RGE effects in global EFT fits

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University of Manchester

LHC EFT WG meeting, 2/12/24

EFT pathway to new physics

$$\mathcal{L}_{\rm eff} = \mathcal{L}^{(4)} + \sum_{D>4} \sum_i \frac{c_i^{(D)}}{\Lambda^{D-4}} \mathcal{O}_i^{(D)}$$

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Processes and observables

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→ Processes and observables

↙ Sensitivity

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→ Processes and observables

→ Sensitivity → Measurements

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→ Sensitivity → Measurements

→ $$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \frac{1}{\Lambda^2} \sum_i c_i^6(\mu) a_{n,i}^6(\mu) + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$ → Constraints on WC

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→ Constraints on WC

→ UV physics

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↓

UV physics

Huge effort to improve each one of these steps!

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→ UV physics

Huge effort to improve each one of these steps!

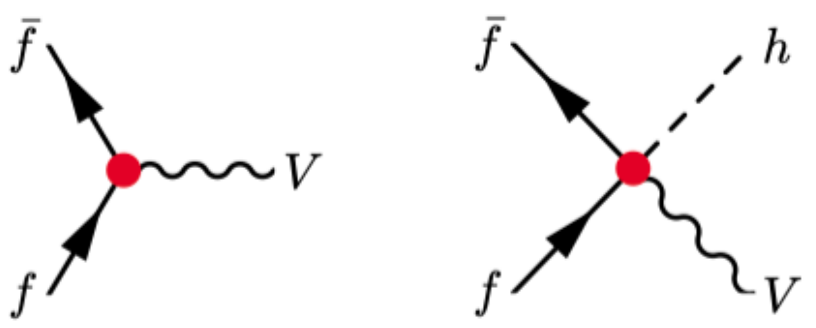
For the best results: Do this in a global fit!

Ingredients of global fits

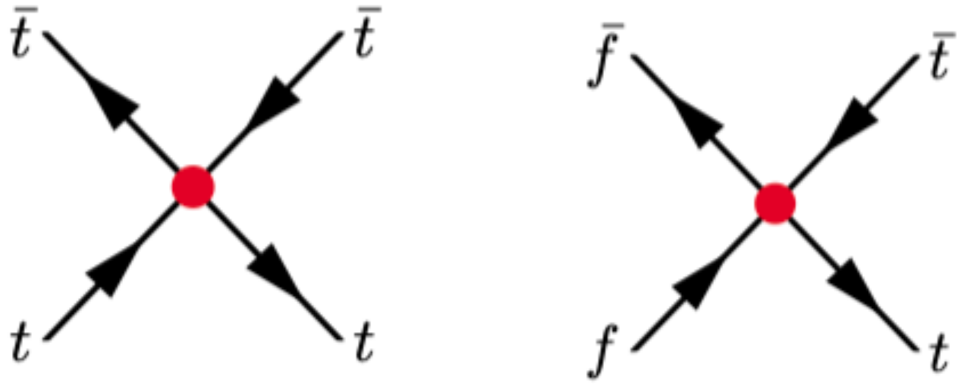
SMEFiT as a global fit example

Flavour assumption:

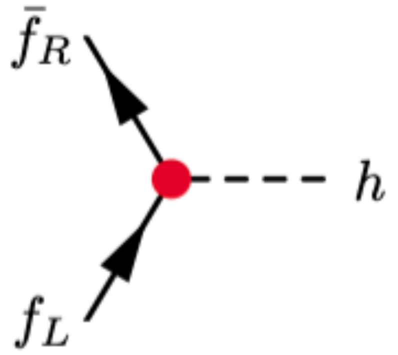
$\mathrm{U}(2)_q \times \mathrm{U}(3)_d \times \mathrm{U}(2)_u \times (\mathrm{U}(1)_\ell \times \mathrm{U}(1)_e)^3$ + Yukawa of bottom, charm and tau



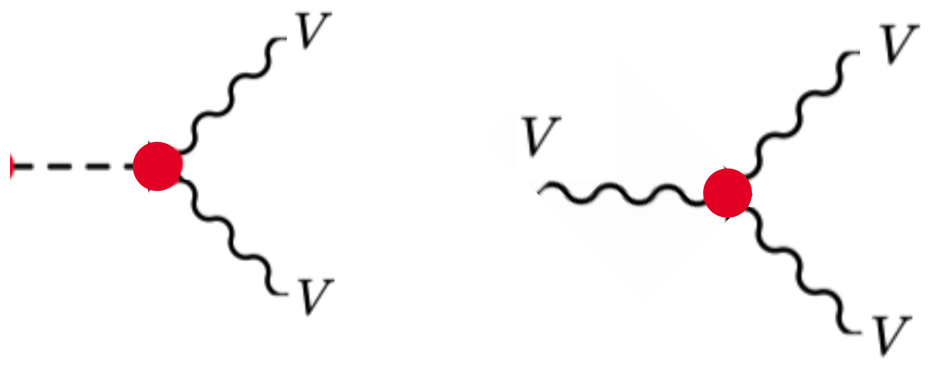
Current-current + Dipoles



4F operators



Yukawas



Bosonic

Experimental data

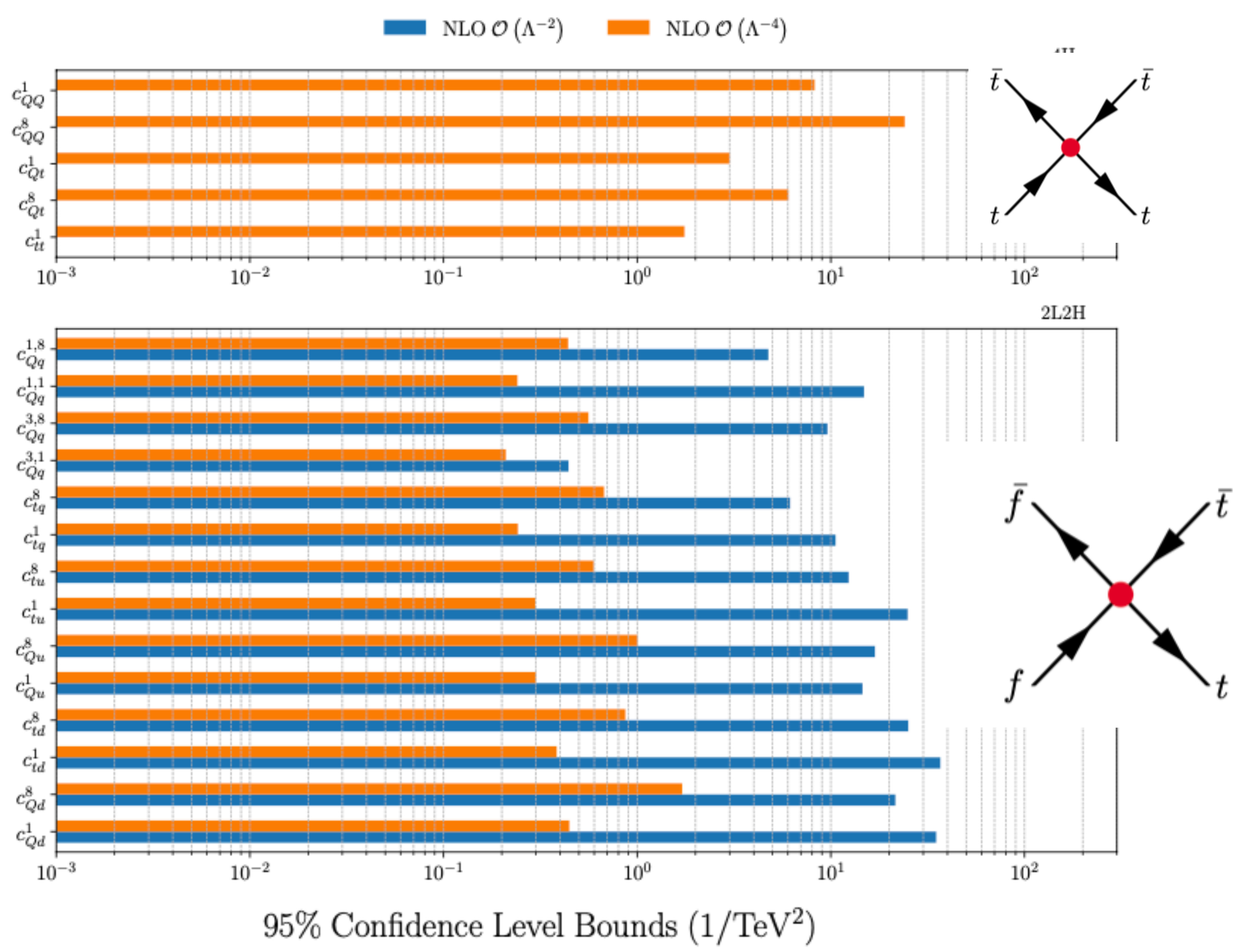
Category	Processes	n_{dat} SMEFiT3.0
Top quark production	$t\bar{t}+X$	115
	$t\bar{t}Z$, $t\bar{t}W$	21
	$t\bar{t}\gamma$	2
	single top (inclusive)	28
	tZ, tW	13
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	12
	Total	**191**
Higgs production and decay	Run I signal strengths	22
	Run II signal strengths	36 (*)
	Run II, differential distributions & STXS	71
	Total	**129**
Diboson production	LEP-2	40
	LHC	41
	Total	**81**
EWPOs	LEP-2	44
Baseline dataset	**Total**	**445**

