

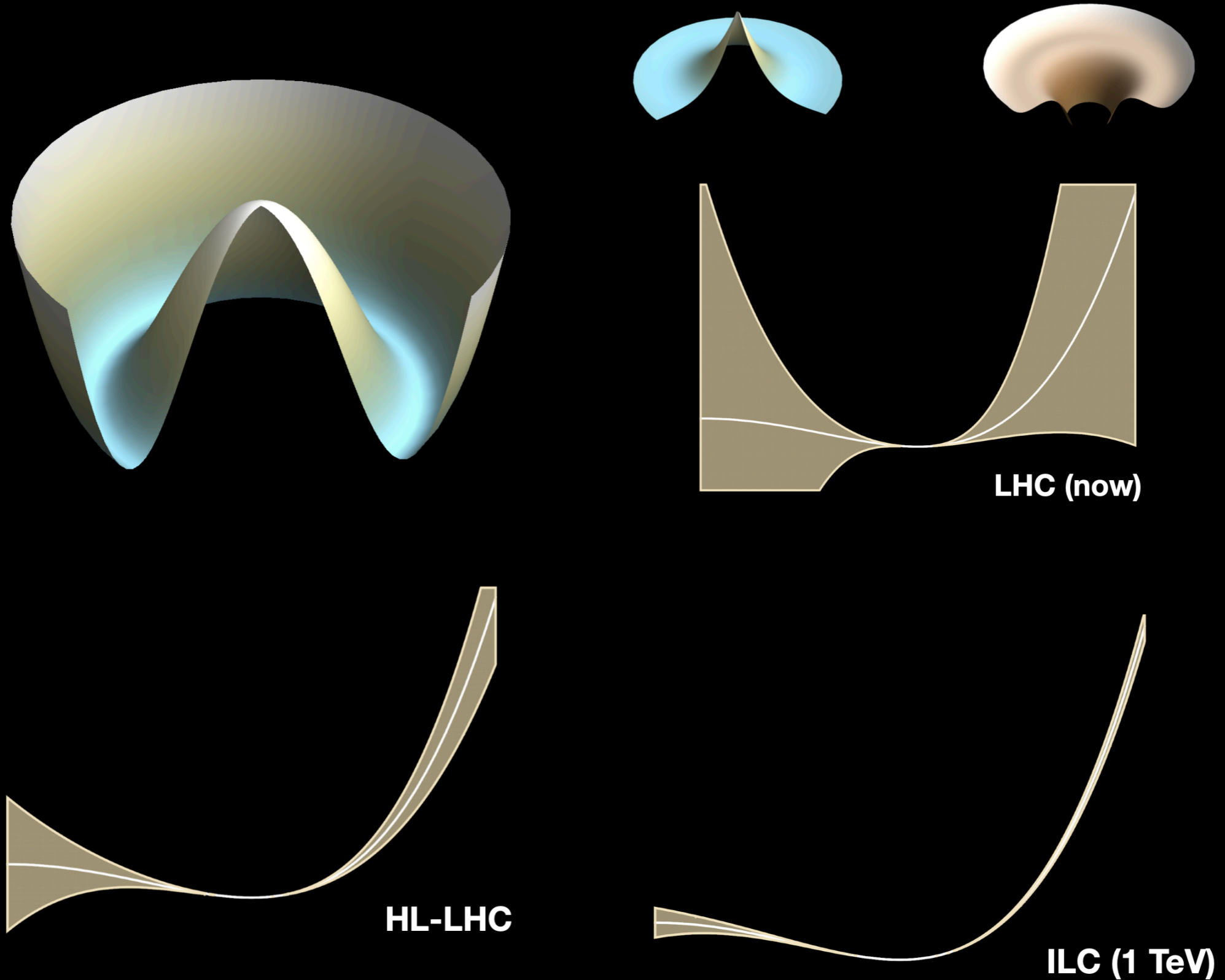
Focus topic: Higgs self-coupling

expert team (3 meetings May 8, June 23, Oct. 6)

Gauthier Durieux (CERN)	Theory
Ricardo Goncalo (Coimbra)	ALTAS / FCC-ee
Sven Heynemeyer (IFT CSIC)	WG1-GLOB / Theory
Michael Peskin (SLAC)	Theory
Philipp Roloff (CERN)	CLIC
Roberto Salerno (LLR/Ecole Polytechnique)	CMS / FCC-ee
Junping Tian (U.Tokyo)	WG1-GLOB / ILC
Jenny List (ex-officio)	

2nd ECFA Workshop on e+e- Higgs/EW/Top Factories
Oct. 11-13, 2023 @ Paestum, Italy

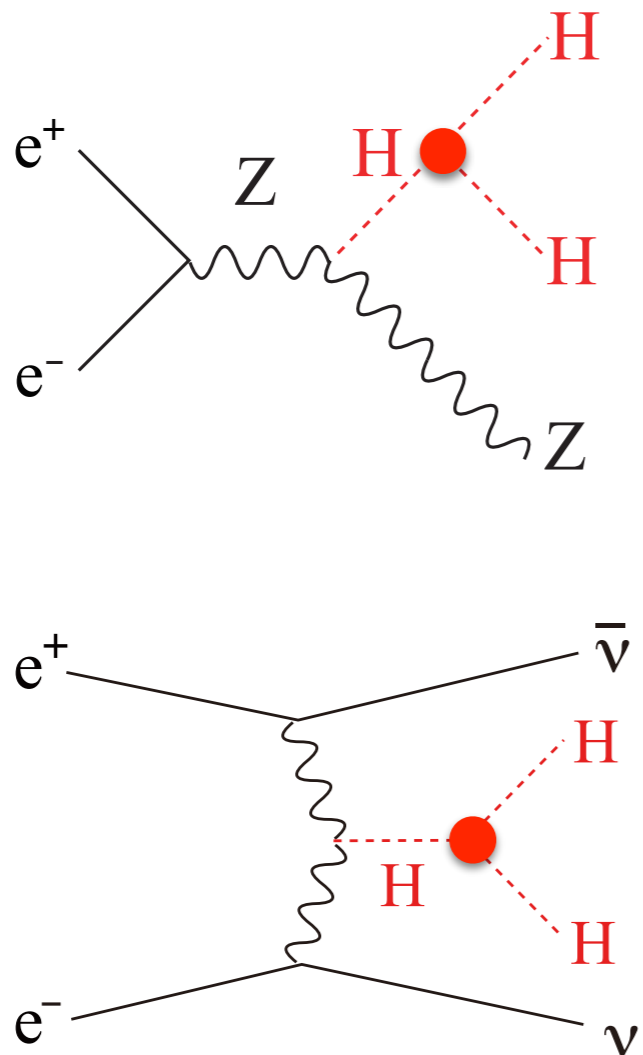
Is it the SM Higgs?



[N. Craig @ LCWS 2023]

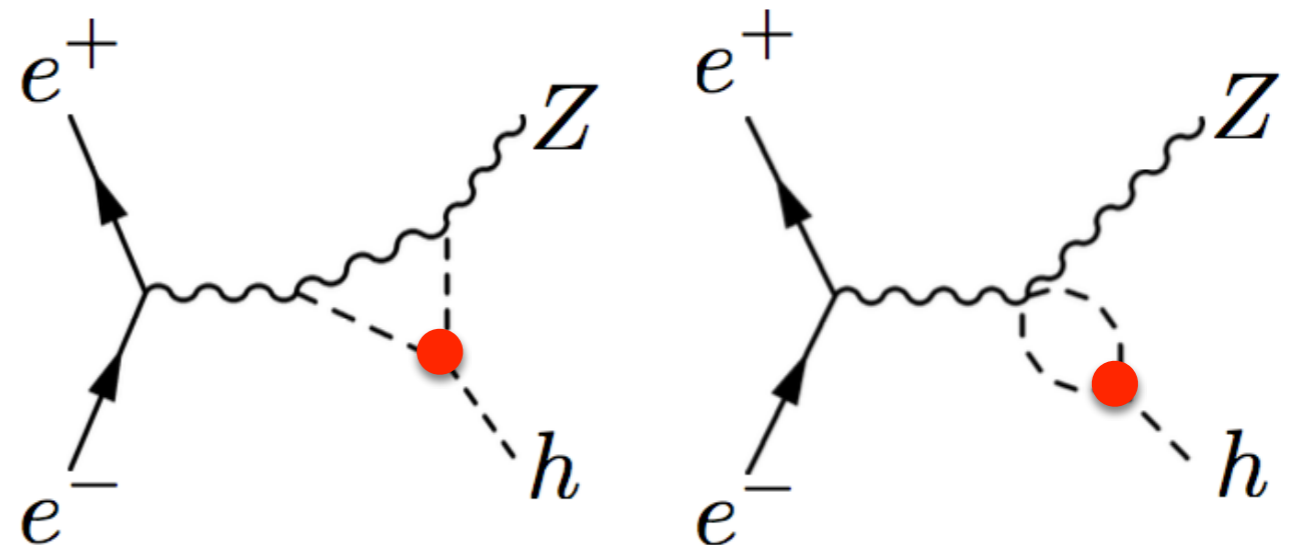
λ_{HHH} : double-Higgs & single-Higgs processes

