Accuracy Complements Energy

Electroweak Precision Tests and the Higgs Self-Coupling at FCC-ee

Victor Maura Breick

Based on **VM**, B. Stefanek and T. You,
2412.14241 and 2503.13719

EPS-HEP 2025, 8 July 2025

Standard Model Effective Field Theory

Effective Field Theory:

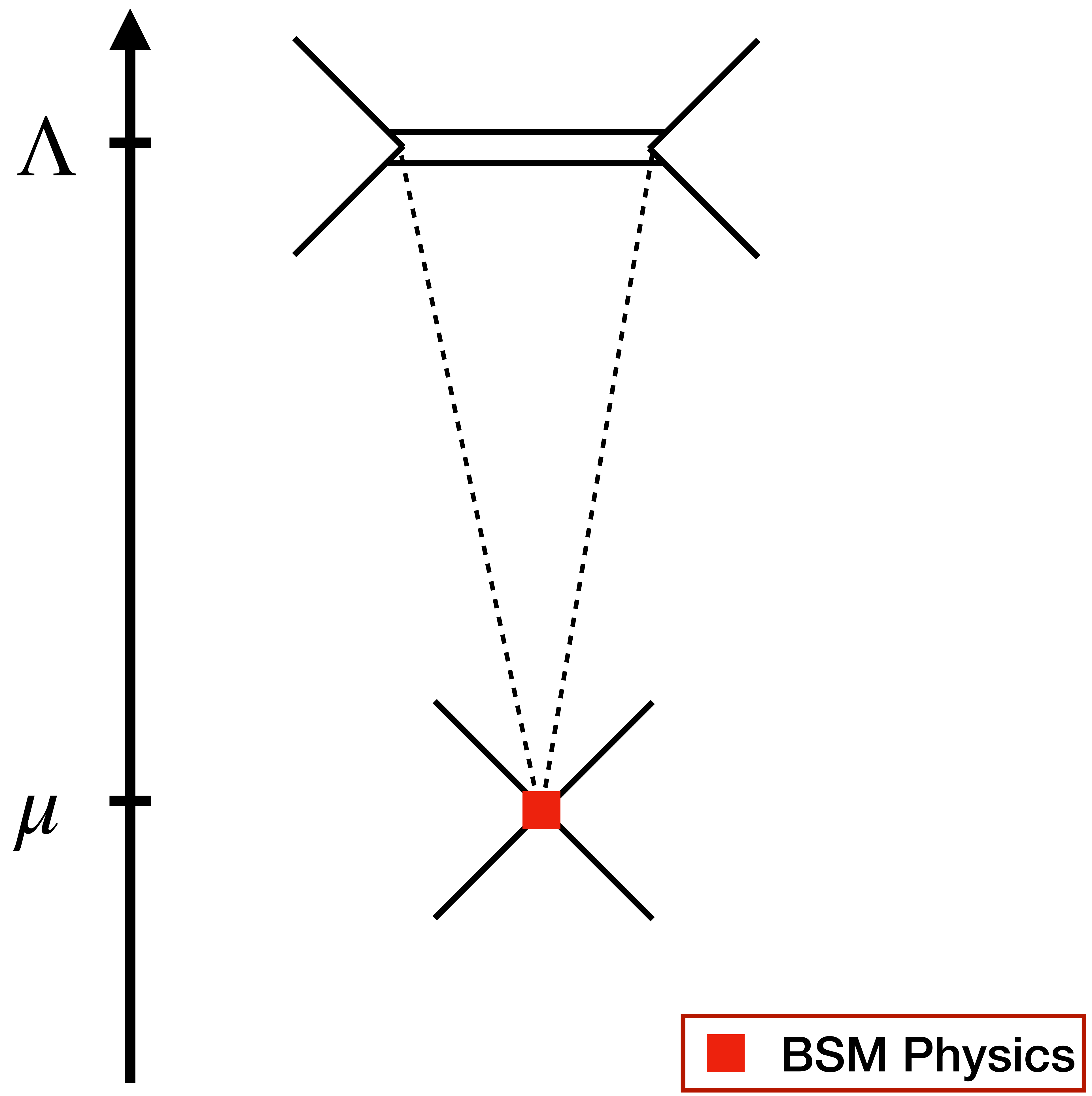
- Non-renormalizable QFT with **clear separation between UV and IR modes** and a **power counting**
- Allows Separation of scales:
  - Operators: IR interactions
  - Size of WC: UV physics

Parametrise New Physics!
Scale Dependent Couplings! ⚡

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

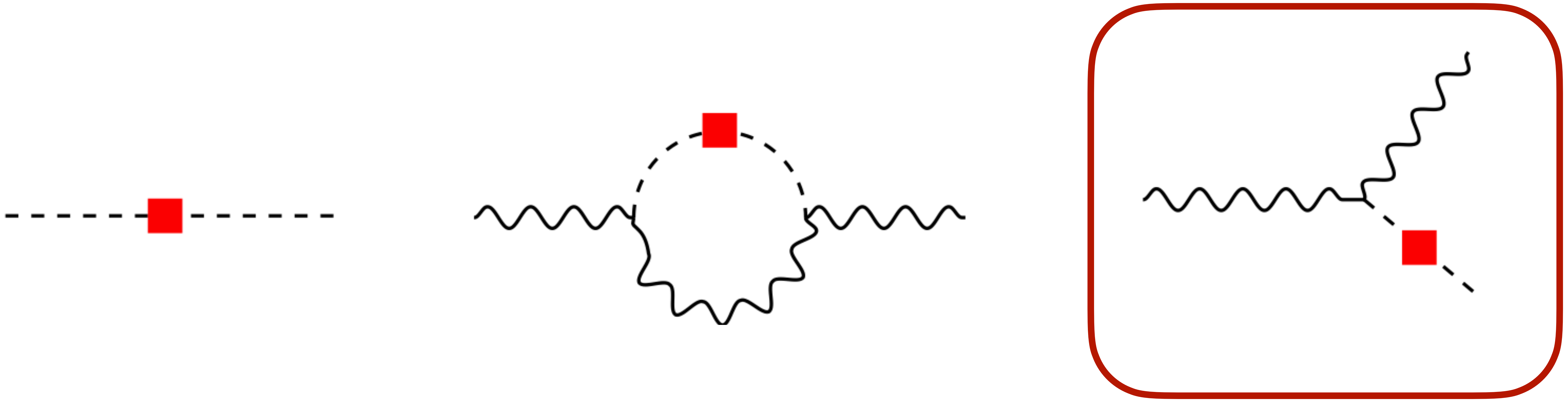
IR physics, always the same

Warsaw Basis



Increasing the Energy:

1. **Direct** (LO) access to New Physics



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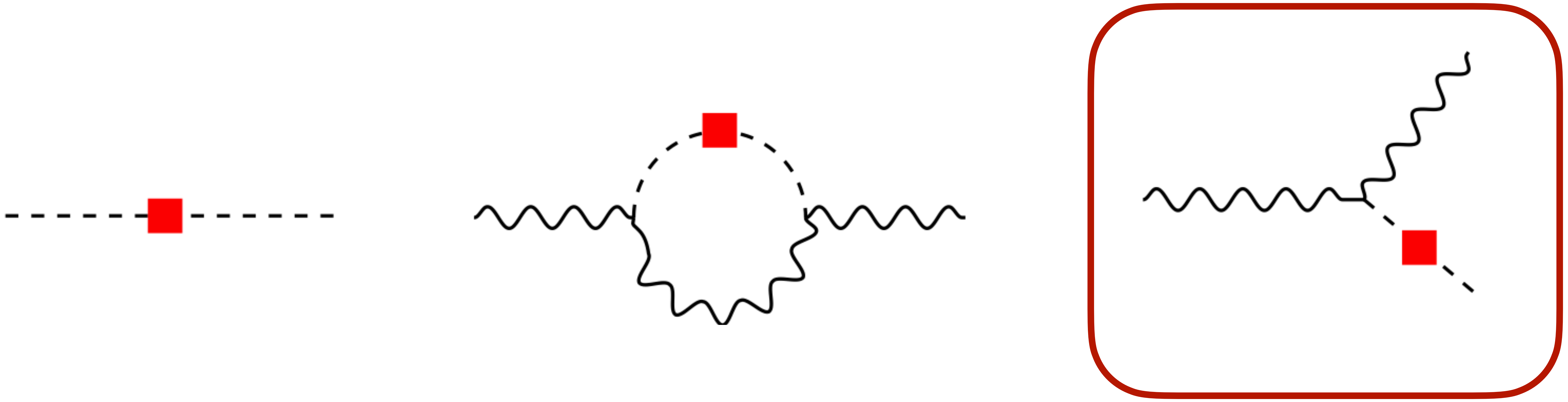
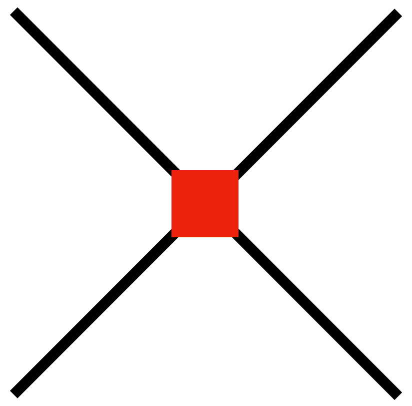


2. New Physics effects may be **energy-enhanced**



$$\Rightarrow \quad \frac{\delta\sigma}{\sigma} \propto \frac{E^2}{\Lambda_{UV}^2}$$

Energy Helps Accuracy!
See: Farina et al. 1609.08157
Corbett et al. 2503.19962

Naive Expectation

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

$$\Delta^{NLO/LO}_{Z/ZH} = \frac{1}{16\pi^2}\overset{\overset{= 10^{-1}}{\downarrow}}{\frac{\epsilon_Z}{\epsilon_{ZH}}}\sqrt{\frac{N_Z}{N_{ZH}}} \gtrsim \mathcal{O}(1)$$

$$\Delta^{LO/LO}_{Z/WW} = \frac{m_Z^2}{E_{WW}^2}\frac{\epsilon_Z}{\epsilon_{WW}}\sqrt{\frac{N_Z}{N_{WW}}} \gtrsim \mathcal{O}(1)$$

