Uncertainties in the determination of the trilinear Higgs coupling from single-Higgs observables

Henning Bahl, Philip Bechtle, Johannes Braathen, Sven Heinemeyer, Jenny List, Murillo Vellasco*, Georg Weiglein

*Physikalisches Institut, University of Bonn, Germany

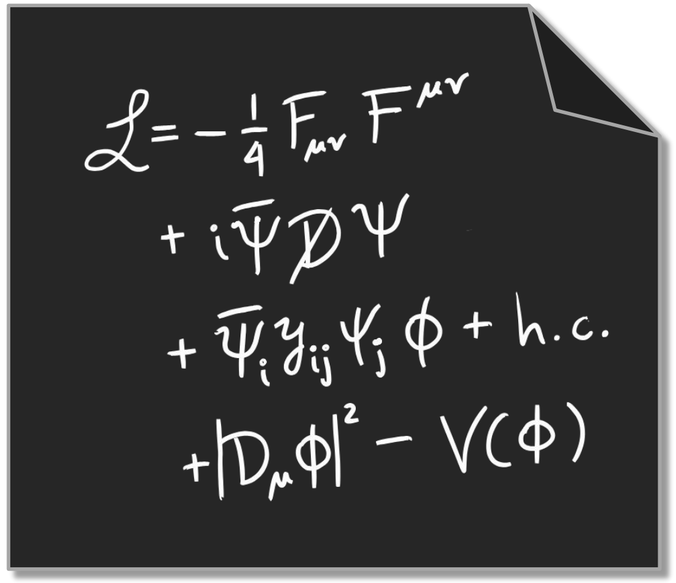
LCWS2026 - November 11th, 2026

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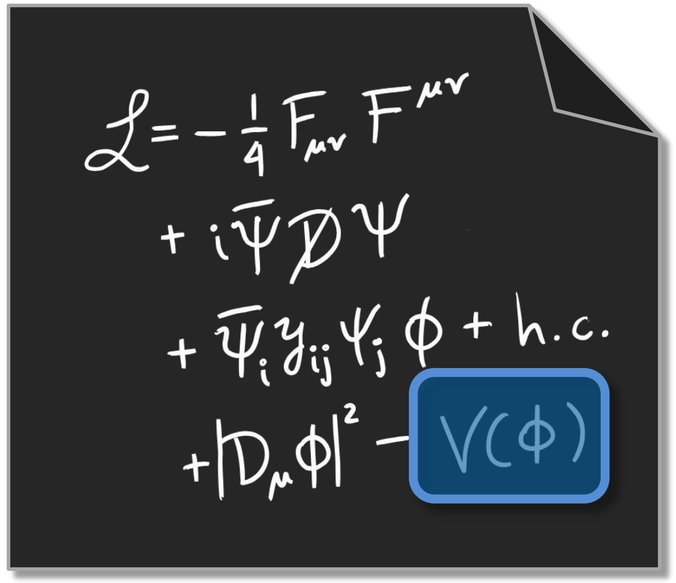
color meets flavor

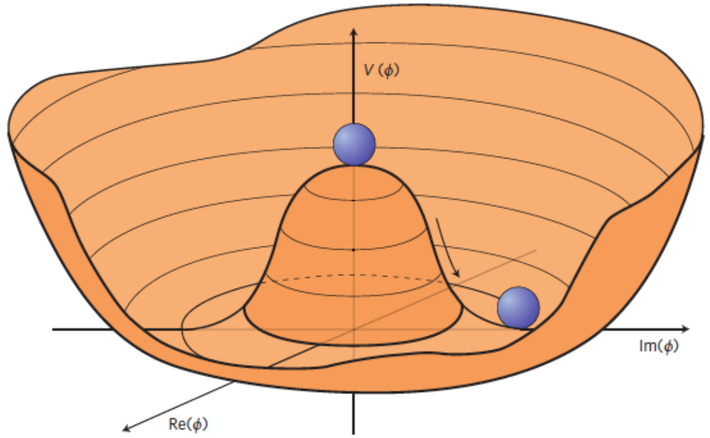
AG Desch Bechtle

The Higgs self-coupling



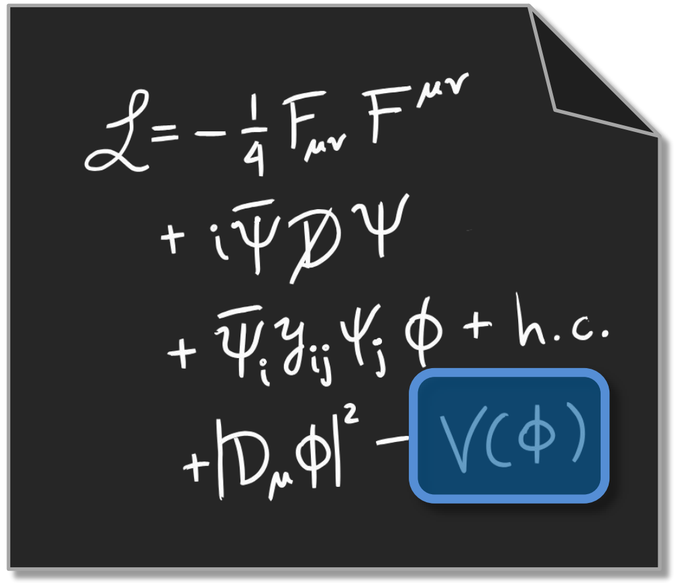
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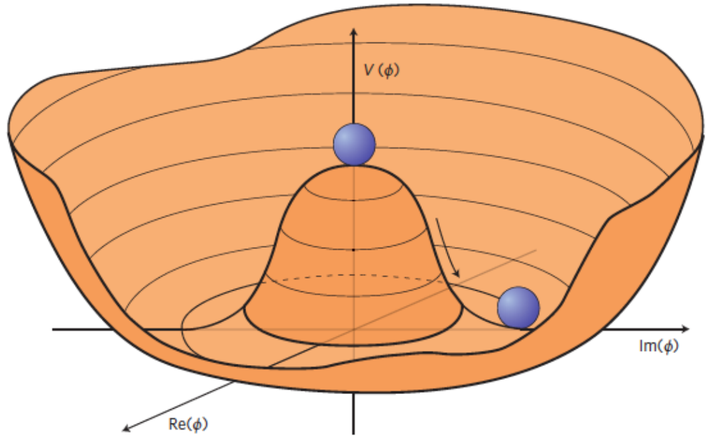




[Ellis 2013]

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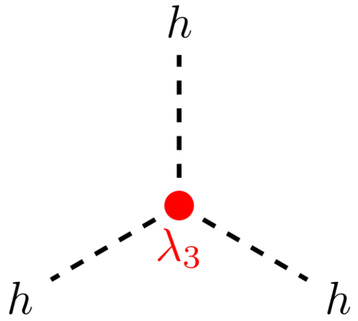


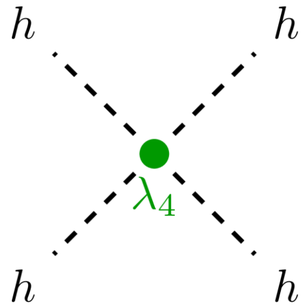


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- After spontaneous symmetry breaking:

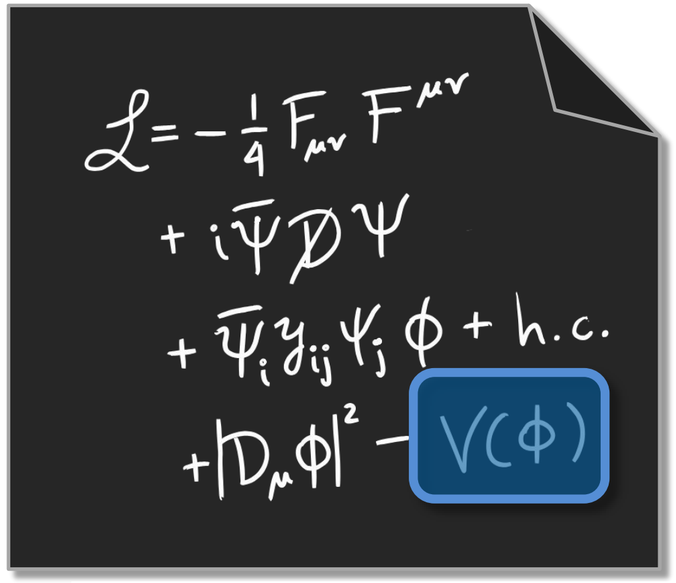
$$V \to \frac{1}{2} m_h^2 h^2 + \lambda_3 v h^3 + \frac{1}{4} \lambda_4 h^4$$

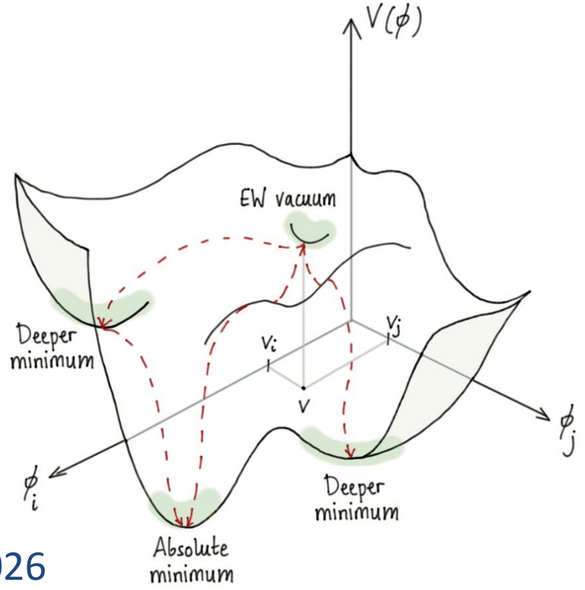




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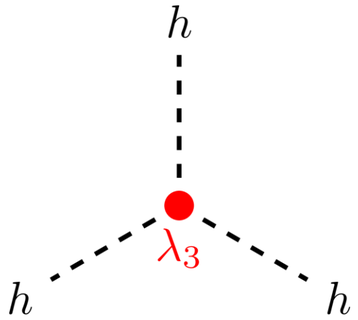


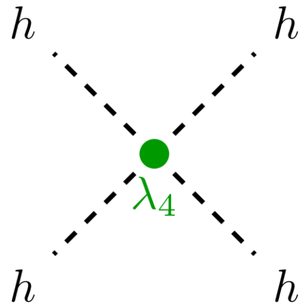


Drawing by Kateryna Radchenko

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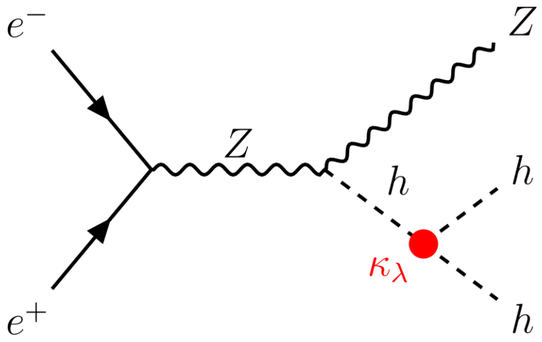


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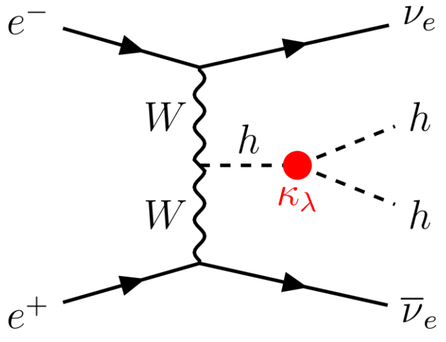
- In BSM contexts, define coupling modifiers: $\kappa_\lambda \equiv \dfrac{\lambda_3}{\lambda_3^{\mathrm{SM}}}$

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

- Ideal way to probe $\kappa_\lambda \equiv \lambda_3/\lambda_3^{\mathrm{SM}}$: hh production:

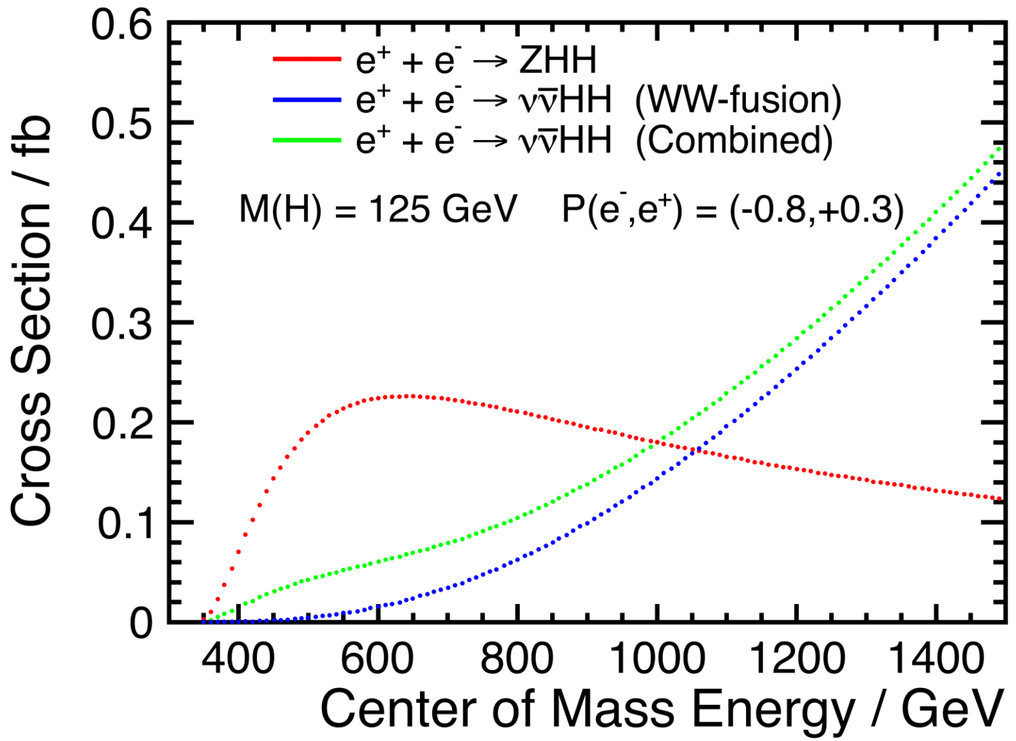


$e^+e^- \to Zhh$



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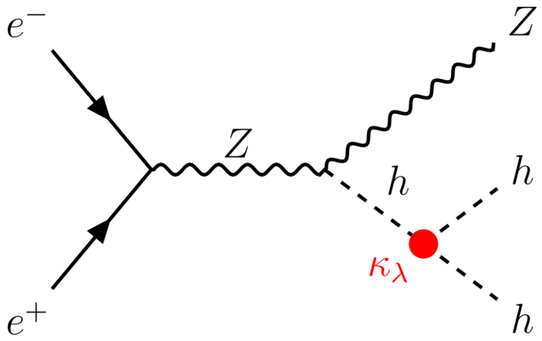
- **"Direct"** or **tree-level** sensitivity [Barklow et al. '17]
- κ_λ extracted from fit to kinematic distributions



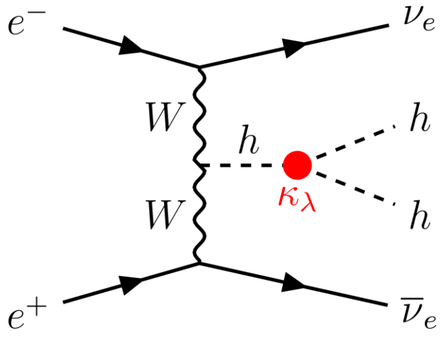
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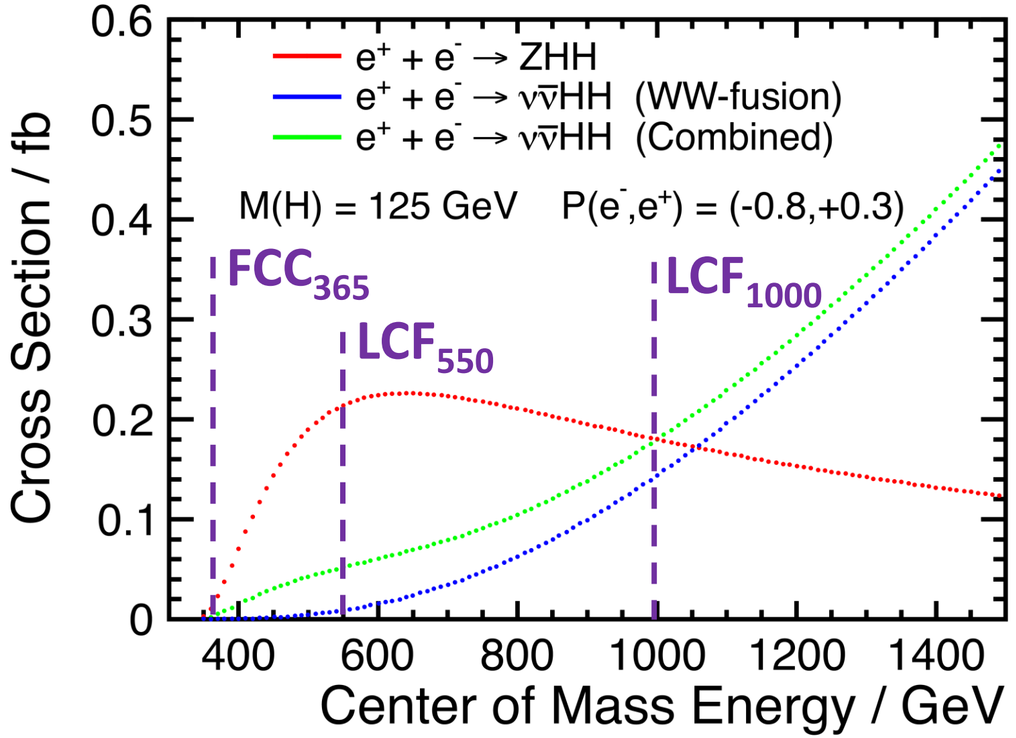


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- **"Direct"** or **tree-level** sensitivity [Barklow et al. '17]
- κ_λ extracted from fit to kinematic distributions
- However: need $\sqrt{s} \gtrsim 500$ GeV
  - ➢ Only achievable at **linear** e^+e^- colliders



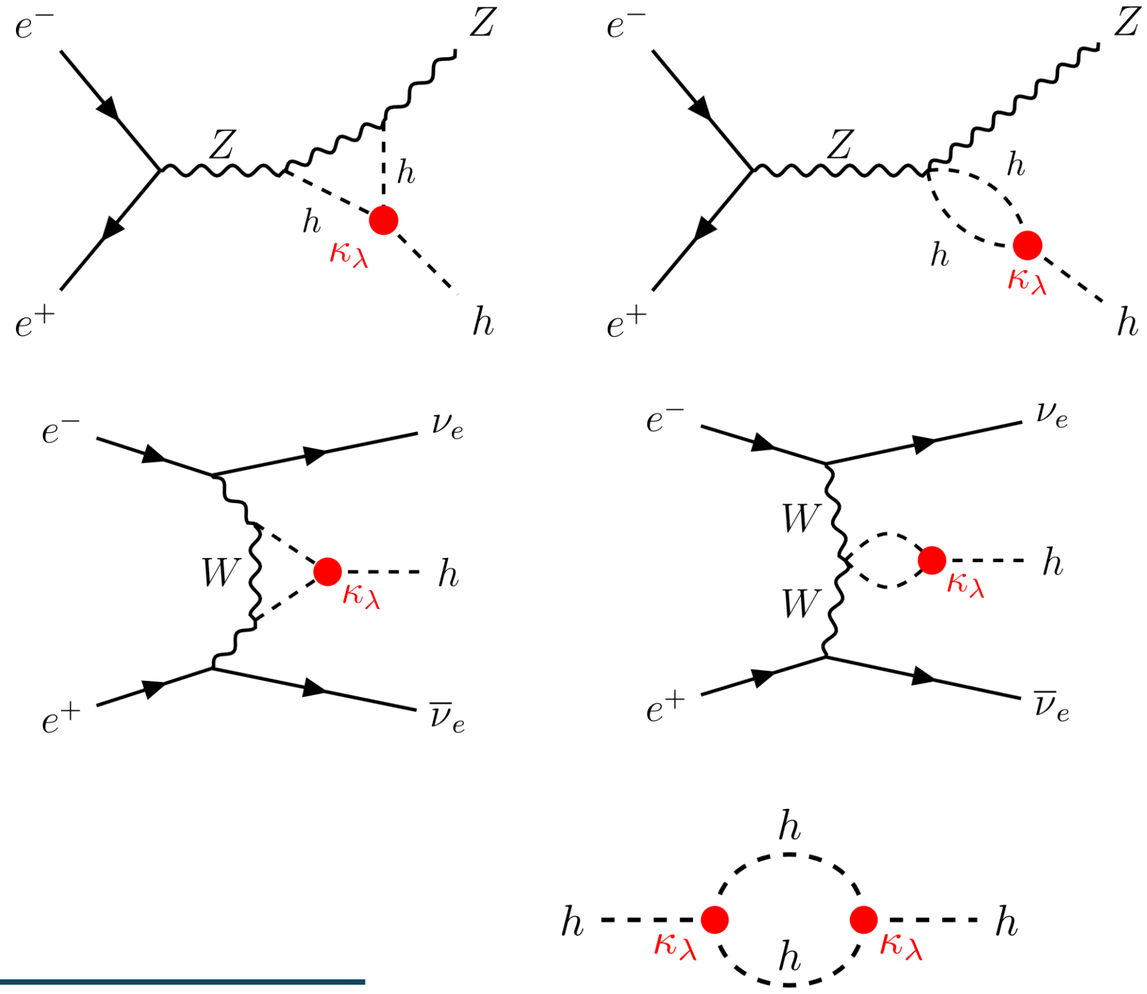
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- Maximum $\sqrt{s}$ at FCC-ee: 365 GeV

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

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

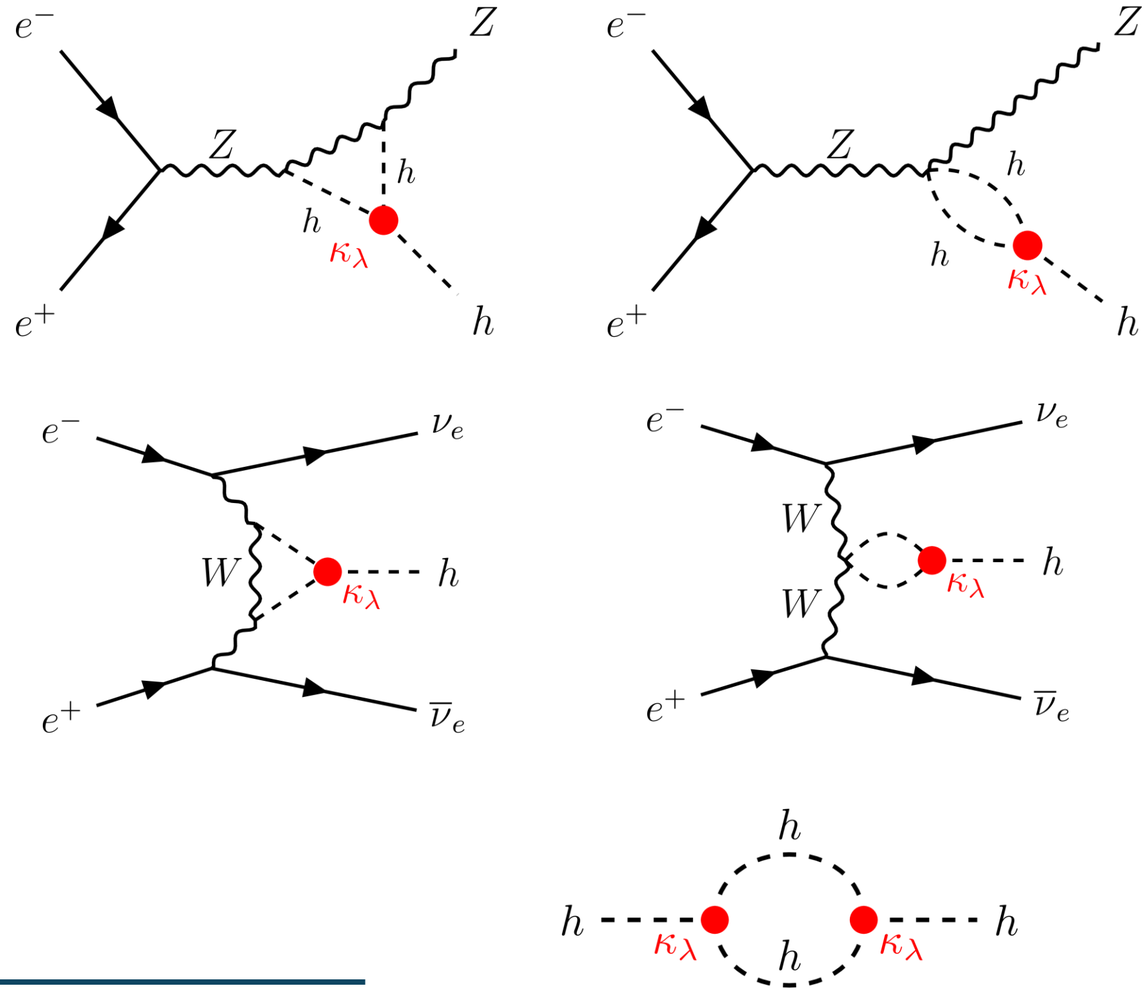
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- **"Indirect"** or **loop-level** sensitivity
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- **Caveat**: sensitivity depends on the BSM theoretical framework, i.e.:
  - BSM particles in the loop
  - Theoretical assumptions



Theoretical Frameworks

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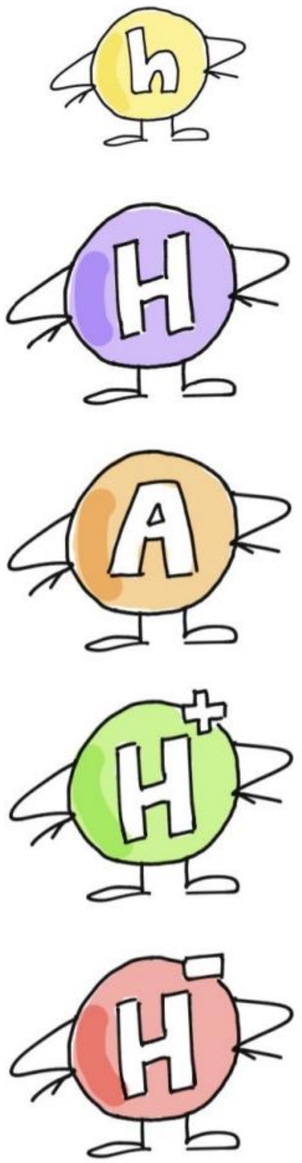
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Goal of the project: **compare** the **EFT approach** with a simple **BSM model**:
Inert Doublet Model (IDM)