$\sqrt{s} \gtrsim 500 \text{ GeV}$



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

$\sqrt{s} \gtrsim 240\text{--}250 \text{ GeV}$

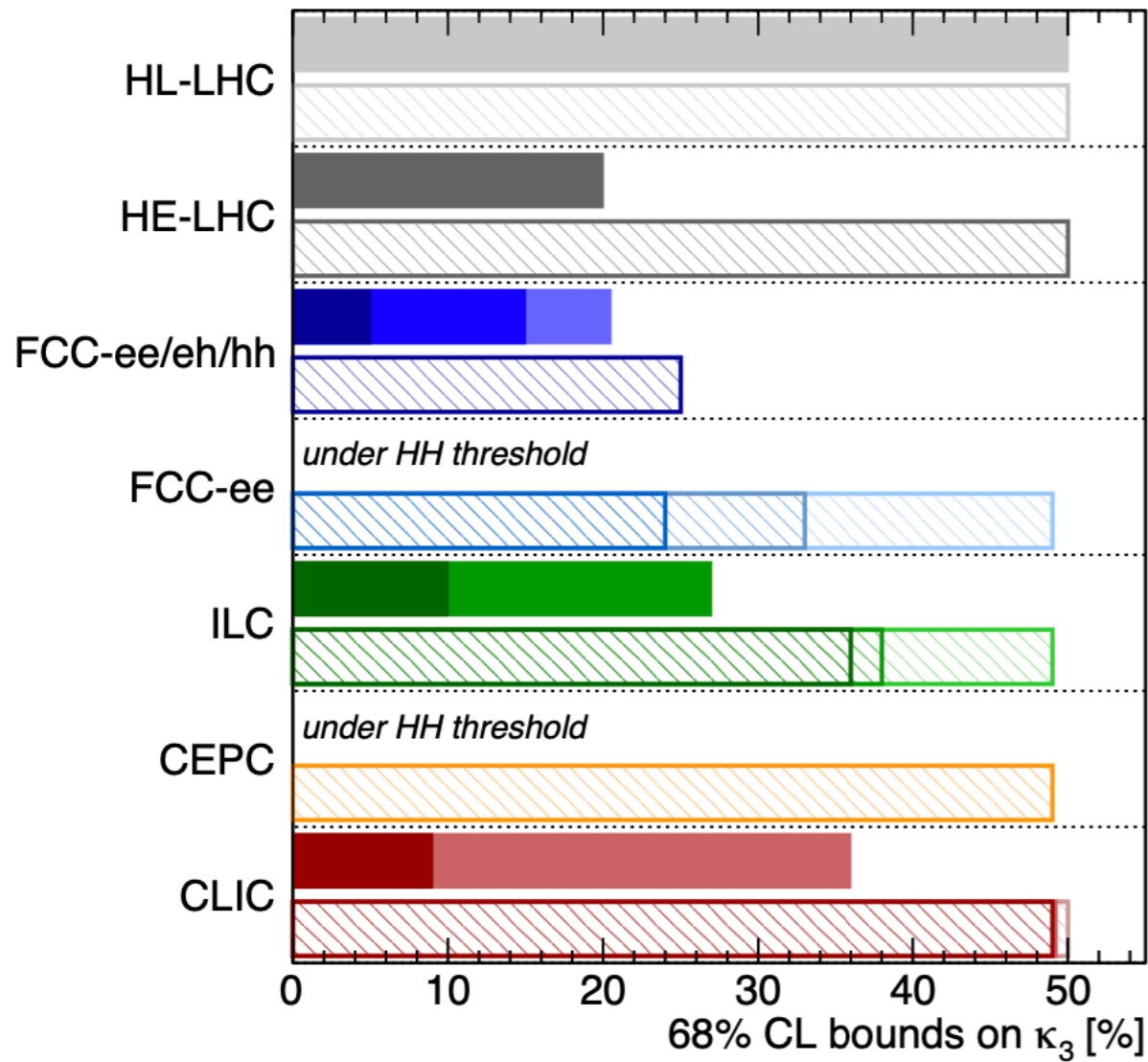


$\delta\sigma_{ZH} \sim O(1\%)$

Starting point: ESU 2020

[Physics Briefing Book, arXiv:1910.11775]

Higgs@FC WG September 2019



di-Higgs		single-Higgs	
HL-LHC	50%	HL-LHC	50%
HE-LHC	[10-20]%	HE-LHC	50%
FCC-ee/eh/hh	5%	FCC-ee/eh/hh	25%
LE-FCC	15%	LE-FCC	n.a.
FCC-eh ₃₅₀₀	-17+24%	FCC-eh ₃₅₀₀	n.a.
		FCC-ee ^{4IP} ₃₆₅	24%
		FCC-ee ₃₆₅	33%
		FCC-ee ₂₄₀	49%
ILC ₁₀₀₀	10%	ILC ₁₀₀₀	36%
ILC ₅₀₀	27%	ILC ₅₀₀	38%
		ILC ₂₅₀	49%
		CEPC	49%
CLIC ₃₀₀₀	-7%+11%	CLIC ₃₀₀₀	49%
CLIC ₁₅₀₀	36%	CLIC ₁₅₀₀	49%
		CLIC ₃₈₀	50%

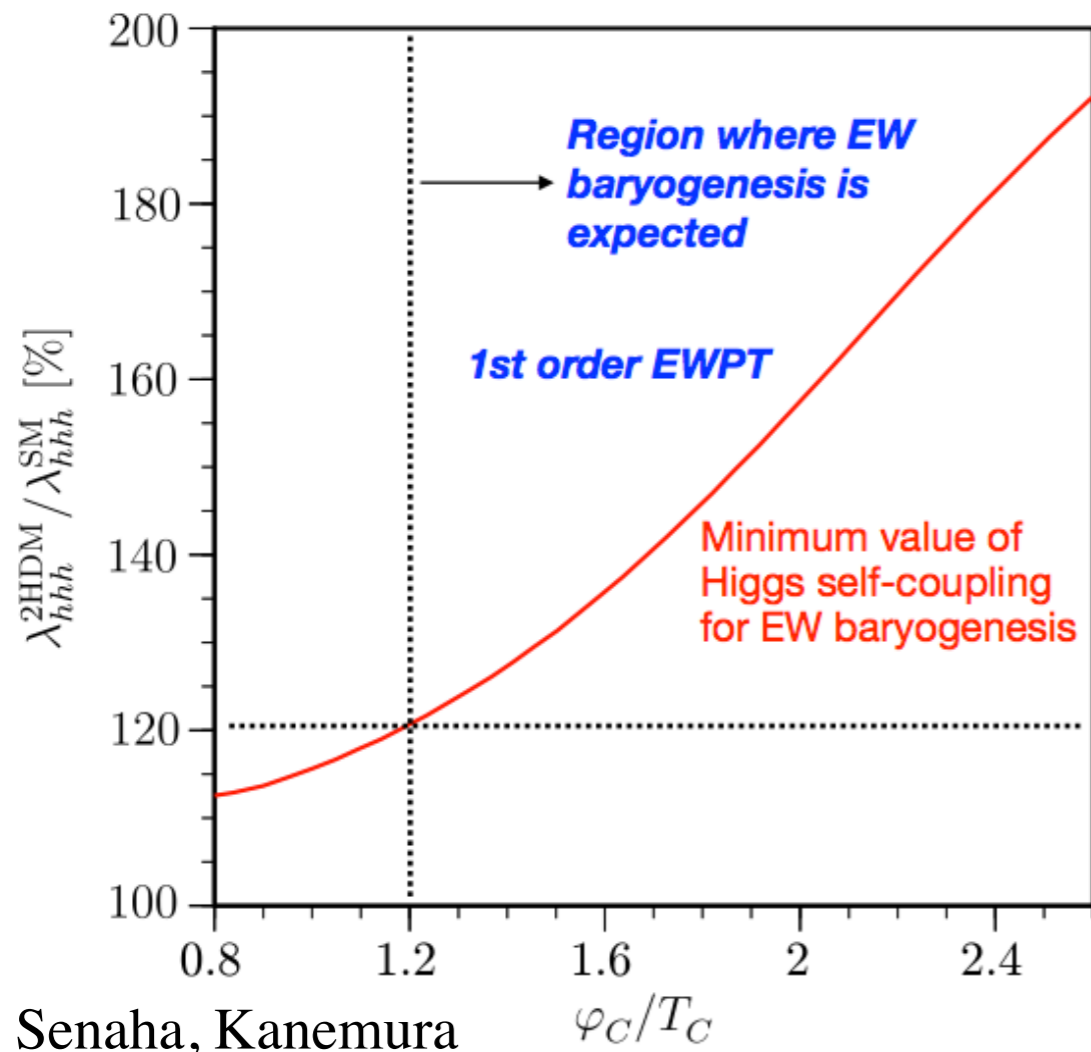
All future colliders combined with HL-LHC

- based on global SMEFT fits
- HL-LHC di-Higgs contribution was always combined

—> a list of questions suggested by expert team to advance the study of this topic

