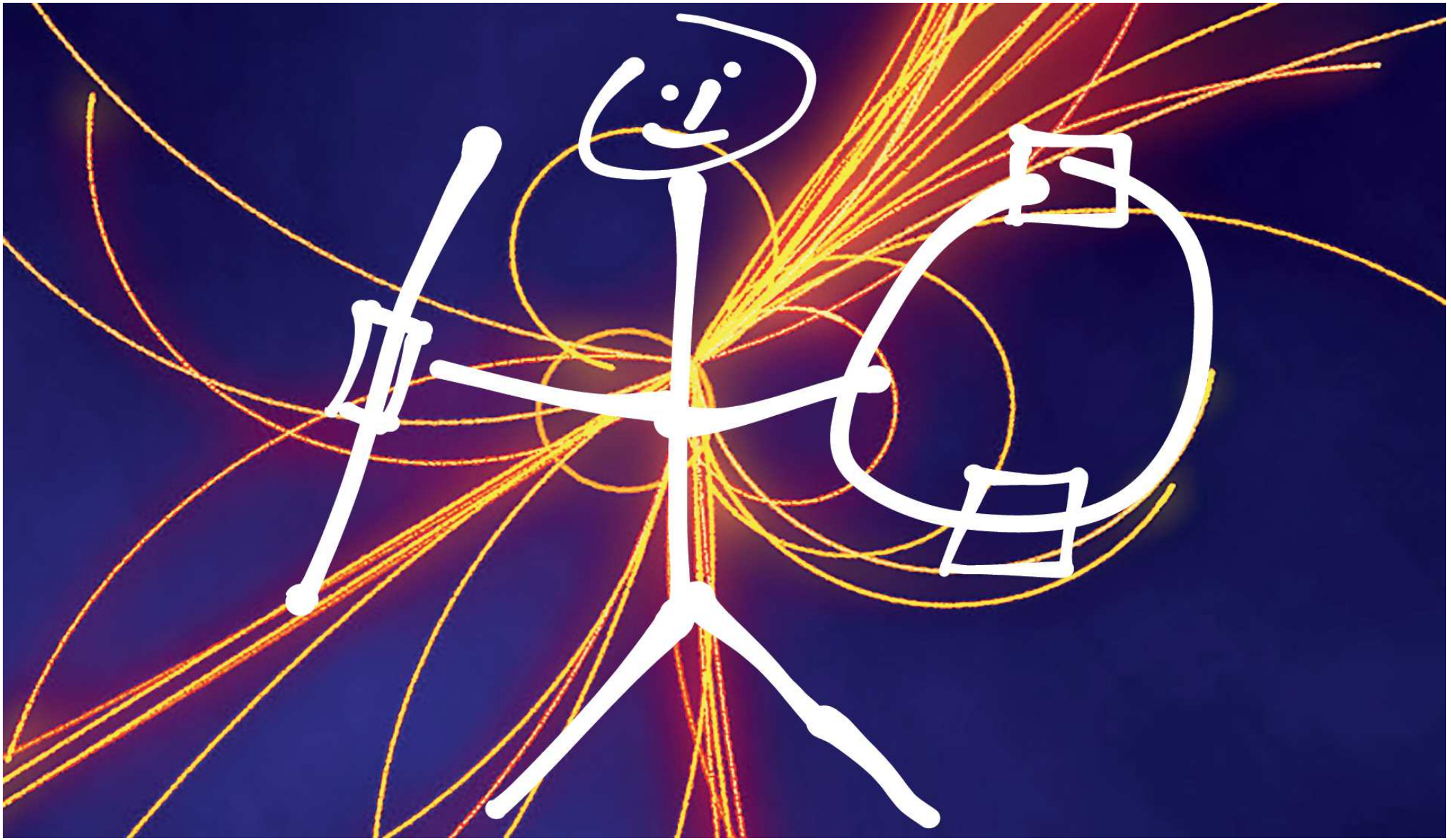

ECFA Higgs/top/EW factory studies

Sven Heinemeyer, IFT (CSIC, Madrid)

Madrid, 11/2024

ECFA Higgs/top/EW factory studies

What can the various e^+e^- collider proposals (ILC, CLIC, FCC-ee, CEPC, C^3) achieve in the field of Higgs/top/EW ?
$\Rightarrow$ input for the next ESPPU

Very hierarchical structure: Top level:

WG1: Physics Performance
Jorge de Blas (U. Granada), Patrick Koppenburg (Nikhef), Jenny List (DESY), Fabio Maltoni (UC Louvain / Bologna)

WG2: Physics Analysis Methods
Patrizia Azzi (INFN-Padova), Fulvio Piccinini (INFN Pavia), Dirk Zerwas (IJCLab/DMLab)

WG3: Detector R&D
Mary-Cruz Fouz (CIEMAT), Giovanni Marchiori (IN2P3, APC Paris), Felix Sefkow (DESY)

$\Rightarrow$ focus here: WG1 $\oplus$ WG2 connections

Very hierarchical structure (cont.):

WG1: Jorge de Blas, P. Koppenburg, J. List, F. Maltoni

WG1-PREC: Adrian Irles (IFIC), Andreas Meyer (DESY), Ayres Freitas (U. Pittsburgh), Paolo Azzurri (INFN Pisa)

WG1-HTE: Chris Hays (U. Oxford), Fabio Maltoni (U. Louvain) Karsten Koeneke (U. Freiburg)

WG1-SRCH: Aleksander Zarnecki (U. Warsaw), Rebeca Gonzalez Suarez (U. Uppsala), Roberto Franceschini (U. Rome 3)

WG1-FLAV: David Marzocca (INFN Trieste), Pablo Goldenzweig (U. Rochester), Stephane Monteil (U. Clermont Auvergne)

WG1-GLOB: Alexander Grohsjean (U. Hamburg), Jorge de Blas (U. Granada), Junping Tian (U. Tokyo), Marcel Vos (IFIC), Sven Heinemeyer (IFT)

But the real work is done now in the **Focus Topics**

Announcement/overview document: arXiv:2401.07564

> In order to stimulate new engagement and trigger some concrete studies in areas where further work would be beneficial towards fully understanding the physics potential of an e^+e^- Higgs / Top / Electroweak factory, we propose to define a set of focus topics. The general reasoning and the proposed topics are described in this document.

