Assessing uncertainties arising in the interpretation of single-Higgs-production observables as a measurement of the triple Higgs coupling

EPS-HEP Marseille 2025 - T08

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DAAD
Deutscher Akademischer Austauschdienst
German Academic Exchange Service

The Higgs self-coupling

The Standard Model Lagrangian

$$\mathcal{L}_{\mathrm{SM}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \overline{\psi}\not{D}\psi + \psi_i y_{ij}\psi_j\Phi + \mathrm{h.c.} + |D_\mu\Phi|^2 - V(\Phi)$$

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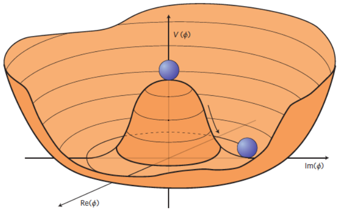

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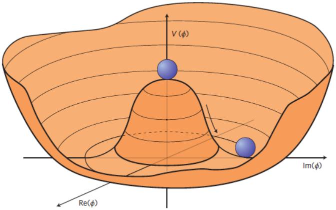

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$$V \rightarrow \frac{1}{2}m_h^2 h^2 + \lambda_3 \nu h^3 + \frac{1}{4}\lambda_4 h^4$$

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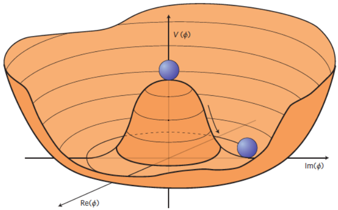

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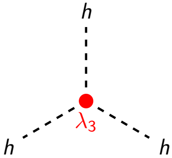

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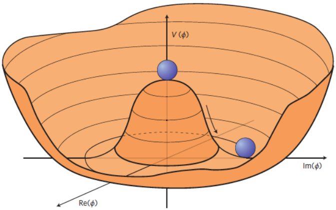

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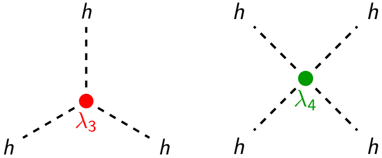

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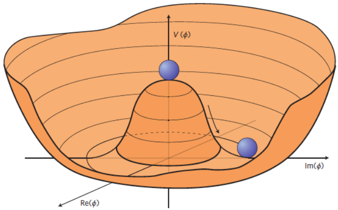

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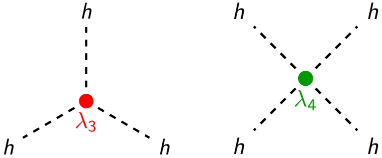

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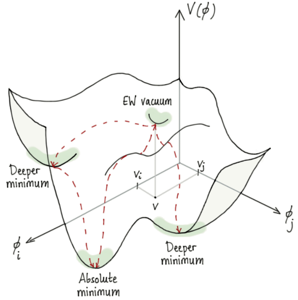

[Radchenko.2024]

After spontaneous symmetry breaking:

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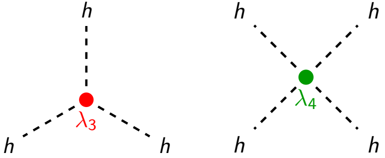

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$$\lambda_3^{\mathrm{SM}} = \lambda_4^{\mathrm{SM}} = \lambda = \frac{m_h^2}{2v^2}$$

- In BSM contexts: define coupling modifiers:

$$\kappa_3 := \frac{\lambda_3}{\lambda_3^{\mathrm{SM}}}, \quad \kappa_4 := \frac{\lambda_4}{\lambda_4^{\mathrm{SM}}}$$

Future e^+e^- colliders

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

- Will provide model-independent measurements of Higgs width and couplings
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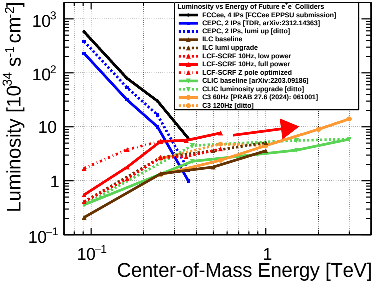
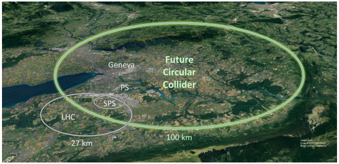


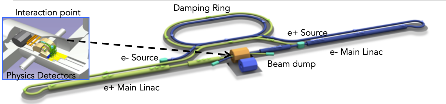
[ILC.Plots.2025]

2 categories:



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

[OPEN-PHO-ACCEL-2019-001]



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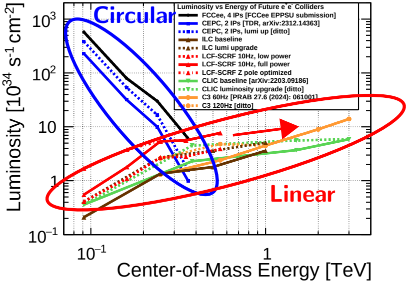

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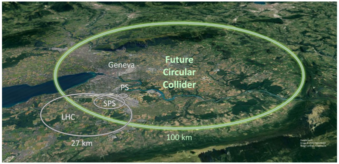

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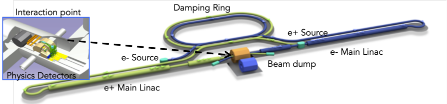

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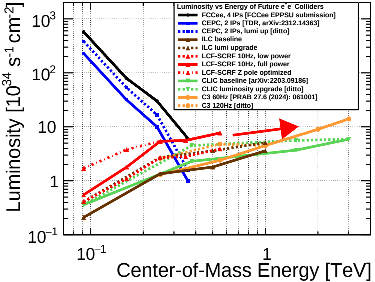

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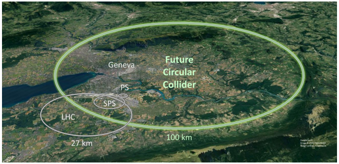

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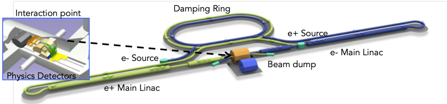

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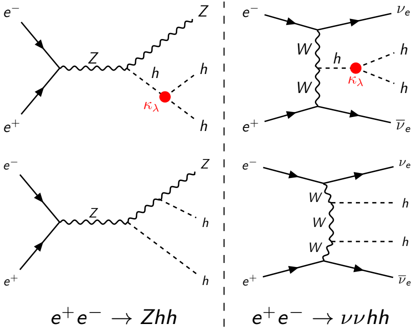
κ_λ at future e^+e^- colliders - direct sensitivity

Ideal way to probe $\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$: *hh* production



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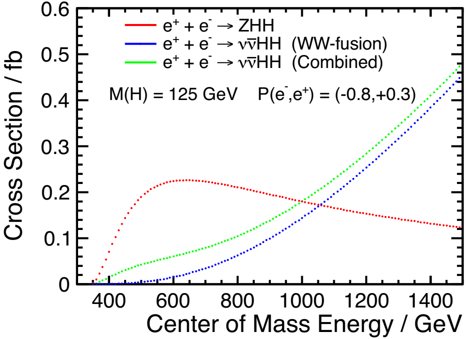

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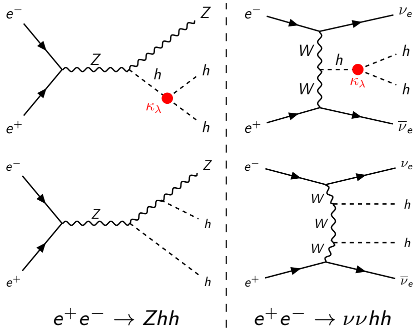

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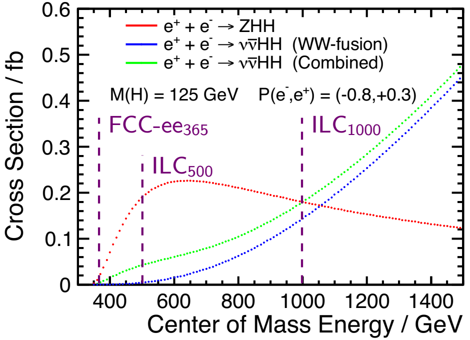
- However: need $\sqrt{s} \gtrsim 500$ **GeV**
  - ➢ Only achievable at **linear** e^+e^- colliders



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Alternative: precision measurements of **single h** observables

- κ_λ only present at **loop-level** — need **high precision!**
- **Profits greatly** from measurements at **two different energies** (e.g. 240 & 365 GeV)
  - ➢ **Disentangle** κ_λ from other couplings
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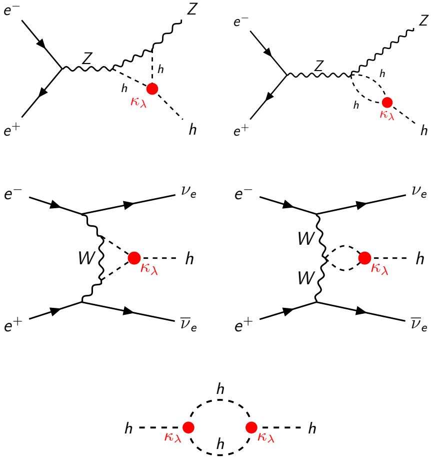

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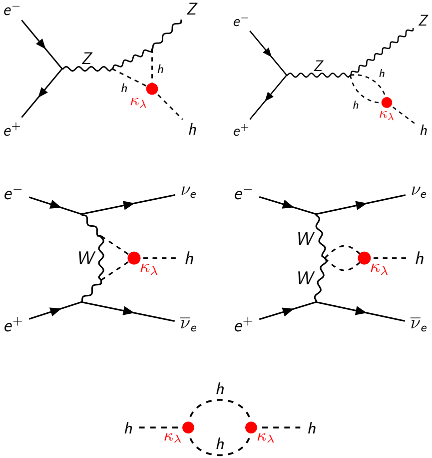
- **Caveat:** sensitivity depends on the BSM theoretical framework, i.e.:
  - ➢ **BSM particles** in the **loop**
  - ➢ Theoretical **assumptions**



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Goal of the project: compare the EFT approach with a simple BSM model: Inert Doublet Model (IDM)

The Inert Doublet Model (IDM)

- 2 Higgs doublets:

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

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  - ➢ No coupling between **BSM Higgs** and **SM fermions** ("inert")
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- **Crucially: parameter space allows for large κ_λ, while keeping all other Higgs couplings $\approx$ SM-like**

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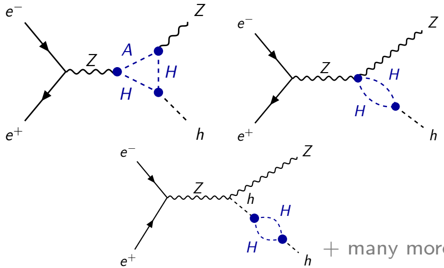
- **HEPfit** [deBlas.2020]
  - ➢ Performs global fits over a variety of BSM models (e.g. SMEFT)
- **Bayesian Analysis Toolkit (BAT)** [Beaujean.2015]
  - ➢ Uses Markov Chain Monte Carlo (MCMC) to obtain Bayesian posterior distributions