(i) beyond SMEFT: large $\delta\lambda_{hhh}$; extra light scalars

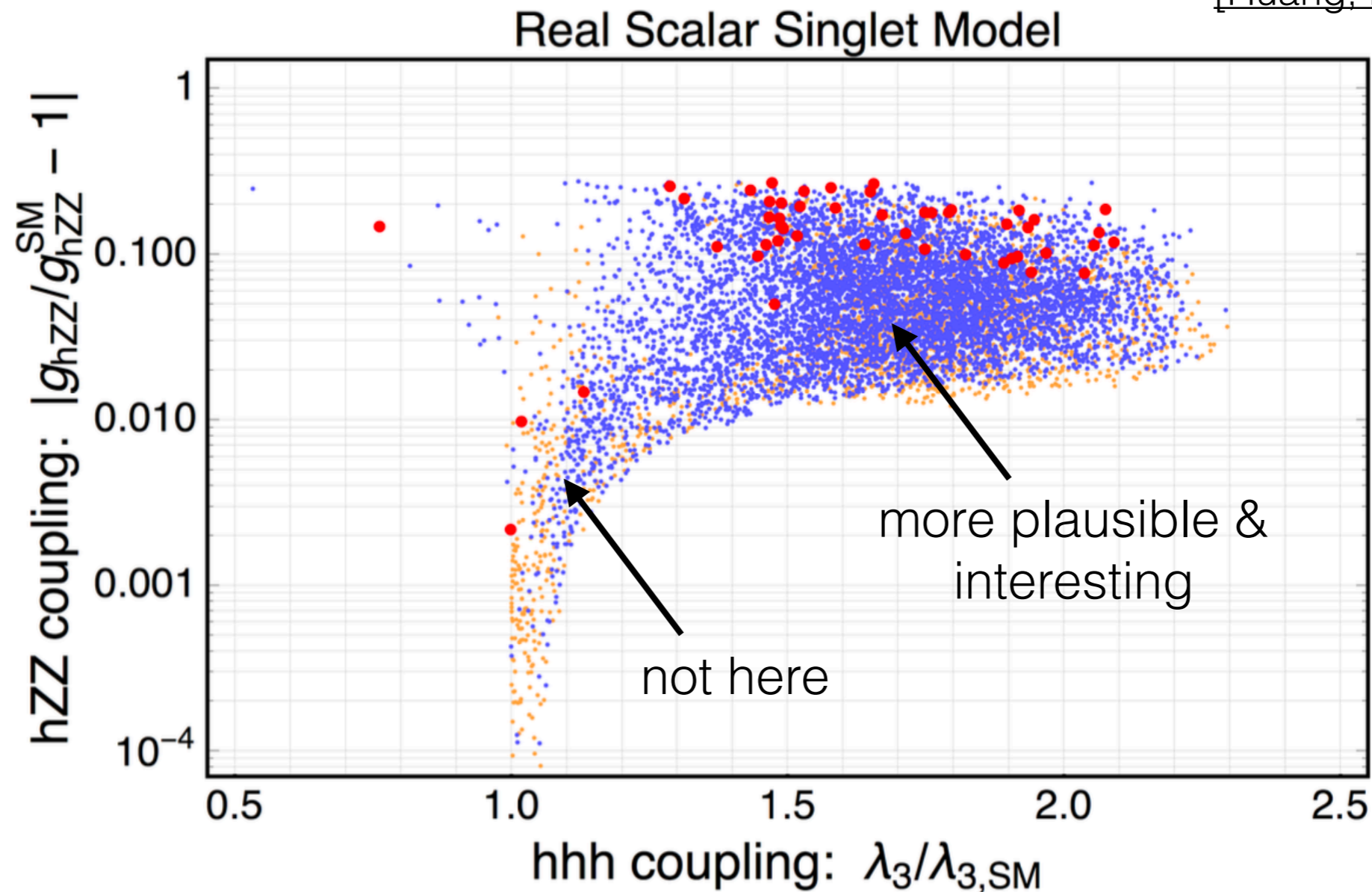
- O(1) deviation on λ_{hhh} (preferred in certain BSM)
- Light degree of freedoms (i.e. extra Higgs bosons)



- ▶ **How current projections of λ_{hhh} measurements would change when $\lambda_{hhh} \neq \lambda_{SM}$ in both methods (di-Higgs & single-Higgs)?**
- ▶ **Searches of light scalars belong to other groups, but how would their existence impact our expectation of λ_{hhh} measurement?**

(i) beyond SMEFT: large $\delta\lambda_{hhh}$; light scalars

[Huang, Long, Wang, '16]



orange: first-order phase transition

blue: strongly first-order phase transition ($v/T > 1.3$)

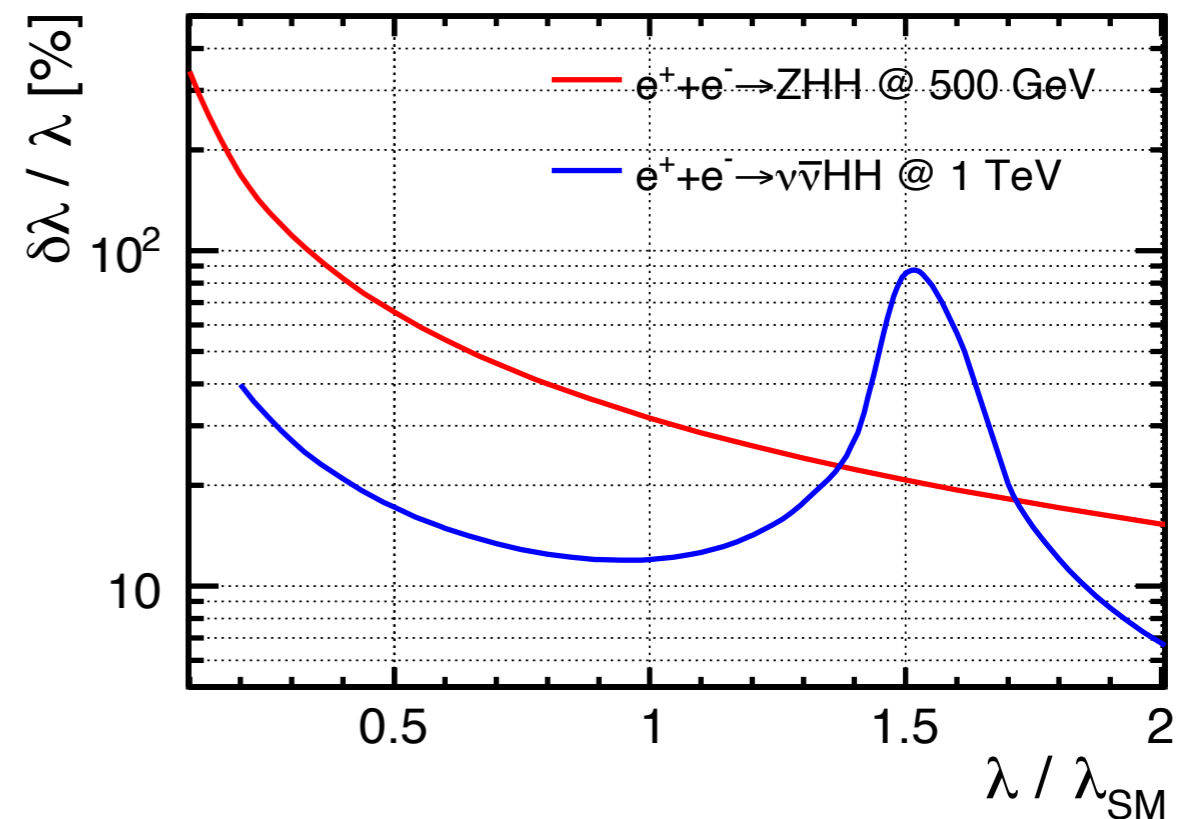
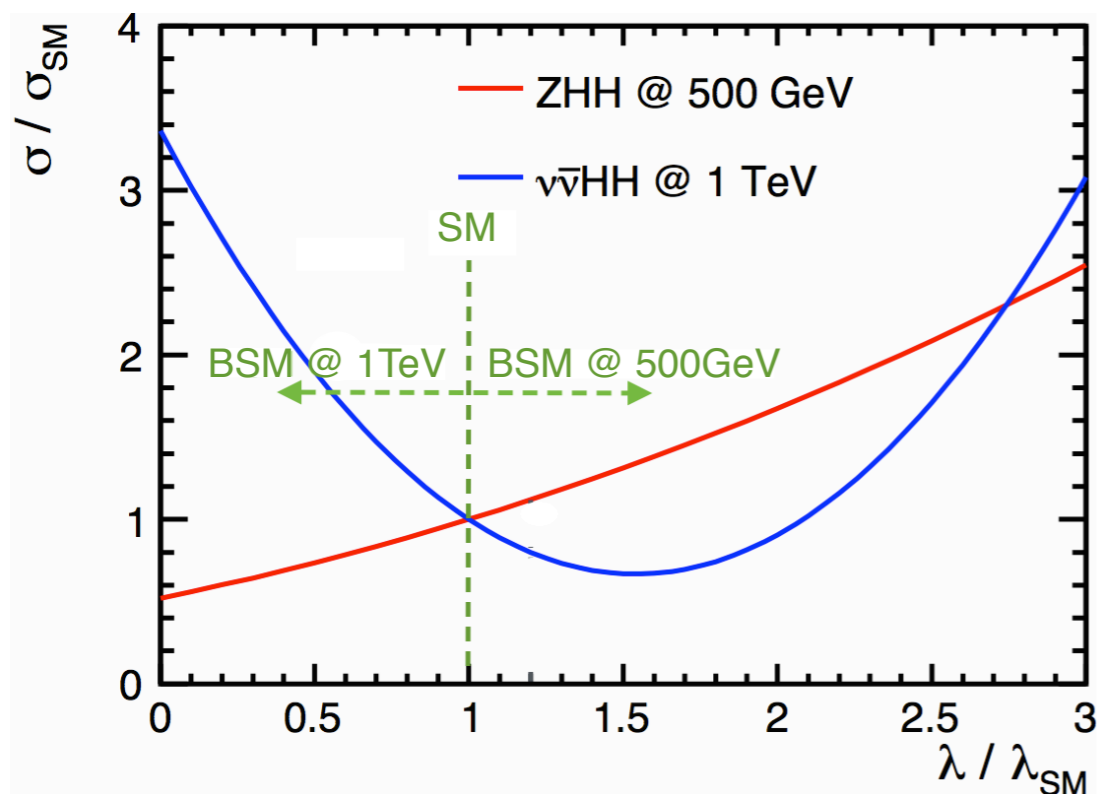
red: very strongly first-order phase transition (GW @ eLISA)

[recent models with even larger hierarchy $\delta_{hhh} / \delta_{hVV}$: [Durieux, McCullough, Salvioni, '22](#)]

