Accuracy complements energy

Electroweak precision tests at Tera-Z

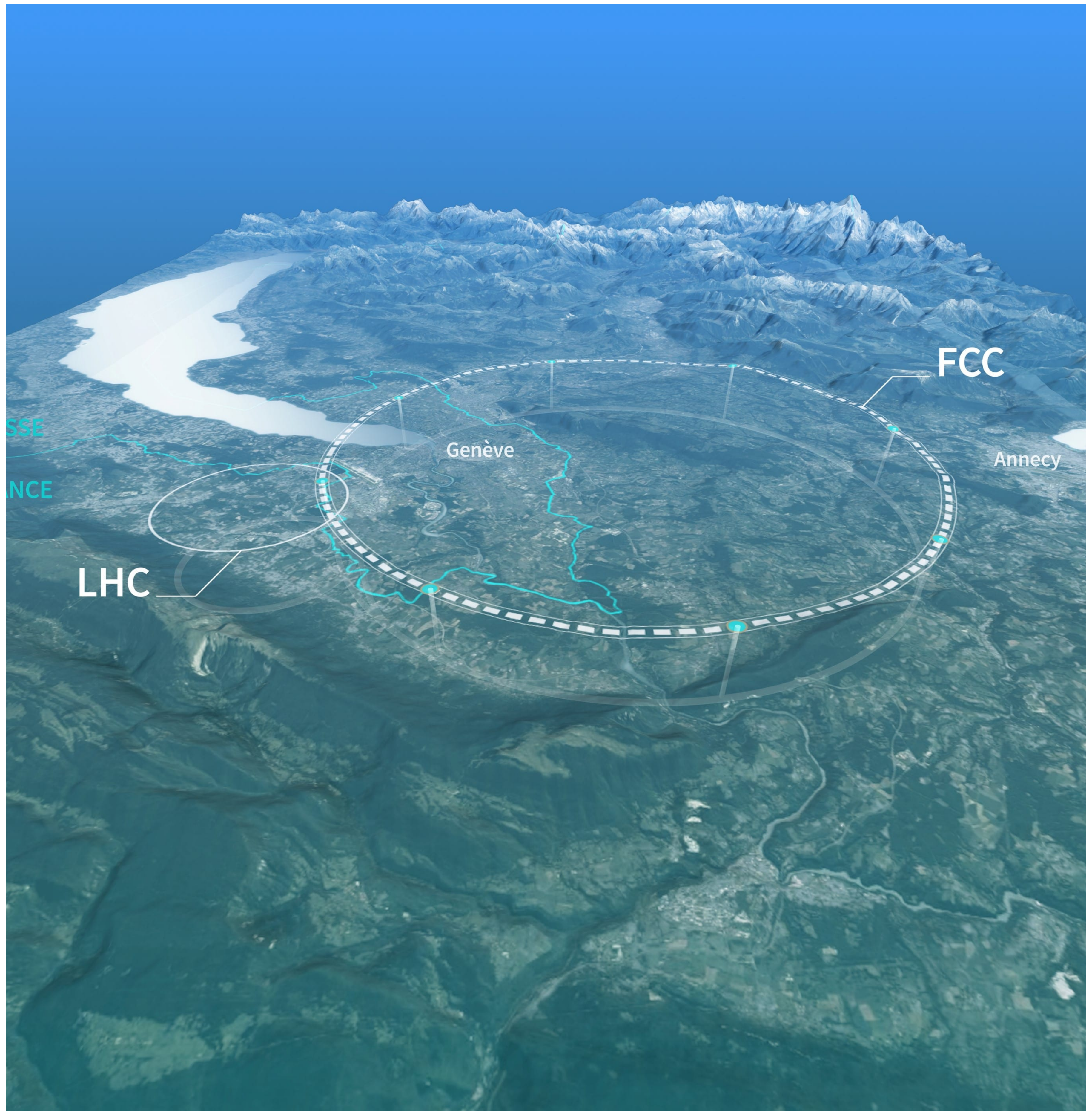
Based on **VM**, Stefanek, You, 2412.14241

Victor Maura Breick, 19.02.2025

FCC Early-Career Forum, 19.02.2025

Overview

1. A theorists' view of FCCee
2. Standard Model Effective Field Theory (SMEFT)
3. Accuracy complements energy (ACE)
4. Implications



* We have 10+10 minutes, so if you have questions, please interrupt me and I will try to address them. Otherwise, save them for the end and I can go more in depth!

A theorist's view of FCCee

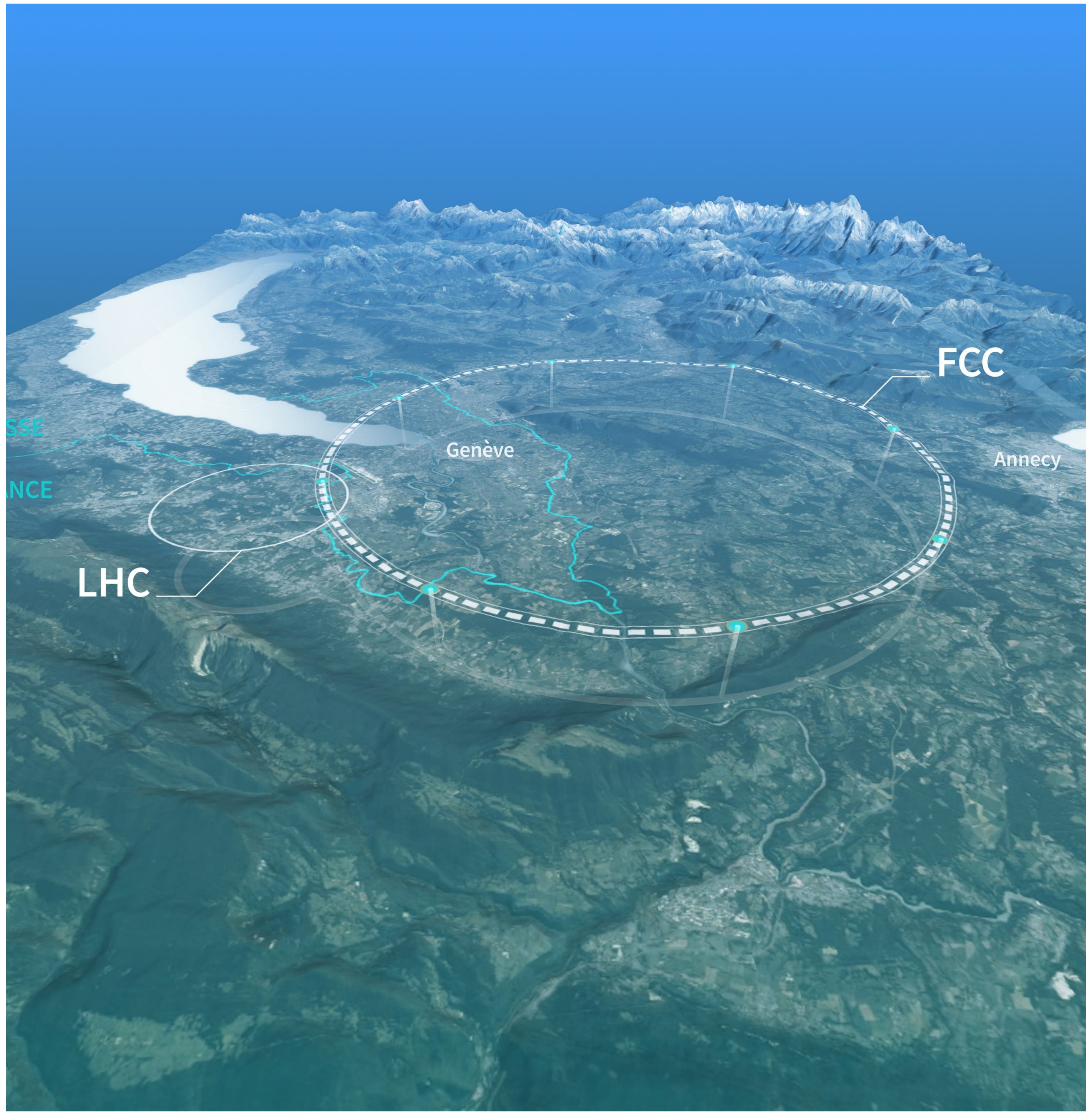
	$Z-$pole	WW	Zh	$t\bar{t}$
Energy [GeV]	91.2	163	240	365
Accuracy	$6\cdot 10^{12}\,Z$	$2.4\cdot 10^{8}\,WW$	$2.2\cdot 10^{6}\,h$	$2\cdot 10^{6}\,t\bar{t}$

On Pole/Z-pole:

$$O_{\text{on-pole}} = \left\{\Gamma_Z, \sigma_{\text{had}}, R_l, A^{0,l}_{\text{FB}}, R_b, R_c, A_b^{\text{FB}}, A_c^{\text{FB}}, A_l, A_b, A_c, A_s, m_W, \Gamma_W\right\}$$

Above/off-pole:

$$O_{\text{off-pole}} = \left\{\sigma\left(e^+e^- \to W^+W^-\right), \sigma\left(e^+e^- \to ZH\right), \sigma\left(e^+e^- \to f\bar{f}\right), \mu_{b\bar{b}}, \mu_{c\bar{c}}, \mu_{\tau\bar{\tau}}, \mu_{\mu\bar{\mu}}\right\}$$



Standard Model Effective Field Theory

Effective Field Theory:

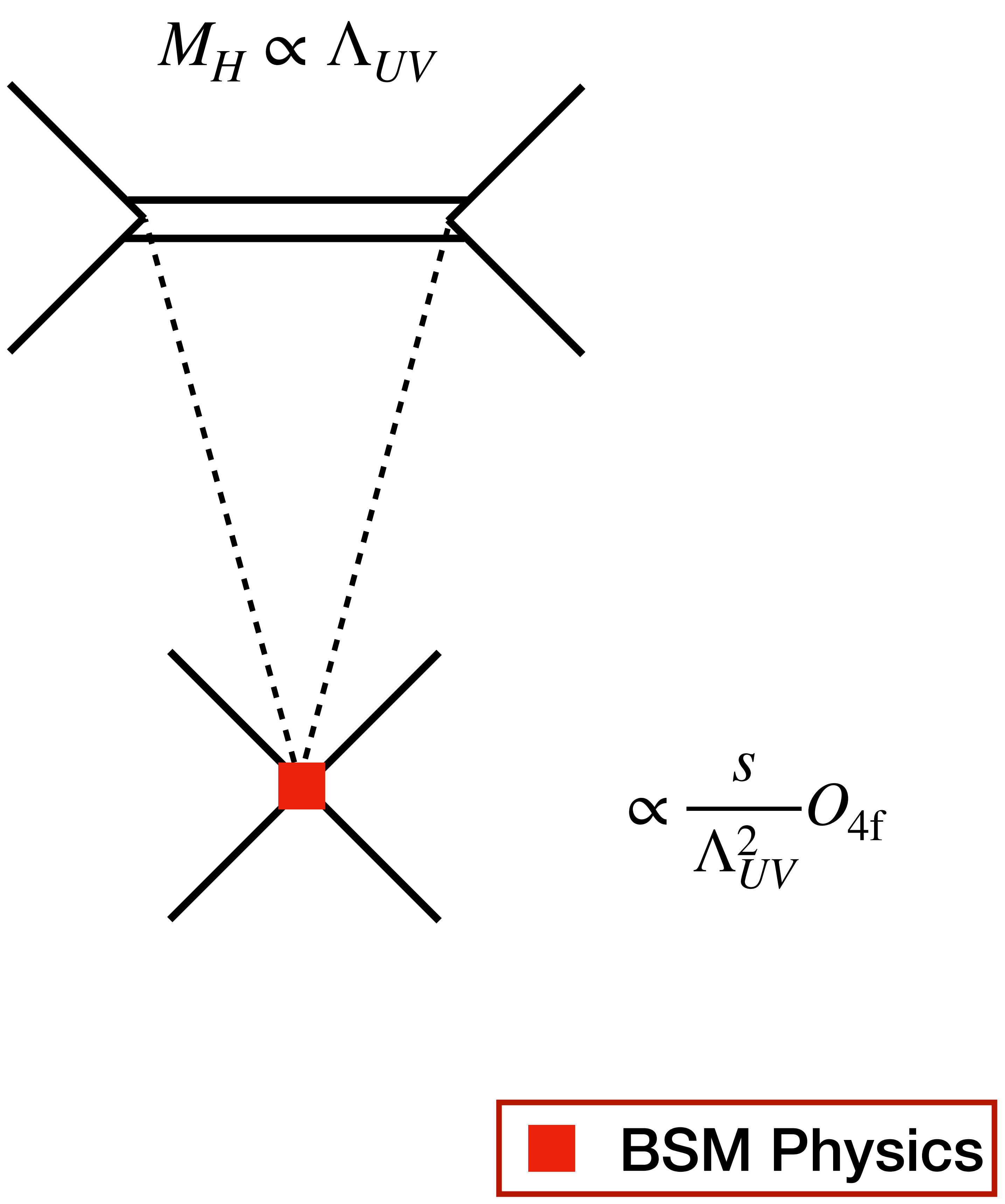
- Non-renormalisable QFT with **clear separation between UV and IR modes** and a **power counting** parametrised by $\alpha \ll 1$
- Allows to separate calculation of observables (LO,NLO…) in the IR and BSM in the UV
- Model independent global fits

SMEFT:

Parametrise New Physics!
Scale Dependent Couplings!

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

IR physics, always the same



Increasing the Energy:

1. New Physics effects are **energy enhanced**

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

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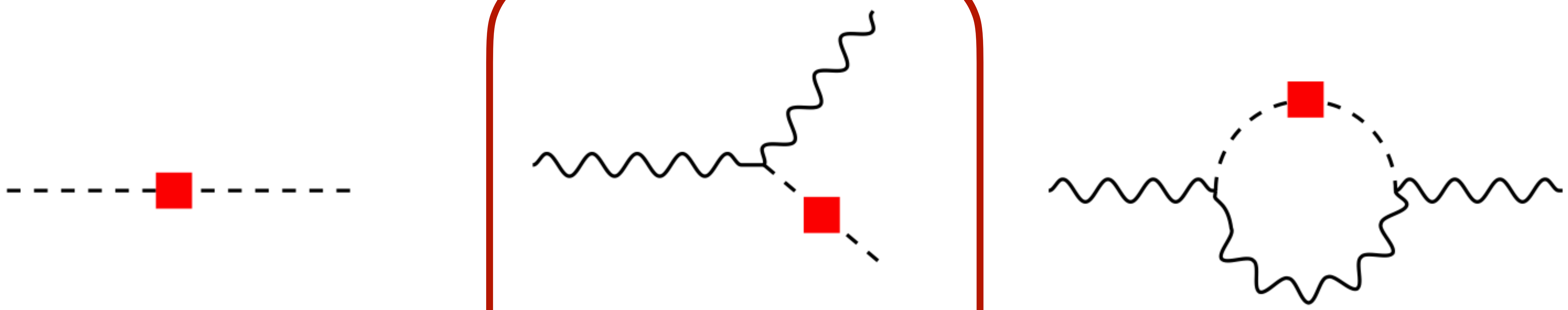
2. **Direct** access to New Physics



(a) Higgs self-energy (b) $e^+e^- \to ZH$ (c) Z-pole oblique params.

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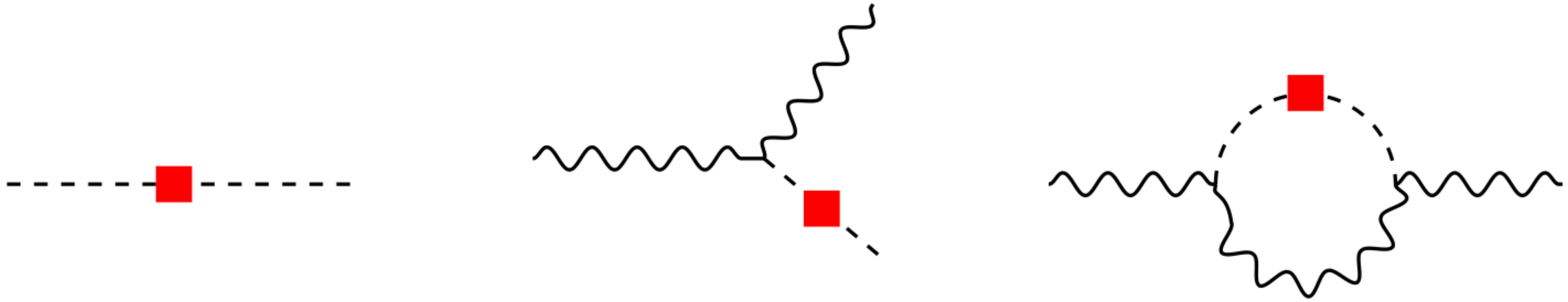

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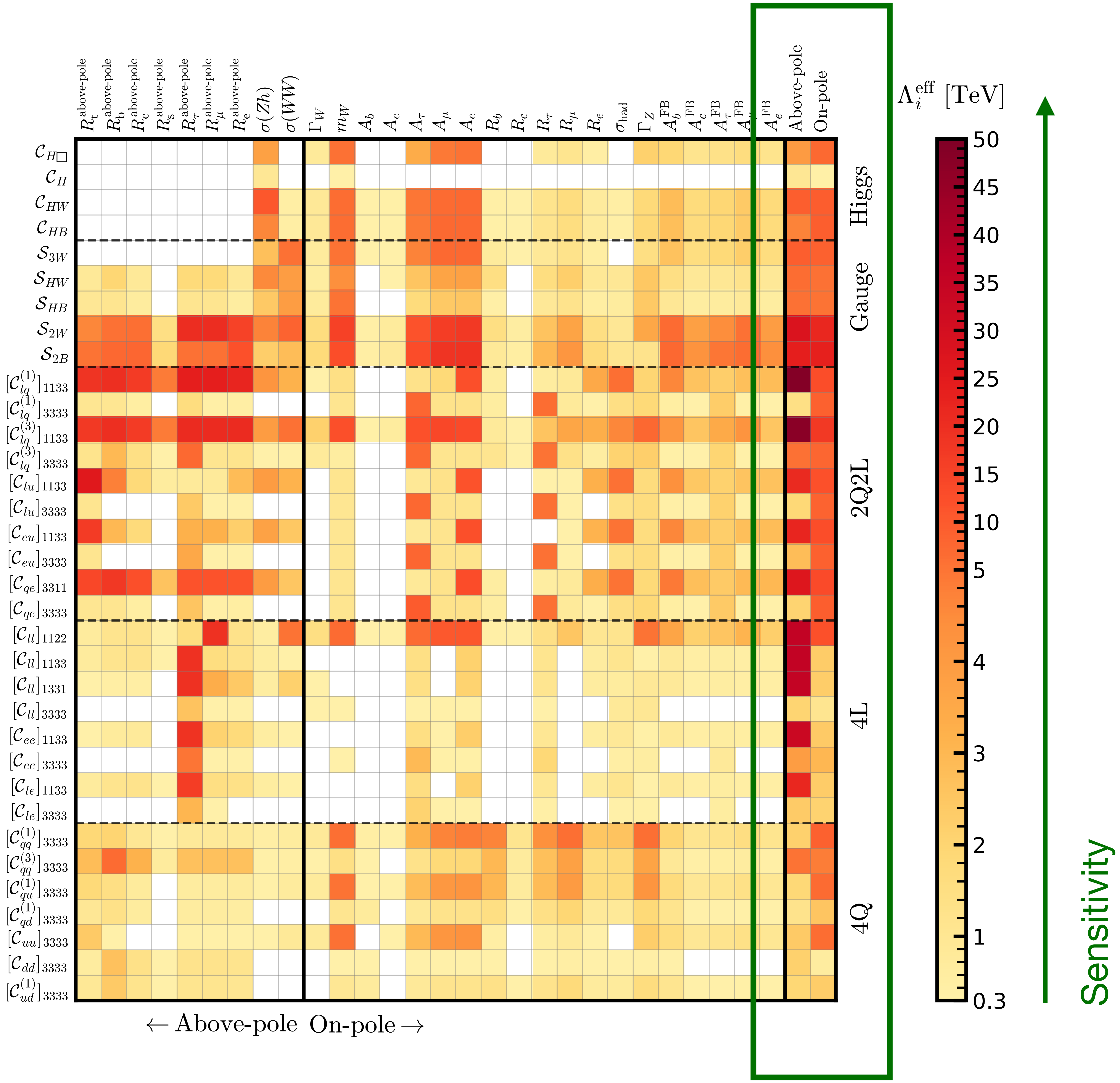
Can the increased precision of the FCCee Z-pole run compensate the relative suppression?

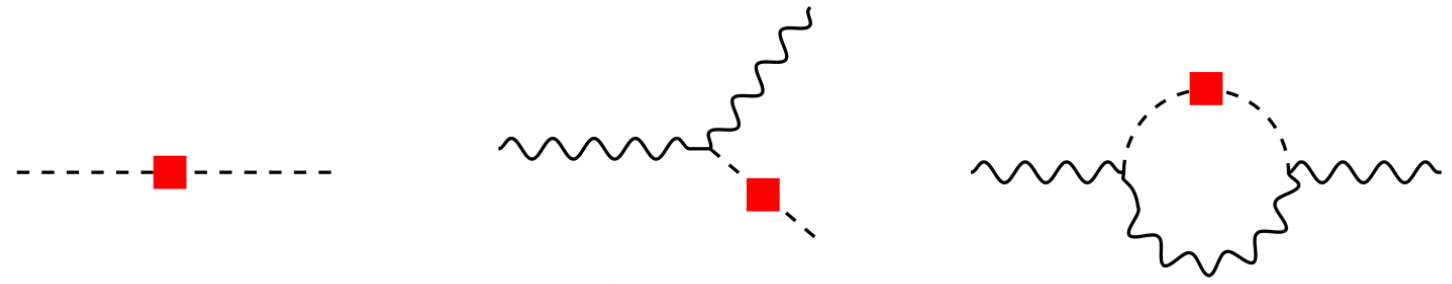
Accuracy Complements Energy

Yes!



