Focus topic: Higgs self-coupling

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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)	

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

ECFA studies towards an e^+e^- Higgs/EWK/top factory

- Study mandated by ECFA to respond coherently to the European Strategy's statement on the highest-priority next collider – ***working together cross-project***

> **High-priority future initiatives** — ***European Strategy Update 2020***
>
> A. An electron-positron Higgs factory is the highest-priority next collider.

- ***ECFA study is intended to:***
  - bring together communities & activities
  - explore synergies
  - discuss challenges

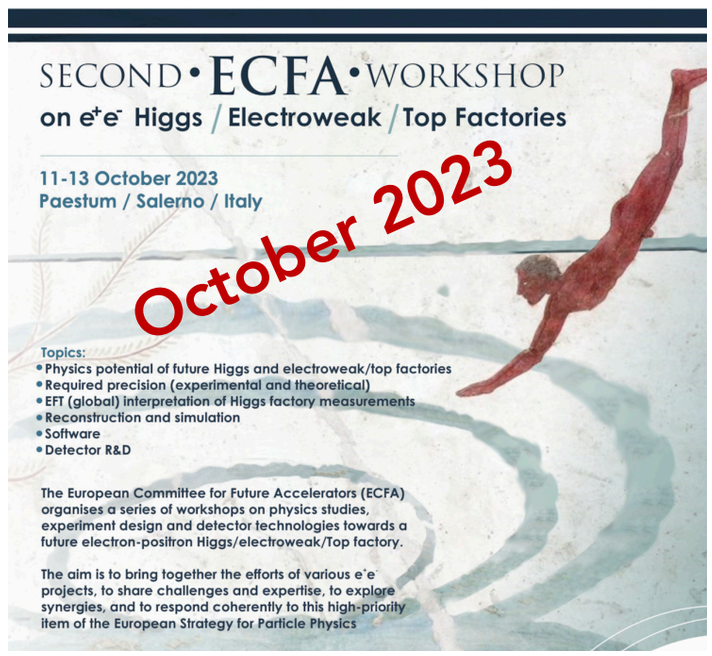
- Structure of the study:

Activities organised via three Working Groups

Two major workshops so far

ECFA Report as input to next European Strategy

Although it is a 'European' study, participation from all regions is strongly welcomed and encouraged!



ECFA Working Group activities

- WG1: **Physics programme** conveners Fabio Maltoni, Jenny List, Jorge de Blas, Patrick Koppenburg
- WG2: **Physics analysis methods** conveners Patrizia Azzi, Fulvio Piccinini, Dirk Zerwas
- WG3: **Detector technologies** conveners Felix Sefkow, Mary Cruz Fouz, Giovanni Marchiori
- study chief editor Aidan Robson, recently joined by Christos Leonidopoulos

–> Rich programme of seminars, topical meetings, mini-workshops open to all to participate

WG1: **Physics programme**

WG1-SRCH: Direct searches (weakly-interacting, directly accessible particles)

Feb 2022 Brainstorming session
May 2022 ECFA HF WG1: 1st Workshop of the WG1-SRCH group
Feb 2023 Heavy Neutral Lepton search potential of future HET factories
Apr 2023 Standard and exotic Scalars at future HET factories
Jun 2023 BSM top quark focus meeting

WG1-PREC: theoretical and experimental precision

Mar 2022 MiniWorkshop: high-precision measurements
Mar 2022 MiniWorkshop: parametric uncertainties: α_s
July 2022 MiniWorkshop: parametric uncertainties: α_em
Nov 2022 MiniWorkshop: collision energy
Dec 2022 MiniWorkshop: luminosity
July 2023 MiniWorkshop: cross-section lineshapes

WG1-HTE: specific Higgs/Top/EW studies (+ connection w/ LHC)

Apr 2022 1st Workshop of the Higgs/Top/EW group
Sept 2022 ECFA HTE meeting on Z pole physics
Feb 2023 mini-workshop on e+e- physics at 125 and 160 GeV
May 2023 mini-workshop on e+e- physics at 160-240 GeV

WG1-GLOB: global interpretations

Sept 2022 Analyses of concrete models
July 2022 Global interpretations in (SM)EFT and UV complete models
Sept 2022 Analyses of concrete models
June 2023 ttbar threshold

March 2023

31 Mar ECFA Higgs Factory seminars: New Particle Searches at Future e+e- colliders

January 2023

20 Jan ECFA Higgs Factory seminars: Top Physics at Future e+e- colliders

November 2022

25 Nov ECFA Higgs Factory seminars: Flavor Physics at Future e+e- colliders

June 2022

10 Jun ECFA Higgs Factory seminars: Precision physics in the e+e- -> WW region

07 Jun - 17 Jun Precision calculations for future e+e– colliders: targets and tools (FC CERN Unit Workshop)

May 2022

06 May ECFA Higgs Factory seminars: Higgs self-coupling

April 2022

08 Apr ECFA Higgs Factory seminars: Physics with light quarks

March 2022

04 Mar ECFA Higgs Factory seminars: Implications of (g-2)_mu for e+e- Higgs factories: an

Focus Topics

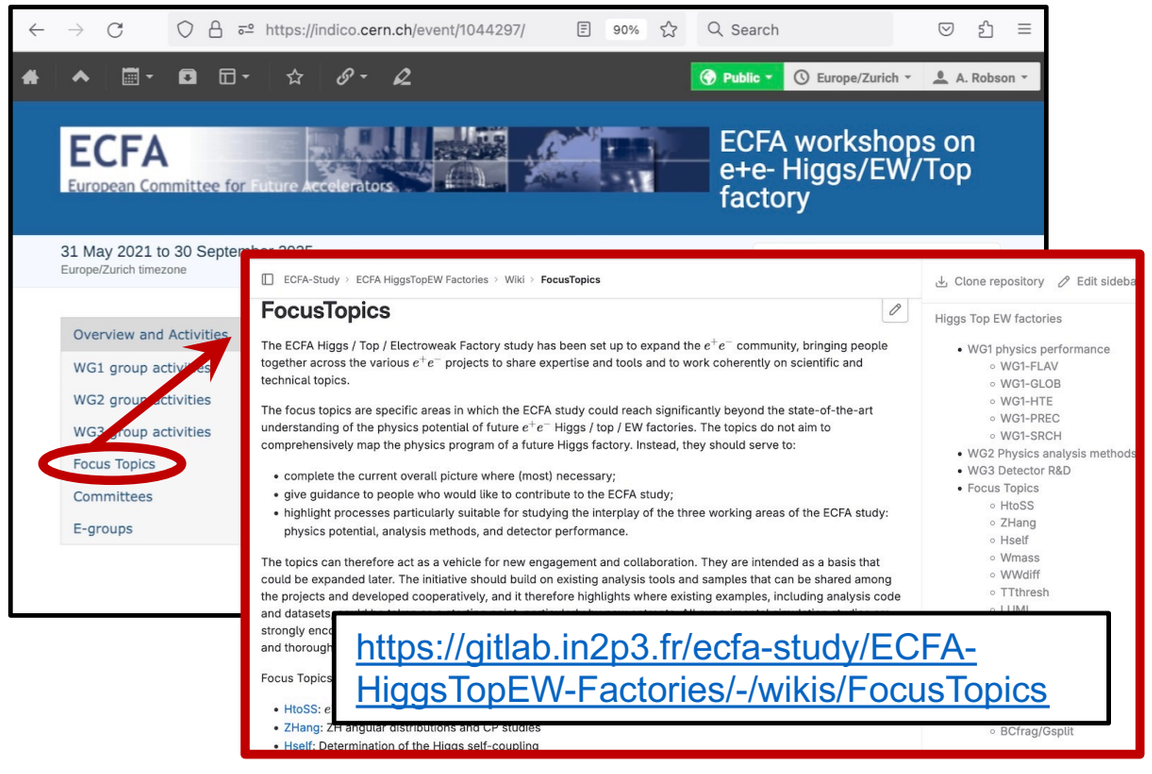
- Major element of 2023 workshop: converging on definition of 14 ***Focus Topics***

Focus topics are intended to encompass a wide range of activities spanning theory & experiment, analysis & algorithm development, and detector requirements & optimisation

- Overall aim: accumulate critical mass working on each topic, reaching publications on timescale of ECFA study
  –> trying to increase effort on e+e– physics & detectors

