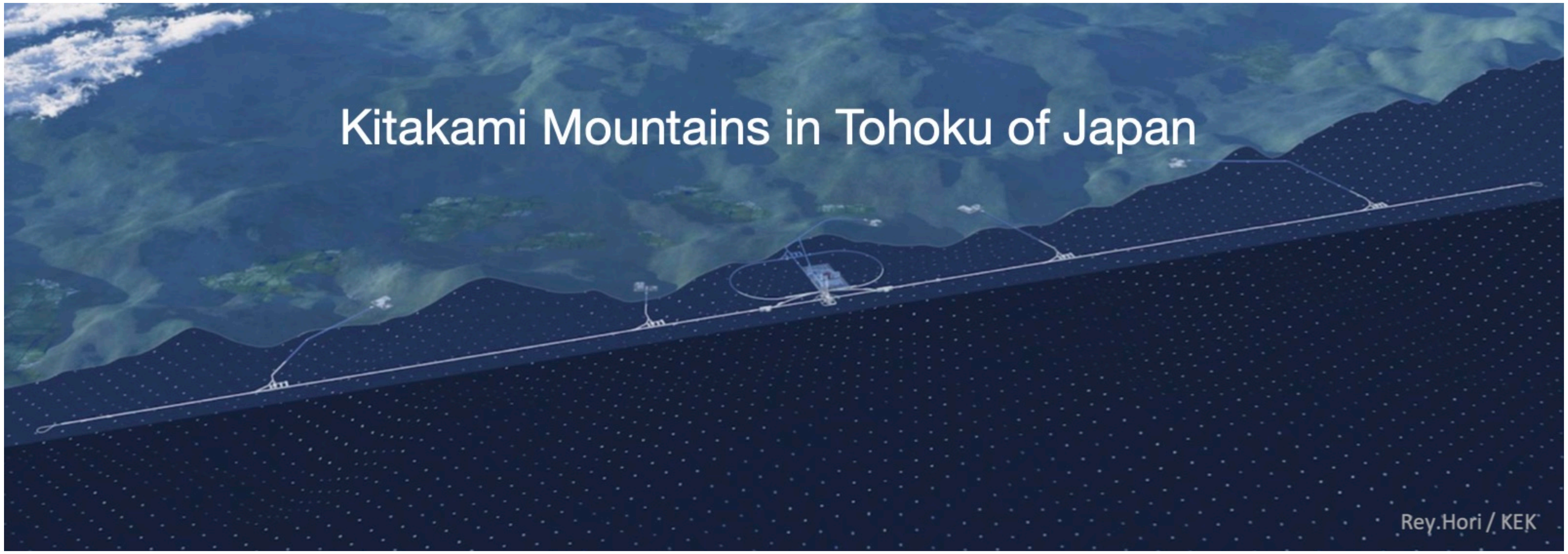
Higgs physics with ILC



ILC Supporters

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

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

ICEPP
The University of Tokyo

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

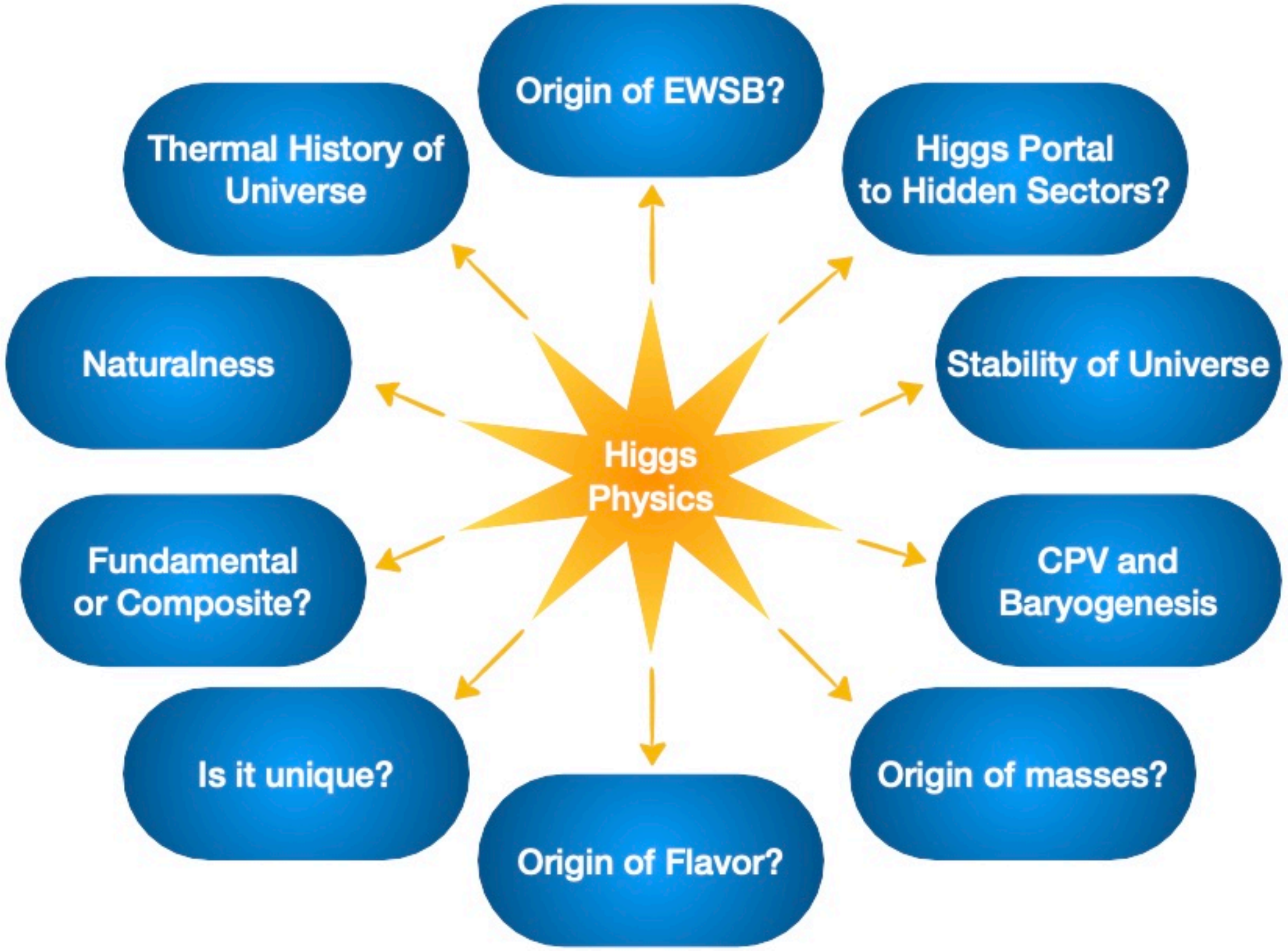
- Recent news of the ILC project

  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]

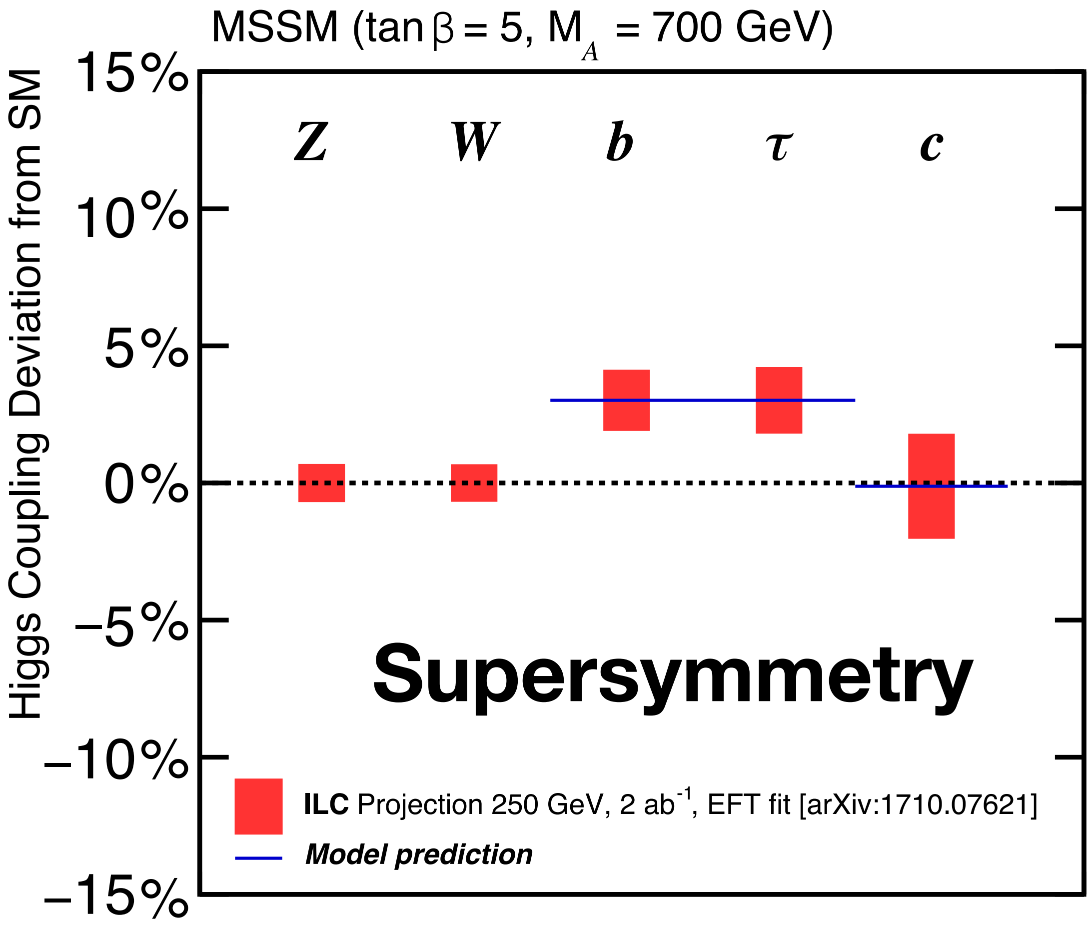
+

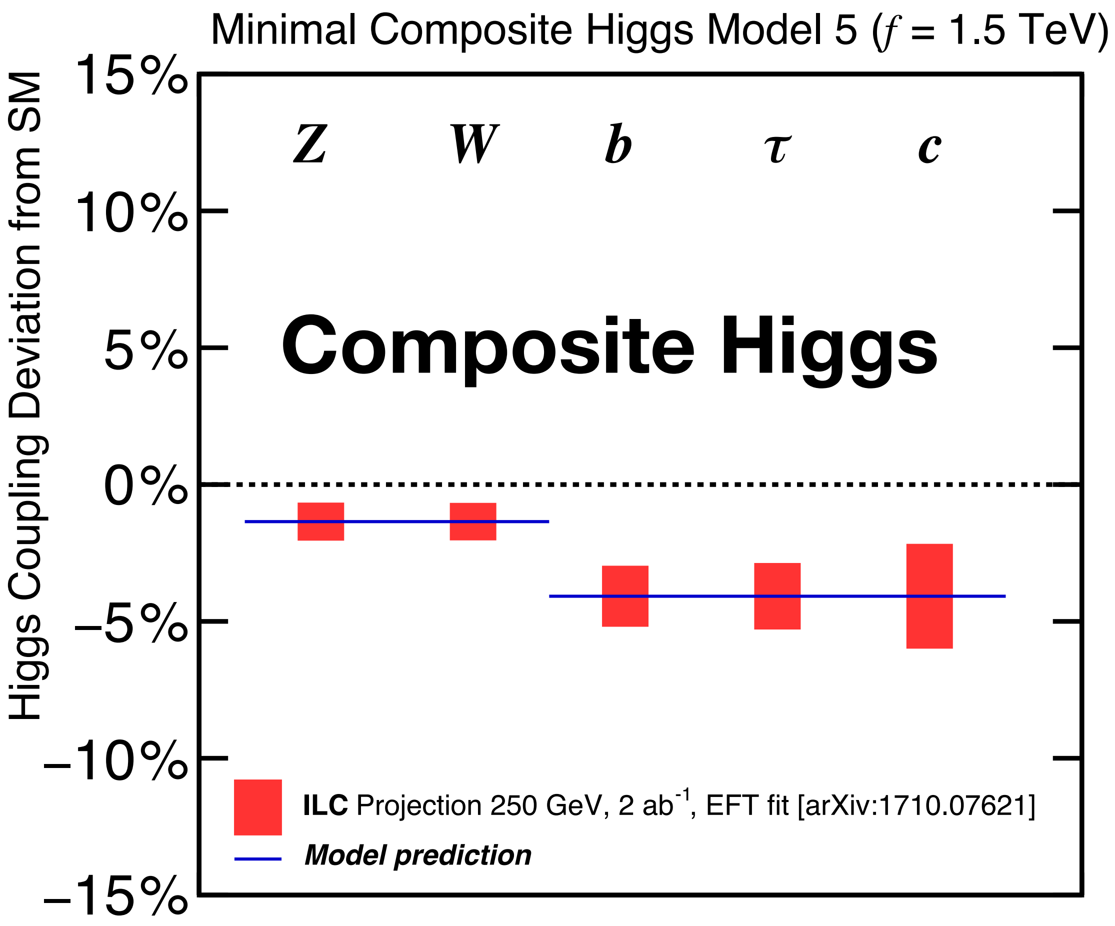
[all talks in this conference]

- 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]

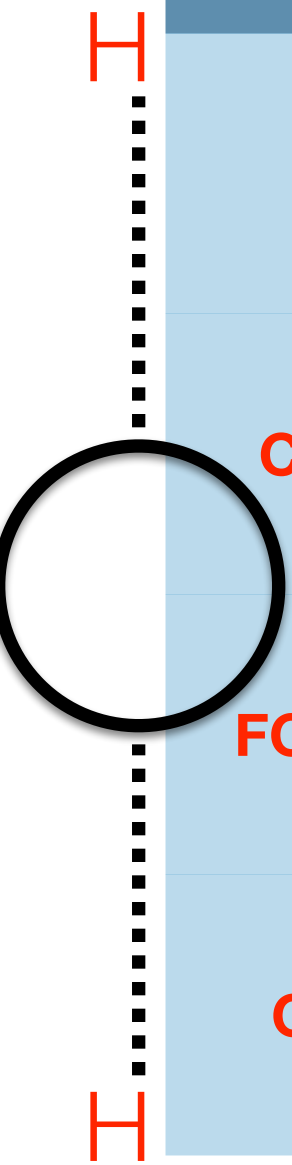
- can not only *discover* BSM physics, but also identify the *nature of BSM* by *precisely* measuring the *deviation pattern*

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

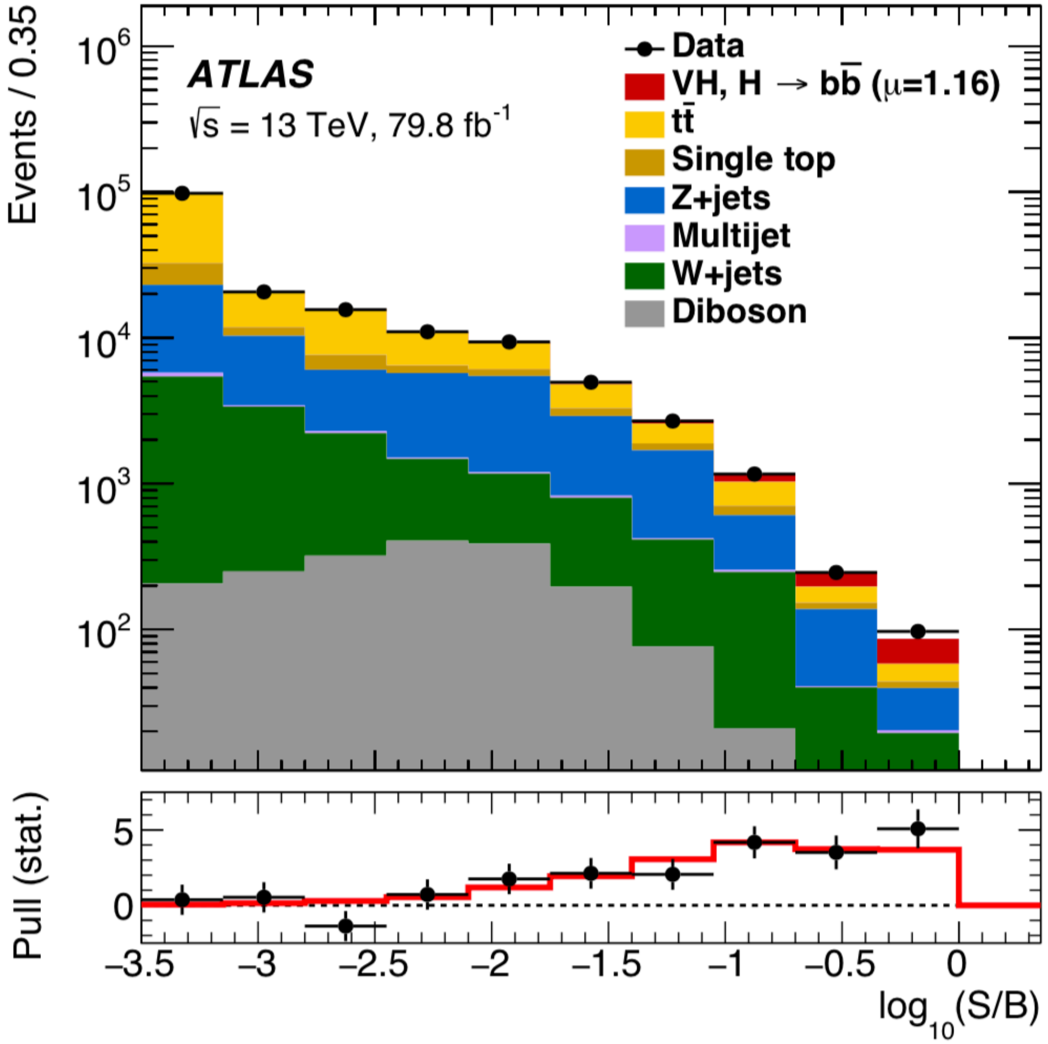
(+ emerging C^3, Muon Colliders, μTristen, etc)

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)



# of Higgs produced: ~4,000,000

significance: 5.4σ

[ATLAS, 1808.08238; CMS, 1808.08242]

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

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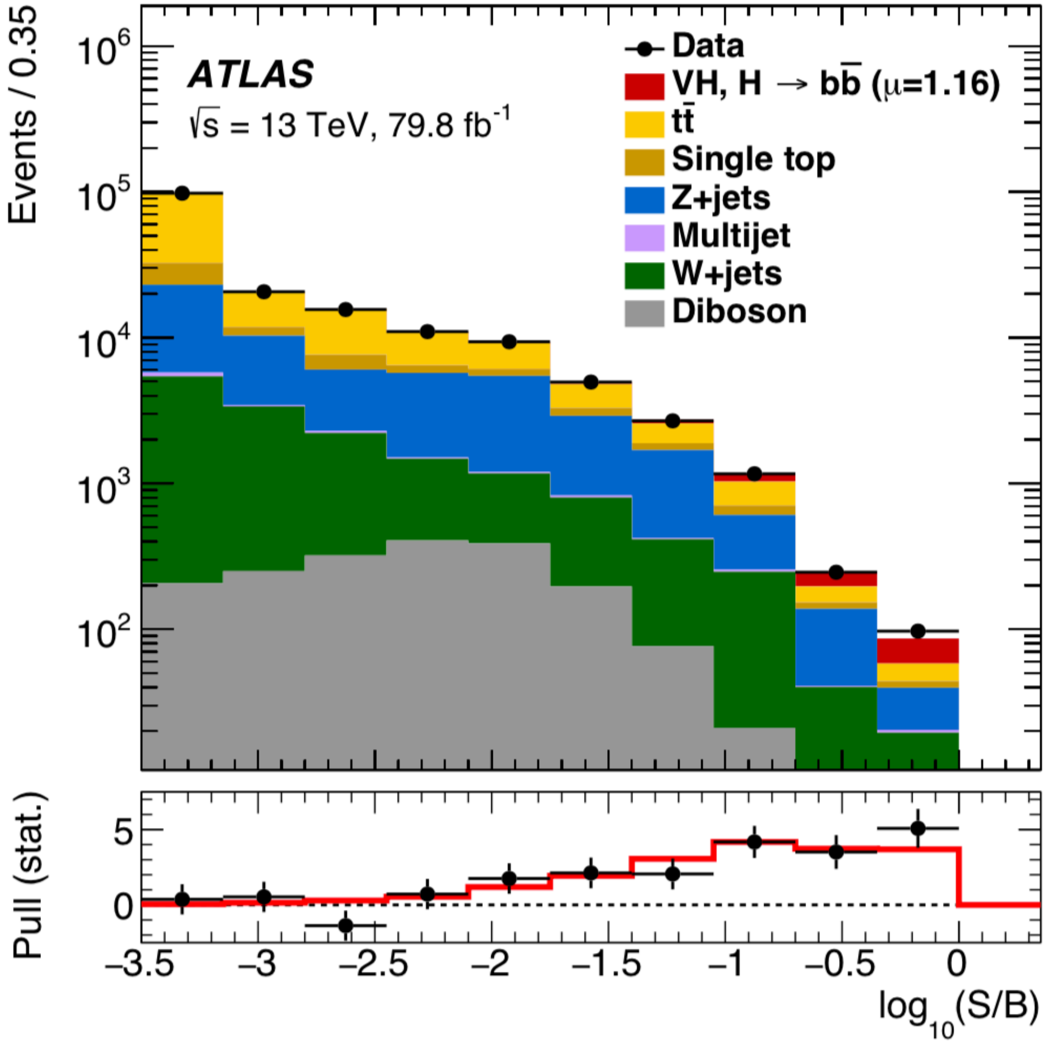