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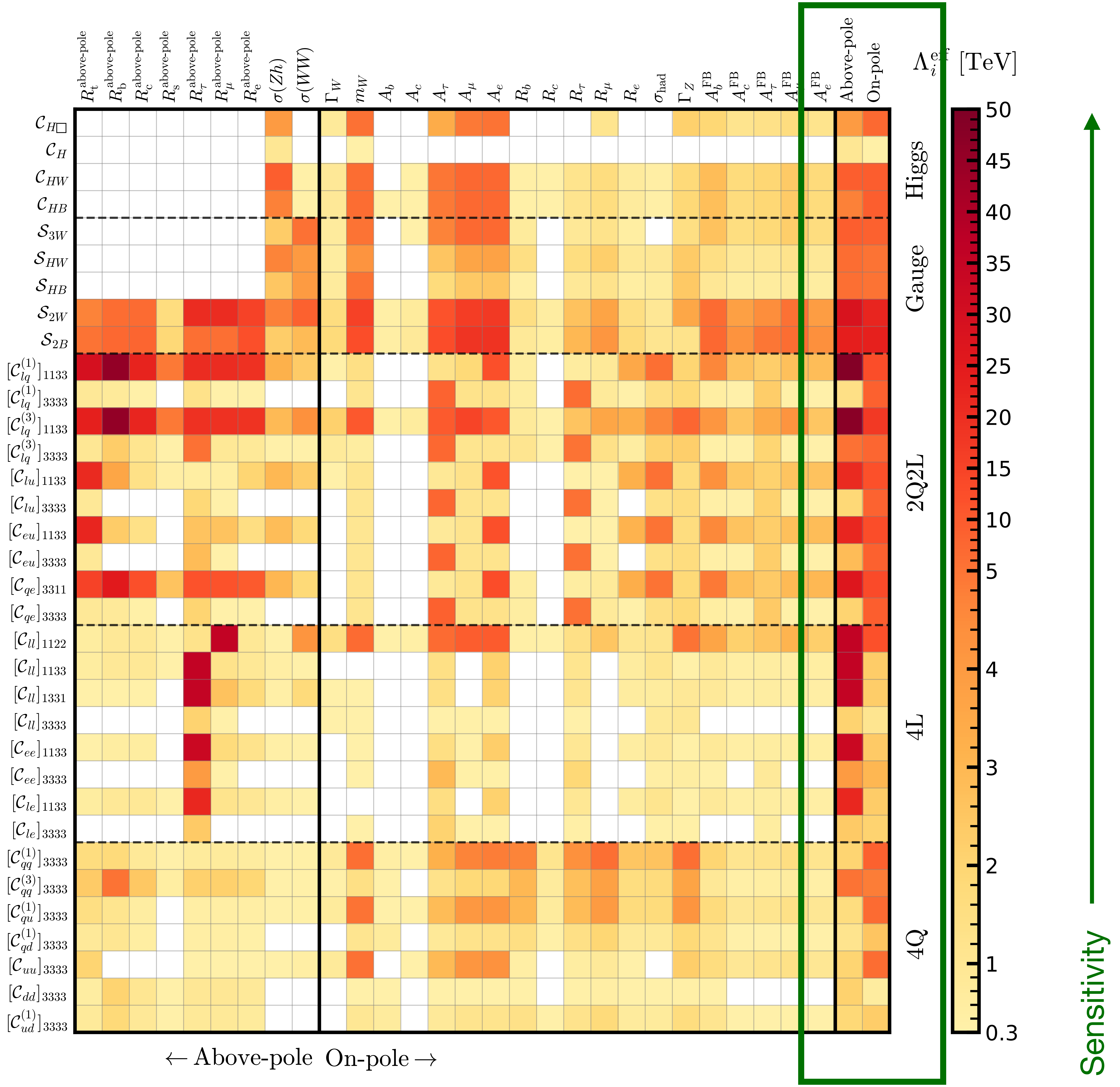
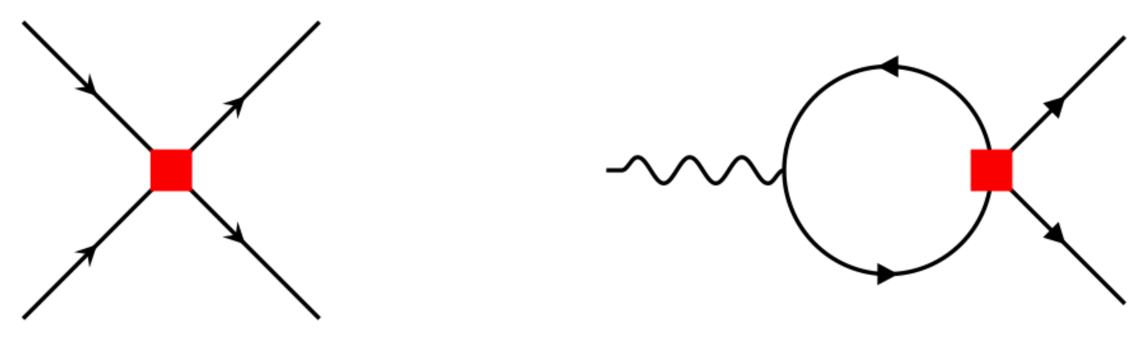
Can the unprecedented sensitivity of a Tera-Z run compensate the relative suppression?

Yes!


$R_t^{\text{above-pole}}$
$R_b^{\text{above-pole}}$
$R_c^{\text{above-pole}}$
$R_s^{\text{above-pole}}$
$R_\tau^{\text{above-pole}}$
$R_\mu^{\text{above-pole}}$
$R_e^{\text{above-pole}}$
$\sigma(Zh)$
$\sigma(WW)$
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 →
Sensitivity

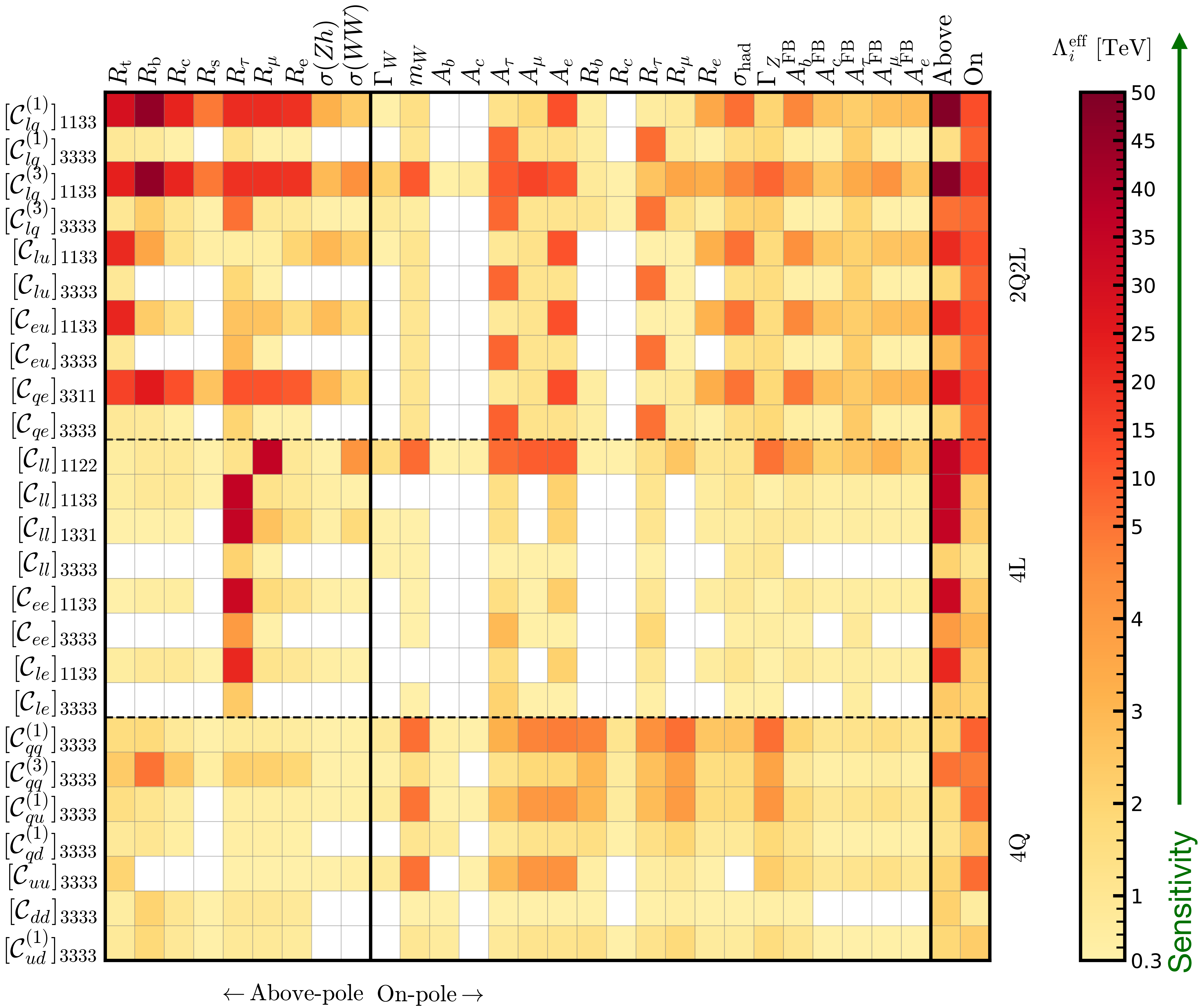
Four Fermion Operators



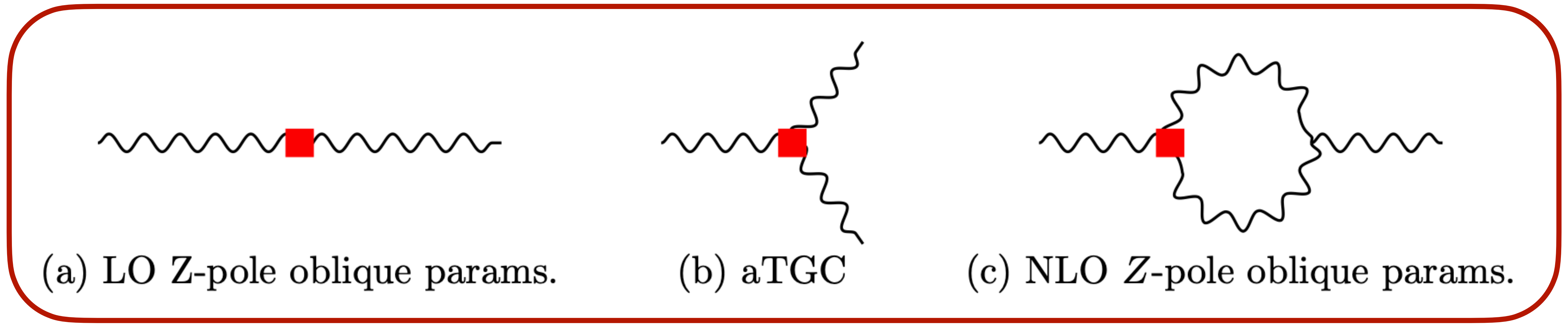
(a) Four-fermion operator (b) Z-vertex correction

- Sensitive to a plethora of 4F operators
- e^+e^- operators enter at LO and are energy enhanced
- Strongest bounds from top enhanced running

Best studied: e.g. Bellafronte et al. 2304.00029, Allwicher et al. 2311.00020, Stefanek 2407.09593, Greljo 2411.02485…