Accuracy Complements Energy

Higgs 2 and 3 pt functions



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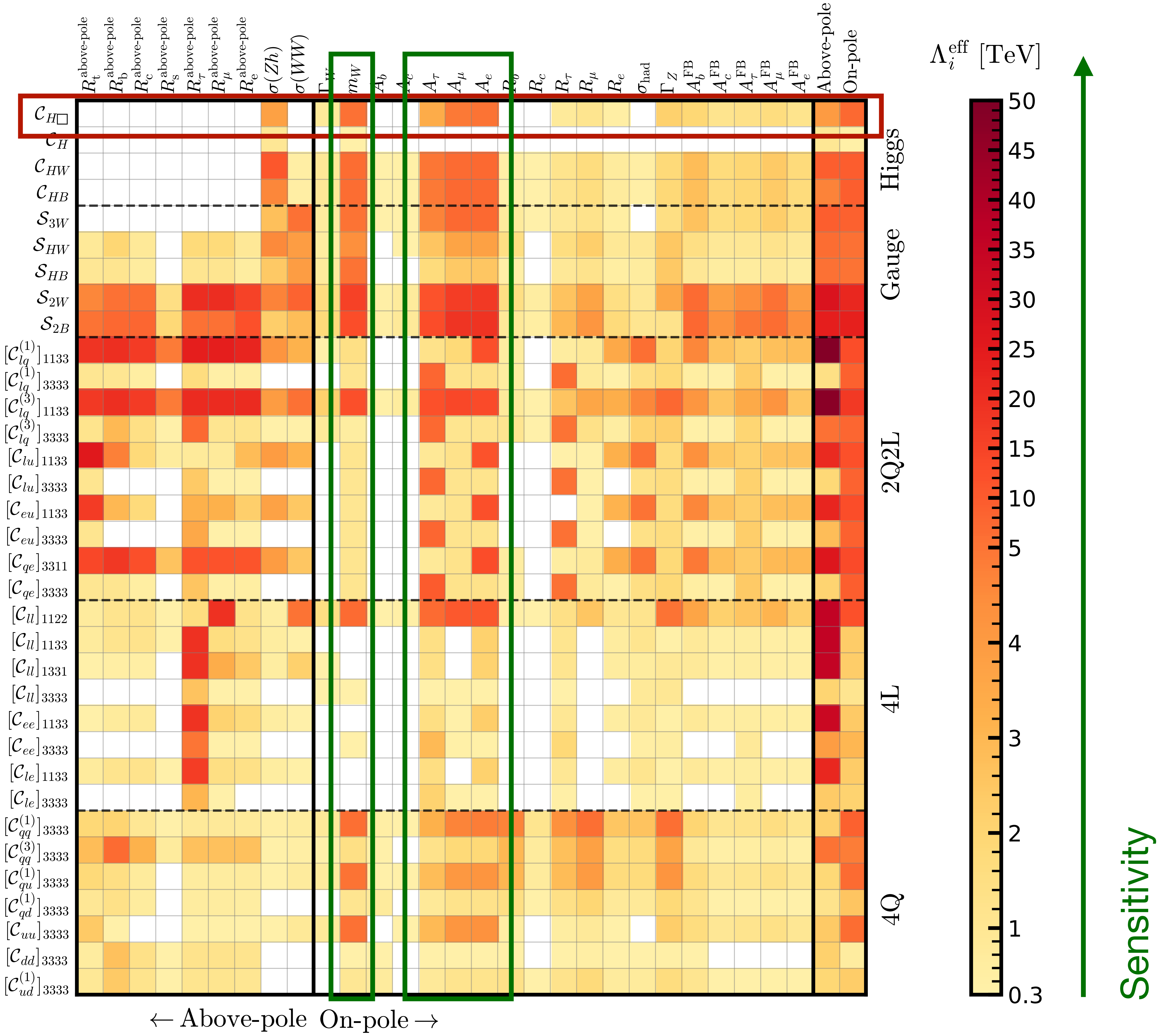

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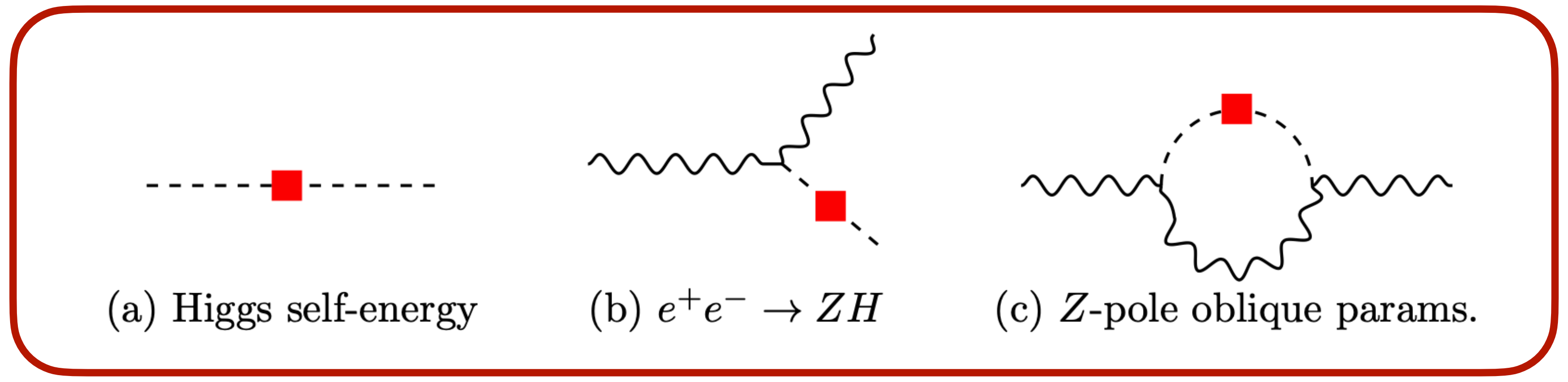
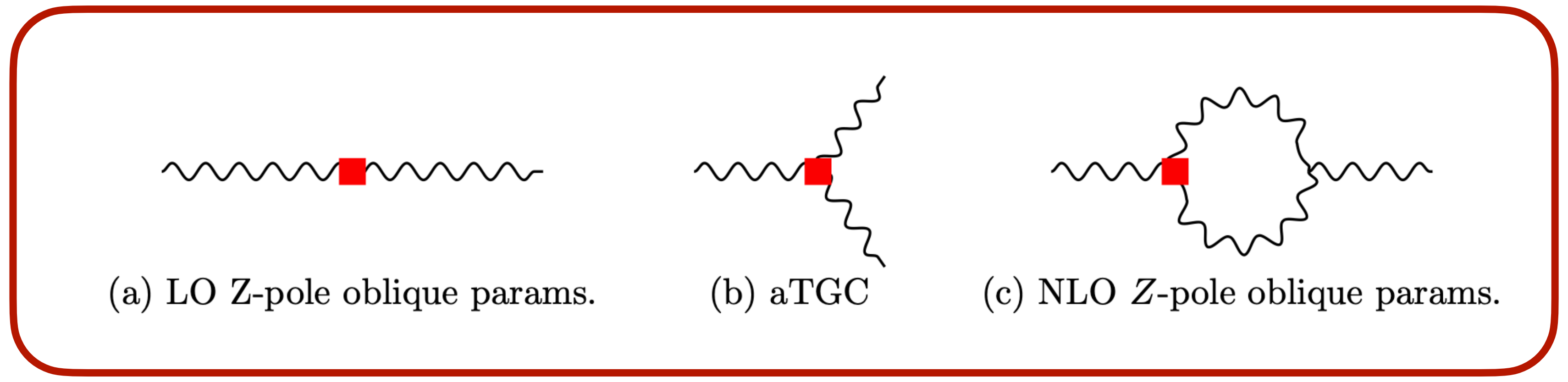
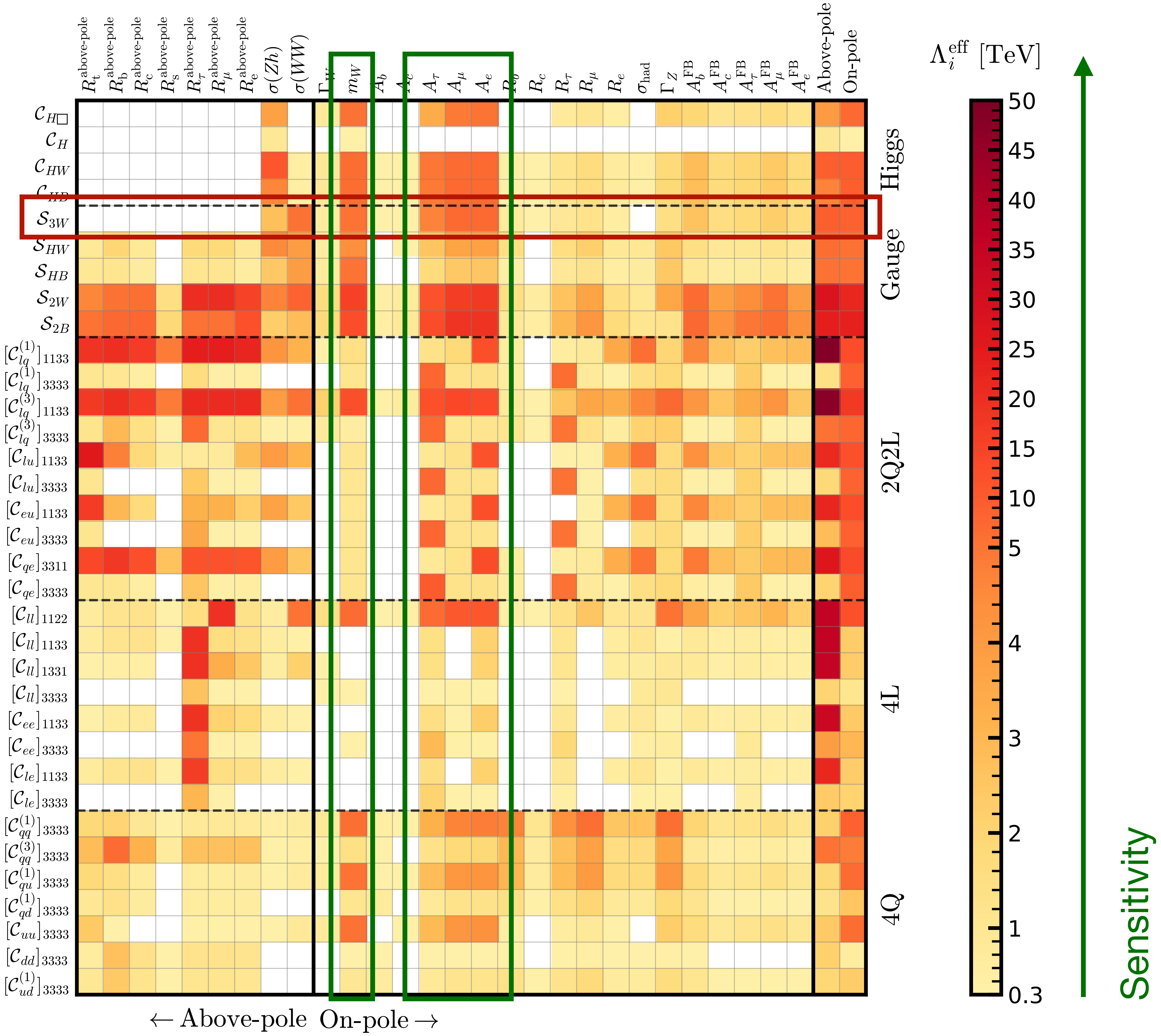


