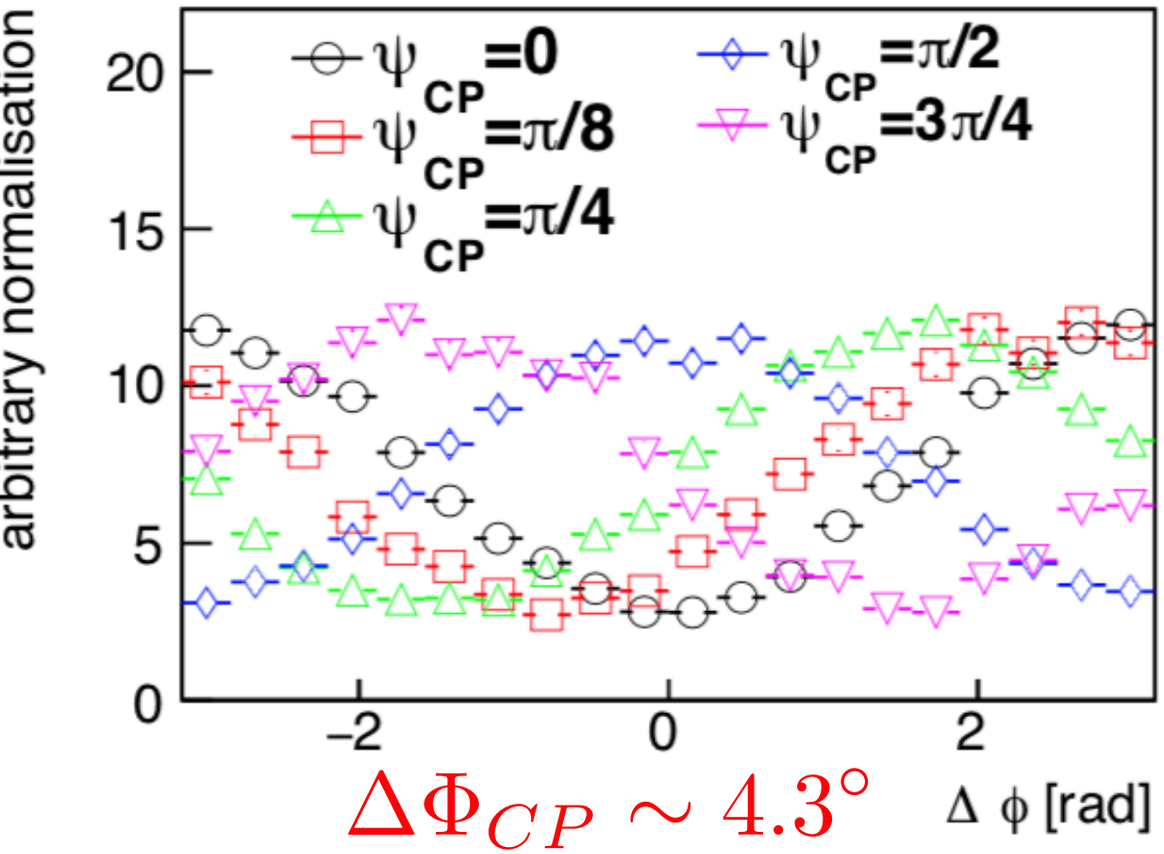
- **what if we include other NLO effects as well, e.g. top?**

Higgs CP: synergy between Hff & HVV?

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

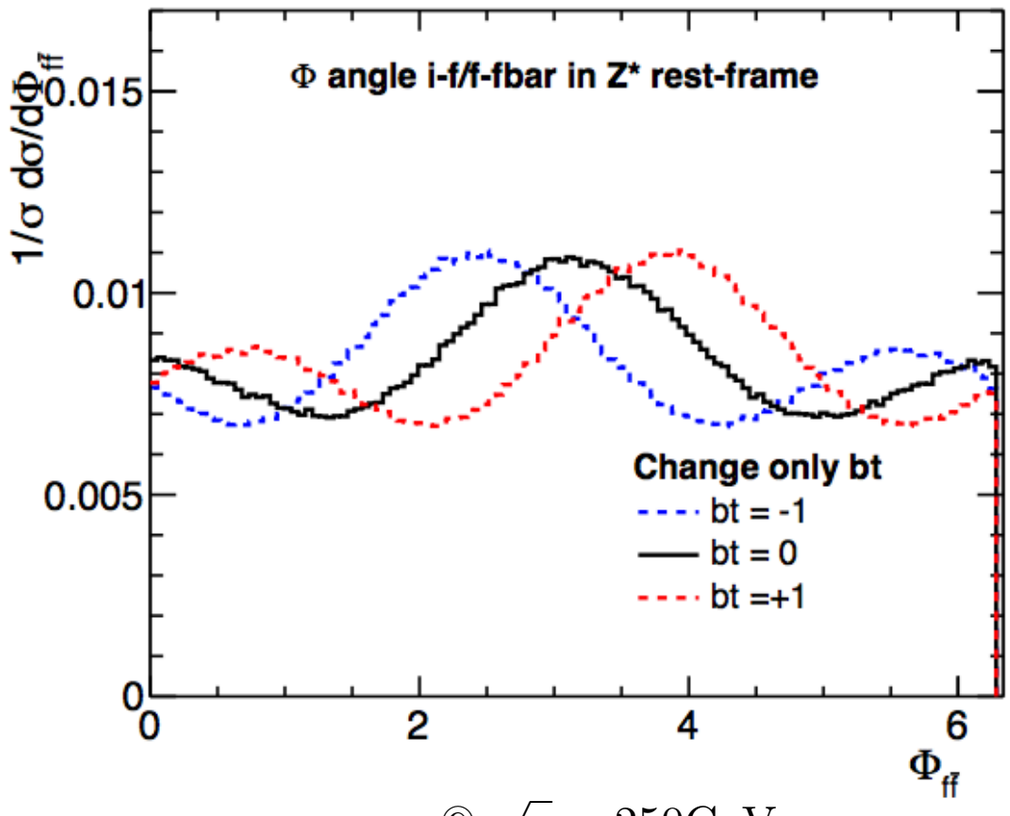
$$L_{hZZ} = M_Z^2(\frac{1}{v} + \frac{a}{\Lambda})hZ_\mu Z^\mu + \frac{b}{2\Lambda}hZ_{\mu\nu}Z^{\mu\nu} + \frac{\tilde{b}}{2\Lambda}hZ_{\mu\nu}\tilde{Z}_{\mu\nu}$$

