THE UNIVERSITY *of* EDINBURGH

Connecting scales in the SMEFT at the LHC and future colliders

DAMTP seminar

Based on arXiv: 2502.20453, 2504.05974

In collaboration with Luca Mantani, Juan Rojo, Alejo Rossia, Eleni Vryonidou

Jaco ter Hoeve

02/05/25

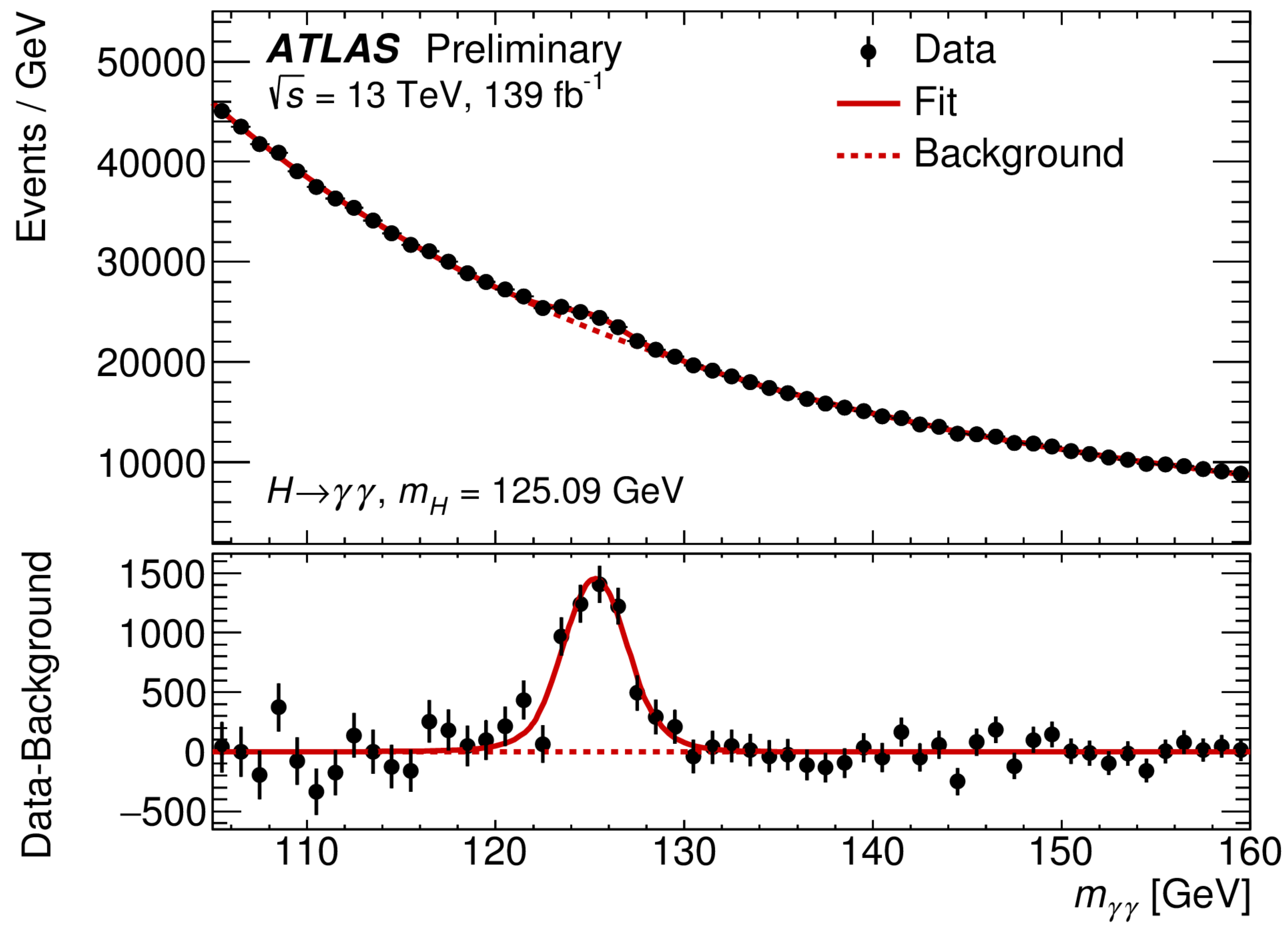
CENTRE FOR THEORETICAL PHYSICS · Higgs

This talk

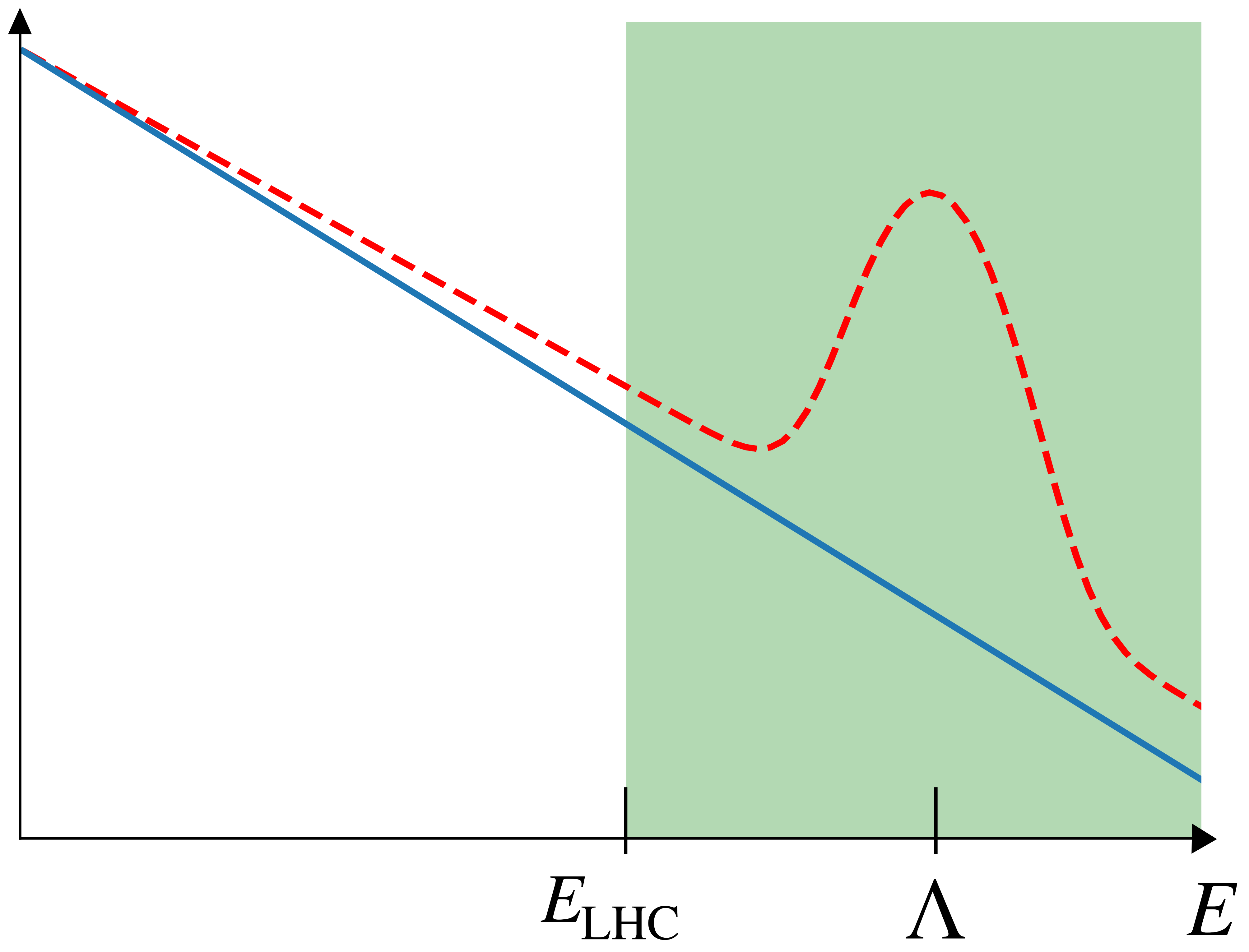
- A brief introduction to the SMEFT
- Renormalisation Group Evolution in global SMEFT fits
- The SMEFT at future colliders
- The Higgs self-coupling at FCC-ee
- Summary

How to look for New Physics

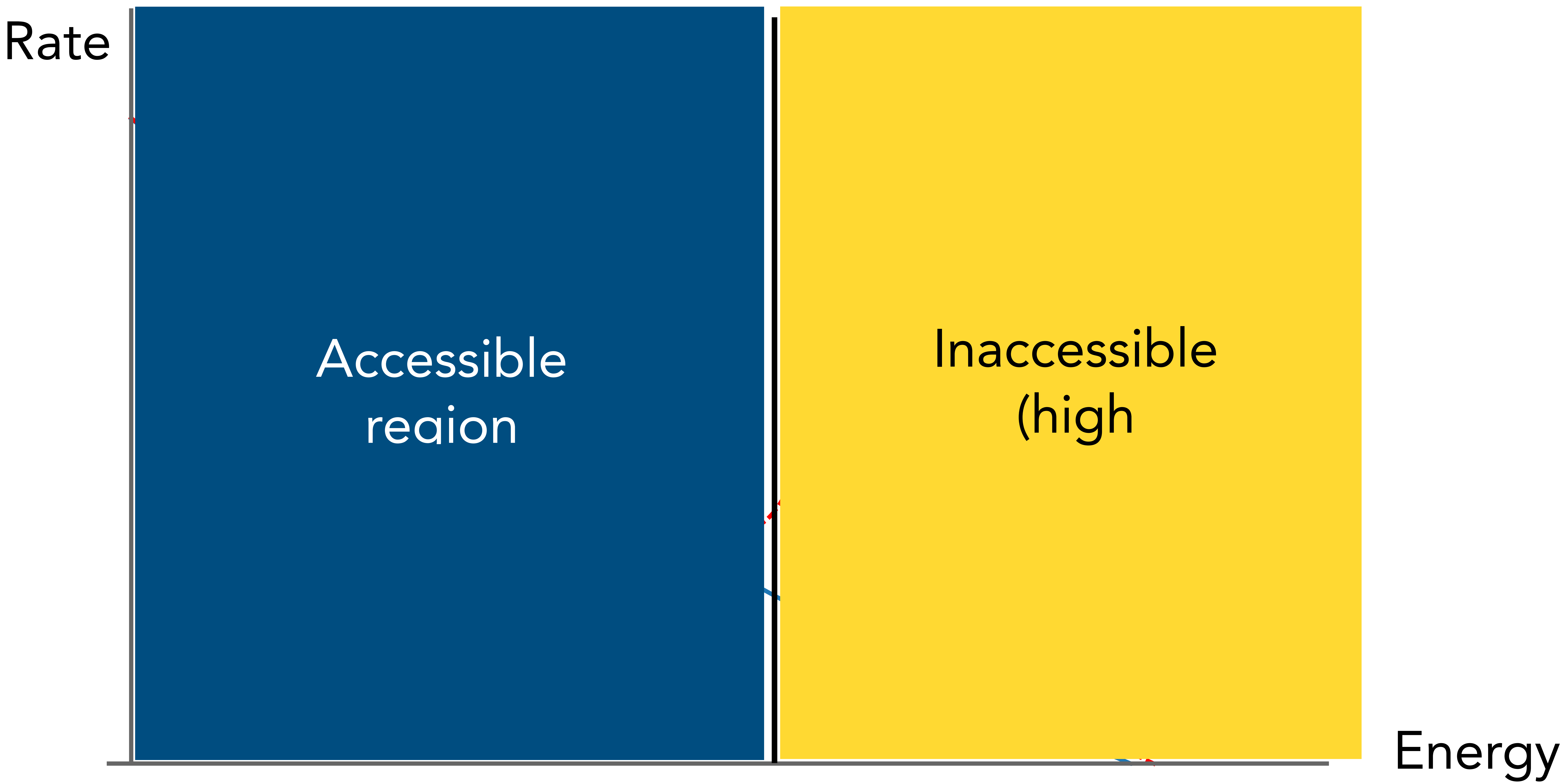
1. Directly: bump hunting



2. Indirectly: tiny deviations in tails



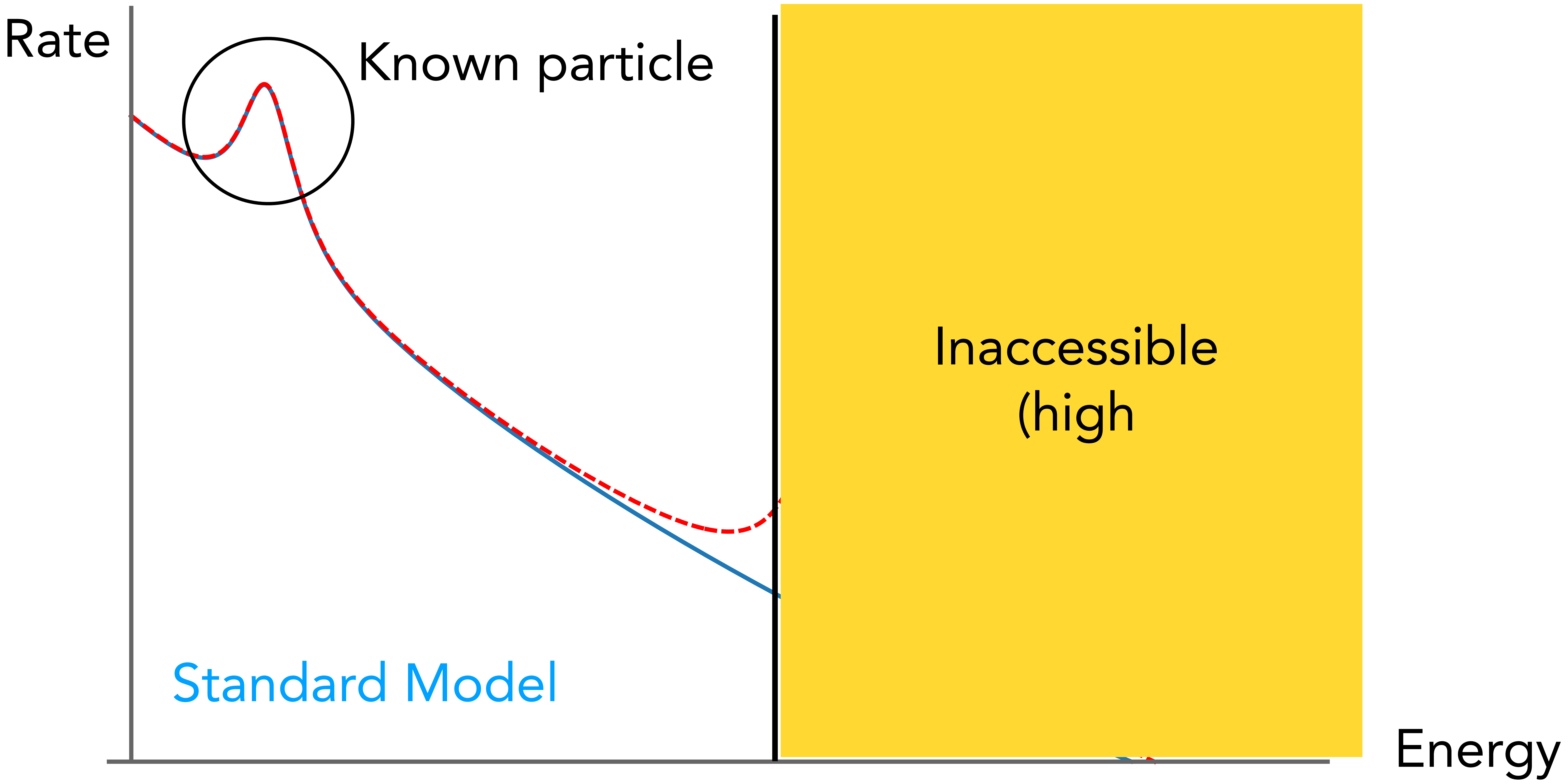
The Standard Model Effective Field Theory



Adapted from E. Vryonidou

The SMEFT: the way to probe new physics beyond the direct collider energy reach

The Standard Model Effective Field Theory



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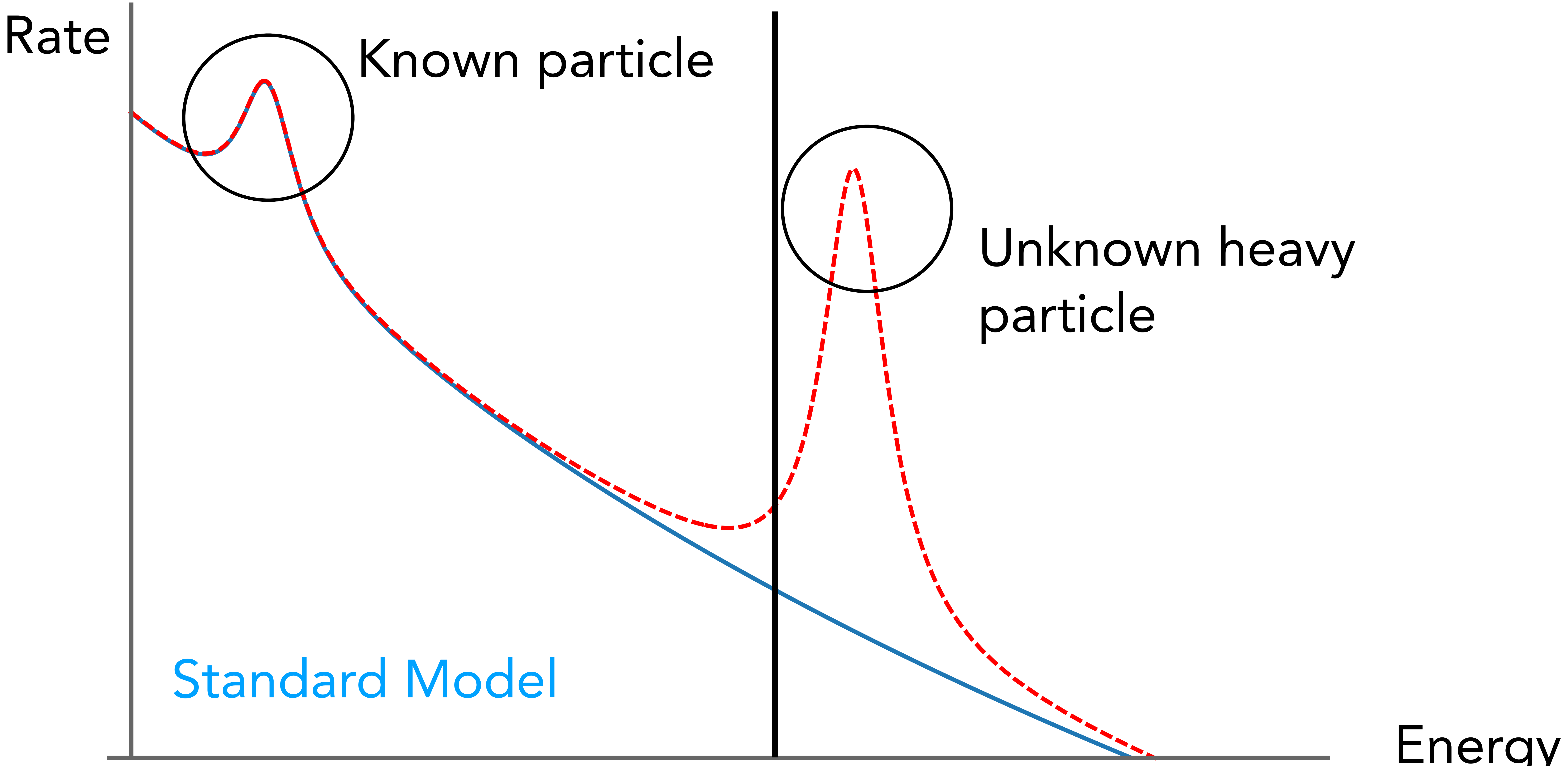

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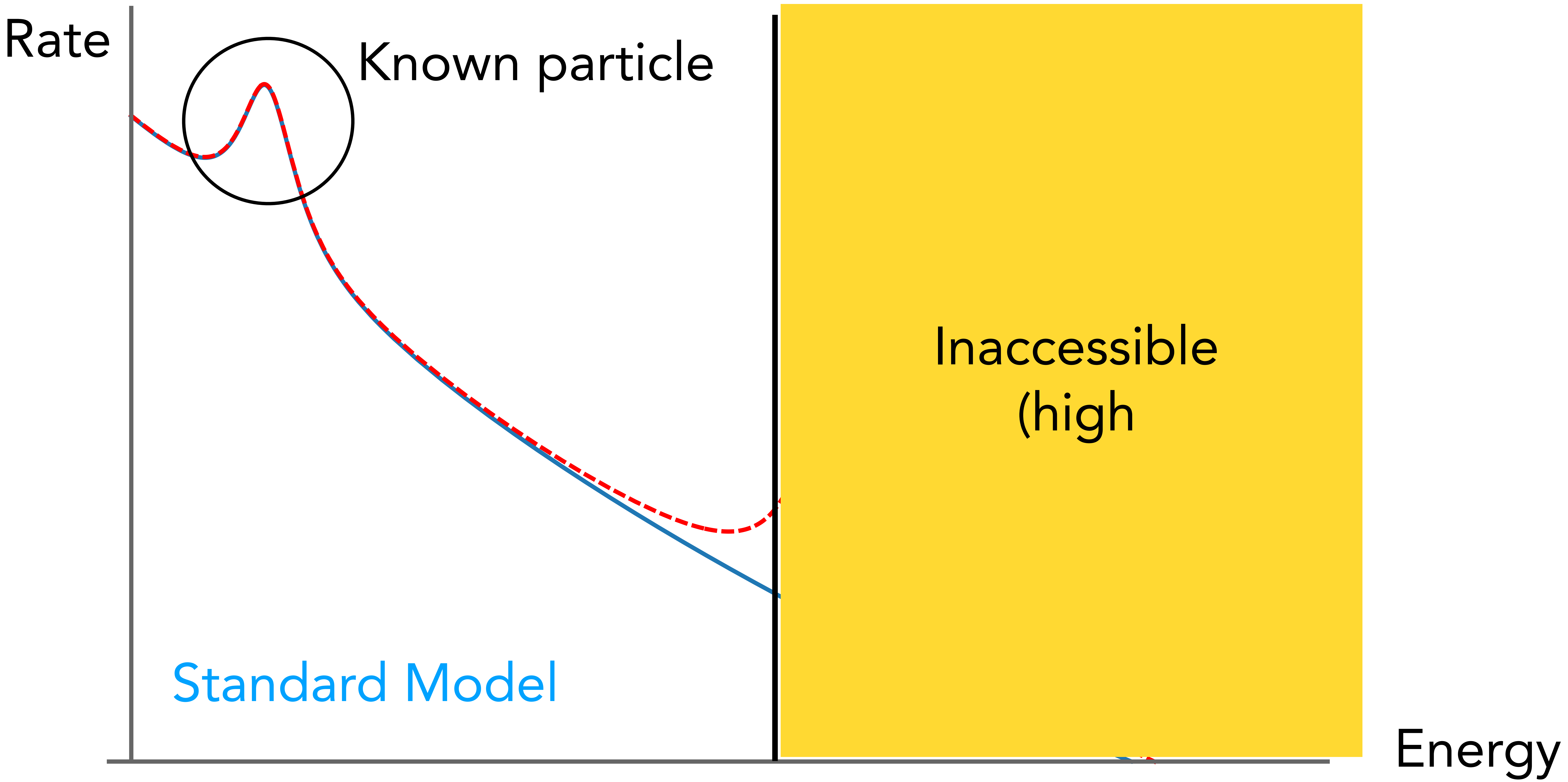

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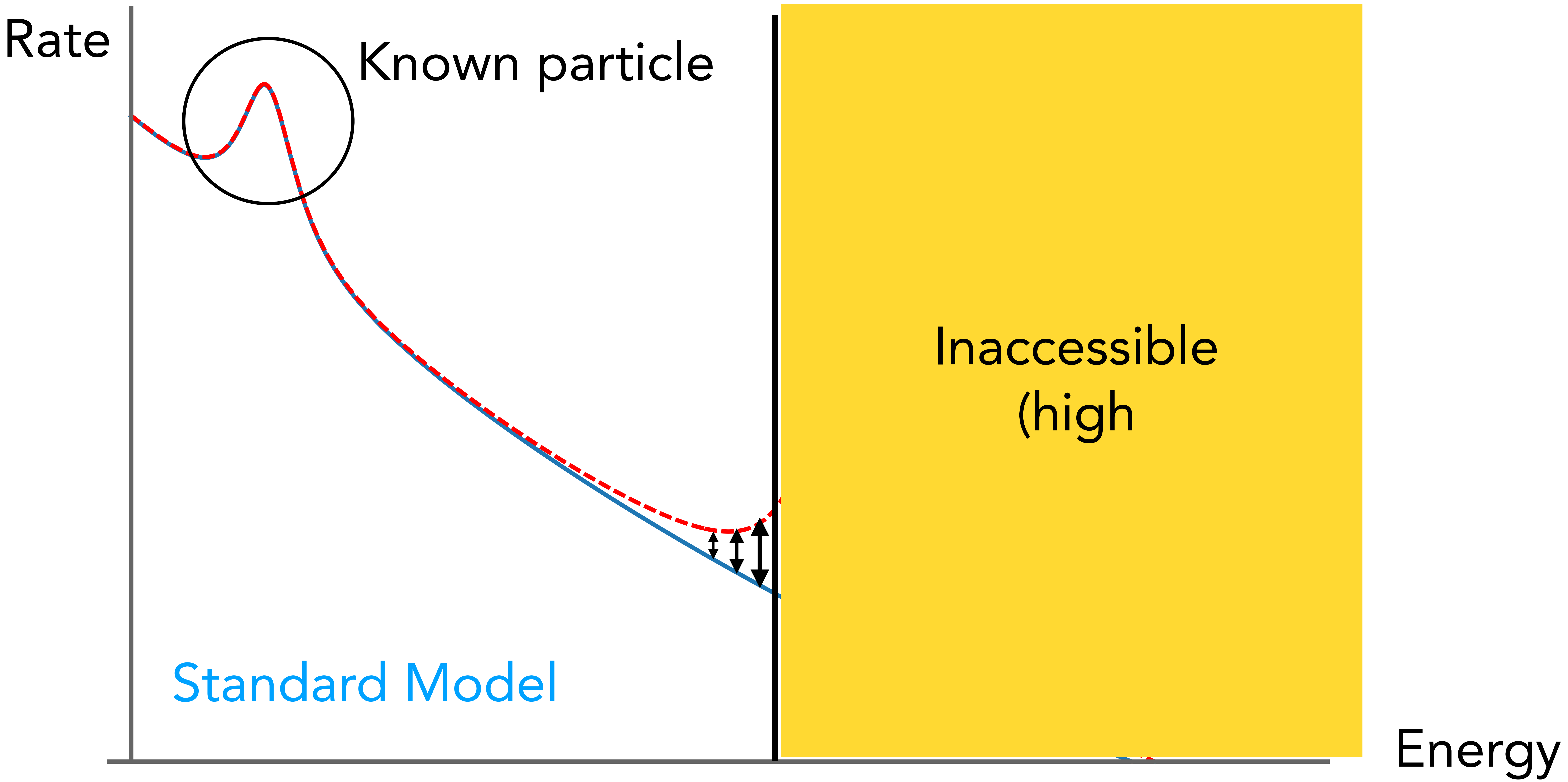

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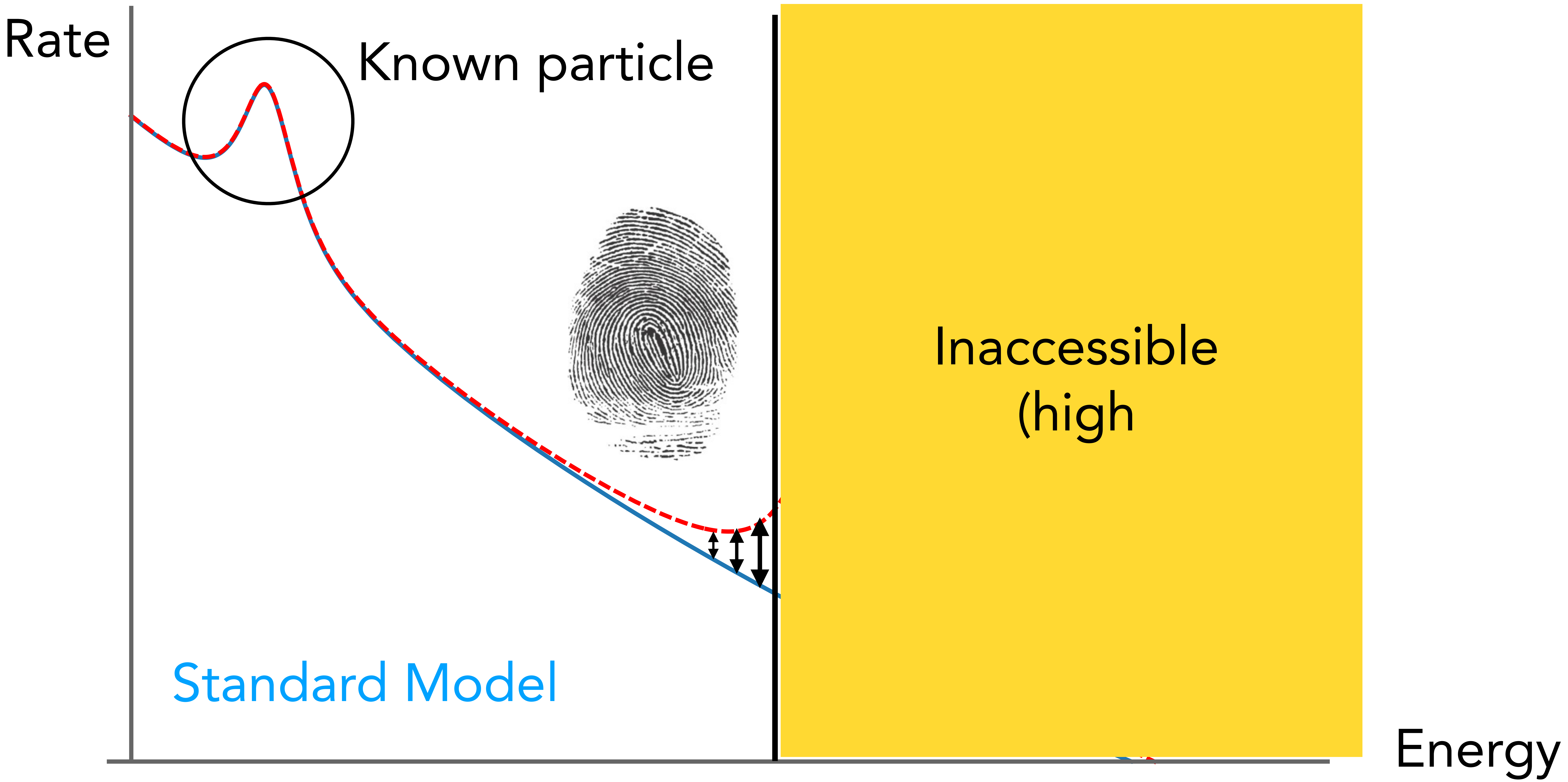
The Standard Model Effective Field Theory



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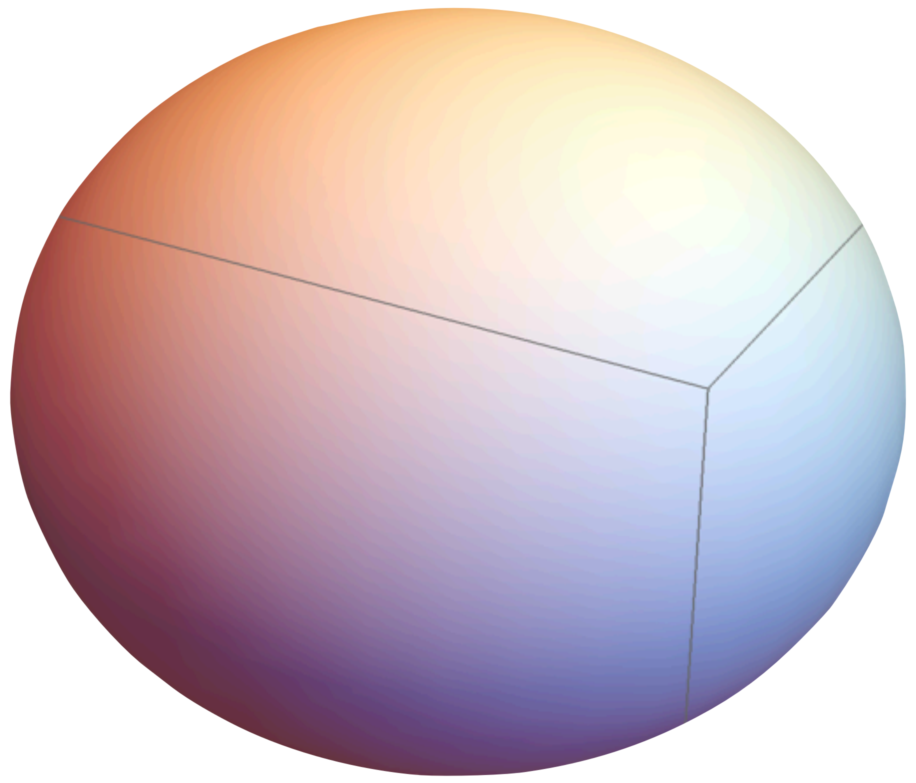
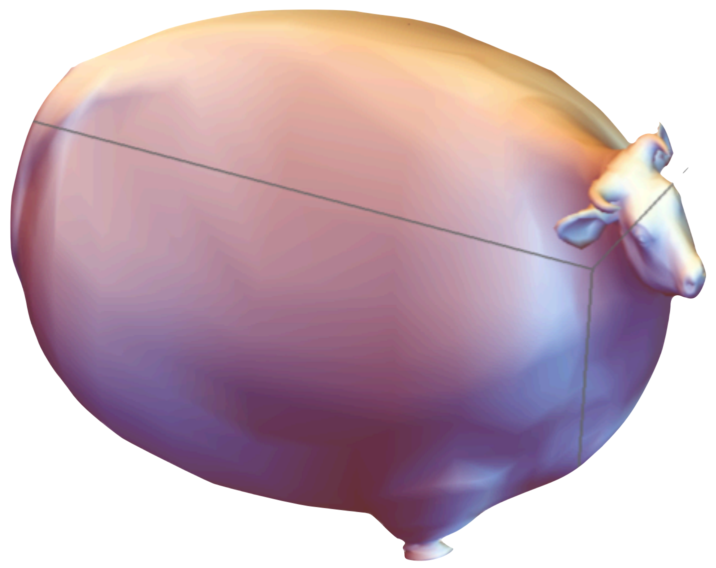
The SMEFT: the way to probe new physics beyond the direct collider energy reach

The SMEFT philosophy

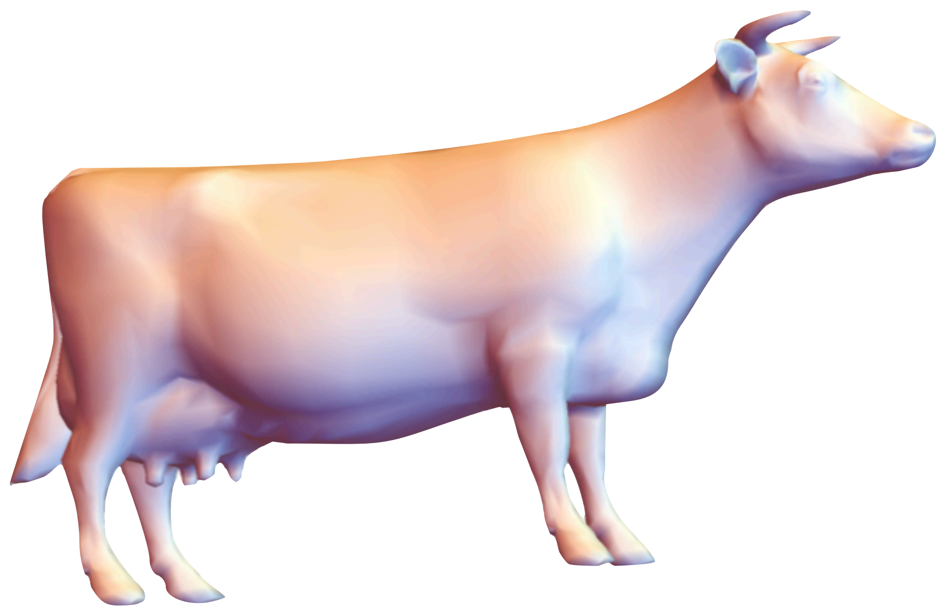
The SM | EFT | New Physics



$+ \; c \cdot$



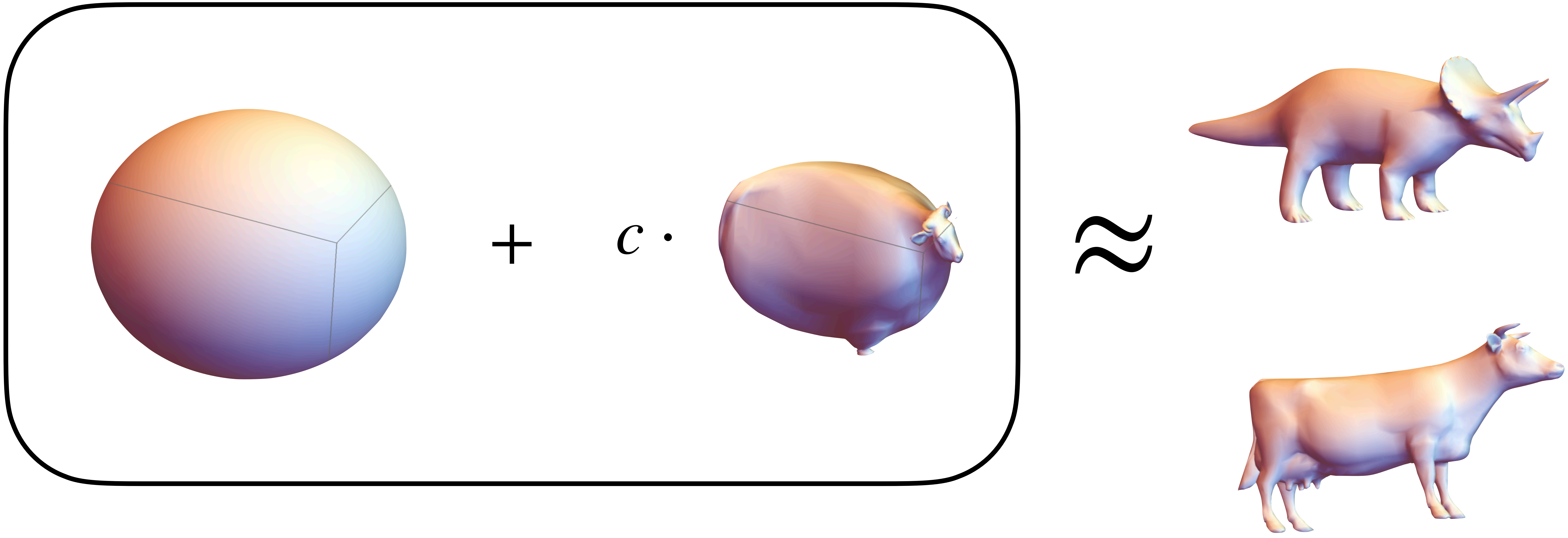
$\approx$



Goal: find the value of c, and precisely!