– what can be done at $\sqrt{s} = 250$ GeV?

– is higher energy beneficial?

– common aspects of the four/five collider proposals

– differences, (dis)advantages, . . .

Focus topics: overview

Topic		Lead group	Relevant $\sqrt{s}$ [GeV]				
			91	161	240–250	350–380	≥ 500
1	HtoSS	HTE			✓	✓	✓
2	ZHang	HTE (GLOB)			✓	✓	✓
3	Hself	GLOB			✓	✓	✓
4	Wmass	PREC		✓	✓	✓	✓
5	WWdiff	GLOB			✓	✓	✓
6	TTthres	GLOB (HTE)				✓	✓
7	LUMI	PREC	✓	✓	✓	✓	✓
8	EXscalar	SRCH			✓	✓	✓
9	LLPs	SRCH	✓	✓	✓	✓	✓
10	EXtt	SRCH				✓	✓
11	CKMWW	FLAV		✓	✓	✓	✓
12	BKtautau	FLAV	✓				
13	TwoF	HTE (PREC)	✓	✓	✓	✓	✓
14	BCfrag and Gsplit	PREC (FLAV)	✓	✓	✓	✓	✓

GLOB, PREC: natural spanish involvement

Focus Topic Expert Teams (I):

1 HtoSS — $e^+e^- \to Zh$: $h \to s\bar{s}$ ($\sqrt{s} = 240/250\,\text{GeV}$)

Expert Team: John Alison, Matthew Basso, Valentina Cairo, Valerio Dao, Loukas Gouskos, Karsten Köneke, Yotam Soreq, Taikan Suehara, Caterina Vernieri

2 ZHang — Zh angular distributions and CP studies

Expert Team: Ivanka Bozovic, Chris Hays, Markus Klute, Sandra Kortner, Cheng Li, Ken Mimasu, Gudrid Moortgat-Pick

GLOB/SH's favorite (I):

3 Hself — Determination of the Higgs self-coupling

Expert Team: Gauthier Durieux, Ricardo Gonçalo, Sven Heinemeyer, Michael Peskin, Philipp Roloff, Roberto Salerno, Junping Tian

Focus Topic Expert Teams (II):

PREC:

4 Wmass — Mass and width of the W boson from the pair-production threshold cross section lineshape and from decay kinematics

Expert Team: Paolo Azzurri, Josh Bendavid, Martin Beneke, Jorge de Blas, Stefan Dittmaier, Ayres Freitas, Adrián Irles, Andreas B. Meyer, Simon Plätzer, Matthias Schott, Raimund Ströhmer, Graham Wilson

GLOB:

5 WWdiff — Full studies of WW and $e\nu W$

Expert Team: Patrizia Azzi, Timothy Barklow, Jorge de Blas, Ansgar Denner, Alexander Grohsjean, Wolfgang Kilian, Jenny List, Frank Siegert

GLOB/MV's favorite(?):

6 TTthres — Top threshold: Detector-level simulation studies of $e^+e^- \to t\bar{t}$ and threshold scan optimisation

Expert Team: Patrizia Azzi, Martin Beneke, Jorge de Blas, Matteo Defranchis, Gauthier Durieux, Roberto Franceschini, André Hoang, Adrián Irles, Abideh Jafari, Victor Miralles, Zohreh Najafabadi, Laura Pintucci, Andrej Saibel, Reinhard Schwienhorst, Frank Simon, Marcel Vos, Aleksander Filip Zarnecki

Focus Topic Expert Teams (III):

PREC:

7 LUMI — Precision luminosity measurement

Expert Team: Paolo Azzuri, Ivanka Bozovic, Mogens Dam, Ayres Freitas, Adrián Irles, Andreas B. Meyer, Fulvio Piccinini, Wiesław Płaczek, André Sailer, Maciej Skrzypek, Graham Wilson

SH's favorite (II):

8 EXscalar — New exotic scalars

Expert Team: Mikael Berggren, Sven Heinemeyer, Abdollah Mohammadi, Tania Robens, Nikolaos Rompotis, Aleksander Filip Zarnecki

9 LLPs — Long-lived particles

Expert Team: Juliette Alimena, Rebeca Gonzalez Suarez, Jan Hajer, Marcin Kucharczyk, Emma Torro Pastor, Sarah Louise Williams, Aleksander Filip Zarnecki

10 EXtt — Exotic top decays

Expert Team: Nuno Castro, Marina Cobal, Gauthier Durieux, Roberto Franceschini, María Teresa Núñez Pardo de Vera, Kirill Skovpen, Marcel Vos

Focus Topic Expert Teams (IV):

11 CKMWW — CKM matrix elements from W decays

Expert Team: Marzia Bordone, Ulrich Einhaus, Pablo Goldenzweig, Zoltan Ligeti, David Marzocca, Stéphane Monteil, Michele Selvaggi