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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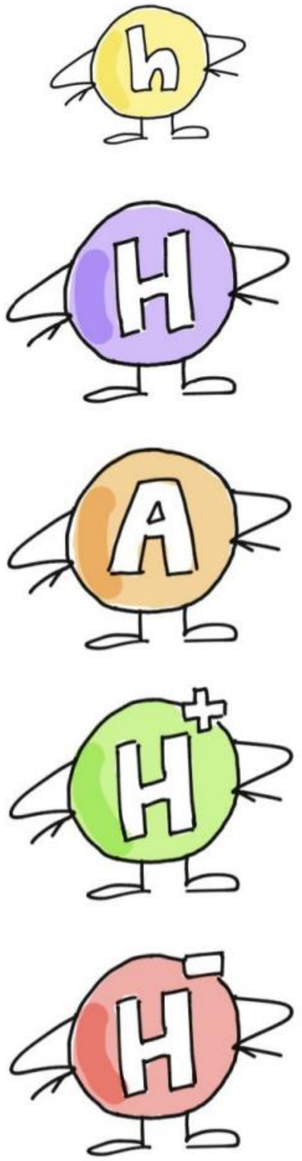
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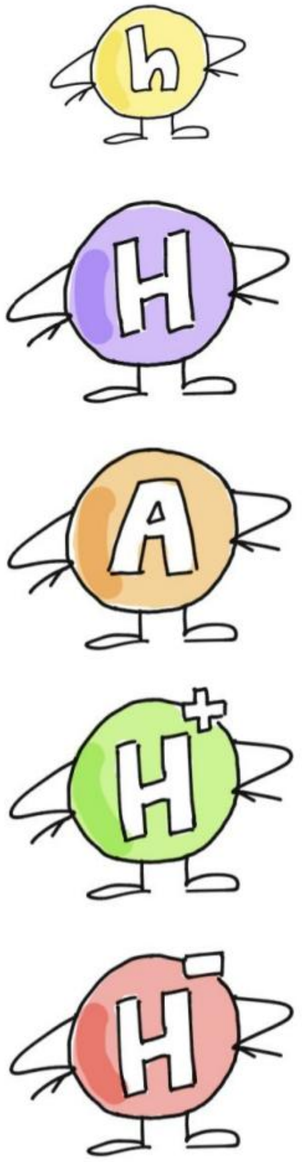
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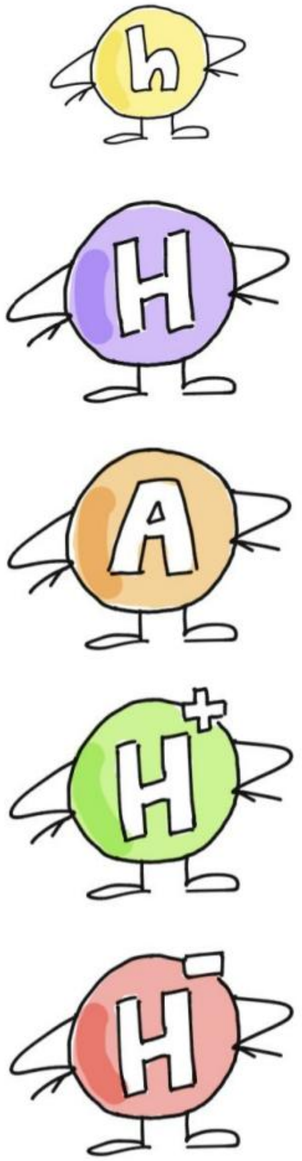
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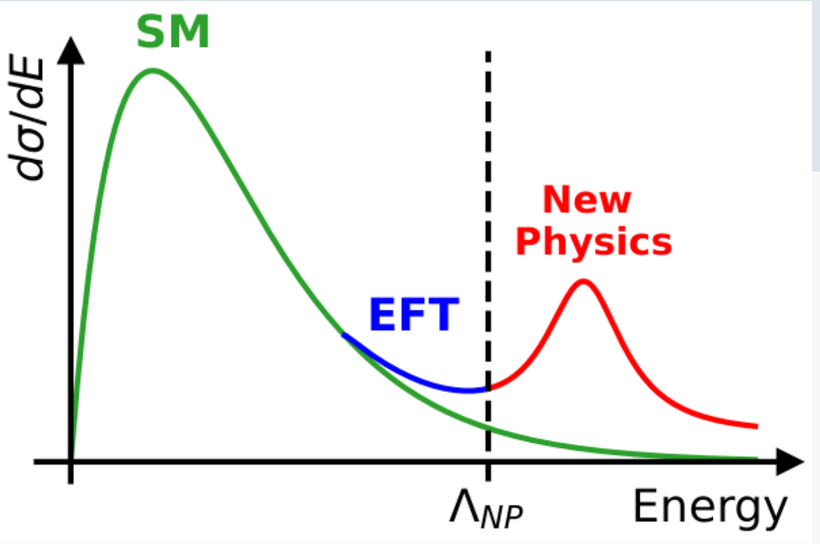
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- Crucially: parameter space allows for large κ_λ, while keeping all other Higgs couplings SM-like (See backup)



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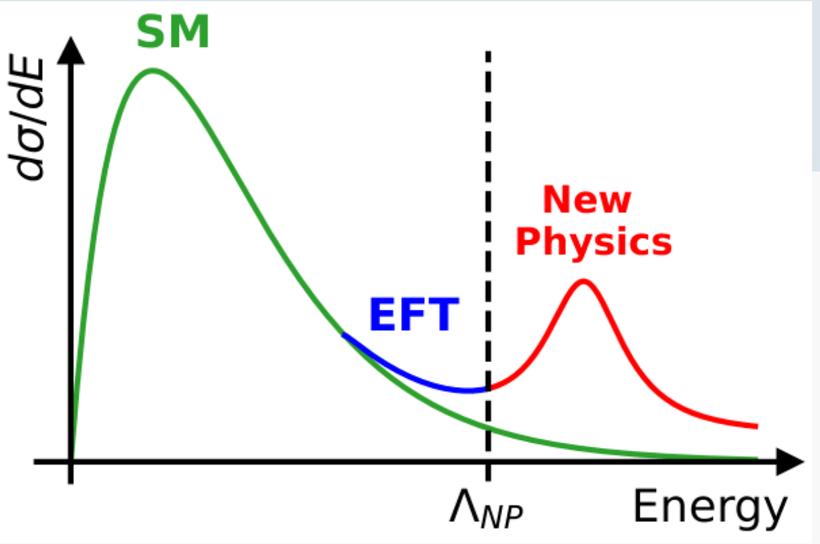
The SMEFT



Standard Model Effective Field Theory (SMEFT)

- Assume **New Physics** has a typical **energy scale Λ_{NP}**
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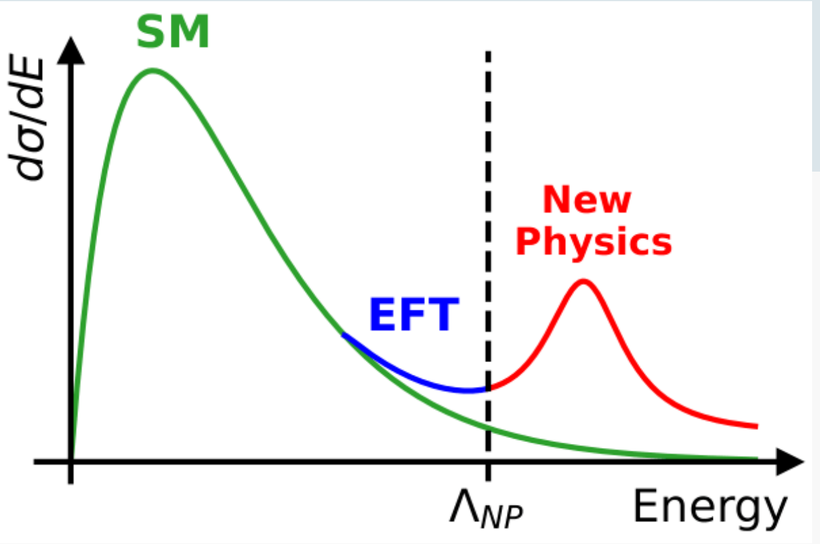


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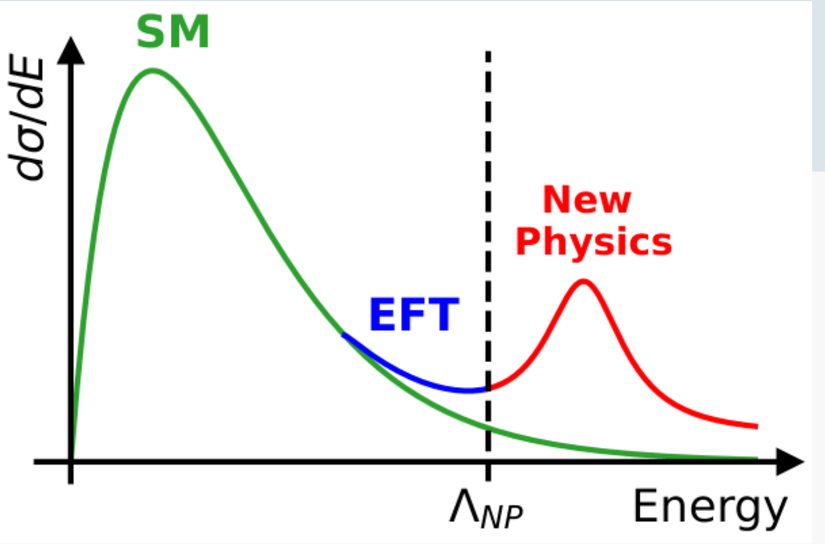


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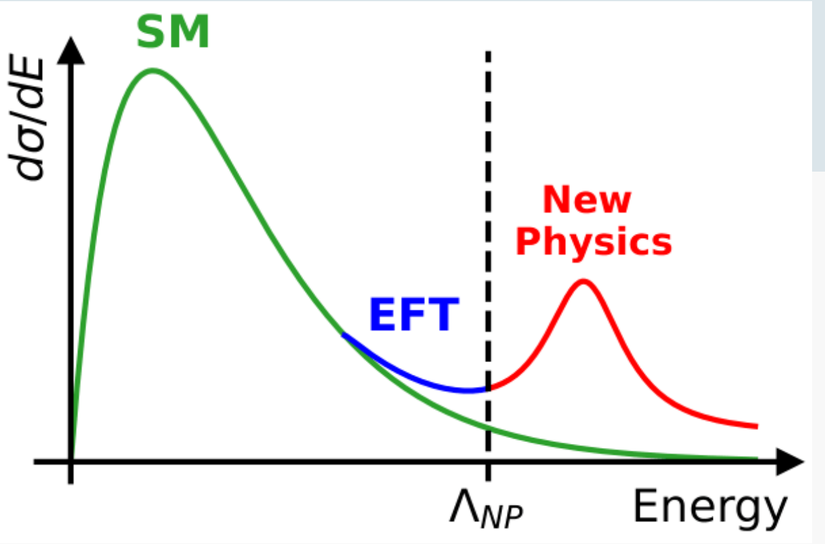
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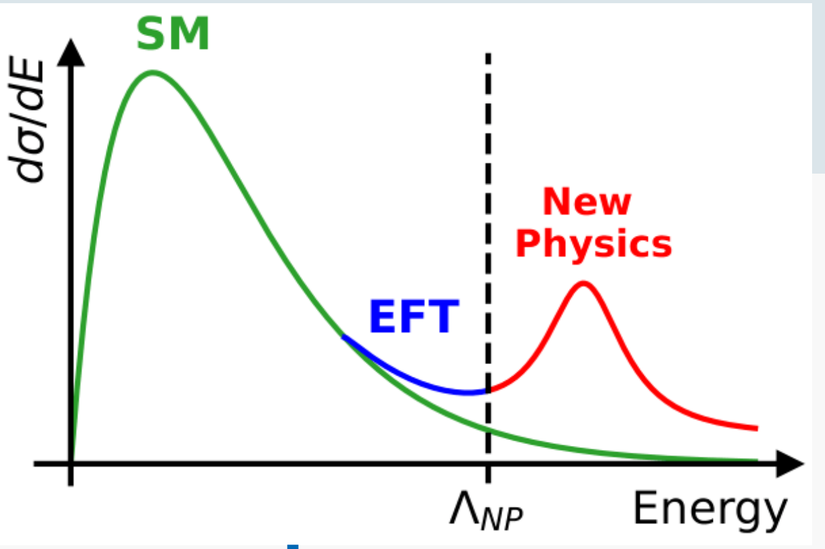
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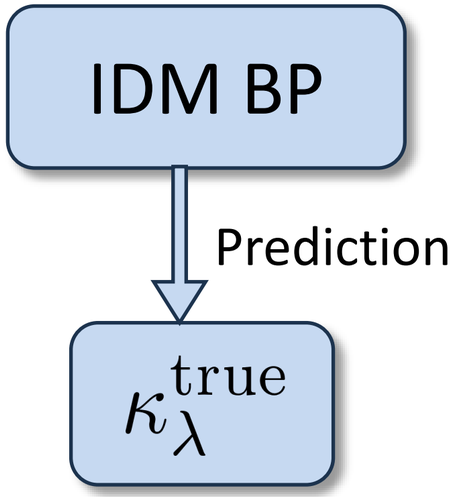
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- Current setup for **indirect** constraints: **dimension-6 SMEFT** $(\sim \mathcal{O}(1/\Lambda_{\text{NP}}^2))$

Methodology: global SMEFT fits

- **Goal**: investigate how well would **indirect** (loop-level) **measurements** determine a **non-SM value of κ_λ**
- Procedure:

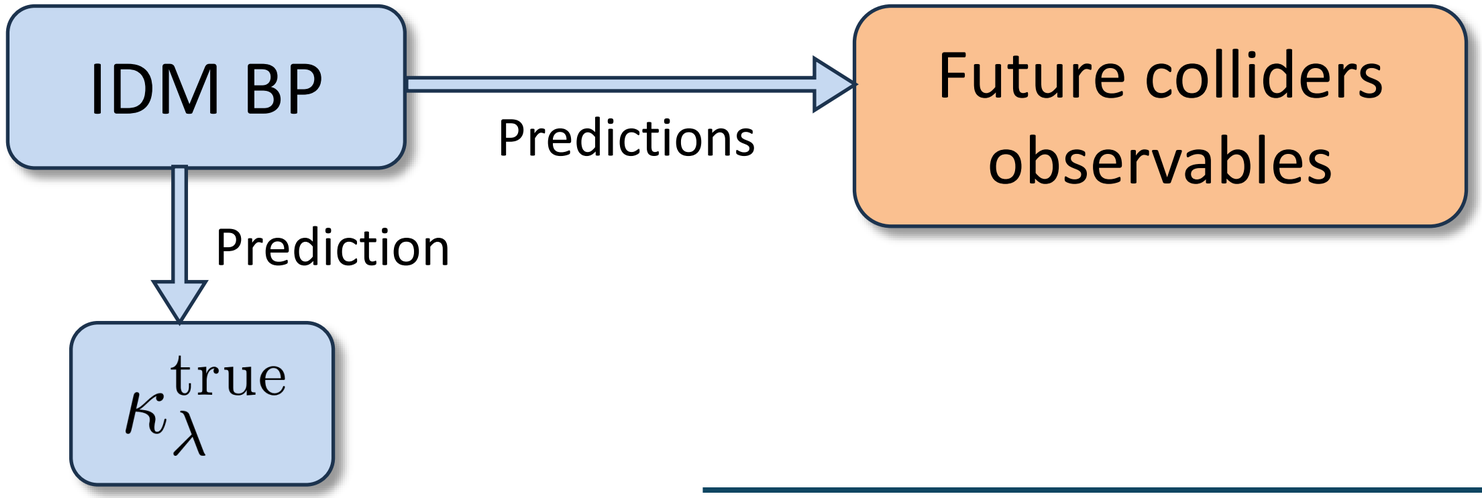
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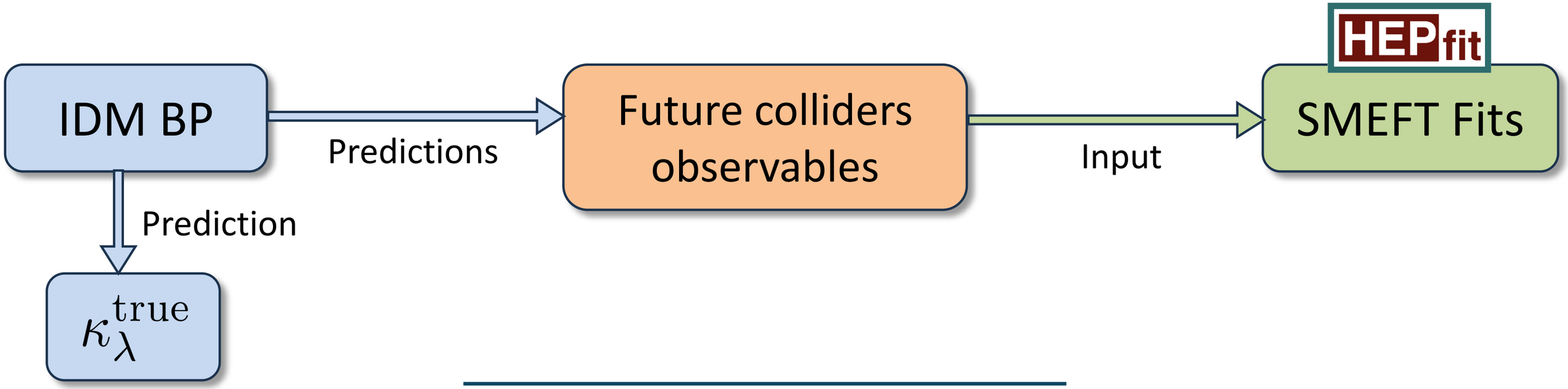
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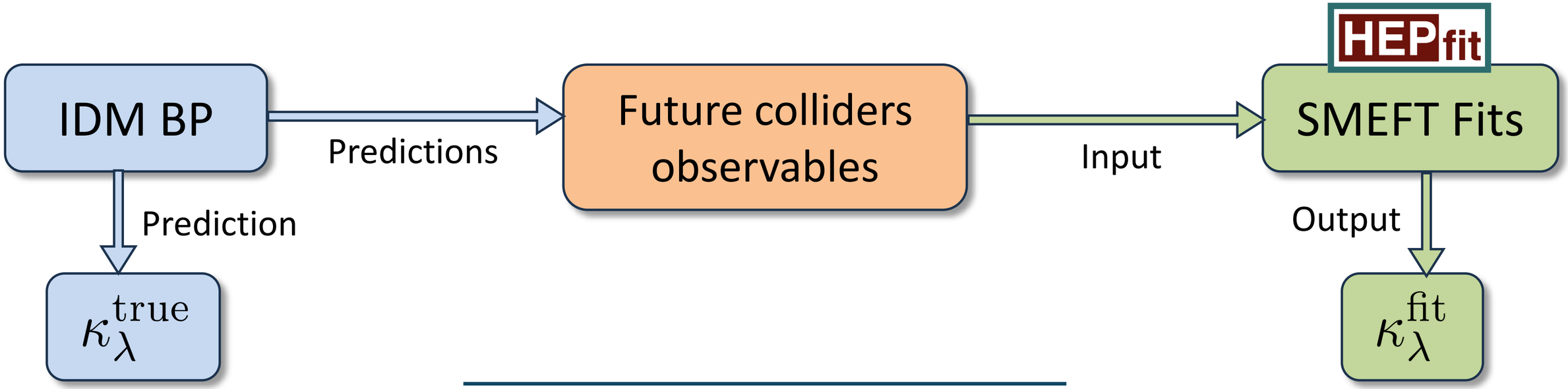
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  3. Use these results as inputs for a **global SMEFT (LO, dim-6) fit**



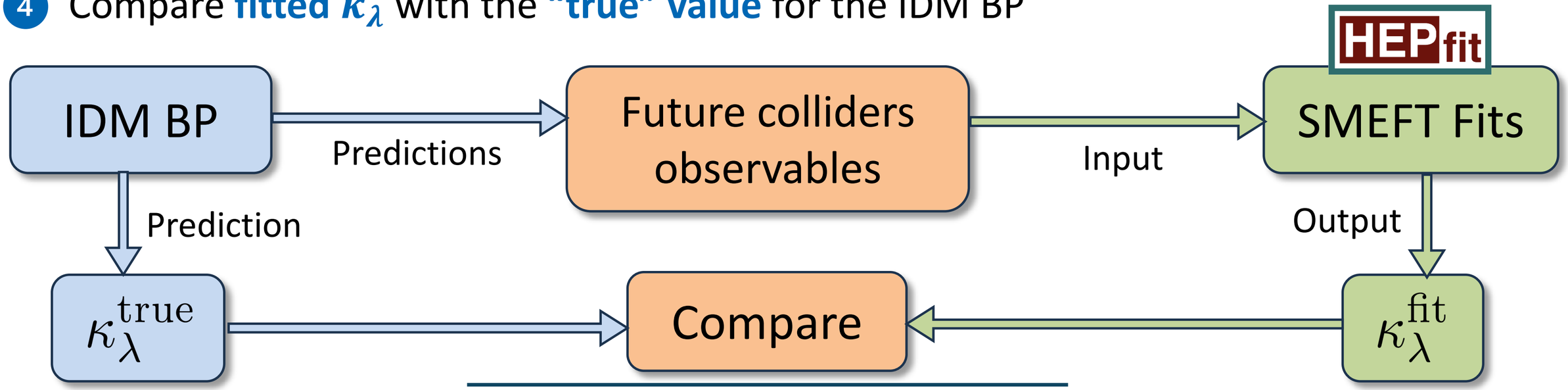
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- **Goal**: investigate how well would **indirect** (loop-level) **measurements** determine a **non-SM value of κ_λ**
- Procedure:
  1. Select set of **IDM benchmark parameter points** (BPs)
  2. For each BP, evaluate **predictions** for **observables** at future colliders
  3. Use these results as inputs for a **global SMEFT (LO, dim-6) fit**



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  4. Compare **fitted κ_λ** with the **"true" value** for the IDM BP



Input measurements: HL-LHC + FCC-ee

Input measurements: Higgs+EW fit from Snowmass 2021 [deBlas et al. '22]

Single-Higgs observables (σ and $\sigma \cdot \mathrm{BR}$)

@ HL-LHC, $\mathrm{FCC\text{-}ee}_{240}$ & $\mathrm{FCC\text{-}ee}_{365}$

Electroweak precision observables (EWPOs)

@ HL-LHC, $\mathrm{FCC\text{-}ee}_{\mathrm{Z}}$ & $\mathrm{FCC\text{-}ee}_{\mathrm{WW}}$

Diboson measurements ($e^+e^- \to WW$)

@ HL-LHC, $\mathrm{FCC\text{-}ee}_{\mathrm{WW}}$, $\mathrm{FCC\text{-}ee}_{240}$ & $\mathrm{FCC\text{-}ee}_{365}$

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

Before

Input measurements: HL-LHC + FCC-ee

Input measurements: Higgs+EW fit from Snowmass 2021 [deBlas et al. '22]

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Collider	Energy	Int. Lumi.
HL-LHC	14 TeV	6 ab^{-1}
$\mathrm{FCC\text{-}ee}_{Z}$	M_Z	205 ab^{-1}
$\mathrm{FCC\text{-}ee}_{WW}$	$2M_W$	19.2 ab^{-1}
$\mathrm{FCC\text{-}ee}_{240}$	240 GeV	10.8 ab^{-1}
$\mathrm{FCC\text{-}ee}_{365}$	365 GeV	2.7 ab^{-1}

Now

Inputs updated according to latest ESPPU projections

Naïve fit results

"Naïve" fits:

- **IDM** predictions at **1-loop** level
- **SMEFT** implementation in **HEPfit**

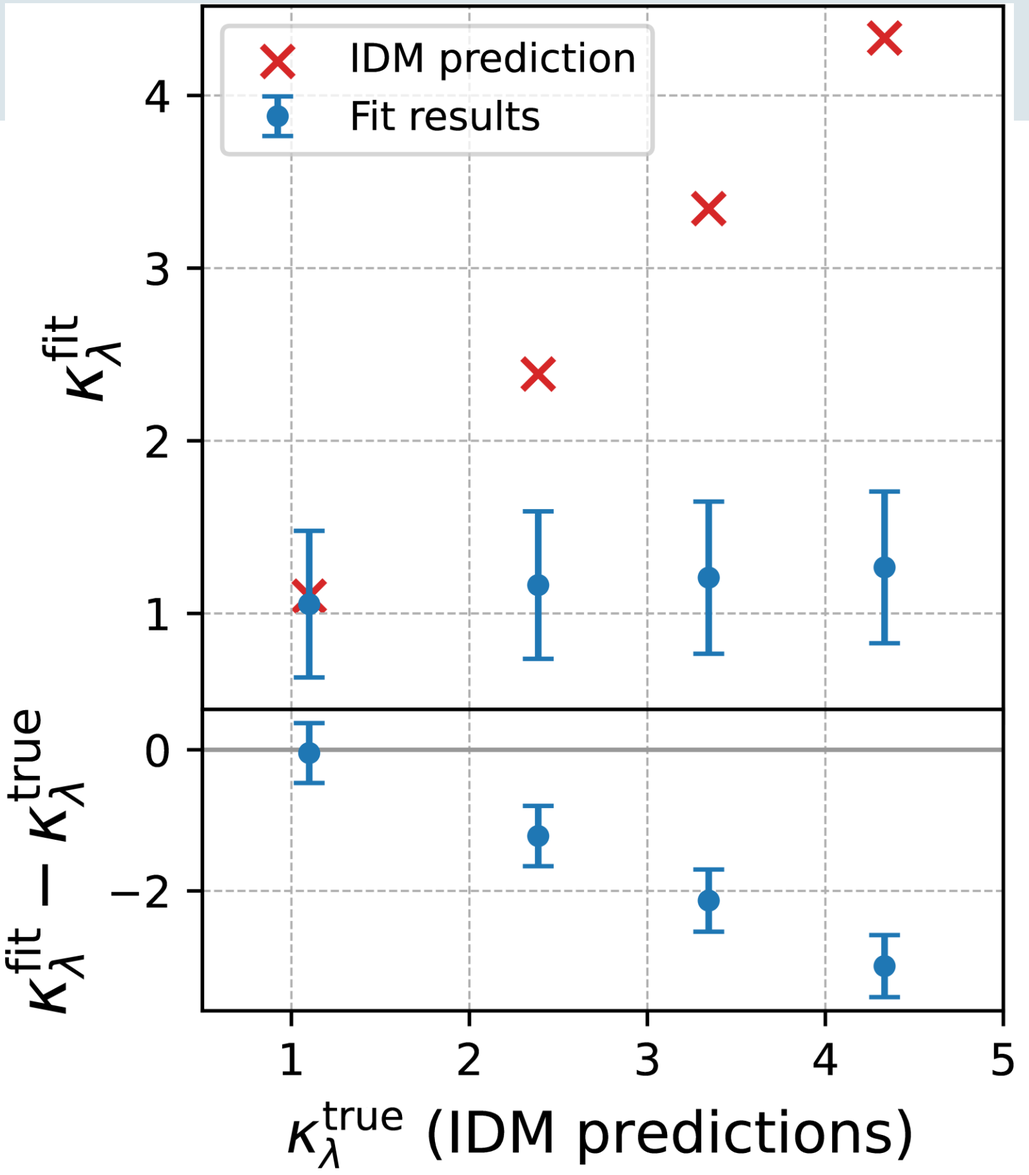
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Fit results:

- **Mismatch** between **fitted κ_λ** value and **IDM κ_λ prediction**
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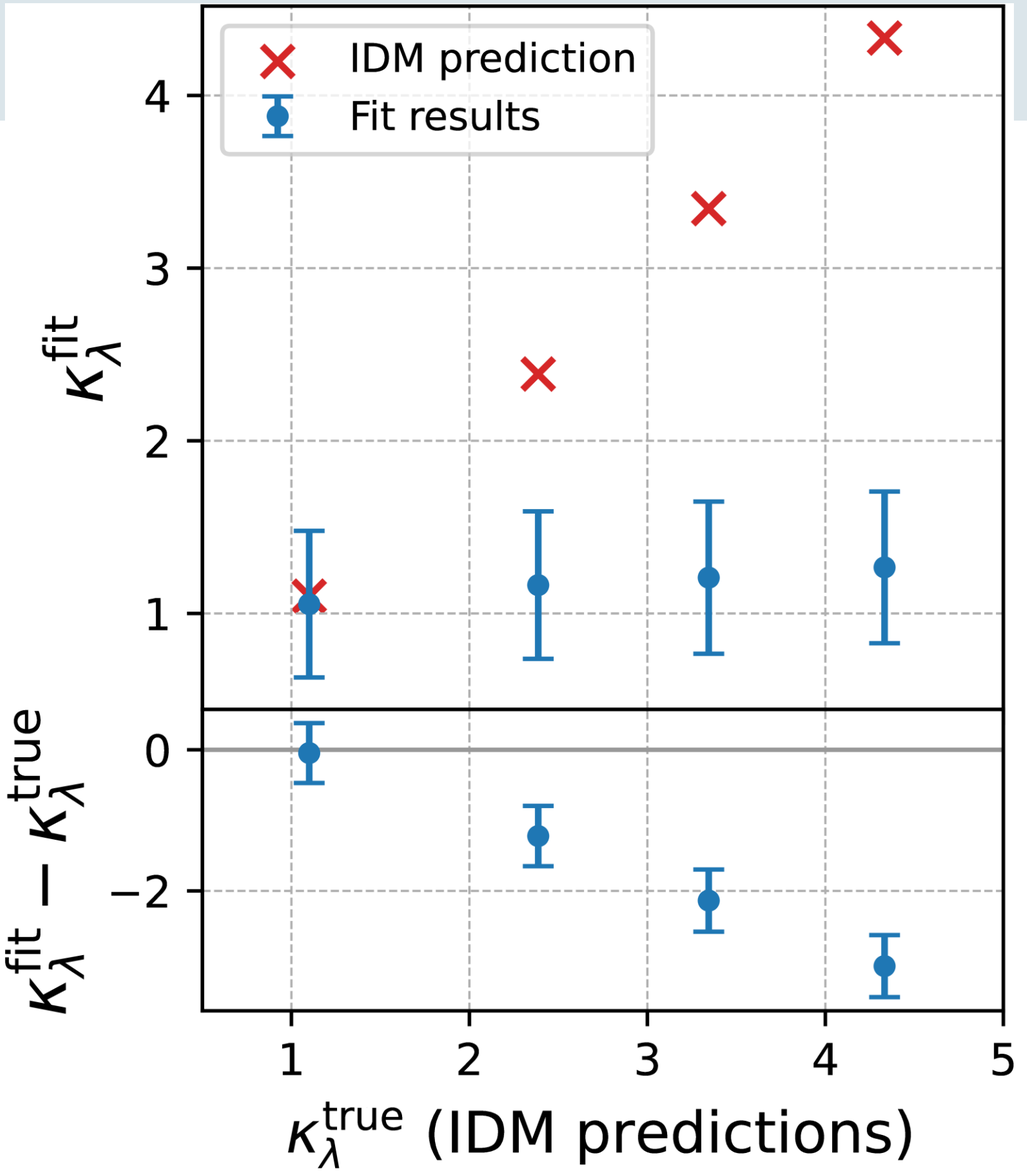
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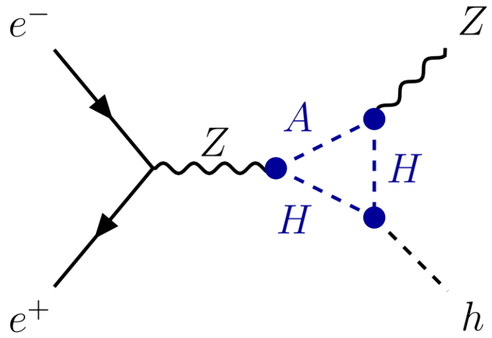
- **Mismatch** between **fitted κ_λ** value and **IDM κ_λ prediction**
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- Another approach: include 1L SM-like diagrams with insertions of κ_λ into IDM predictions (see next slide)

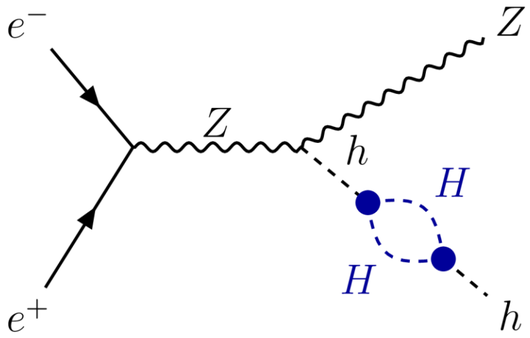


σ_{Zh} prediction: IDM vs. SMEFT

IDM calculation

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

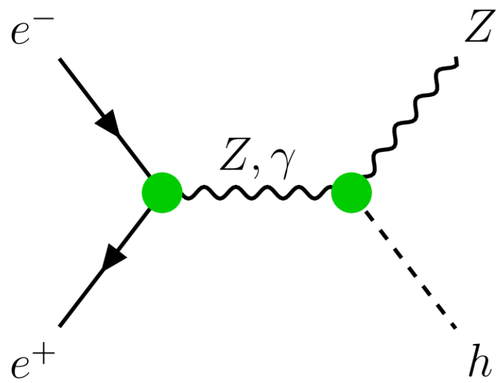


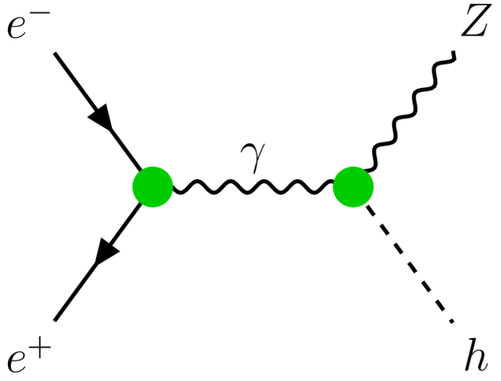


+ many more

SMEFT calculation

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



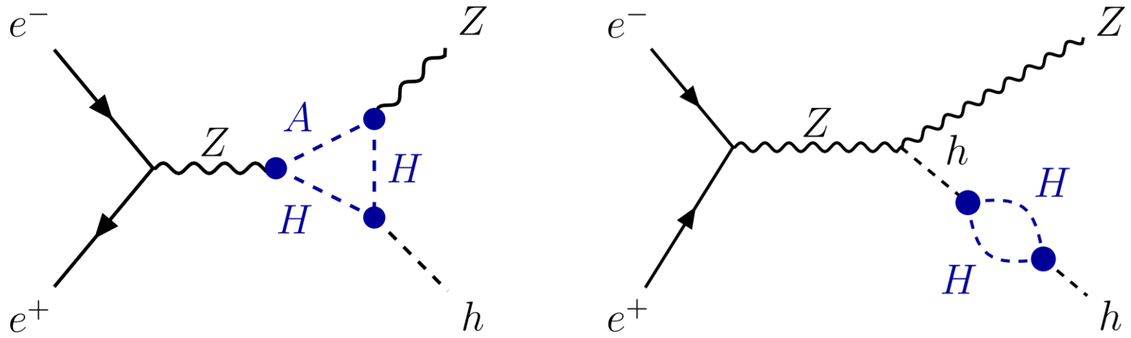


+ many more

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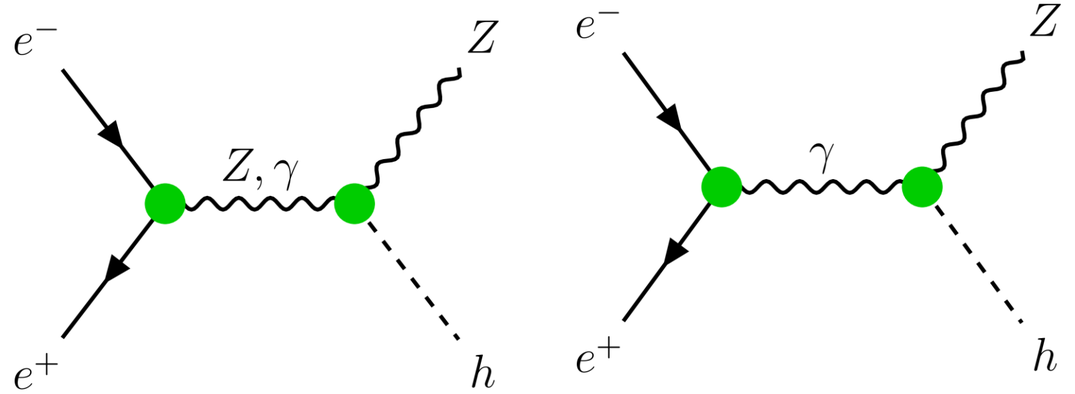
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+ many more

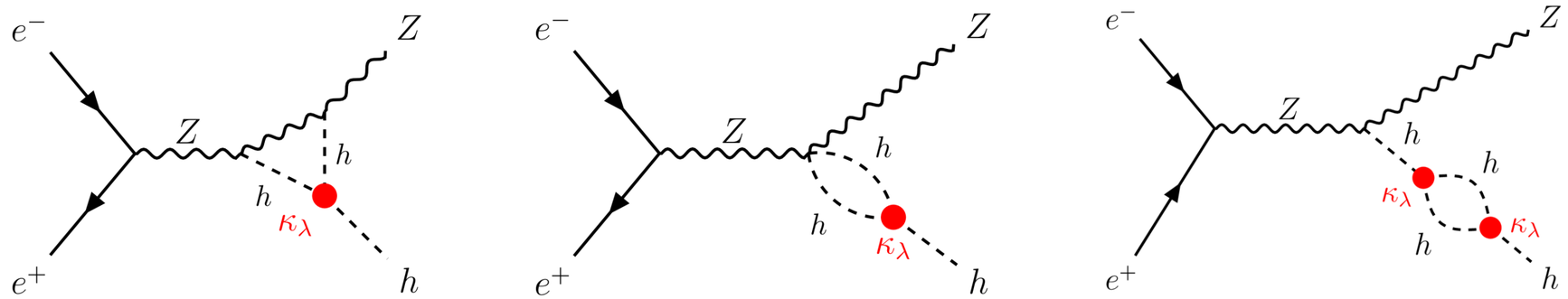
SMEFT calculation

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



+ many more

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



σ_{Zh} expression in SMEFT

- Assuming $\kappa_\lambda \neq 1$, one can parametrize the Zh cross-section as: [Degrassi et al. '16]

$$\sigma_{\kappa_\lambda} = Z_{h,\kappa_\lambda}\sigma_{\mathrm{LO}}(1 + \kappa_\lambda C_1)$$

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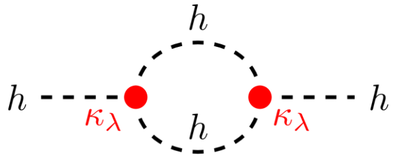
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- $Z_{h,\kappa_\lambda} = (1 - \kappa_\lambda^2 \delta Z_h)^{-1}$ is the resummed κ_λ^2 contribution to the wave function renormalization (WFR) constant of the Higgs field, with

$$\delta Z_h = -\frac{9}{16\sqrt{2}\pi^2}\left(\frac{2\pi}{3\sqrt{3}} - 1\right) G_F m_h^2 \simeq -1.536 \times 10^{-3}$$



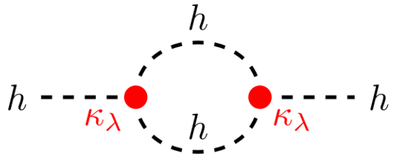
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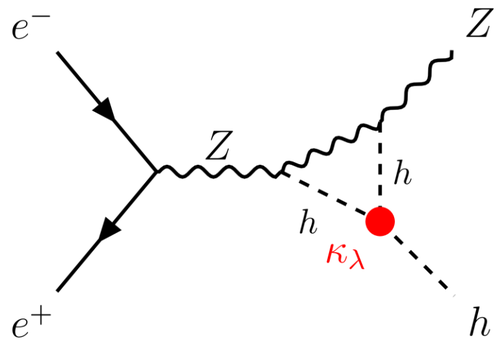
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- C_1 corresponds to the momentum-dependent contributions to the ZZh vertex [Di Vita et al. '17]



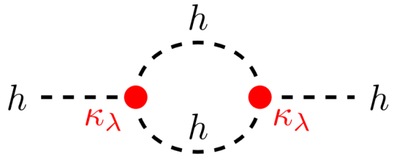
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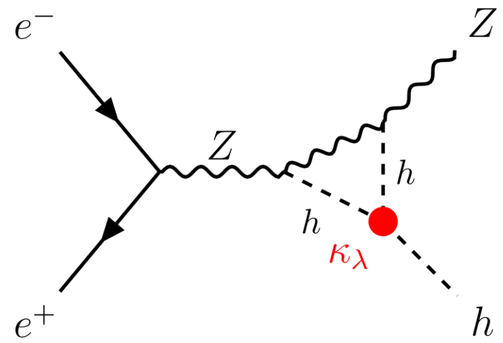
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- The ratio of the cross-section with respect to the SM value is then:

- C_1 corresponds to the momentum-dependent contributions to the ZZh vertex [Di Vita et al. '17]



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

Truncation σ_{Zh} of the expression in SMEFT

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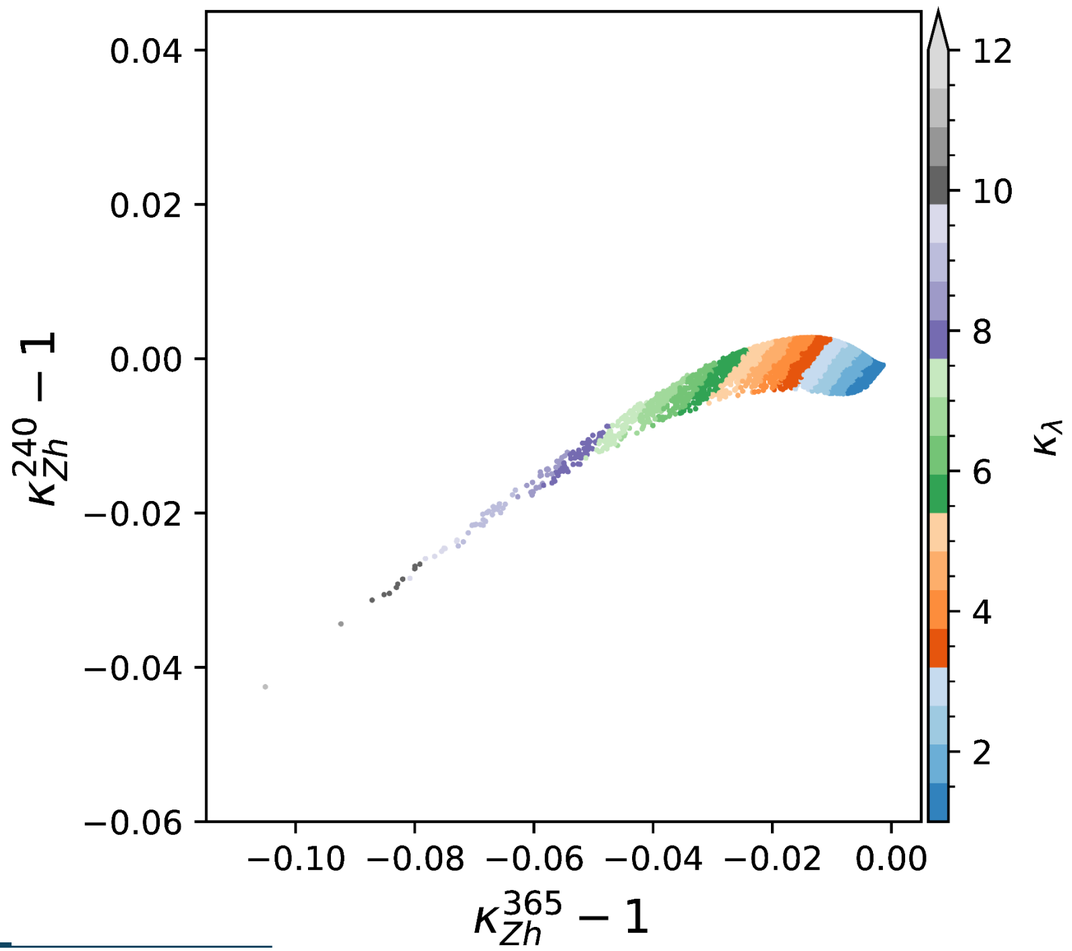
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Choice of expression → theoretical uncertainty!

Estimating theoretical uncertainties on σ_{Zh}

Scatter points: IDM predictions for σ_{Zh} at $\sqrt{s} = 240, 365$ GeV

$$(k_{Zh})^2 \equiv \frac{\sigma_{Zh}}{\sigma_{Zh}^{\mathrm{SM}}}$$

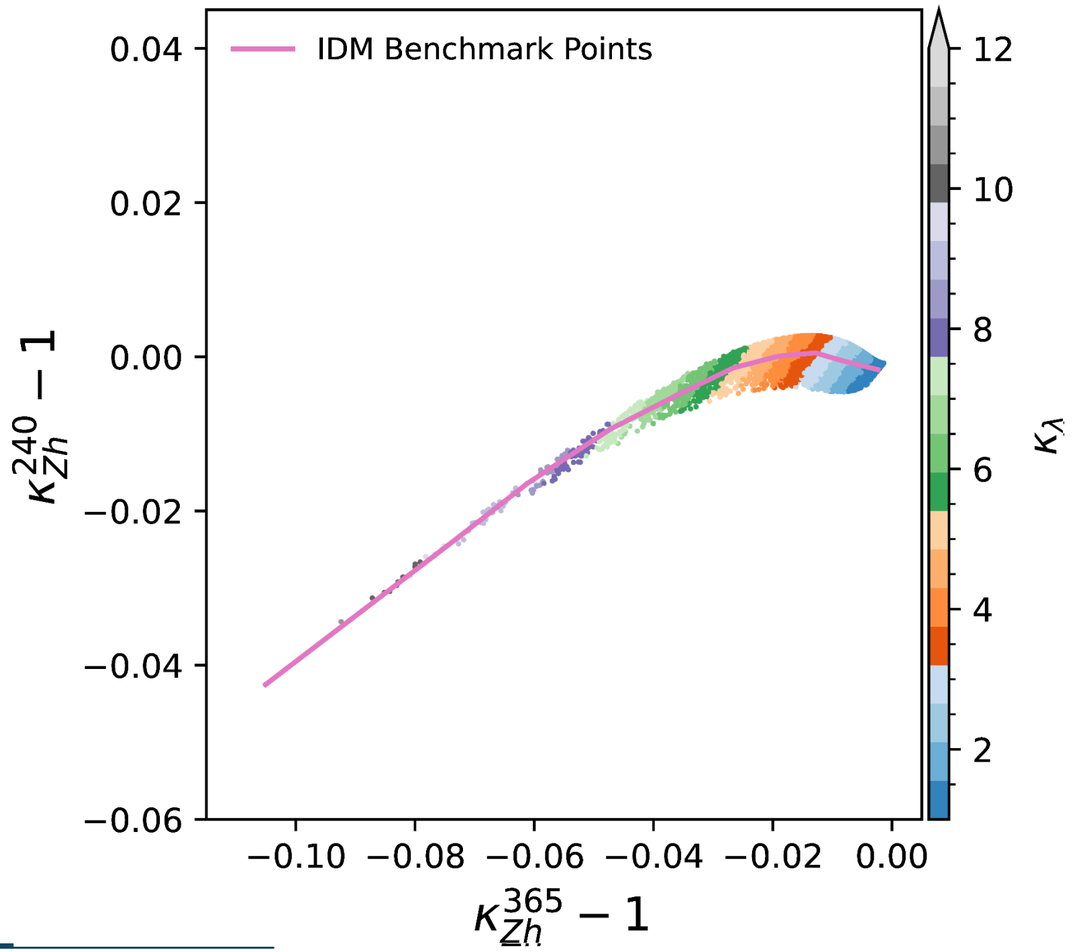


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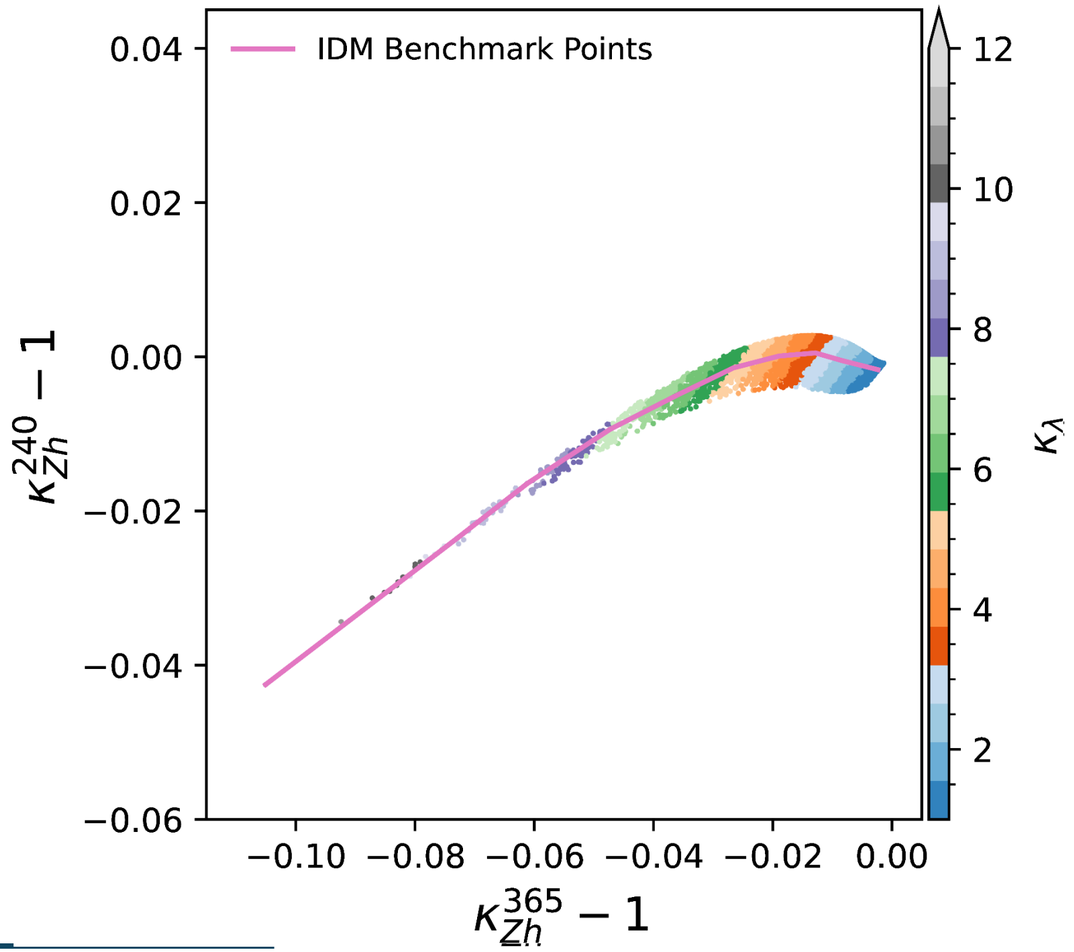


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- Apply simplified “matching” to SMEFT



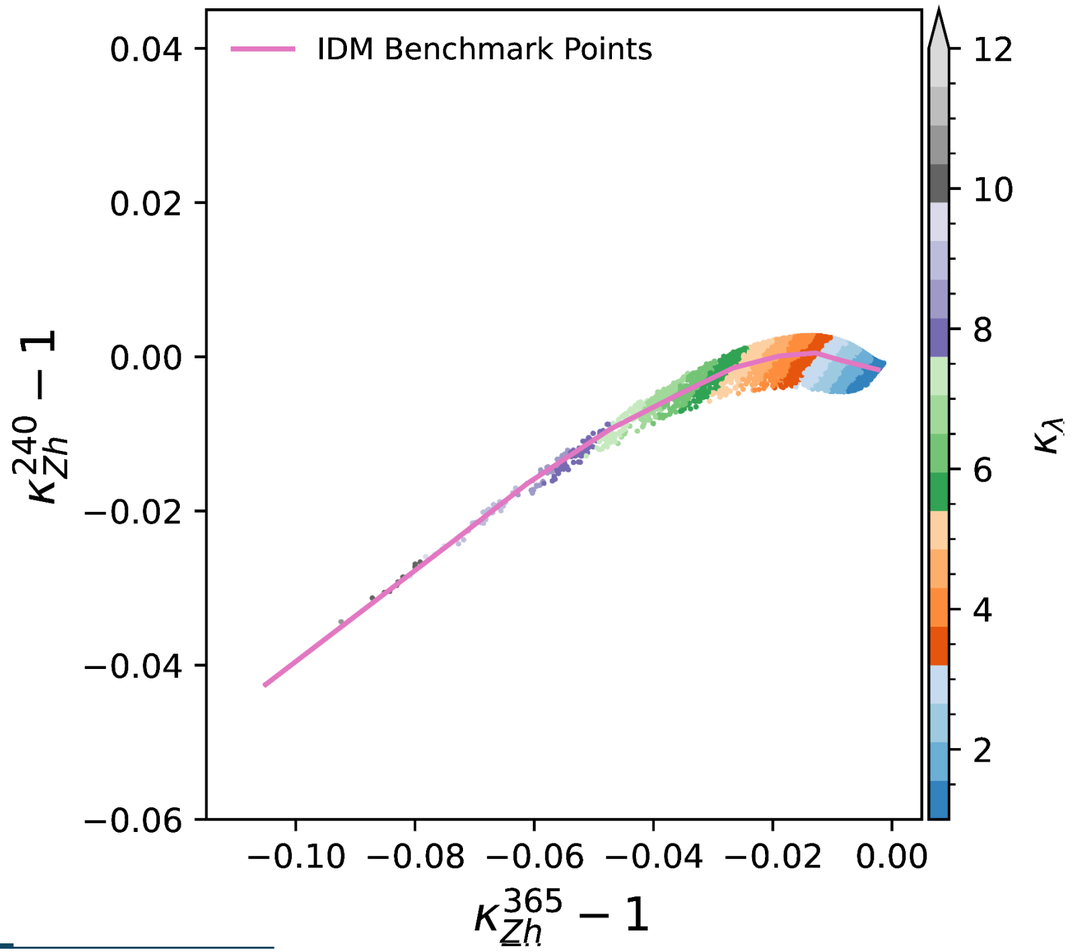
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IDM BP

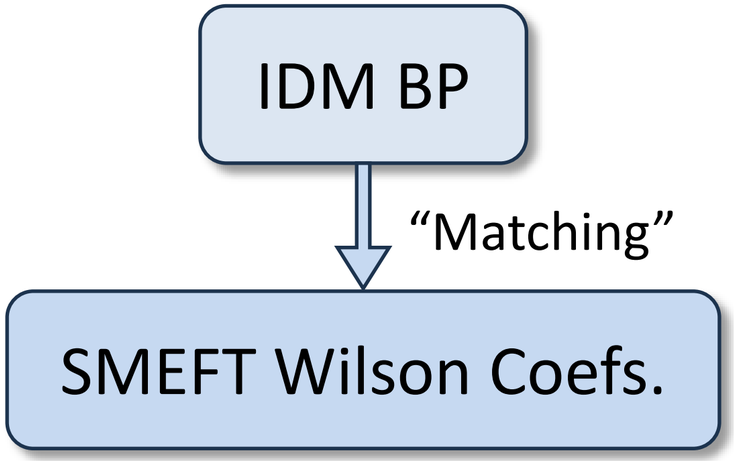


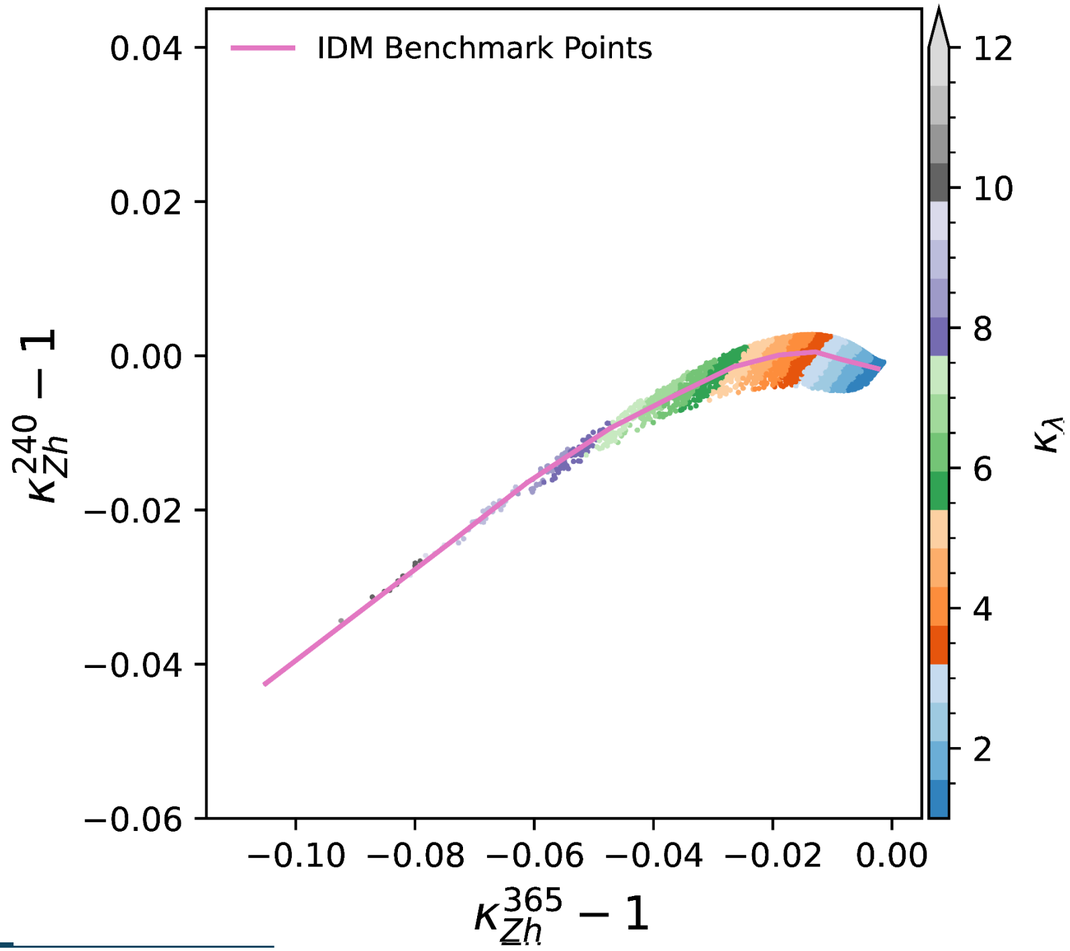
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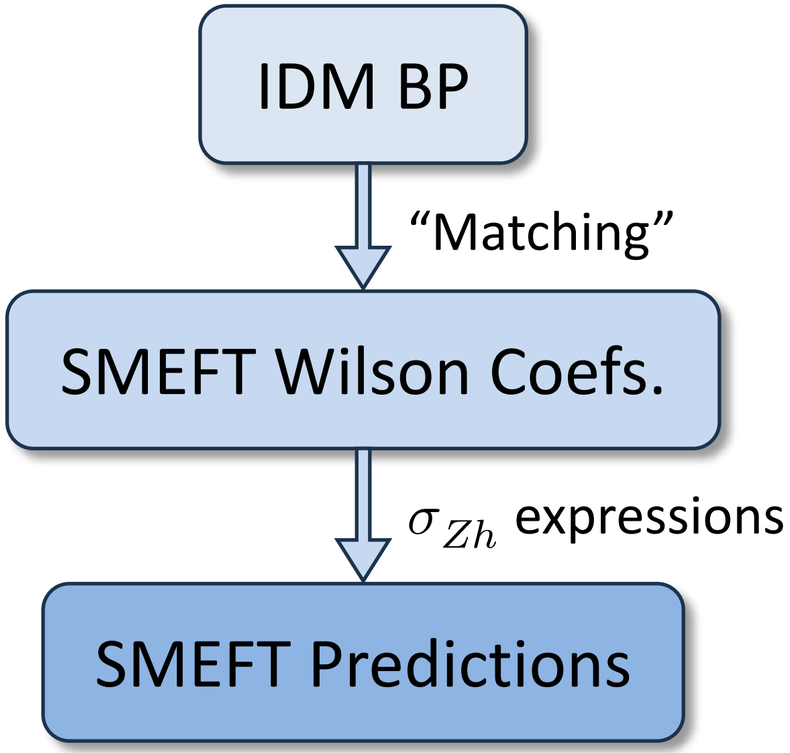