σ_{Zh} prediction: IDM vs. SMEFT

IDM calculation:

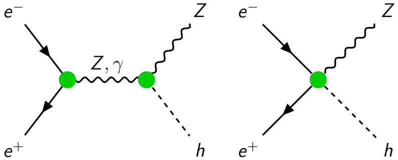
- Full 1-loop **BSM** $Z \to Zh$ vertex and external leg corrections, e.g.:



+ many more

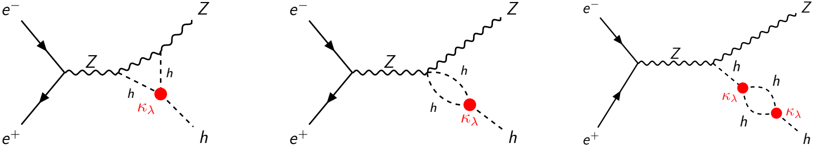
SMEFT calculation:

- Full dim-6 tree-level **SMEFT**



+ many more

+ contributions involving κ_λ (1-loop SM-like diagrams with insertions of one or two powers of κ_λ; formally of 2-/3-loop order)



Truncation of σ_{Zh} expression in SMEFT

Assuming $\kappa_\lambda \neq 1$, with $\lambda_3 = \kappa_\lambda \lambda_3^{\mathrm{SM}}$, one can parametrize the Zh cross-section as:

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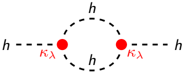
- σ_{LO} is the leading-order cross-section
- $Z_{h,\kappa_\lambda} = (1 - \kappa_\lambda^2 \delta Z_h)^{-1}$ is the resummed κ_λ^2 contribution to the wave function renormalization (WFR) constant of the Higgs field, with:

$$\delta Z_h = -\frac{9}{16\sqrt{2}\pi^2}\left(\frac{2\pi}{3\sqrt{3}} - 1\right) G_F m_h^2 \simeq$$



$$\simeq -1.536 \times 10^{-3}$$

Truncation of σ_{Zh} expression in SMEFT

Assuming $\kappa_\lambda \neq 1$, with $\lambda_3 = \kappa_\lambda \lambda_3^{\text{SM}}$, one can parametrize the Zh cross-section as:

$$\sigma_{\kappa_\lambda} = Z_{h,\kappa_\lambda} \cdot \sigma_{\text{LO}} \cdot (1 + \kappa_\lambda C_1) \quad , \quad \text{where:}$$

- σ_{LO} is the leading-order cross-section
- $Z_{h,\kappa_\lambda} = (1 - \kappa_\lambda^2 \delta Z_h)^{-1}$ is the resummed κ_λ^2 contribution to the wave function renormalization (WFR) constant of the Higgs field, with:

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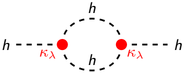
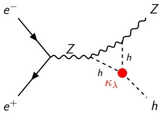


$$\simeq -1.536 \times 10^{-3}$$

- C_1 corresponds to the momentum-dependent contributions to the Zh vertex



Then, one can write the ratio of the cross-section with respect to the SM value as:

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

Truncation of σ_{Zh} expression in SMEFT (cont.)

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

Expanding the ratio in powers of $(\kappa_\lambda - 1)$ gives different possible expressions:

(Exact formulas in the backup slides)

Truncation of σ_{Zh} expression in SMEFT (cont.)

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Expanding the ratio in powers of $(\kappa_\lambda - 1)$ gives different possible expressions:

- No $\boldsymbol{\mathcal{O}(1/\Lambda^4)}$ contributions: expand up to $\boldsymbol{\mathcal{O}((\kappa_\lambda - 1)^1)}$ terms

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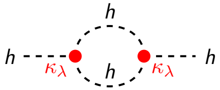
- Including $\boldsymbol{\mathcal{O}((\kappa_\lambda-1)^3)}$ terms
- Use **full** expression

(Exact formulas in the backup slides)

σ_{Zh} prediction: IDM vs. SMEFT

Potential **drawbacks** of the current SMEFT approach:

1. **Power counting**: description of **large** κ_λ values requires $\mathcal{O}(1/\Lambda^4_{\mathbf{NP}})$ **terms**
   - ➢ Significant κ_λ^2 contribution to σ_{Zh}



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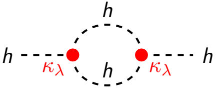

2. **Lack of full NLO**: apart from κ_λ **contributions**, no other 1-loop contributions are included (in the public version of HEPfit)
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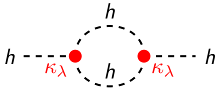

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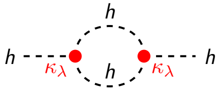

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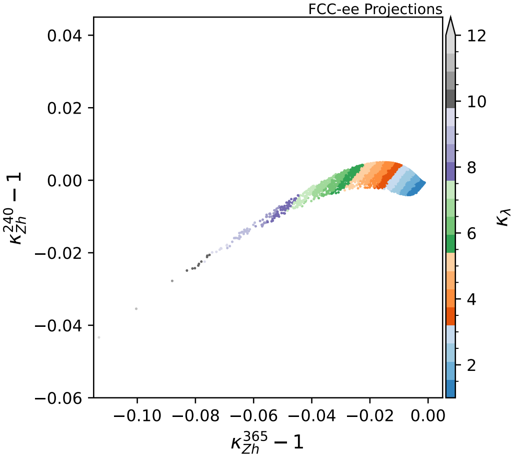
3. **Truncation** of σ_{Zh} expression in terms of $(\kappa_\lambda - 1)$ (see backup for details)
4. **SMEFT vs. IDM mismatch**: potentially due to **light new physics** (not in **decoupling limit** described by **SMEFT**)

Estimating theoretical uncertainties on σ_{Zh}

IDM predictions for σ_{Zh} at $\sqrt{s} = 240$, 365 GeV (scatter points)

- Includes only κ_λ-dependent terms + BSM contributions to the Higgs external-leg



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

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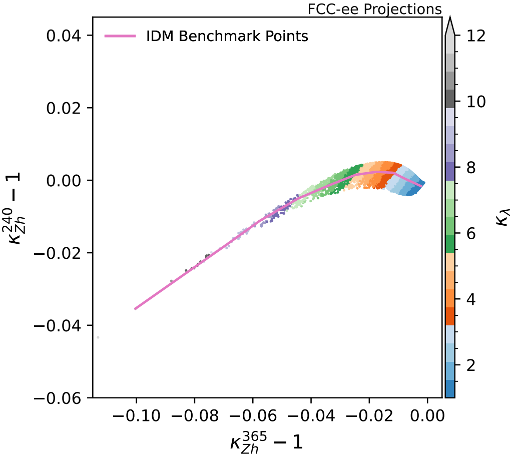

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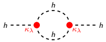

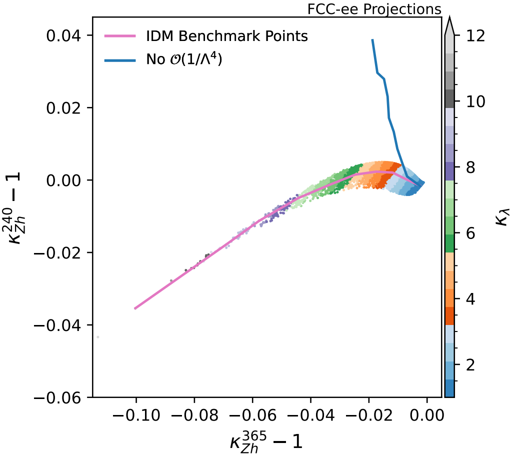

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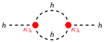

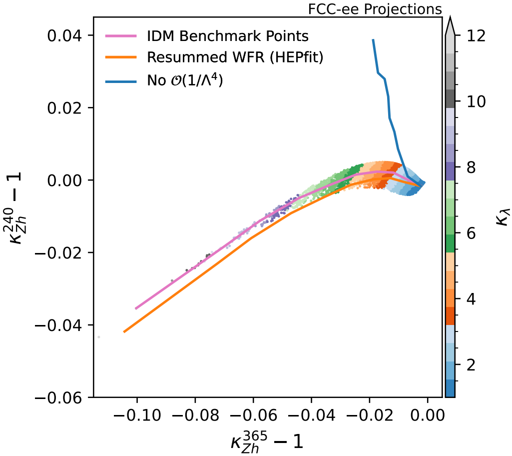

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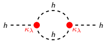

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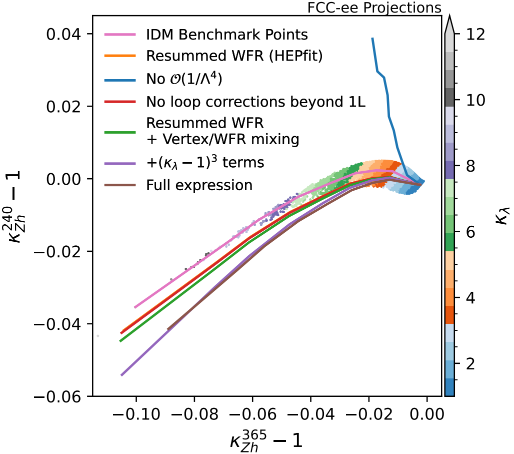

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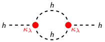

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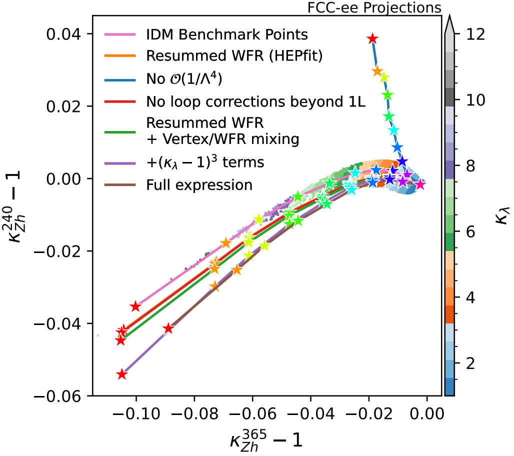

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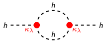

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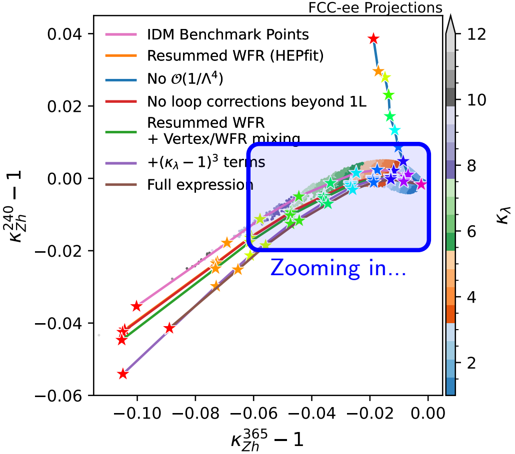