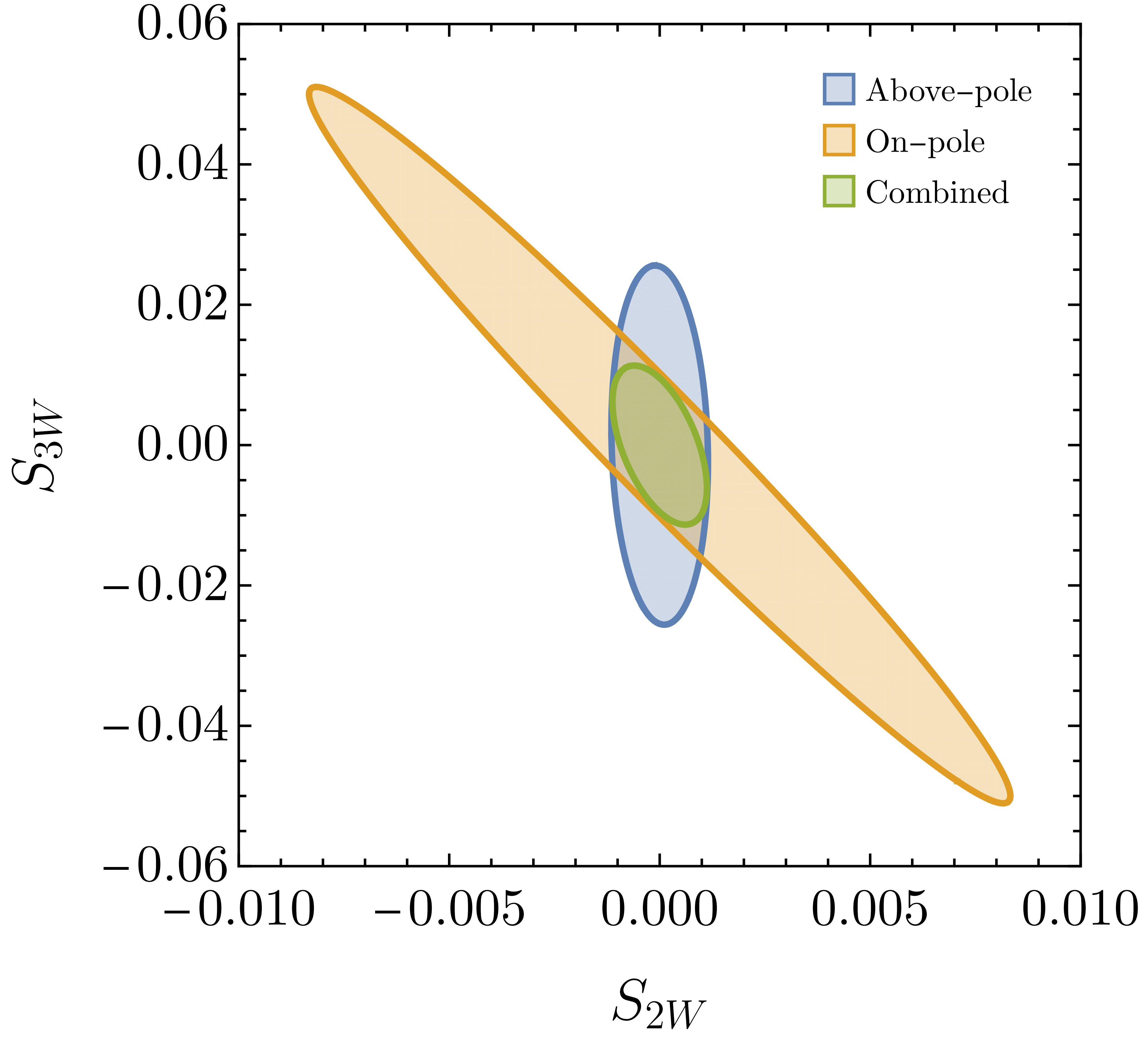
Gauge Operators

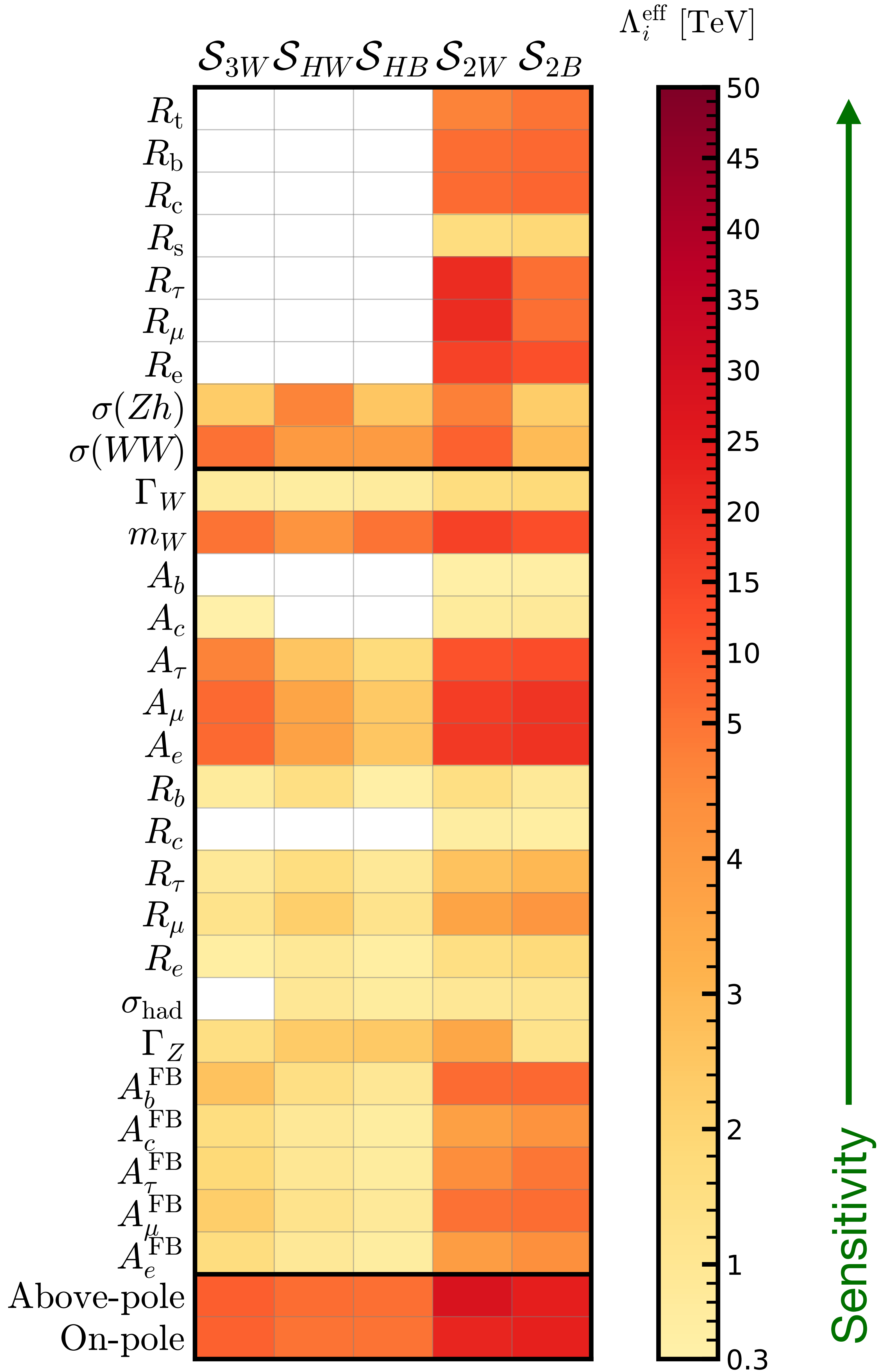


(a) LO Z-pole oblique params.

(b) aTGC

(c) NLO Z-pole oblique params.





$$S_{2B} = -\frac{1}{2}(\partial^\mu B_{\mu\nu})(\partial_\rho B^{\rho\nu}) = \frac{\hat{Y}}{m_W^2}$$

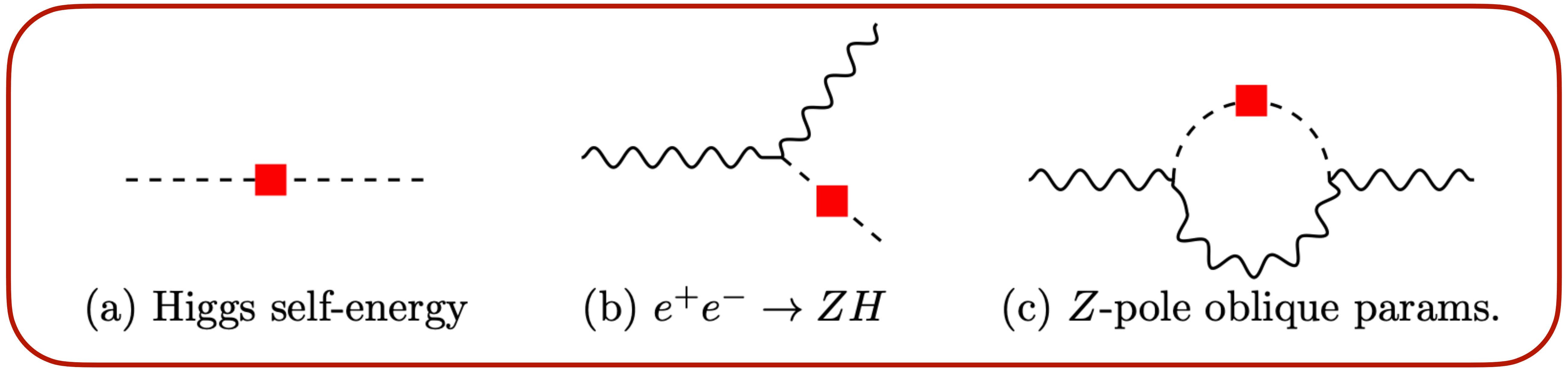
$$S_{2W} = -\frac{1}{2}(D^\mu W^I_{\mu\nu})(D_\rho W^{I\rho\nu}) = \frac{\hat{W}}{m_W^2}$$

$$S_{HW} = i(D^\mu H)^\dagger \tau^I (D^\nu H) W^I_{\mu\nu}$$

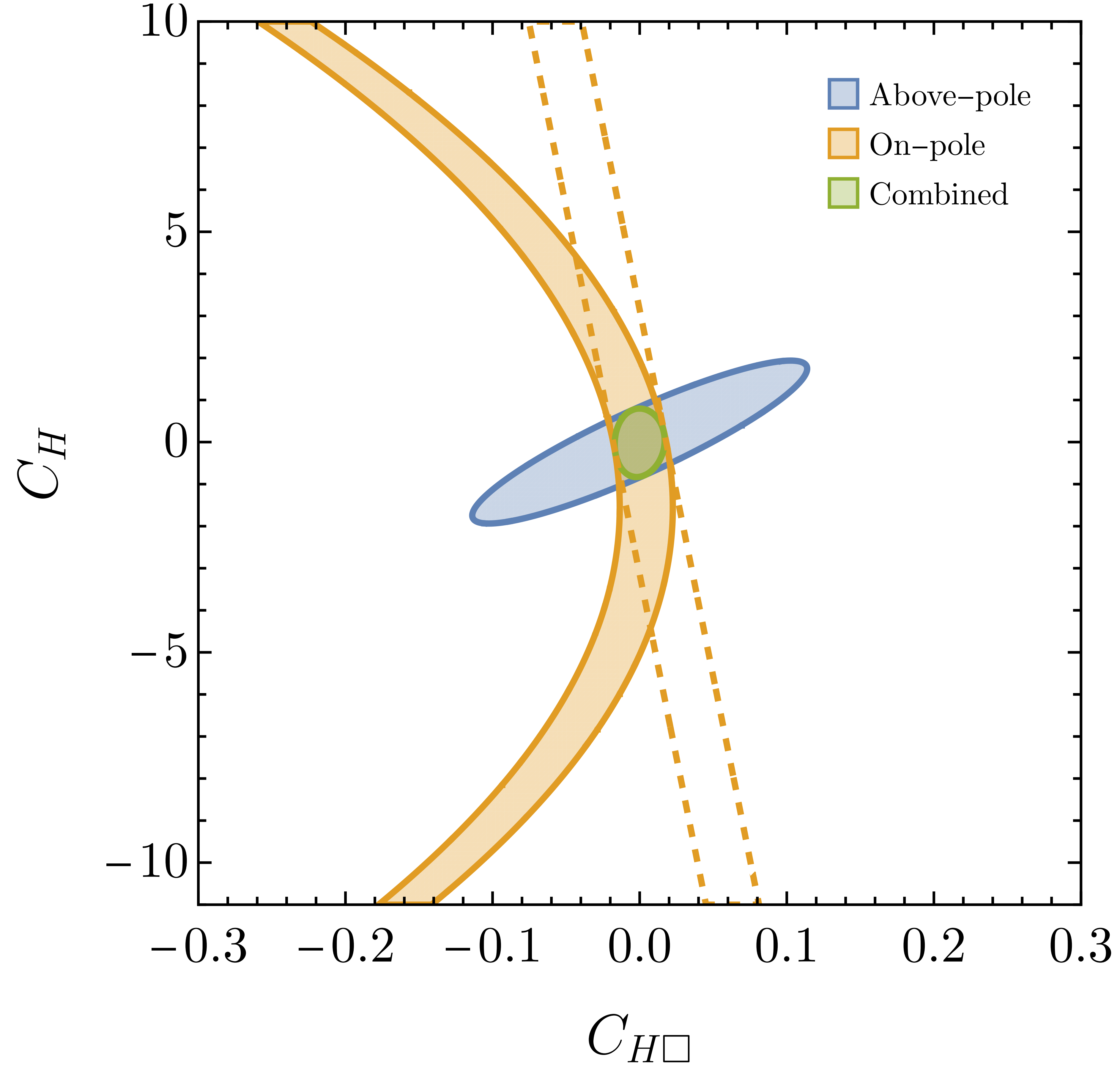
$$S_{HB} = i(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$