(CP-odd)



$\Delta\Phi_{CP} \sim 4.3°$

[Jeans et al, arXiv:1804.01241]



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

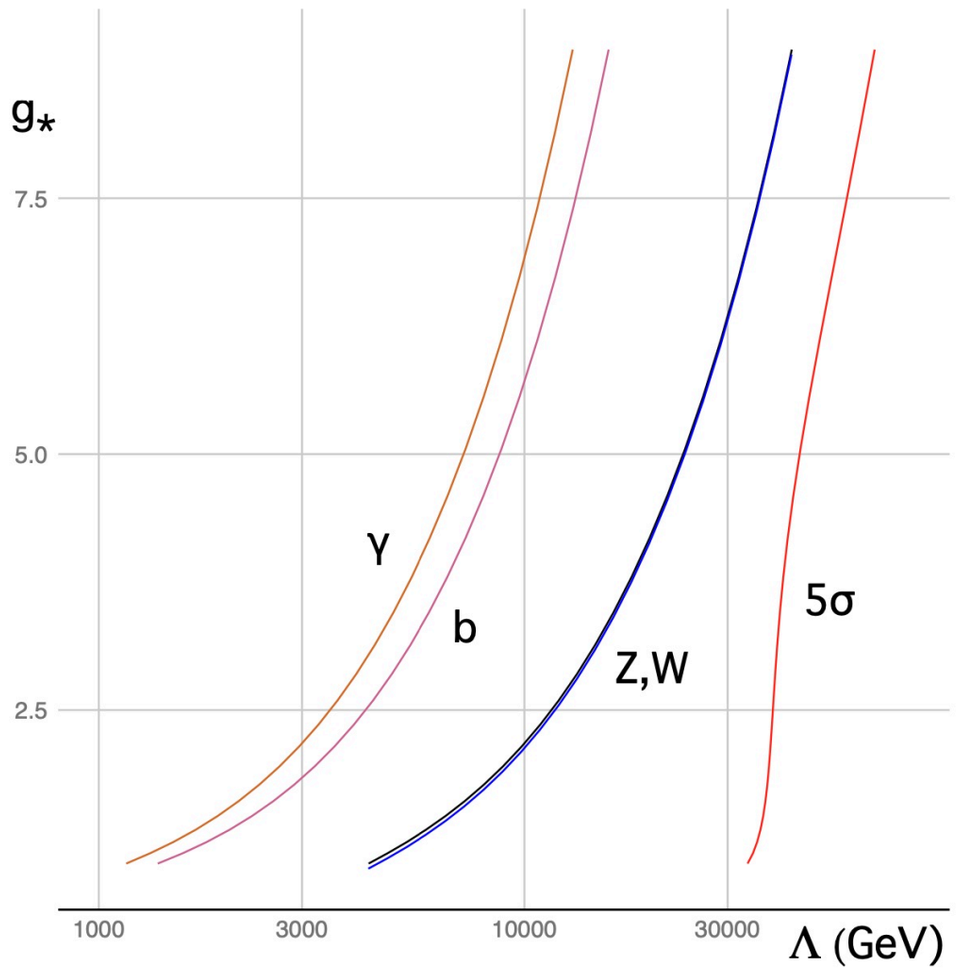
$\Delta\tilde{b} \sim 0.016$ (for Λ=1TeV)

[Ogawa et al, arXiv:1712.09772]