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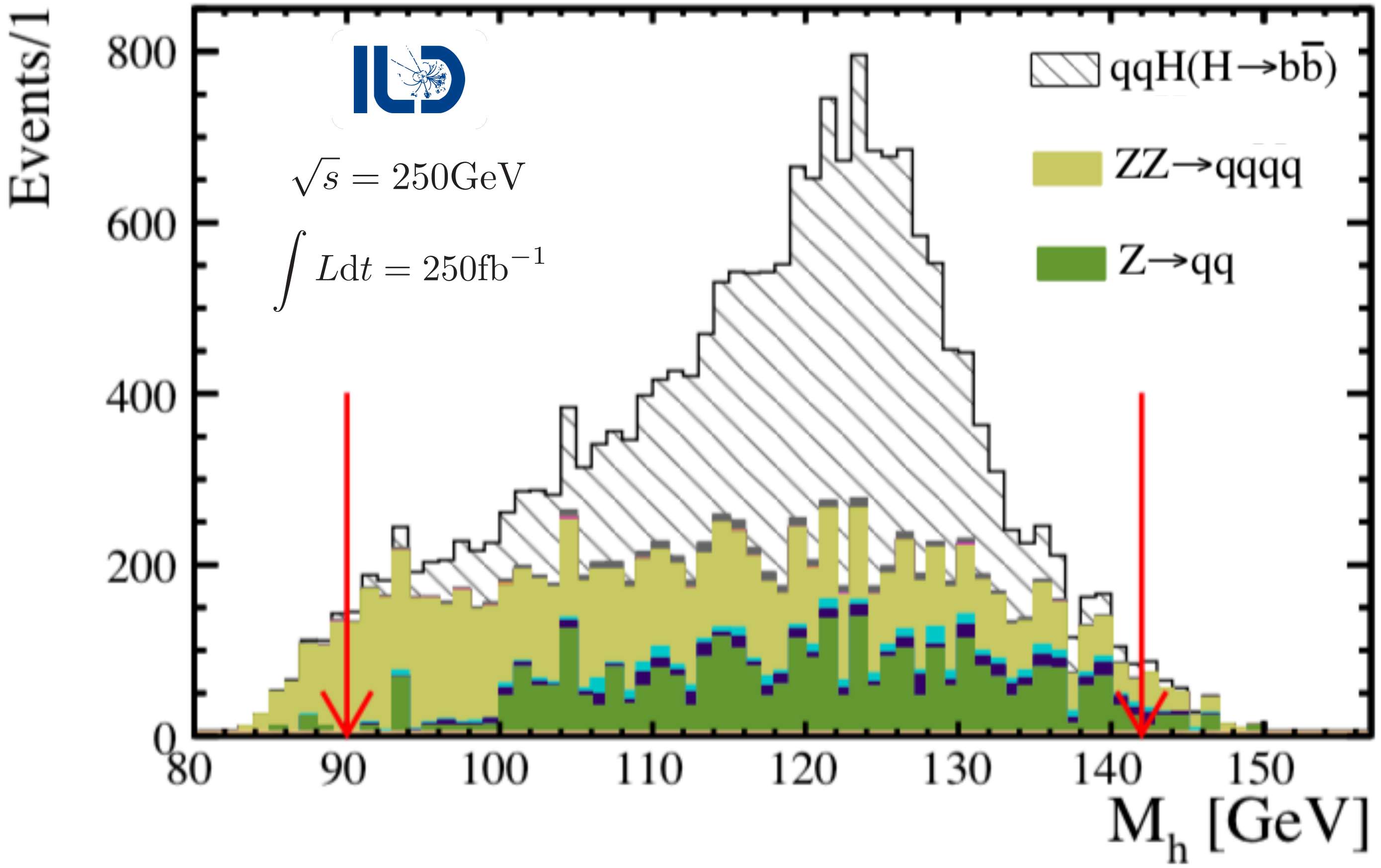


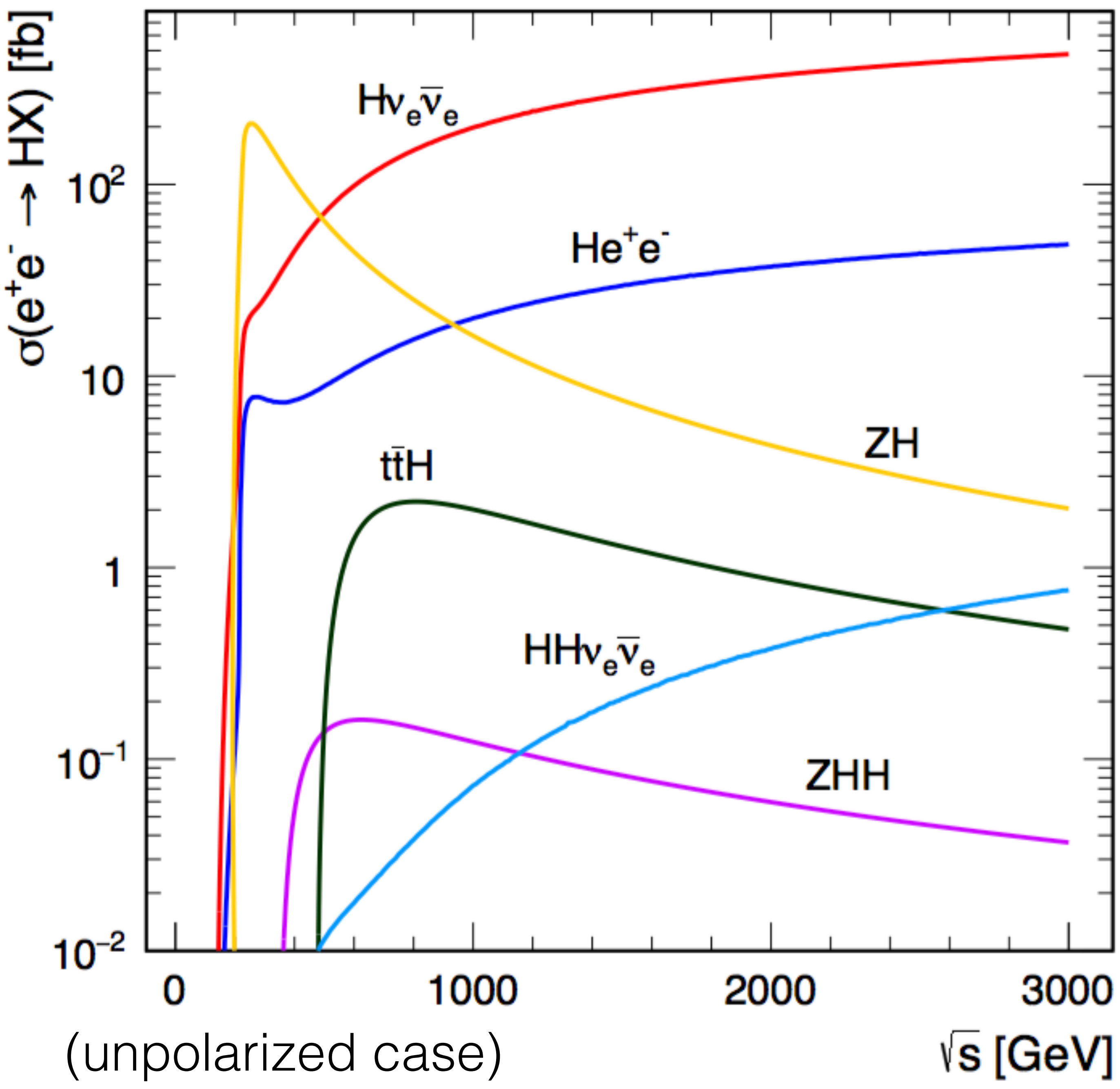
full detector simulation

~400

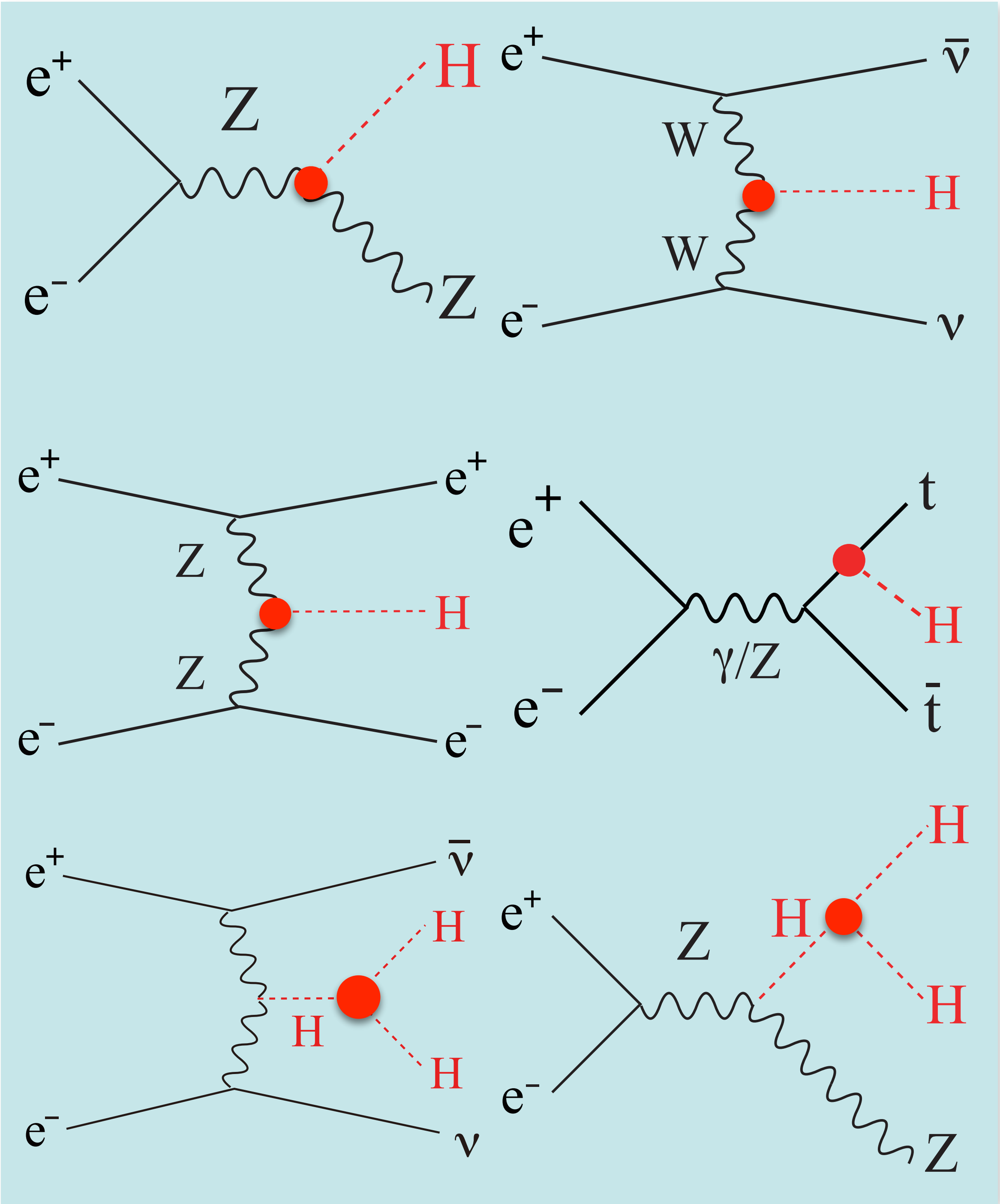
5.2σ

[Ogawa, PhD Thesis (Sokendai '18)]

Higgs productions at e+e-

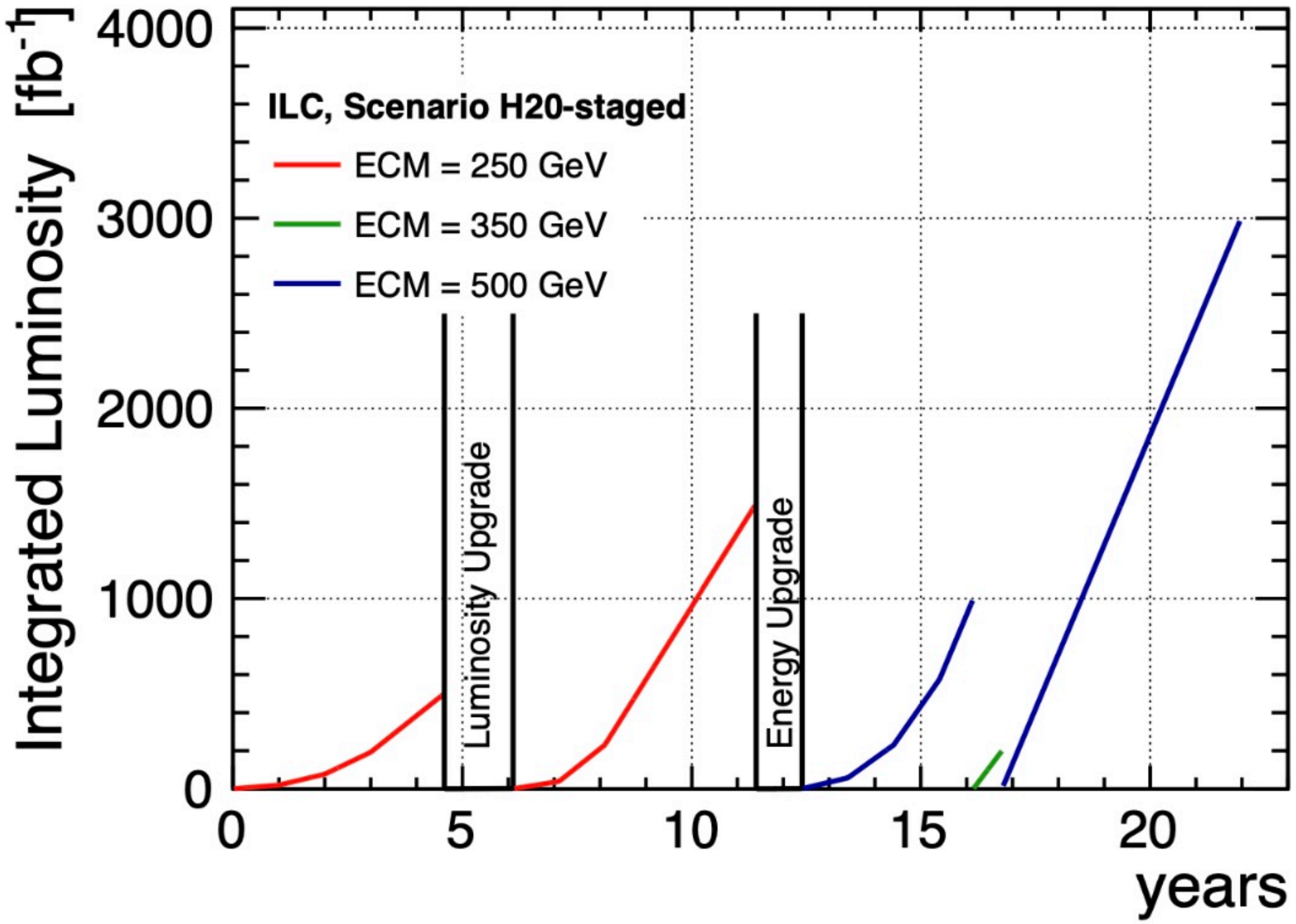


(unpolarized case)



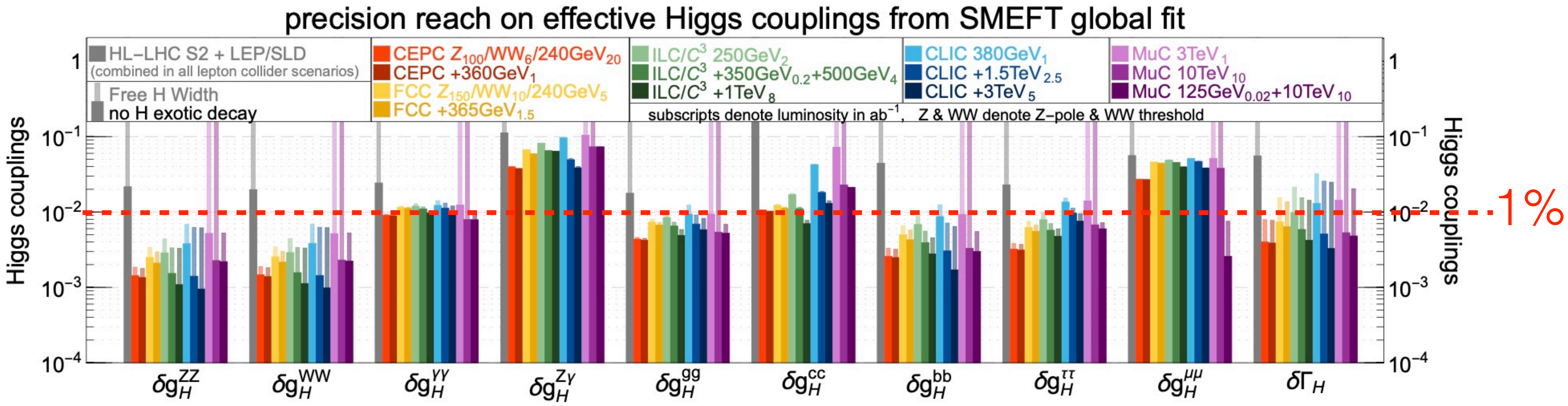
- two apparent important thresholds: √s ~ 250 GeV for ZH, ~500-600 GeV for ZHH and ttH
- + another threshold for t t-bar, important for Higgs physics as well

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

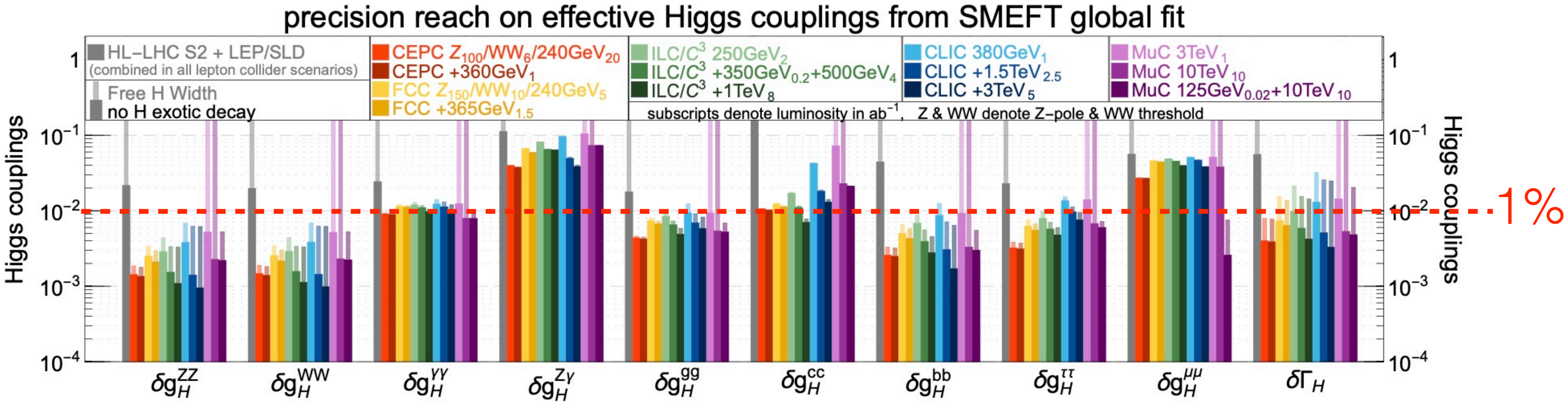
Projections of Higgs coupling precisions



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

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

Projections of Higgs coupling precisions

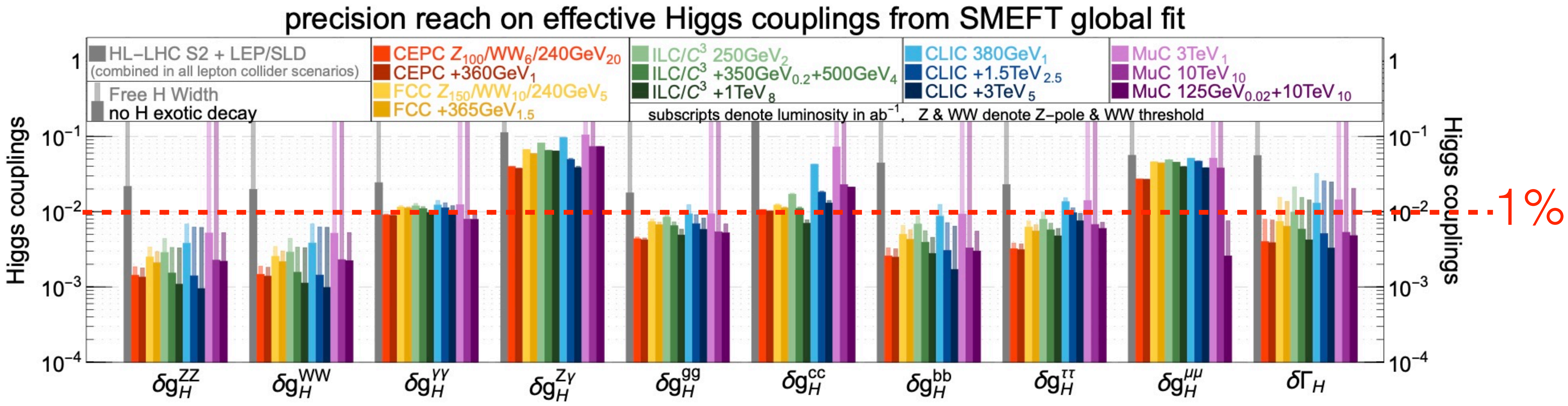


gauge bosons .... H .... ***fermions***

[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

Projections of Higgs coupling precisions



gauge bosons .... H .... ***fermions***

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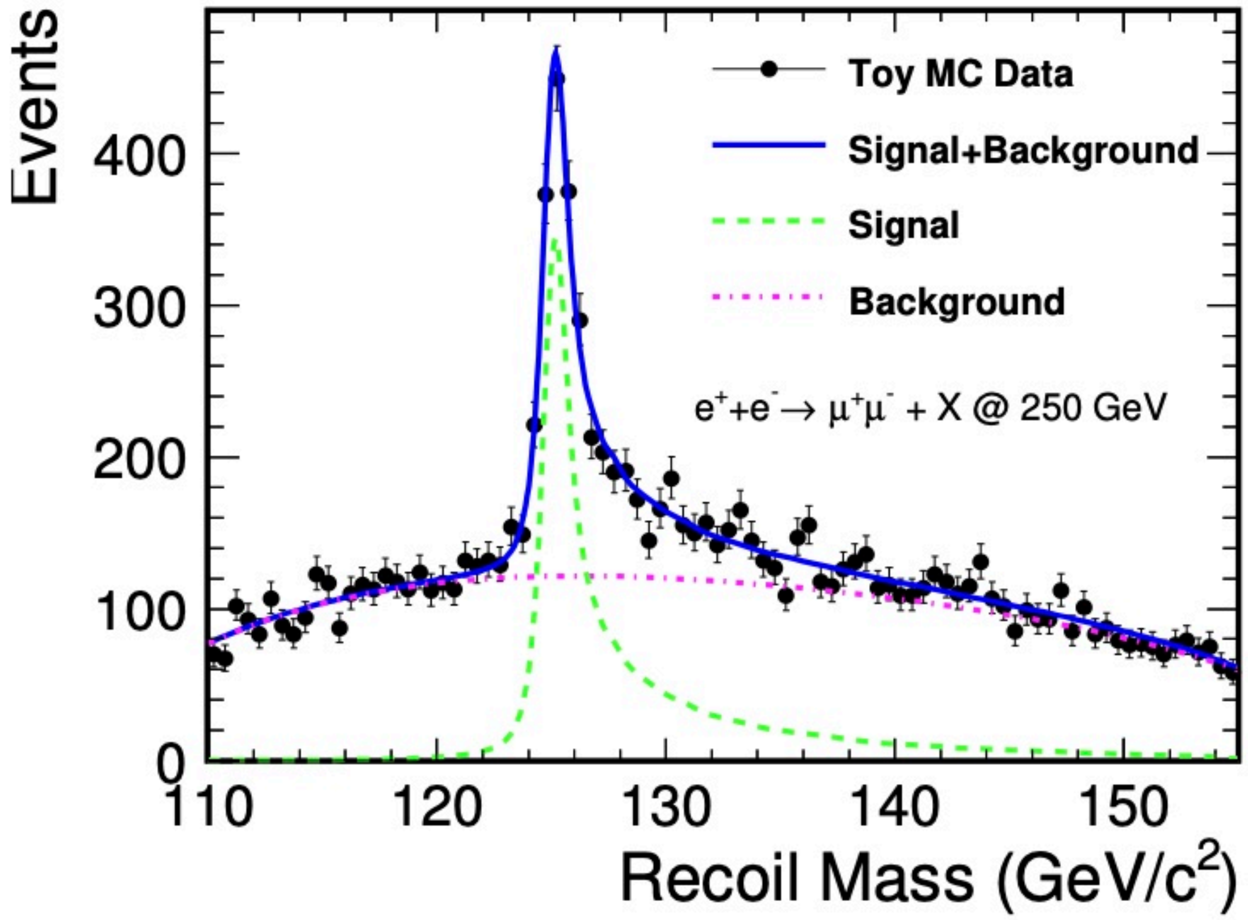
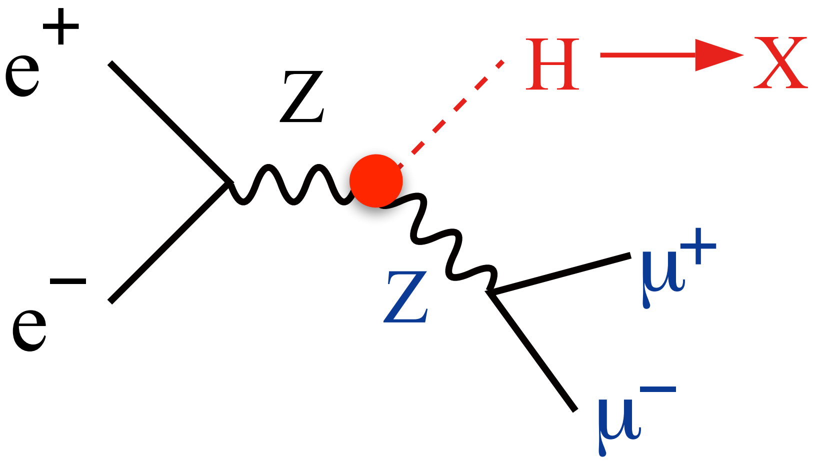
- 1% or below reachable by ILC as well as other Higgs factories
- no question on "which one *should* be realized", important is "which one *can*" given the preferred time and available resource
  - (ii) highlight a few key measurements, elaborate what understanding of Higgs properties is *qualitatively*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

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

☆ measure absolute *σ*, instead of *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

δg^{HZZ} ~ 0.3%

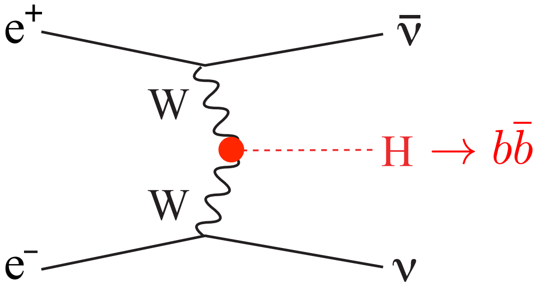
(ii-2) H total width: model-independent determination?

