KING'S College LONDON

The Higgs Self-Coupling

at a Circular Electron-Positron Collider

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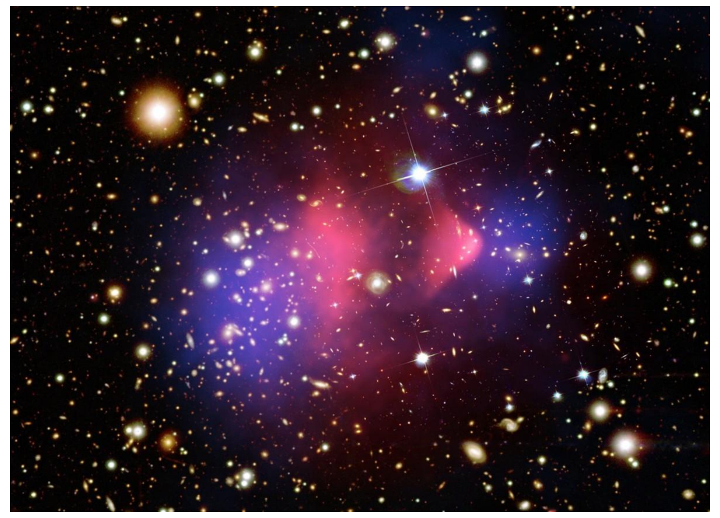
Based on VM, B. Stefanek and T. You, 2503.13719

International CEPC Meeting, 16 June 2025

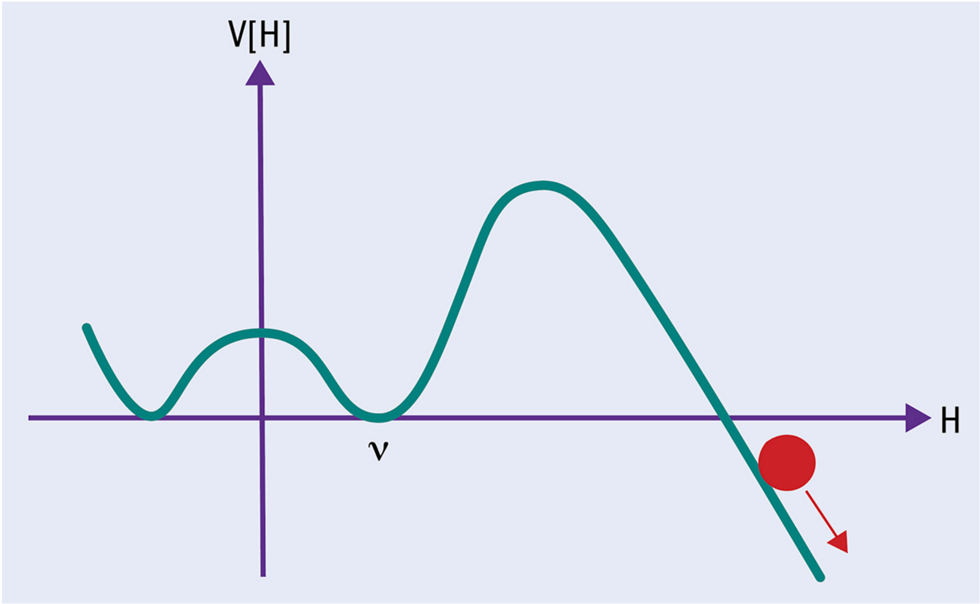
Open Problems in Particle Physics

Baryon Asymmetry

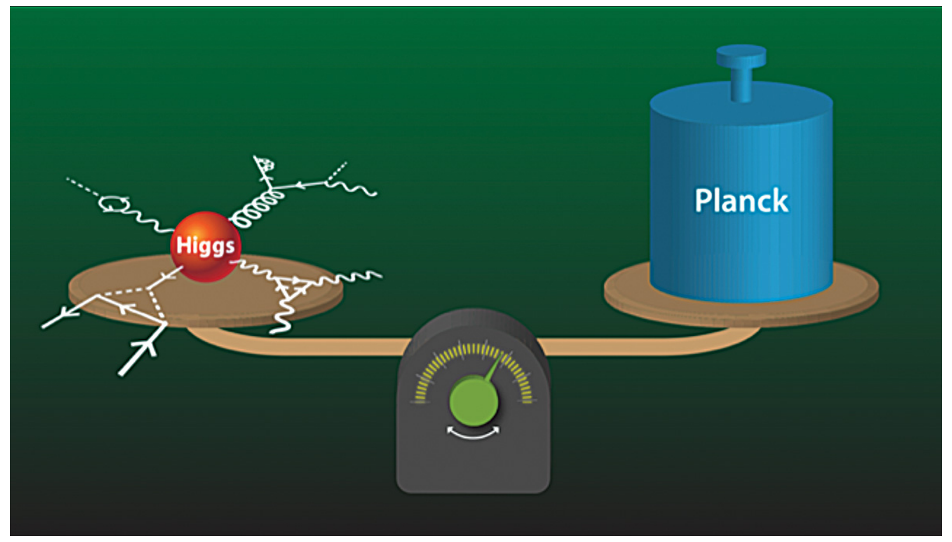
Dark Matter



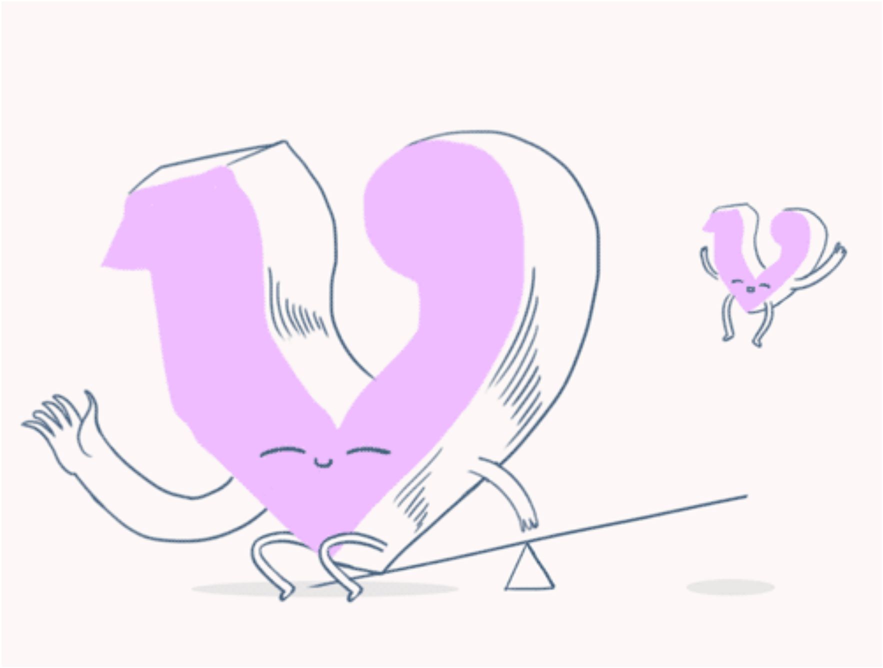
Vacuum Stability



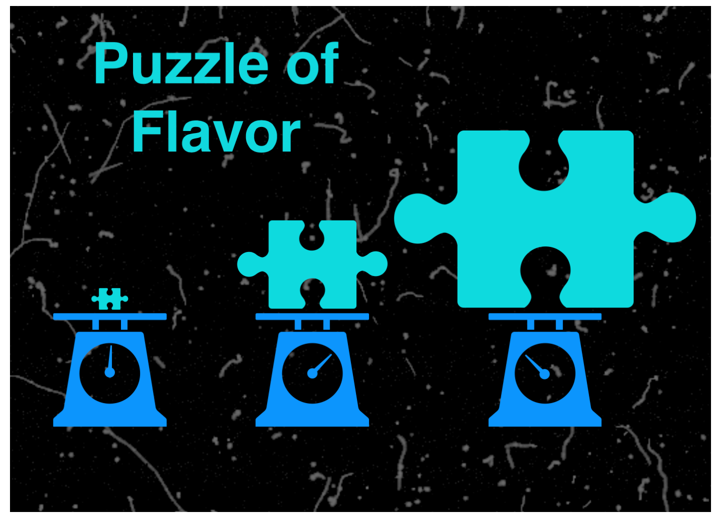
Hierarchy Problem

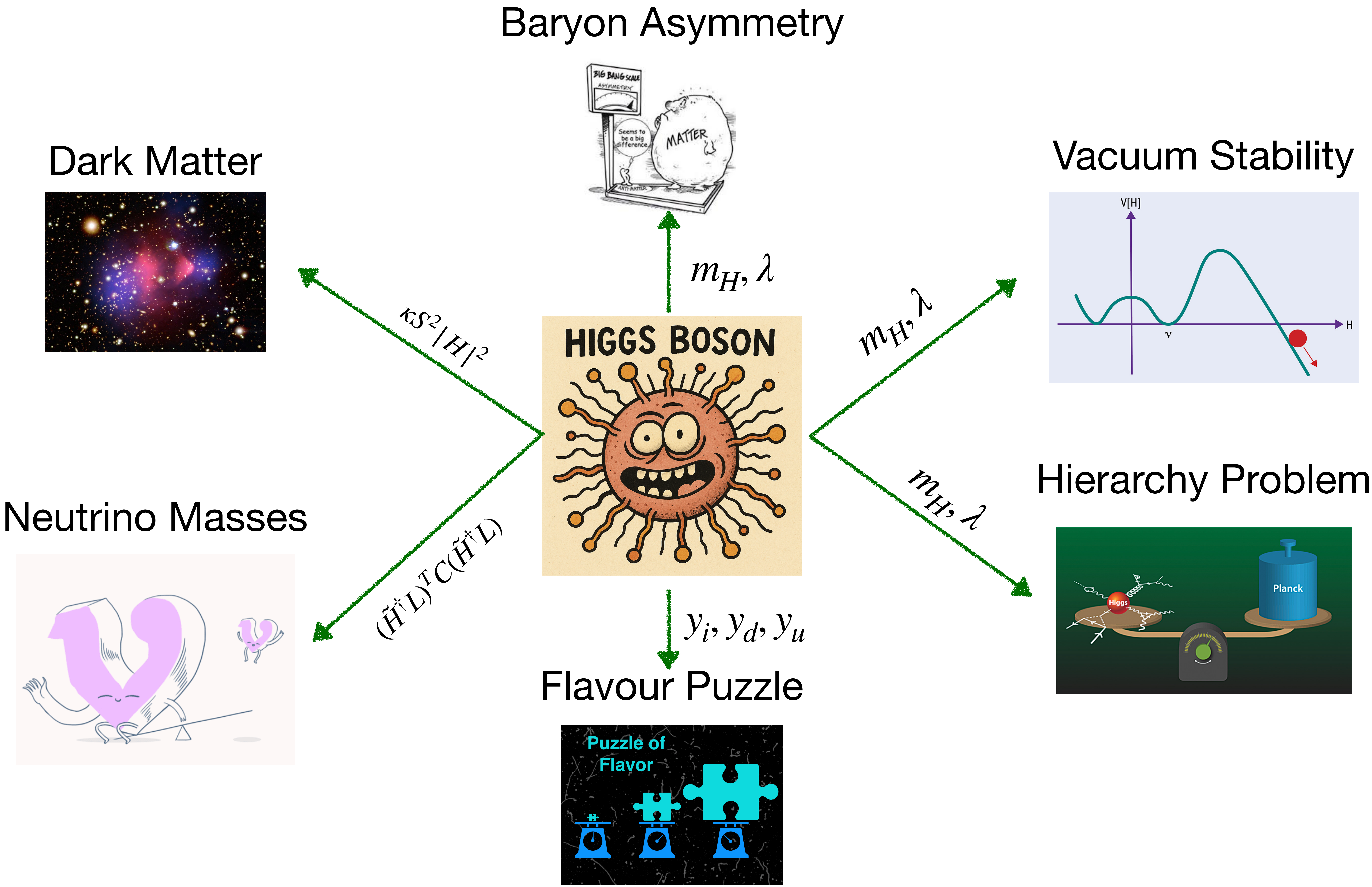


Neutrino Masses



Flavour Puzzle




Baryon Asymmetry
MATTER
Seems to be a big difference
m_H, λ
Dark Matter
$\kappa S^2 |H|^2$
Vacuum Stability
V[H]
H
v
m_H, λ
HIGGS BOSON
Neutrino Masses
$(\tilde{H}^\dagger L)^T C (\tilde{H}^\dagger L)$
Hierarchy Problem
m_H, λ
Higgs
Planck
Flavour Puzzle
y_l, y_d, y_u
Puzzle of Flavor

