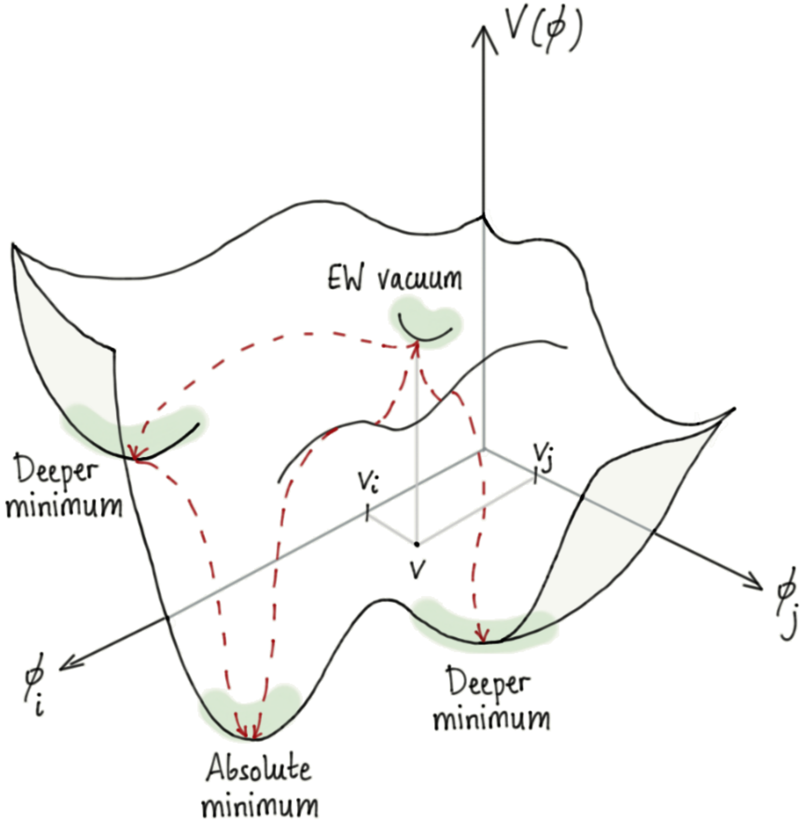
Di-Higgs and Trilinear Coupling at e+e- Colliders

QU DiHiggs meeting 2026
DESY, June 2, 2026

Jenny List [1]

[1] Deutsches Elektronen-Synchrotron DESY



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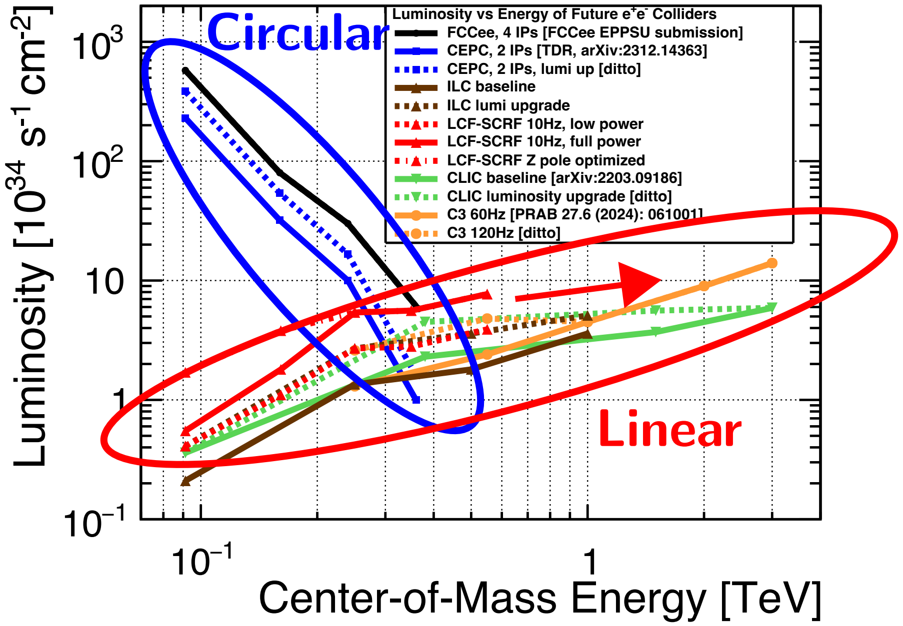
Introduction

Future Colliders

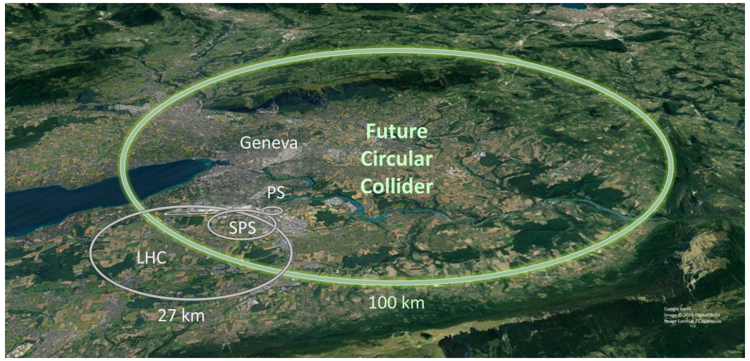
> **"An electron-positron Higgs factory is the highest-priority next collider."** [ESPP.2020]

- Model-independent measurements of Higgs width and couplings
- Direct and/or indirect sensitivity to κ_λ
- Electroweak precision observables (EWPOs) at sub-per-mille precision

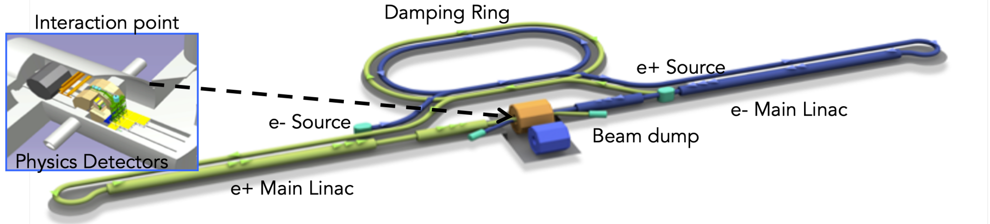
2 categories:



[ILC.Plots.2025]



(a) Circular colliders (FCC-ee, CEPC)

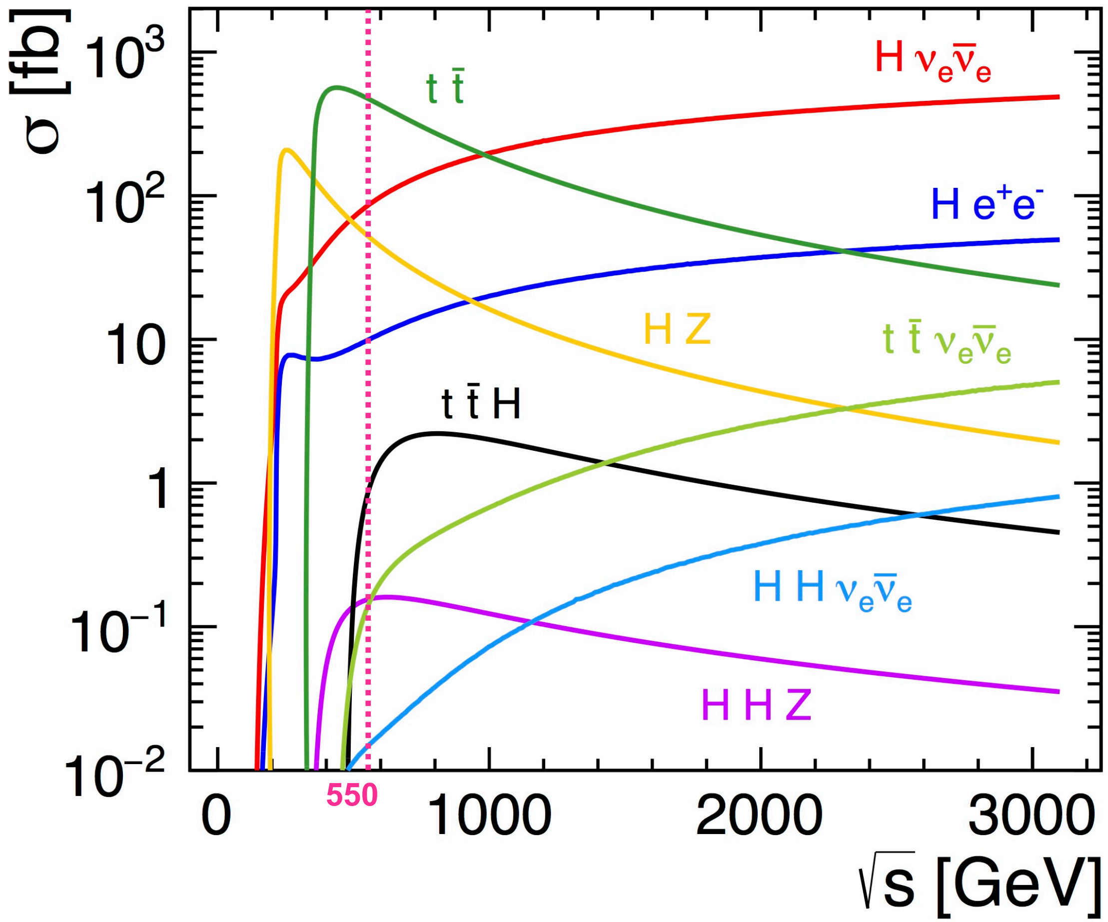


(b) Linear colliders (LCF, ILC, CLIC)

e+e- Colliders

are not hadron colliders :)

- **colliding elementary, electroweak particles**
  - no pdfs, little QCD
  - ~no pile-up
  - detector design not driven by radiation hardness / readout speed
  - no triggers
- **controlled and well-know initial state**
  - four-momentum
  - spin configuration
  - scanning of energy



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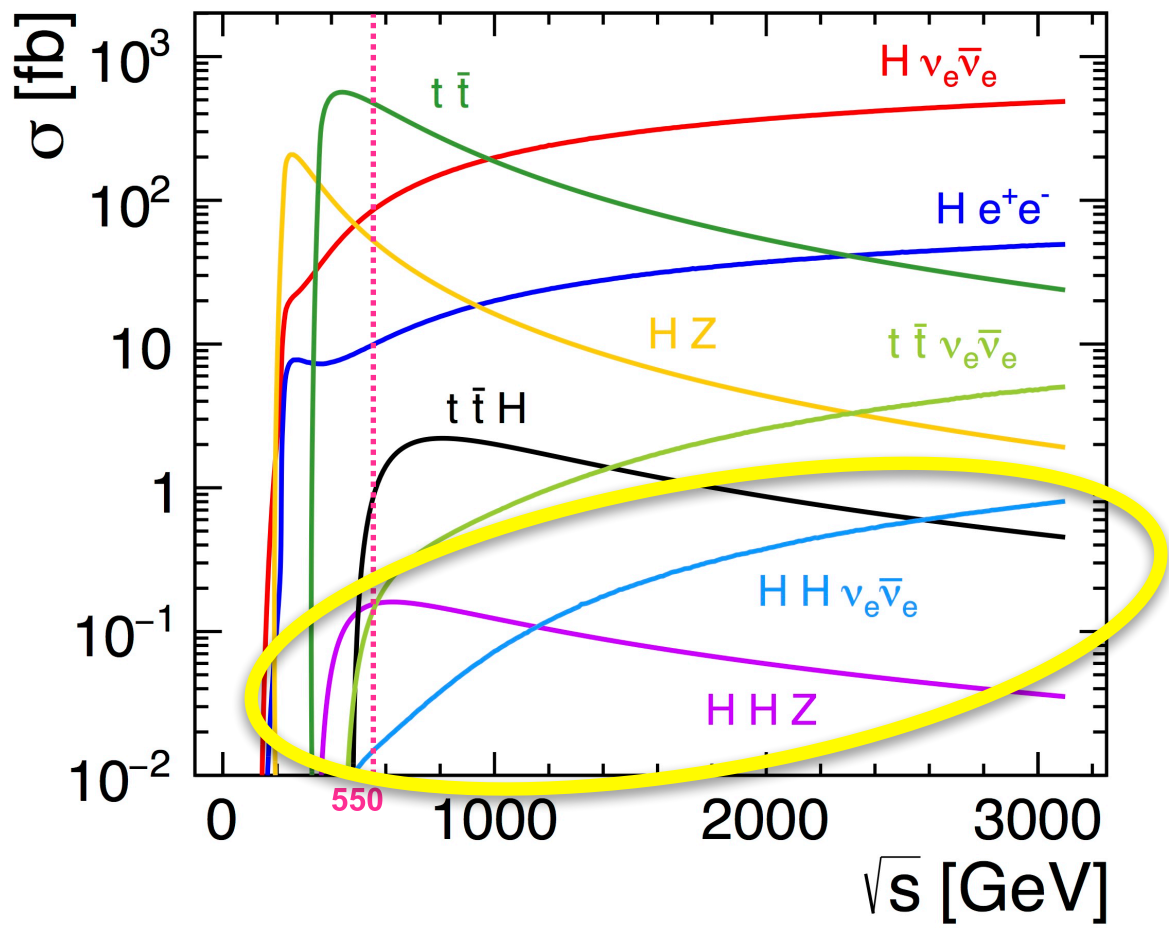

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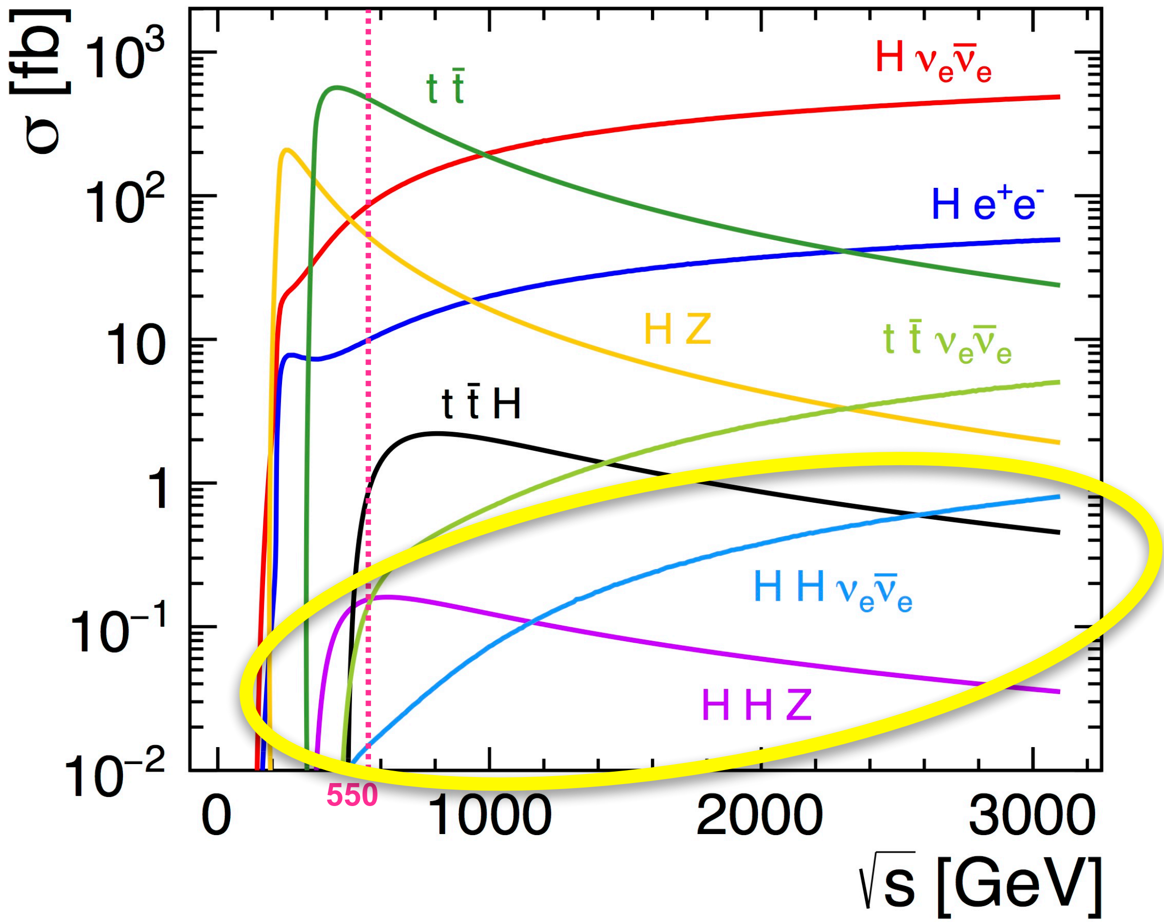


Higgs pair production requires at least ~500 GeV

Typical e+e- Collider Detectors (here: ILD)

Implemented in detailed Geant4-based simulations, gauged against testbeam performance of prototypes

Key requirements from Higgs physics:

- **p_t resolution** (total ZH x-section)

  $\sigma(1/p_t) = 2 \times 10^{-5}\ \mathrm{GeV}^{-1} \oplus 1 \times 10^{-3} / (p_t \sin^{1/2}\theta)$

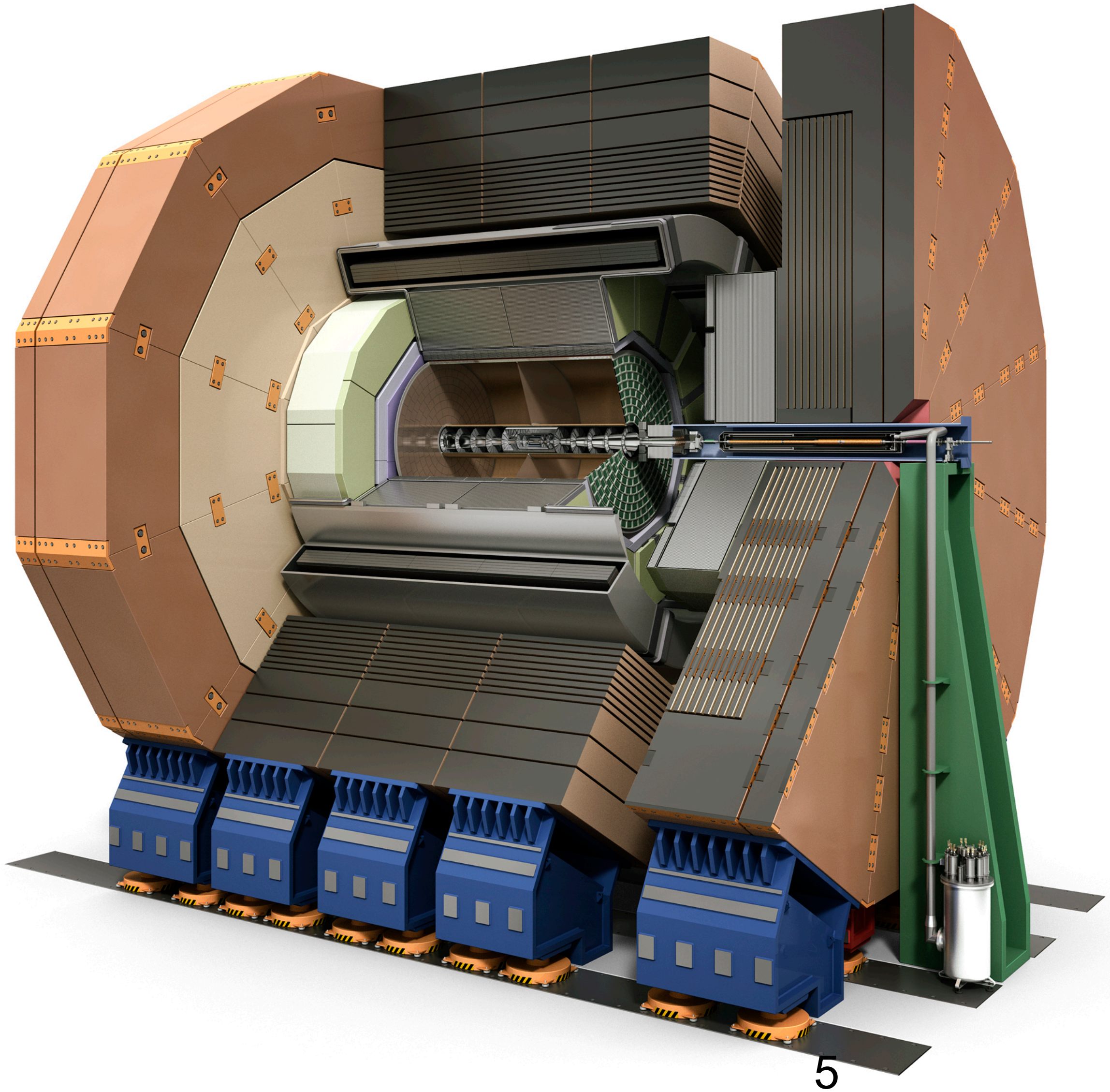
- **vertexing** ($H \to bb/cc/\tau\tau$)

  $\sigma(d_0) < 5 \oplus 10 / (p[\mathrm{GeV}] \sin^{3/2}\theta)\ \mu m$

- **jet energy resolution** ($H \to$ invisible) 3-4%
- **hermeticity** ($H \to$ invis, BSM) $\theta_{min} = 5$ mrad

Determine to key features of the detector:

- **low mass tracker:**
  eg VTX: 0.15% rad. length / layer)
- **highly-granular calorimeters,** optimised for particle flow
- **3.5-4T** solenoidal **B-field**



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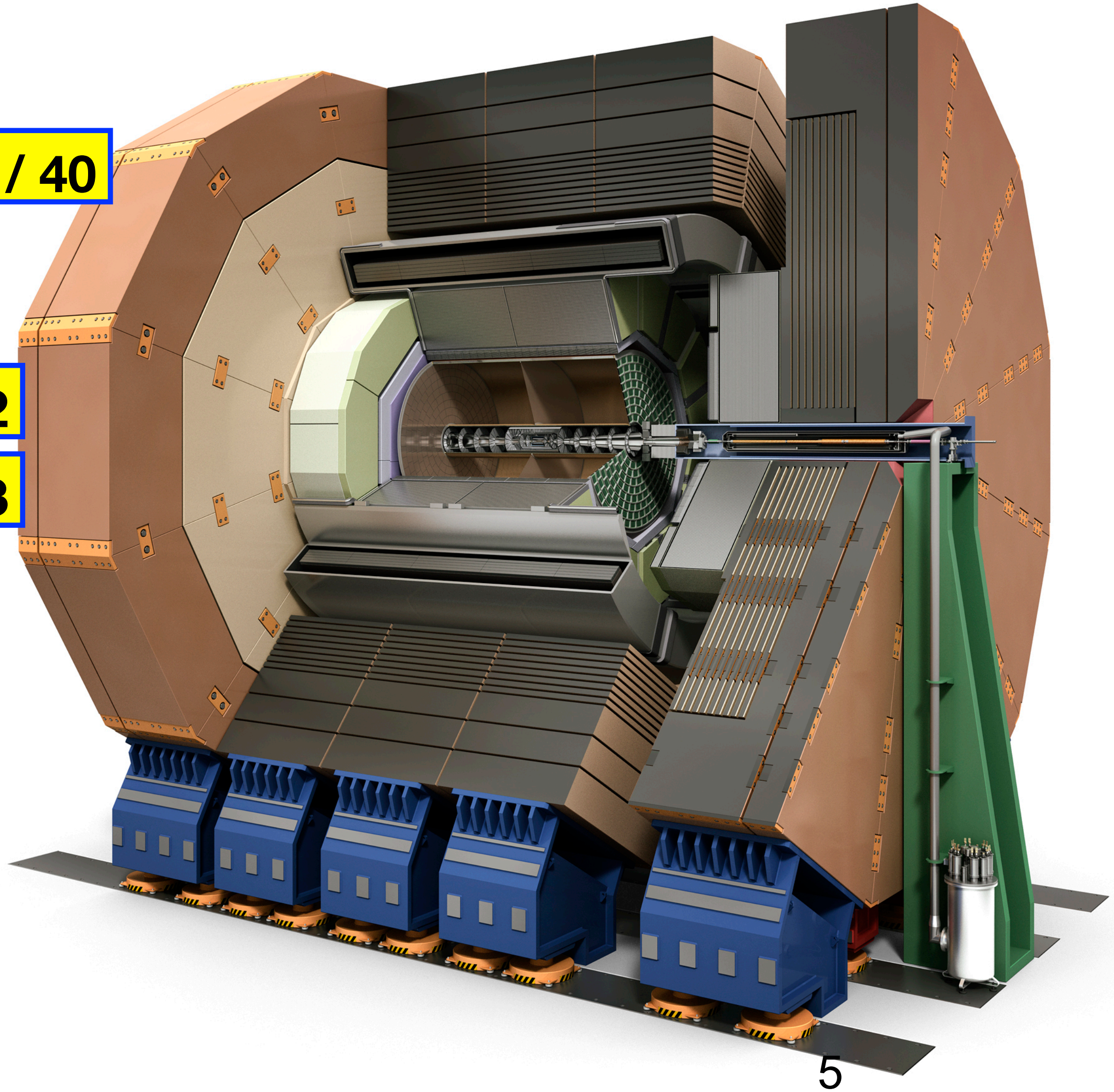

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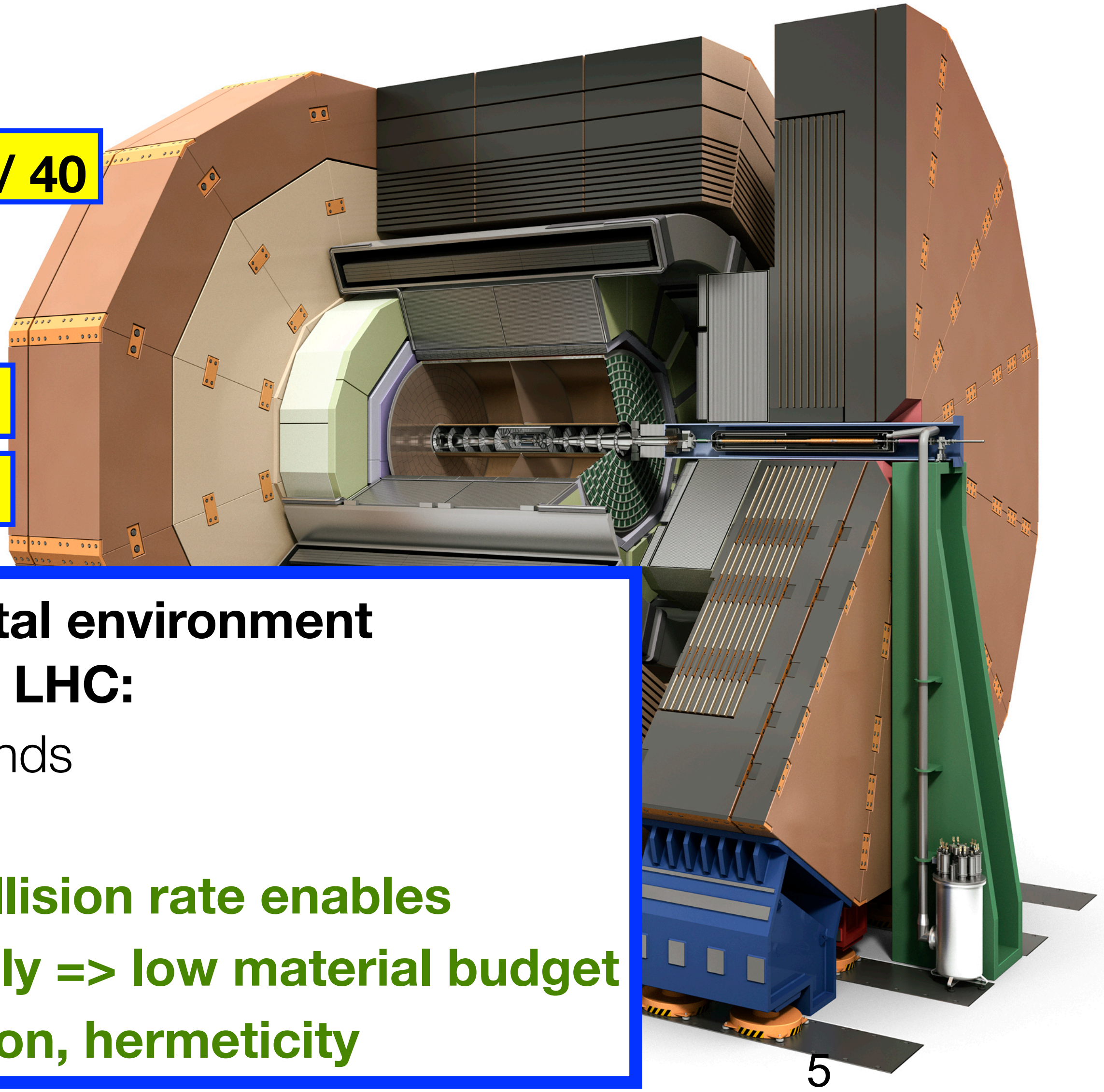


Possible since experimental environment in e+e- very different from LHC:

- much lower backgrounds
- much less radiation

Linear Colliders: lower collision rate enables

- **passive cooling only => low material budget**
- **triggerless operation, hermeticity**

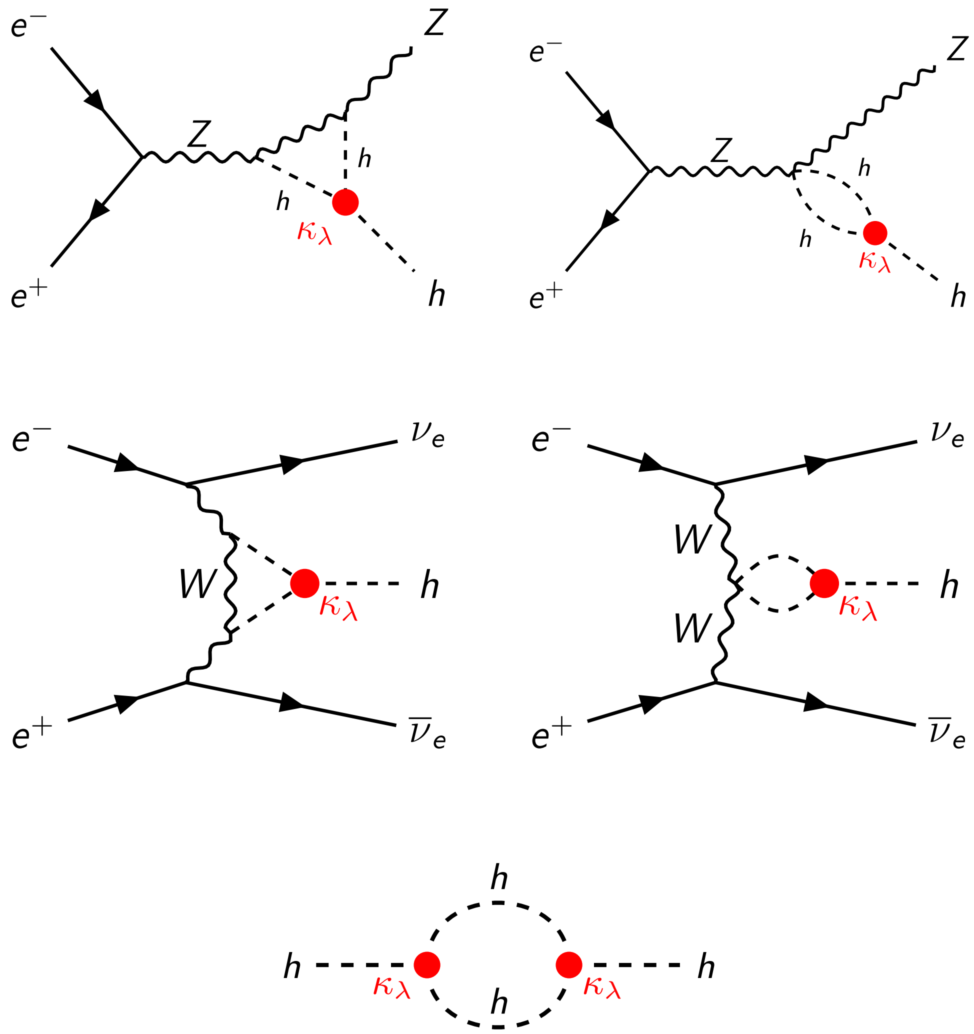
Constraining the trilinear coupling at energies < 500 GeV

Precision measurements of single-Higgs processes

Kala only present at loop-level

- *The only way* at circular colliders and low-energy stages of linear colliders
- Studied by several groups [deBlas.2025, ten Hoeve.2025, Maura.2025]
- Requires:
  - High-precision measurements of **ZH, vvH, ..**
  - At min. 2 different energies to resolve ambiguities (e.g. 240 & 365 GeV)
    => this will not work with LEP3
  - High-precision theory, beyond NLO

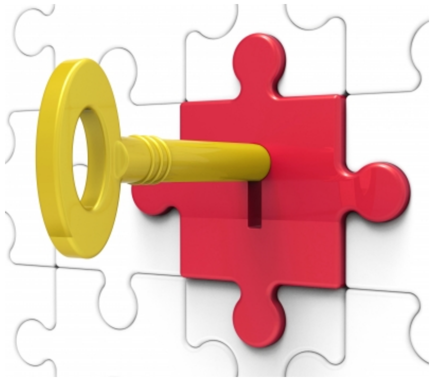
> - **Caveat:** sensitivity depends on the BSM theoretical framework, i.e.:
>   - ➢ **BSM particles** in the **loop**
>   - ➢ Theoretical **assumptions**

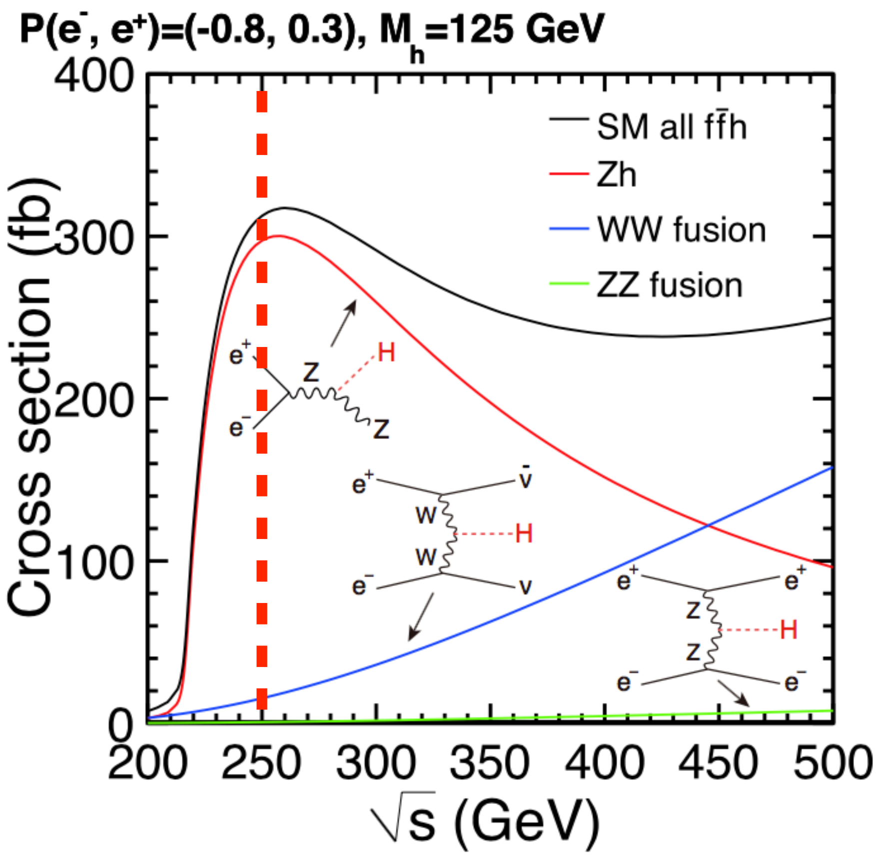


Absolute Higgs Production Rate

Absolute normalisation of Higgs couplings & total decay width

- Higgs factory at 240/250 GeV: **e+e- → ZH**
- **can measure its total cross section: *the key*** to model-independent determination of **absolute** couplings
- measurable independently of Higgs decays modes via **recoil technique**
- only possible at e+e- collider due **to known momentum of colliding particles**
- **enables a plethora of further precision measurements**





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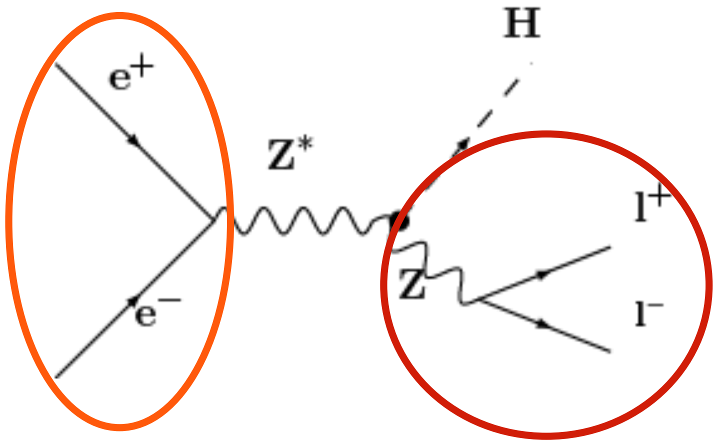

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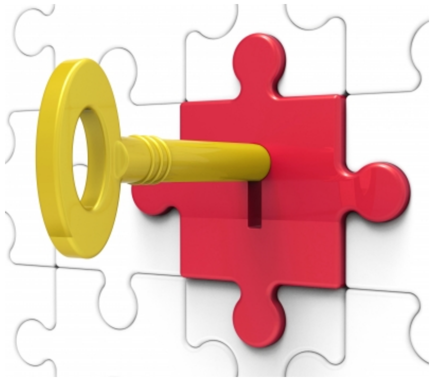

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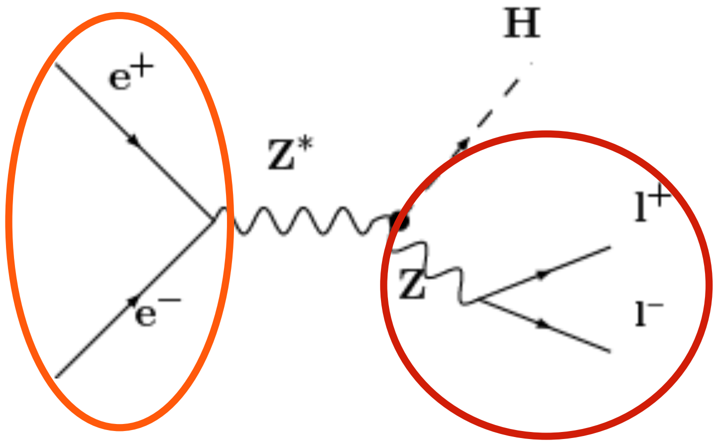

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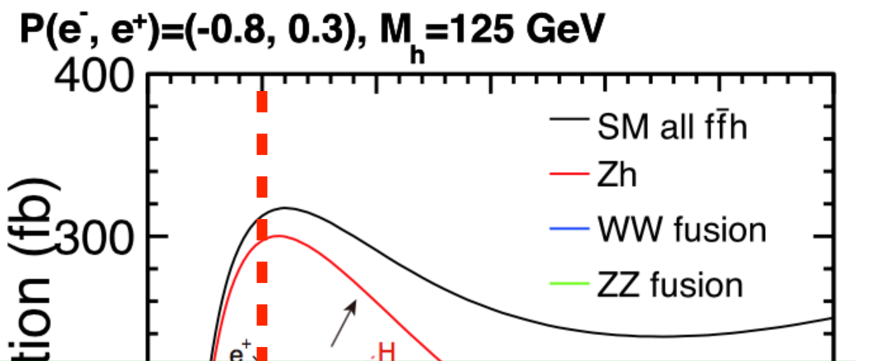

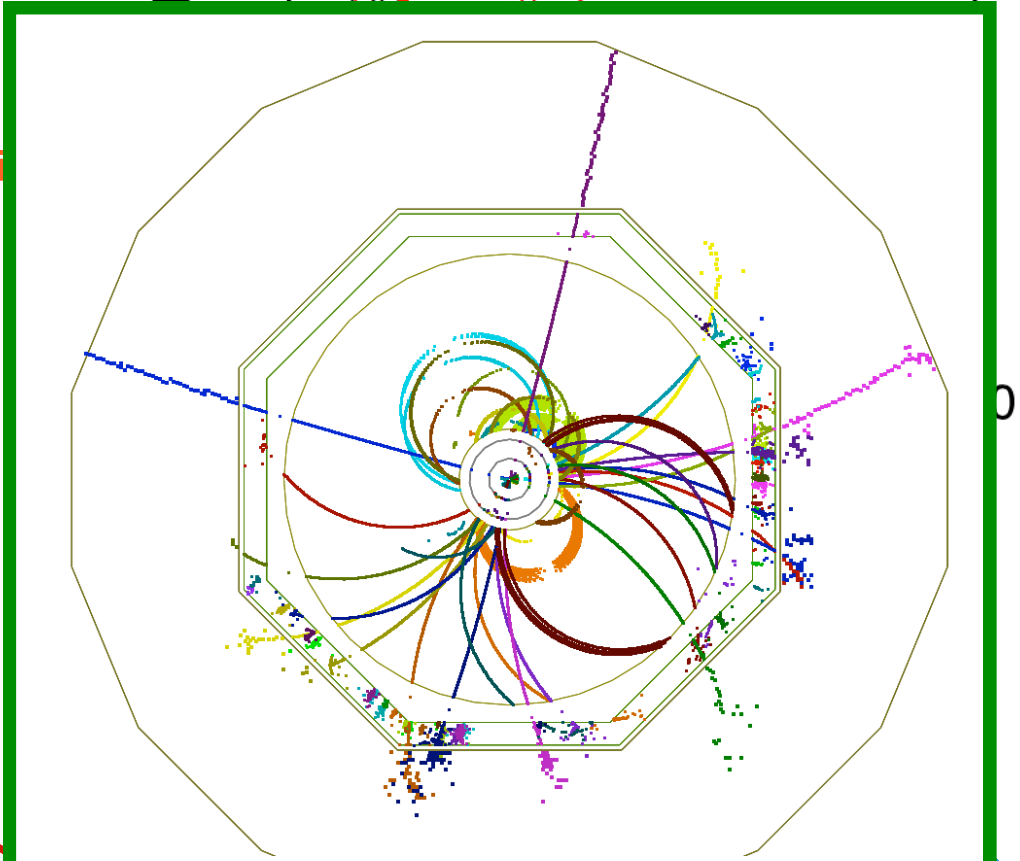

e+e- → μ+μ-H → μ+μ- bb in ILD detector

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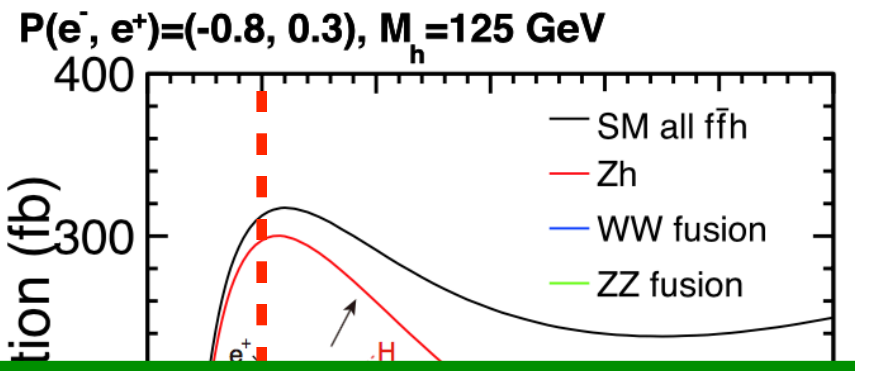