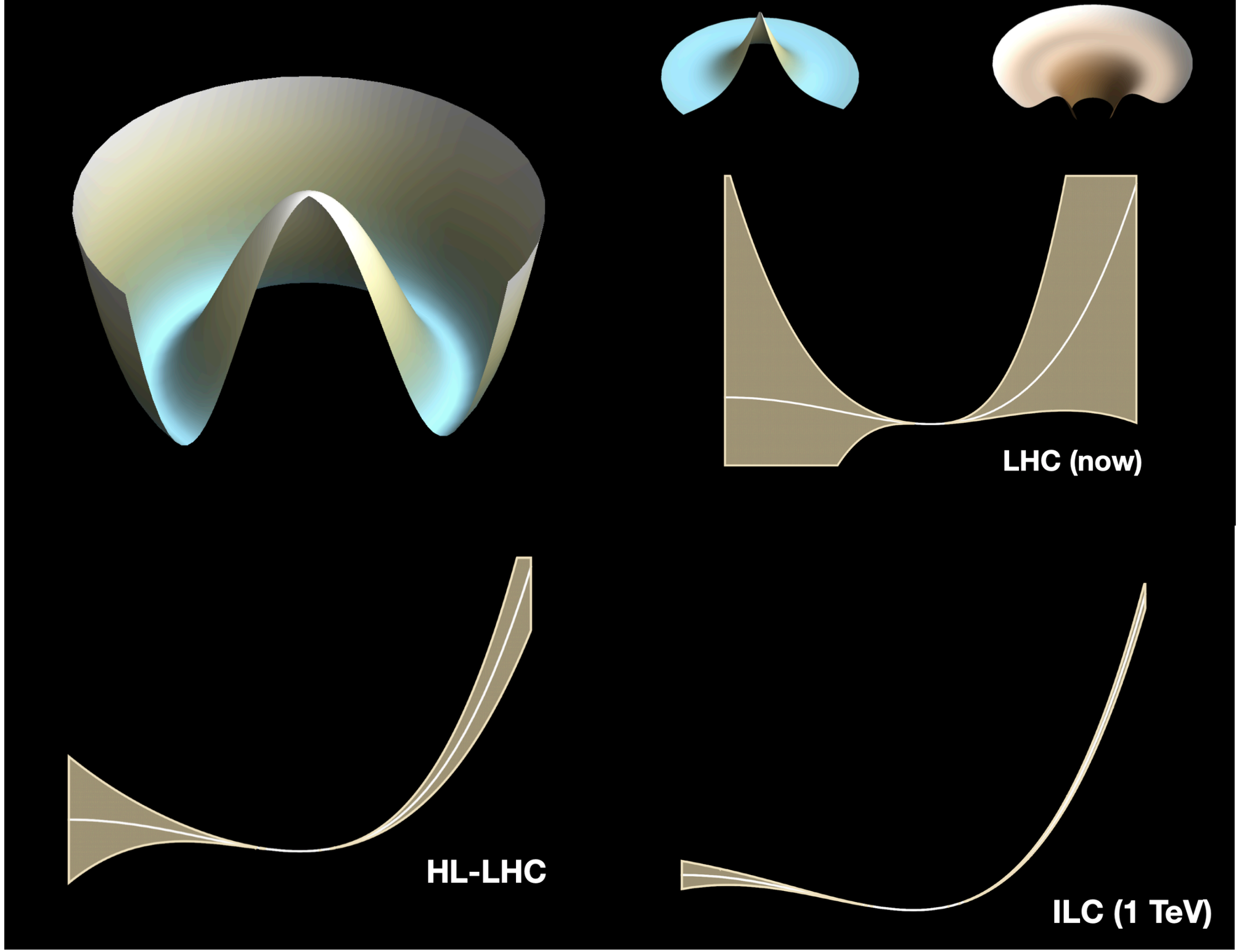
- HtoSS: $e^+e^- \to Zh$: $h \to ss$
- ZHang: ZH angular distributions and CP studies
- Hself: Determination of the Higgs self-coupling
- Wmass: Mass and width of the W boson
- WWdiff: Full studies of WW and evW
- TTthresh: Top threshold - detector-level studies of $e^+e^- \to t\bar{t}$
- LUMI: Precision luminosity measurement
- EXscalar: New exotic scalars
- LLPs: Long-lived particles
- EXtt: Exotic top decays
- CKMWW: CKM matrix elements with on-shell and boosted W decays
- BKtautau: $B^0 \to K^{0*}\tau^+\tau^-$
- TwoF: EW precision - 2-fermion final states
- BCfrag/Gsplit: Measurement of b- and c-fragmentation functions and hadronisation rates and measurement of gluon splitting to bb / cc

https://indico.cern.ch/event/1044297/



https://gitlab.in2p3.fr/ecfa-study/ECFA-HiggsTopEW-Factories/-/wikis/FocusTopics

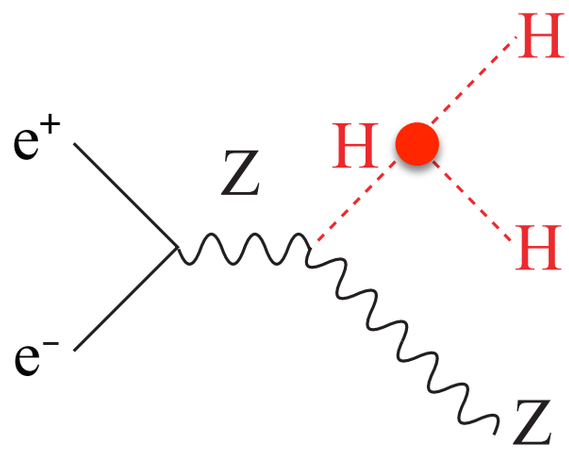
Is it the SM Higgs?

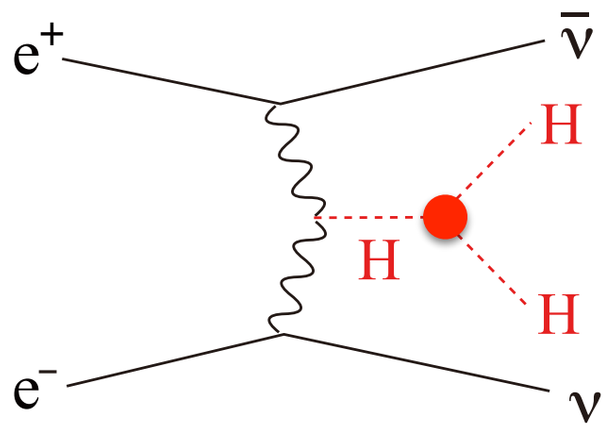


[N. Craig @ LCWS 2023]

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

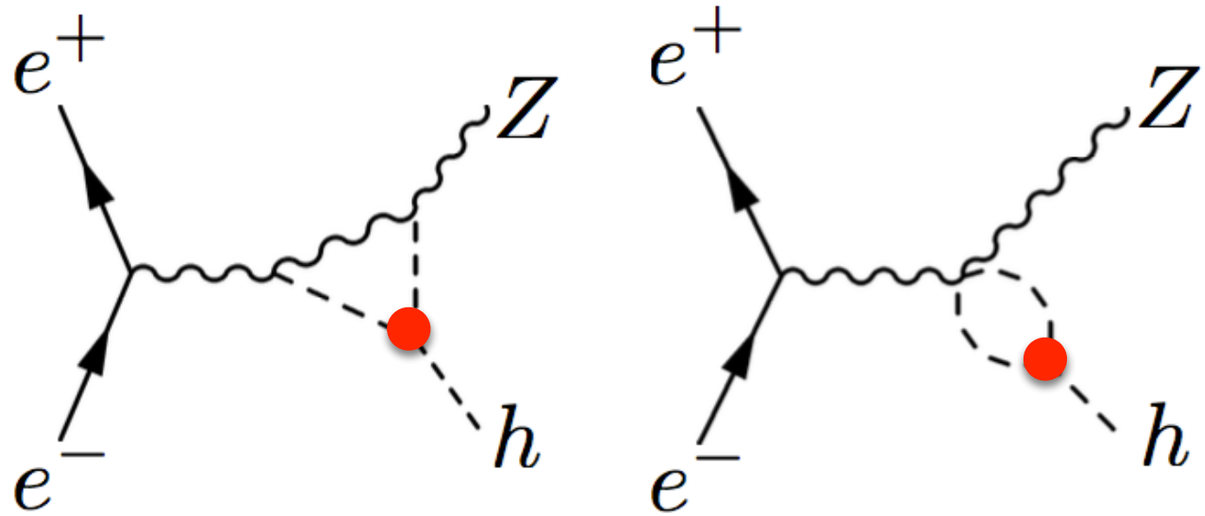
$\sqrt{s} \gtrsim 500$ GeV





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

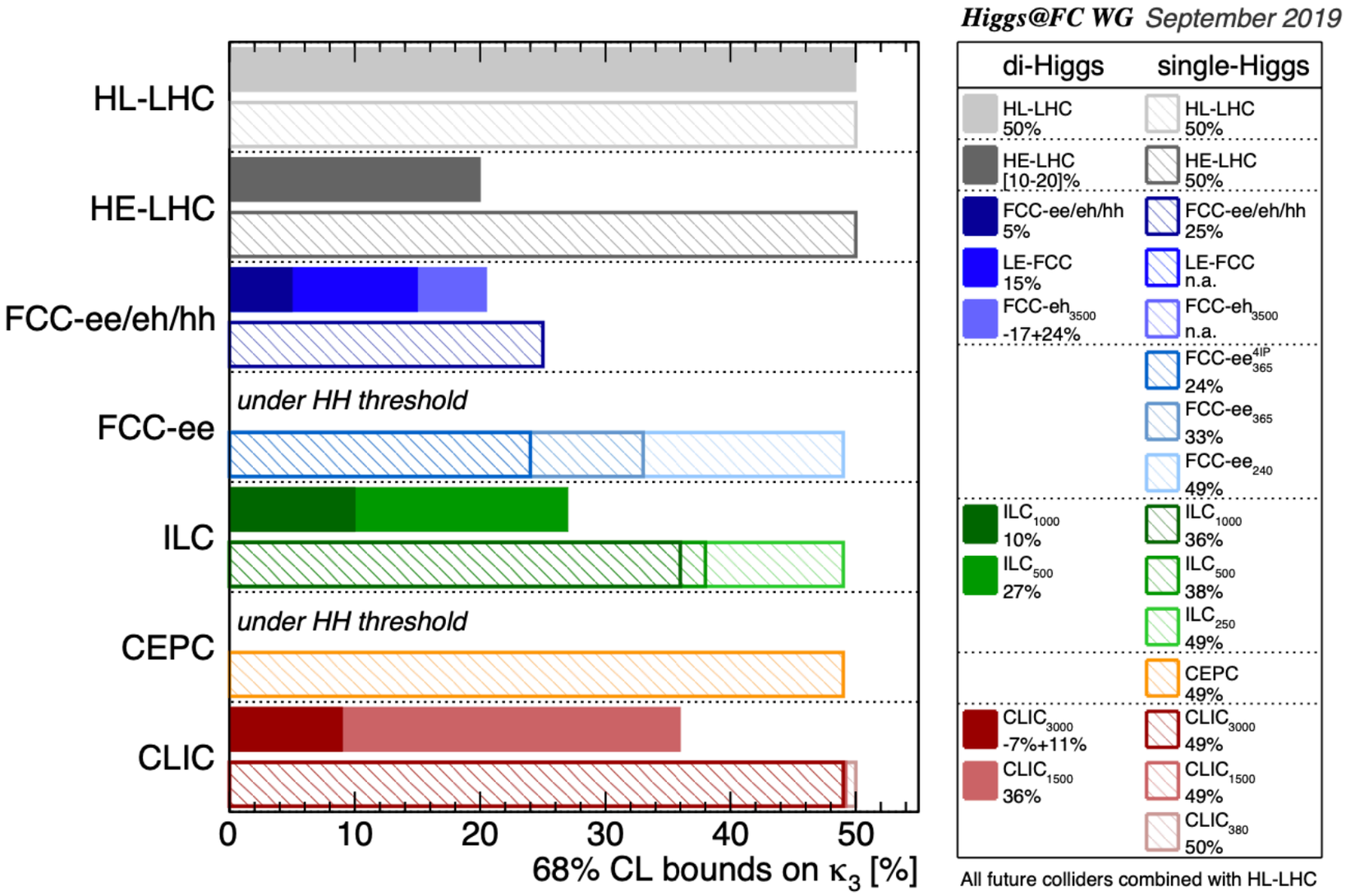
$\sqrt{s} \gtrsim 240$-250 GeV



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

Starting point: ESU 2020

[Physics Briefing Book, arXiv:1910.11775]