The SMEFT philosophy

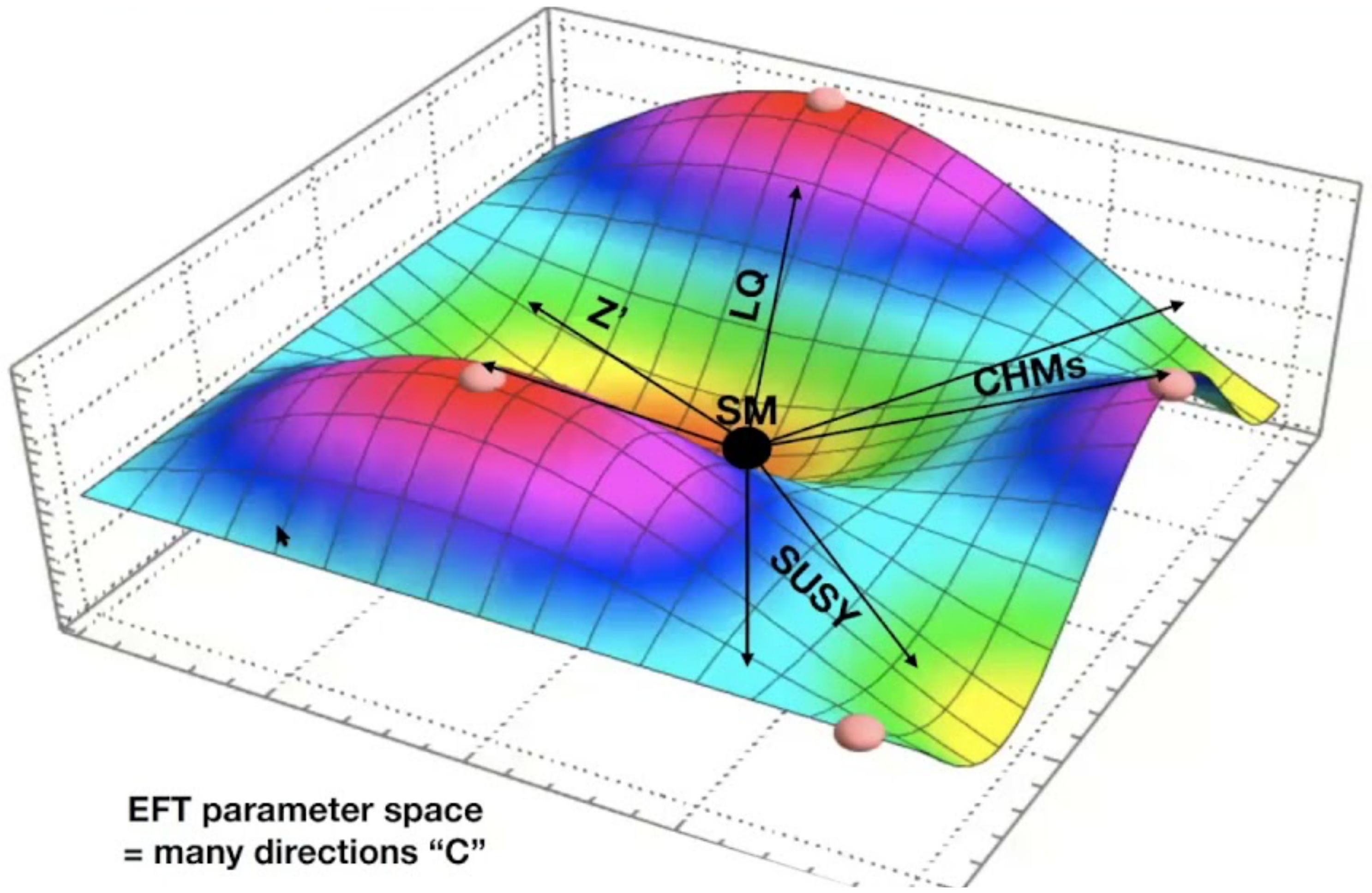
The SM EFT New Physics



Goal: find the value of c, and precisely!

SMEFT requirements

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_{i}^{N_{d5}} \frac{c_i}{\Lambda} \mathcal{O}_i^{(5)} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$



EFT parameter space
= many directions "C"

- The SMEFT parameterises the **theory space around the SM**
- Defines a perfectly valid QFT that is **renormalisable** order by order in Λ
- Operators are constructed out of **SM fields only**
- Respects the SM **symmetries**
- Forms a **complete basis** at any given mass dimension

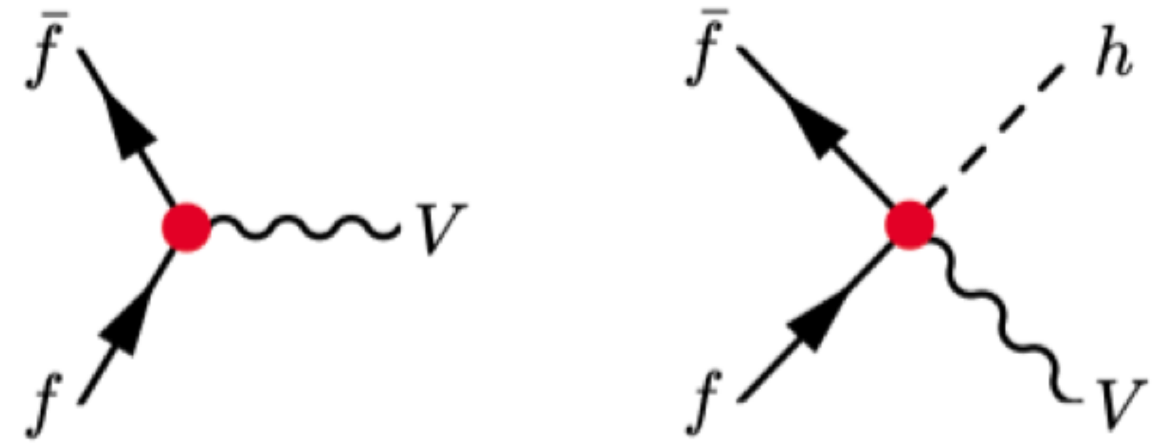
The Warsaw basis

arXiv: 1008.4884

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

Current operators

Adapted from K. Mimasu



- Shift SM $f\bar f V$ couplings
- $f\bar f V h$ contact interactions

Contact interactions grow with energy and thus provide a sensitive probe in the TeV region

The Warsaw basis

arXiv: 1008.4884

Adapted from
K. Mimasu

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
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$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
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$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

Contact interactions grow with energy and thus provide a sensitive probe in the TeV region

The Warsaw basis

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$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\,\widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\,W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\,B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\,\widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\,G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
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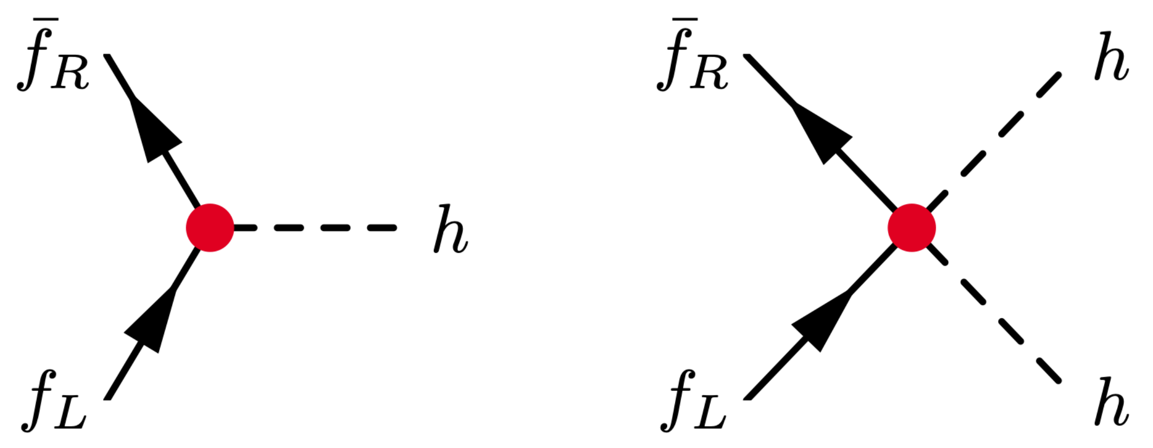
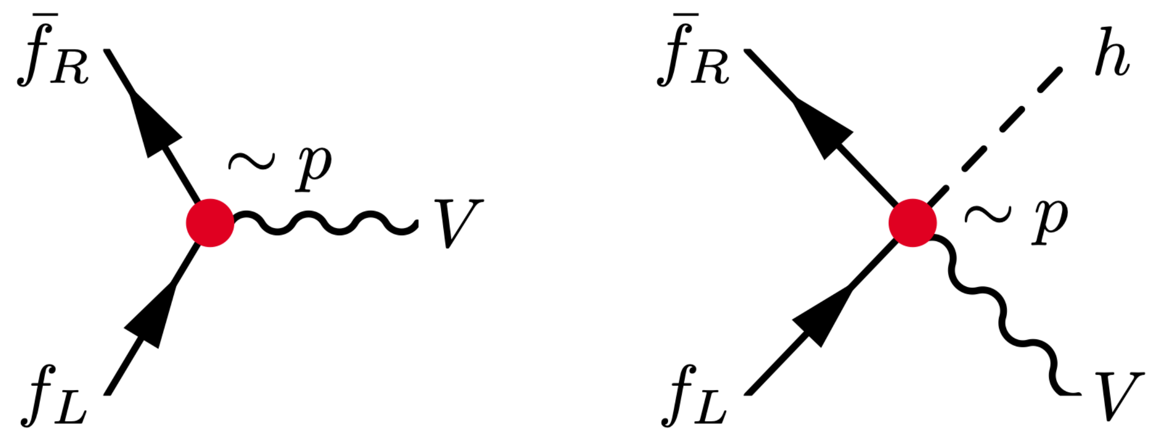
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\,\widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\,B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Yukawa operators



- Decouple m_f and y_f
- $f\bar{f}hh(h)$ contact interactions

Dipole operators



- Chirality flipping $f\bar{f}V$ couplings
- $f\bar{f}Vh(h)$ contact interactions
- Momentum dependent vertex

The Warsaw basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$
$Q_{\widetilde{W}}$	$\varepsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$	Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$	Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
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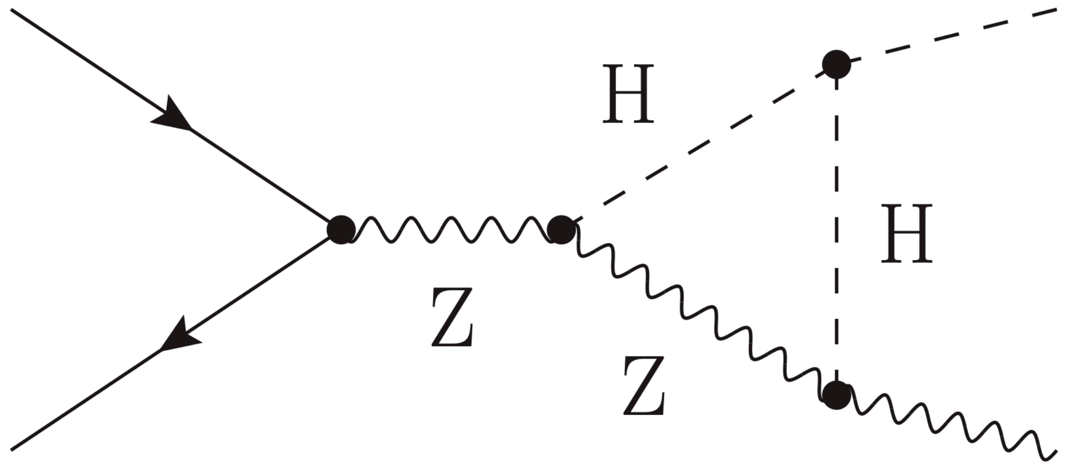
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

Bosonic operators



- H^6 modifies the Higgs self-coupling
- Enters at NLO EW in $e^+e^- \to ZH$

arXiv: 2406.03557

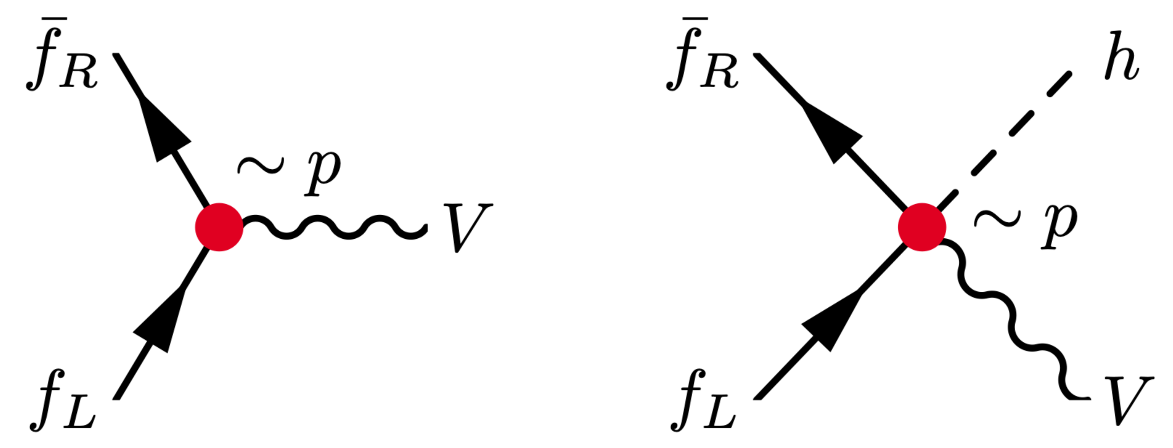
The Warsaw basis

X^3	φ^6 and $\varphi^4 D^2$	$\psi^2\varphi^3$
Q_G		
$Q_{\widetilde G}$		
Q_W		
$Q_{\widetilde W}$		
$Q_{\varphi G}$		
$Q_{\varphi \widetilde G}$		
$Q_{\varphi W}$		
$Q_{\varphi \widetilde W}$		
$Q_{\varphi B}$		
$Q_{\varphi \widetilde B}$		
$Q_{\varphi WB}$		
$Q_{\varphi \widetilde W B}$		

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

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

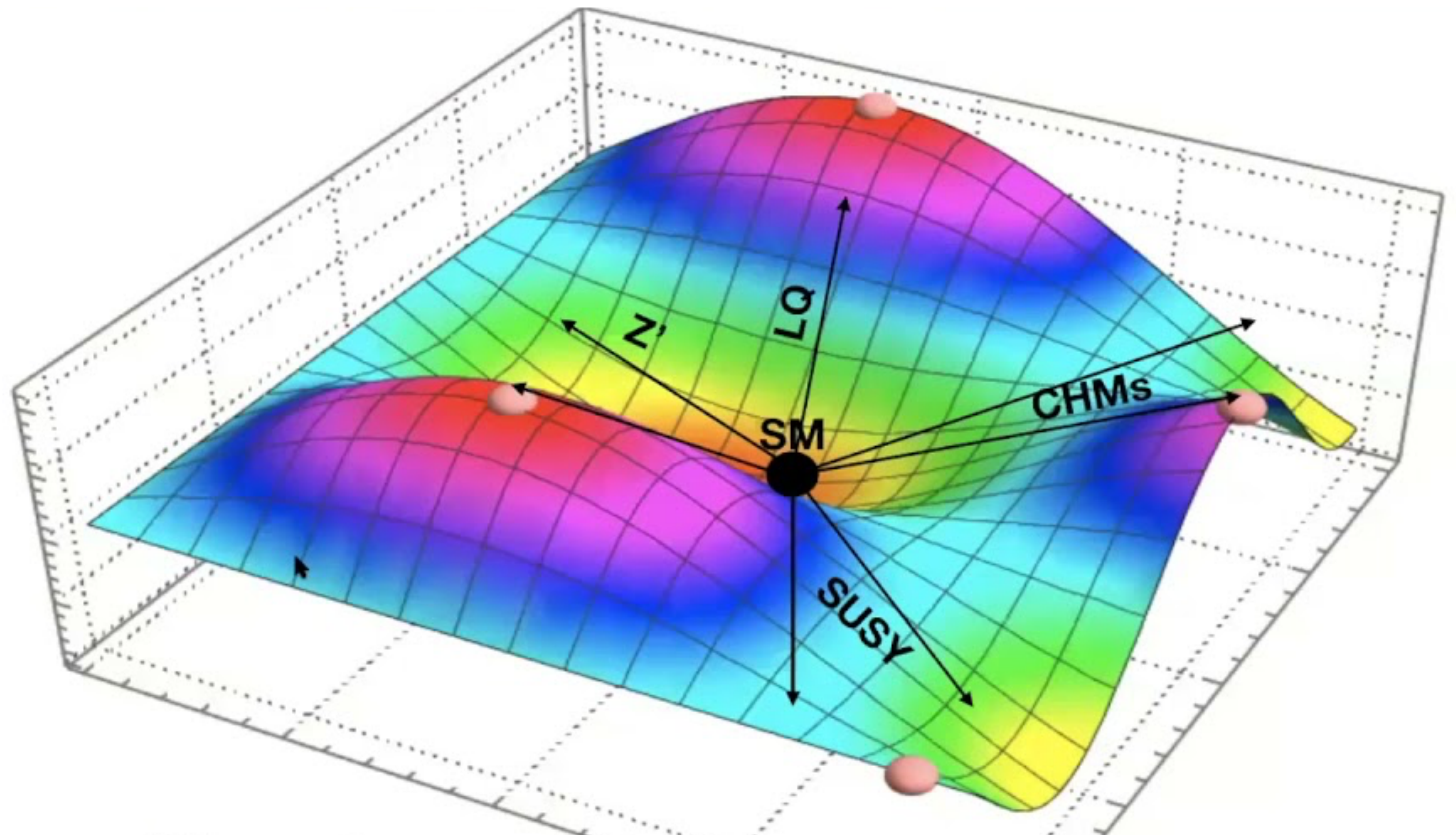
Four-fermion operators



- Contact interactions
- 2205 B/L preserving

SMEFT predictions

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \sum_{i}^{N_{d5}} \frac{c_i}{\Lambda} \mathcal{O}_i^{(5)} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} \mathcal{O}_i^{(6)} + \dots$$



EFT parameter space
= many directions "C"

$$\sigma_{\rm SMEFT}(c,\Lambda) = \sigma_{\rm SM} \times \left(1 + \sum_{i}^{N_{d6}} \kappa_i \frac{c_i}{\Lambda^2} + \sum_{i<j}^{N_{d6}} \tilde{\kappa}_{ij} \frac{c_i \cdot c_j}{\Lambda^4} + \mathcal{O}\left(\Lambda^{-6}\right) \right)$$

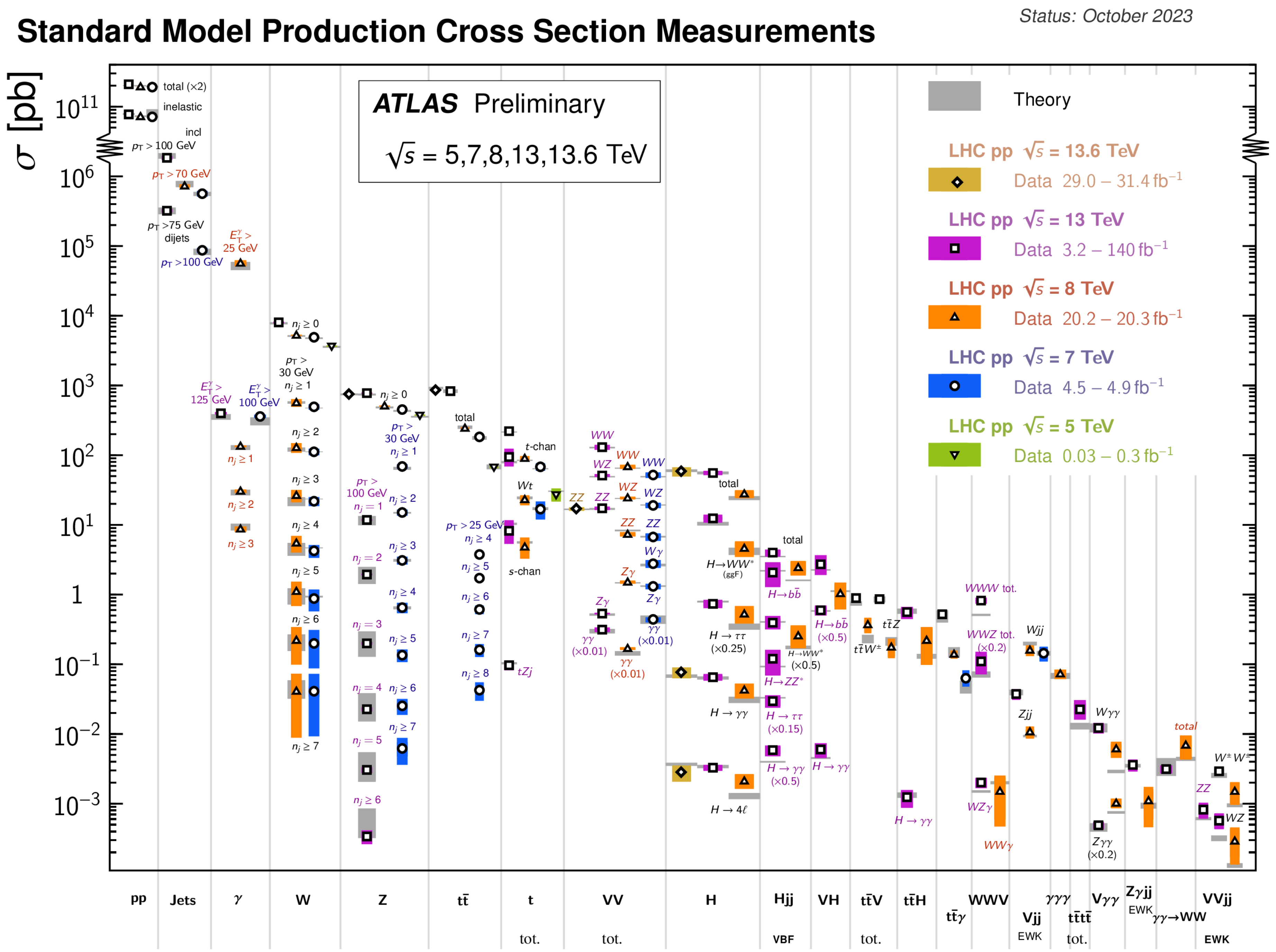
Linear EFT corrections:
interference with SM

Quadratic EFT corrections

Building the likelihood

$$\chi^2 = \frac{1}{n_{\rm dat}} \sum_{i,j=1}^{n_{\rm dat}} \left(\sigma_{i,{\rm SMEFT}}(c) - \sigma_{i,{\rm exp}}\right) \left({\rm cov}^{-1}\right)_{ij} \left(\sigma_{j,{\rm SMEFT}}(c) - \sigma_{j,{\rm exp}}\right)$$

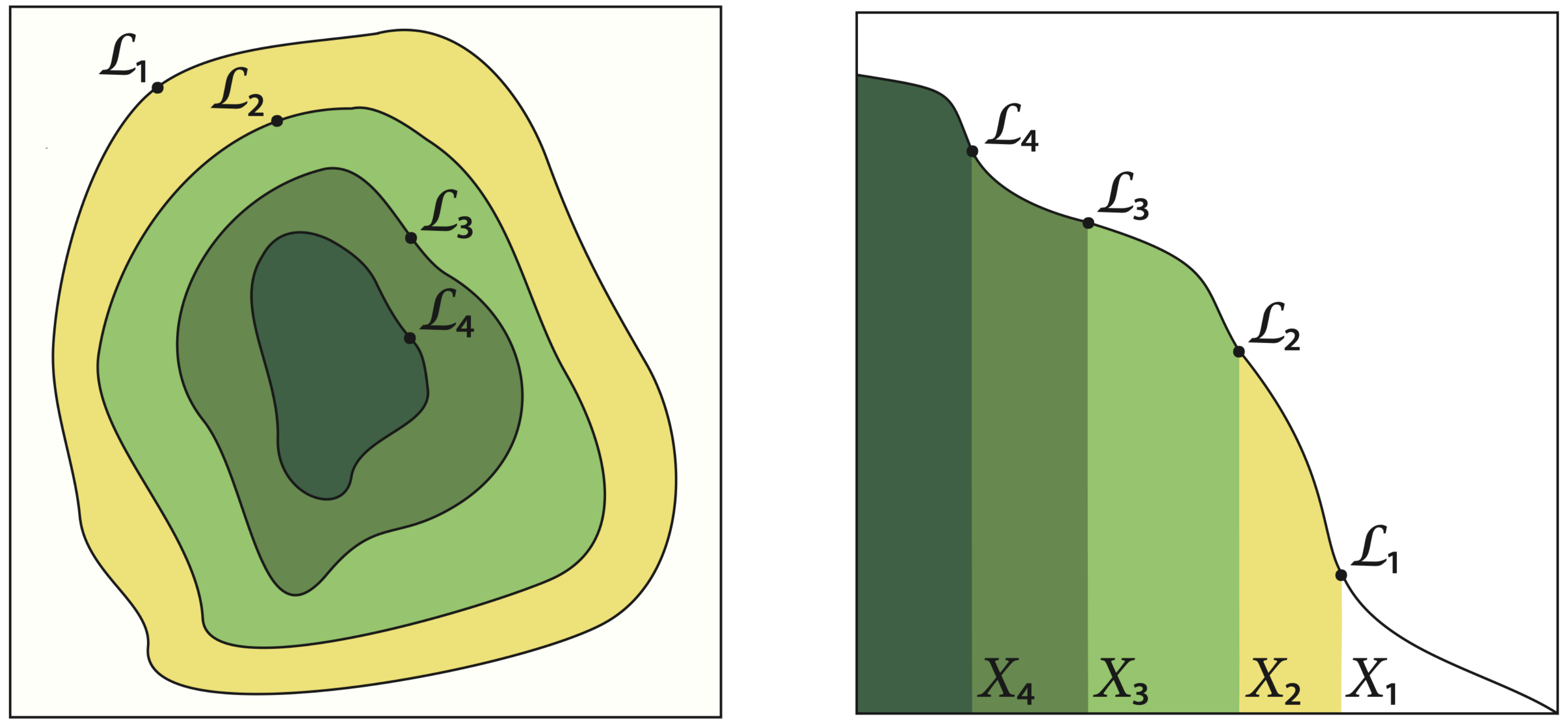
[ATL-PHYS-PUB-2023-039]



$${\rm cov}^{({\rm tot})}_{ij} = {\rm cov}^{({\rm th})}_{ij} + {\rm cov}^{({\rm exp})}_{ij}$$

Analytic if $\mathcal{O}\left(\Lambda^{-2}\right)$, fast!

Nested Sampling $\mathcal{O}\left(\Lambda^{-2}\right)$ or $\mathcal{O}\left(\Lambda^{-4}\right)$

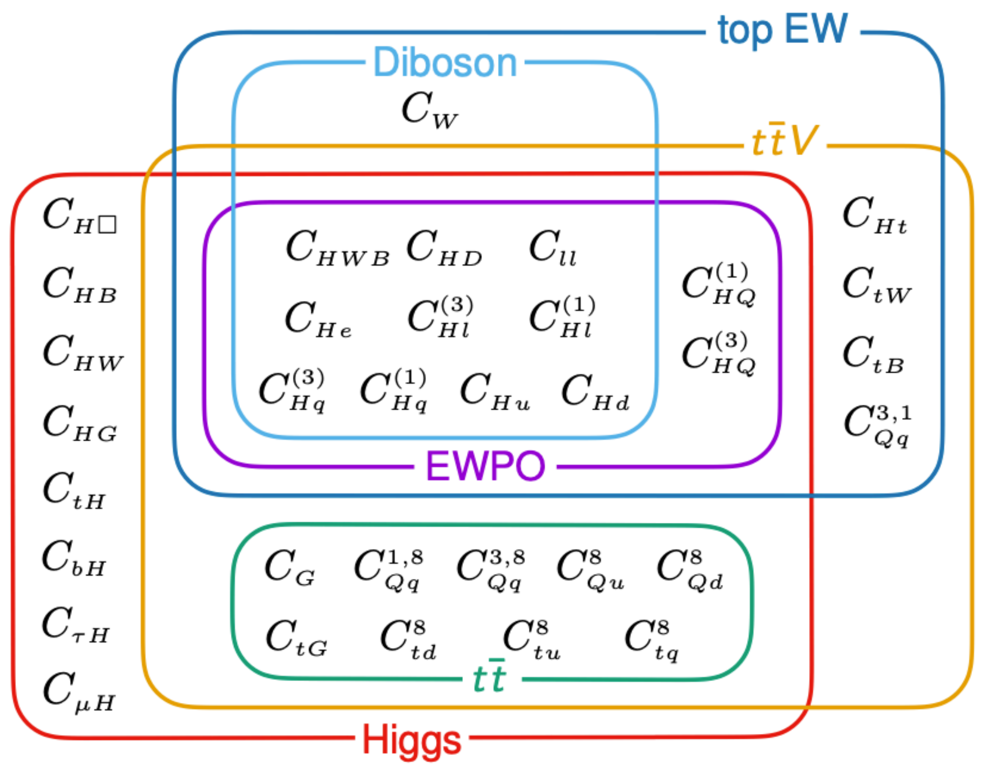


Feroz et al [1306.2144]

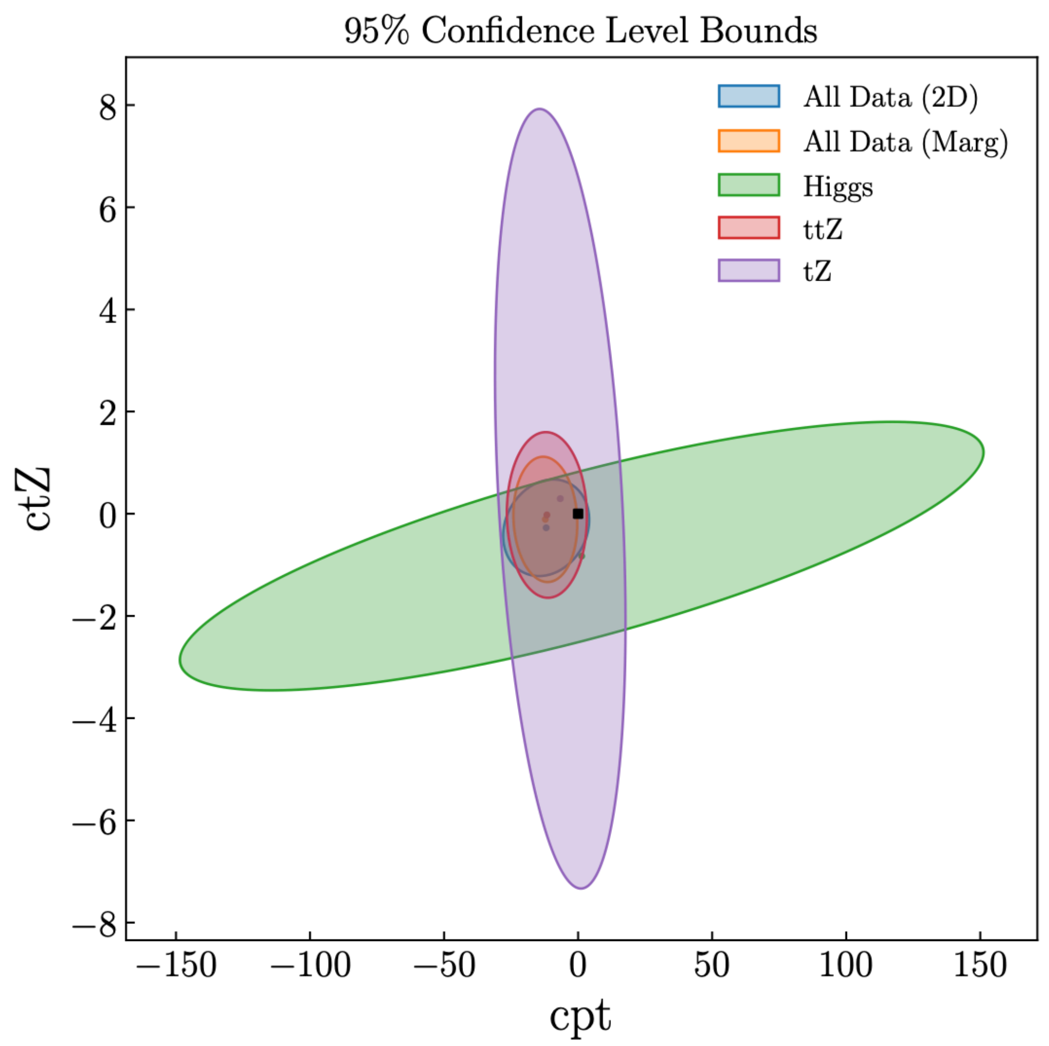
Why global SMEFT fits?

- **Cross-talk** between Higgs, top, diboson and EWPO (and flavour and low energy observables) requires a global analysis

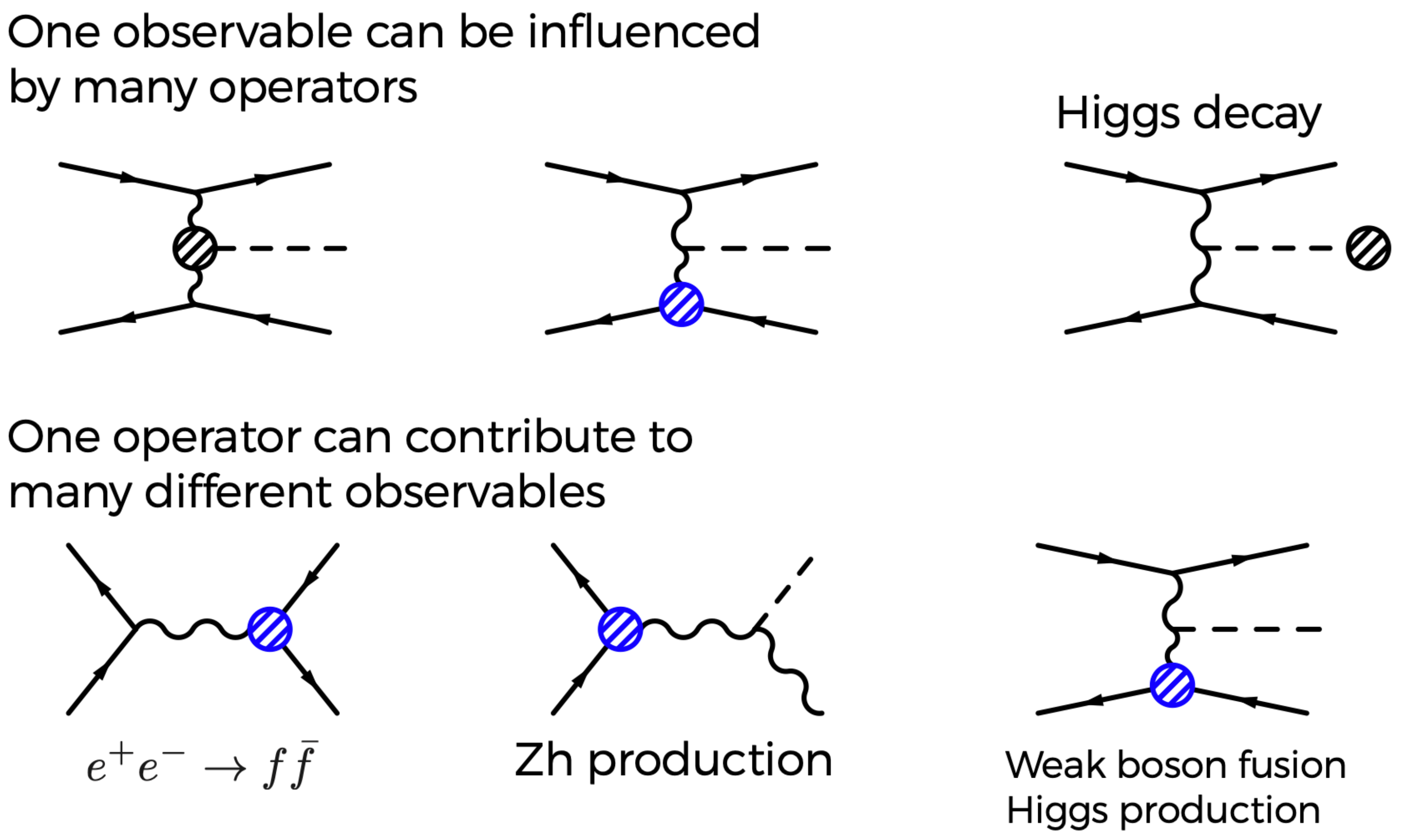
- **Challenge**: a large number of operators, with many datasets needed to break degeneracies



[2012.02779] Fitmaker collaboration

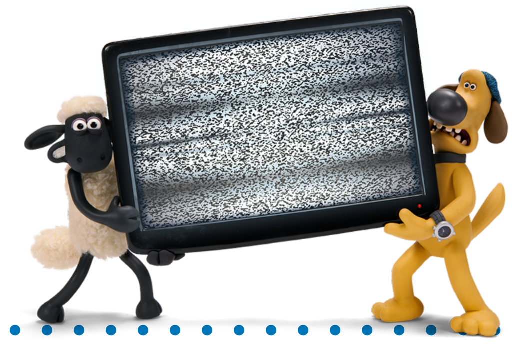


[2105.00006] SMEFiT collaboration

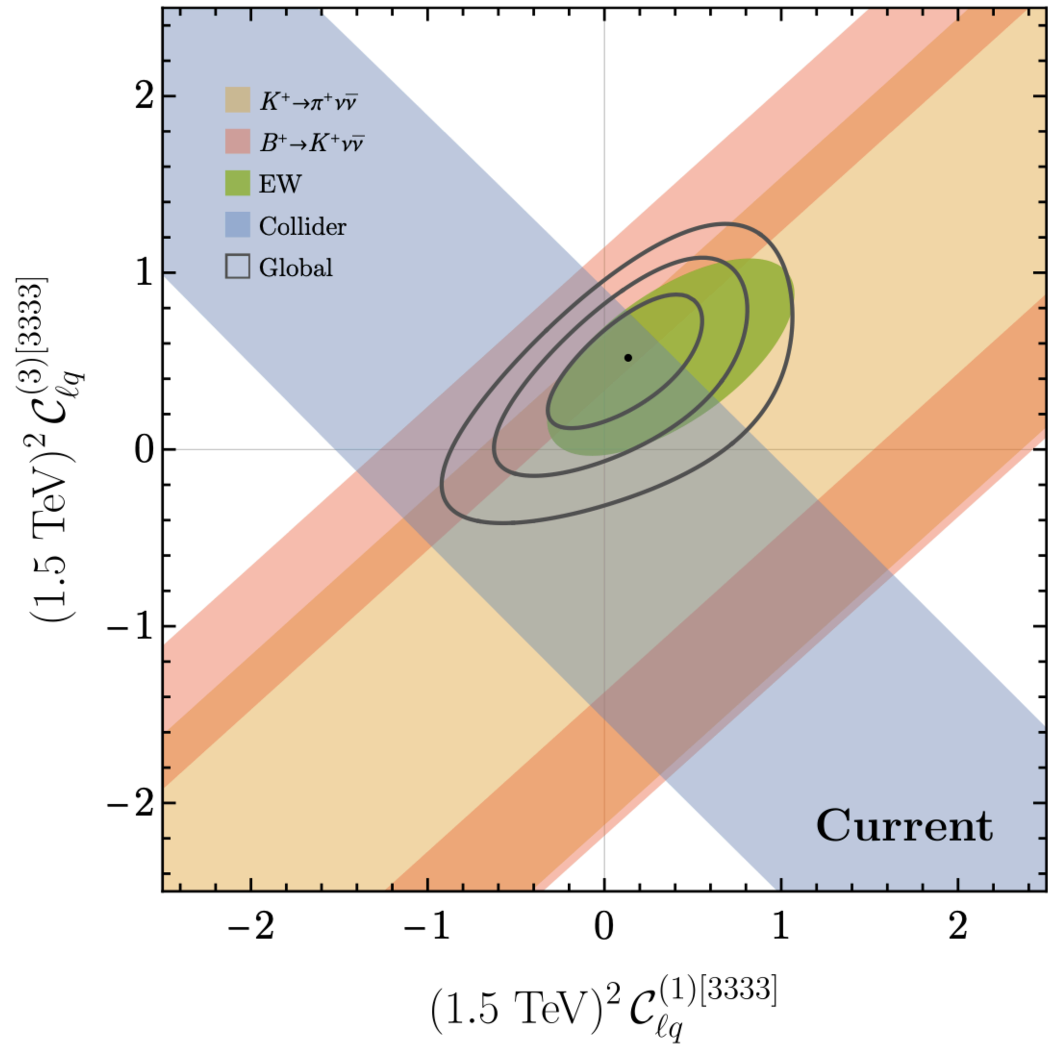


Anke Biekötter - HET seminar Brookhaven

Previously on global fits…



- **SMEFiT**: EW + Higgs + diboson + top + projections, NLO, quadratic - *[2105.00006, 2309.04523 , 2404.12809]*
- **ATLAS**: EW + Higgs, LO, quadratic - *[ATL-PHYS-PUB-2022-037]*
- **simuNET:** simultaneous EFT + PDF fit in EW + Higgs + diboson + top, NLO, linear - *[2402.03308]*
- **Fitmaker**: EW + Higgs + top + diboson, linear - *[2012.02779, 2204.05260]*
- **SFitter**: EW + Higgs, top, NLO, quadratic - *[1812.07587, 1910.03606]*
- **HEPfit:** EW, flavour, projections, LO, linear - *[1910.14012]*
- **TopFitter:** top, linear, LO - *[1901.03164]*
- **EFTfitter:** top + DY + flavour, LO, quadratic, RG effects - *[1605.05585, 2304.12837]*
- **Mainz group:** EW + Higgs + top + flavour + dijet + PV + lepton scattering, NLO, linear - *[2311.04963]*
- **Zurich group:** EW + flavour + (DY, LEPII, Jet observables), individual, RG effects - *[2311.00020]*
- ………