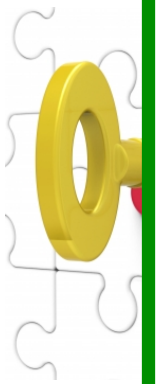

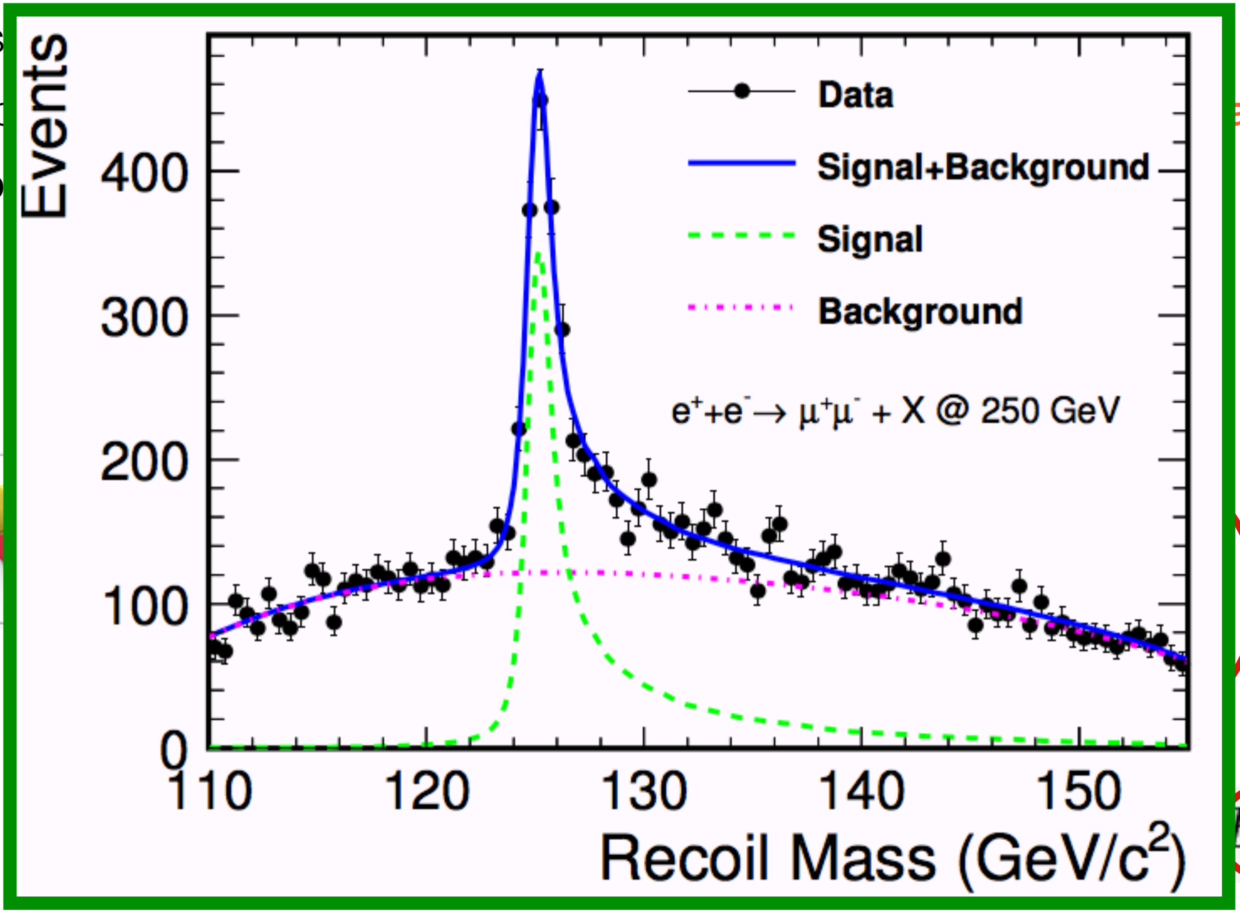

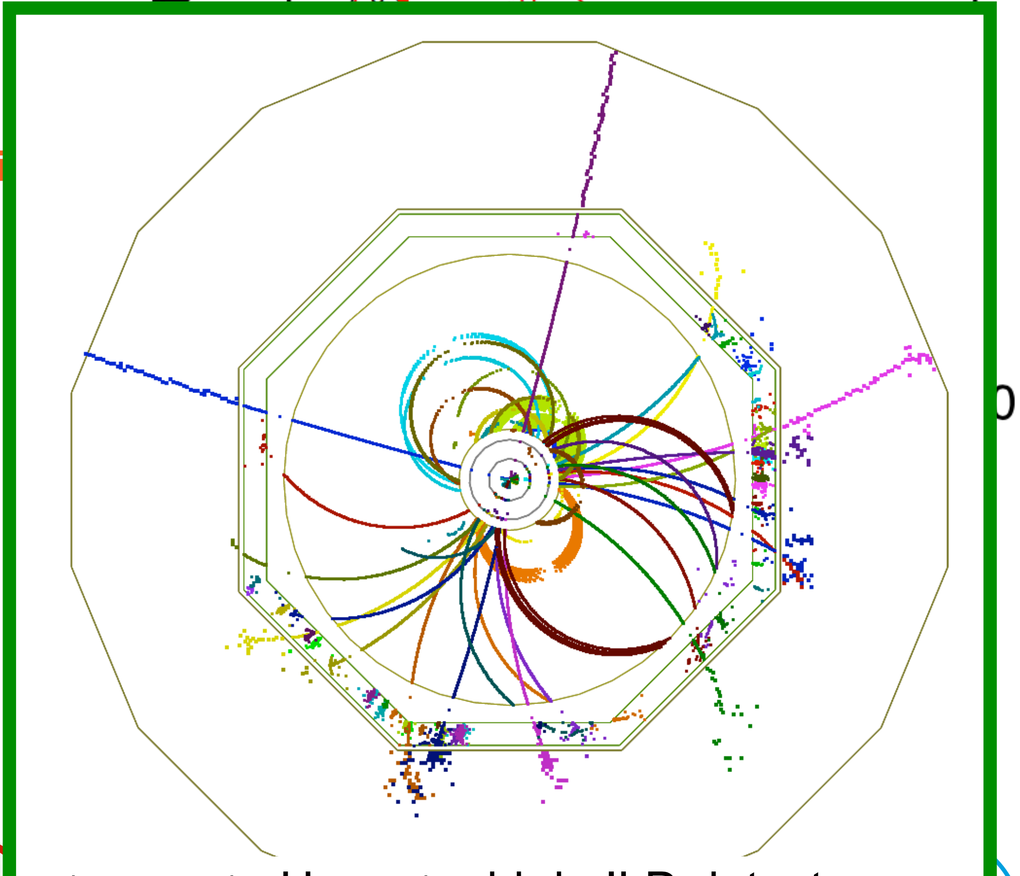

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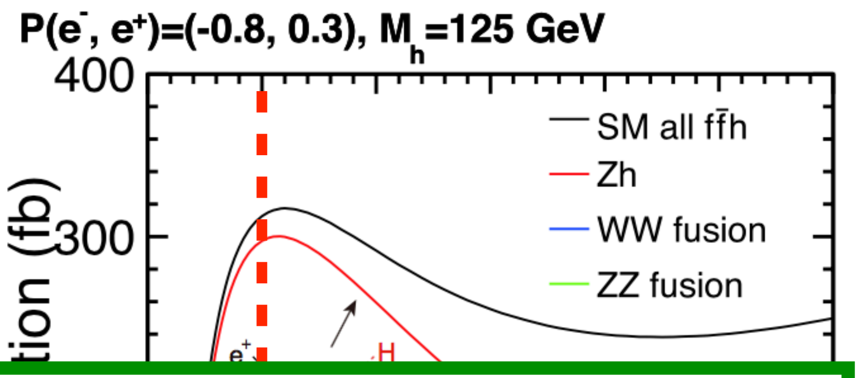

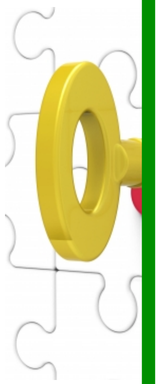

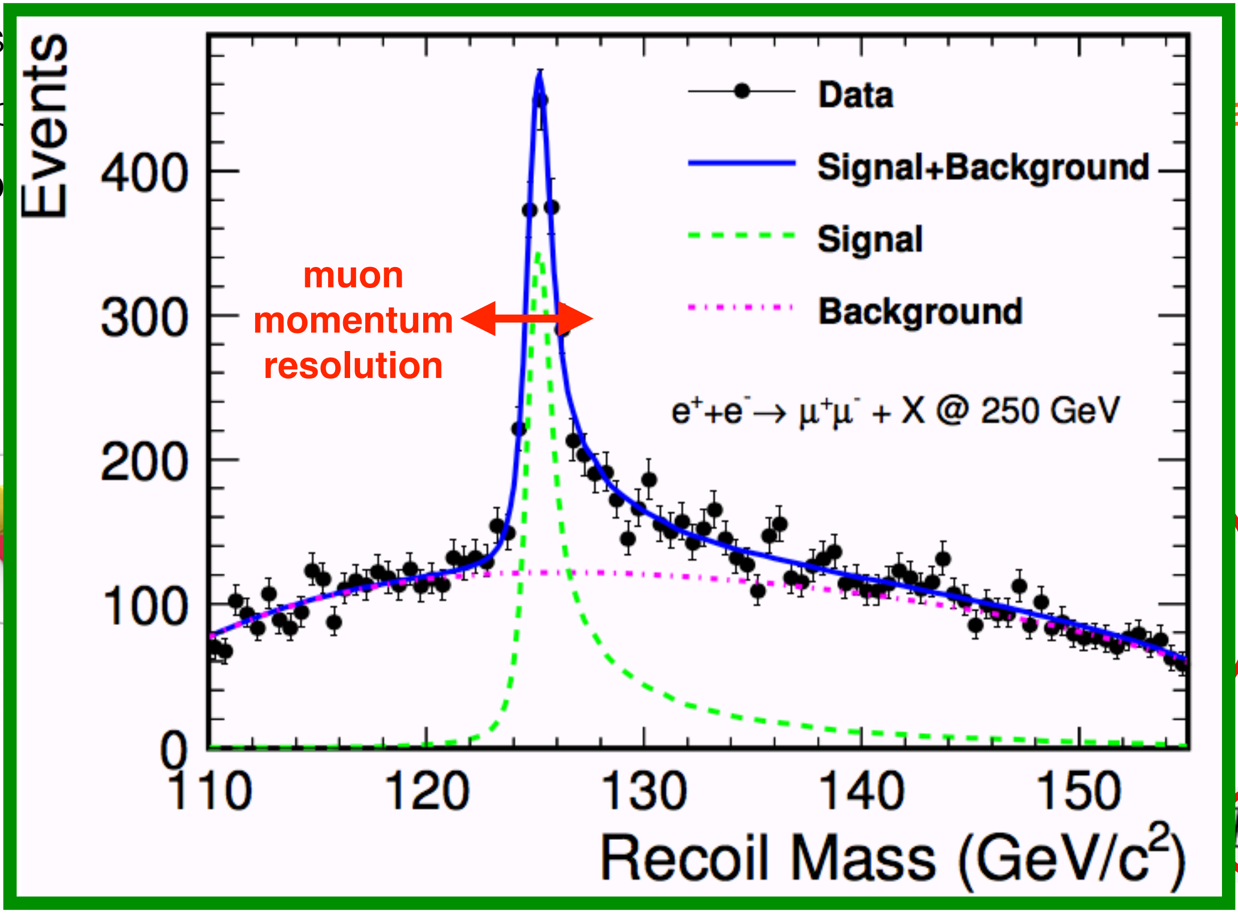

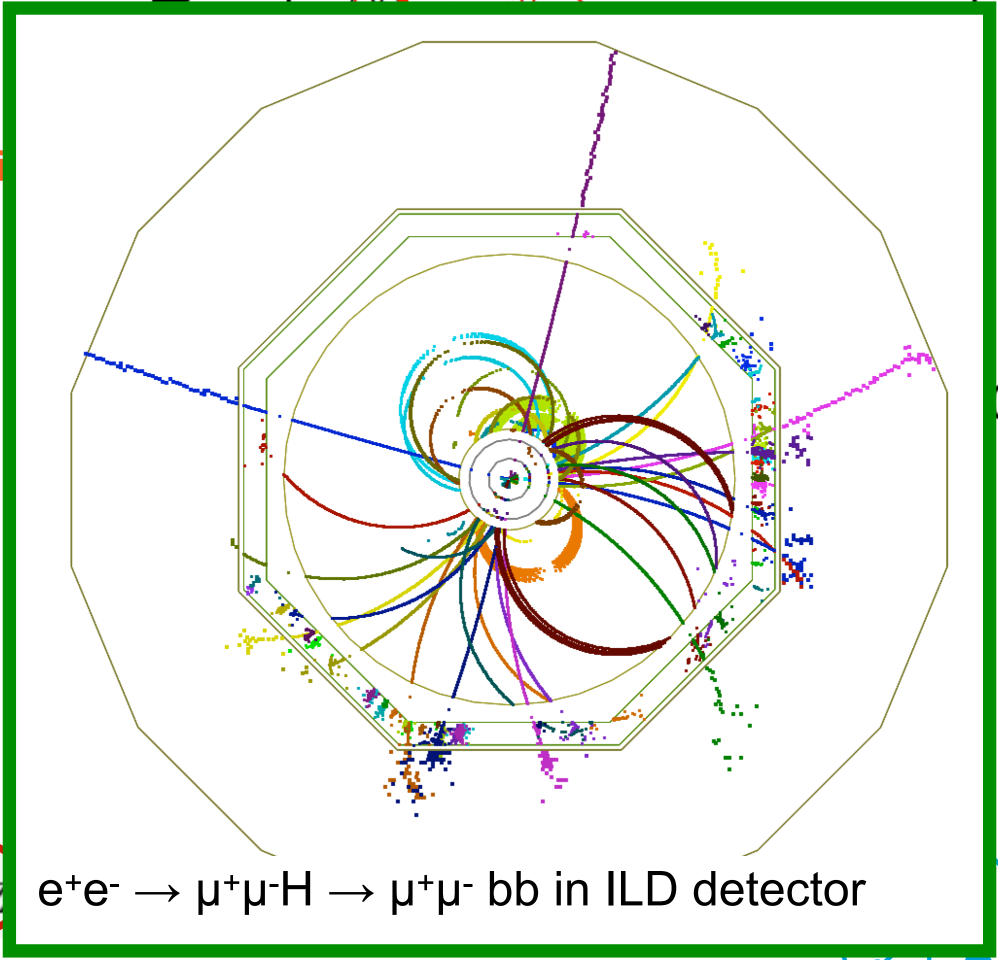

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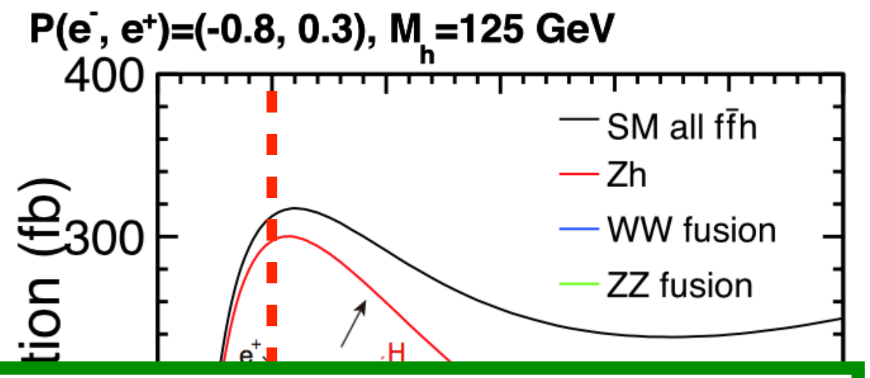

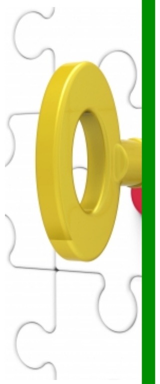

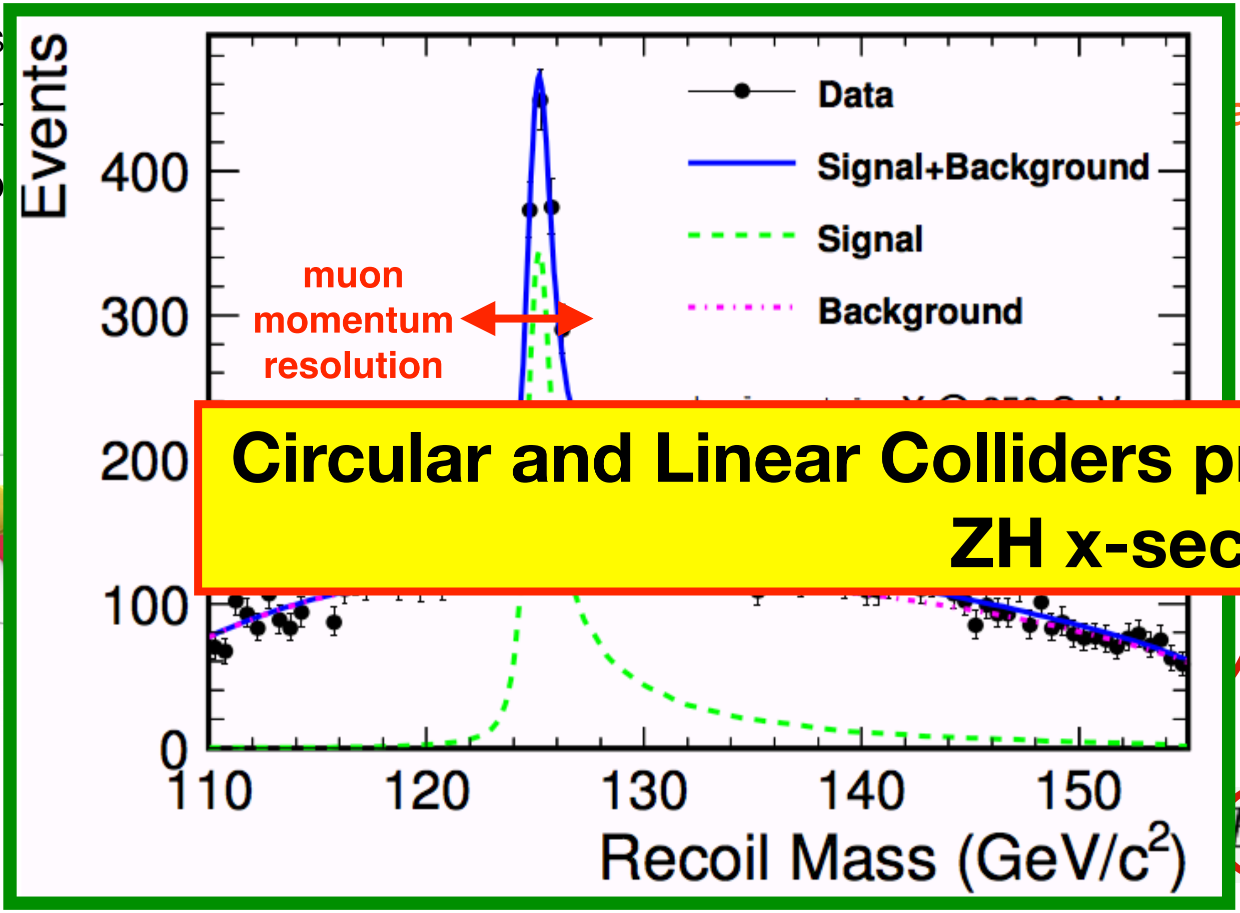

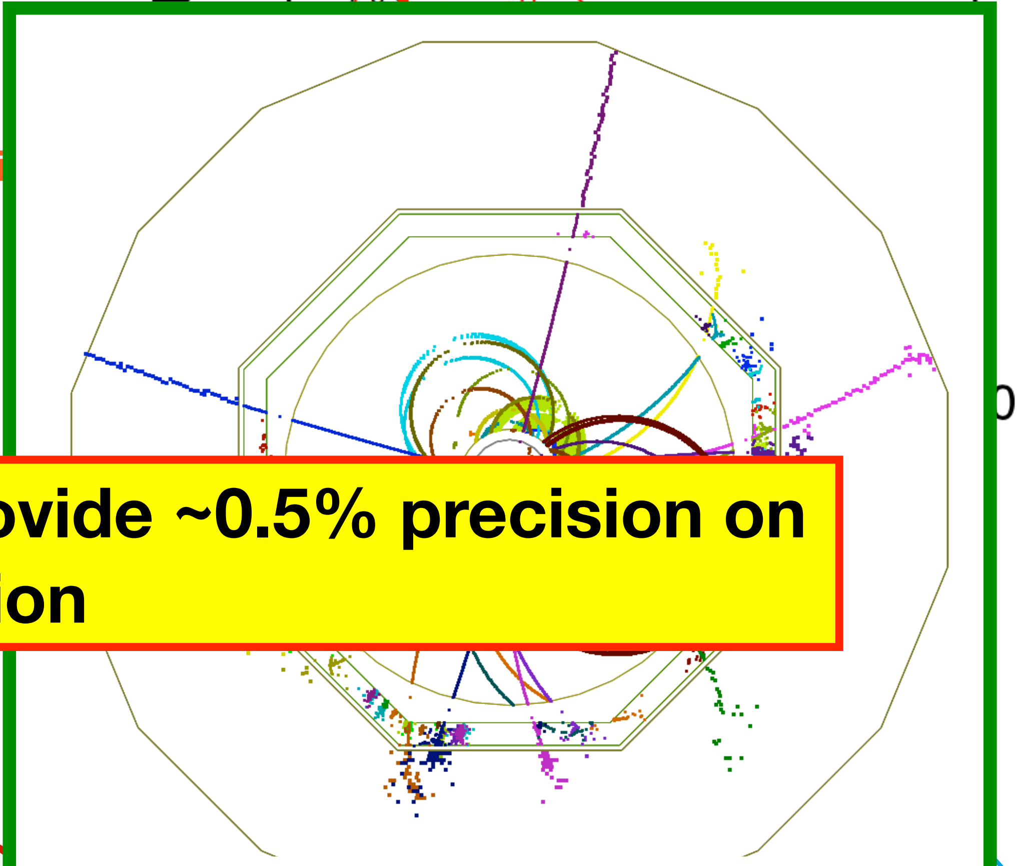

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Circular and Linear Colliders provide ~0.5% precision on ZH x-section

Theoretical Frameworks & Uncertainties

Some frequently used examples

1. **kappa-framework**: Higgs couplings are modified by numerical factors
   - e.g. $\Gamma_{h\to bb} \to \kappa_b^2 \cdot \Gamma^{SM}_{h\to bb}$
   - **Not fully consistent** (cannot apply to different energies)
2. **Effective Field Theories (EFTs)** (e.g. SMEFT)
   - (Some) **model-independence**
   - **Which operators** to include and where to **truncate** the **EFT expansion**?
3. **UV-complete models** (e.g. 2HDM)
   - Very **vast model landscape**

Theory uncertainties in Standard Model (i.e. no BSM) as assumed in Briefing Book

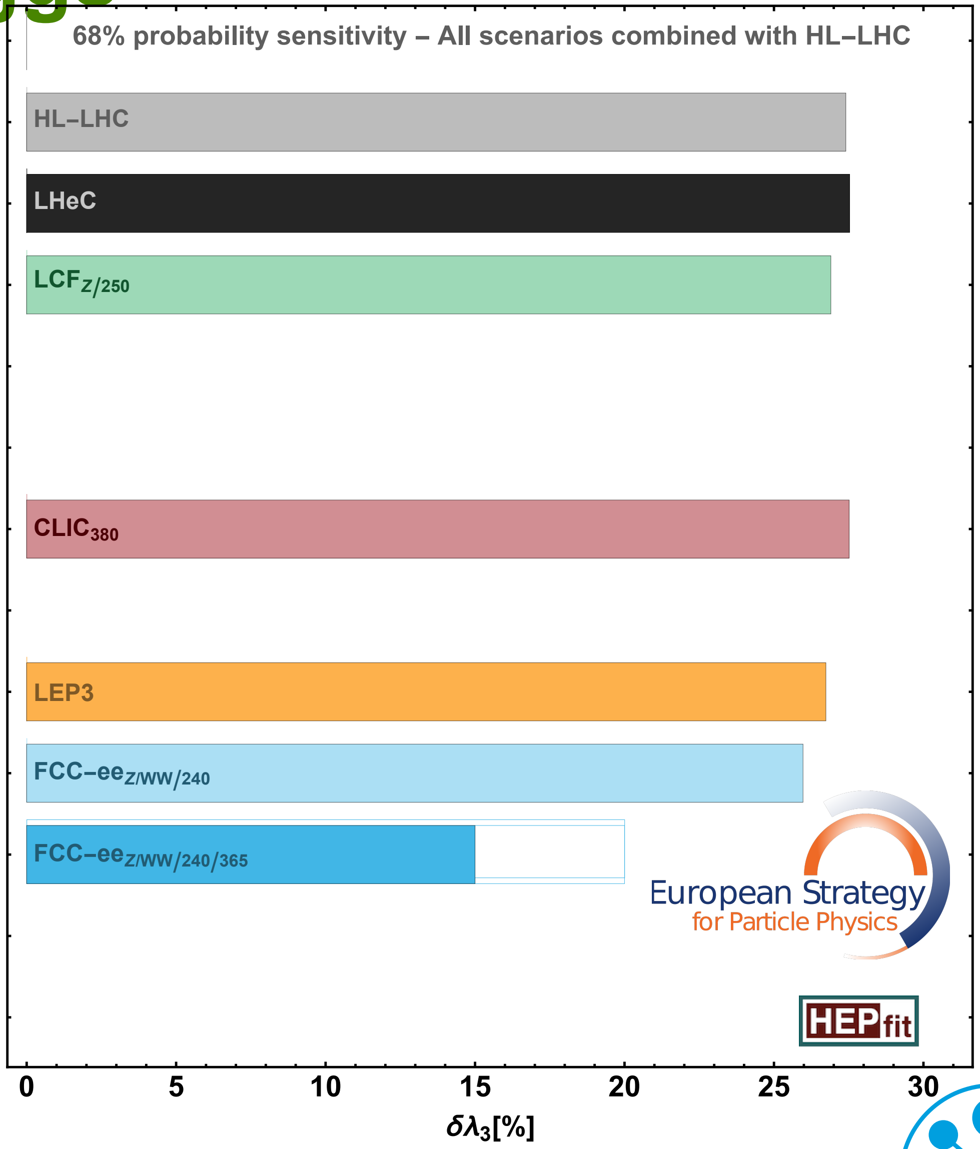
Table 3.3: Current and projected theory uncertainties (in percent) for the SM predictions of partial Higgs boson decay widths and production cross-sections. A dash indicates that there is no projection for this uncertainty and it will be considered negligible.

Process	Current	Conservative	Aggressive
$H \to bb/cc$ (%)	< 0.4	0.2	0.1
$H \to \tau\tau/\mu\mu$ (%)	< 0.3	< 0.1	—
$H \to WW^*/ZZ^*$ (%)	0.5	0.3	—
$H \to gg$ (%)	3.2	1.0	0.5
$H \to \gamma\gamma$ (%)	< 1.0	< 1.0	0.4
$H \to Z\gamma$ (%)	1.5	1.5	—
$e^+e^- \to ZH$ (%)	0.3	< 0.1	—
$e^+e^- \to \nu\bar{\nu}H$ (%)	~ 1	~ 0.1	—

Trilinear Coupling from single-Higgs

From Briefing Book

- Based on dim-6 U(2)^5-symmetric SMEFT
- Using the *aggressive* theory uncertainties, e.g. zero uncertainty on the ee->ZH cross-section predictions
- Single-energy e+e– colliders offer no improvement on lambda3 wrt HL-LHC
- Two-energy e+e– colliders add information
- Quantitative gain highly-dependent on chosen model, theory uncertainties etc



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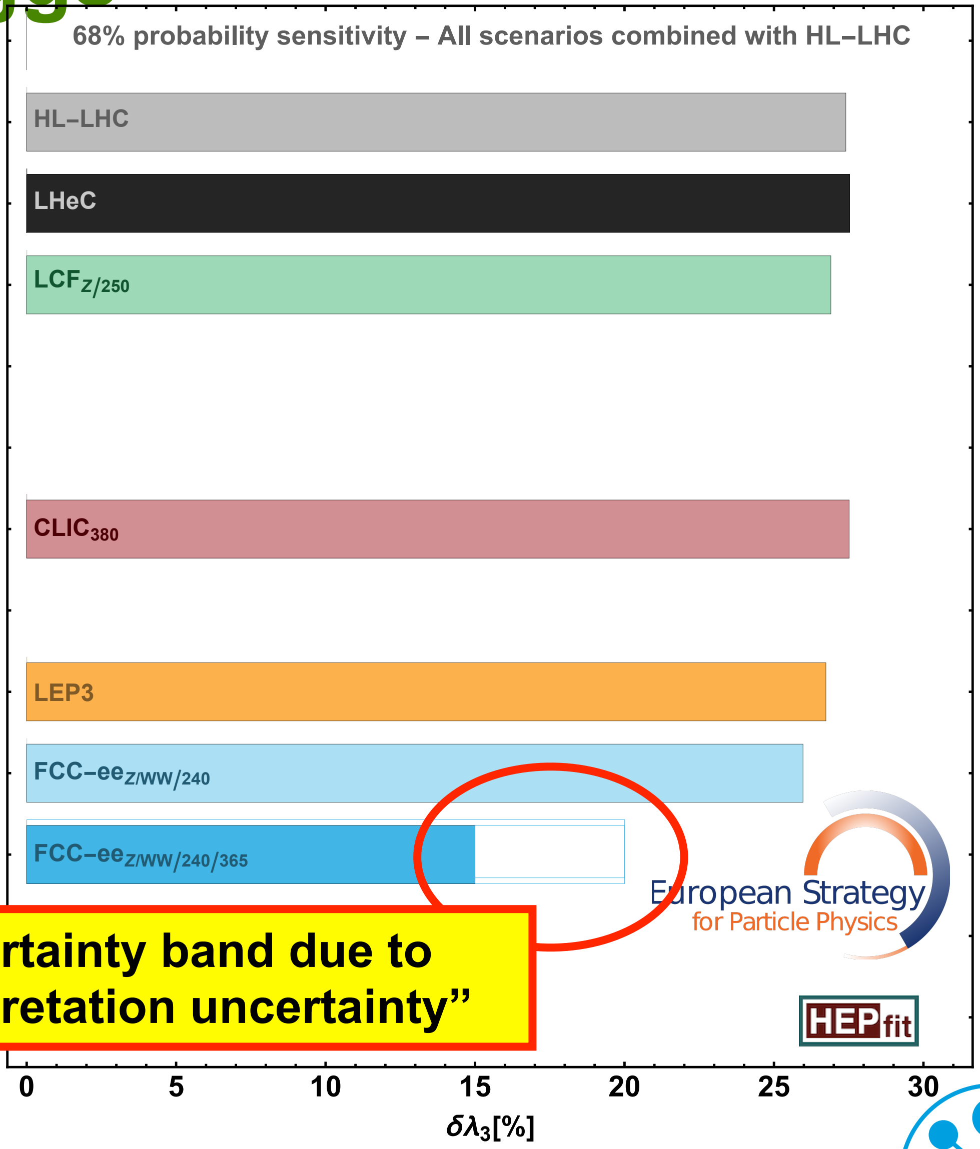

Uncertainty band due to "interpretation uncertainty"

Just one aspect to give you a flavour…

Where / how to truncate your SMEFT expression for sigma(ZH)?

$$\frac{\sigma_{Zh}^{\kappa_\lambda}}{\sigma_{Zh}^{\kappa_\lambda=1}} = \frac{1-\delta Z_h}{1-\kappa_\lambda^2 \delta Z_h} \frac{1+\kappa_\lambda C_1}{1+C_1}$$

Expanding in powers of $\boldsymbol{\delta\kappa_\lambda \equiv (\kappa_\lambda - 1) = \mathcal{O}(1/\Lambda_{\text{NP}}^2)}$ gives different possible expressions:

- No $\mathcal{O}(1/\Lambda_{\text{NP}}^4)$ contributions: expand up to $\mathcal{O}((\delta\kappa_\lambda)^1)$ terms
- Expansion up to $\mathcal{O}((\delta\kappa_\lambda)^2)$ terms
- Expansion up to $\mathcal{O}((\delta\kappa_\lambda)^2)$ terms, **excluding WFR/vertex** mixing ($\propto C1 \cdot \delta Z_h$) — implemented in **HEPfit**
- No loop corrections beyond 1L: **no resummation** of δZ_h contribution
- Including $\mathcal{O}((\delta\kappa_\lambda)^3)$ terms
- Use **full** expression

Choice of expression → theoretical uncertainty!

Just one aspect to give you a flavour…

Murillo Vellasco

Where / how to truncate your SMEFT expression for si

$$\frac{\sigma_{Zh}^{\kappa_\lambda}}{\sigma_{Zh}^{\kappa_\lambda=1}} = \frac{1-\delta Z_h}{1-\kappa_\lambda^2 \delta Z_h} \frac{1+\kappa_\lambda \cdots}{1+C \cdots}$$

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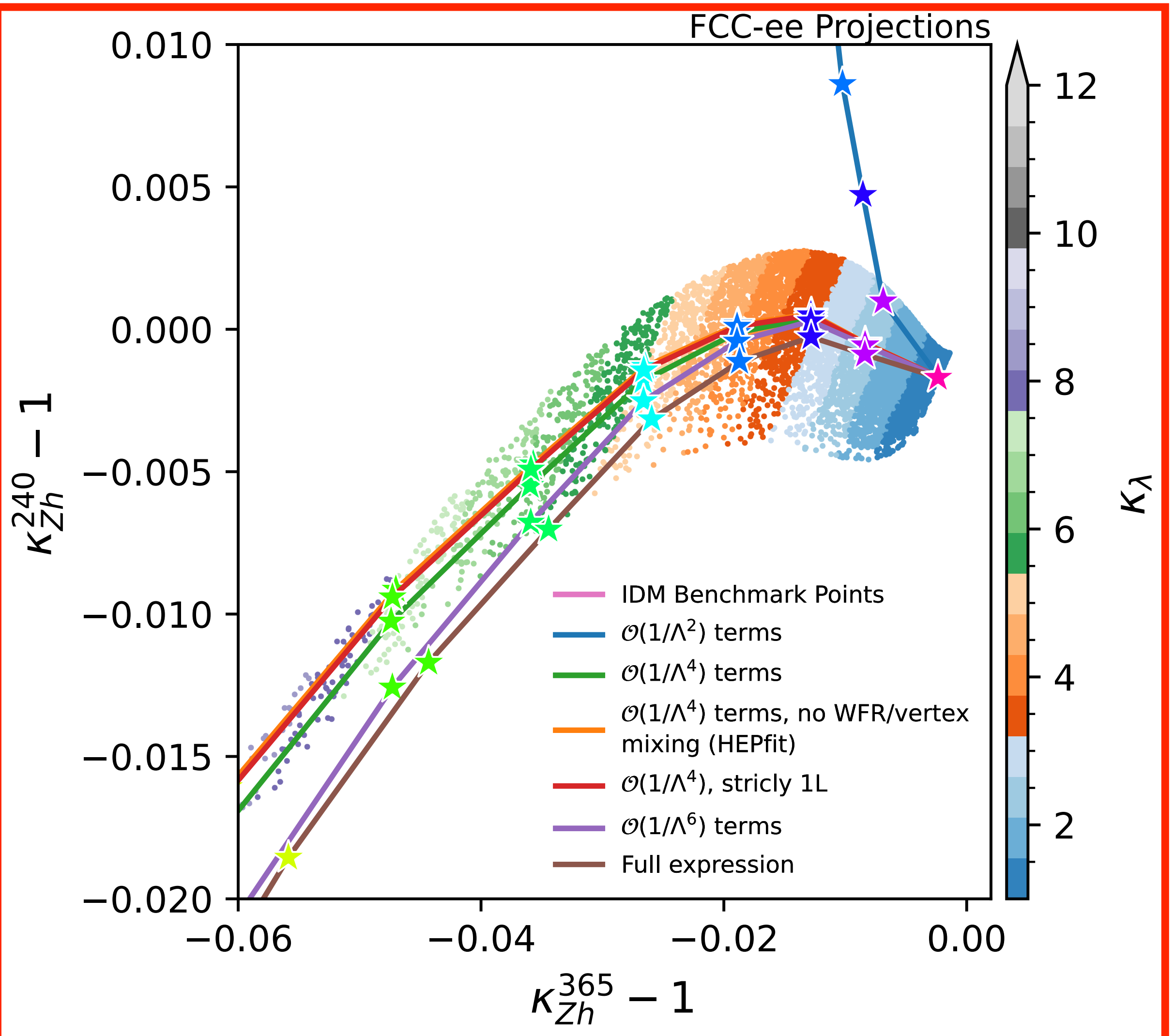

where $(\kappa_{Zh})^2 := \frac{\sigma_{Zh}}{\sigma_{Zh}^{SM}}$

Choice of expression → theoretical

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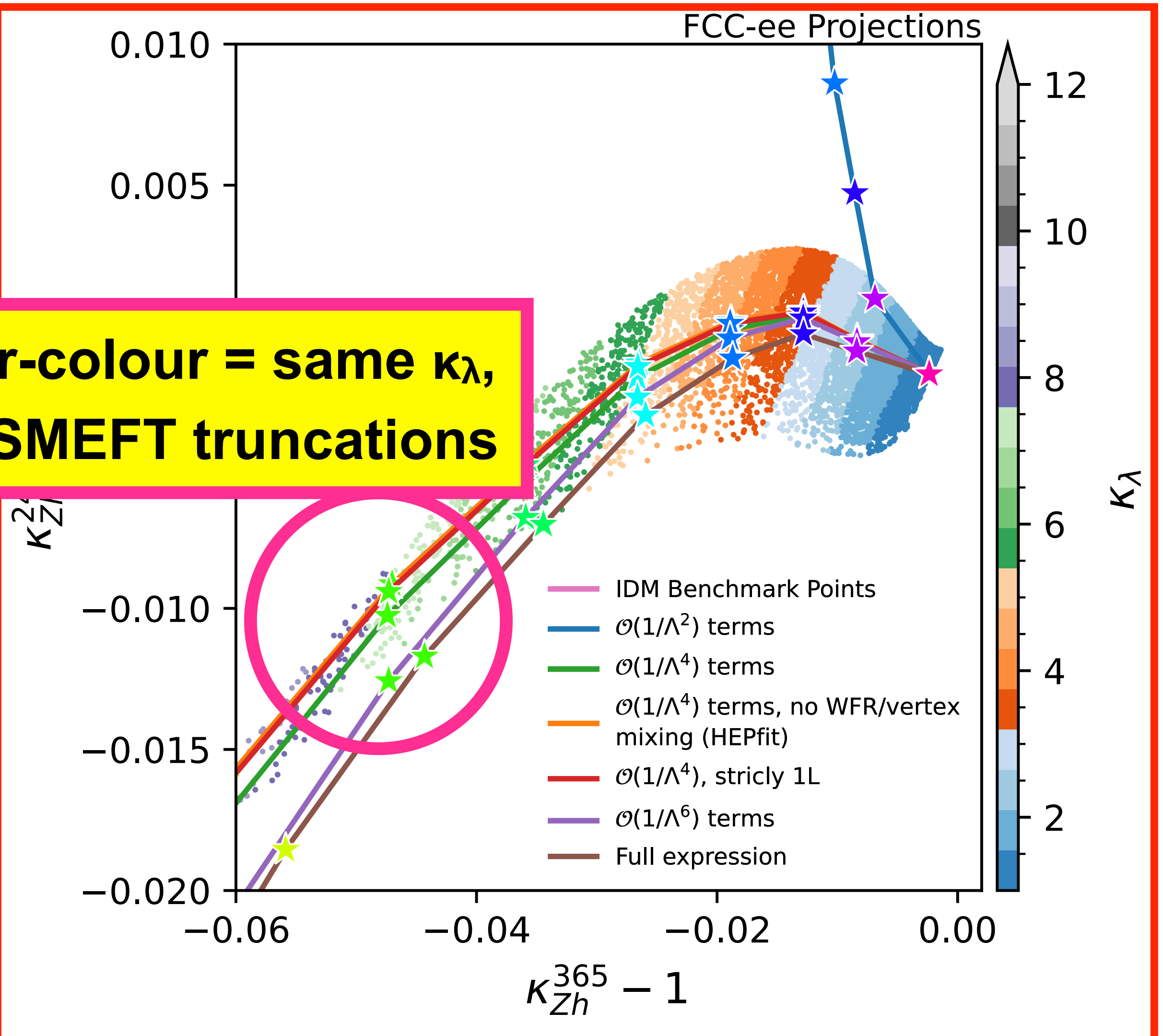
Same star-colour = same κλ, different SMEFT truncations



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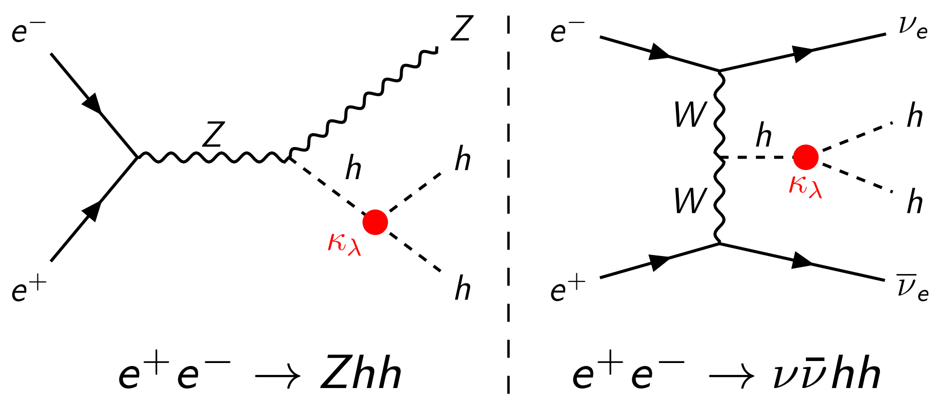
Choice of expression → theoretical u

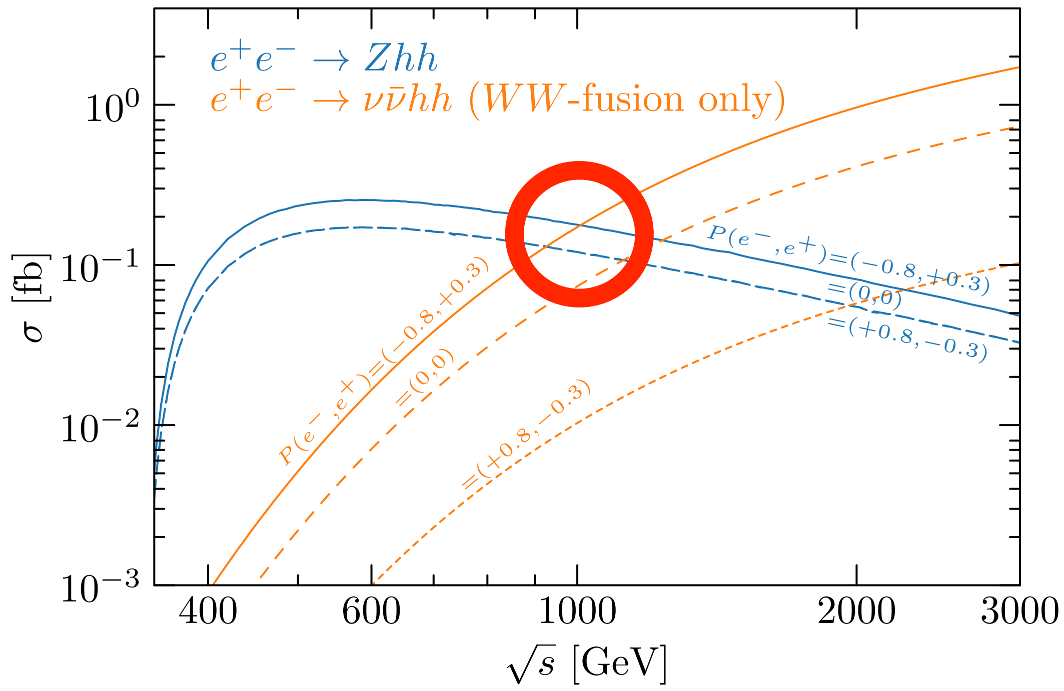
Higgs Pair Production

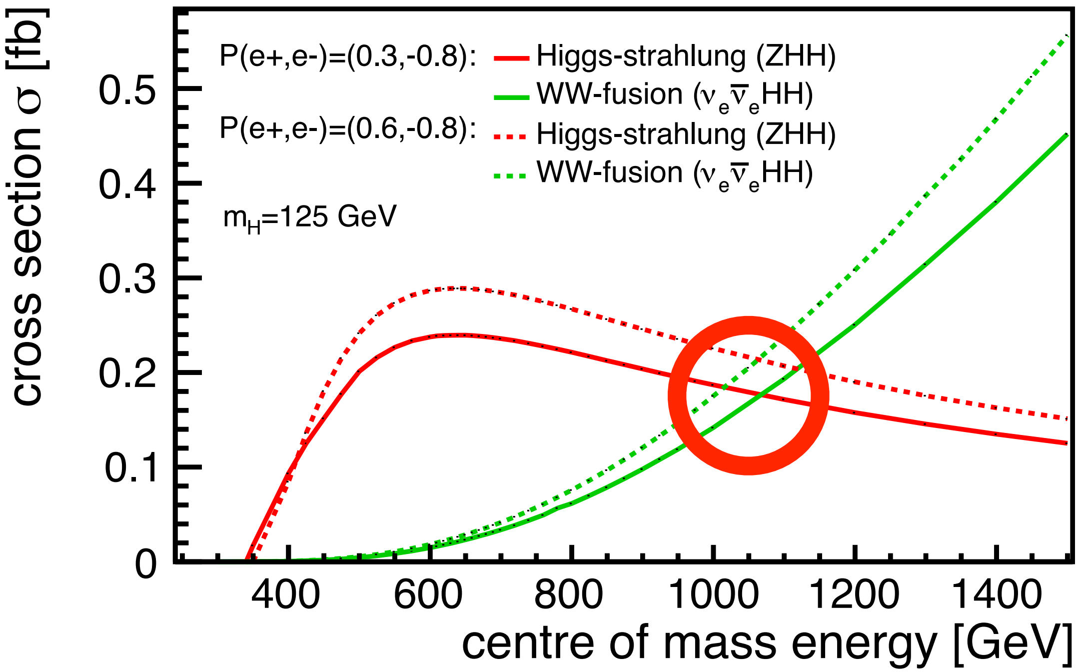
Higgs Pair Production in e+e-

Cross-sections

two main production modes: double Higgs-strahlung “ZHH” and WW fusion “vvHH”:





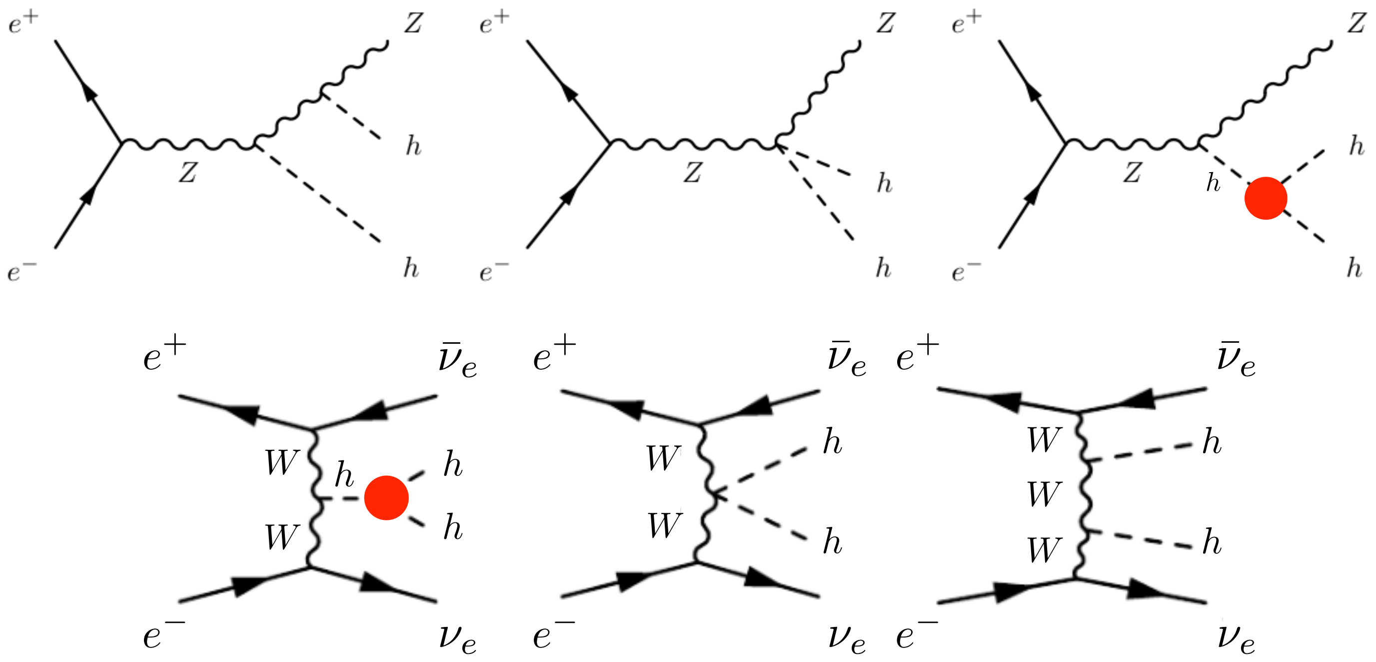


ZHH and vvHH have similar P=(-80%,+30%) cross section at 1 TeV : 0.18 fb

Feynman-Diagrams and self-coupling dependence

Based on total cross-sections

- Interference of diagrams with / without triple Higgs vertex ●
  => "total cross-section sensitivity factor" k:= (δλ/λ)/(δσ/σ) != 0.5
- "the smaller the better"
- k depends on: process, E_{CM} ***and the value of λ***



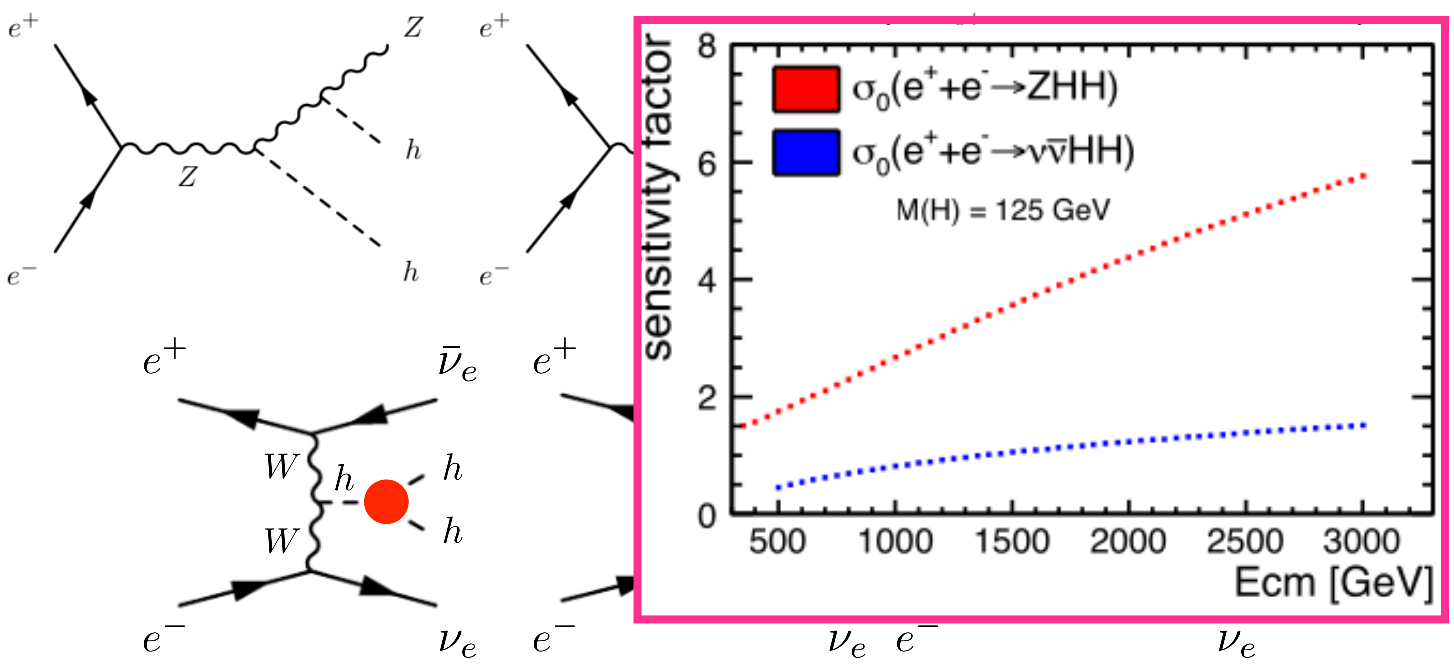
effect for $\delta\sigma/\sigma$ = 10% as *arbitrary* example

	500 GeV ZHH	1 TeV vvHH	1.4 TeV vvHH
$\delta\sigma/\sigma$	**10 %**	**10 %**	**10 %**
k$_{SM}$	1.64	0.76	1.22
$\delta\lambda/\lambda\,\|_{SM}$	16.2 %	7.6 %	12.2 %

Feynman-Diagrams and self-coupling dependence

Based on total cross-sections

- Interference of diagrams with / without triple Higgs vertex
  => "total cross-section sensitivity factor" k:= $(\delta\lambda/\lambda)/(\delta\sigma/\sigma)$!= 0.5
- "the smaller the better"
- k depends on: process, E_{CM} ***and the value of λ***



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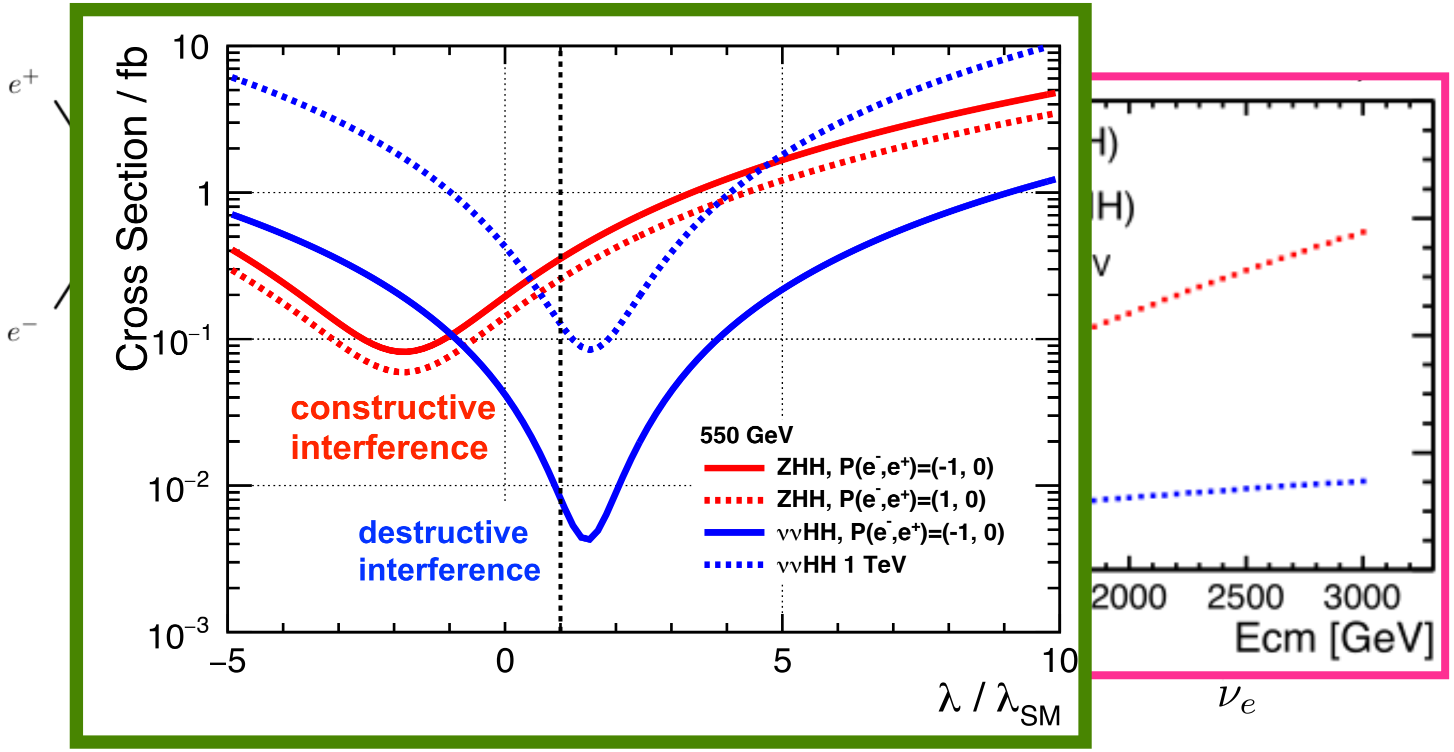

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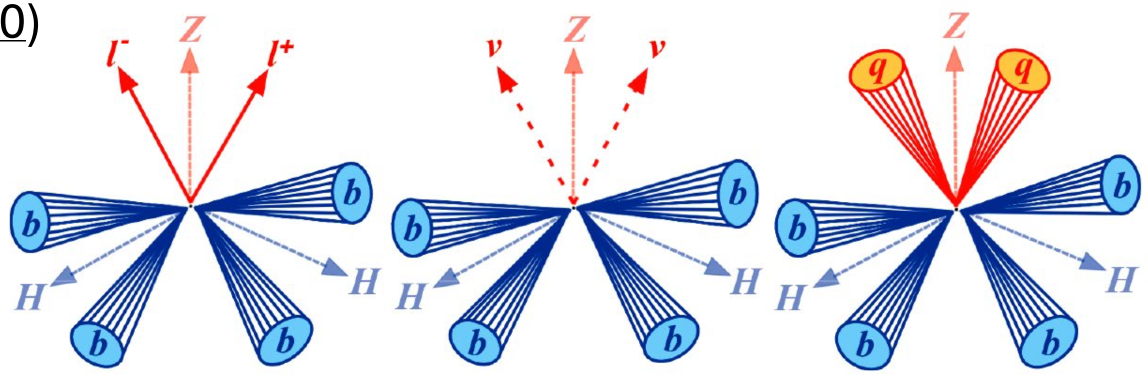
Higgs Pairs at 500/550 GeV

The previous ZHH Analysis

ILC500, Claude Duerig (UHH), 2014-2016

- extensive projections at ILC500 (DESY-Thesis-16-027)
  - based on ILD detector concept (DBD2013, IDR2020) and *fully simulated* event samples
  - 17 background and 3 signal channels considered
  - multivariate (MVA) tools for multiple steps
    e.g. lepton and flavor tagging, background rejection etc.
  - event counting weighted by m_{HH}^2
    for further sensitivity enhancement



Lepton, neutrino and hadron channel of the signal process ZHH.
From [Du16]

- precision reach after running 4ab^{-1} at 500 GeV $\left(\text{HH} \rightarrow \text{b}\bar{\text{b}}\text{b}\bar{\text{b}} + \text{HH} \rightarrow \text{b}\bar{\text{b}}\text{W}^{\pm}\text{W}^{\mp}\right)$

$$\Delta\sigma_{\text{ZHH}}/\sigma_{\text{ZHH}} = 16.8\%$$

$$\Delta\lambda_{\text{SM}}/\lambda_{\text{SM}} = 26.6\% \quad (10\% \text{ with additional upgrade to 1 TeV})$$

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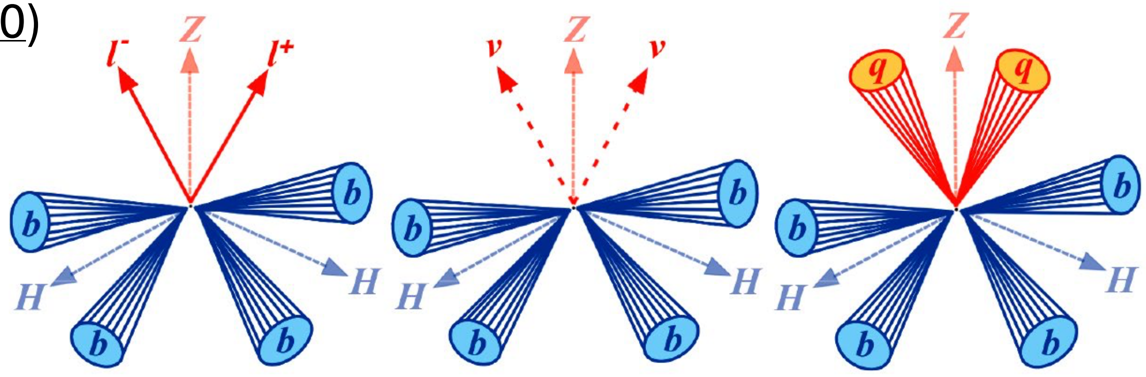

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8 σ observation of ee -> ZHH

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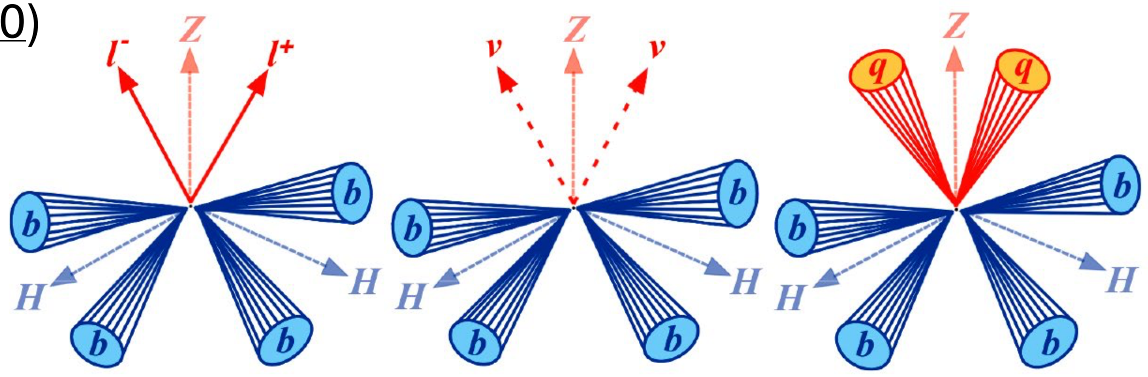

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$\Delta\lambda_{\text{SM}}/\lambda_{\text{SM}} = 26.6\%$ (10% with additional upgrade to 1 TeV) **only 3.x σ observation of λ_{SM}**

Bottlenecks of the ZHH analysis

As identified during 2016 analysis and (relative) improvement impact

- jet pairing and jet misclustering: “perfect“ jet clustering → 40% improvement
  improve di-jet mass resolution
- removal of $\gamma\gamma$ overlay: 15% improvement expected
  also: improve ISR reconstruction
- flavor tagging: 11% improvement expected from 5% eff. increase with newer LCFIPlus
  important as $H \rightarrow b\bar{b}$ is the dominant Higgs decay channel
- adding $Z \rightarrow \tau\tau$ 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)

Expected relative improvements from DESY-Thesis-16-027

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  include a yet
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  improvement
- separation of ZHH diagrams with/without the self-coupling
  would directly improve the sensitivity on λ (lower sensitivity factor)

conclusion in 2016:
if 25% (rel.) improvement out of (a combination) of these
=> 5 σ discovery of λ_{SM}

Expected relative improvements from DESY-Thesis-16-027

Towards a full re-analysis: ILD public note for Briefing Book

B.Bliewert, J.Torndal et al, September 2025

- ECM = 550 GeV
- Detailed simulation of ILD detector concept (SGV & Geant4), few 100 million events
- Re-analysis of electron & muon channels
  - Flavour tag: particle transformer (parT) separating 11-classes
  - Kinematic fit with ErrorFlow (jet covariance matrices based on ParticleFlow)
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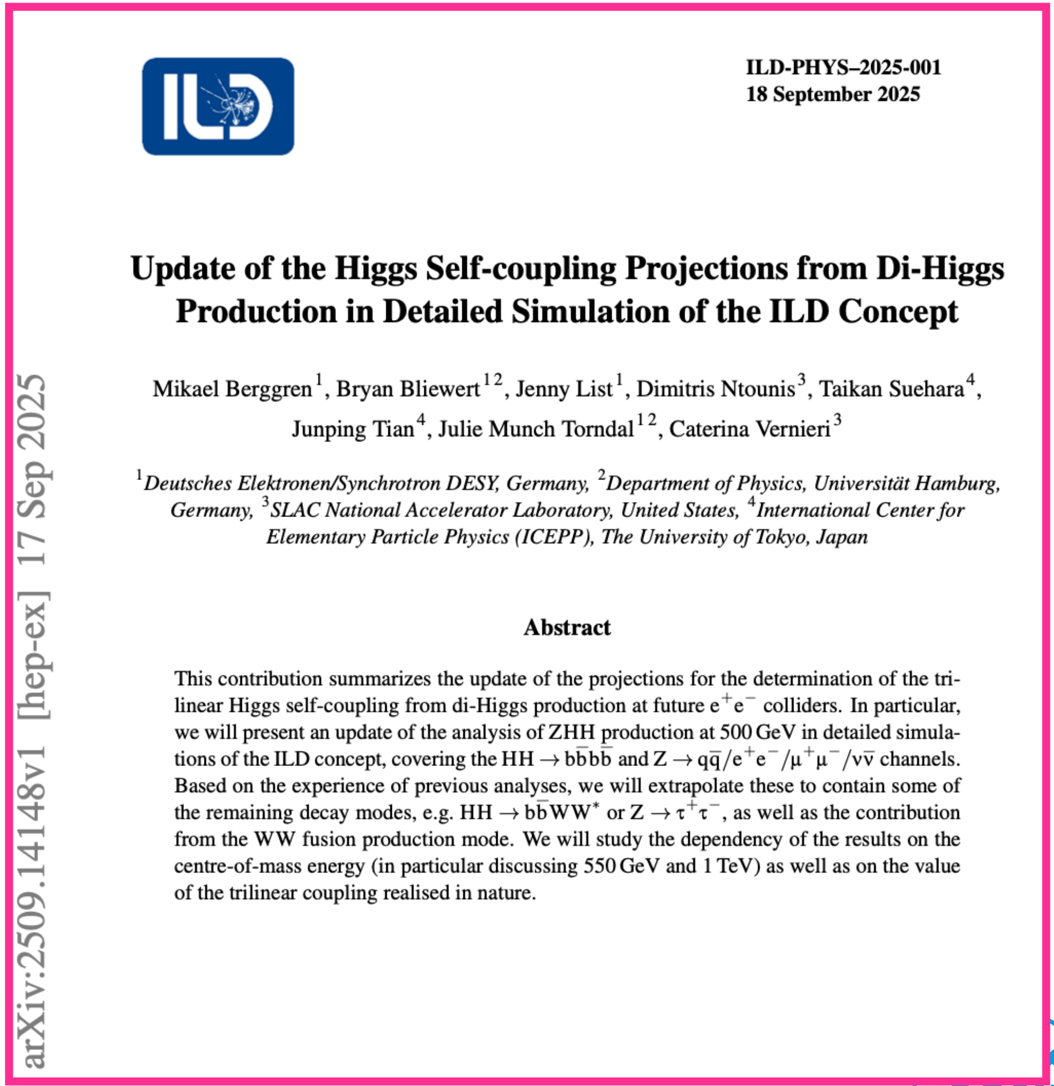
ILD-PHYS–2025-001
18 September 2025

Update of the Higgs Self-coupling Projections from Di-Higgs Production in Detailed Simulation of the ILD Concept

Mikael Berggren[1], Bryan Bliewert[1 2], Jenny List[1], Dimitris Ntounis[3], Taikan Suehara[4], Junping Tian[4], Julie Munch Torndal[1 2], Caterina Vernieri[3]

[1]*Deutsches Elektronen/Synchrotron DESY, Germany,* [2]*Department of Physics, Universität Hamburg, Germany,* [3]*SLAC National Accelerator Laboratory, United States,* [4]*International Center for Elementary Particle Physics (ICEPP), The University of Tokyo, Japan*

Abstract

This contribution summarizes the update of the projections for the determination of the trilinear Higgs self-coupling from di-Higgs production at future e^+e^- colliders. In particular, we will present an update of the analysis of ZHH production at 500 GeV in detailed simulations of the ILD concept, covering the $HH \to b\bar{b}b\bar{b}$ and $Z \to q\bar{q}/e^+e^-/\mu^+\mu^-/\nu\bar{\nu}$ channels. Based on the experience of previous analyses, we will extrapolate these to contain some of the remaining decay modes, e.g. $HH \to b\bar{b}WW^*$ or $Z \to \tau^+\tau^-$, as well as the contribution from the WW fusion production mode. We will study the dependency of the results on the centre-of-mass energy (in particular discussing 550 GeV and 1 TeV) as well as on the value of the trilinear coupling realised in nature.

arXiv:2509.14148v1 [hep-ex] 17 Sep 2025

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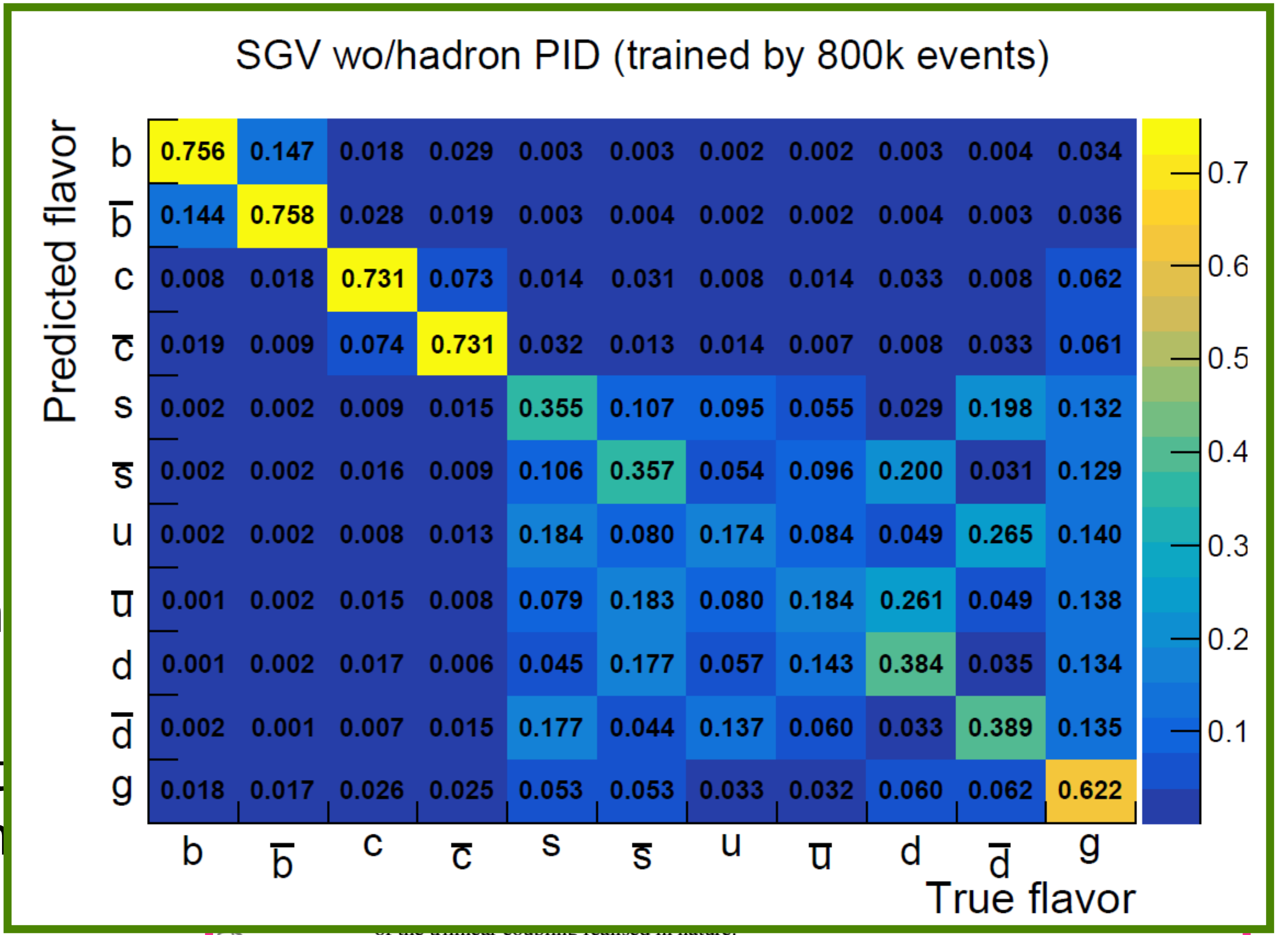

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B.Bliewert, J.Torndal et al, September 2025

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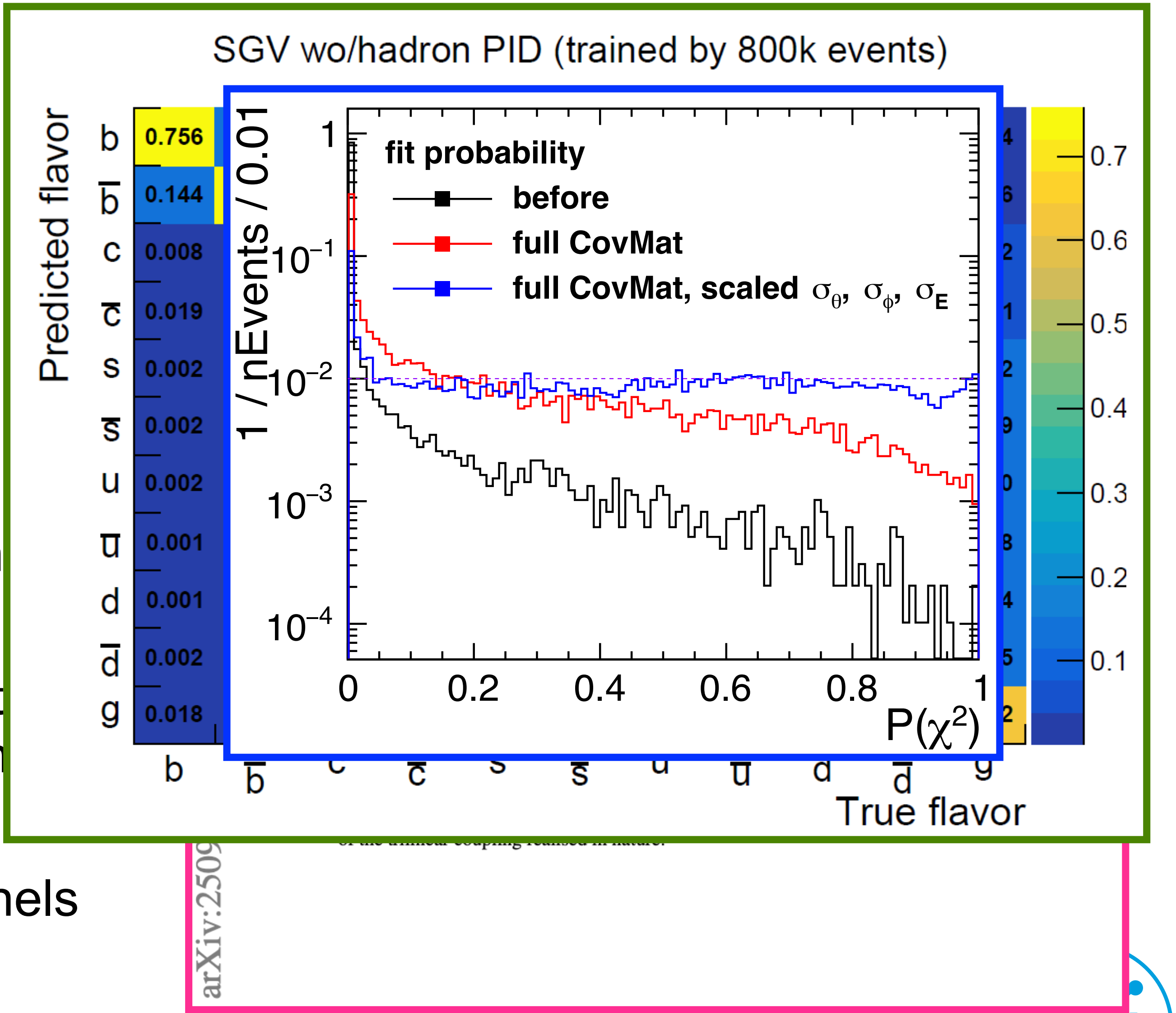

Towards a full re-analysis: ILD public note for Briefing Book

B.Bliewert, J.Torndal et al, September 2025

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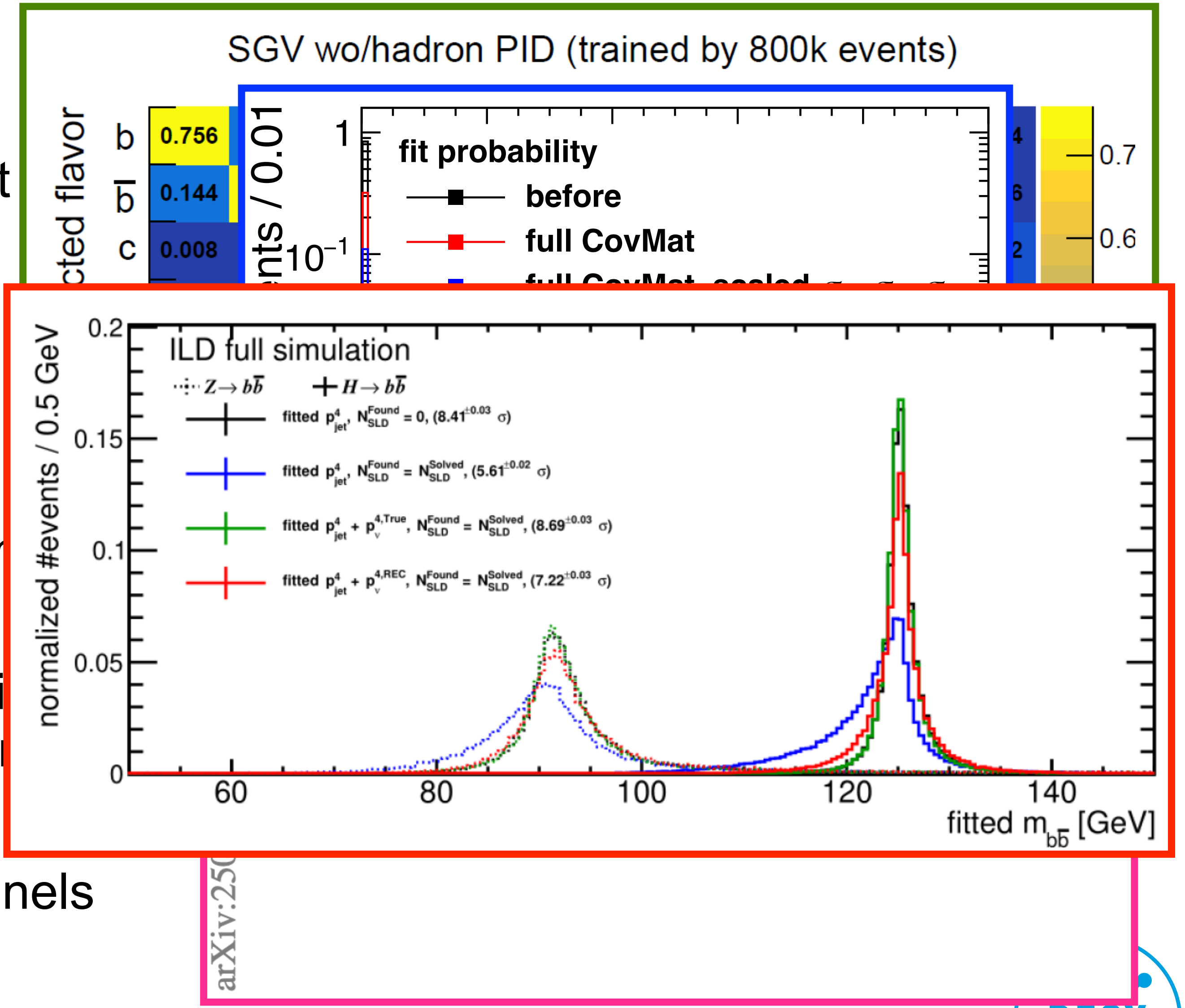

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  - k… r…
  - i… c… b…
- Extr…
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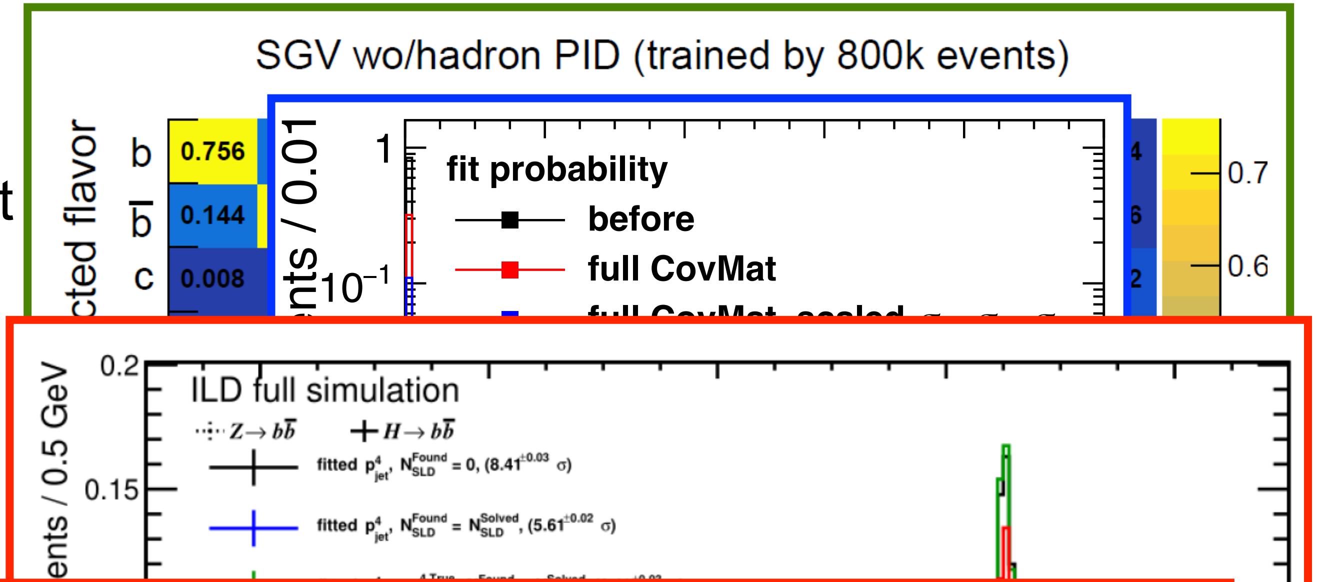
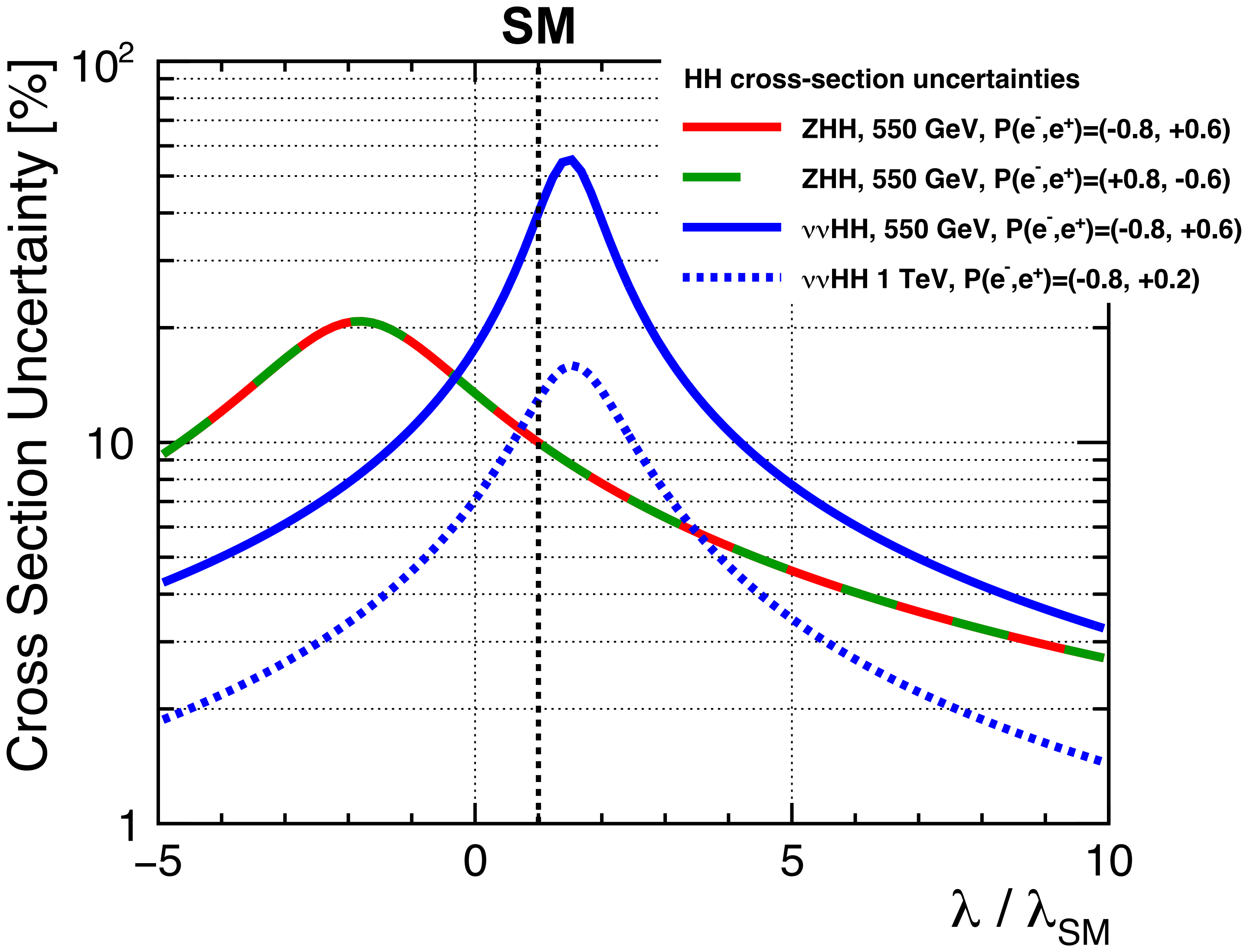


E.g. S/sqrt(S+B) in electron channel, 2ab-1 P(e-,e+)=(-80%,+30%):

- 2016 analysis: **0.84**
- Extrapolation 2024/5: **1.15 => Briefing Book LCF results based on this!**
- First shot at re-analysis 2025: **1.23**
- **Hot of the press May 2026**, multi-class ML selection: **1.75**
  => all on this in talk by Julie @ QU day!