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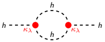

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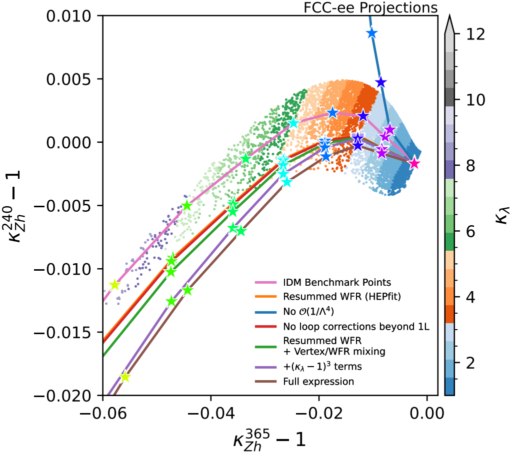

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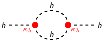

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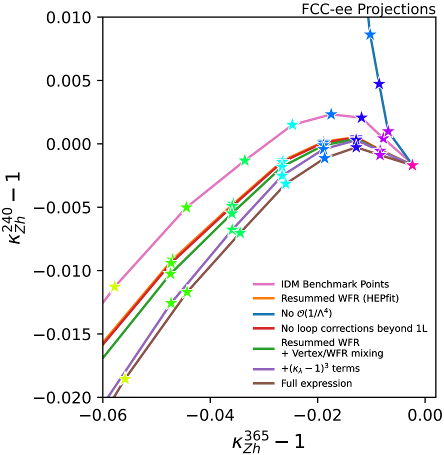

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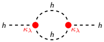

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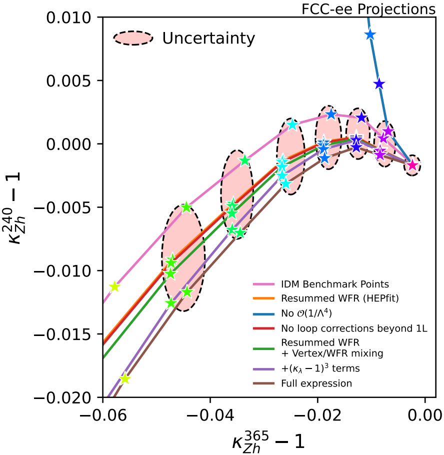
- Estimate **uncertainties** by drawing ellipses around the points



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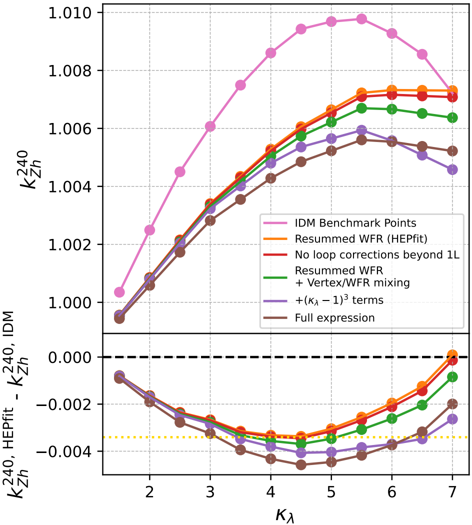
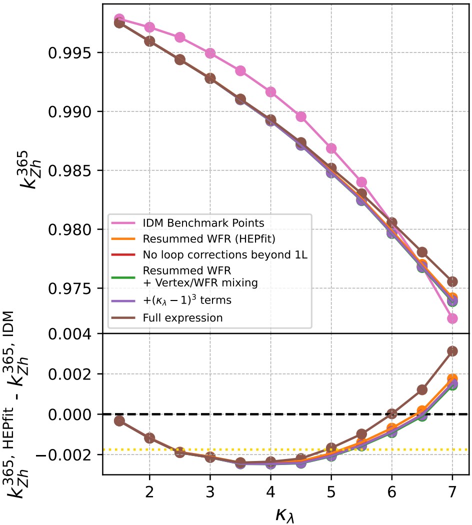
Discrepancy between IDM and HEPfit predictions: κ_{Zh}^{240}



- Other source of systematic error: mismatch between **IDM** and **SMEFT** predictions:
  - ➢ Departure from **decoupling limit**
  - ➢ Unknown **higher orders** in **IDM** predictions
- Performed full fit with IDM inputs, obtained C_H, $C_{H\Box}$, C_{HD}, C_{HW}, C_{HB}, C_{HWB}, compared $\kappa_{Zh}^{240}/\kappa_{Zh}^{365}$ predictions
- Introduced another 2 new **nuisance parameters** to parametrize discrepancy
- Again assign average (yellow line) of uncertainties for $2 \lesssim \kappa_\lambda \lesssim 6$:

$$\texttt{NPmismatch\_FCCee240} = 0.67\%$$
$$\texttt{NPmismatch\_FCCee365} = 0.35\%$$

Discrepancy between IDM and HEPfit predictions: κ_{Zh}^{365}



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Results

Input measurements

Input measurements: Higgs+EW fit from **Snowmass 2021** [deBlas.2022]

- Single-Higgs observables (σ and $\sigma \cdot$ BR)
  ➢ @ HL-LHC, FCC-ee$_{240}$ & FCC-ee$_{365}$
- Electroweak precision observables (EWPOs)
  ➢ @ HL-LHC, FCC-ee$_{Z}$ & FCC-ee$_{WW}$
- Diboson measurements ($e^+e^- \to W^+W^-$)
  ➢ @ HL-LHC, FCC-ee$_{WW}$, FCC-ee$_{240}$ & FCC-ee$_{365}$

Collider	Energy	Int. Lumi.
HL-LHC	14 TeV	6 ab^{-1}
FCC-ee$_{Z}$	M_Z	150 ab^{-1}
FCC-ee$_{WW}$	$2M_W$	10 ab^{-1}
FCC-ee$_{240}$	240 GeV	5 ab^{-1}
FCC-ee$_{365}$	365 GeV	1.5 ab^{-1}

Adapted from [deBlas.2022]

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FCC-ee$_{240}$	240 GeV	5 ab^{-1}
FCC-ee$_{365}$	365 GeV	1.5 ab^{-1}

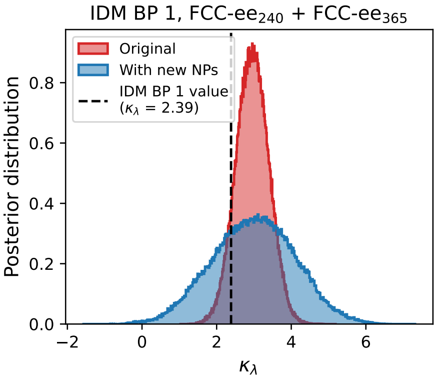
Adapted from [deBlas.2022]

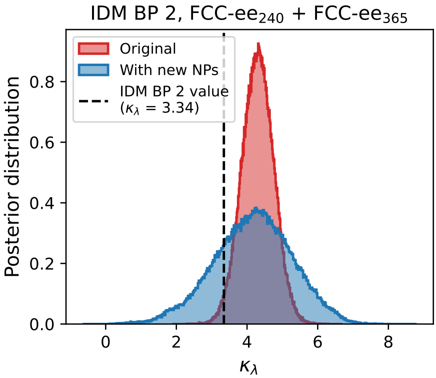
Caveat: inputs have since been updated for ESPPU

- FCC-ee **luminosities** have **increased**, 4 IPs instead of 2
- **HL-LHC** κ_λ constraint projection **improved** considerably
  - ➢ Now $\approx 28\%$ (rel. uncertainty, assuming $\kappa_\lambda = 1$) [ECFAHiggs.2025]
  - ➢ Combined with FCC-ee$_{240}$ +FCC-ee$_{365}$: $\approx 15\%$ [deBlas.2025]

Inputs for this analysis will be **updated**, but relative **impact of NPs** should only **increase!**

BP 1 and BP 2 Results

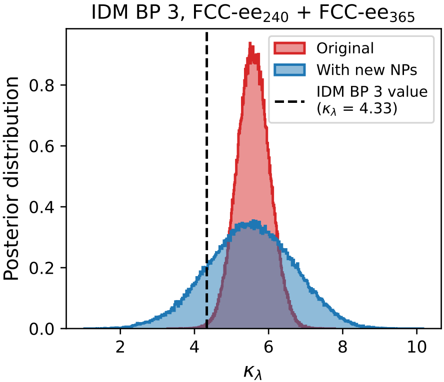




- **Indirect** (i.e. single-Higgs) constraints → **overestimation** of κ_λ
  - BP 1: $\kappa_\lambda^{\text{true}} \approx 2.4$, $\kappa_\lambda^{\text{fit}} \approx 3.0$
  - BP 2: $\kappa_\lambda^{\text{true}} \approx 3.3$, $\kappa_\lambda^{\text{fit}} \approx 4.3$
  - Different interpretations in terms of evolution of **early universe** [Biekötter.2023]
- Inclusion of new **nuisance parameters** improves **fit agreement considerably**

BP 3

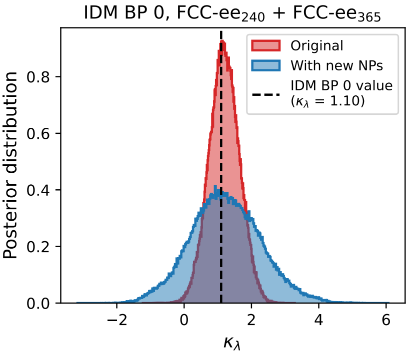
- For BP 3, original fit results in a 3σ **tension** w.r.t. to the IDM prediction!
- Reduced to $\approx 1\sigma$ with new NPs
- Indicates that **higher-order effects**, which justify the introduction of the **new NPs**, are **responsible** for the **overestimation** of κ_λ



- Future **improvements** in **theory predictions** will help **alleviate** this

BP 0 and summary

- For comparison: IDM point with κ_λ closest to 1 (BP 0)
  - ➢ $\kappa_\lambda \approx 1.1$
- Presence of new NPs again increases uncertainty on κ_λ



	True value	Original fit	With new NPs
BP 0	1.1	1.19 ± 0.44 [37%]	1.23 ± 1.03 [83%]
BP 1	2.39	2.96 ± 0.44 [15%]	2.99 ± 1.09 [37%]
BP 2	3.34	4.30 ± 0.45 [10%]	4.17 ± 1.10 [26%]
BP 3	4.33	5.59 ± 0.44 [7.8%]	5.51 ± 1.15 [21%]

Discussion and conclusions

Loop-level extraction of κ_λ via $e^+e^- \to Zh$:

- **Can detect** the presence of **BSM physics**
- But: **overestimates** κ_λ (up to 3σ tension)
- (Partially) addressed by new **nuisance parameters**:
  - ➢ **Truncation** of the SMEFT σ_{Zh} **expression**
  - ➢ Possible **departure from decoupling limit** in SMEFT (unnoticed given **consistent goodness-of-fit** results)
  - ➢ With NPs: absolute κ_λ **uncertainty** increases by a **factor of** ≈ 2.5
- Additional **higher-order corrections** needed to **control uncertainties**
- **Open issues** remaining: lack of full NLO and power counting inconsistency

Direct constraints are much **less susceptible** to these uncertainties [Barklow.2018, LCVision.2025]

- *hh* production: κ_λ (or C_H in SMEFT) at tree-level

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Back-up

The Higgs self-coupling in the SMEFT

In the Warsaw SMEFT basis, the dim-6 operators which contribute to the Higgs self-coupling are:

$$\mathcal{O}_H = (H^\dagger H)^3 \qquad \mathcal{O}_{H\Box} = (H^\dagger H)\Box(H^\dagger H) \qquad \mathcal{O}_{HD} = (H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$$

The ratio $\boldsymbol{\kappa_\lambda} := \lambda_3/\lambda_3^{\text{SM}}$ is then:

$$\boldsymbol{\kappa_\lambda} = 1 - \frac{2\nu^2}{m_h^2}\frac{\nu^2}{\Lambda^2}\cdot C_H + \frac{3\nu^2}{\Lambda^2}\left(C_{H\Box} - \frac{1}{4}C_{HD}\right) ,$$

(where ν is the Higgs vacuum expectation value (VEV) and Λ is the scale of New Physics.)