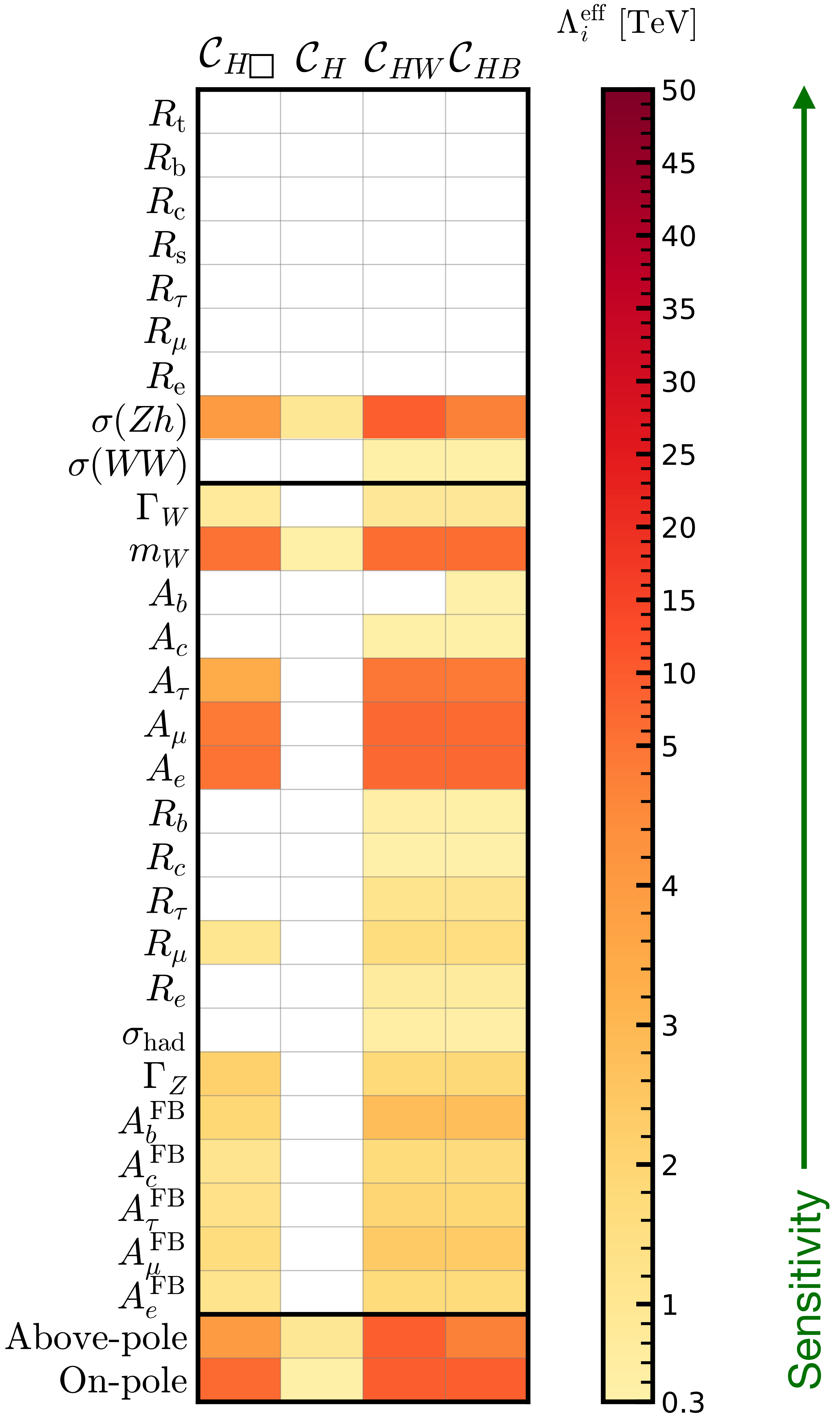
$$S_{3W} = \varepsilon_{IJK} W^{I\nu}_{\mu} W^{J\rho}_{\nu} W^{K\mu}_{\rho}$$

Higgs Operators



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





Real Singlet Scalar

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

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

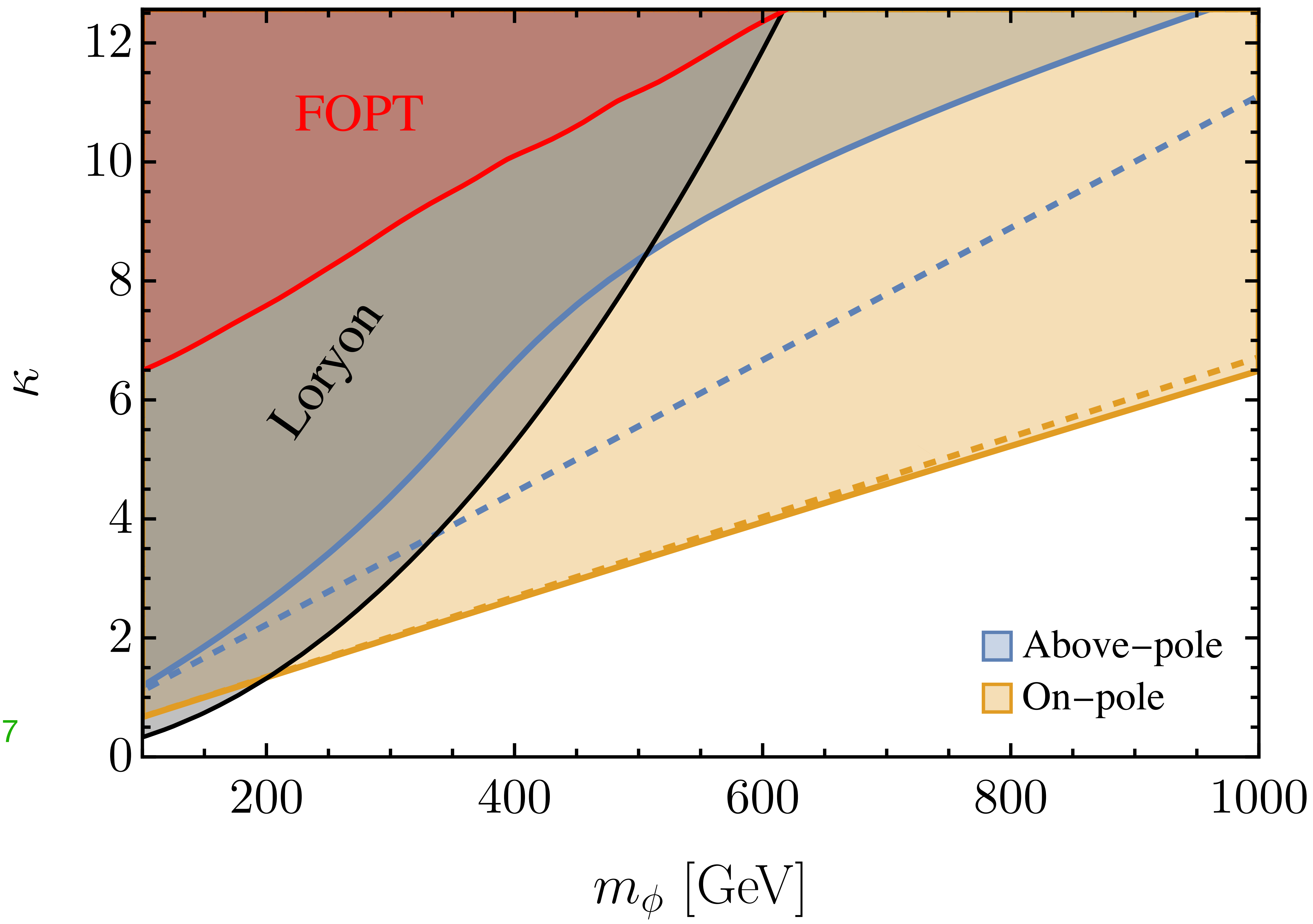
- Only generates C_H and $C_{H\Box}$ at NLO
- Simplest extension of the SM that allows for a first order EW phase transition

Jiang et al.1811.08878 , Haisch et al. 2003.05936

- Hardest "loryon" to probe experimentally

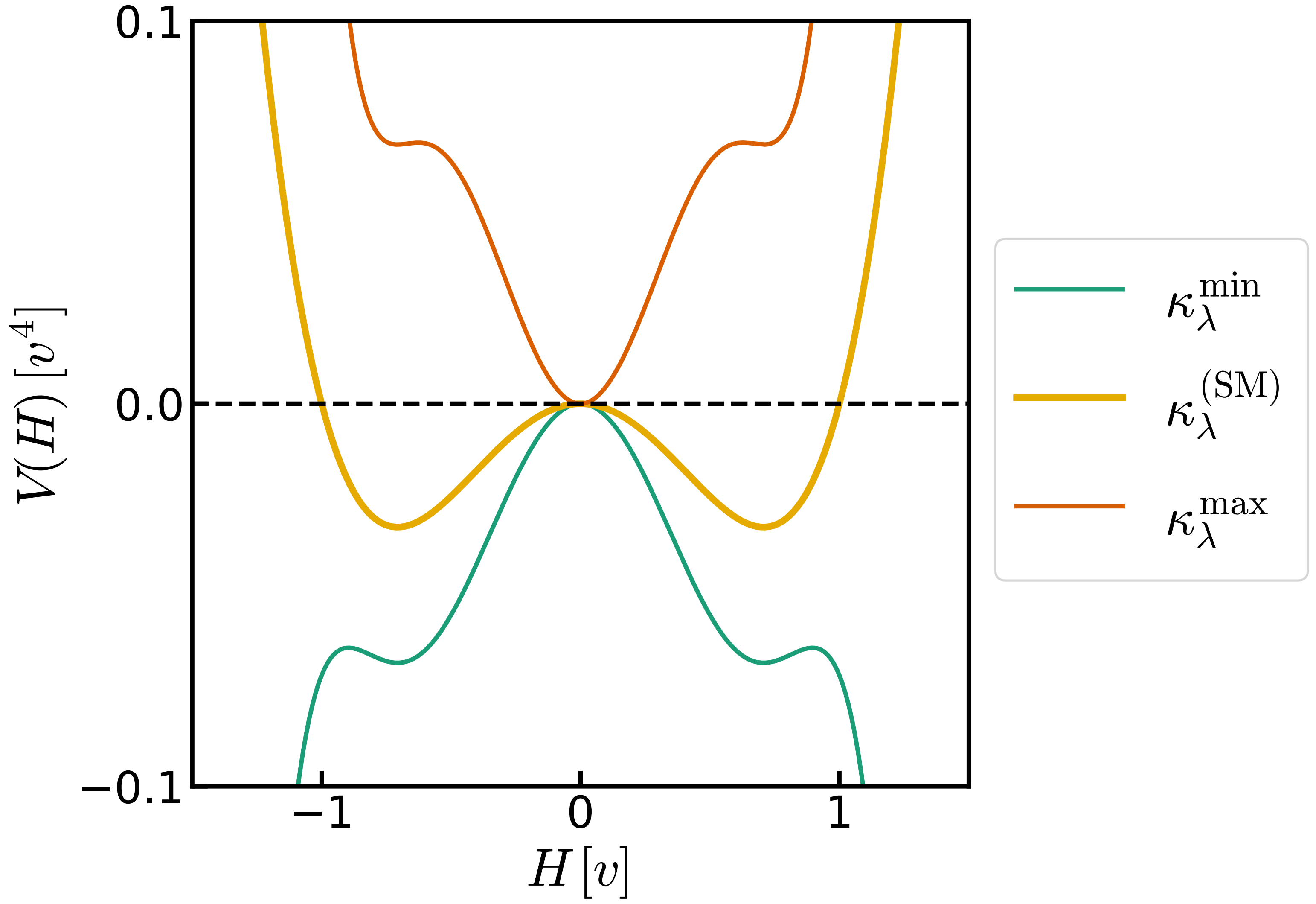
Banta et al. 2110.02967, Crawford and Sutherland 2409.18177