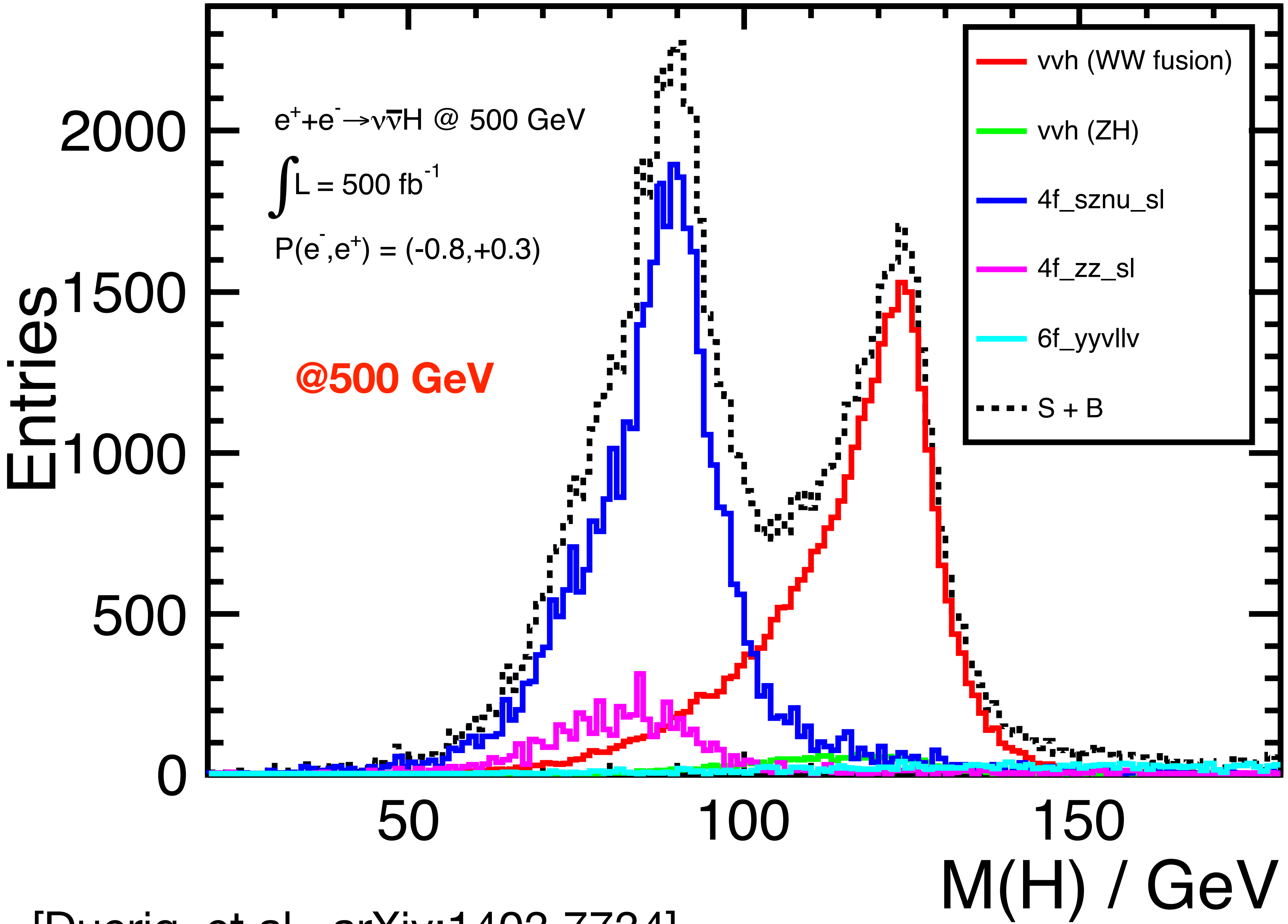
$$\Gamma_H = \frac{\Gamma_{HZZ}}{\mathrm{Br}(H \to ZZ^*)} \propto \frac{g^2_{HZZ}}{\mathrm{Br}(H \to ZZ^*)}$$

—>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



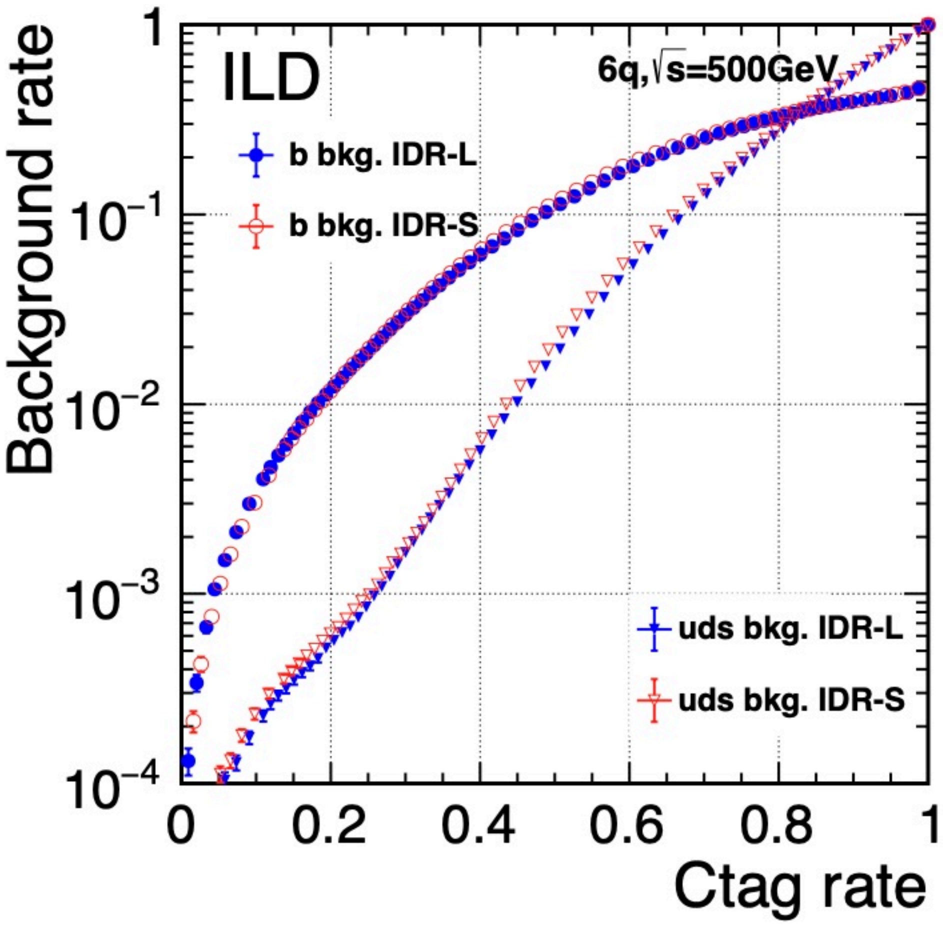


$\delta\Gamma_H \sim 1\%$

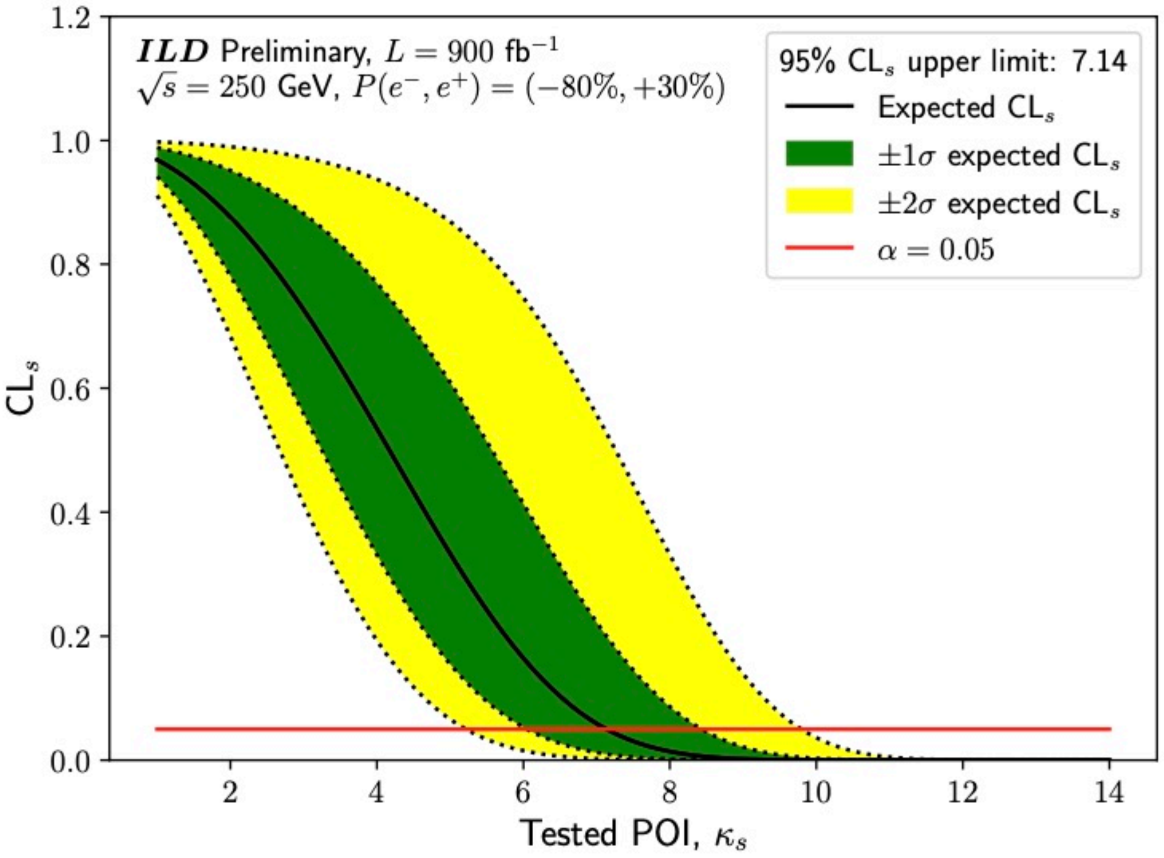
[Duerig, et al., arXiv:1403.7734]

(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%

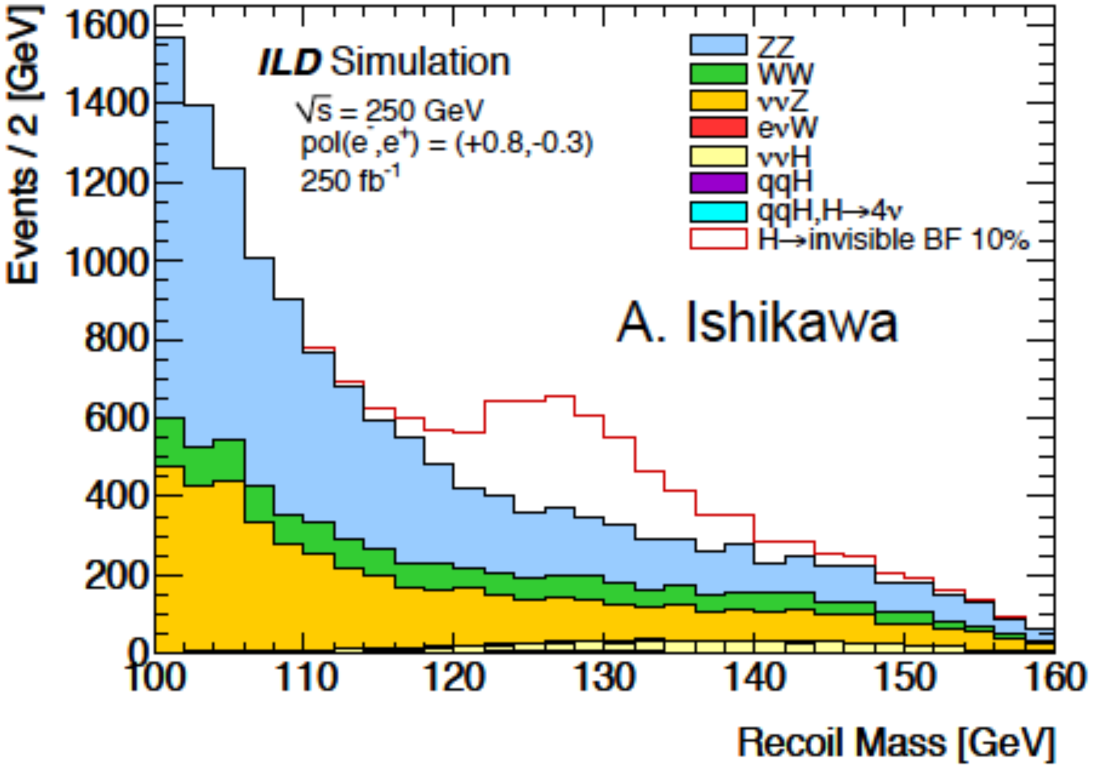


s-Yukawa < 7SM reachable at ILC250

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

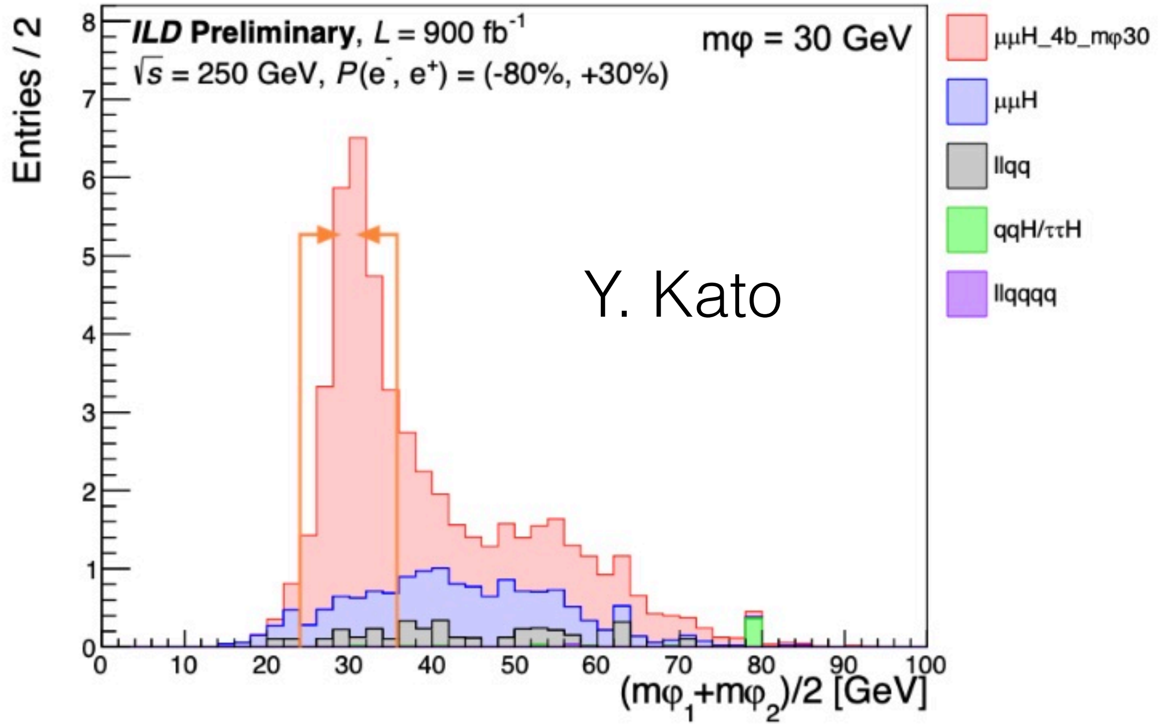
(ii-4) exotic decays: access the hidden sectors?

H—>Invisible



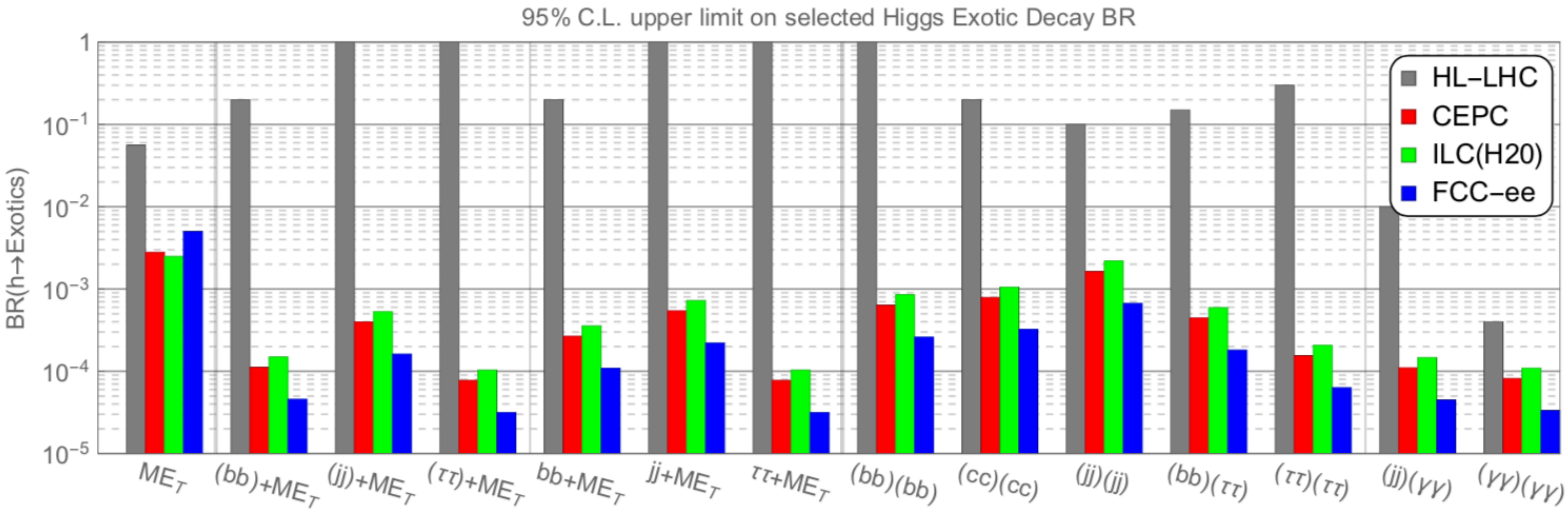
A. Ishikawa

H—>φφ—>4-b



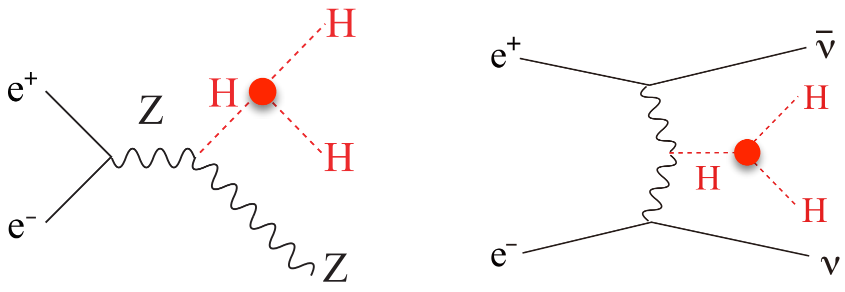
Y. Kato

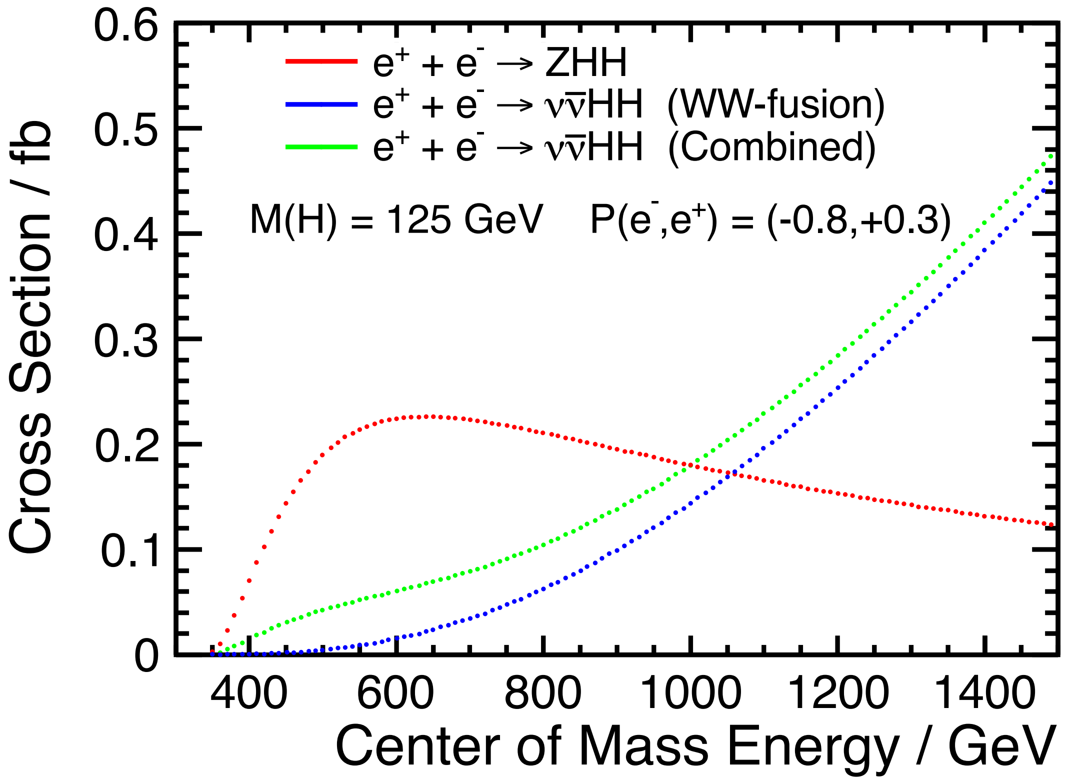
a few exotic decays of BR~0.1% confirmed by full simulation