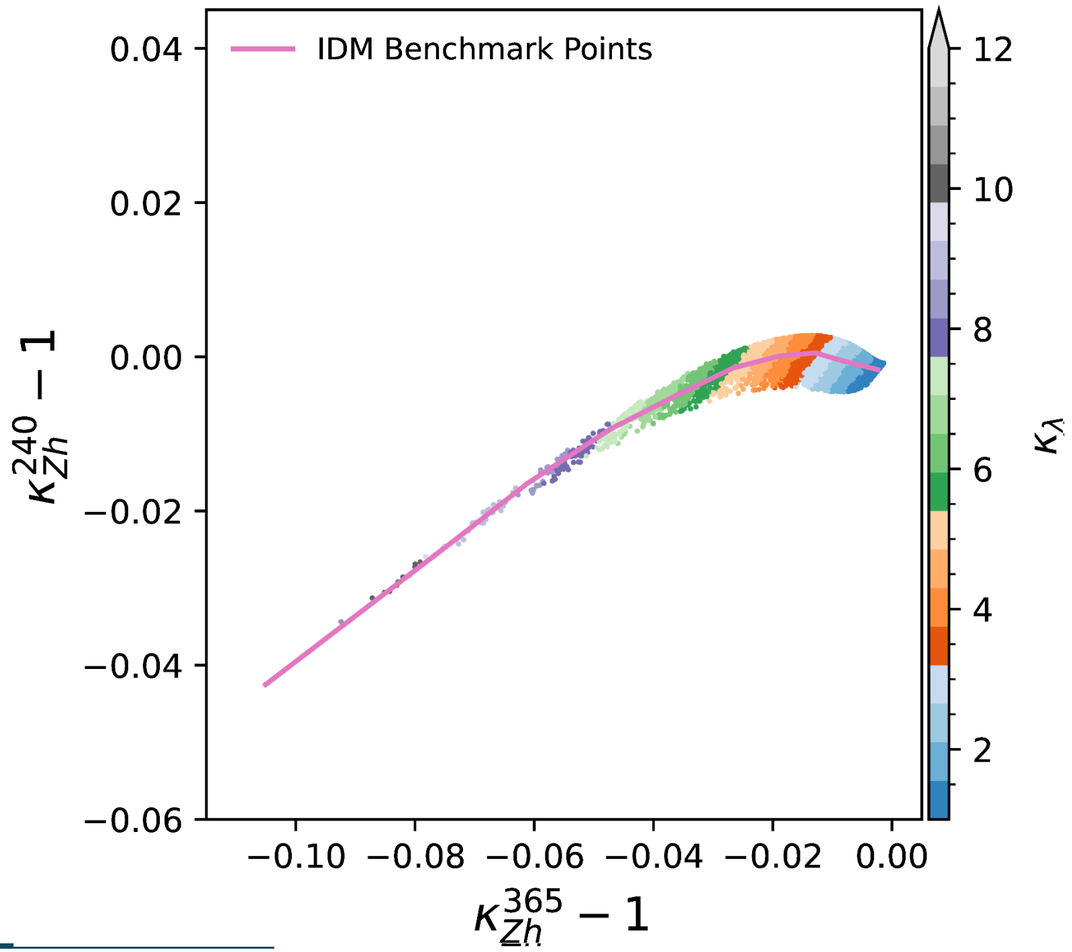
Estimating theoretical uncertainties on σ_{Zh}

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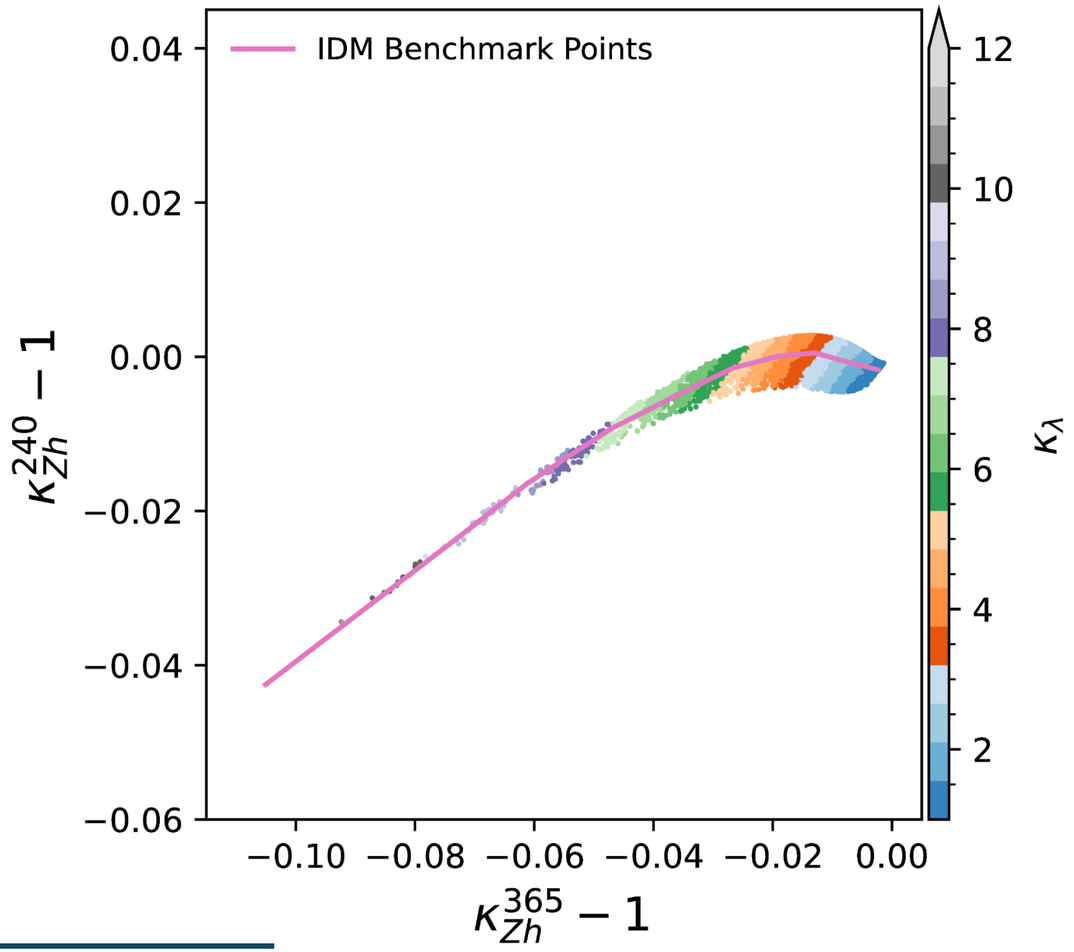




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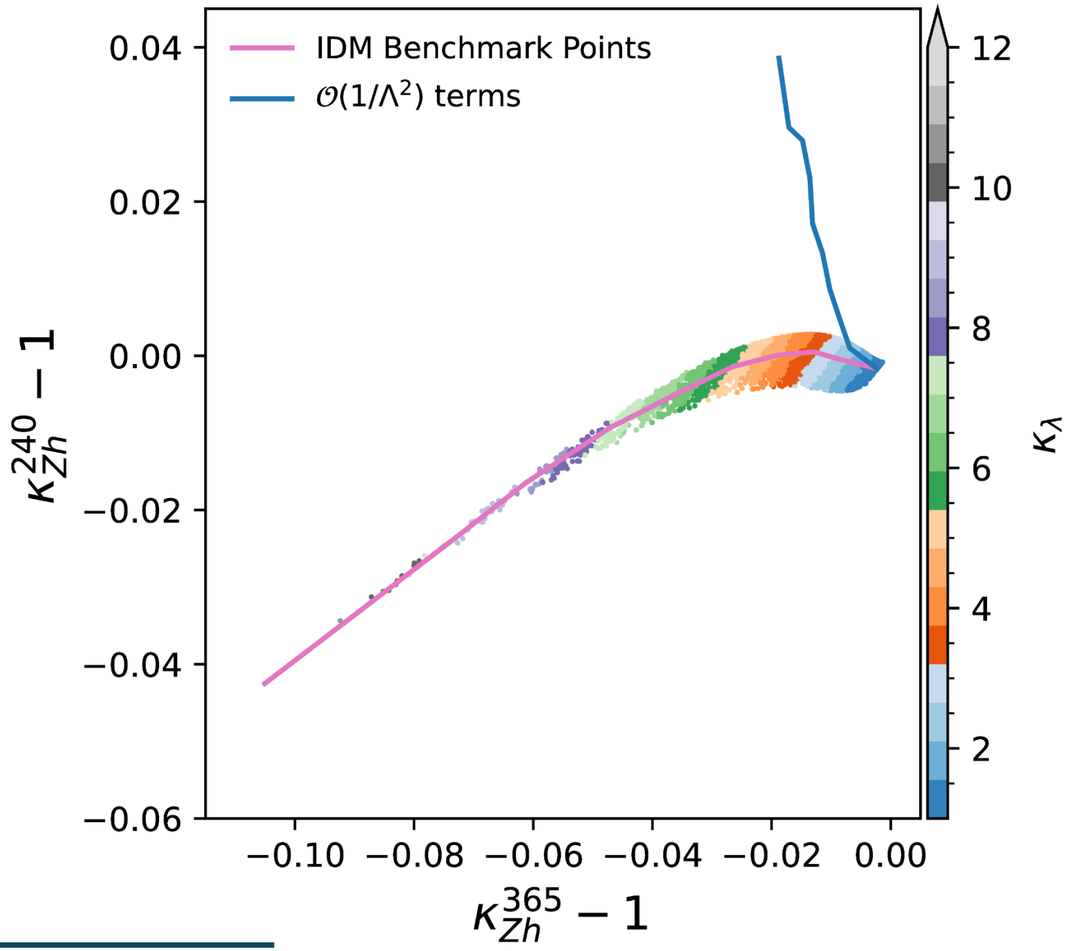


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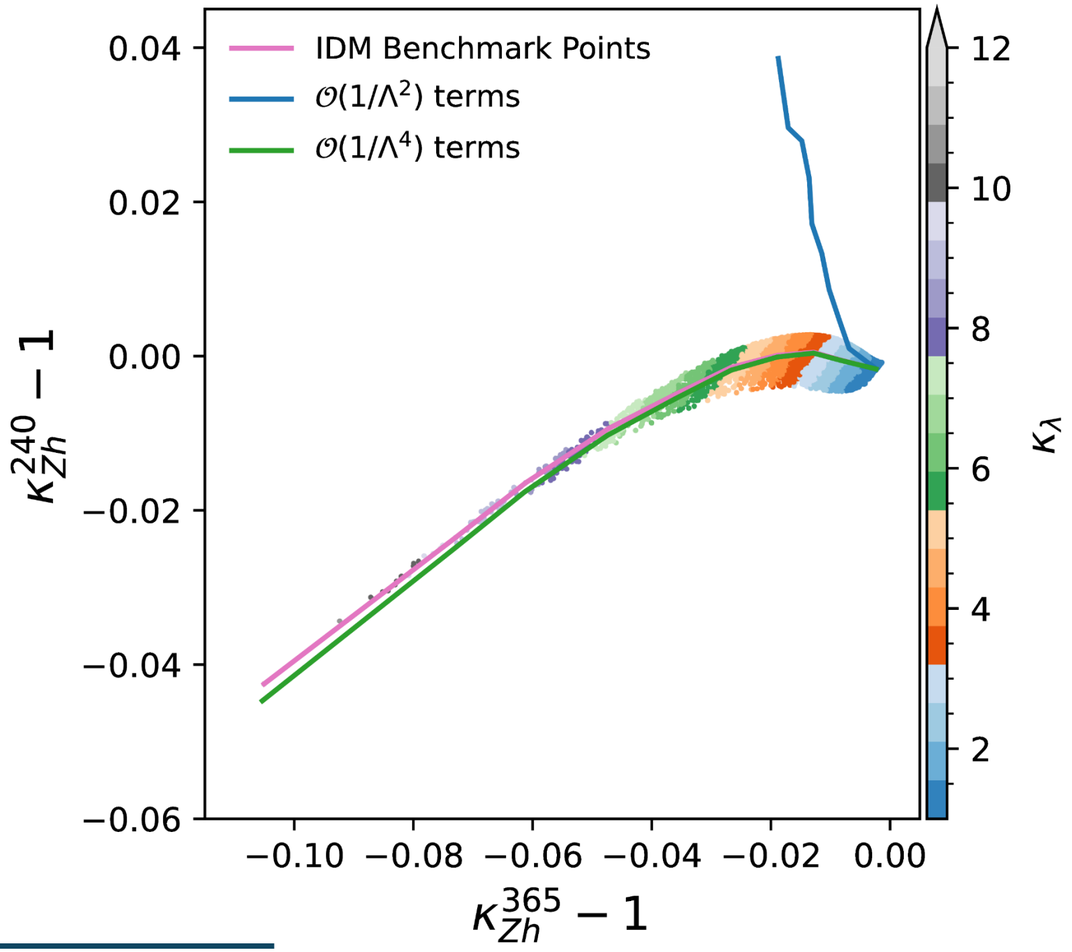


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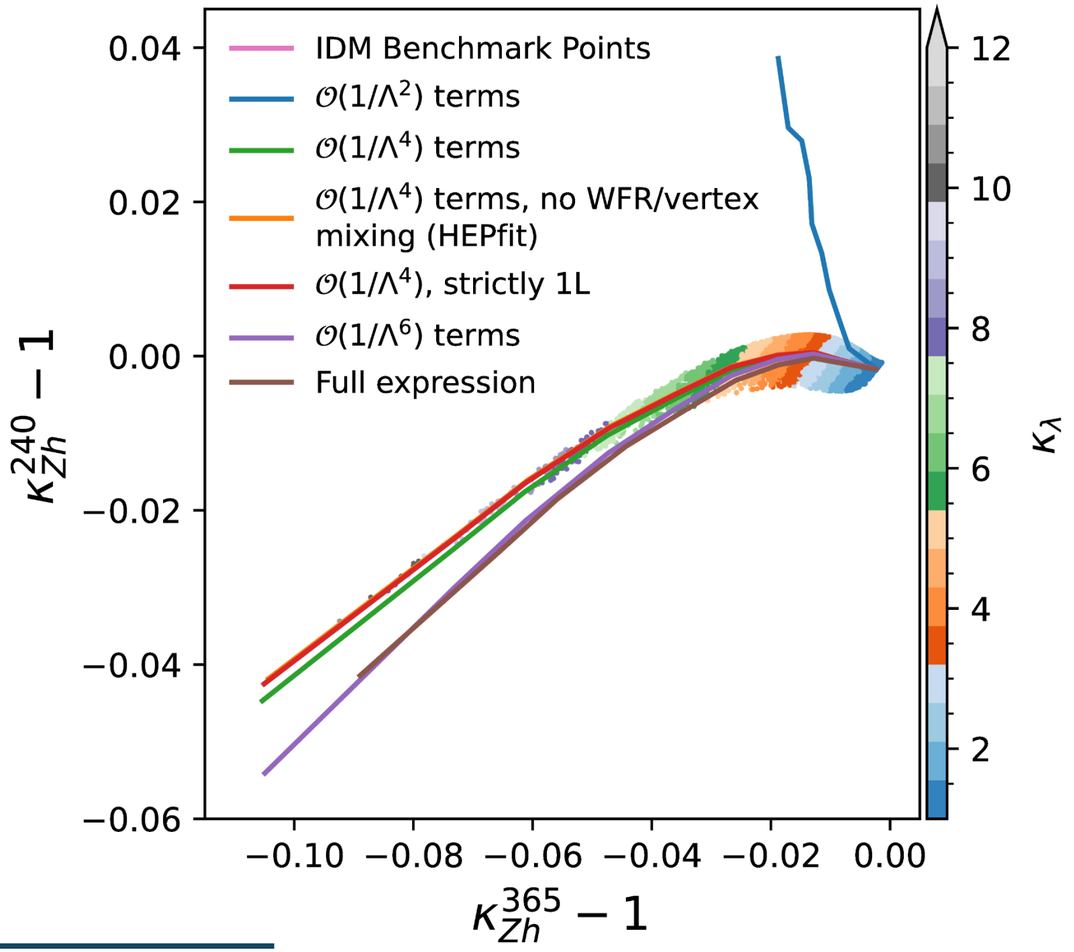


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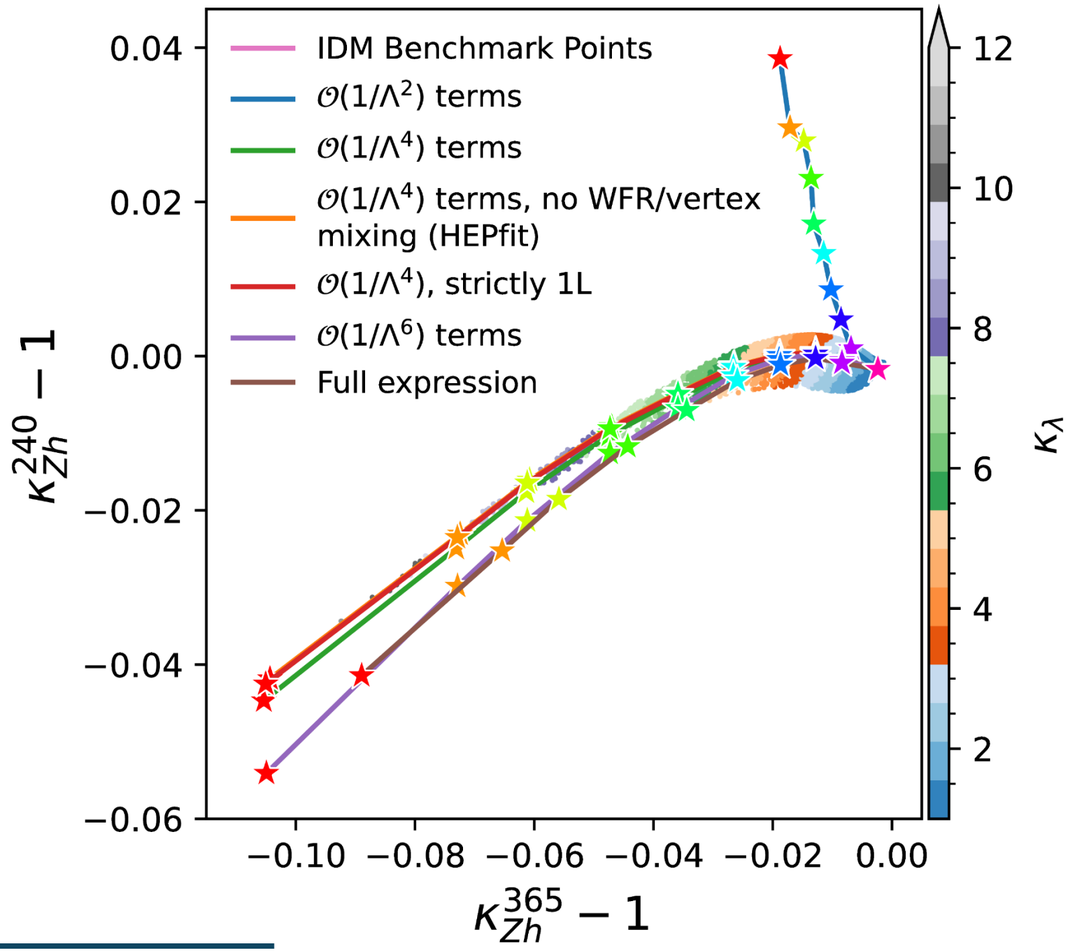


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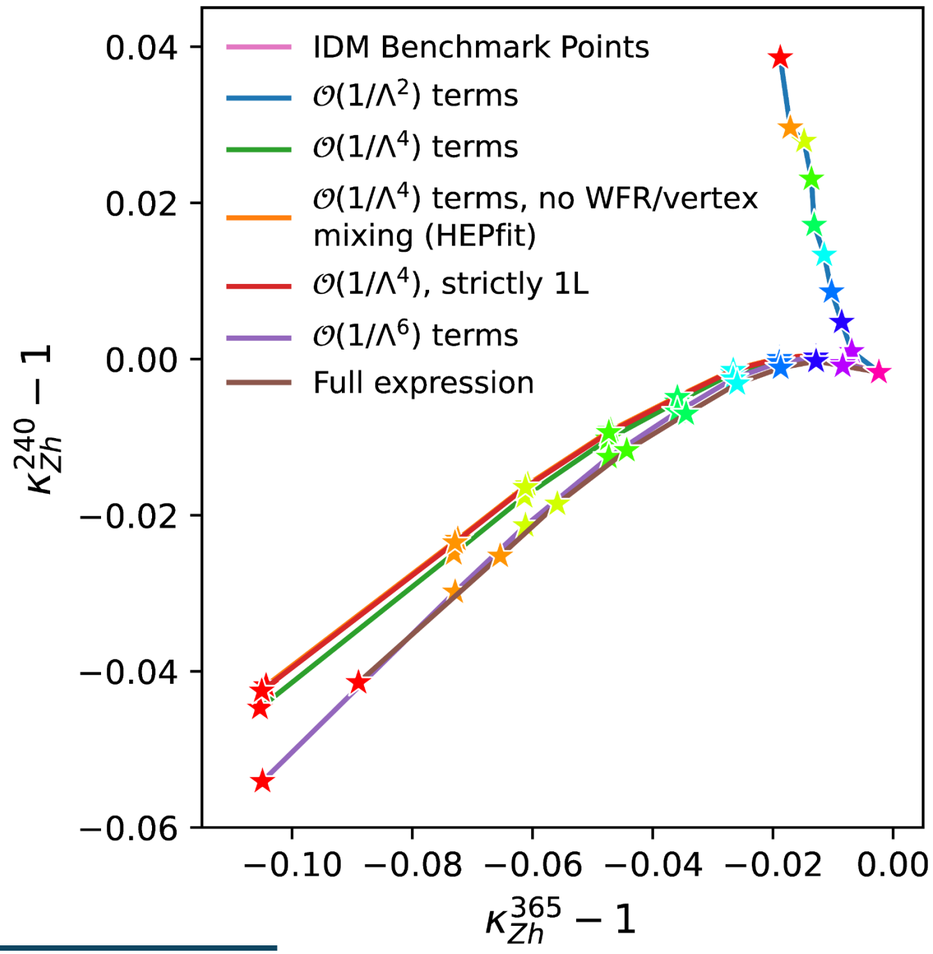


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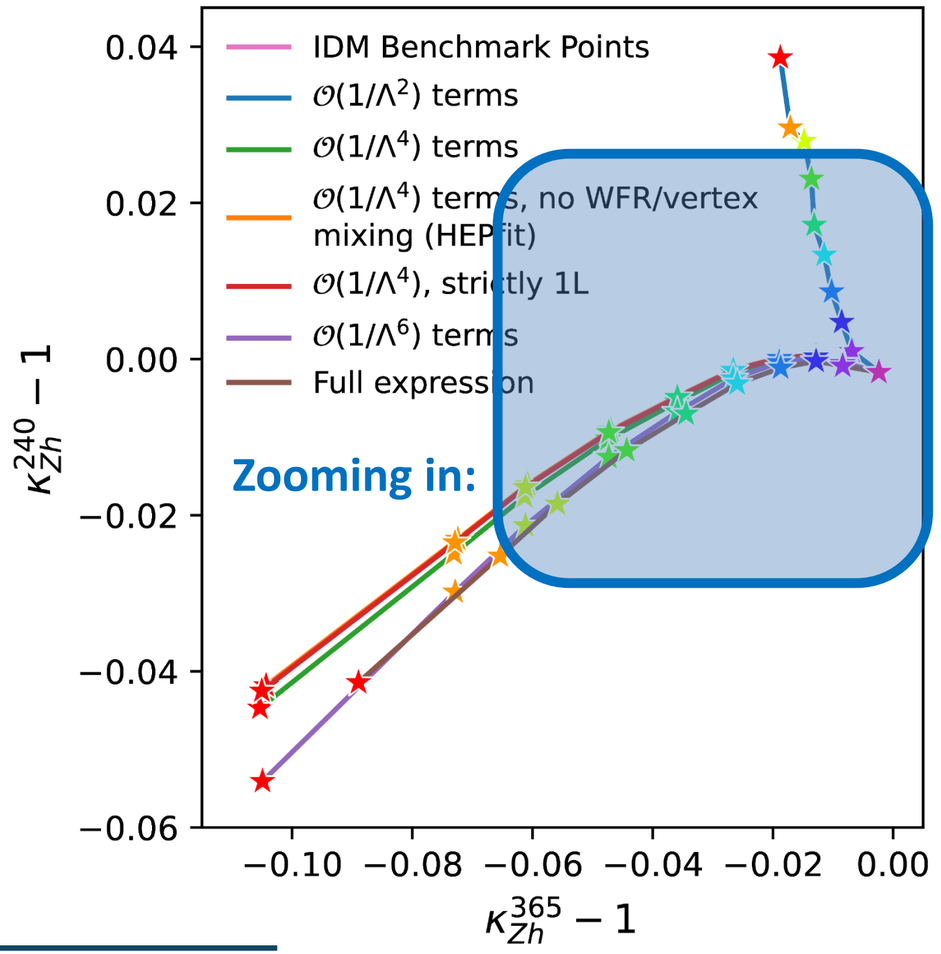