Assuming $C_{H\Box} \approx C_{HD} \approx 0$, requiring the ν is a global mininum and that the potential is bounded from below, we have [Degrassi.2016]:

$$-\frac{m_h^2}{v^2} < C_H < 0 \quad \rightarrow \quad 1 < \boldsymbol{\kappa_\lambda} < 3 .$$

- **Valid** κ_λ **range** in SMEFT is **restricted**
- 2HDM: **dim-8** have been shown **not** to be negligible [Dawson.2022]

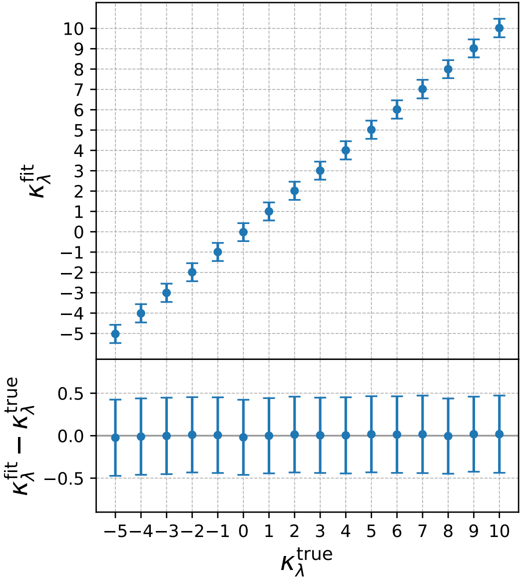
"Self-consistent" fits with $\kappa_\lambda = -5, \ldots, 10$

- Important **cross-check**: in a **self-consistent** fit within the SMEFT framework, the **off-shell** (single-Higgs) constraints by themselves should be able to **determine the "true"** κ_λ

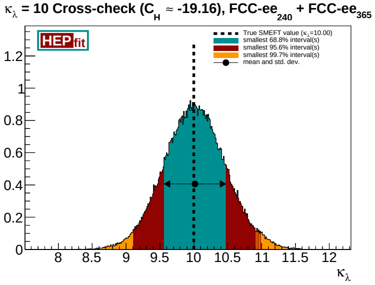
- The steps to check this are:
  1. Set C_H to correspond to $\kappa_\lambda = -5, \ldots, 10$, all other WCs to zero
     - $C_H \leftarrow -\frac{m_h^2 \Lambda^2}{2v^4}(\kappa_\lambda - 1)$
  2. **Evaluate all fit observables** at this parameter point
  3. Set these results as **central values** for the fit
  4. **Run** full fit with HEPfit

- In all cases, the fits find the "true" model $\kappa_\lambda = -5, \ldots, 10$, respectively

"Self-consistent" fits with $\kappa_\lambda = -5, \ldots, 10$ (cont.)

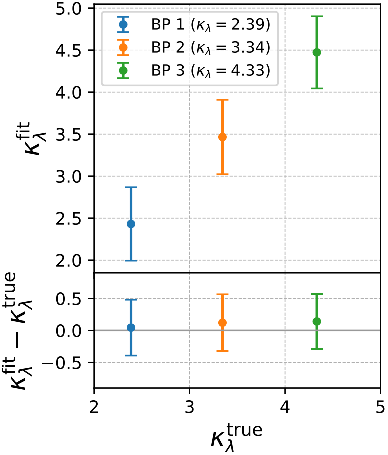


- Perfect fit match to "true" κ_λ values (modulo statistical fluctuations) ✓
- Similar results when using same fit scripts used for the IDM inputs → no bias

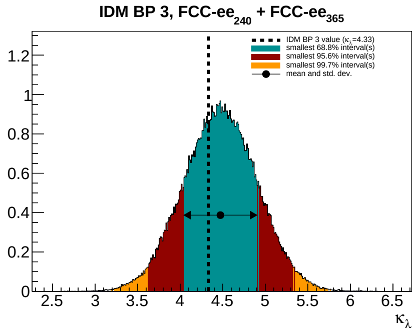


Fits using HEPfit formulas for Higgs observables

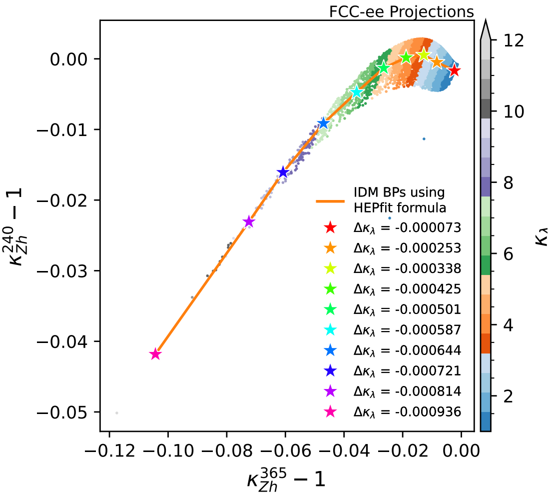
- Important **cross-check**: using the HEPfit expressions for Higgs production XS and BRs at FCC-ee, the **off-shell** (single-Higgs) constraints should be able to **determine the "true"** κ_λ



- **Good agreement** between $\kappa_\lambda^{\text{fit}}$ and $\kappa_\lambda^{\text{true}}$ ✓

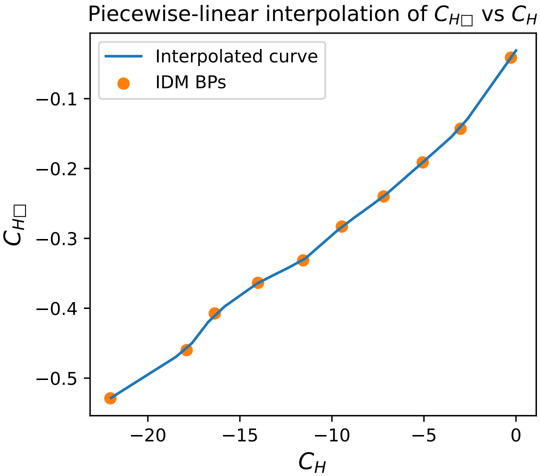


Uncertainty in truncation of the SMEFT σ_{Zh} expression (1)



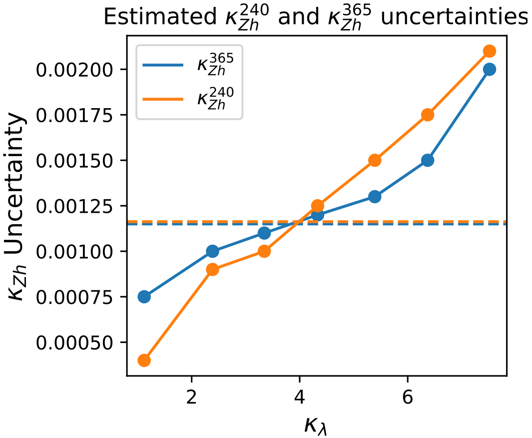
- For IDM points: isolate C_H and $C_{H\Box}$ contributions by using:
  - ➢ κ_λ-dependent HEPfit expressions for σ_{Zh}
  - ➢ BSM contributions to Higgs external-leg ($C_{H\Box}$)
- Invert HEPfit σ_{Zh} expressions to obtain C_H and $C_{H\Box}$:
  - ➢ $(\kappa_{Zh}^{240}, \kappa_{Zh}^{365}) \mapsto (C_H, C_{H\Box})$
  - ➢ For each IDM point (★)
- $\Delta\kappa_\lambda$: difference between IDM prediction and κ_λ obtained inverting the HEPfit expressions
  - ➢ Cross-check: should observe $\Delta\kappa_\lambda \approx 0$ ✓

Uncertainty in truncation of the SMEFT σ_{Zh} expression (2)



- Interpolated relation between C_H and $C_{H\Box}$ for IDM points
- Used $(C_H, C_{H\Box})$ values to obtain SMEFT predictions using different truncations of the σ_{Zh} expression

Uncertainty in truncation of the SMEFT σ_{Zh} expression (3)



- Goal: implement these uncertainties as new **nuisance parameters (NPs)**
- For simplicity: assume **constant**, **uncorrelated** uncertainties in the range $2 \lesssim \kappa_\lambda \lesssim 6$
- Assign values to new fit nuisance parameters:

`theoerr_FCCee240` $= 0.23\%$
`theoerr_FCCee365` $= 0.23\%$

Uncertainty in (SM normalized) cross-section: $\sigma = \kappa^2 \rightarrow \Delta\sigma \approx 2\kappa\Delta\kappa$

Truncation of σ_{Zh} expression in SMEFT

Expanding the ratio in powers of $(\kappa_\lambda - 1)$ gives different possible expressions:

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

"Full" expression

Truncation of σ_{Zh} expression in SMEFT

Expanding the ratio in powers of $(\kappa_\lambda - 1)$ gives different possible expressions:

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

$$\simeq 1 + (\kappa_\lambda - 1) C_1 + 2(\kappa_\lambda - 1)\frac{\delta Z_h}{1-\delta Z_h} + (\kappa_\lambda - 1)^2 \delta Z_h \frac{1+3\delta Z_h}{(1-\delta Z_h)^2} +$$

HEPfit expression

Truncation of σ_{Zh} expression in SMEFT

Expanding the ratio in powers of $(\kappa_\lambda - 1)$ gives different possible expressions:

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

No loop corrections beyond 1L

Truncation of σ_{Zh} expression in SMEFT

Expanding the ratio in powers of $(\kappa_\lambda - 1)$ gives different possible expressions:

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

No $\mathcal{O}(1/\Lambda^4)$ contributions

Truncation of σ_{Zh} expression in SMEFT

Expanding the ratio in powers of $(\kappa_\lambda - 1)$ gives different possible expressions:

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

$$\simeq 1 + (\kappa_\lambda - 1) C_1 + 2(\kappa_\lambda - 1)\frac{\delta Z_h}{1-\delta Z_h} + (\kappa_\lambda - 1)^2 \delta Z_h \frac{1+3\delta Z_h}{(1-\delta Z_h)^2} +$$

$$+ 2(\kappa_\lambda - 1)^2 C_1 \frac{\delta Z_h}{1-\delta Z_h} +$$

Including missing C1 term

Truncation of σ_{Zh} expression in SMEFT

Expanding the ratio in powers of $(\kappa_\lambda - 1)$ gives different possible expressions:

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

$$\simeq 1 + (\kappa_\lambda - 1) C_1 + 2(\kappa_\lambda - 1)\frac{\delta Z_h}{1-\delta Z_h} + (\kappa_\lambda - 1)^2 \delta Z_h \frac{1+3\delta Z_h}{(1-\delta Z_h)^2} +$$

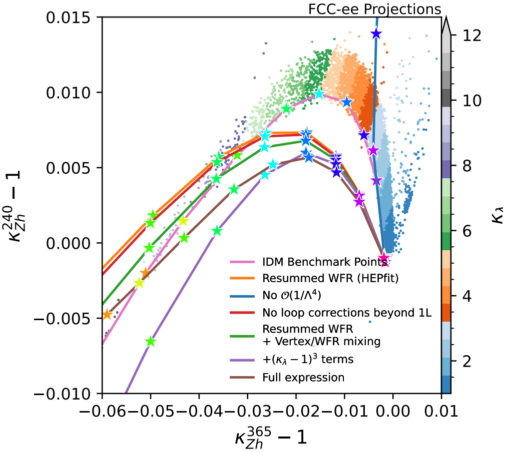
$$+ 2(\kappa_\lambda - 1)^2 C_1 \frac{\delta Z_h}{1-\delta Z_h} +$$

$$+ 4(\kappa_\lambda - 1)^3 \delta Z_h^2 \frac{1+\delta Z_h}{(1-\delta Z_h)^3} + (\kappa_\lambda - 1)^3 C_1 \delta Z_h \frac{1+3\delta Z_h}{(1-\delta Z_h)^2}$$

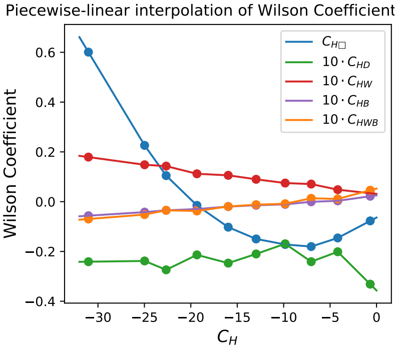
Including terms $\propto (\kappa_\lambda - 1)^3$

Parametrizing IDM vs. SMEFT mismatch

- Performed full fit with IDM inputs, obtained C_H, $C_{H\square}$, C_{HD}, C_{HW}, C_{HB}, C_{HWB}



- Interpolated relation between C_H and other WCs for IDM points
- Used WCs to obtain SMEFT predictions using different truncations of the σ_{Zh} expression



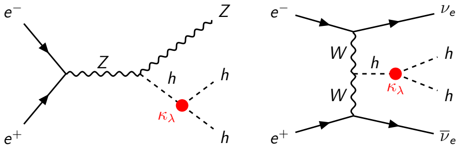
New nuisance parameters: summary

We define 2 pairs of new nuisance parameters (NPs)

- `theoerr_FCCee240` and `theoerr_FCCee365`: theoretical uncertainties due to **truncation** of $(\kappa_\lambda - 1)$ expansion in SMEFT
- `NPmismatch_FCCee240` and `NPmismatch_FCCee365`: quantify **mismatch** between **IDM** and **SMEFT** predictions
- For simplicity, we assume **constant**, **uncorrelated** uncertainties
- Implemented as model parameters with Gaussian priors in HEPfit
- Values are multiplied by $\sqrt{2.3}$ (2-dimensional factor to account for coverage of 68% C.L.)
- Lack of full NLO and power counting issues are still **not addressed**

κ_λ at future e^+e^- colliders - direct sensitivity

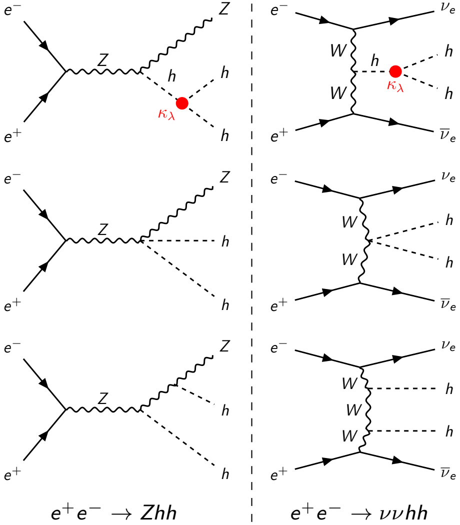
Ideal way to probe $\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$: *hh* production



- Occurs at **tree-level**
- **"Direct"** or **"on-shell"** sensitivity

κ_λ at future e^+e^- colliders - direct sensitivity

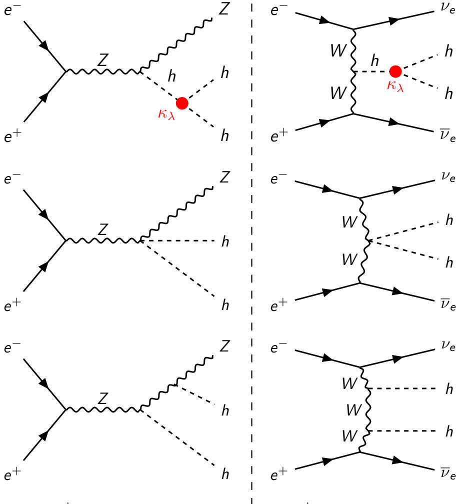
Ideal way to probe $\kappa_\lambda = \lambda_3/\lambda_3^{SM}$: *hh* production



- Occurs at **tree-level**
- **"Direct"** or **"on-shell"** sensitivity

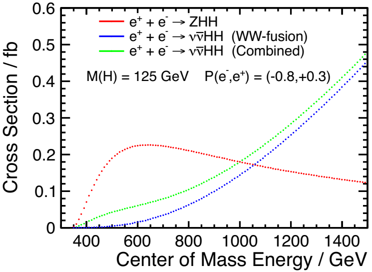
κ_λ at future e^+e^- colliders - direct sensitivity

Ideal way to probe $\kappa_\lambda = \lambda_3/\lambda_3^{\text{SM}}$: *hh* production



$e^+e^- \to Zhh$ $e^+e^- \to \nu\nu hh$

- Occurs at **tree-level**
- **"Direct"** or **"on-shell"** sensitivity
- However: need $\sqrt{s} \gtrsim 500$ **GeV**
  - ➢ Only achievable at **linear** e^+e^- colliders



[Bambade.2019]

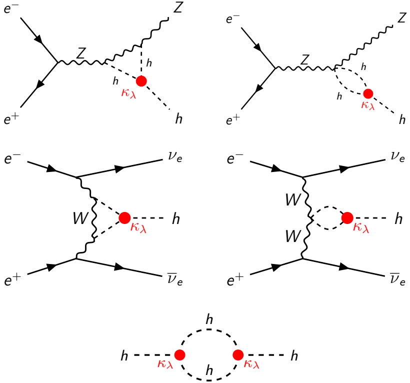
κ_λ at future e^+e^- colliders - indirect sensitivity

Alternative: precision measurements of **single** h observables

- κ_λ only present at **loop-level** — need **high precision!**
- **"Indirect"** or **"off-shell"** sensitivity
  - ➢ **Circular** e^+e^- colliders

Uncertainties [%]	FCC-ee$_{240}$ 5ab^{-1}		FCC-ee$_{365}$ 1.5 ab^{-1}	
Prod.	ZH	$\nu\nu H$	ZH	$\nu\nu H$
σ	0.5	-	0.5	0.9
$\sigma \times BR_{bb}$	0.3	3.1	0.14	1.59
$\sigma \times BR_{cc}$	2.2	-	6.5	10
$\sigma \times BR_{gg}$	1.9	-	3.5	4.5
$\sigma \times BR_{ZZ}$	4.4	-	12	10
$\sigma \times BR_{WW}$	1.2	-	2.6	(3.6)
$\sigma \times BR_{\tau\tau}$	0.9	-	1.8	8
$\sigma \times BR_{\gamma\gamma}$	9	-	18	22
$\sigma \times BR_{\gamma Z}$	(17*)	-	-	-
$\sigma \times BR_{\mu\mu}$	19	-	40	(100)
$\sigma \times BR_{inv.}$	0.3	-	0.60	-

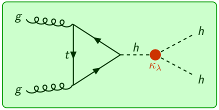
Adapted from [deBlas.2022]

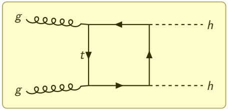


- **Caveat:** sensitivity depends on the BSM theoretical framework, i.e.:
  - ➢ **Other particles** in the **loop**
  - ➢ Theoretical **assumptions**

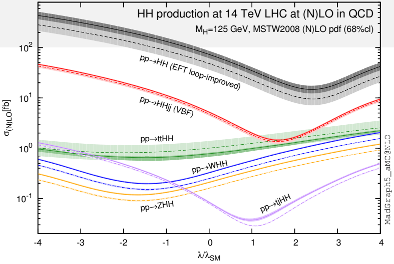
κ_λ at the HL-LHC

At HL-LHC: dihiggs production measurements possible, but challenging

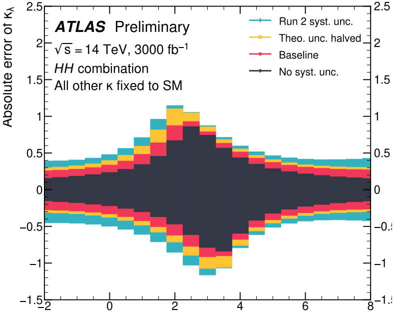




- Triangle and box diagrams interfere **destructively** $\rightarrow \sigma(hh)/\sigma(h) \approx 0.1\%$
- Cross-section has mininum $\rightarrow$ **low sensitivity**
- Mitigated by analyzing the m_{hh} spectrum
  - ➢ Helps **break the degeneracy** of $\sigma(hh)$ as function of κ_λ
- Limits of κ_λ assume all other Higgs couplings to be SM-like $\rightarrow$ restricted interpretation



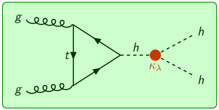
[Frederix.2014]

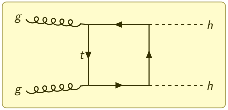


[ATL-PHYS-PUB-2025-006]