- **Z pole covers Loryon parameter space!**



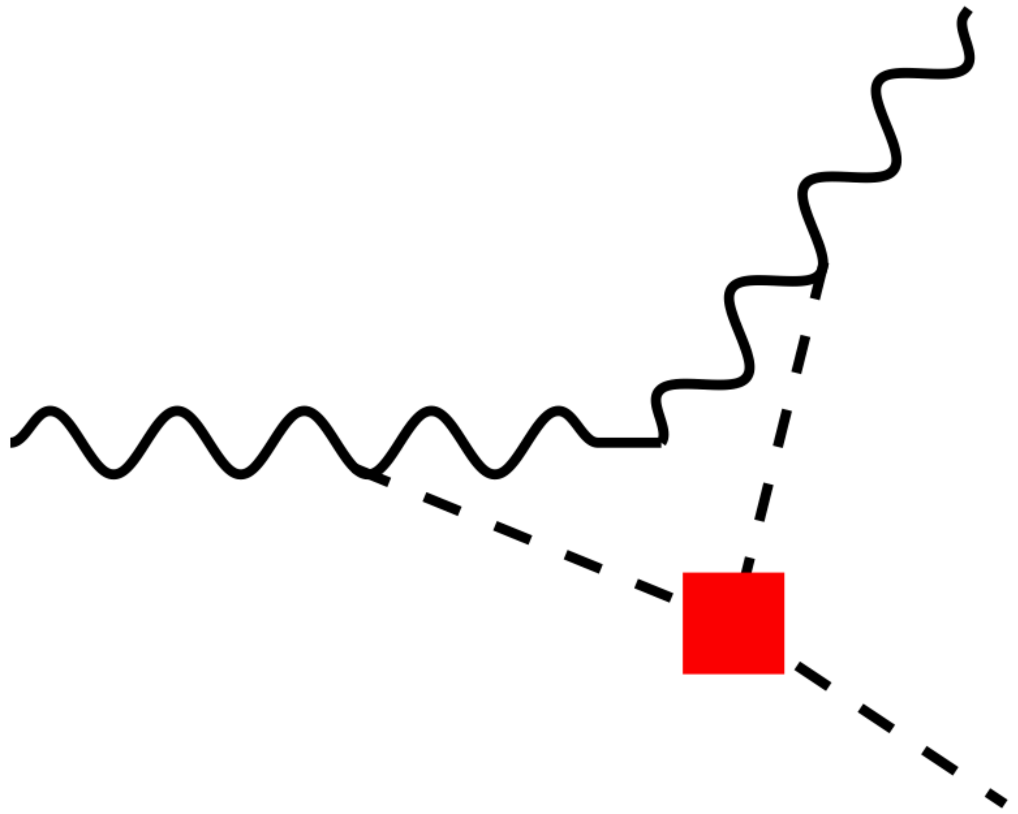
The Higgs Self-Coupling at FCC-ee

Motivation



- One of the few **remaining parameters to be determined precisely**
- Slight modifications have **severe phenomenological implications**!
- Because we can! Thanks to Asteriadis et al. 2409.11466
- Constrained **indirectly at NLO** in $e^+e^- \to ZH$

  McCullough 1312.3322 Di Vita et al. 1711.03978
- Meaningful interpretation only in consistent framework



=> SMEFT at NLO allowing for all possible variations!

The indirect way

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

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

C_H

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

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

$[C_{Hl}^{(3)}]_{11}, [C_{Hl}^{(3)}]_{22}, [C_{Hl}^{(3)}]_{33},$

$[C_{He}]_{11}, [C_{He}]_{22}, [C_{He}]_{33},$

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

$[C_{Hq}^{(3)}]_{11}, [C_{Hq}^{(3)}]_{22}, [C_{Hq}^{(3)}]_{33},$

$[C_{Hu}]_{11}, [C_{Hu}]_{22}, [C_{Hu}]_{33},$

$[C_{Hd}]_{11}, [C_{Hd}]_{22}, [C_{Hd}]_{33},$

$[C_{ll}]_{1111}, [C_{ll}]_{1122}, [C_{ll}]_{1133}, [C_{ll}]_{1221}, [C_{ll}]_{1331},$

$[C_{lq}^{(1)}]_{1111}, [C_{lq}^{(1)}]_{1122}, [C_{lq}^{(1)}]_{1133},$

$[C_{lq}^{(3)}]_{1111}, [C_{lq}^{(3)}]_{1122},$

$[C_{lq}^{(3)}]_{1133}, [C_{lq}^{(3)}]_{2233},$

$[C_{ee}]_{1111}, [C_{ee}]_{1122}, [C_{ee}]_{1133},$

$[C_{eu}]_{1111}, [C_{eu}]_{1122}, [C_{eu}]_{1133},$

$[C_{ed}]_{1111}, [C_{ed}]_{1122}, [C_{ed}]_{1133},$

$[C_{le}]_{1111}, [C_{le}]_{1122}, [C_{le}]_{1133}, [C_{le}]_{2211}, [C_{le}]_{3311},$

$[C_{lu}]_{1111}, [C_{lu}]_{1122}, [C_{lu}]_{1133},$

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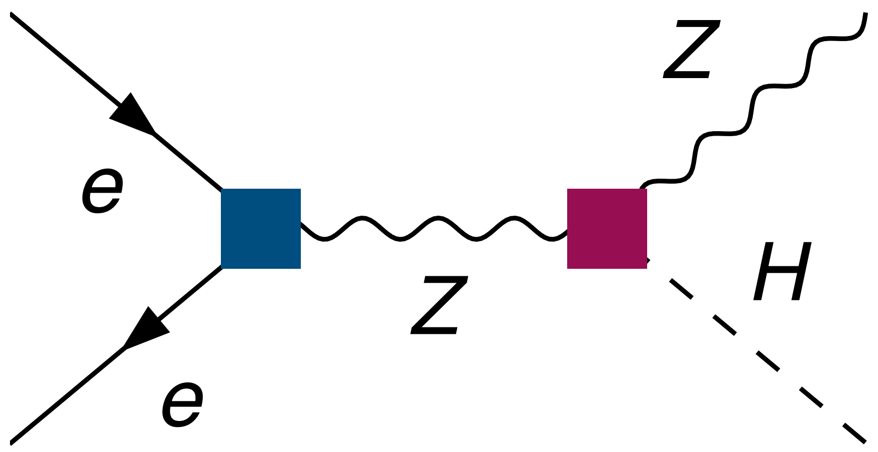

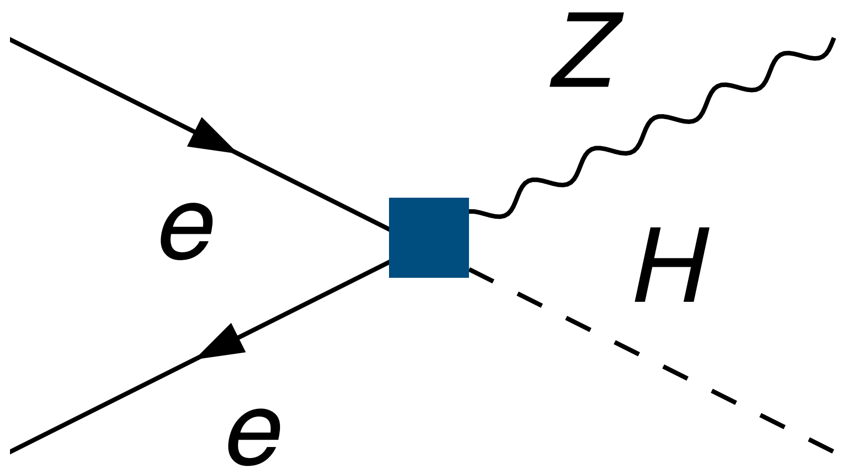

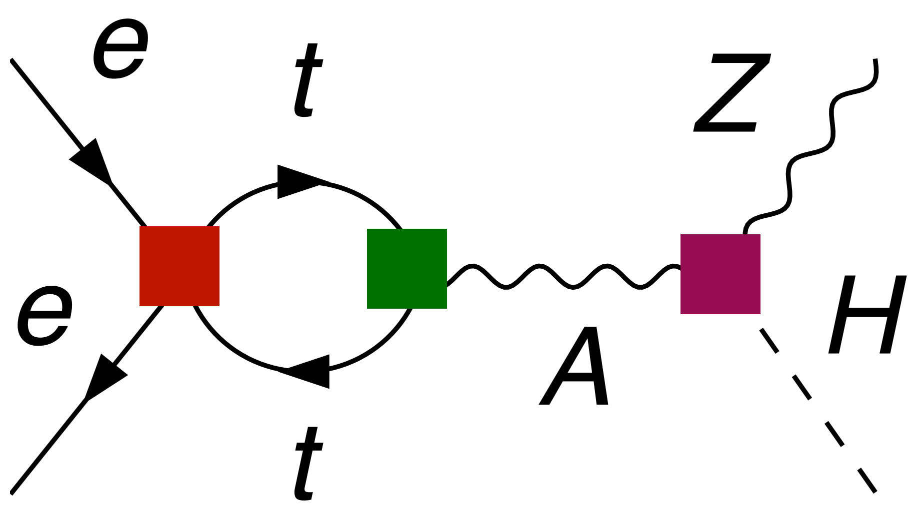

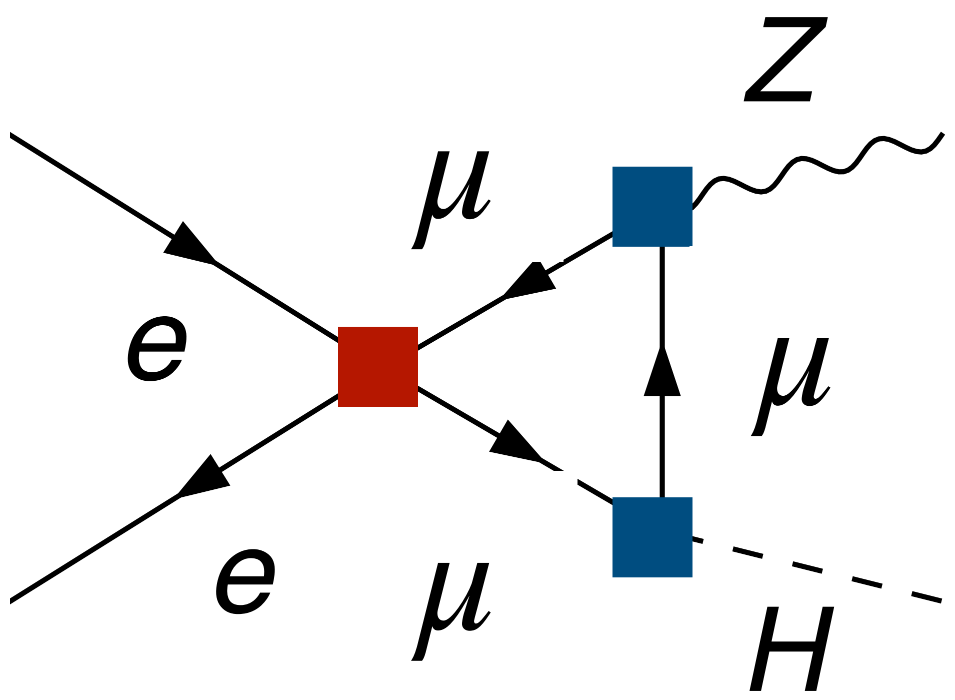

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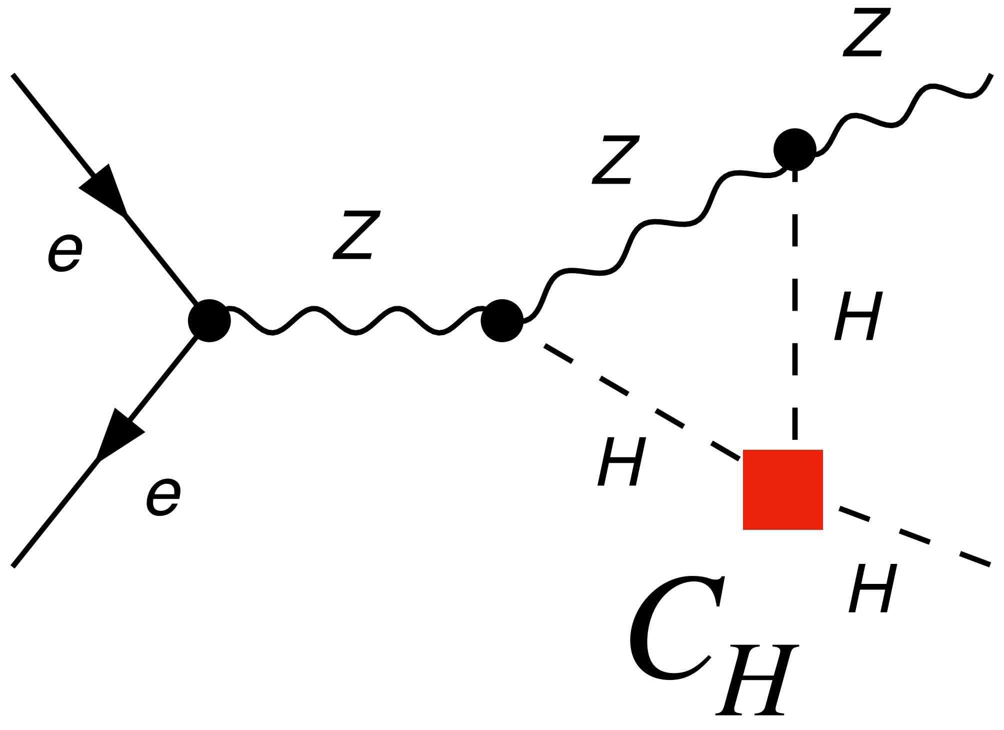
VS