The Current Picture: SM

$$V(H) = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

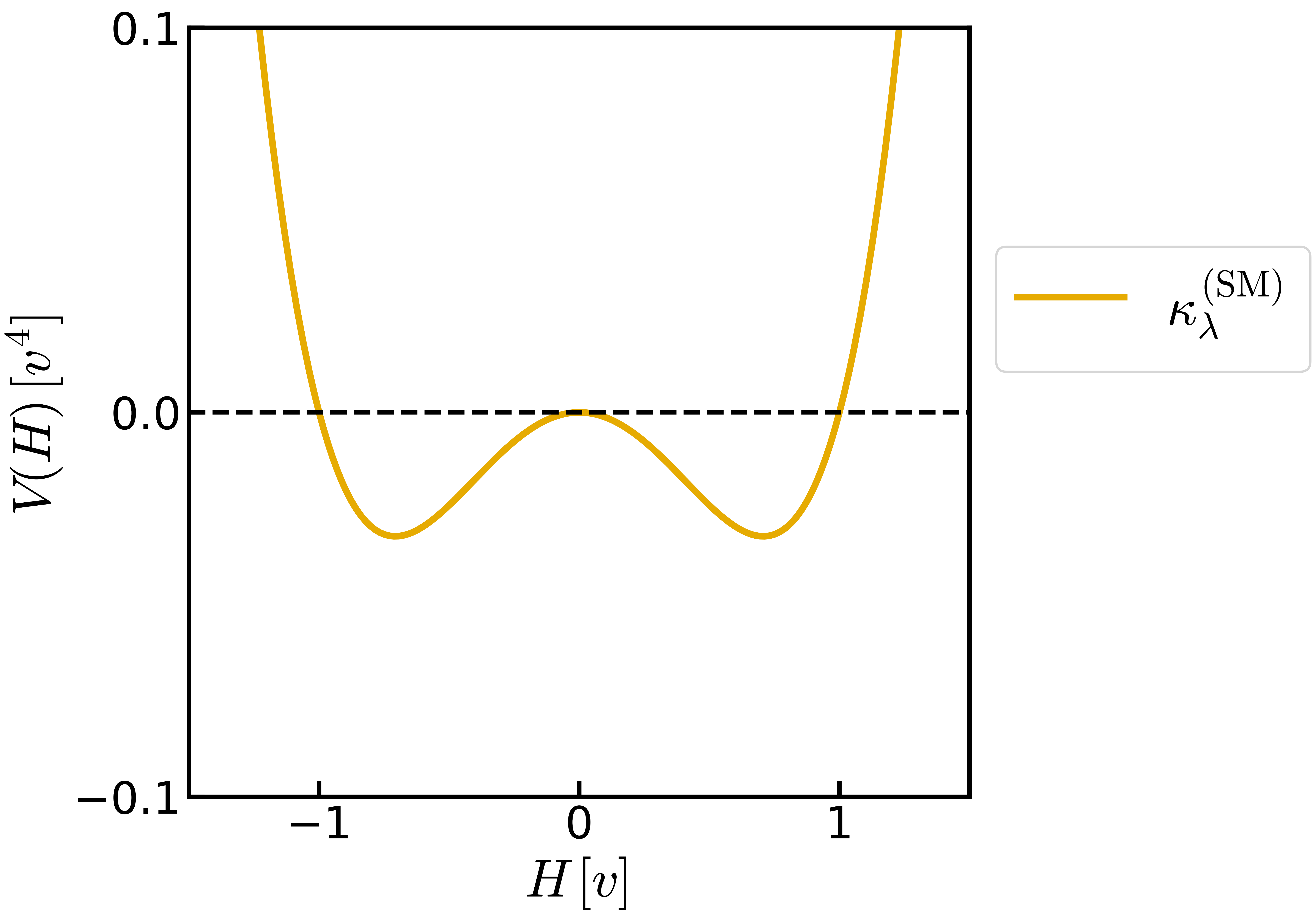
Requiring m_H and v as measured

$$\mu^2 = -\lambda_{SM} v^2$$

$$\lambda = \lambda_{SM} = \frac{m_H^2}{2v^2}$$

Gives **fixed Higgs trilinear and quartic** couplings after EWSB

$$V(h) = \frac{1}{2} m_h^2 h^2 + \lambda_{SM} v h^3 + \frac{\lambda_{SM}}{4} h^4$$



The Current Picture: BSM

$$V(H) = \mu^2 H^\dagger H + \lambda(H^\dagger H)^2 + C_6 \frac{\lambda_{SM}}{v^2}(H^\dagger H)^3$$

Requiring m_H and v as measured

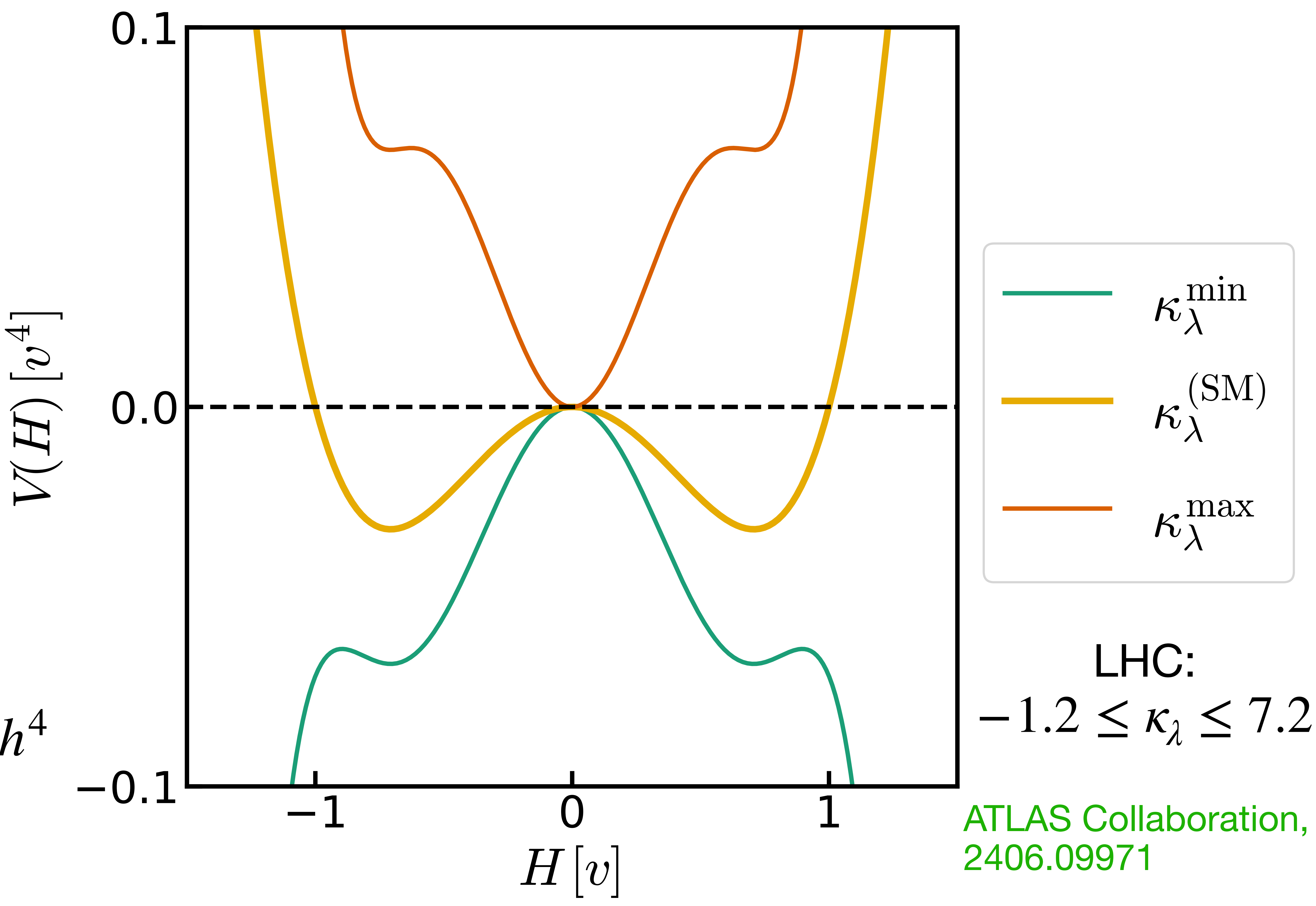
$$\mu^2 = -\left(1 - \frac{3}{4}C_6\right)\lambda_{SM} v^2$$

$$\lambda = \left(1 - \frac{3}{2}C_6\right)\lambda_{SM}$$

Correlated **shifts** of Higgs **tri-linear** and **quartic couplings** after EWSB

$$V(h) = \frac{1}{2}m_h^2 h^2 + \kappa_\lambda \lambda_3^{SM} v h^3 + \kappa_4 \frac{\lambda_4^{SM}}{4} h^4$$

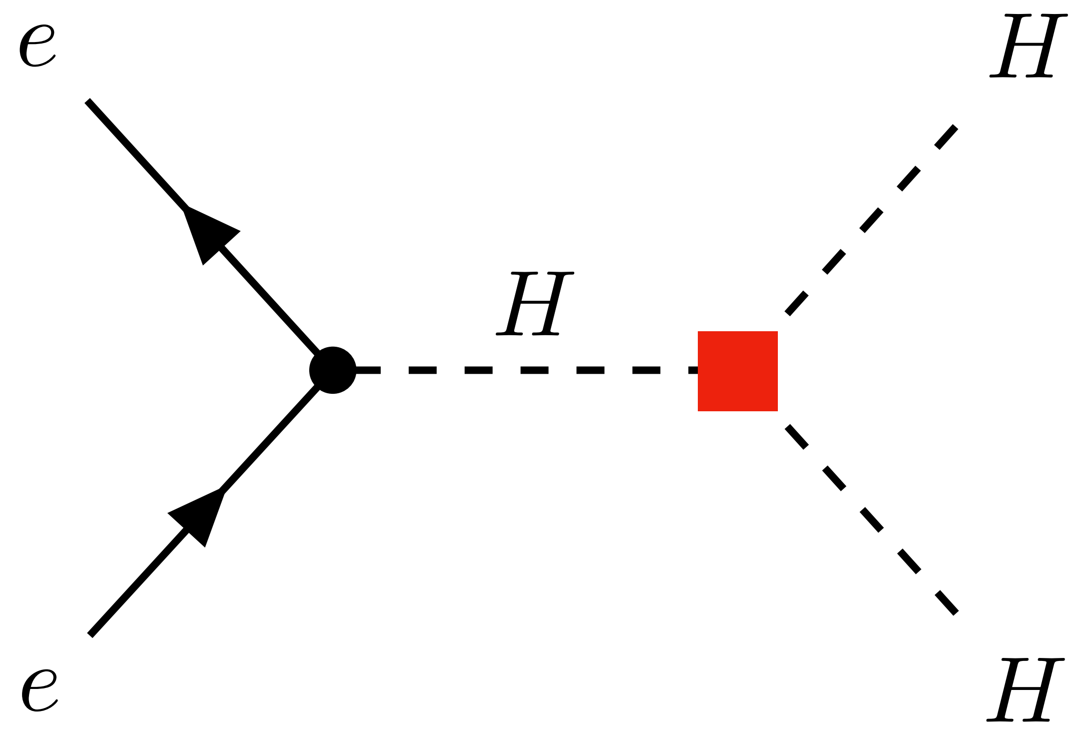
$$\kappa_\lambda = \frac{\lambda_3}{\lambda_3^{SM}} \qquad \kappa_4 = \frac{\lambda_4}{\lambda_4^{SM}}$$