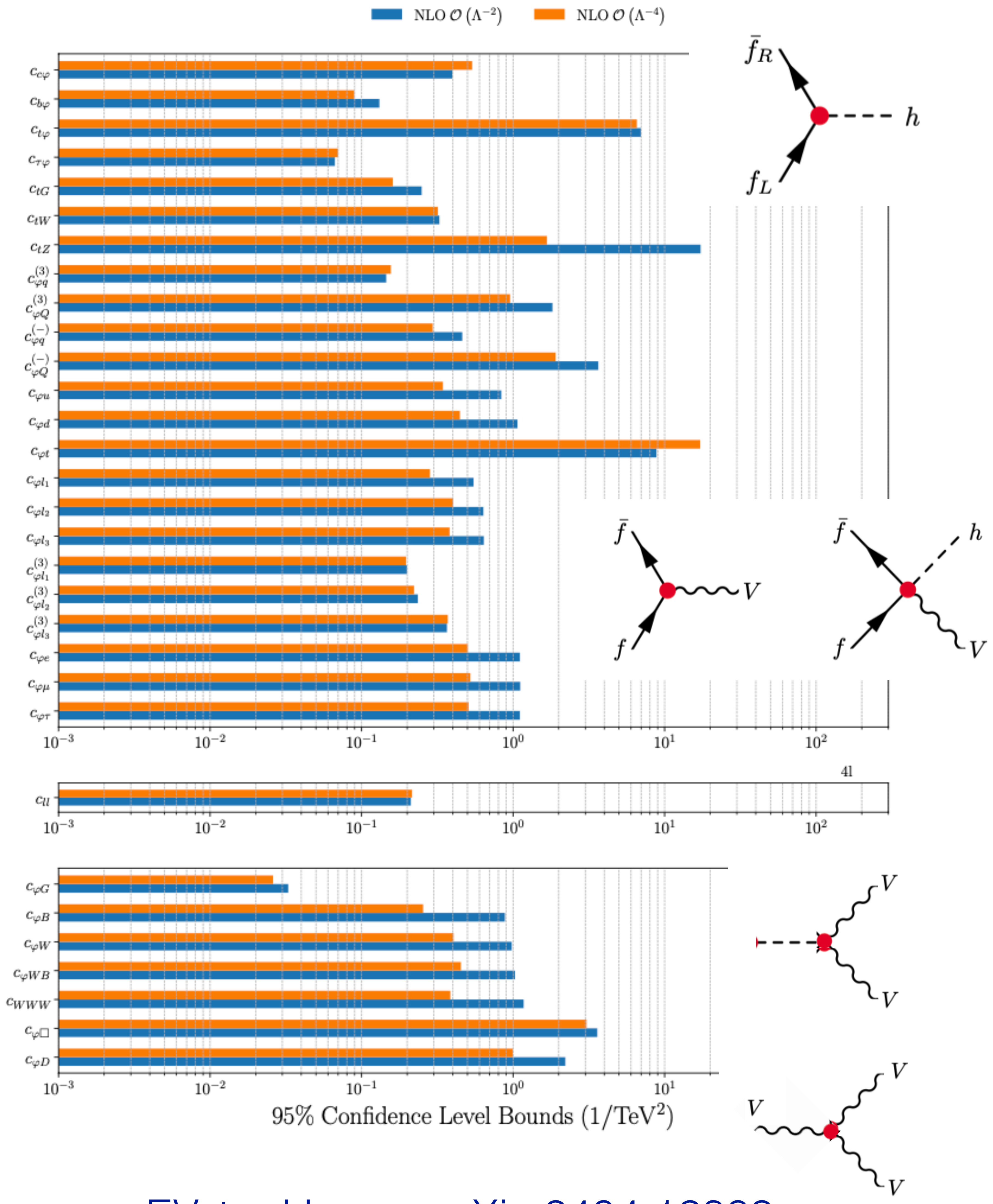
50 degrees of freedom: 2F, 2L2H, 4H, Bosonic

SMEFiT3.0 Celada, Giani, Mantani, Rojo, Rossia, Thomas, EV, ter Hoeve arXiv:2404.12809

See also: FitMaker arXiv:2012.02779, HEPfit arXiv:1910.14012

Global fit results





- Bounds varying between operators
- Most Wilson coefficient bounds below 1 for Λ=1 TeV
- Quadratic terms important especially for 4F operators
- Least constrained coefficients are 4-top operators

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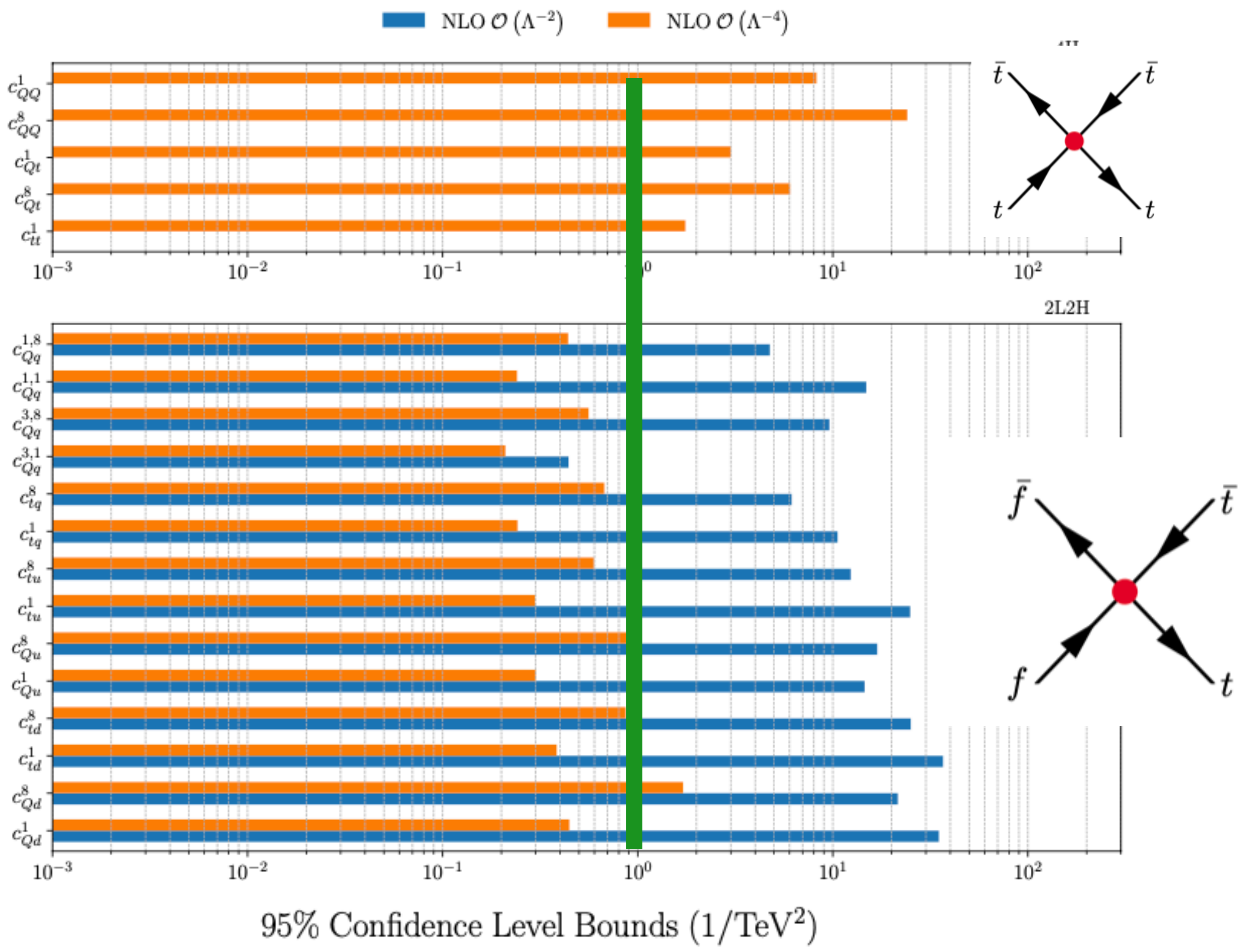