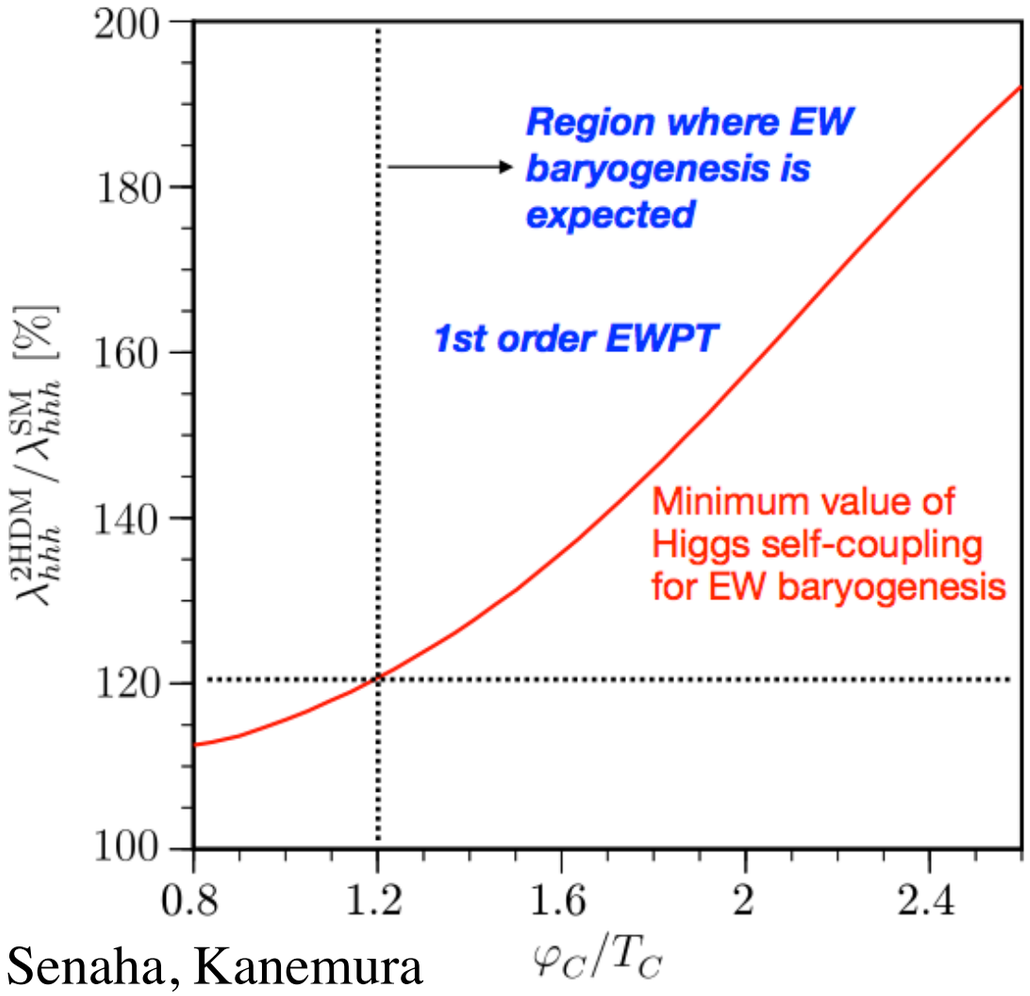


- based on global SMEFT fits
- HL-LHC di-Higgs contribution was always combined

—> 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)

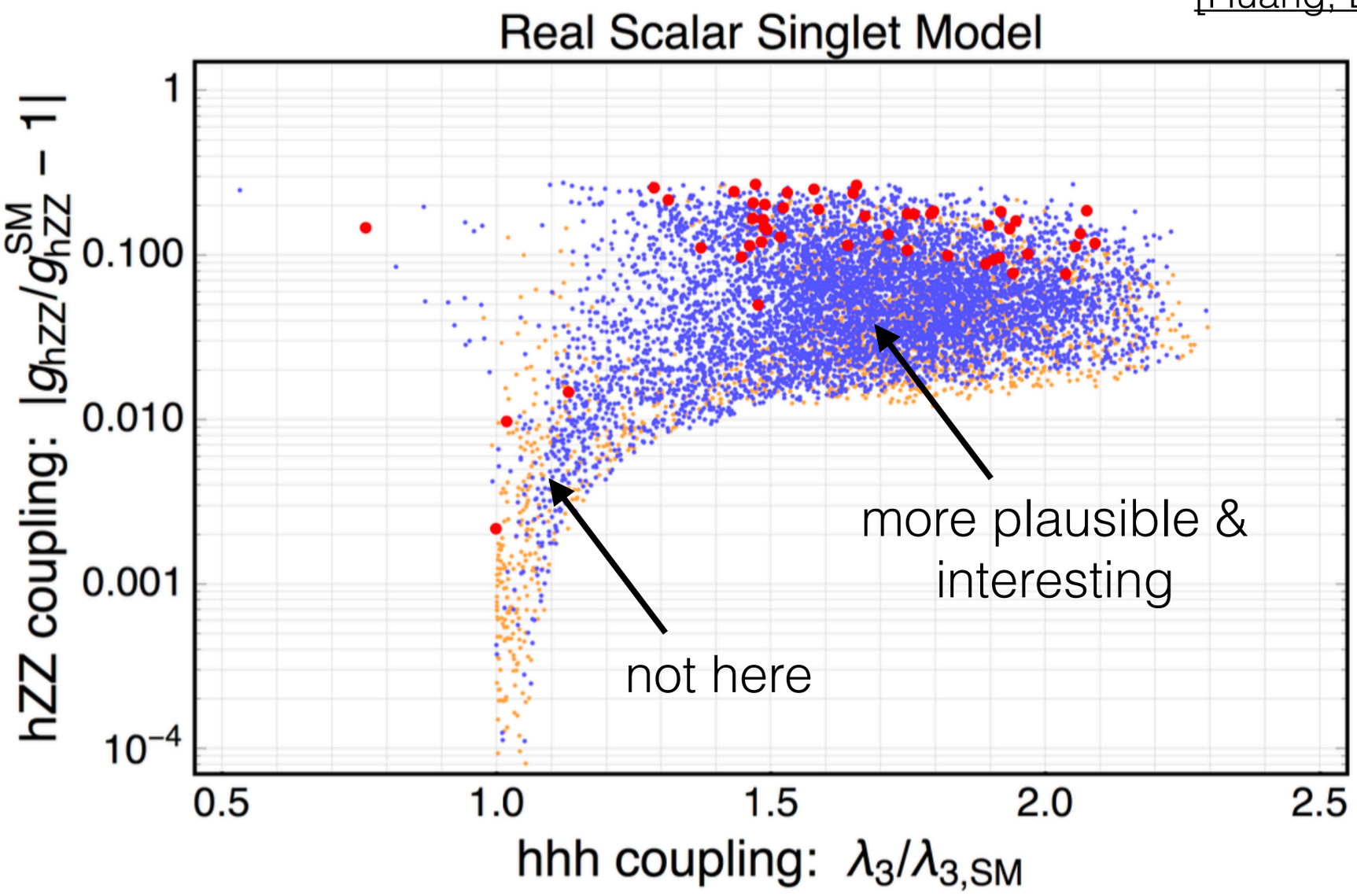


Senaha, Kanemura

- **How current projections of λ_{hhh} measurements would change when λ_{hhh} != λ_{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)

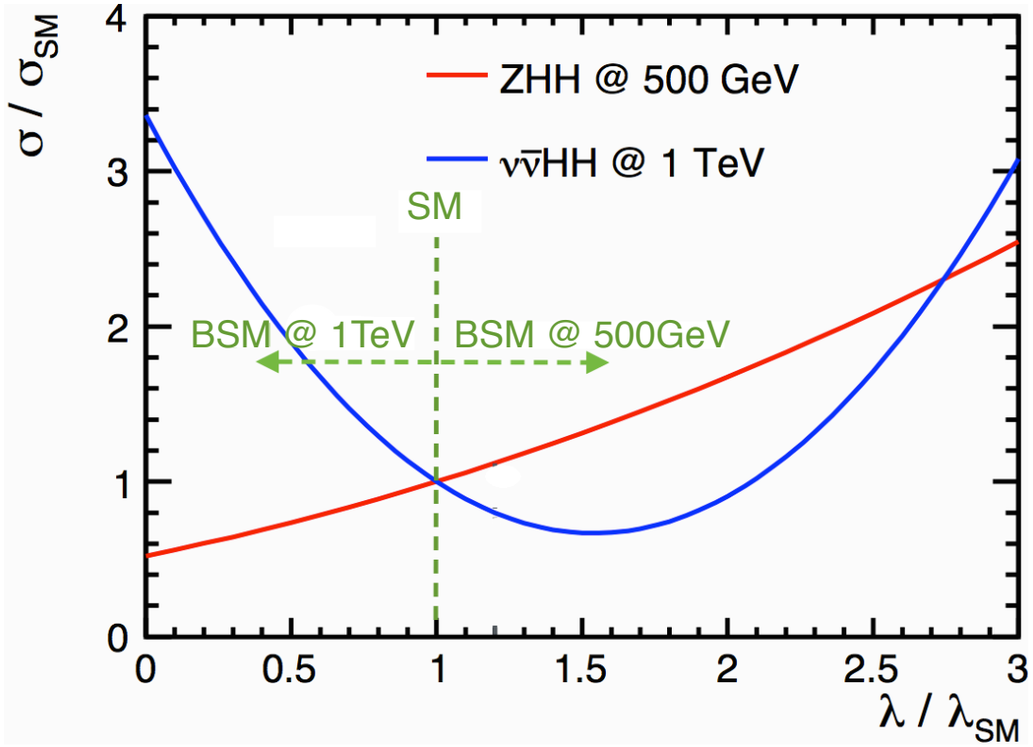
red: very strongly first-order phase transition (GW @ eLISA)