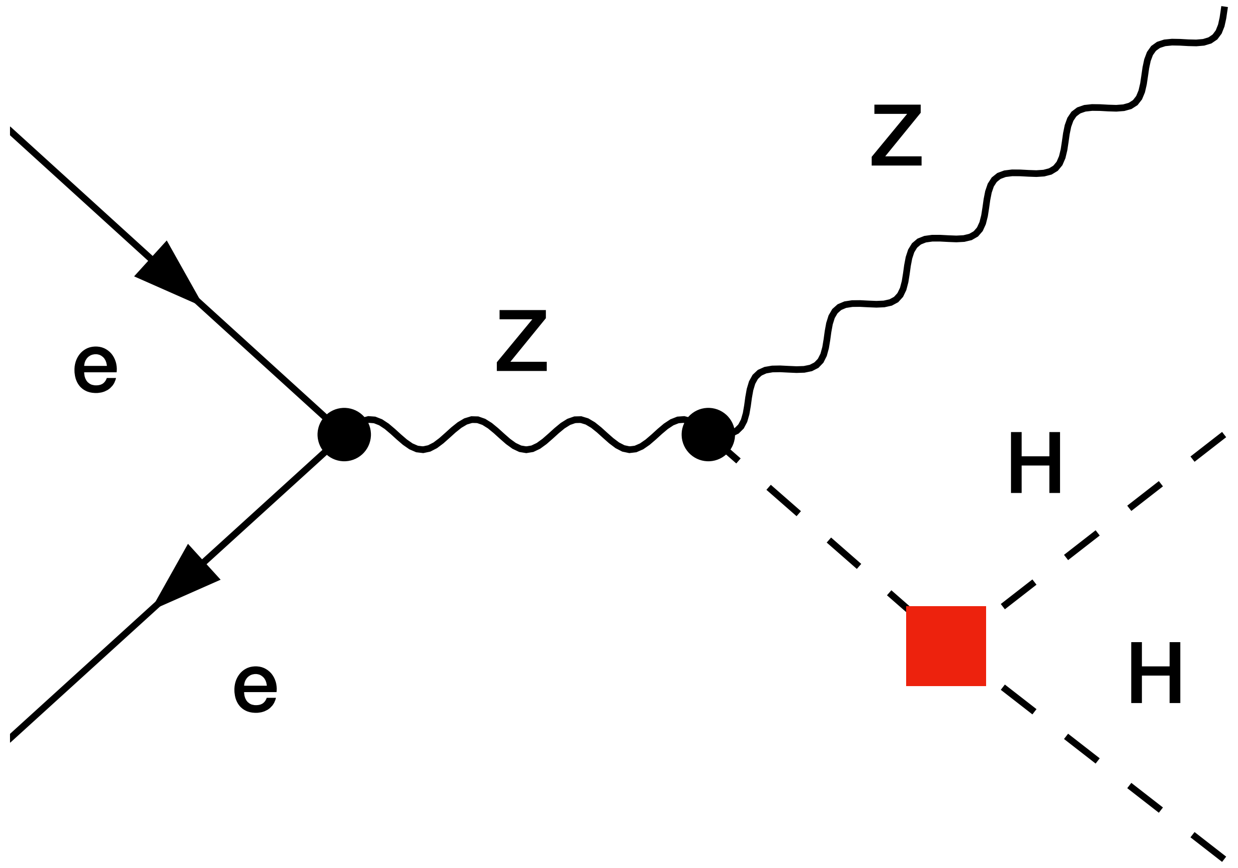


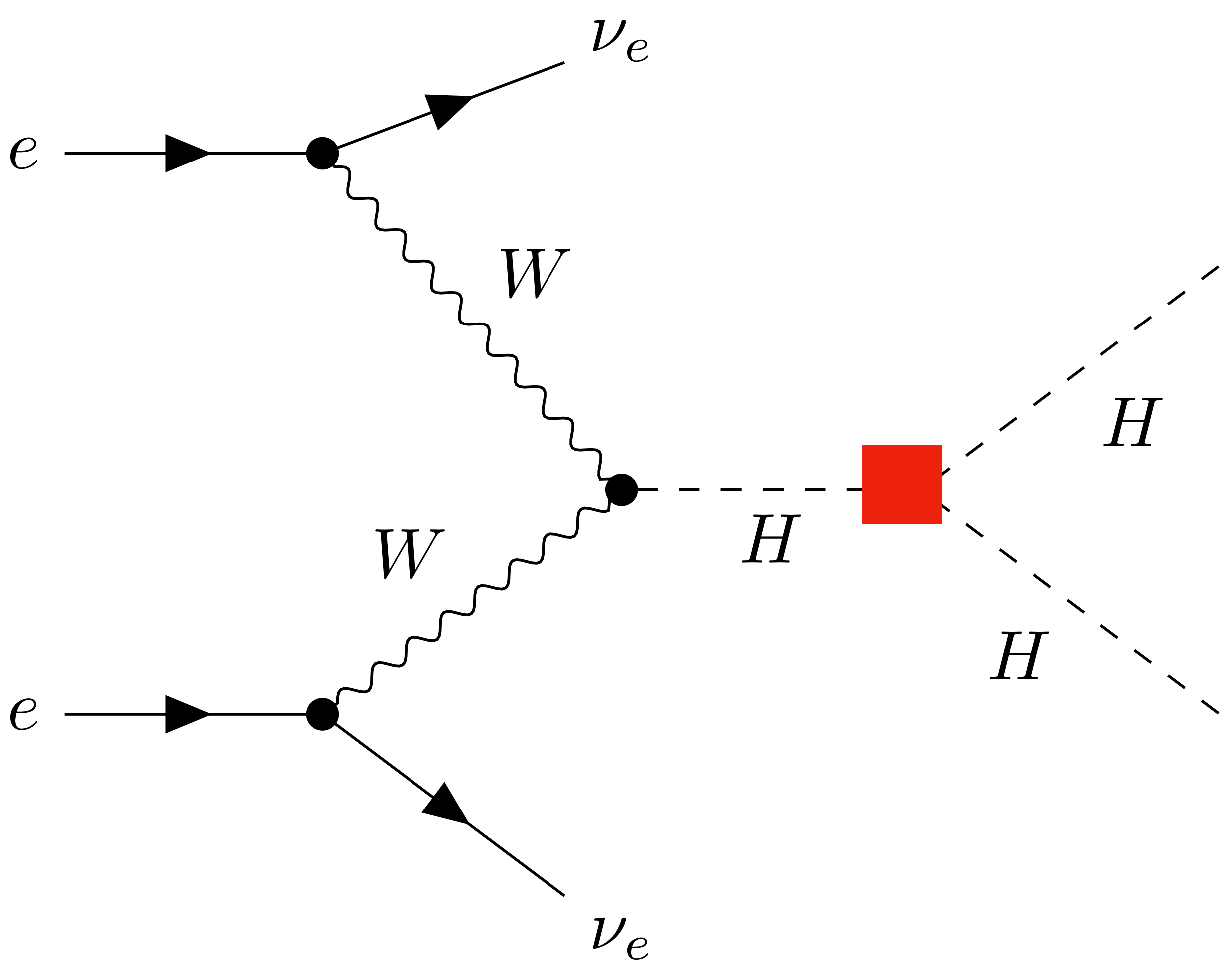
LHC:
$-1.2 \leq \kappa_\lambda \leq 7.2$

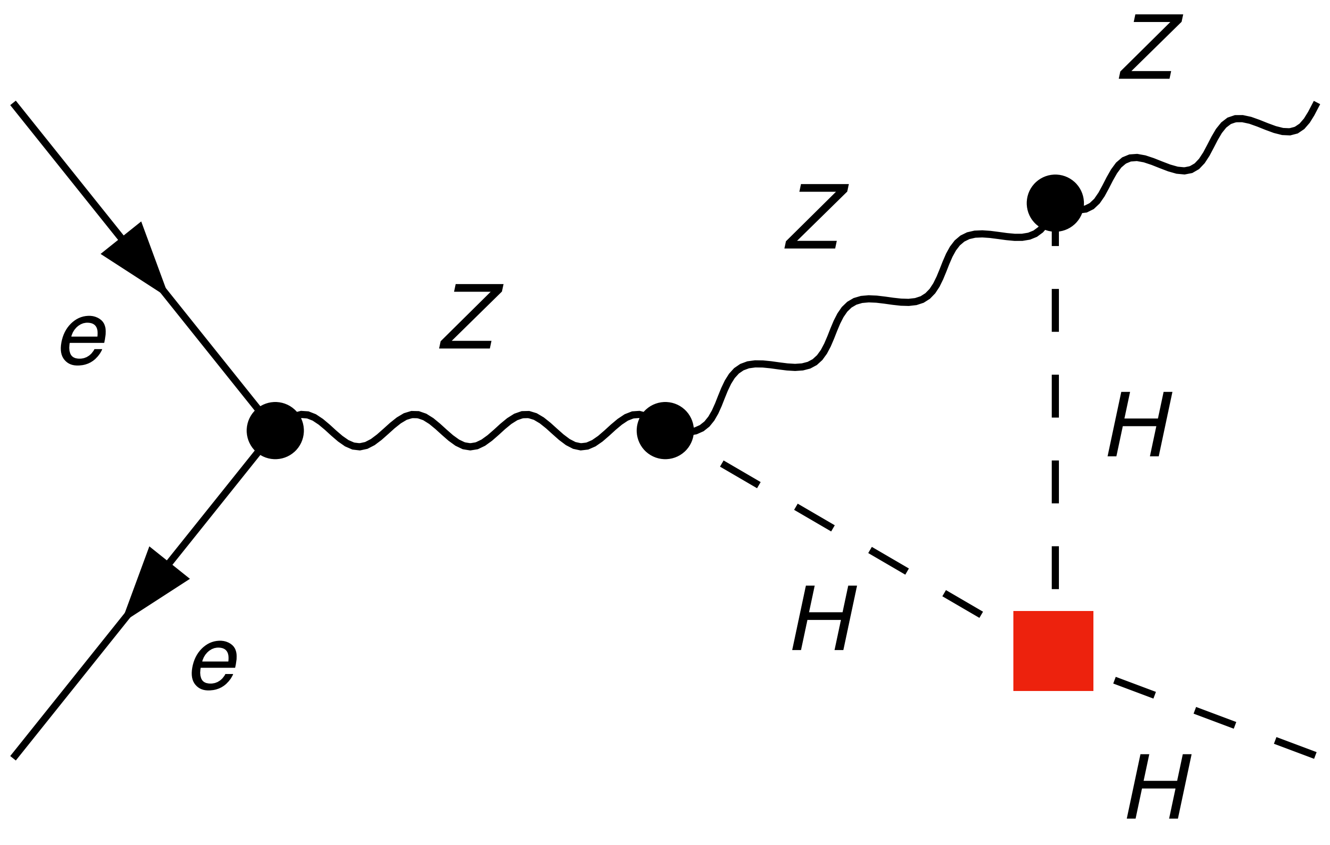
ATLAS Collaboration, 2406.09971

How do we measure it at a CEPC?