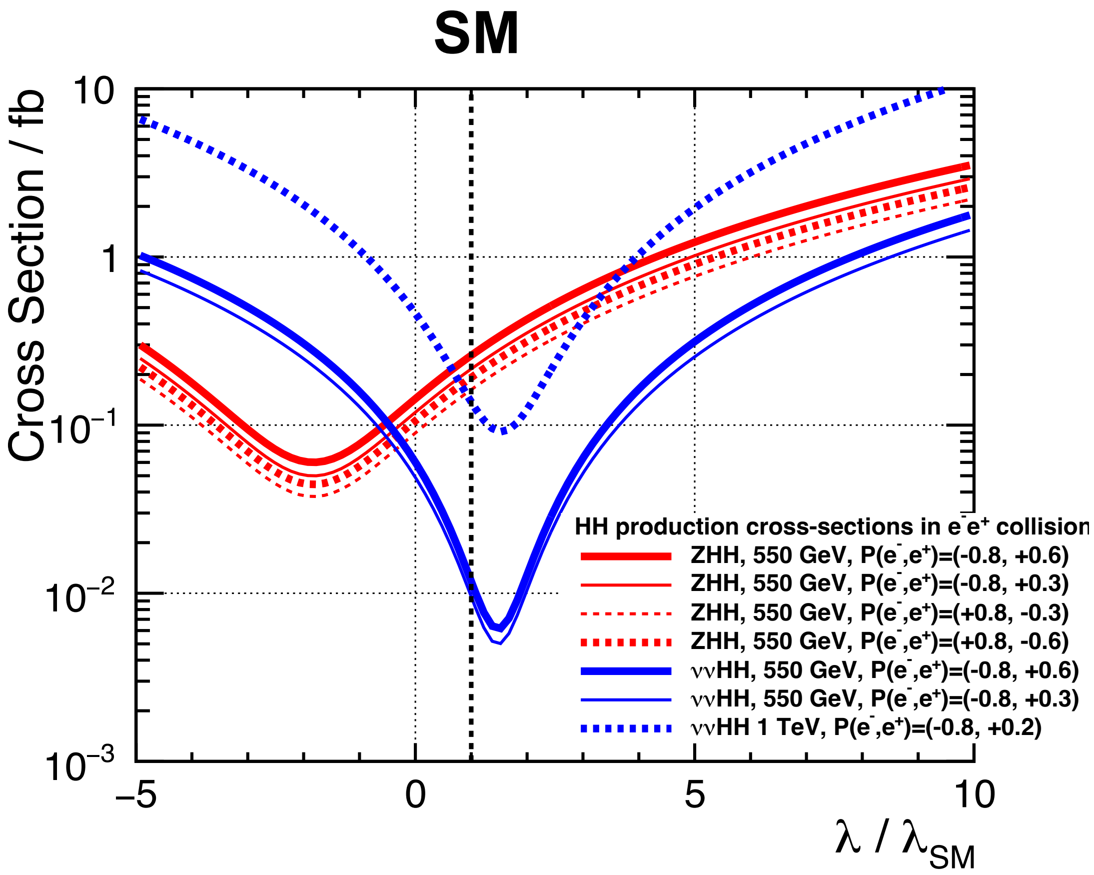
Di-Higgs cross-section precision

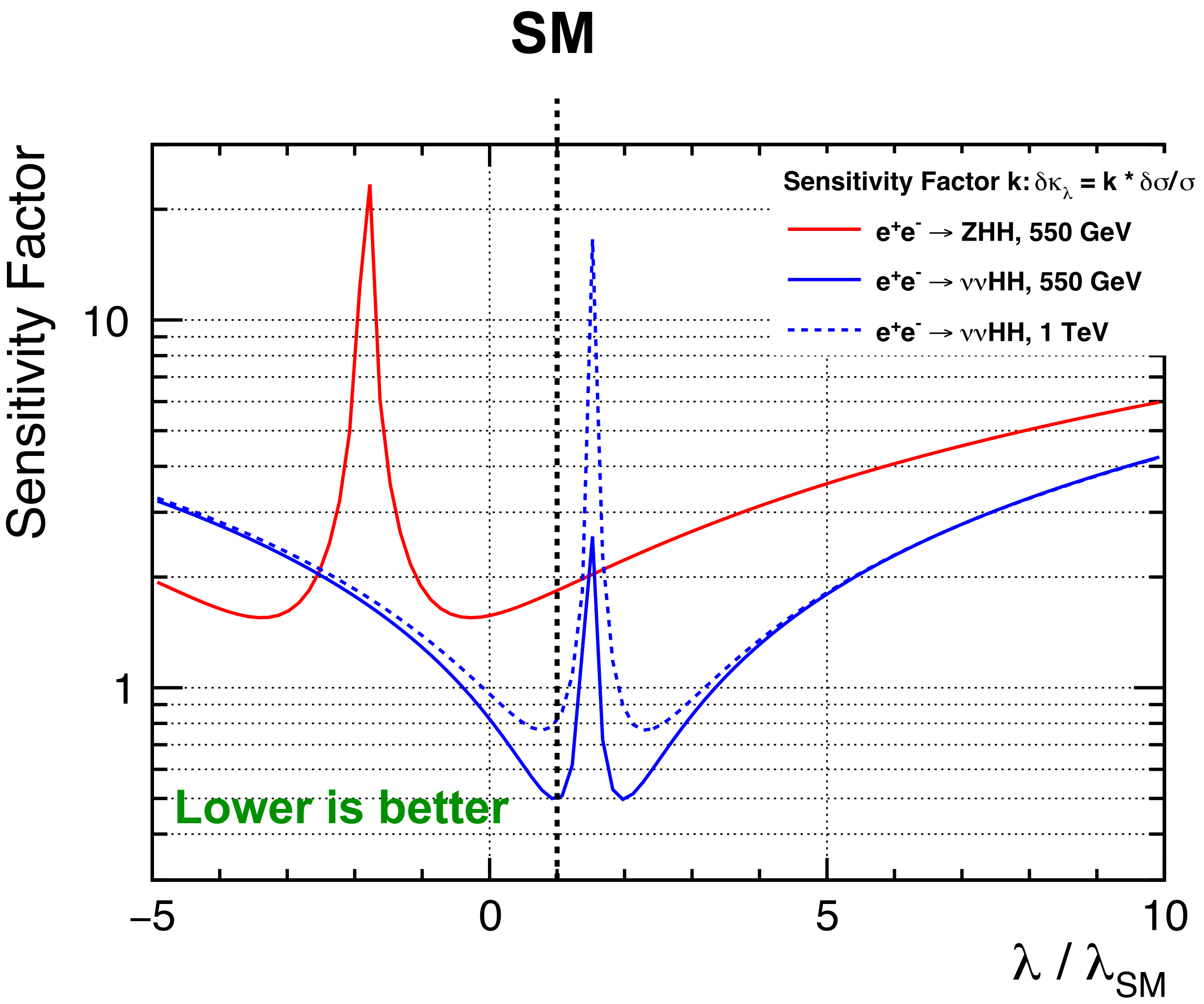
Input for Briefing Book fits



From total cross-section to κλ

Input for Briefing Book fits



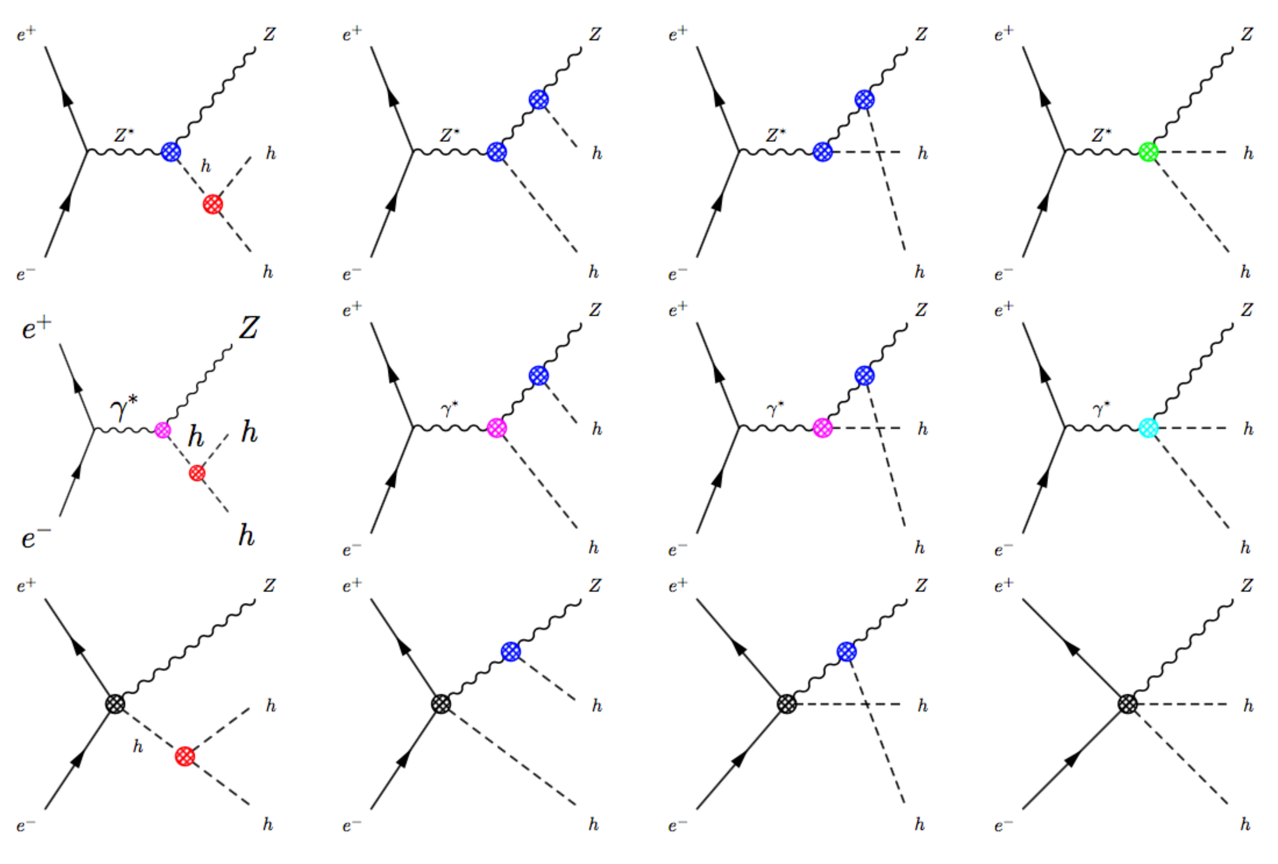


SMEFT extraction of λ from ZHH cross-section

Phys.Rev.D 97 (2018) 5, 053004

- **Is the 1-parameter extraction via “sensitivity factor” valid in dim6 SMEFT ?**
- full evaluation of ee->ZHH cross-section in dim6 SMEFT in 2018
- with
    - all σxBF measurements from ZH
    - and from ννH
    - and TGC constraints from WW
    - and polarised beams (A_{LR}(ZH))
- residual uncertainty on **λ** from other SMEFT operators **=5%**

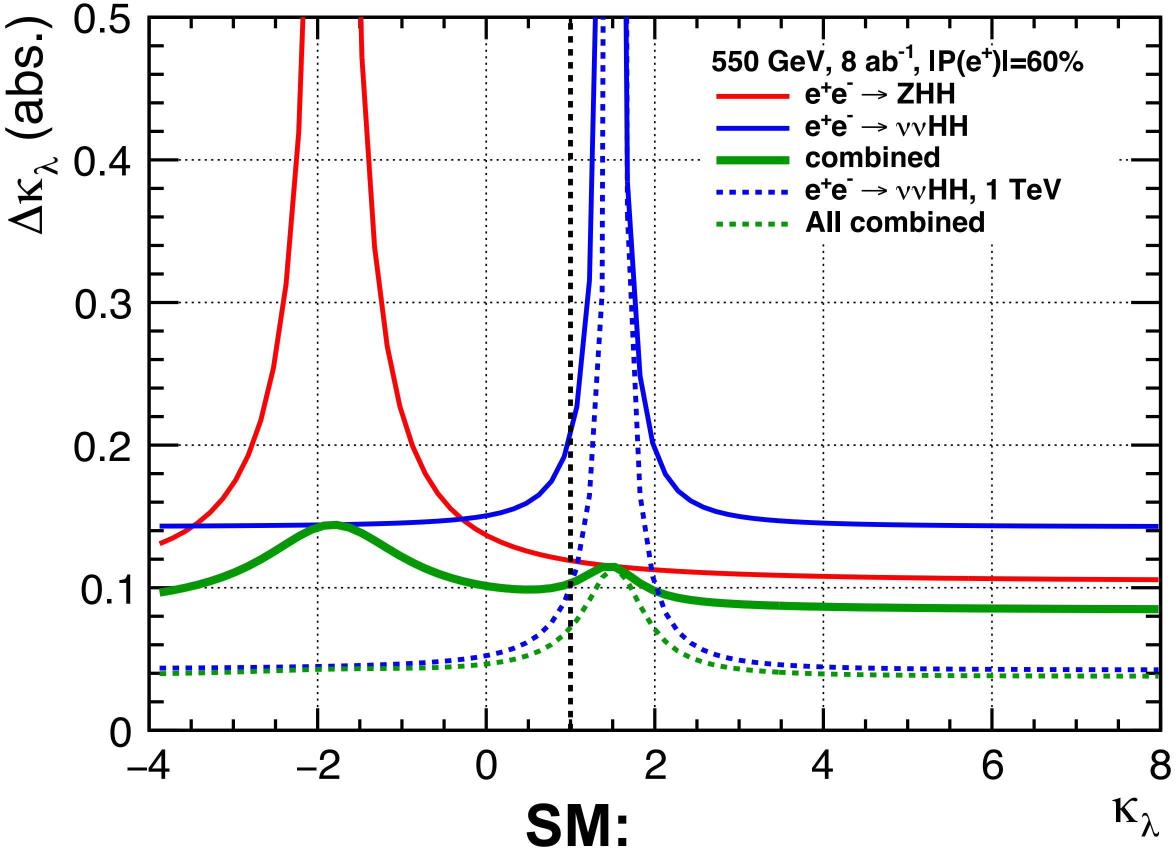
  (using ~2016 single Higgs projections)



- **needs to be considered when δλ/λ approaches 10%**
- afaik analogous study not yet done for ννH (VBF)

Self-coupling Projections

LCF & Briefing Book



SM:

LCF550 11%

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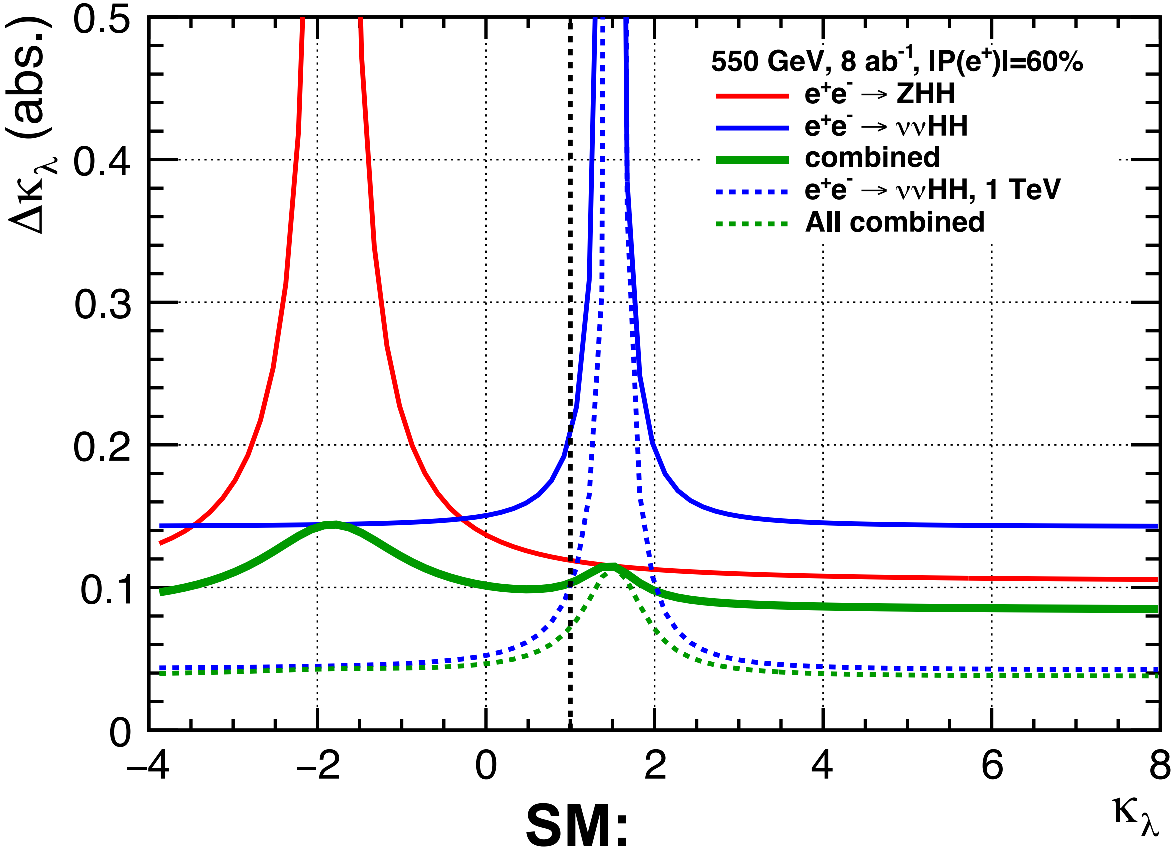

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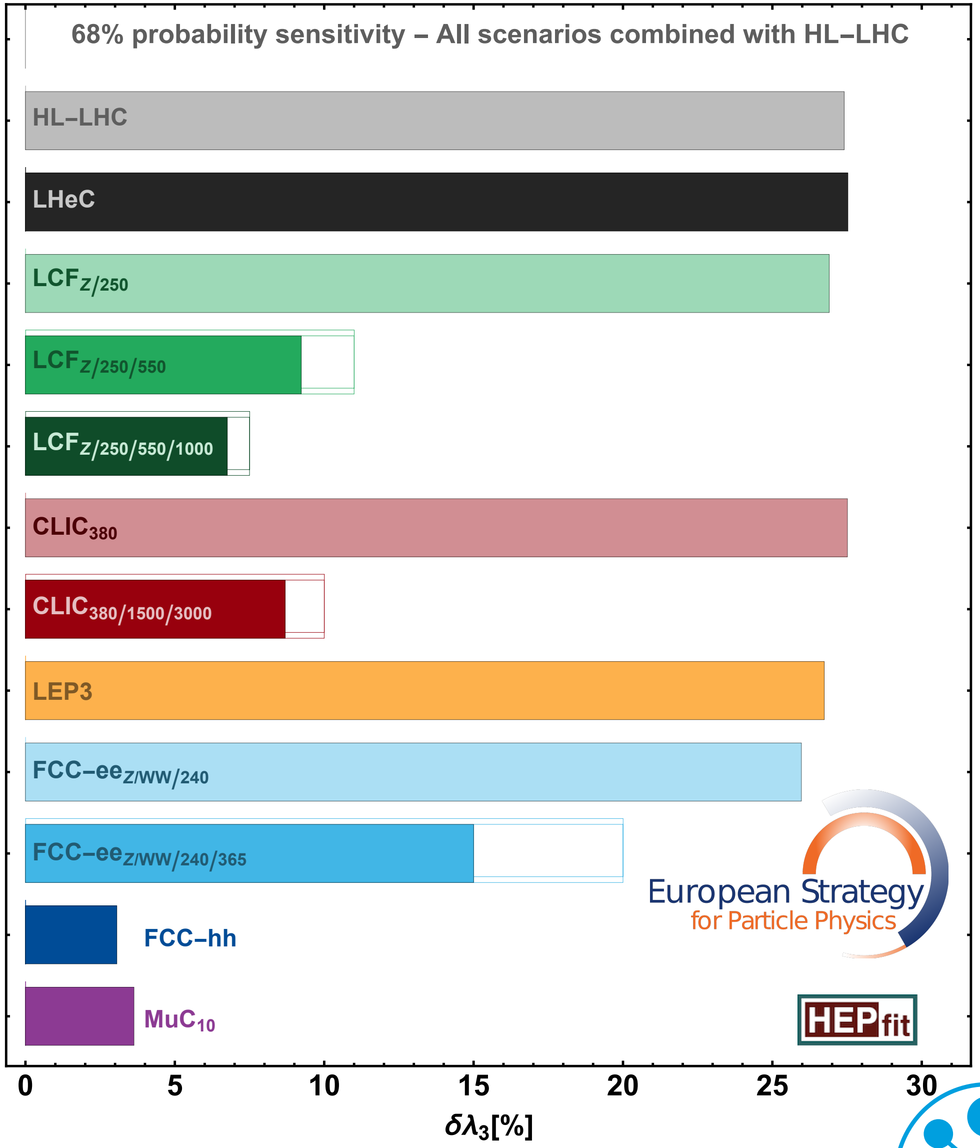

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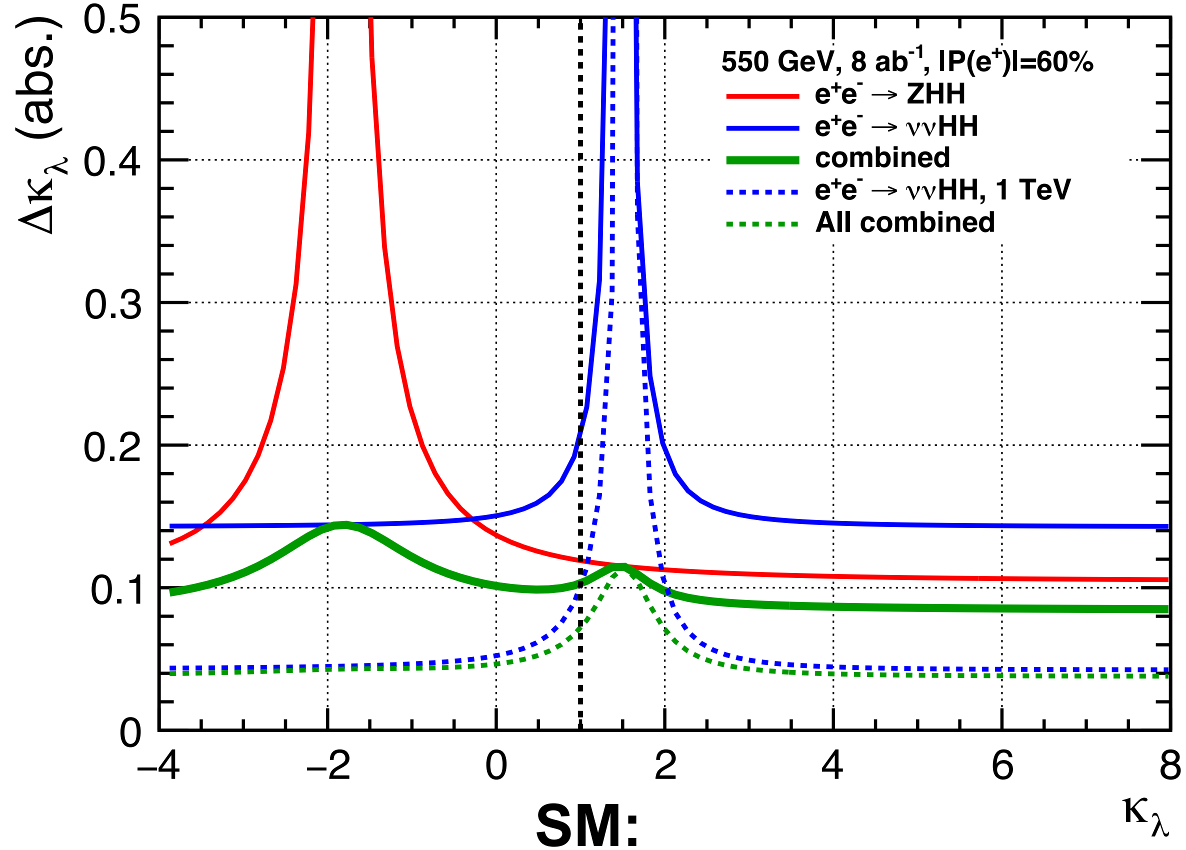

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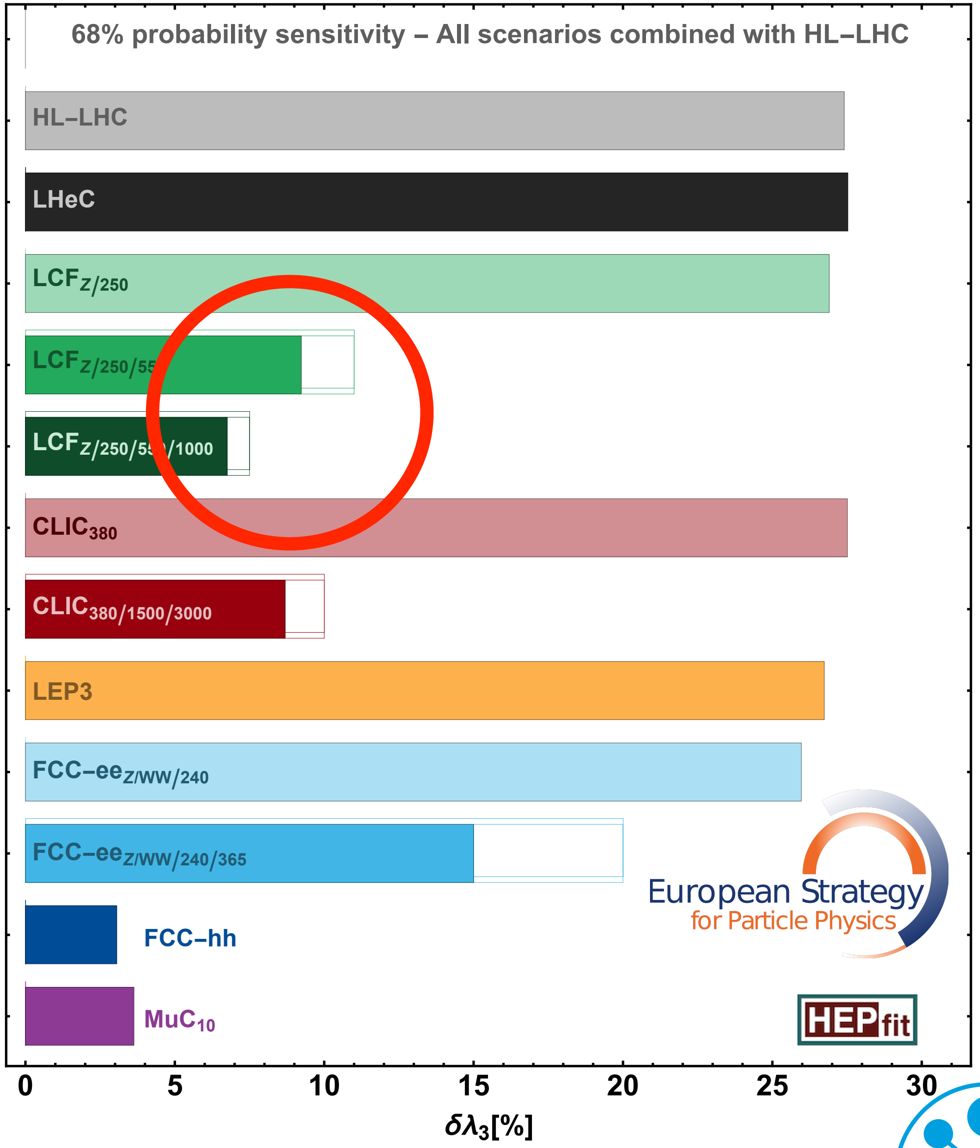
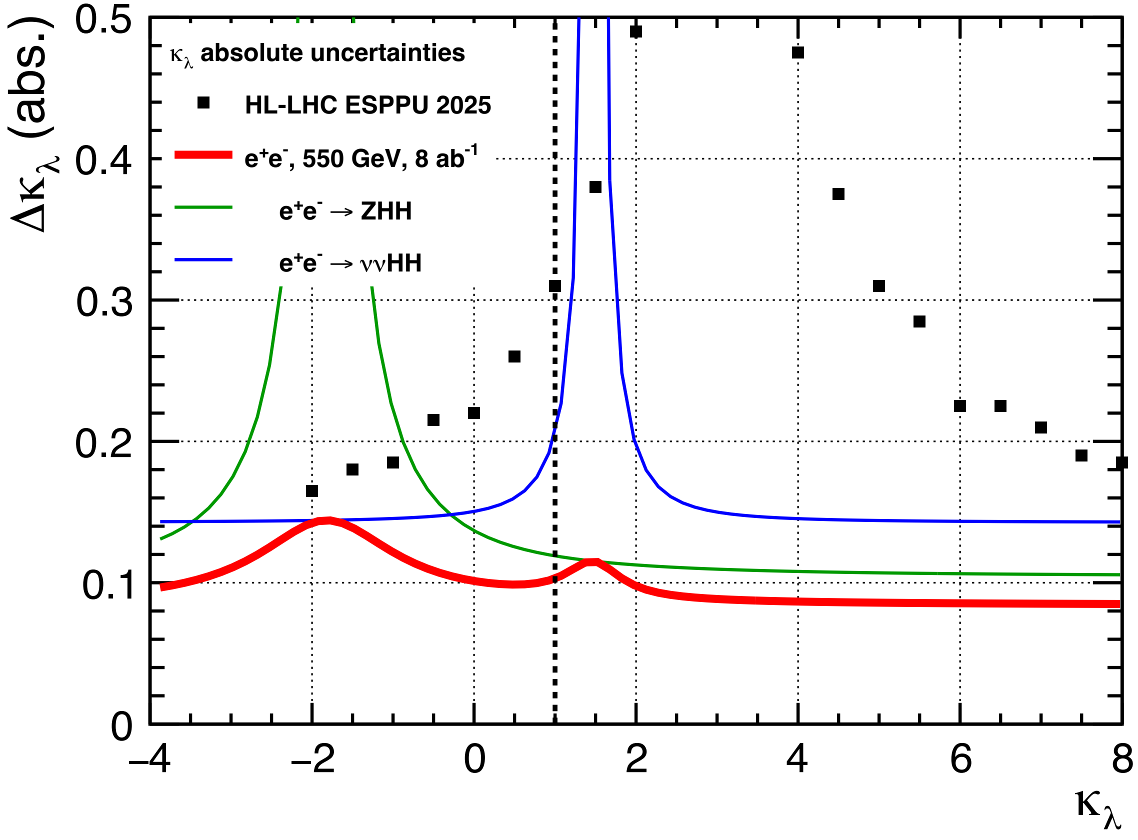


Beyond SM case in wider context

HL-LHC, e+e-, gamma-gamma



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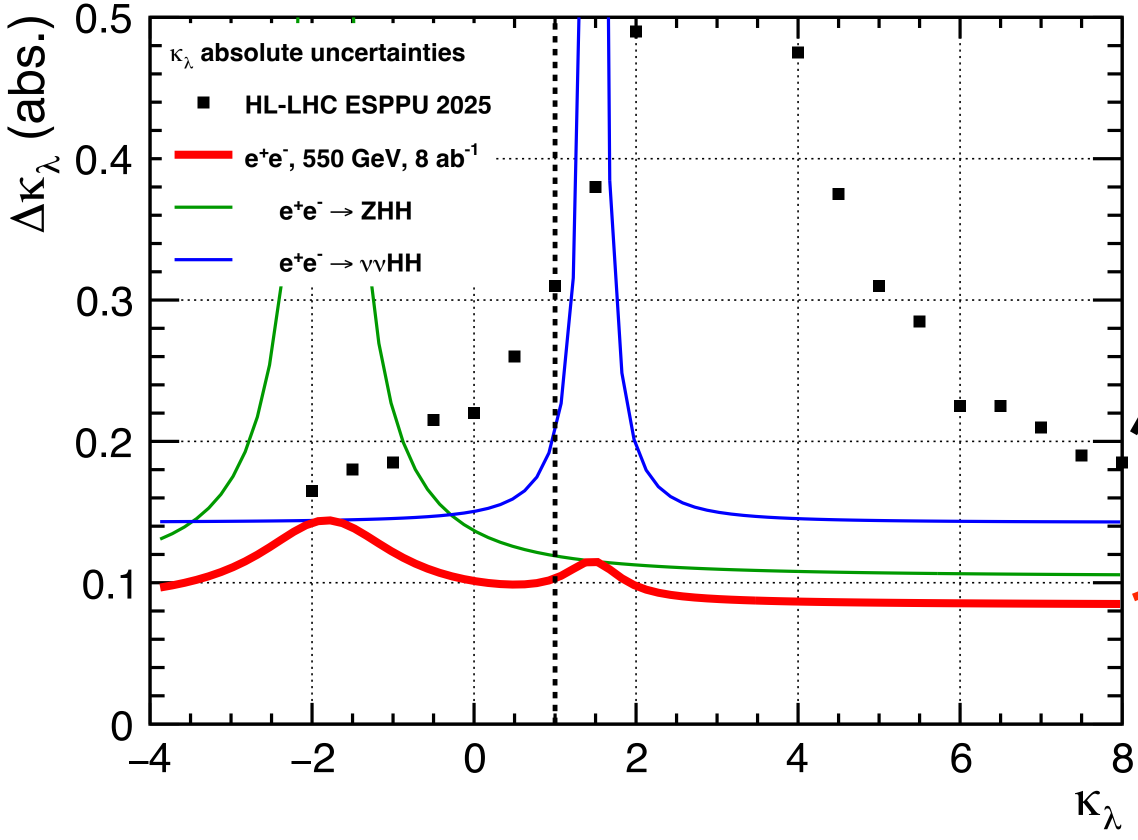

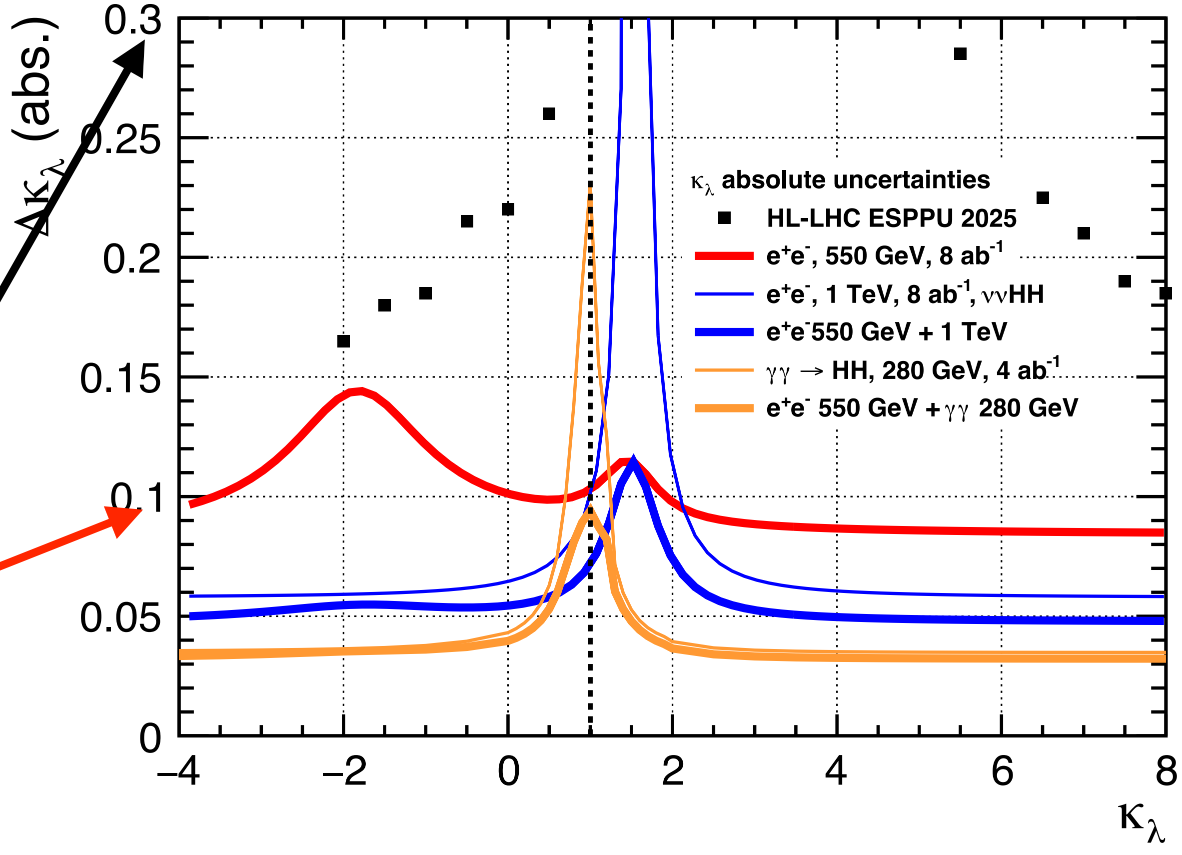

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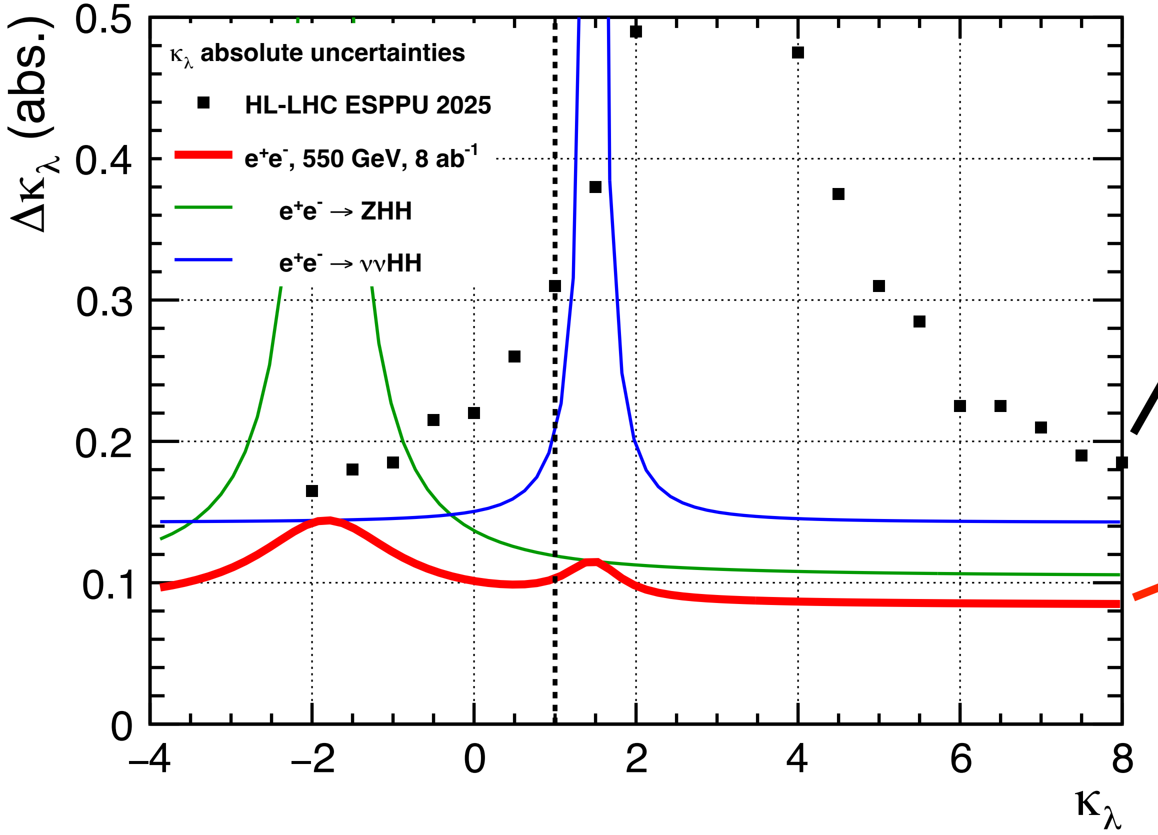
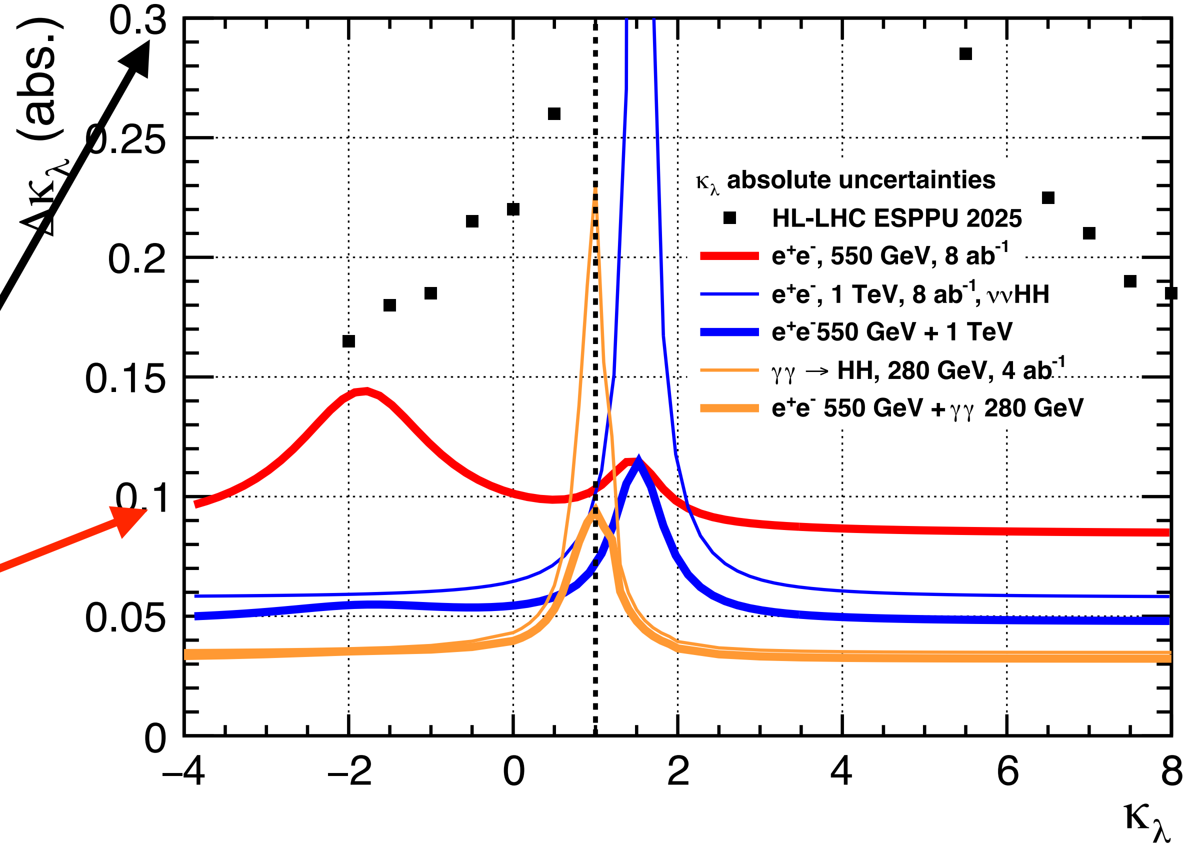




Combination of e+e- 550 GeV with either 1 TeV or a 280 GeV photon collider gives very comparable precision to FCC-hh
(bit worse for SM case, better BSM)

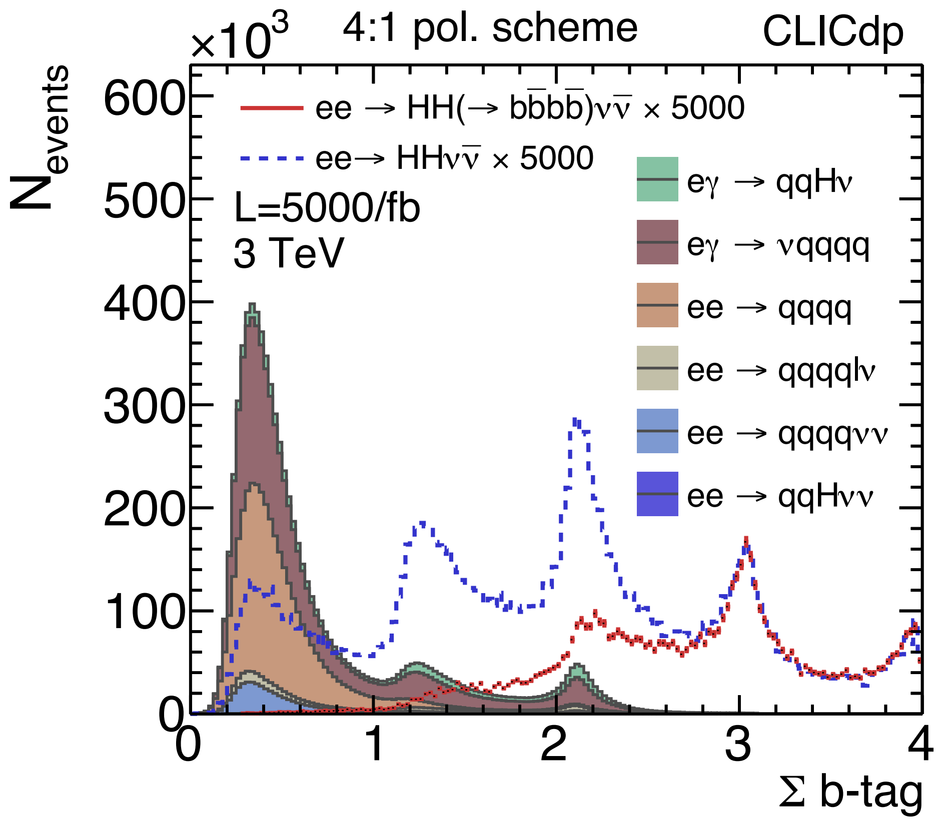
Higgs Pairs in the TeV regime

CLIC Analysis

Overview

Eur. Phys. J. C 80, 1010 (2020)

- **full Geant4-based simulation for HH->bbbb and bbWW***
  - 1.4 TeV: ZHH & vvHH
  - 3 TeV: vvHH (also ZHH studied in arxiv:2008.05198)
  - main SM backgrounds considered
  - polarisation only partially exploited
- **status of tools: pre-2018**
  - PandoraPFA, no kinematic fit, no SLD correction, …
  - LCFIPlus flavour tag, BDT selection



$\sqrt{s}$ (TeV)	$\mathcal{L}$	Decay channel(s)	$\frac{\Delta[\sigma(HH\nu\bar{\nu})]}{\sigma(HH\nu\bar{\nu})}$ (%)
1.4	2.5 ab^{-1}	$b\bar{b}b\bar{b}$ & $b\bar{b}WW^*$	28
3	5 ab^{-1}	$b\bar{b}b\bar{b}$	7.4
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Eur. Phys. J. C 80, 1010 (2020)

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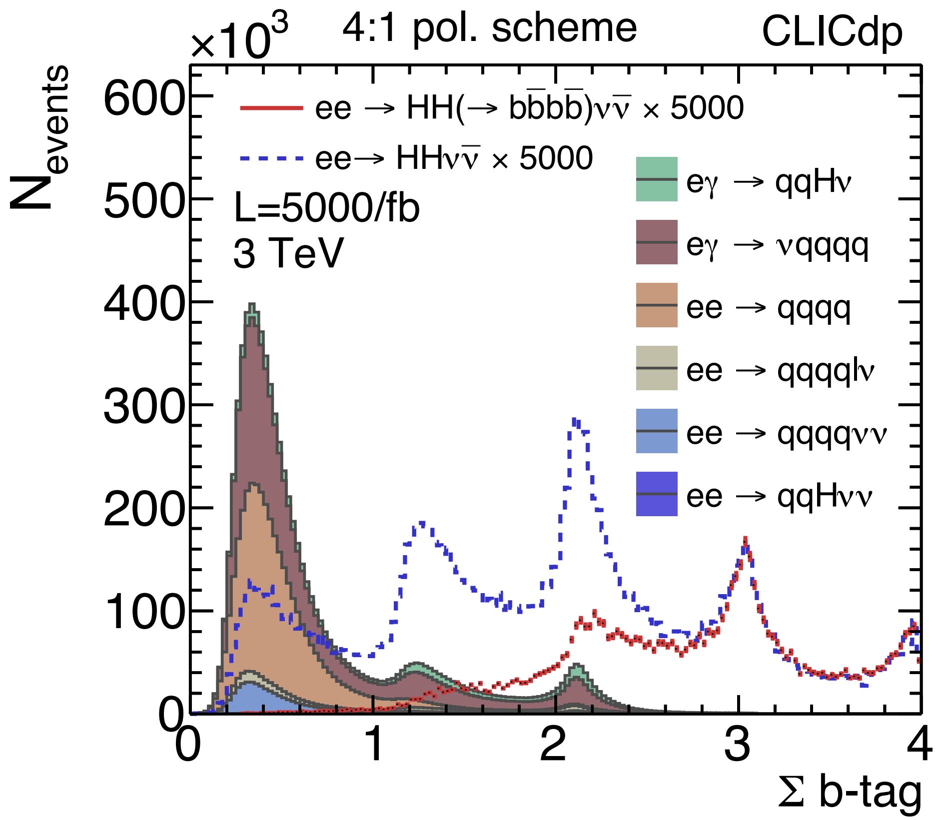

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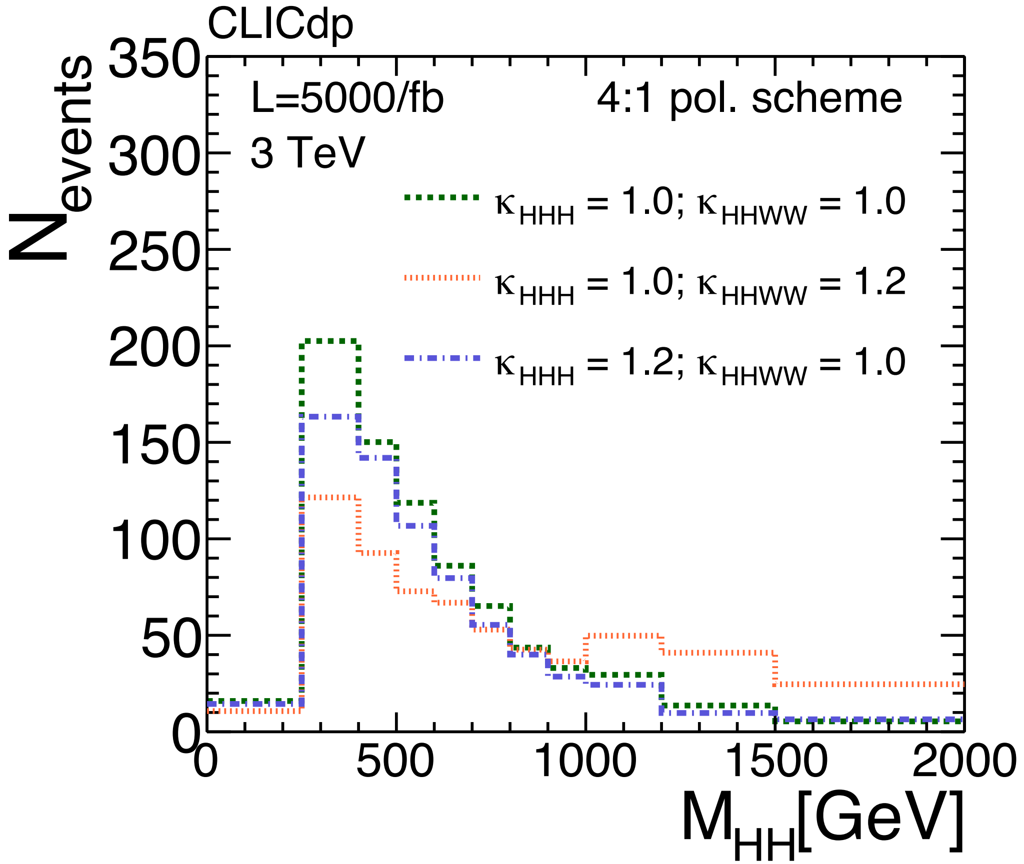
note:
- EPPSU25: accelerator optimisation => L (1.5 TeV) = 4 ab^{-1}
- very conservative due to old analysis
- factor 2 improvement possible (JL's guess)