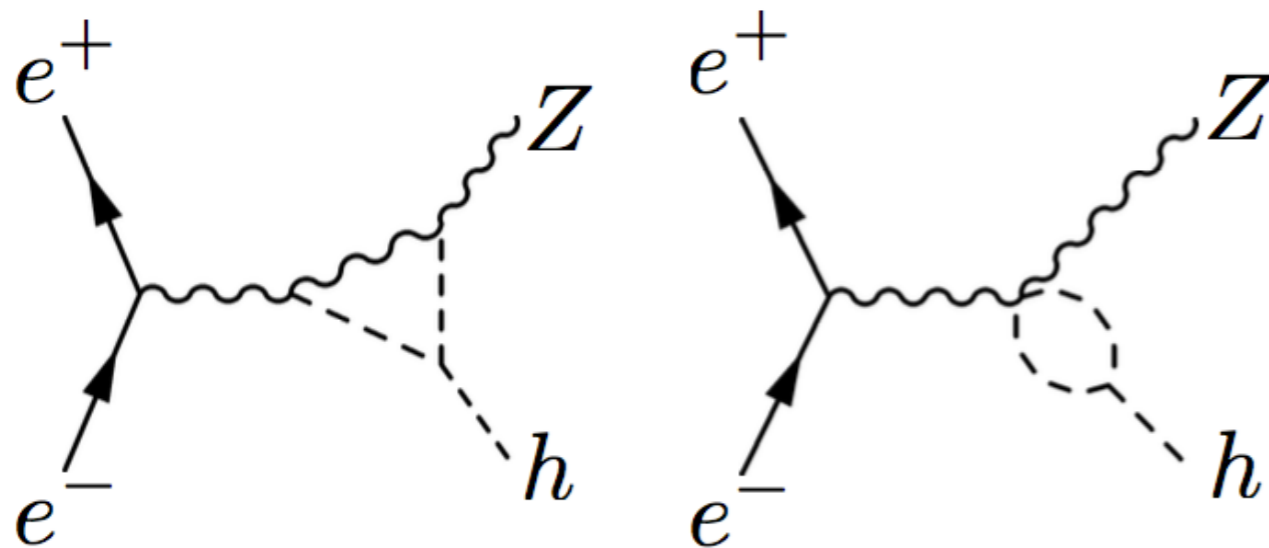
(i) beyond SMEFT: large $\delta\lambda_{hhh}$; light scalars

(examples)

- profound effect on di-Higgs processes
- complementarity between ZHH & $\nu\bar{\nu}HH$ (& LHC): different interference
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be *discovered* ($\sim 13\%$) using ZHH at 500 GeV e^+e^-



(ii) questions related to single-Higgs process



[McCullough, '13]

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

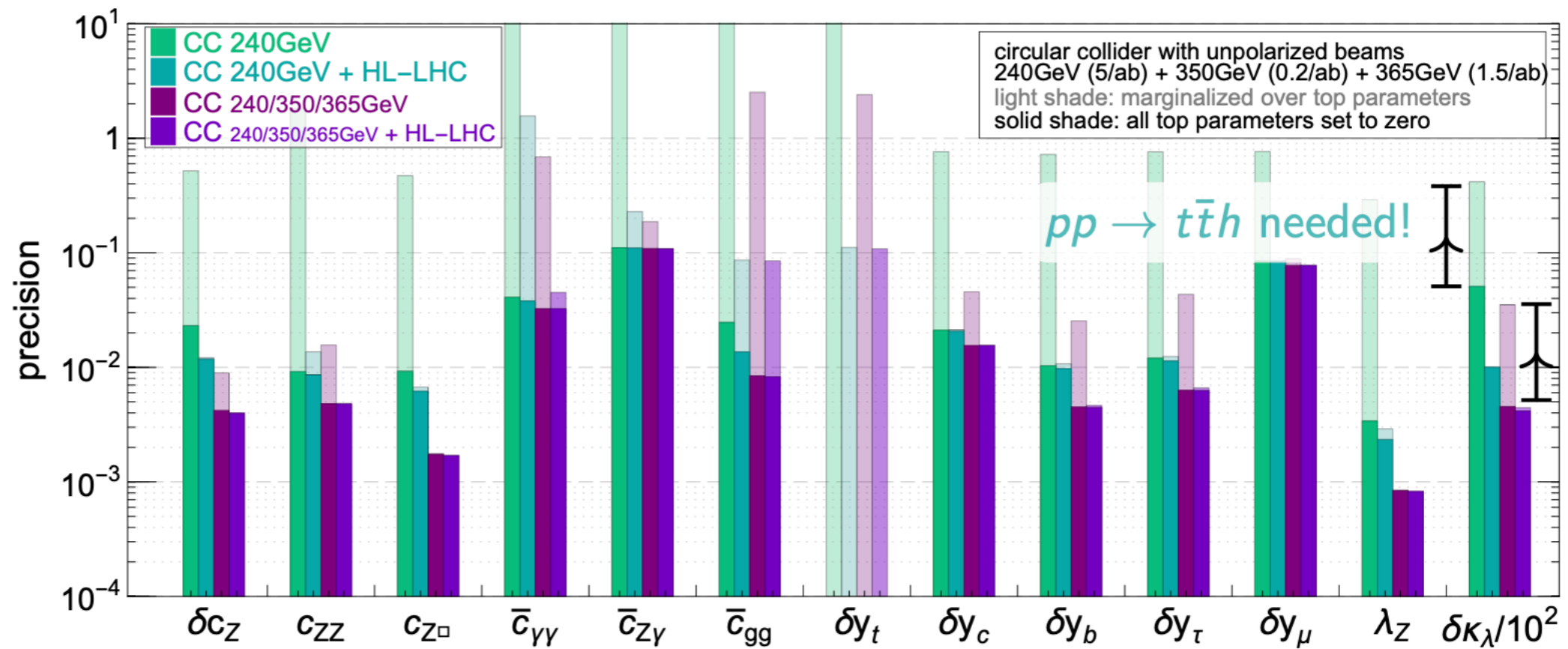
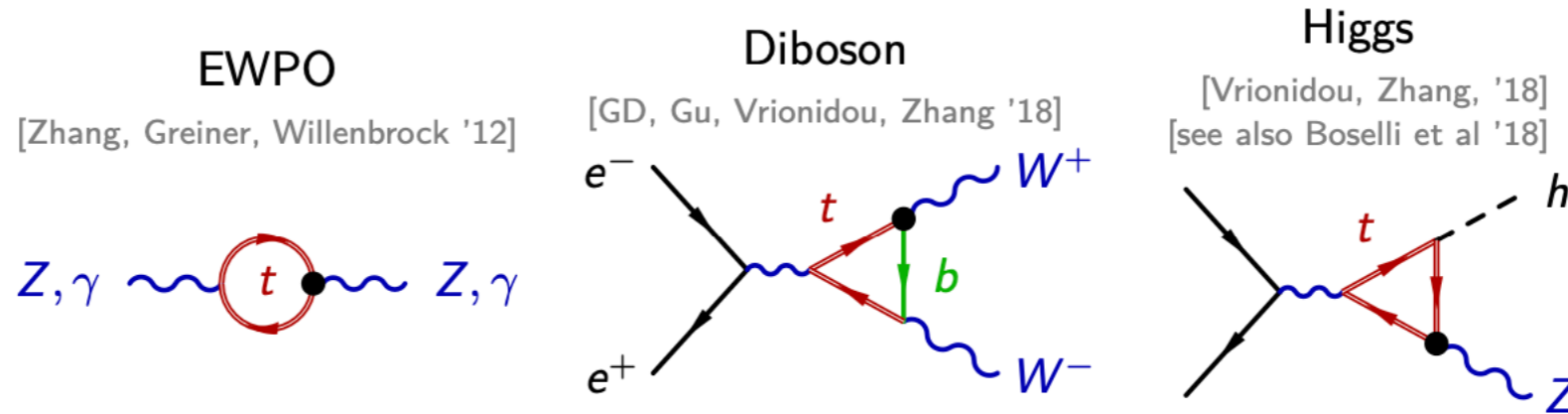
- if only δh is deviated $\rightarrow \delta h \sim 28\%$ [ILC as example]
- if both δz and δh deviated $\rightarrow \delta h \sim 90\%$
- $\delta\sigma$ could receive contributions from many other sources
 - $\rightarrow \delta h \sim 500\%$ at 250GeV only; [Gu, et al, arXiv:1711.03978]
 - $\rightarrow \delta h \sim 50\% + 350/500\text{GeV}$ [Peskin, Yong, JT, paper in preparation]

► can we lift the degeneracies by new observables, e.g. ZHang?