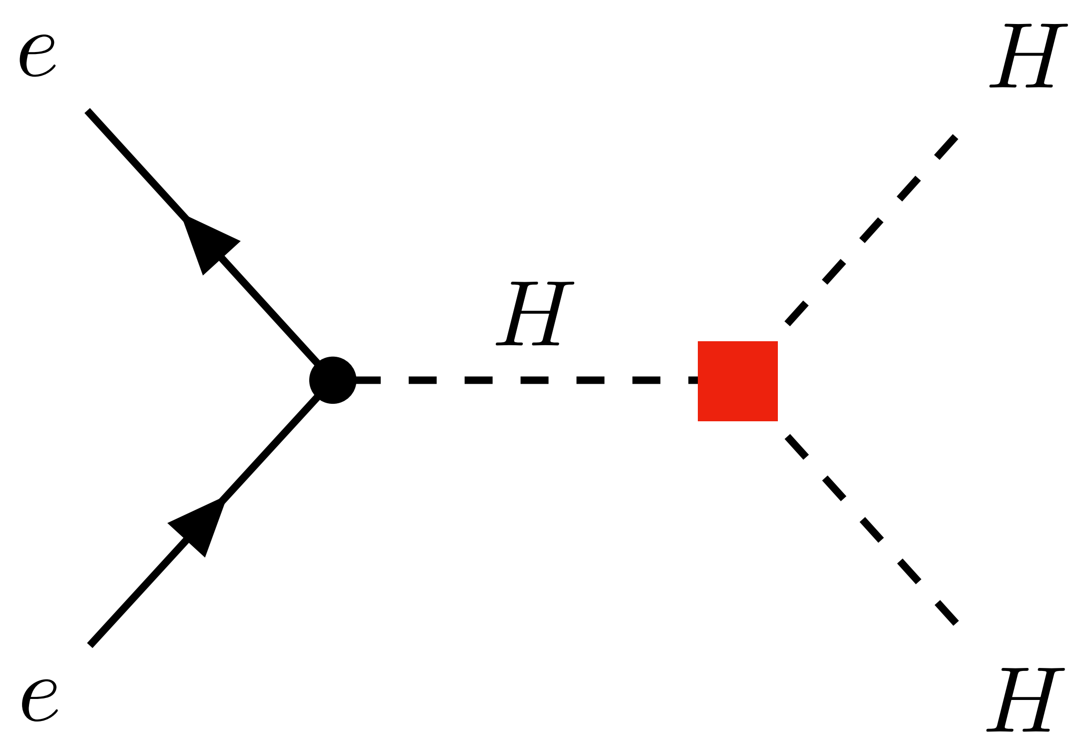


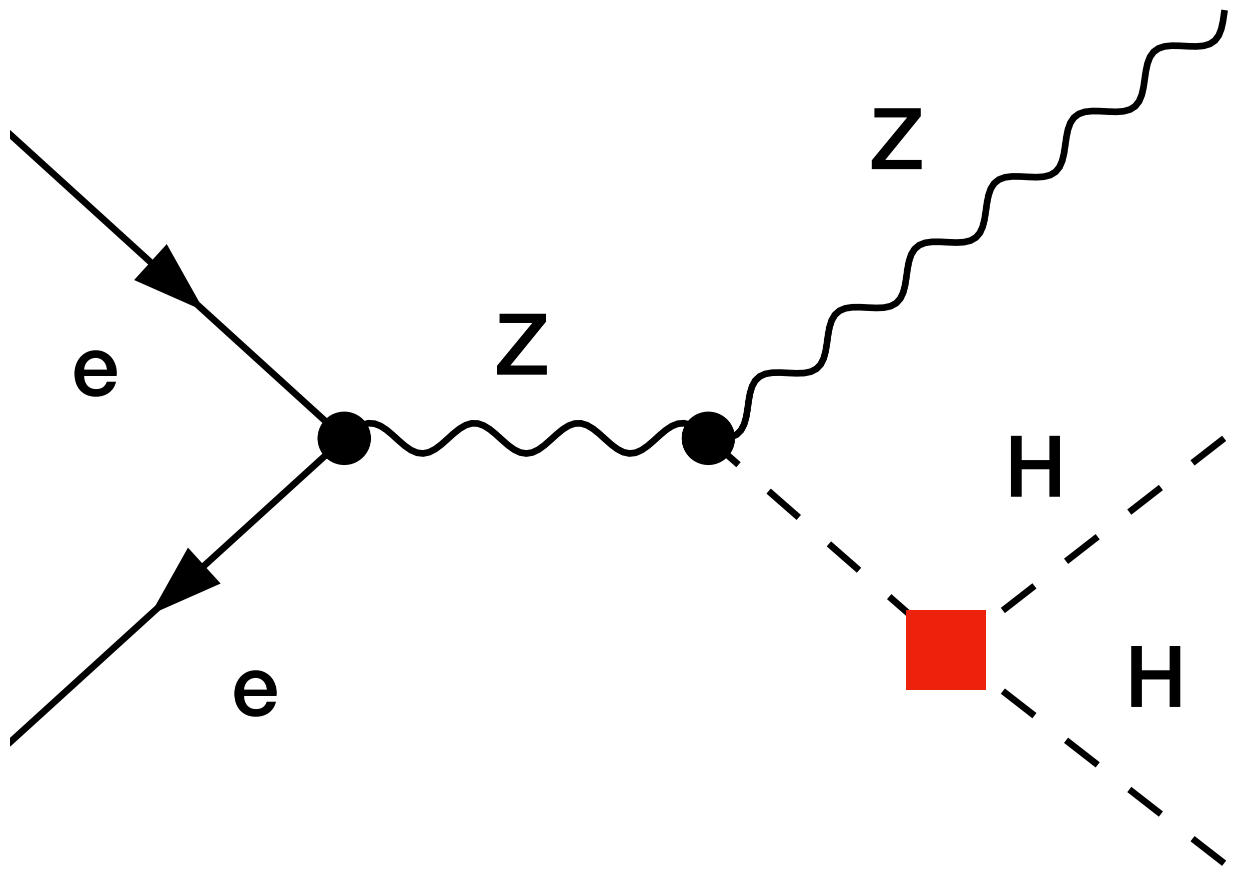


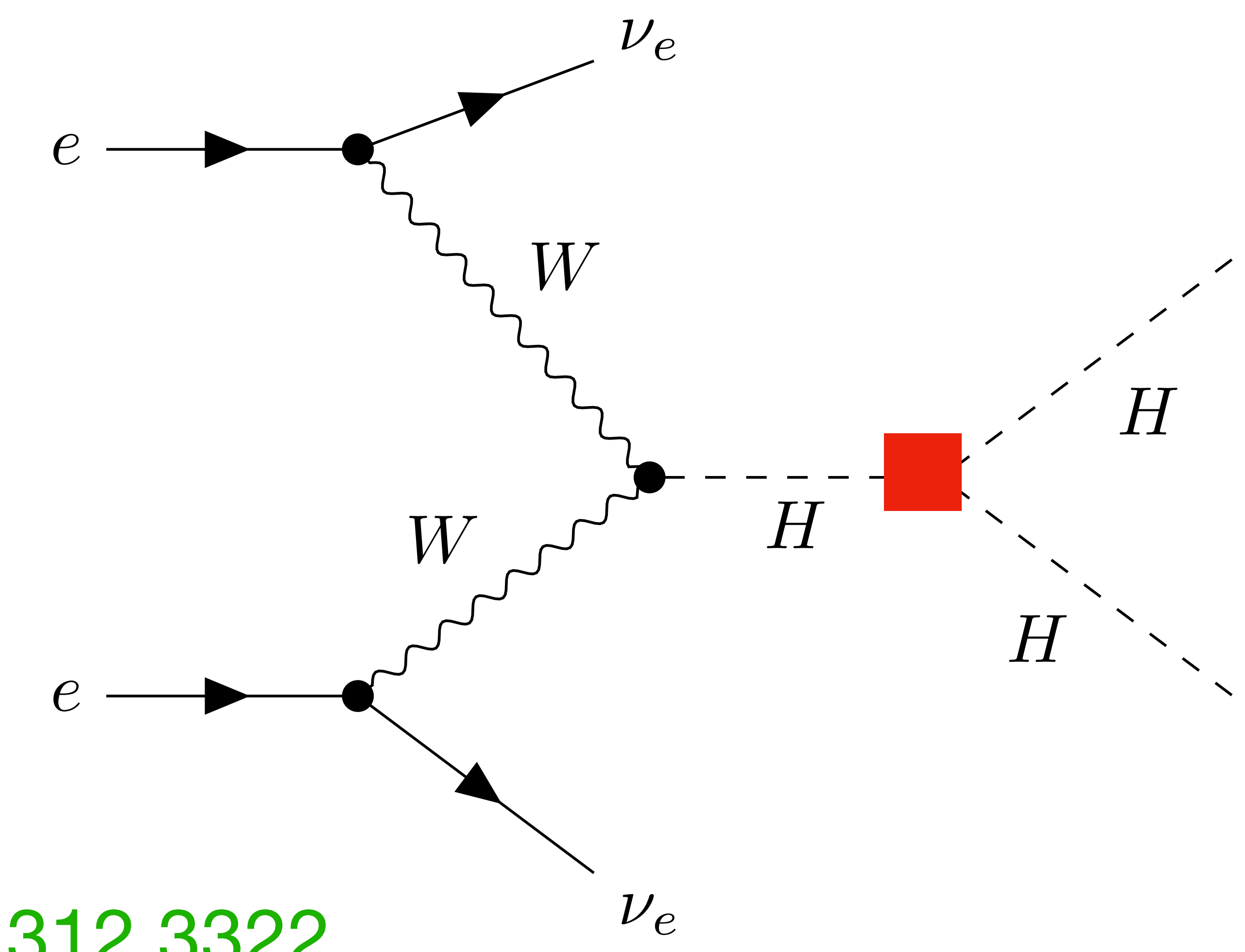


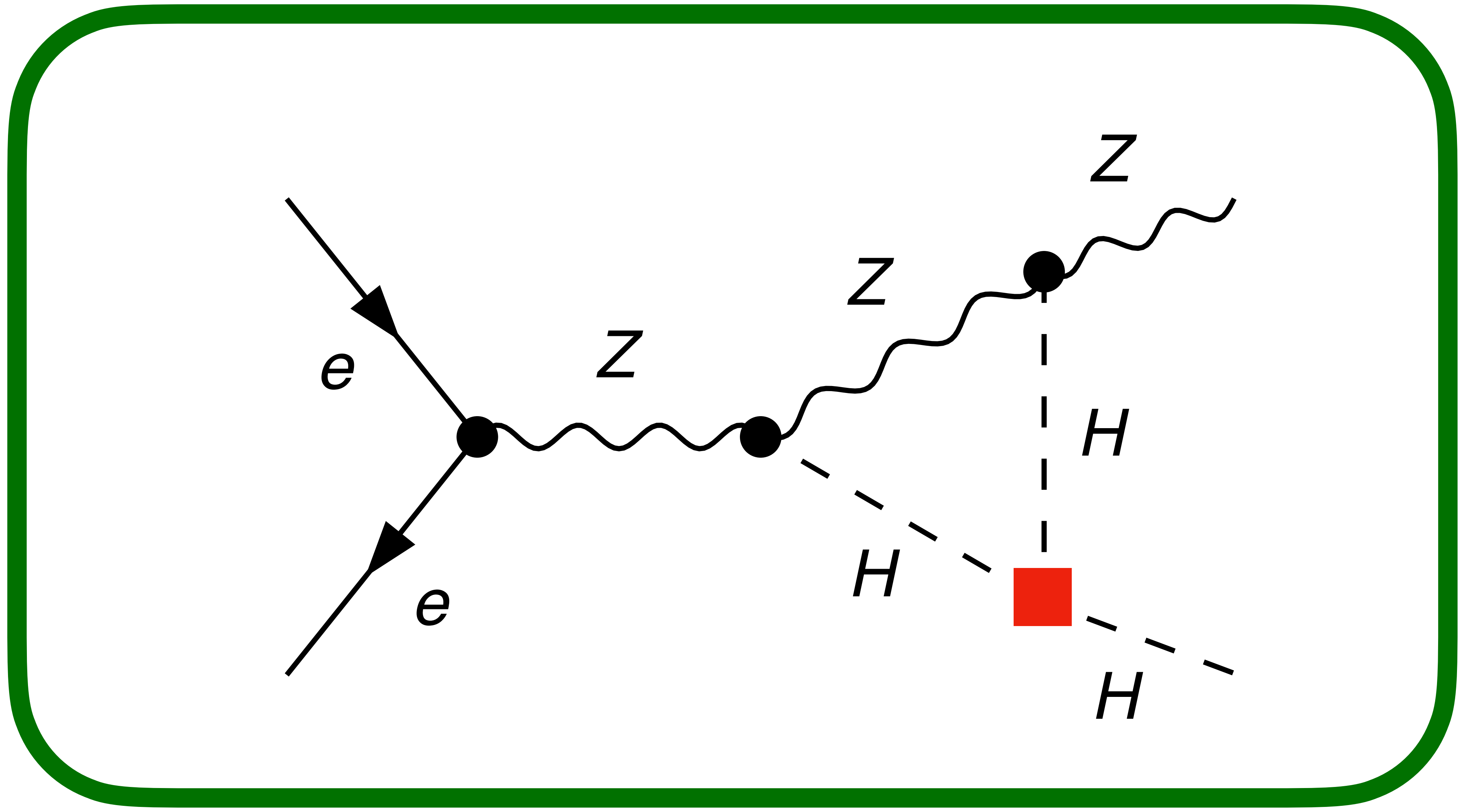


How do we measure it at a CEPC?









McCullough 1312.3322,
Di Vita et al. 1711.03978

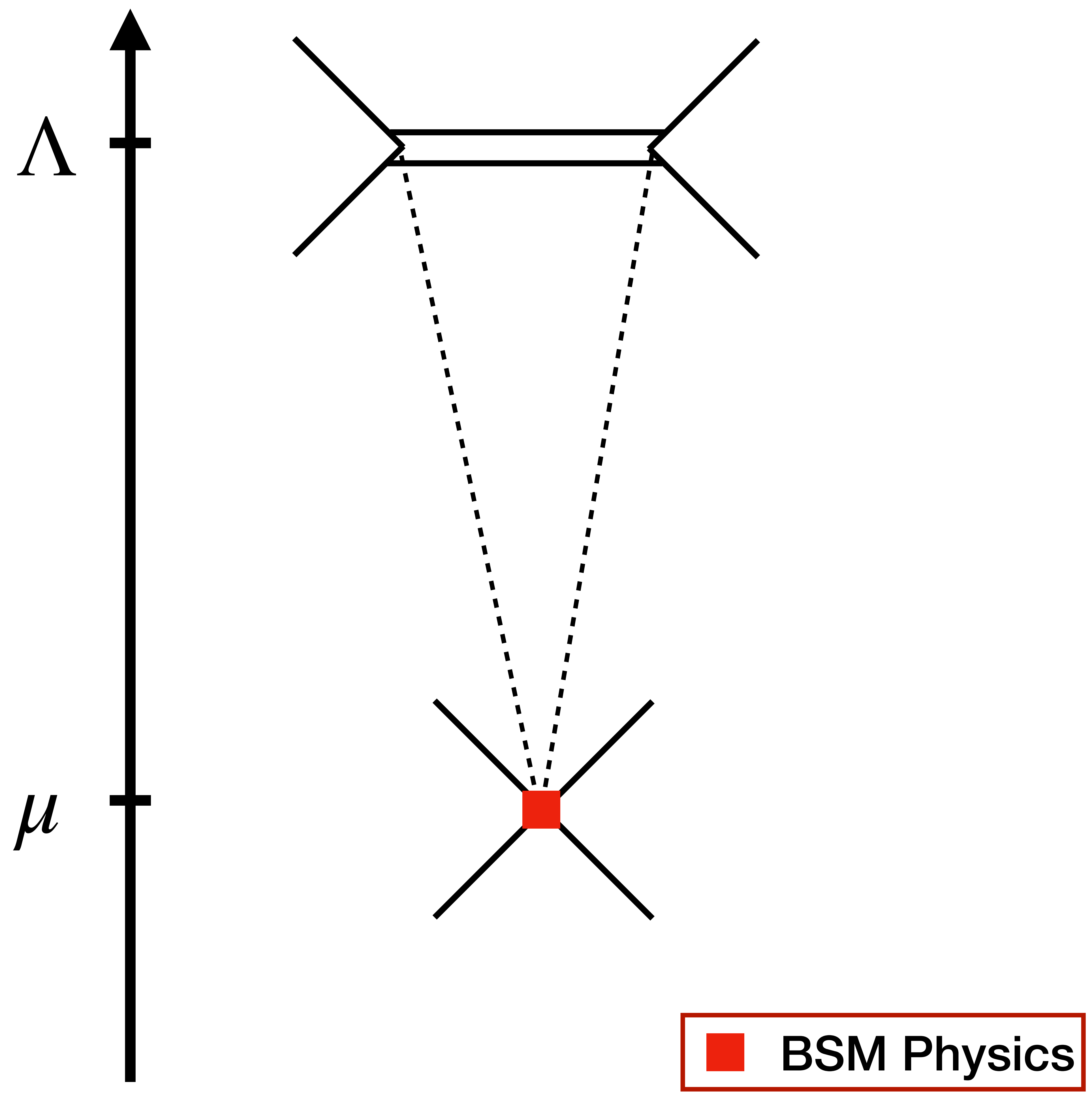
At low energies, loop contribution is most sensitive probe!

Standard Model Effective Field Theory

Effective Field Theory:

- Non-renormalizable QFT with **clear separation between UV and IR modes** and a **power counting** parametrised by δ