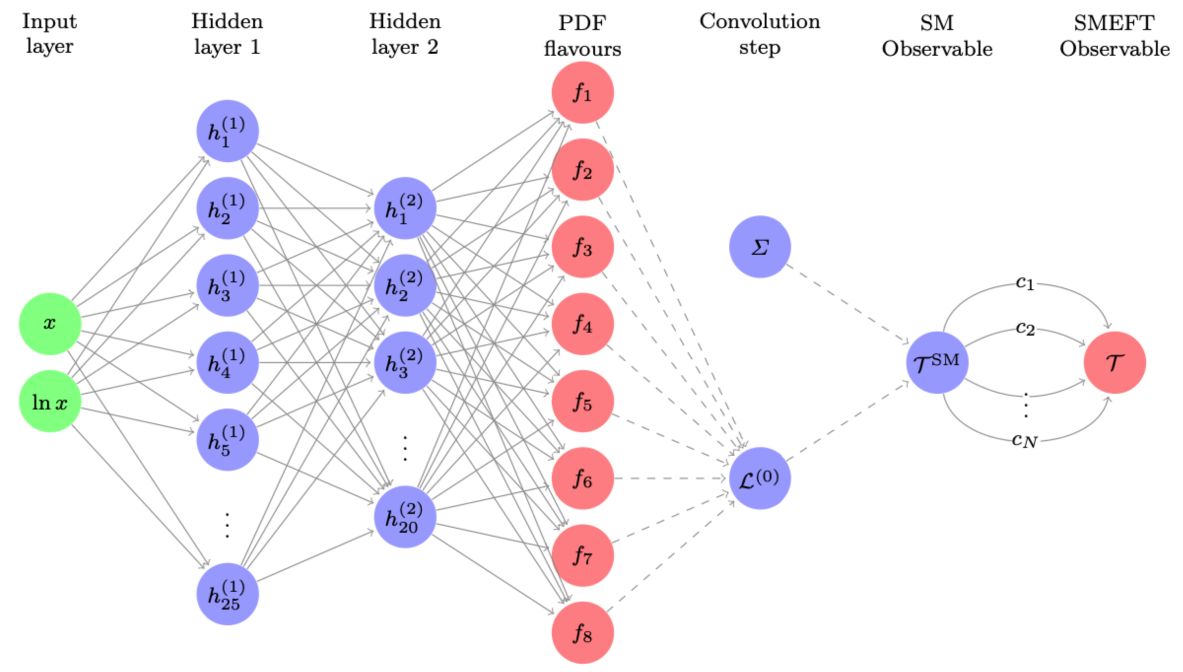


arXiv:2311.00020

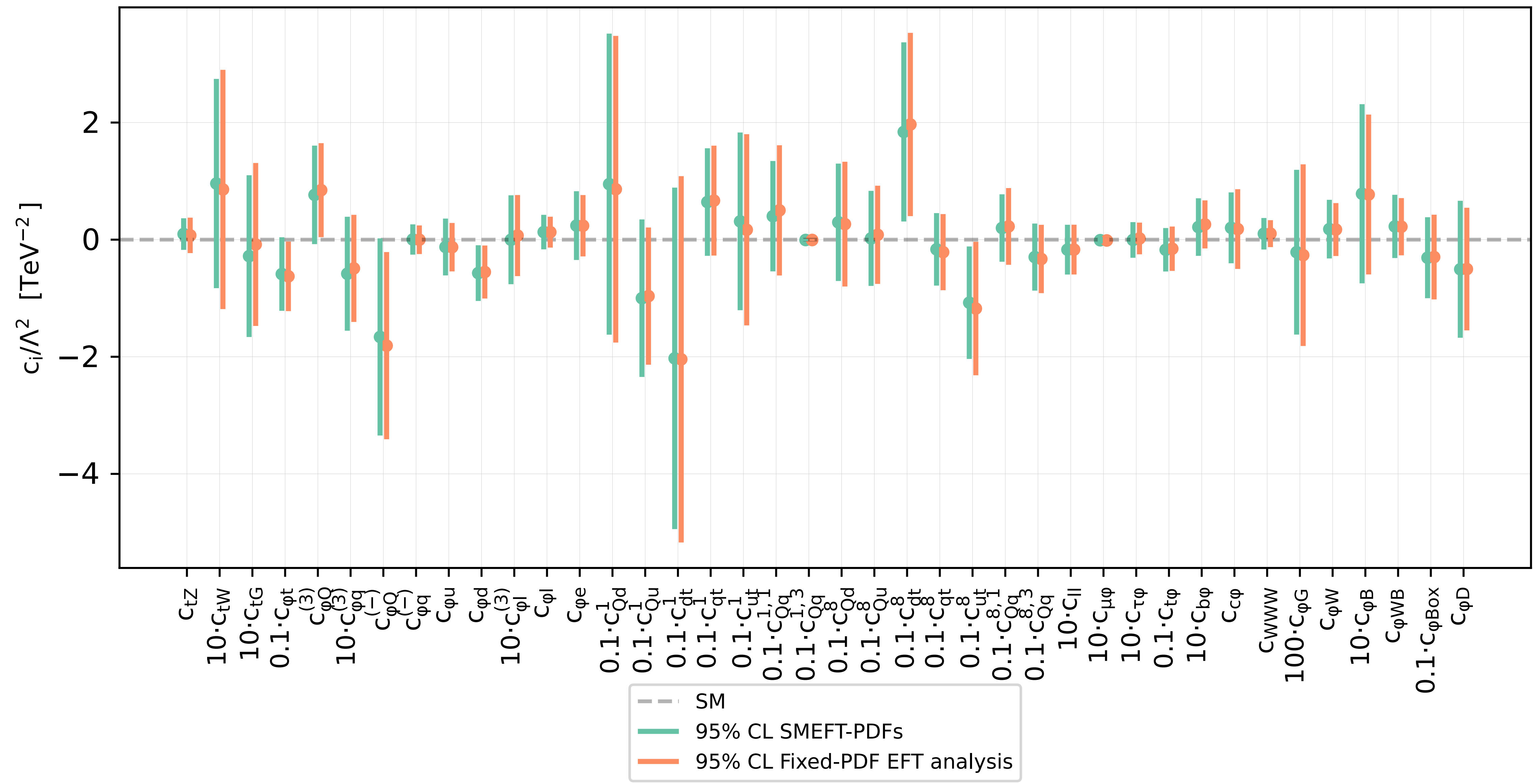
simuNET: a simultaneous PDF + EFT fit

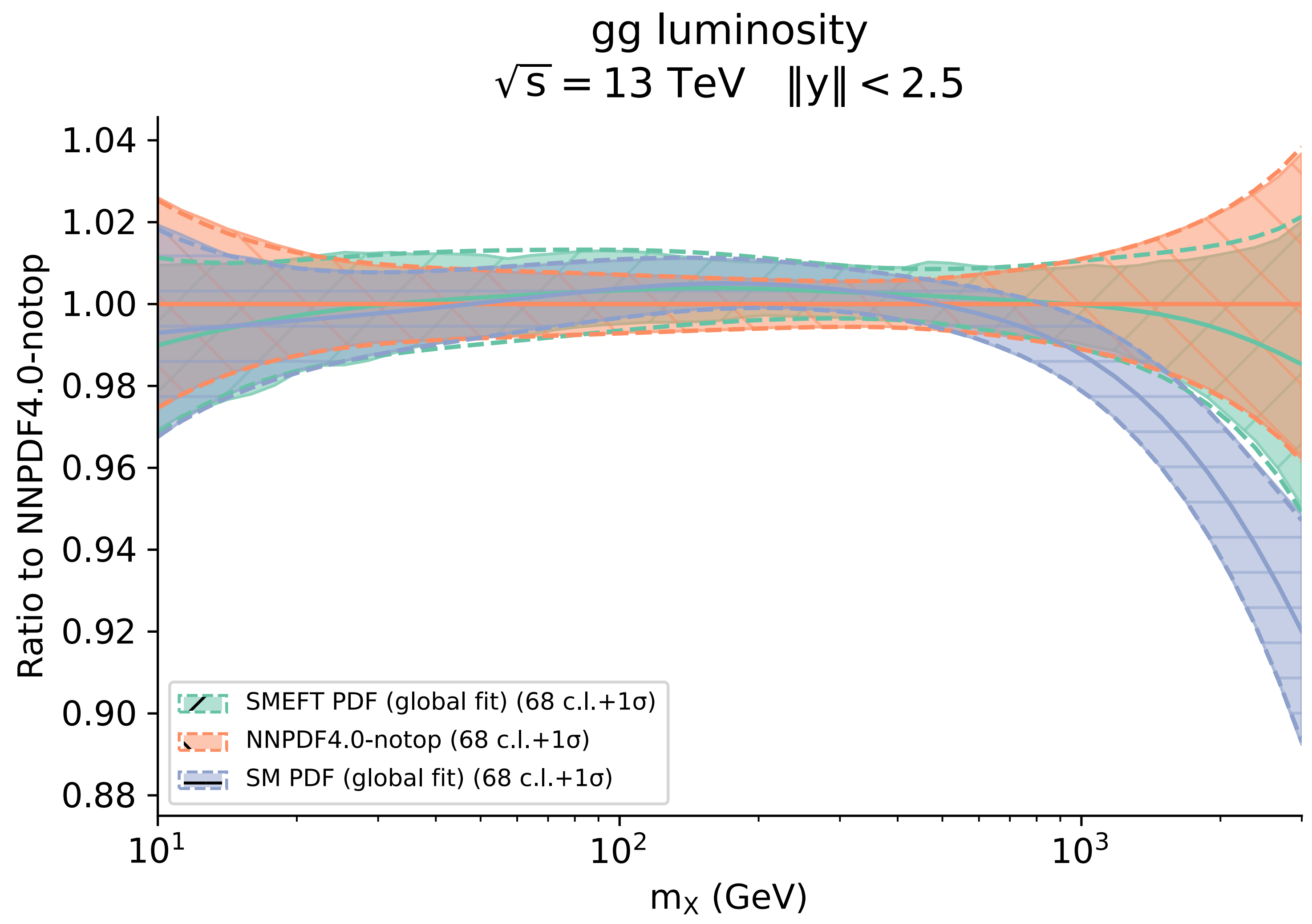
Costantini, Hammou, Madigan, Mantani, Moore, Morales, Ubiali [2402.03308]

- Most EFT global fits assume a fixed PDF set. Ideally, a full treatment fits the EFT and PDF parameters **simultaneously**, as done by simuNET



- EFT parameters are stable, while the PDF fits undergo **shifts** at high invariant mass in e.g. the gluon-gluon luminosity





RGE in the SMEFT

Connecting scales

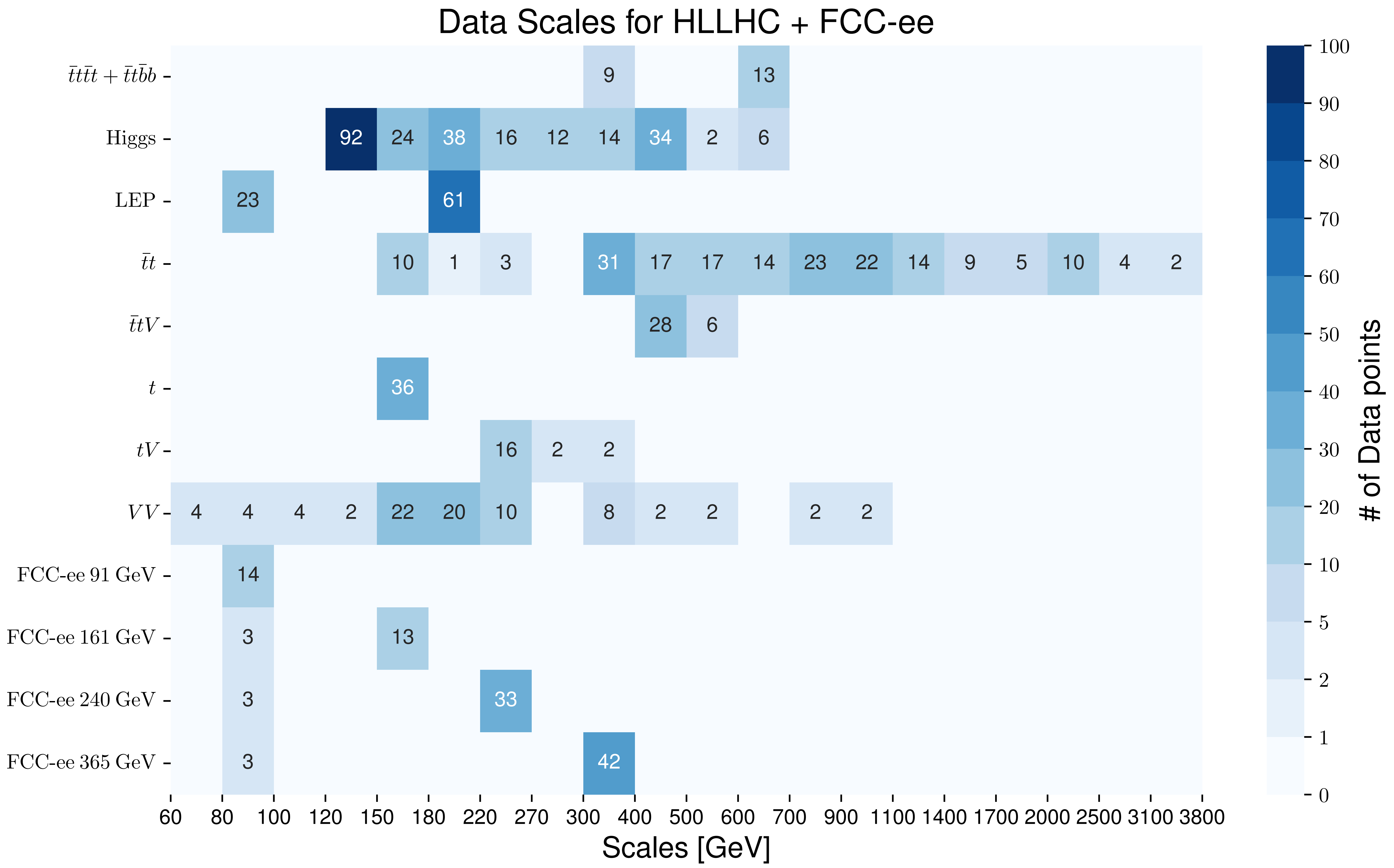
- Experimental input to global fits spans **a wide range of different energy scales,** from m_Z at LEP to $m_{t\bar{t}} \sim 3\,\mathrm{TeV}$ in tails at LHC

- Wilson coefficients run with energy

$$\frac{dc_i(\mu)}{d\ln\mu} = \sum_{j=1}^{n_{\rm op}} \gamma_{ij}^{(6)}(\bar{g})\, c_j(\mu)$$

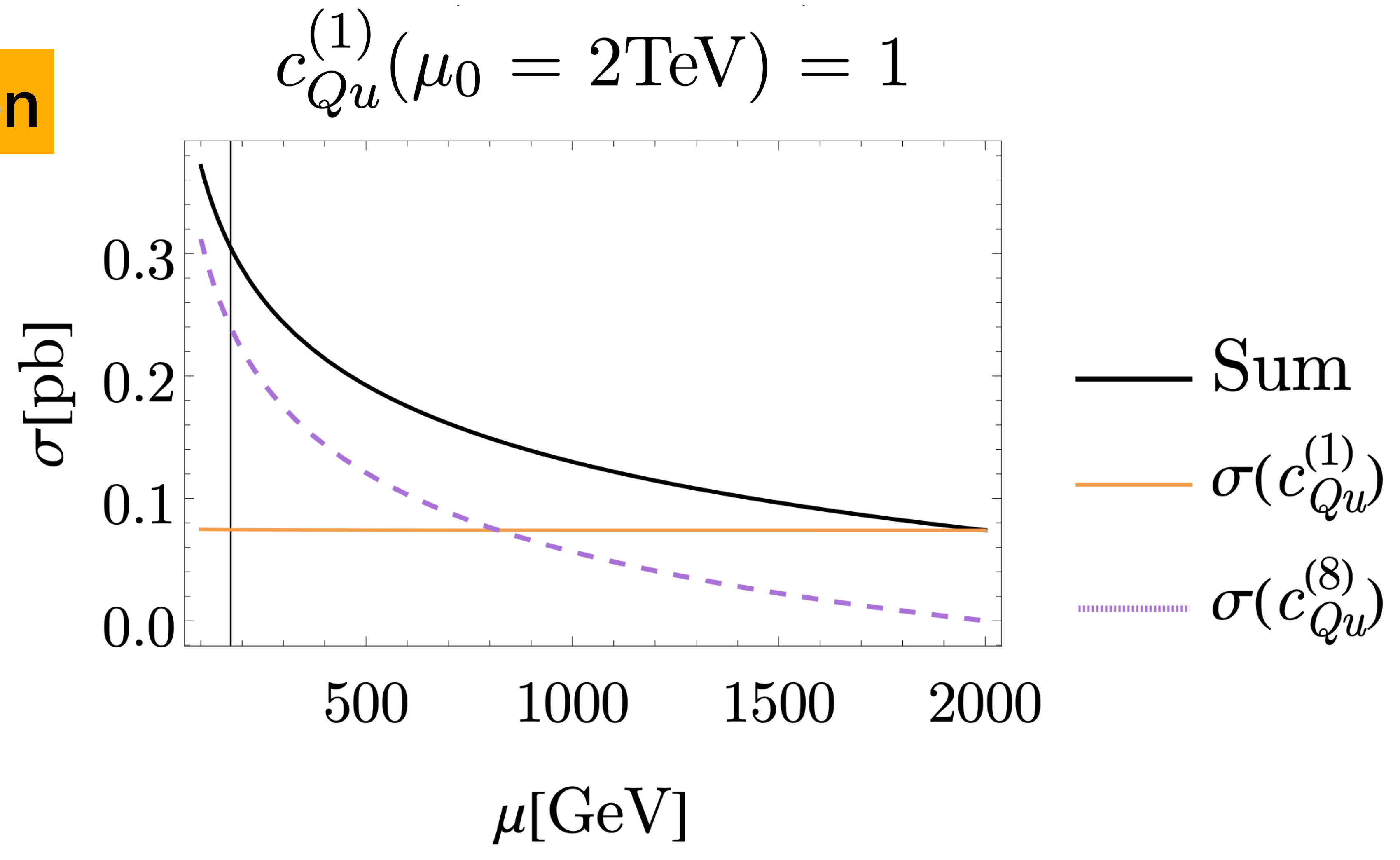
Jenkins, Manohar, Trott, Alonso
arXiv:1308.2627, 1310.4838, 1312.2014

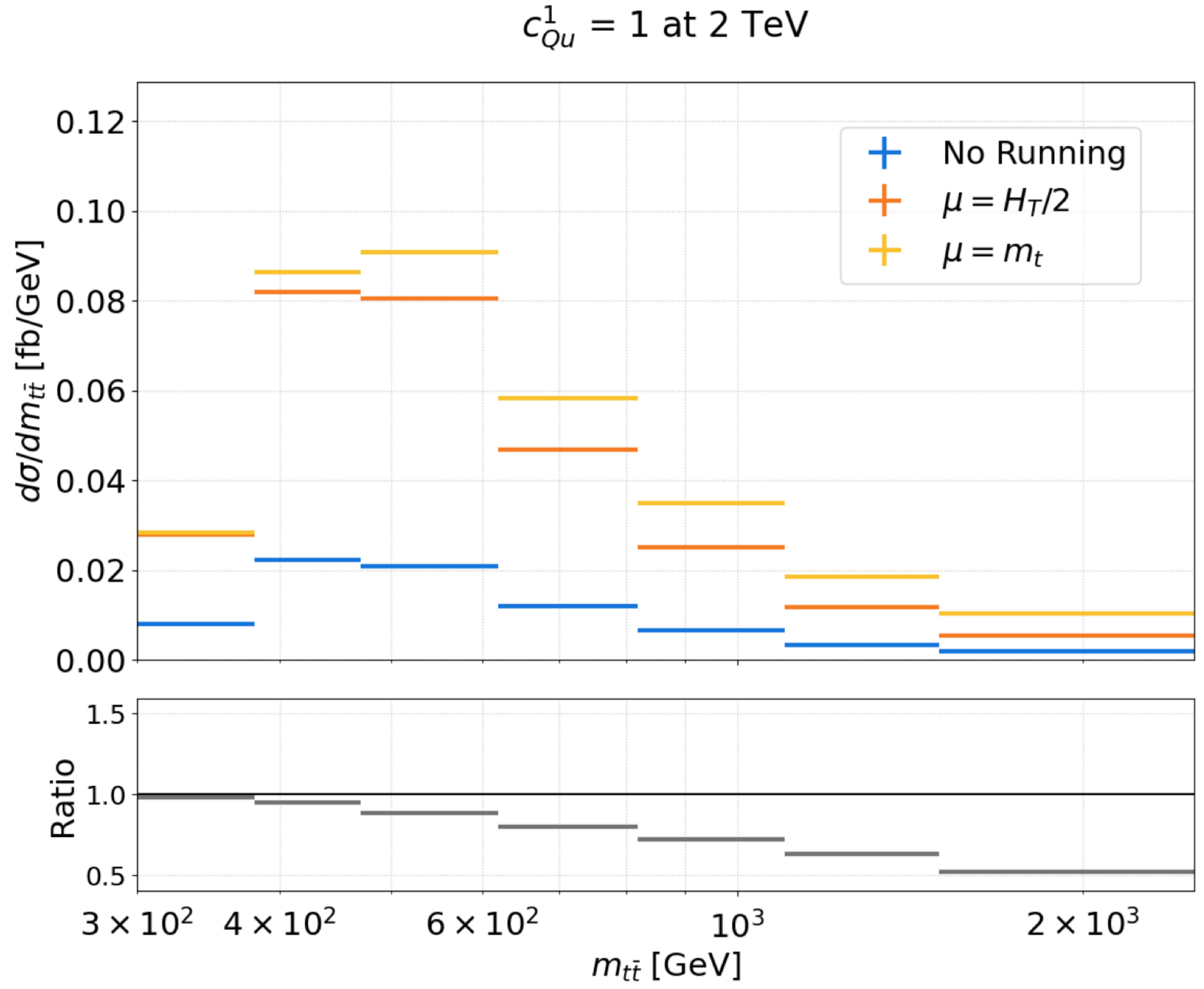
- Operator mixing through the anomalous dimension



RGE in SMEFT phenomenology

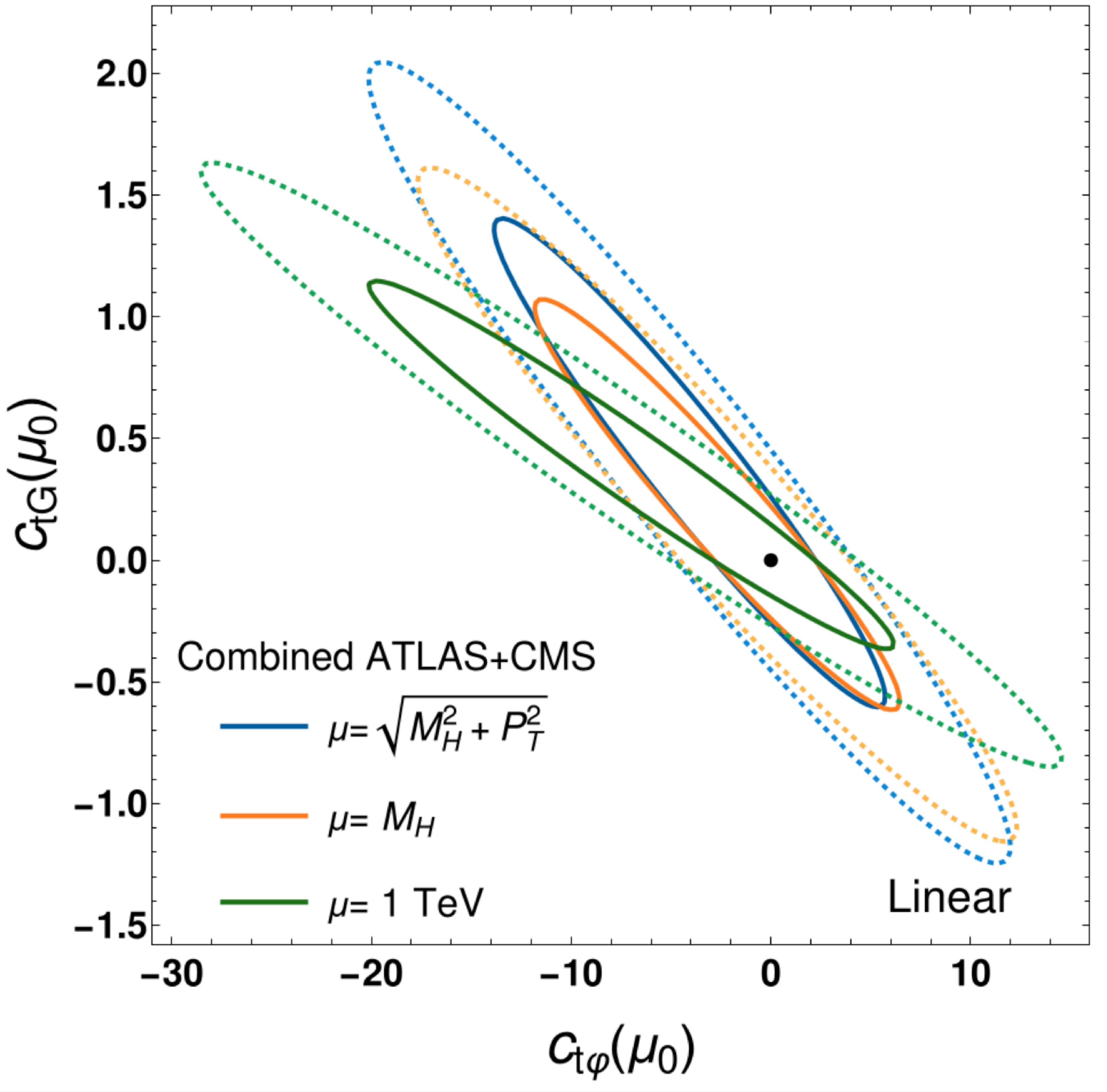
Top pair production





Aoude et al.
arXiv: 2212.05067

Higgs production



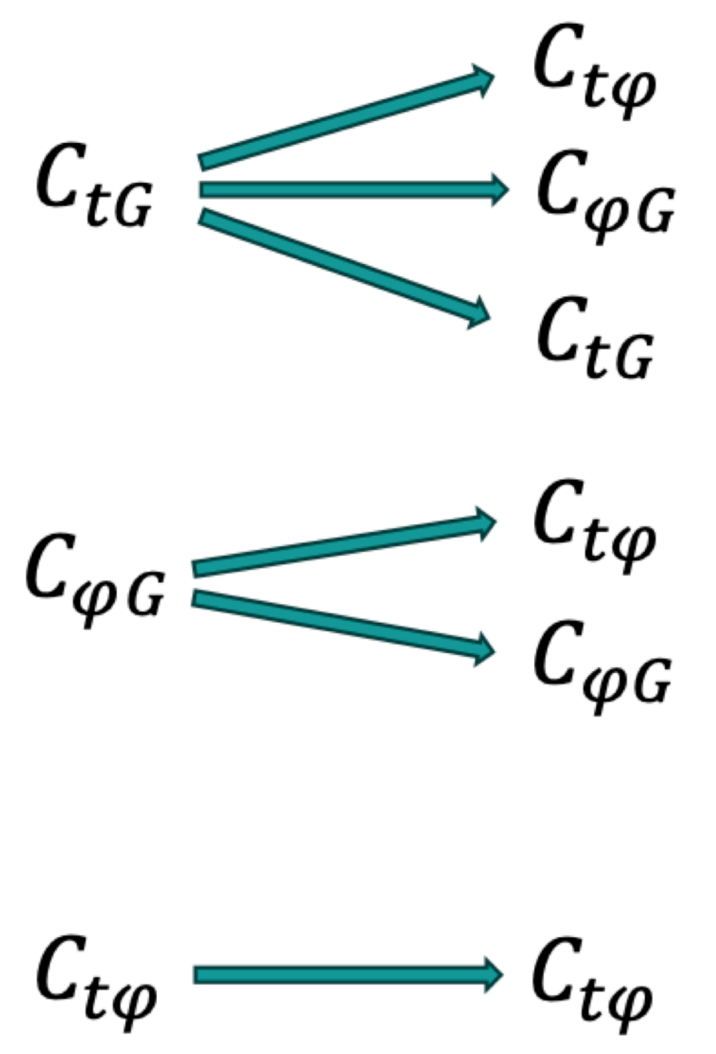
Maltoni, Ventura, Vryonidou
arXiv: 2406.06670

RGE in SMEFiT

- We include RG effects in the **Matrix evolution approximation** interfaced to Wilson

$$c_i(\mu) = \sum_{j=1}^{n_{\rm op}} \Gamma_{ij}(\mu, \mu_0; \alpha_s, \alpha) c_j(\mu_0)$$

[1804.05033] Aebischer, Kumar, Straub



- Express theory predictions at a common scale μ_0

$$\begin{aligned} T_{\rm EFT}(\boldsymbol{c}(\mu)/\Lambda^2) &= T_{\rm SM} + \sum_{i=1}^{n_{\rm op}} \kappa_i \frac{c_i(\mu)}{\Lambda^2} + \sum_{i,j=1}^{n_{\rm op}} \widetilde{\kappa}_{ij} \frac{c_i(\mu) c_j(\mu)}{\Lambda^4} \\ &= T_{\rm SM} + \sum_{i,j=1}^{n_{\rm op}} \kappa_i \Gamma_{ij} \frac{c_j(\mu_0)}{\Lambda^2} + \sum_{i,j,k,\ell=1}^{n_{\rm op}} \widetilde{\kappa}_{ij} \Gamma_{ik} \Gamma_{j\ell} \frac{c_k(\mu_0) c_\ell(\mu_0)}{\Lambda^4} \\ &= T_{\rm SM} + \sum_{j=1}^{n_{\rm op}} \kappa'_j \frac{c_j(\mu_0)}{\Lambda^2} + \sum_{k,\ell=1}^{n_{\rm op}} \widetilde{\kappa}'_{k\ell} \frac{c_k(\mu_0) c_\ell(\mu_0)}{\Lambda^4} \end{aligned}$$

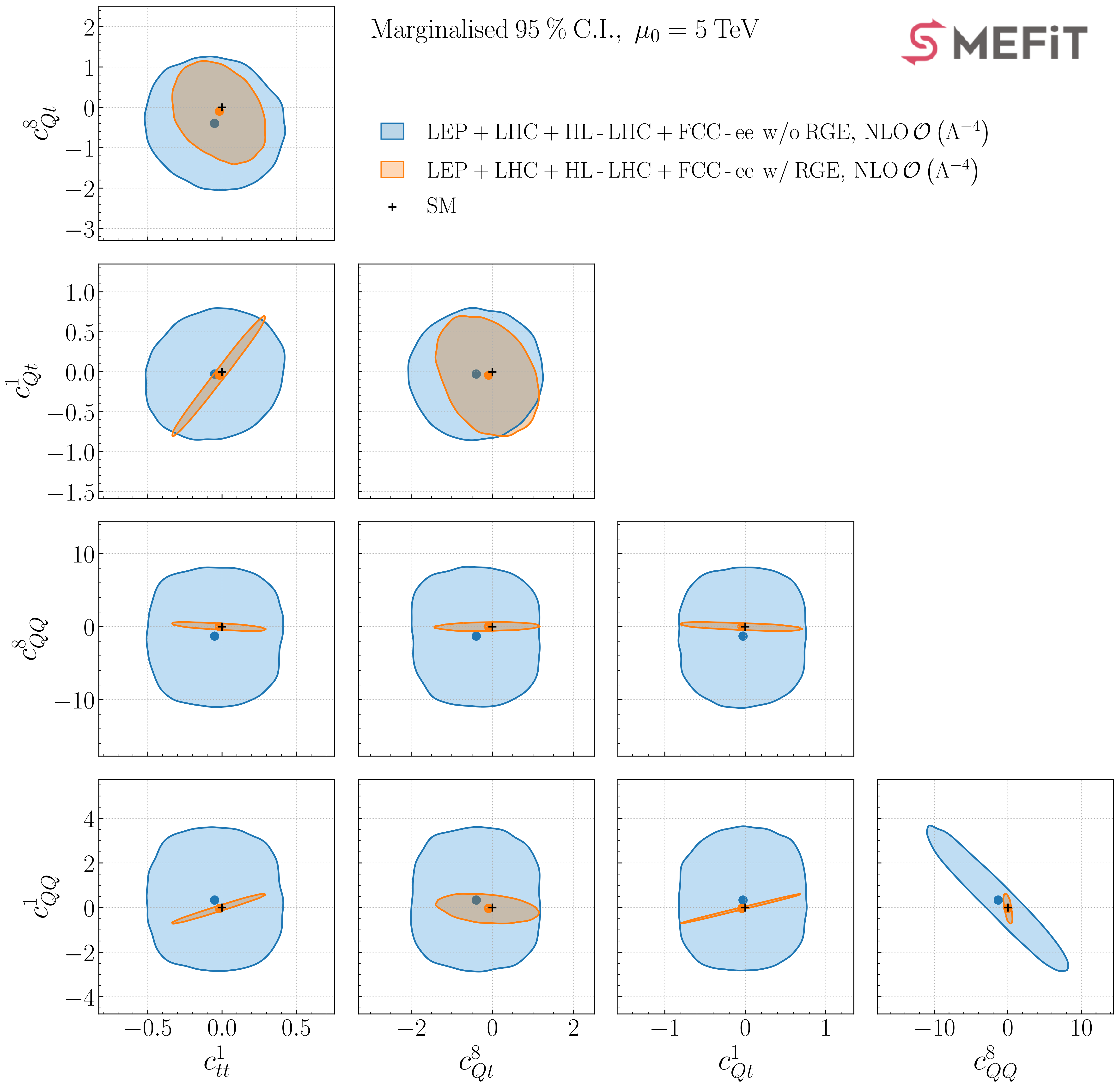
RGE in SMEFiT

- We associate a fixed characteristic scale choice μ to **each bin**
- "Event by event" running was performed in by Aoude et al in arXiv: 2212.05067
- We have studied the impact of our scale choice by varying $\mu \to \tilde{\mu} = \kappa\mu$

Process	**Scale Choice** μ	**Process**	**Scale Choice** μ
Higgs (ggF)	$\sqrt{m_H^2 + (p_T^H)^2}$	$t\bar{t}b\bar{b}$	$2m_t$
Higgs (VBF)	$\sqrt{m_H^2 + (p_T^H)^2}$	$t\bar{t}V$	$\sqrt{(2m_t + m_V)^2 + (p_T^V)^2}$
VH	$\sqrt{(m_V + m_H)^2 + (p_T^V)^2}$	tV	$m_t + m_V$ or $\sqrt{(m_t + m_V)^2 + (p_T^t)^2}$
$t\bar{t}H$	$\sqrt{(2m_t + m_H)^2 + (p_T^H)^2}$	W-helicities	m_t
tH	$m_t + m_H$	WZ	m_T^{WZ} or $\sqrt{(m_Z + m_W)^2 + (p_T^Z)^2}$
$t\bar{t}$	m_{tt}	WW	$m_{e\mu}$
Single-t	m_t	V pole (incl. EWPOs)	m_V
$t\bar{t}\gamma$	$2m_t$	Bhabha scattering	$\sqrt{s}$
$t\bar{t}t\bar{t}$	$4m_t$	$e^+e^- \to WW\,/\,t\bar{t}\,/\,f\bar{f}$	$\sqrt{s}$
HH	$2m_H$	$e^+e^- \to ZH$	$\sqrt{s}$

RG in restricted operator basis

*Mantani, Rojo, Rossia, Vryonidou, **JtH***
arXiv: 2502.20453

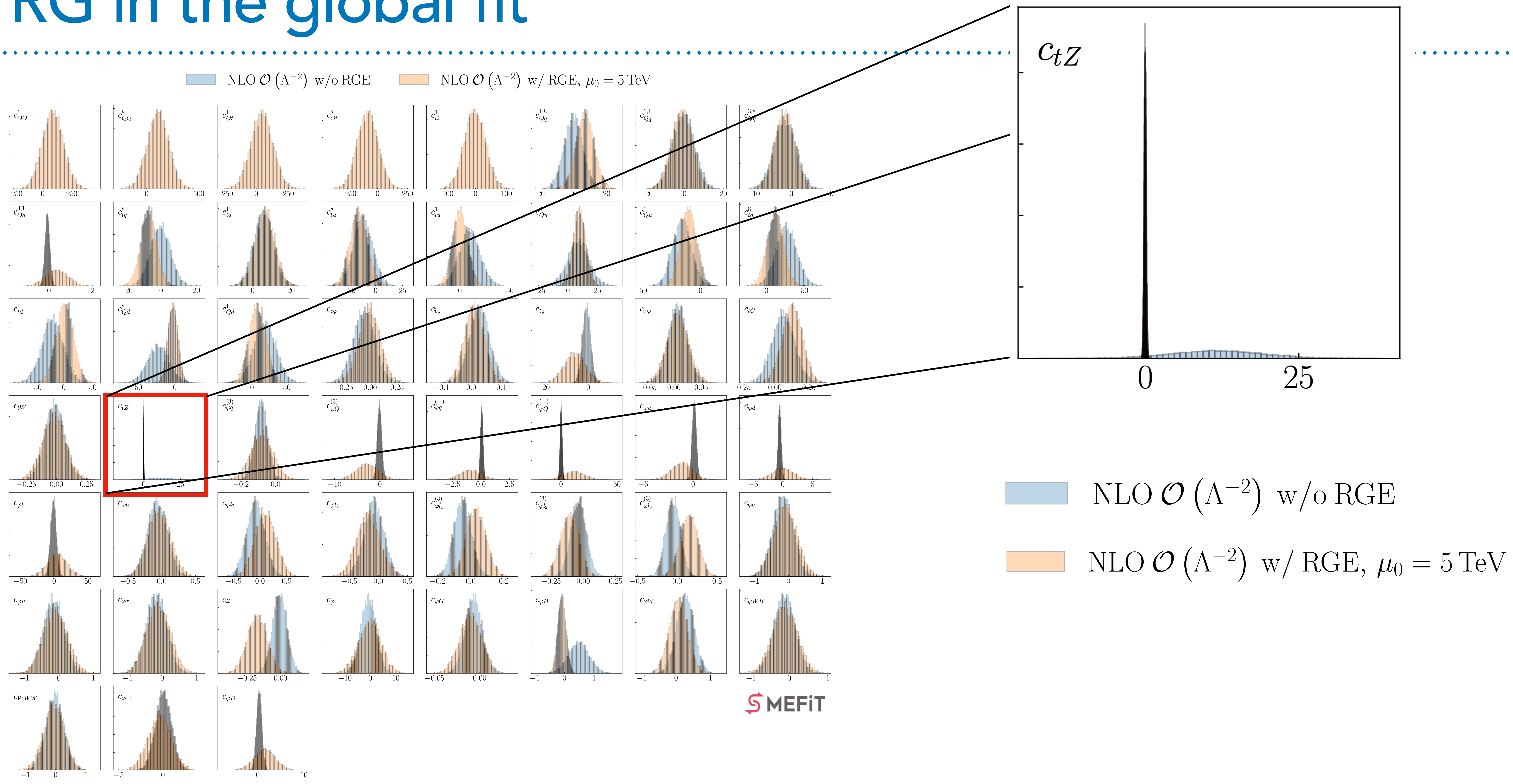


Example: 4 heavy operators flow into operators sensitive to the EWPOs at low energy