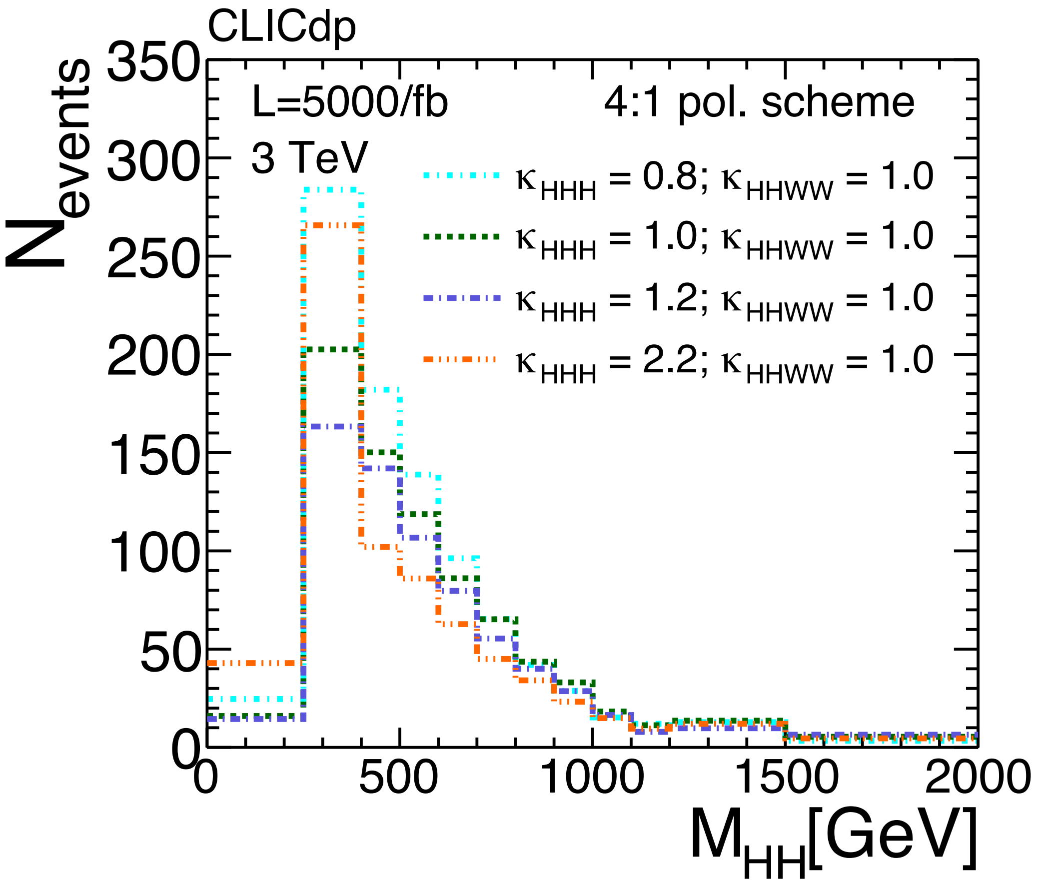
Eur. Phys. J. C 80, 1010 (2020)

CLIC Coupling Extraction

1- and 2-parameter fits

- **1.4 TeV: total cross-sections, k_λ only**
- **3 TeV: total cross-section and differential in m_{HH}, k_λ and k_{HHWW}**





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Eur. Phys. J. C 80, 1010 (2020)

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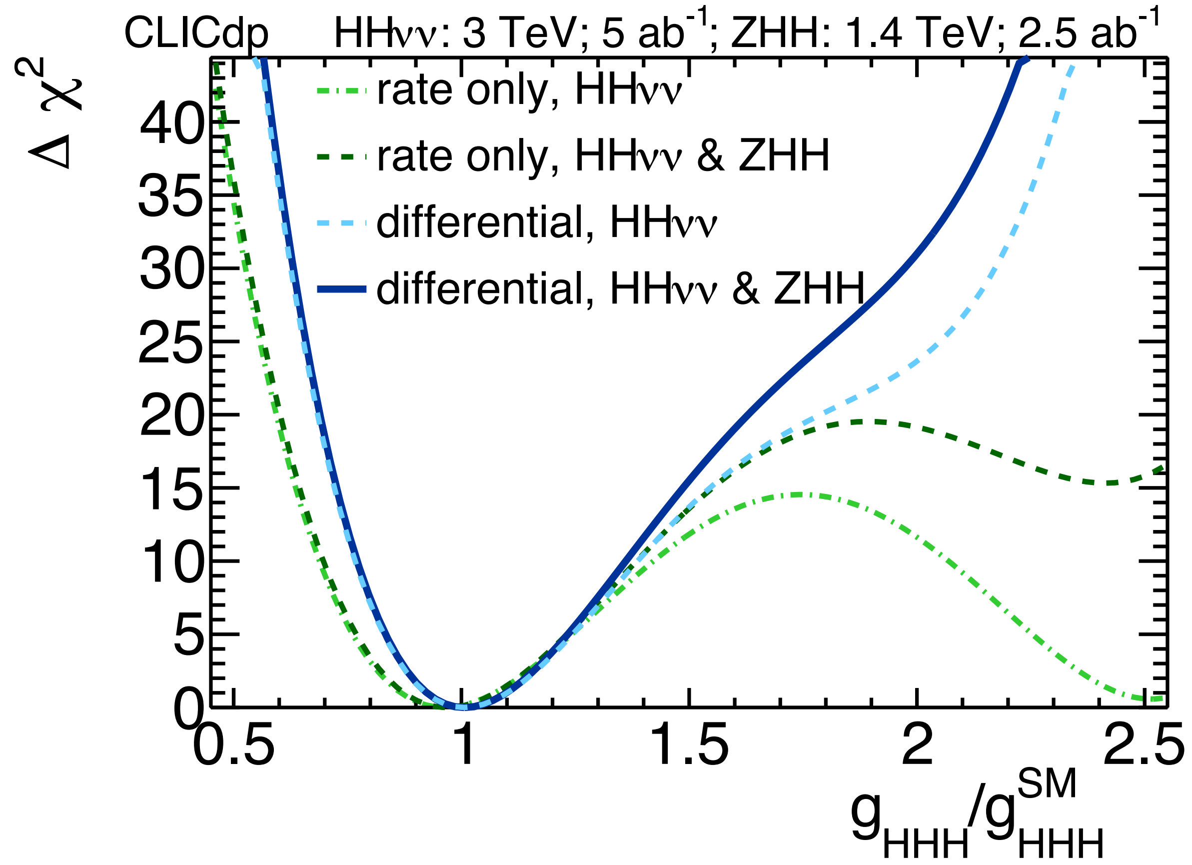

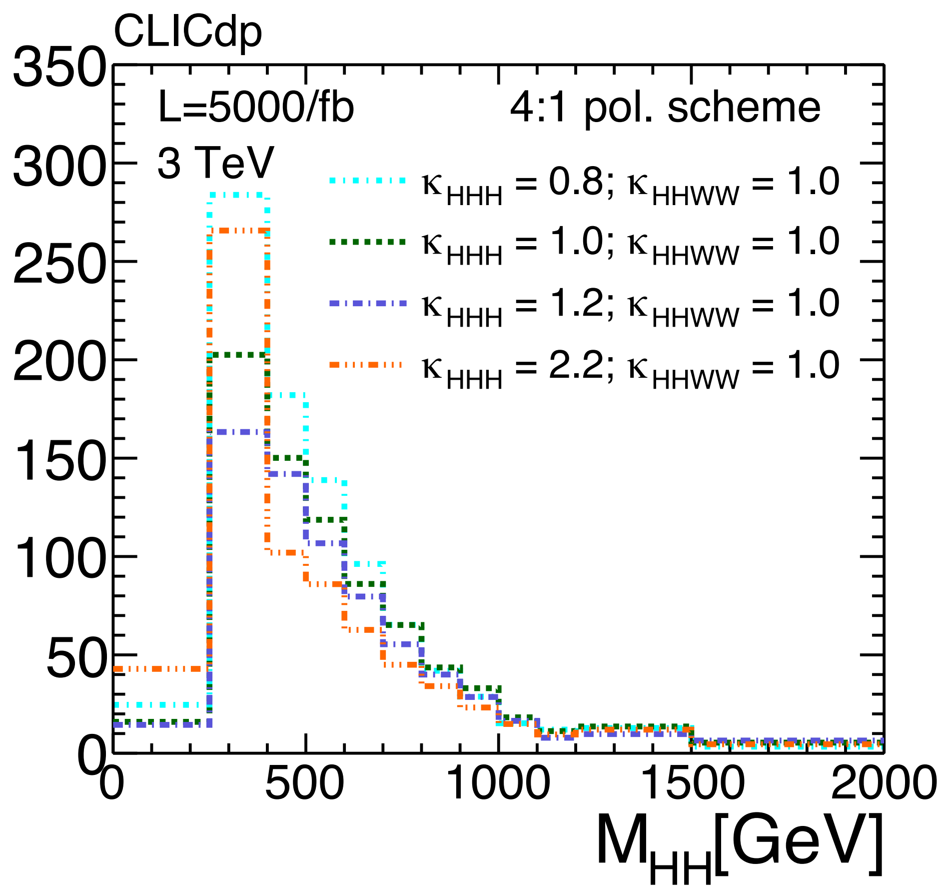

Eur. Phys. J. C 80, 1010 (2020)

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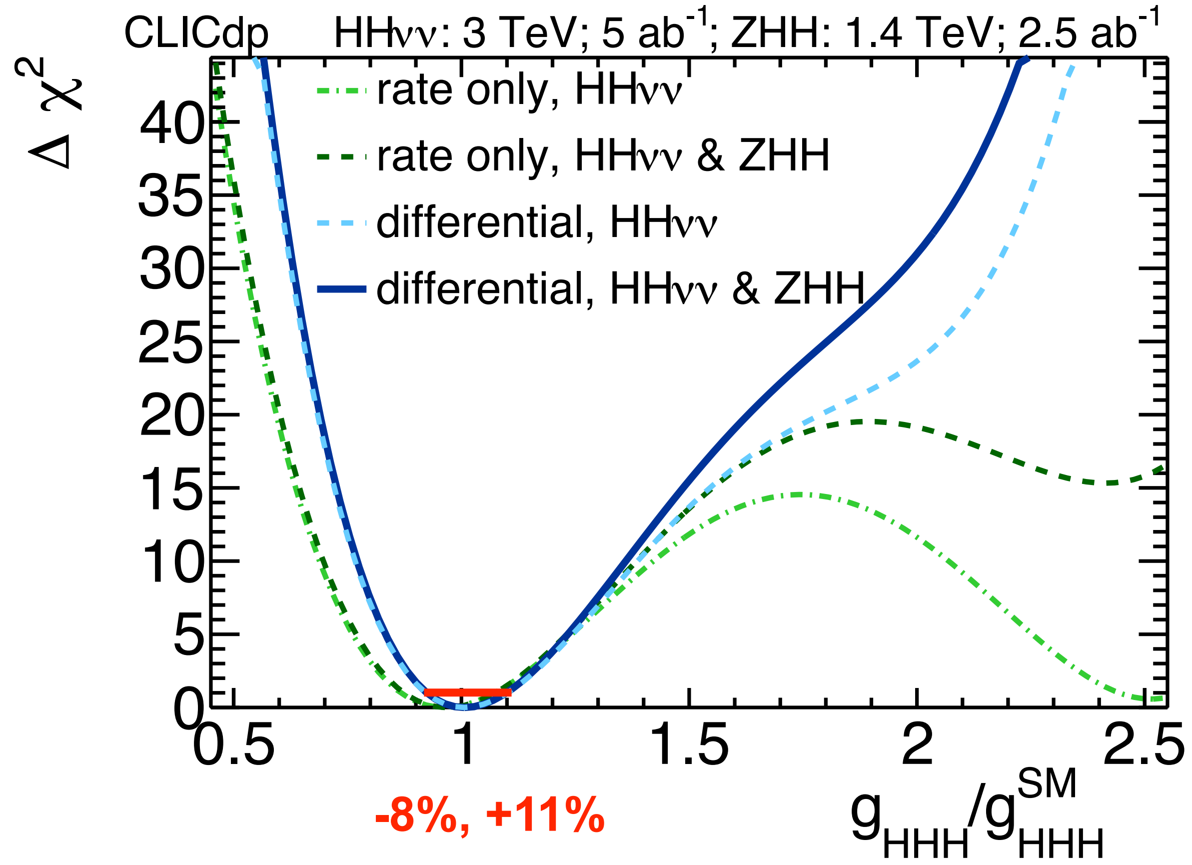
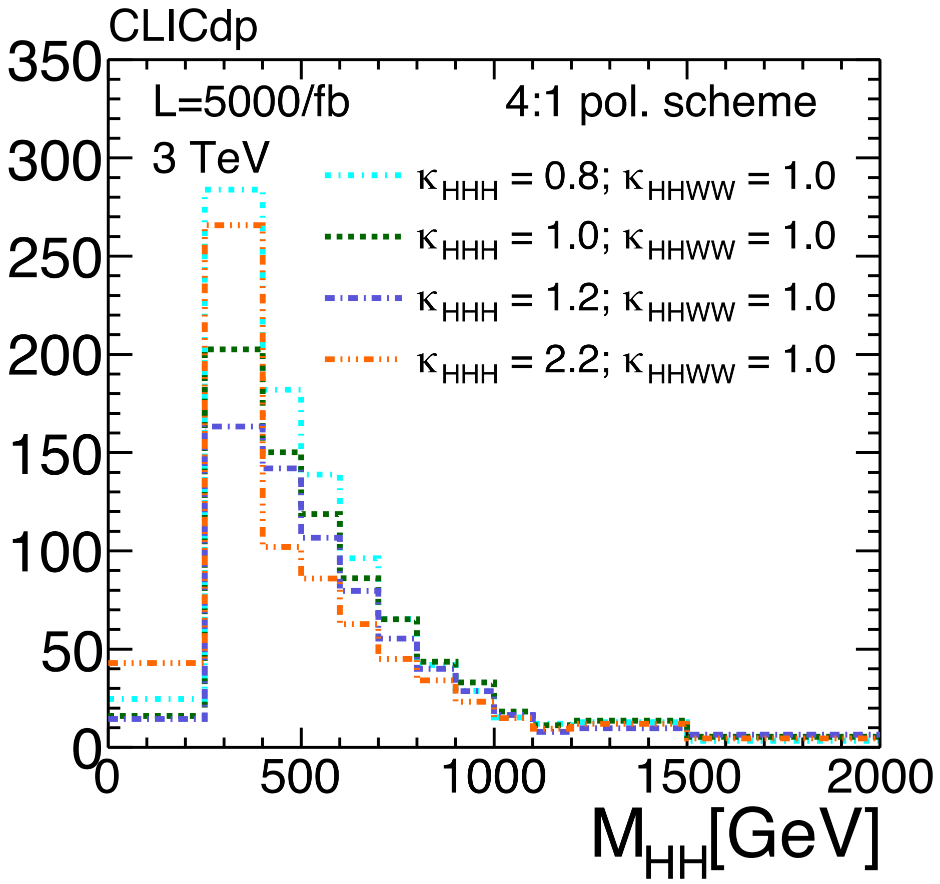


-8%, +11%



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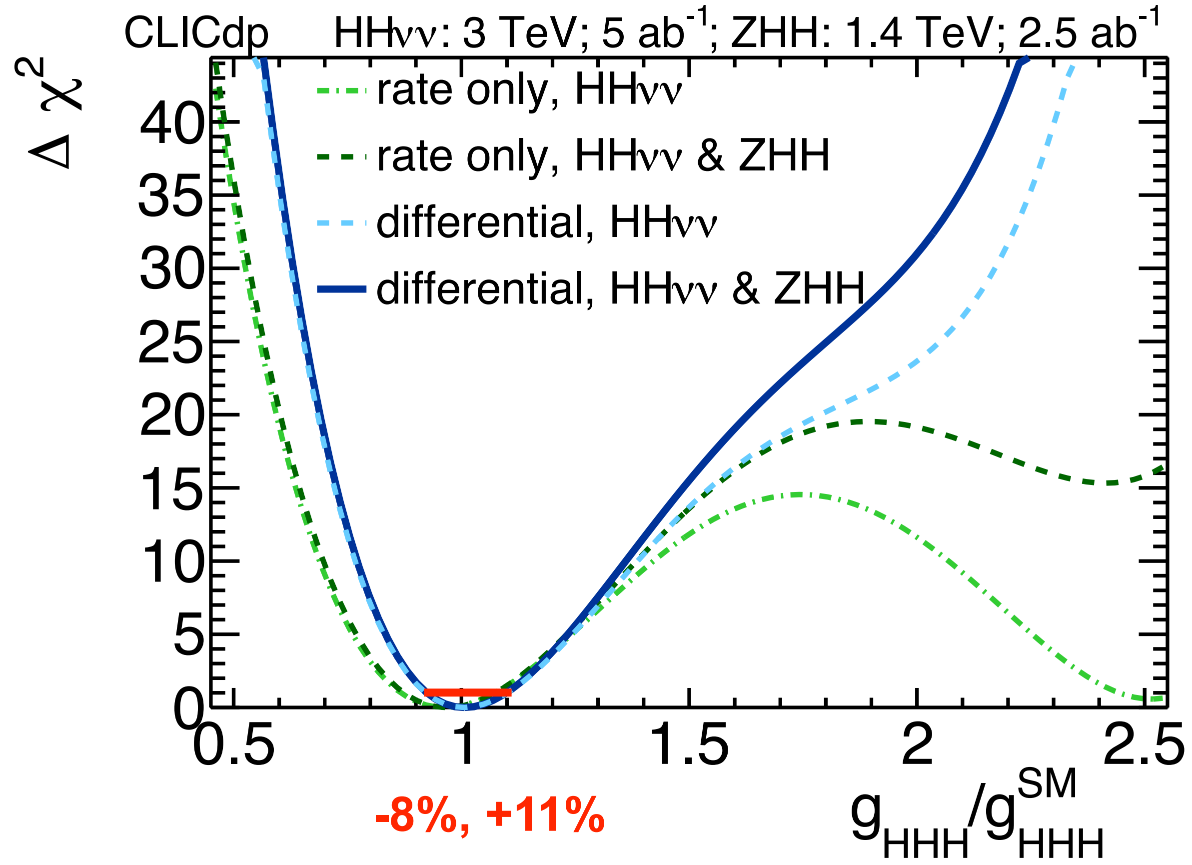
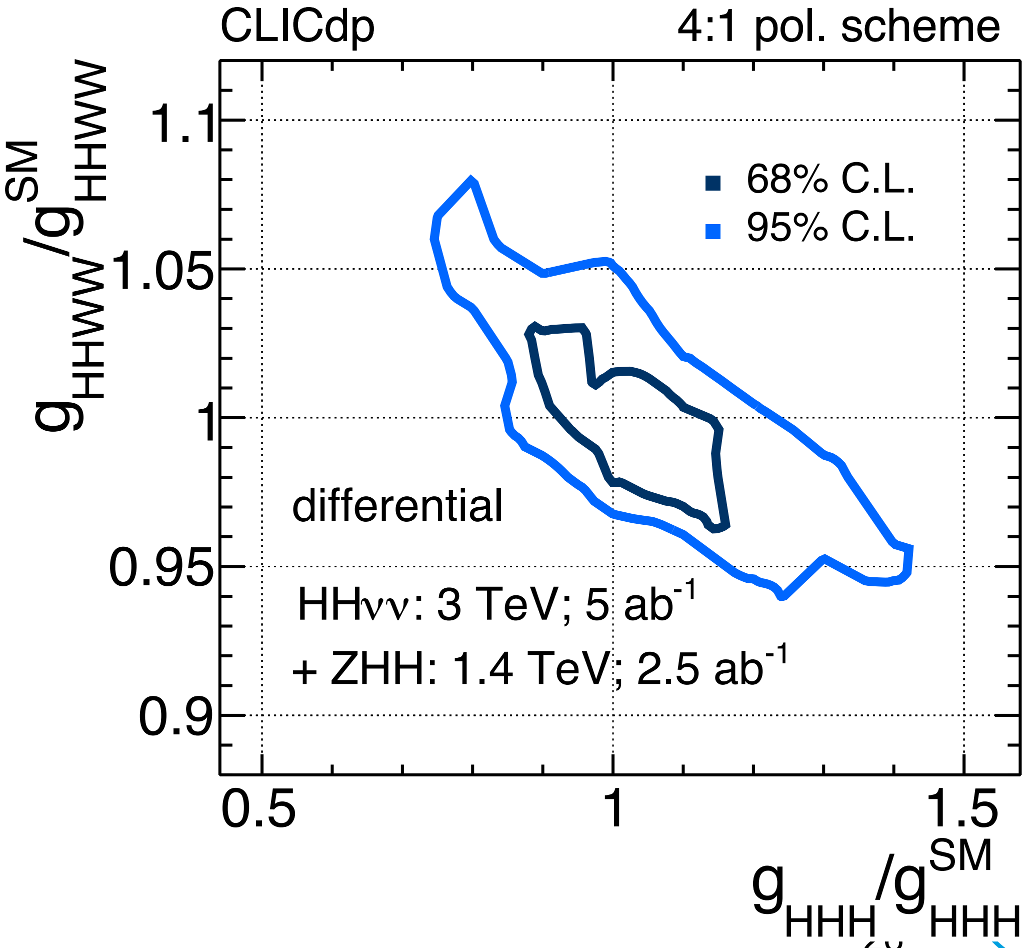


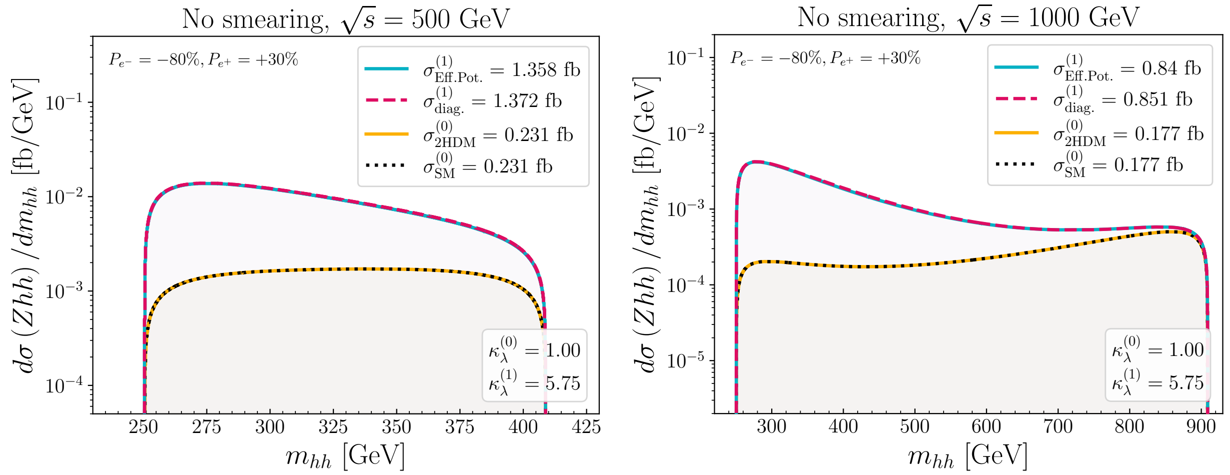


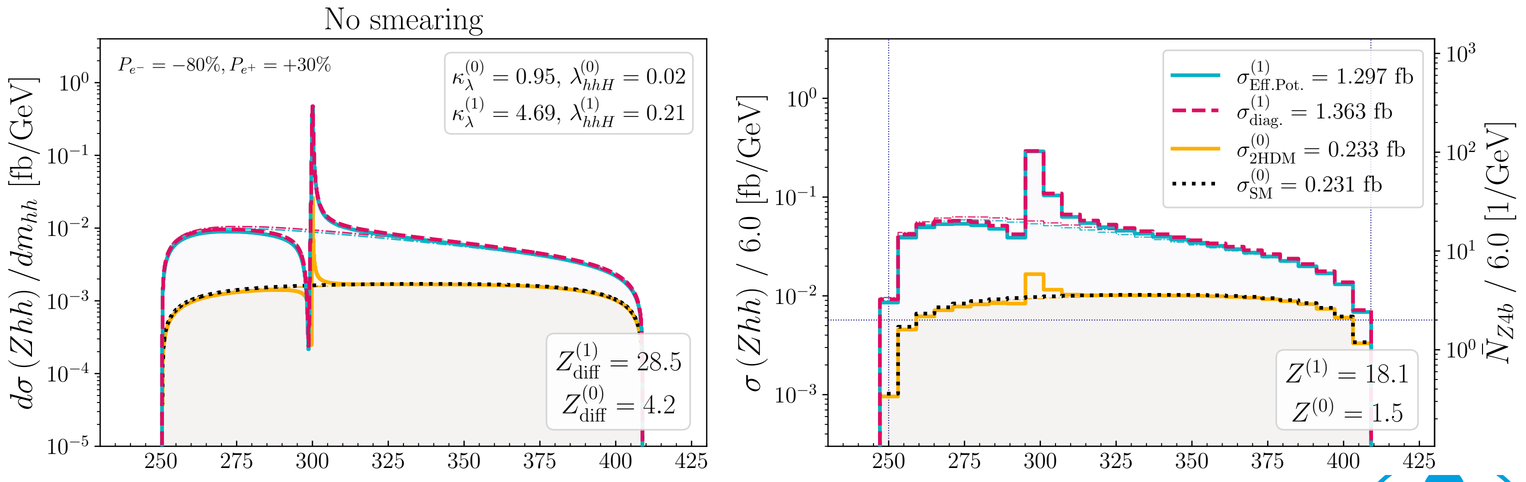
Theory-level Studies

NLO enhancement in BSM scenarios

https://arxiv.org/abs/2505.02947

- **BSM: NLO (at least) is essential**
  - 2HDM example with m_H=400 GeV, m_A=$m_{H\pm}$=800 GeV, alignment limit
  - 1-loop cross-section 2-4 times larger than LO
- If heavy Higgses light enough, expect sharp dip-peak resonance structure
- **detectability depends strongly on m_{HH} resolution**
- **ILD achieves 2% in llbbbb**
  - other channels w.i.p.





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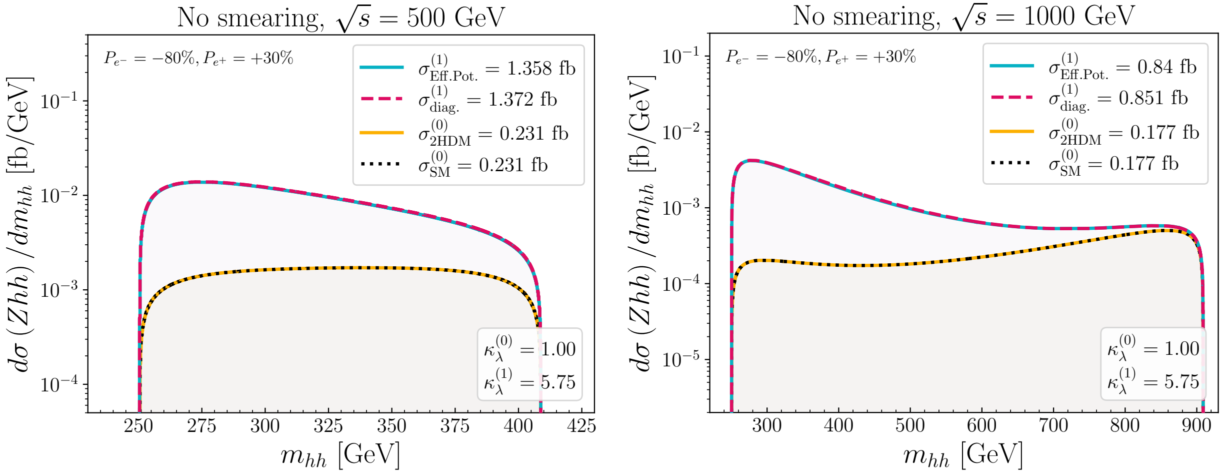

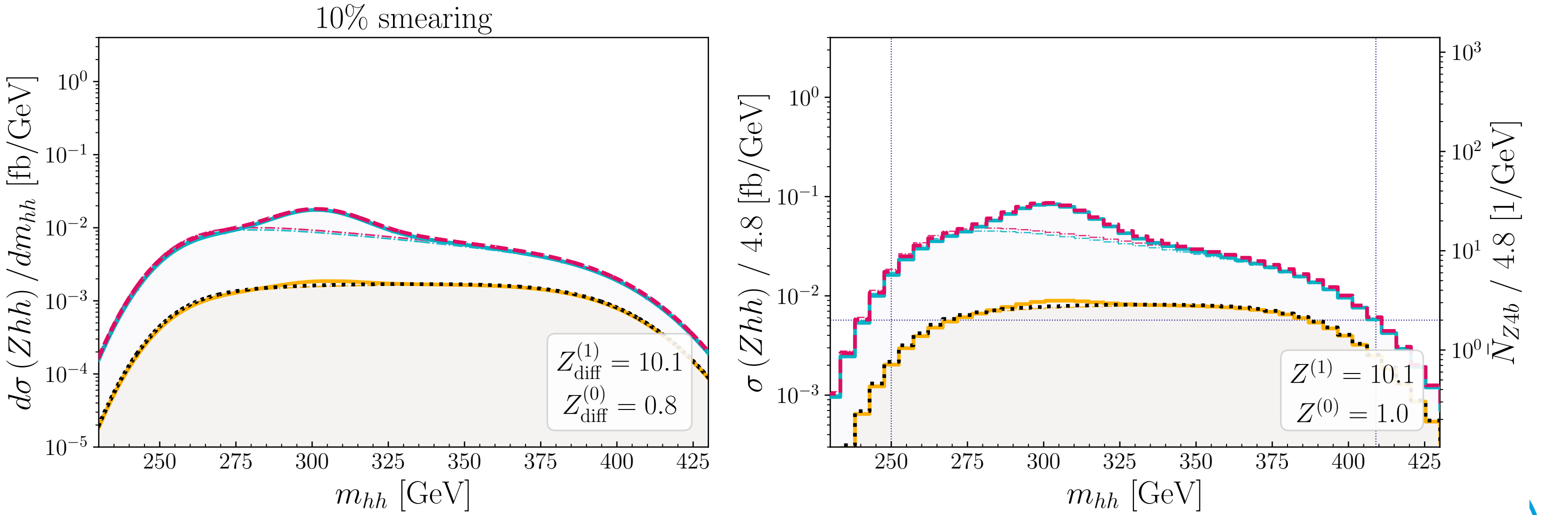

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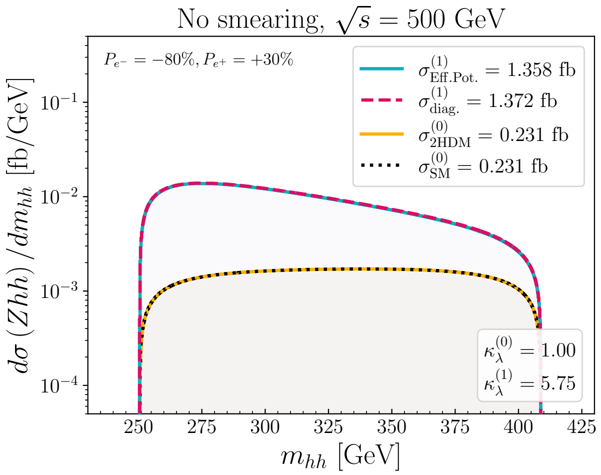

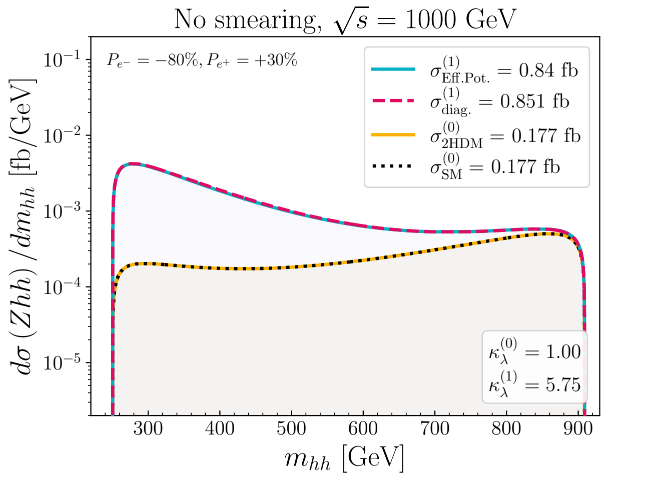

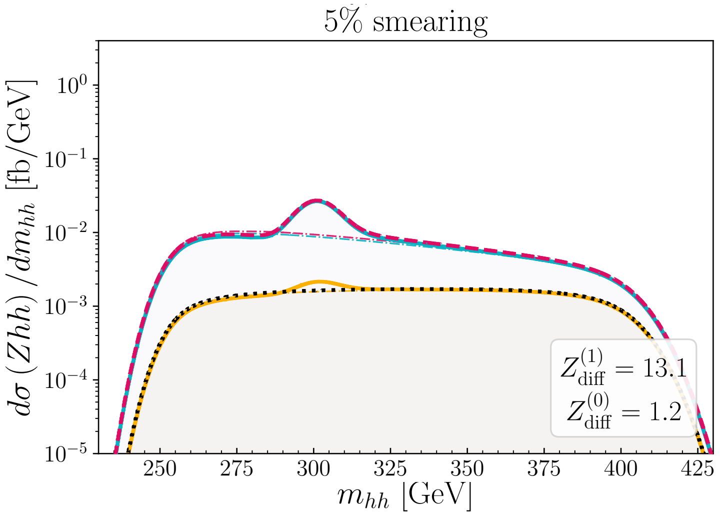

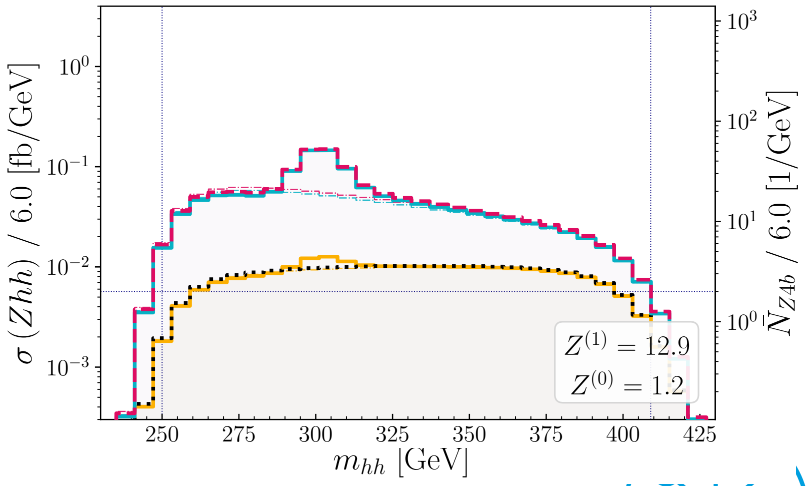

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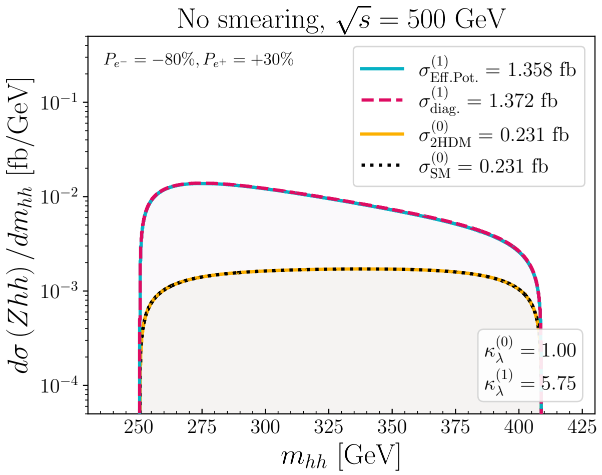

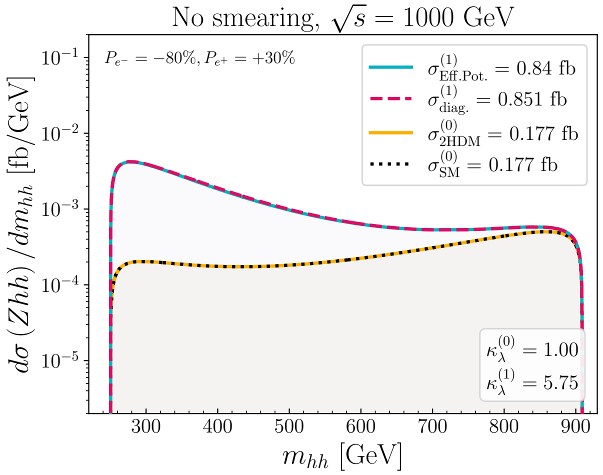

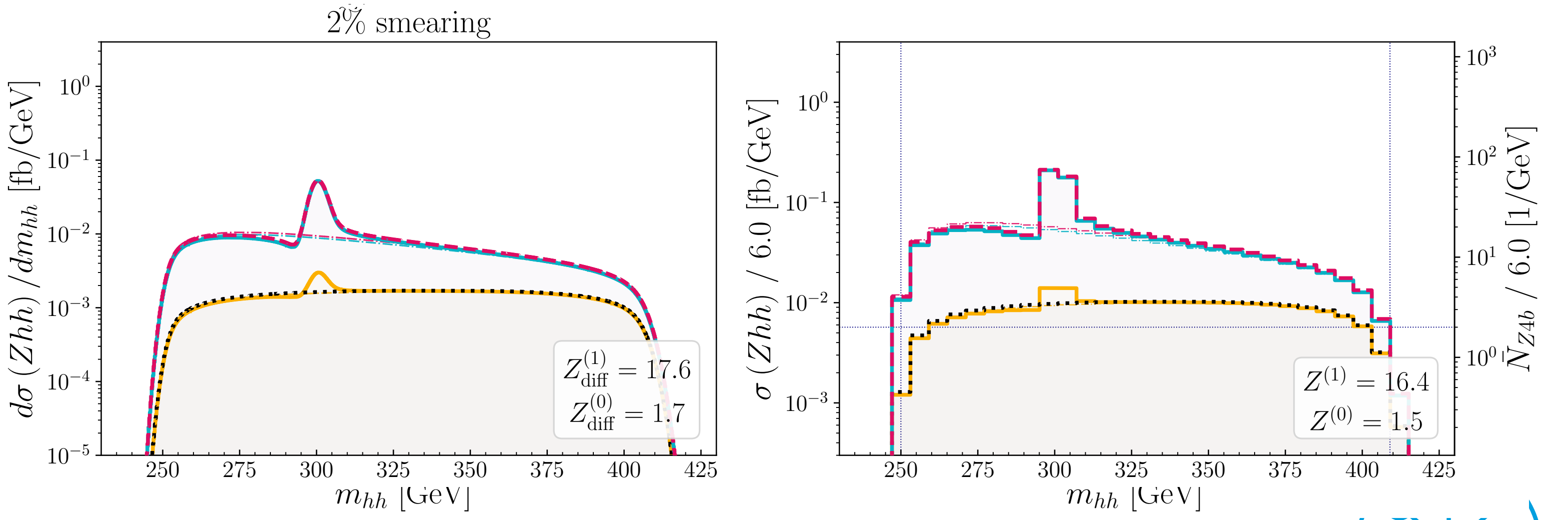

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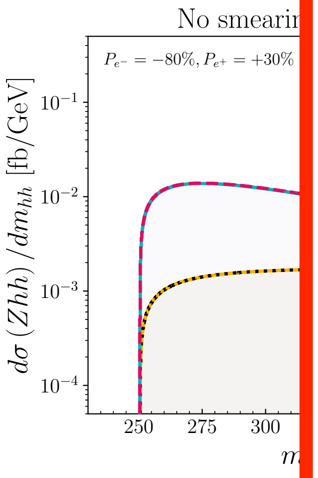
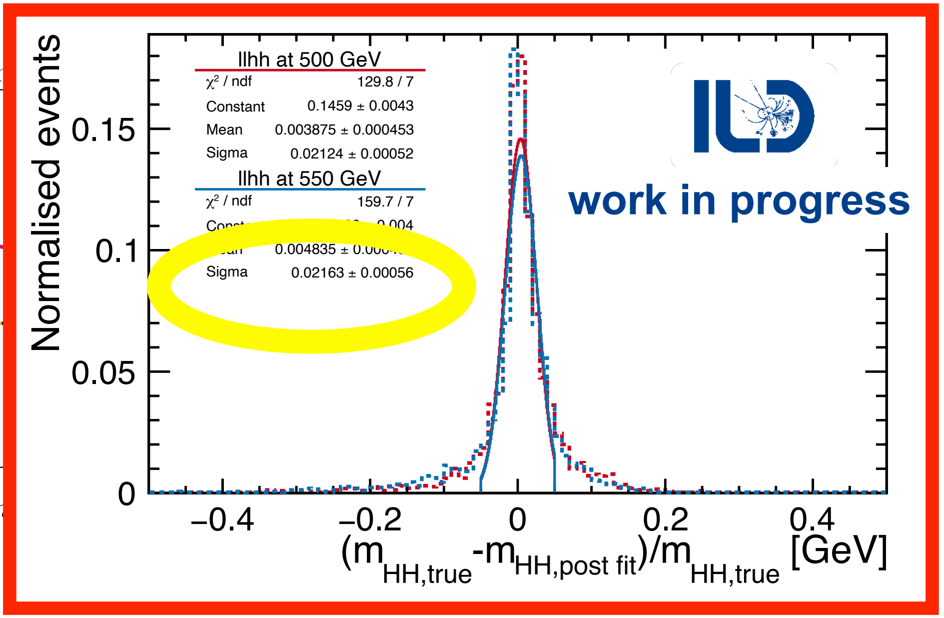
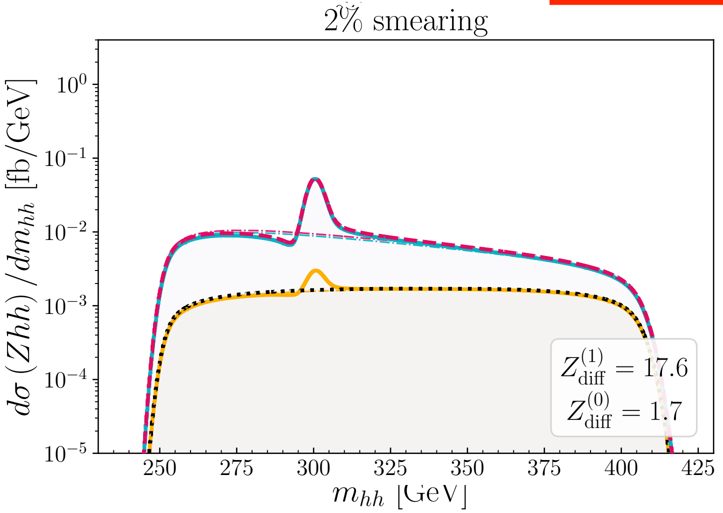
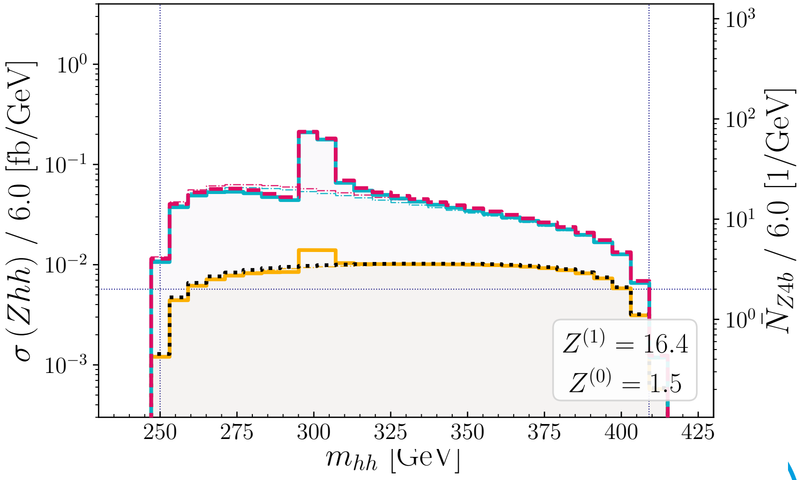