- Separation of scales:
  - Operators: IR interactions
  - Size of WC: UV physics

$$\mathscr{L}_{\text{EFT}}(\varphi_l, \partial_\mu \varphi_l) = \sum_k \delta^k \sum_{i \in S_k} C_i O_i(\varphi_l, \partial_\mu \varphi_l)$$



Standard Model Effective Field Theory

SMEFT:

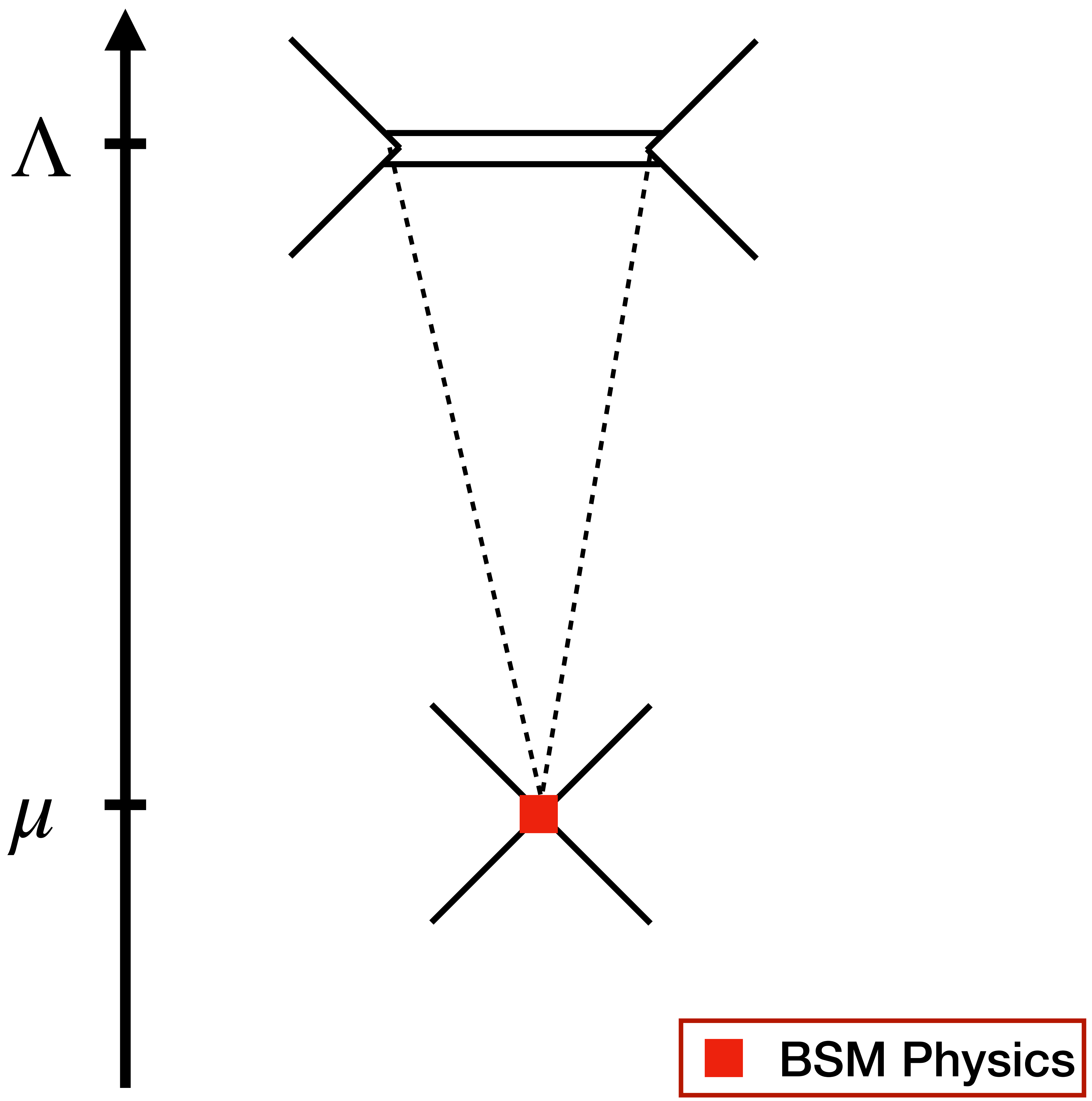
1. Light fields: SM fields
2. Power counting: Mass dimension $[O_i]$
3. Symmetry: $SU(3)_C \times SU(2)_L \times U(1)_Y$
   (+ Global Symmetries)