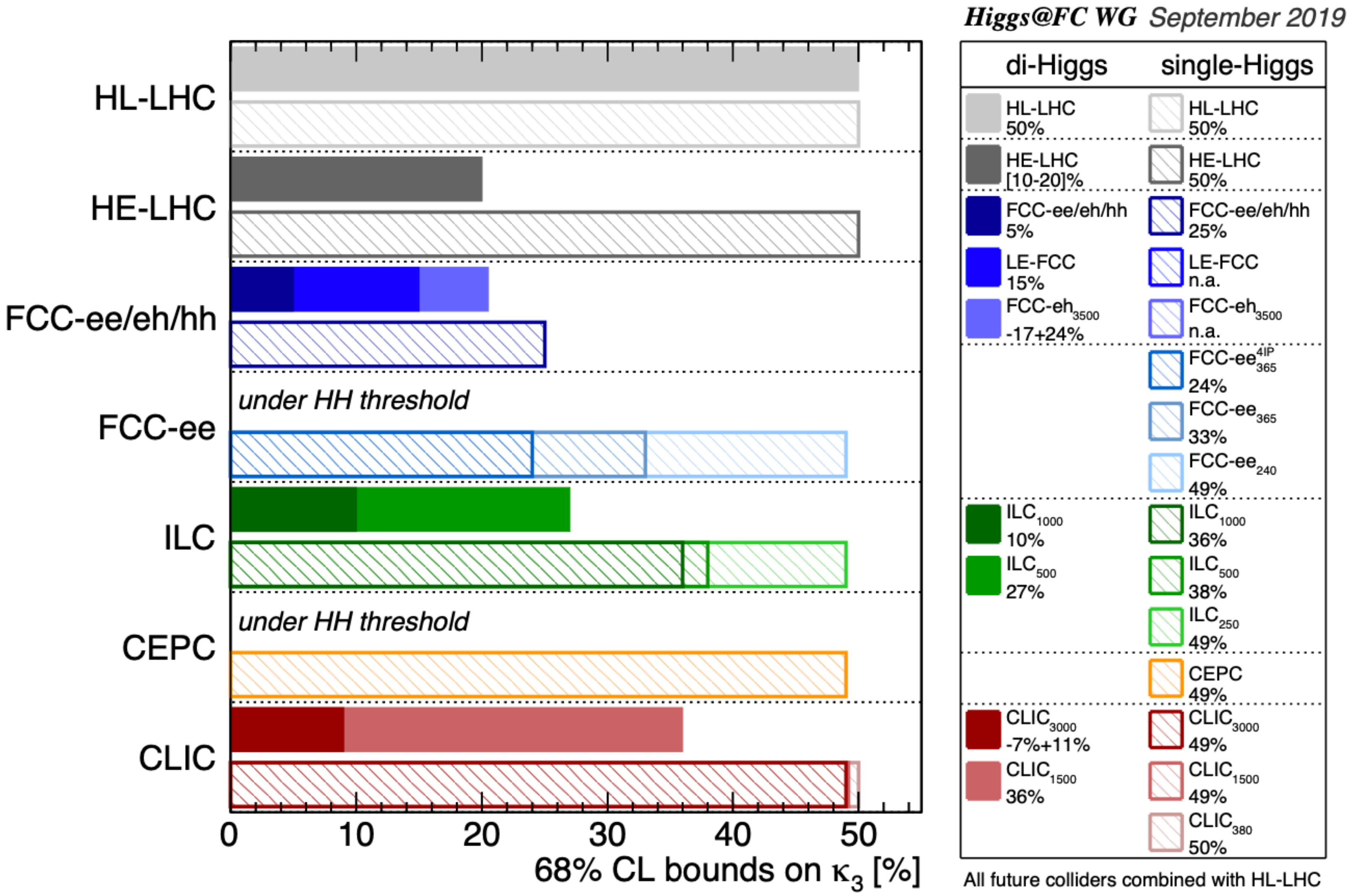


[Liu, Wang, Zhang, arXiv:1612.09284]

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



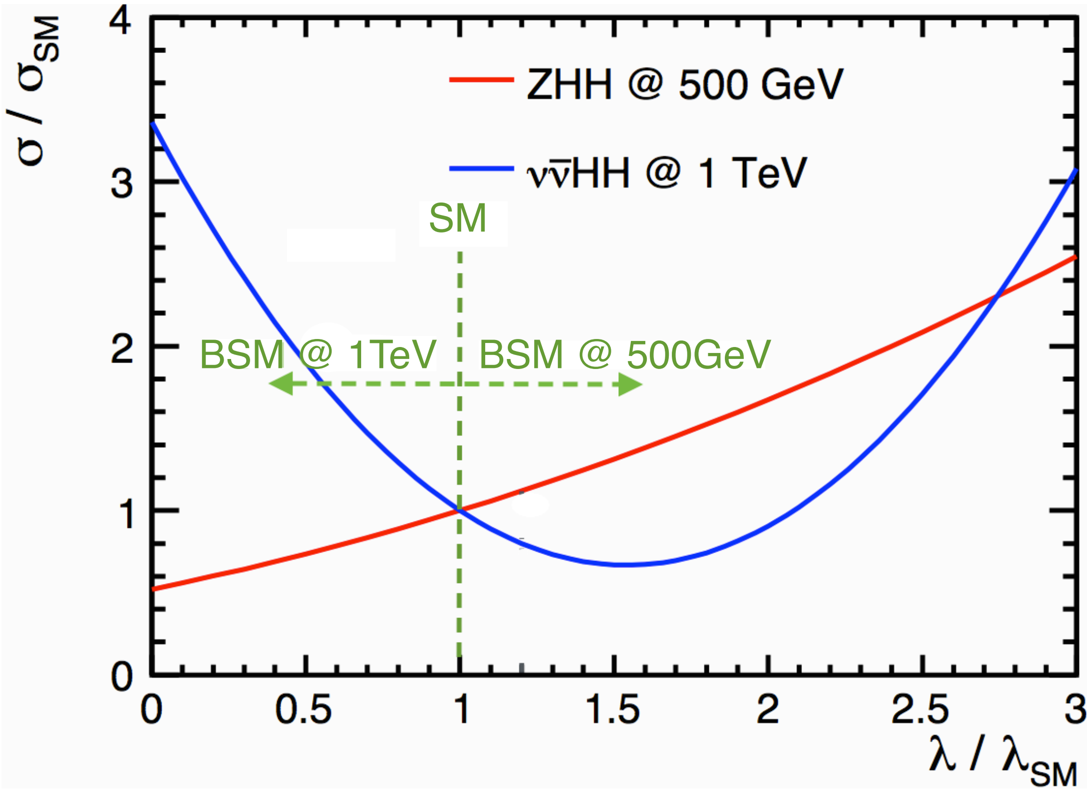


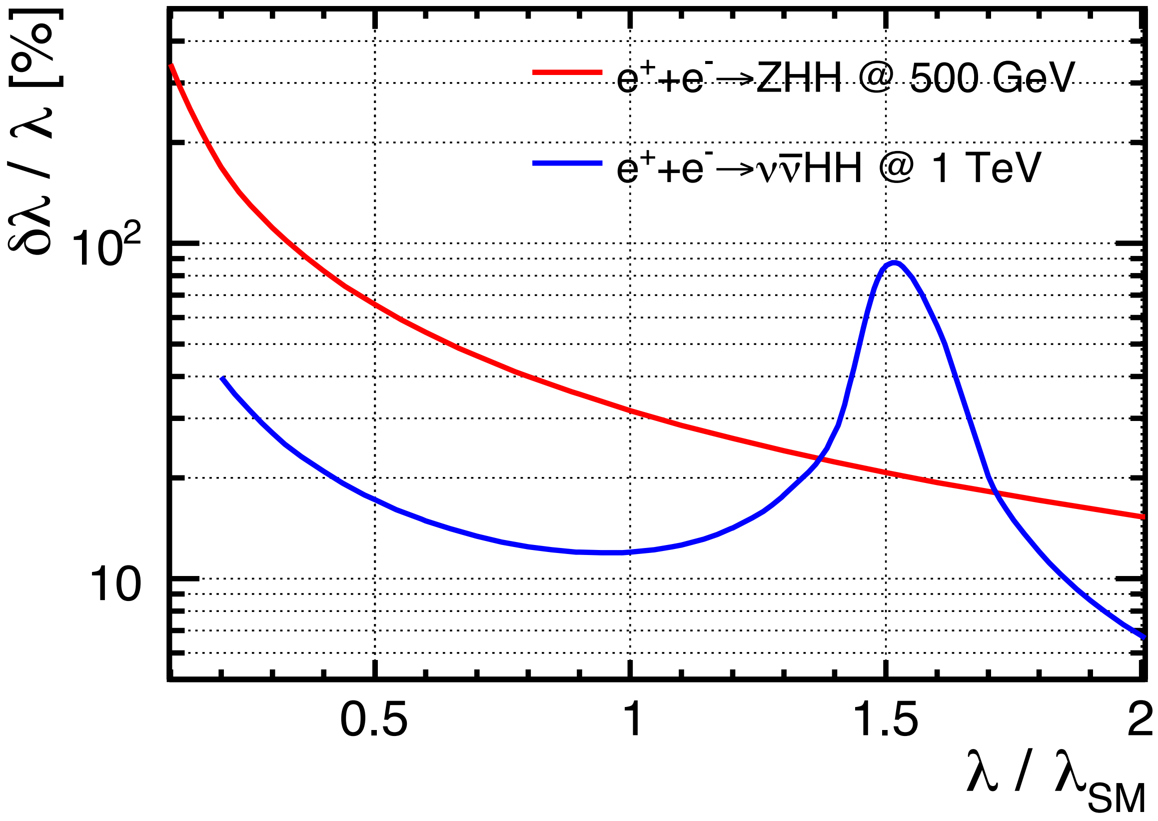


(ESU 2020 Physics Briefing Book, arXiv:1910.11775)

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

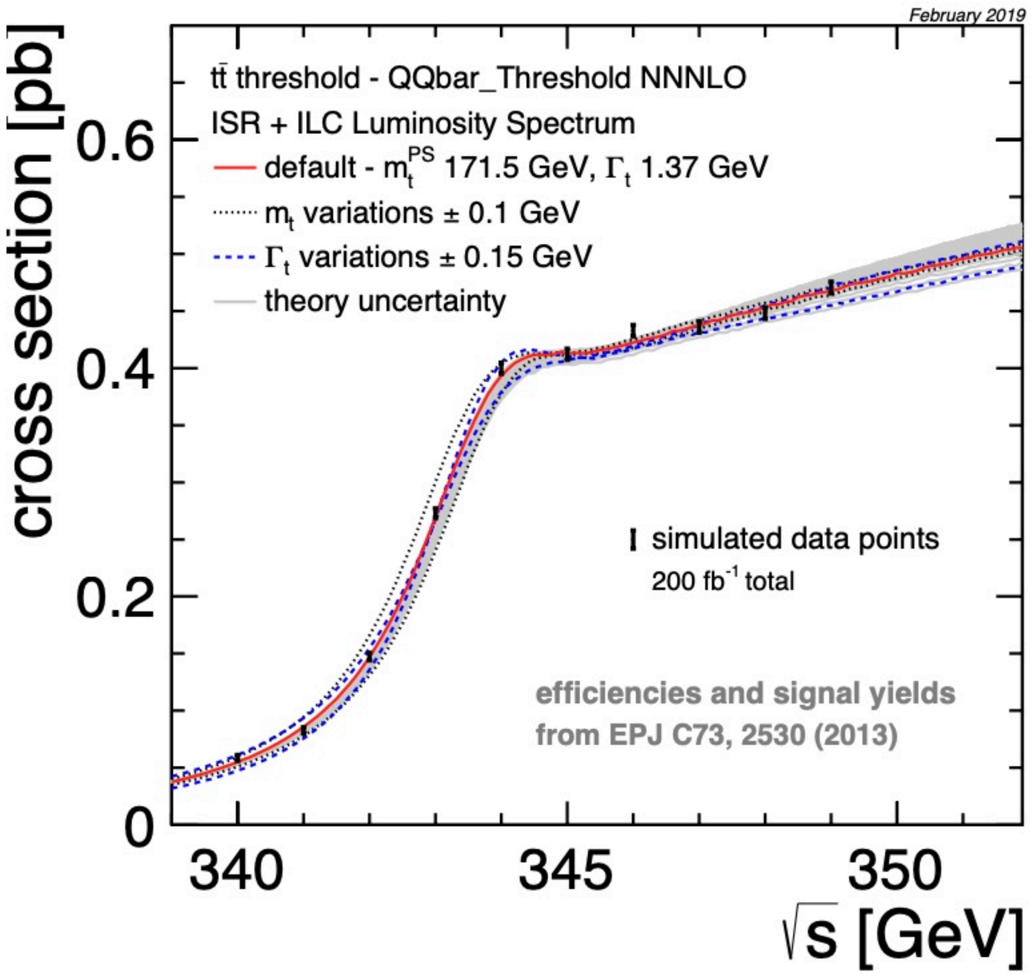
- complementarity between ZHH & ννHH (& LHC): different interference
- λ_{HHH} : possibly large deviation in BSM
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be measured to ~13% using ZHH at 500 GeV e+e-



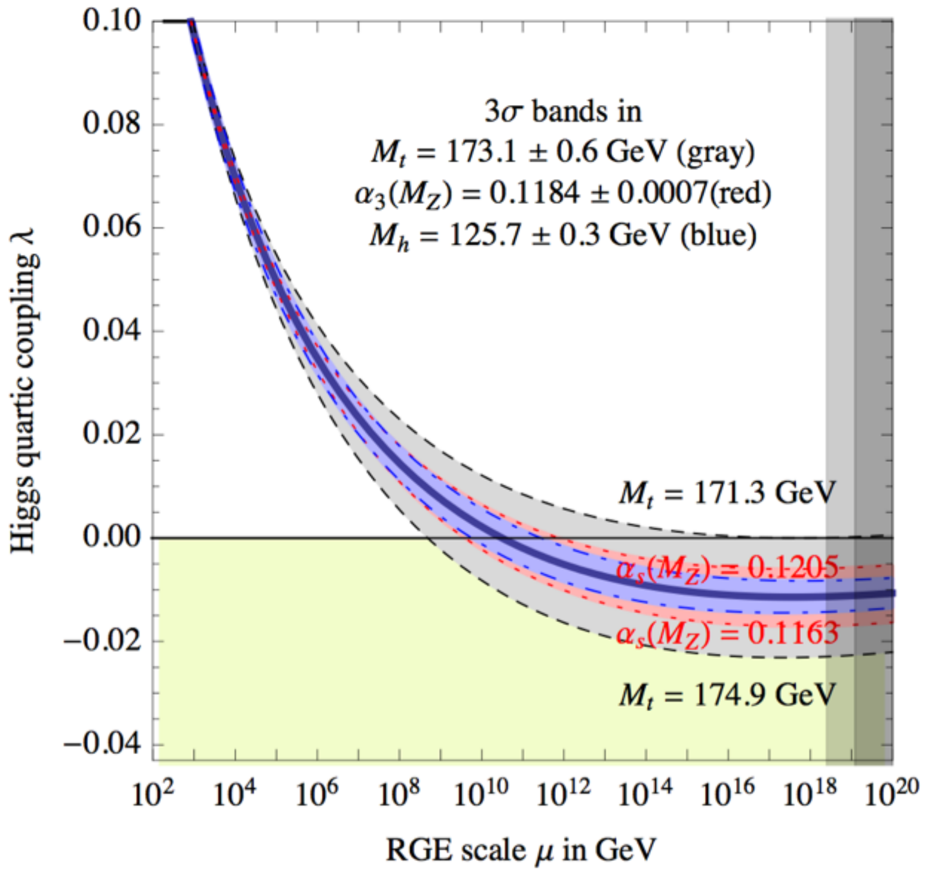


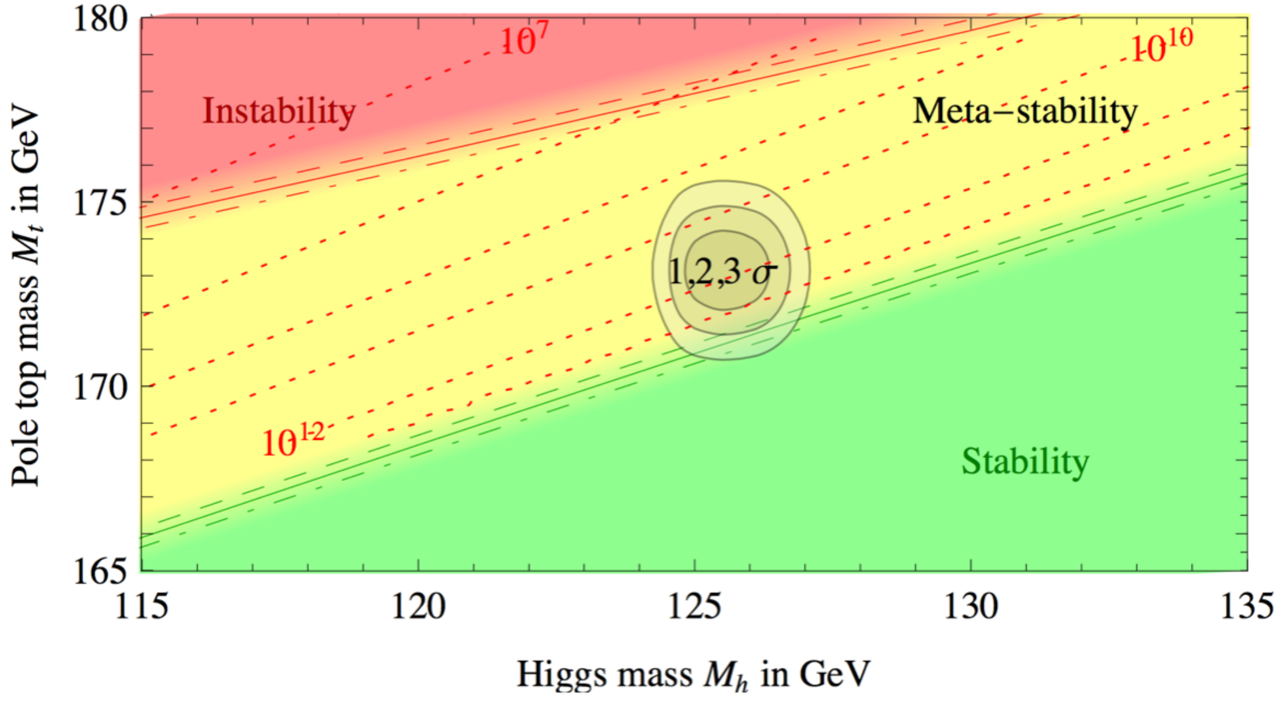
references for large deviations e.g. Grojean, et al., PRD71, 036001; Kanemura, et al., 1508.03245; Kaori, Senaha, PHLTA,B747,152; Perelstein, et al., JHEP 1407, 108

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



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)

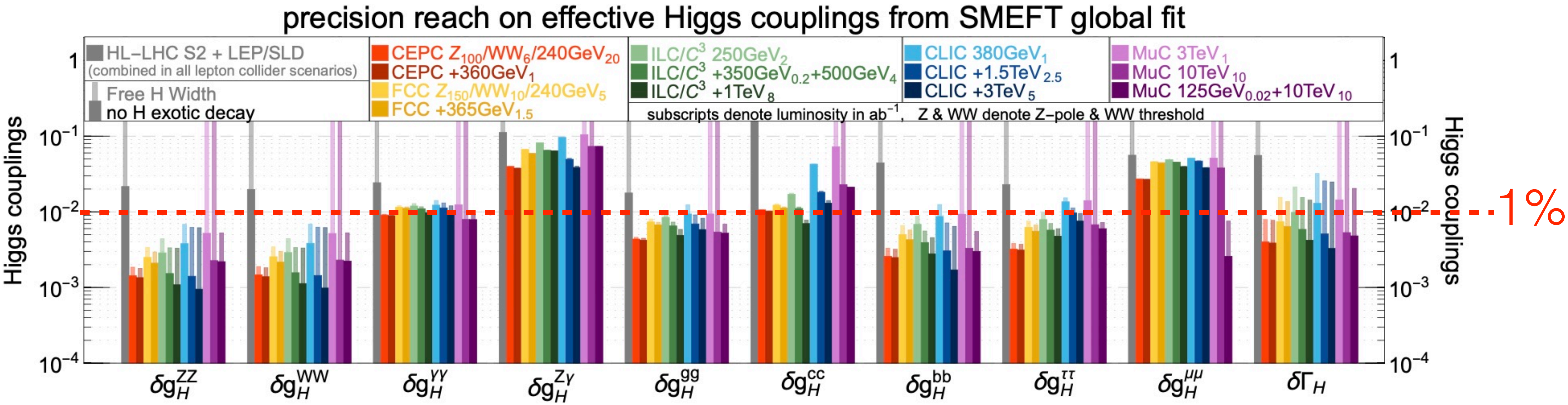
(iii) open questions

[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]