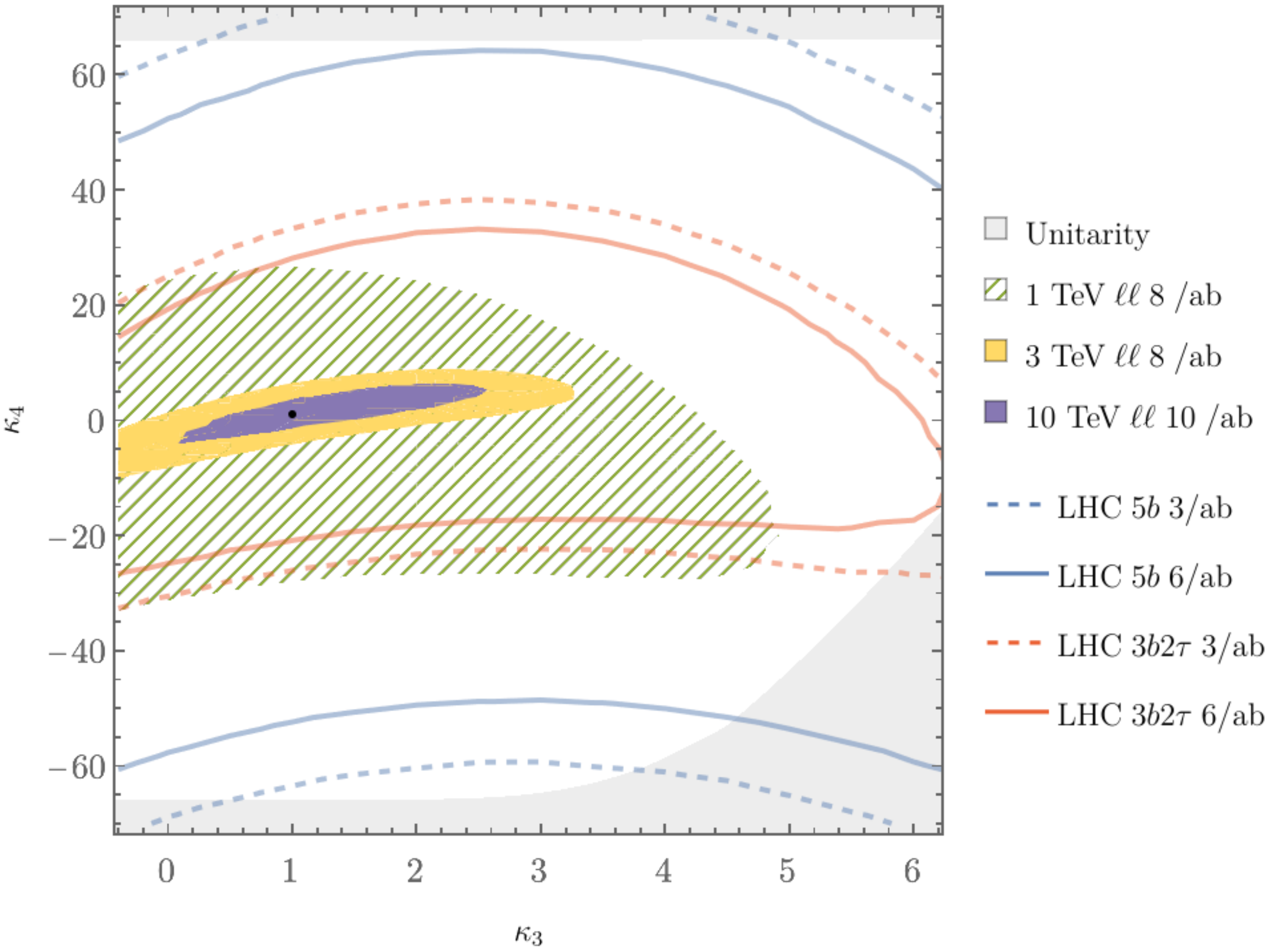




Triple-Higgs Production at Lepton Colliders

Eur. Phys. J. C 84 (2024) 366 (updated for https://arxiv.org/abs/2503.19983)

- study of e+e- / μ+μ- -> HHH
  - extraction of κ_3 and κ_4
- no information from HH included (yet)
- already HL-LHC will give significant constraints beyond those from unitarity
- κ_3 < 1:
  - 1 TeV lepton collider ≈ HL-LHC
  - gain from complementarity & combination
- κ_3 > 1:
  - 1 TeV lepton collider sensitivity improves, more stringent than HL-LHC
- 3 and 10 TeV lepton collider drastically improve sensitivity

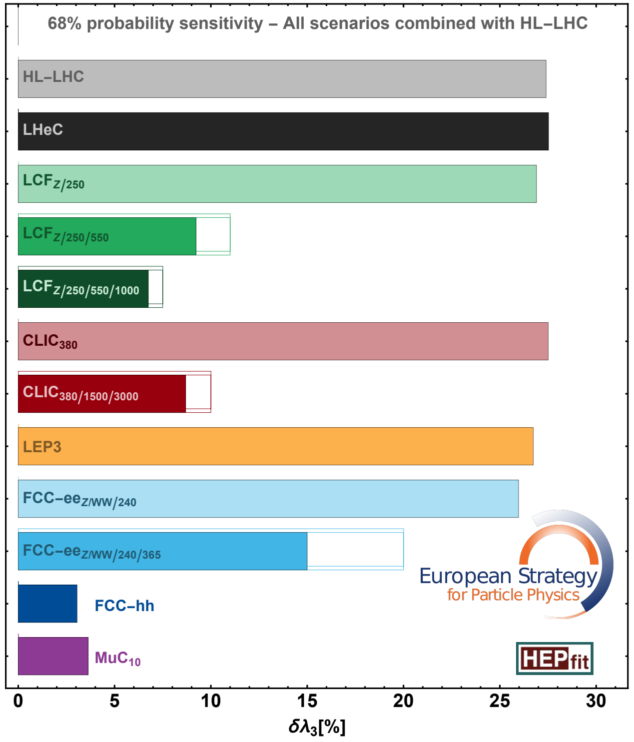


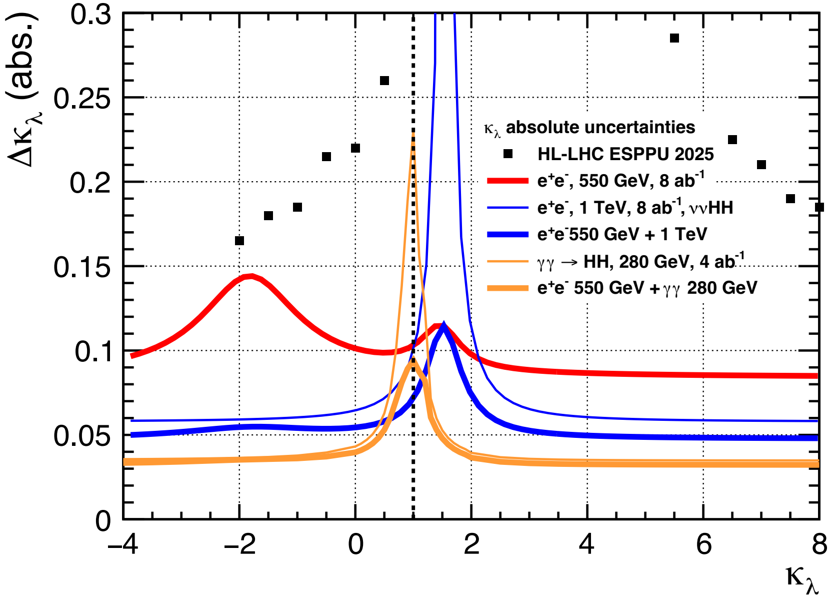
Conclusions

Conclusions

and outlook

- **Higgs Pair production in e+e- collisions requires > 450 GeV**
- **Lower energies:**
    - constraints on **λ** from single-Higgs observables
    - at least 2 energies needed to improve beyond HL-LHC
    - significant model-uncertainties
- **Double Higgs-strahlung in e+e- has very different BSM behaviour than vector-boson fusion (in e+e- or pp)**
- **e+e- 550 GeV:**
    - tremendous improvement for ESPPU'25
    - for SM case and LCF running scenario: 11% on **λ**
    - Absolute uncertainty on κ_λ ~= 0.1, early flat as function of **λ**
- **γγ -> HH very competitive already at 280 GeV, with again complementary BSM behaviour**
- **still a lot of room for improvement**
    - Multi-class ML selection shows another significant improvement
    - update more projections to modern reco & analysis tools
    - differential distributions
    - interpretation in HEFT, concrete models, ….
    - EW NLO ?





Any Questions?

The second stage

550 GeV incl ttbar theshold

- equipping the additional tunnel with SCRF
- **+ 5.46 BCHF**
- 10 Hz trains of 2625 bunches
  => 7.7 x 10^{34} / cm^2 / s
- **AC power 322 MW**
- target 8 ab^{-1}

important: this can come after a number of years of physics data-taking at lower operating costs than FCCee
=> can afford the upgrade again!

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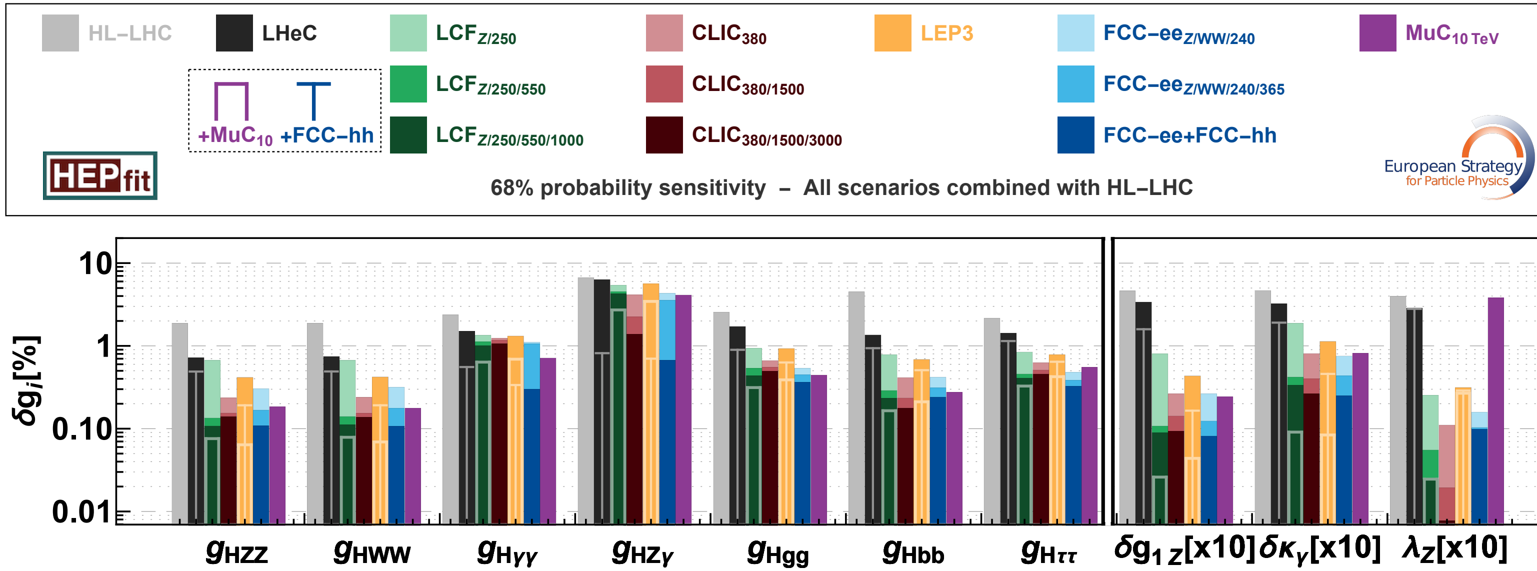

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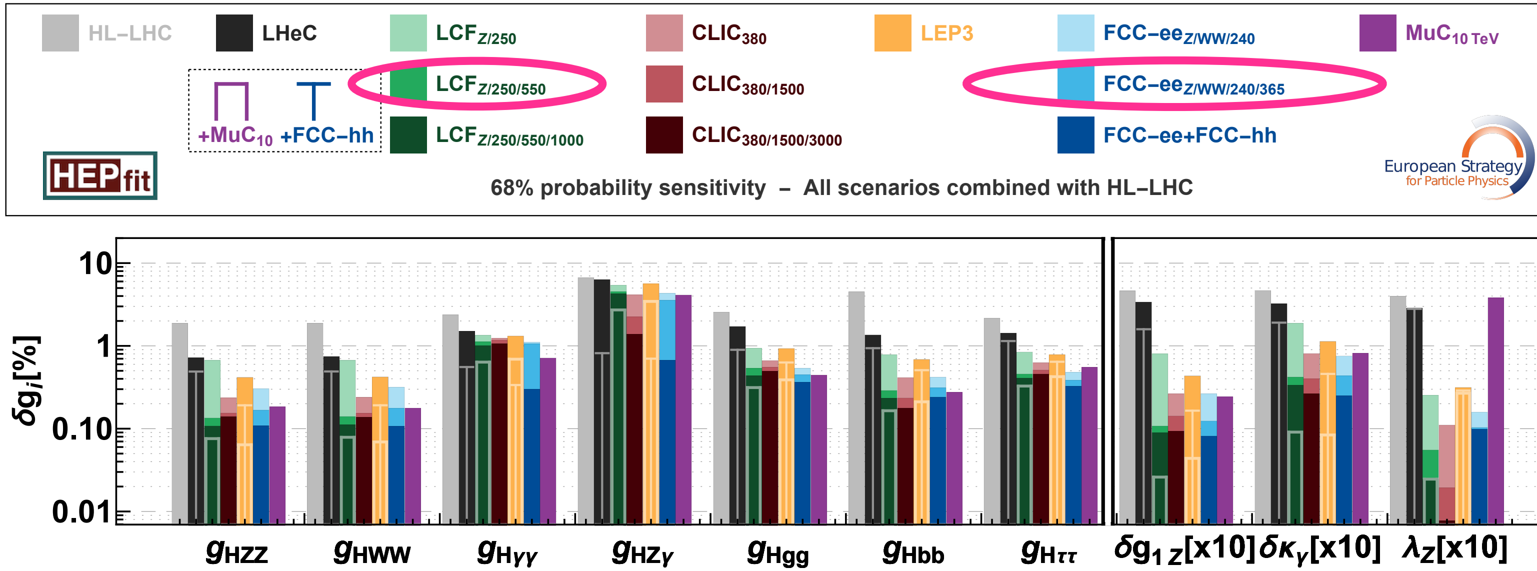

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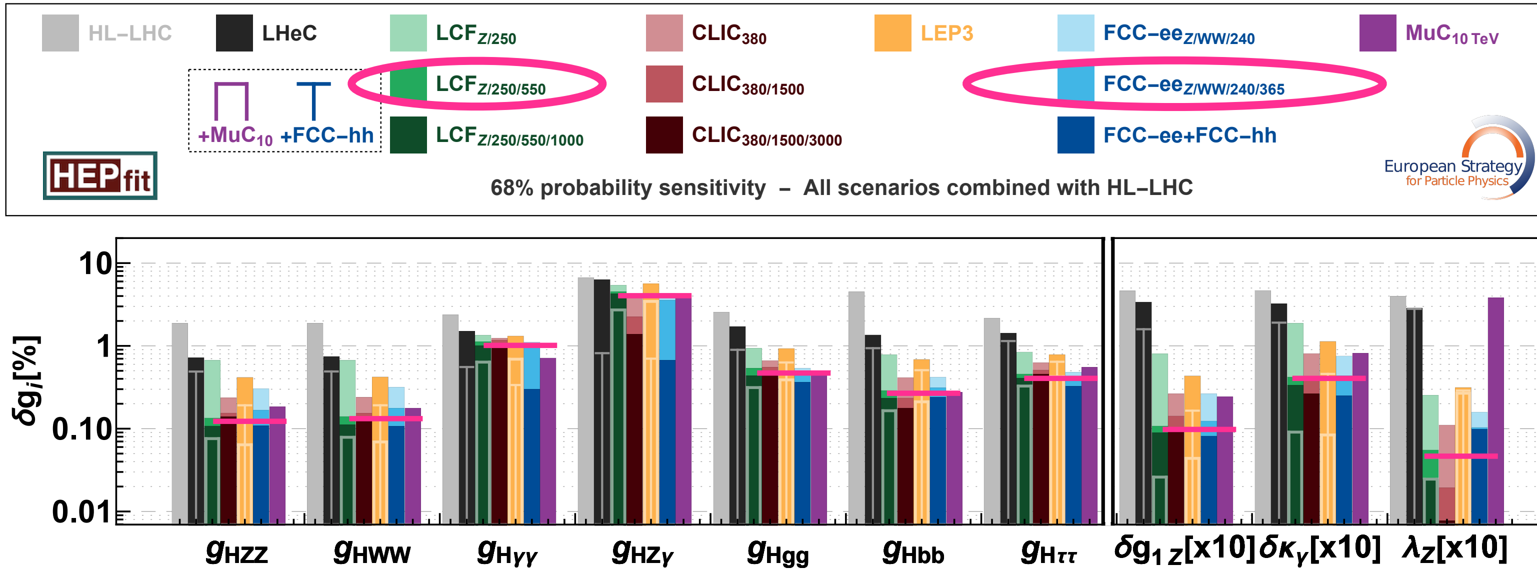

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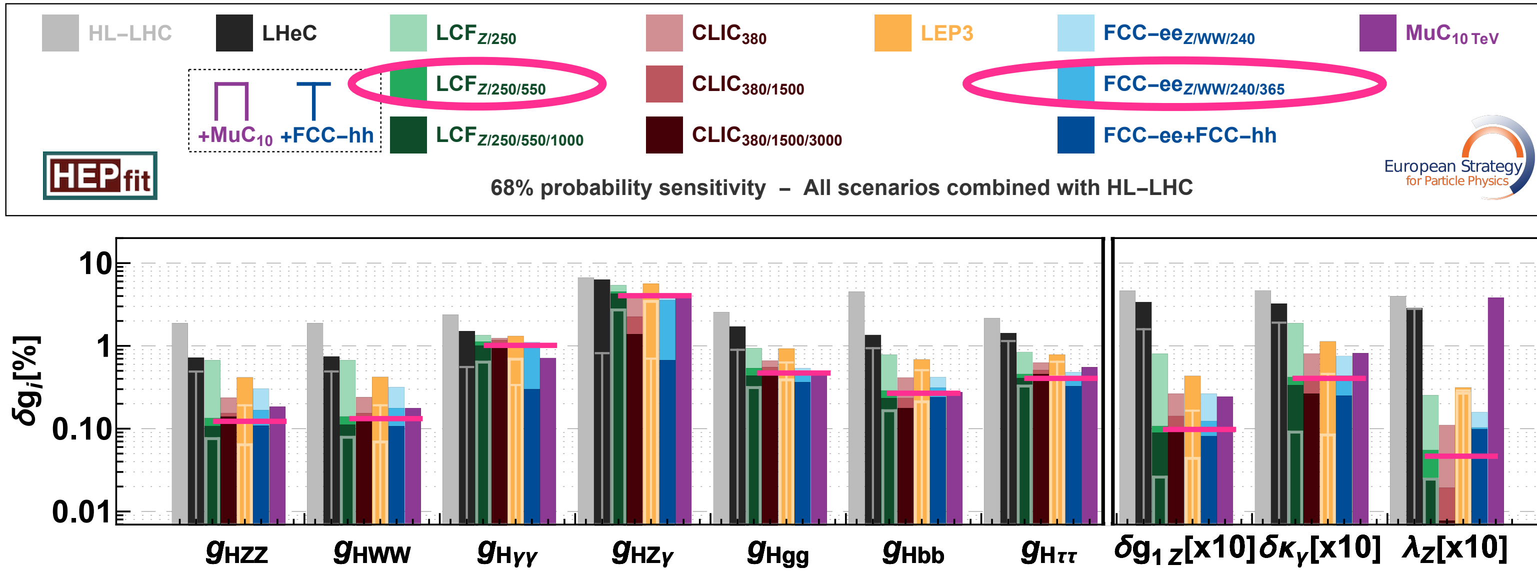

LCF550 and FCCee365 give very similar Higgs precision

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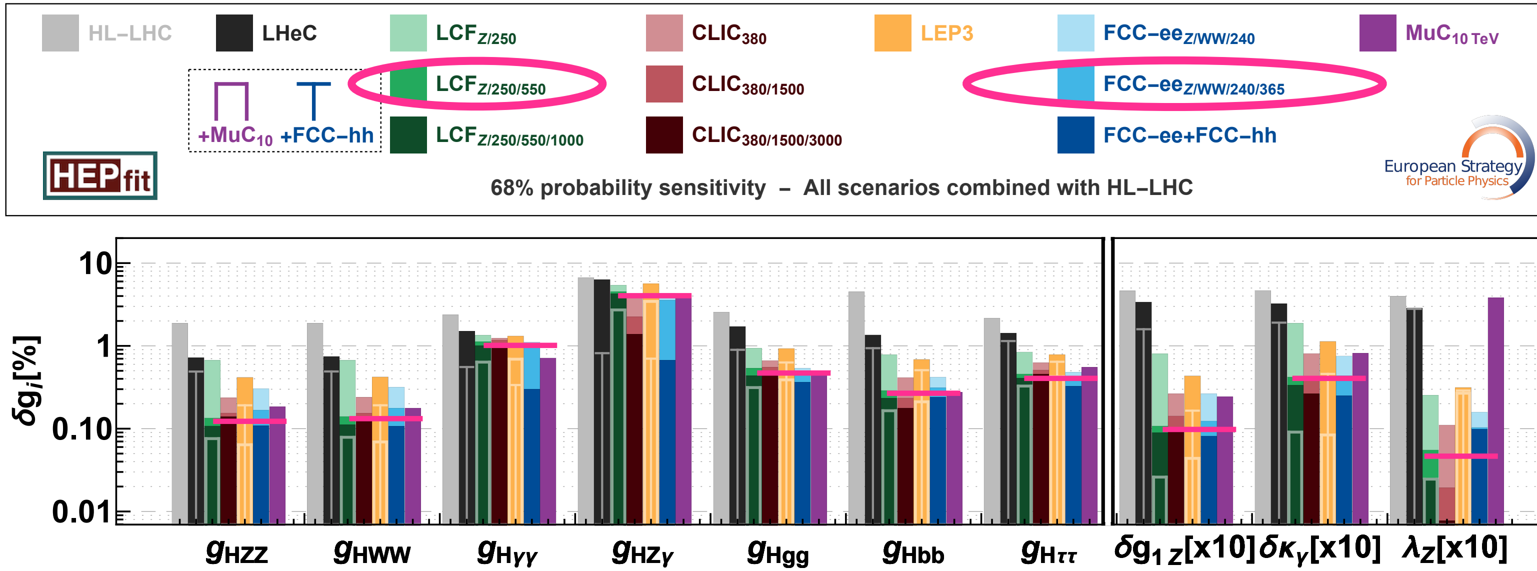

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Higgs physics at 550 GeV and beyond:

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  => complementary set of observables
  => independent verification of anomalies observed at 250 GeV
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  - **ttH:** tree-level sensitivity to top-Yukawa 1-2%
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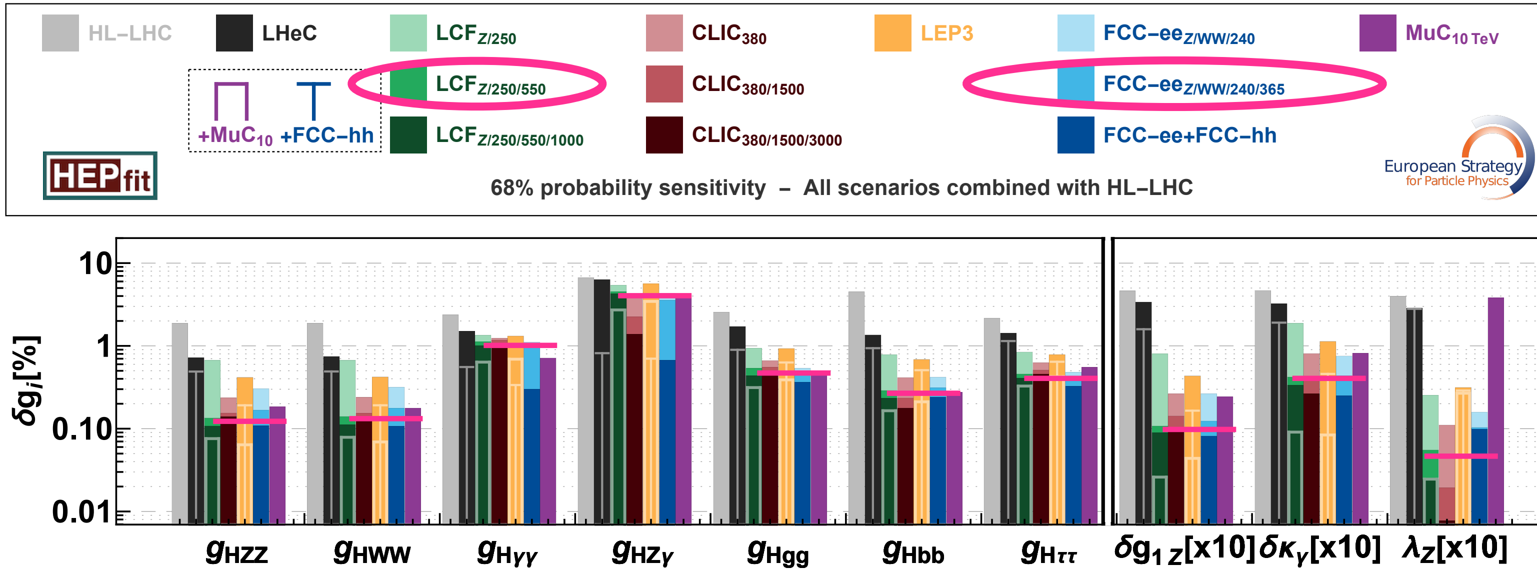

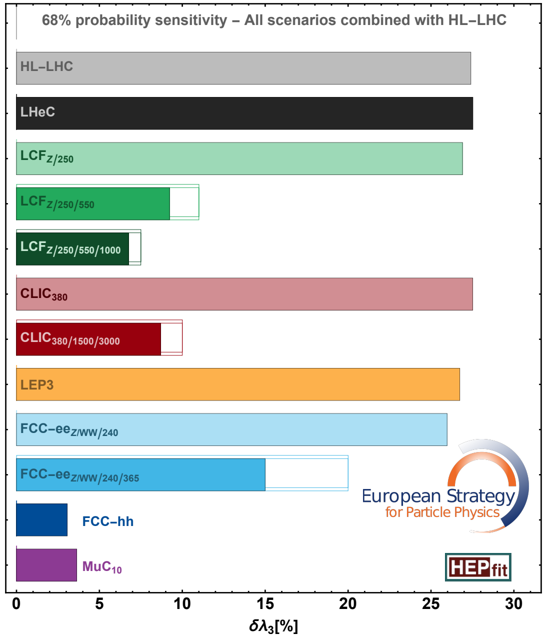

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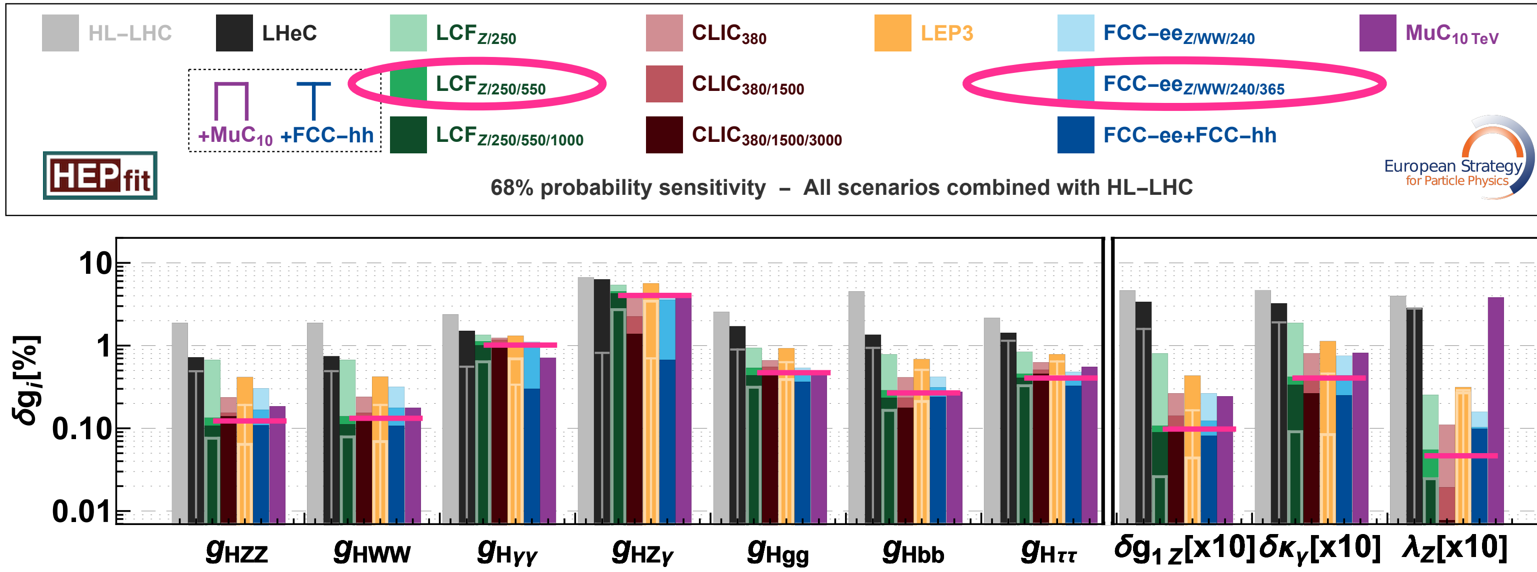

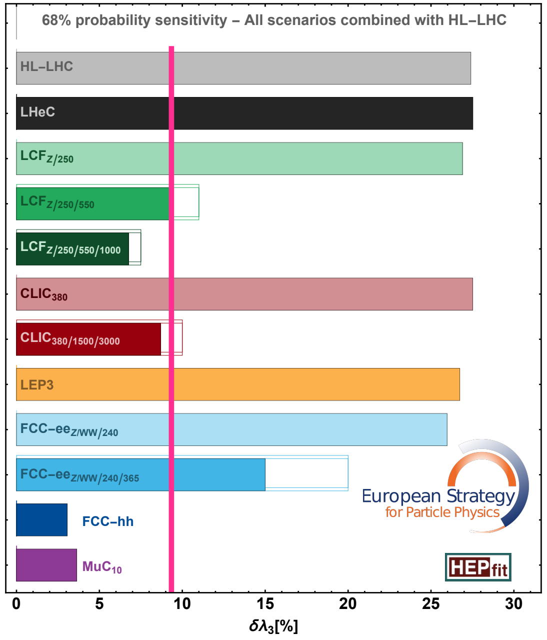

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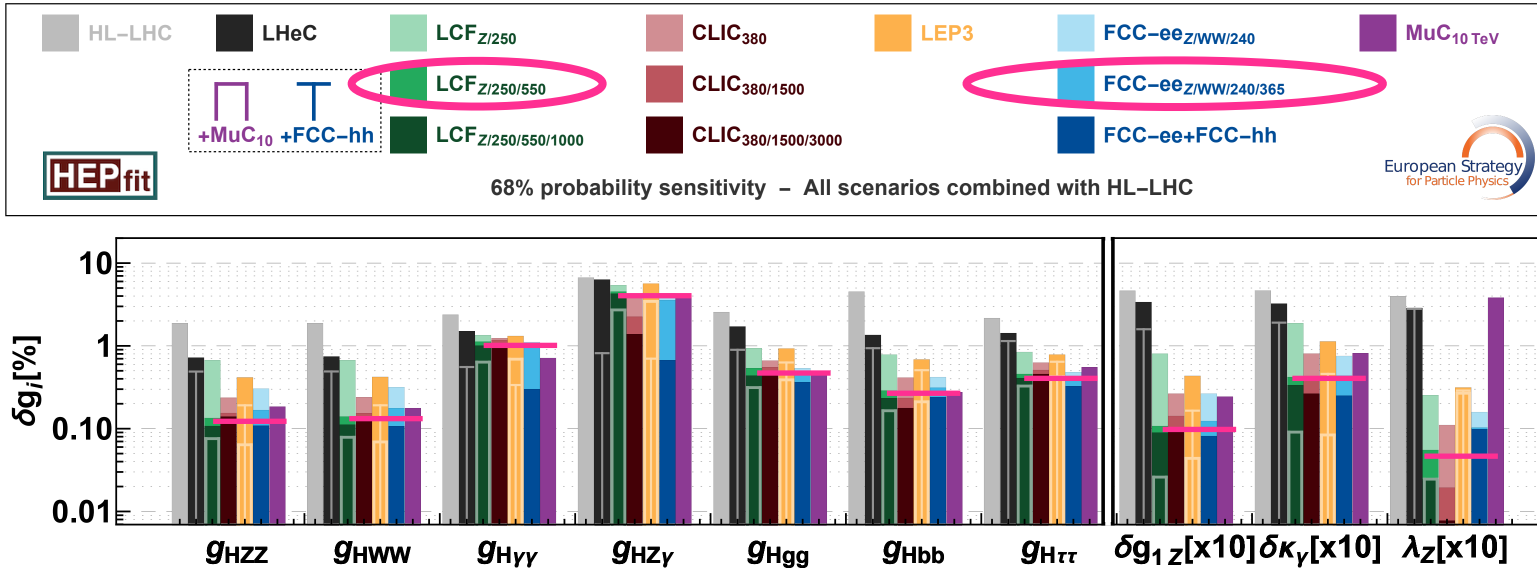

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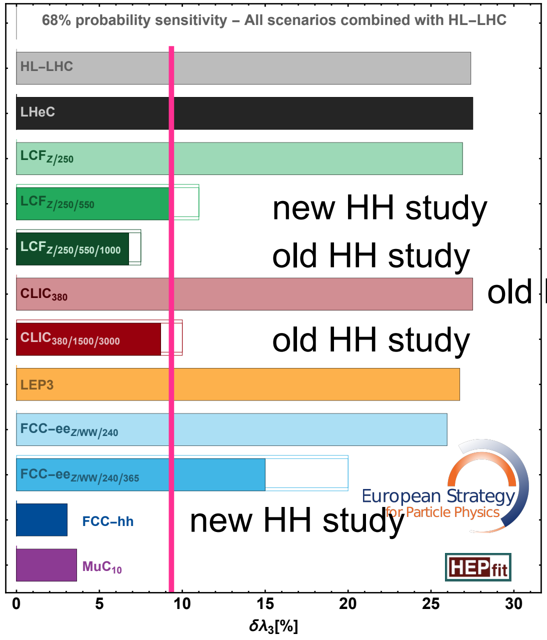

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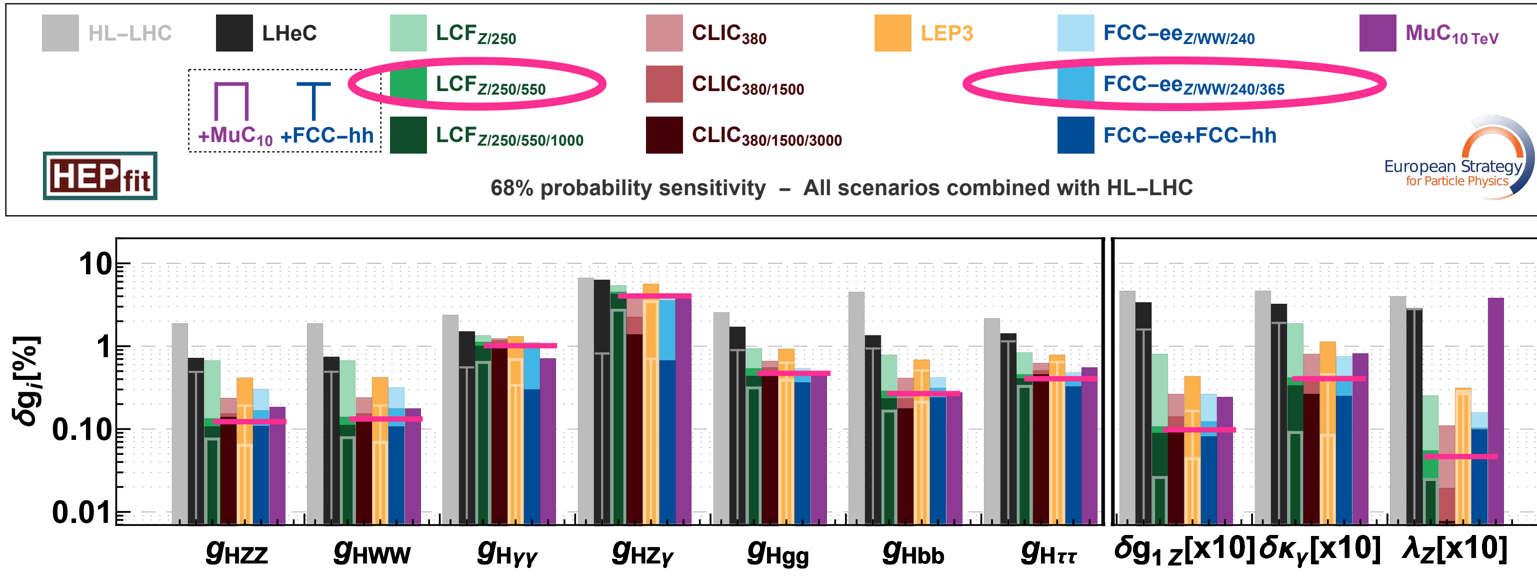

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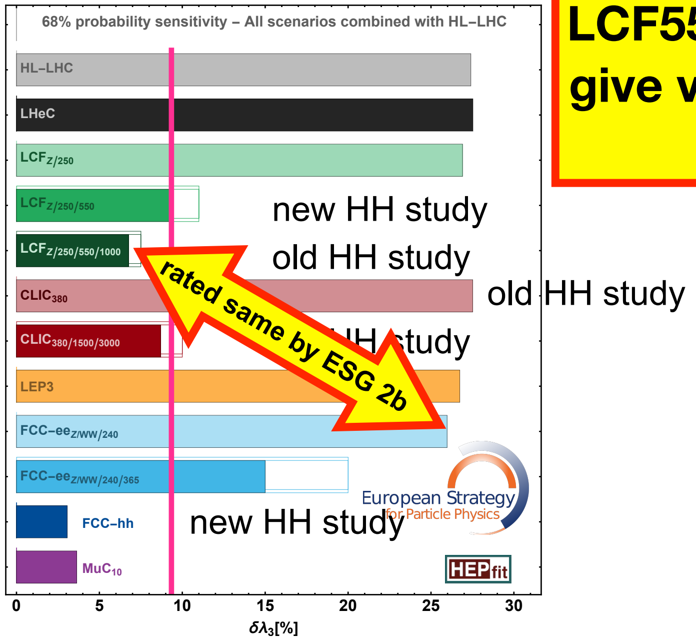

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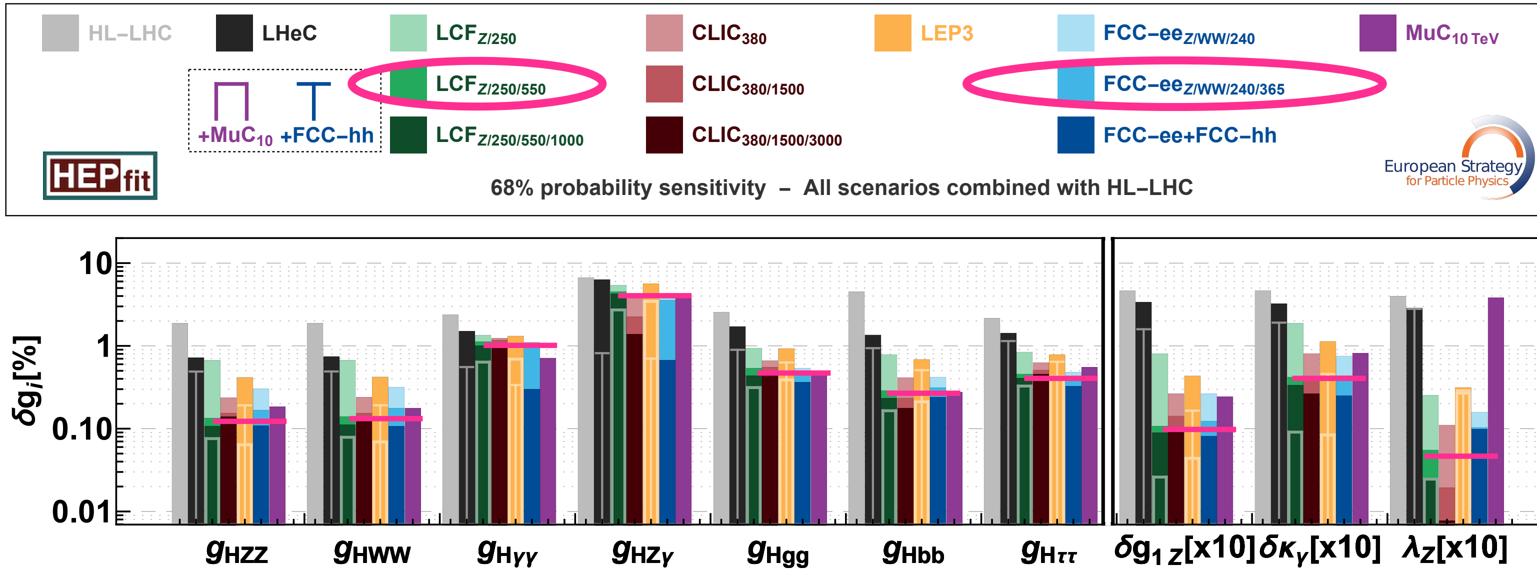

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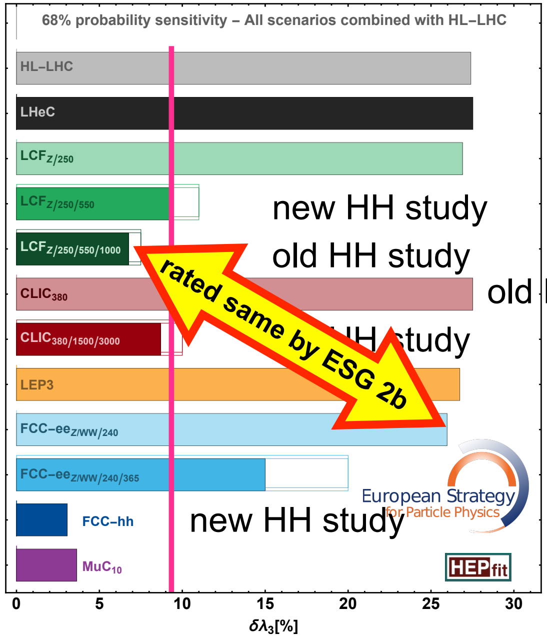
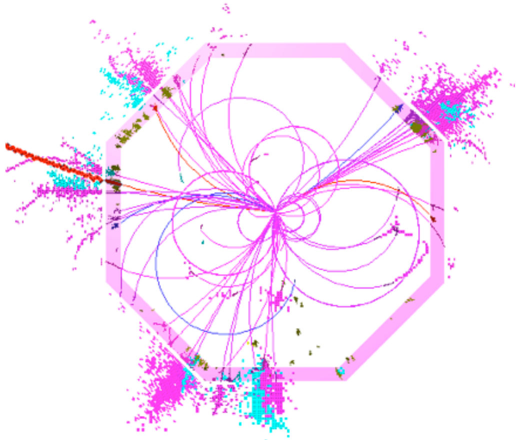


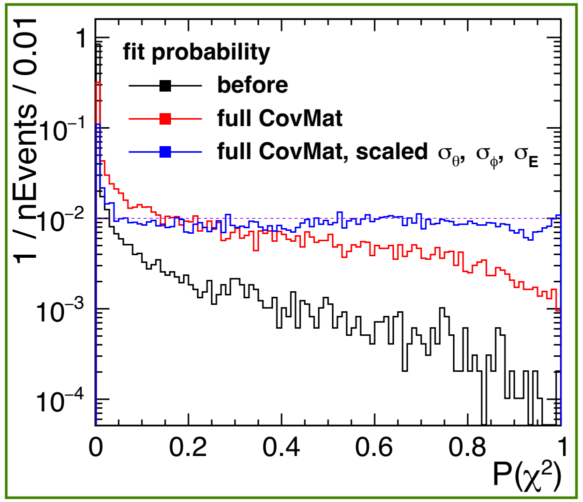
assumes SM value of λ_3 , i.e. $\kappa_\lambda = 1$

ErrorFlow and correction for semi-leptonic b-decays

PhD thesis Y.Radkhorrami, arxiv:2212.07264

- **ParticleFlow: optimised detectors reconstruct**
  - every particle (PFO) in a jet
  - 4-momentum and its **covariance matrix for each PFO**
  - charged: track fit - neutrals: calorimeters
  - modulo mistakes of PFlow algorithm => “confusion”