Parametrise New Physics!
Scale Dependent Couplings!

$$\mathscr{L} = \mathscr{L}_{SM} + \sum_{i \in S_2} \left(\frac{1}{\Lambda_{UV}} \right)^2 c_i(\mu) O_i + \mathcal{O}(\Lambda^{-3})$$

Warsaw Basis

IR physics, always the same



How to tame a beast

$C_W, C_{H\Box}, C_{HD}$

C_{HB}, C_{HW}, C_{HWB}

C_H

$[C_{uW}]_{33}, [C_{uB}]_{33}$

$[C_{Hl}^{(1)}]_{11}, [C_{Hl}^{(1)}]_{22}, [C_{Hl}^{(1)}]_{33}$

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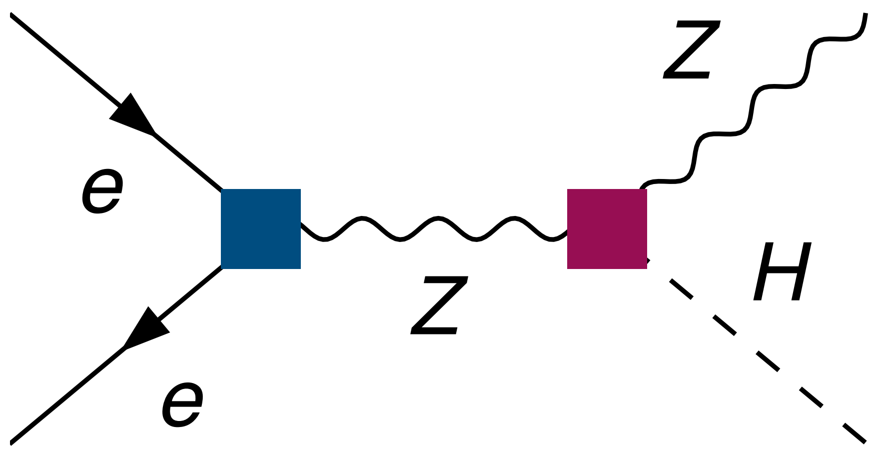

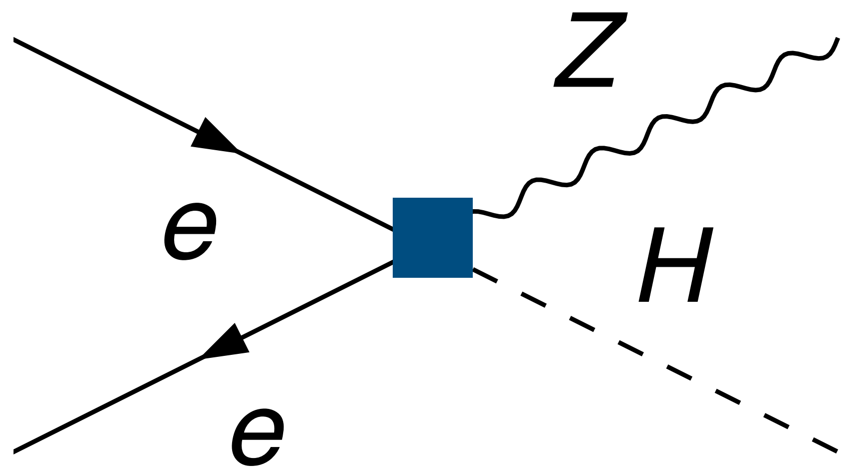

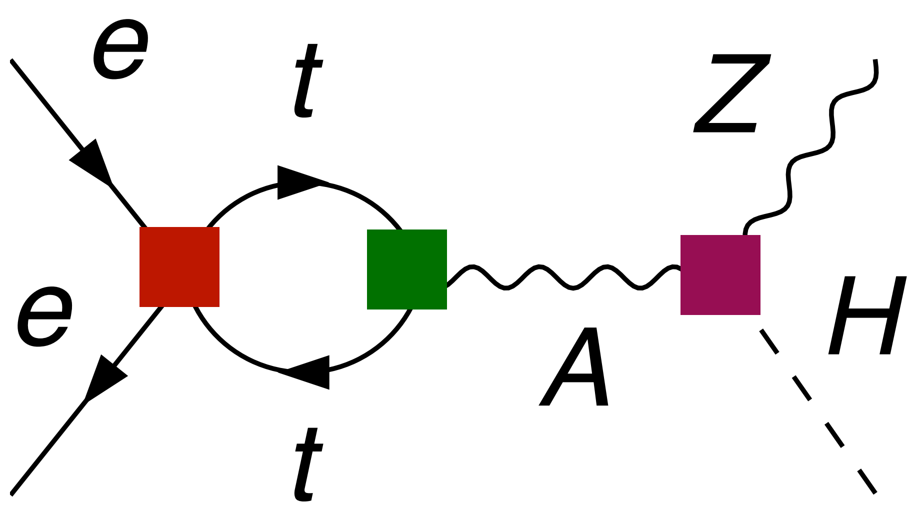

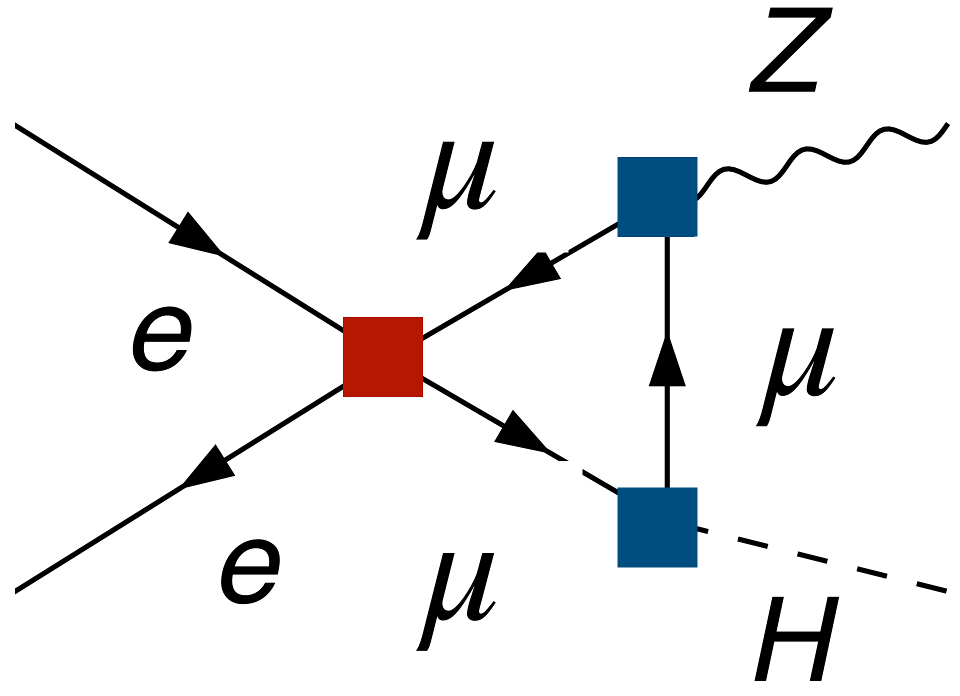

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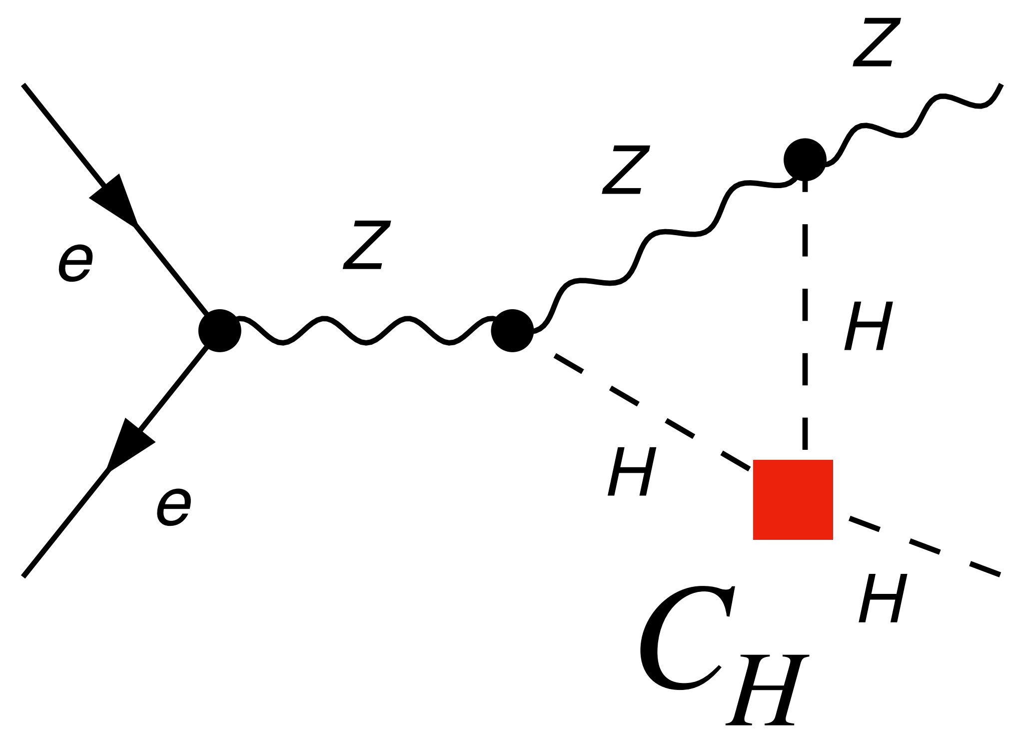
VS

$$\sigma(e^+e^- \to ZH) \times 2$$



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VS

Flavour Symmetries

$\sigma(e^+e^- \to ZH) \times 2$

Top, Higgs, Diboson, Drell-Yan from **HL-LHC**

Di-fermion, Diboson and EWPO from **FCC-ee**

Di-fermion, Diboson from **LEP**

Current Flavour data

“Boundary Condition”