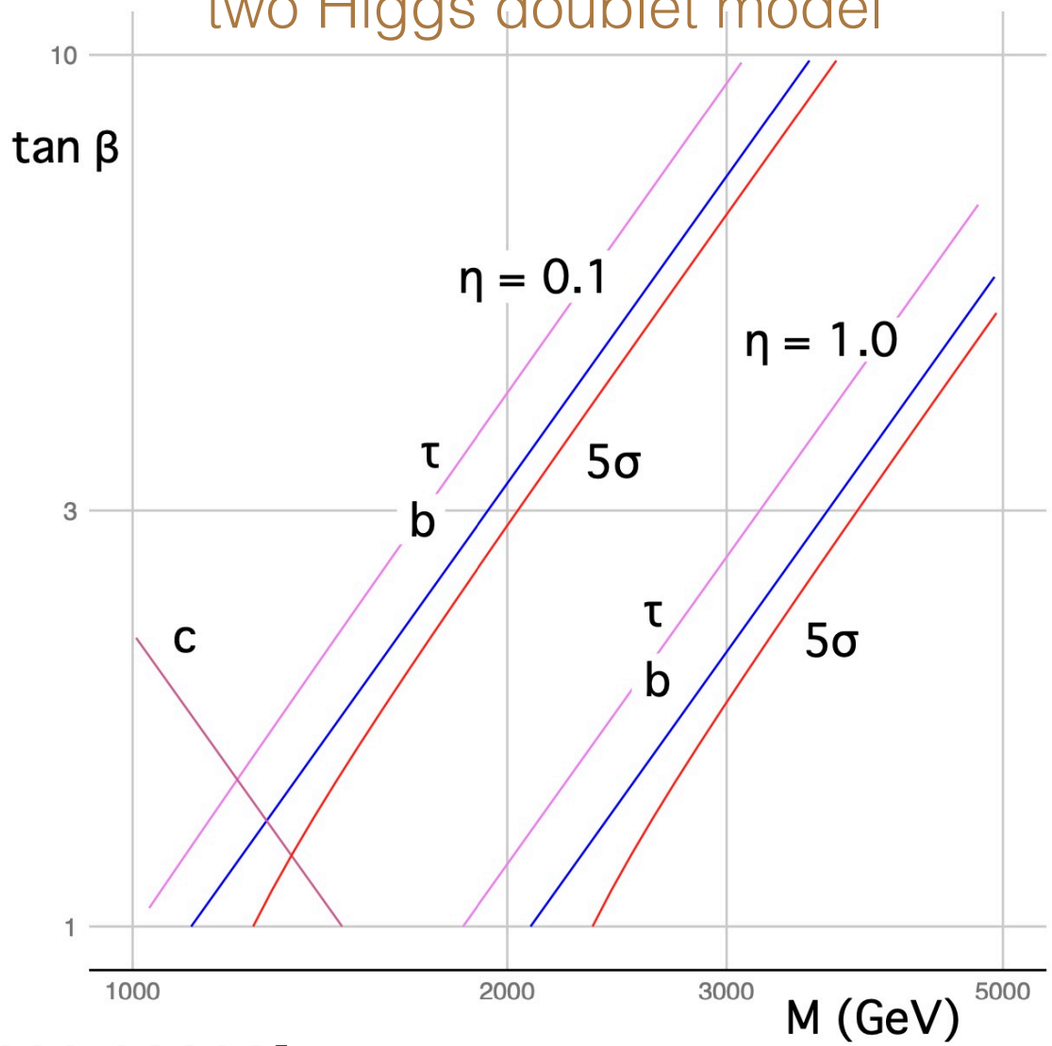
synergy between direct & indirect searches

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

strongly interacting little Higgs



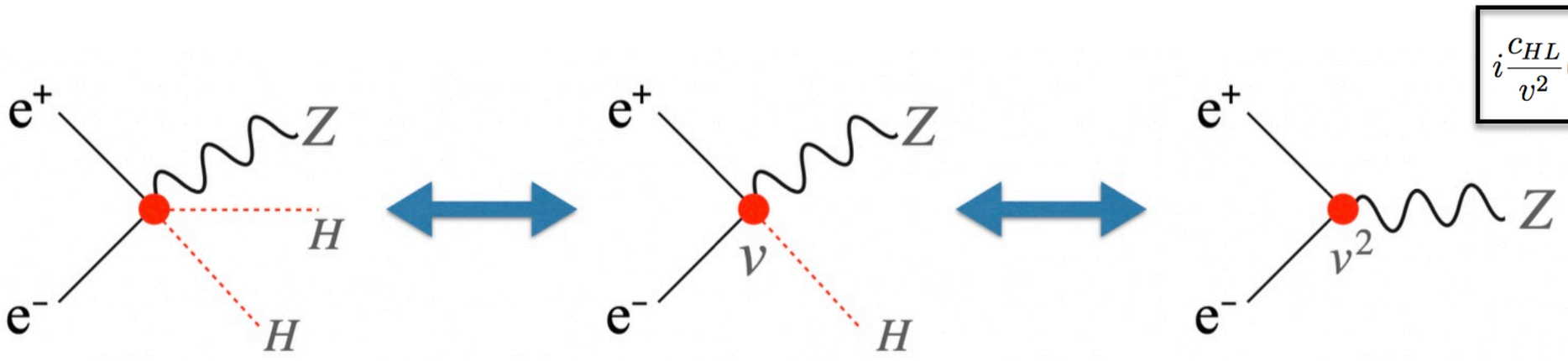
two Higgs doublet model



[Peskin, arXiv:2209.03303]

- continuous explorations along this line is very important for realizing a Higgs factory

Global interpretation: Higgs is not alone



[Snowmass EF04 Report, arXiv:2209.08078]