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

(ii) NLO @ single-Higgs: from top-quark

[talk by G. Durieux at ECFA mini-work HTE 2023]



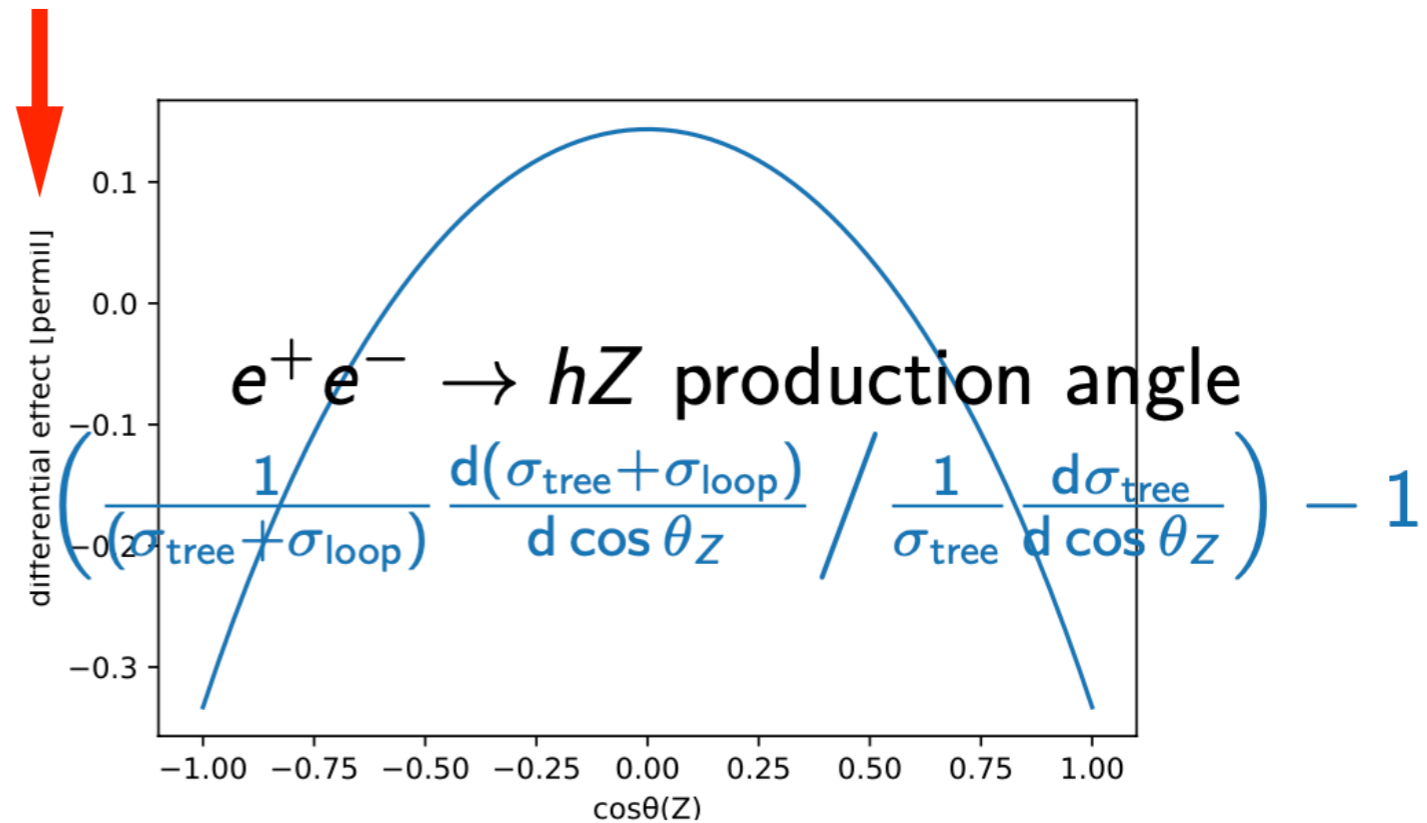
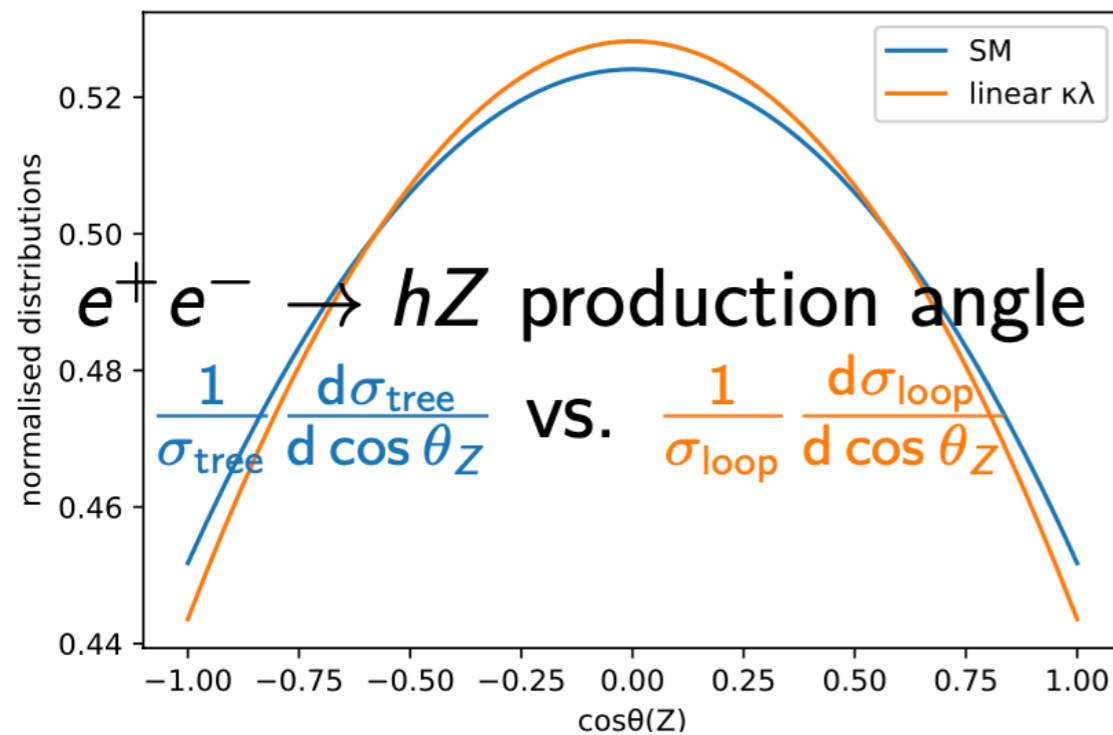
Top-quark uncertainties can impede Higgs precision!

[Durieux, Gu, Vrionidou, Zhang, '18]

[Jung, Lee, Perello, JT, Vos, '20]

(ii) single-Higgs: lift degeneracies

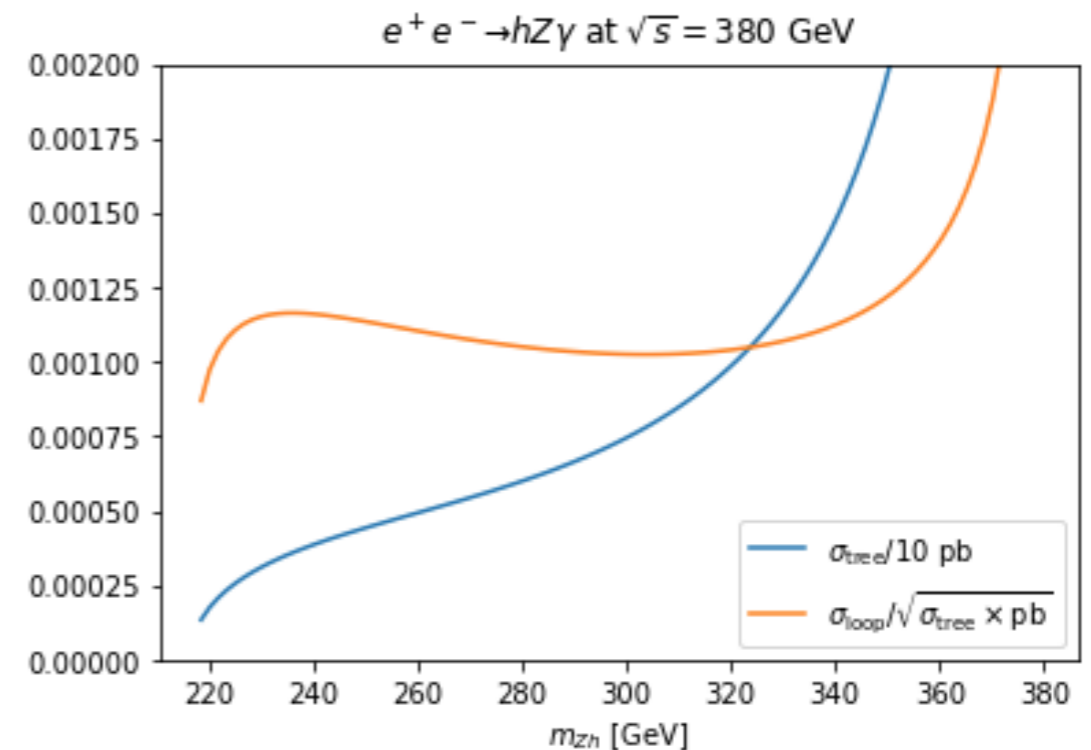
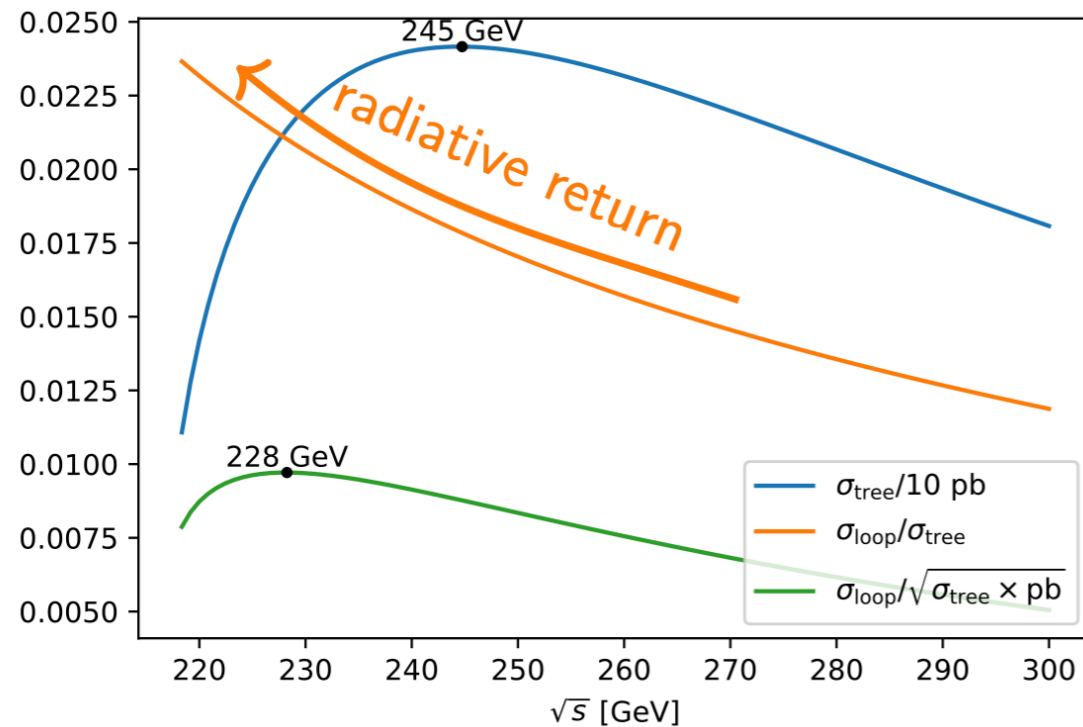
► can differential cross sections help?