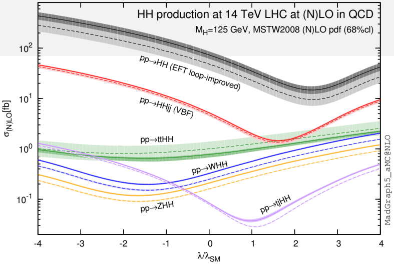
κ_λ at the HL-LHC

At HL-LHC: dihiggs production measurements possible, but challenging

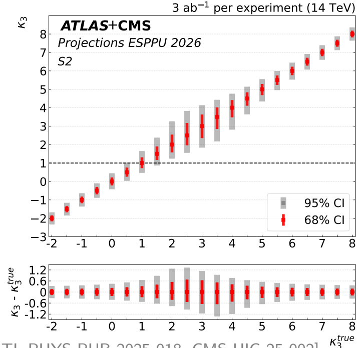




- Triangle and box diagrams interfere **destructively** $\rightarrow \sigma(hh)/\sigma(h) \approx 0.1\%$
- Cross-section has mininum $\rightarrow$ **low sensitivity**
- Mitigated by analyzing the m_{hh} spectrum
  - ➢ Helps **break the degeneracy** of $\sigma(hh)$ as function of κ_λ
- Limits of κ_λ assume all other Higgs couplings to be SM-like $\rightarrow$ restricted interpretation



[Frederix.2014]

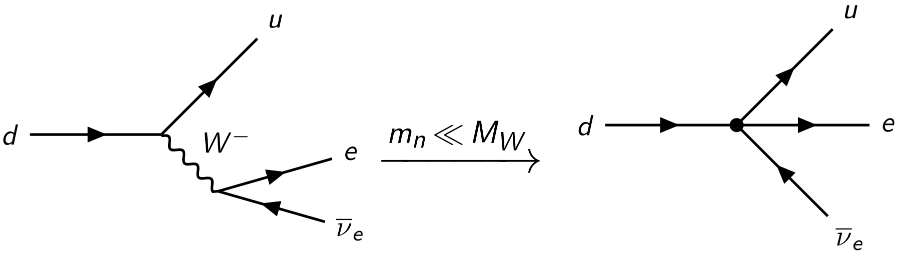


[ATL-PHYS-PUB-2025-018, CMS-HIG-25-002]

Effective Field Theories

It would be great to have a *less model-biased way* to describe physics beyond the Standard Model (BSM)

- One approach: **Standard Model Effective Field Theory (SMEFT)**
- Fields for particles with higher masses are integrated out of the Lagrangian
- EFT example: Fermi theory for β-decay ($\Lambda = M_W$):



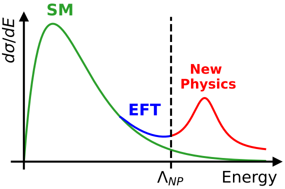
(a) UV theory diagram

(b) EFT diagram

The SMEFT

Standard Model Effective Field Theory (SMEFT)

- Assume **New Physics** has some typical **energy scale Λ_{NP}**
- SMEFT can **parametrize** BSM physics at energies $\ll \Lambda_{NP}$



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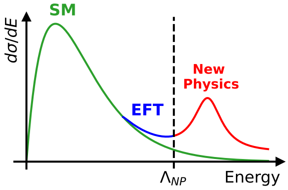

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}}^{(4)} +$$

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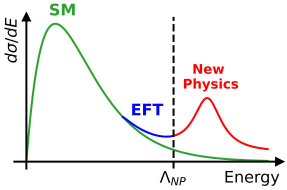

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda_{\text{NP}}} \sum_k C_k^{(5)} O_k^{(5)} + \frac{1}{\Lambda_{\text{NP}}^2} \sum_k C_k^{(6)} O_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda_{\text{NP}}^3}\right)$$

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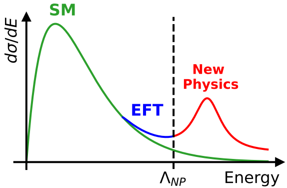

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- Includes **all possible (nonrenormalizable) operators** consistent with Lorentz and SM gauge symmetries

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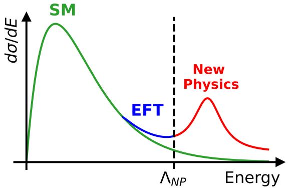

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}}^{(4)} + \frac{1}{\Lambda_{\text{NP}}} \sum_k \boxed{C_k^{(5)}} O_k^{(5)} + \frac{1}{\Lambda_{\text{NP}}^2} \sum_k \boxed{C_k^{(6)}} O_k^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda_{\text{NP}}^3}\right)$$

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- The C_k are called **Wilson Coefficients (WC)** $\rightarrow$ Dimensionless!

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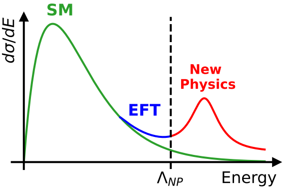

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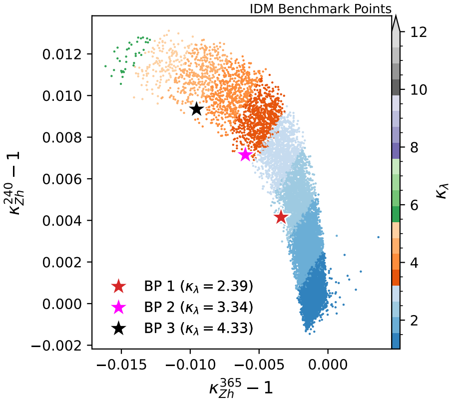
- Includes **all possible (nonrenormalizable) operators** consistent with Lorentz and SM gauge symmetries
- The C_k are called **Wilson Coefficients (WC)** → Dimensionless!
- Most relevant operator for κ_λ: $O_H = \left(\Phi^\dagger \Phi\right)^3$

Benchmark Point (BP) selection



The IDM BPs are constrained to satisfy:

- Perturbative unitarity
- Boundedness-from-below of the potential
- $|\kappa - 1| < 5\%$ for all single Higgs coupling modifiers κ

They also satisfy the following experimental constraints:

- Dark matter phenomenology
- Electroweak precision observables (EWPOs)
- Collider searches

Final selection includes 3 BPs

	μ_2^2 [GeV^2]	λ_1 [GeV]	λ_2 [GeV]	λ_3 [GeV]	λ_4 [GeV]	λ_5 [GeV]	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]
BP 1	3.666×10^5	0.2581	3.084	11.46	-5.68	-5.109	622.2	834.8	845.1
BP 2	3.922×10^5	0.2581	10.06	14.19	-6.974	-6.407	645.6	897.3	906.8
BP 3	3.432×10^5	0.2581	8.985	15.83	-7.704	-7.4	604.3	902.1	907.2

SMEFT and HEPfit

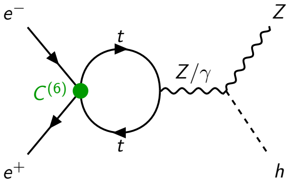
HEPfit implementation of SMEFT:

- Same setup as used in other studies of indirect sensitivity to κ_λ (e.g. Snowmass 2021)
- Assumes that κ_λ is the **main deviation from SM at next-to-leading-order** (NLO)

SMEFT and HEPfit

HEPfit implementation of SMEFT:

- Same setup as used in other studies of indirect sensitivity to κ_λ (e.g. Snowmass 2021)
- Assumes that κ_λ is the **main deviation from SM at next-to-leading-order** (NLO)
  - ➢ Recent study shows **other operators** are significantly correlated with κ_λ
  - ➢ Likely **underestimates** the projected κ_λ uncertainty



- Truncates the SMEFT expansion up to $\mathcal{O}(1/\Lambda_{\mathrm{NP}}^2)$, except for external-leg corrections (up to $\mathcal{O}(1/\Lambda_{\mathrm{NP}}^4)$)

Fit Parameters - SM parameters

Parameter	Central value	Gaussian Unc.	Flat Unc.
$\alpha_s(M_Z)$	0.1180	0.0002	0
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02758	0.00012989	0
m_t [GeV]	173.2	0.4	0
M_h [GeV]	125.1	0.014	0
M_Z [GeV]	91.1882	0	0.015

Fit Parameters - Wilson Coefficients (1)

Wilson Coefficient	Operator	Central value	Gaussian Unc.	Flat Unc.
C_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	0	0	2
C_{HG}	$(H^\dagger H) G_{\mu\nu}^A G^{A\mu\nu}$	0	0	2
C_{HWB}	$(H^\dagger \sigma^a H) W_{\mu\nu}^a B^{\mu\nu}$	0	0	2
$(C_{HWHB})_{\gamma\gamma}$	$\sin\theta_W \mathcal{O}_{HW} + \cos\theta_W \mathcal{O}_{HB}$*	0	0	2
$(C_{HWHB})_{\gamma\gamma\text{orth}}$	$-\cos\theta_W \mathcal{O}_{HW} + \sin\theta_W \mathcal{O}_{HB}$*	0	0	2
C_{HD}	$\left\|H^\dagger D_\mu H\right\|^2$	0	0	2
$C_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	0	0	4
C_H	$(H^\dagger H)^3$	0	0	25
$(C_{HL}^{(1)})_{11}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{L^1}\gamma^\mu L^1)$	0	0	2
$(C_{HL}^{(1)})_{22}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{L^2}\gamma^\mu L^2)$	0	0	2
$(C_{HL}^{(1)})_{33}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{L^3}\gamma^\mu L^3)$	0	0	2

*$\mathcal{O}_{HW} = (H^\dagger H) W_{\mu\nu}^a W^{a\mu\nu}$, $\mathcal{O}_{HB} = (H^\dagger H) B_{\mu\nu} B^{\mu\nu}$

Fit Parameters - Wilson Coefficients (2)

Wilson Coefficient	Operator	Central value	Gaussian Unc.	Flat Unc.
$(C_{HL}^{(3)})_{11}$	$i(H^\dagger \overleftrightarrow{D}^a_\mu H)(\overline{L^1}\gamma^\mu\sigma^a L^1)$	0	0	2
$(C_{HL}^{(3)})_{22}$	$i(H^\dagger \overleftrightarrow{D}^a_\mu H)(\overline{L^2}\gamma^\mu\sigma^a L^2)$	0	0	2
$(C_{HL}^{(3)})_{33}$	$i(H^\dagger \overleftrightarrow{D}^a_\mu H)(\overline{L^3}\gamma^\mu\sigma^a L^3)$	0	0	2
$(C_{He})_{11}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{E^1}\gamma^\mu E^1)$	0	0	2
$(C_{He})_{22}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{E^2}\gamma^\mu E^2)$	0	0	2
$(C_{He})_{33}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{E^3}\gamma^\mu E^3)$	0	0	2
$(C_{HQ}^{(1)})_{11}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{Q^1}\gamma^\mu Q^1)$	0	0	4
$(C_{HQ}^{(1)})_{33}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{Q^3}\gamma^\mu Q^3)$	0	0	7
$(C_{HQ}^{(3)})_{11}$	$i(H^\dagger \overleftrightarrow{D}^a_\mu H)(\overline{Q^1}\gamma^\mu\sigma^a Q^1)$	0	0	4
$(C_{Hu})_{11}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{U^1}\gamma^\mu U^1)$	0	0	4
$(C_{Hd})_{11}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{D^1}\gamma^\mu D^1)$	0	0	4
$(C_{Hd})_{33}$	$i(H^\dagger \overleftrightarrow{D}_\mu H)(\overline{D^3}\gamma^\mu D^3)$	0	0	4