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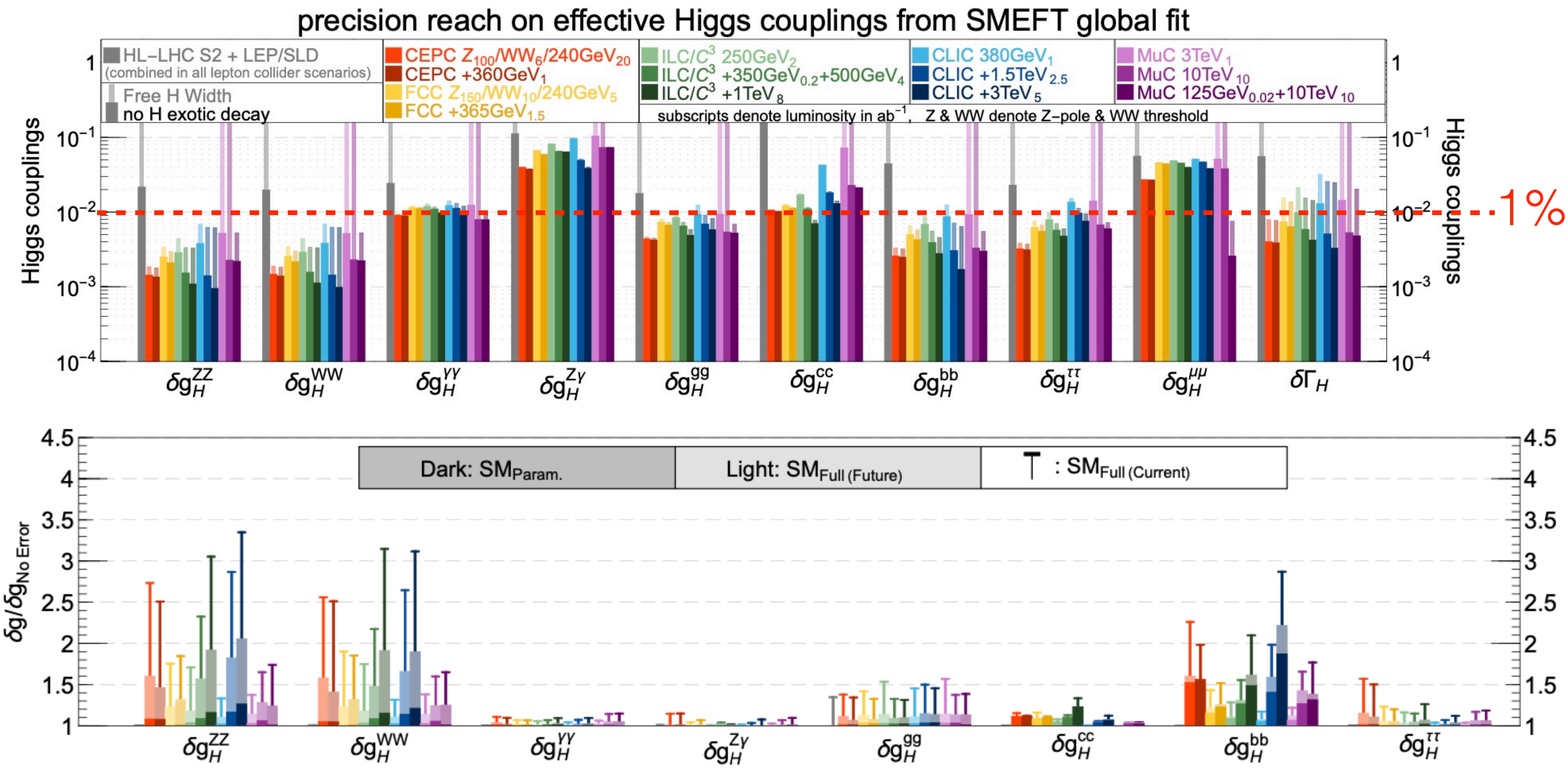
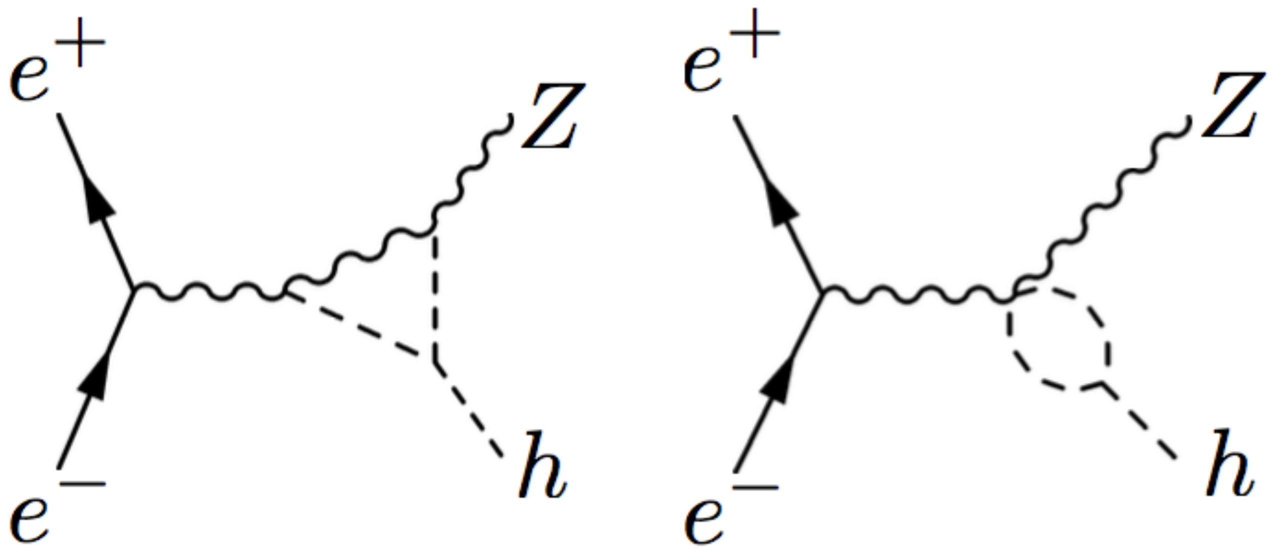


[arXiv:2206.08326]

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



McCullough, arXiv:1312.3322

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

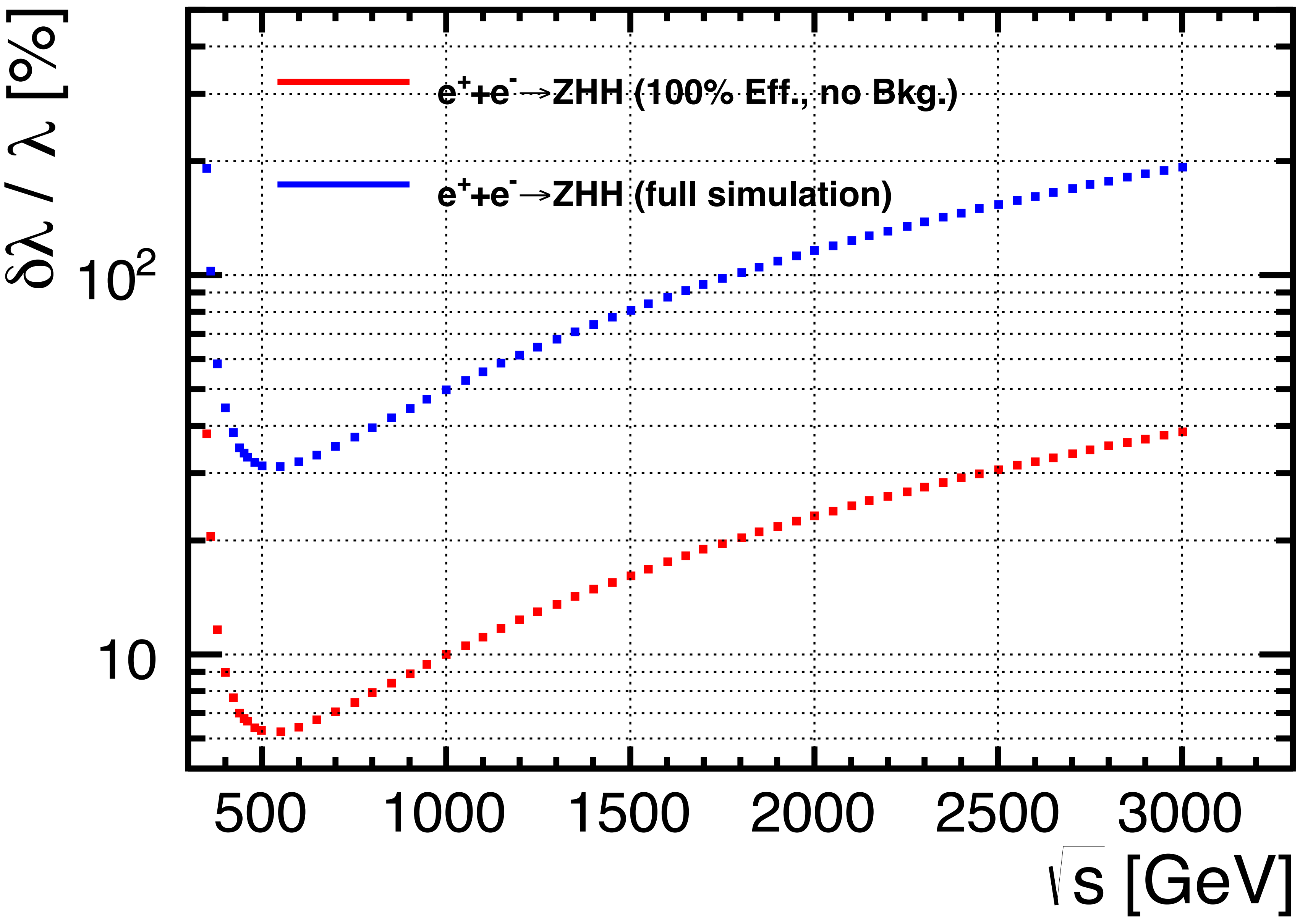
- if only δh is deviated —> δh ~ 28%
- if both δz and δh deviated —> δh ~ 90%
- δσ could receive contributions from many other sources

—> **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?**

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



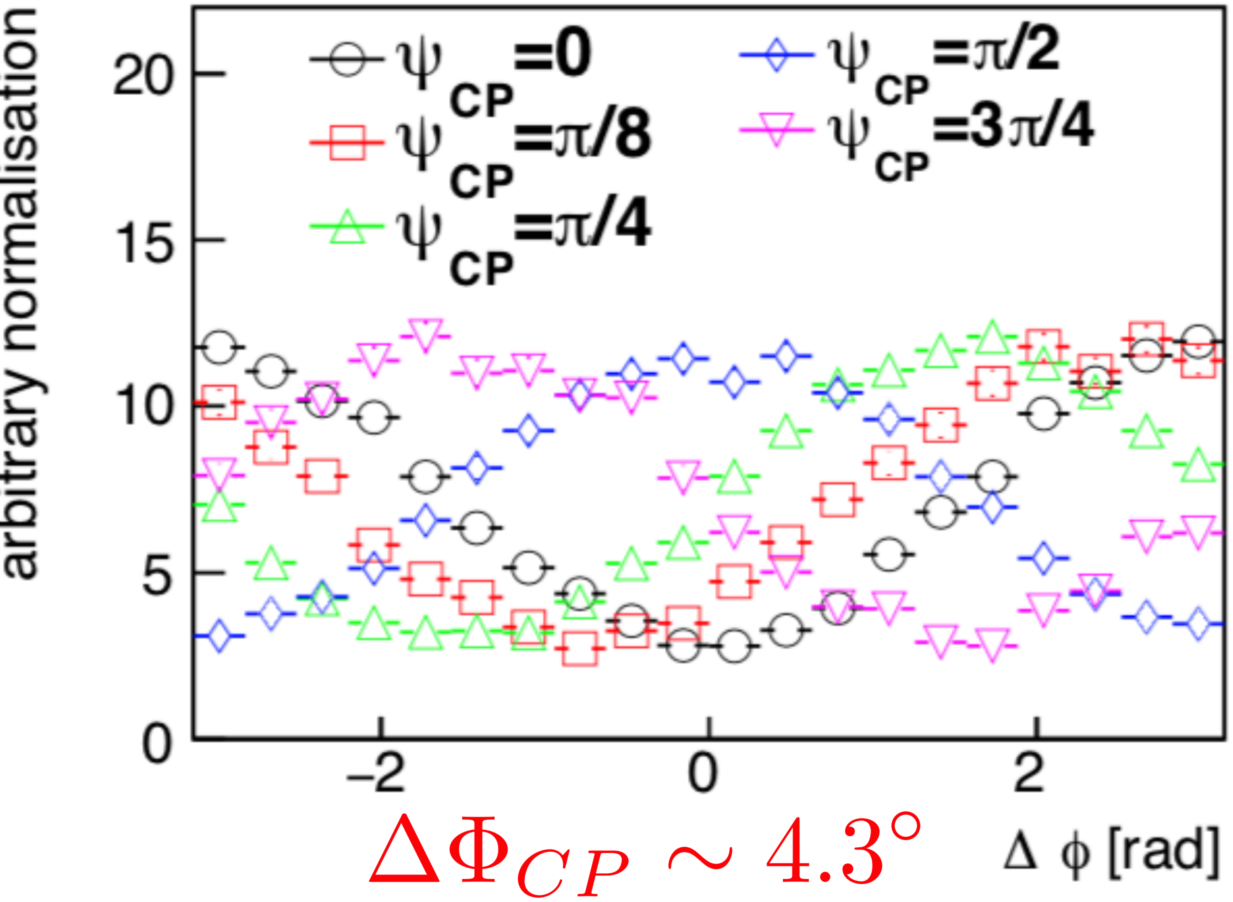
a lot of room for improvement by advanced analysis technique:
flavor tagging, jet-clustering, kinematic fitting, AI, etc

Higgs CP: synergy between Hff & HVV?

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

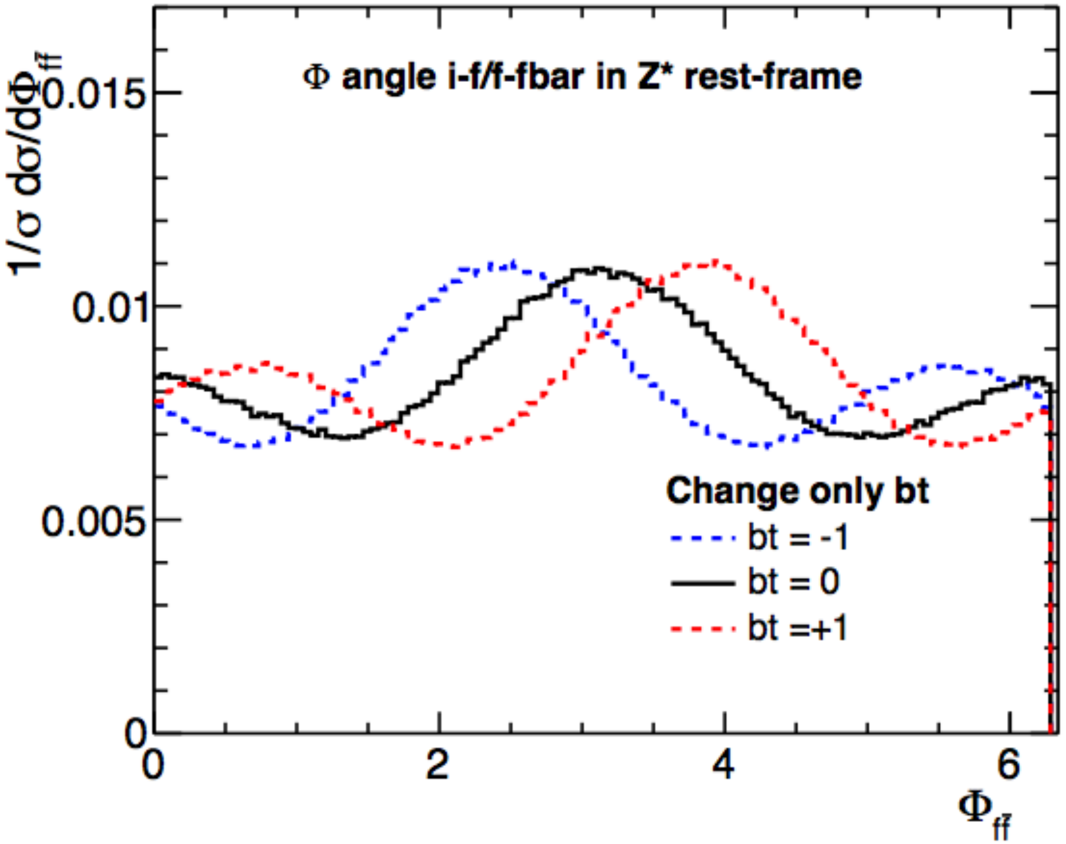
$$L_{hZZ} = M_Z^2(\frac{1}{v} + \frac{a}{\Lambda})hZ_\mu Z^\mu + \frac{b}{2\Lambda} hZ_{\mu\nu}Z^{\mu\nu} + \underline{\frac{\tilde{b}}{2\Lambda} hZ_{\mu\nu}\tilde{Z}_{\mu\nu}}$$

(CP-odd)



$\Delta\Phi_{CP} \sim 4.3°$

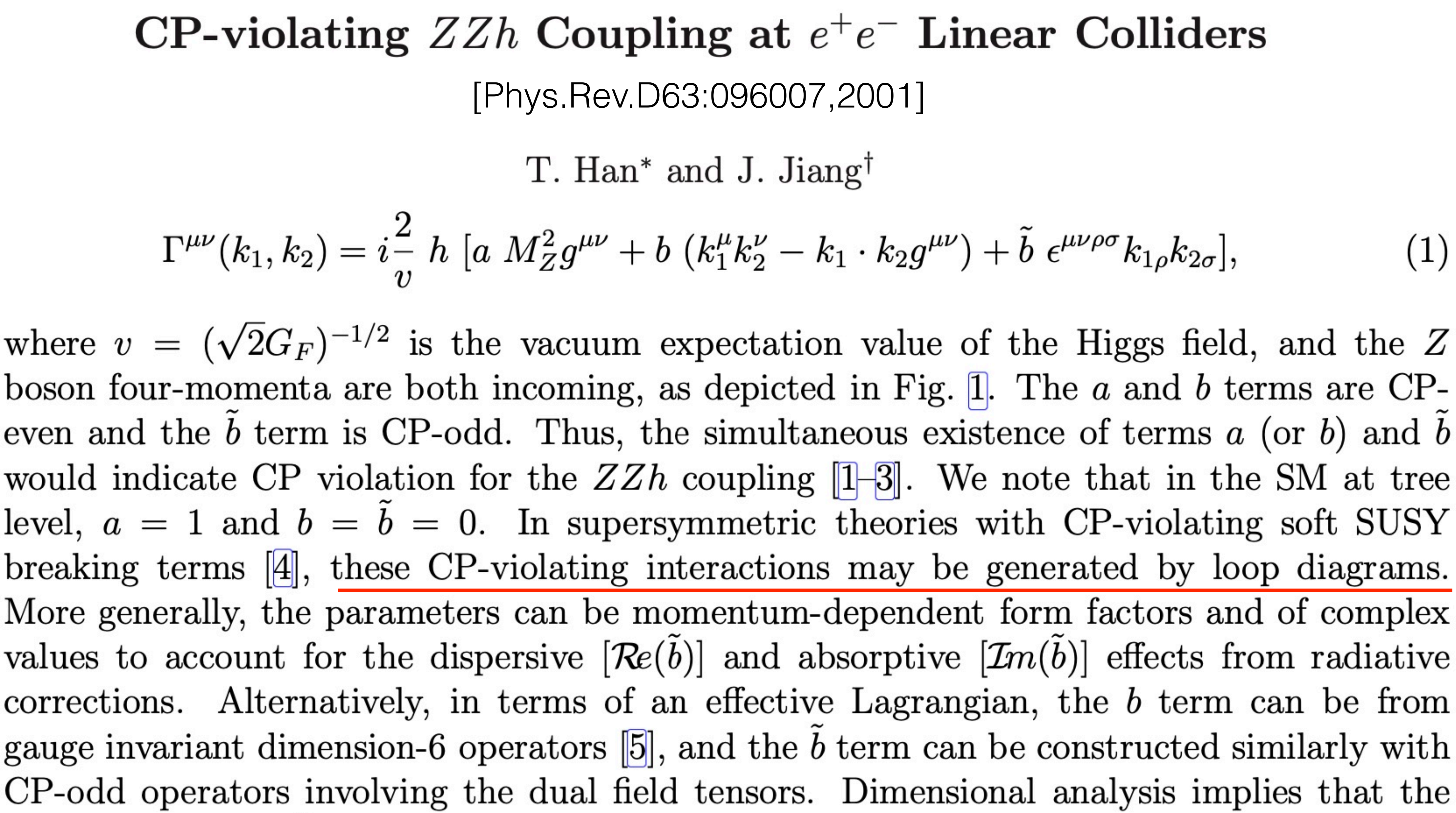
[Jeans et al, arXiv:1804.01241]



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

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

[Ogawa et al, arXiv:1712.09772]



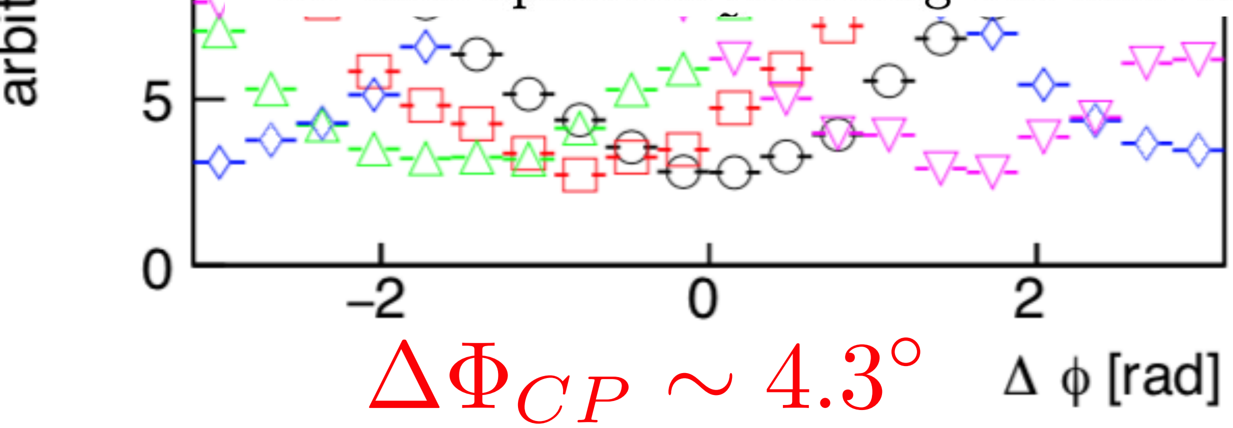
CP-violating ZZh Coupling at e^+e^- Linear Colliders

[Phys.Rev.D63:096007,2001]

T. Han* and J. Jiang†

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

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



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

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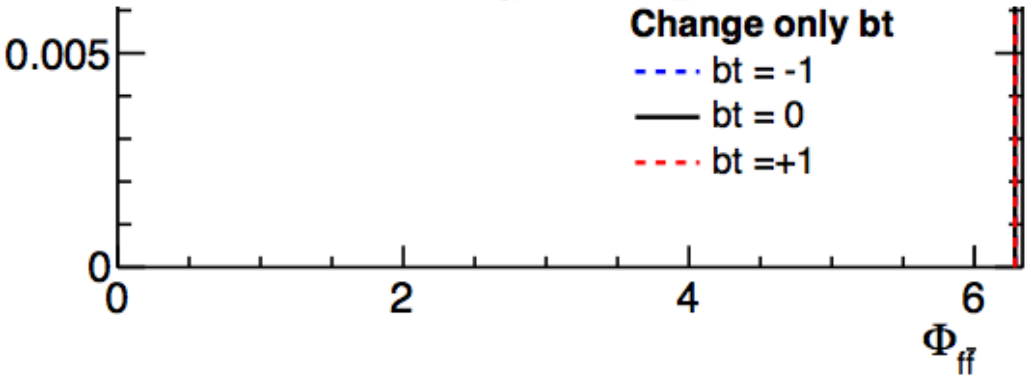