12 BKtautau — $B^0 \to K^{0*}\tau^+\tau^-$

Expert Team: Paula Collins, Pablo Goldenzweig, Jernej Kamenik, Matt Kenzie, Elisa Manoni, David Marzocca, Tristan Miralles, Stéphane Monteil, Fabrizio Palla, Luiz Vale Silva, Aidan Wiederhold

13 TwoF — EW precision: 2-fermion final states ($\sqrt{s} = M_Z$ and beyond)

Expert Team: Emanuele Bagnaschi, Adrián Irles, Daniel Jeans, Alessandro Vicini

PREC:

14 BCfrag and Gsplit — Heavy quark fragmentation and hadronisation, gluon splitting and quark-gluon separation

Expert Team: Paolo Azzurri, Eli Ben Haim, Loukas Gouskos, Ayres Freitas, Adrián Irles, Andreas B. Meyer, Simon Plätzer, Andrzej Siodmok, Torbjörn Sjöstrand, Maria Ubiali

Expert team

Responsible WG1-SRCH convener: A. Filip Żarnecki
WG1 coordination contact: Jenny List

- FCCee contact: Sven Heinemeyer
- ILD contact: Mikael Berggren
- CLIC contact: A. FIlip Żarnecki
- Theory contact: Tania Robens

  LHC contacts:
  - Nikolaos Rompotis (ATLAS)
  - Abdollah Mohammadi (CMS, C^3)

Two different "light scalar topics" to be studied:

[*taken from A. Zarnecki '23*]

Theoretical and phenomenological targets

Higgs factories are best suited to search for light exotic scalars in the process:

$$e^+e^- \to Z\,\phi$$

Production of new scalars can be tagged, independent of their decay, based on the recoil mass.

We should look for different scalar decay channels e.g. $b\bar{b}$, $W^{+(*)}W^{-(*)}$, $\tau^+\tau^-$ or invisible
Non-standard decays channels of the new scalar should also be looked for.

For maximum sensitivity, feasibility of including hadronic Z decays should be explored.

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For maximum sensitivity, feasibility of including hadronic Z decays should be explored.

Theoretical and phenomenological targets (2)

As as second benchmark scenario for the EXscalar focus topic,
light scalar pair-production in 125 GeV Higgs boson decays is proposed:

$$e^+e^- \to Z\,H \to Z\,\phi\,\phi$$

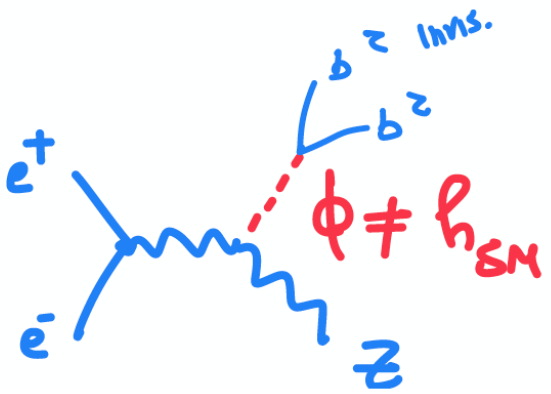
Here again, different decay channels should be considered, both SM-like and exotic.

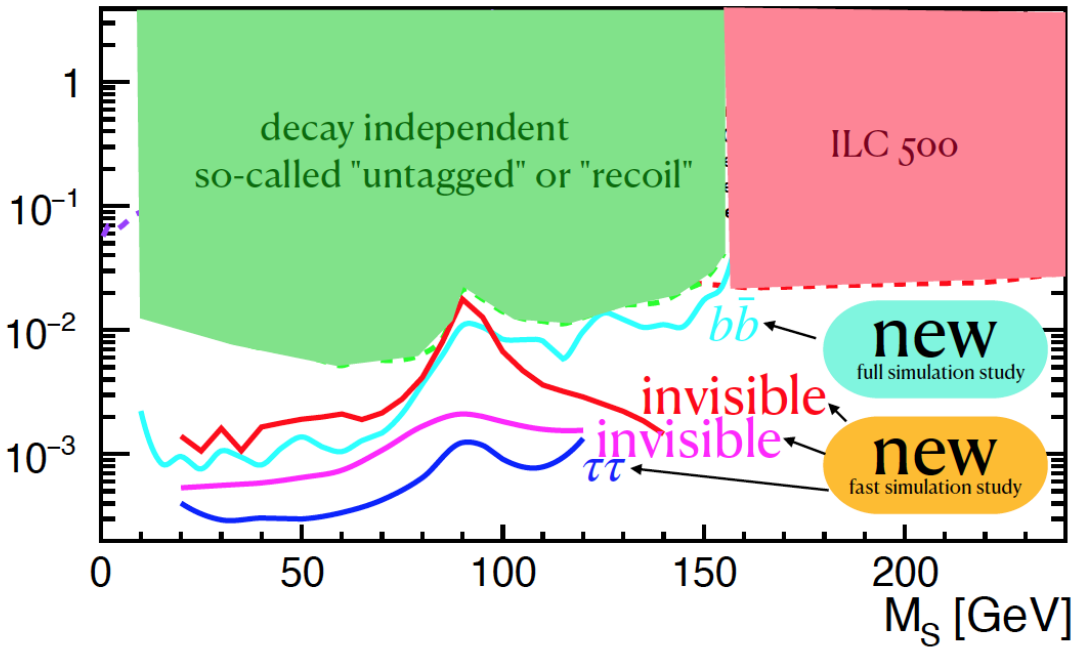
While new scalar states could in general be long-lived, only scenarios with prompt decays are included in this focus topic (while a dedicated topic focuses on LLPs, see next presentation).