Fit Parameters - Wilson Coefficients (3)

Wilson Coefficient	Operator	Central value	Gaussian Unc.	Flat Unc.
$\mathrm{Re}\left[(C_{eH})_{22}\right]$	$\left(H^\dagger H\right)\left(\overline{L^2}\, H E^2\right)$	0	0	4
$\mathrm{Re}\left[(C_{eH})_{33}\right]$	$\left(H^\dagger H\right)\left(\overline{L^3}\, H E^3\right)$	0	0	4
$\mathrm{Re}\left[(C_{uH})_{22}\right]$	$\left(H^\dagger H\right)\left(\overline{Q^2}\, \widetilde{H} U^2\right)$	0	0	4
$\mathrm{Re}\left[(C_{uH})_{33}\right]$	$\left(H^\dagger H\right)\left(\overline{Q^3}\, \widetilde{H} U^3\right)$	0	0	4
$\mathrm{Re}\left[(C_{dH})_{33}\right]$	$\left(H^\dagger H\right)\left(\overline{Q^3}\, H D^3\right)$	0	0	4
$(C_{LL})_{1221}$	$\left(\overline{L^1}\,\gamma^\mu L^2\right)\left(\overline{L^2}\,\gamma_\mu L^1\right)$	0	0	2

Theoretical Uncertainties - Future Colliders

Table 19. Partial decay widths for the Higgs boson to specific final states and the uncertainties in their calculation [97]. The uncertainties arise either from intrinsic limitations in the theoretical calculation ($\mathrm{Th}_{\mathrm{Intr}}$) and parametric uncertainties ($\mathrm{Th}_{\mathrm{Par}}$). The parametric uncertainties are due to the finite precision on the quark masses, $\mathrm{Th}_{\mathrm{Par}}(m_q)$, on the strong coupling constant, $\mathrm{Th}_{\mathrm{Par}}(\alpha_s)$, and on the Higgs boson mass, $\mathrm{Th}_{\mathrm{Par}}(M_H)$. The columns labelled "partial width" and "current uncertainty" and refer to the current precision [97], while the predictions for the future are taken from ref. [131]. For the future uncertainties, the parametric uncertainties assume a precision of $\delta m_b = 13$ MeV, $\delta m_c = 7$ MeV, $\delta m_t = 50$ MeV, $\delta \alpha_s = 0.0002$ and $\delta M_H = 10$ MeV.

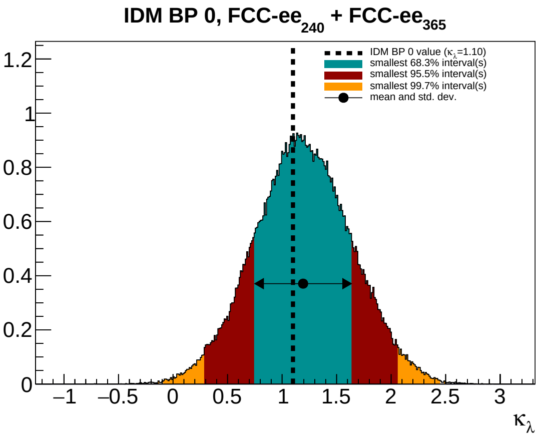
Decay	Partial width	current unc. $\Delta\Gamma/\Gamma$ [%]				future unc. $\Delta\Gamma/\Gamma$ [%]			
	[keV]	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}(m_q)$	$\mathrm{Th}_{\mathrm{Par}}(\alpha_s)$	$\mathrm{Th}_{\mathrm{Par}}(m_H)$	$\mathrm{Th}_{\mathrm{Intr}}$	$\mathrm{Th}_{\mathrm{Par}}(m_q)$	$\mathrm{Th}_{\mathrm{Par}}(\alpha_s)$	$\mathrm{Th}_{\mathrm{Par}}(m_H)$
$H \to b\bar{b}$	2379	< 0.4	1.4	0.4	–	0.2	0.6	< 0.1	–
$H \to \tau^+\tau^-$	256	< 0.3	–	–	–	< 0.1	–	–	–
$H \to c\bar{c}$	118	< 0.4	4.0	0.4	–	0.2	1.0	< 0.1	–
$H \to \mu^+\mu^-$	0.89	< 0.3	–	–	–	< 0.1	–	–	–
$H \to W^+W^-$	883	0.5	–	–	2.6	0.4	–	–	0.1
$H \to gg$	335	3.2	< 0.2	3.7	–	1.0	–	0.5	–
$H \to ZZ$	108	0.5	–	–	3.0	0.3	–	–	0.1
$H \to \gamma\gamma$	9.3	< 1.0	< 0.2	–	–	< 1.0	–	–	–
$H \to Z\gamma$	6.3	5.0	–	–	2.1	1.0	–	–	0.1

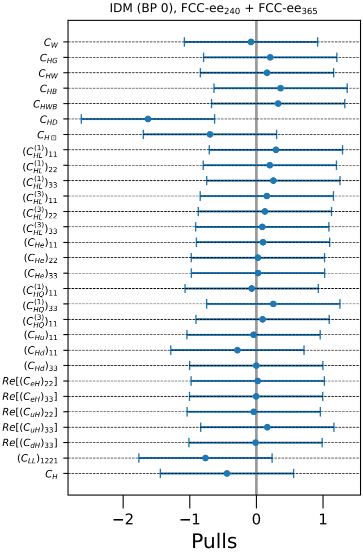
de Blas et al. (2019) [1905.03764]

Theoretical Uncertainties - Future Colliders

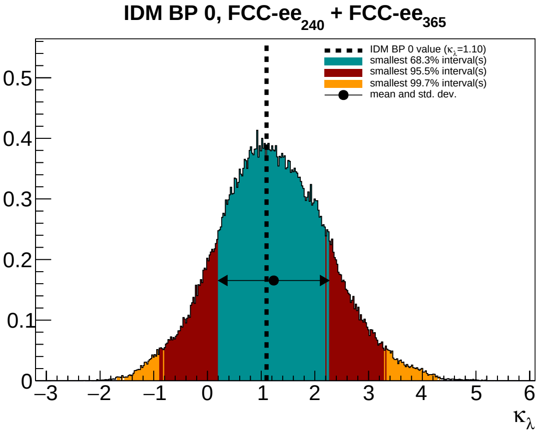
- Parametric and intrinsic uncertainties taken from S. Heinemeyer et al. [1906.05379]: *"Theoretical uncertainties for electroweak and Higgs-boson precision measurements at FCC-ee"*
- Assumed to be **energy independent**
- Assumed precision for parametric uncertainties: $\delta m_b = 13\,\text{MeV}$, $\delta m_c = 7\,\text{MeV}$, $\delta m_t = 50\,\text{MeV}$, $\delta \alpha_s = 0.0002$, $\delta M_H = 10\,\text{MeV}$

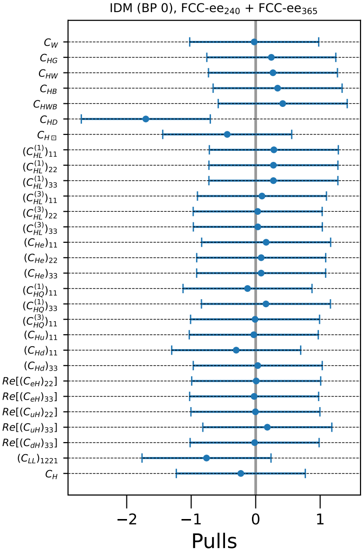
BP 0 Results (Original)



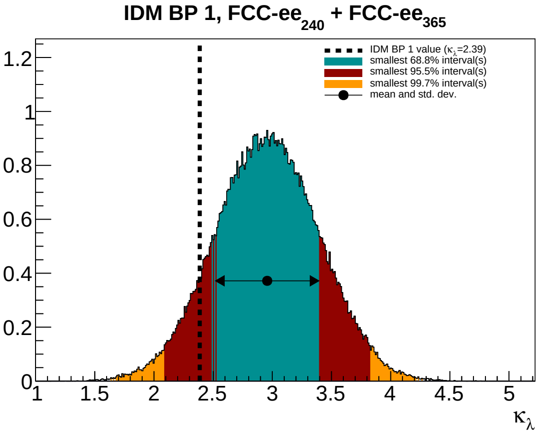


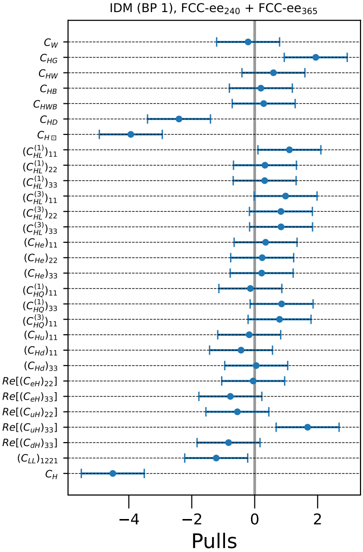
BP 0 Results (with new NPs)



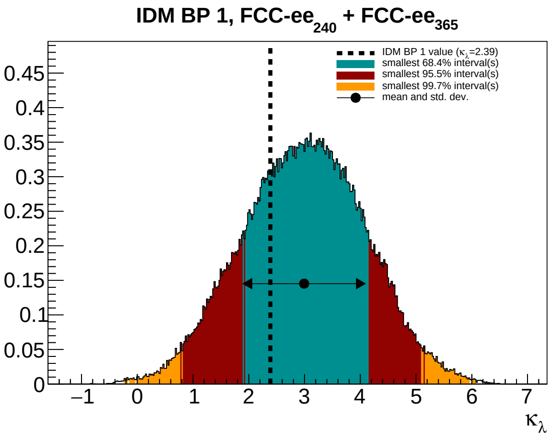


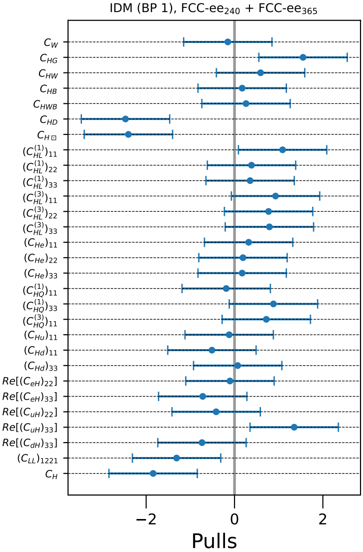
BP 1 Results (Original)