@ $\sqrt{s} = 250\text{GeV}$

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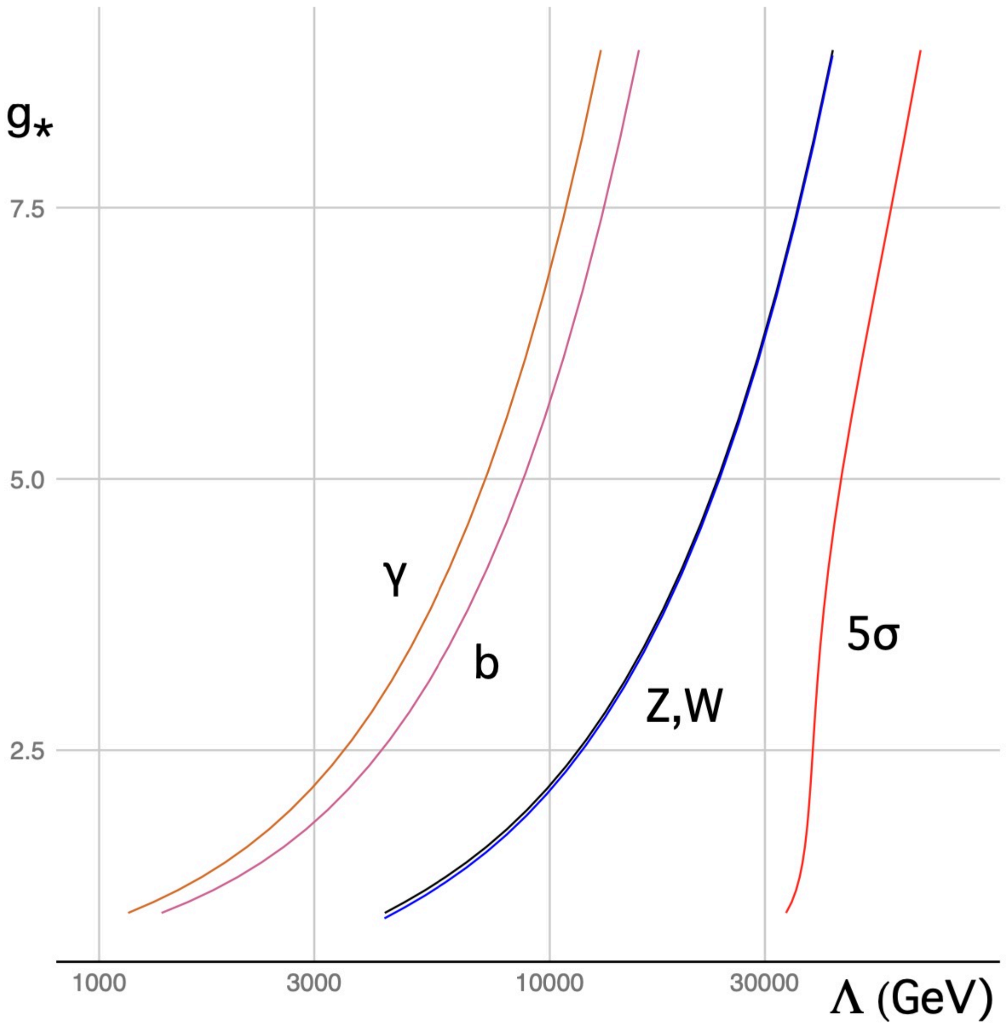
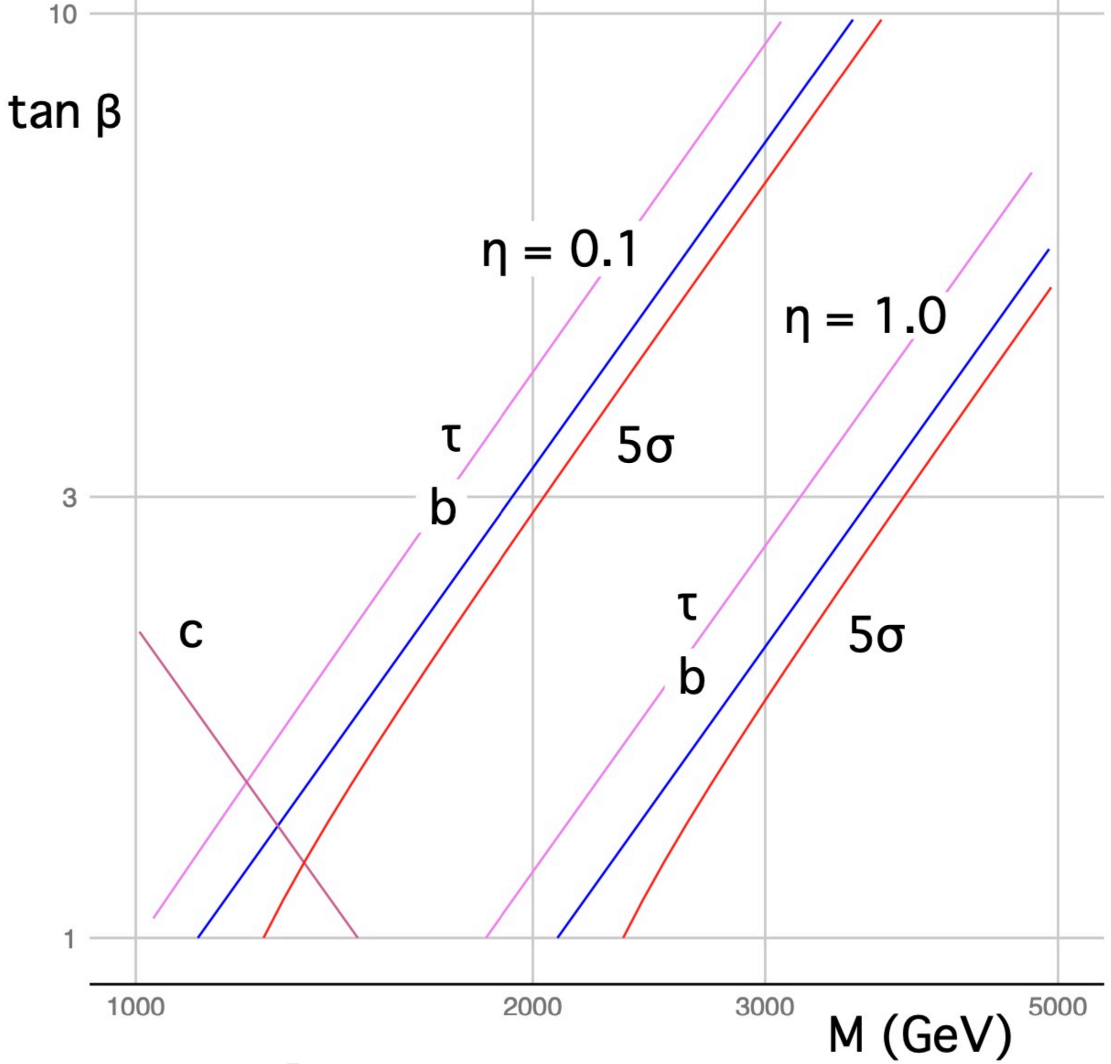
synergy between direct & indirect searches

- 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

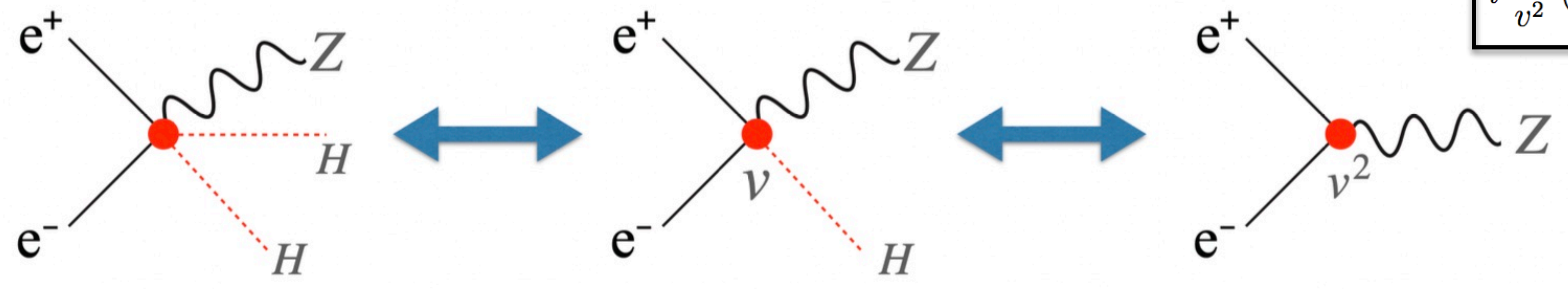


[Peskin, arXiv:2209.03303]

- 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]

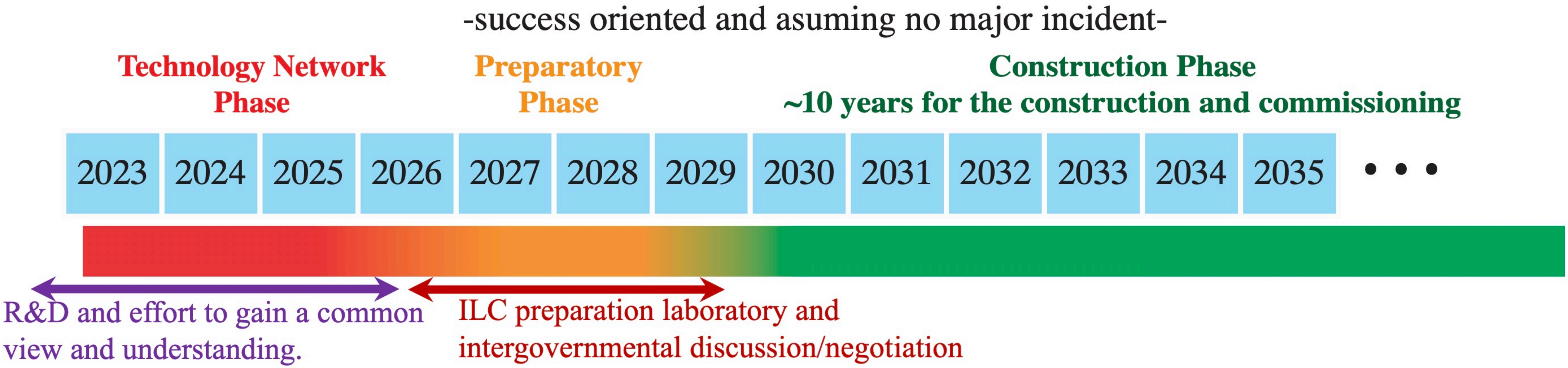
- Have we explored all the important synergies between Higgs and EW/Top/2f, between e+e- and LHC/low-energy measurements, which are naturally established by SMEFT?

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

(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)



-success oriented and asuming no major incident-

Technology Network Phase

Preparatory Phase

Construction Phase
~10 years for the construction and commissioning

R&D and effort to gain a common view and understanding.

ILC preparation laboratory and intergovernmental discussion/negotiation

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

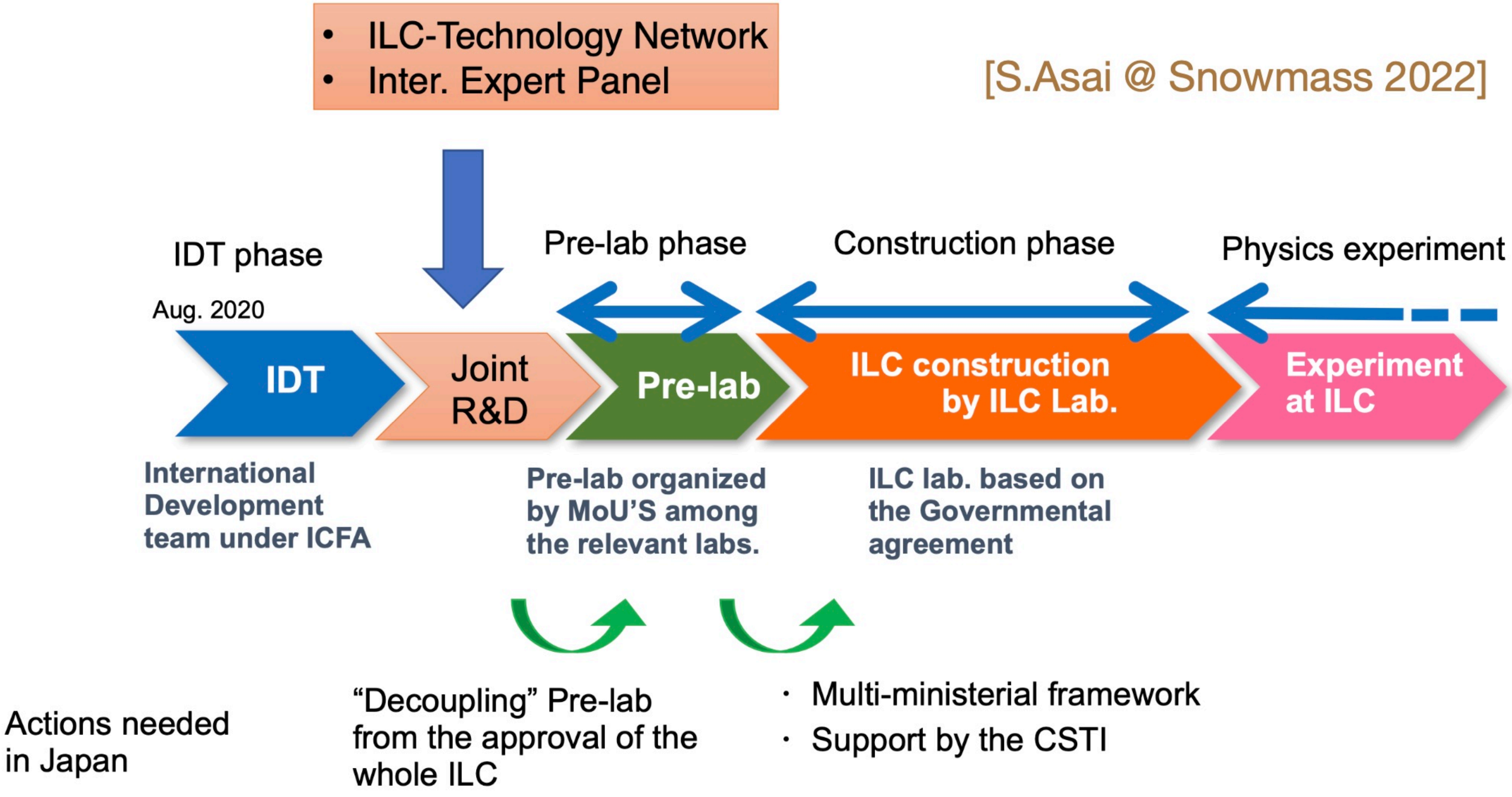
get engaged in ILC physics studies

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

backup

ILC Project News

current plan



- ILC-Technology Network
- Inter. Expert Panel

[S.Asai @ Snowmass 2022]

IDT phase

Aug. 2020

Pre-lab phase

Construction phase

Physics experiment

IDT

Joint R&D

Pre-lab

ILC construction by ILC Lab.

Experiment at ILC

International Development team under ICFA

Pre-lab organized by MoU'S among the relevant labs.

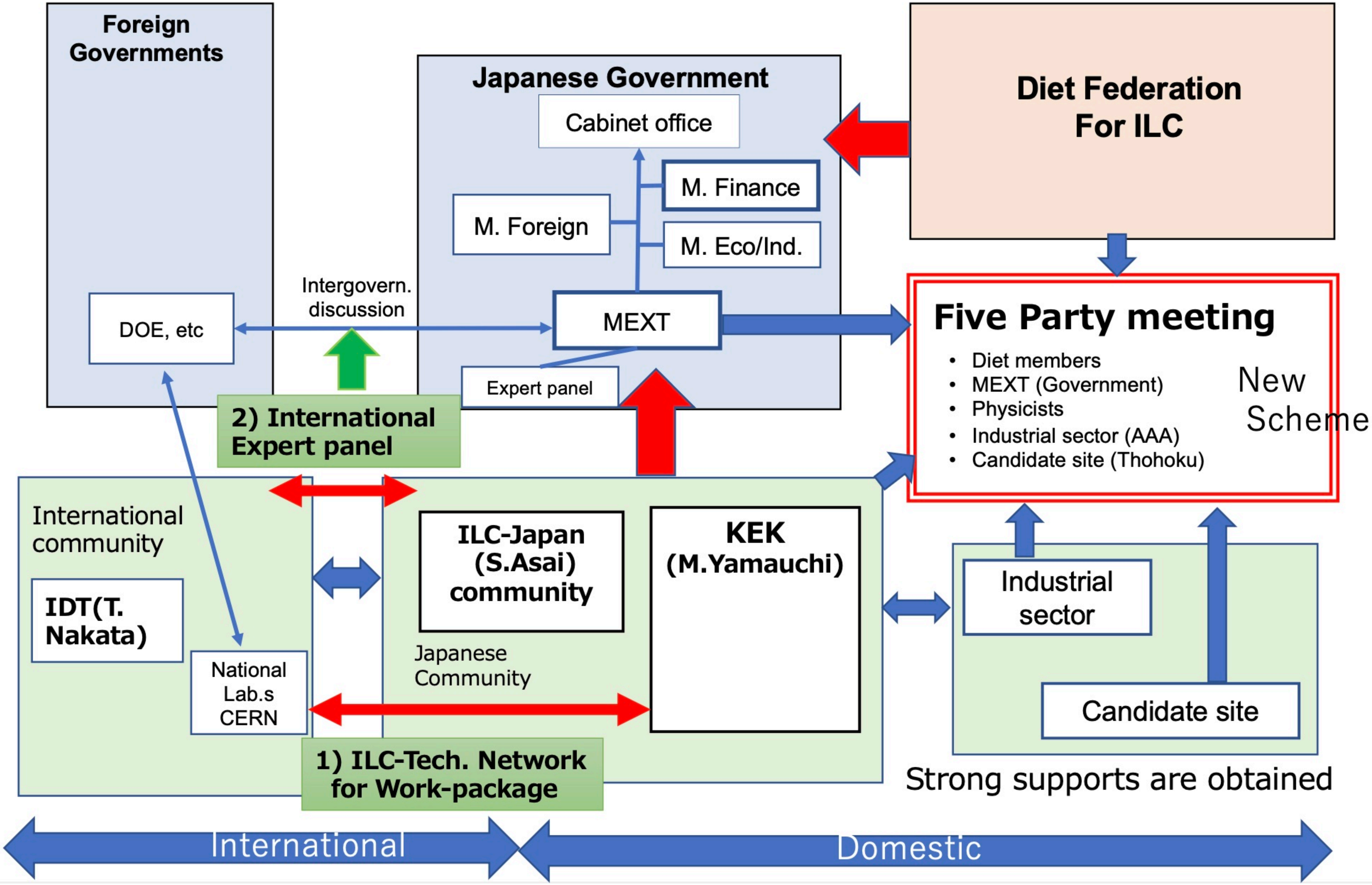
ILC lab. based on the Governmental agreement

Actions needed in Japan

"Decoupling" Pre-lab from the approval of the whole ILC

- Multi-ministerial framework
- Support by the CSTI

Promotion scheme of ILC / relation of Stakeholder



Foreign Governments

DOE, etc

Intergovern. discussion

Japanese Government

Cabinet office

M. Finance

M. Foreign

M. Eco/Ind.

MEXT

Expert panel

2) International Expert panel

Diet Federation For ILC

Five Party meeting

- Diet members
- MEXT (Government)
- Physicists
- Industrial sector (AAA)
- Candidate site (Thohoku)

New Scheme

International community

IDT(T. Nakata)

National Lab.s CERN

ILC-Japan (S.Asai) community

Japanese Community

KEK (M.Yamauchi)

1) ILC-Tech. Network for Work-package

Industrial sector

Candidate site

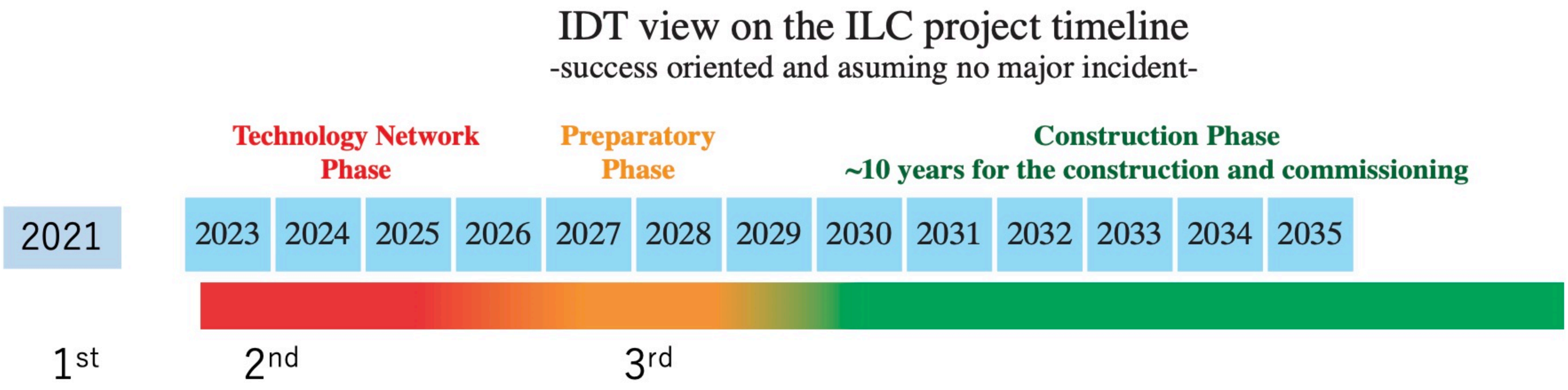
Strong supports are obtained

International

Domestic

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)

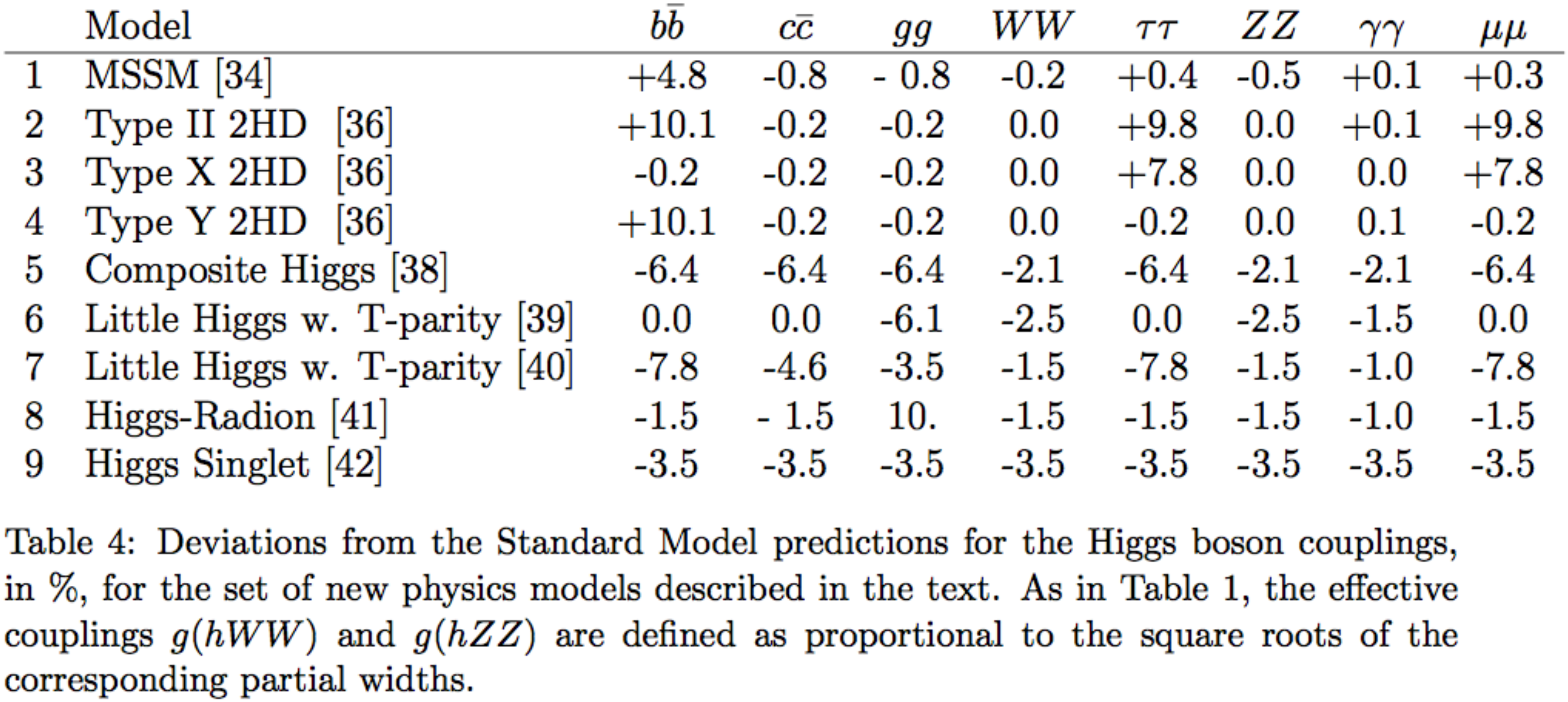
3rd Stage Governments discuss cost sharing/responsibility of ILC (as Global project)