New scalars

related to Higgs and electroweak

- The SM Higgs boson may not be the only one!
- Difficult to imagine new scalars to not be related to the SM Higgs or electroweak boson or both
- Lots of possible scenarios in which HTE factory can do very well, expanding significantly searches at the HL-LHC
  - new scalar heavier than 125 GeV
  - new scalar lighter than 125 GeV





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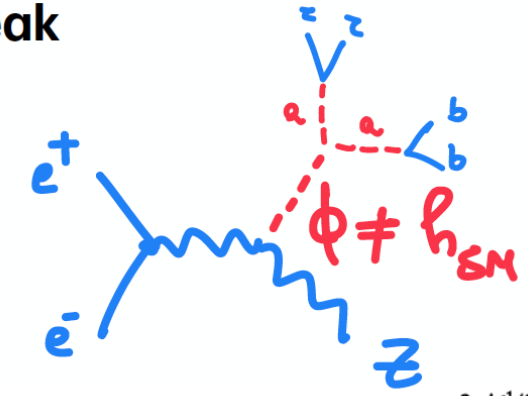
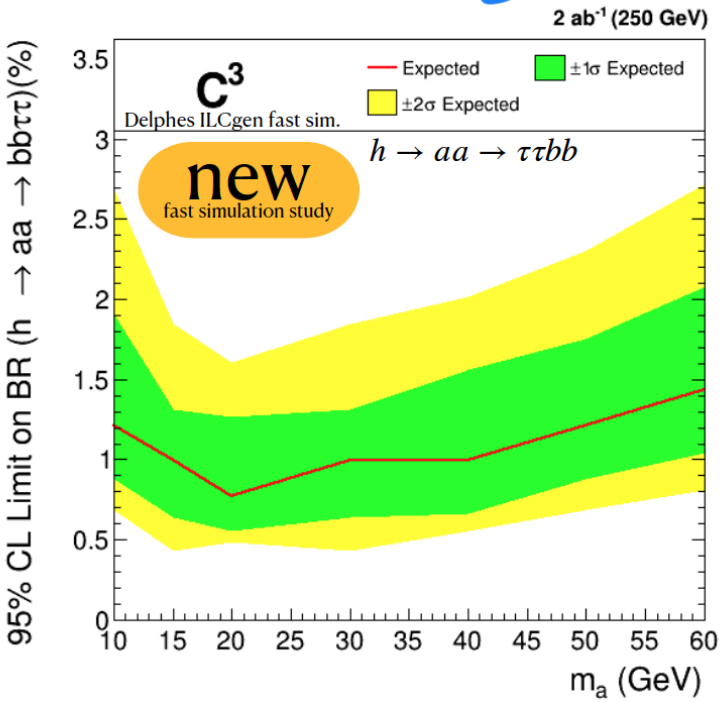


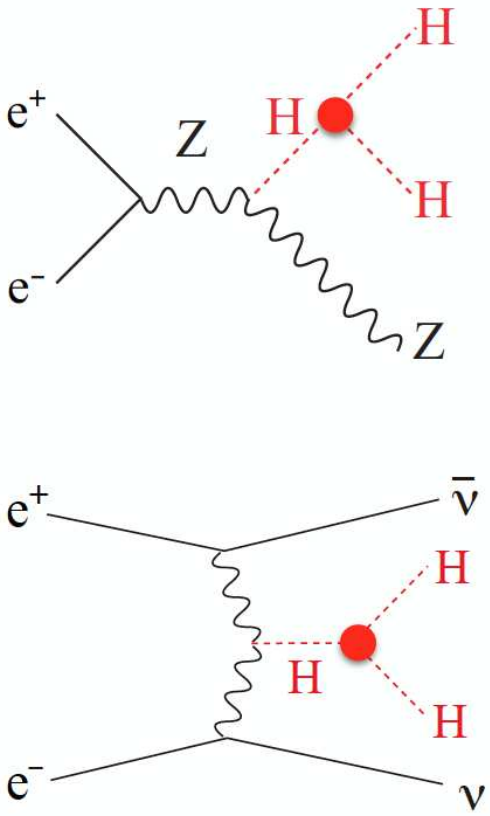


Focus Topic 3: HSelf

The simple THC case:

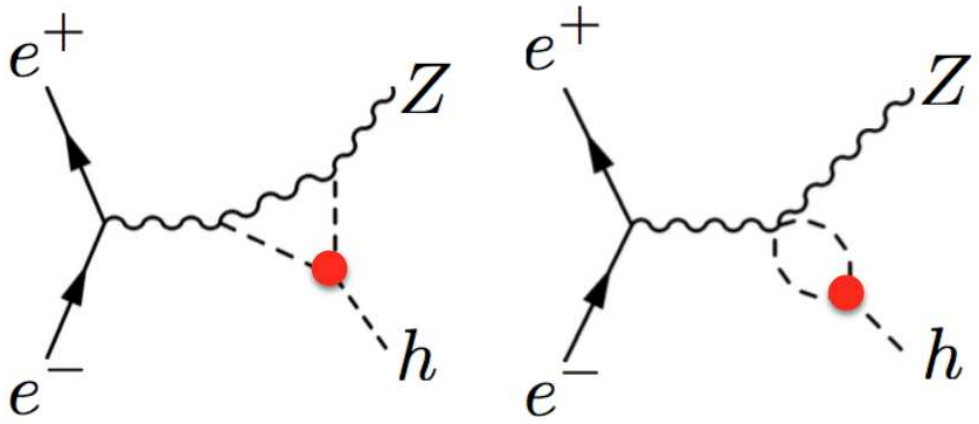
[*taken from J. Tian*]