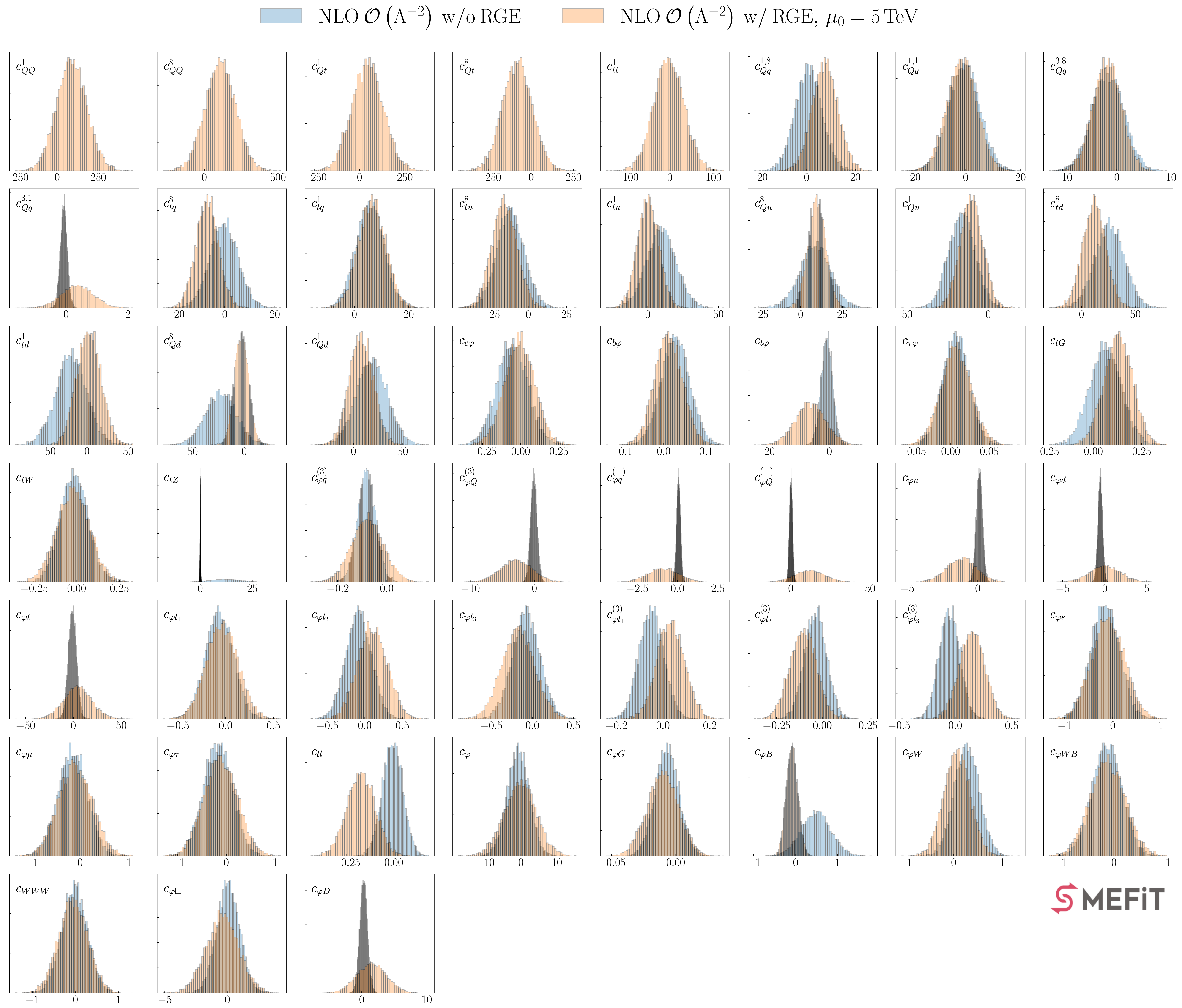
In general one may see two competing effects:

- Ill constrained operators may flow into a precisely determined observable
- More operators enter the same observable, making bounds weaker

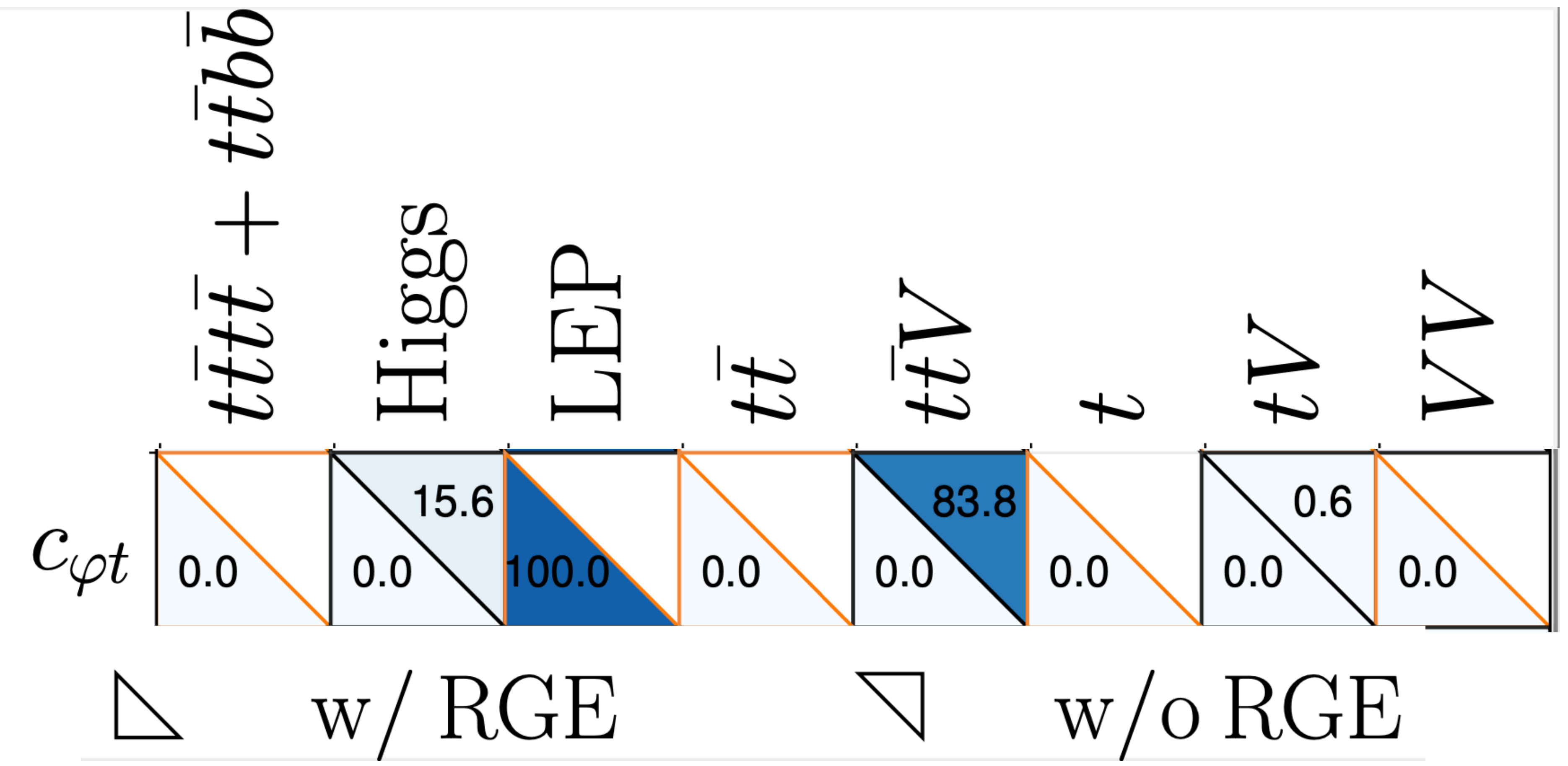
RG in the global fit

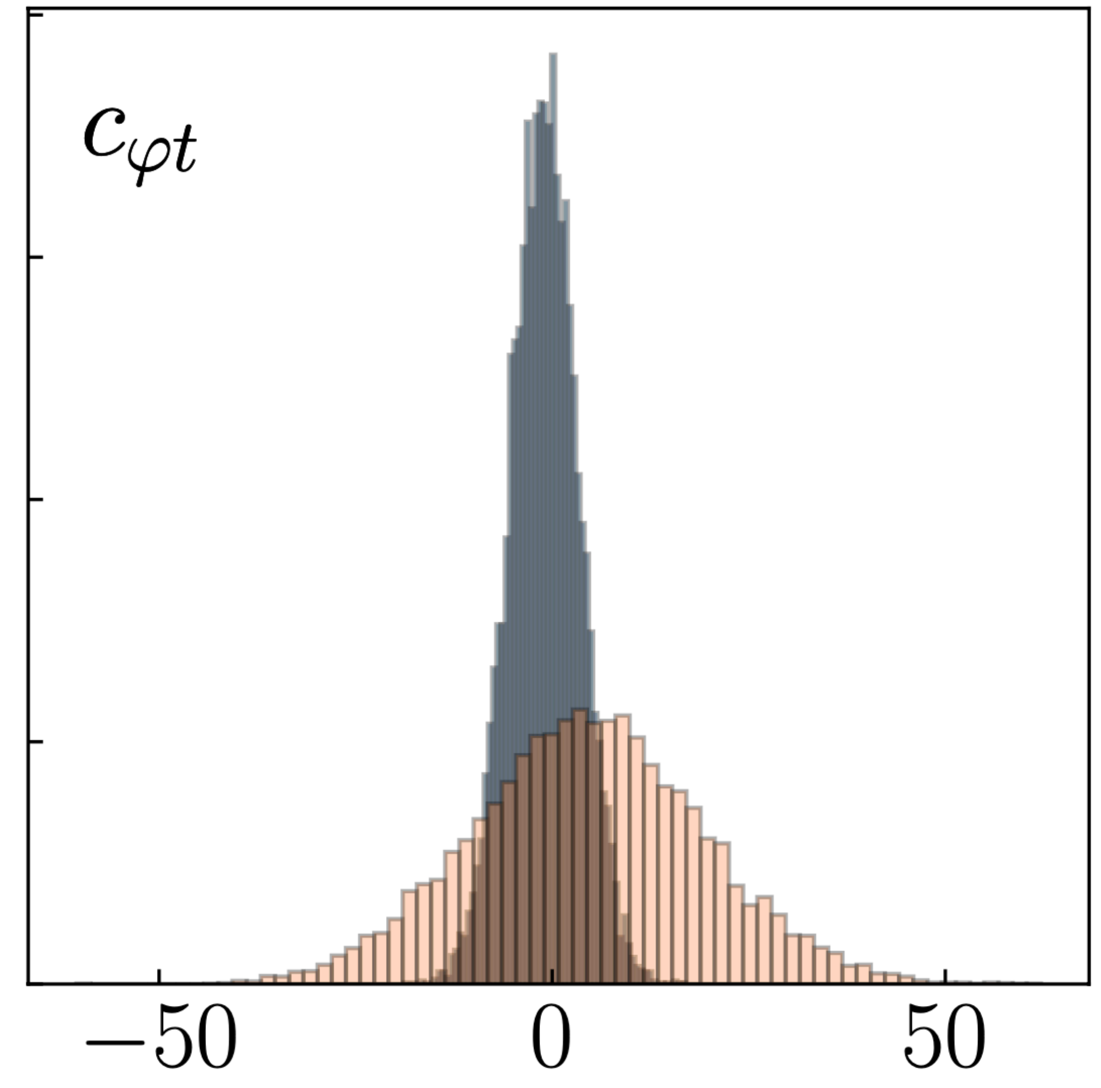


RG effects in the global fit

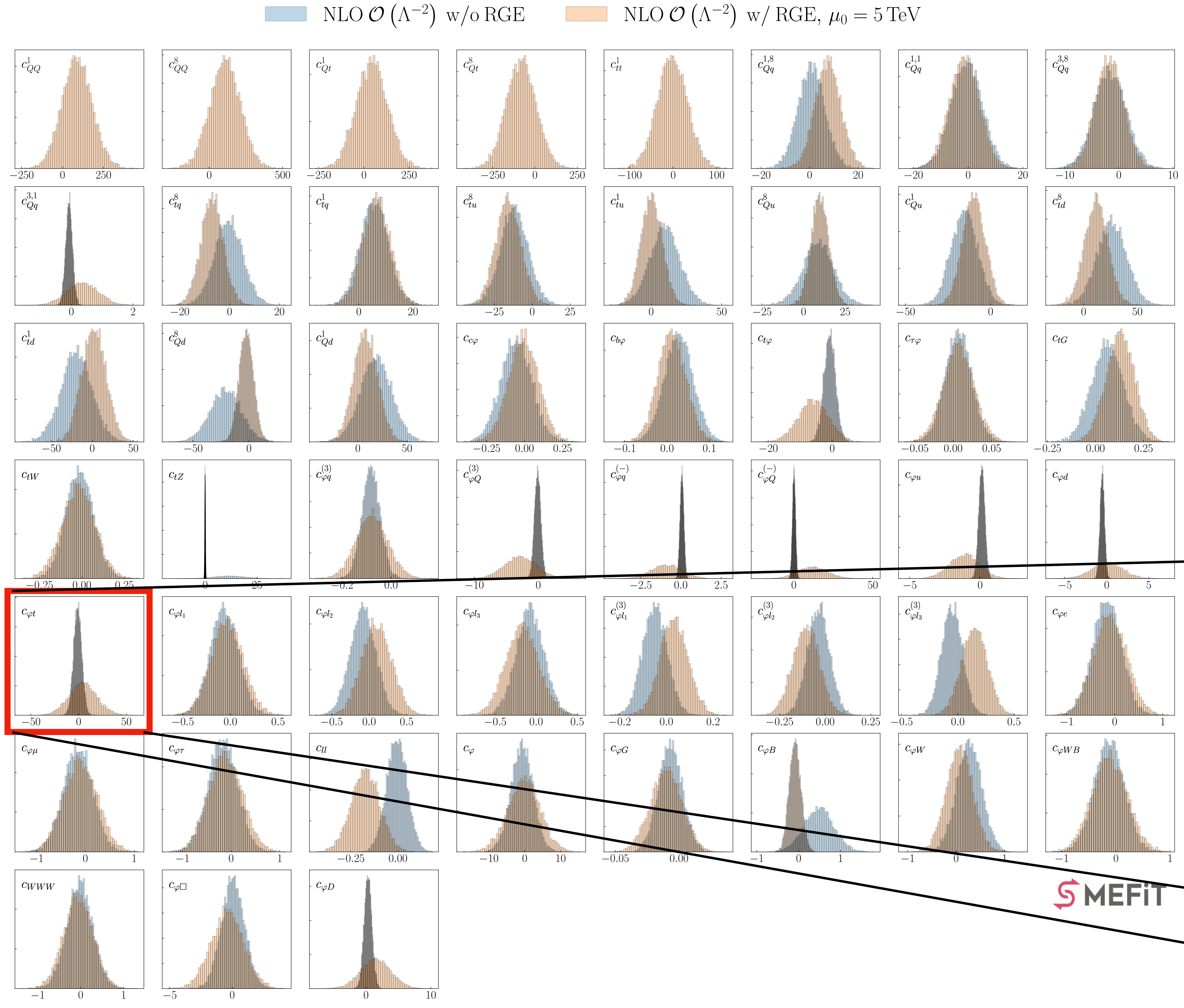


Fisher information moves from $t\bar{t}V$ to LEP





RG effects in the global fit



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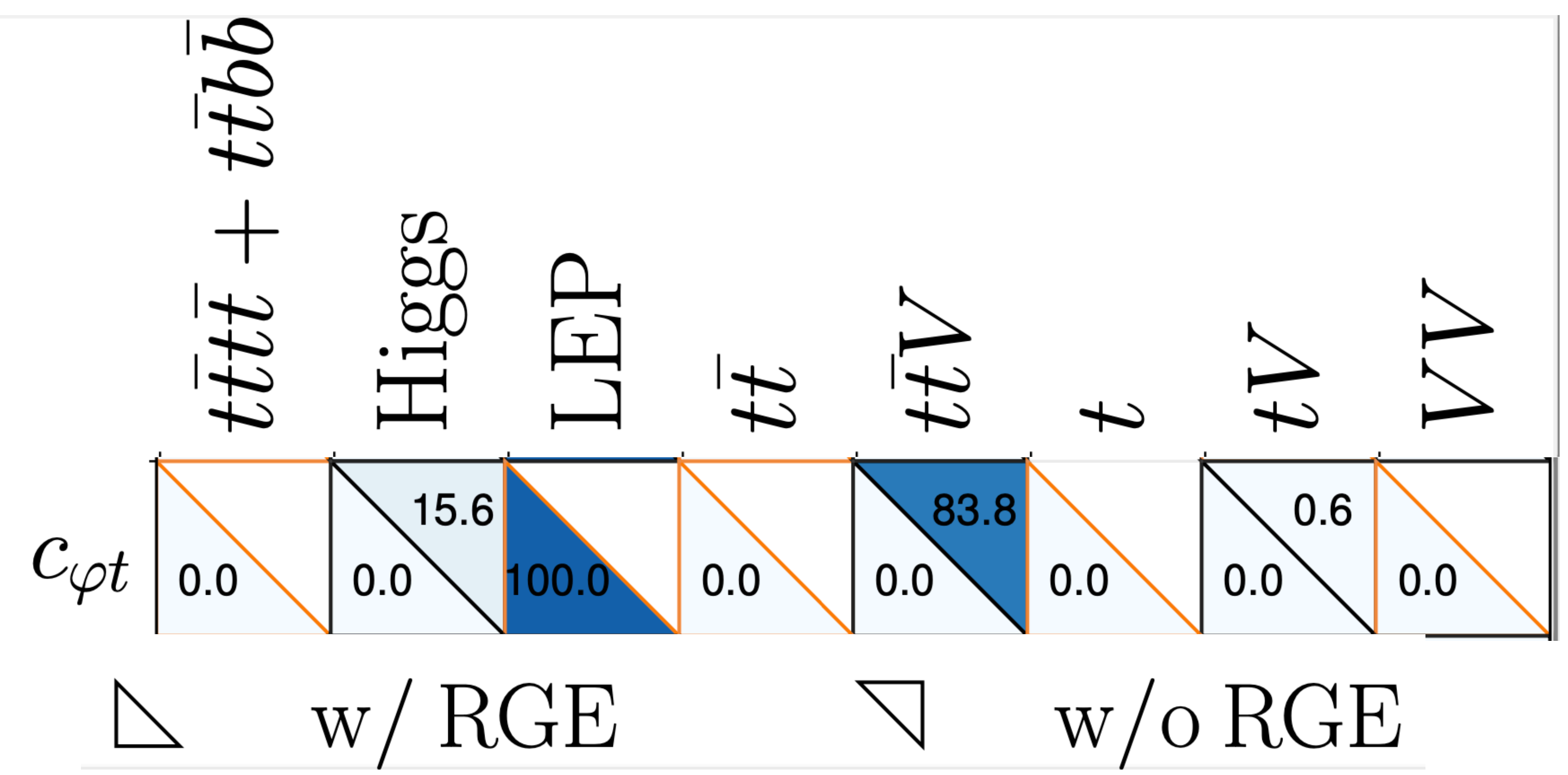
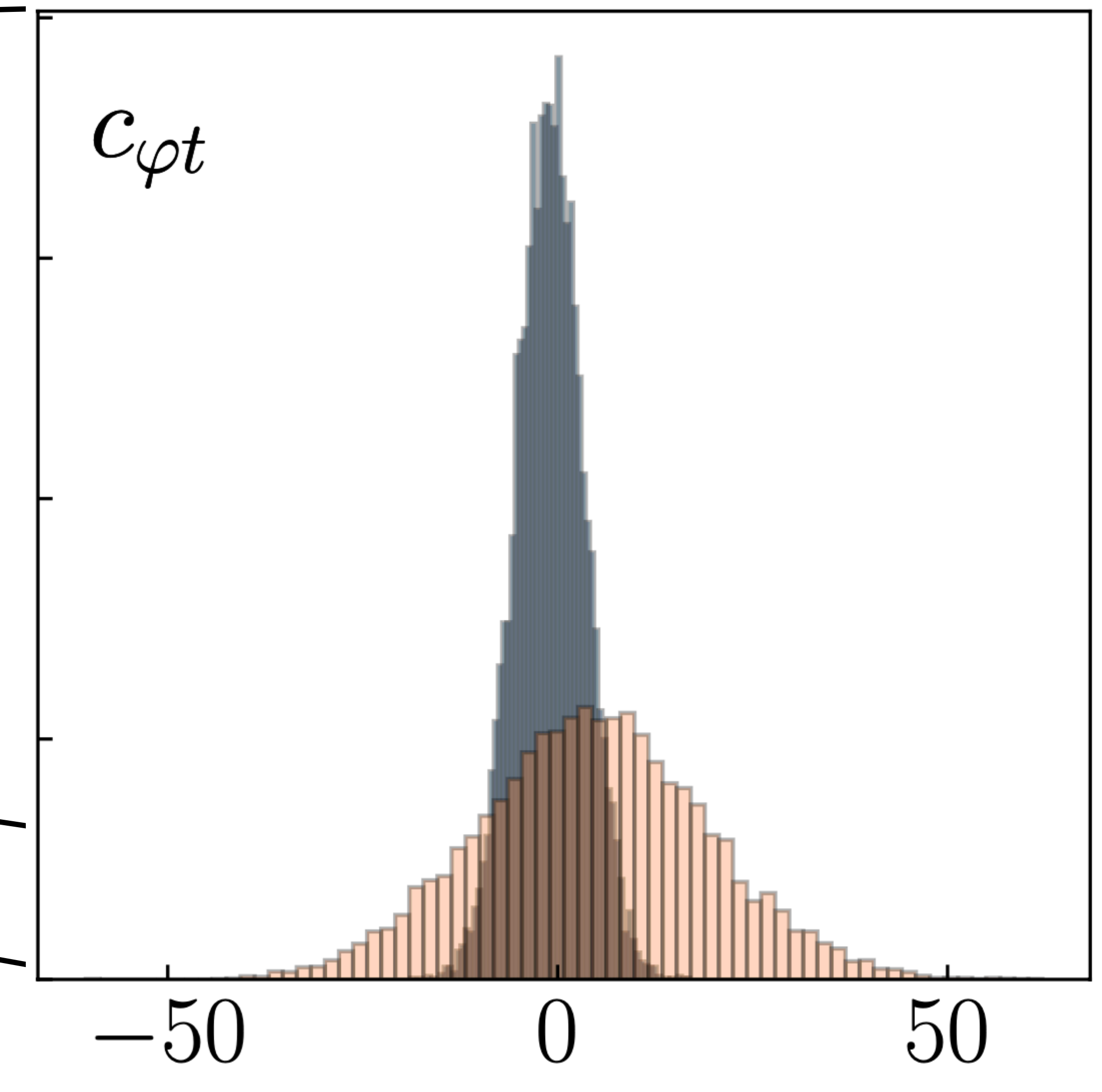
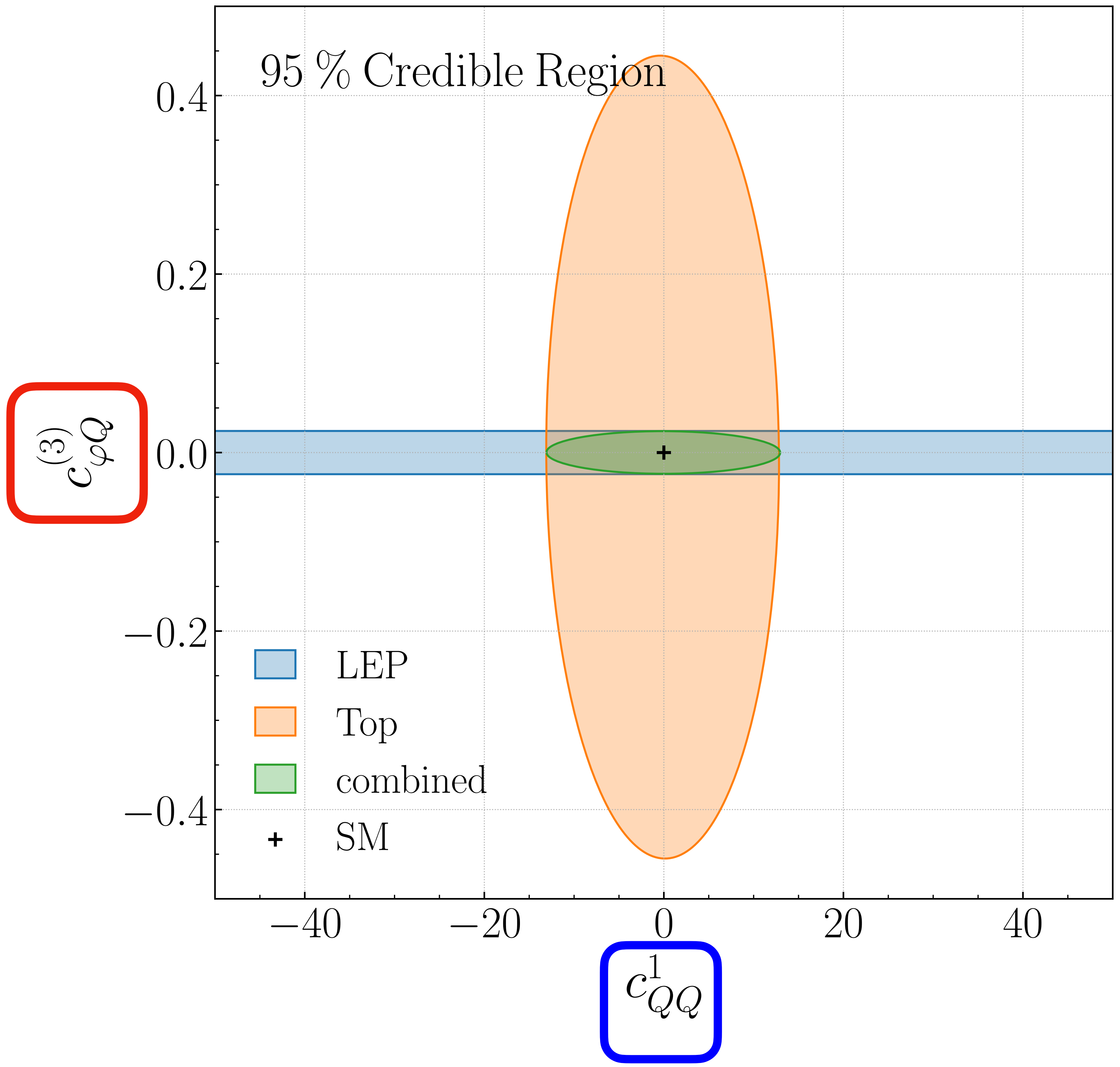
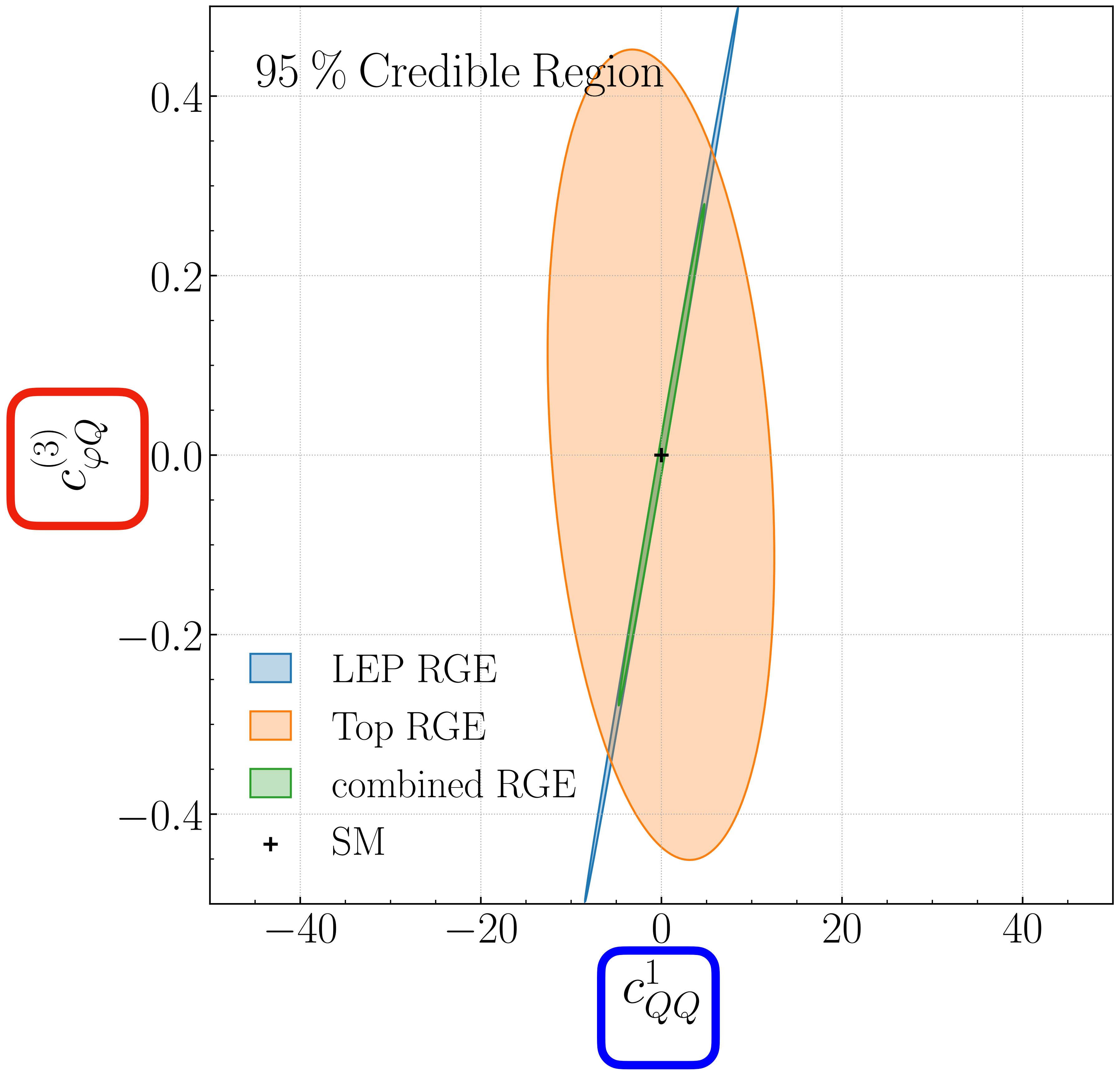


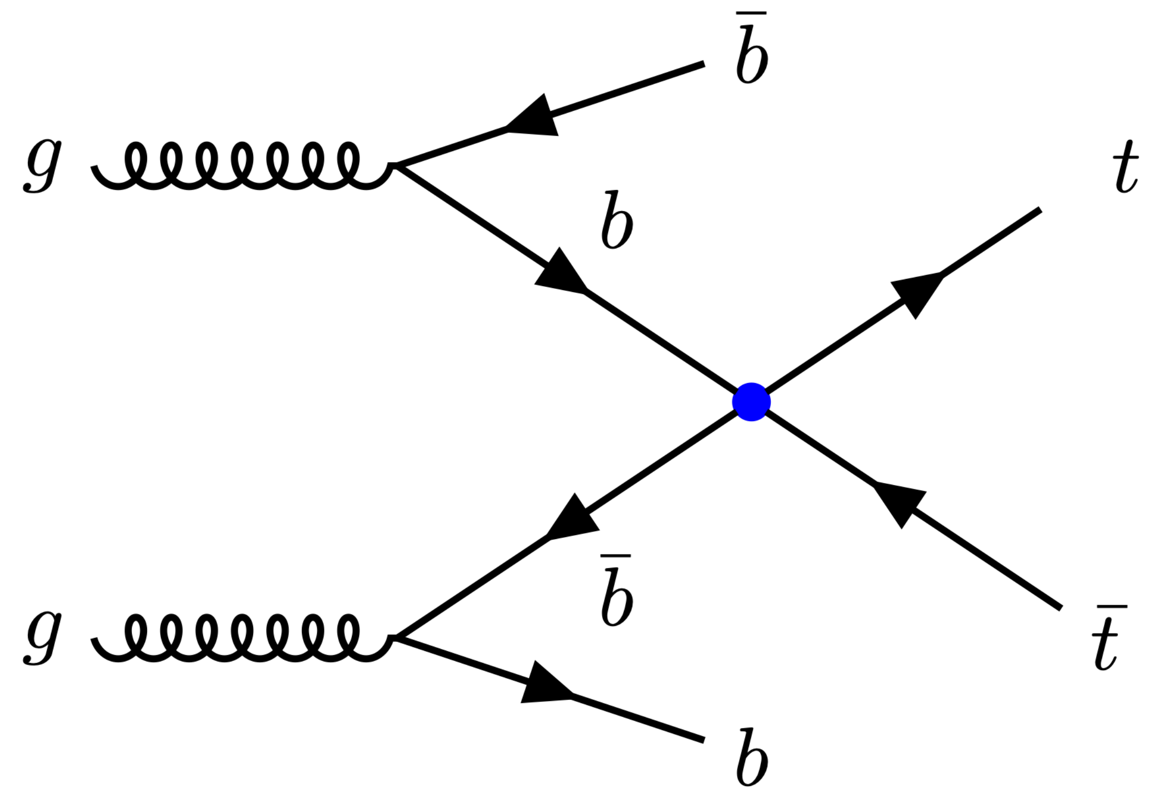


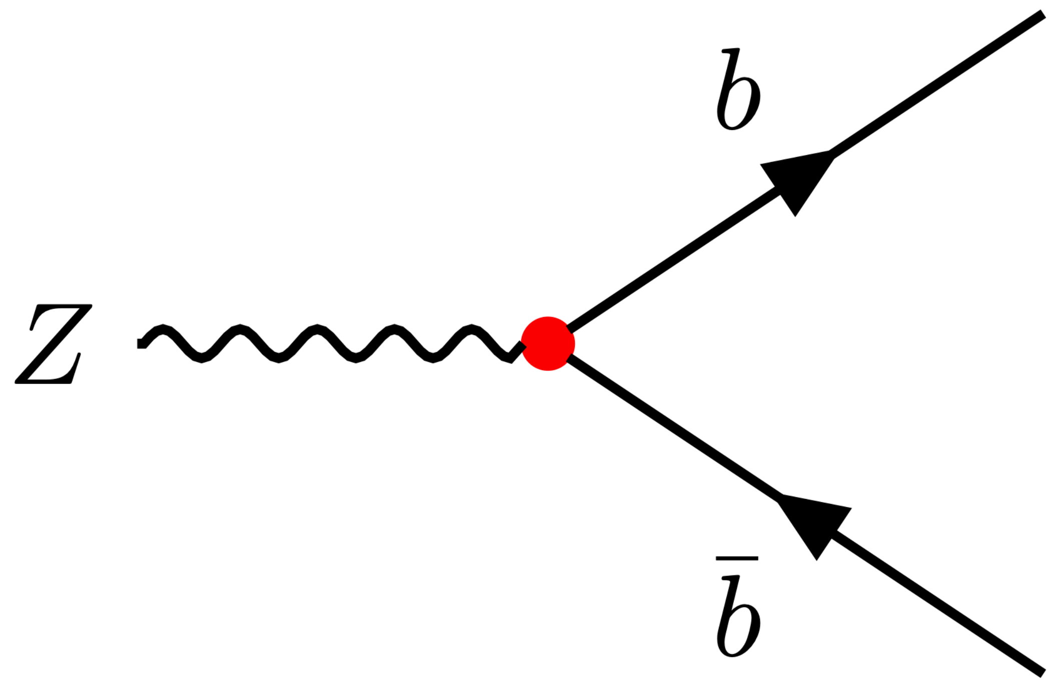
RG effects in the global fit

Global fits neglecting RGE effects can severely overestimate the bounds!