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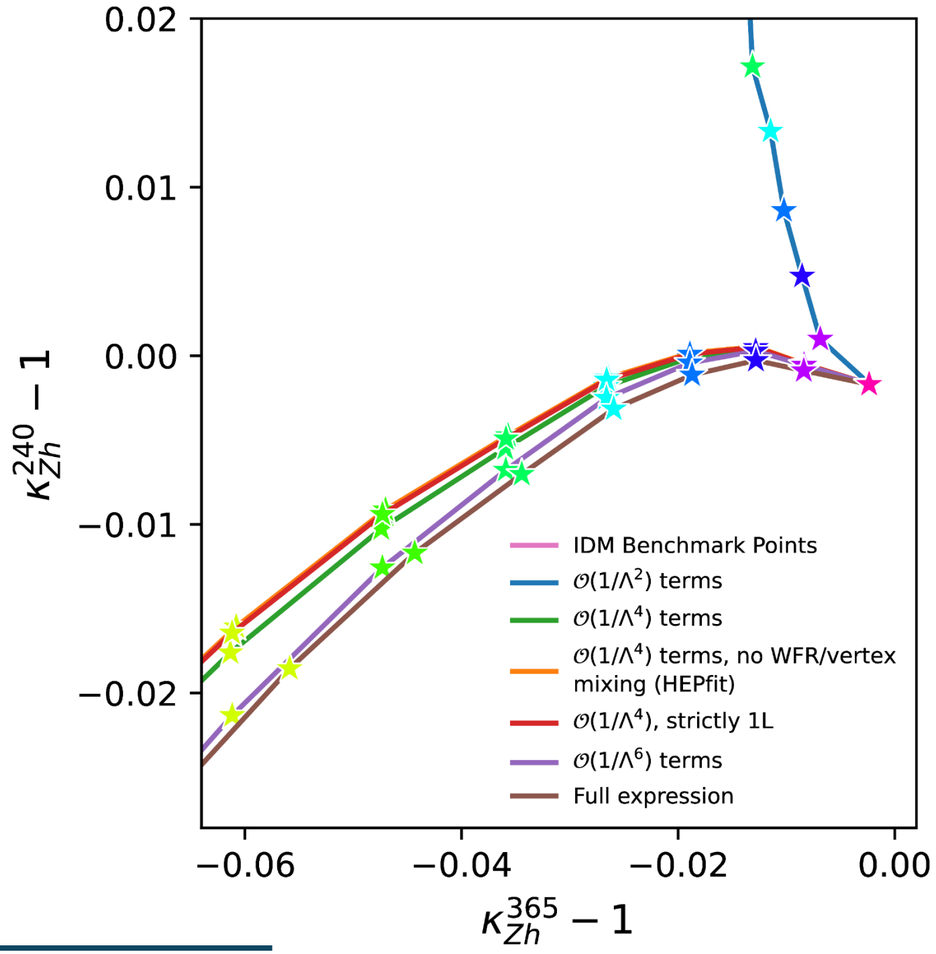


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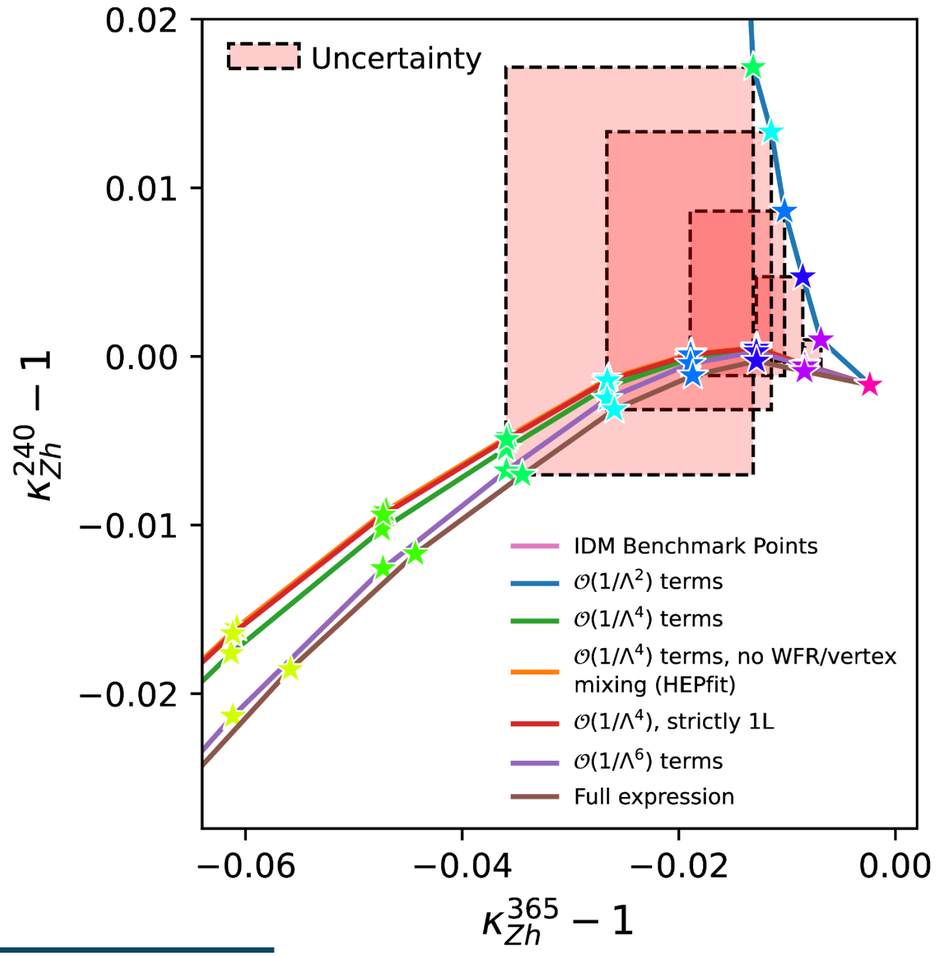


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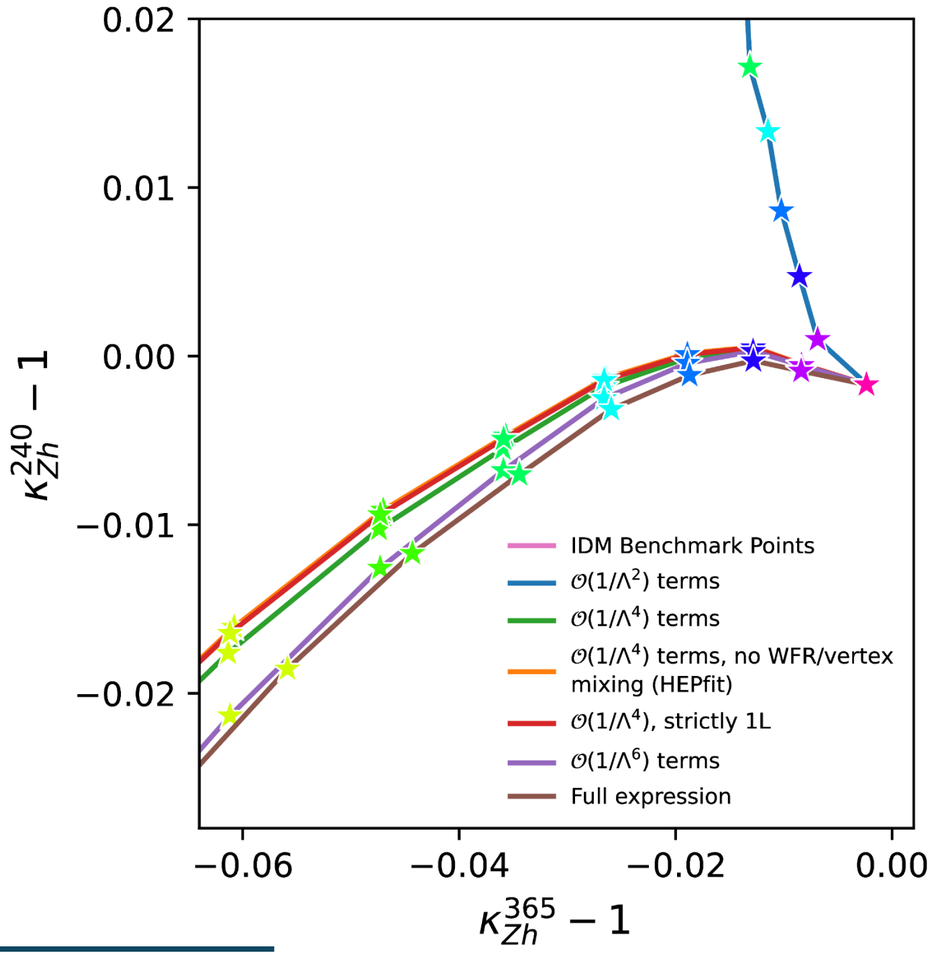


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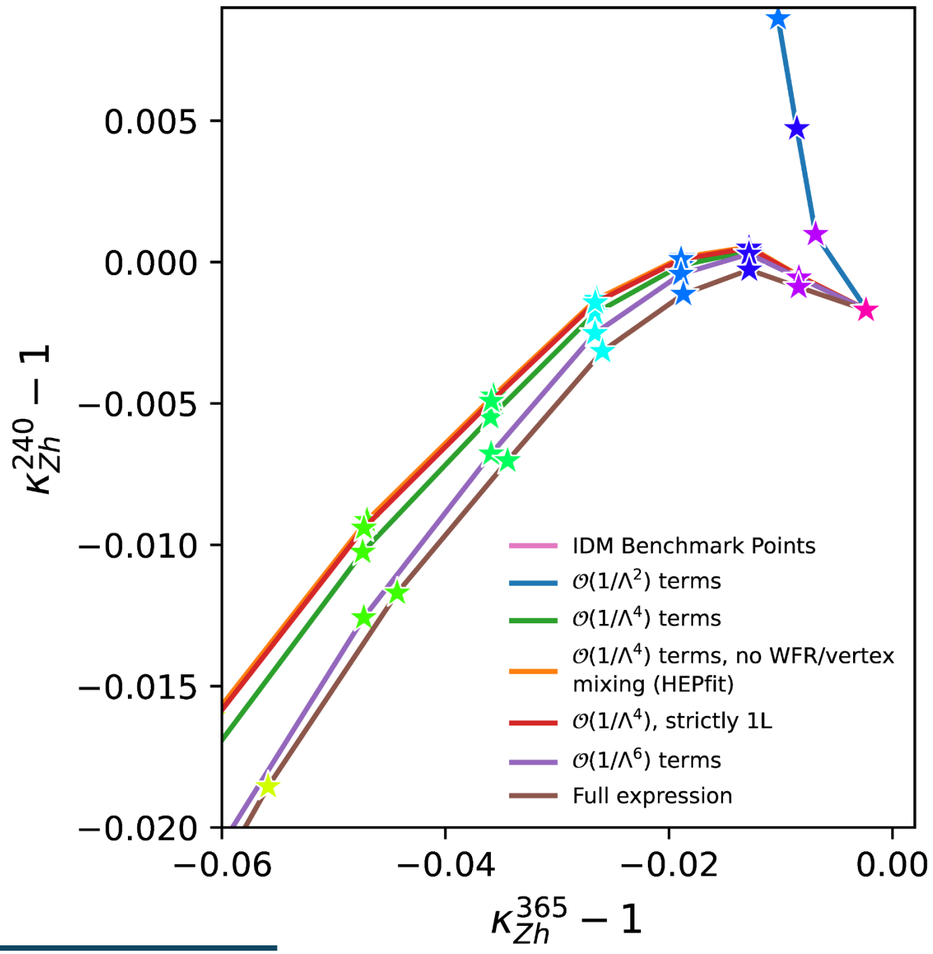


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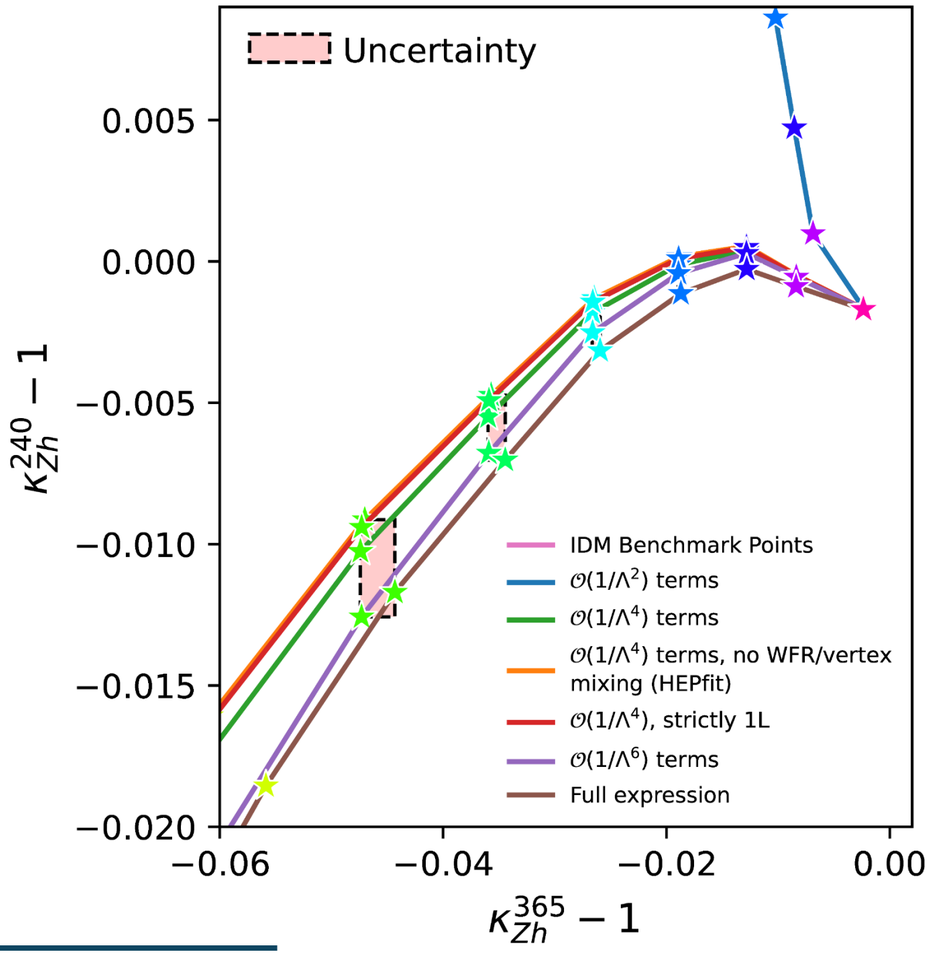


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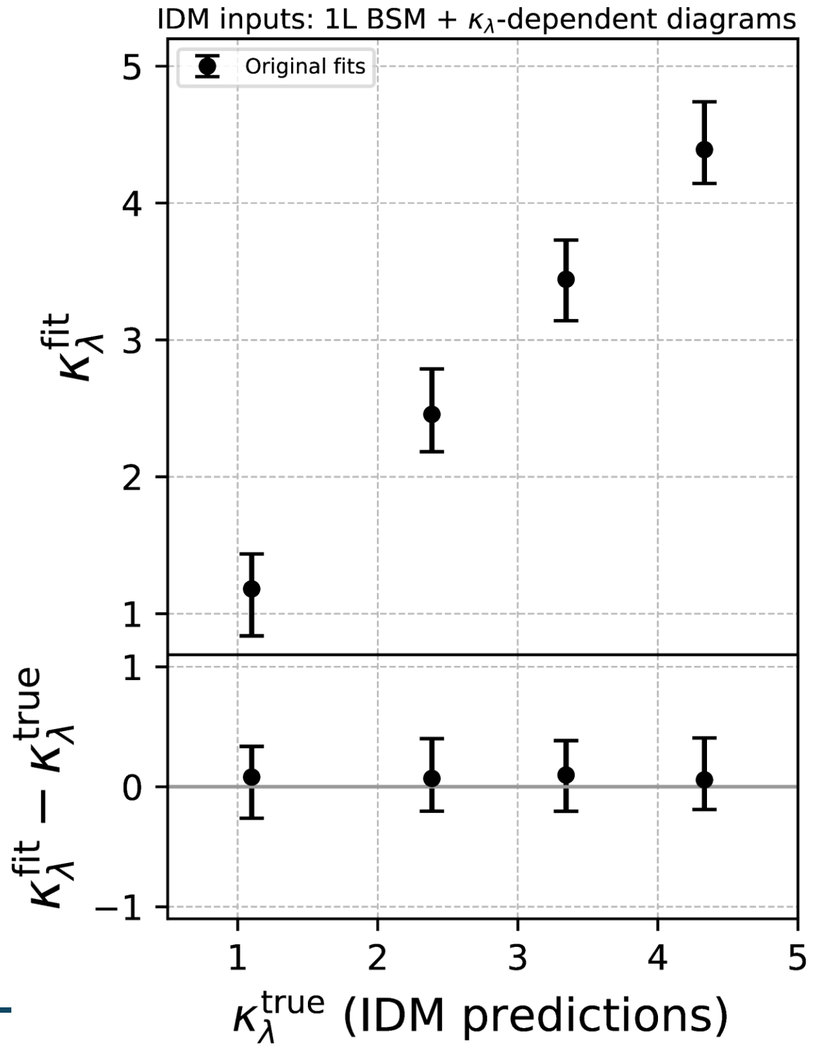
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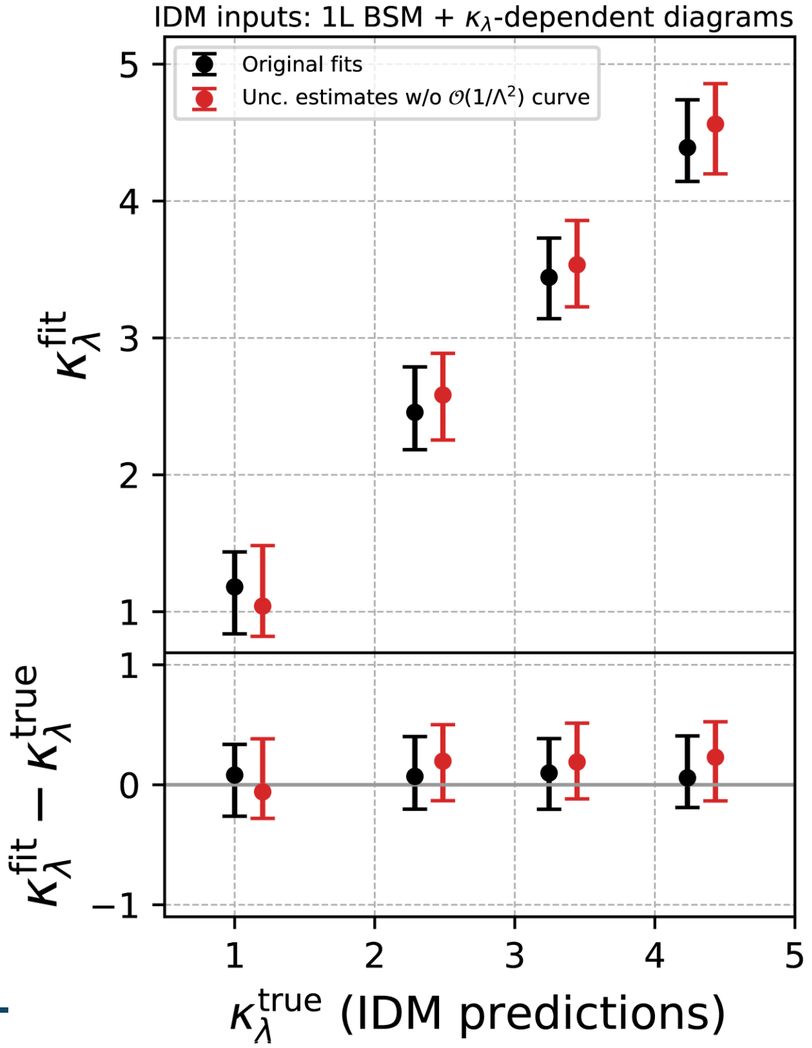
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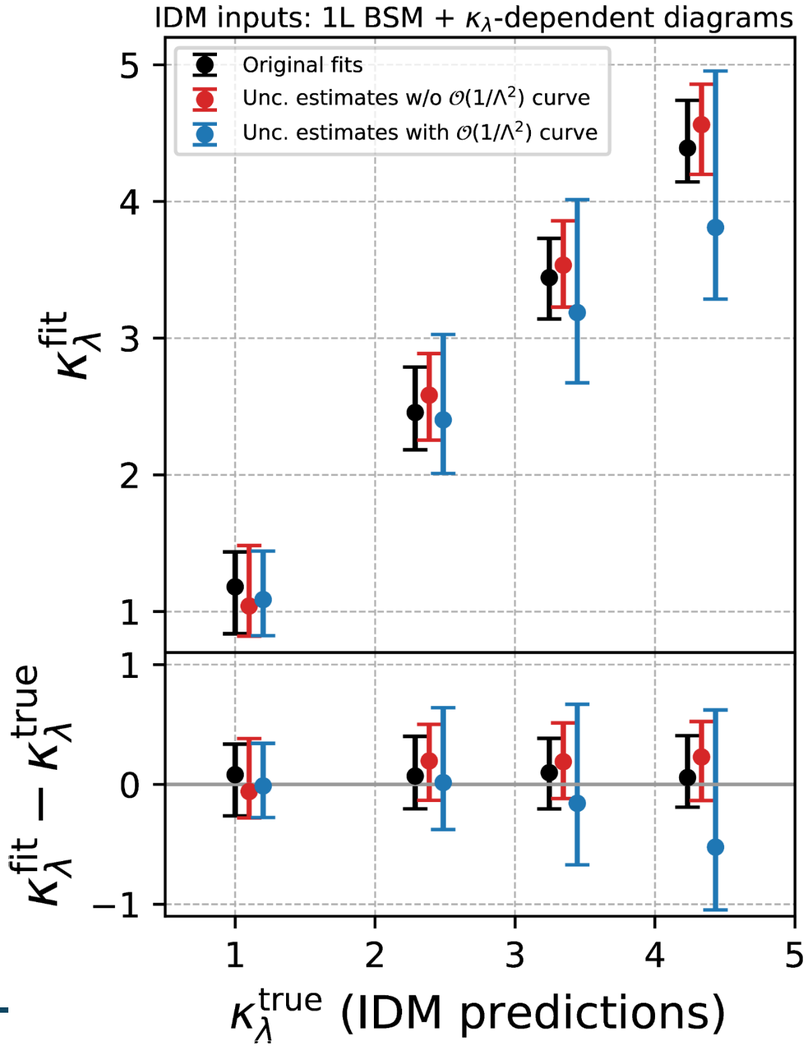
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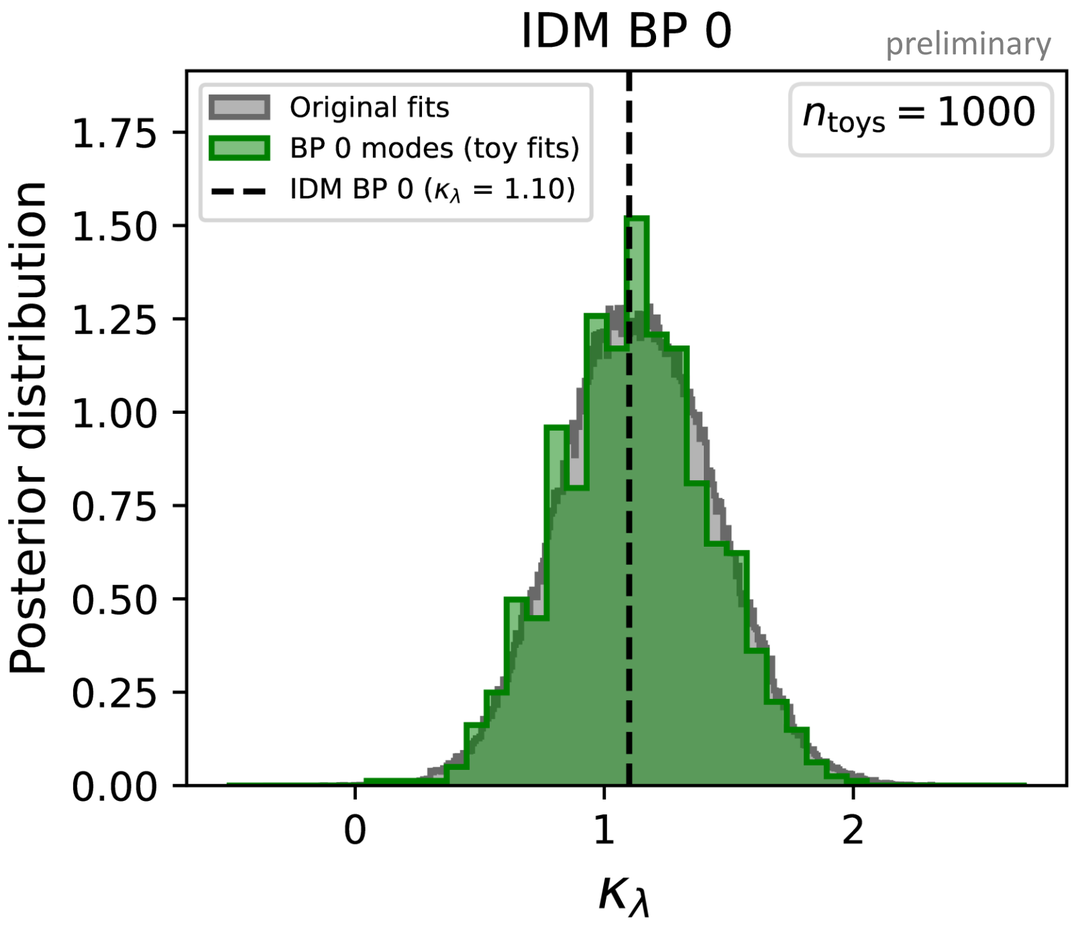
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Statistical analysis with toy fit studies