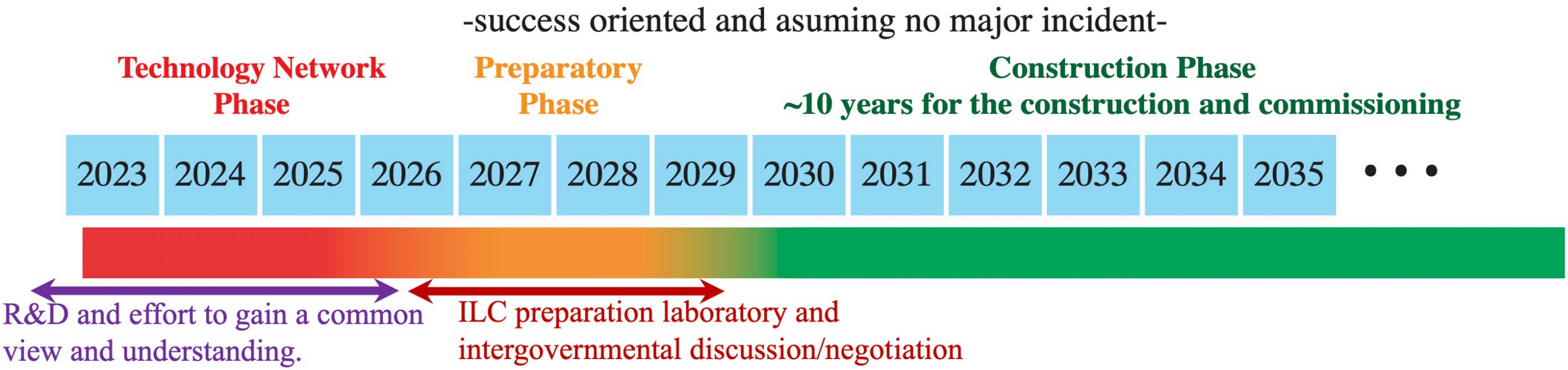
- Have we explored all the important synergies between Higgs and EW/Top/2f, between e+e- and LHC/low-energy measurements, which are naturally established by SMEFT?

- SMEFT is now the standard framework for Higgs coupling determination, but we know its limitations, what would be the alternative strategy?

(iv) ILC project status

[T.Nakada & S. Asai's LCWS 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)



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

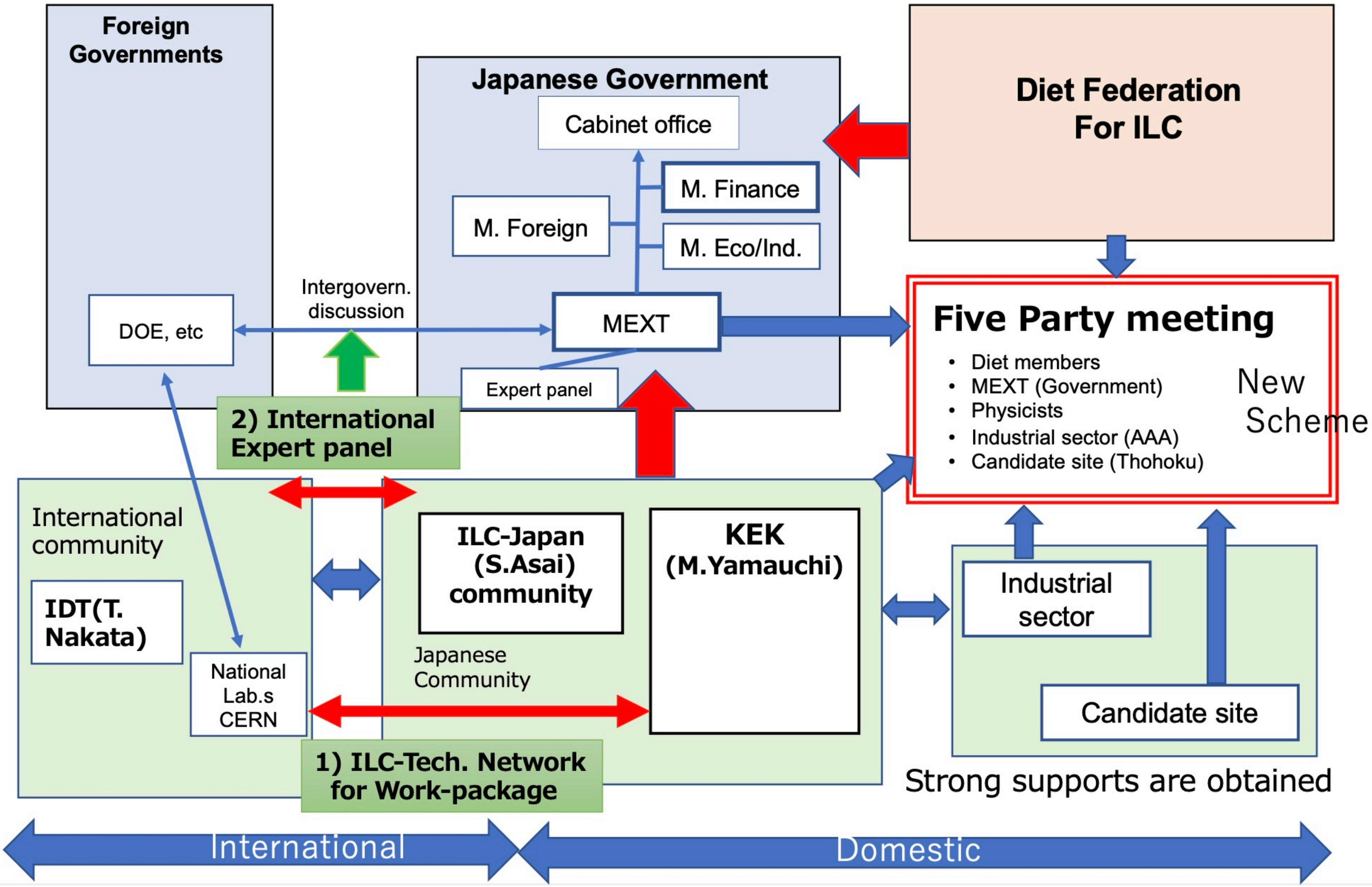
- IDT-WG3 Physics Group: monthly open meeting