[Durieux, et al, preliminary]

(ii) single-Higgs: lift degeneracies

- ▶ can energy scan around 240-250 help? or using radiative return from 365/380 GeV?

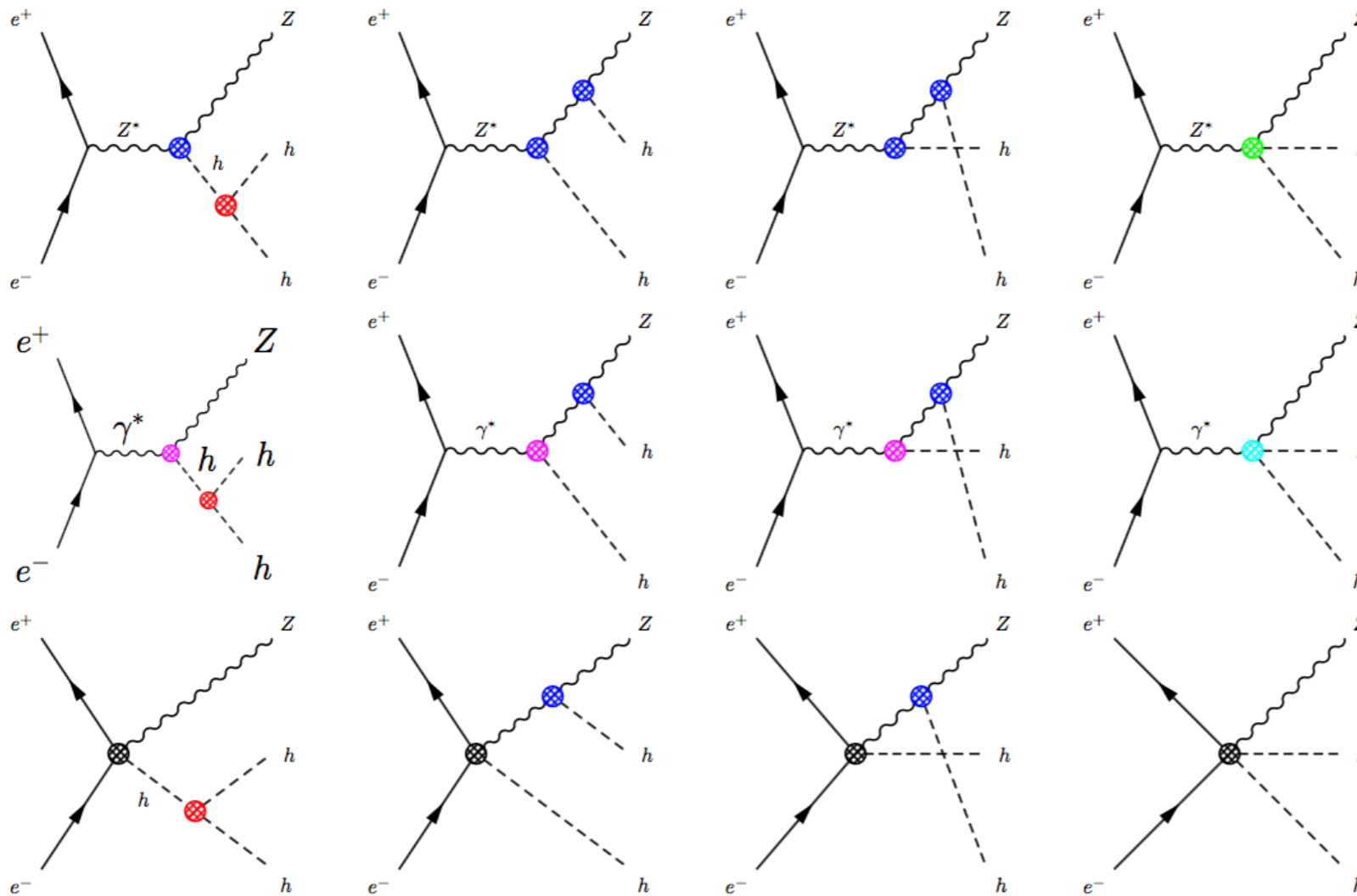


[Durieux, et al, preliminary]

(ii) single-Higgs: other questions

- ▶ **can we clarify the importance of each input measurement for the λ_{hhh} in the global fit?**
- ▶ **do we expect any update from experimental analyses about sing-Higgs observables?**
- ▶ **single-Higgs contribution at $\sqrt{s} \geq 500$ GeV should be combined with double-Higgs for λ_{hhh}**
- ▶ ...

(iii) questions related to double-Higgs process

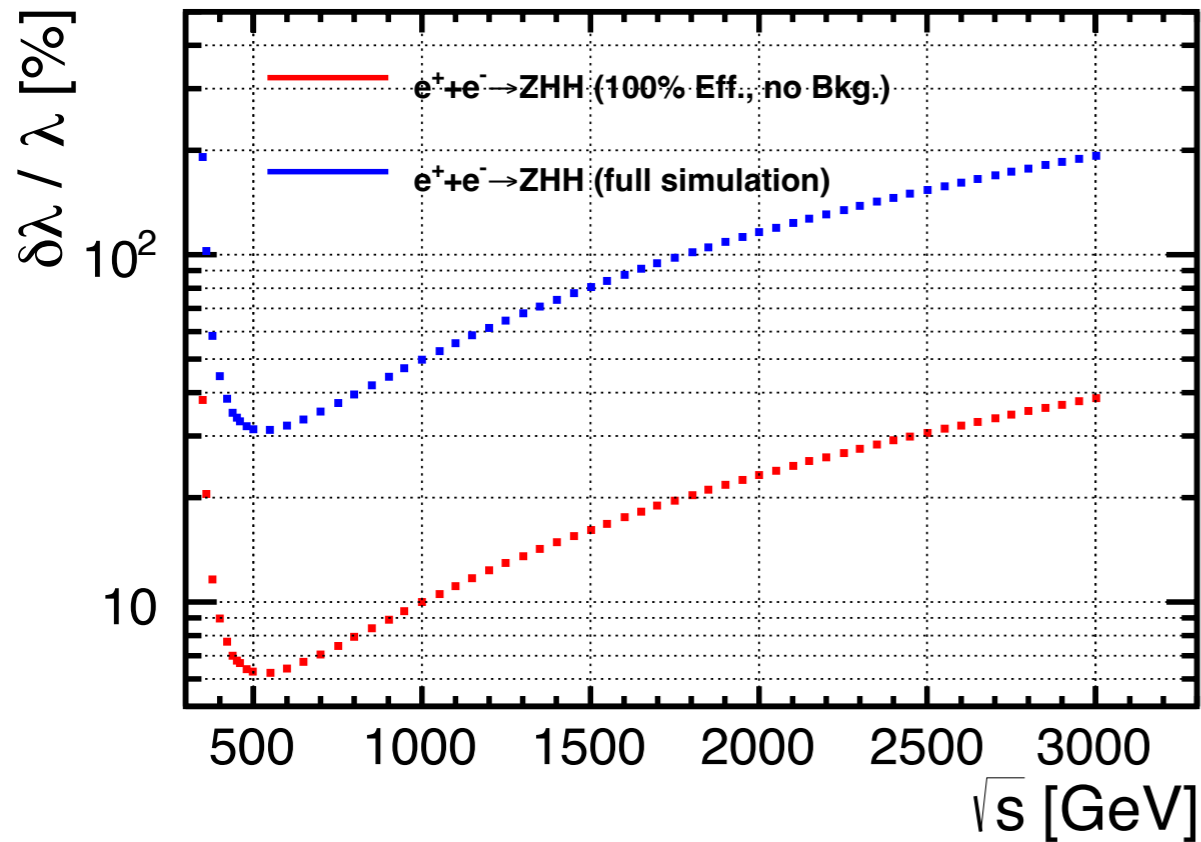


[Barklow, Fujii, Jung, Peskin, JT, '17]