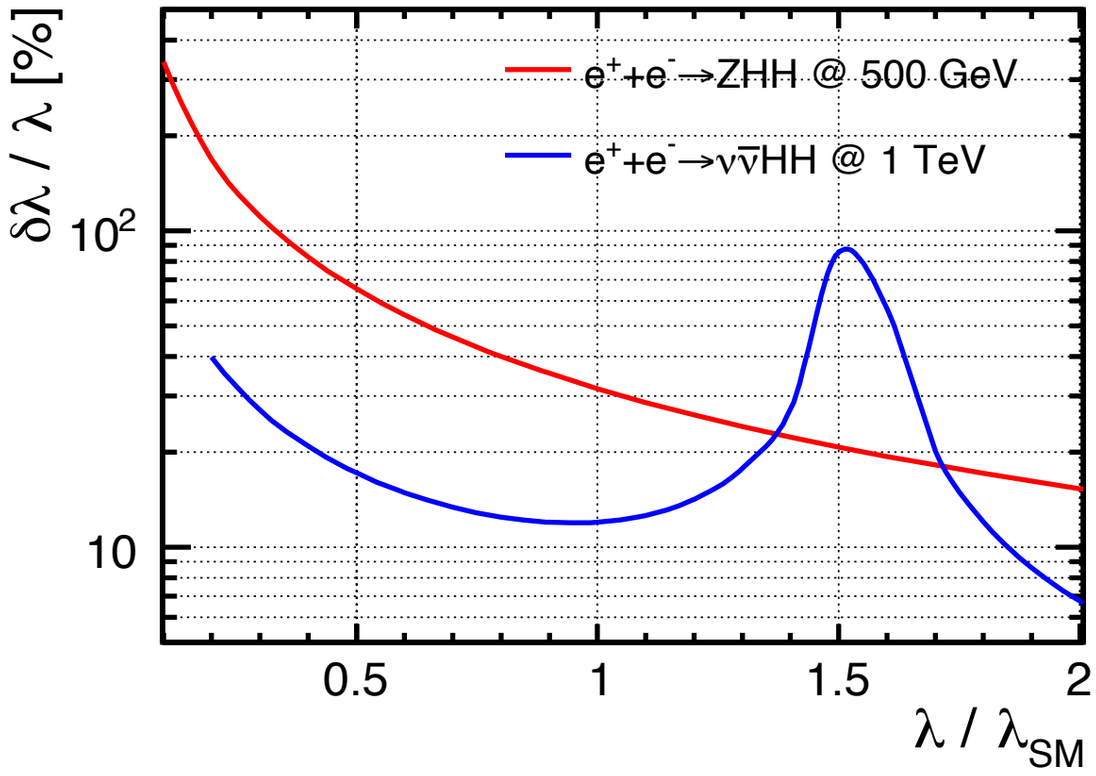
[recent models with even larger hierarchy δ_{hhh} / δ_{hVV}: Durieux, McCullough, Salvioni, '22]

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

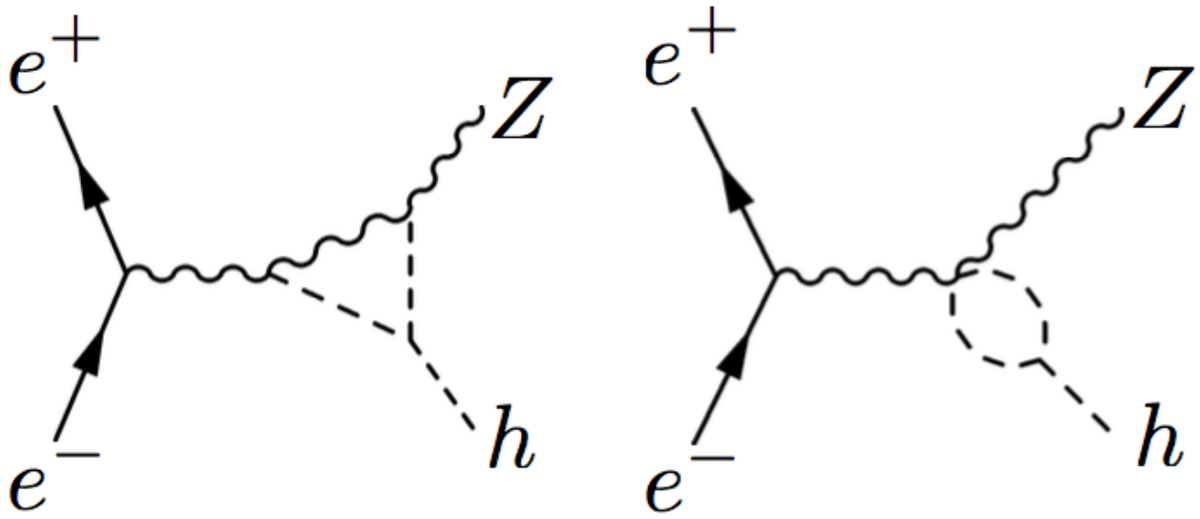
(examples)

- profound effect on di-Higgs processes
- complementarity between ZHH & vvHH (& LHC): different interference
- if $\lambda_{HHH} / \lambda_{SM} = 2$, λ_{HHH} be *discovered* (~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 —> δh ~ 28% [ILC as example]
- 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 [Peskin, Yong, JT, paper in preparation]

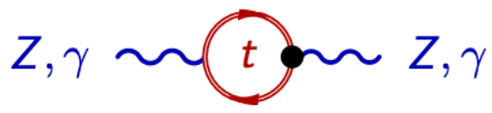
- **can we lift the degeneracies by new observables, e.g. ZHang?**
- **what if we include other NLO effects as well, e.g. top?**

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

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

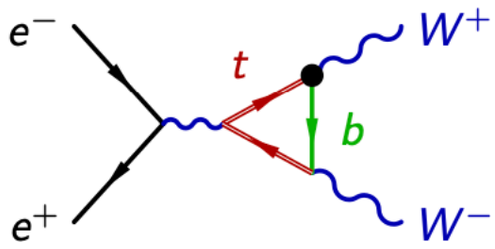
EWPO

[Zhang, Greiner, Willenbrock '12]



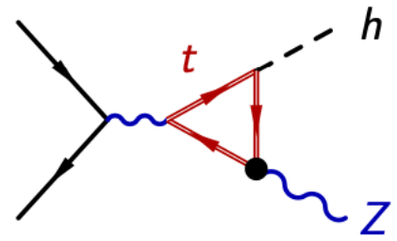
Diboson

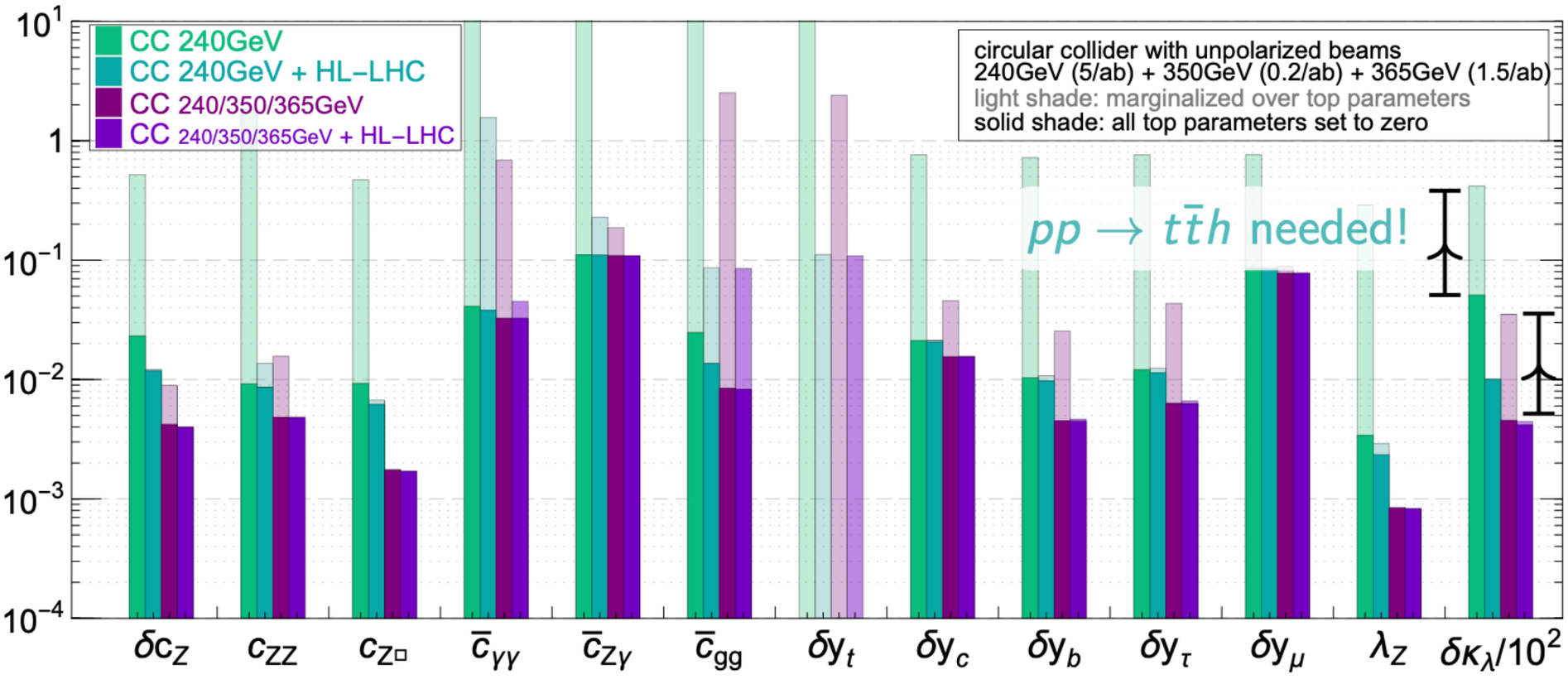
[GD, Gu, Vrionidou, Zhang '18]



Higgs

[Vrionidou, Zhang, '18]
[see also Boselli et al '18]