- ILC-Japan Physics Group: general meeting / 2-3 months

- ECFA Study on Higgs / EW / Top factories

backup

Promotion scheme of ILC / relation of Stakeholder



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

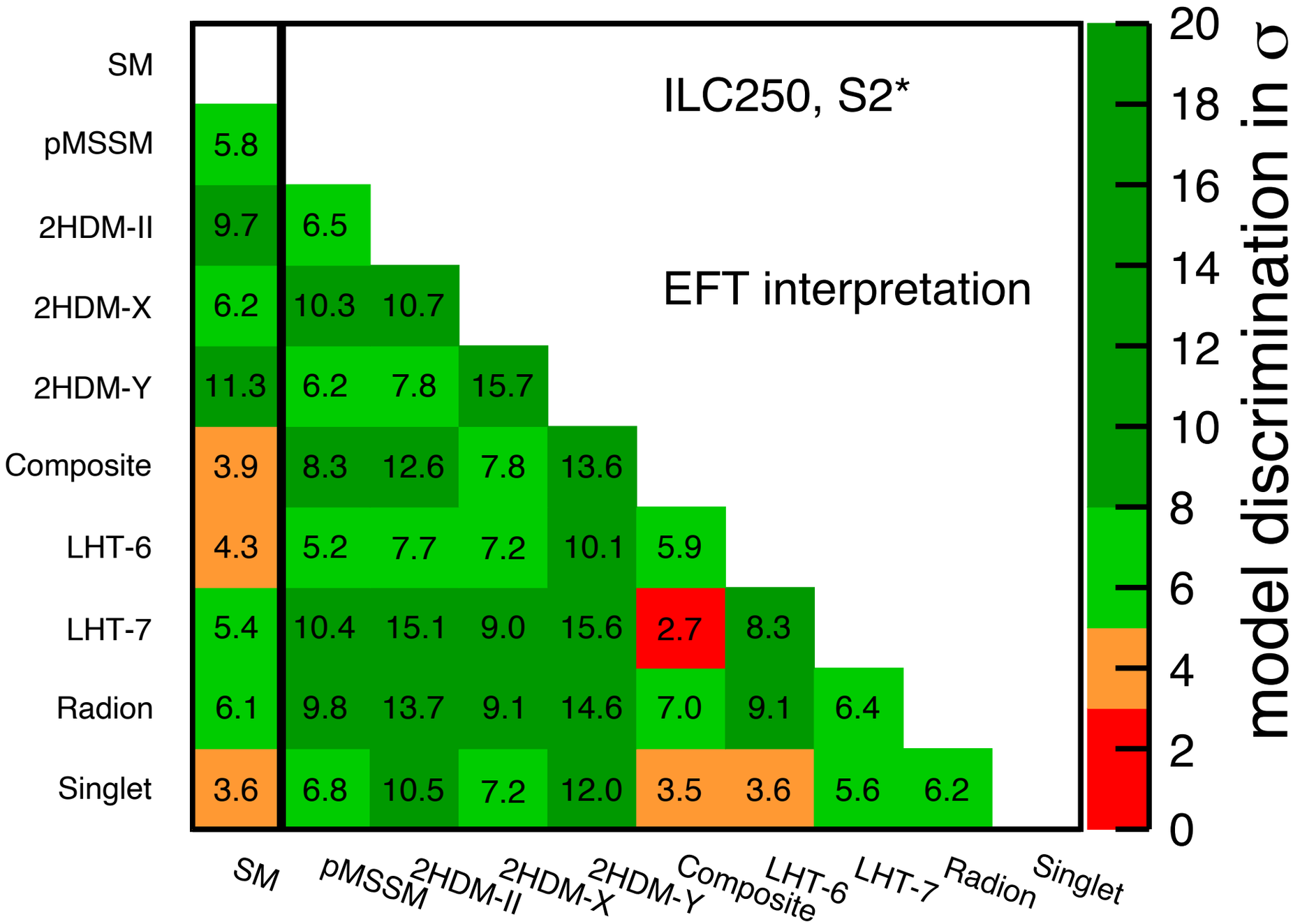
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> quantitative assessment for models discrimination