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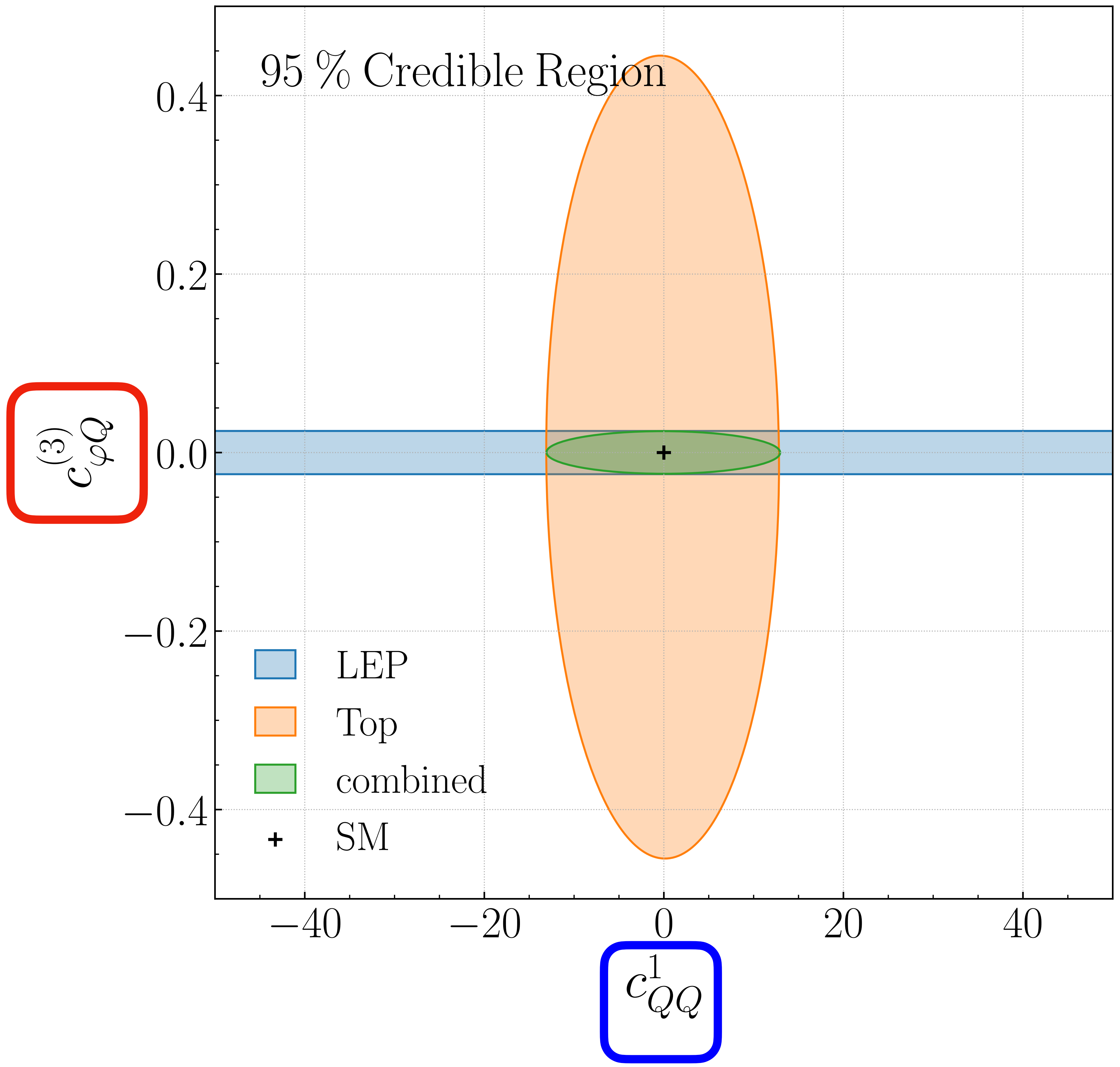

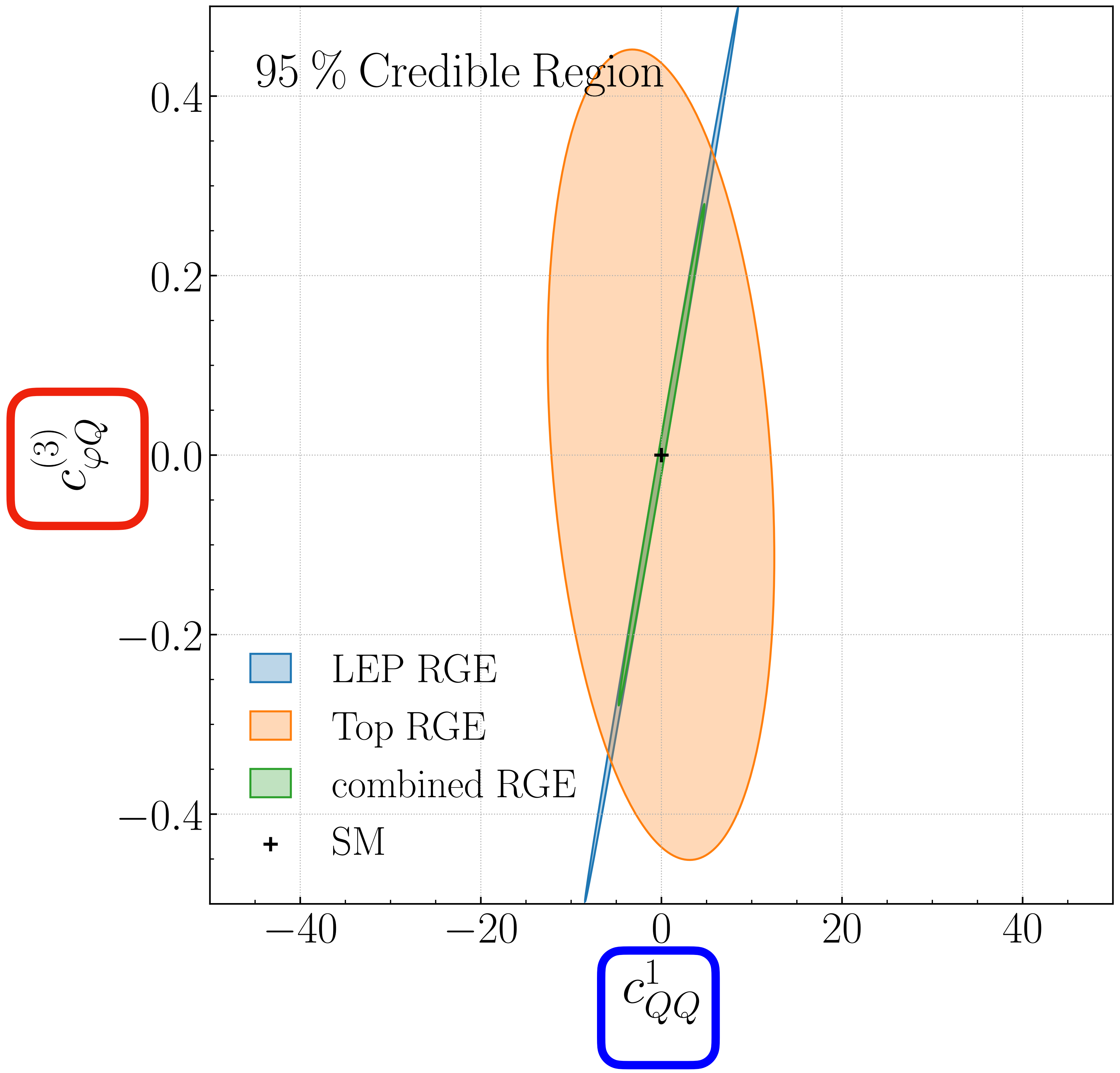

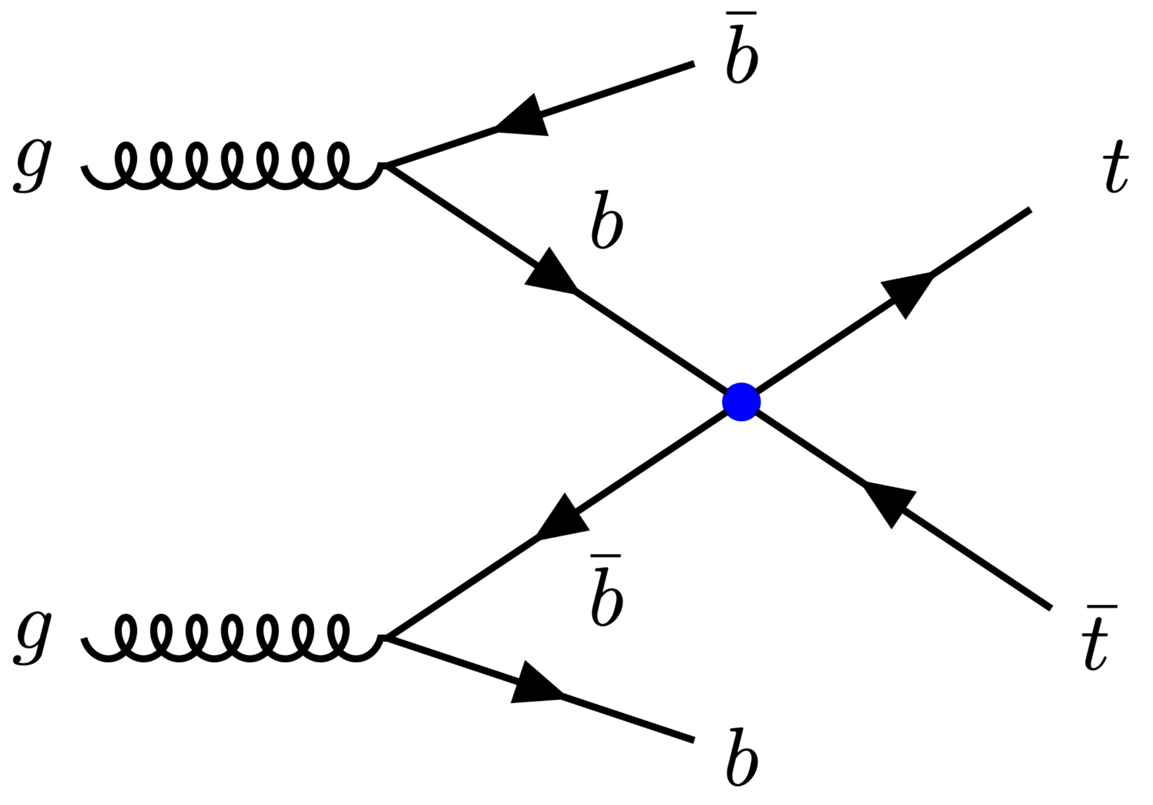

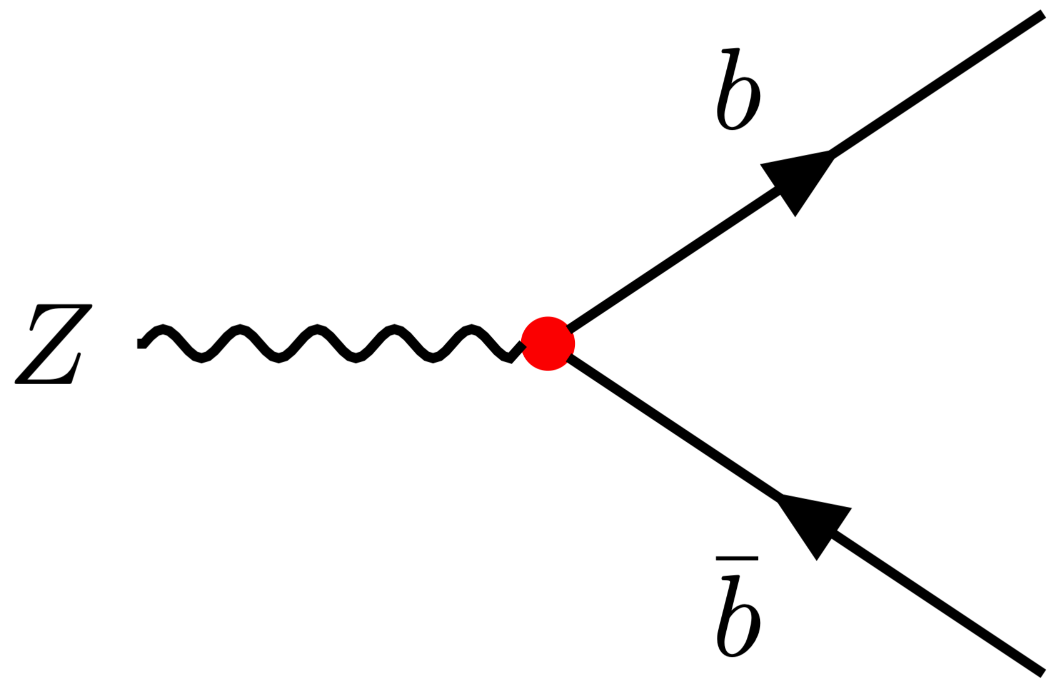

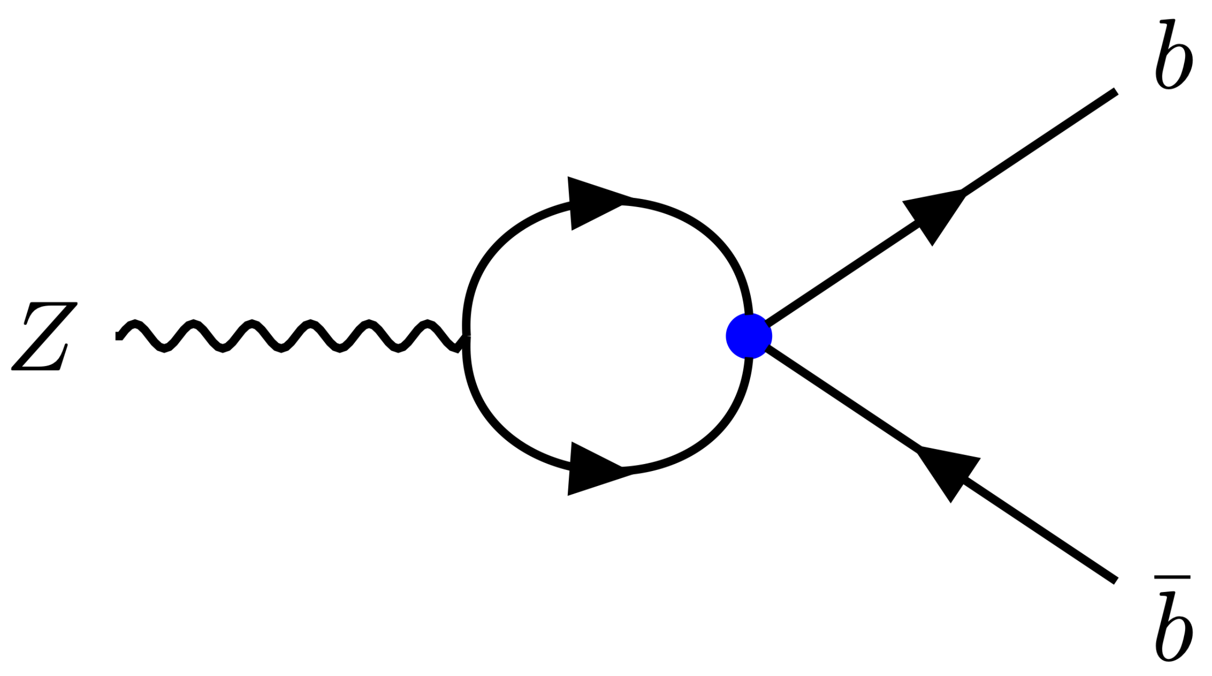

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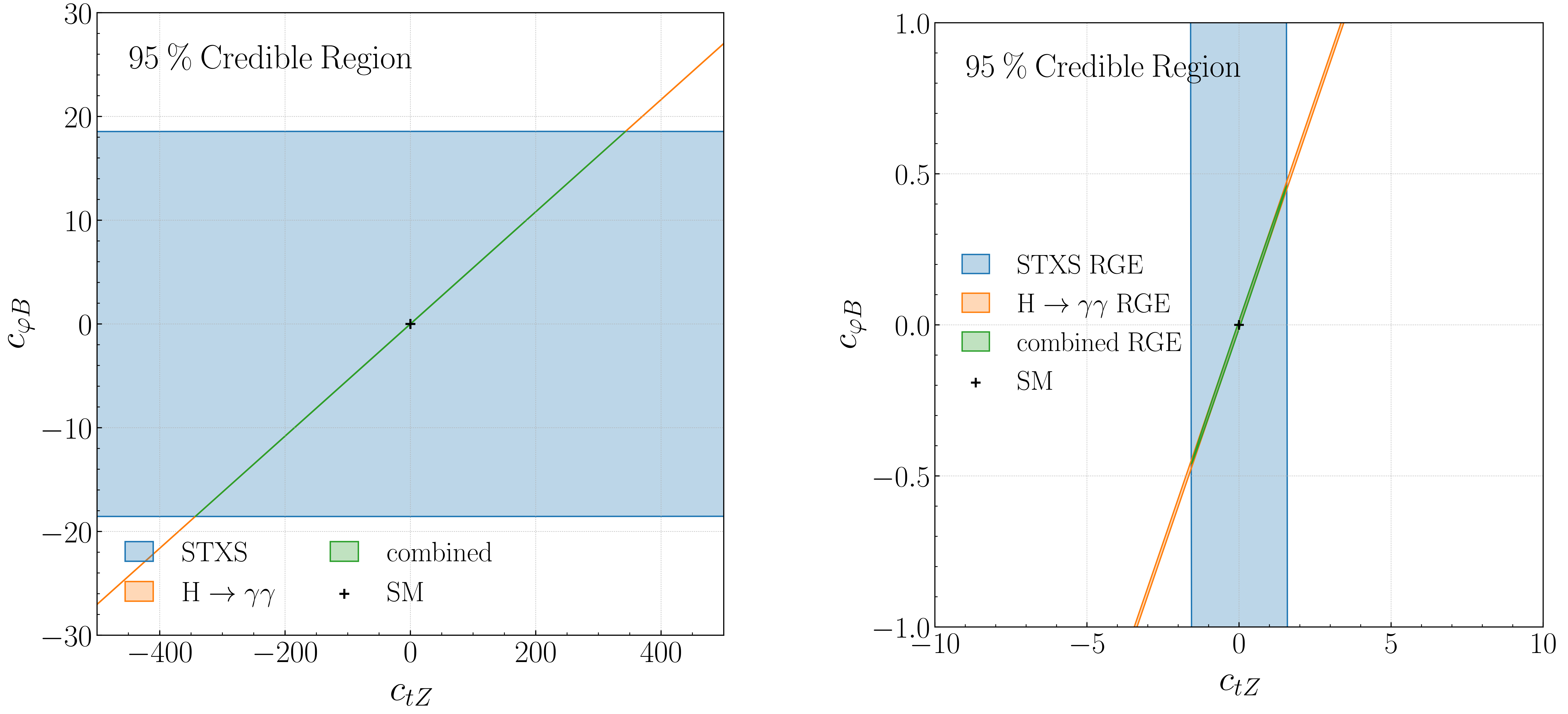
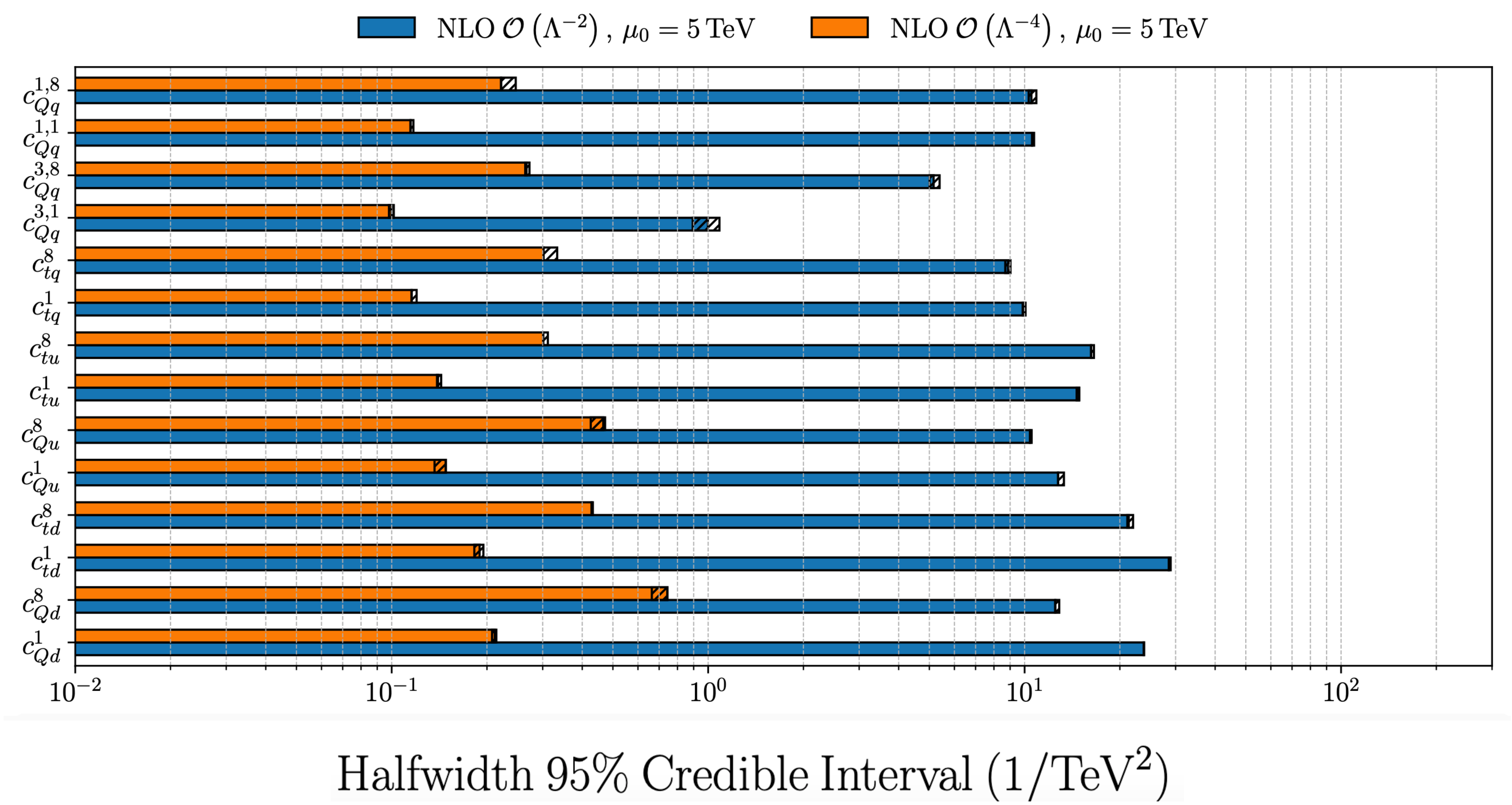
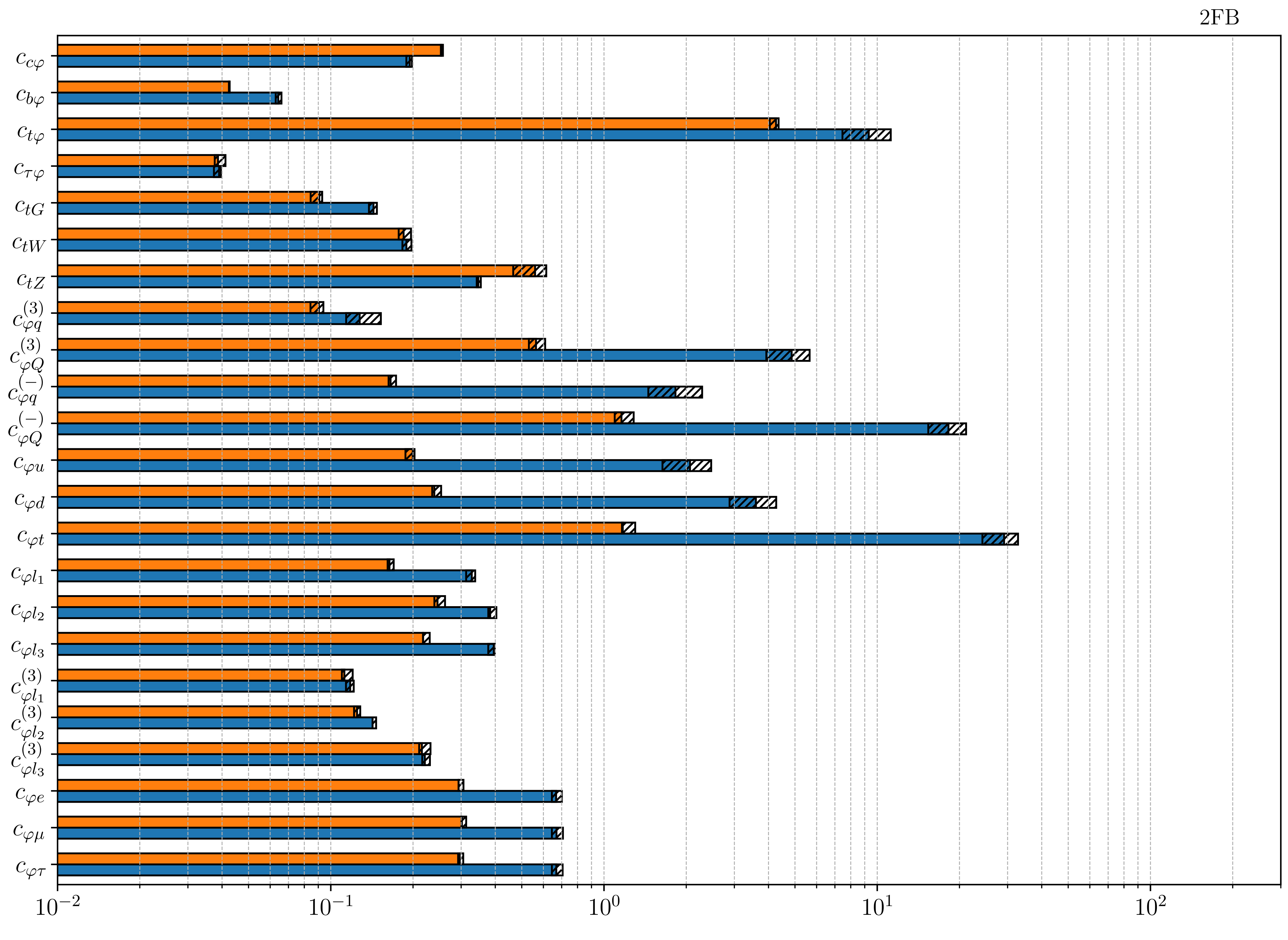


Impact of scale choice

Scale uncertainties are mild, as probed by varying the scale choice in each bin up and down by a factor 2, $\mu \rightarrow \tilde{\mu} = \kappa\mu$





SMEFT at future colliders

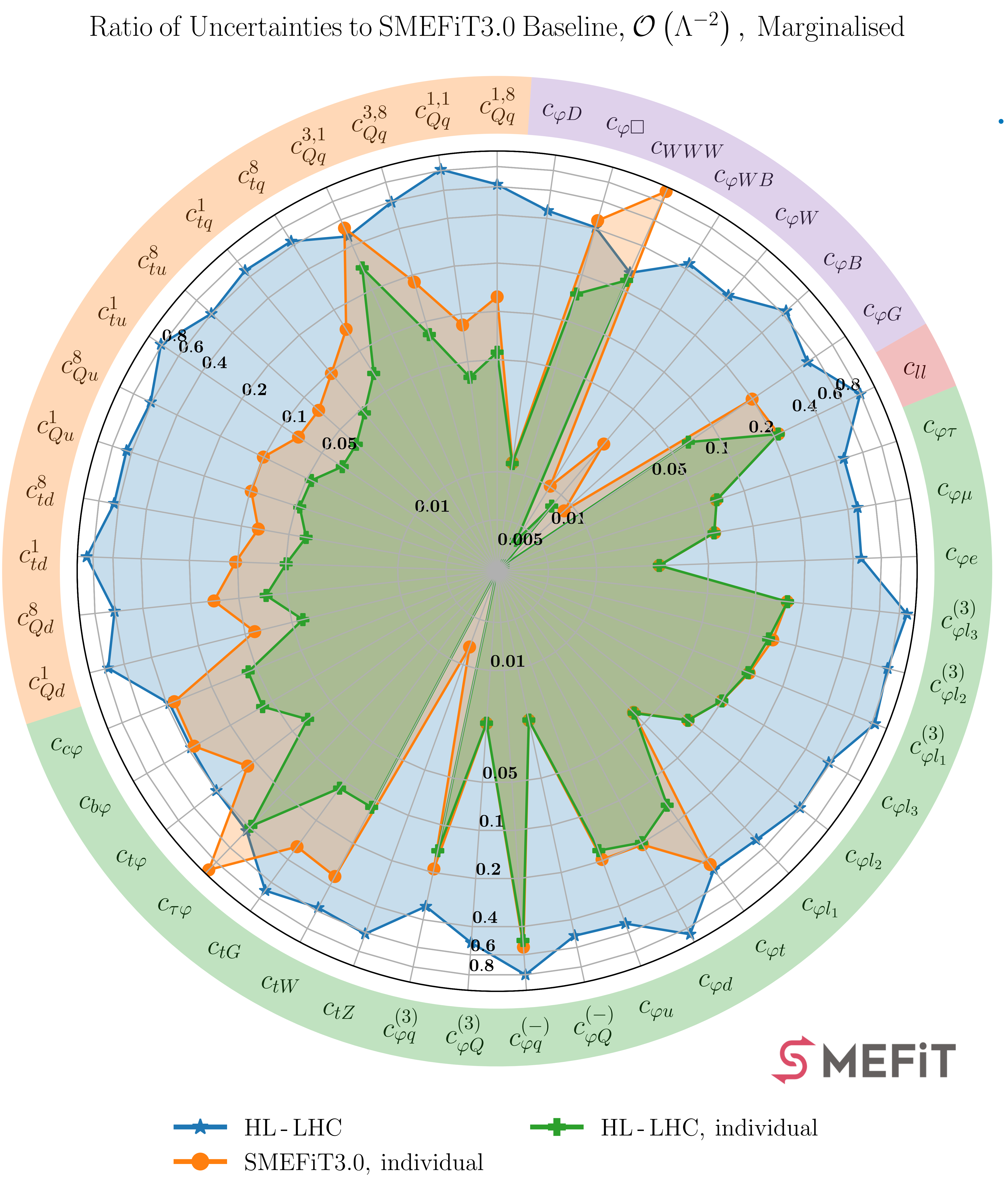
The SMEFT at HL-LHC

arXiv: 2404.12809

- We project all RunII datasets from the SMEFiT 3.0 baseline: one for each process and final state see backup for details

- We see an improvement ranging from 20 to 70 % in the marginalised fit

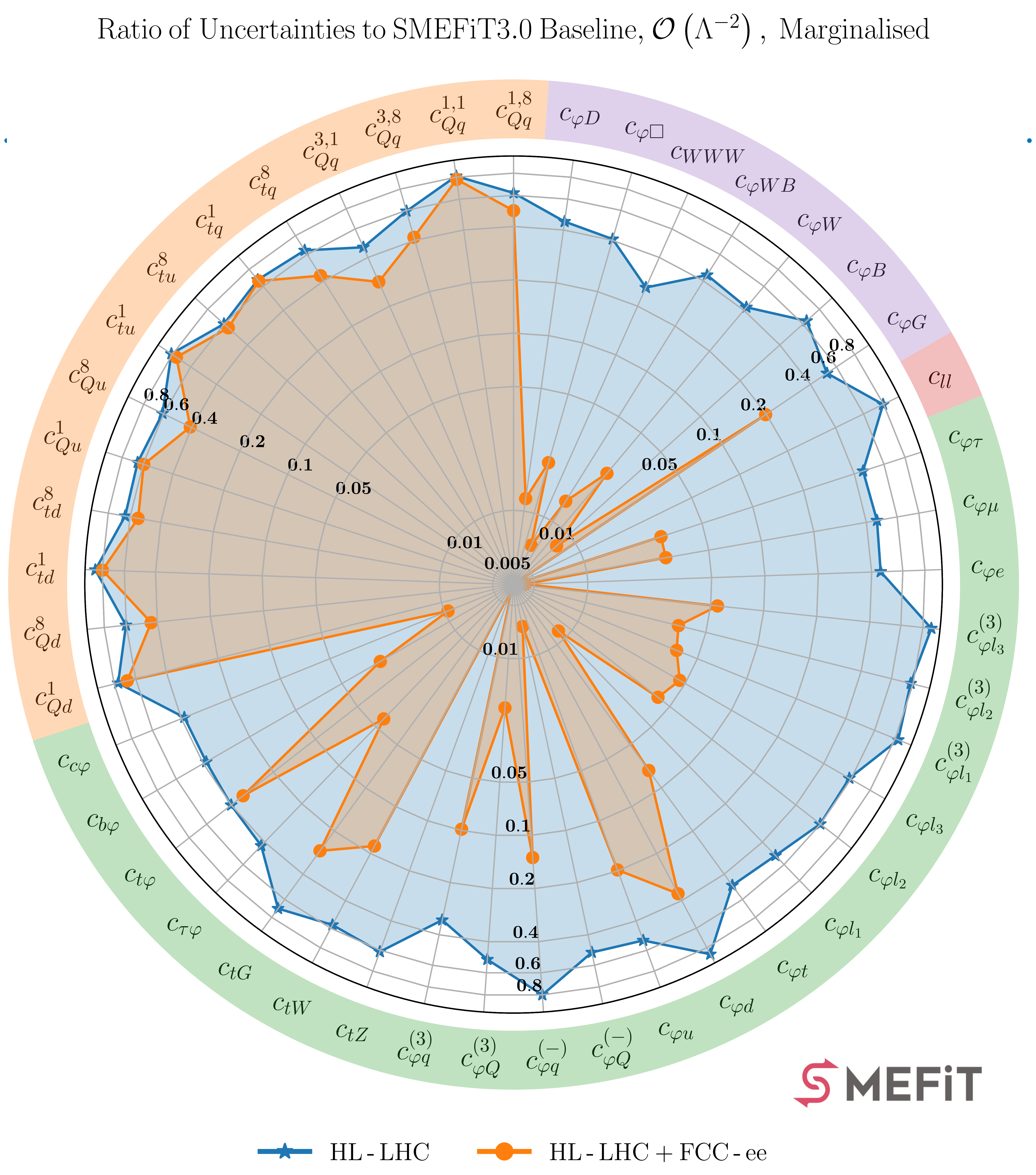
- EW operators improve only in the marginalised fit



The SMEFT at FCC-ee

- EWPOs at the Z-pole
- Light fermion pair prediction
- Higgstrahlung and VBF
- Gauge boson pair production
- Top-quark pair production
- Optimal Observables

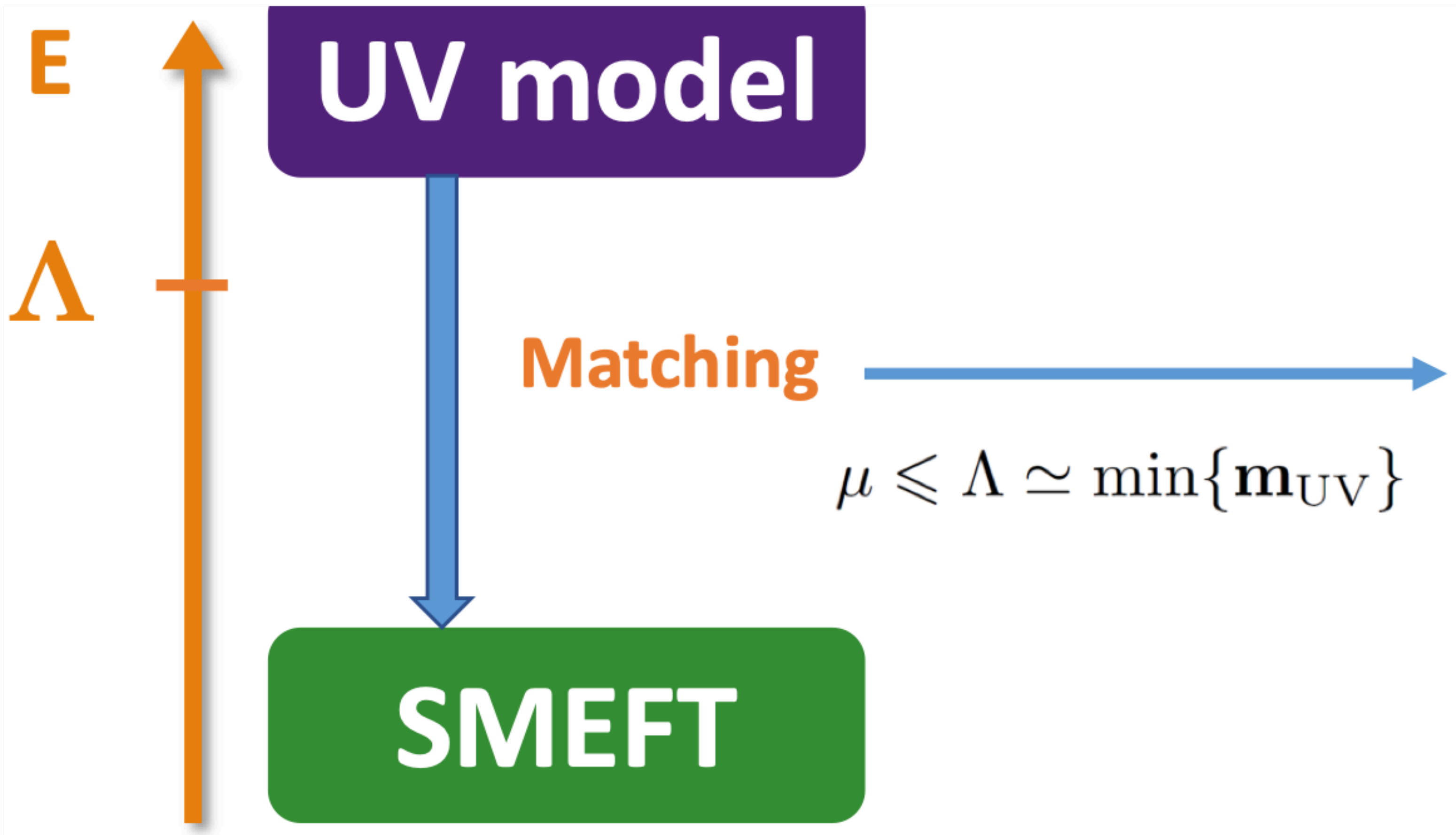
Energy ($\sqrt{s}$)	$\mathcal{L}_{\text{int}}$ (Run time)	
	FCC-ee	CEPC
91 GeV (Z-pole)	300 ab^{-1} (4 years)	100 ab^{-1} (2 years)
161 GeV ($2\,m_W$)	20 ab^{-1} (2 years)	6 ab^{-1} (1 year)
240 GeV	10 ab^{-1} (3 years)	20 ab^{-1} (10 years)
350 GeV	0.4 ab^{-1} (1 years)	-
365 GeV ($2\,m_t$)	3 ab^{-1} (4 years)	1 ab^{-1} (5 years)



UV complete models

*Mantani, Rojo, Rossia, Vryonidou, **JtH***
arXiv: 2502.20453

The ultimate goal of the EFT program at the LHC is to bridge the gap to explicit UV models



$$\mu \leqslant \Lambda \simeq \min\{\mathbf{m}_{\rm UV}\}$$

$$\frac{c_{\varphi\Box}}{\Lambda^2} = -\frac{g_1^4}{7680\pi^2}\frac{1}{m_\phi^2} - \frac{g_2^4}{2560\pi^2}\frac{1}{m_\phi^2} - \frac{3}{32\pi^2}\frac{\lambda_\phi^2}{m_\phi^2},$$

$$\frac{c_{t\varphi}}{\Lambda^2} = -\frac{\lambda_\phi\,(y_\phi^u)_{33}}{m_\phi^2} - \frac{g_2^4 y_t^{\rm SM}}{3840\pi^2}\frac{1}{m_\phi^2} + \frac{y_t^{\rm SM}}{16\pi^2}\frac{\lambda_\phi^2}{m_\phi^2} + \frac{\left(4\,(y_b^{\rm SM})^2 - 13\,(y_t^{\rm SM})^2\right)}{64\pi^2}\frac{\lambda_\phi\,(y_\phi^u)_{33}}{m_\phi^2}$$
$$- \left(12\lambda_\varphi^{\rm SM} + (y_b^{\rm SM})^2 - 11\,(y_t^{\rm SM})^2\right)\frac{y_t^{\rm SM}}{64\pi^2}\frac{(y_\phi^u)_{33}^2}{m_\phi^2} + \frac{3}{128\pi^2}\frac{\lambda_\phi\,(y_\phi^u)_{33}^3}{m_\phi^2},$$

$$\frac{\mathbf{c}}{\Lambda^n} = f(\mathbf{g}_{\rm UV}, \mathbf{m}_{\rm UV})$$

$$\sigma(\mathbf{c}) \longrightarrow \sigma(\mathbf{g}_{\rm UV})$$

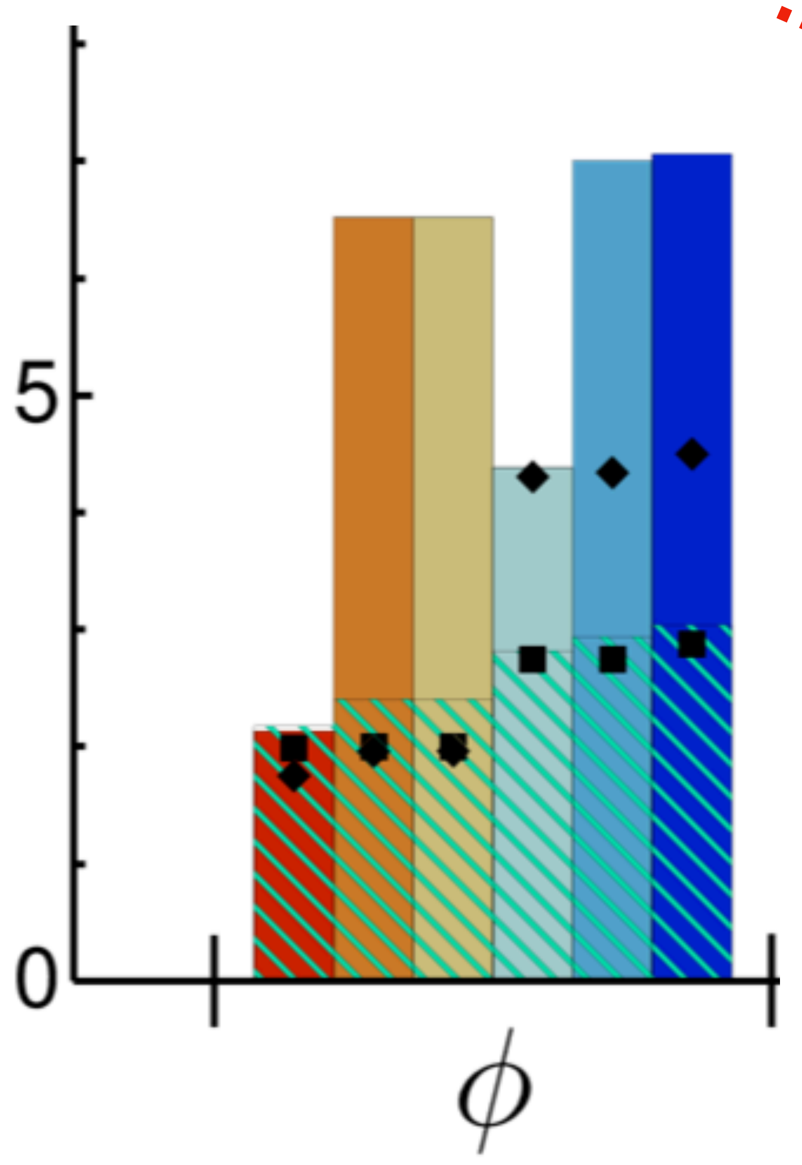
- **Less parameters**
- **Stronger correlations**
- **Model dependent**
- **Sharper interpretation**

Slide from A. Rossia at SMEFT-tools 2025

UV complete models

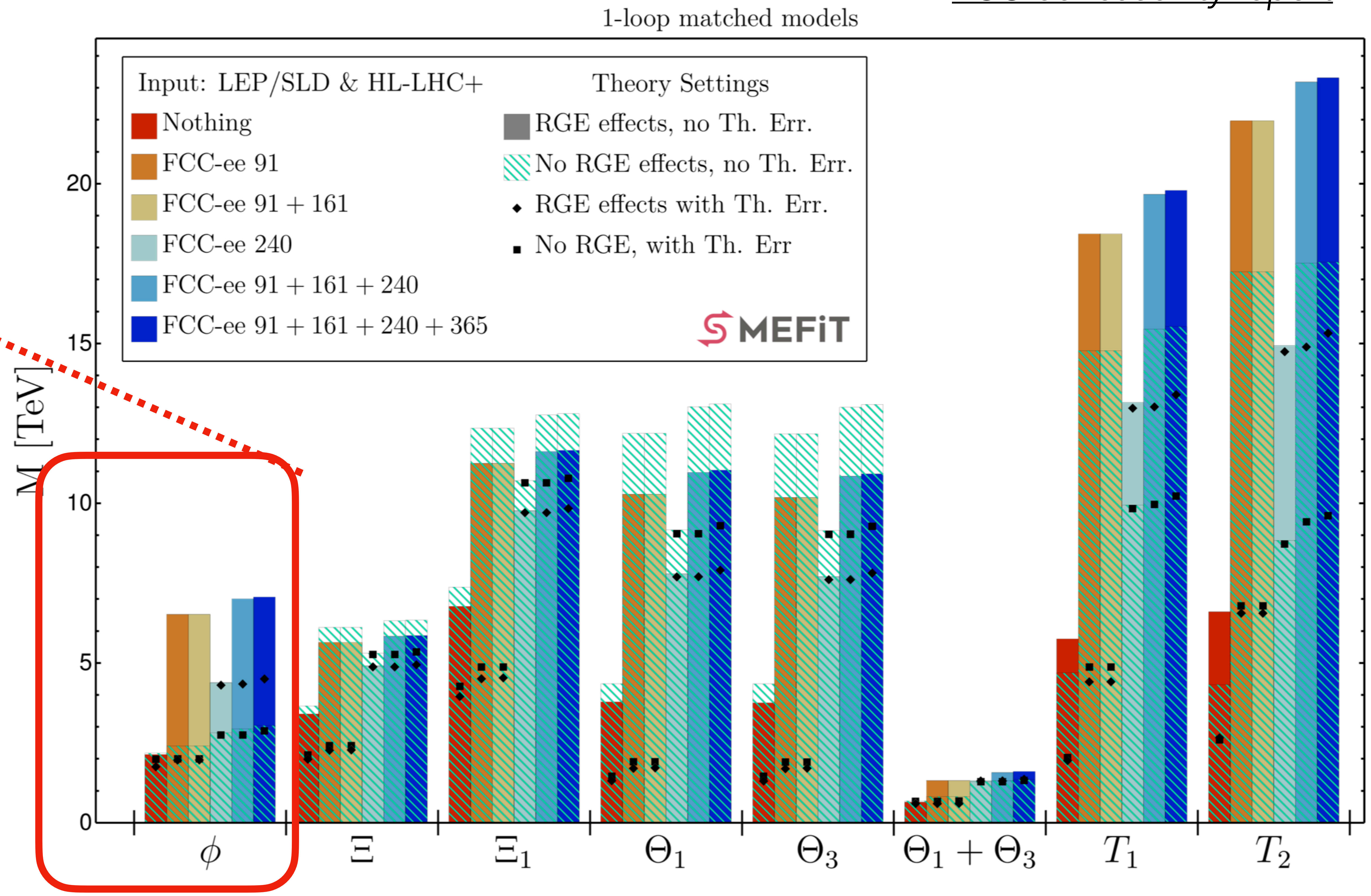
*Mantani, Rojo, Rossia, Vryonidou, **JtH***
arXiv: 2502.20453

RGE effects matter, and so do theory uncertainties!