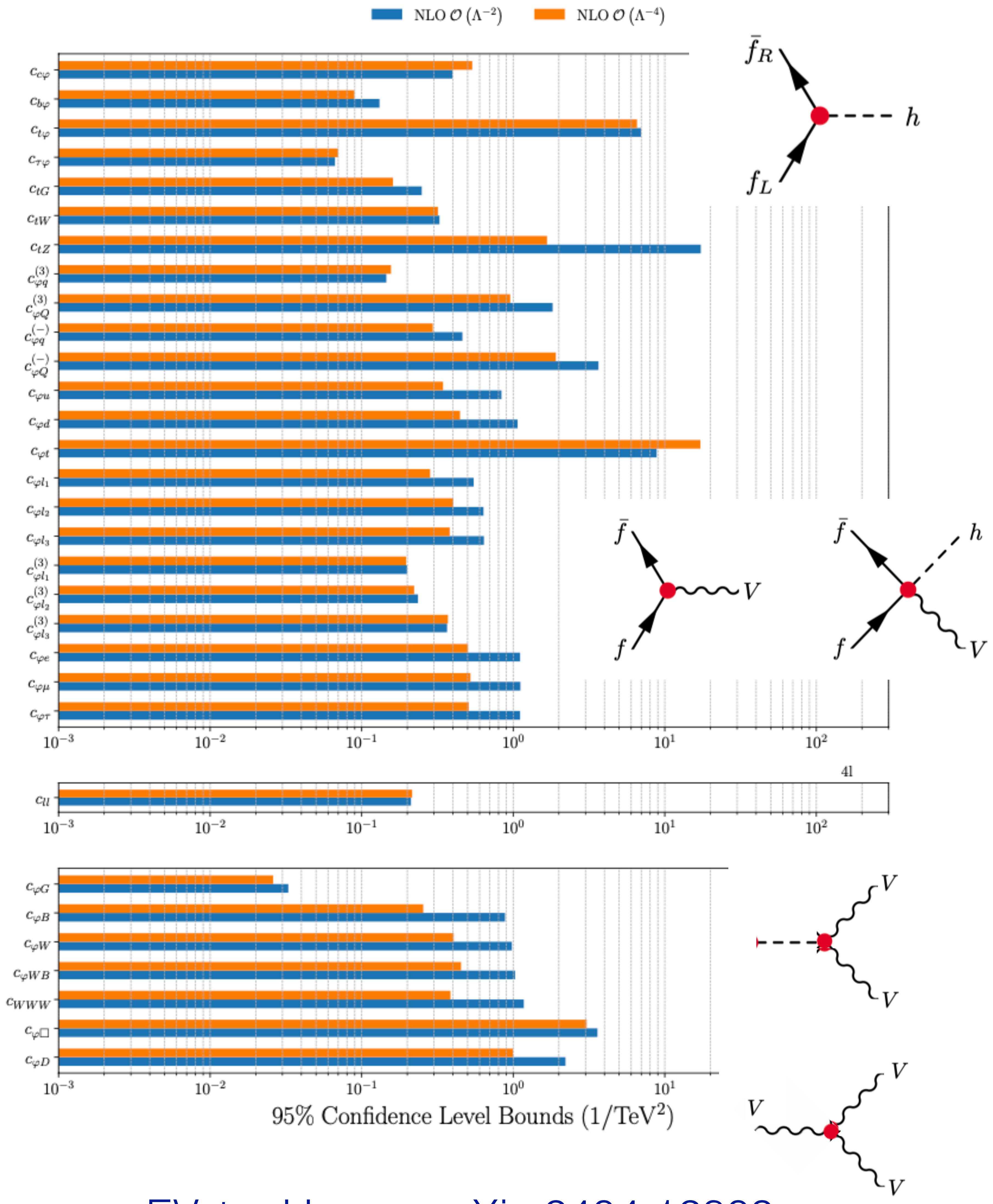

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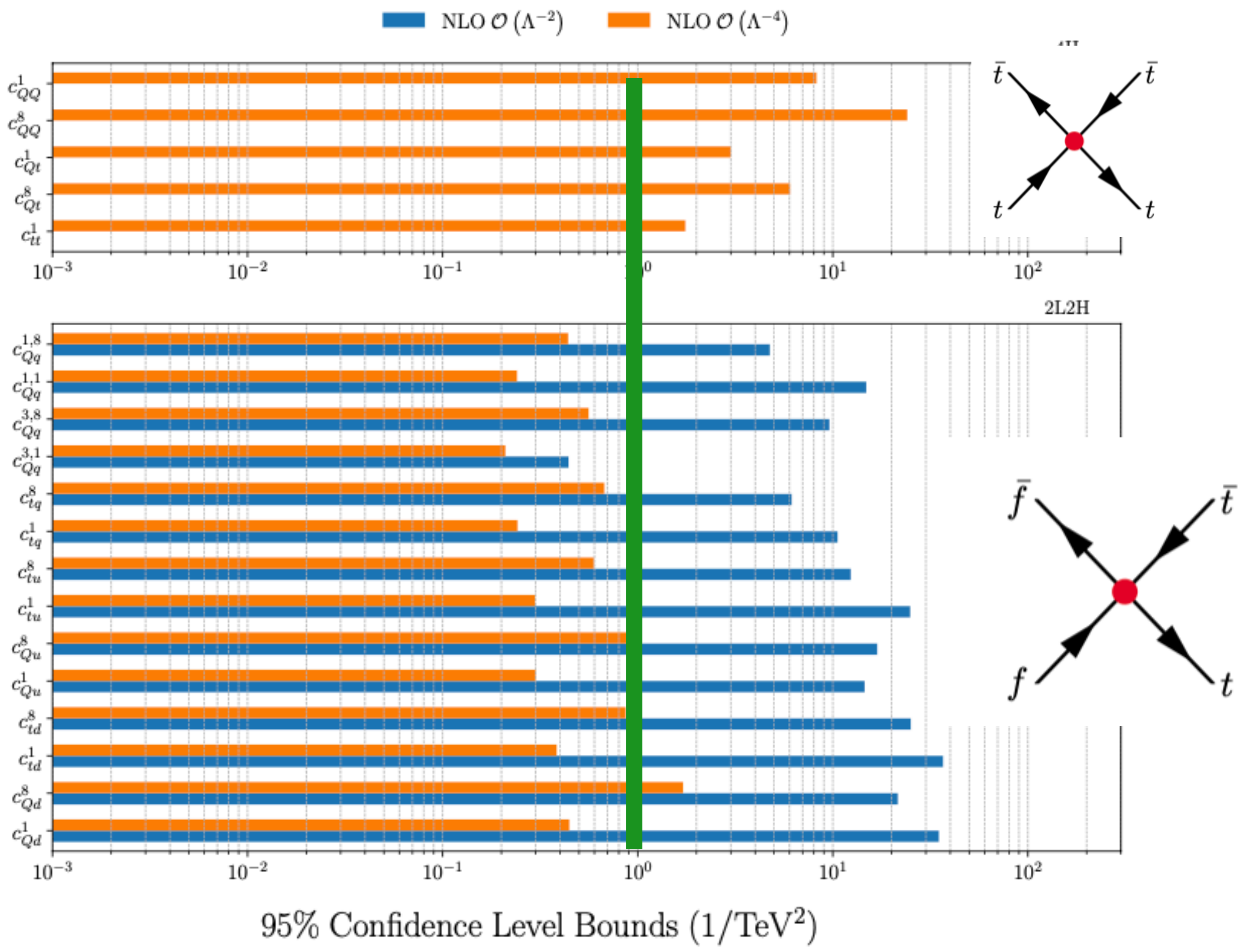

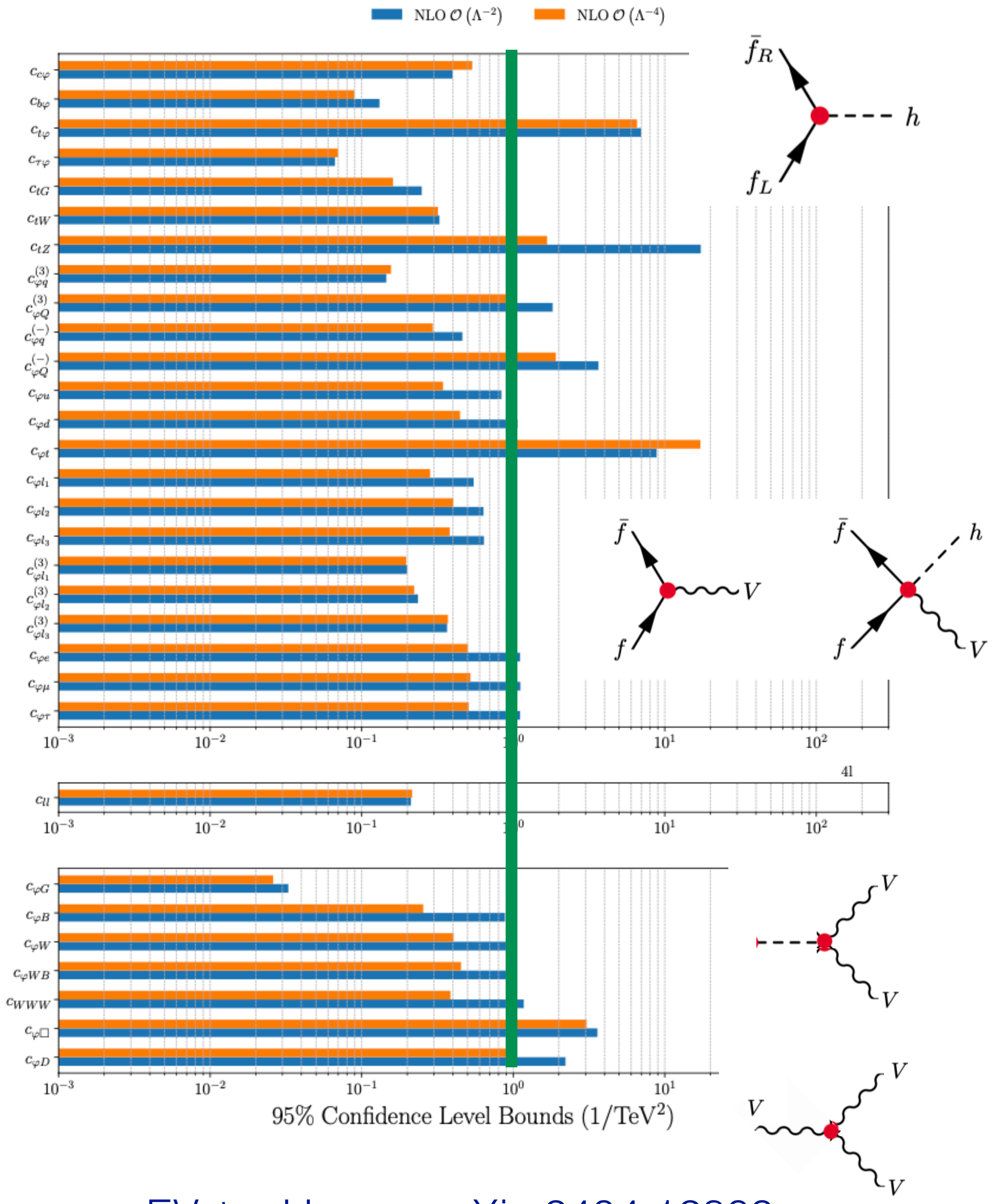

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Future of global fits

How can we improve fits?

More observables:
- Particle level observables
- New final states
- Better description: EFT in backgrounds

More/less/different operators:
- Different flavour assumptions
- UV inspired scenarios

Better EFT predictions

Higher Orders in $1/\Lambda^4$
- squared dim-6 contributions
- double insertions of dim-6
- dim-8 contributions

Higher Orders in QCD and EW

EFT is a QFT, renormalisable order-by order in $1/\Lambda^2$

$$\mathcal{O}(\alpha_s, \alpha_{ew}) + \mathcal{O}\left(\frac{1}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_s}{\Lambda^2}\right) + \mathcal{O}\left(\frac{\alpha_{ew}}{\Lambda^2}\right)$$

SMEFT computations at dimension-6

$$\Delta \text{Obs}_n = \text{Obs}_n^{\text{EXP}} - \text{Obs}_n^{\text{SM}} = \sum_i \frac{c_i^6(\mu)}{\Lambda^2} \boxed{a_{n,i}^6(\mu)} + \mathcal{O}\left(\frac{1}{\Lambda^4}\right)$$

NLO QCD & loop-induced: Done (SMEFT@NLO)

Degrande, Durieux, Maltoni, Mimasu, EV, Zhang arXiv:2008.11743

http://feynrules.irmp.ucl.ac.be/wiki/SMEFTatNLO

NLO EW: Some examples available, progress towards automating these as well (see next talk)

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How about this μ? When should we worry about it?

- Observables with different natural scales (flavour, EW, Higgs, top, 4-tops)
- Differential distributions: e.g. in a typical top fit bins of reaching 2 TeV
- Eventually we want to match to the UV

What is next for global fits?