Gauge 2 and 3 pt functions





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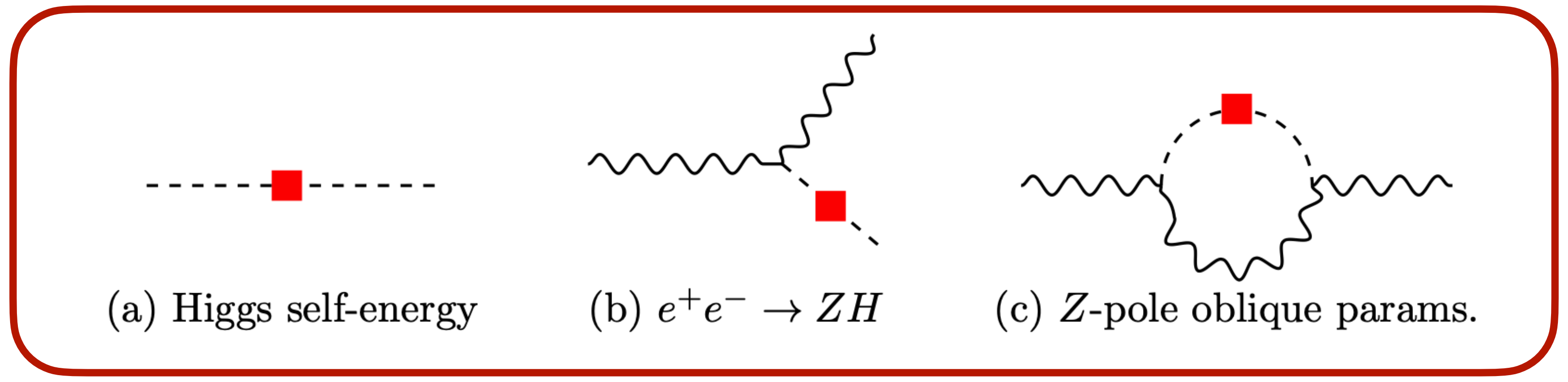

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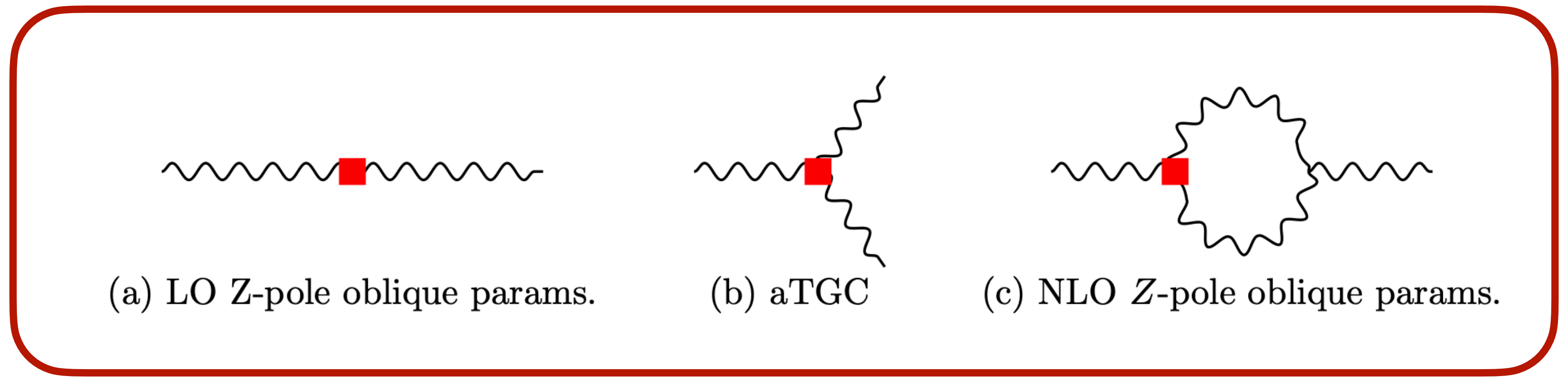
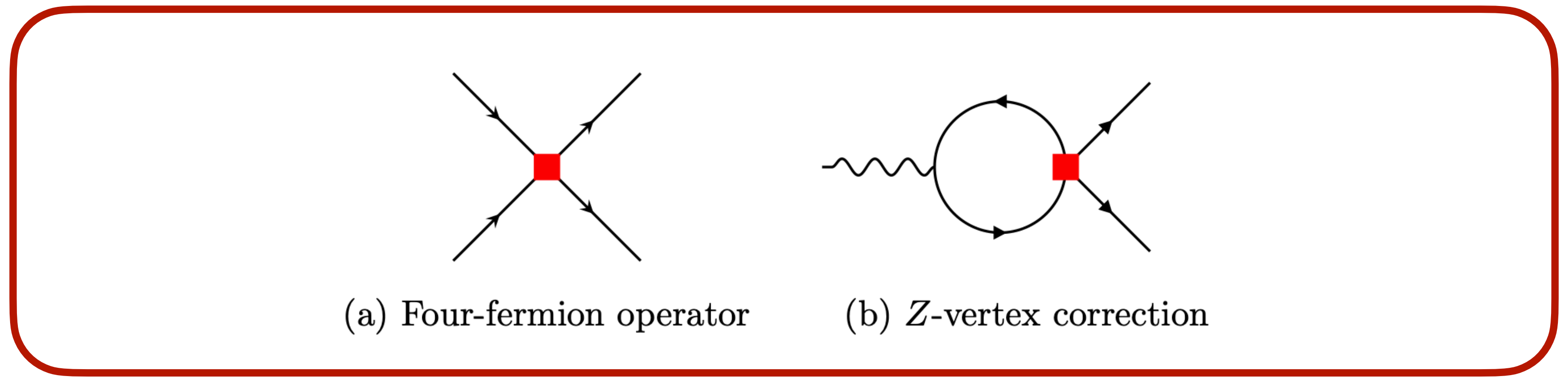
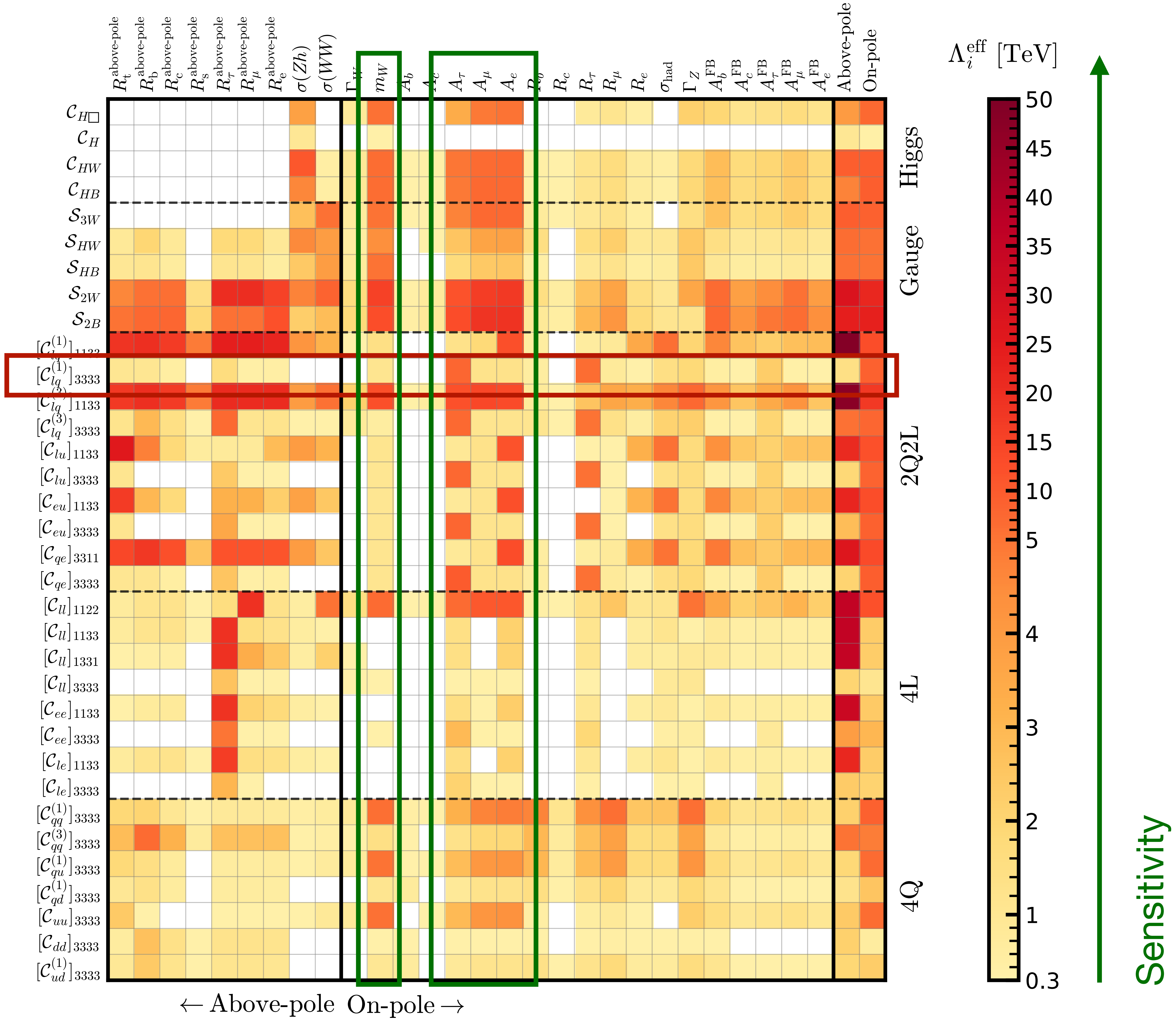