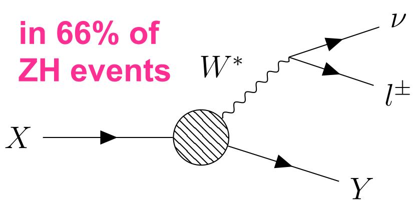


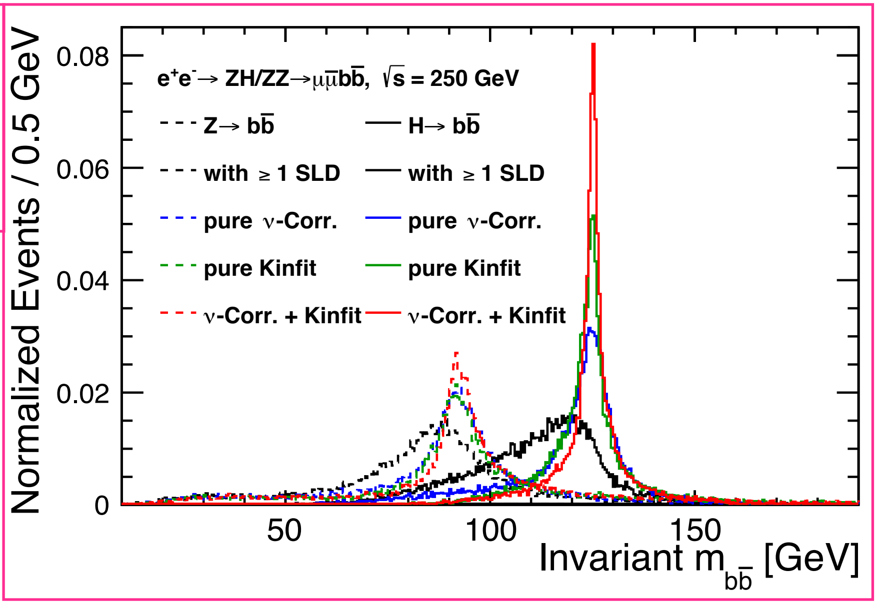


- **ErrorFlow:** jet covariance matrix propagated from jet PFOs
  - much better error estimates wrt parametrised approach
  - fit probability much closer to unifomity

- **semi-leptonic decay (SLD) correction**
  - charged lepton in b-tagged jet?
  - calculate ν momentum up to 2-fold ambiguity from visible momentum, 2ndary vertex position, B mass
  - propagate ν momentum uncertainty to jet cov. mat.
  - let kinematic fit resolve ambiguity
  - **impressive improvement in m_{bb} reconstruction!**

in 66% of ZH events





available in ilcsoft/key4hep

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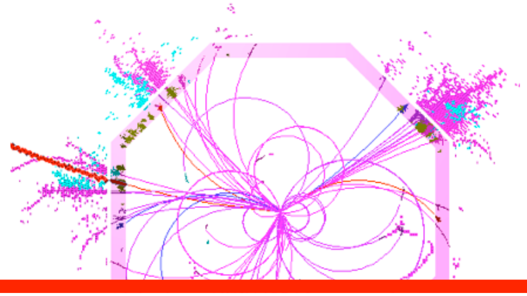
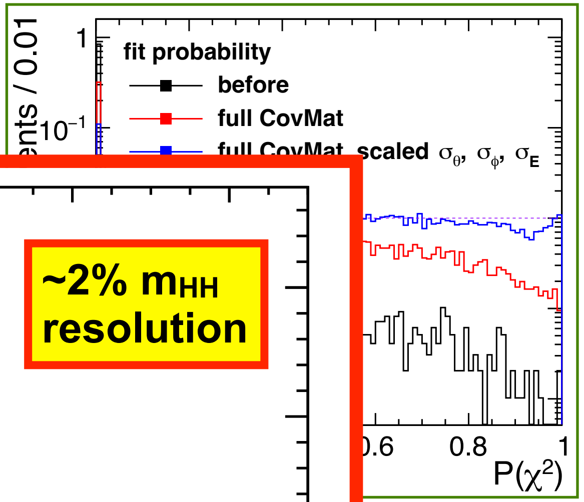
PhD thesis Y.Radkhorrami, arxiv:2212.07264





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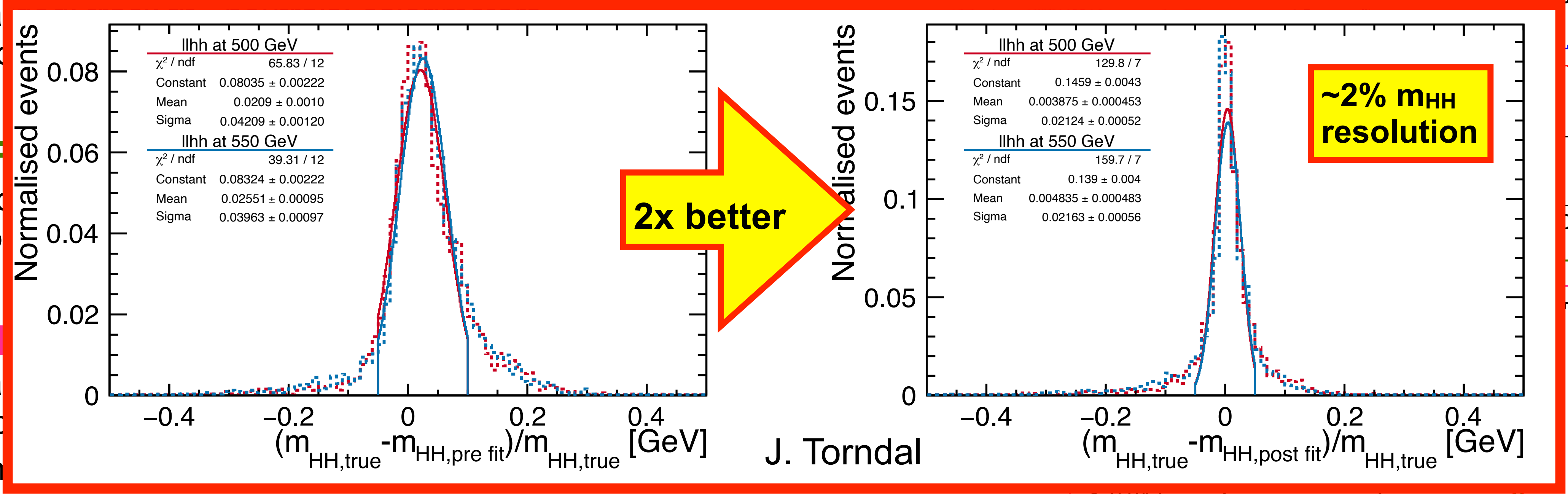
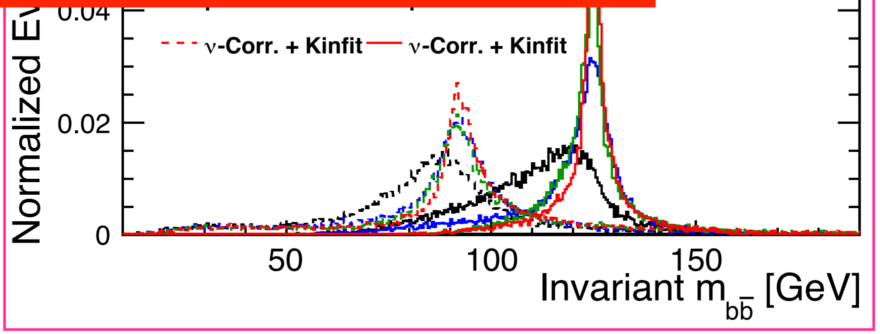
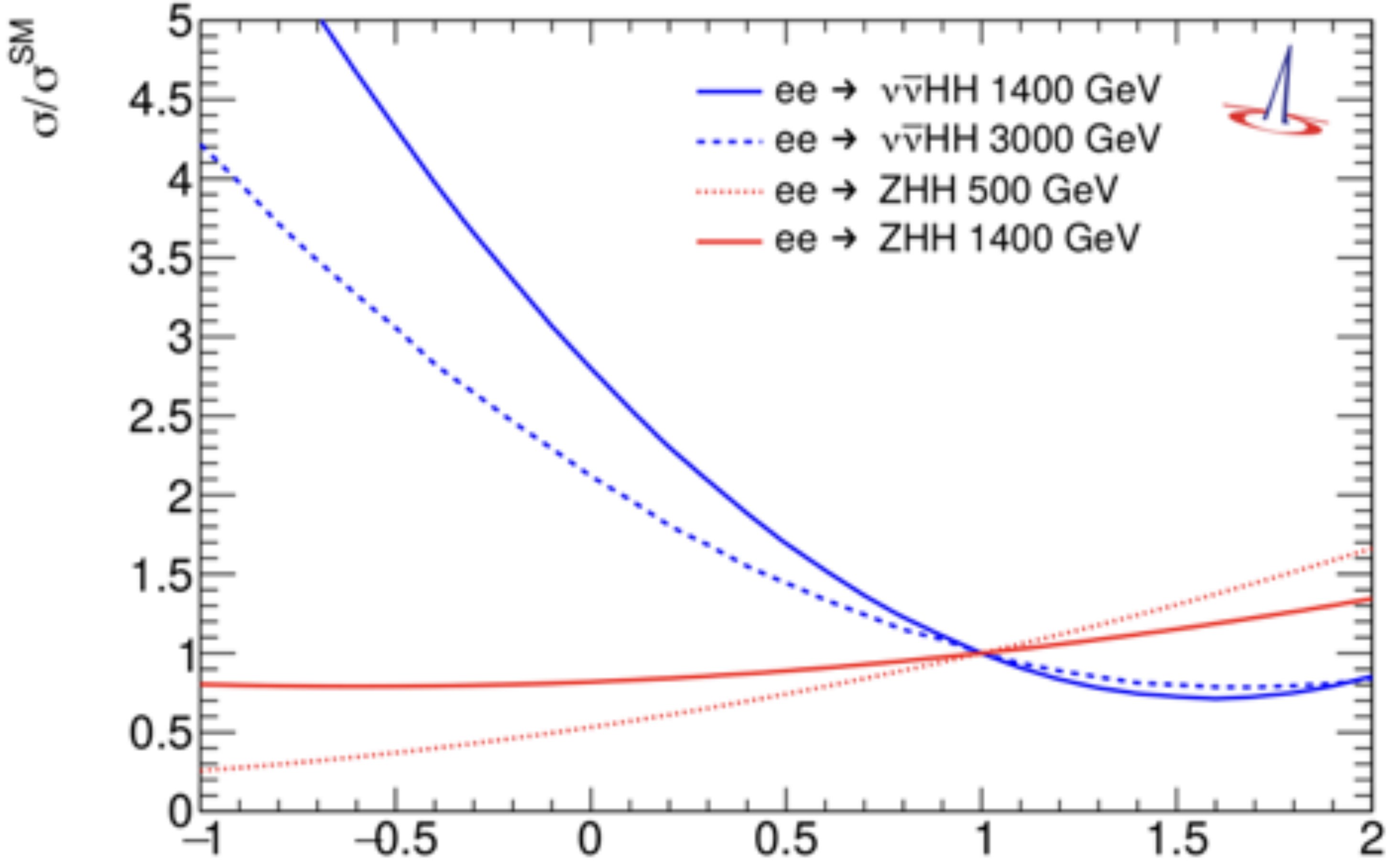




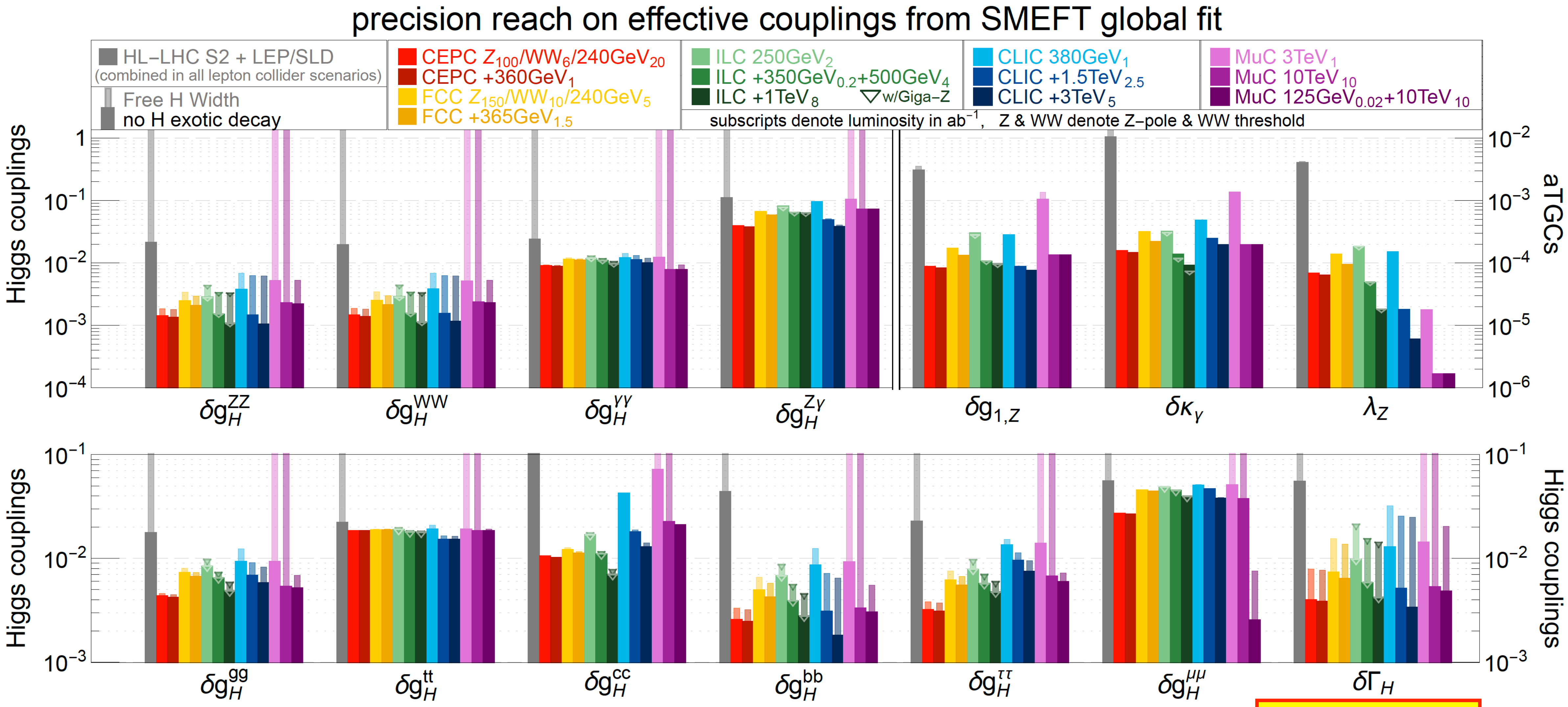
available in ilcsoft/key4hep

sigma vs lambda zoom



Higgs Couplings: The Snowmass SMEFT fit

Rainbow-Manhattans



arXiv:2206.08326

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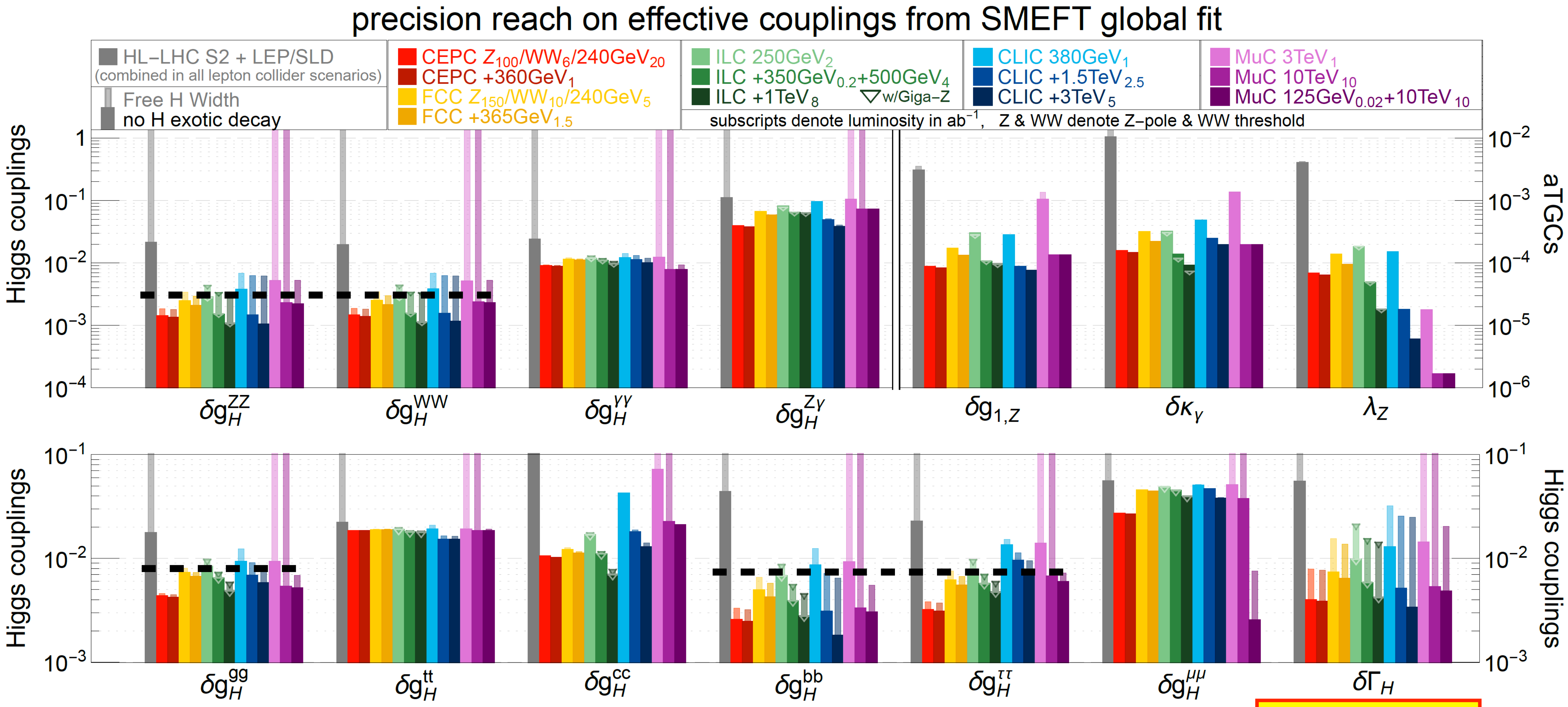

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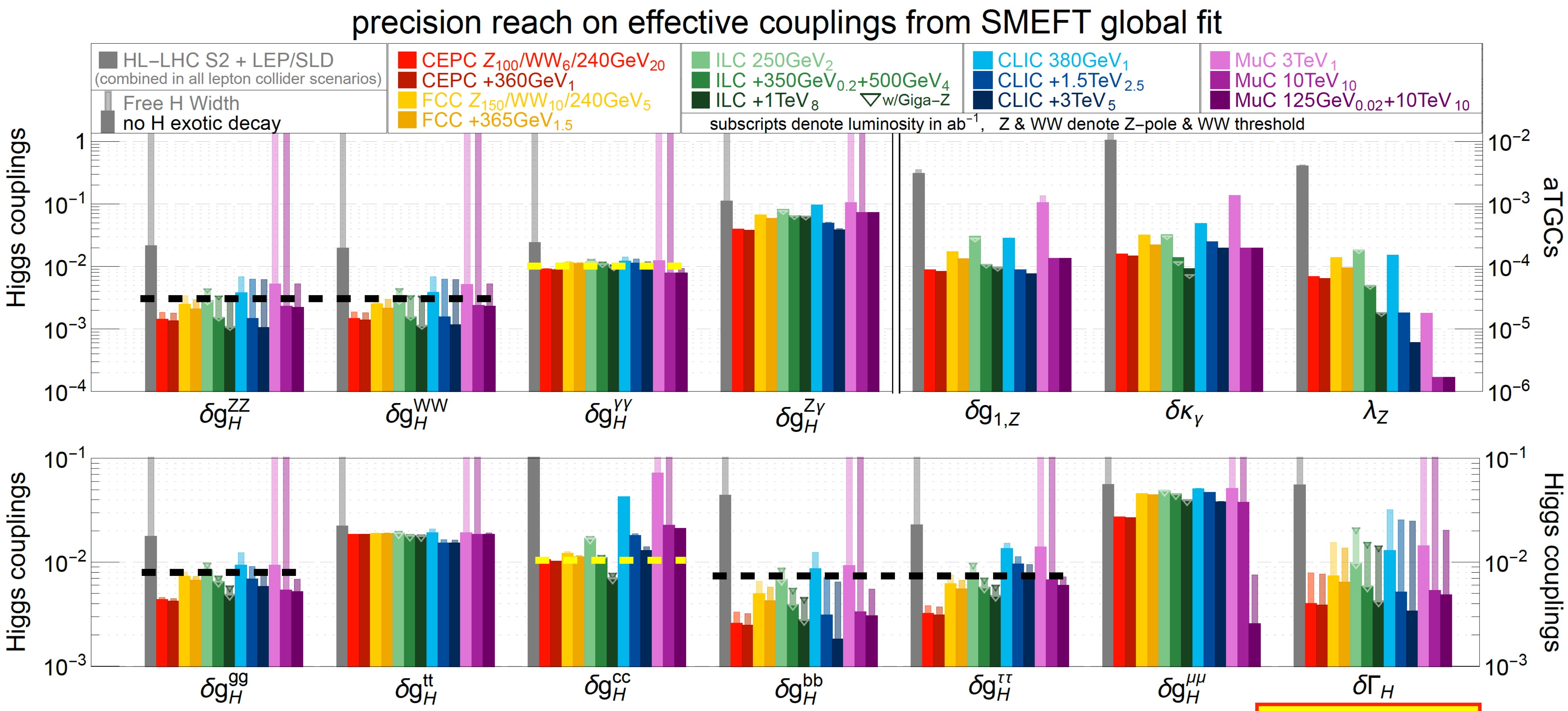

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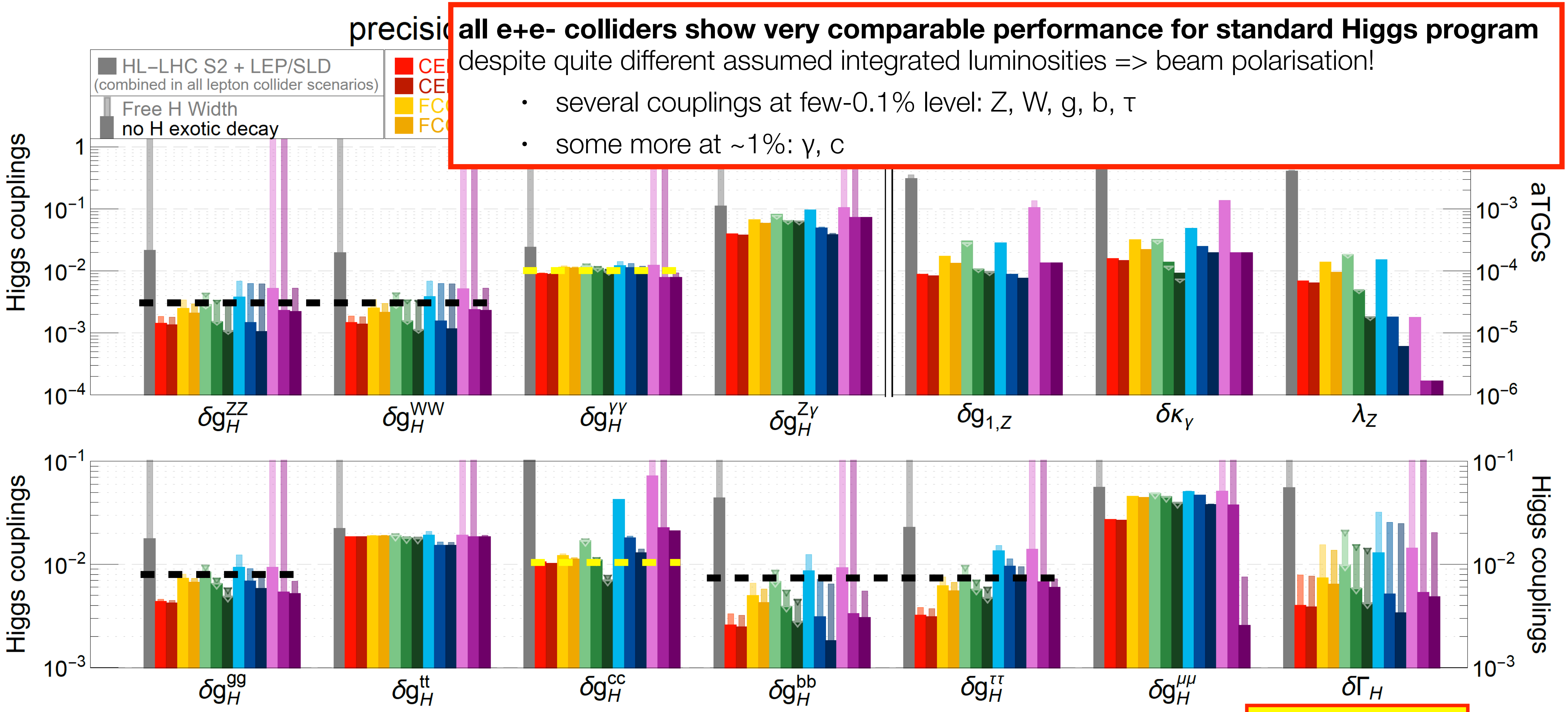
all e+e- colliders show very comparable performance for standard Higgs program
despite quite different assumed integrated luminosities => beam polarisation!

- several couplings at few-0.1% level: Z, W, g, b, τ
- some more at ~1%: γ, c



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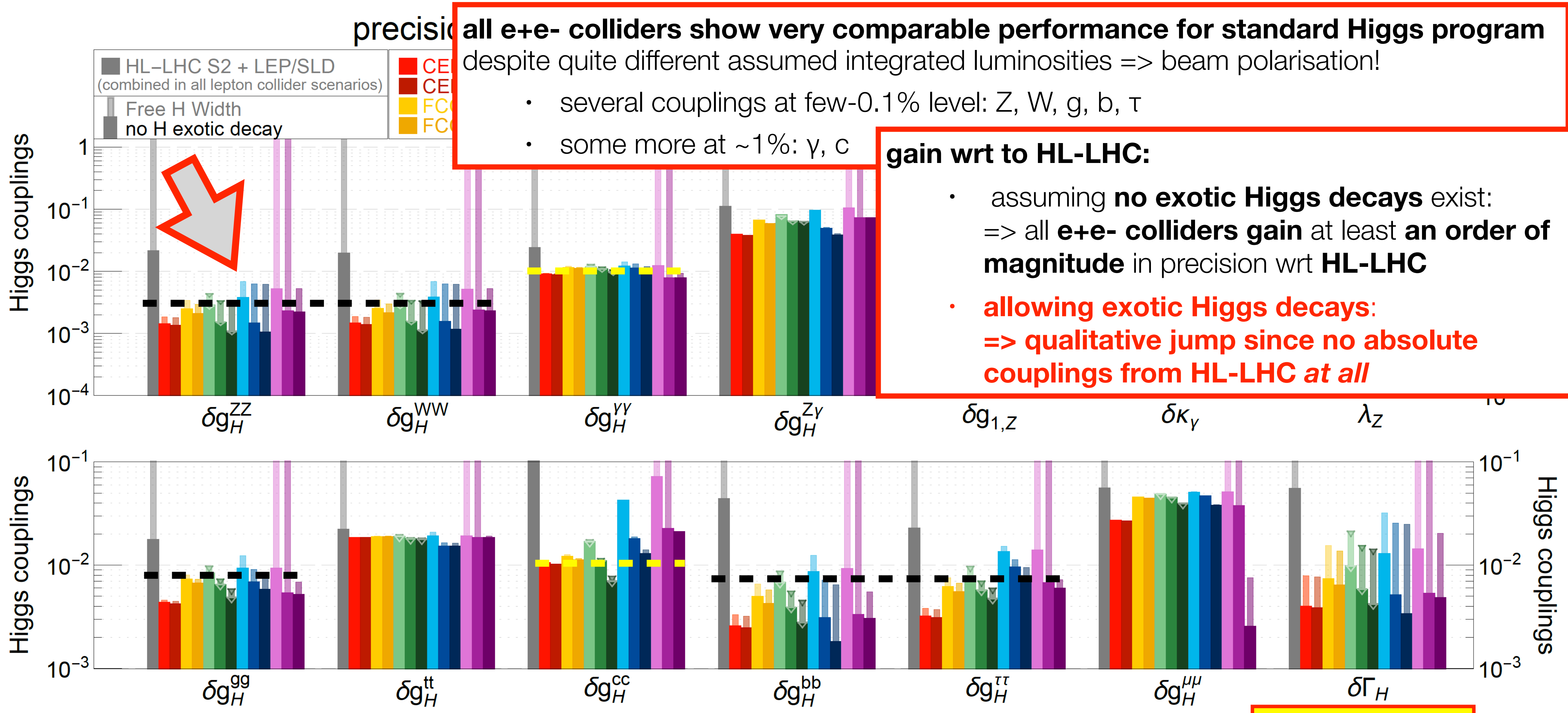

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gain wrt to HL-LHC:

- assuming **no exotic Higgs decays** exist: => all **e+e- colliders gain** at least **an order of magnitude** in precision wrt **HL-LHC**
- **allowing exotic Higgs decays: => qualitative jump since no absolute couplings from HL-LHC *at all***

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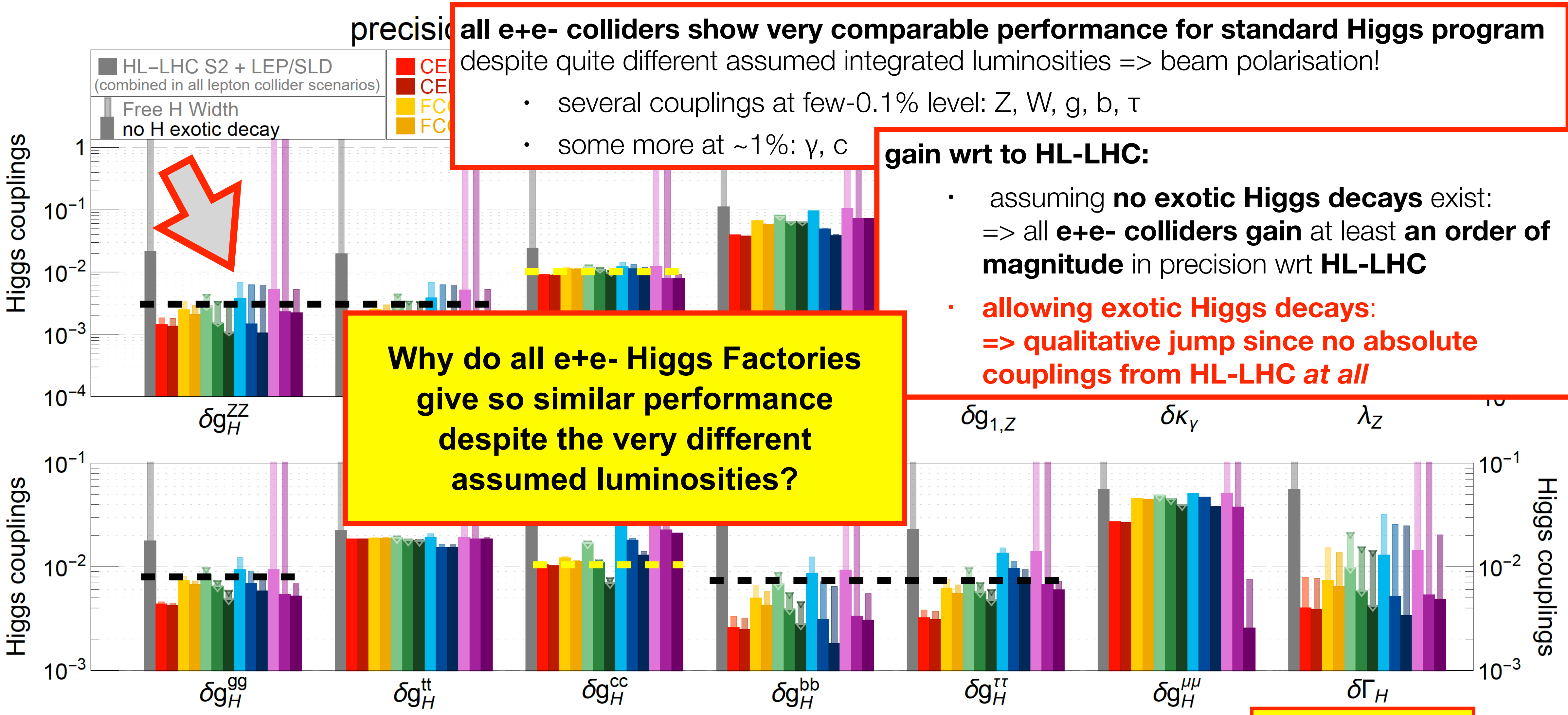

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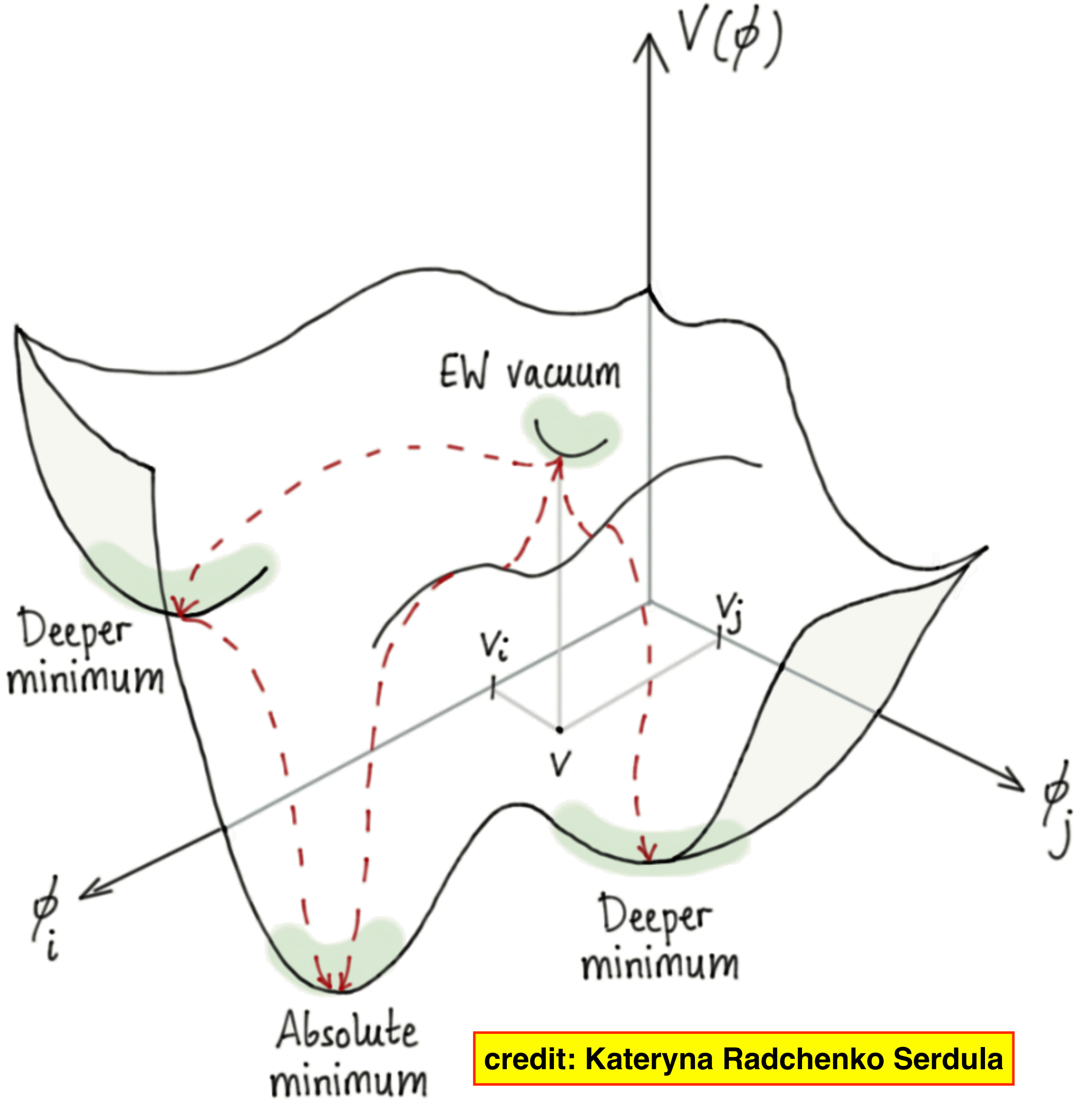
Why do all e+e- Higgs Factories give so similar performance despite the very different assumed luminosities?

arXiv:2206.08326

Higgs potential in extended Higgs Sectors

“Mexican hat” turns into complex landscape

- more Higgs fields => much more complex potential “landscape” (even at zero-temperature)
- extra Higgs bosons
- several triple-Higgs couplings among them
- several minima
- EW vaccuum not necessarily global minimum => vacuum stability?



credit: Kateryna Radchenko Serdula

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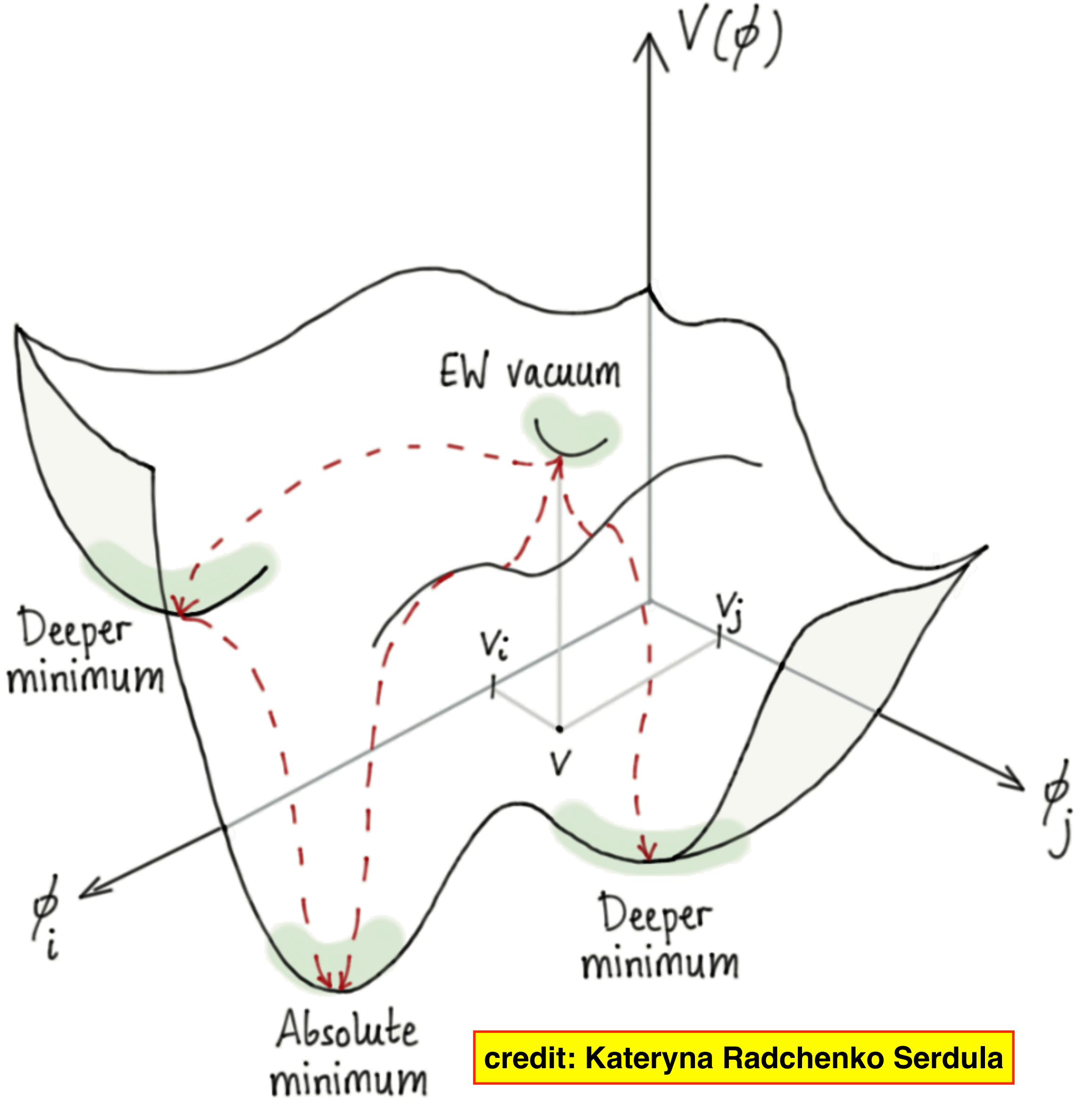
measure as many physical observables with least model-assumptions to explore this landscape - just assuming everything is like in the SM and extract one value is not sufficient!

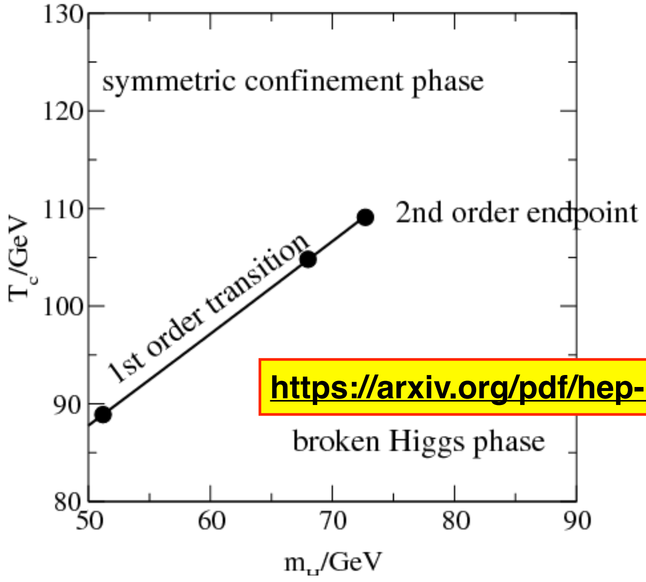


credit: Kateryna Radchenko Serdula

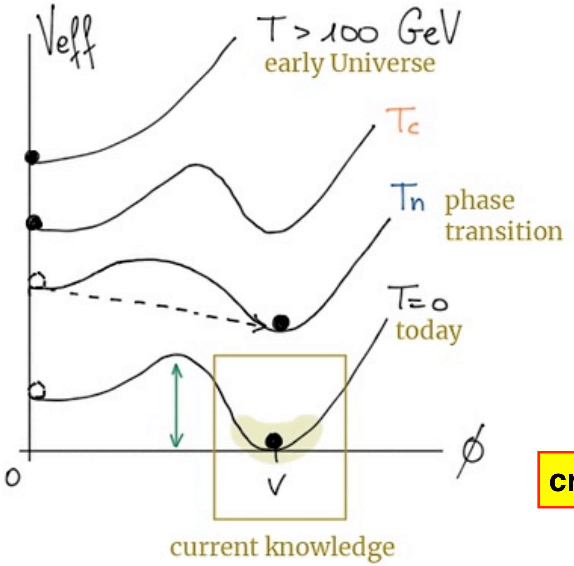
Electroweak Symmetry Breaking and Baryogenesis

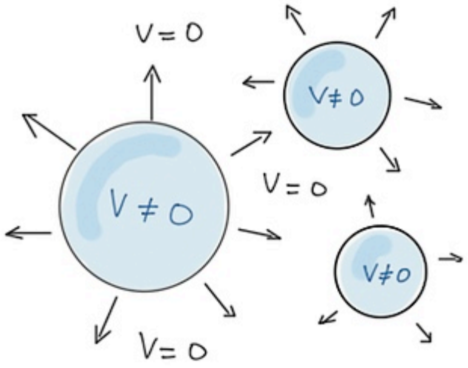
Evolution of the universe

- temperature evolution of Higgs potential ?
- phase diagram of the SM!
- for M_H > 75 GeV, there is no phase transition in the SM
- thus in SM no out-of-equilibrium state of the early universe for baryogenesis (requires 1st order phase transition, cf Sacharov conditions)
- in many **extended Higgs sectors**, 1st order phase transition for $\lambda_3 > \lambda_{SM}$
- need to
  - **measure** whether self-coupling λ_3 = 0.13 as predicted by SM - with the least possible prejudice! (eg “everything else” SM-like)
  - **check** whether Higgs field is indeed just one $SU(2)_L$ doublet



https://arxiv.org/pdf/hep-ph/0010275





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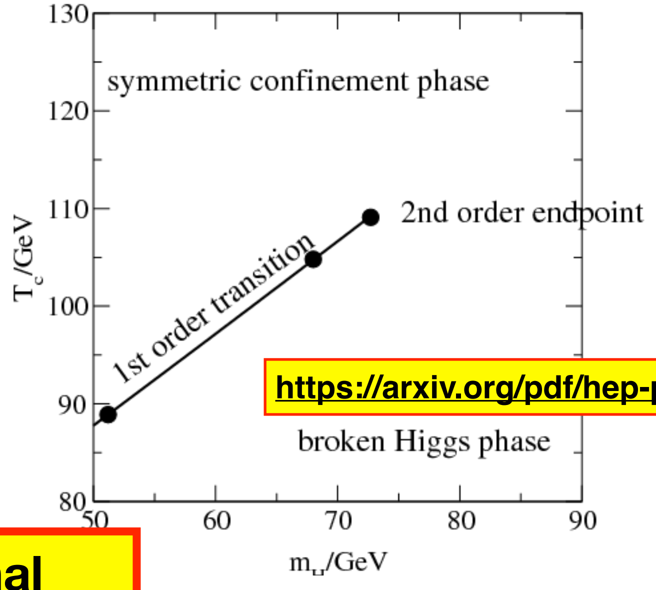
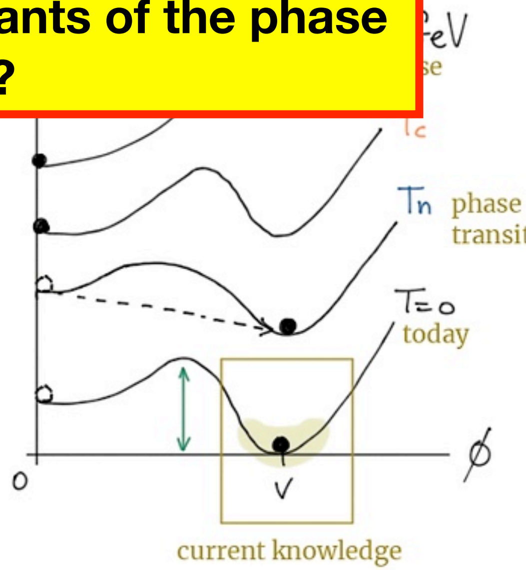
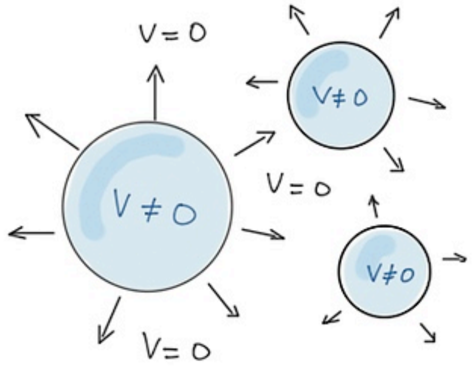


https://arxiv.org/pdf/hep-ph/0010275

Interesting interplay with gravitational waves: detect direct remnants of the phase transition?