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



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$[C_{ed}]_{1111}, [C_{ed}]_{1122}, [C_{ed}]_{1133},$

$[C_{le}]_{1111}, [C_{le}]_{1122}, [C_{le}]_{1133}, [C_{le}]_{2211}, [C_{le}]_{3311},$

$[C_{lu}]_{1111}, [C_{lu}]_{1122}, [C_{lu}]_{1133},$

$[C_{ld}]_{1111}, [C_{ld}]_{1122}, [C_{ld}]_{1133},$

$[C_{qe}]_{1111}, [C_{qe}]_{2211}, [C_{qe}]_{3311}$

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**

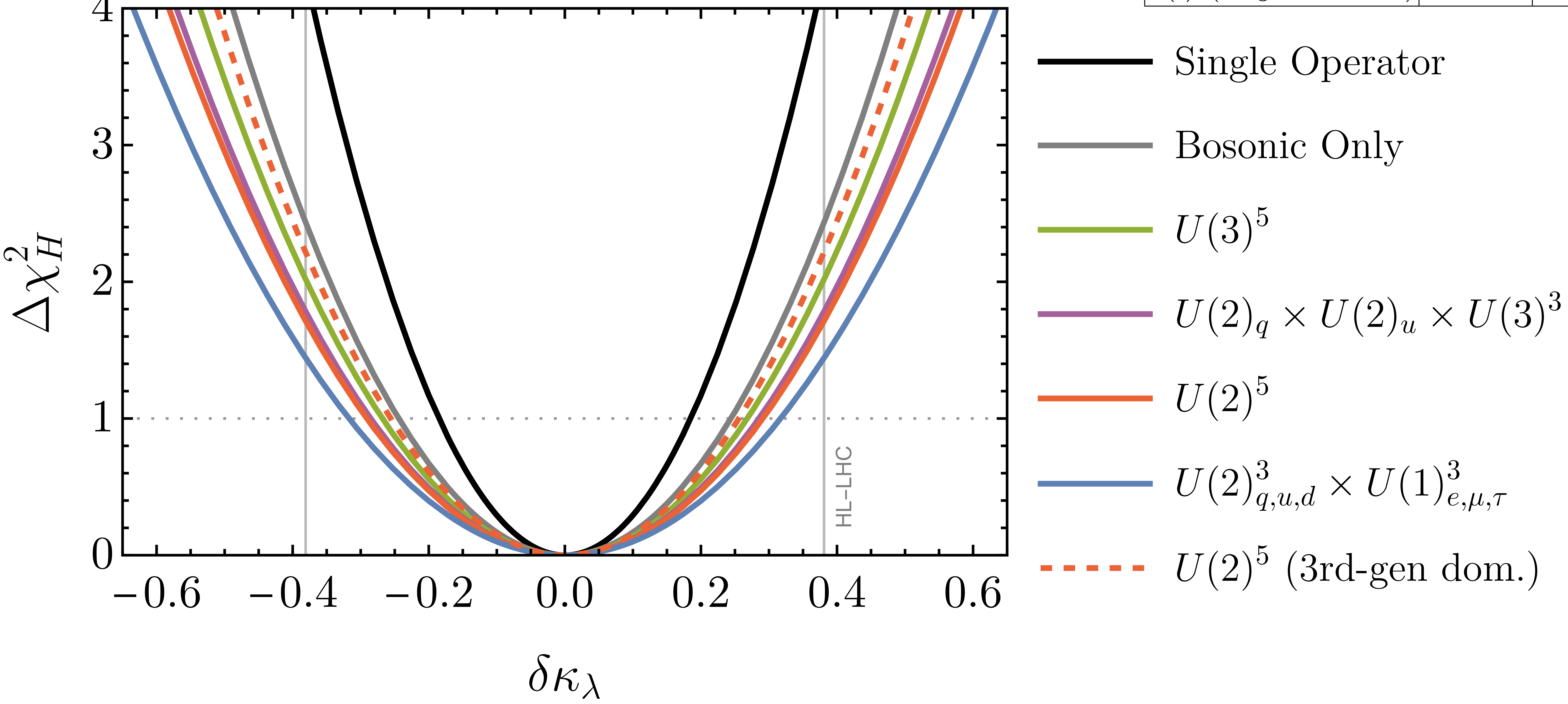
Di-fermion, Diboson from **LEP**

Current Flavour data

“Boundary Condition”

FCC-ee 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

- Extreme precision at Z-pole can **compensate for a loop suppression or energy enhancement** in the cross section
- A Tera-Z run is **extremely versatile**
- Any FCC-ee fit needs to **include NLO Z-pole observables + RGE**
- Higgs Self-Coupling bound robustly to $\delta\kappa_\lambda \lesssim 30\,\%$ at FCC-ee
- Beautiful **complementarity between all FCC-ee runs!**

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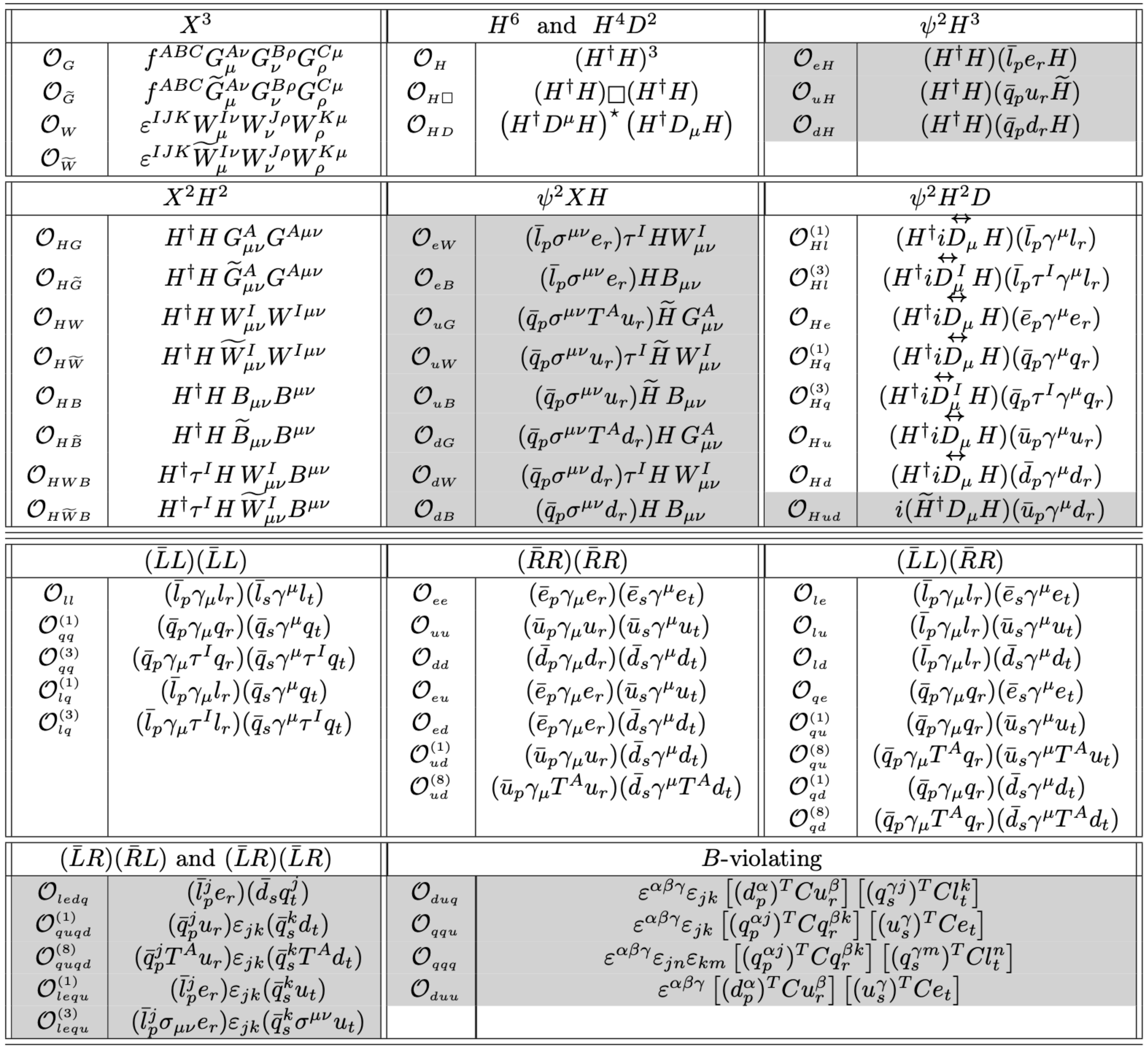
Thank you for your attention!

Backup Slides

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	
$\mathcal{O}_{HG}$	$H^\dagger H\, G^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eW}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I H W^I_{\mu\nu}$	$\mathcal{O}_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$
$\mathcal{O}_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$	$\mathcal{O}_{eB}$	$(\bar{l}_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$\mathcal{O}_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$\mathcal{O}_{HW}$	$H^\dagger H\, W^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	$\mathcal{O}_{He}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$
$\mathcal{O}_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$	$\mathcal{O}_{uW}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\, W^I_{\mu\nu}$	$\mathcal{O}_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$
$\mathcal{O}_{HB}$	$H^\dagger H\, B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{uB}$	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\, B_{\mu\nu}$	$\mathcal{O}_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$\mathcal{O}_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dG}$	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)H\, G^A_{\mu\nu}$	$\mathcal{O}_{Hu}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$
$\mathcal{O}_{HWB}$	$H^\dagger\tau^I H\, W^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dW}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I H\, W^I_{\mu\nu}$	$\mathcal{O}_{Hd}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$
$\mathcal{O}_{H\widetilde{W}B}$	$H^\dagger\tau^I H\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{dB}$	$(\bar{q}_p\sigma^{\mu\nu}d_r)H\, B_{\mu\nu}$	$\mathcal{O}_{Hud}$	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p\gamma^\mu d_r)$
$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	$\mathcal{O}_{ee}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	$\mathcal{O}_{le}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{uu}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{lu}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$\mathcal{O}_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{dd}$	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{ld}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	$\mathcal{O}_{eu}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	$\mathcal{O}_{qe}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	$\mathcal{O}_{ed}$	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating			
$\mathcal{O}_{ledq}$	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	$\mathcal{O}_{duq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$		
$\mathcal{O}_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	$\mathcal{O}_{qqu}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$		
$\mathcal{O}_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	$\mathcal{O}_{qqq}$	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$		
$\mathcal{O}_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	$\mathcal{O}_{duu}$	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$		
$\mathcal{O}_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$				