Condition

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

Start construction.

benchmark BSM models



	Model	$b\bar{b}$	$c\bar{c}$	gg	WW	$\tau\tau$	ZZ	$\gamma\gamma$	$\mu\mu$
1	MSSM [34]	+4.8	-0.8	- 0.8	-0.2	+0.4	-0.5	+0.1	+0.3
2	Type II 2HD [36]	+10.1	-0.2	-0.2	0.0	+9.8	0.0	+0.1	+9.8
3	Type X 2HD [36]	-0.2	-0.2	-0.2	0.0	+7.8	0.0	0.0	+7.8
4	Type Y 2HD [36]	+10.1	-0.2	-0.2	0.0	-0.2	0.0	0.1	-0.2
5	Composite Higgs [38]	-6.4	-6.4	-6.4	-2.1	-6.4	-2.1	-2.1	-6.4
6	Little Higgs w. T-parity [39]	0.0	0.0	-6.1	-2.5	0.0	-2.5	-1.5	0.0
7	Little Higgs w. T-parity [40]	-7.8	-4.6	-3.5	-1.5	-7.8	-1.5	-1.0	-7.8
8	Higgs-Radion [41]	-1.5	- 1.5	10.	-1.5	-1.5	-1.5	-1.0	-1.5
9	Higgs Singlet [42]	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5	-3.5

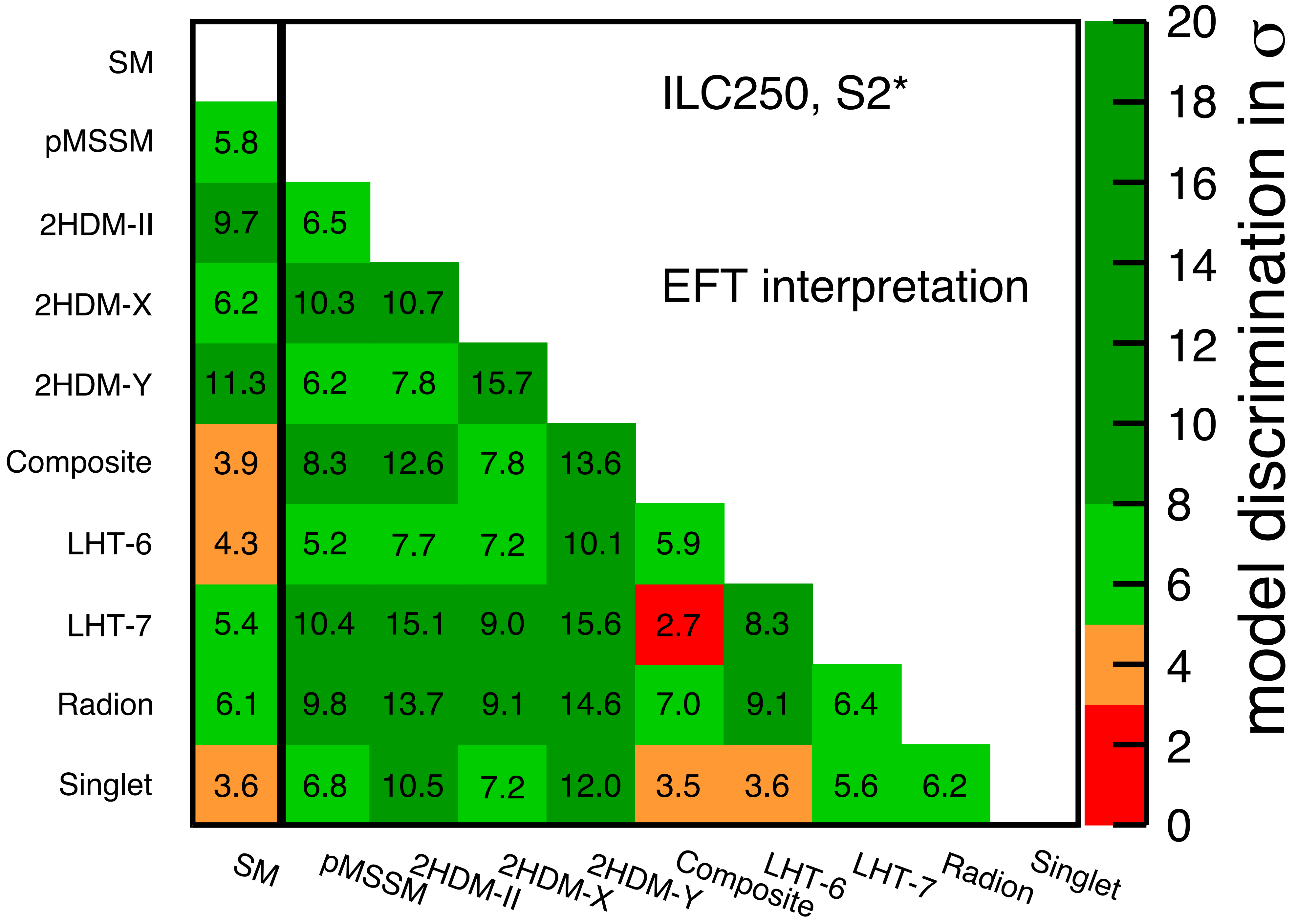
Table 4: Deviations from the Standard Model predictions for the Higgs boson couplings, in %, for the set of new physics models described in the text. As in Table 1, the effective couplings $g(hWW)$ and $g(hZZ)$ are defined as proportional to the square roots of the corresponding partial widths.

—> quantitative assessment for models discrimination

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

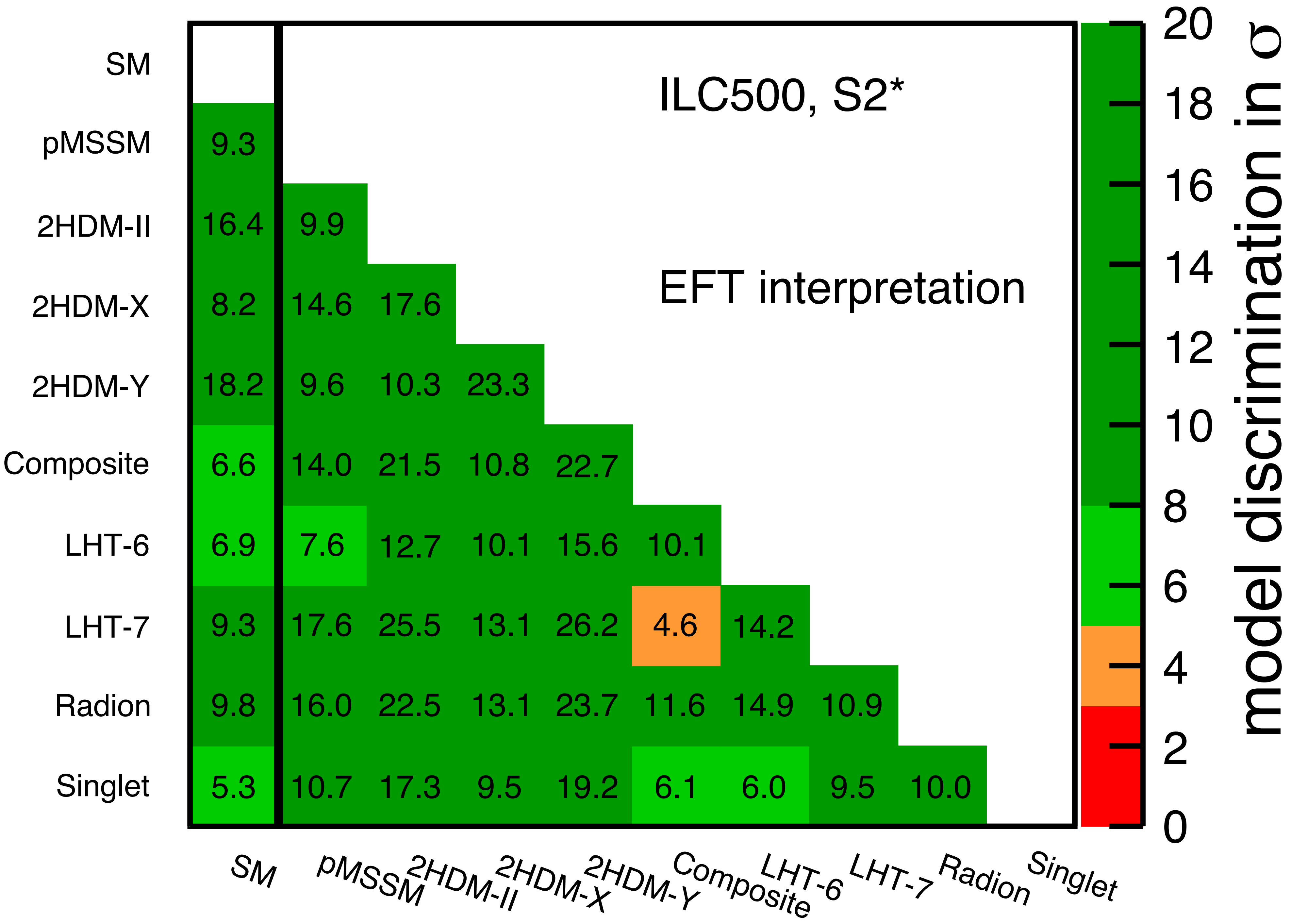
- a PMSSM model with b squarks at 3.4 TeV, gluino at 4 TeV
- a Type II 2 Higgs doublet model with $m_A = 600 \text{ GeV}, \tan\beta = 7$
- a Type X 2 Higgs doublet model with $m_A = 450 \text{ GeV}, \tan\beta = 6$
- a Type Y 2 Higgs doublet model with $m_A = 600 \text{ GeV}, \tan\beta = 7$
- a composite Higgs model MCHM5 with $f = 1.2 \text{ TeV}, m_T = 1.7 \text{ TeV}$
- a Little Higgs model with T-parity with $f = 785 \text{ GeV}, m_T = 2 \text{ TeV}$
- A Little Higgs model with couplings to 1st and 2nd generation with $f = 1.2 \text{ TeV}, m_T = 1.7 \text{ TeV}$
- A Higgs-radion mixing model with $m_r = 500 \text{ GeV}$
- a model with a Higgs singlet at 2.8 TeV creating a Higgs portal to dark matter and large λ for electroweak baryogenesis

BSM benchmark models discrimination at ILC250



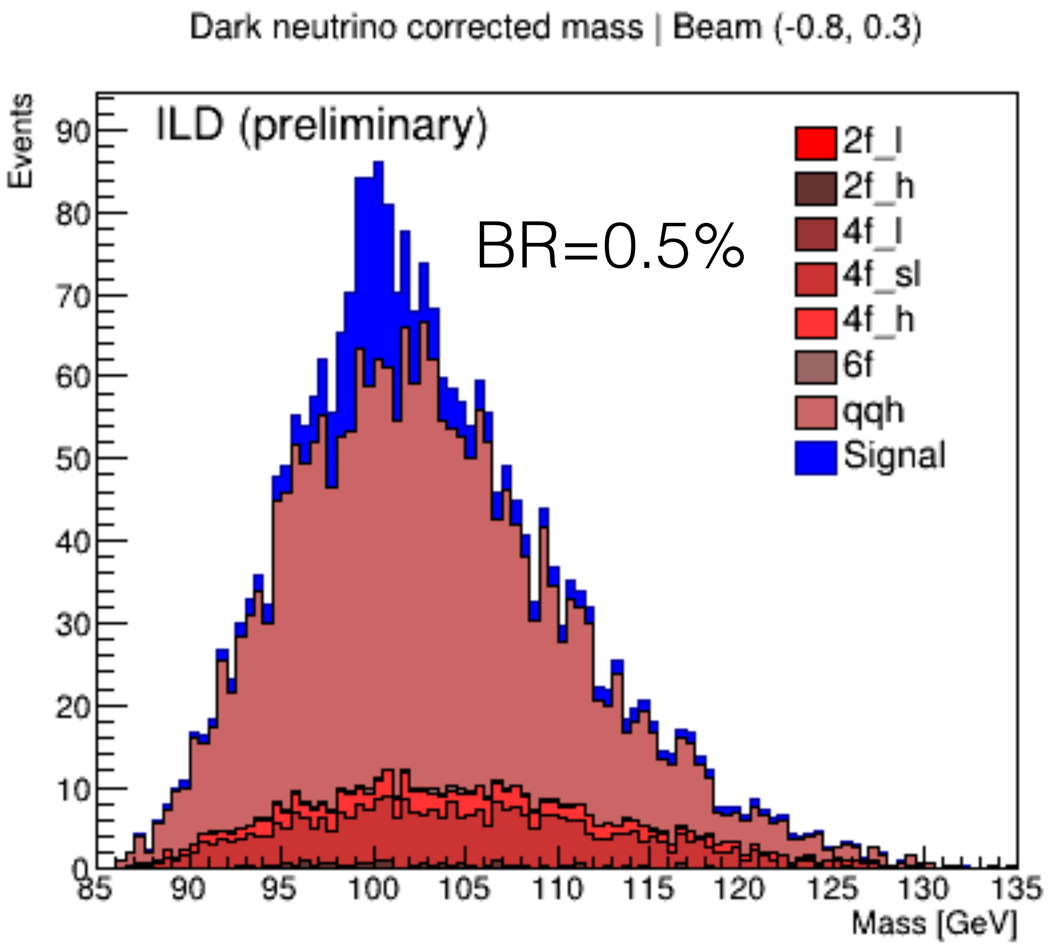
	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	5.8									
2HDM-II	9.7	6.5								
2HDM-X	6.2	10.3	10.7							
2HDM-Y	11.3	6.2	7.8	15.7						
Composite	3.9	8.3	12.6	7.8	13.6					
LHT-6	4.3	5.2	7.7	7.2	10.1	5.9				
LHT-7	5.4	10.4	15.1	9.0	15.6	2.7	8.3			
Radion	6.1	9.8	13.7	9.1	14.6	7.0	9.1	6.4		
Singlet	3.6	6.8	10.5	7.2	12.0	3.5	3.6	5.6	6.2	

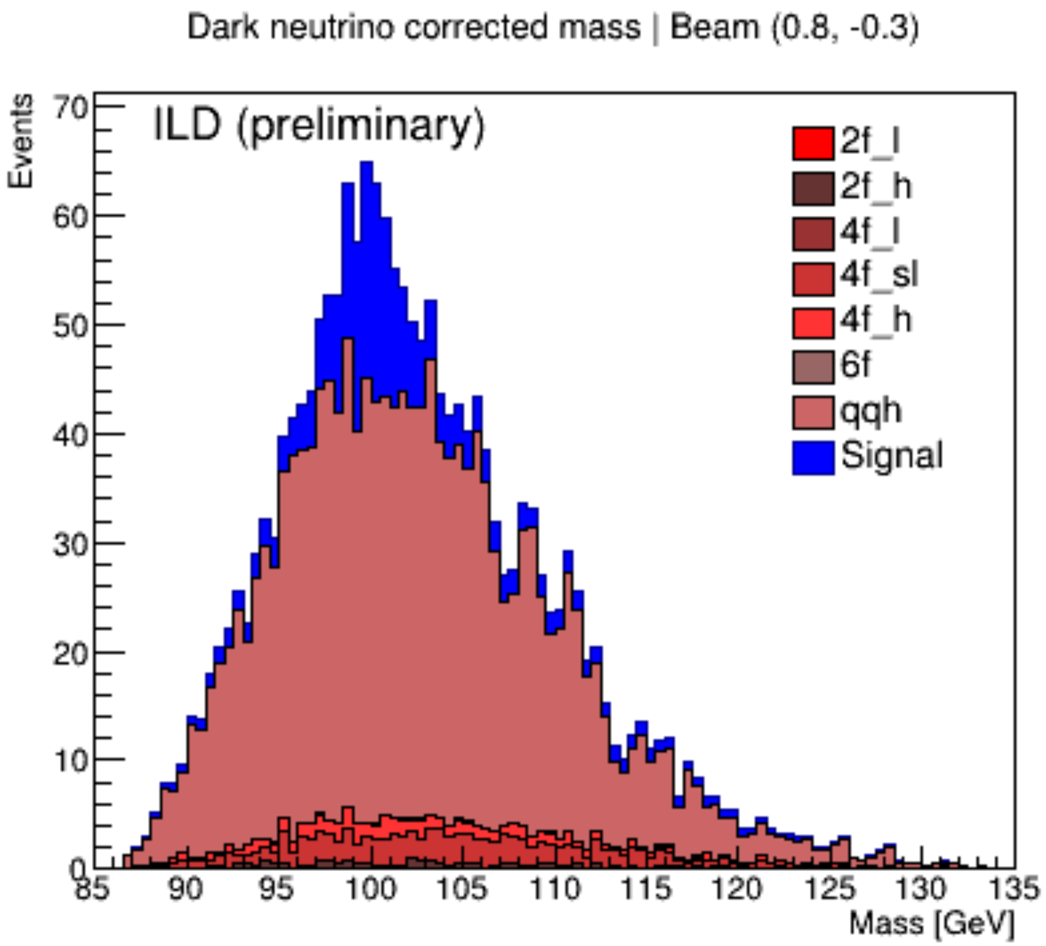
effect of improvement from TGC, ννH, ZH at 500GeV



	SM	pMSSM	2HDM-II	2HDM-X	2HDM-Y	Composite	LHT-6	LHT-7	Radion	Singlet
SM										
pMSSM	9.3									
2HDM-II	16.4	9.9								
2HDM-X	8.2	14.6	17.6							
2HDM-Y	18.2	9.6	10.3	23.3						
Composite	6.6	14.0	21.5	10.8	22.7					
LHT-6	6.9	7.6	12.7	10.1	15.6	10.1				
LHT-7	9.3	17.6	25.5	13.1	26.2	4.6	14.2			
Radion	9.8	16.0	22.5	13.1	23.7	11.6	14.9	10.9		
Singlet	5.3	10.7	17.3	9.5	19.2	6.1	6.0	9.5	10.0	

exotic decays: H—>νN, N—>Wl



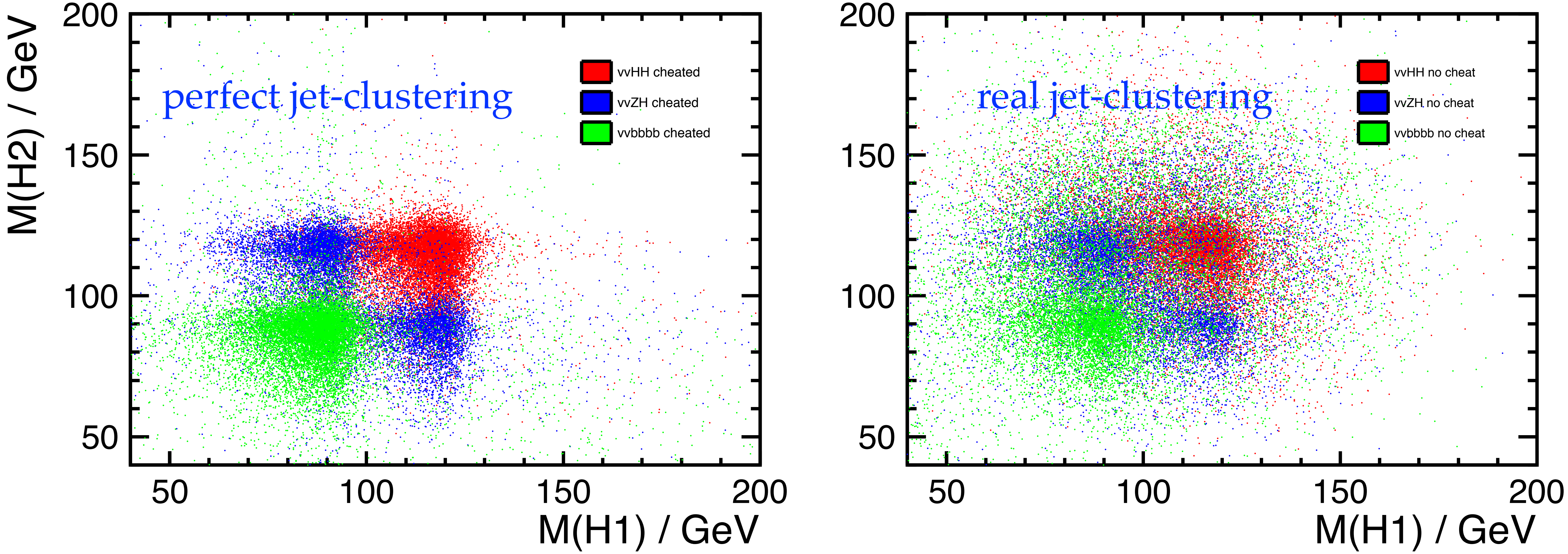


[Simon Thor, ongoing ILD analysis]

improving jet-clustering algorithm?