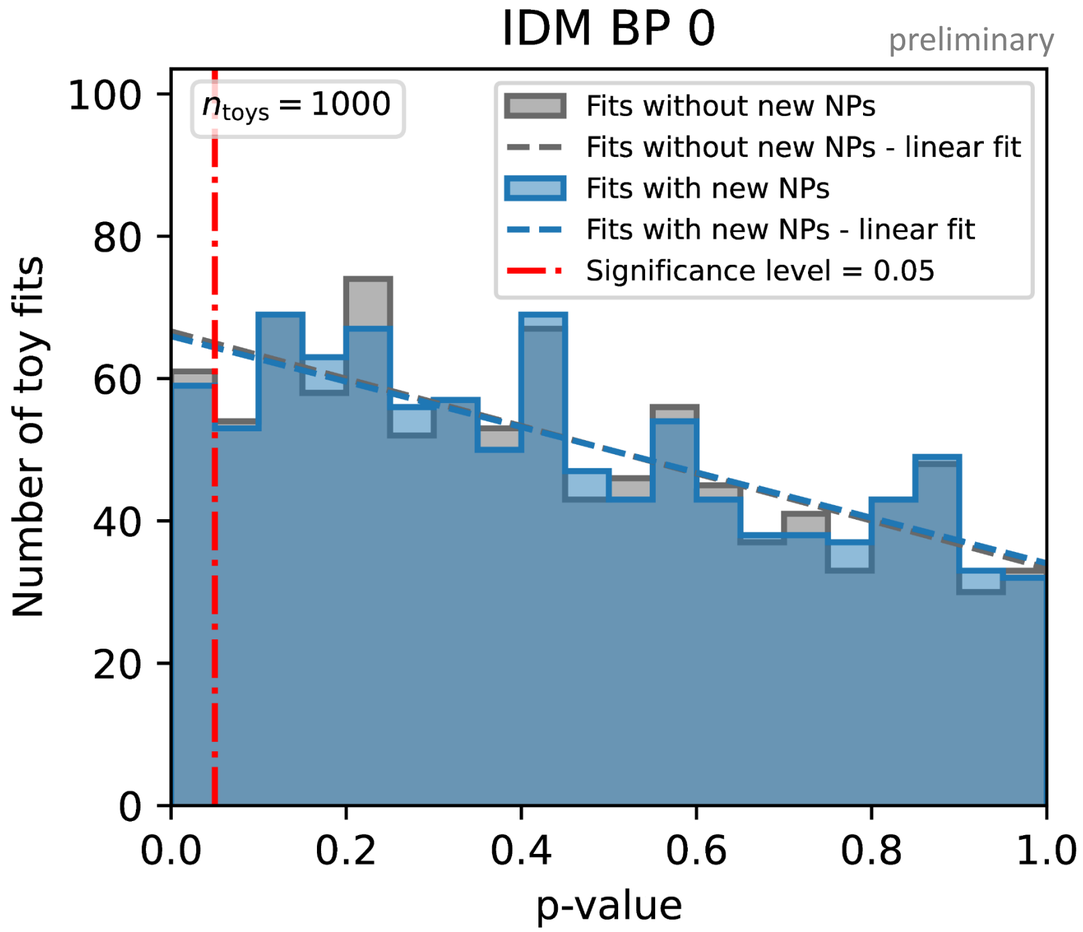


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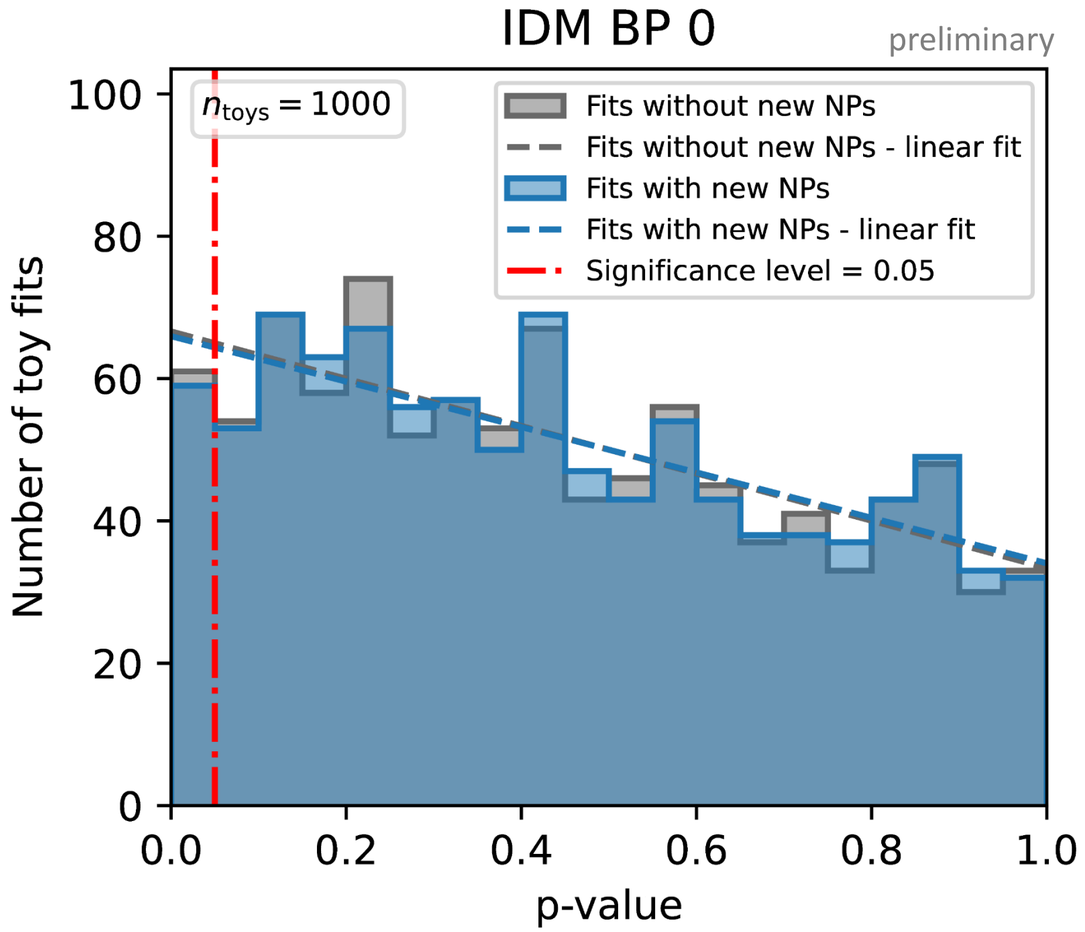
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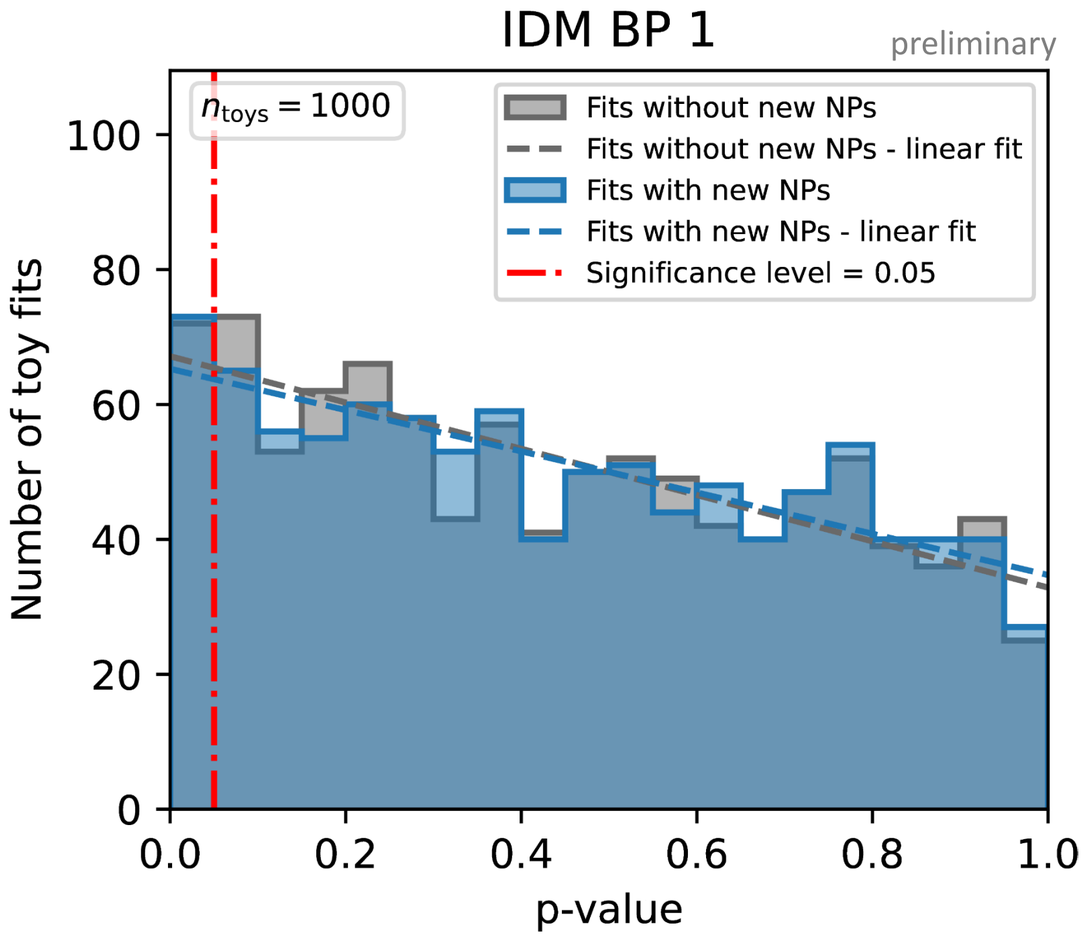
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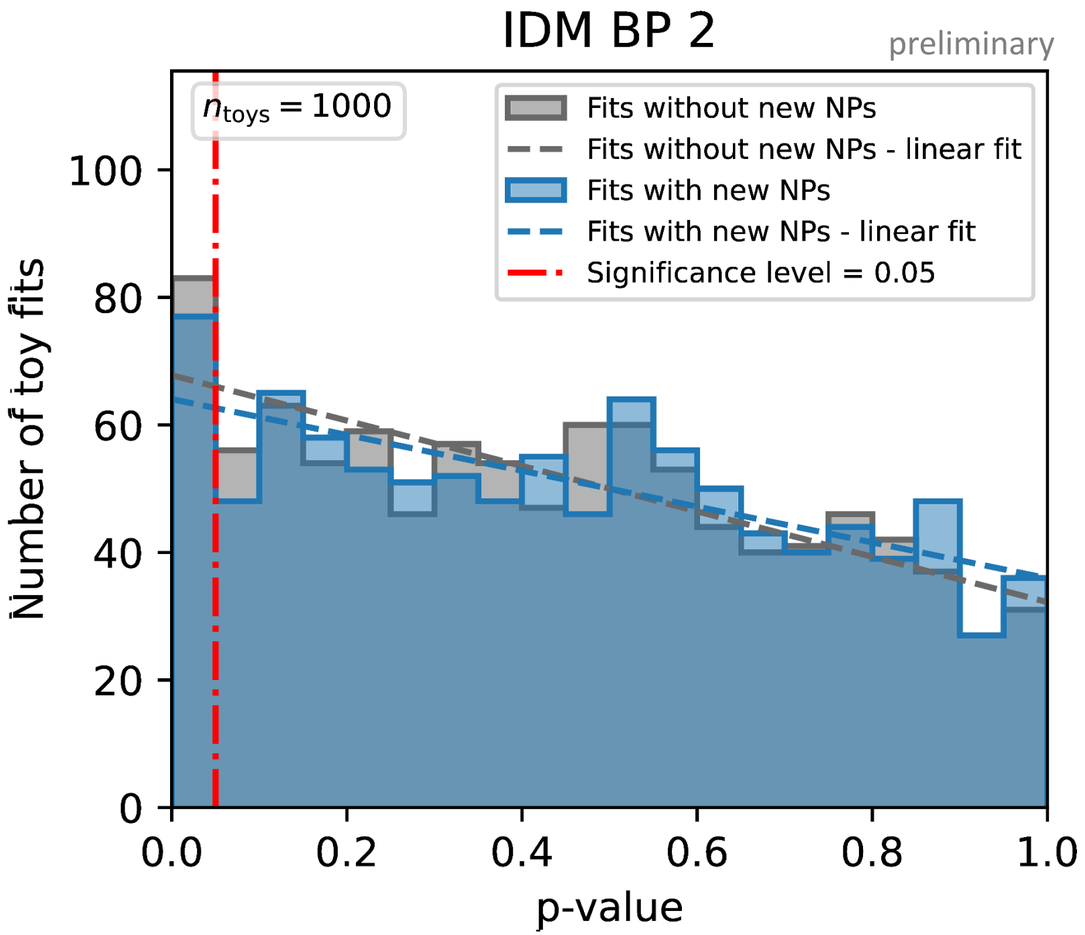
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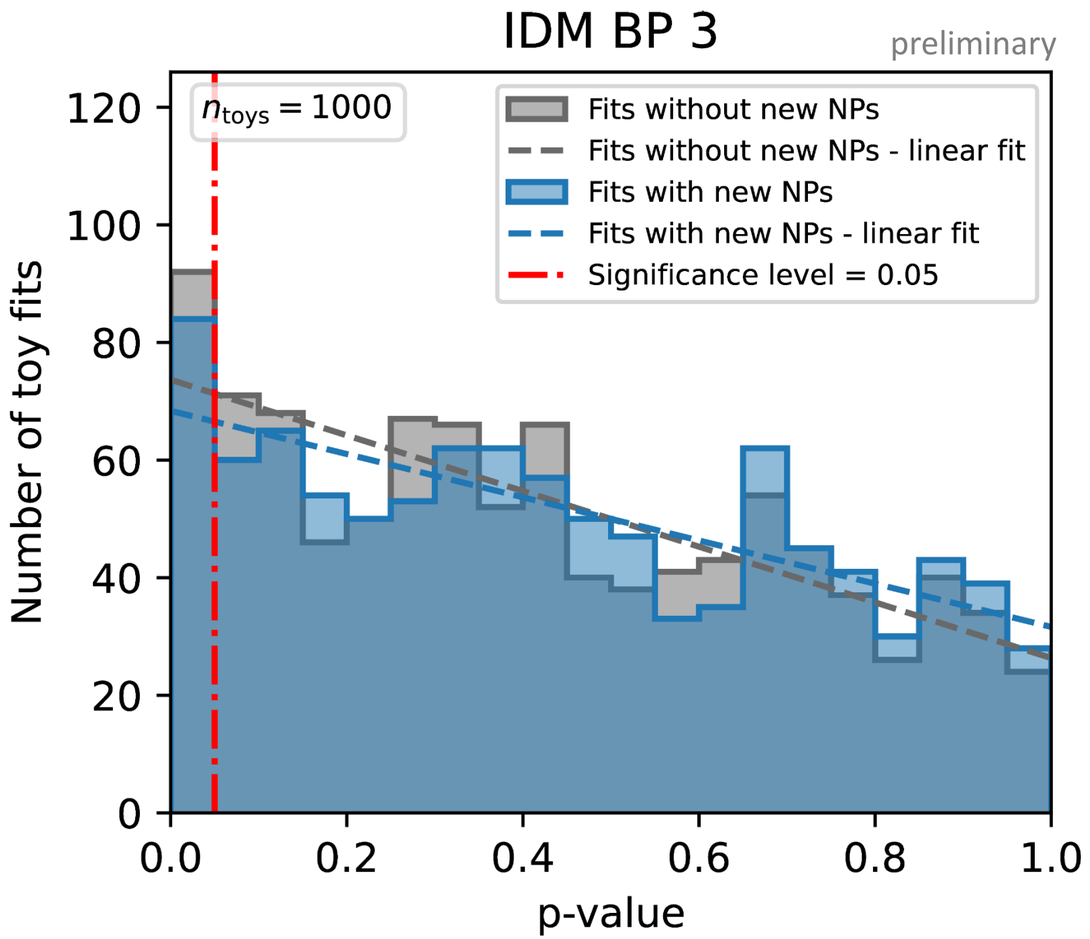
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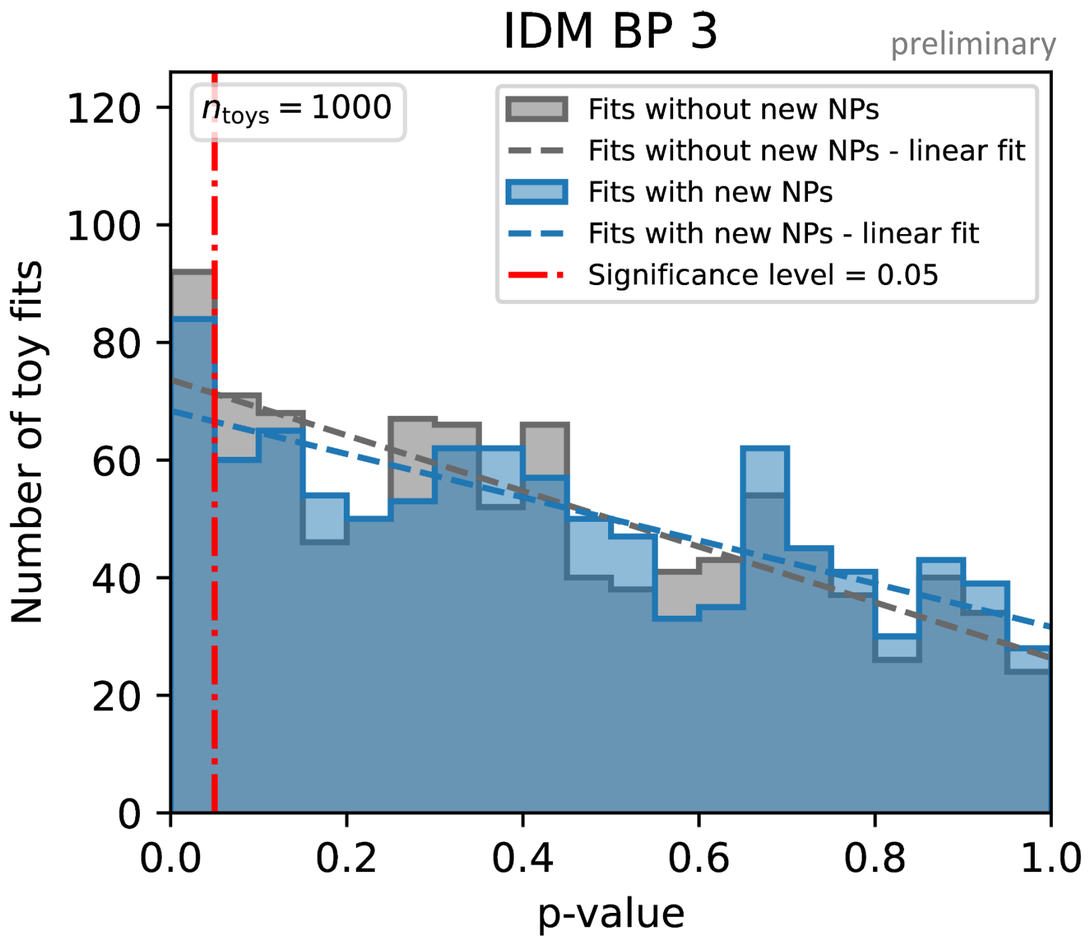
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Loop-level extraction of $\boldsymbol{\kappa_\lambda}$ via $e^+e^- \to Zh$:

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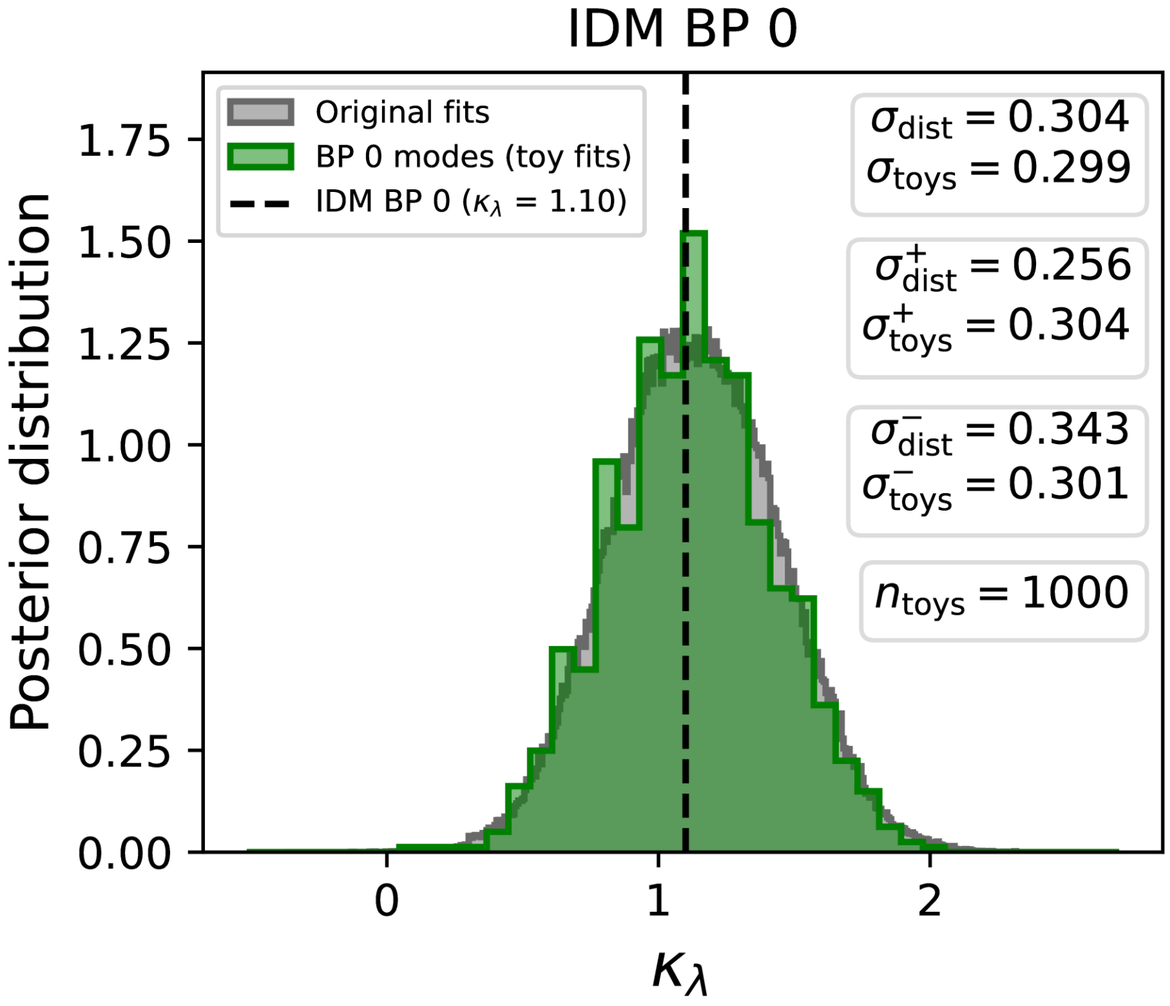
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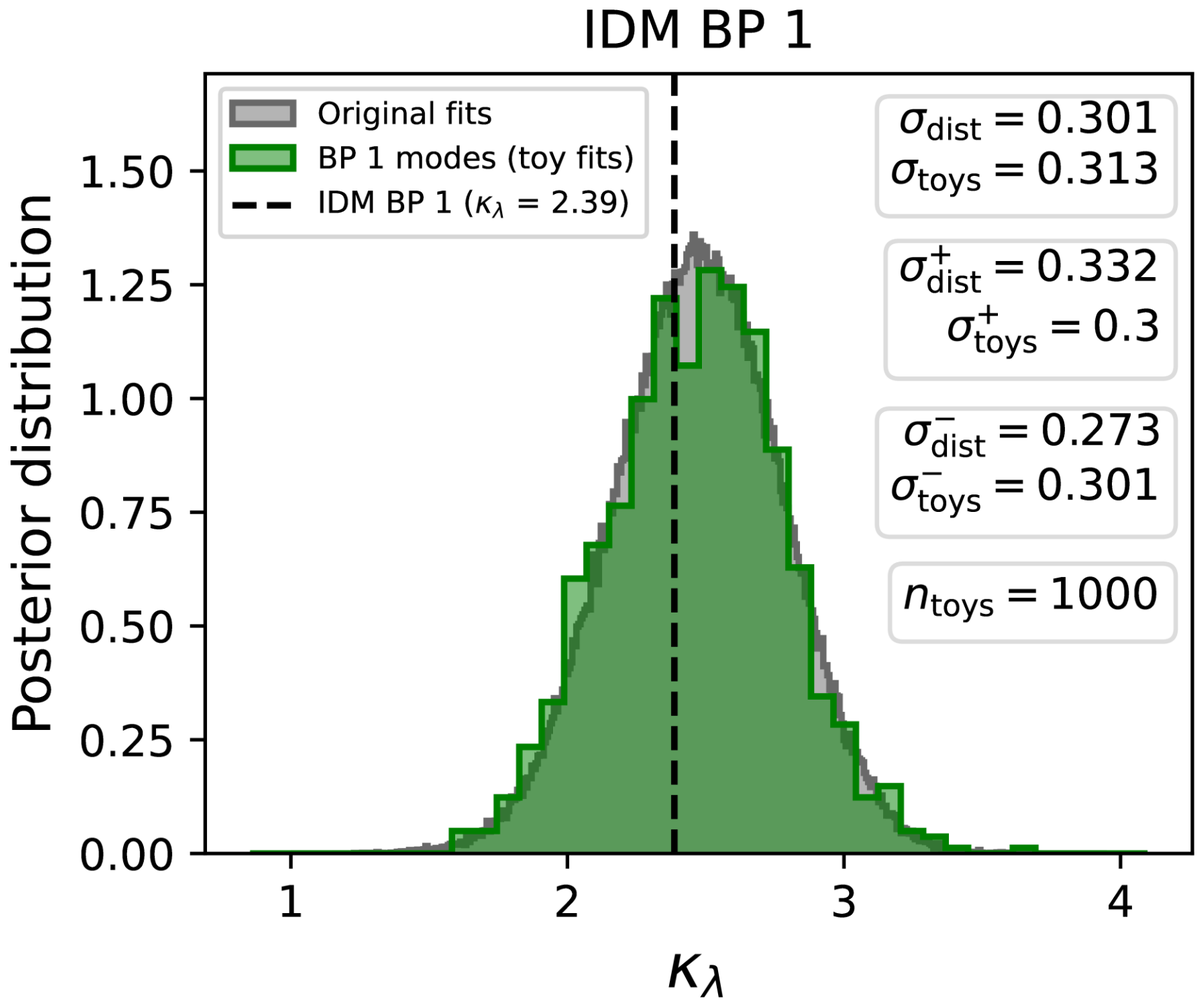
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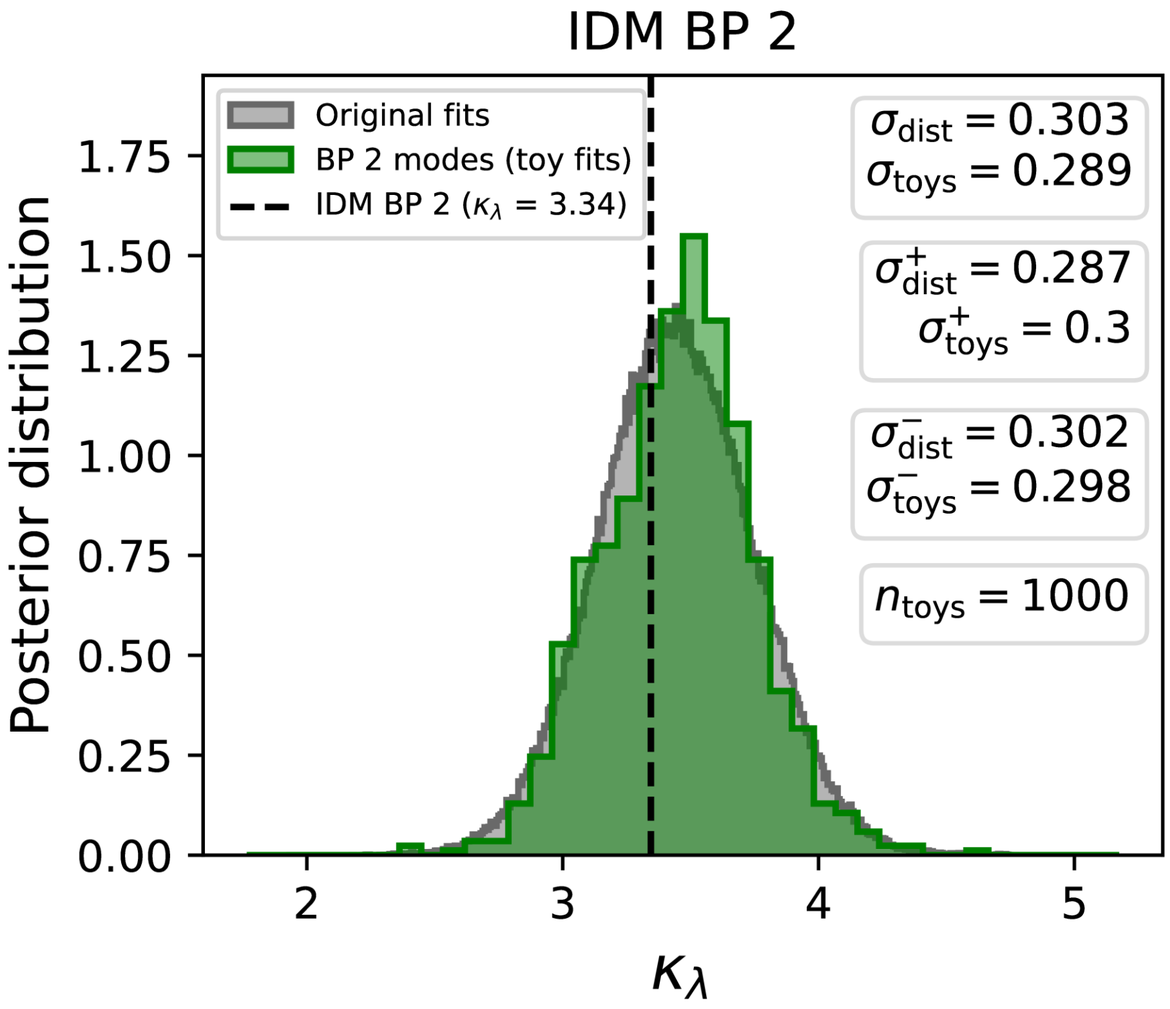
Back up