How to tame a beast

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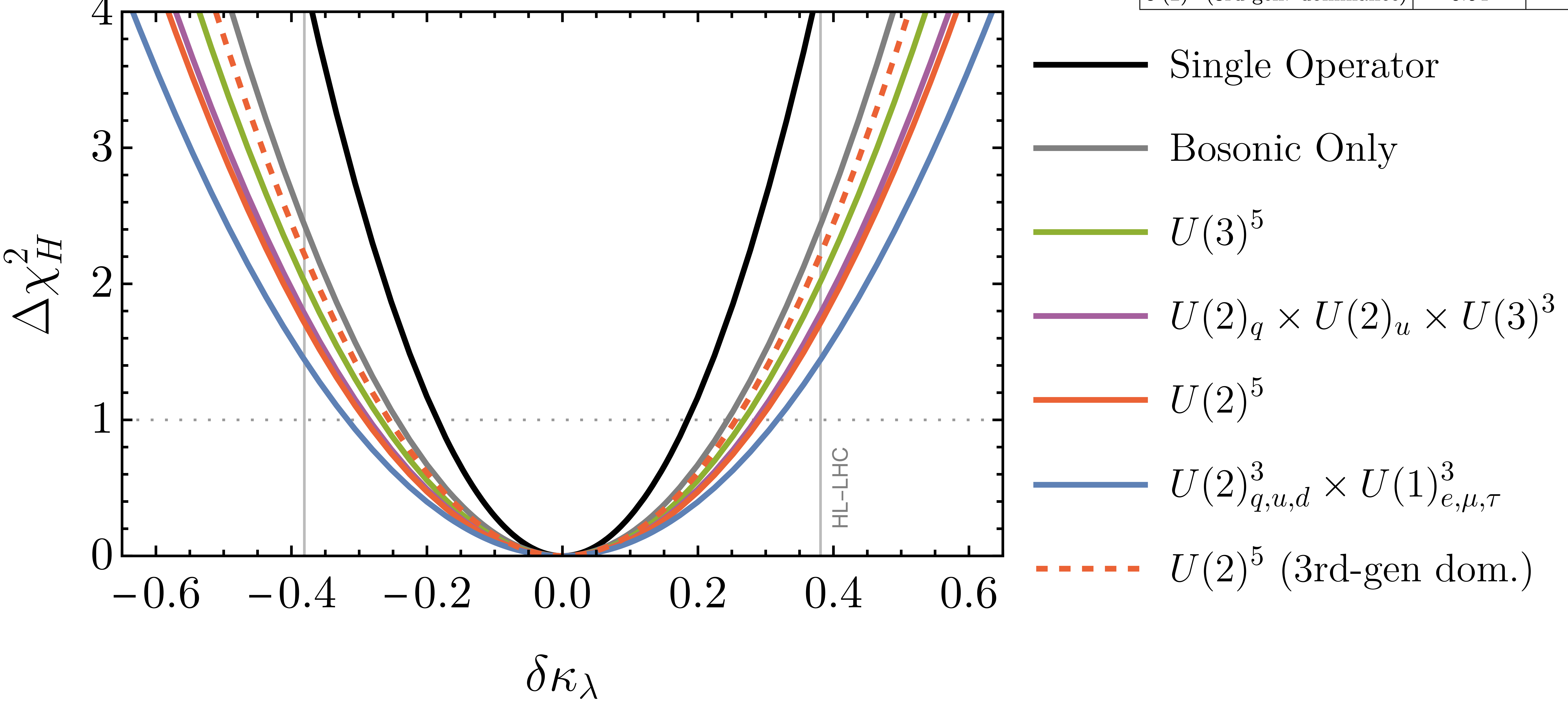
Current Flavour data

“Boundary Condition”

Projected sensitivity

Scenario	$\sigma_H [\text{TeV}^{-2}]$	68% CL $\delta\kappa_\lambda$
C_H Only	0.39	18%
Bosonic Only	0.52	24%
$U(3)^5$	0.57	27%
$U(2)_q \times U(2)_u \times U(3)^3$	0.61	29%
$U(2)^5$	0.62	29%
$U(2)^3_{q,u,d} \times U(1)^3_{e,\mu,\tau}$	0.68	32%
$U(2)^5$ (3rd-gen. dominance)	0.54	25%



Conclusion

- Leading Probe of the Higgs-Self Coupling **at NLO** for a low energy CEPC
- Meaningful bound requires **consistent inclusion** of all **new physics** effects appearing **at the same order**
- Higgs Self-Coupling bound robustly to $\delta\kappa_\lambda \lesssim \mathbf{30}\,\%$ at a CEPC within the SMEFT
- **Insensitive to** generic **Flavour assumptions**
- True strength lies in the **complementary exploration of the Electroweak sector!**

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Thank you!

Any further Questions?
Feel free to email me:

victor.maura_breick@kcl.ac.uk

Backup Slides

	Name	Description
FCCee	Z/W-pole	Electroweak Precision Observables
	Single H	Inclusive $e^+e^- \to ZH$, $\nu\bar{\nu}H$ cross sections
	Diboson	Total cross sections at $163, 240, 365$ GeV
	Di-fermion	Cross sections and A_{FB} at $163, 240, 365$ GeV
LEP	Diboson	Diboson total and differential cross sections
	Di-lepton	Di-lepton production for $\sqrt{s} > m_Z$
HL-LHC	Top	t, $t\bar{t}$, $t\bar{t}V$, $t\bar{t}t\bar{t}$ and $b\bar{b}t\bar{t}$ (diff.) cross section
	Higgs	Higgs signal strengths and STXS data
	Diboson	Fiducial differential dist. for VV and Zjj
	Drell-Yan	Di- and mono-lepton high-p_{T} tails
	Flavour	$\Delta F = 2$, $b \to c\tau\nu$, $b \to s\ell\ell$, and $b \to s\nu\nu$

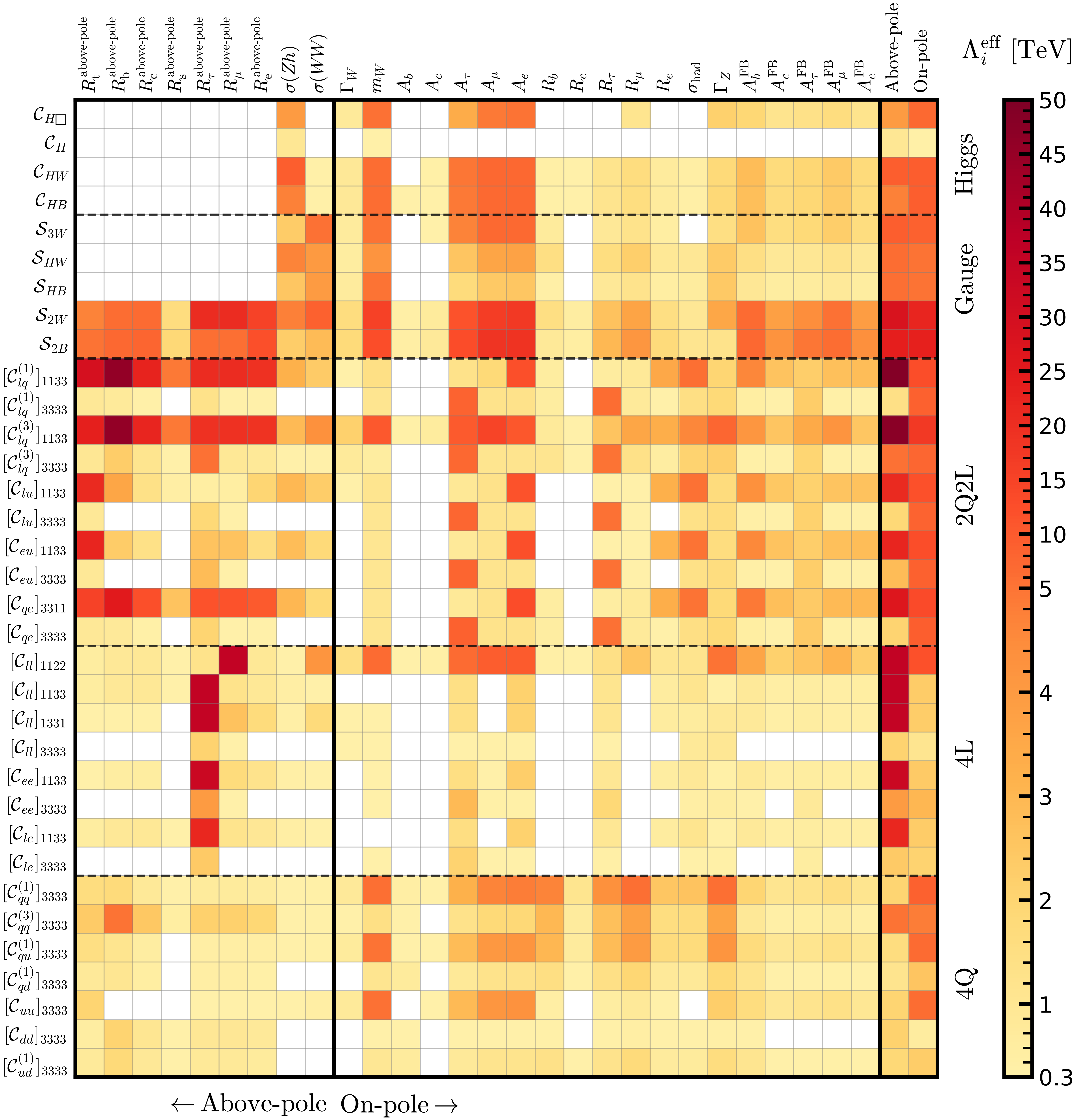
Warsaw Basis

X^3		H^6 and H^4D^2		ψ^2H^3	
$\mathcal{O}_G$	$f^{ABC}G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_H$	$(H^\dagger H)^3$	$\mathcal{O}_{eH}$	$(H^\dagger H)(\bar l_p e_r H)$
$\mathcal{O}_{\widetilde G}$	$f^{ABC}\widetilde G_\mu^{A\nu}G_\nu^{B\rho}G_\rho^{C\mu}$	$\mathcal{O}_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	$\mathcal{O}_{uH}$	$(H^\dagger H)(\bar q_p u_r \widetilde H)$
$\mathcal{O}_W$	$\varepsilon^{IJK}W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$	$\mathcal{O}_{HD}$	$\left(H^\dagger D^\mu H\right)^\star\left(H^\dagger D_\mu H\right)$	$\mathcal{O}_{dH}$	$(H^\dagger H)(\bar q_p d_r H)$
$\mathcal{O}_{\widetilde W}$	$\varepsilon^{IJK}\widetilde W_\mu^{I\nu}W_\nu^{J\rho}W_\rho^{K\mu}$				

X^2H^2		ψ^2XH		ψ^2H^2D	
$\mathcal{O}_{HG}$	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar l_p\sigma^{\mu\nu}e_r)\tau^I H W_{\mu\nu}^I$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar l_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde G}$	$H^\dagger H\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar q_p\sigma^{\mu\nu}T^A u_r)\widetilde H\, G_{\mu\nu}^A$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar e_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde W}$	$H^\dagger H\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W_{\mu\nu}^I$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar q_p\sigma^{\mu\nu}u_r)\widetilde H\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar q_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde B}$	$H^\dagger H\, \widetilde B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar q_p\sigma^{\mu\nu}T^A d_r)H\, G_{\mu\nu}^A$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar u_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar q_p\sigma^{\mu\nu}d_r)\tau^I H\, W_{\mu\nu}^I$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar d_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde WB}$	$H^\dagger\tau^I H\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar q_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde H^\dagger D_\mu H)(\bar u_p\gamma^\mu d_r)$

$(\bar LL)(\bar LL)$		$(\bar RR)(\bar RR)$		$(\bar LL)(\bar RR)$	
$\mathcal{O}_{ll}$	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar e_p\gamma_\mu e_r)(\bar e_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar l_p\gamma_\mu l_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar u_p\gamma_\mu u_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar l_p\gamma_\mu l_r)(\bar u_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar q_p\gamma_\mu\tau^I q_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar d_p\gamma_\mu d_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar l_p\gamma_\mu l_r)(\bar d_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_p\gamma_\mu l_r)(\bar q_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar e_p\gamma_\mu e_r)(\bar u_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar q_p\gamma_\mu q_r)(\bar e_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_p\gamma_\mu\tau^I l_r)(\bar q_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar e_p\gamma_\mu e_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar u_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar u_p\gamma_\mu u_r)(\bar d_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar u_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar u_p\gamma_\mu T^A u_r)(\bar d_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar q_p\gamma_\mu q_r)(\bar d_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar q_p\gamma_\mu T^A q_r)(\bar d_s\gamma^\mu T^A d_t)$