→ Need for RGE running and mixing:

Different scales and Dynamical scales

Anomalous dimension matrix known at 1-loop:

Jenkins et al arXiv:1308.2627, 1310.4838, Alonso et al 1312.2014

- 2499x2499 anomalous dimension matrix available
- Including both QCD, weak, Yukawa terms
- Implemented in various tools: e.g. Wilson: Aebischer et al 1712.05298, RGESolver: Di Noi and Silvestrini arXiv:2210.06838

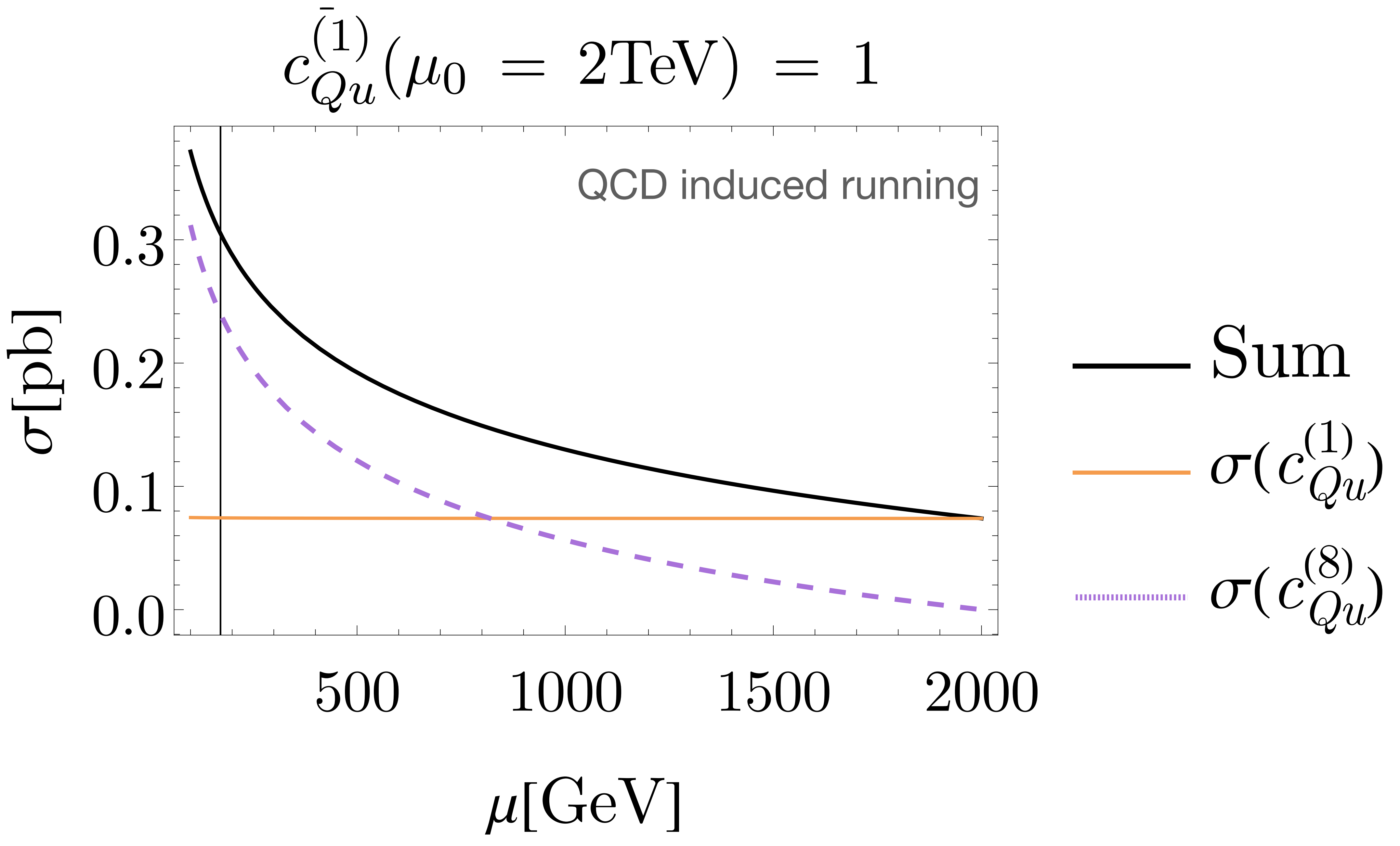
2-loop RGE: **not known in general (some pieces known, typically from flavour physics and recent computations: see e.g. arXiv:2410.07320)