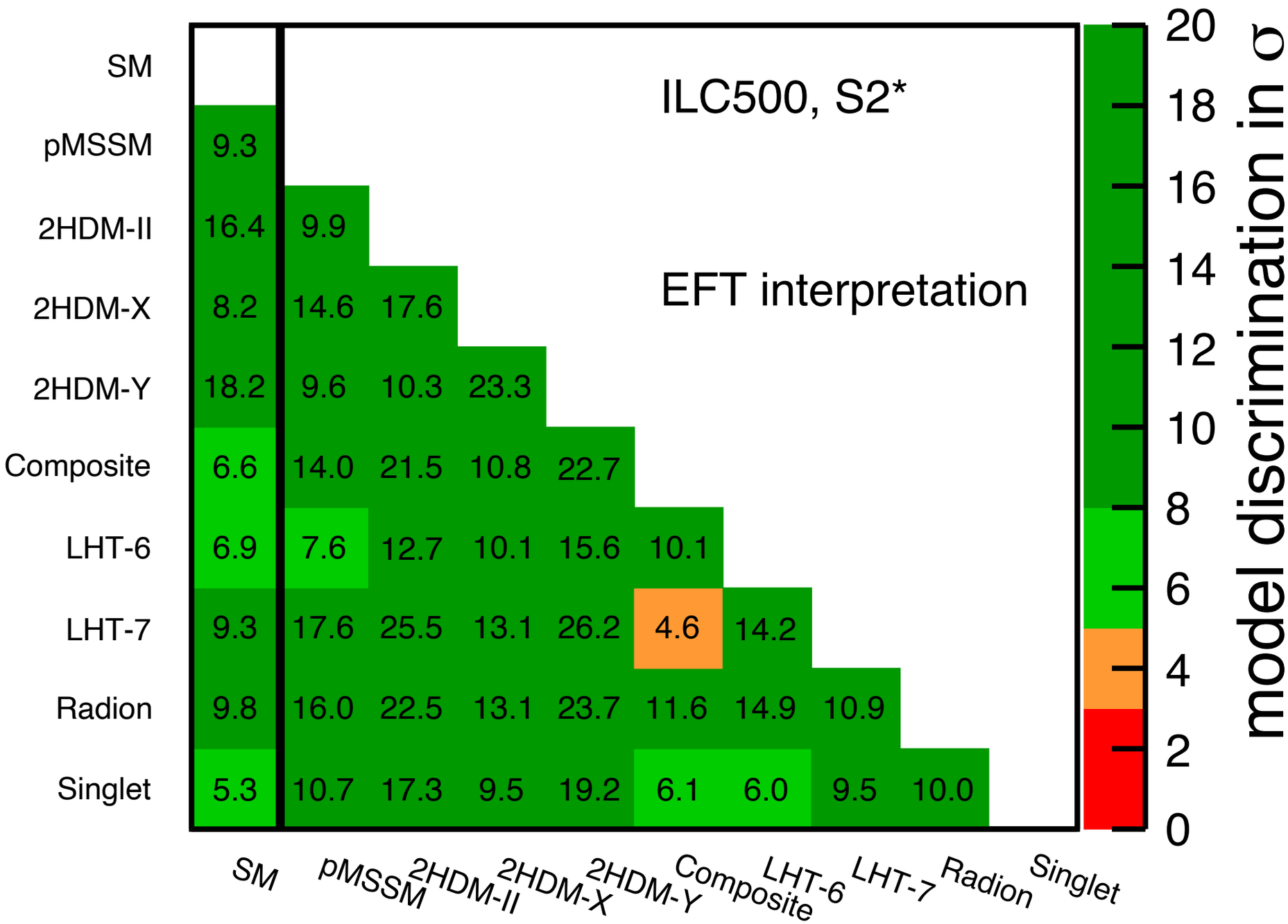
model parameters (chosen as escaping direct search at HL-LHC)

- 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

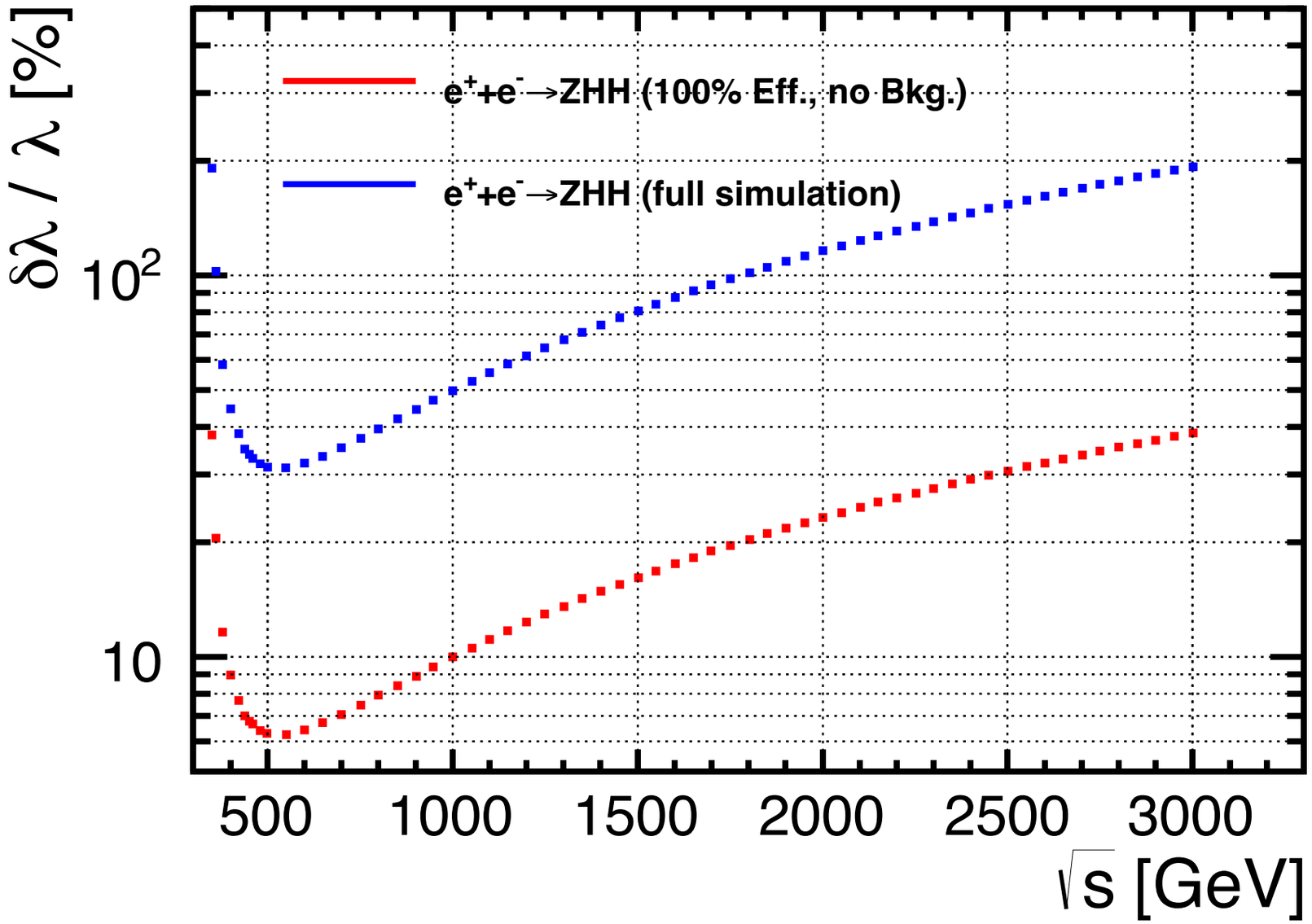
BSM benchmark models discrimination at ILC250