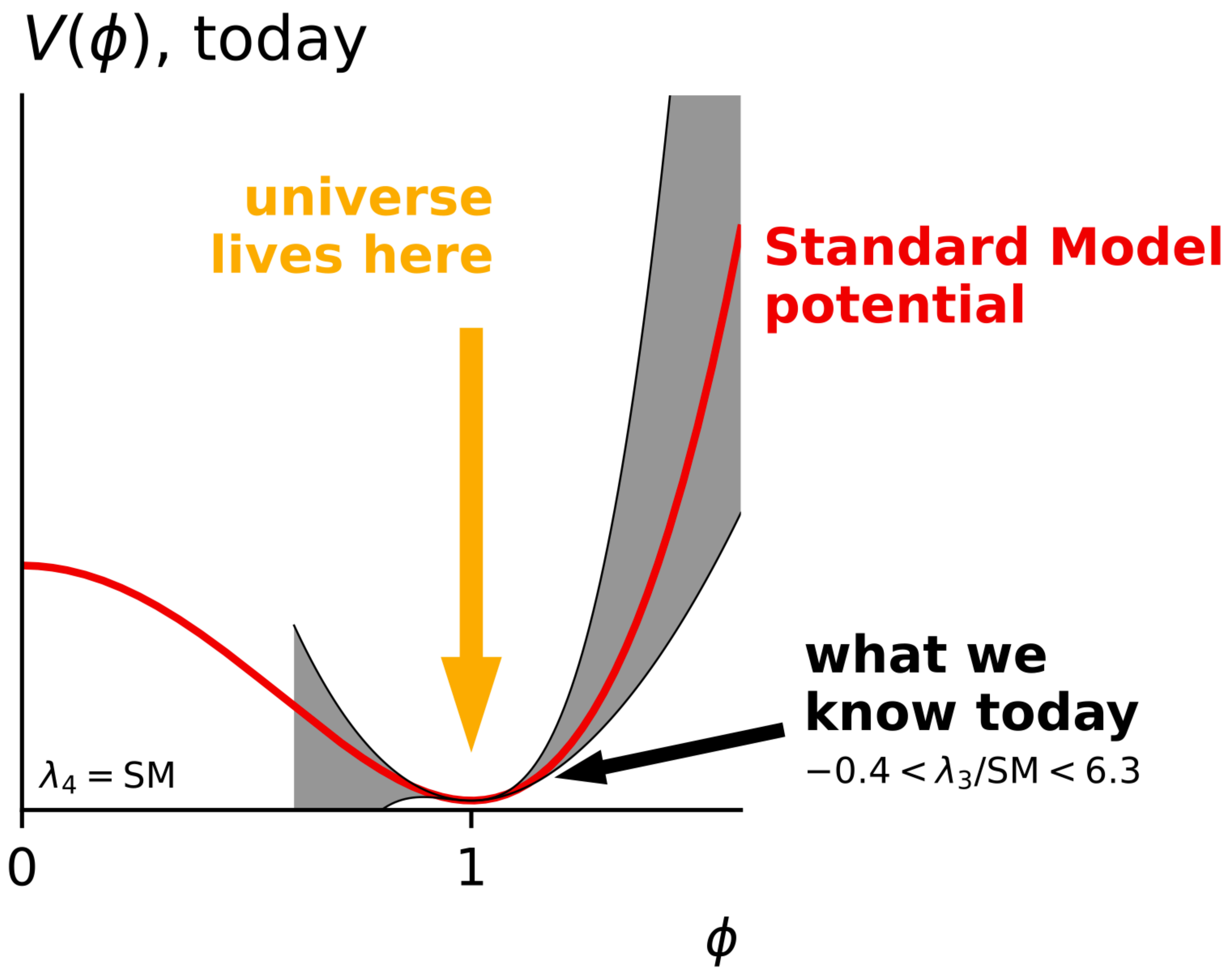
$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + |D_\mu\phi|^2 - m_\phi^2\phi^\dagger\phi - \Big((y_\phi^e)_{ij}\,\phi^\dagger\bar{e}_R^i\ell_L^j + (y_\phi^d)_{ij}\,\phi^\dagger\bar{d}_R^i q_L^j + (y_\phi^u)_{ij}\,\phi^\dagger i\sigma_2\bar{q}_L^{T,i}u_R^j + \lambda_\phi\,\phi^\dagger\varphi|\varphi|^2 + \text{h.c.}\Big) - \text{scalar potential}$$

FCC-ee feasbility report



The Higgs self-coupling in the SMEFT

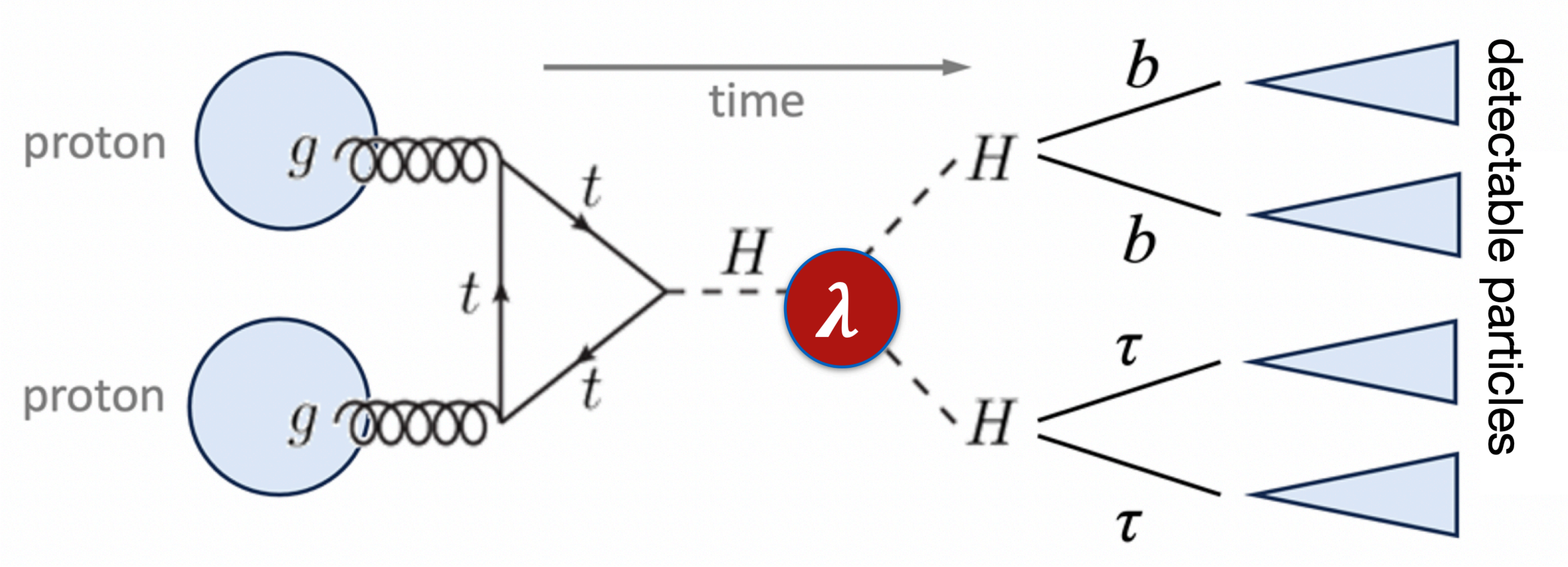
*Mantani, Rojo, Rossia, Vryonidou, **JtH***
arXiv: 2504.05974, submitted to PRL



From Gavin Salam

The Higgs potential sheds light on …

- the vacuum stability of our universe
- EW phase transition
- Matter anti-matter asymmetry



$$\delta\kappa_3 = -\frac{2v^4}{m_h^2}\frac{c_\varphi}{\Lambda^2} + \frac{3v^2}{\Lambda^2}\left(c_{\varphi\Box} - \frac{1}{4}c_{\varphi D}\right)$$

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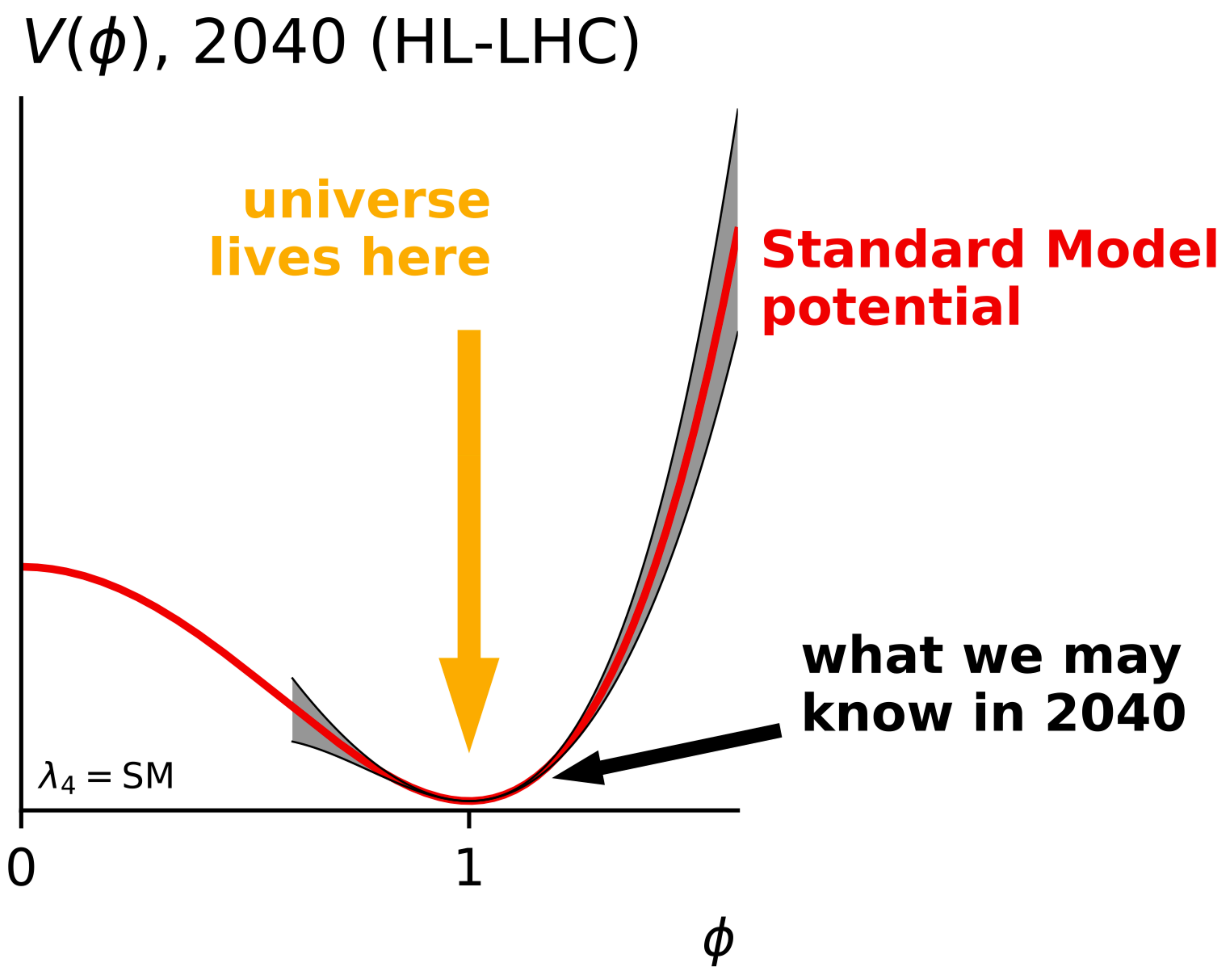

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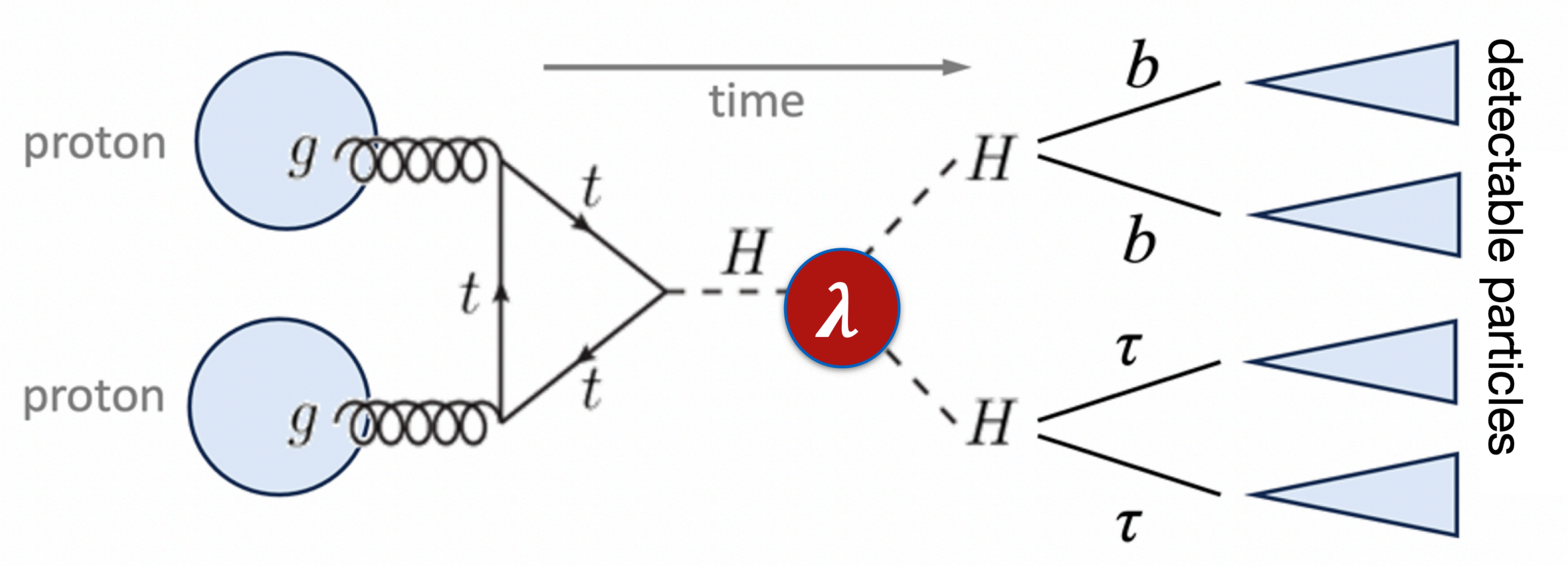

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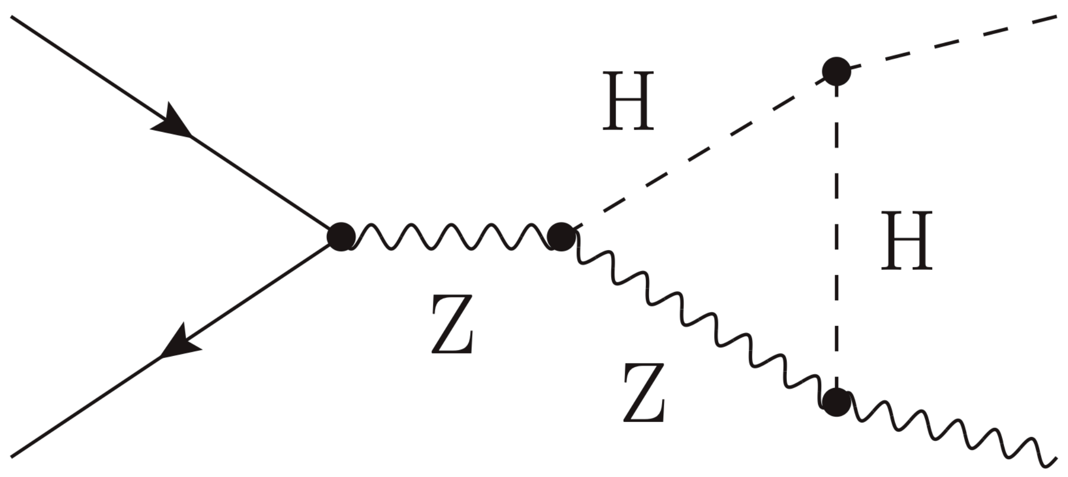
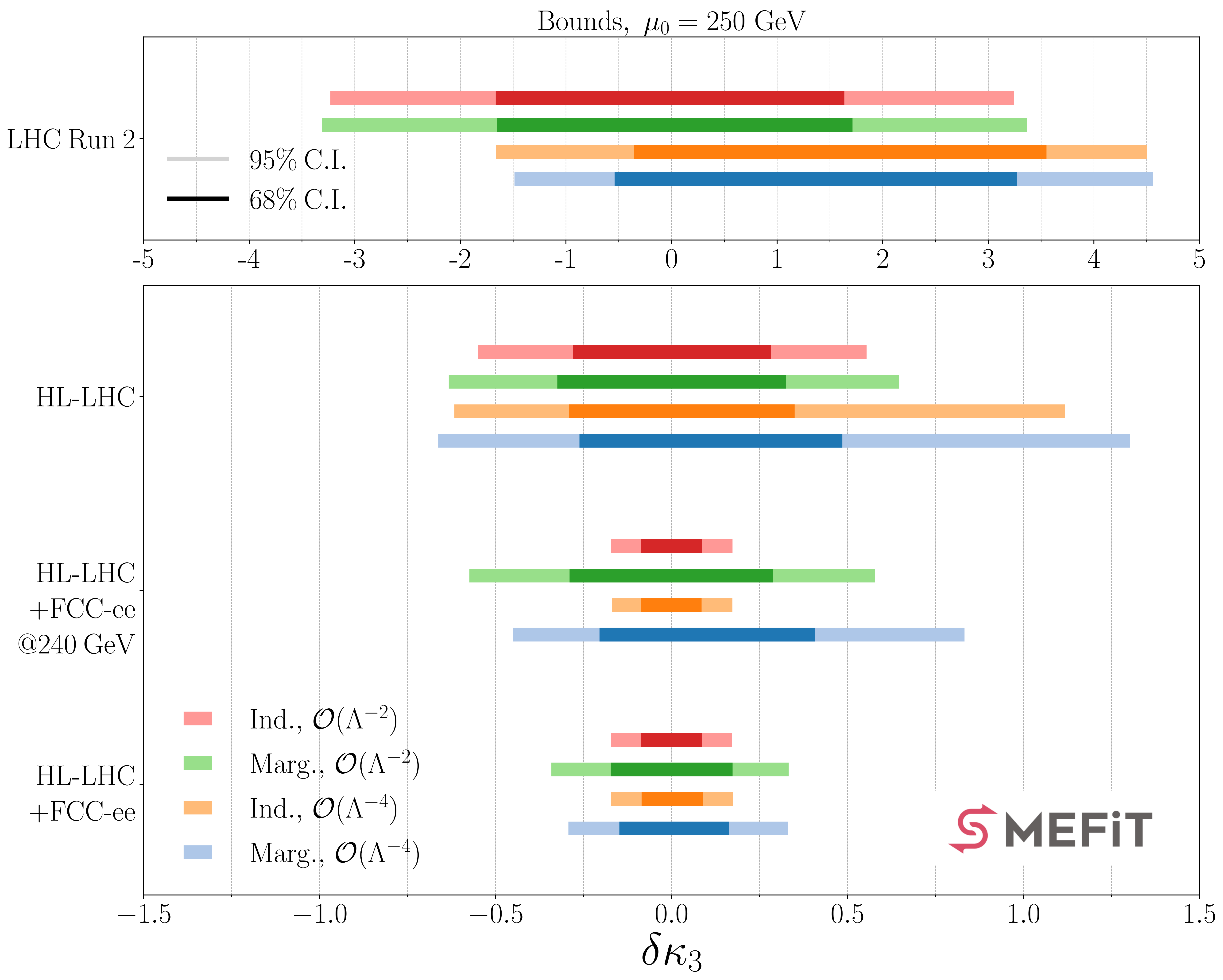
The Higgs self-coupling in the SMEFT

- HL-LHC + FCC-ee can pin down the Higgs self coupling to 15%
- Individual and marginalised bounds on κ_3 no longer agree at FCC-ee
- Significantly improving on HL-LHC is not possible without the 365 GeV run



arXiv: 2406.03557



Summary and conclusion

- The SMEFT provides a convenient tool to search for new physics in an agnostic way
- The impact of RGE effects on the SMEFT parameter space is non trivial and should be included
- Complementarity between the different FCC-ee runs is key to pin down the Higgs trilinear coupling to 15%
- The SMEFiT code is open source and can be installed from

lhcfitnikhef.github.io/smefit_release

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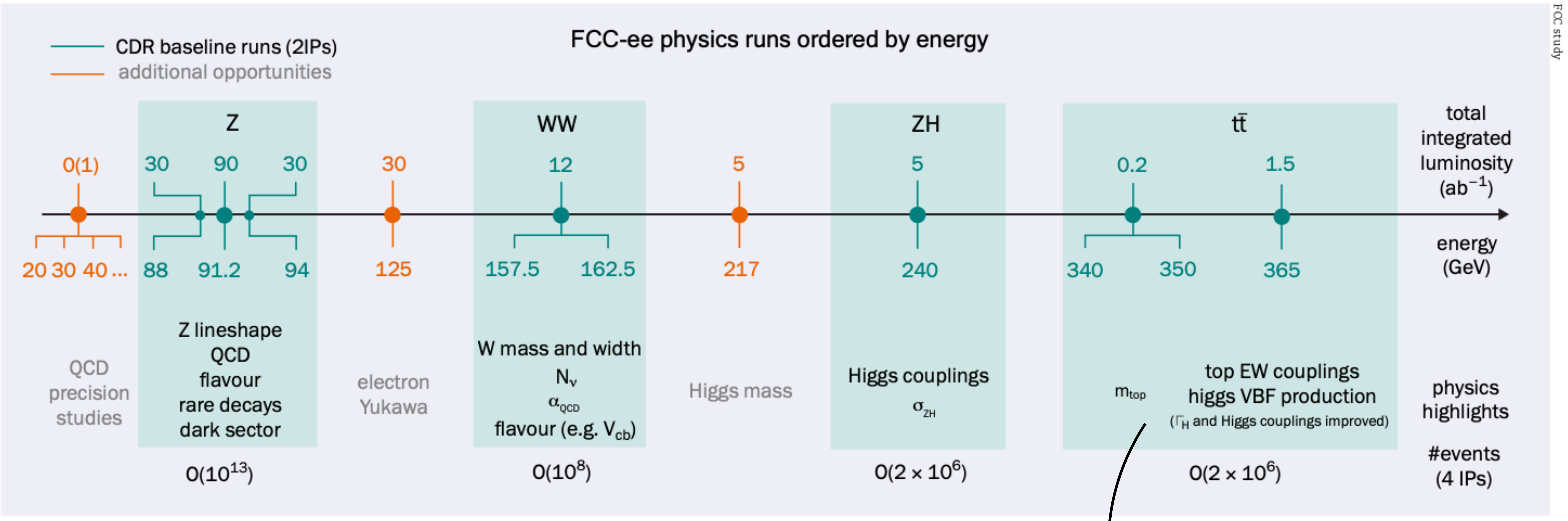
Contact: jaco.ter.hoeve@ed.ac.uk **Thanks for your attention!**

Backup

Future colliders

- At the FCC-ee, we will separately target Z-pole EWPOs, diboson, Higgs and top pair production, each with an unprecedented luminosity!
- Expected production: $6 \cdot 10^{12}$ Z bosons, $2.4 \cdot 10^{8}$ W pairs, $2 \cdot 10^{6}$ H bosons and $2 \cdot 10^{6}$ top quark pairs within 16 years



Impossible to produce with an e^+e^- collider in the LHC tunnel!

Dataset upgrade

We extended SMEFiT2.0 with recent Run II datasets from top, diboson and Higgs production

Category	Processes	n_{dat} SMEFiT2.0	n_{dat} SMEFiT3.0
Top quark production	$t\bar{t}+X$	94	115
	$t\bar{t}Z$, $t\bar{t}W$	14	21
	$t\bar{t}\gamma$	-	2
	single top (inclusive)	27	28
	tZ, tW	9	13
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6	12
	Total	**150**	**189**
Higgs production and decay	Run I signal strengths	22	22
	Run II signal strengths	40	40
	Run II, differential distributions & STXS	35	71
	Total	**97**	**133**
Diboson production	LEP-2	40	40
	LHC	30	41
	Total	**70**	**81**
Z-pole EWPOs	LEP-2	-	44
Baseline dataset	**Total**	**317**	**449**

SMEFiT

lhcfitnikhef.github.io/smefit_release

Theory

SM: (N)NLO QCD + NLO EW

EFT: NLO QCD, linear and quadratics, with SMEFT@NLO

NNPDF4.0 no top

Data

447 measurements from **Higgs, top, diboson** and **EWPO**

Full experimental **correlations**

SMEFiT

dataset_X.json

```
{
  "best_sm": [3.0],
  "scales": [91.0],
  "theory_cov": [[1.0]],
  "LO": {"SM":  1.0, "Op1":  -0.2, "Op1*Op1":  0.4},
  "NLO_QCD": {"SM":  1.5, "Op1":  -0.3, "Op1*Op1":  0.6}
}
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```
dataset_name: ATLAS_ttW_13TeV_2016
doi: 10.1103/PhysRevD.99.072009
location: Figure 13 arxiv preprint
arxiv: 1901.03584
hepdata: https://www.hepdata.net/record/ins1713423
units: fb
description: inclusive ttW cross-section
luminosity: 36.1
num_data: 1
num_sys: 1
data_central: 3.1
statistical_error: 0.1
systematics:
  - 0.2
sys_names: UNCORR
sys_type: MULT
```

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Projections

HL-LHC, FCCee, CEPC

+ Automatic projection module

SMEFiT

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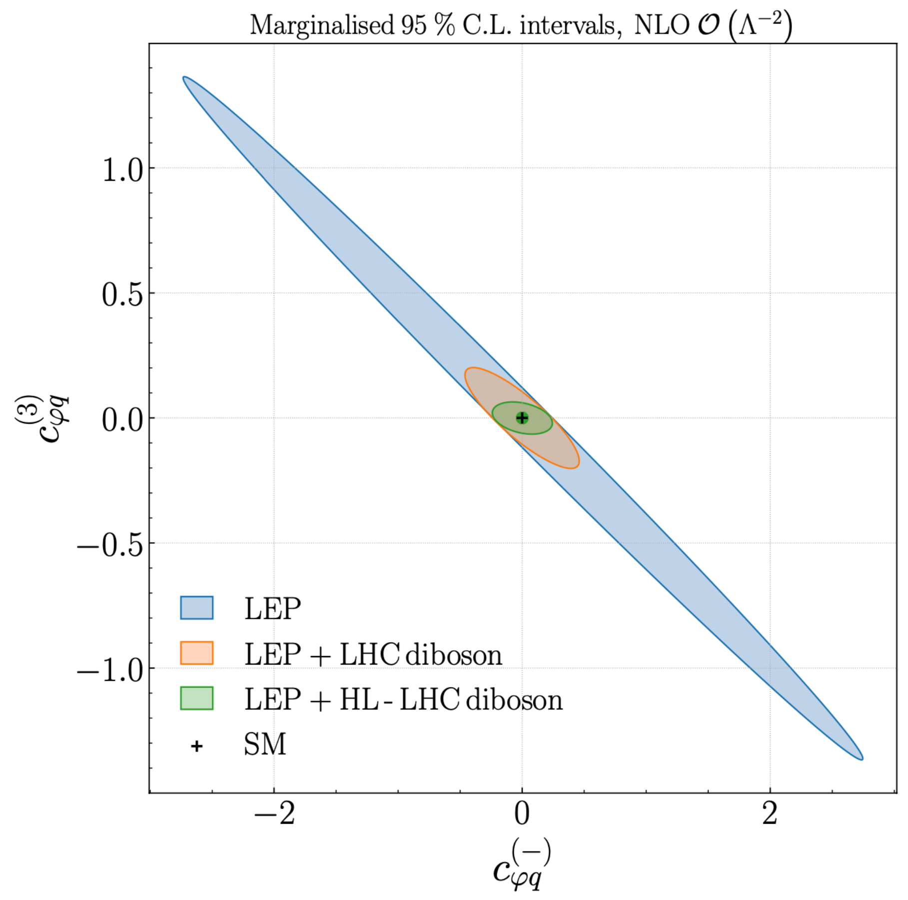
Analysis tools

Report module

Automatised fit reports that analyse the SMEFiT results

Analysis tools



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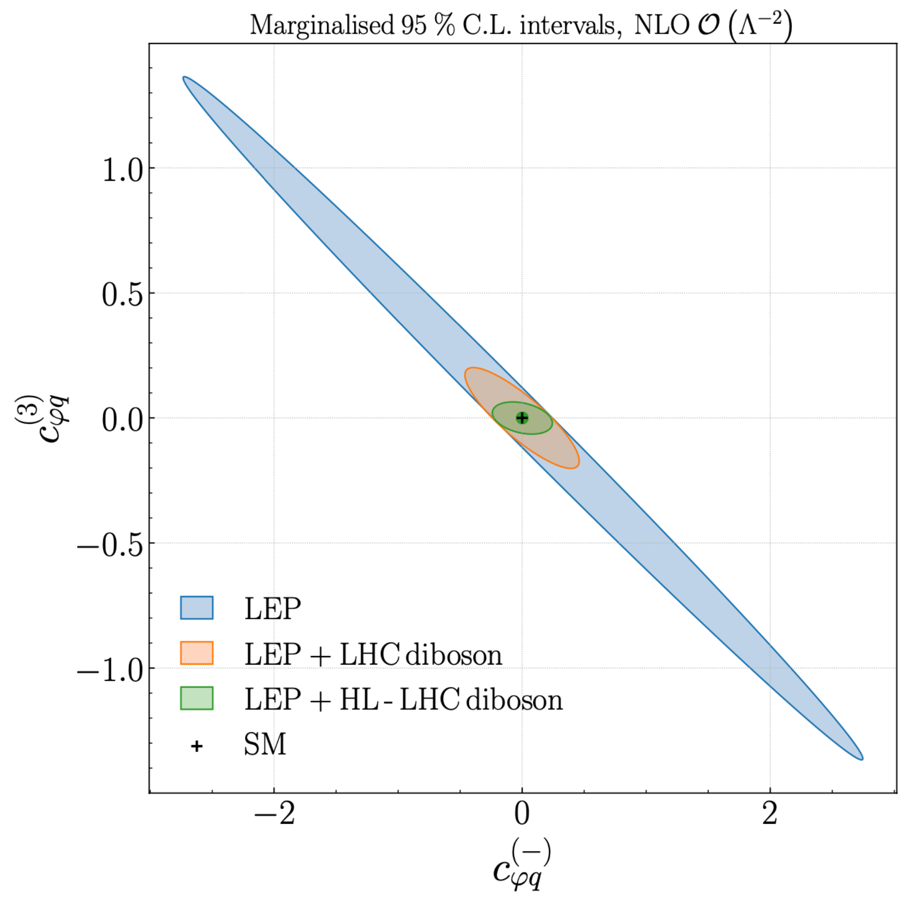

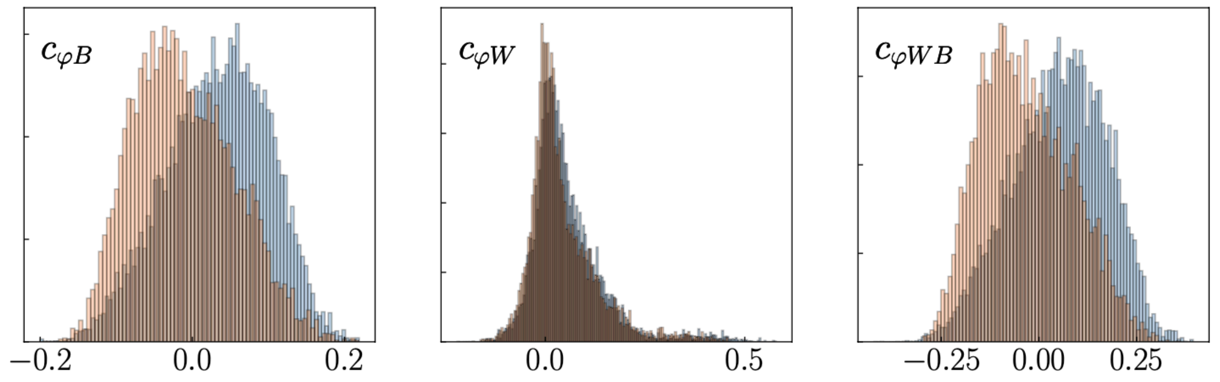

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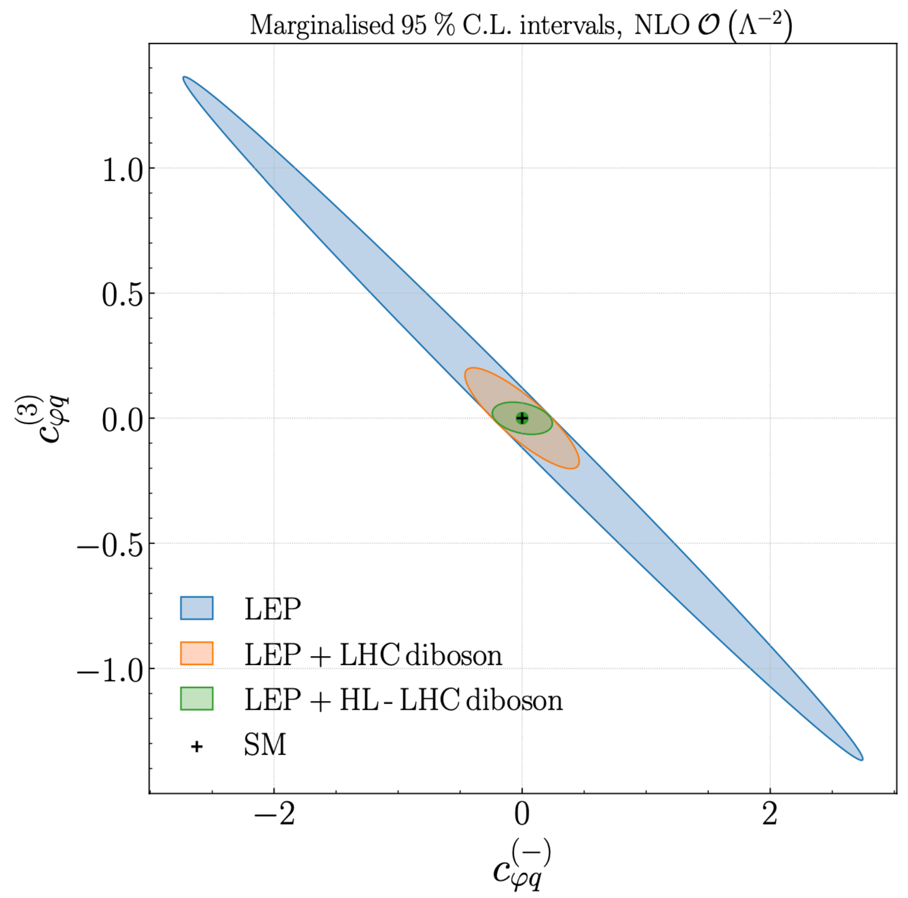