The Future Circular e^+e^- collider

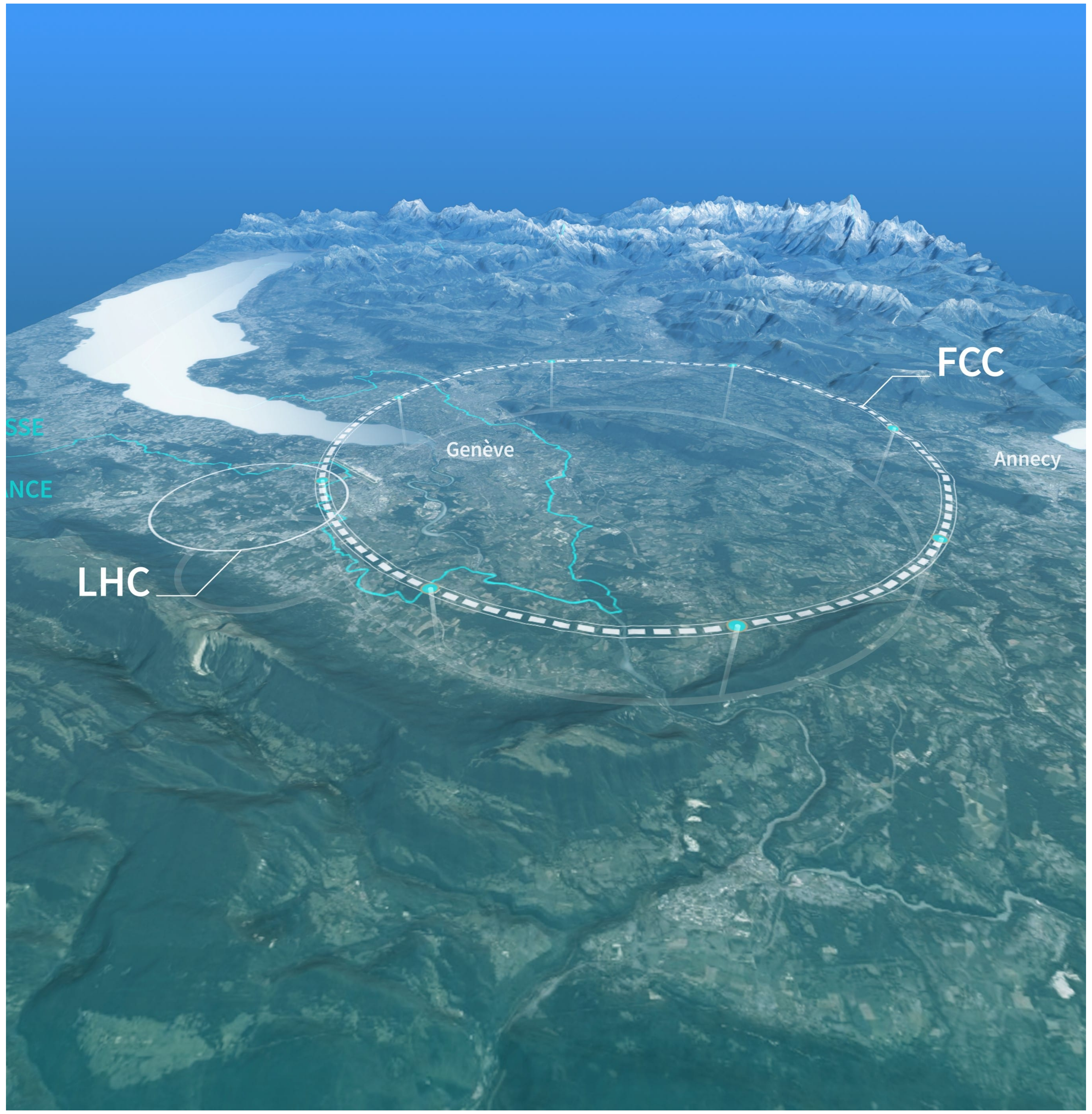
	$Z-$pole	WW	Zh	$t\bar{t}$
Energy [GeV]	91.2	163	240	365
“Accuracy”	$6 \cdot 10^{12}\, Z$	$2.4 \cdot 10^{8}\, WW$	$2.2 \cdot 10^{6}\, h$	$2 \cdot 10^{6}\, t\bar{t}$

On Pole:

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

Above pole:

$$O_{\text{above-pole}} = \left\{ \sigma\left(e^+e^- \to W^+W^-\right), \sigma\left(e^+e^- \to ZH\right), \sigma\left(e^+e^- \to f\bar{f}\right) \right\}$$



EWPO

$$\Gamma_Z \equiv \sum_f \Gamma\left(Z \to f\bar{f}\right)$$

$$A_{\mathrm{FB}}^{0,l} \equiv \frac{3}{4} A_e A_l$$

$$\sigma_{\mathrm{had}} \equiv \frac{12\pi}{m_Z^2} \frac{\Gamma(Z \to e^+e^-)\Gamma(Z \to q\bar{q})}{\Gamma_Z^2}$$

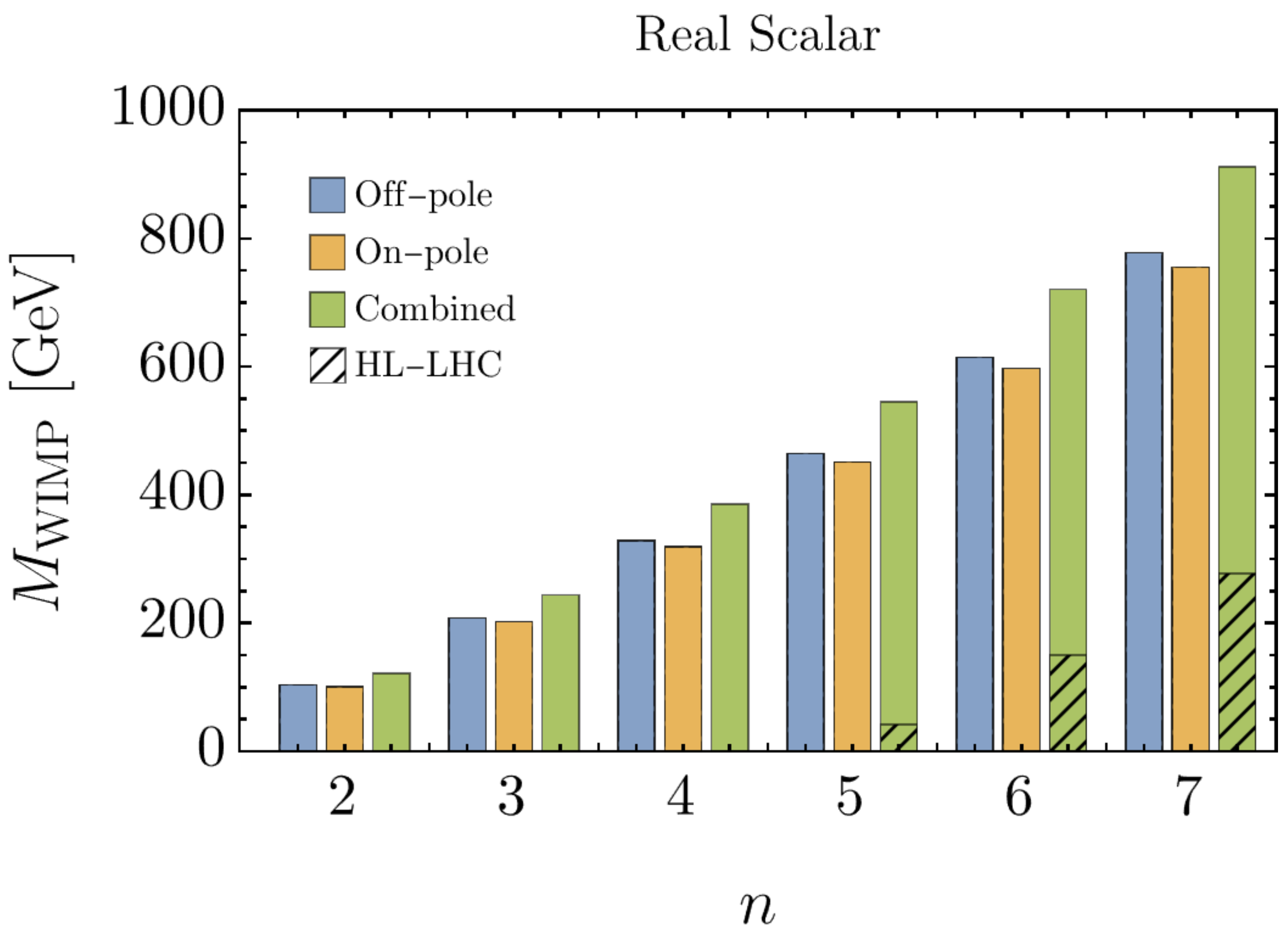
$$A_f \equiv \frac{\Gamma(Z \to f_L^+ f_L^-) - \Gamma(Z \to f_R^+ f_R^-)}{\Gamma(Z \to f^+ f^-)}$$

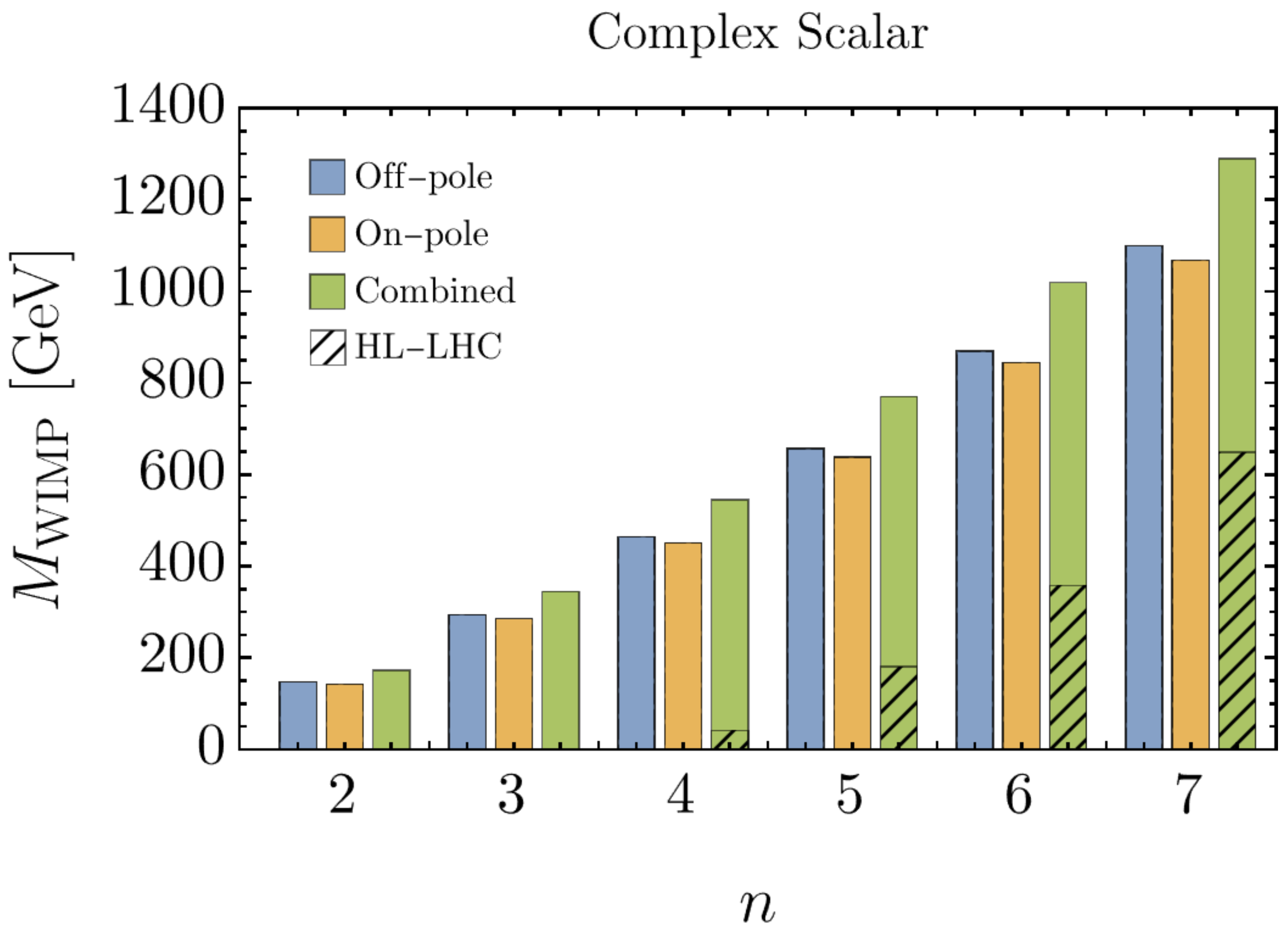
$$R_l \equiv \frac{\sum_q \Gamma(Z \to q\bar{q})}{\Gamma(Z \to l^+ l^-)}$$