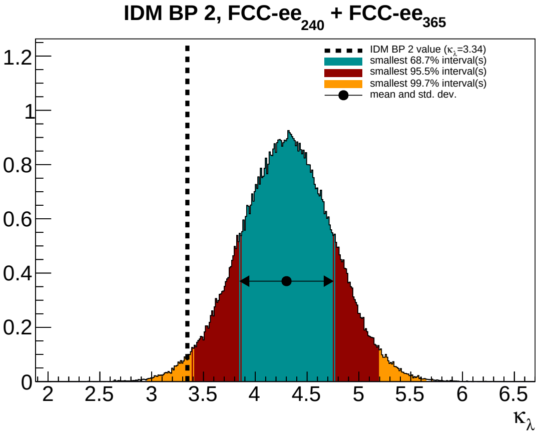


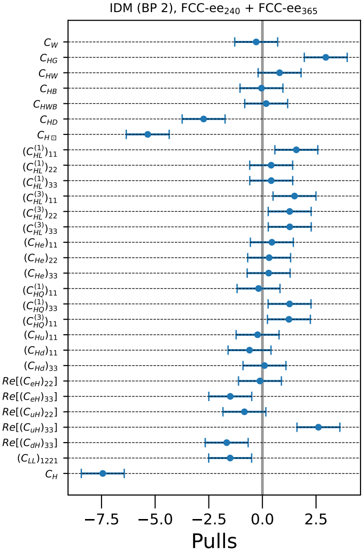
BP 1 Results (with new NPs)



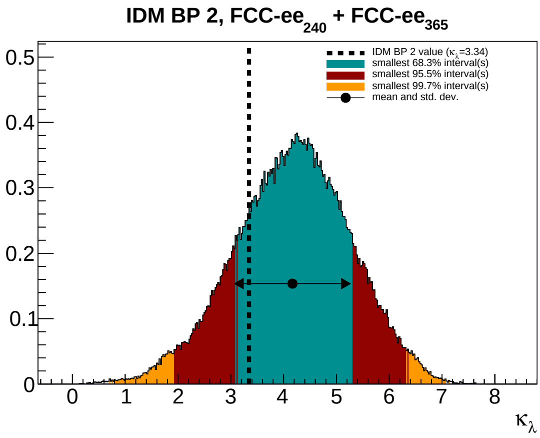


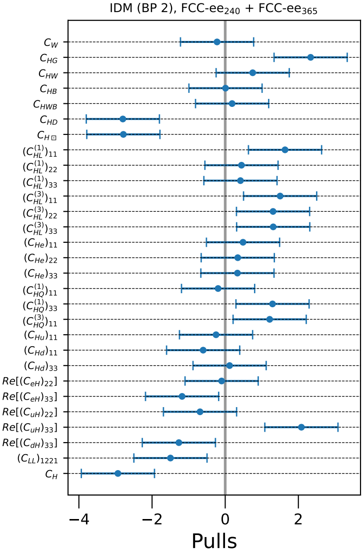
BP 2 Results (Original)



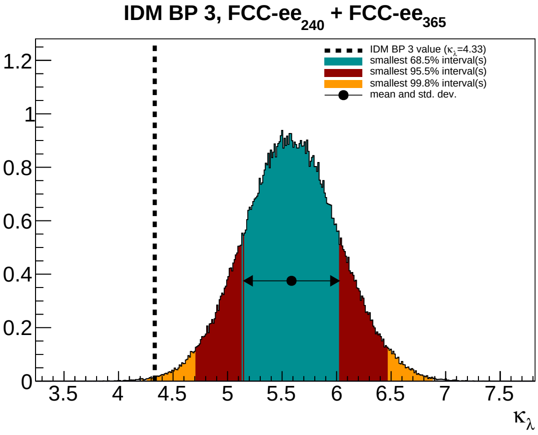


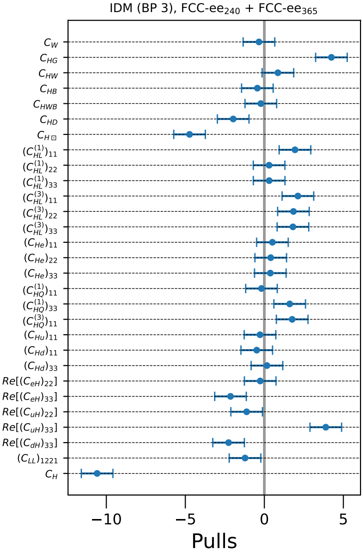
BP 2 Results (with new NPs)



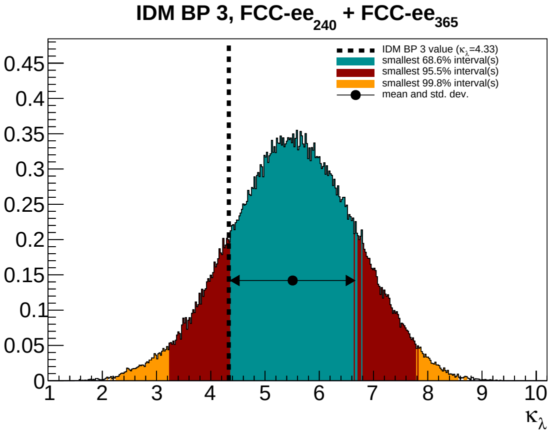


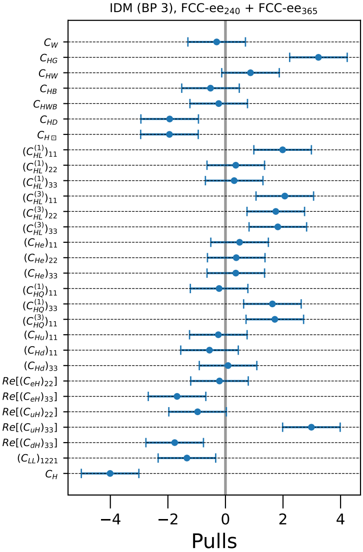
BP 3 Results (Original)



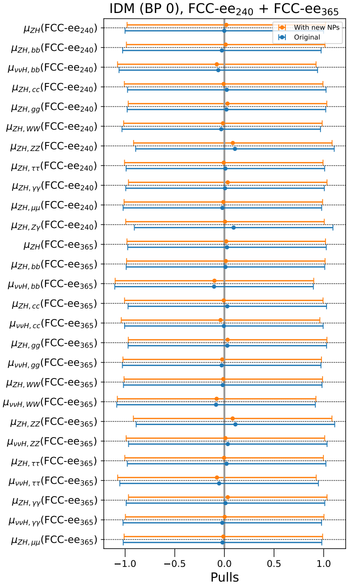


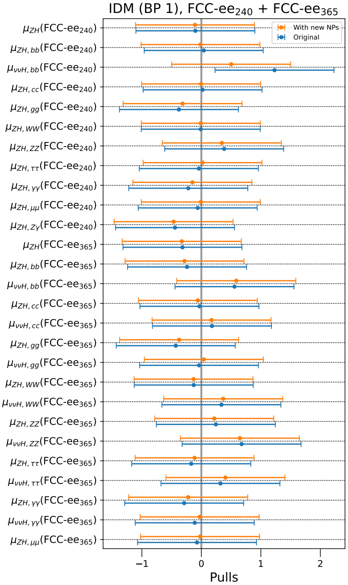
BP 3 Results (with new NPs)



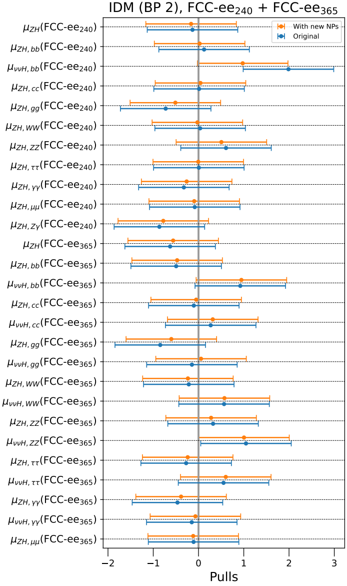


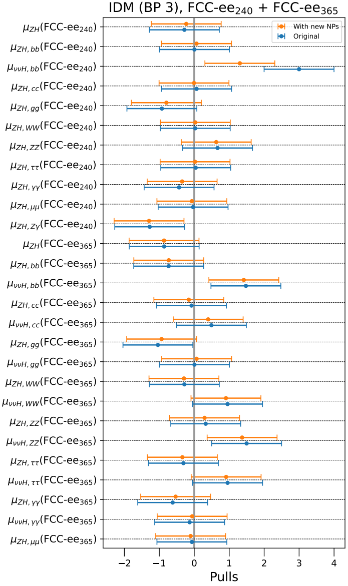
Pulls for single-Higgs observables (1)





Pulls for single-Higgs observables (2)





The Inert Doublet Model (IDM)

- 2 Higgs doublets:

$$\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$$

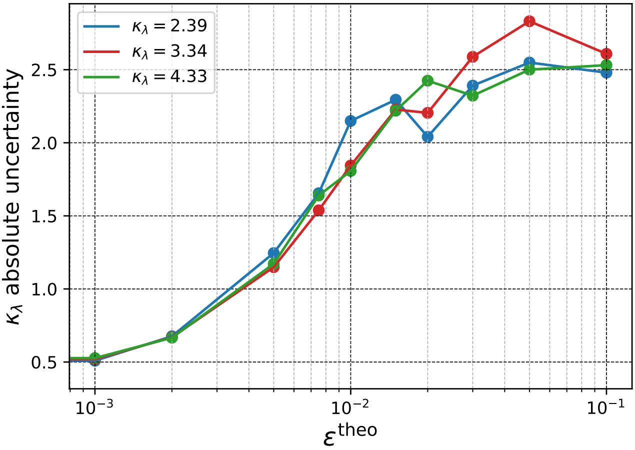
- Impose invariance under a **$\mathbb{Z}_2$-symmetry**: $\Phi_1 \to \Phi_1$, and $\Phi_2 \to -\Phi_2$
- Restrict parameter space such that $\mathbb{Z}_2$-symmetry is **not spontaneously broken**: $\langle \Phi_1 \rangle = \frac{v}{\sqrt{2}}$, $\langle \Phi_2 \rangle = 0$
  - ➢ No coupling between **BSM Higgs** and **SM fermions** ("inert")
  - ➢ **No** tree-level **flavour changing neutral currents** (FCNC)
  - ➢ Exact **alignment** in the Higgs sector to **all orders** in perturbation theory

Higgs potential:

$$V = \mu_1^2|\Phi_1|^2 + \mu_2^2|\Phi_2|^2 + \frac{\lambda_1}{2}|\Phi_1|^4 + \frac{\lambda_2}{2}|\Phi_2|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \\ + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + \frac{\lambda_5}{2}\left[(\Phi_1^\dagger\Phi_2)^2 + h.c.\right]$$

- **Crucially: parameter space allows for large κ_λ, while keeping all other Higgs couplings $\approx$ SM-like**

Effect of new nuisance parameters on κ_λ uncertainty



- Setting all NPs to $\sqrt{2.3} \cdot \epsilon^{\text{theo}}$
- Uncertainty roughly independent of κ_λ