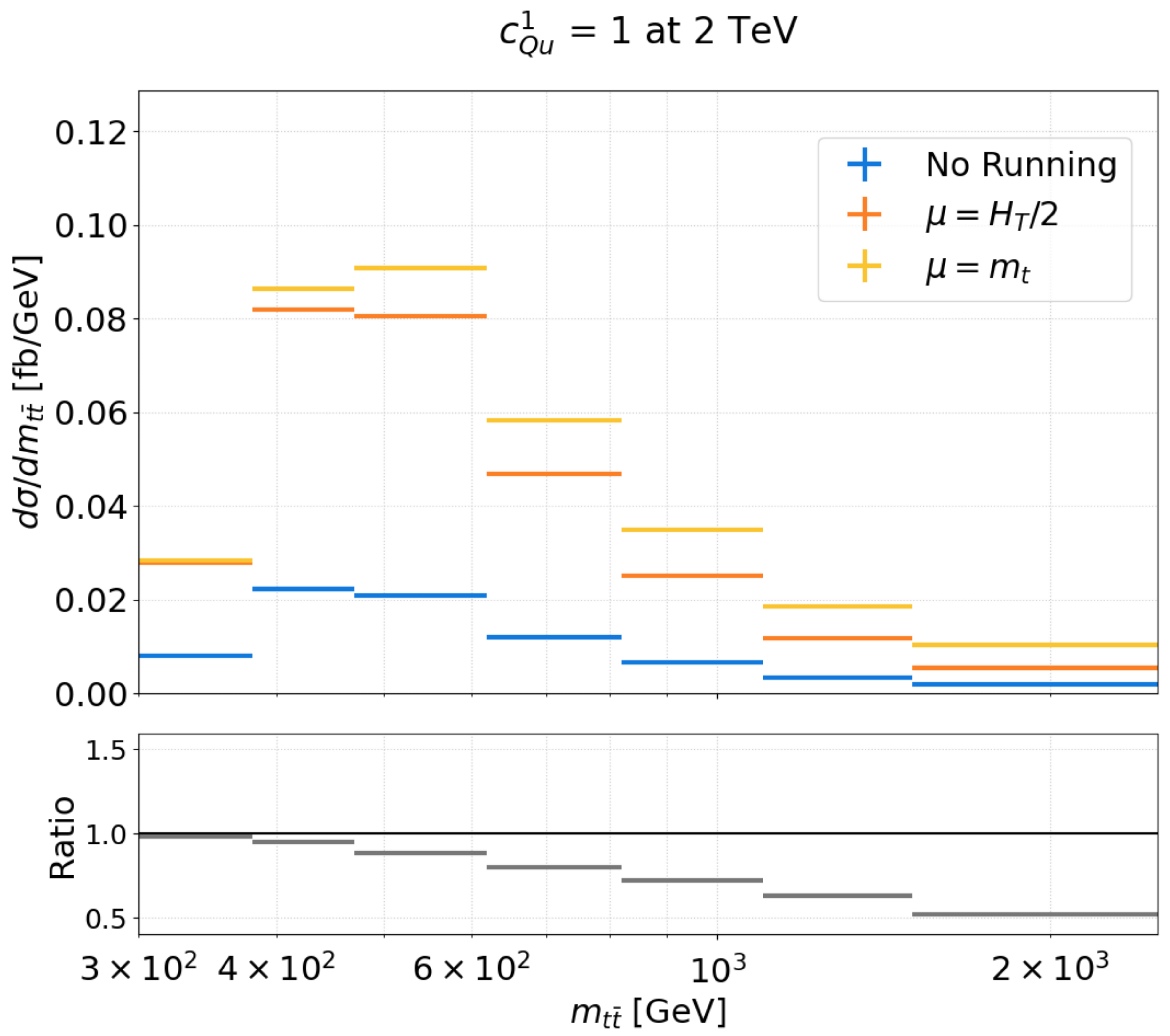
Example 1: top physics

$$\frac{dc_i(\mu)}{d\log\mu} = \gamma_{ij}\, c_j(\mu)$$

Example: Turn on 1 operator at high-scale

Compute effect on top pair cross-section





Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

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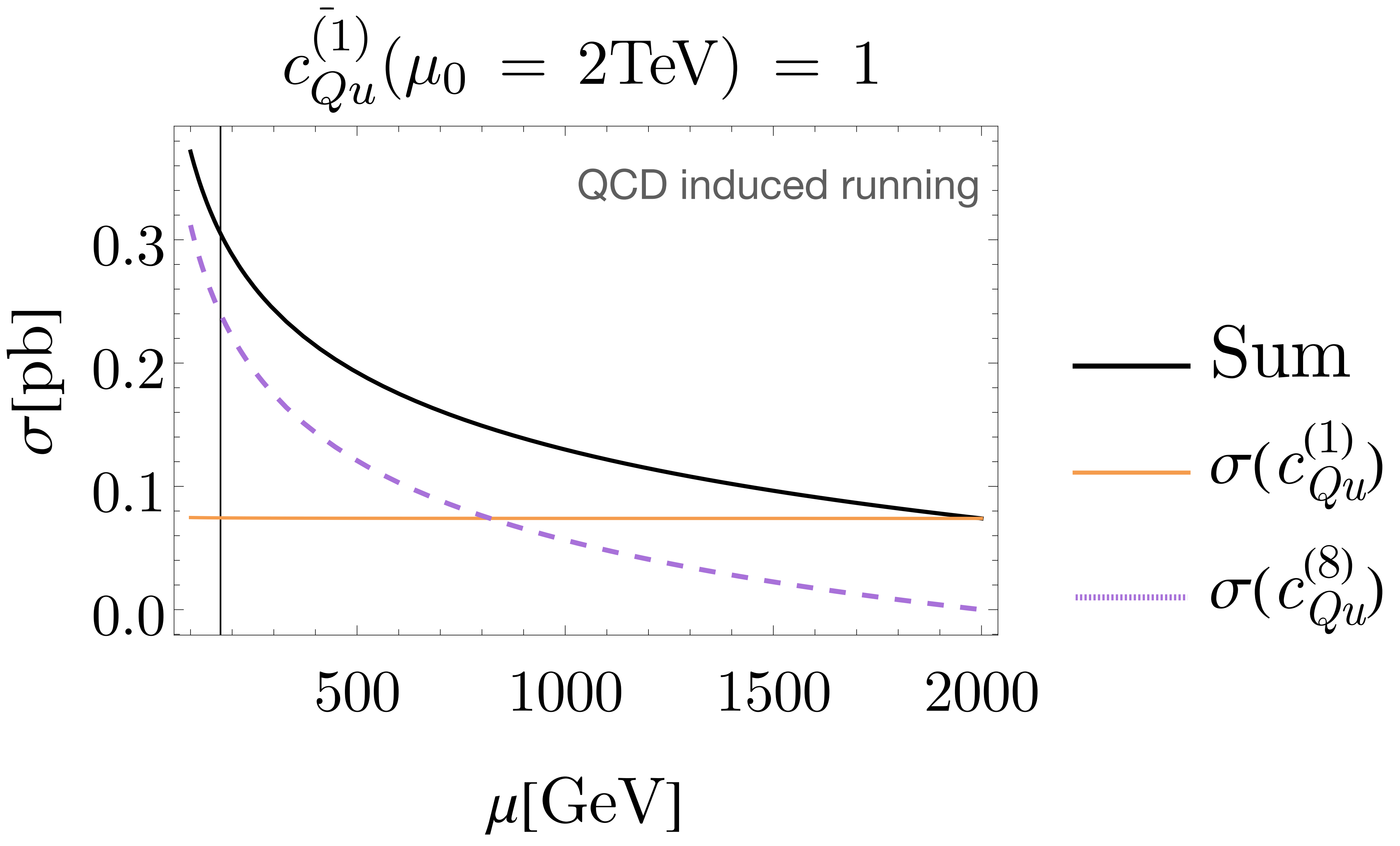
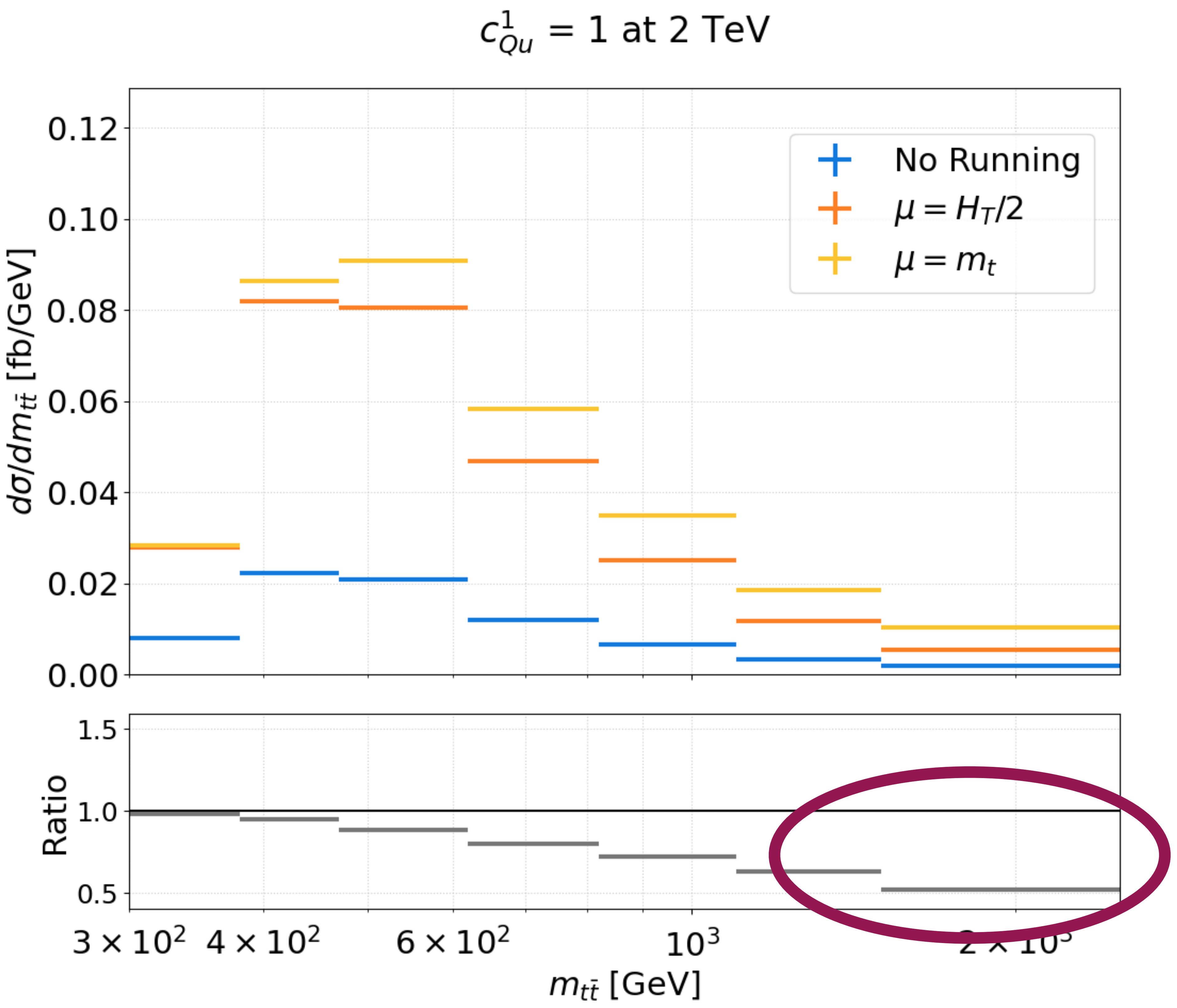




Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

Implementation of RGE in Monte Carlo

How to get RGE improved predictions?

- ☑ Anomalous dimension included in UFO model
- ☑ Running code extracted automatically by MG5_aMC
- ☑ Define coefficients at given scale, and run to preferred scale
- ☑ Options in run_card.dat

```
#***********************************************************************
# CONTROL The additional running scale (not QCD)                       *
#    Such running is NOT include in systematics computation            *
#***********************************************************************
 True = fixed_other_scale ! False means dynamical scale
 1000  =  muo_ref_fixed ! scale to use if fixed scale mode
 1.0   =  muo_over_ref  ! ratio to mur if dynamical scale
```

→

Fixed scale or a dynamical (as for alphas)

Dynamical scale a function of usual μ_R

Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

Example 2: Higgs physics

$$\frac{dc_i(\mu)}{d\log\mu} = \gamma_{ij}\, c_j(\mu)$$

$$\mathcal{O}_{\varphi G} = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) G^a_{\mu\nu} G^{\mu\nu}_a$$

$$\mathcal{O}_{t\varphi} = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right) \bar{Q}\tilde{\varphi} t + \text{h.c.}$$

$$\mathcal{O}_{tG} = i g_s (\bar{Q}\tau^{\mu\nu} T^a \tilde{\varphi} t) G^a_{\mu\nu} + \text{h.c.}$$

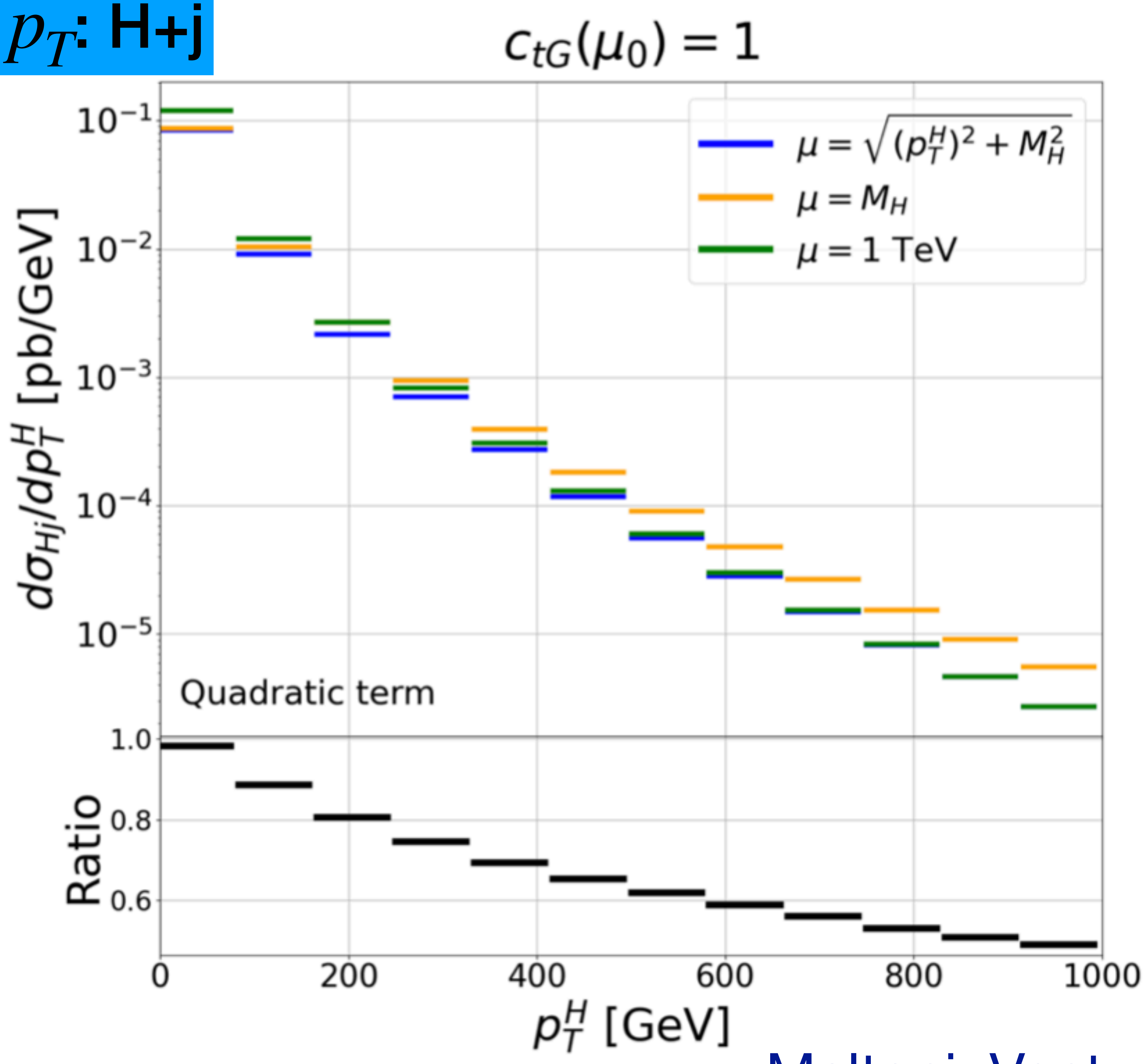
$C_{tG} \to C_{t\varphi},\ C_{\varphi G},\ C_{tG}$