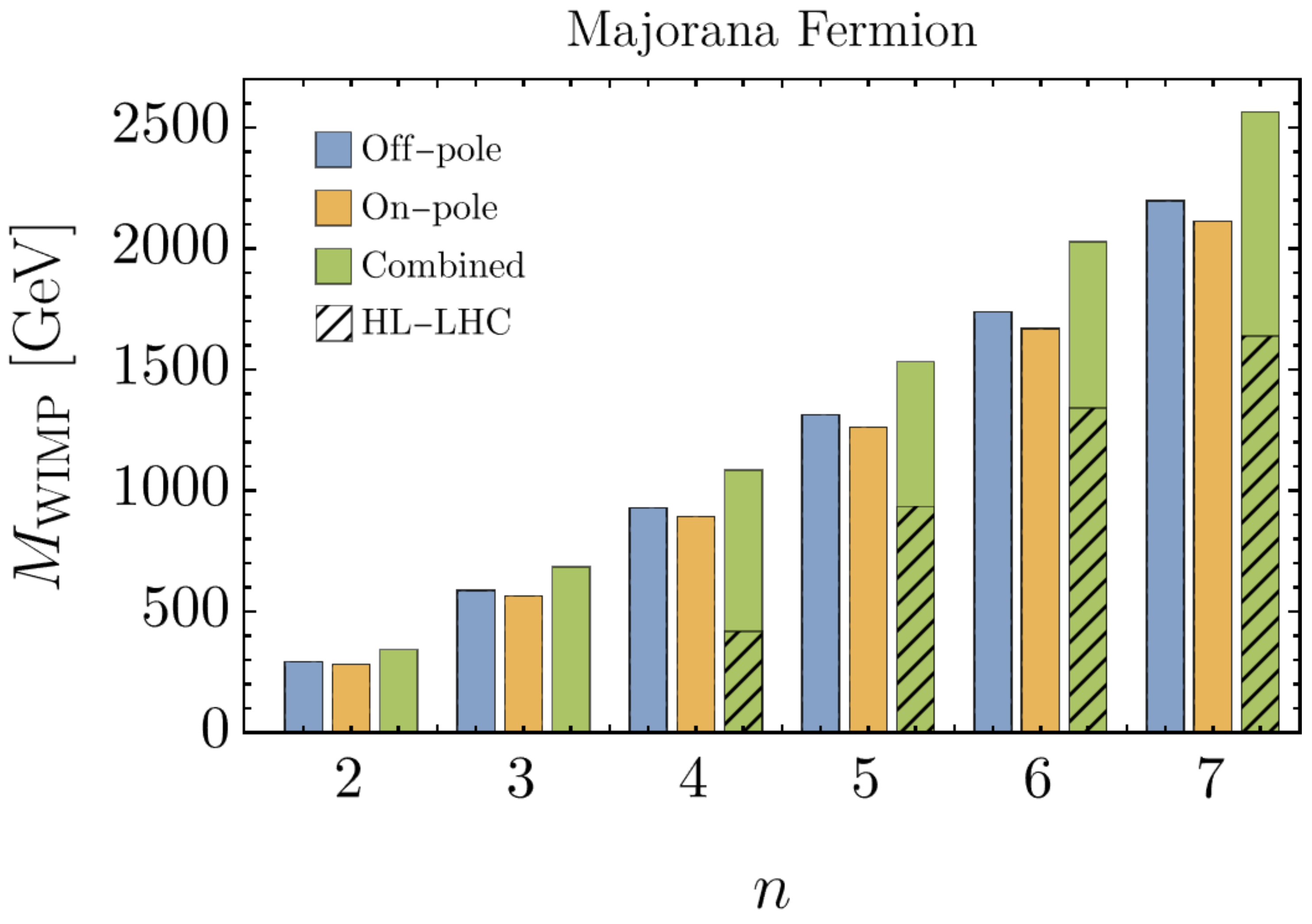
$$R_q \equiv \frac{\Gamma(Z \to q\bar{q})}{\sum_{q_i} \Gamma(Z \to q_i\bar{q}_i)}$$

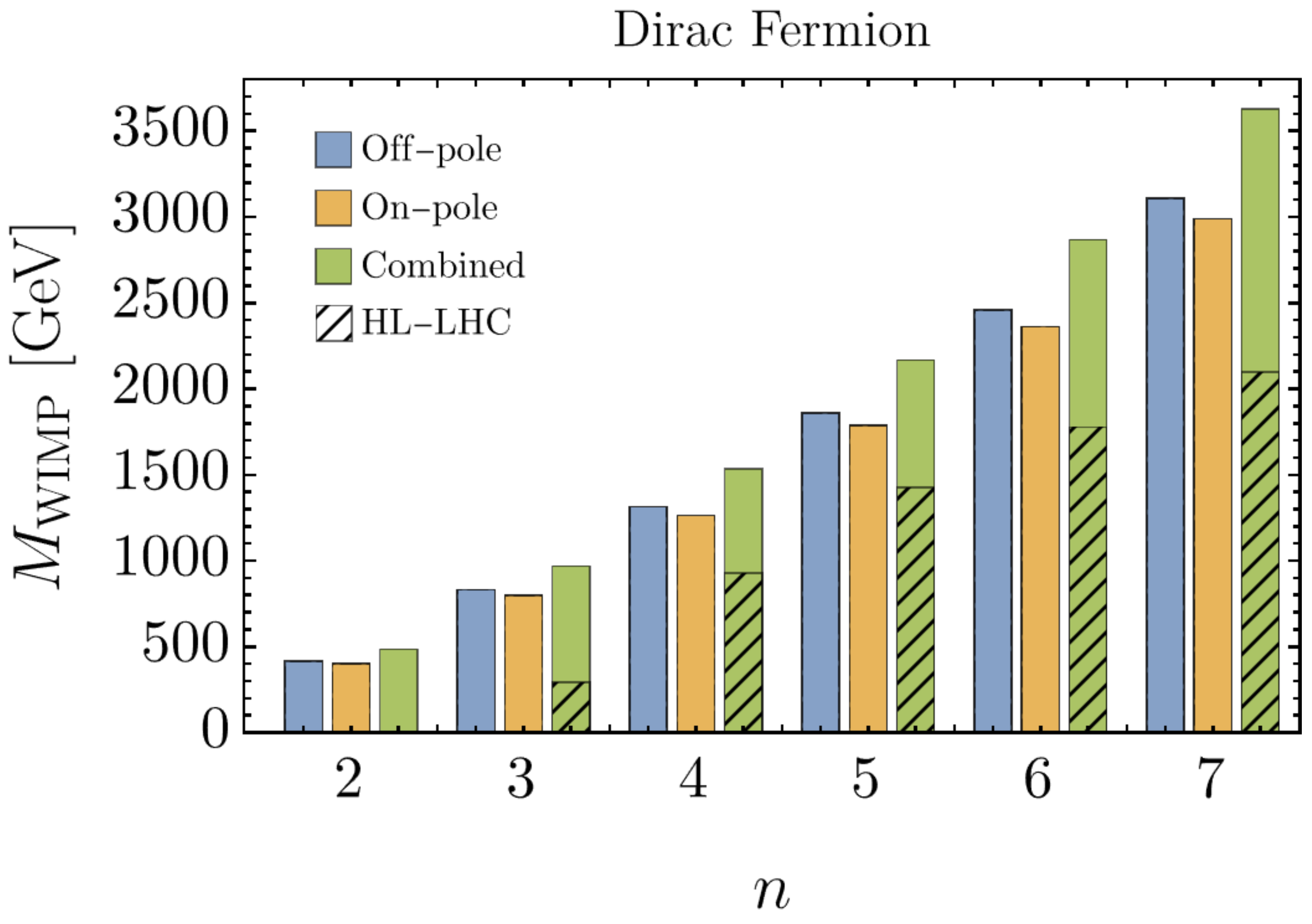
ACE in action: WIMPs

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

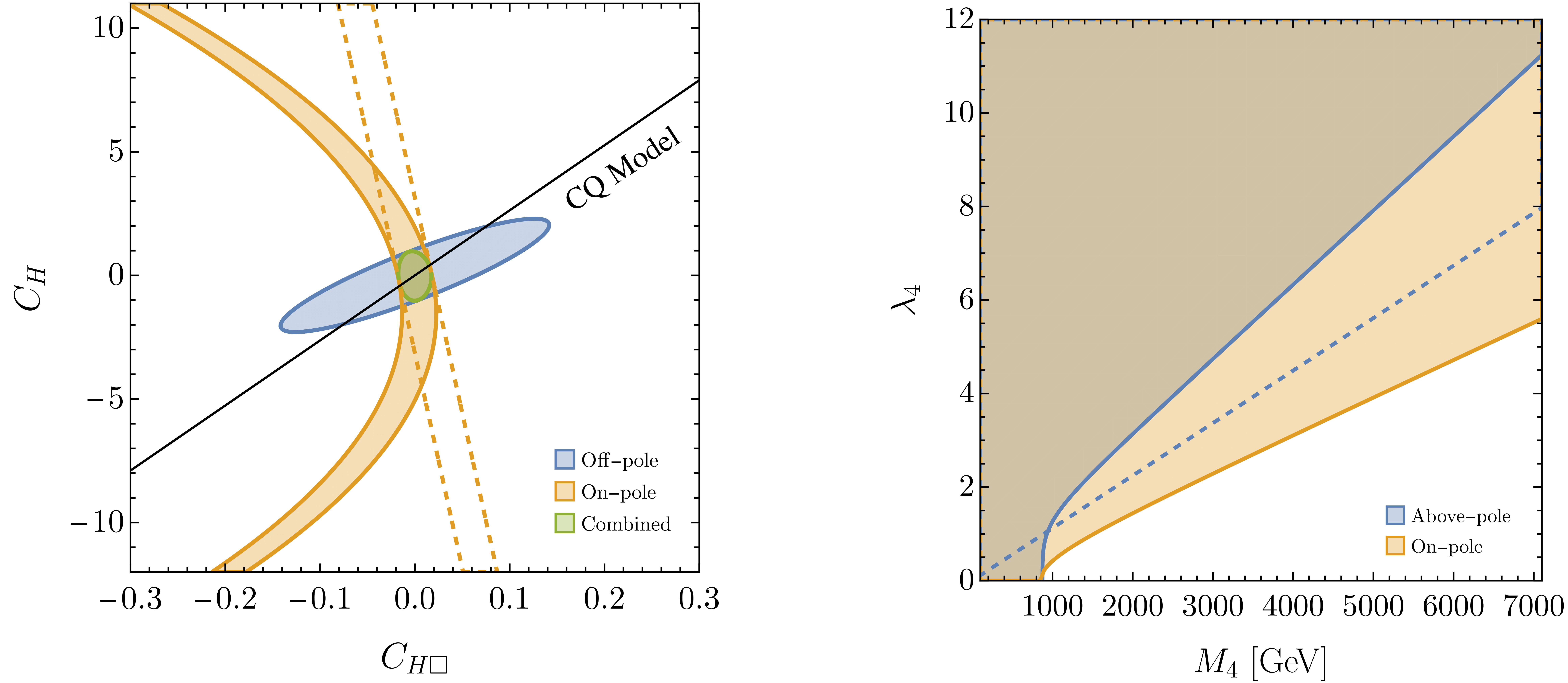








Custodial Quadruplet



	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 $b \to s\nu\nu$