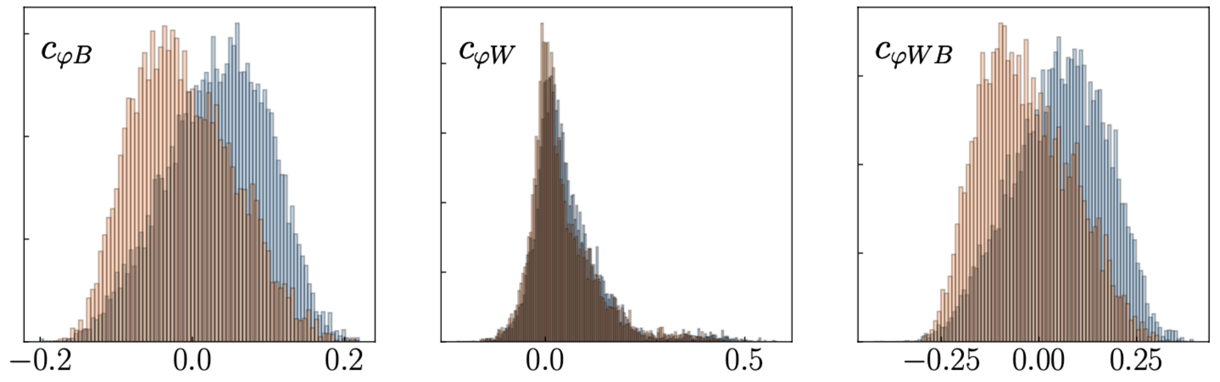

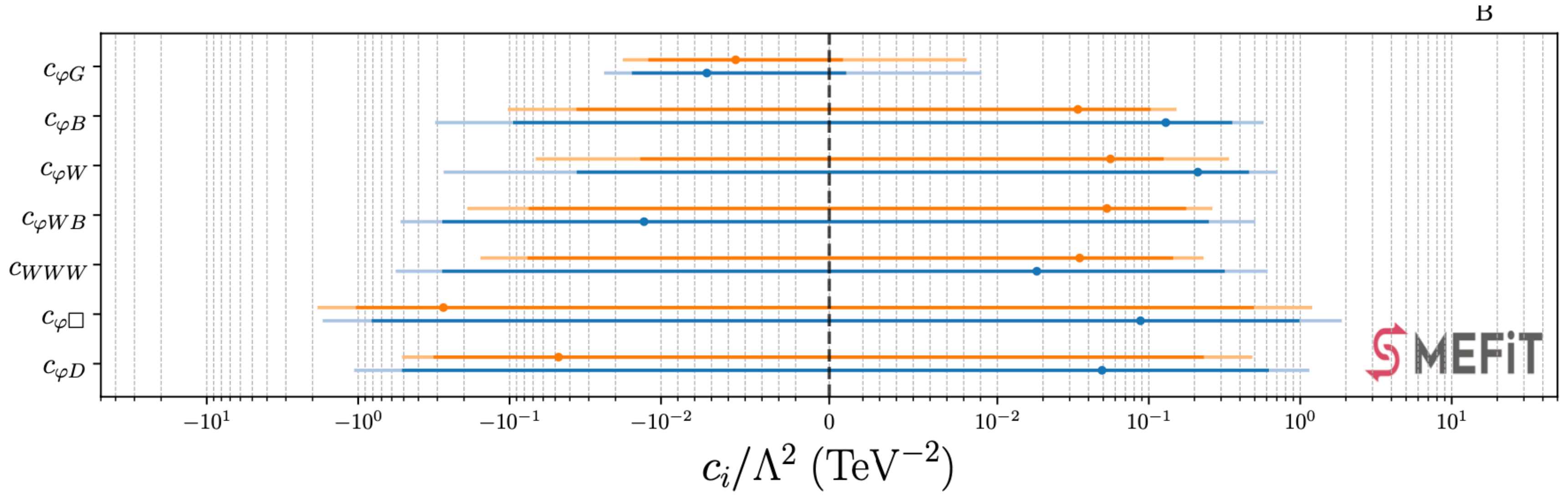

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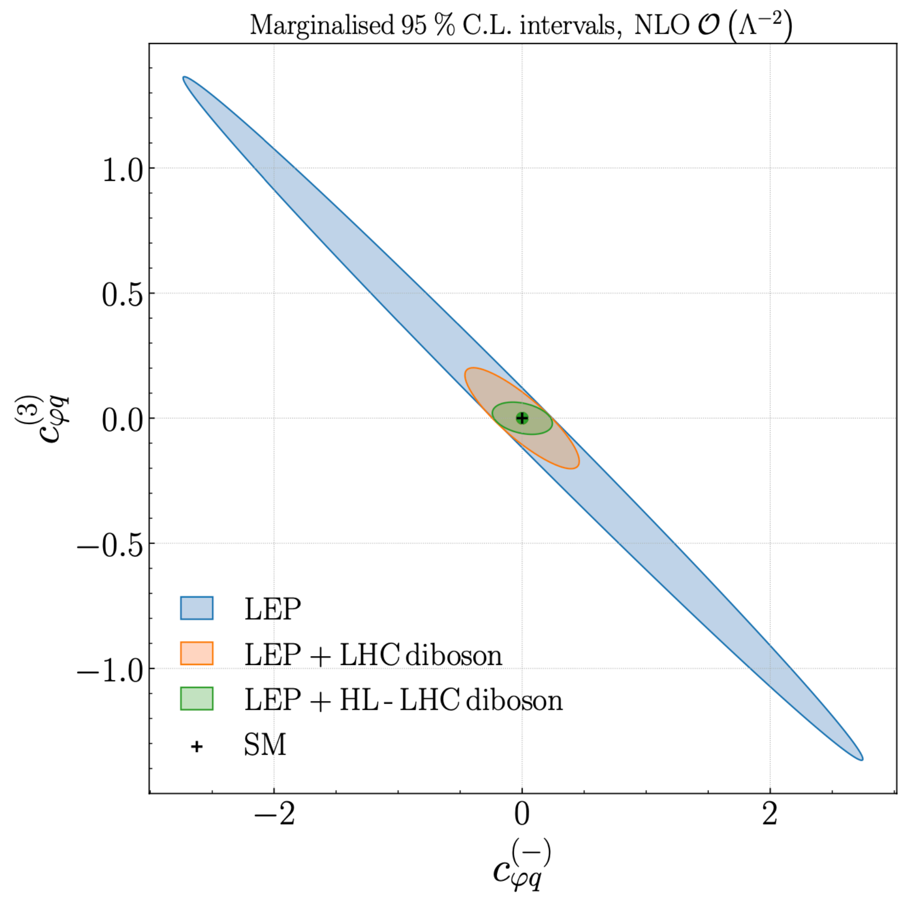

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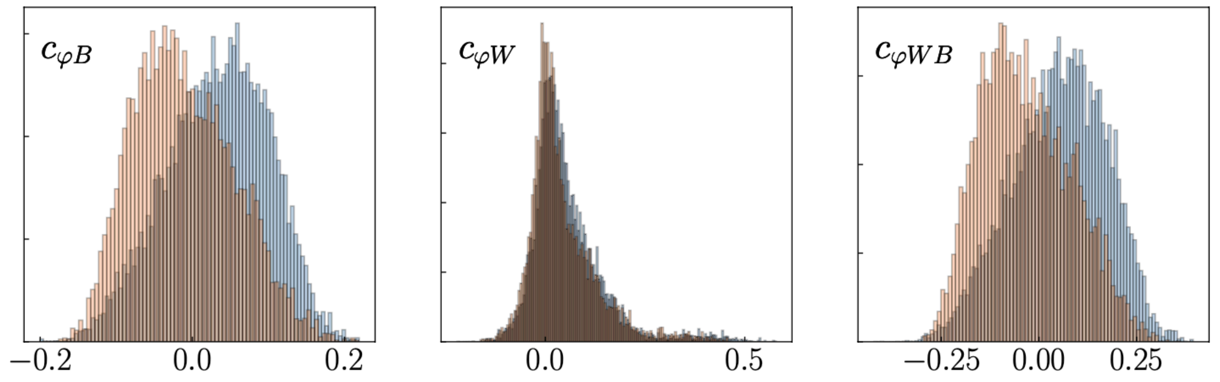

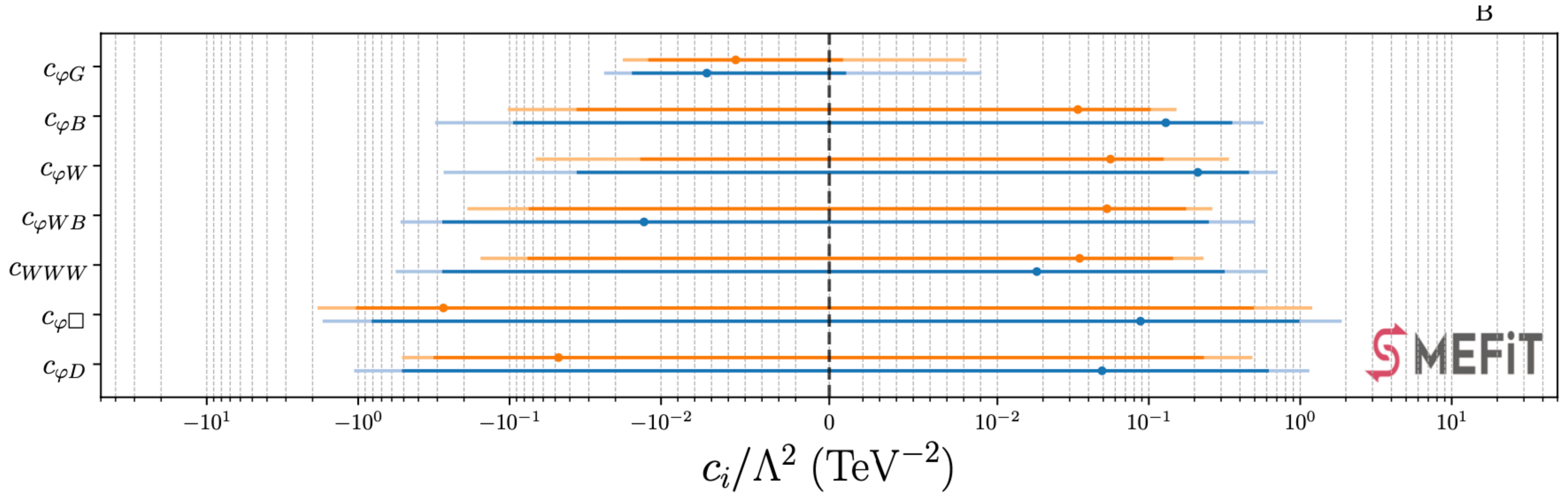

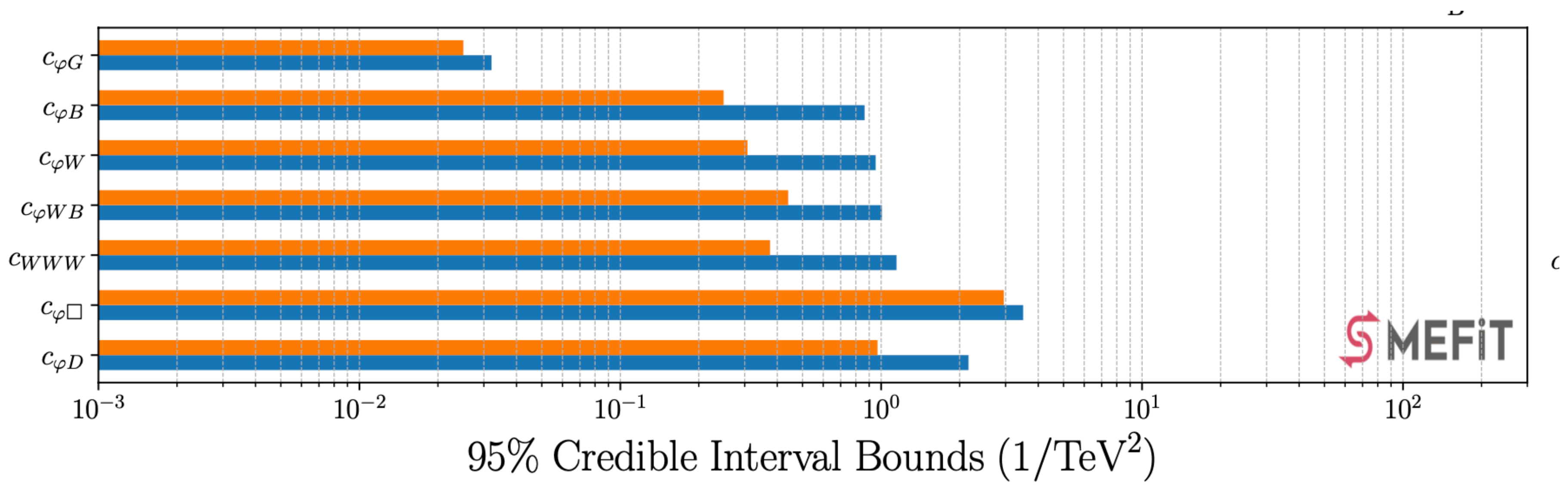

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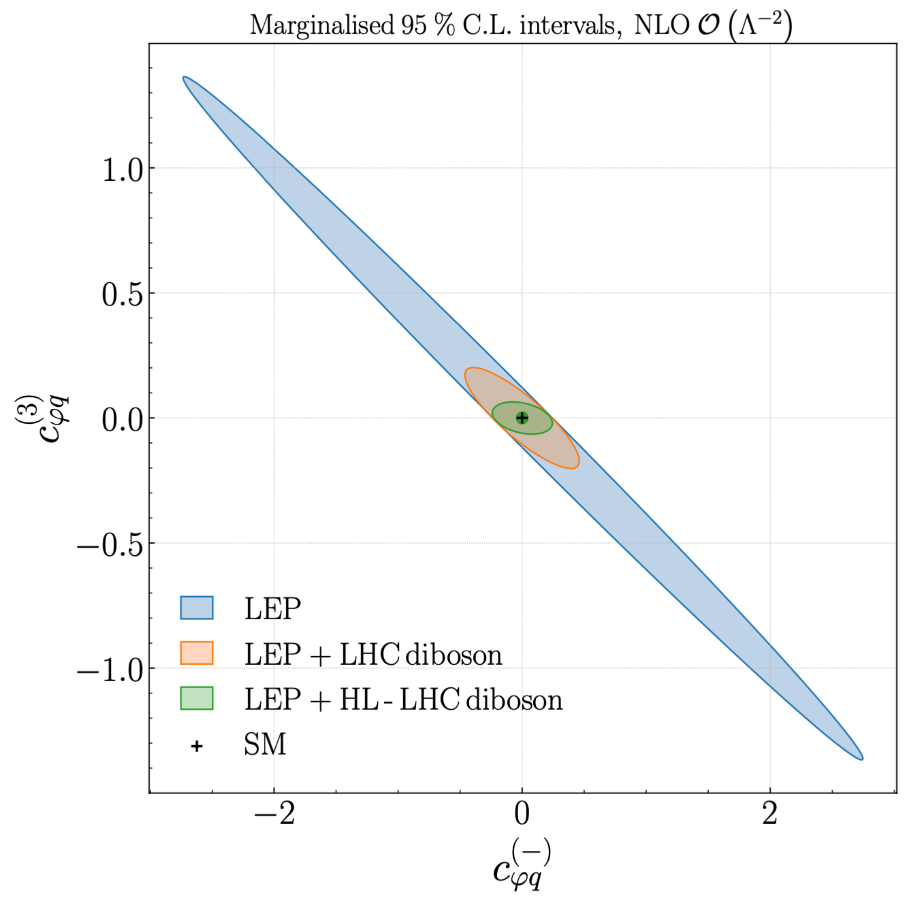

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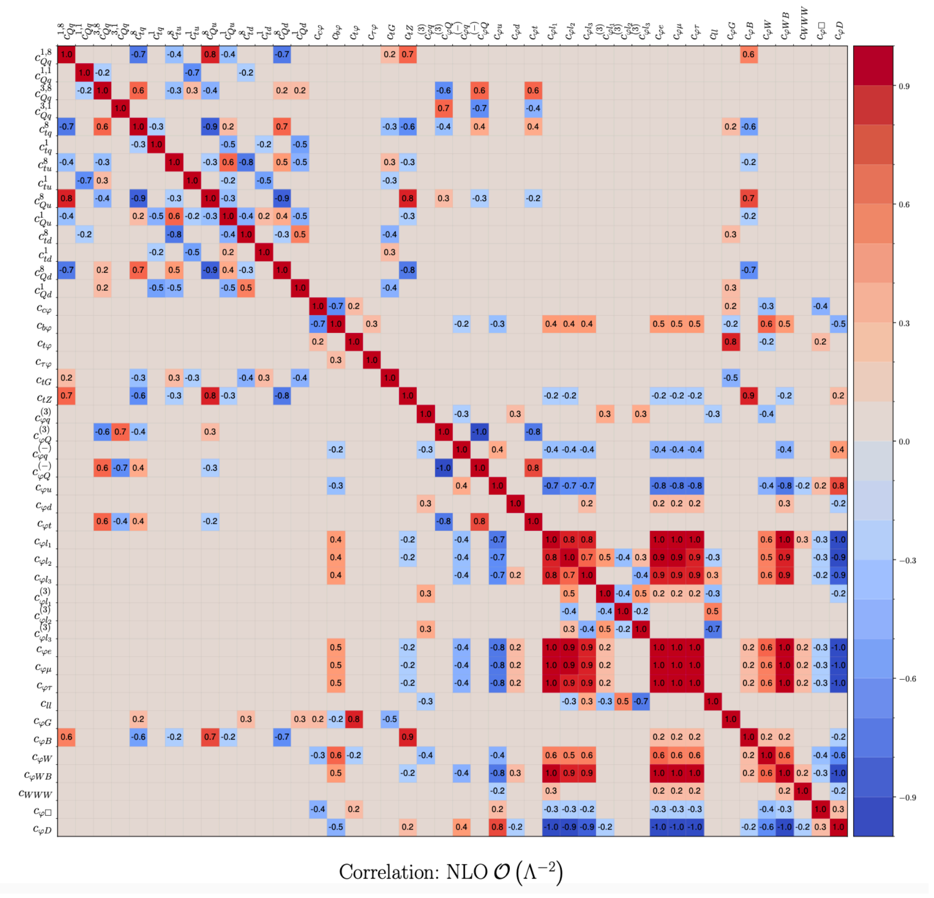

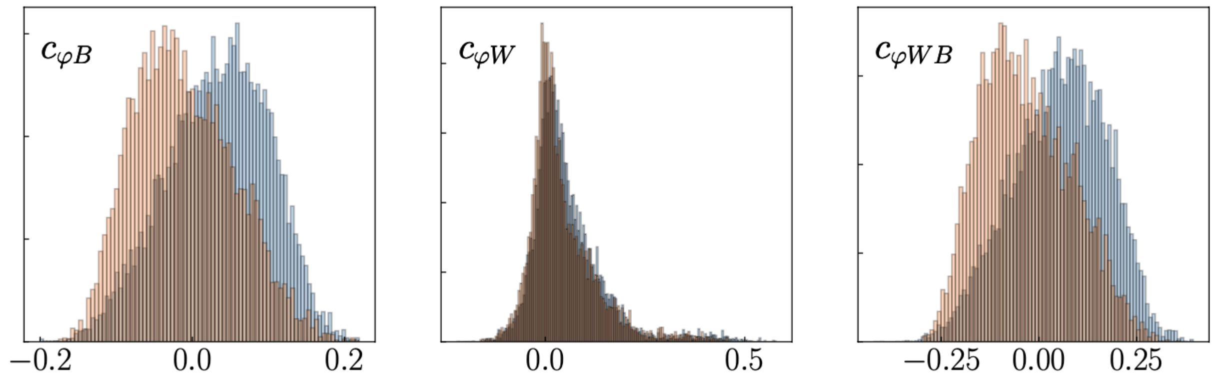

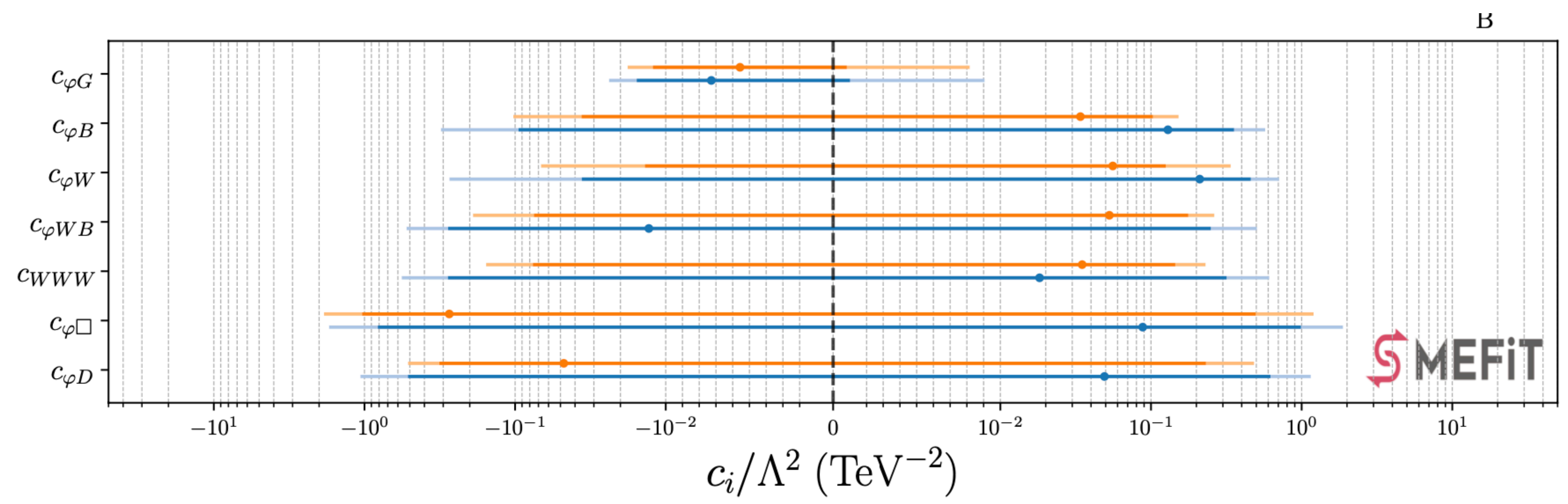

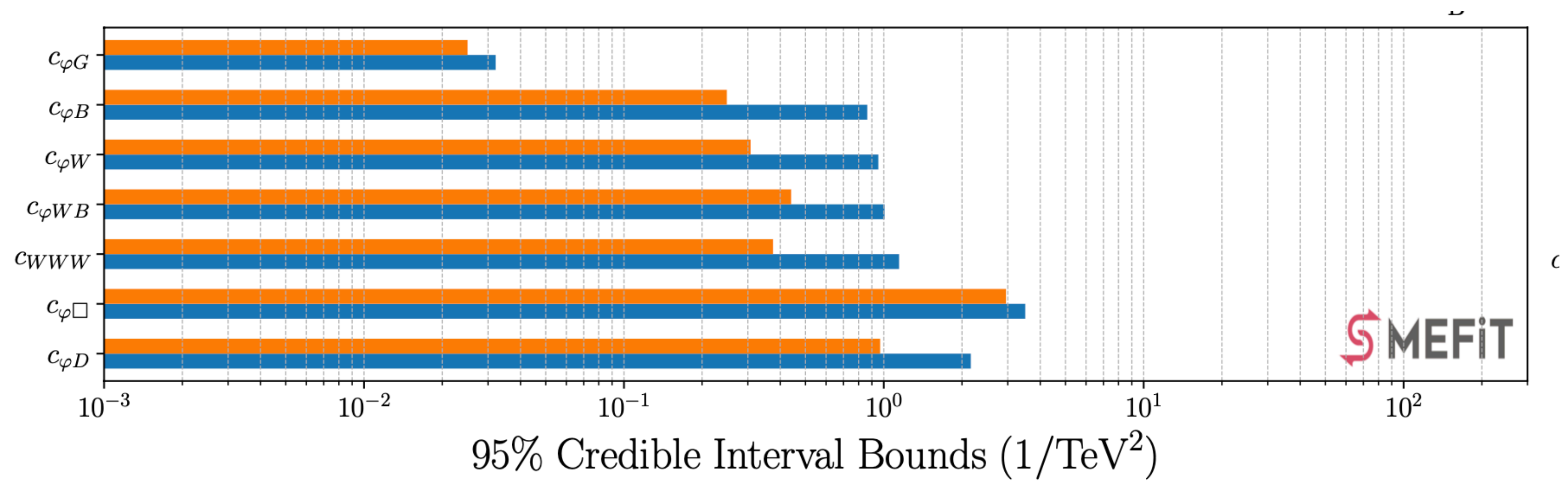

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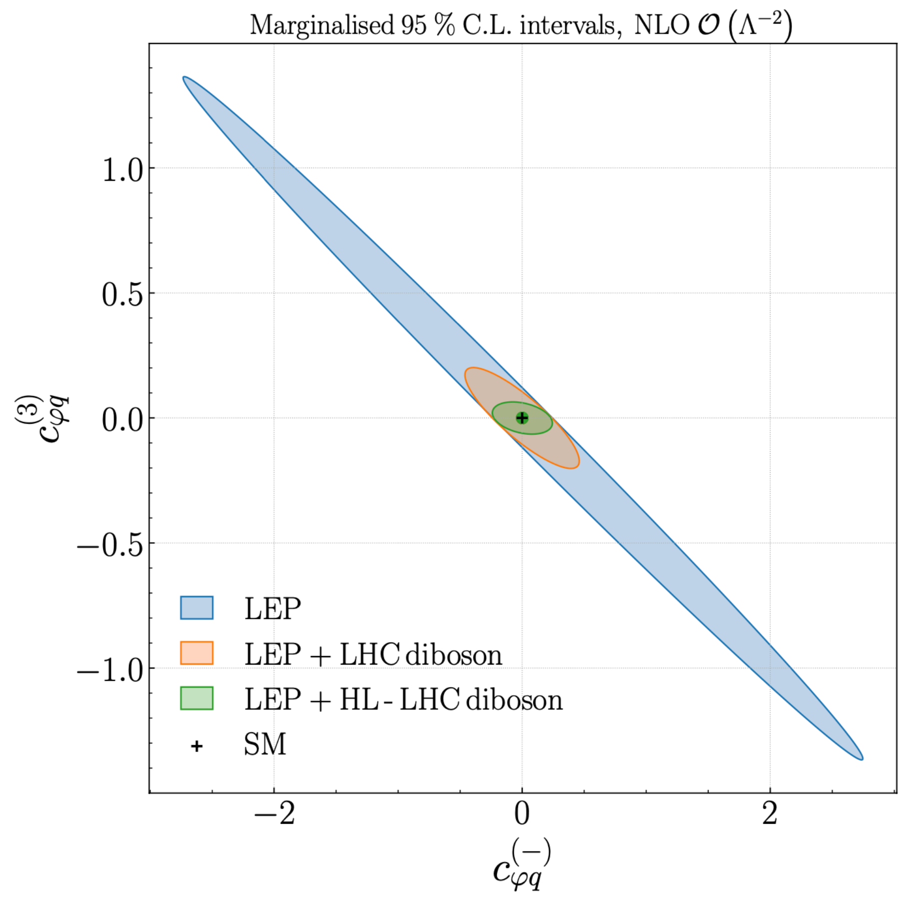

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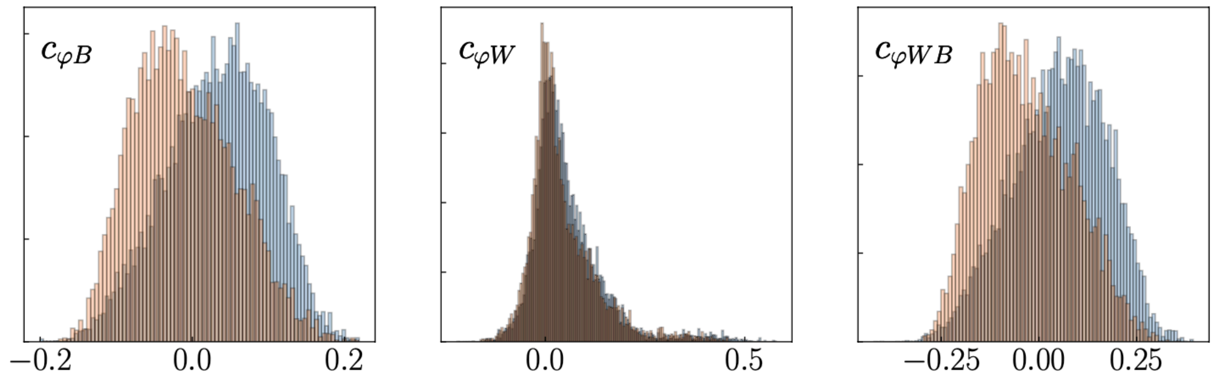
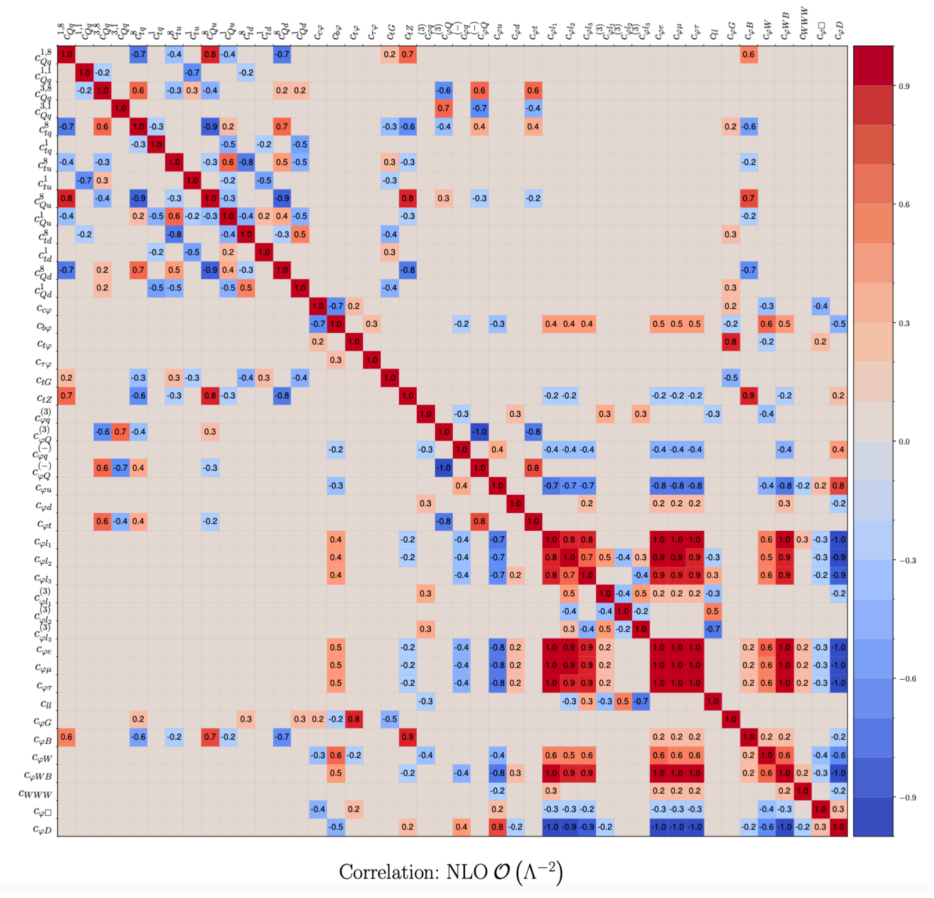
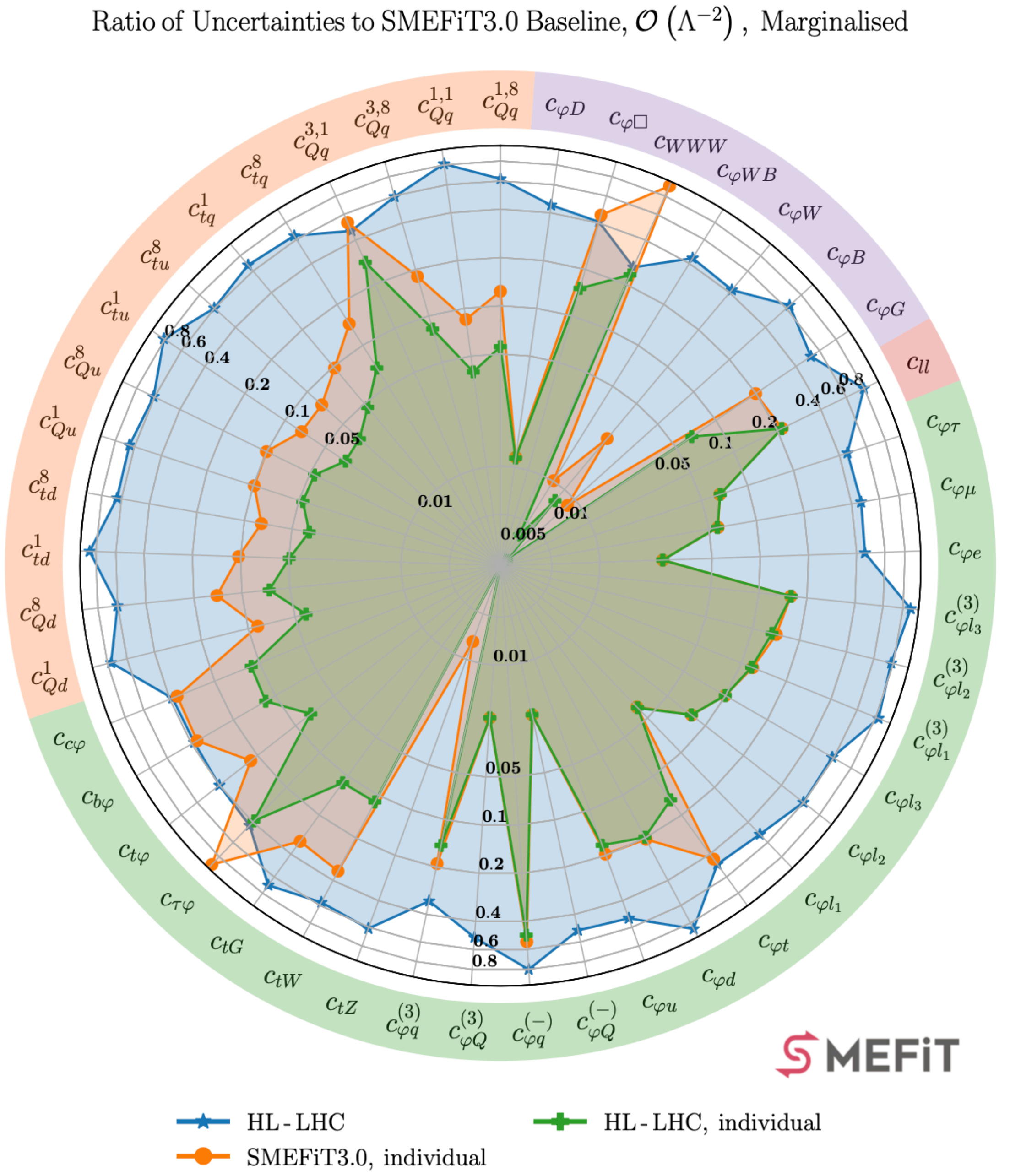
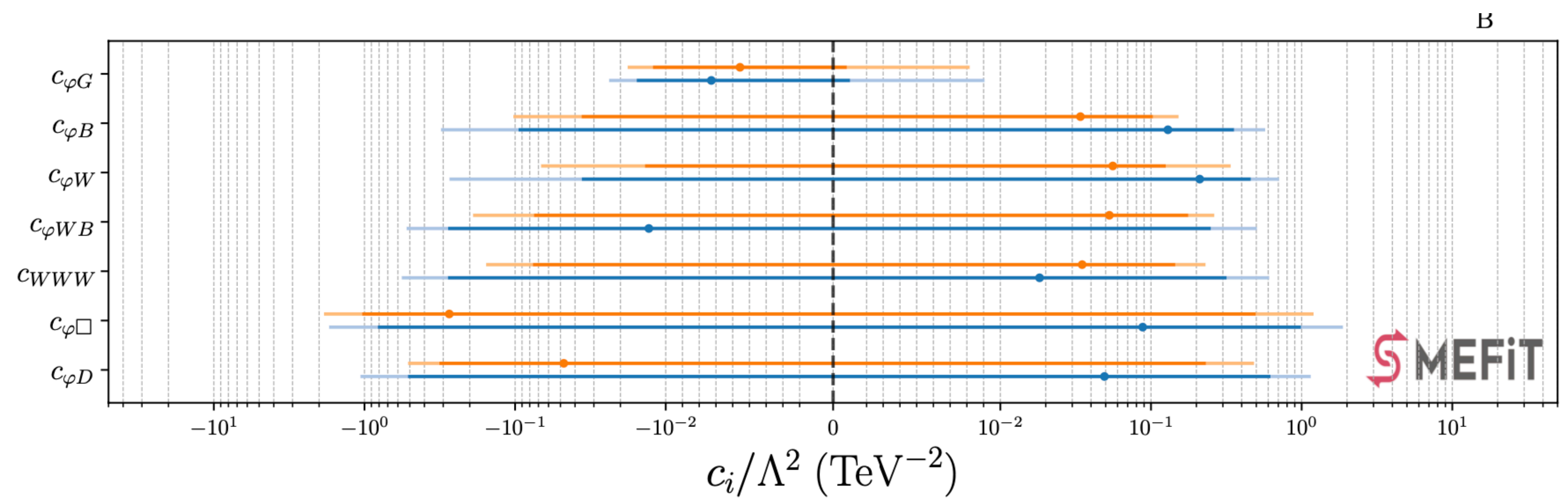
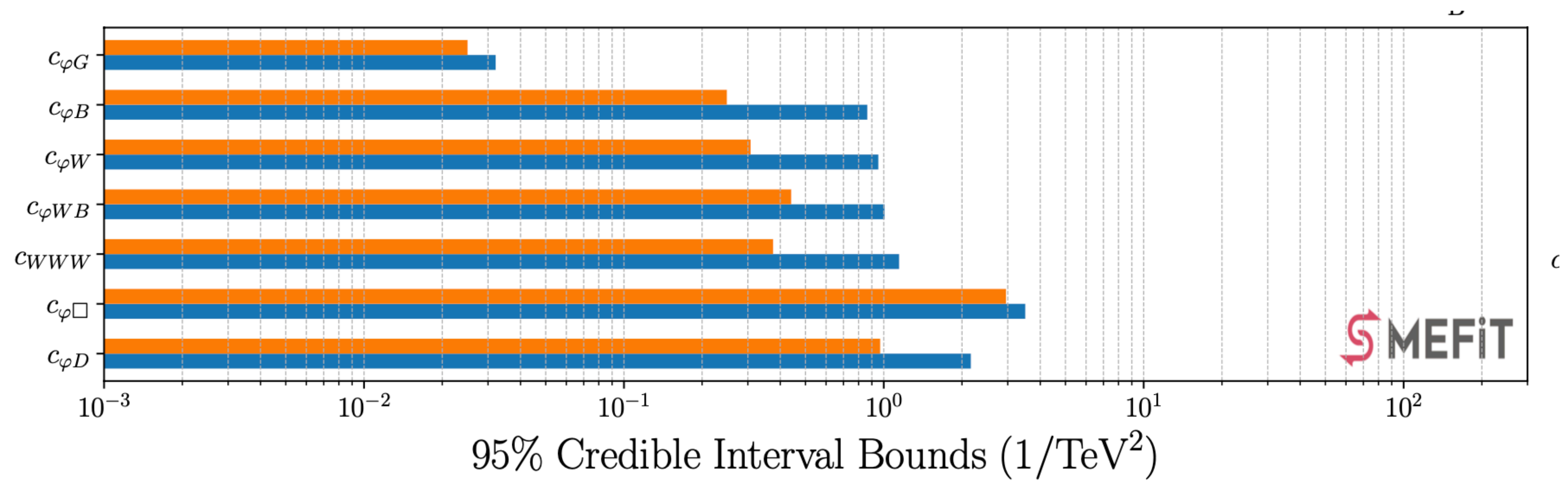




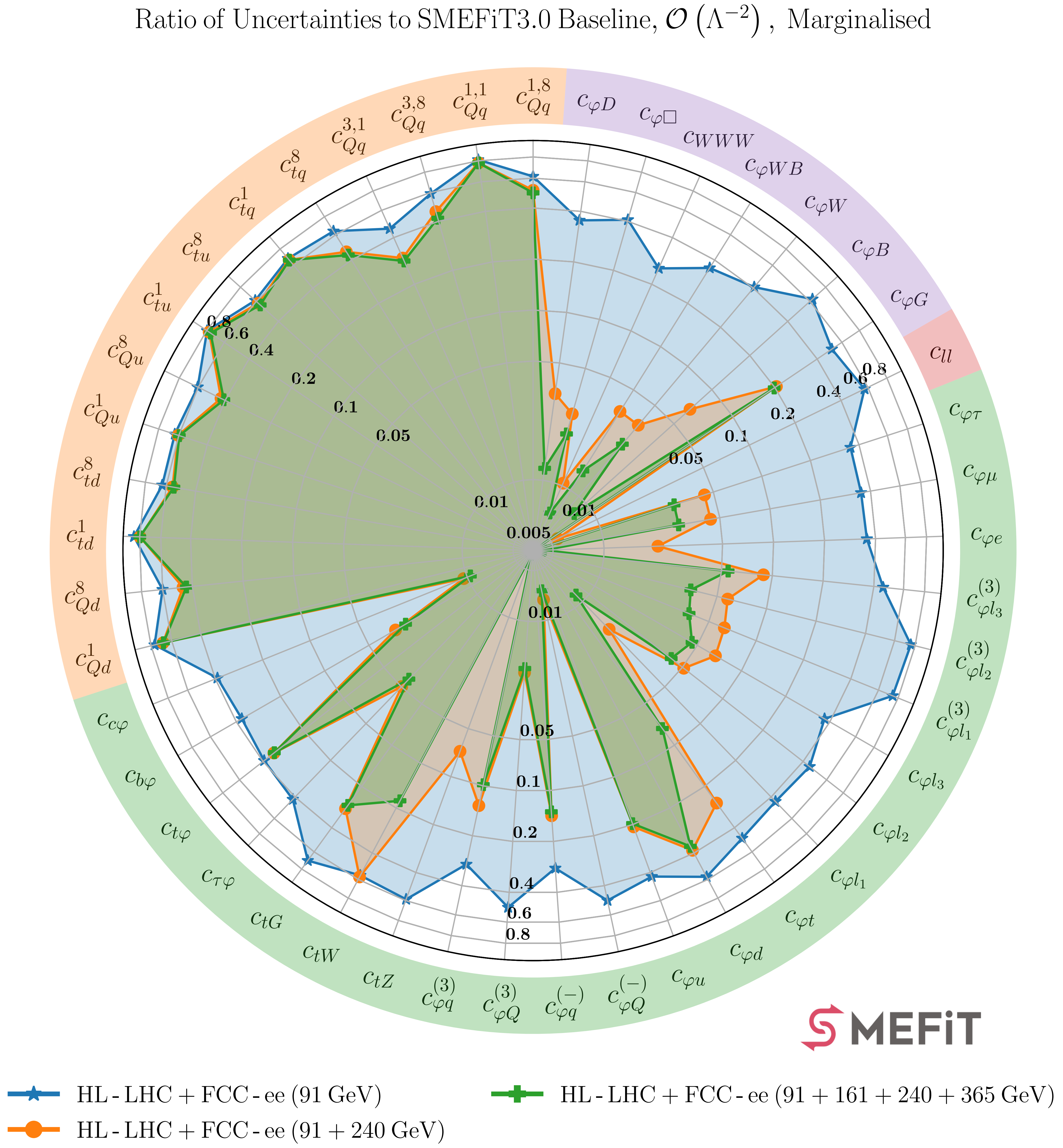






Result: FCC-ee energy breakdown

- The FCC-ee plans to operate **sequentially** , hence we need to study the impact at the various energies
- Largest impact for Z-pole at 91 GeV plus the Higgs factory run at 240 GeV
- We can try other combinations too in order to find the most optimal run order for the SMEFT