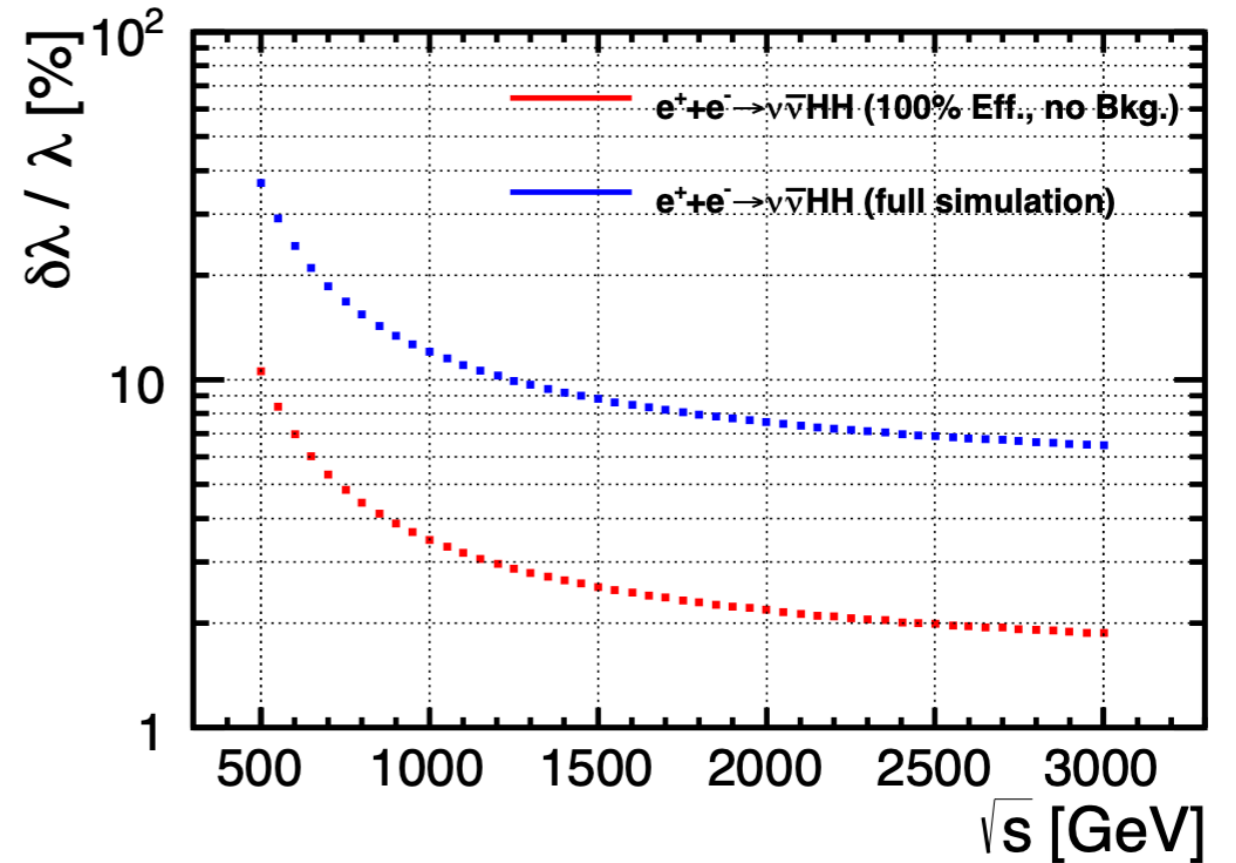
- Much less challenge from degeneracies
- Main questions are related to how we can improve experimental analyses

(iii) di-Higgs: can we improve $\Delta\lambda_{HHH}$ by a factor of 5?

ZHH



$\nu\nu HH$



[Duerig, PhD Thesis, 2016]

a lot of room for improvement by advanced analysis technique:
flavor tagging, jet-clustering, kinematic fitting, matrix element method, machine learning, etc

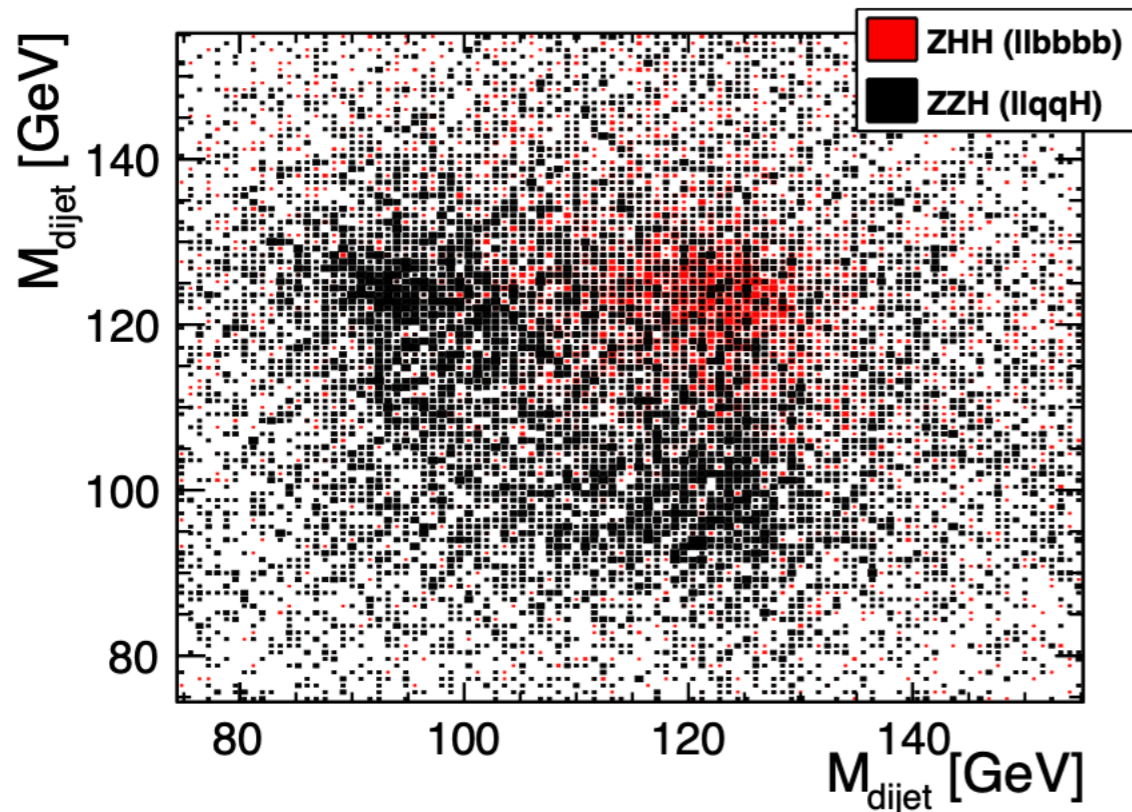


[talk by T.Suehara]

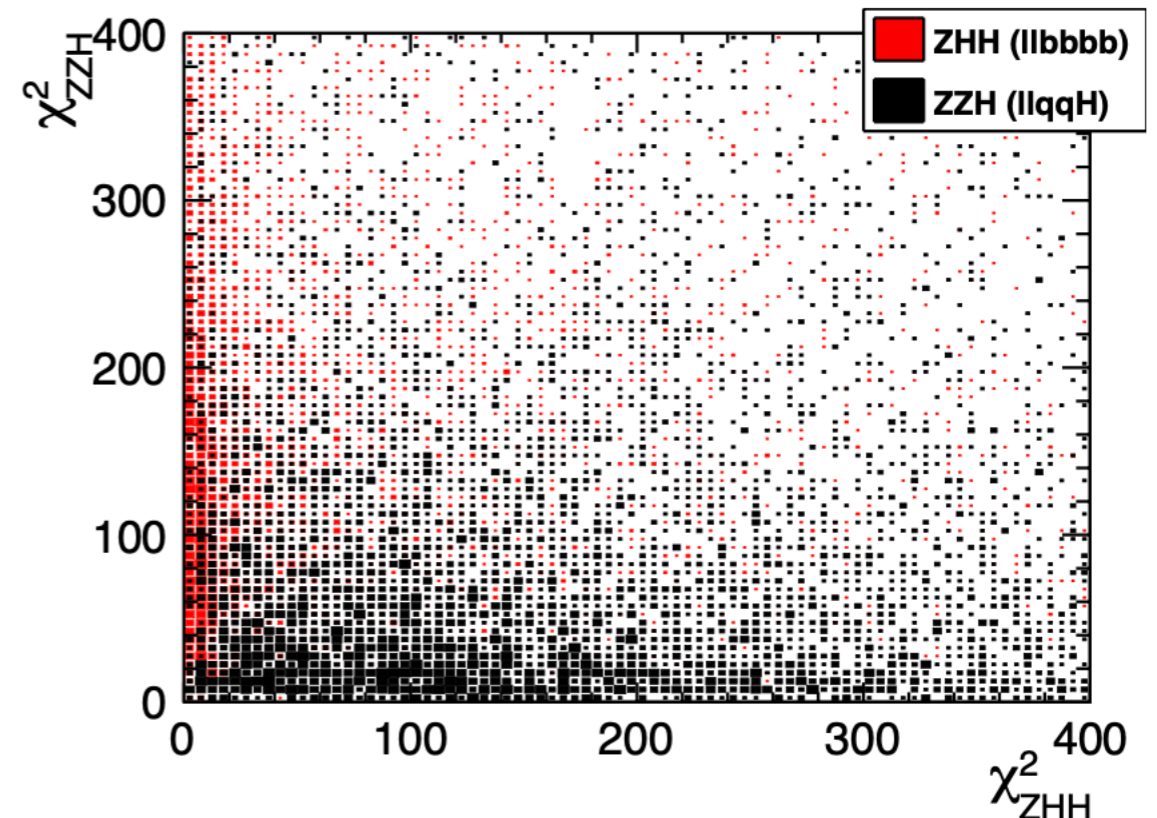


[talk by B.Bliewert]

(iii) potential improvement by kinematic fitting?