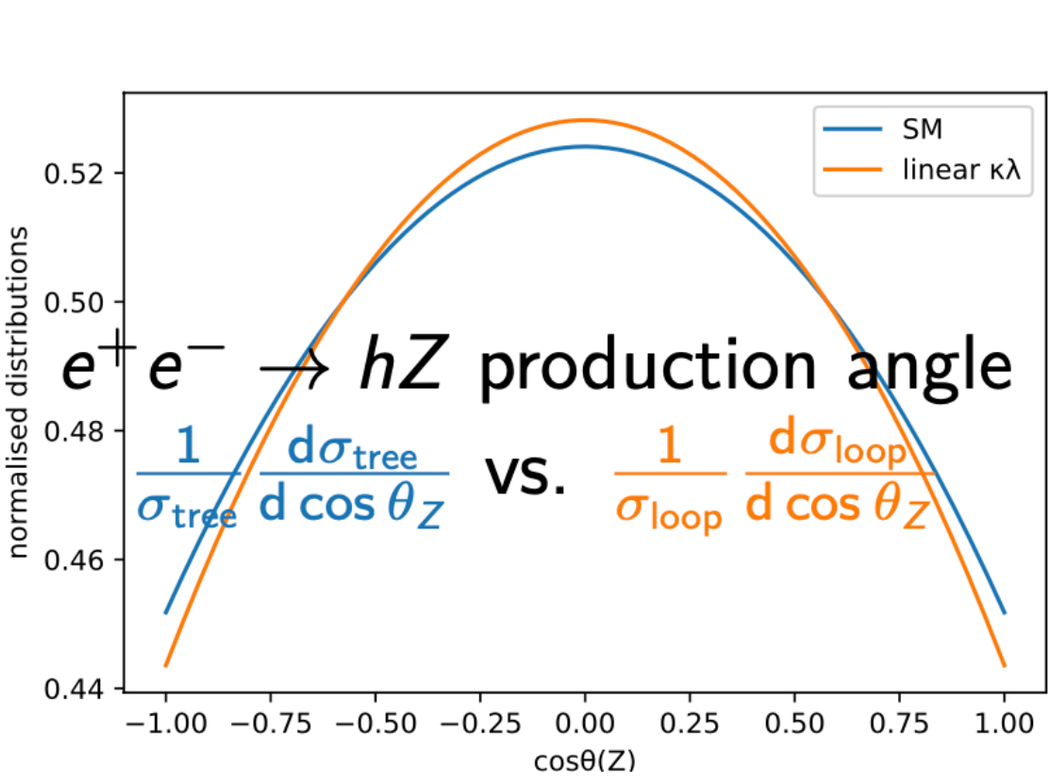
Top-quark uncertainties can impede Higgs precision!

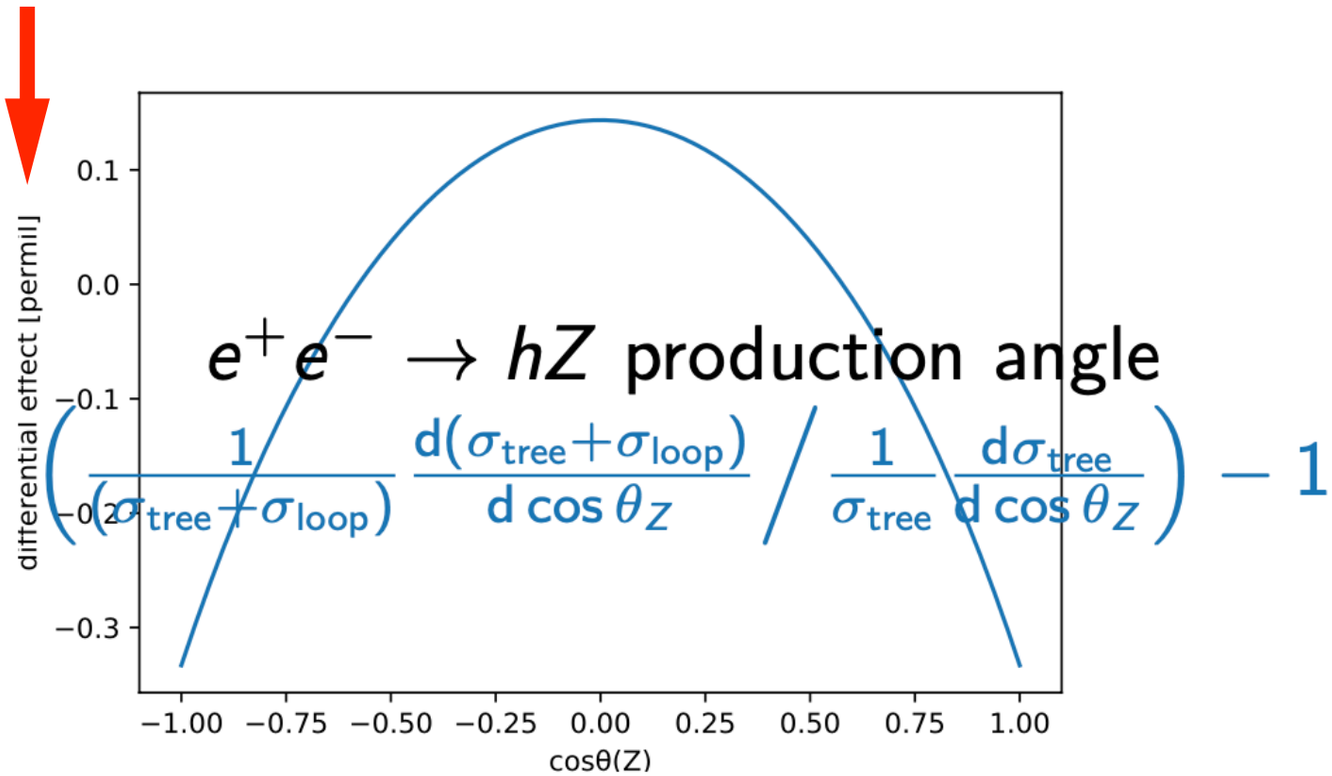
[Durieux, Gu, Vyronidou, Zhang, '18]

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

(ii) single-Higgs: lift degeneracies

- **can differential cross sections help?**

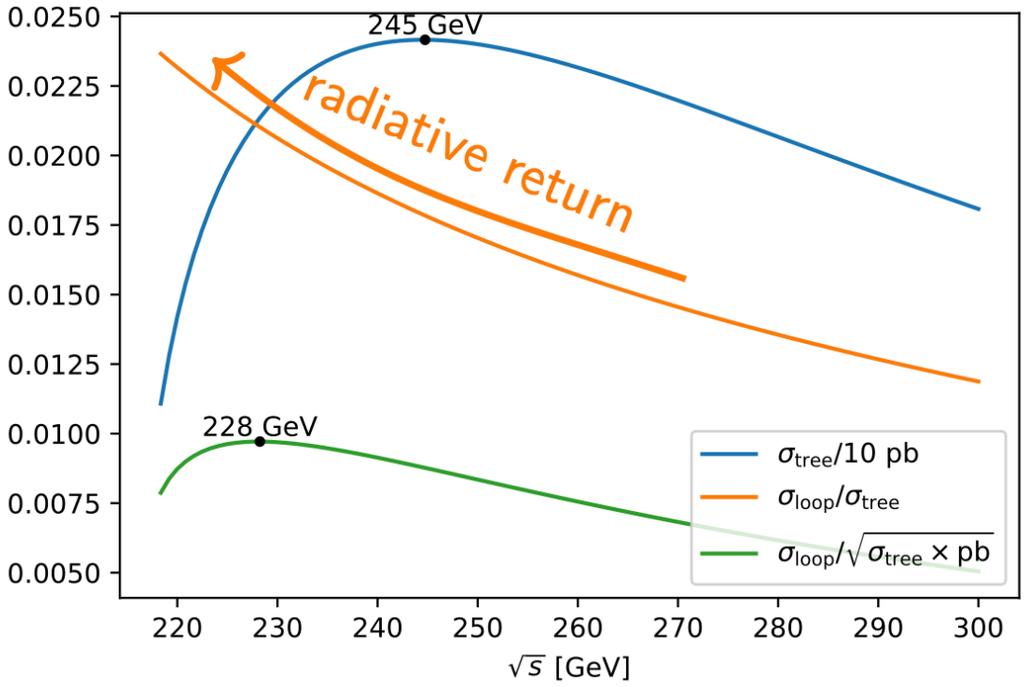


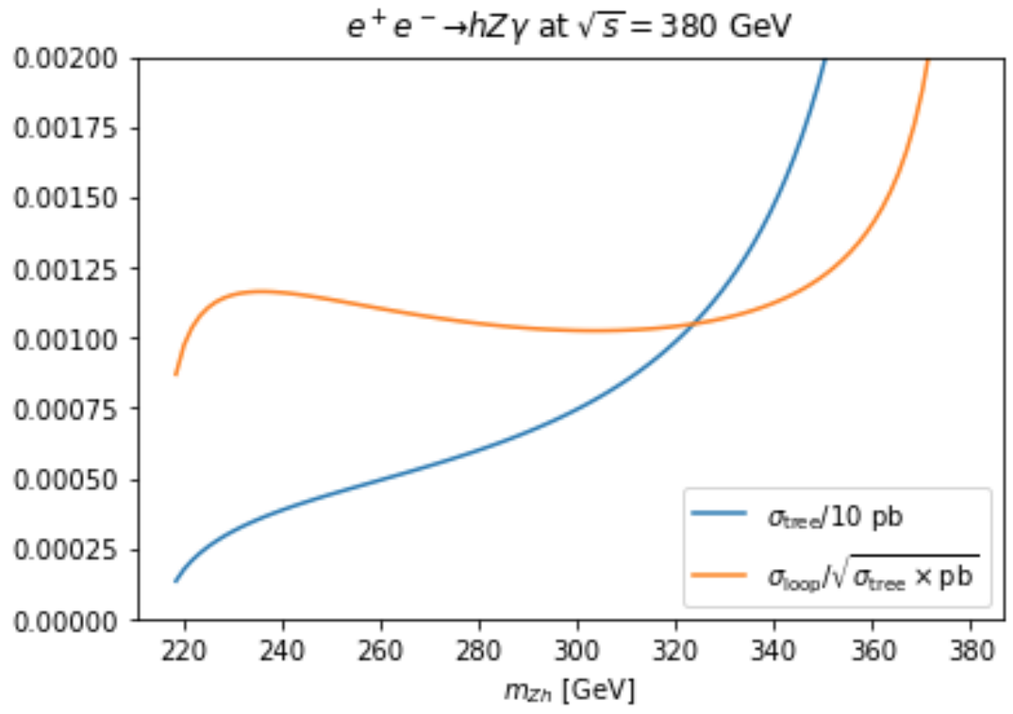


[Durieux, et al, preliminary]