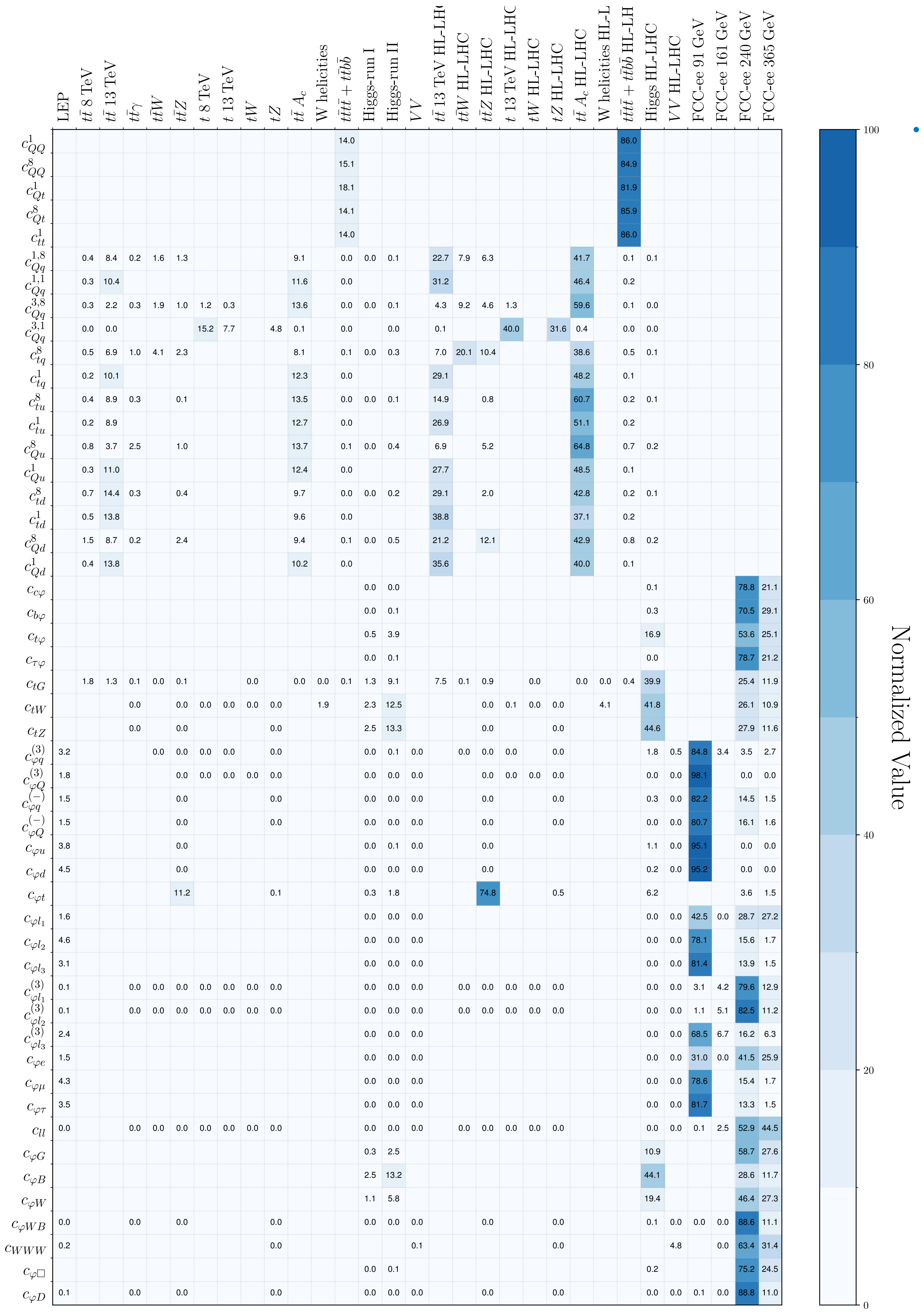
Fisher information study

- The sensitivity of the EFT parameters to the Run II, HL-LHC and FCC-ee datasets is quantified by the **fisher information**

$$I_{ij} = \sum_{m=1}^{n_{\rm dat}} \frac{\sigma^{(\rm eft)}_{m,i}\,\sigma^{(\rm eft)}_{m,j}}{\delta^2_{{\rm exp},m}}$$

- The highest sensitivity in the 2FB sector comes in via the FCC-ee

- The FCC-ee run at 161 GeV is the least sensitive for the SMEFT



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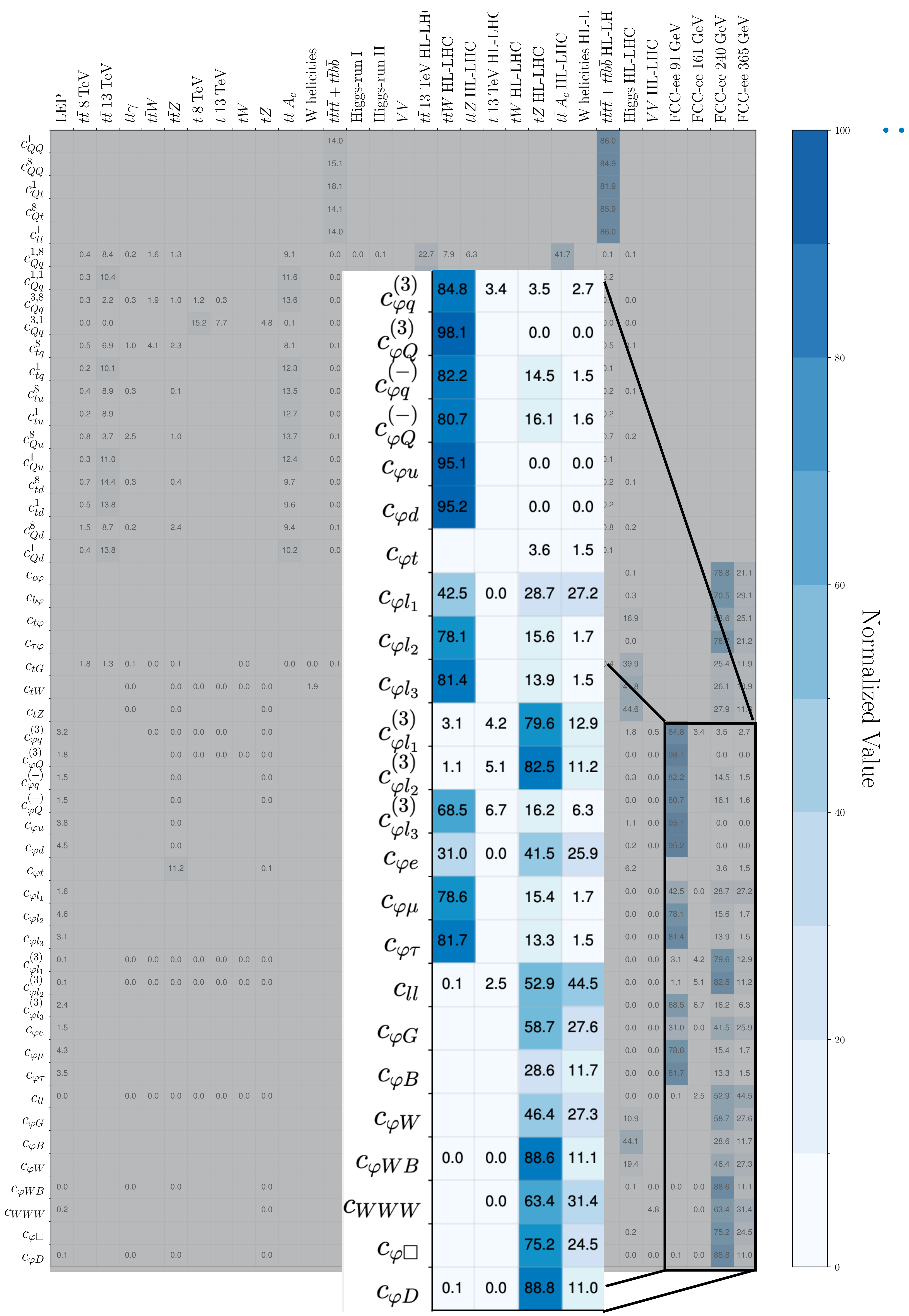
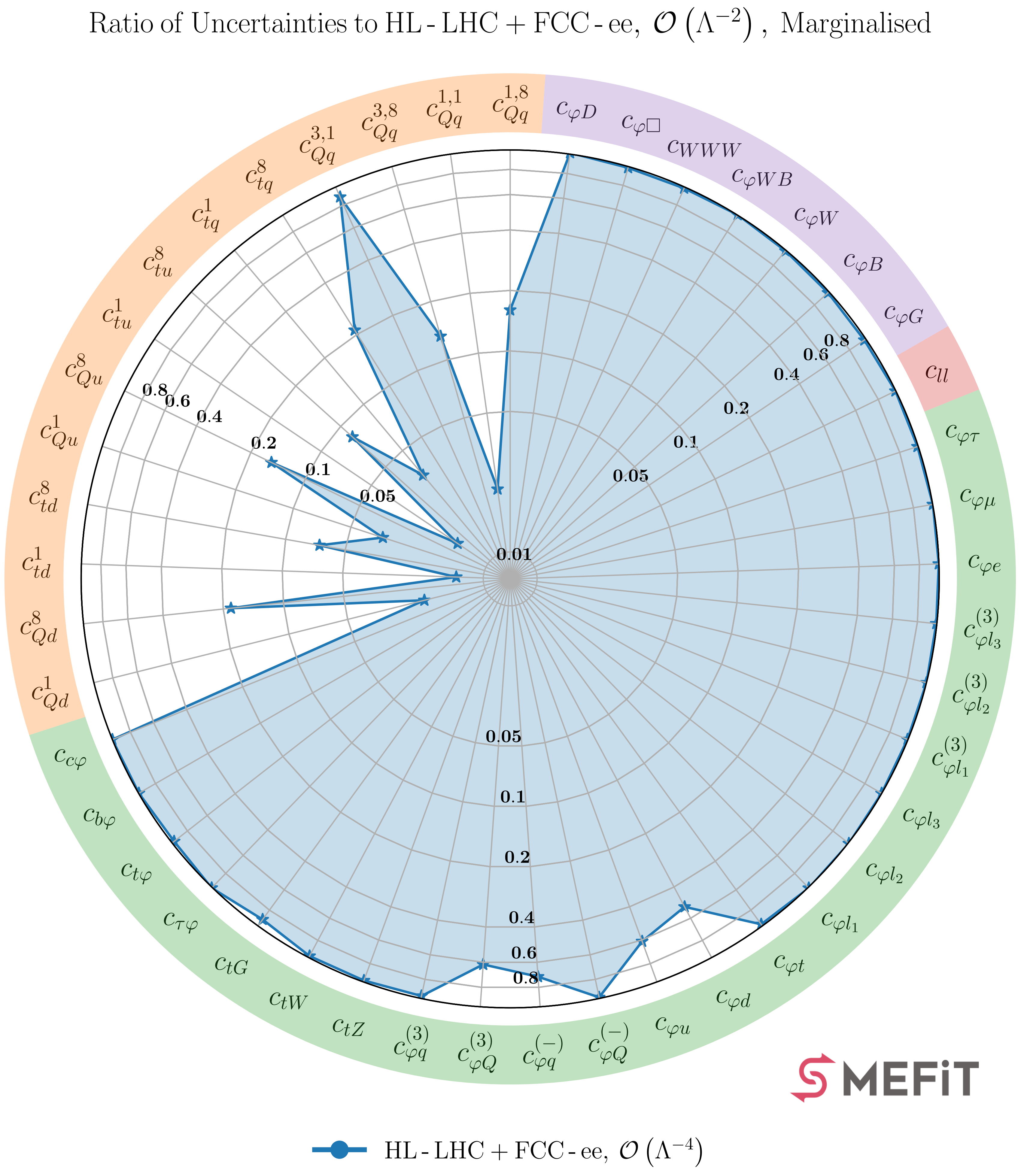
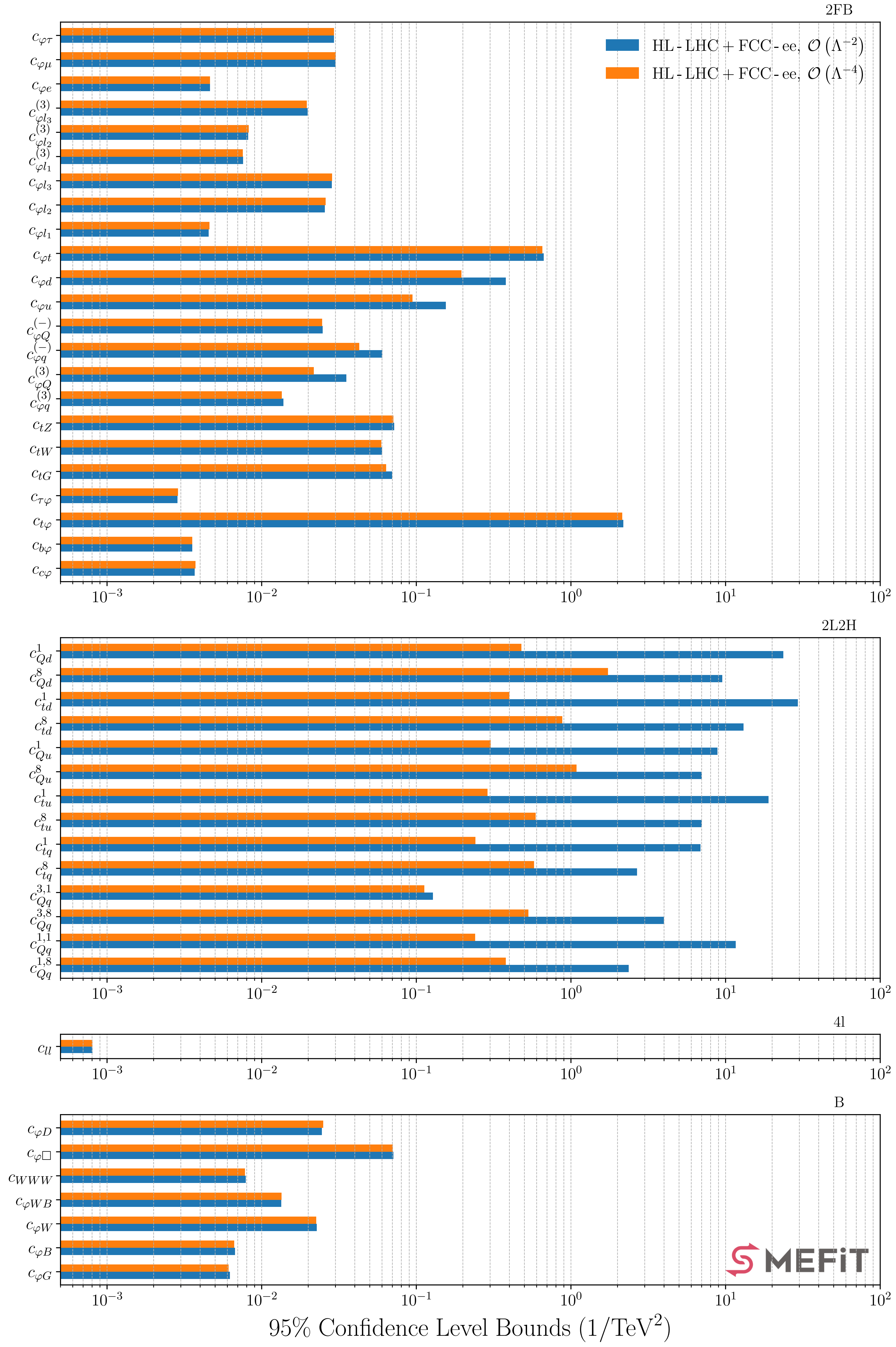


Impact of quadratics





Conclusion and outlook

- Presented **SMEFiT3.0**, a global fit of 50 Wilson coefficients to Higgs, top, diboson and EWPOs, including **quadratic corrections**
- We are becoming **increasingly sensitive** to possible new physics effects, both through (still) expanding LHC datasets, as well as through future colliders
- The FCC-ee offers an **unprecedented indirect mass reach** on new heavy particles
- RGE effects are crucial to include to connect experiments at widely separated scales
- Outlook: the inclusion of other proposed future colliders

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Contact: jaco.ter.hoeve@ed.ac.uk

Thanks for your attention!

SM predictions

Category	Process	SM	Code/Ref	SMEFT
Top quark production	$t\bar{t}$ (incl)	NNLO QCD	MG5_aMC NLO + NNLO K-fact	NLO QCD
	$t\bar{t}+V$	NLO QCD	MG5_aMC NLO	LO QCD + NLO SM K-fact
	single-t (incl)	NNLO QCD	MG5_aMC NLO + NNLO K-fact	NLO QCD
	$t+V$	NLO QCD	MG5_aMC NLO	LO QCD + NLO SM K-fact
	$t\bar{t}t\bar{t}$, $t\bar{b}t\bar{b}$	NLO QCD	MG5_aMC NLO	LO QCD + NLO SM K-fact
Higgs production and decay	$gg \to h$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	VBF	NNLO QCD + NLO EW	HXSWG	LO QCD
	$h+V$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	$ht\bar{t}$	NNLO QCD + NLO EW	HXSWG	NLO QCD
	$h \to X$	NNLO QCD + NLO EW	HXSWG	NLO QCD ($X = b\bar{b}$) LO QCD ($X \neq b\bar{b}$)
Diboson production	$e^+e^- \to W^+W^-$	NNLO QCD + NLO EW	LEP EWWG	LO QCD
	$pp \to VV'$	NNLO QCD	MATRIX	NLO QCD

HL-LHC projected datasets

Dataset	$\mathcal{L}$ (fb^{-1})	Info	Observables	$n_{\rm dat}$	Ref.
ATLAS_STXS_RunII_13TeV_2022	139	ggF, VBF, Vh, $t\bar{t}h$, th	$d\sigma/dp_T^h$ $d\sigma/dm_{jj}$ $d\sigma/dp_T^V$	36	[55]
CMS_ggF_aa_13TeV	77.4	ggF, $h \to \gamma\gamma$	$\sigma_{ggF}(p_T^h, N_{\rm jets})$	6	[83]
ATLAS_ggF_ZZ_13TeV	79.8	ggF, $h \to ZZ$	$\sigma_{ggF}(p_T^h, N_{\rm jets})$	6	[84]
ATLAS_ggF_13TeV_2015	36.1	ggF, $h \to ZZ, h \to \gamma\gamma$	$d\sigma({\rm ggF})/dp_T^h$	9	[85]
ATLAS_WH_Hbb_13TeV	79.8	$Wh, h \to b\bar{b}$	$d\sigma^{\rm (fid)}/dp_T^W$ (stage 1 STXS)	2	[86]
ATLAS_ZH_Hbb_13TeV	79.8	$Zh, h \to b\bar{b}$	$d\sigma^{\rm (fid)}/dp_T^Z$ (stage 1 STXS)	2	[86]
CMS_H_13TeV_2015_pTH	35.9	$h \to b\bar{b}, h \to \gamma\gamma, h \to ZZ$	$d\sigma/dp_T^h$	9	[87]
ATLAS_WW_13TeV_2016_memu	36.1	fully leptonic	$d\sigma^{\rm (fid)}/dm_{e\mu}$	13	[88]
ATLAS_WZ_13TeV_2016_mTWZ	36.1	fully leptonic	$d\sigma^{\rm (fid)}/dm_T^{WZ}$	6	[89]
CMS_WZ_13TeV_2016_pTZ	35.9	fully leptonic	$d\sigma^{\rm (fid)}/dp_T^Z$	11	[90]
CMS_WZ_13TeV_2022_pTZ	137	fully leptonic	$d\sigma/dp_T^Z$	11	[56]

Dataset	$\mathcal{L}$ (fb^{-1})	Info	Observables	n_{dat}	Ref.
ATLAS_tt_13TeV_ljets_2016_Mtt	36.1	ℓ+jets	$d\sigma/dm_{t\bar{t}}$	7	[91]
CMS_tt_13TeV_dilep_2016_Mtt	35.9	dilepton	$d\sigma/dm_{t\bar{t}}$	7	[92]
CMS_tt_13TeV_Mtt	137	ℓ+jets	$1/\sigma d\sigma/dm_{t\bar{t}}$	14	[57]
CMS_tt_13TeV_ljets_inc	137	ℓ+jets	$\sigma(t\bar{t})$	1	[57]
ATLAS_tt_13TeV_asy_2022	139	ℓ + jets	A_C	5	[59]
CMS_tt_13TeV_asy	138	ℓ + jets	A_C	3	[58]
ATLAS_Whel_13TeV	139	W-helicity fraction	F_0, F_L	2	[60]
ATLAS_ttbb_13TeV_2016	36.1	lepton + jets	$\sigma_{tot}(t\bar{t}b\bar{b})$	1	[93]
CMS_ttbb_13TeV_2016	35.9	all-jets	$\sigma_{tot}(t\bar{t}b\bar{b})$	1	[94]
CMS_ttbb_13TeV_dilepton_inc	35.9	dilepton	$\sigma_{tot}(t\bar{t}b\bar{b})$	1	[68]
CMS_ttbb_13TeV_ljets_inc	35.9	lepton + jets	$\sigma_{tot}(t\bar{t}b\bar{b})$	1	[68]
ATLAS_tttt_13TeV_run2	139	multi-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[95]
CMS_tttt_13TeV_run2	137	same-sign or multi-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[96]
ATLAS_tttt_13TeV_slep_inc	139	single-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[64]
CMS_tttt_13TeV_slep_inc	35.8	single-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[65]
ATLAS_tttt_13TeV_2023	139	multi-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[66]
CMS_tttt_13TeV_2023	139	same-sign or multi-lepton	$\sigma_{tot}(t\bar{t}t\bar{t})$	1	[67]
CMS_ttZ_13TeV_pTZ	77.5	$t\bar{t}Z$	$d\sigma(t\bar{t}Z)/dp_T^Z$	4	[97]
ATLAS_ttZ_13TeV_pTZ	139	$t\bar{t}Z$	$d\sigma(t\bar{t}Z)/dp_T^Z$	7	[61]
ATLAS_ttW_13TeV_2016	36.1	$t\bar{t}W$	$\sigma_{tot}(t\bar{t}W)$	1	[98]
CMS_ttW_13TeV	35.9	$t\bar{t}W$	$\sigma_{tot}(t\bar{t}W)$	1	[99]
ATLAS_t_tch_13TeV_inc	3.2	t-channel	$\sigma_{tot}(tq), \sigma_{tot}(\bar{t}q)$	2	[100]
CMS_t_tch_13TeV_2019_diff_Yt	35.9	t-channel	$d\sigma/d\|y_t\|$	5	[101]
ATLAS_t_sch_13TeV_inc	139	s-channel	$\sigma(t+\bar{t})$	1	[69]
ATLAS_tW_13TeV_inc	3.2	multi-lepton	$\sigma_{tot}(tW)$	1	[102]
CMS_tW_13TeV_inc	35.9	multi-lepton	$\sigma_{tot}(tW)$	1	[103]
CMS_tW_13TeV_slep_inc	36	single-lepton	$\sigma_{tot}(tW)$	1	[71]
ATLAS_tZ_13TeV_run2_inc	139	multi-lepton + jets	$\sigma_{fid}(t\ell^+\ell^-q)$	1	[104]
CMS_tZ_13TeV_pTt	138	multi-lepton + jets	$d\sigma_{fid}(tZj)/dp_T^t$	3	[70]

FCC-ee and CEPC datasets

EWPOs

Z-pole EWPOs ($\sqrt{s} = 91.2$ GeV)		
$\mathcal{O}_i$	$\delta/\Delta\ \mathcal{O}_i$	
	FCC-ee	CEPC
$\alpha(m_Z)^{-1}\ (\times 10^3)$	$\Delta = 2.7\ (1.2)$	$\Delta = 17.8$
Γ_W (MeV)	$\Delta = 0.85\ (0.3)$	$\Delta = 1.8\ (0.9)$
Γ_Z (MeV)	$\Delta = 0.0028\ (0.025)$	$\Delta = 0.005\ (0.025)$
$A_e\ (\times 10^5)$	$\Delta = 0.5\ (2)$	$\Delta = 1.5$
$A_\mu\ (\times 10^5)$	$\Delta = 1.6\ (2.2)$	$\Delta = 3.0\ (1.8)$
$A_\tau\ (\times 10^5)$	$\Delta = 0.35\ (20)$	$\Delta = 1.2\ (6.9)$
$A_b\ (\times 10^5)$	$\Delta = 1.7\ (21)$	$\Delta = 3\ (21)$
$A_c\ (\times 10^5)$	$\Delta = 14\ (15)$	$\Delta = 6\ (30)$
$\sigma^0_{\rm had}$ (pb)	$\Delta = 0.025\ (4)$	$\Delta = 0.05\ (2)$
$R_e\ (\times 10^3)$	$\delta = 0.0028\ (0.3)$	$\delta = 0.003\ (0.2)$
$R_\mu\ (\times 10^3)$	$\delta = 0.0021\ (0.05)$	$\delta = 0.003\ (0.1)$
$R_\tau\ (\times 10^3)$	$\delta = 0.0021\ (0.1)$	$\delta = 0.003\ (0.1)$
$R_b\ (\times 10^3)$	$\delta = 0.001\ (0.3)$	$\delta = 0.005\ (0.2)$
$R_c\ (\times 10^3)$	$\delta = 0.011\ (1.5)$	$\delta = 0.02\ (1)$

Zh and VBF ($h\nu\nu$)

$e^+e^- \to Zh$				
	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
$\mathcal{O}_i$	$\delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\rm exp}\mathcal{O}_i$ (CEPC)	$\delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\rm exp}\mathcal{O}_i$ (CEPC)
σ_{Zh}	0.0035	0.0026	0.0064	0.014
$\sigma_{Zh} \times {\rm BR}_{b\bar{b}}$	0.0021	0.0014	0.0035	0.009
$\sigma_{Zh} \times {\rm BR}_{c\bar{c}}$	0.0156	0.0202	0.046	0.088
$\sigma_{Zh} \times {\rm BR}_{gg}$	0.0134	0.0081	0.0247	0.034
$\sigma_{Zh} \times {\rm BR}_{ZZ}$	0.0311	0.0417	0.0849	0.2
$\sigma_{Zh} \times {\rm BR}_{WW}$	0.0085	0.0053	0.0184	0.028
$\sigma_{Zh} \times {\rm BR}_{\tau^+\tau^-}$	0.0064	0.0042	0.0127	0.021
$\sigma_{Zh} \times {\rm BR}_{\gamma\gamma}$	0.0636	0.0302	0.127	0.11
$\sigma_{Zh} \times {\rm BR}_{\gamma Z}$	0.12	0.085	-	-

$e^+e^- \to h\nu\nu$				
	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
$\mathcal{O}_i$	$\delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\rm exp}\mathcal{O}_i$ (CEPC)	$\delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\delta_{\rm exp}\mathcal{O}_i$ (CEPC)
$\sigma_{h\nu\nu} \times {\rm BR}_{b\bar{b}}$	0.0219	0.0159	0.0064	0.011
$\sigma_{h\nu\nu} \times {\rm BR}_{c\bar{c}}$	-	-	0.0707	0.16
$\sigma_{h\nu\nu} \times {\rm BR}_{gg}$	-	-	0.0318	0.045
$\sigma_{h\nu\nu} \times {\rm BR}_{ZZ}$	-	-	0.0707	0.21
$\sigma_{h\nu\nu} \times {\rm BR}_{WW}$	-	-	0.0255	0.044
$\sigma_{h\nu\nu} \times {\rm BR}_{\tau^+\tau^-}$	-	-	0.0566	0.042
$\sigma_{h\nu\nu} \times {\rm BR}_{\gamma\gamma}$	-	-	0.156	0.16

FCC-ee and CEPC datasets

Light fermion production

$e^+e^- \to f\bar{f}$				
	$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
$\mathcal{O}_i$	$\Delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\Delta_{\rm exp}\mathcal{O}_i$ (CEPC)	$\Delta_{\rm exp}\mathcal{O}_i$ (FCC-ee)	$\Delta_{\rm exp}\mathcal{O}_i$ (CEPC)
$\sigma_{\rm tot}(e^+e^-)$ [fb]	2.29	1.62	2.74	4.68
$A_{\rm FB}(e^+e^-)$	$9.79 \cdot 10^{-6}$	$6.92 \cdot 10^{-6}$	$2.83 \cdot 10^{-5}$	$4.83 \cdot 10^{-5}$
$\sigma_{\rm tot}(\mu^+\mu^-)$ [fb]	0.405	0.287	0.48	0.82
$A_{\rm FB}(\mu^+\mu^-)$	$1.98 \cdot 10^{-4}$	$1.397 \cdot 10^{-4}$	$5.69 \cdot 10^{-4}$	$9.7 \cdot 10^{-4}$
$\sigma_{\rm tot}(\tau^+\tau^-)$ [fb]	0.374	0.264	0.443	0.756
$A_{\rm FB}(\tau^+\tau^-)$	$2.17 \cdot 10^{-4}$	$1.53 \cdot 10^{-4}$	$6.24 \cdot 10^{-4}$	0.00106
$\sigma_{\rm tot}(c\bar{c})$ [fb]	0.088	0.062	0.102	0.175
$A_{\rm FB}(c\bar{c})$	0.000813	$5.74 \cdot 10^{-4}$	0.00238	0.00405
$\sigma_{\rm tot}(b\bar{b})$ [fb]	0.151	0.107	0.171	0.29
$A_{\rm FB}(b\bar{b})$	$4.86 \cdot 10^{-4}$	$3.44 \cdot 10^{-4}$	0.00142	0.00243

$e^+e^- \to W^+W^-$						
$\mathcal{O}_i$	$\sqrt{s} = 161$ GeV		$\sqrt{s} = 240$ GeV		$\sqrt{s} = 365$ GeV	
	$\delta_{\rm exp}$ (FCC-ee)	$\delta_{\rm exp}$ (CEPC)	$\delta_{\rm exp}$ (FCC-ee)	$\delta_{\rm exp}$ (CEPC)	$\delta_{\rm exp}$ (FCC-ee)	$\delta_{\rm exp}$ (CEPC)
σ_{WW}	$1.36 \cdot 10^{-4}$	$2.48 \cdot 10^{-4}$	$1.22 \cdot 10^{-4}$	$8.63 \cdot 10^{-5}$	$2.81 \cdot 10^{-4}$	$4.87 \cdot 10^{-4}$
${\rm BR}_{W\to\ell_i\nu_i}$	$2.72 \cdot 10^{-4}$	$4.95 \cdot 10^{-4}$	$2.44 \cdot 10^{-4}$	$1.73 \cdot 10^{-4}$	$5.63 \cdot 10^{-4}$	$9.75 \cdot 10^{-4}$

HL-LHC projections

- The central values of the pseudo data are fluctuated around the SM

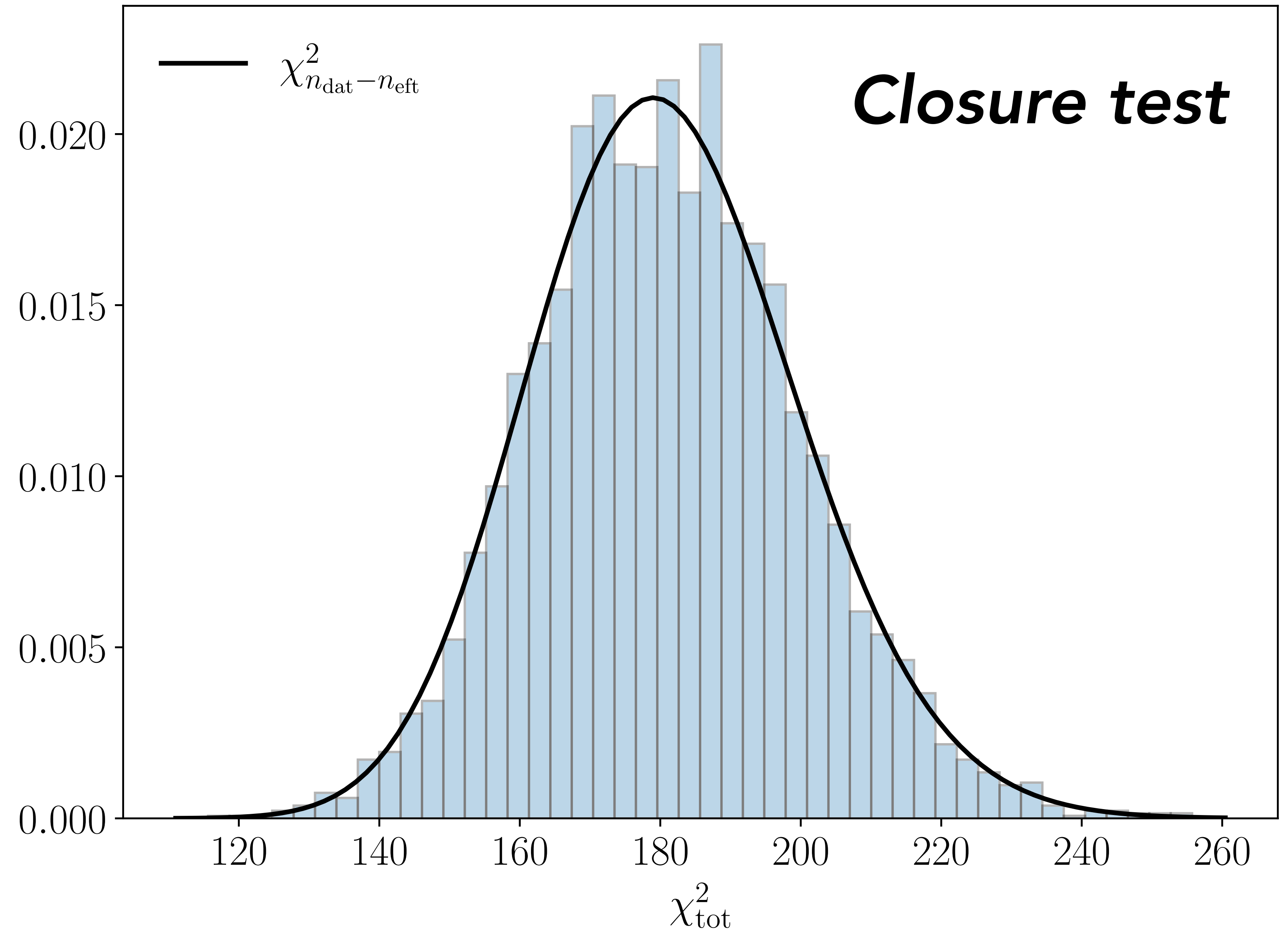
$$\mathcal{O}_i^{(\mathrm{exp})} = \mathcal{O}_i^{(\mathrm{th})}\left(1 + r_i\delta_i^{(\mathrm{stat})} + \sum_{k=1}^{n_{\mathrm{sys}}} r_{k,i}\delta_{k,i}^{(\mathrm{sys})}\right)$$

- Statistical uncertainties we rescale according to the improved luminosity

$$\delta_i^{(\mathrm{stat})} = \tilde{\delta}_i^{(\mathrm{stat})}\sqrt{\frac{\mathcal{L}_{\mathrm{Run2}}}{\mathcal{L}_{\mathrm{HLLHC}}}}$$

$$\delta_{k,i}^{(\mathrm{sys})} = \tilde{\delta}_{k,i}^{(\mathrm{sys})} \times f_{\mathrm{red}}^{(k)} \qquad k = 1, \ldots, n_{\mathrm{sys}}$$

- While systematics are rescaled by an overall factor, namely 1/2 for all datasets

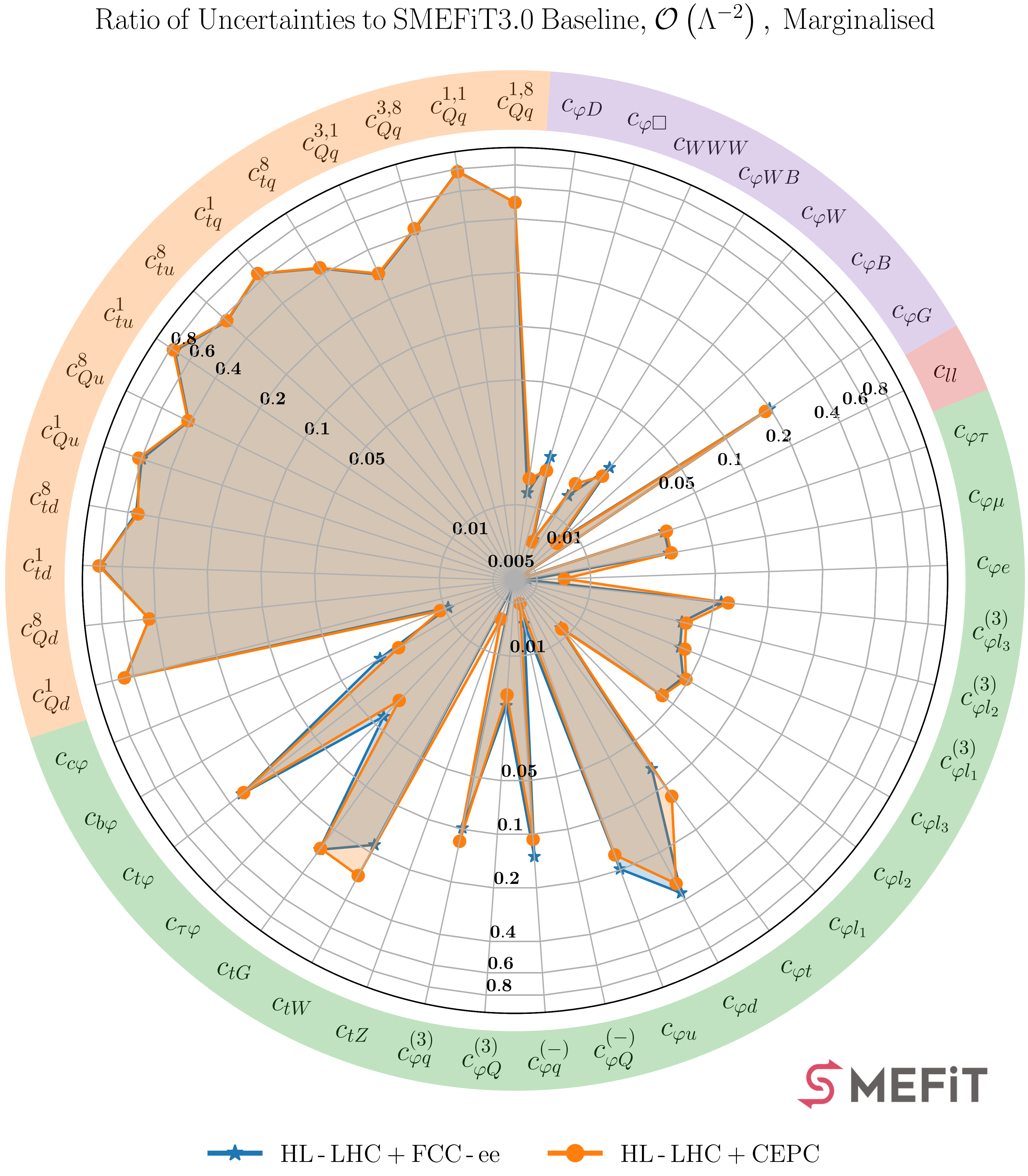


+ flexible framework that can project any Run II dataset

+ SMEFT predictions can be recycled

- No additional bins in the tails

FCC-ee and CEPC



1-loop & multi-particle matching