$C_{\varphi G} \to C_{t\varphi},\ C_{\varphi G}$

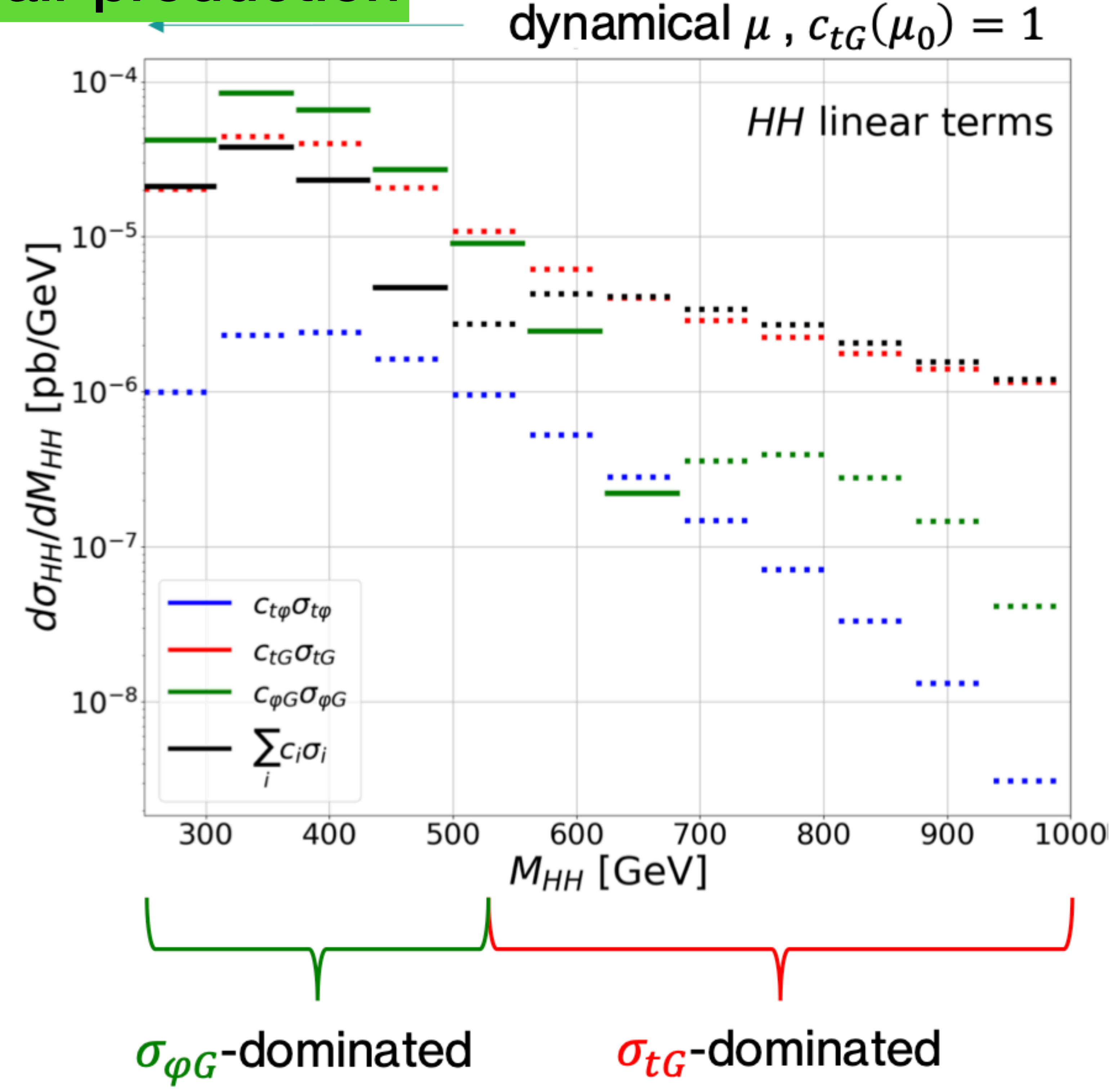
$C_{t\varphi} \to C_{t\varphi}$

QCD induced running

Higgs p_T: H+j



Higgs pair production

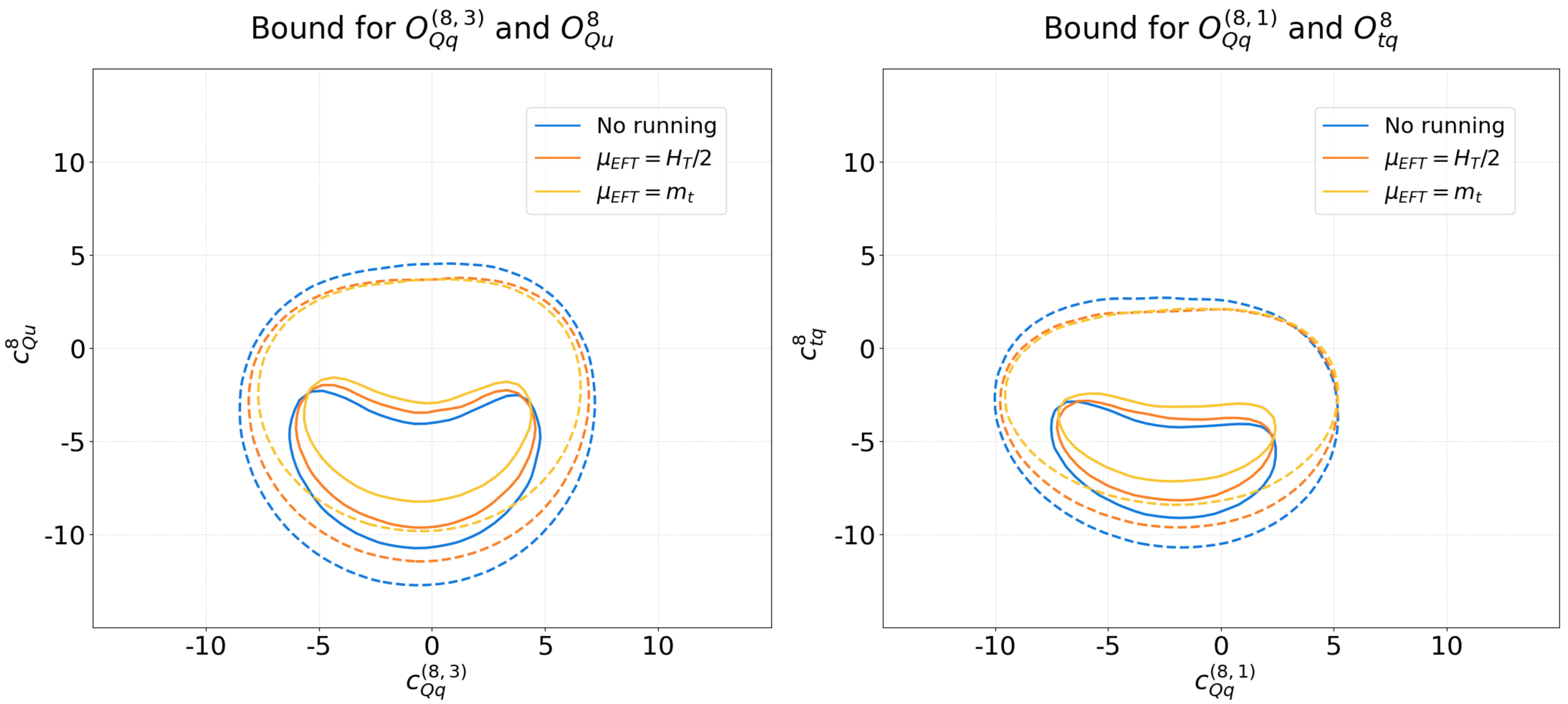


Maltoni, Ventura, EV arXiv:2406.06670

Impact of RGE on constraints

How does running and mixing impacts the constraints?

Top sector fit:



RGE evolution within MC:

PS by PS point computation of coefficients: dynamical scale e.g. $H_T/2$

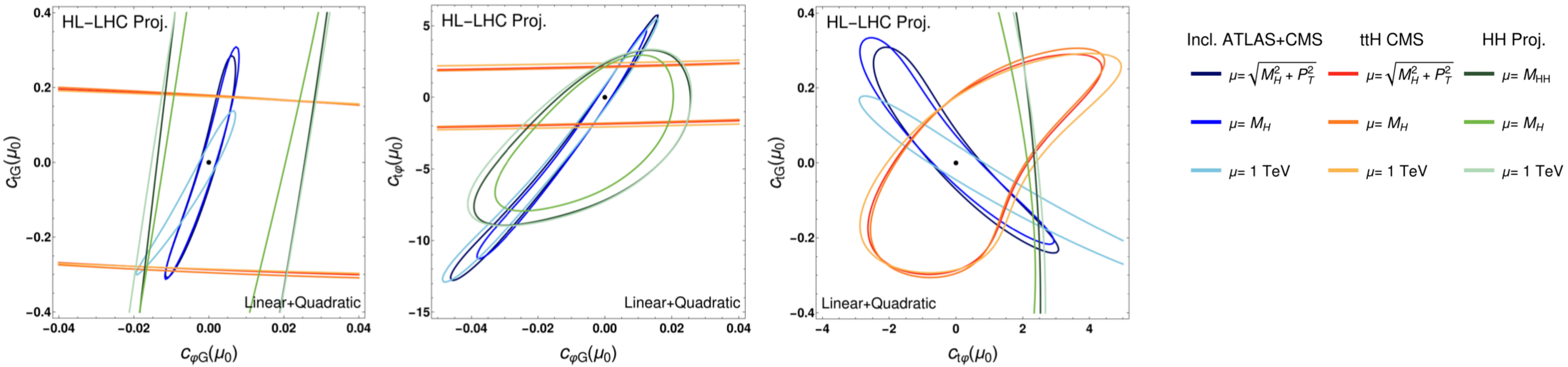
Aoude, Maltoni, Mattelaer, Severi, EV arXiv:2212.05067

More important for differential distributions & measurements with very different scales

Impact of RGE on constraints

How does running and mixing impacts the constraints?