- Pre-fitted dijet-masses show large overlap between signal (*ZHH*) and background (*ZZH*)



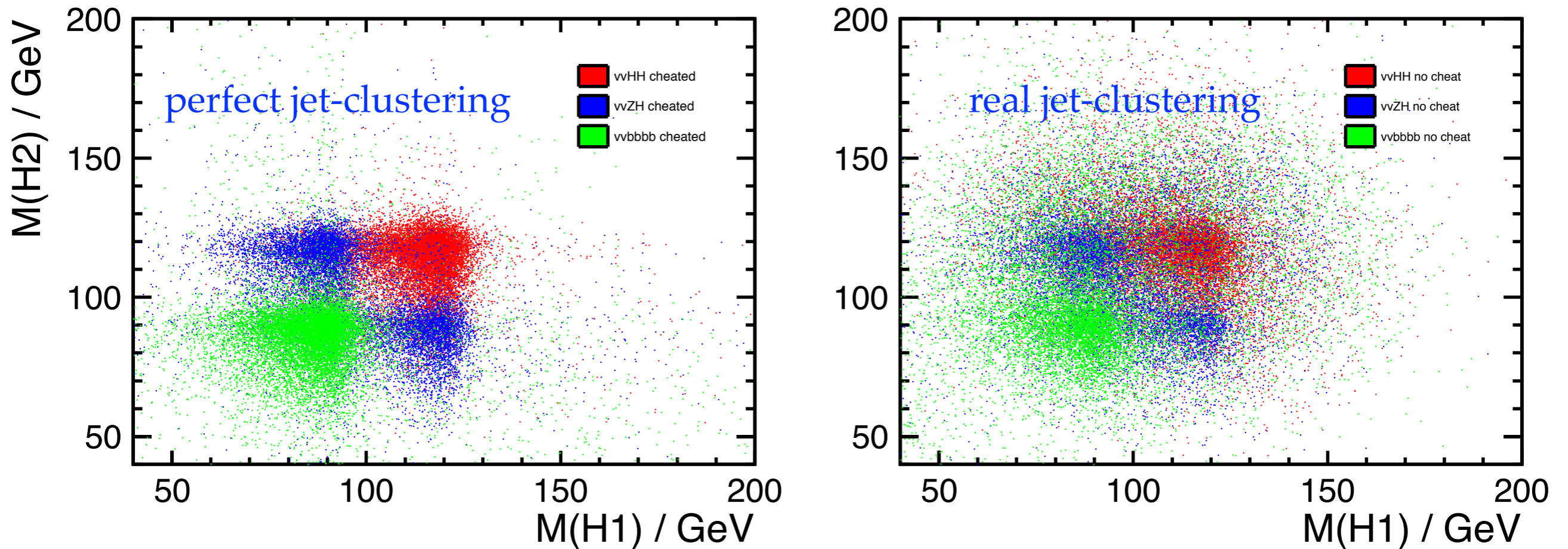
- With ErrorFlow → larger separation of signal (*ZHH*) and background (*ZZH*)

[Torndal, talk at LCWS 2023]

(iii) improving jet-clustering algorithm?

ZHH->vvbbbb (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%

(iii) double-Higgs: other questions

- ▶ **would energy slightly above 500 help the analysis?
e.g. from more boosted jets**
- ▶ **since large λ_{hhh} alter significantly the event shape,
can we do some simulation analysis with non-SM
value of λ_{hhh} ?**
- ▶ **how significantly other algorithms such as b-tagging
can be improved? e.g. by machine learning**

summary

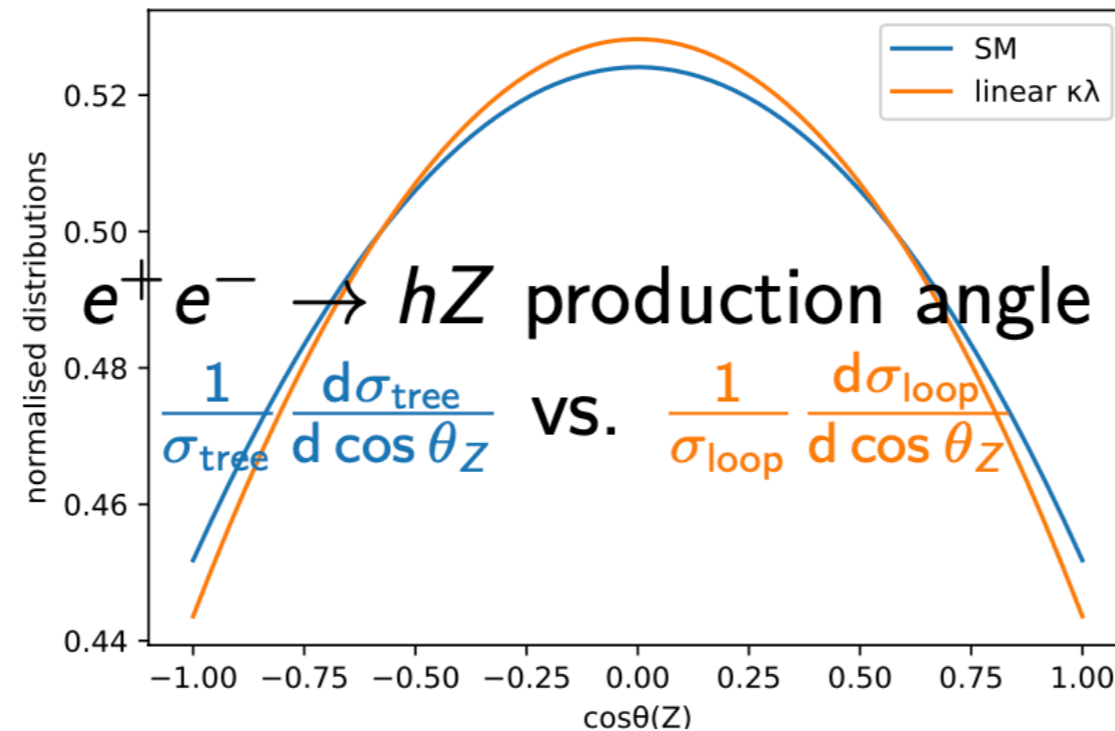
- Hself focus topic is being actively explored under the ECFA H/EW/T framework; a list of well defined questions / goals by expert team
- Both single-Higgs and double-Higgs processes have great potential to probe Higgs self-coupling; many of the related questions are of common interest among circular & linear e+e- communities
- Welcome to join the efforts

For Discussion Session

(some of my random thoughts)

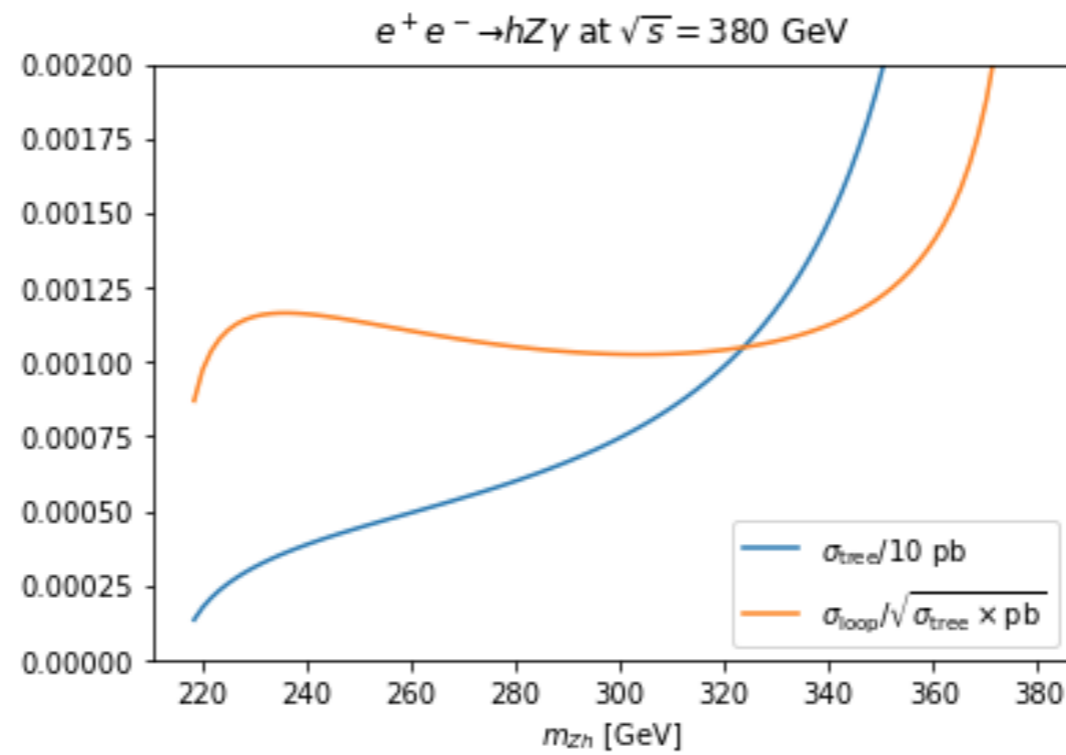
- Any comment or addition to the proposed list of questions by expert team?
- How would we get the real work started?
- As a community effort, it might be helpful to unify the strategy when different groups are working to address similar questions
- Some examples which are really ready to be picked up

example: how to incorporate angular observables consistently



- * like standard template different cross section?
(complicated to exchange)
- * optimal observables (convenient based on Snowmass global fit experience; easy to achieve consistency for different colliders)
- * “condense” all the angular effects into few effective parameters

example: common generators



*** ISR here is crucial to achieve the effective scan of \sqrt{s}**

example: common effort on new analysis techniques

- * much improved flavor tagging by machine learning: cross check and share tasks such as samples**
- * jet-clustering algorithms are not only important for HH (e.g. linear colliders), but also for hadronic ZH (all e+e-)**

clear need of new state-of-art Global SMEFT Fits

- * include as complete as possible NLO effect to address λ in single-Higgs**
- * include ZH (or / and others) angular observables in the fit to address their impact**

clear need of benchmark BSM models

*** with extra (light) Higgs bosons**

*** non-SM value of λ**

backup