$\sqrt{s} \gtrsim 500$ GeV



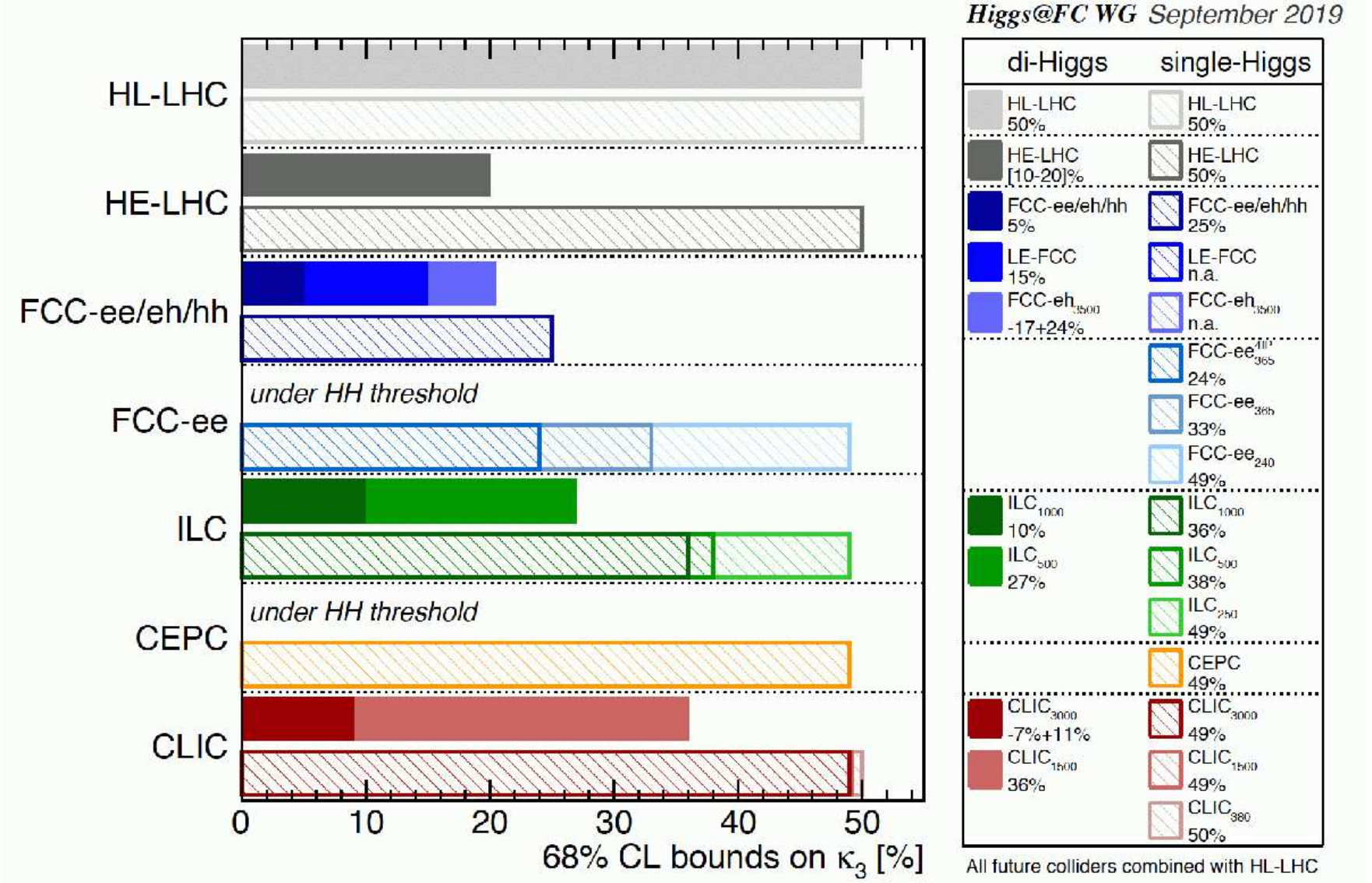
$\sigma_{HH} \sim O(0.1)$ fb

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



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

SM triple Higgs coupling: comparison of all colliders:



⇒ Many remaining open questions!

$\kappa_\lambda := \lambda_{hhh}/\lambda_{hhh}^{\mathrm{SM}}$

Open question I:

Analysis focuses on $\kappa_\lambda \equiv 1$ (SM case)
Requirement of FOEWPT may yield $\kappa_\lambda \sim 2$

Q: how do the experimental precisions change for $\kappa_\lambda \neq 1$?

Open question II/III:

Analysis assumes that only one Higgs boson exists (SM case)
Requirement of FOEWPT easily results in additional Higgs bosons

Q: Impact of additional Higgs boson on κ_λ determination?

Q: Determination of BSM THCs?