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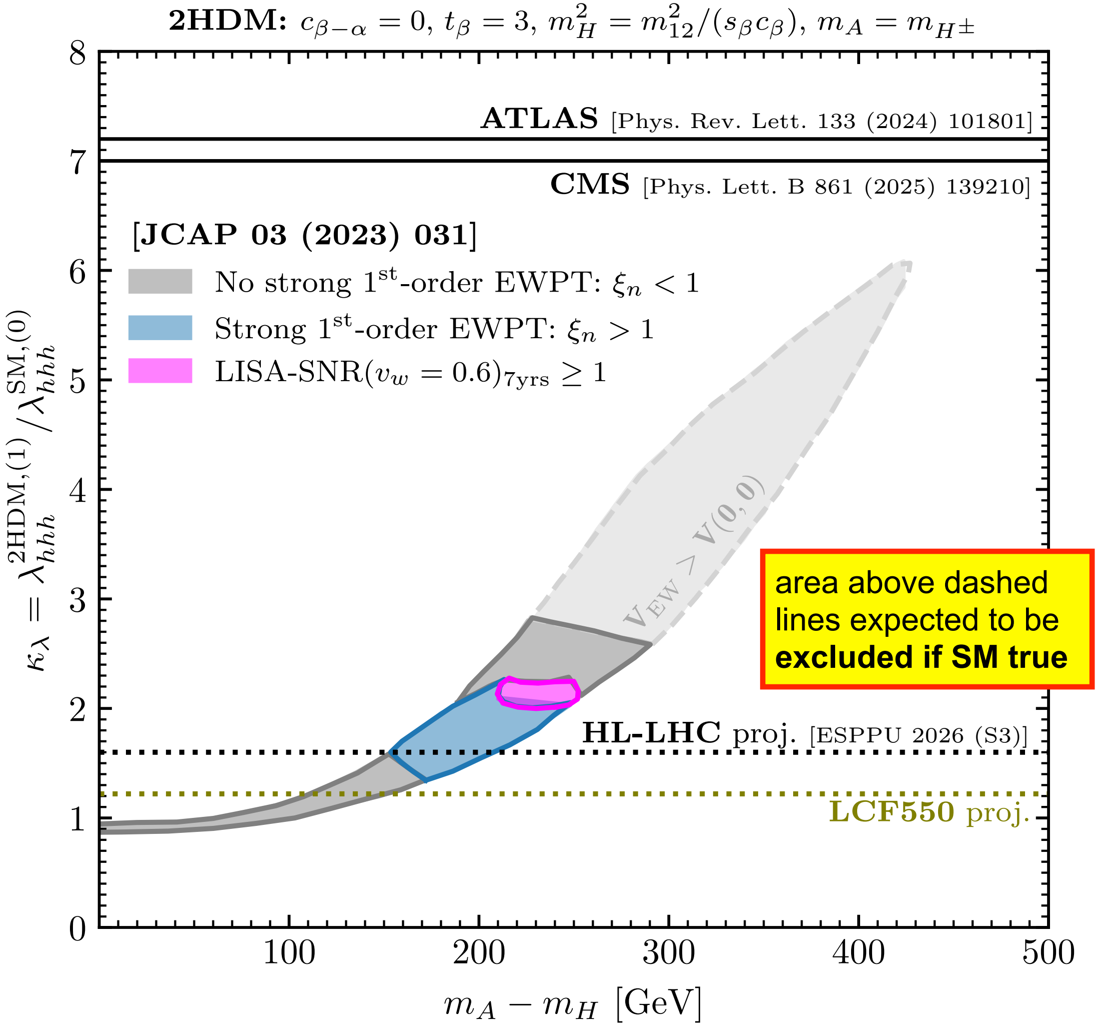
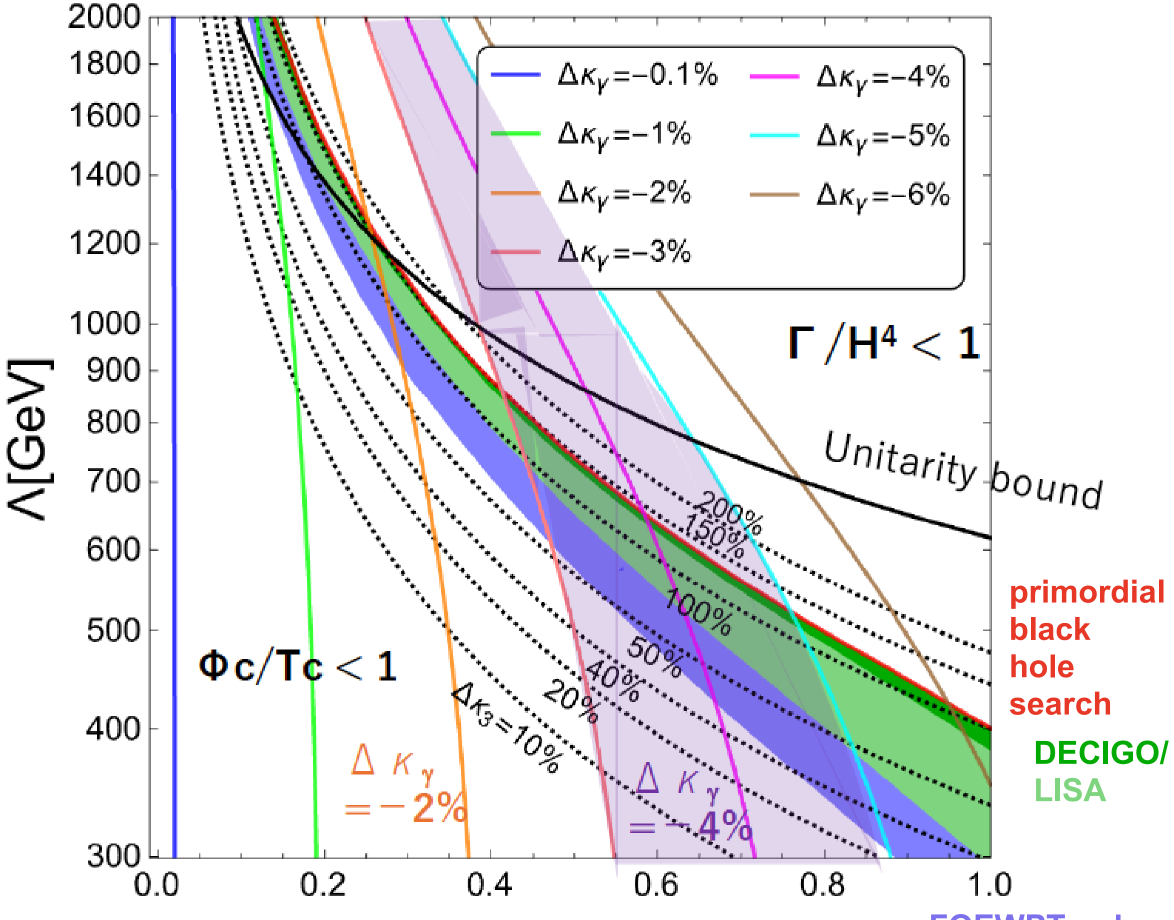
Interplay with Gravitational Wave detection

Need to assume specific extended Higgs sector to quantify effects



area above dashed lines expected to be **excluded if SM true**



Phys.Lett.B 856 (2024) 138940

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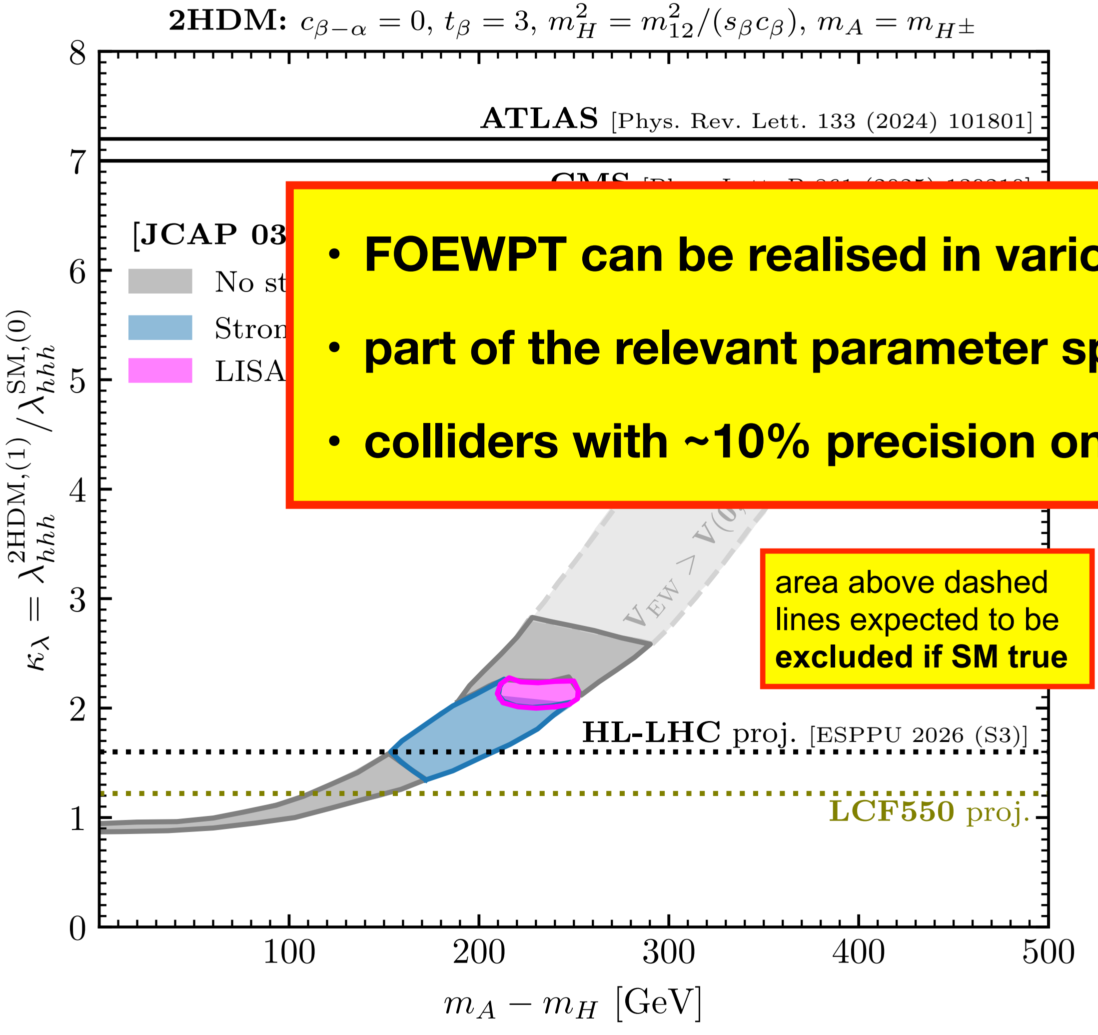

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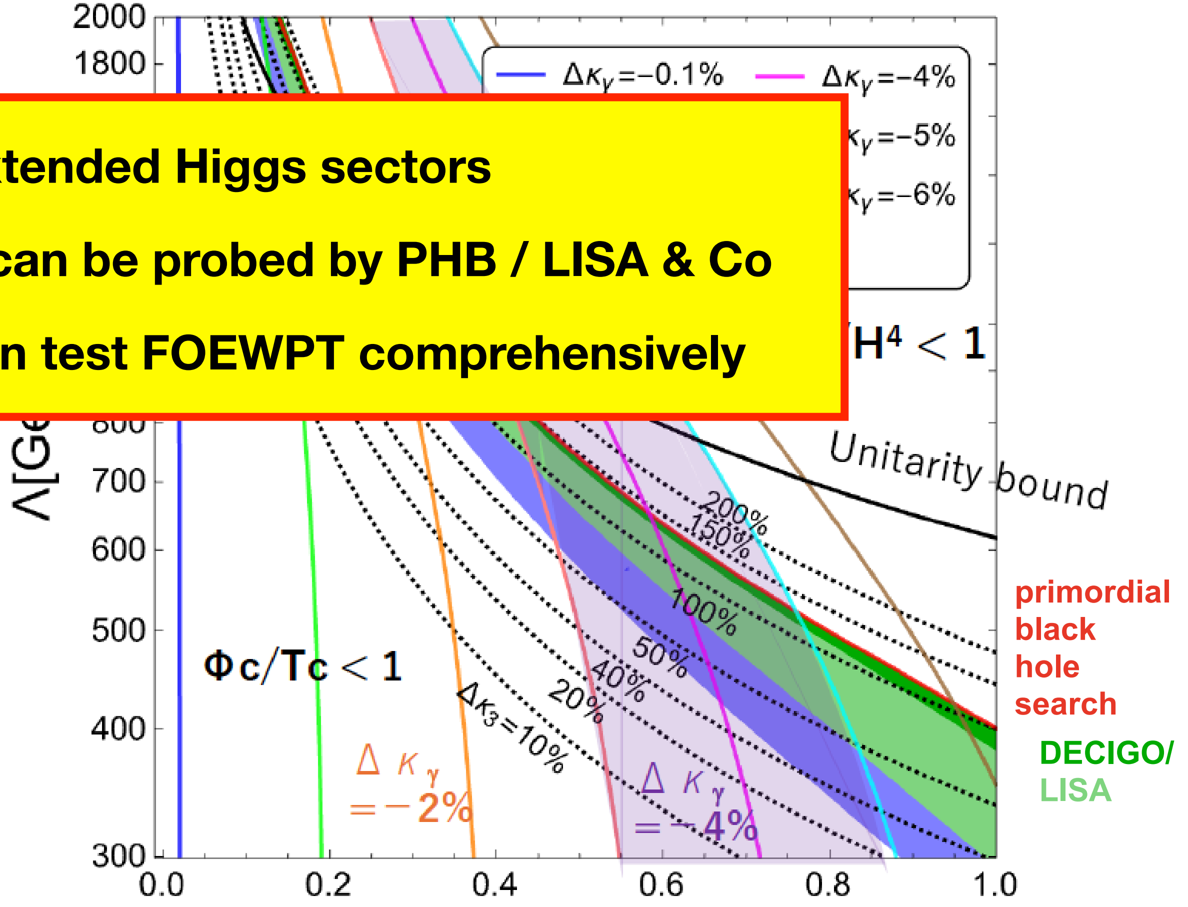
- **FOEWPT can be realised in various extended Higgs sectors**
- **part of the relevant parameter space can be probed by PHB / LISA & Co**
- **colliders with ~10% precision on κ_λ can test FOEWPT comprehensively**



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Interlude: Chirality in Particle Physics

Just a quick reminder…

- Gauge group of weak x electromagnetic interaction: $SU(2)_L$ x U(1)
- L: left-handed, spin anti-|| momentum*
  R: right-handed, spin || momentum*

- **left-handed particles are fundamentally different from right-handed ones:**
  - only left-handed fermions (e^-) and right-handed anti-fermions (e^+) take part in the charged weak interaction, i.e. couple to the W bosons
  - there are (in the SM) no right-handed neutrinos
  - right-handed quarks and charged leptons are singlets under $SU(2)_L$
  - also couplings to the Z boson are different for left- and right-handed fermions

$$P = \frac{N_R - N_L}{N_R + N_L}$$

- **checking whether the differences between L and R are as predicted in the SM is a very sensitive test for new phenomena!**

* for massive particles, there is of course a difference between chirality and helicity, no time for this today, ask at the end in case of doubt!

Physics benefits of polarised beams

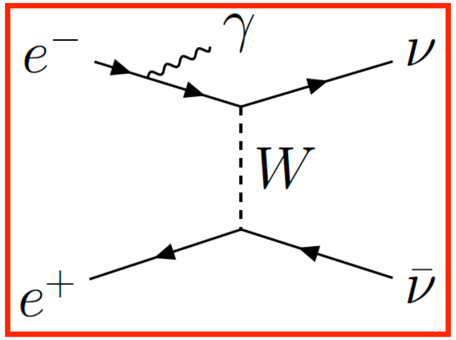
Much more than statistics!

General references on polarised e^+e^- physics:

- **arXiv:1801.02840**
- **Phys. Rept. 460 (2008) 131-243**

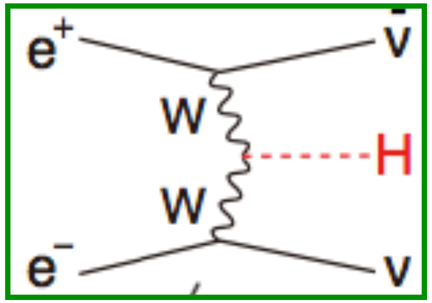
background suppression:

- $e^+e^- \rightarrow WW$ / $\nu_e \nu_e$ strongly P-dependent since t-channel only for $e^-_L e^+_R$



signal enhancement:

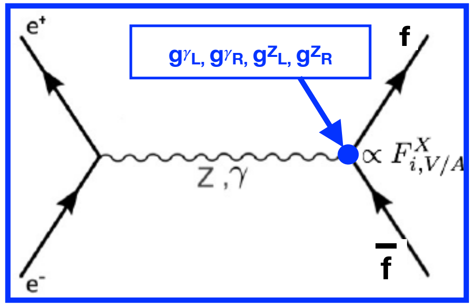
- Higgs production in WW fusion
- many BSM processes



have strong polarisation dependence => higher S/B

chiral analysis:

- SM: Z and γ differ in couplings to left- and right-handed fermions



- BSM:
chiral structure unknown, needs to be determined!

redundancy & control of systematics:

- "wrong" polarisation yields "signal-free" control sample
- flipping *positron* polarisation controls nuisance effects on observables relying on *electron* polarisation
- essential: fast helicity reversal for *both* beams!

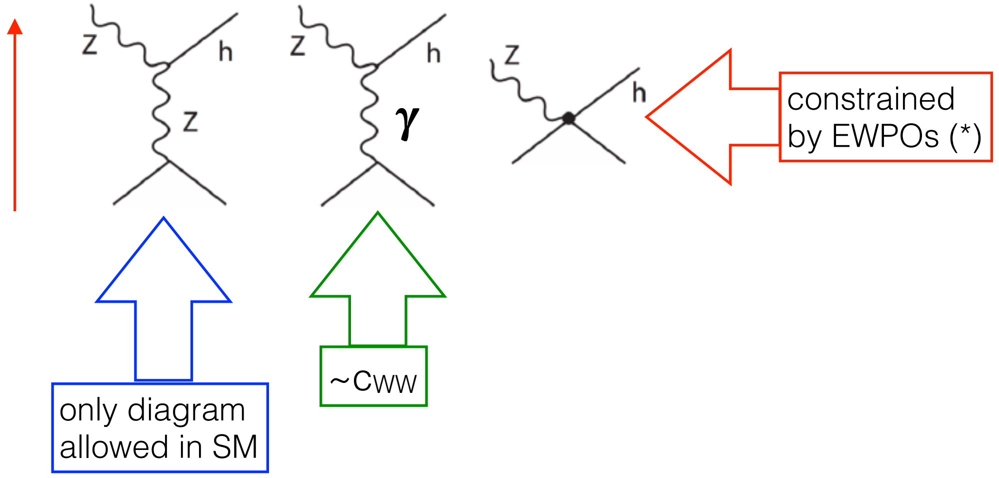
Polarisation & Higgs Couplings

A relationship only appreciated a few years ago…

- **THE key process** at a Higgs factory:

  Higgsstrahlung $e^+e^- \to Zh$

- **A_{LR}** of Higgsstrahlung: very important to **disentangle** different **SMEFT operators!**



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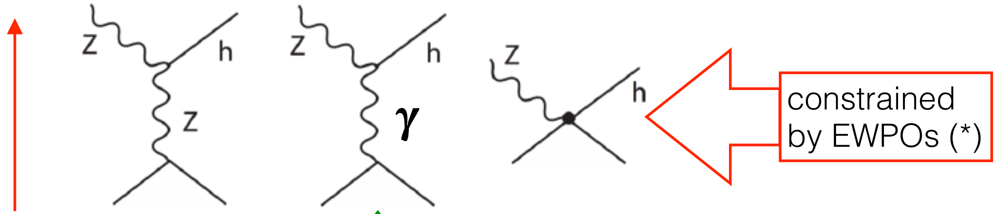

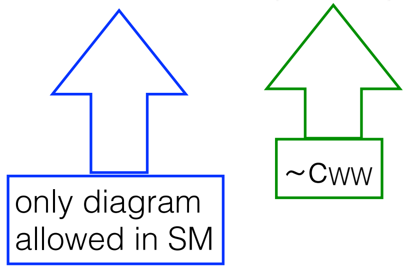

spin reversal $e^-_R \leftrightarrow e^-_L$:

- 1st diagram **flips** sign
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⇒ A_{LR} lifts degeneracy between operators!

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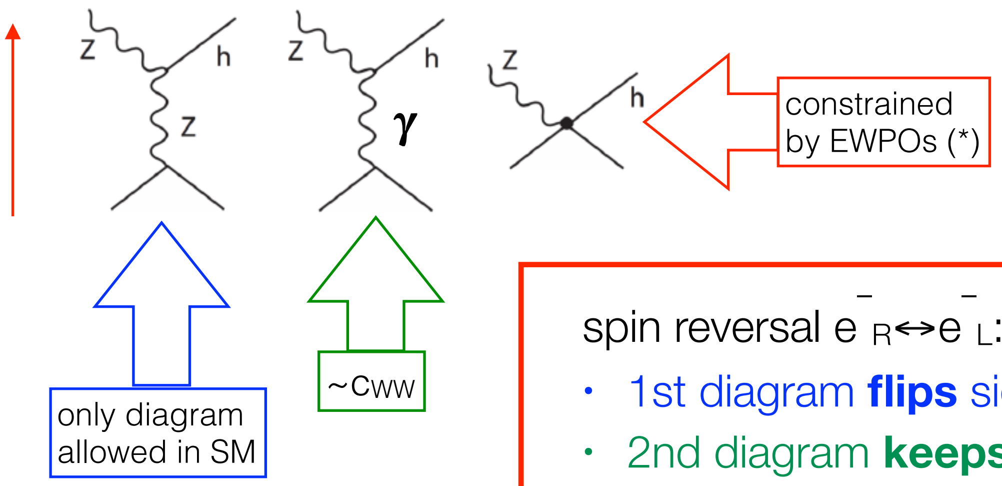

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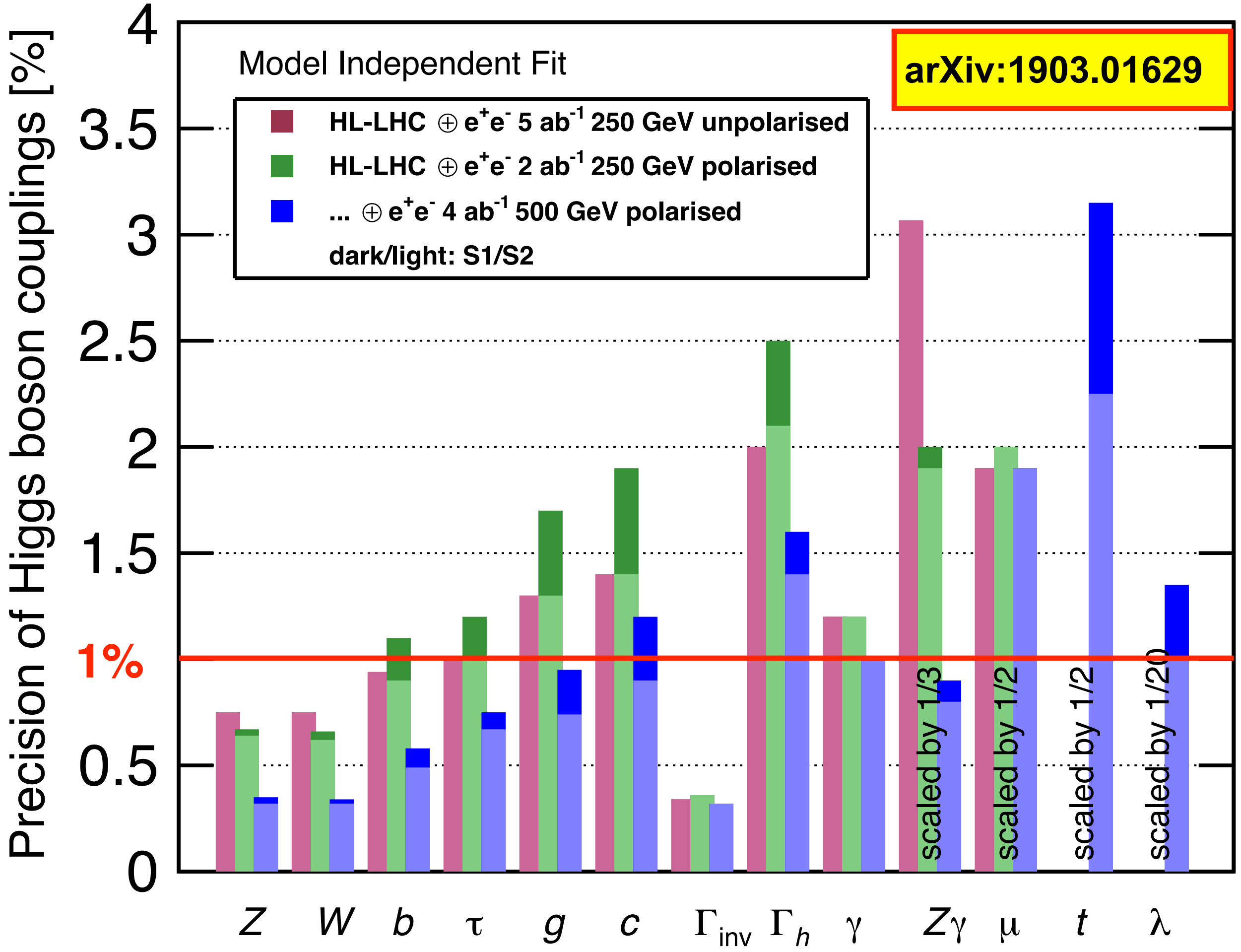

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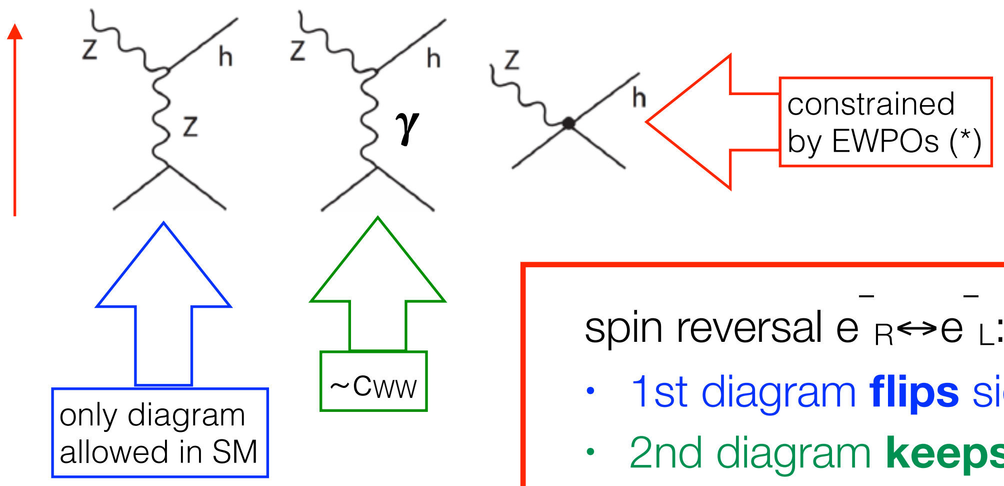

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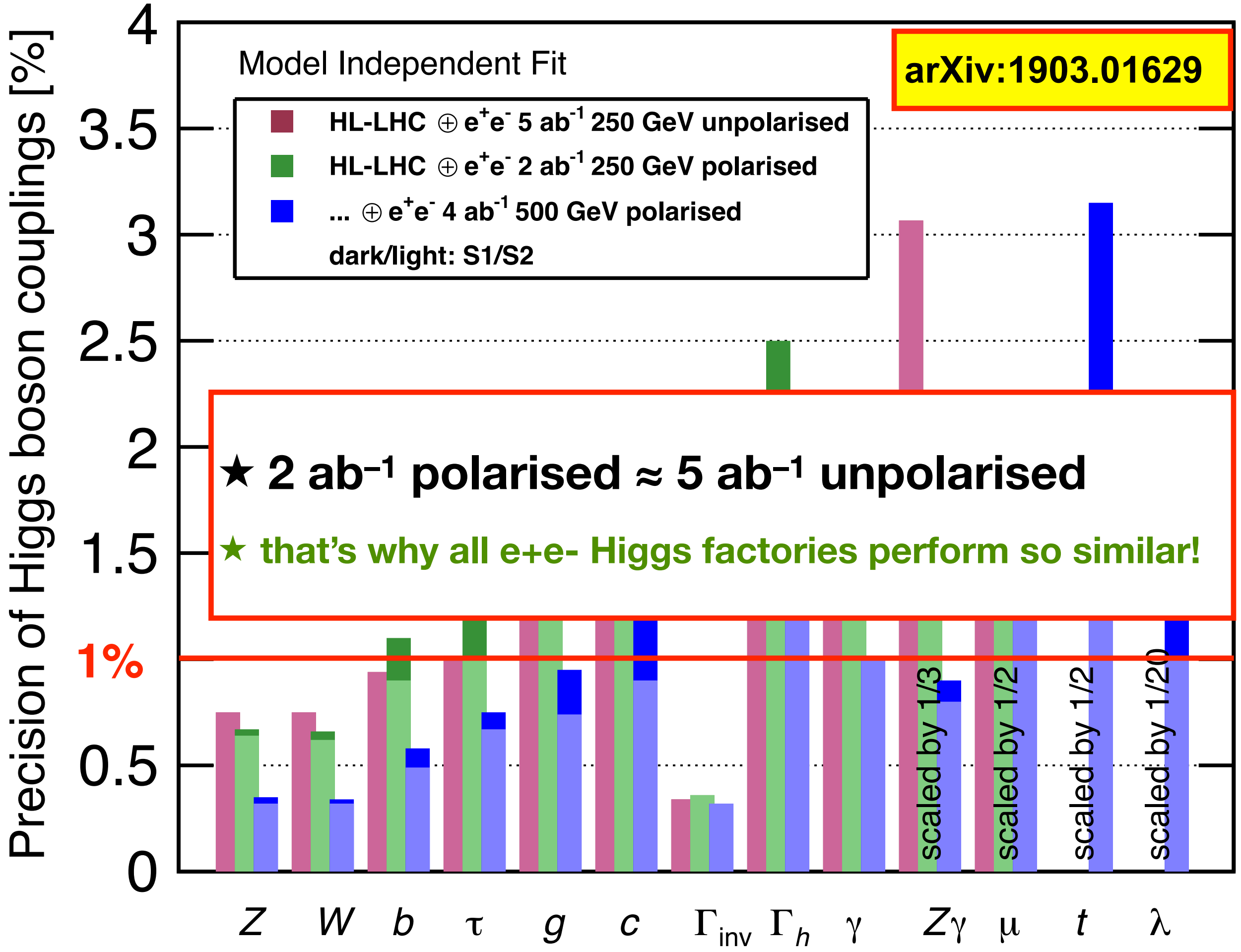
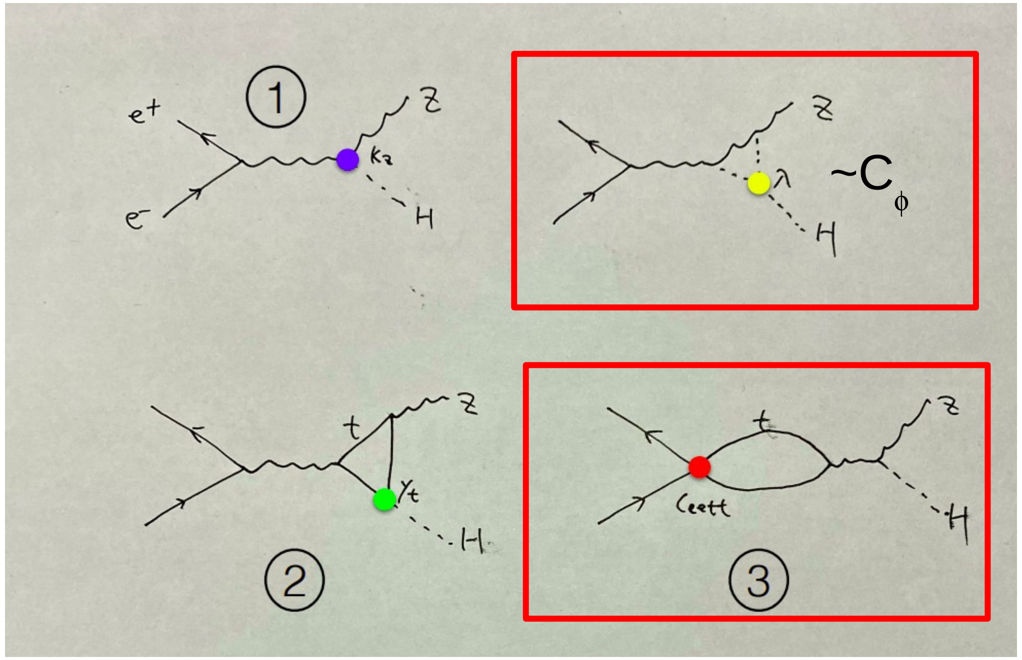


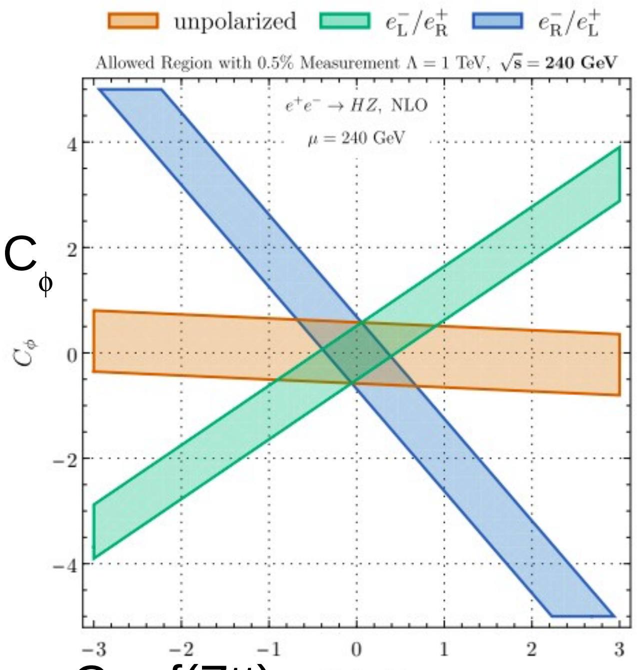
Entanglement - SMEFT NLO

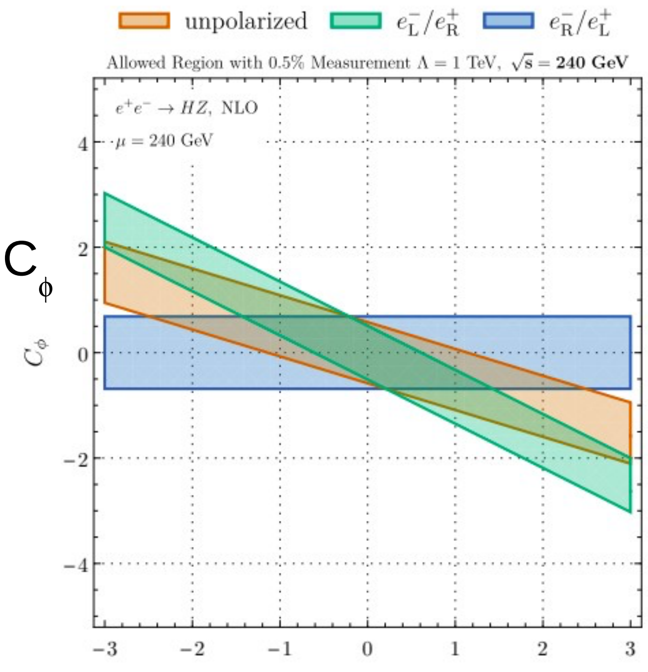
NLO Contributions to ee->HZ



One important contribution is eett Vertex

Correlation C_ϕ to tt-Vertices arxiv:2409.11466





- NLO SMEFT introduces sensitivity to and constrains C_ϕ and operators involving top vertices
- Disentangling of constraints using beam polarisation
- Final word would come from higher energy measurements
- Note that C_{lq} is strongly energy dependent (-> would benefit from higher energies)

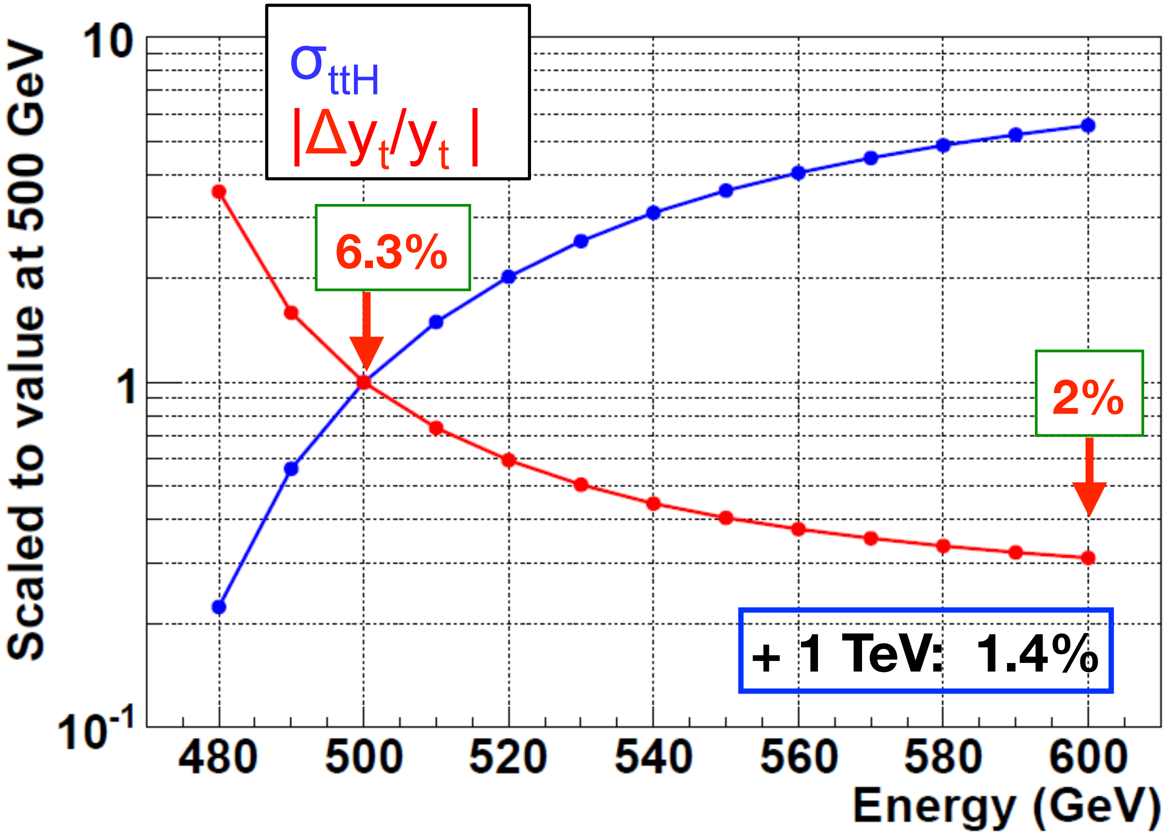
Top Yukawa coupling

Choosing the right energy

- **absolute size of $|y_t|$:**
  - **HL-LHC:**
    - **$\delta\kappa_t$ = 3.2% with $|\kappa_V| \leq 1$ or 3.4% in $SMEFT_{ND}$**
  - **e+e- LC:**
    - current full simulation achieved **6.3% at 500 GeV**
    - ***strong dependence*** on exact choice of E_{CM}, e.g. **2% at 600 GeV**
    - *not* included:
      - experimental improvement with higher energy (boost!)
      - other channels than H->bb

The Higgs and the Top

[Phys.Rev. D84 (2011) 014033 & arXiv:1506.07830]



to-do: real, full sim study @ 600 GeV!

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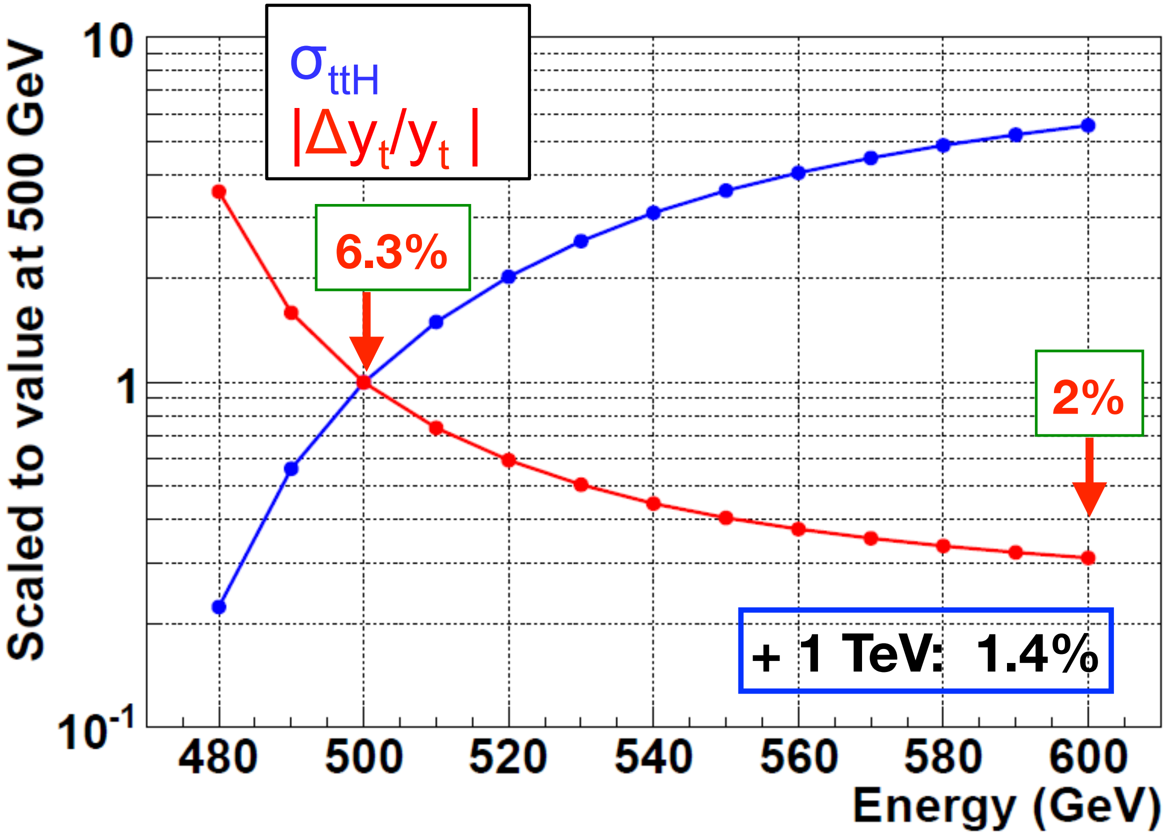
- **full coupling structure** of tth vertex, incl. CP:
  - **e^+e^- at E_{CM} ≥ ~600 GeV**
    => *few percent sensitivity to CP-odd admixture*
  - **beam polarisation essential!**

[Eur.Phys.J. C71 (2011) 1681]



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