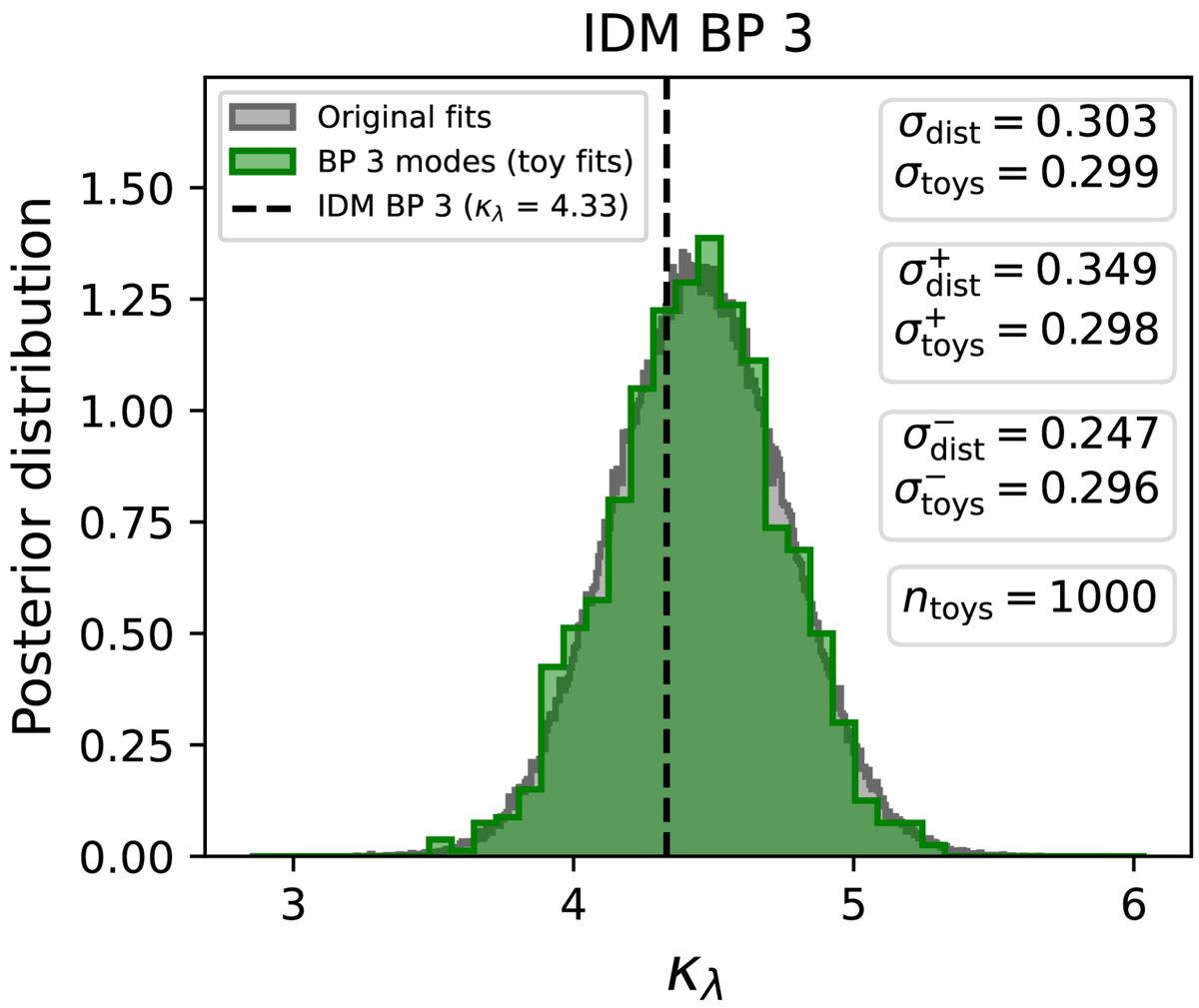
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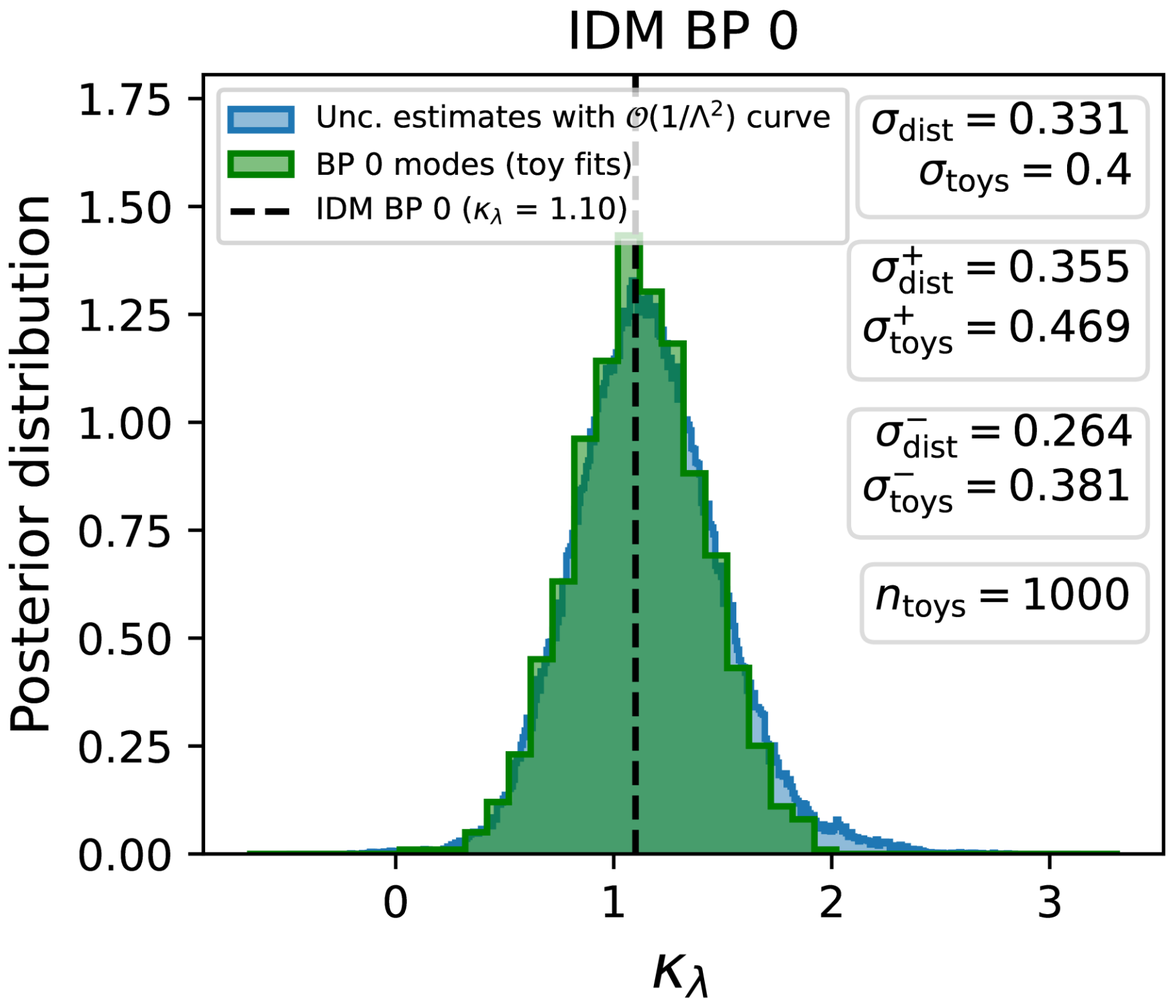


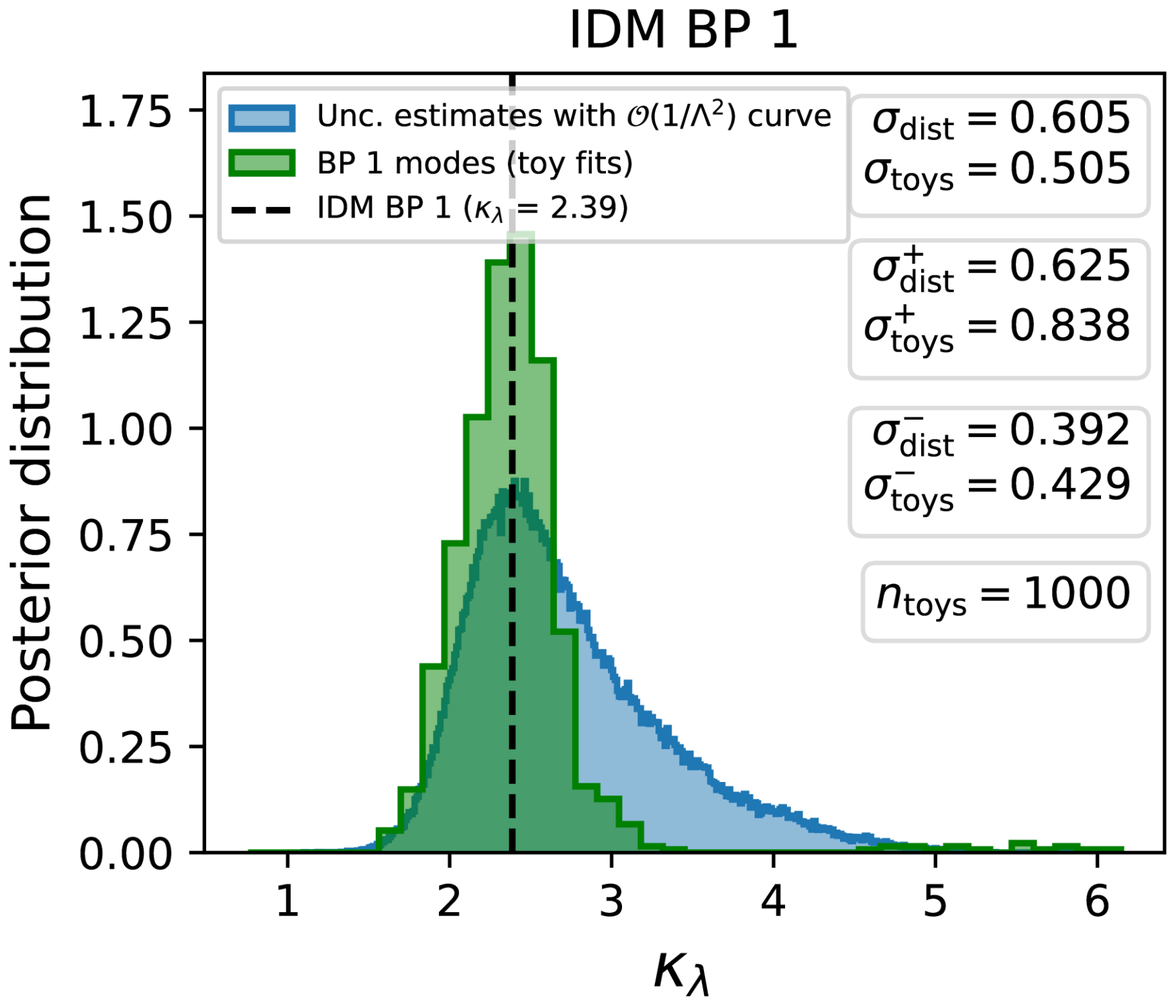
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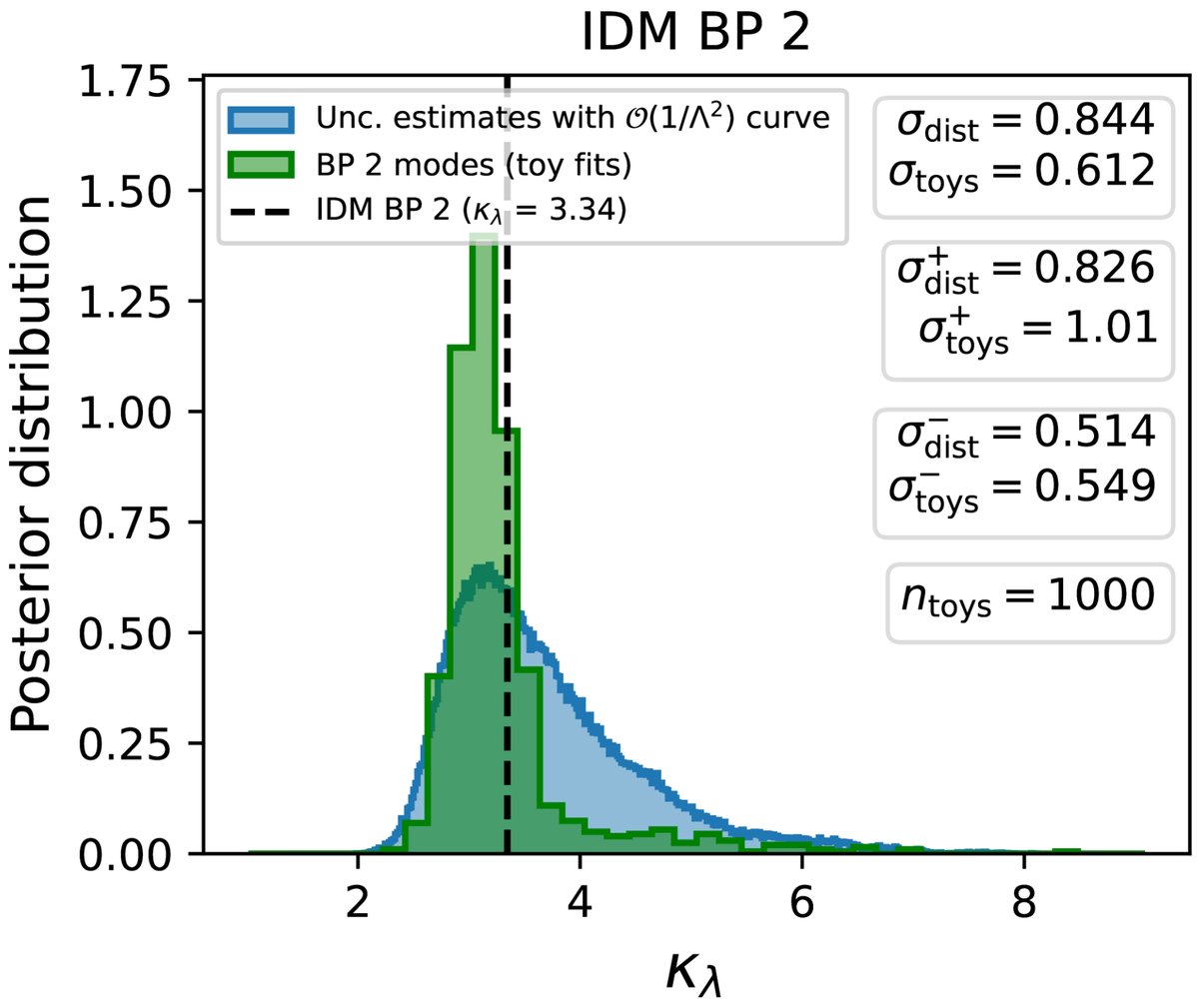


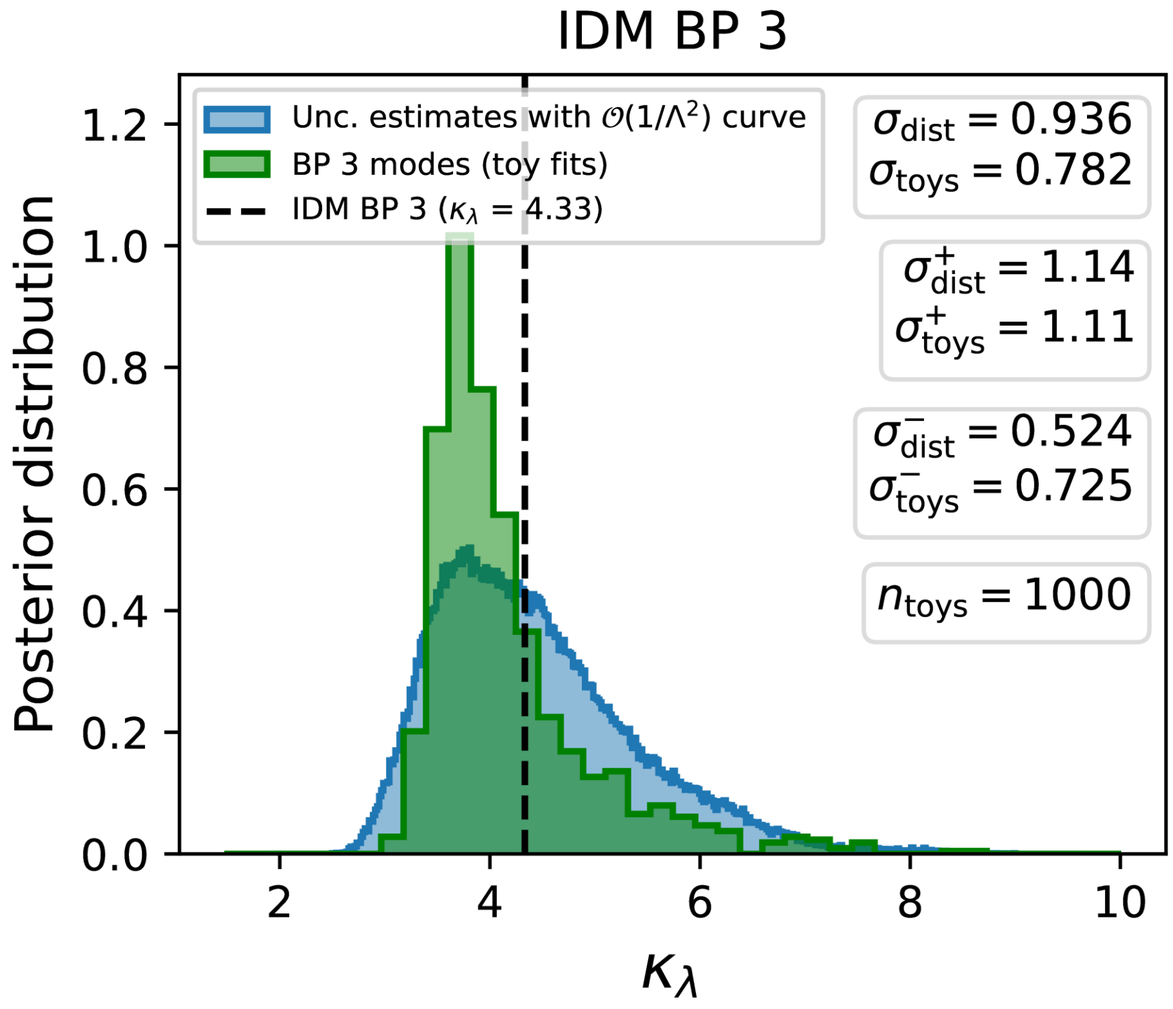
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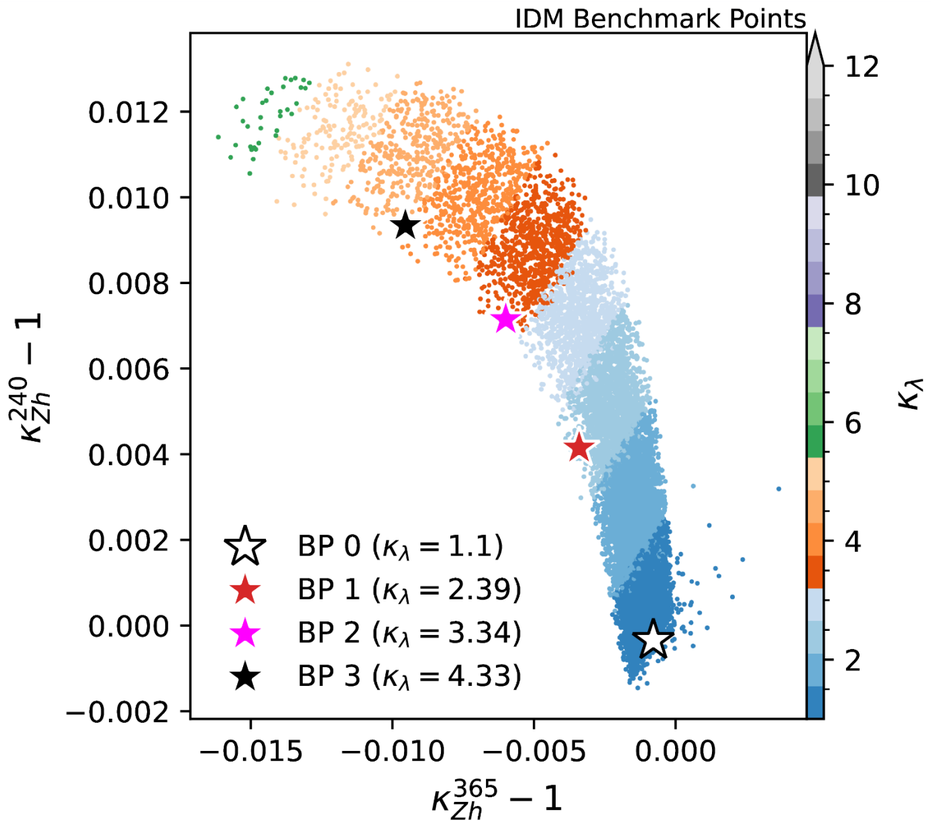


Toy fits **with** new NPs κ_λ distributions (2)





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

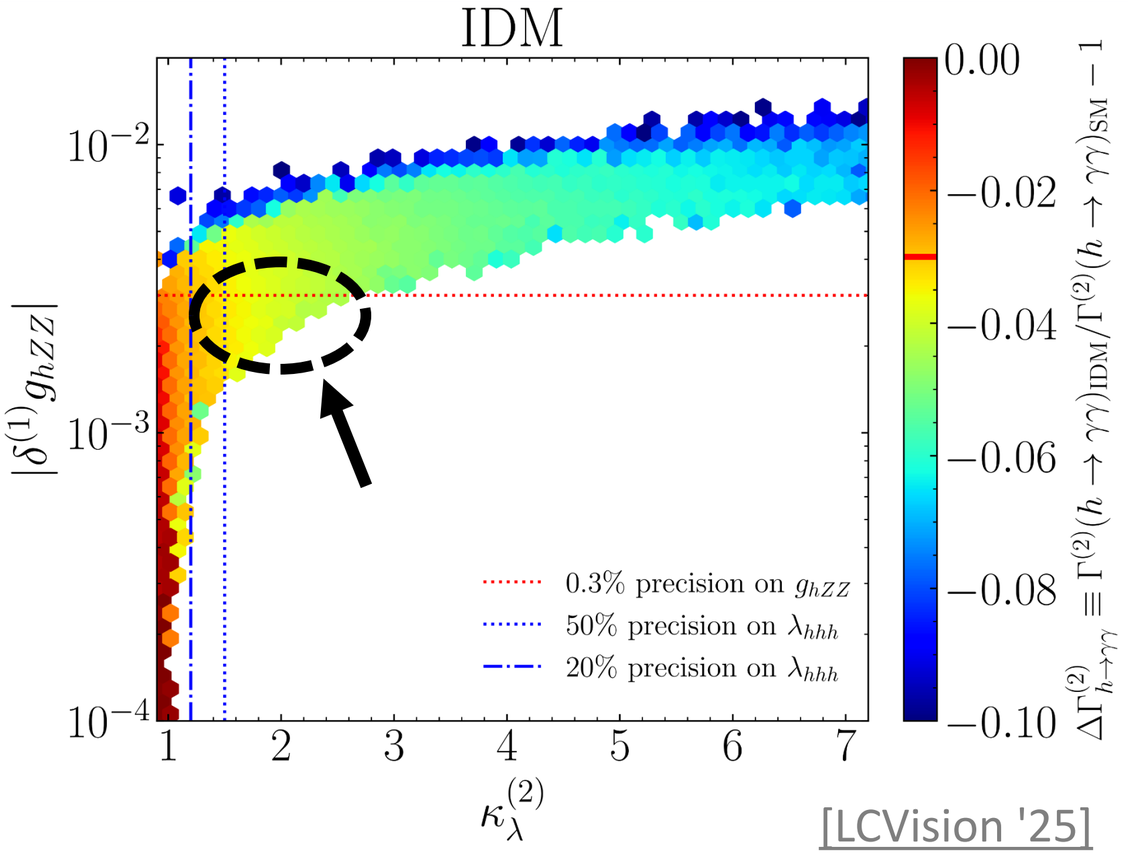
They also satisfy the following experimental constraints:

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

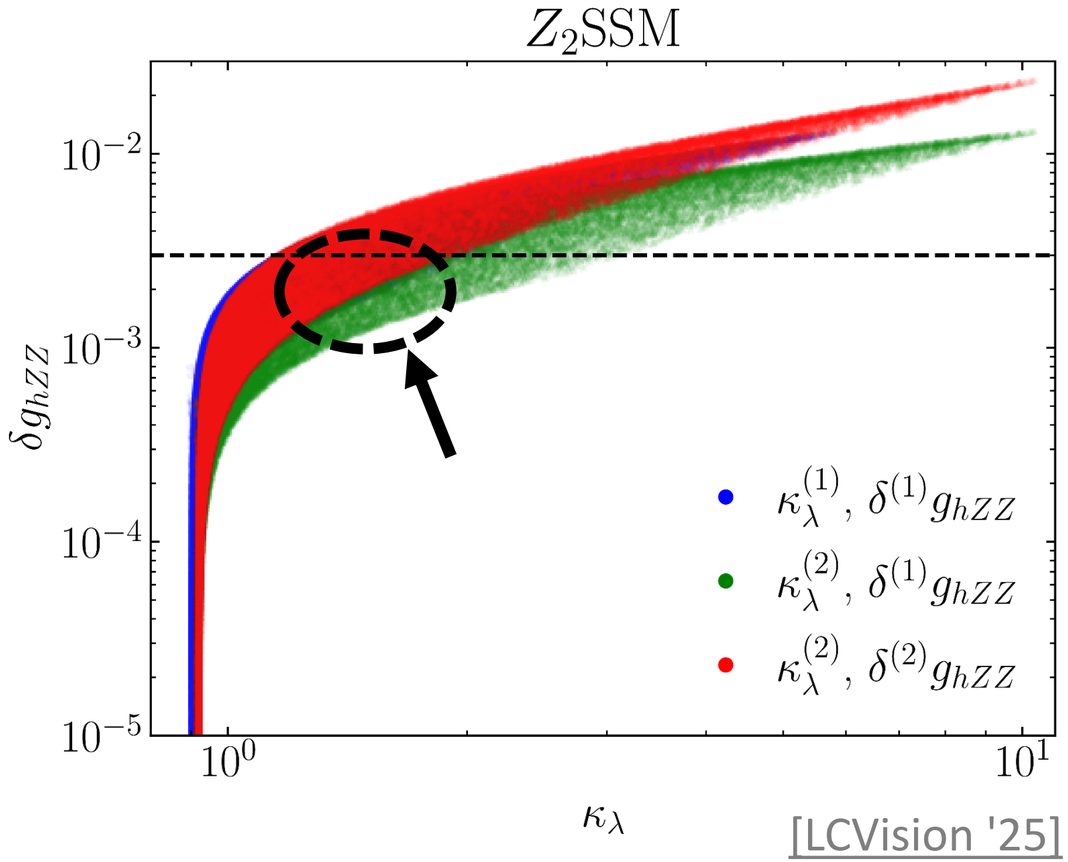
Final selection includes 4 BPs

	μ_2^2 [GeV^2]	λ_1	λ_2	λ_3	λ_4	λ_5	m_H [GeV]	m_A [GeV]	$m_{H^\pm}$ [GeV]	κ_λ
BP 0	1.178×10^6	0.2581	6.213	7.169	−4.512	−3.143	1079	1164	1181	1.1
BP 1	3.666×10^5	0.2581	3.084	11.46	−5.68	−5.109	622.2	834.8	845.1	2.387
BP 2	3.922×10^5	0.2581	10.06	14.19	−6.974	−6.407	645.6	897.3	906.8	3.345
BP 3	3.432×10^5	0.2581	8.985	15.83	−7.704	−7.4	604.3	902.1	907.2	4.333

hhh vs. hZZ couplings



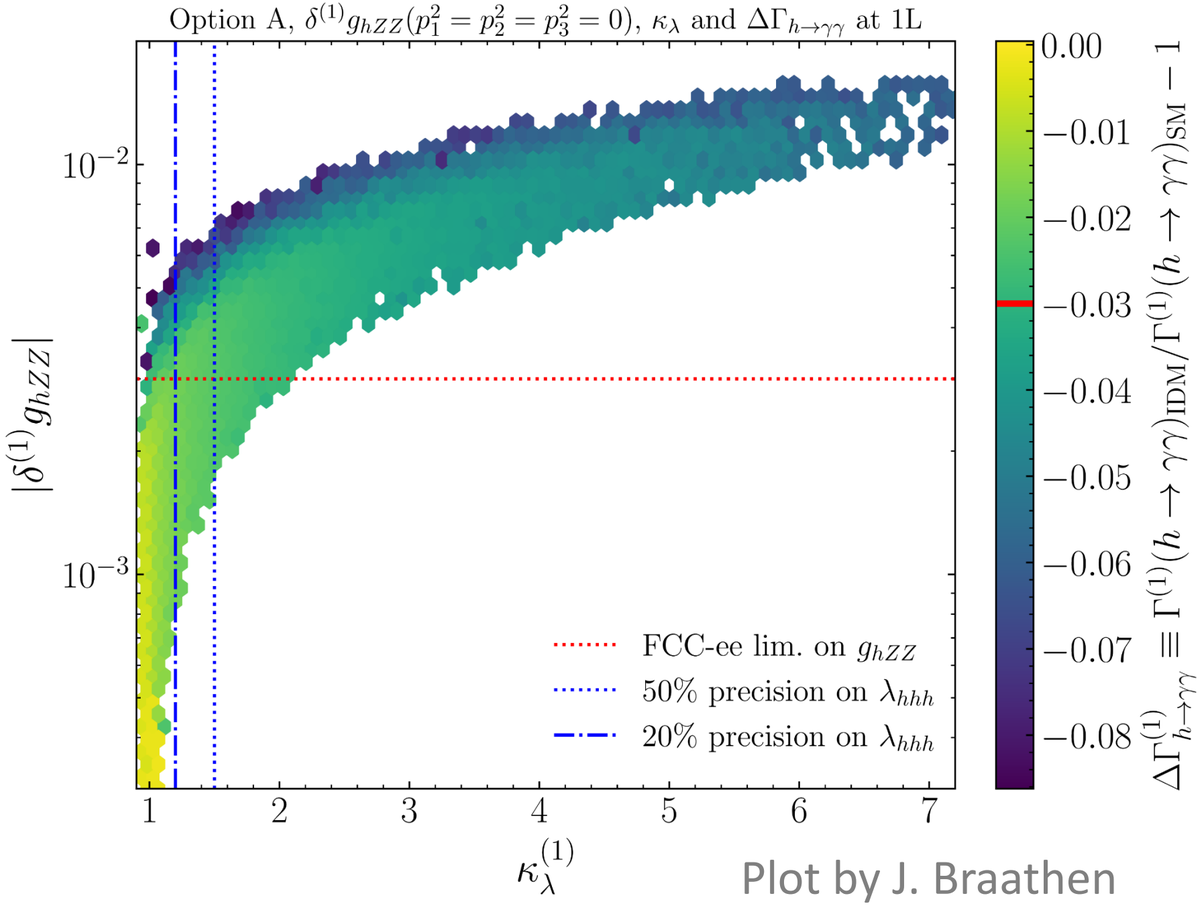
[LCVision '25]