Improvements: κ_λ from di-Higgs

[M. Vos '24]

The Higgs self-coupling from di-Higgs production

LHC experiments are deploying a huge effort to observe pair production; more aggressive HL-LHC projections are appearing (ESPPU '19: 50% precision)

Bottlenecks in the ZHH analysis

- jet pairing and jet misclustering: "perfect" jet clustering → 40% improvement
  improve di-jet mass resolution
- removal of $\gamma\gamma$ overlay: 15% improvement expected
  important to tackle initial state radiation (ISR)
- flavor tagging: 11% improvement expected from 5% eff. increase with newer LCFIPlus
  important as $H \to b\bar{b}$ is the dominant Higgs decay channel
- adding $Z \to \tau\tau$ channel: 8% improvement expected
  include a yet unaccounted decay channel
- more modern ML architectures for signal/background selection
  improvement expected when transitioning from BDTs to (e.g.) transformer-based models etc.
- separation of ZHH diagrams with/without the self-coupling
  would directly improve the sensitivity on λ (lower sensitivity factor)

All improvements are relative

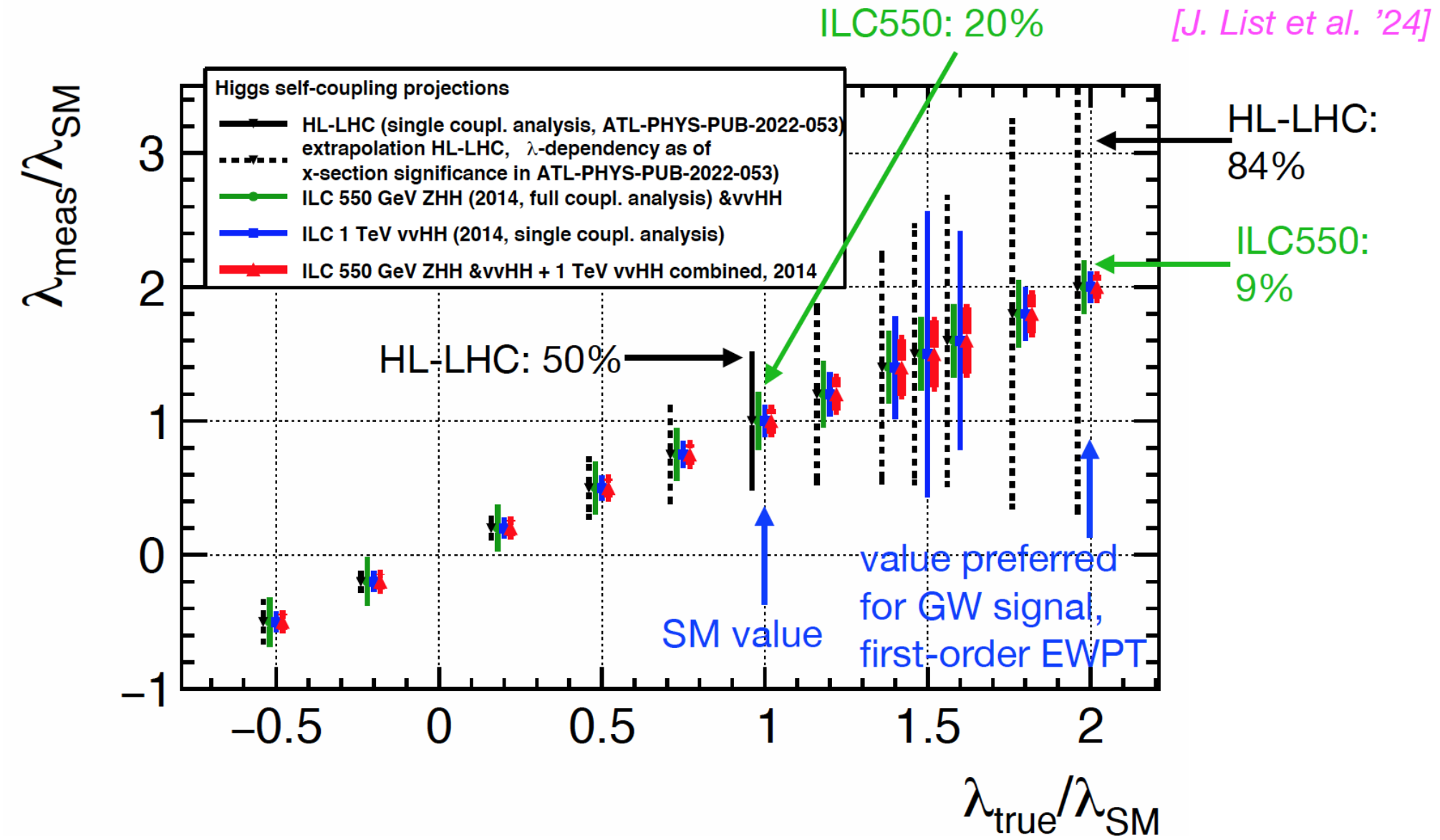
Expected improvements from DESY-Thesis-16-027

- **Better than 20% sensitivity on λ in reach** through demonstrated reconstruction improvements **<20%!!!**

Higgs self-coupling measurement at ILD via the ZHH Process at multiple COM energies | 3rd ECFA Workshop on e+e- Higgs/EW/Top Factories | 2024/10/10 | Paris | Bryan Bliewert

Also Higgs factory projections have a lot of room for improvement!!

Improvements: κ_λ from di-Higgs



⇒ note: these are other 20%! overall improvement even better!