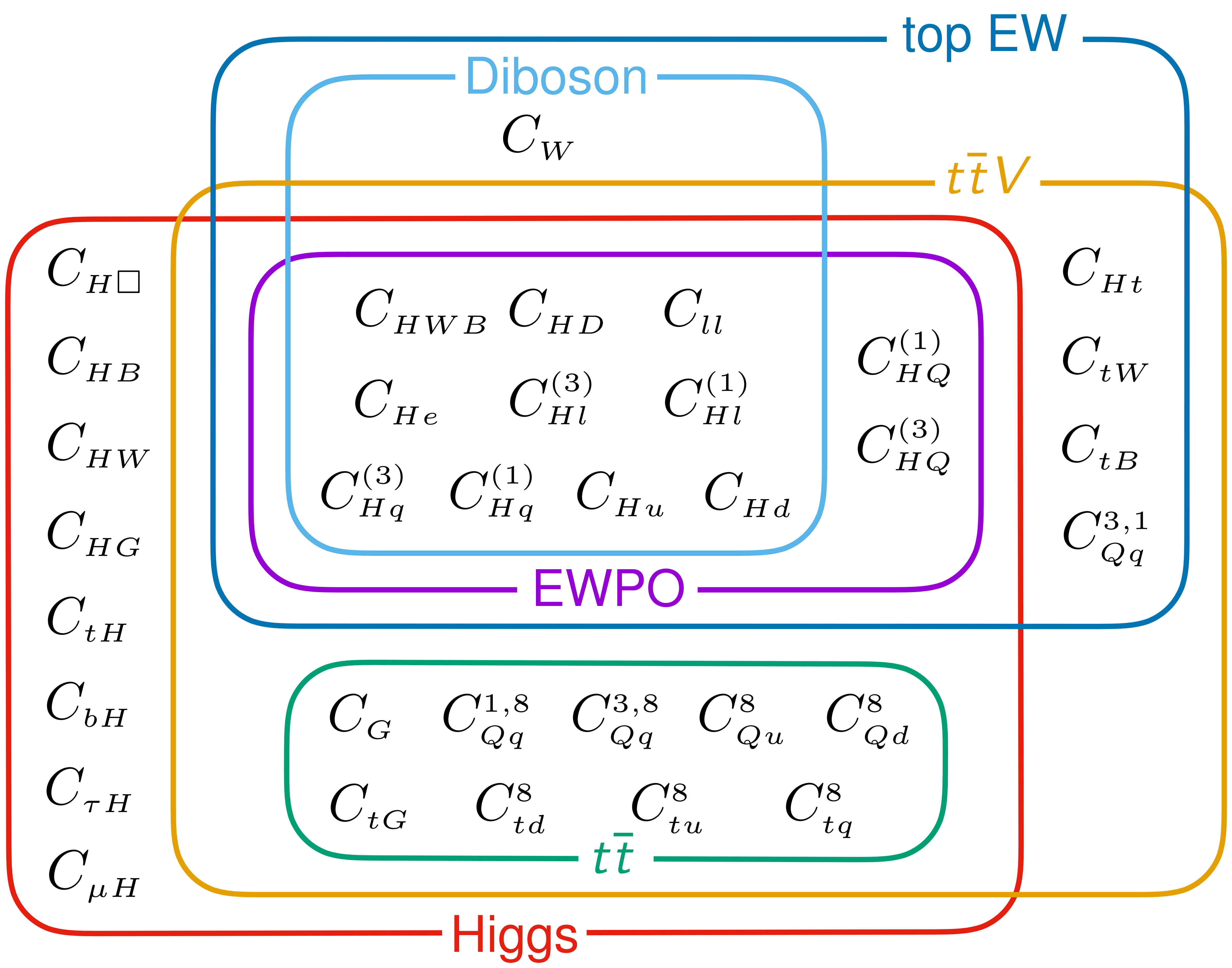
4 Fermion Operators





Best studied e.g. 2311.00020, 2407.09593, 2304.00029, 2411.02485…

ACE: Negative Aspects



*Adapted from 2012.02779

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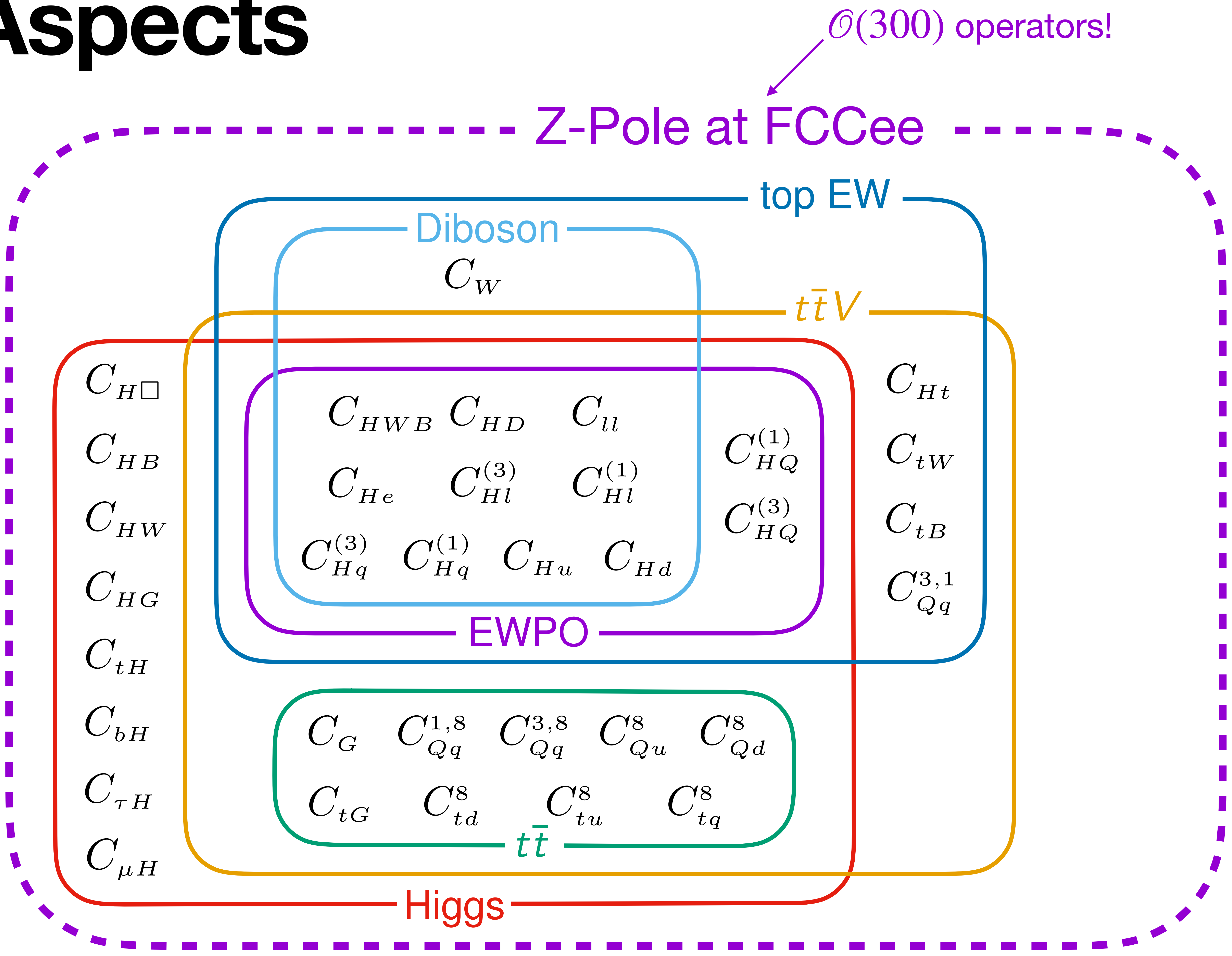