Higgs sector fit



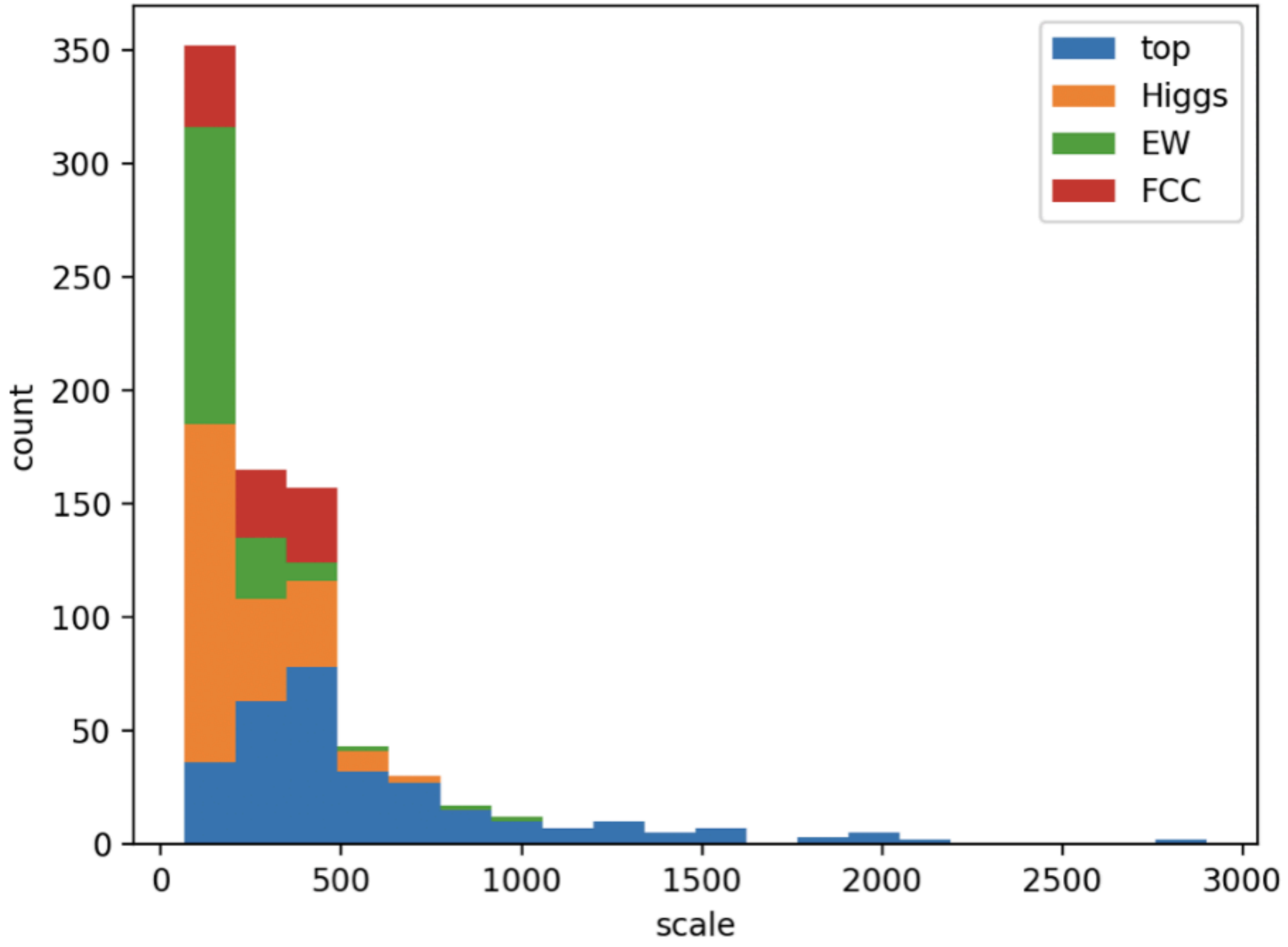
Maltoni, Ventura, EV arXiv:2406.06670

See also Battaglia, Grazzini, Spira, Wiesemann arXiv: 2109.02987
Di Noi, Grober arXiv:2312.11327
Di Noi, Grober, Mandal arXiv: 2408.03252

Eventually need to be taken into account in a global fit!

How about a real global fit?

How to practically include these effects in a global fit?



Data points cover a large range of scales from M_Z to 2-3 TeV

Ideally we would like a fully dynamical scale setup as often employed in SM predictions

That requires rerunning the MC for every single theoretical prediction

Reasonable approximation?

Assign one scale to each data point

How about a real global fit?

How to practically include these effects in a global fit?

Practical SMEFiT implementation:

- Associate one scale to each observable (445 datapoints)

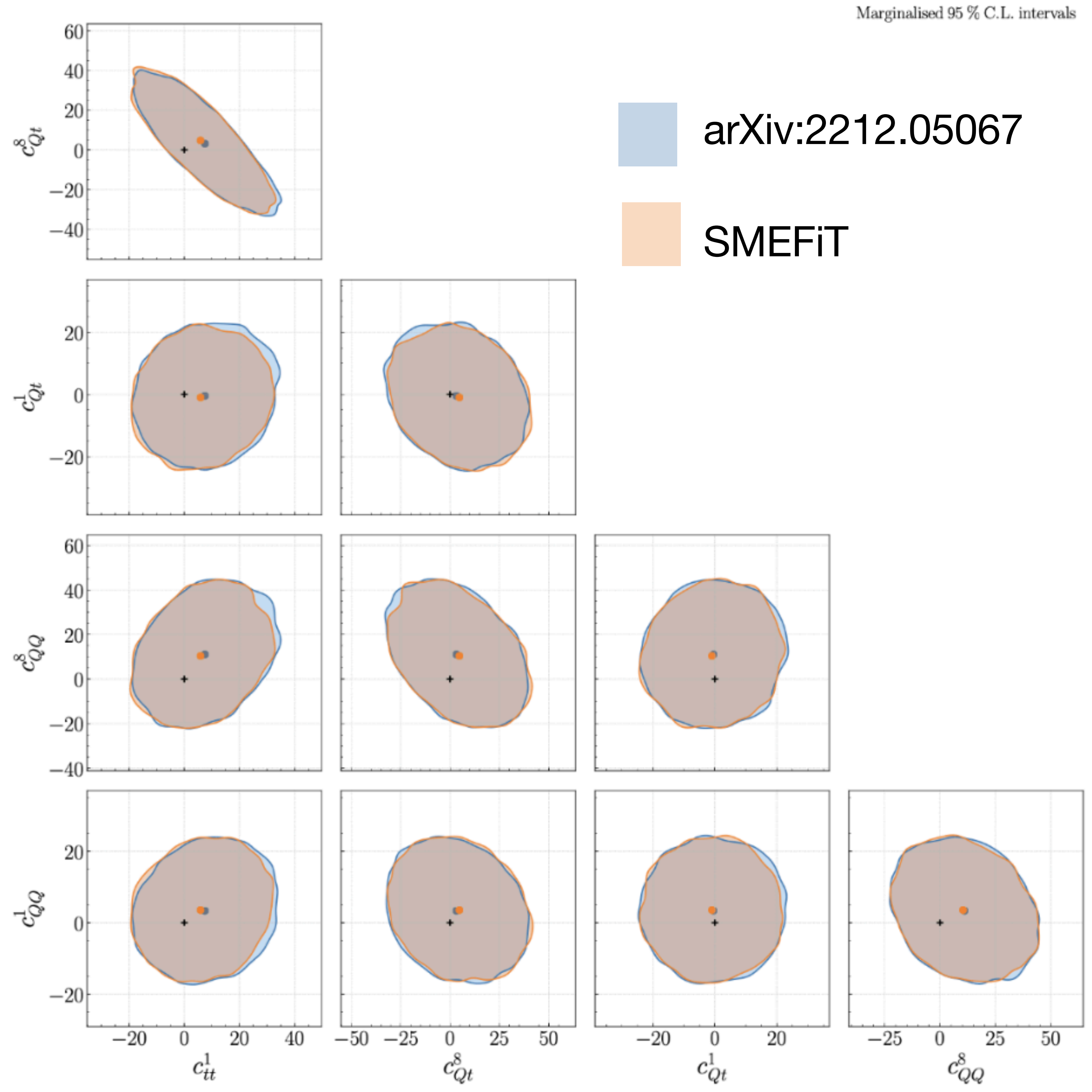
- Use Wilson to do the running between chosen starting and the scale of each datapoint

$$\Gamma(\mu, \mu_0; \alpha_s, \alpha) = \exp\left(\int_{\mu_0}^{\mu} d\log(\mu')\gamma(\alpha_s, \alpha)\right)$$

Evolution matrix

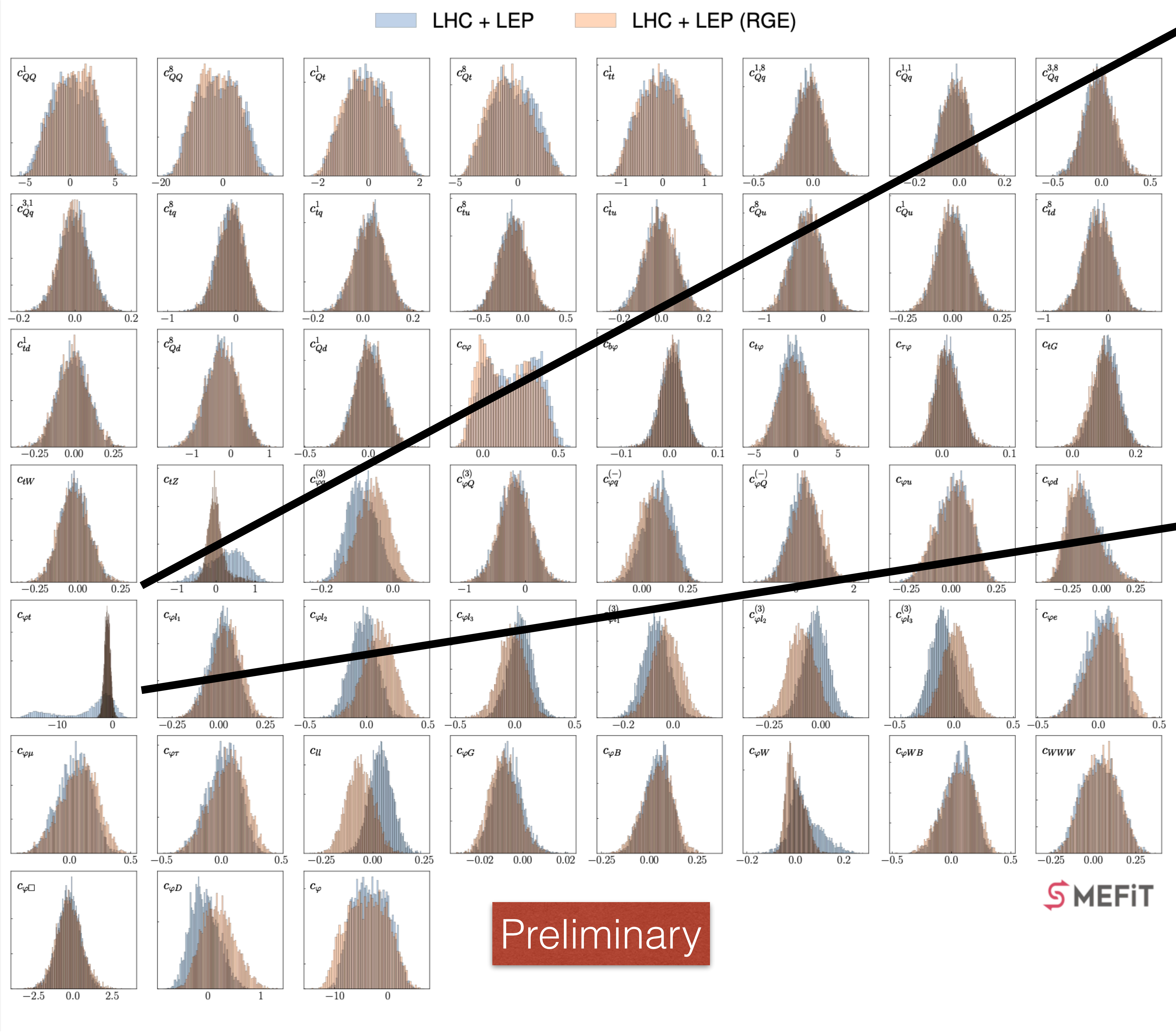
$$T_{\rm EFT}(\boldsymbol{c}(\mu)/\Lambda^2) = T_{\rm SM} + \sum_{i=1}^{n_{\rm op}} \kappa_i \frac{c_i(\mu)}{\Lambda^2} \quad \Rightarrow \quad T_{\rm EFT}(\boldsymbol{c}(\mu_0)/\Lambda^2) = T_{\rm SM} + \sum_{i,j=1}^{n_{\rm op}} \kappa_i \Gamma_{ij} \frac{c_j(\mu_0)}{\Lambda^2}$$