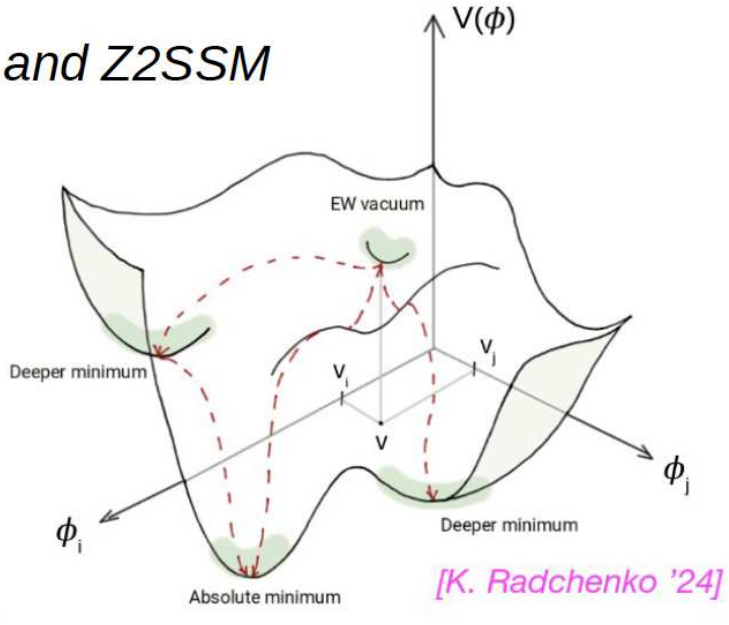
BSM Higgs sectors can behave very different from SM Higgs [M. Vos '24]

The Higgs self-coupling is he holy grail of HEP*

*Georg Weiglein

λ_{hhh} can **deviate significantly from SM prediction** (by up to a factor **~10**), for otherwise theoretically and experimentally allowed points, due to **mass-splitting effects in radiative corrections involving BSM scalars**

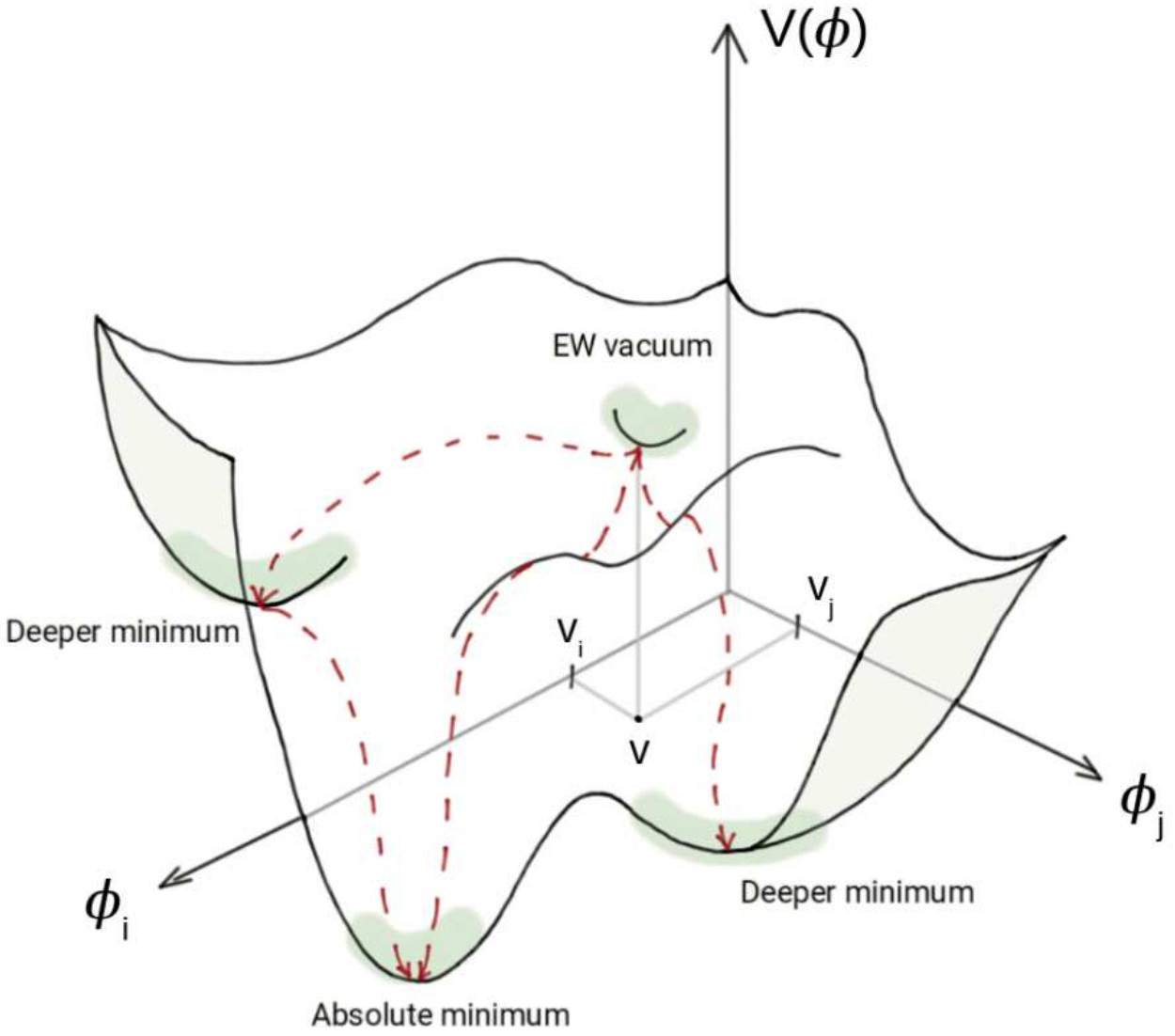
Johannes Braathen, discussing Inert Doublet Models and Z2SSM



⇒ much more complicated structure, huge radiative corrections

BSM Higgs sectors can behave very different from SM Higgs

[*K. Radchenko '24*]