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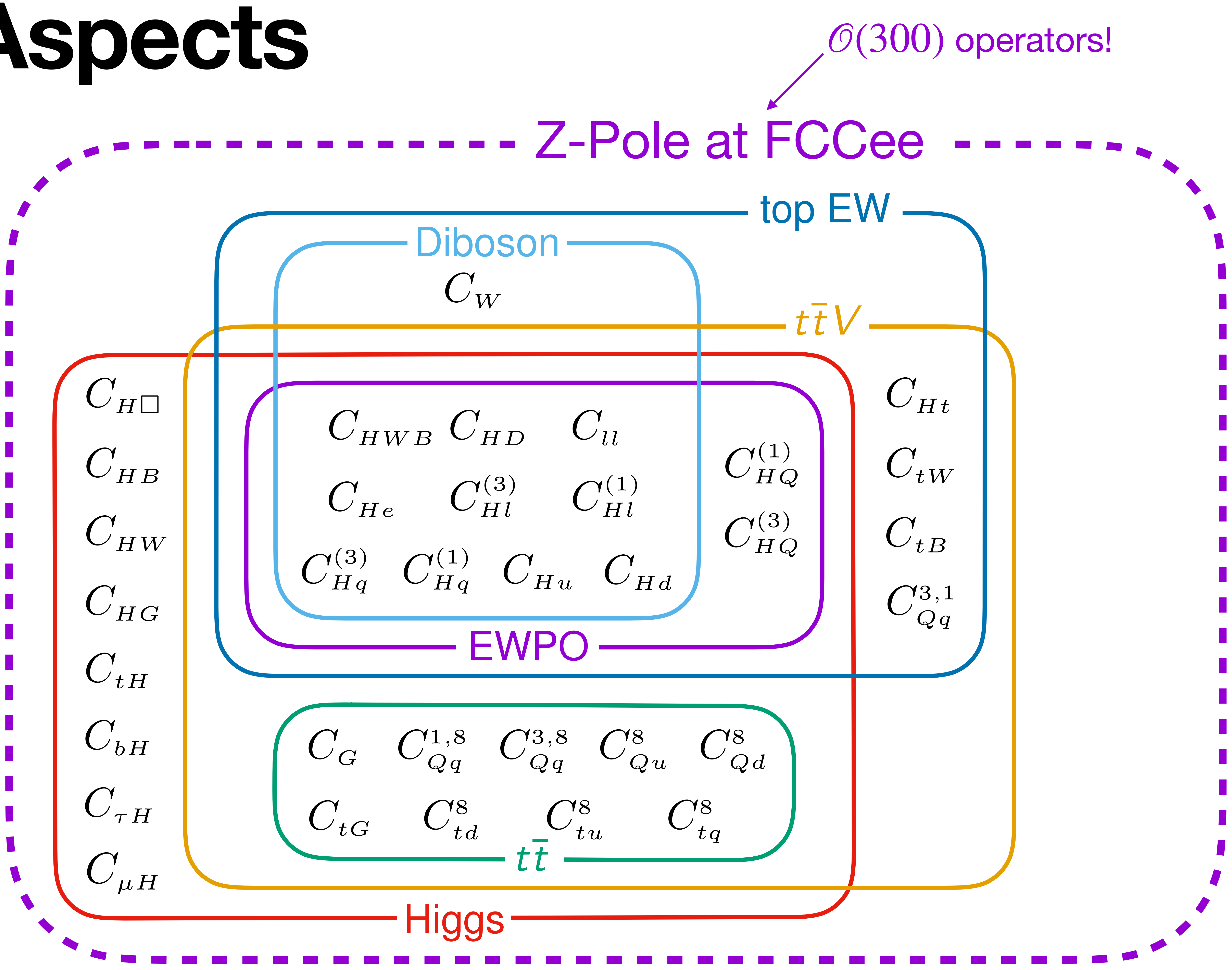
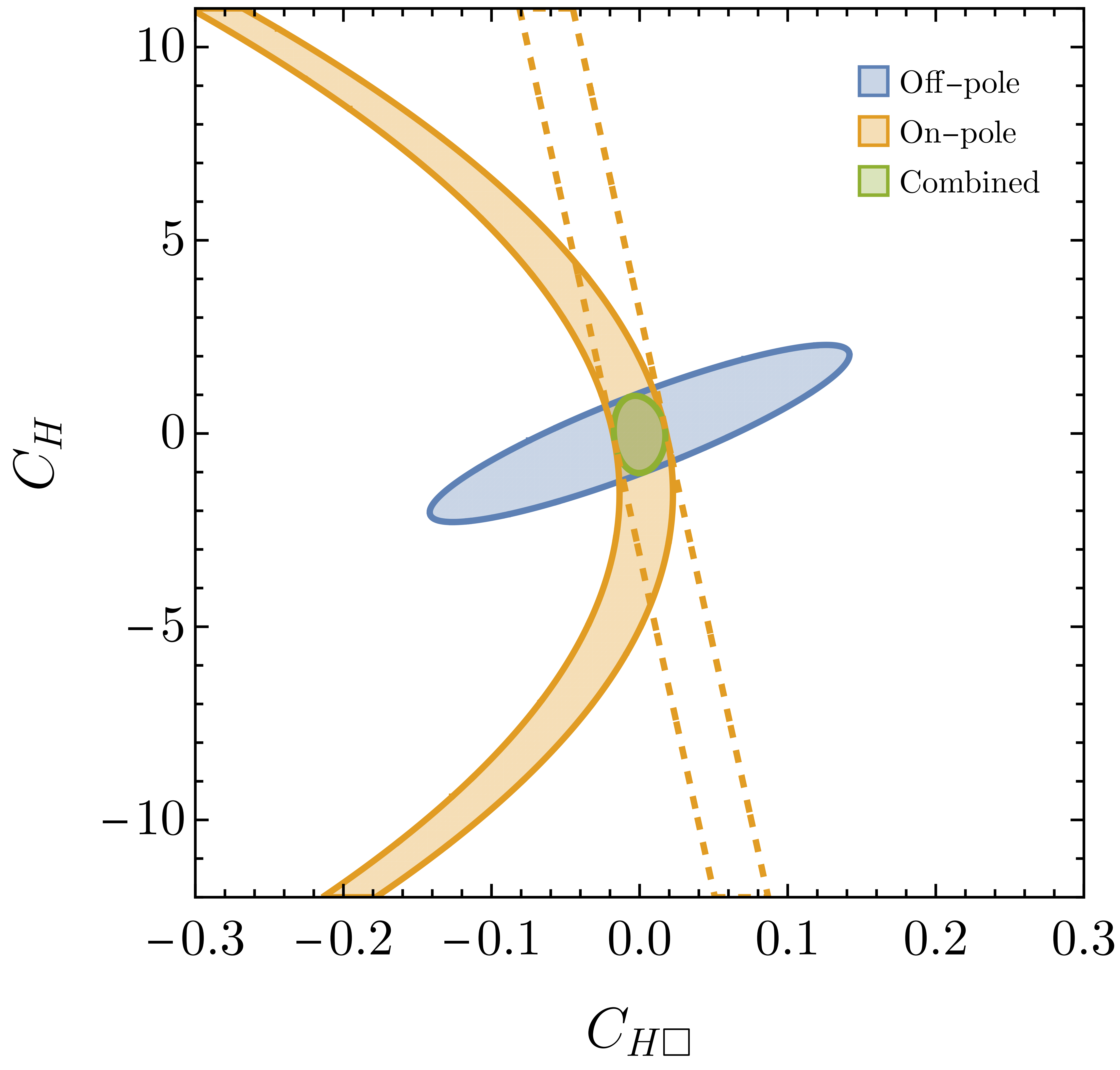
ACE: Negative Aspects

- Access to many operators at the Z pole!
- Running and NLO effects on Z-pole are not negligible!
- Flavour assumptions matter!
- **Closed global fits very complicated!**



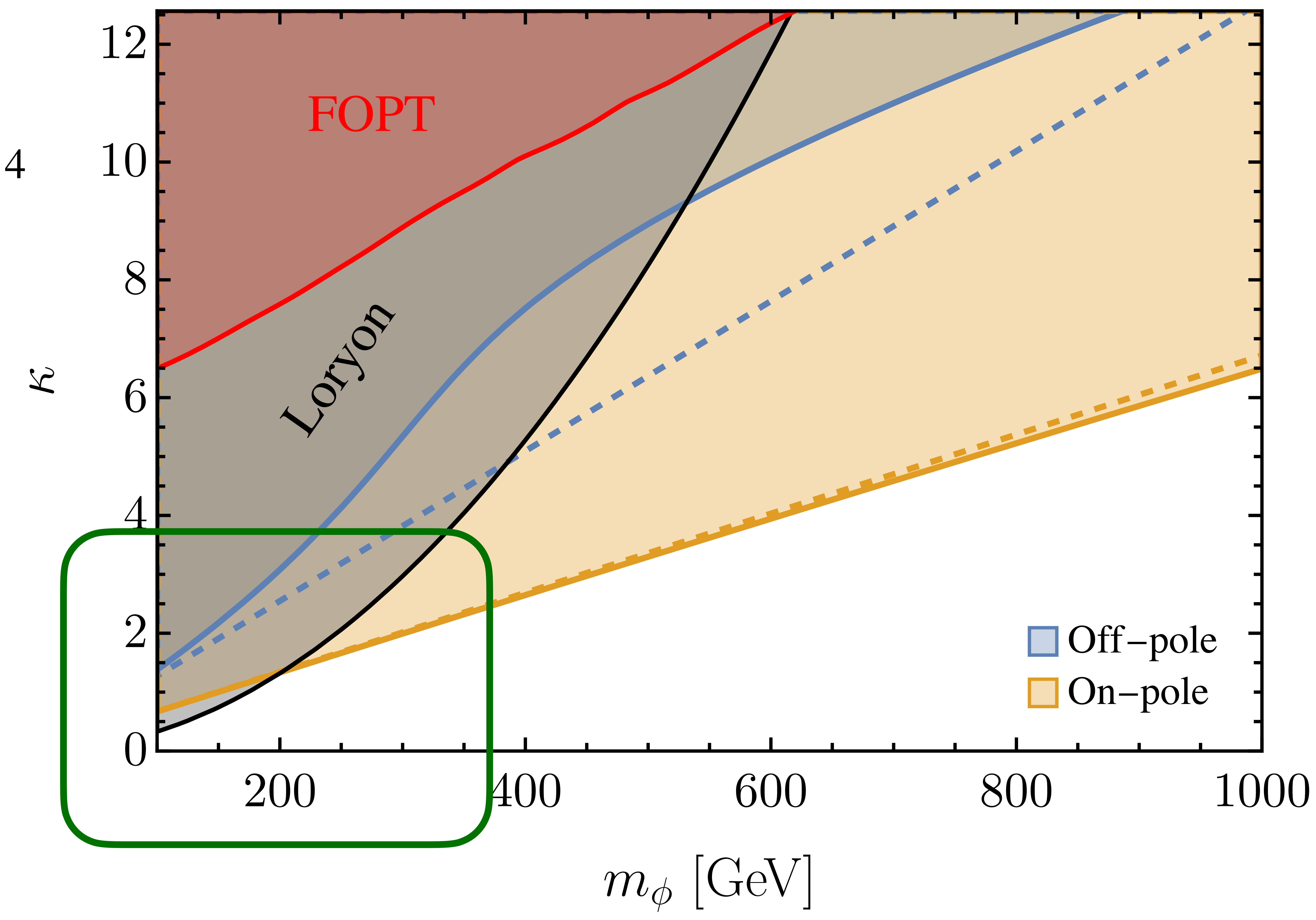
ACE: Bright Side

- **Access to many operators at the Z pole!**
- Global flat directions, but overall volume of parameter space allowed shrinks
- BSM models activate correlated operators controlled by few params
- For concrete BSM models, this is **undoubtedly good news!**



ACE in action: Real Singlet Scalar

- Real Singlet Scalar with $\mathbb{Z}_2$-symmetry
- $\mathscr{L} \supset \left(\partial_\mu \phi\right)^2 - \frac{1}{2} m_\phi^2 \phi^2 - \frac{1}{2} \kappa \phi^2 |H|^2 - \frac{1}{4!} \lambda \phi^4$
- **Mass** contribution from Higgs $\propto \kappa v^2$
- **Loryon:** Most of the mass comes from the Higgs
- Only loryon still allowed after FCCee (2409.18177)
- **Z pole covers entire parameter space!**



**EFT breaks down Full two loop calculation: WIP (VM, Stefanek, You, 25xx.xxxxx)

Conclusion

- Extreme precision at Z pole can **compensate for an O(100) suppression or enhancement** in the cross section
- Loop effects + RGE have **significant phenomenological implications**
- Any fit should be done **globally including full NLO Z-pole observables + RGE**
- Z-pole run is extremely versatile and **will likely herald any new physics** that can be further explored at higher energy runs
- Beautiful **complementarity between ALL FCCee runs**

Accuracy Complements Energy

Thank you for your attention!

Questions?

Questions?

- Why are there two lines in the Singlet scalar plot?
- You have a constraint on C_H at the Z-pole, where is that coming from?
- What do you mean by “flavour assumptions matter”?
- Can you elaborate why you say that RGE effects are important?
- Are there other models for which this is relevant?
- ….