(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

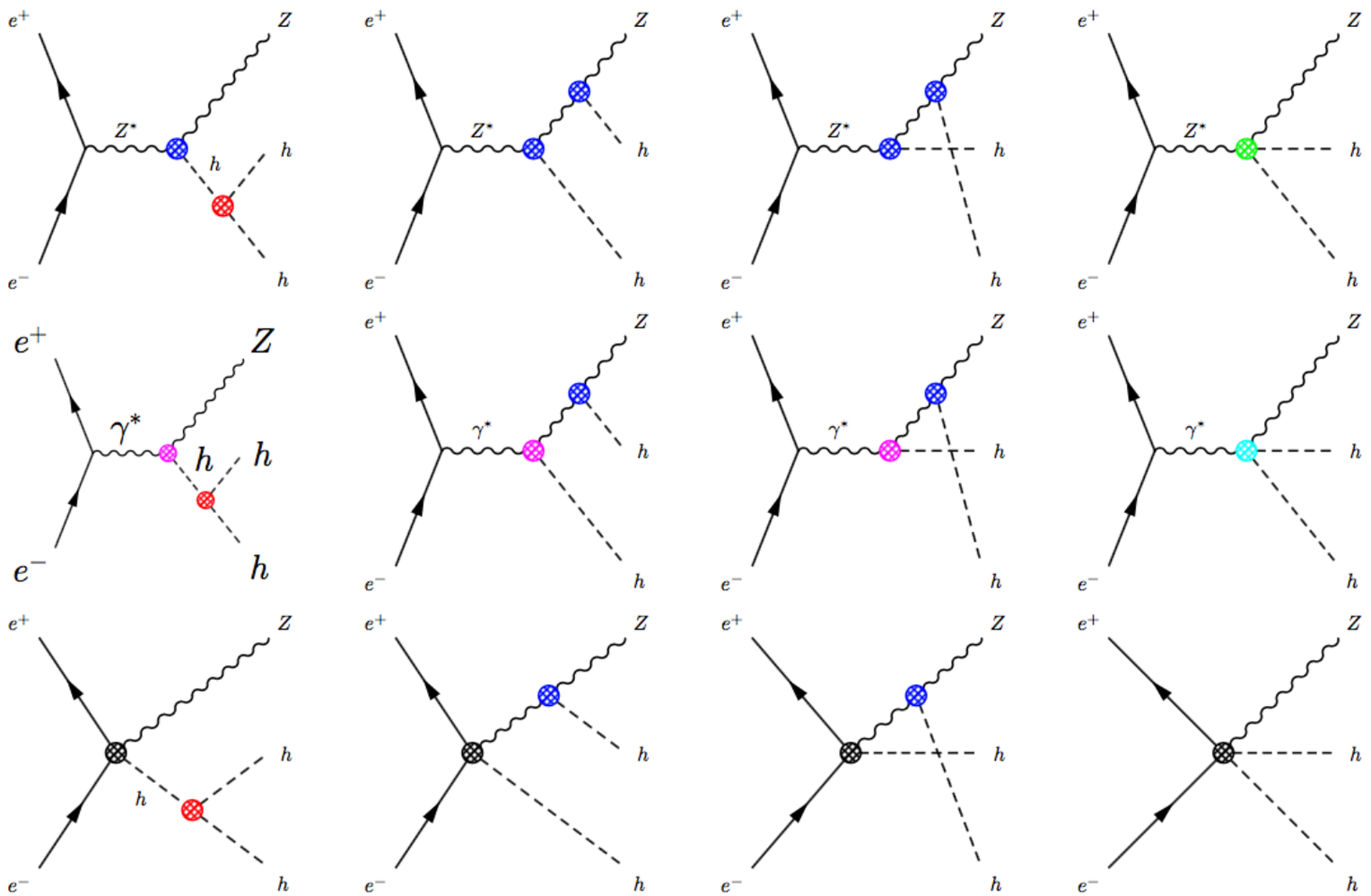
- **can we clarify the importance of each input measurement for the λ_{hhh} in the global fit?**

- **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

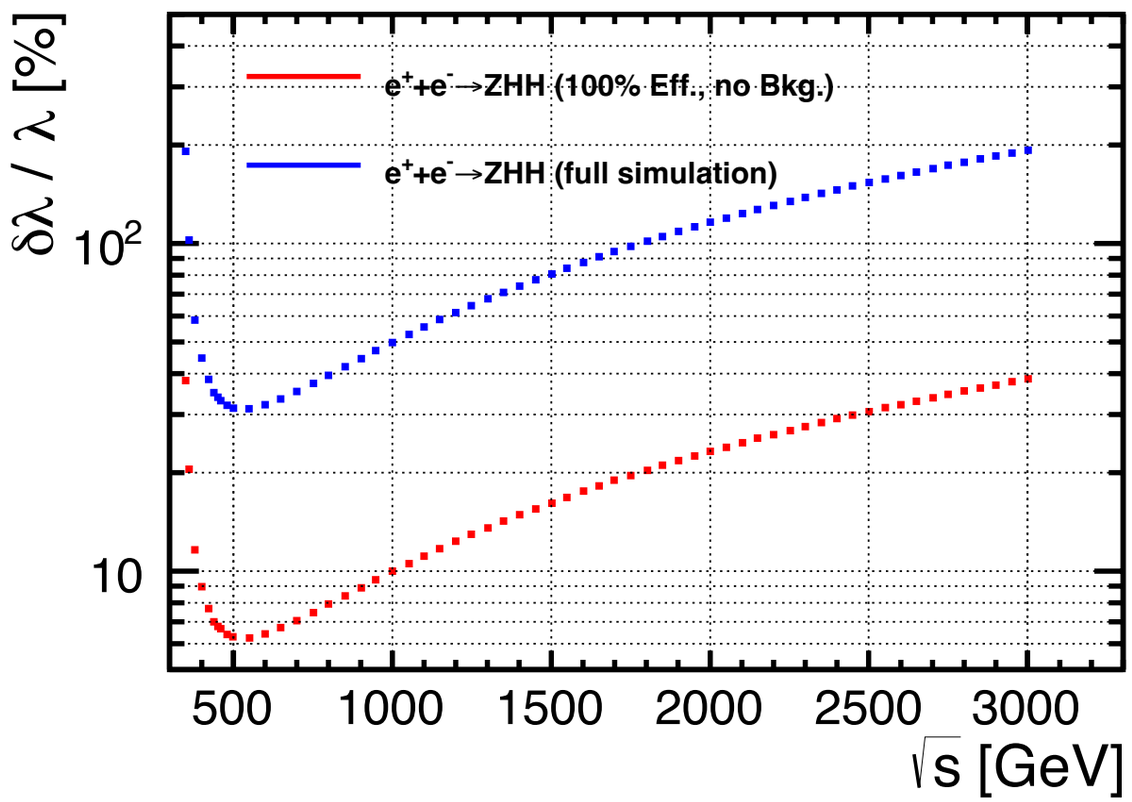


[Barklow, Fujii, Jung, Peskin, JT, '17]

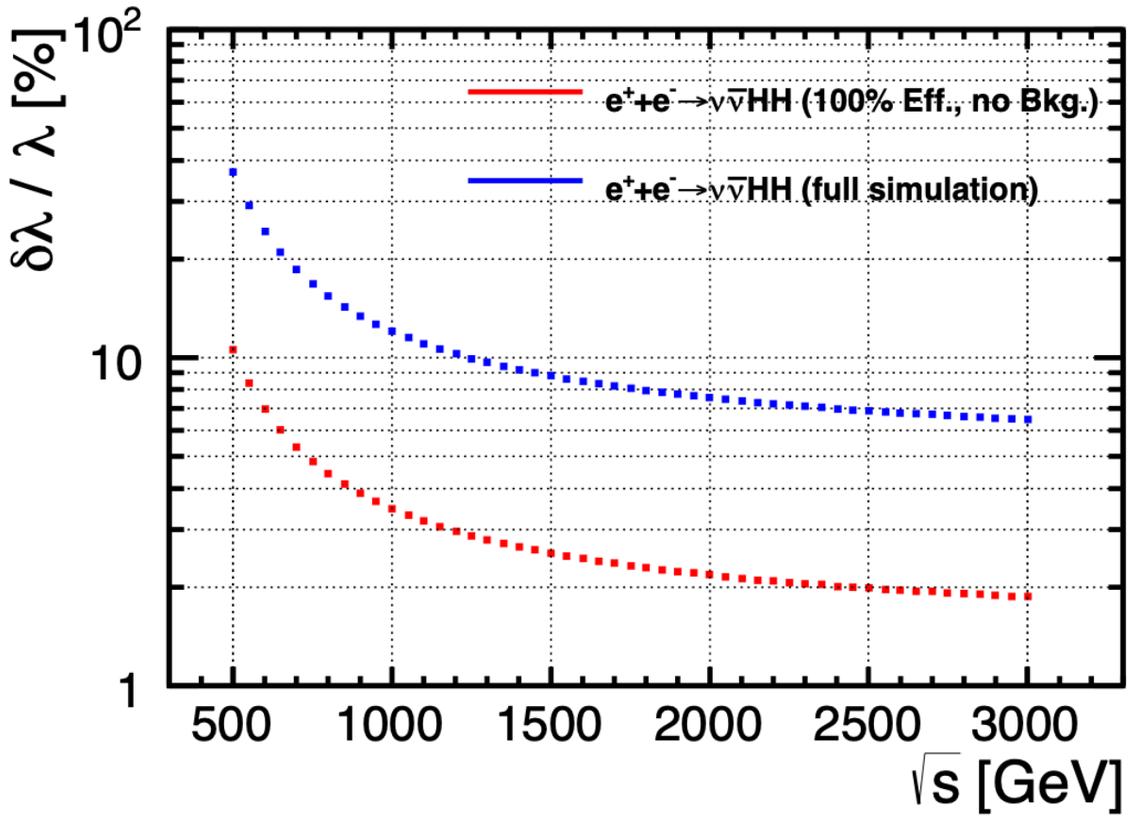
- Much less challenge from degeneracies
- Main questions are related to how we can improve experimental analyses