$(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$		B-violating	
$\mathcal{O}_{ledq}$	$(\bar l_p^j e_r)(\bar d_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$\mathcal{O}_{quqd}^{(1)}$	$(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{quqd}^{(8)}$	$(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$\mathcal{O}_{lequ}^{(1)}$	$(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$\mathcal{O}_{lequ}^{(3)}$	$(\bar l_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar q_s^k\sigma^{\mu\nu}u_t)$		



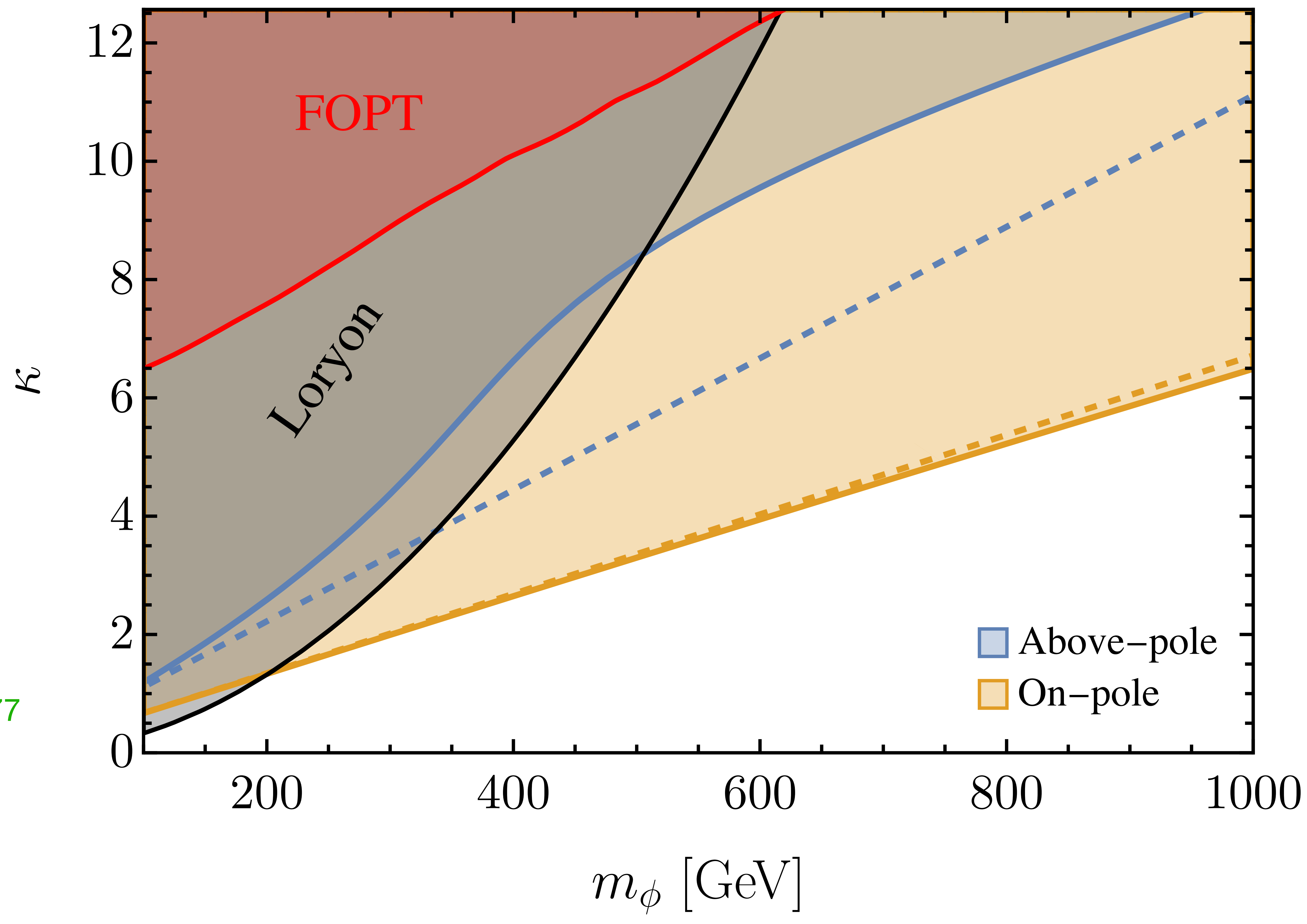
$R_t^{\text{above-pole}}$ $R_b^{\text{above-pole}}$ $R_c^{\text{above-pole}}$ $R_s^{\text{above-pole}}$ $R_\tau^{\text{above-pole}}$ $R_\mu^{\text{above-pole}}$ $R_e^{\text{above-pole}}$ $\sigma(Zh)$ $\sigma(WW)$ Γ_W m_W A_b A_c A_τ A_μ A_e R_b R_c R_τ R_μ R_e σ_{had} Γ_Z A_b^{FB} A_c^{FB} A_τ^{FB} A_μ^{FB} A_e^{FB} Above-pole On-pole
Λ_i^{eff} [TeV]
$\mathcal{C}_{H\Box}$
$\mathcal{C}_H$
$\mathcal{C}_{HW}$
$\mathcal{C}_{HB}$
$\mathcal{S}_{3W}$
$\mathcal{S}_{HW}$
$\mathcal{S}_{HB}$
$\mathcal{S}_{2W}$
$\mathcal{S}_{2B}$
$[\mathcal{C}_{lq}^{(1)}]_{1133}$
$[\mathcal{C}_{lq}^{(1)}]_{3333}$
$[\mathcal{C}_{lq}^{(3)}]_{1133}$
$[\mathcal{C}_{lq}^{(3)}]_{3333}$
$[\mathcal{C}_{lu}]_{1133}$
$[\mathcal{C}_{lu}]_{3333}$
$[\mathcal{C}_{eu}]_{1133}$
$[\mathcal{C}_{eu}]_{3333}$
$[\mathcal{C}_{qe}]_{3311}$
$[\mathcal{C}_{qe}]_{3333}$
$[\mathcal{C}_{ll}]_{1122}$
$[\mathcal{C}_{ll}]_{1133}$
$[\mathcal{C}_{ll}]_{1331}$
$[\mathcal{C}_{ll}]_{3333}$
$[\mathcal{C}_{ee}]_{1133}$
$[\mathcal{C}_{ee}]_{3333}$
$[\mathcal{C}_{le}]_{1133}$
$[\mathcal{C}_{le}]_{3333}$
$[\mathcal{C}_{qq}^{(1)}]_{3333}$
$[\mathcal{C}_{qq}^{(3)}]_{3333}$
$[\mathcal{C}_{qu}^{(1)}]_{3333}$
$[\mathcal{C}_{qd}^{(1)}]_{3333}$
$[\mathcal{C}_{uu}]_{3333}$
$[\mathcal{C}_{dd}]_{3333}$
$[\mathcal{C}_{ud}^{(1)}]_{3333}$
Higgs
Gauge
2Q2L
4L
4Q
50 45 40 35 30 25 20 15 10 5 4 3 2 1 0.3
← Above-pole On-pole →

Real Singlet Scalar

- Real Singlet Scalar with $\mathbb{Z}_2$-symmetry

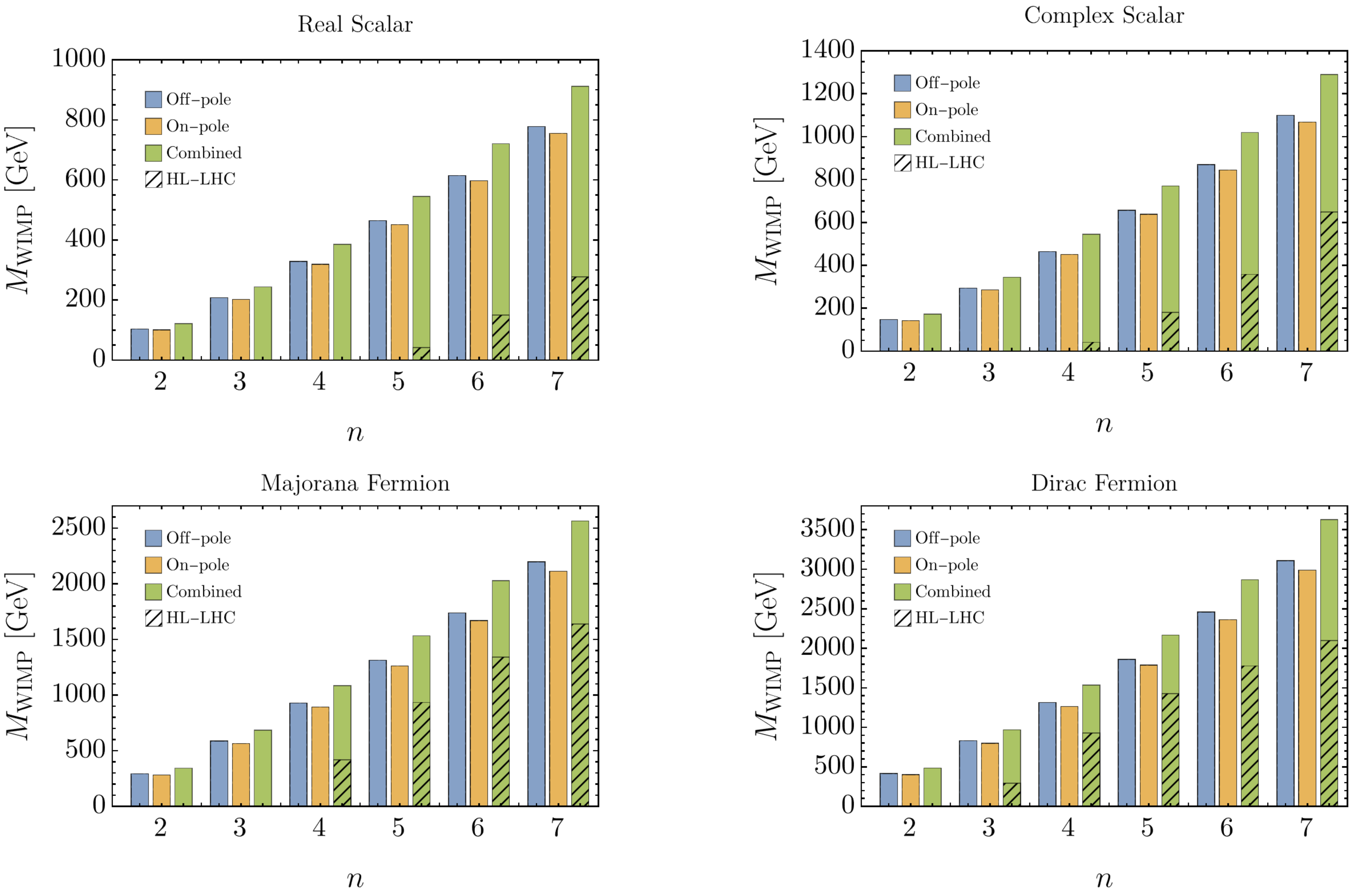
$$\mathscr{L} \supset \frac{1}{2}\left(\partial_\mu \phi\right)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{2}\kappa\phi^2 |H|^2 - \frac{1}{4!}\lambda\phi^4$$

- Only generates C_H and $C_{H\Box}$ at NLO
- Simplest extension of the SM that allows for a first order EW phase transition
  Jiang et al.1811.08878 , Haisch et al. 2003.05936
- Hardest "loryon" to probe experimentally
  Banta et al. 2110.02967, Crawford and Sutherland 2409.18177
  (or next talk by Graeme!)
- **Z pole covers Loryon parameter space!**



ACE in action: WIMPs

- Higher dimensional Representations of $SU(2)_L$
- Could be Dark Matter
- Can **significantly improve upon HL-LHC** constraints



Custodial Quadruplet