[LCVision '25]

- δg_{hZZ}: deviation of the hZZ coupling relative to the SM
- Even in simple models, can have $|\delta g_{hZZ}| < 0.3\%$ (FCC-ee projection) **and** large κ_λ
- True irrespective of details of the theoretical predictions

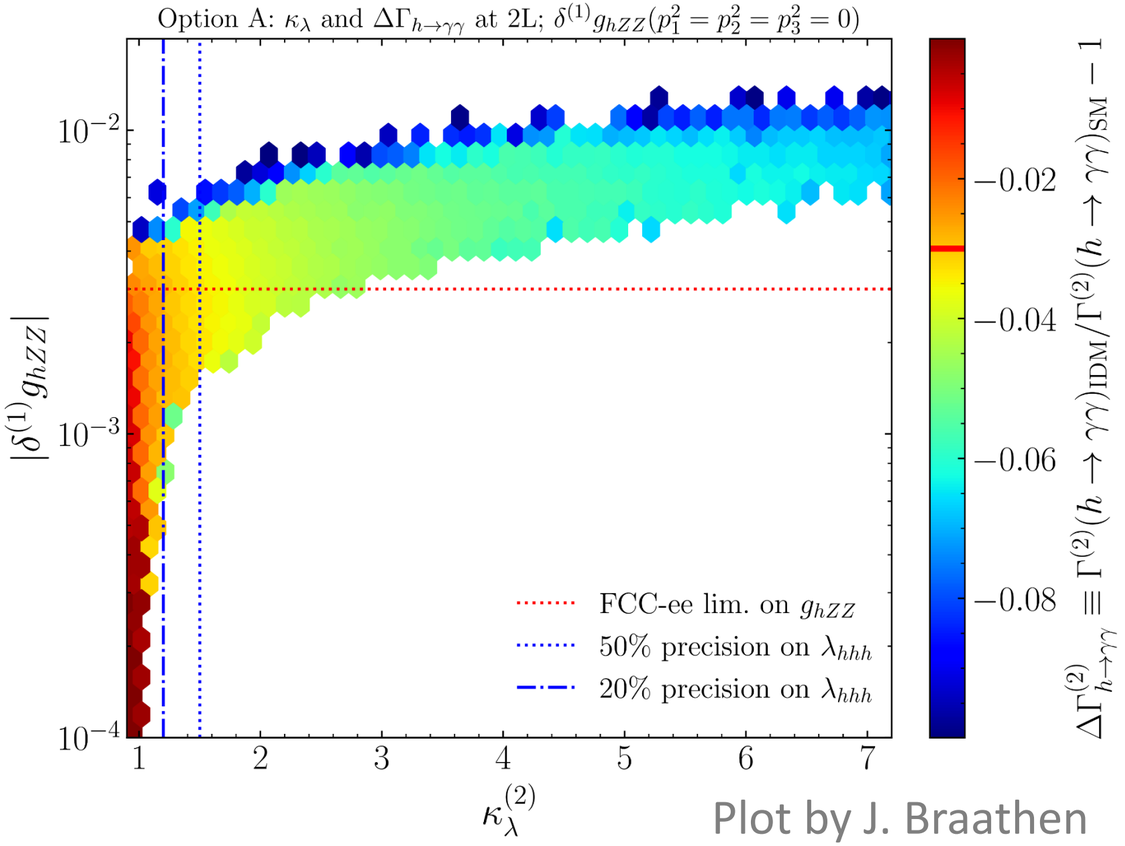
δg_{hZZ} vs. κ_λ in the IDM (1)



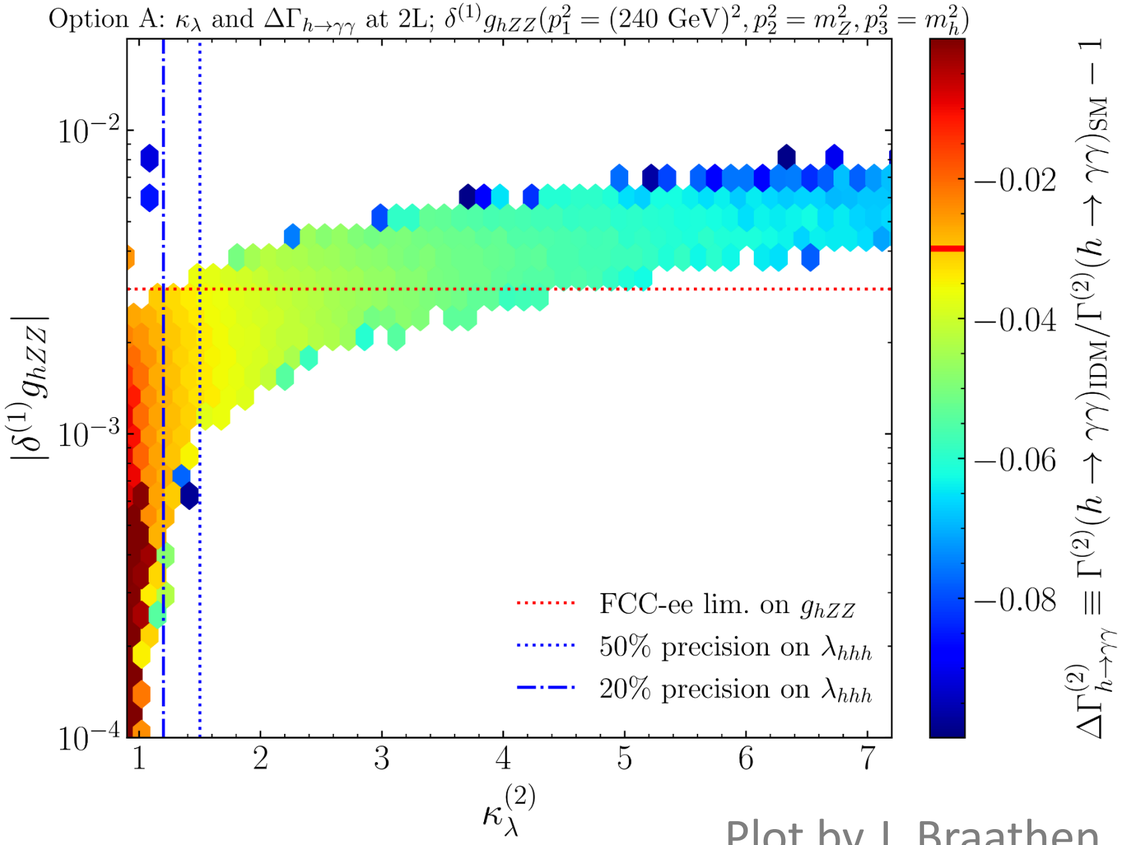
Plot by J. Braathen

- κ_λ and $\Delta\Gamma_{h\to\gamma\gamma}$: 1-loop level
- δg_{hZZ}: **strictly 1-loop level** (only BSM vertex and external-leg corrections)
- $\sqrt{s} = 0$ GeV (left) and $\sqrt{s} = 240$ GeV (right)

δg_{hZZ} vs. κ_λ in the IDM (2)



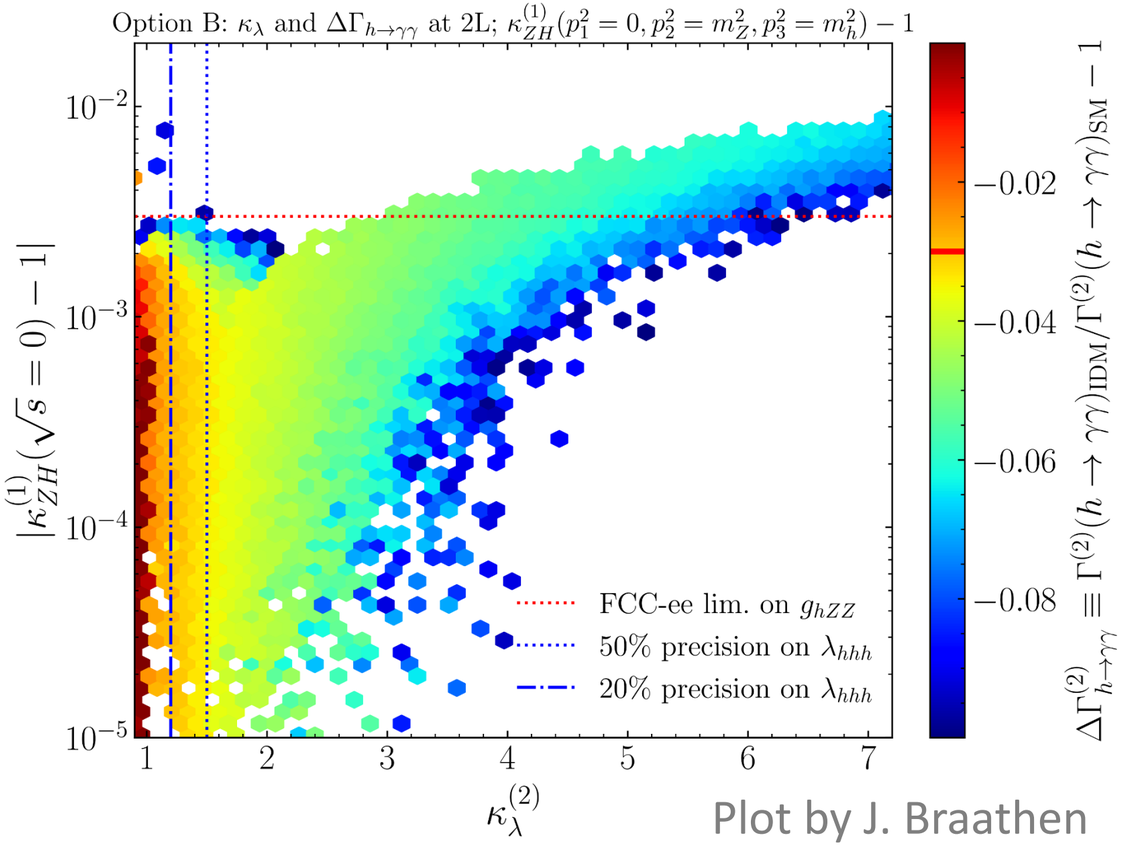
Plot by J. Braathen



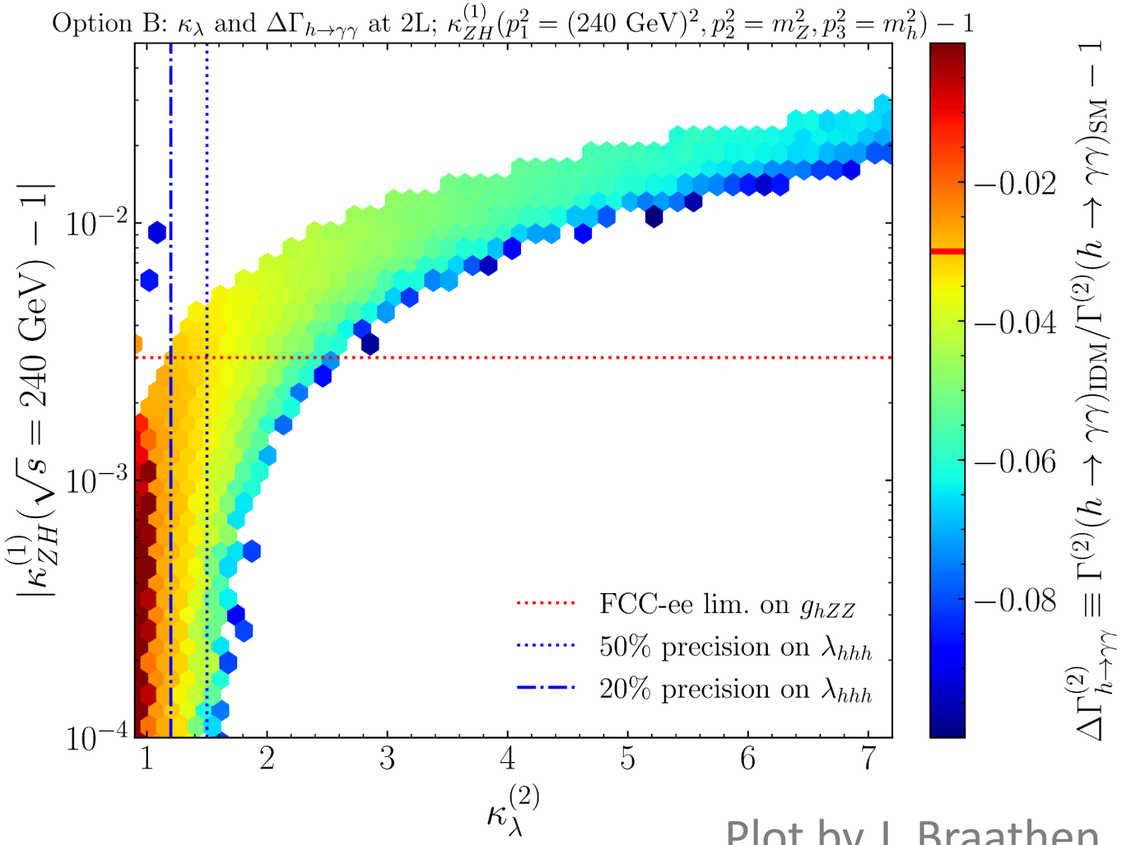
Plot by J. Braathen

- κ_λ and $\Delta\Gamma_{h\to\gamma\gamma}$: 2-loop level
- δg_{hZZ}: **strictly 1-loop level** (only BSM vertex and external-leg corrections)
- $\sqrt{s} = 0$ GeV (left) and $\sqrt{s} = 240$ GeV (right)

δg_{hZZ} vs. κ_λ in the IDM (3)



Plot by J. Braathen



Plot by J. Braathen

- κ_λ and $\Delta\Gamma_{h\to\gamma\gamma}$: 2-loop level
- δg_{hZZ}: **1L BSM corrections + 1L SM-like diagrams with 1 insertion of κ_λ**
- $\sqrt{s}=0$ GeV (left) and $\sqrt{s}=240$ GeV (right)

The Inert Doublet Model (IDM)

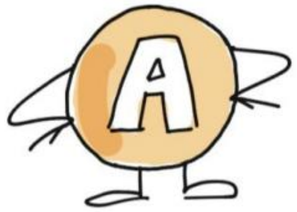
- 2 Higgs doublets: $\Phi_1 = \begin{pmatrix} G^+ \\ \frac{1}{\sqrt{2}}(v + h + iG^0) \end{pmatrix}, \quad \Phi_2 = \begin{pmatrix} H^+ \\ \frac{1}{\sqrt{2}}(H + iA) \end{pmatrix}$



- 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



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





- Crucially: parameter space allows for large κ_λ, while keeping all other Higgs couplings SM-like (See backup)

Drawing by Kateryna Radchenko

The Higgs self-coupling in the SMEFT

In the Warsaw SMEFT basis, the dim-6 operators which contribute to the λ_3 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 $\kappa_\lambda \equiv \lambda_3/\lambda_3^{\mathrm{SM}}$ is then:

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

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

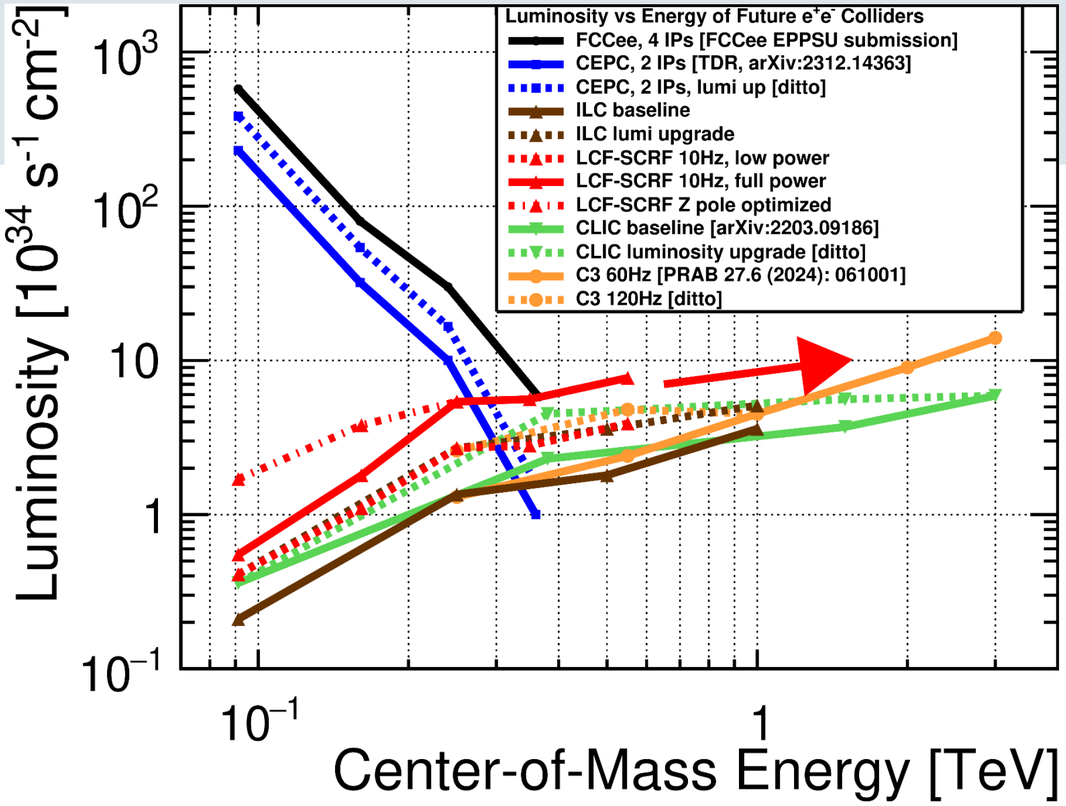
- Assuming $C_{H\Box} \approx C_{HD} \approx 0$, requiring the v is a global minimum and that the potential is bounded from below, we have [Degrassi et al. '16]:

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

- Valid κ_λ range in SMEFT is restricted
- 2HDM: dim-8 have been shown not to be negligible [Dawson et al. '22]

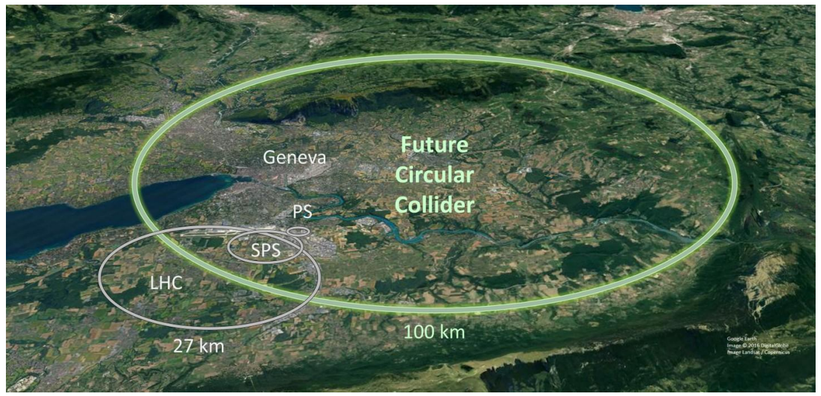
Future e^+e^- colliders

- 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

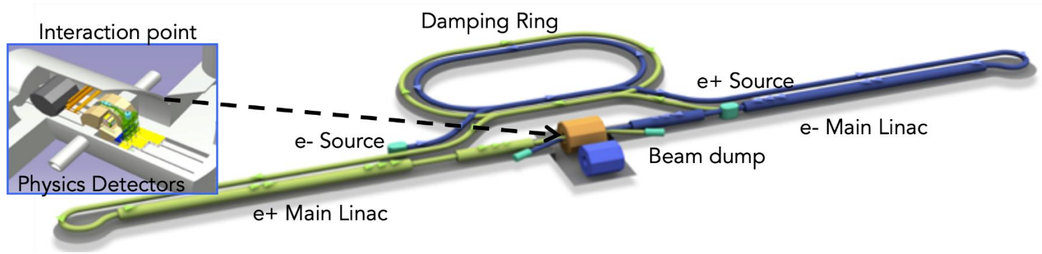


[https://github.com/linearcollider/ILC_plots_and_graphics]

[OPEN-PHO-ACCEL-2019-001]



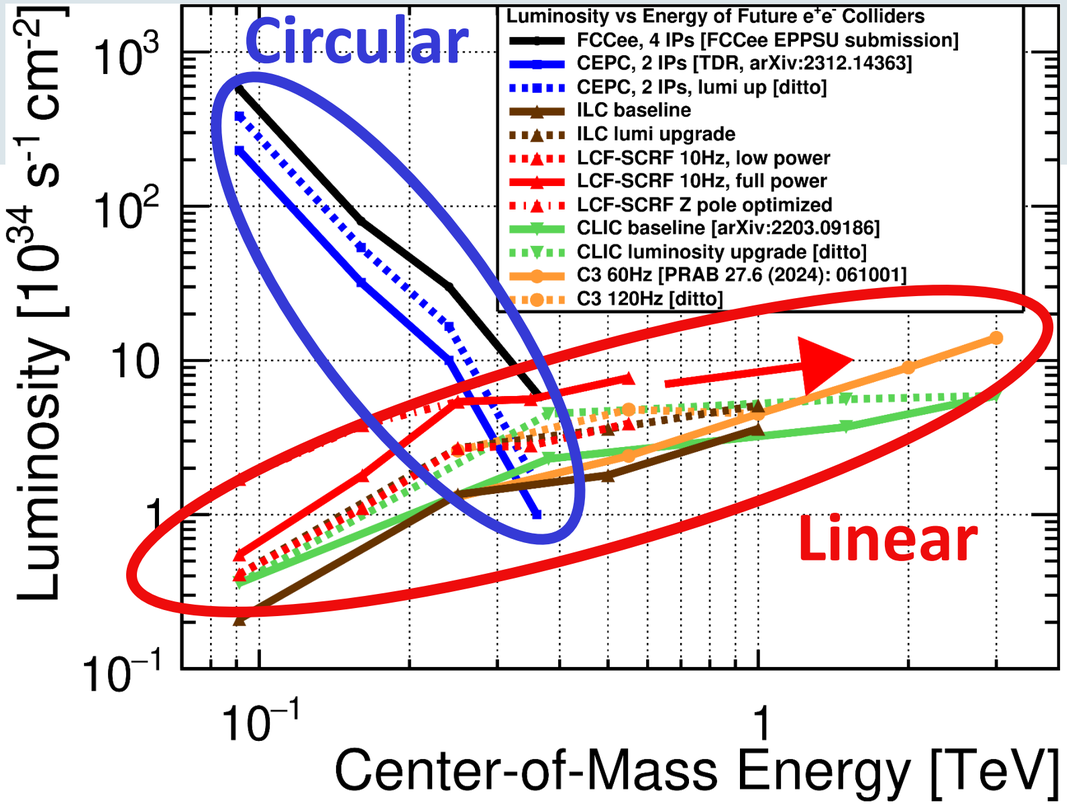
(a) Circular colliders (FCC-ee, CEPC)



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

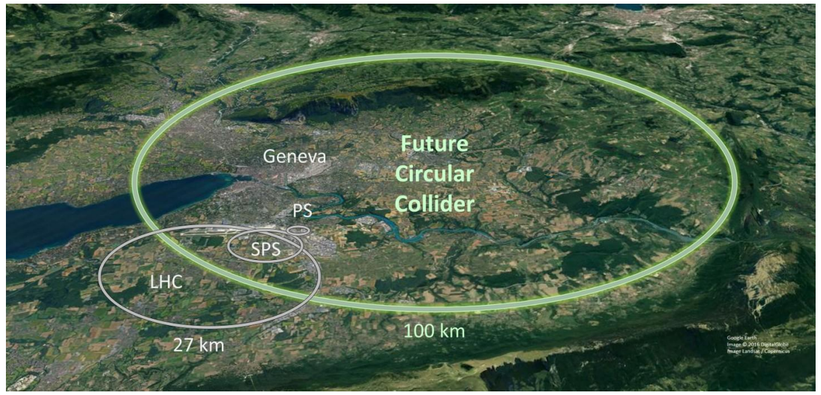
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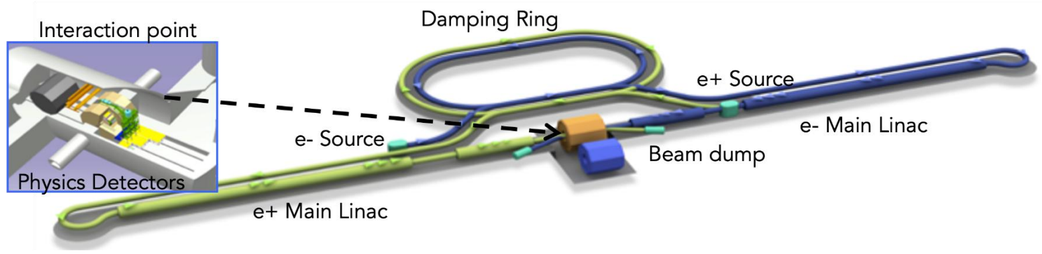


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[OPEN-PHO-ACCEL-2019-001]



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



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