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

ZHH



ννHH

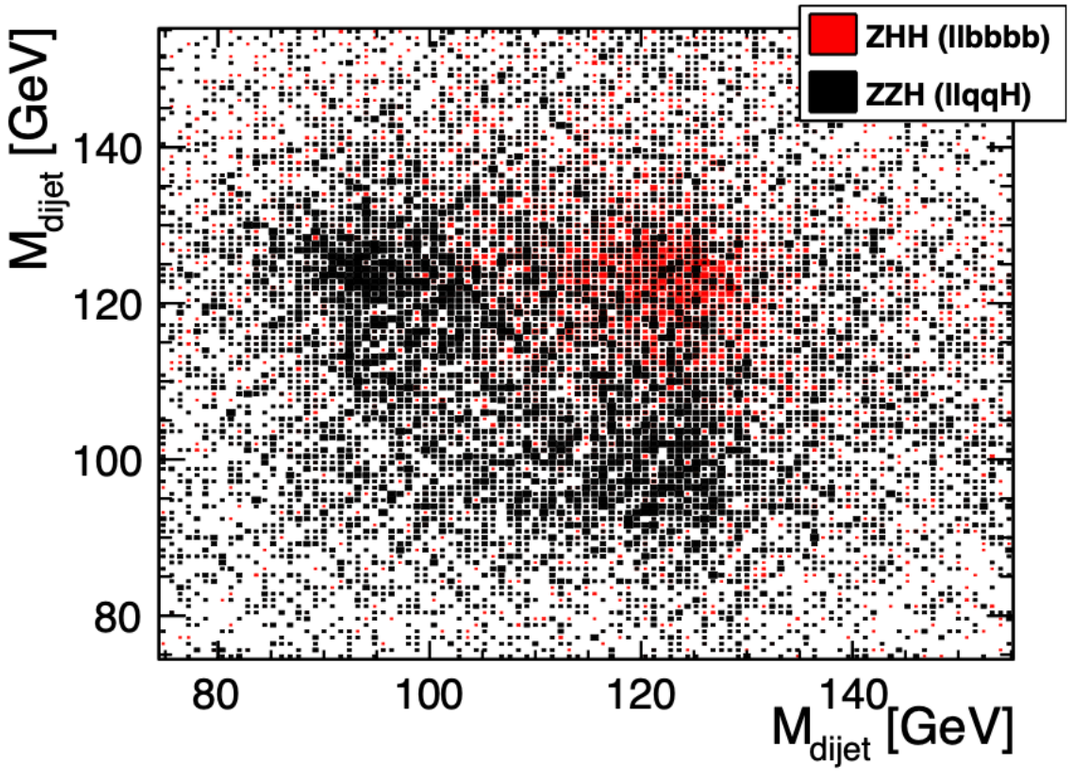


[Duerig, PhD Theis, 2016]

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

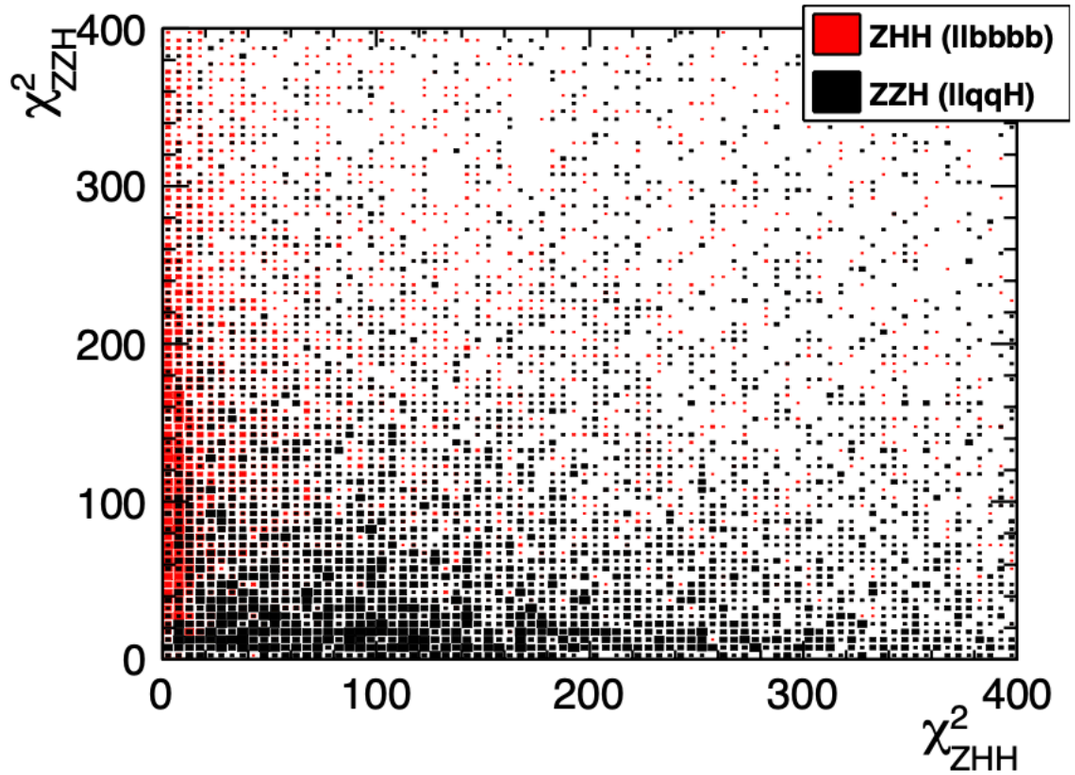
[talk by T.Suehara]

(iii) potential improvement by kinematic fitting?



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

→



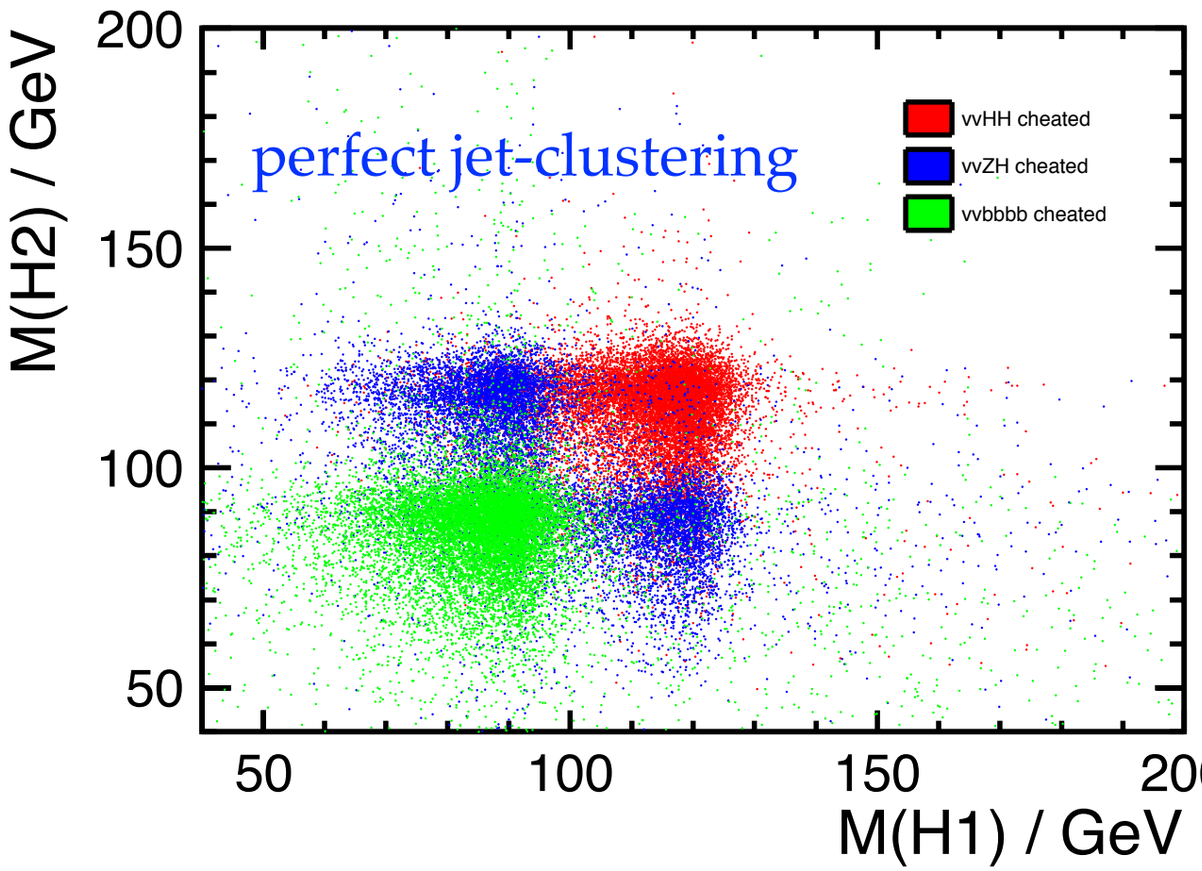
- With ErrorFlow → larger separation of signal (*ZHH*) and background (*ZZH*)

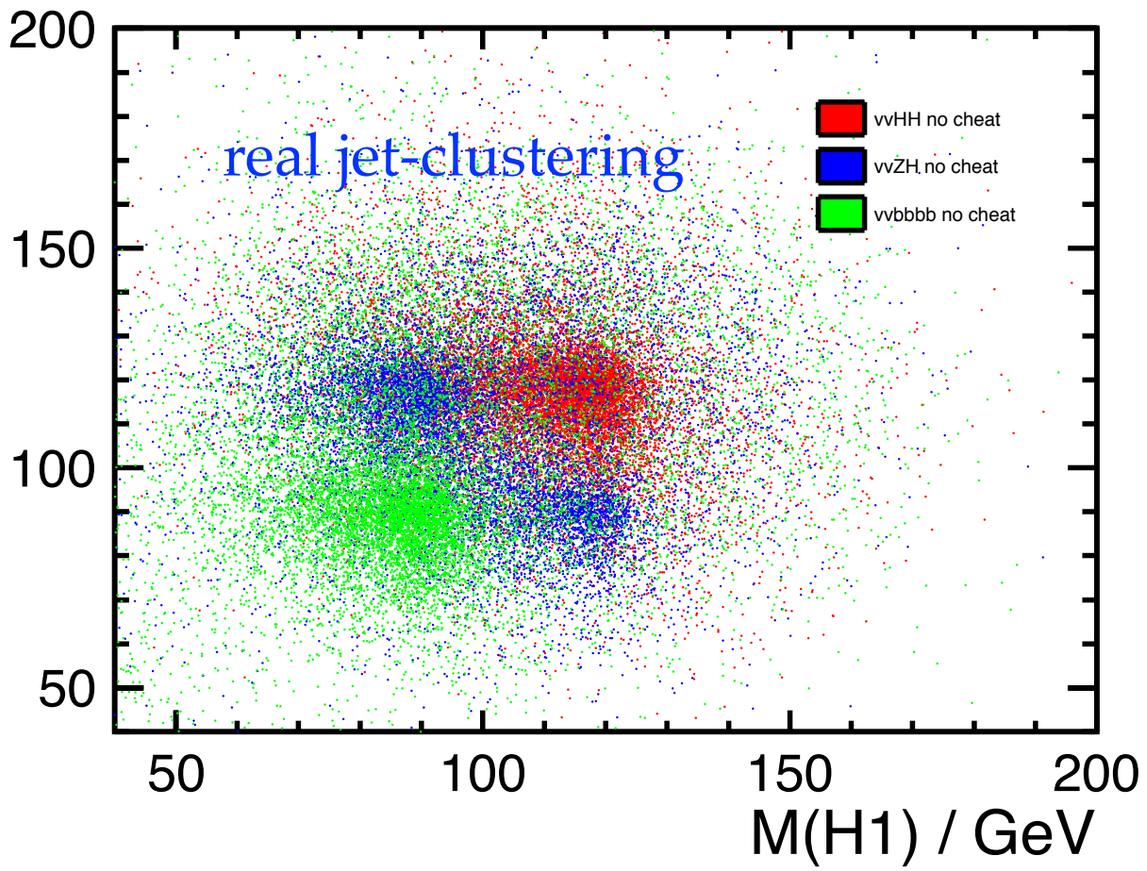
[Torndal, talk at LCWS 2023]

(iii) improving jet-clustering algorithm?