ZHH->ννbbbb (BG: ZZH and ZZZ)

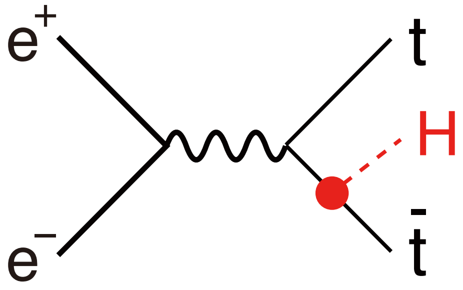
scatter plot of two Higgs masses



- 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%

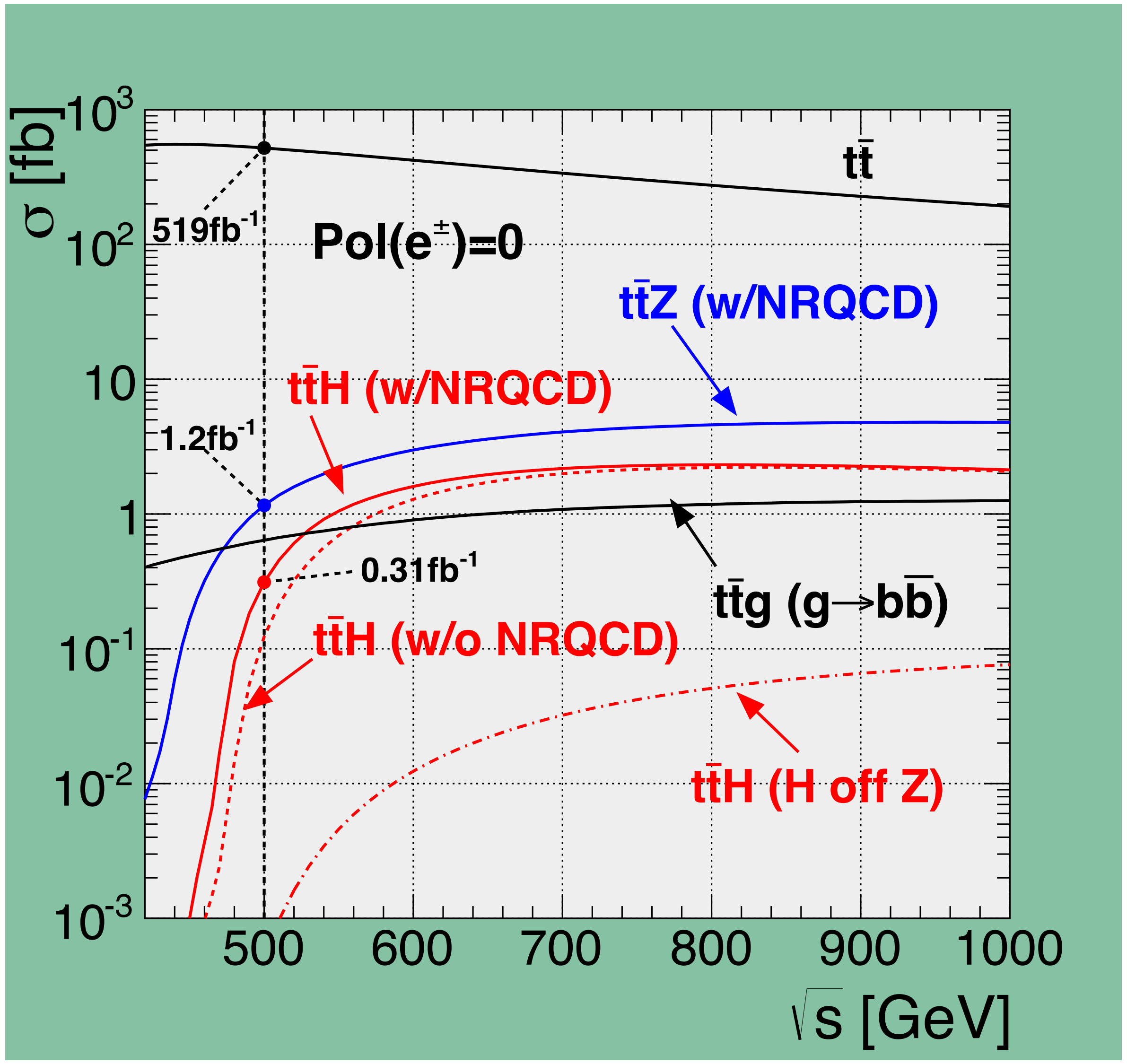
(ii-6) Top-Yukawa coupling

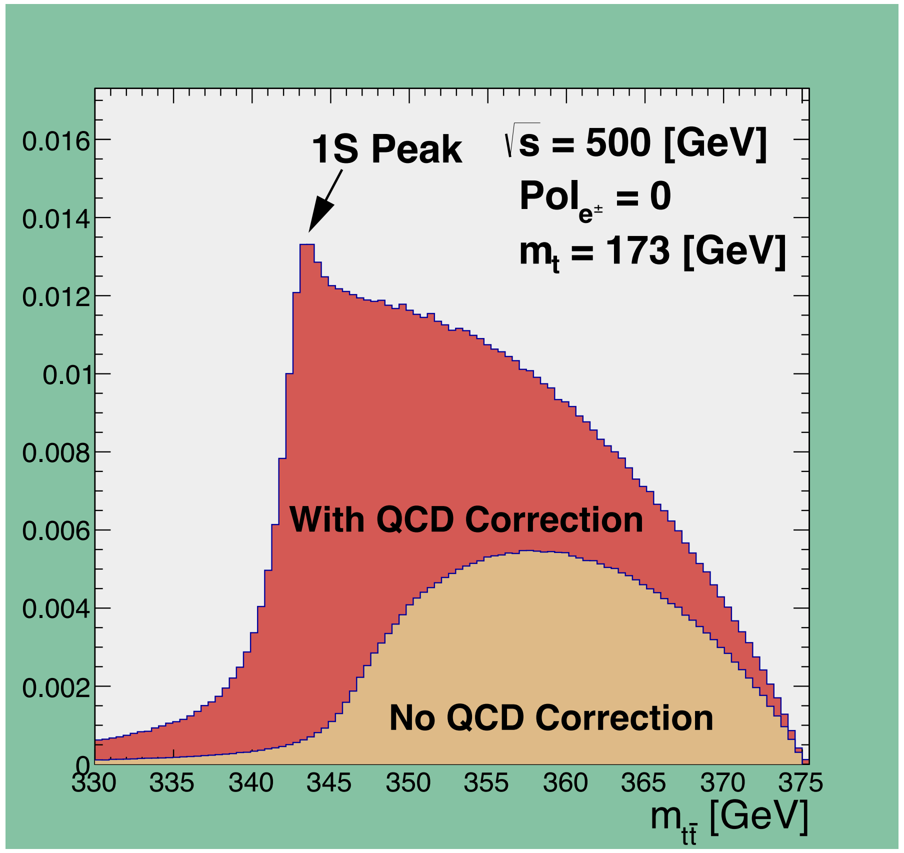
- largest Yukawa coupling; crucial role
- non-relativistic tt-bar bound state correction: enhancement by ~2 at 500 GeV
- Higgs CP measurement



H-> bb

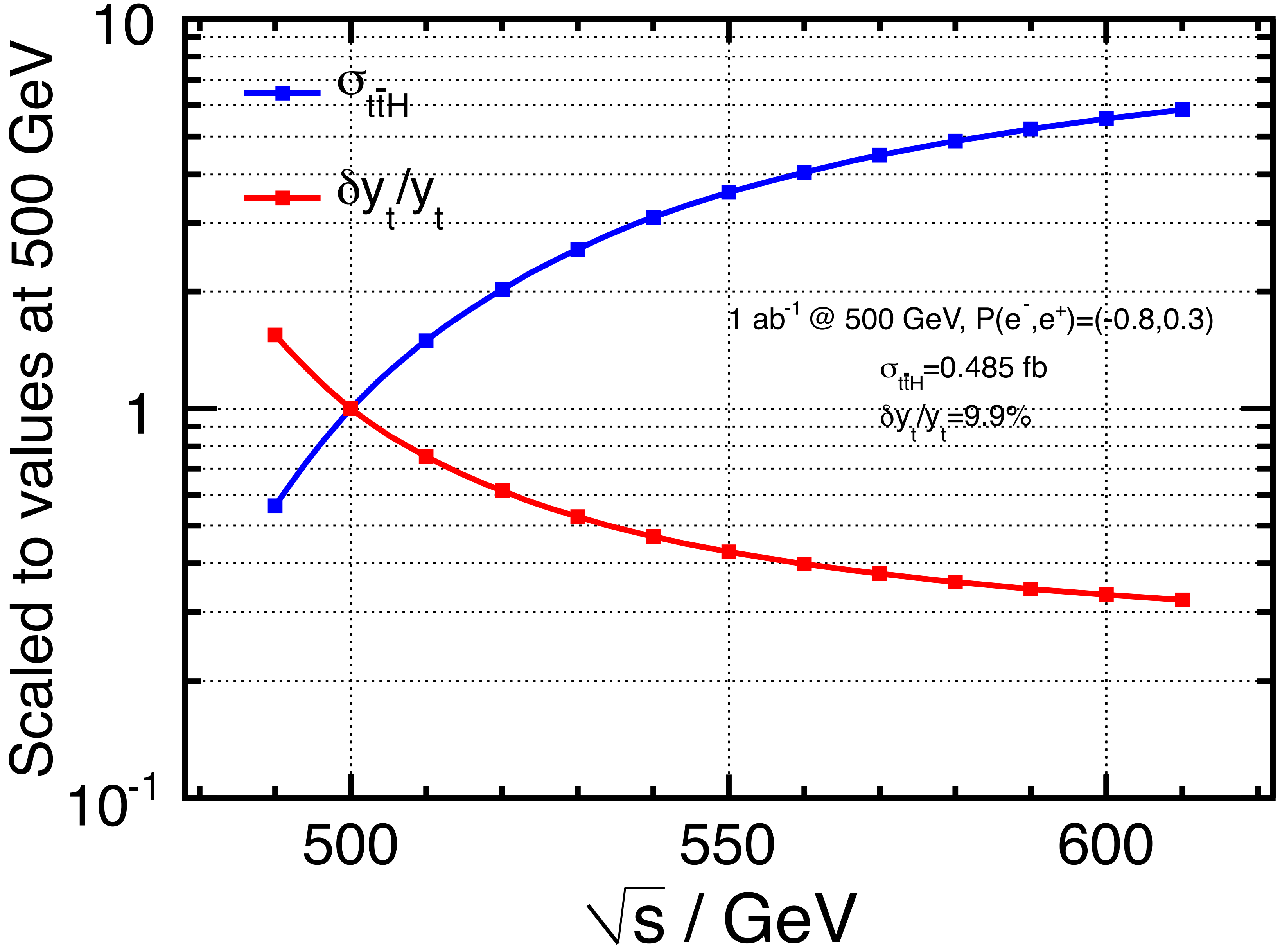
$\Delta g_{ttH}/g_{ttH}$	500 GeV	+ 1 TeV
ILC	6.3%	1.5%





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

Top-Yukawa coupling: impact of √s



[Y. Sudo]

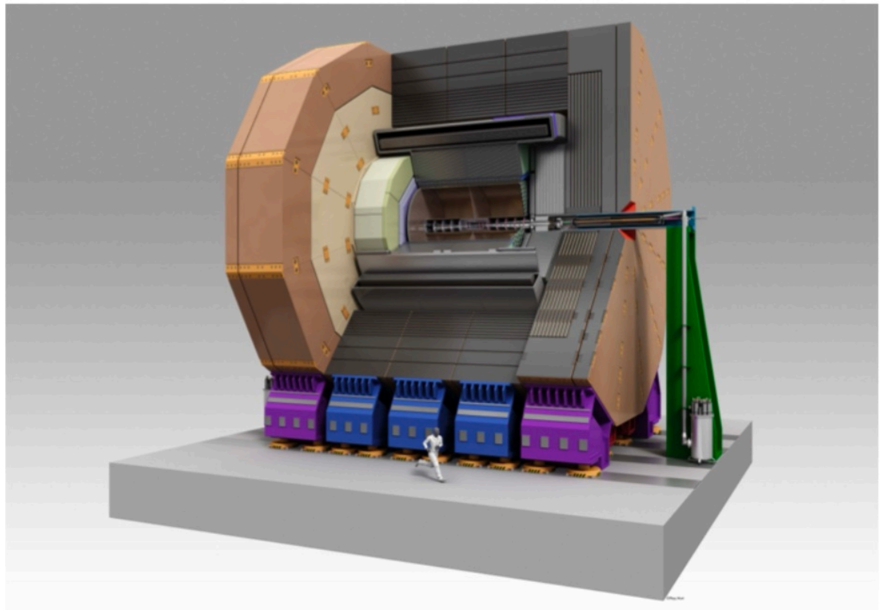
- increase √s slightly by 50GeV can improve δy_t by a factor of 2

Detector for Linear Colliders

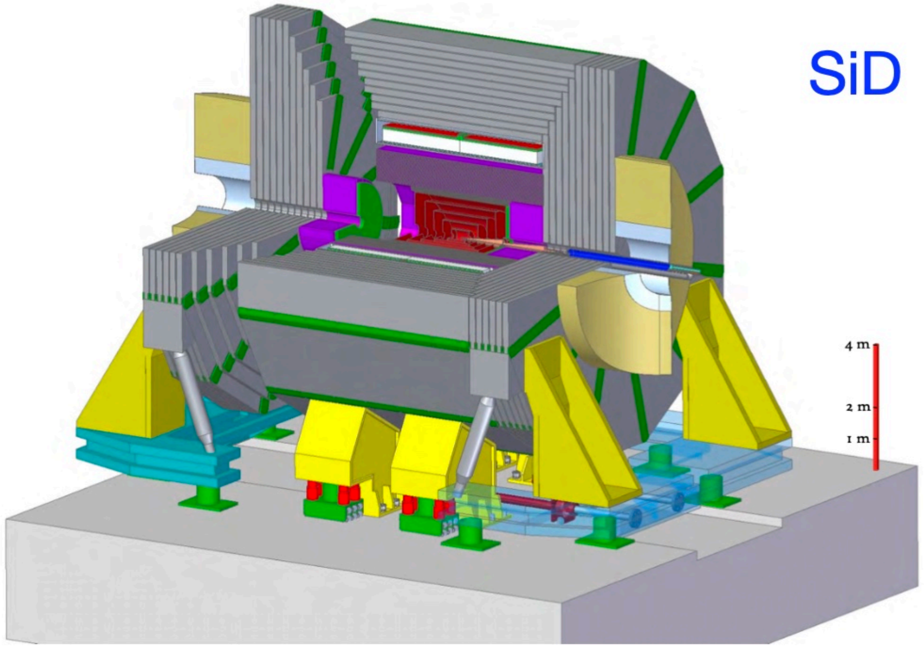
lineup

- 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

- “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

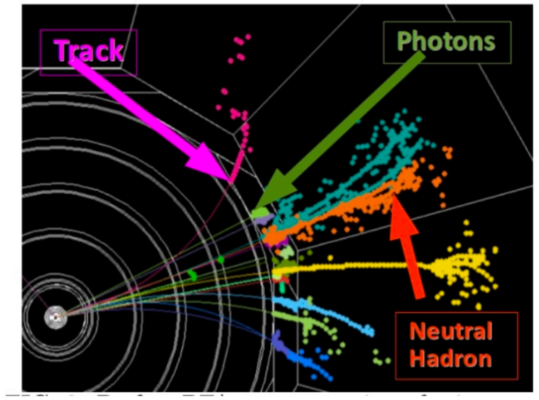
detector performance		physics performance
▷ Impact Parameter resolution	$5\ \mu\mathrm{m} \oplus \frac{10\ \mu\mathrm{m\ GeV}/c}{p\ \sin^{3/2}\theta}$	○ flavor tagging, e.g. hadronic Higgs BR meas. for bb/cc/gg
▷ Momentum resolution	$\Delta(1/p) = 2\times10^{-5}\ (\mathrm{GeV/c})^{-1}$	○ leptonic recoil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

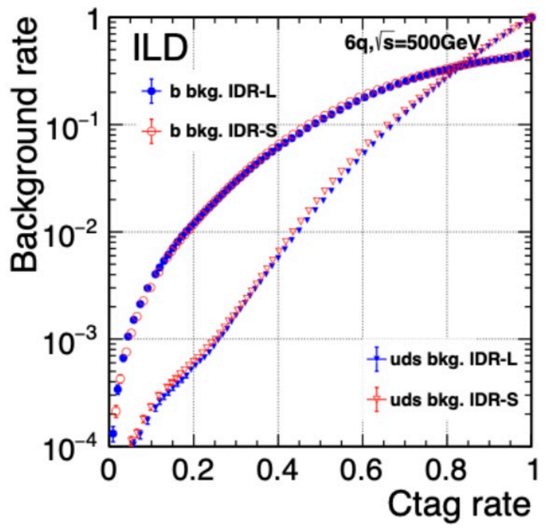
(asymptotic resolution)

Detector Concepts

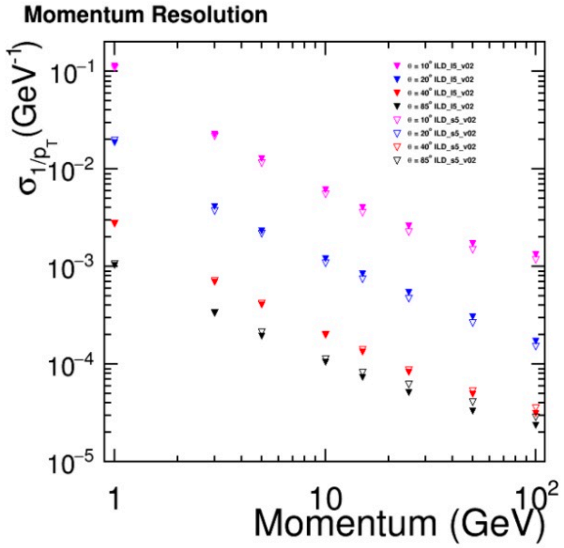
meet the requirements

- 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

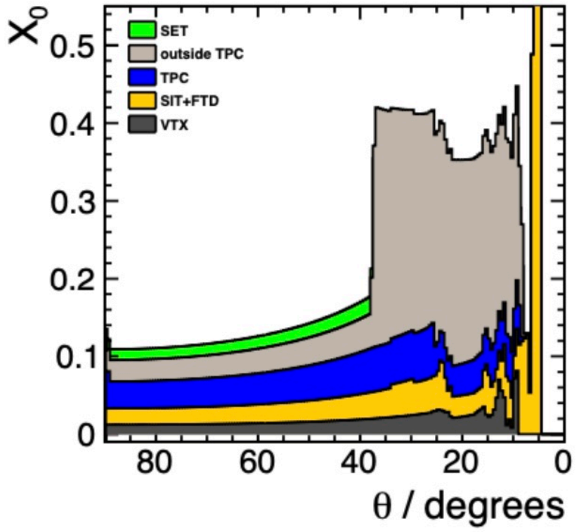




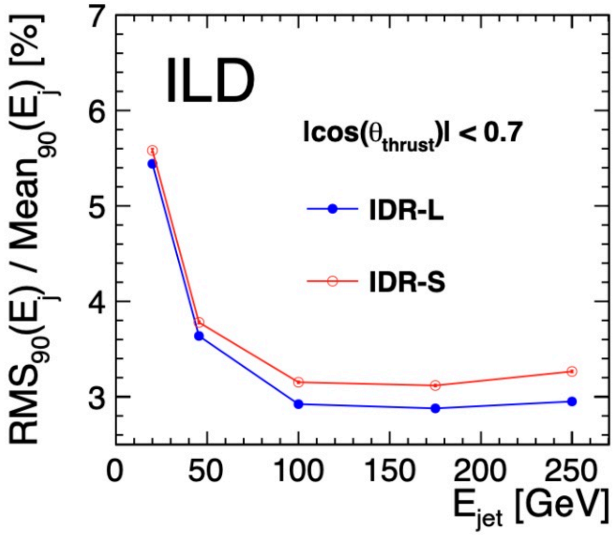
charm tagging



momentum resolution

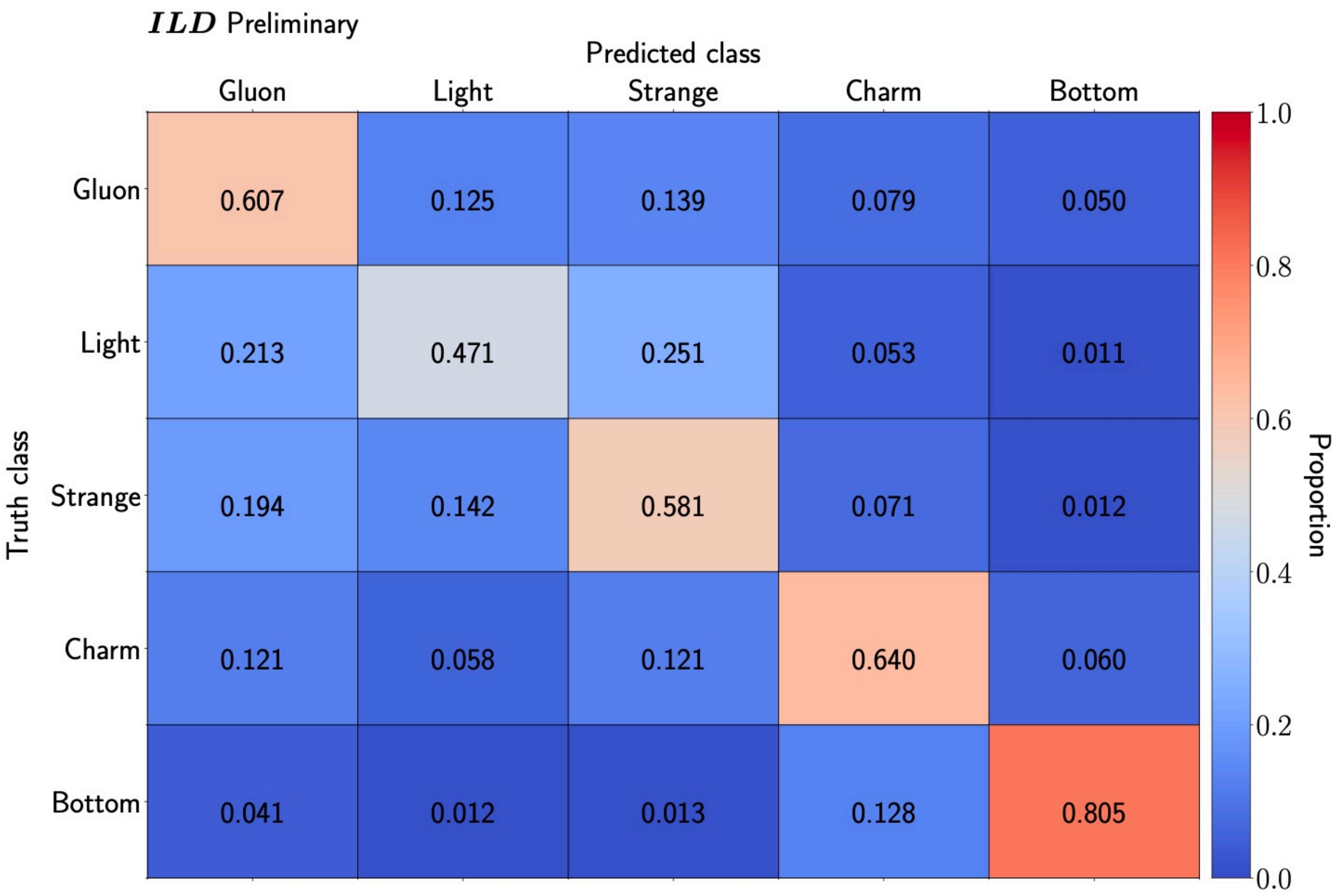


material budget



jet energy resolution

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



Truth class \ Predicted class	Gluon	Light	Strange	Charm	Bottom
Gluon	0.607	0.125	0.139	0.079	0.050
Light	0.213	0.471	0.251	0.053	0.011
Strange	0.194	0.142	0.581	0.071	0.012
Charm	0.121	0.058	0.121	0.640	0.060
Bottom	0.041	0.012	0.013	0.128	0.805

Figure 6: Confusion matrix for the output of the described jet flavour tagger, Eq. 5. Each truth class (i.e., row) is normalised to 1.