⇒ much more complicated structure, huge radiative corrections

[M. Vos '24]

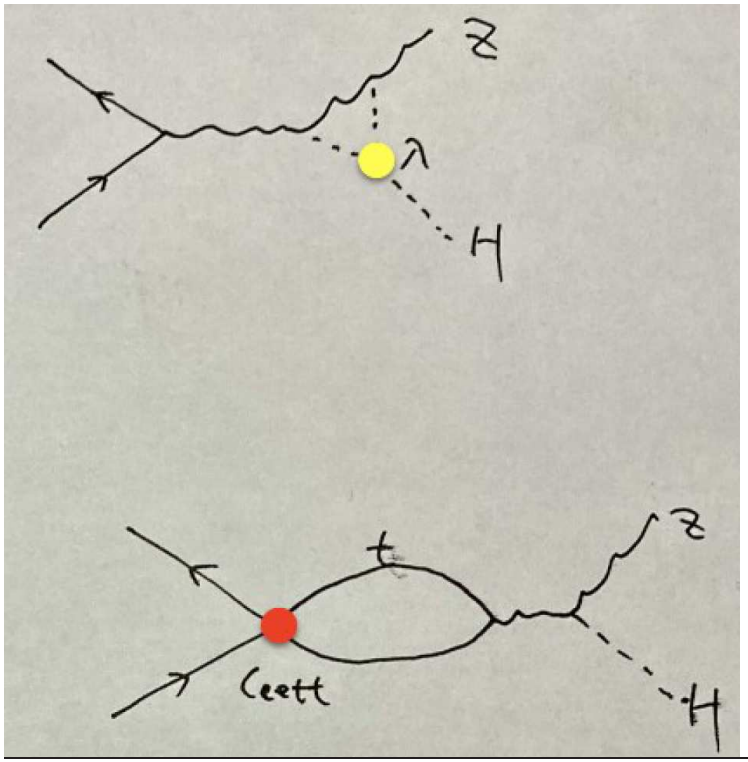
A truly global analysis of Higgs self-coupling from ZH

Indirect model-dependent probe of the Higgs self-coupling

Matthew McCullough

Phys. Rev. D **90**, 015001 – Published 1 July 2014; Erratum Phys. Rev. D **92**, 039903 (2015)

Pier Paolo Giardino: calculation of loop effects of top operators on ZH cross section, arXiv:2406.03557, arXiv:2409.11466



Analyses so far:

1L EFT contributions

- only upper diagram taken into account
- lower-type diagram can give similar contributions
- single Higgs EFT analysis "too optimistic"

⇒ has to be redone

[C. Leonidopoulos '24]

The Big Picture

- Capture the Physics Case & ECFA study activities
  - Demonstrate what can be achieved at a future collider
  - Encourage synergies among projects & build e^+e^- community
- Physics Performance (WG1)
  - Forum to collect and discuss physics potential
  - Particular initiative: Develop thematic areas to concentrate common work → Focus topics
- Analysis Methods (WG2) & Detector Technologies (WG3)
  - Cross-referenced with Physics Topics (WG1)
  - Legacy: Common software, common studies/discussions

- Report:
  - Coherent & self-contained: should be a useful document
  - Focus on new studies (avoid already published material)
  - With references to more detailed notes/papers, when available

[C. Leonidopoulos '24]

Timeline: what has happened

- 20 October: deadline for analysis teams to submit 2-page summary
- 20 Oct – 10 Nov: Compilation & editing by WG1 subgroup conveners & editors and WG2/WG3 editors (+coordinators & chief editors)

98 contributions in total

[C. Leonidopoulos '24]

Timeline: the next steps

- 20 October: deadline for analysis teams to submit 2-page summary
- 20 Oct – 10 Nov: Compilation & editing by WG1 subgroup conveners & editors and WG2/WG3 editors (+coordinators & chief editors)
- 10 – 27 Nov: Editing by WG1 coordinators, WG2/3 editors & coordinators, and chief editors

WG coordinators & chief editors

- Physics program - WG1 coordinators: Fabio Maltoni, Jenny List, Jorge de Blas, Patrick Koppenburg (ECFA-WHF-WG1-coords@cern.ch)
- Physics analysis methods - WG 2 coordinators: Patrizia Azzi, Fulvio Piccinini, Dirk Zerwas (ECFA-WHF-WG2-coords@cern.ch)
- Detector technologies - WG3 coordinators: Felix Sefkow, Mary Cruz Fouz, Giovanni Marchiori (ECFA-WHF-WG3-coords@cern.ch)

- Chief editors: Christos Leonidopoulos, Aidan Robson

WG2 editors

Section editors
Andre Sailer, Frank Gaede, Gerardo Ganis
Carlo Carloni Calame, Juergen Reuter, Marco Zaro
Alan Price
Thorsten Ohl, Daniel Schulte
Andre Sailer, Brieuc Francois, Daniel Jeans
Loukas Gouskos, Taikan Suehara, Ulrich Einhaus

[C. Leonidopoulos '24]

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- 27 Nov – 18 Dec: Editing by chief editors
- 18 December: circulation of 1st draft to contributors, IAC, P-ECFA/R-EFCA
- 17 January: Deadline for comments on 1st draft
- 24 January: Deadline for final results/plots from contributors
- February: incorporation of comments & latest results/plots
- 21 February: Final version sent to P-ECFA/R-ECFA
- 7-8 March: R-ECFA approval during country visit, followed by arXiv submission

[C. Leonidopoulos '24]

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⇒ I hope it is worth the effort!!


Further Questions?