ZHH->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%

(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

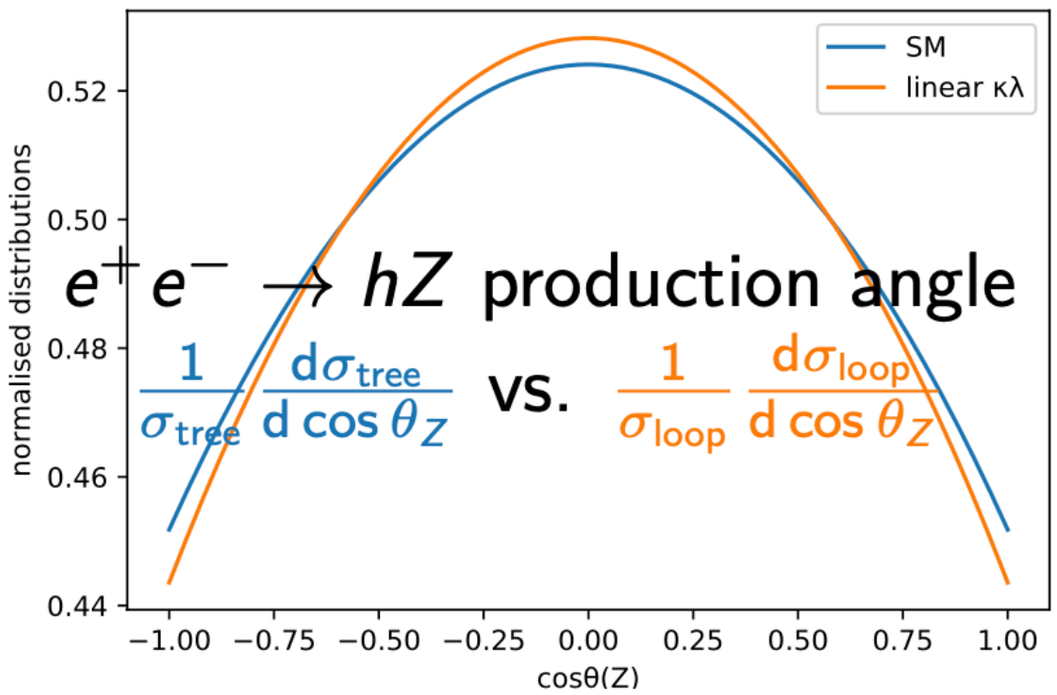
- Hself focus topic is being actively explored under the ECFA H/EW/T framework; a list of well defined questions / goals by expert team
- Both single-Higgs and double-Higgs processes have great potential to probe Higgs self-coupling; many of the related questions are of common interest among circular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

For Discussion Session

(some of my random thoughts)

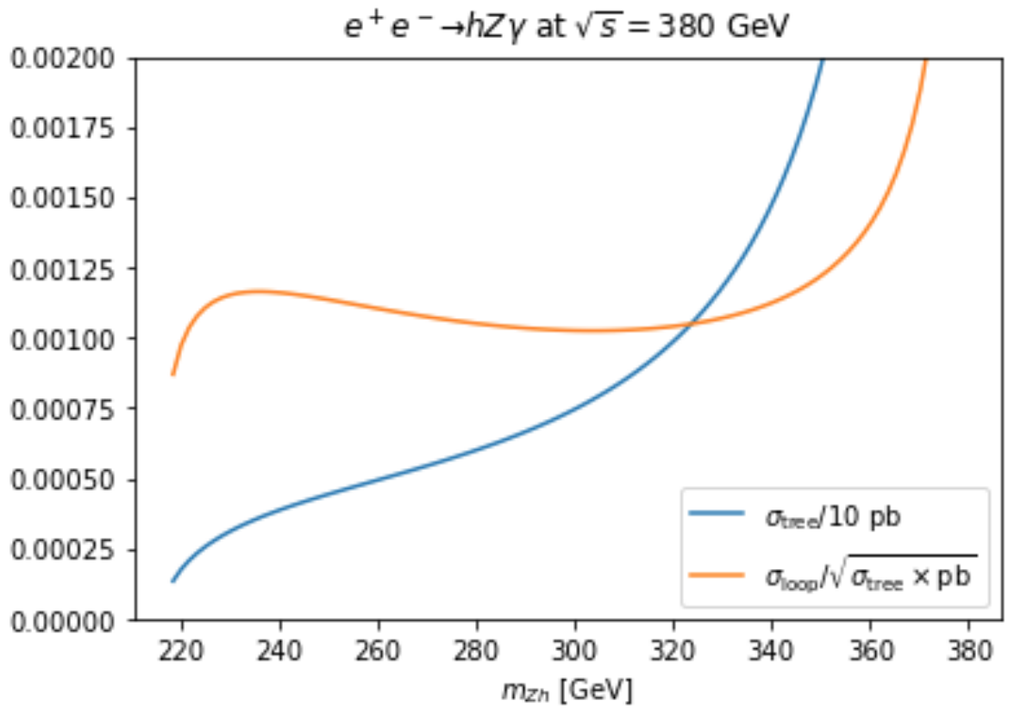
- Any comment or addition to the proposed list of questions by expert team?
- How would we get the real work started?
- As a community effort, it might be helpful to unify the strategy when different groups are working to address similar questions
- Some examples which are really ready to be picked up

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 √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

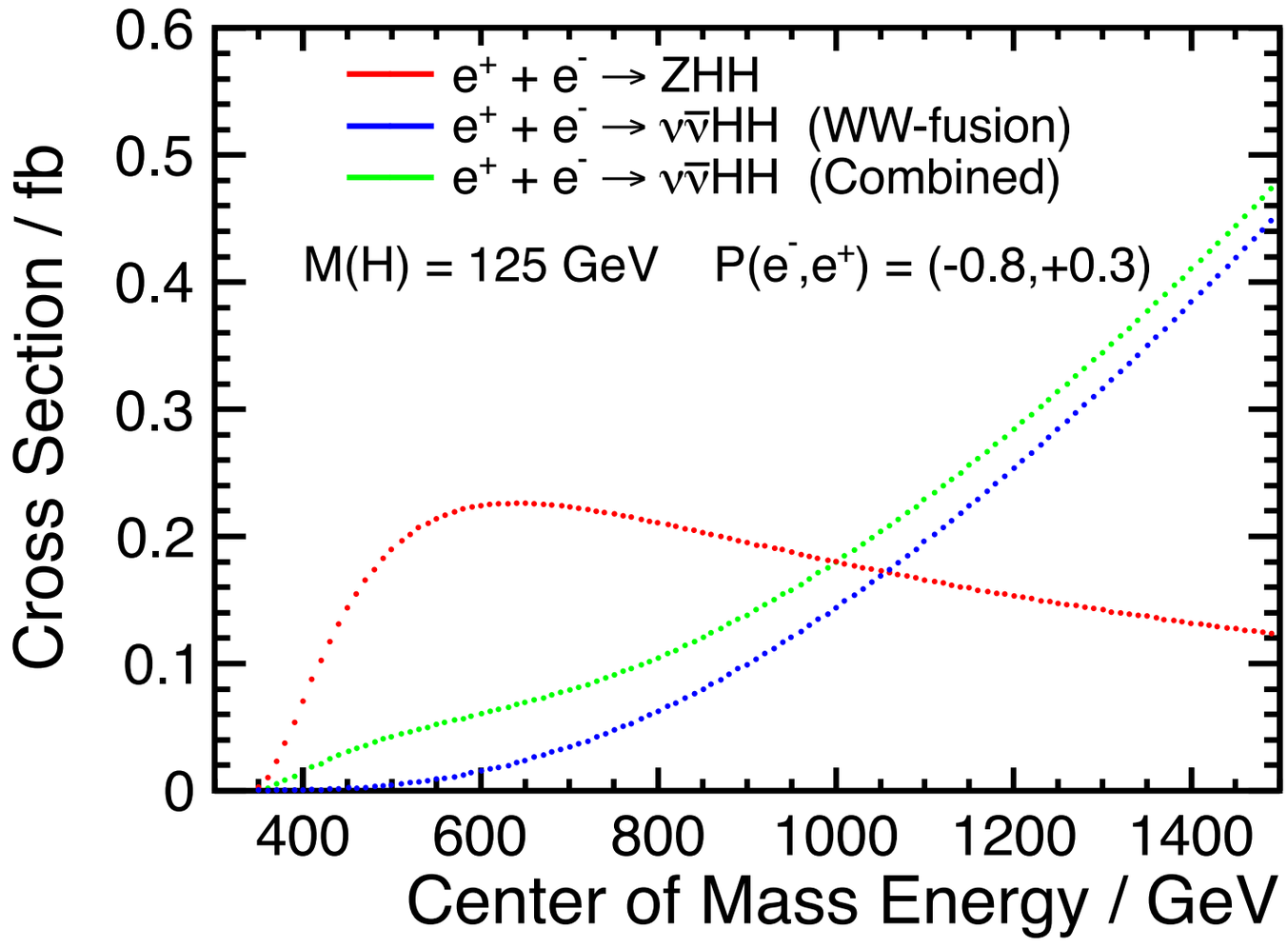
- **include as complete as possible NLO effect to address λ in single-Higgs**

- **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


$e^+ + e^- \rightarrow ZHH$
$e^+ + e^- \rightarrow \nu\bar{\nu}HH$ (WW-fusion)
$e^+ + e^- \rightarrow \nu\bar{\nu}HH$ (Combined)
M(H) = 125 GeV P(e^-,e^+) = (-0.8,+0.3)
Cross Section / fb
0
0.1
0.2
0.3
0.4
0.5
0.6
400
600
800
1000
1200
1400
Center of Mass Energy / GeV