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



can we improve $\Delta\lambda_{HHH}$ by a factor of 5?

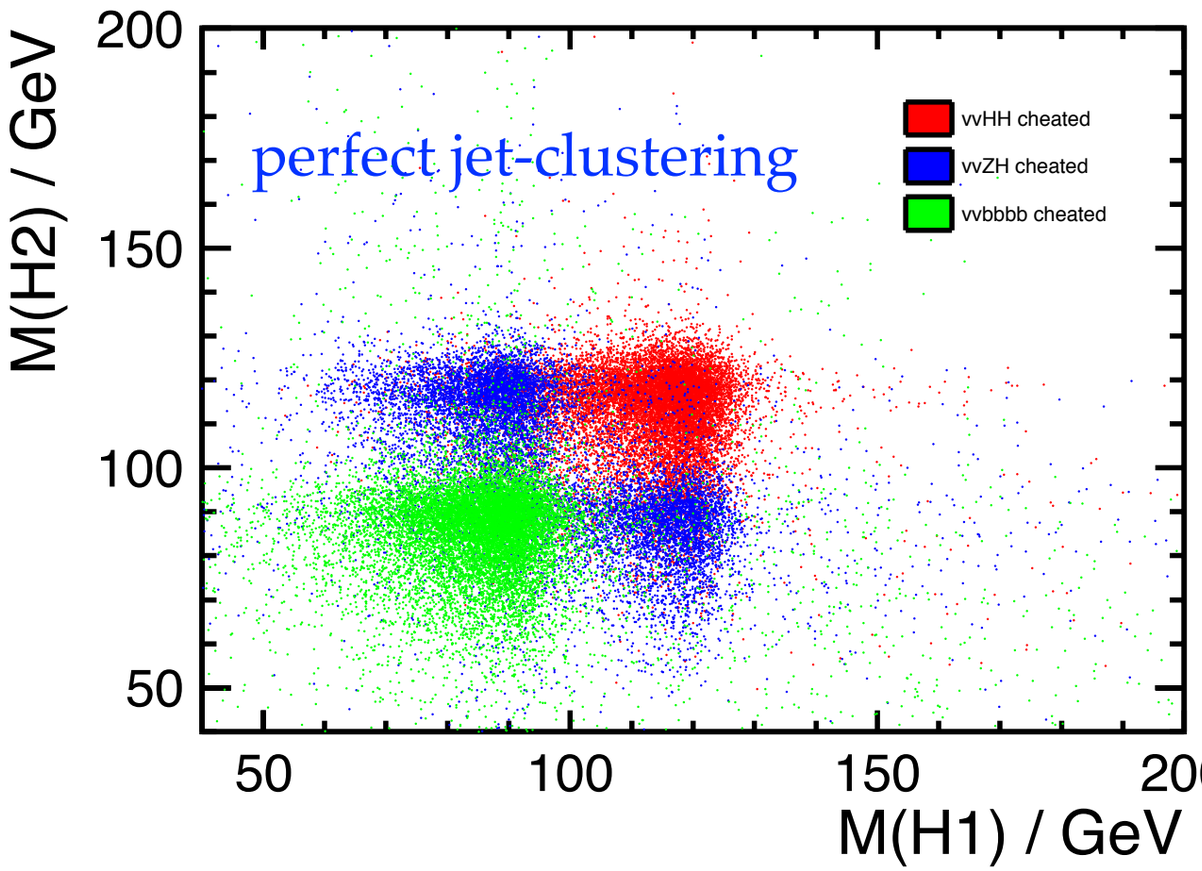


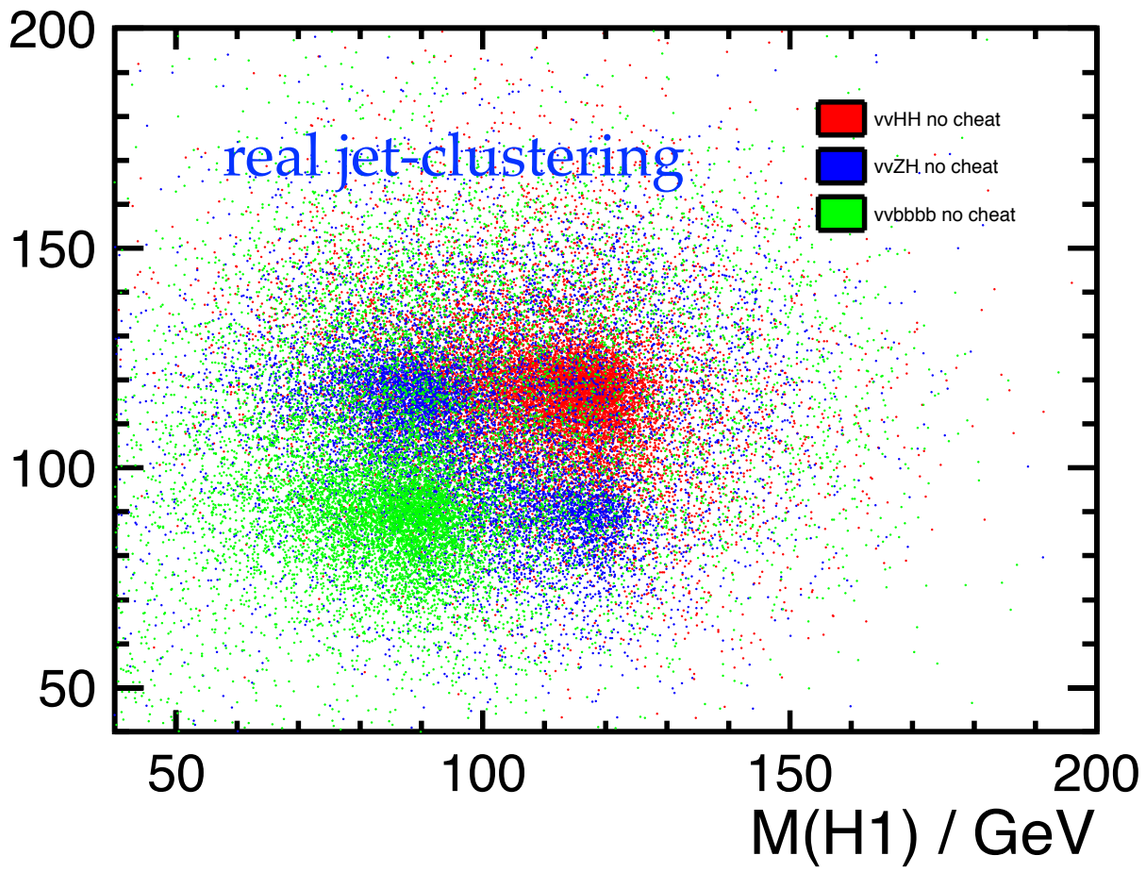
Di Micco et al, arXiv:1910.00012

improving jet-clustering algorithm?

ZHH->ννbbbb (BG: ZZH and ZZZ)

scatter plot of two Higgs masses



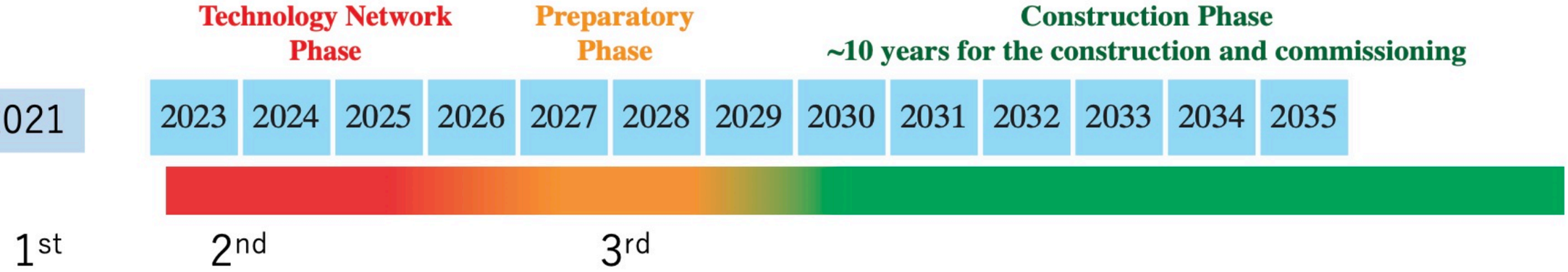


- the mis-clustering of particles degrades significantly the separation between signal and BG.
- it is studied that using perfect color-singlet-jet-clustering can improve $\delta\lambda/\lambda$ by 40%

7. Timeline / Step-by-Step ILC promotion

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

IDT view on the ILC project timeline
-success oriented and asuming no major incident-



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.