Backup Slides

ACE in action: Real Singlet Scalar

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

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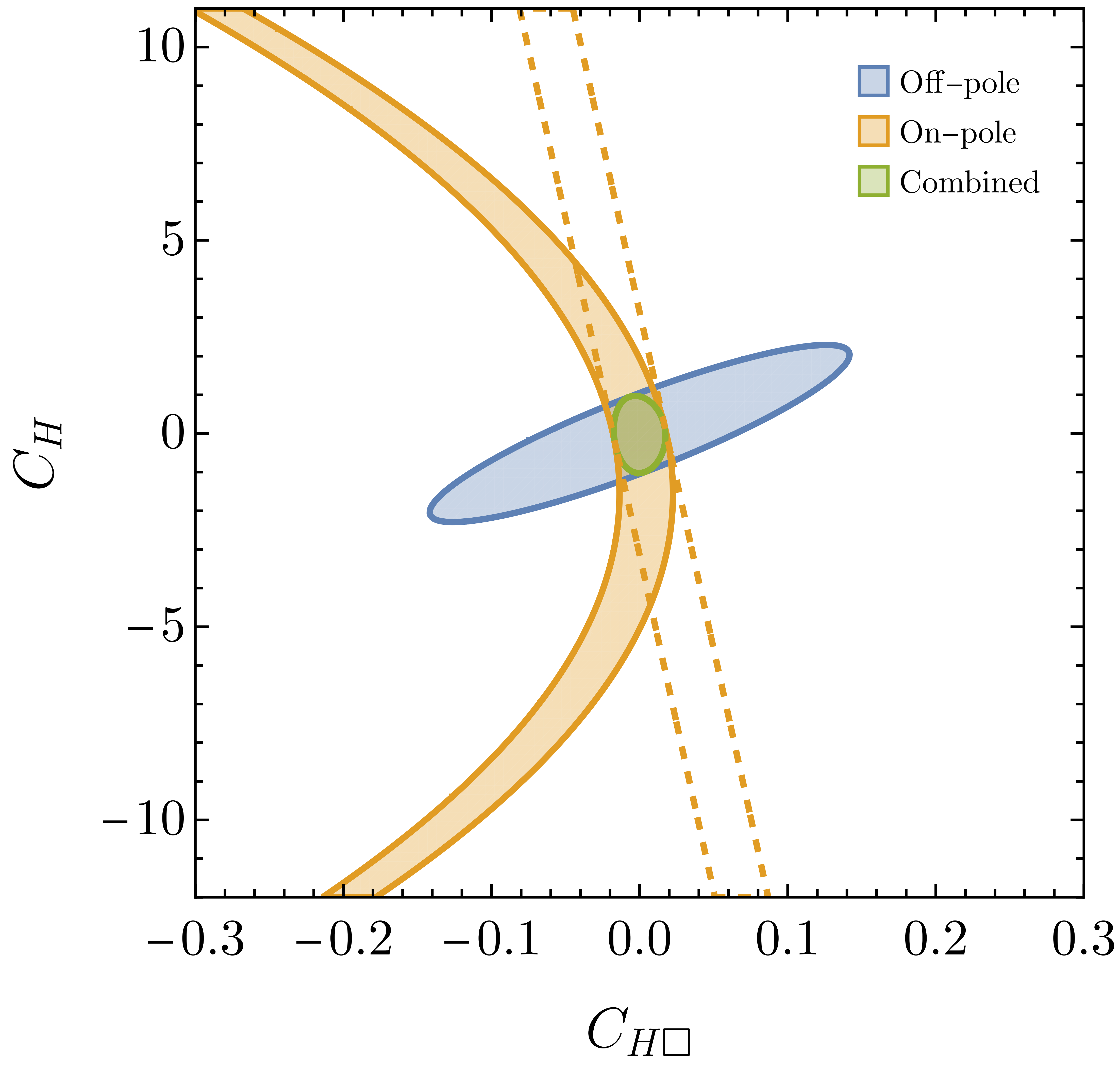

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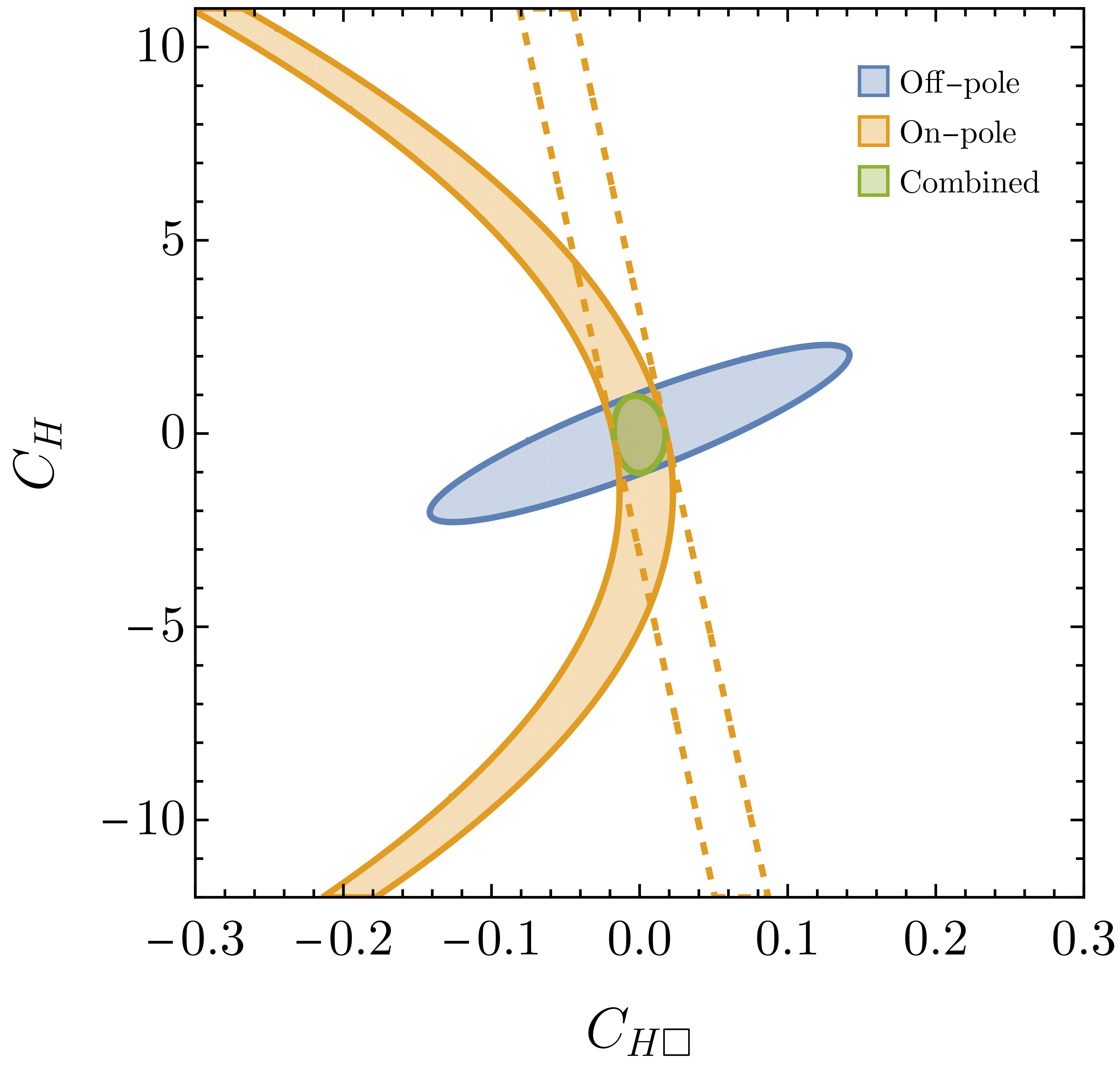

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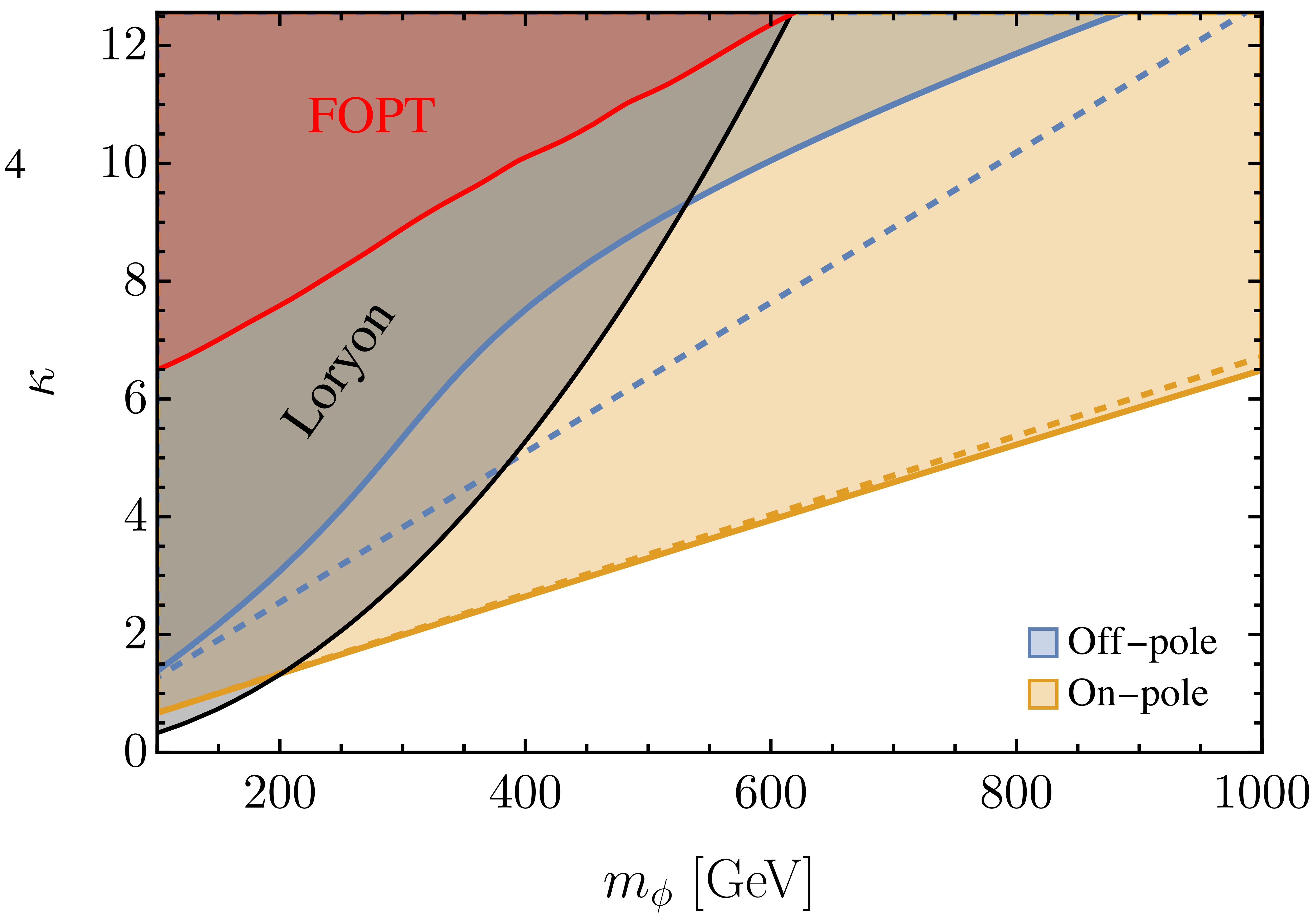
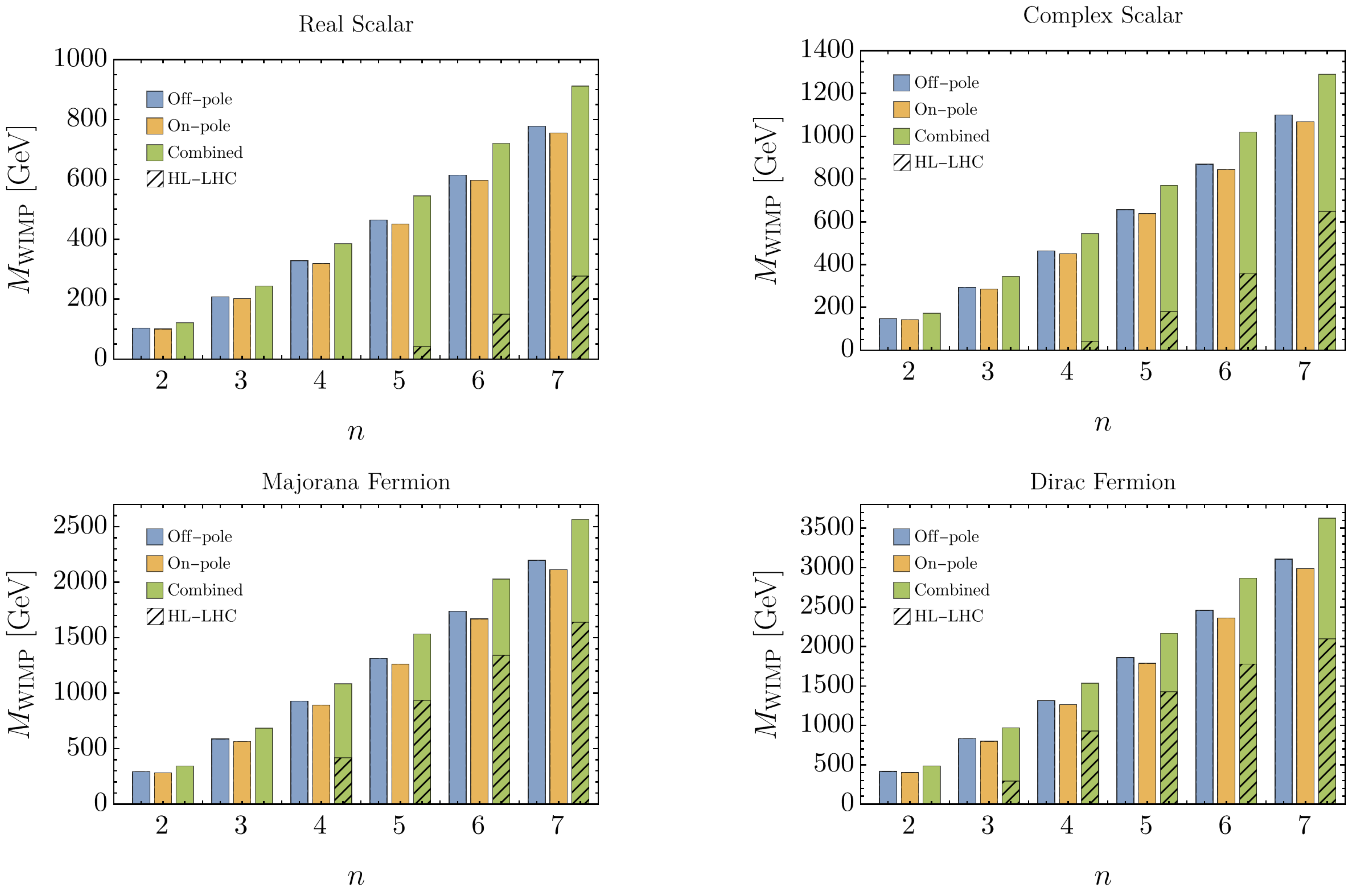
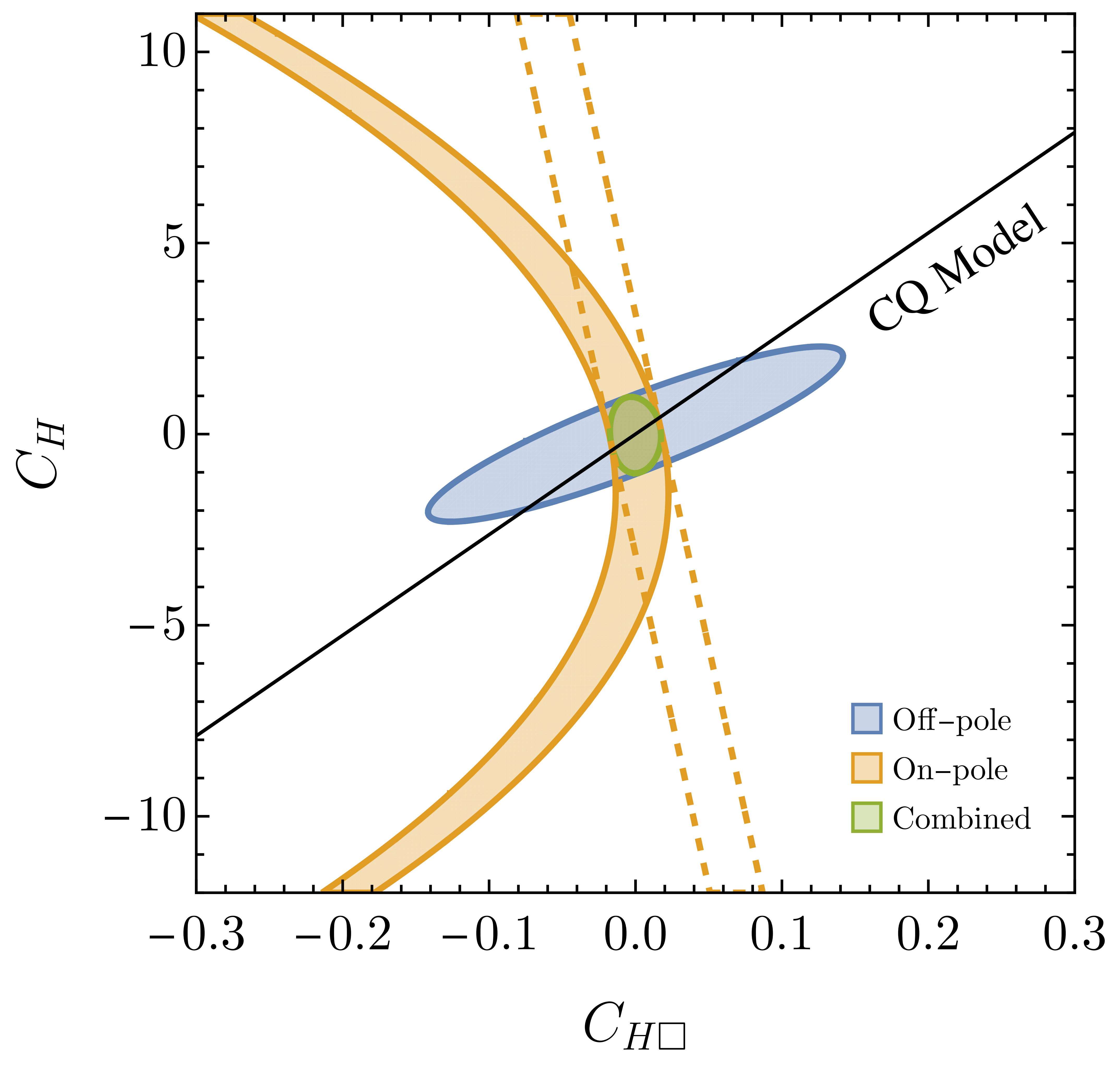


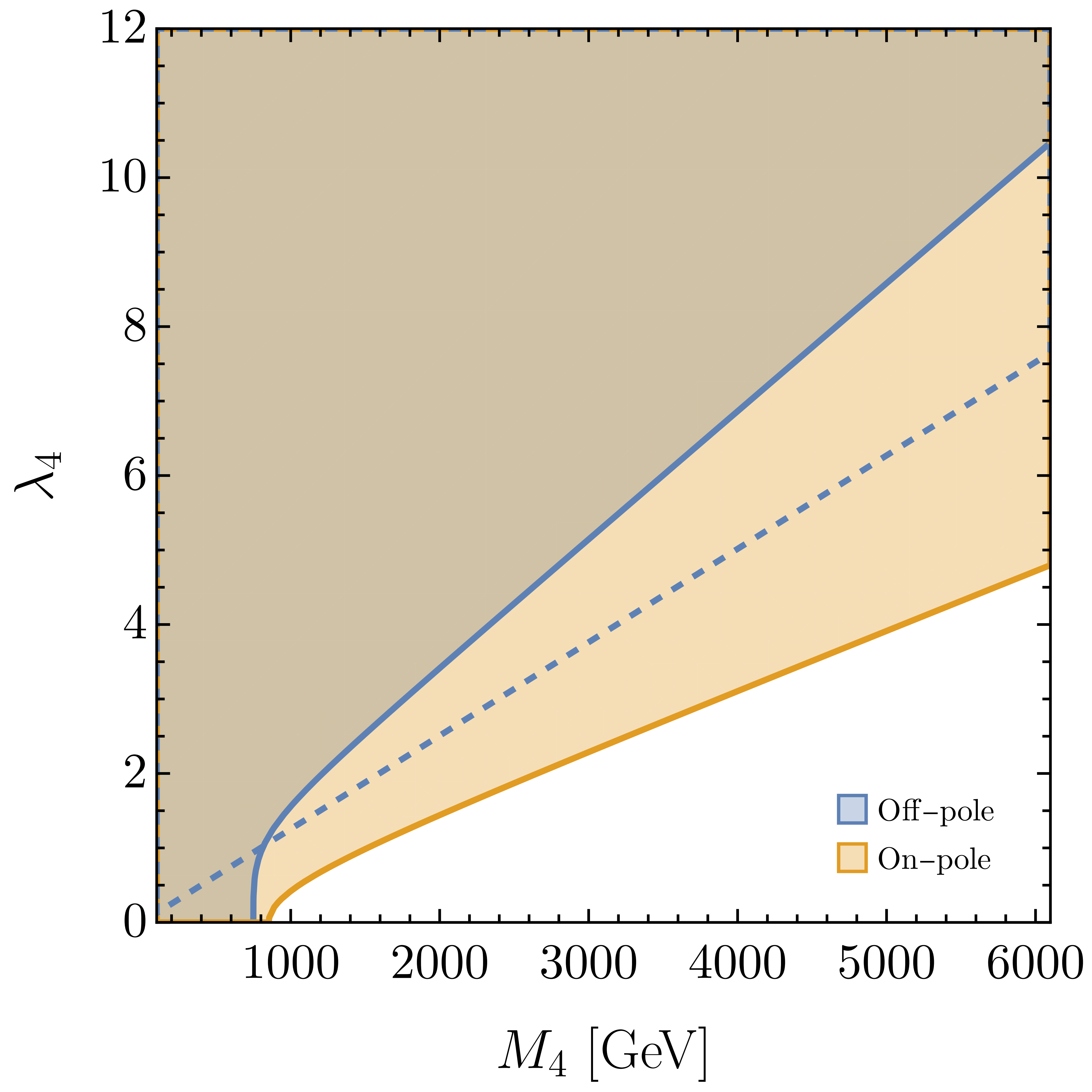
ACE in action: WIMPs

- Higher dimensional Representations of $SU(2)_L$
- Could be Dark Matter
- Can **significantly improve upon HL-LHC** constraints
- Competitive with direct production of low n multiplets!



Custodial Quadruplet





Warsaw Basis

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

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

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

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

Feynman Diagrams