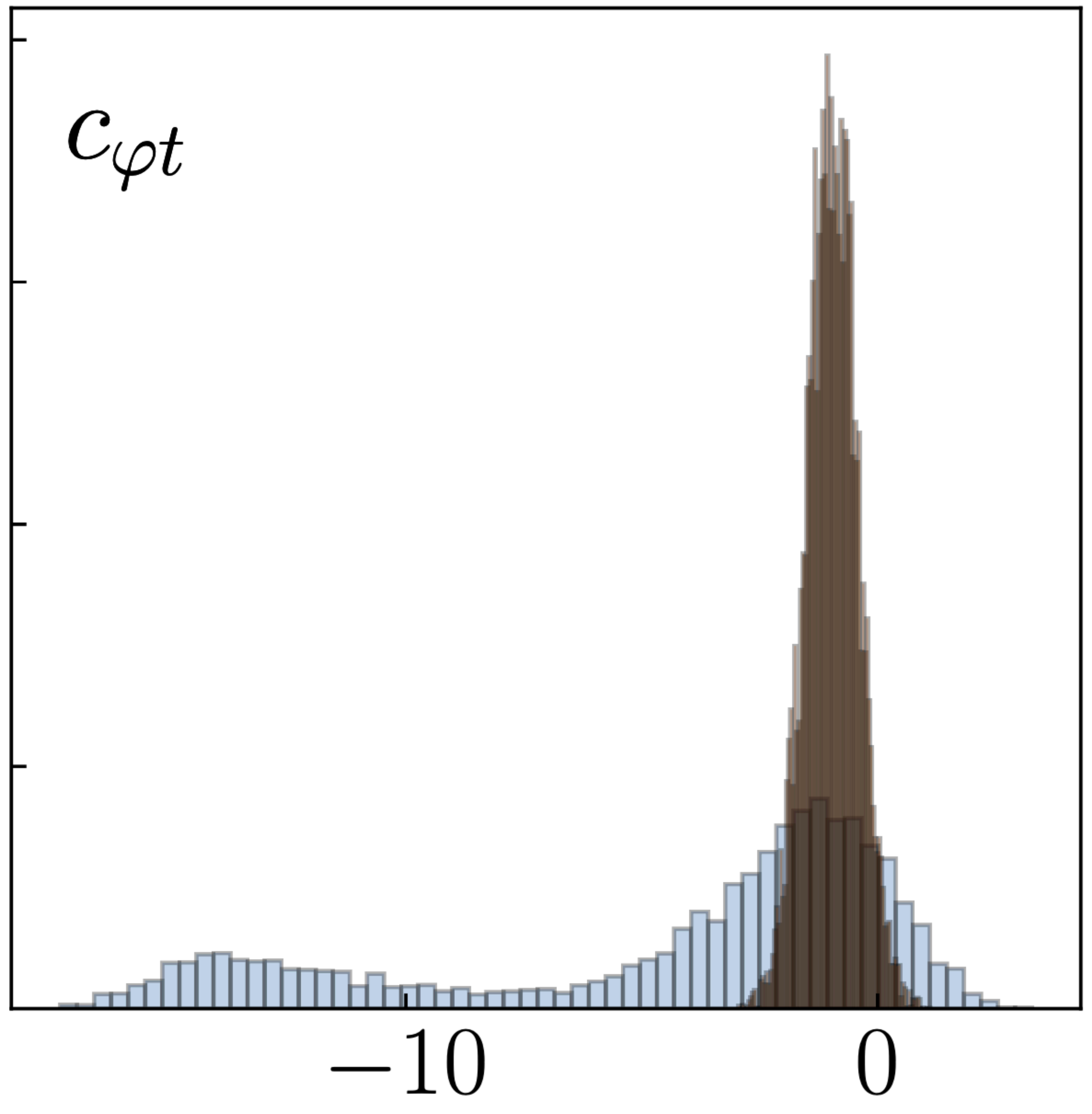
$$= T_{\rm SM} + \sum_{j=1}^{n_{\rm op}} \kappa'_j \frac{c_j(\mu_0)}{\Lambda^2}$$

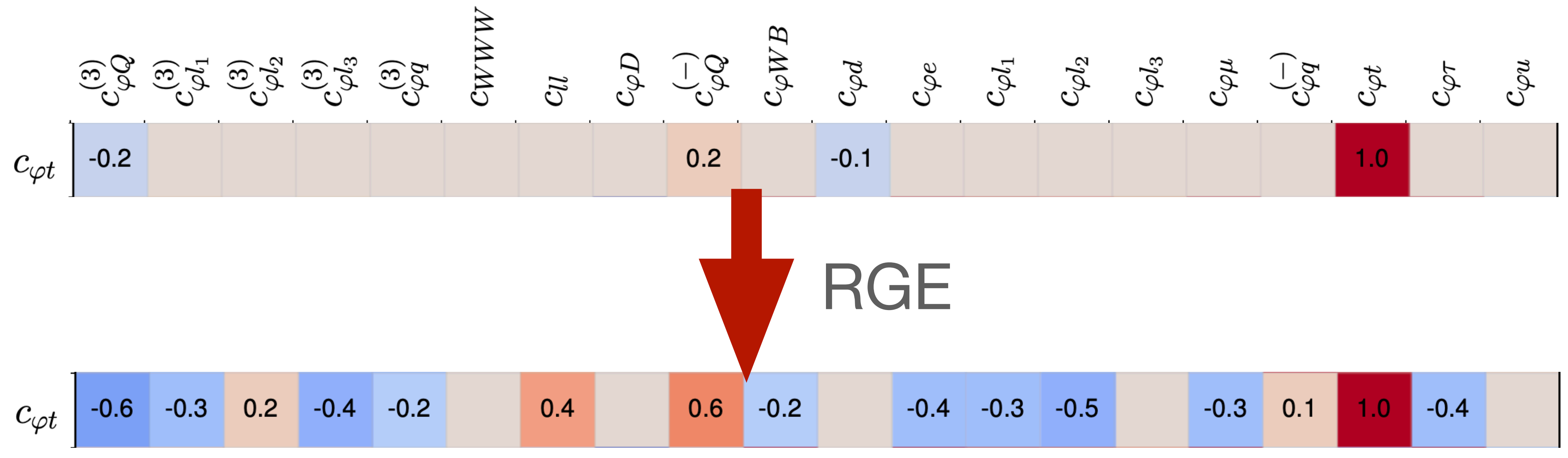


Validation with arXiv:2212.05067

Global fit results







ter Hoeve, Mantani, Rojo, Rossia, EV in preparation

Some operators get better constrained as they enter in more observables

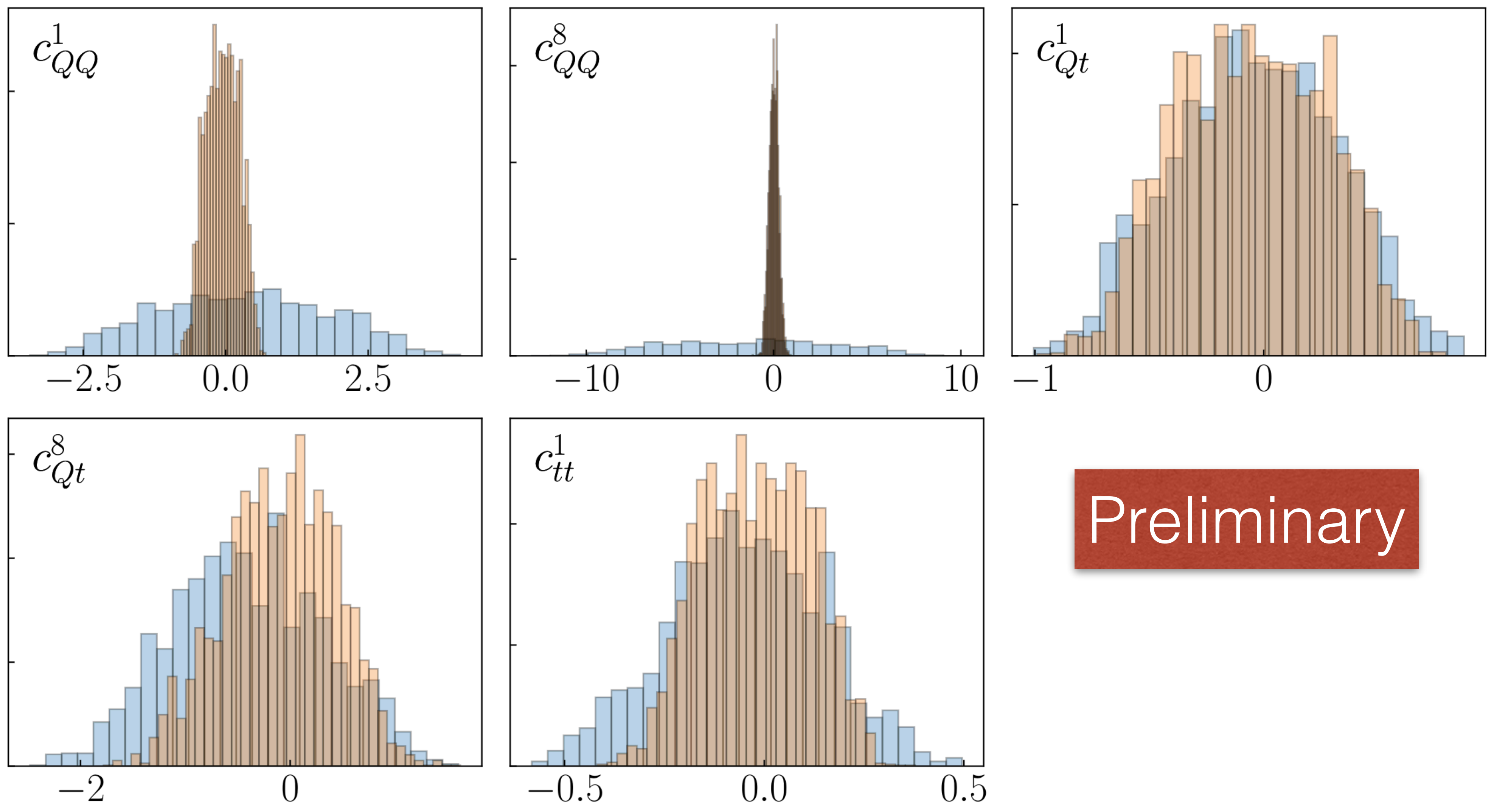
Correlation patterns change

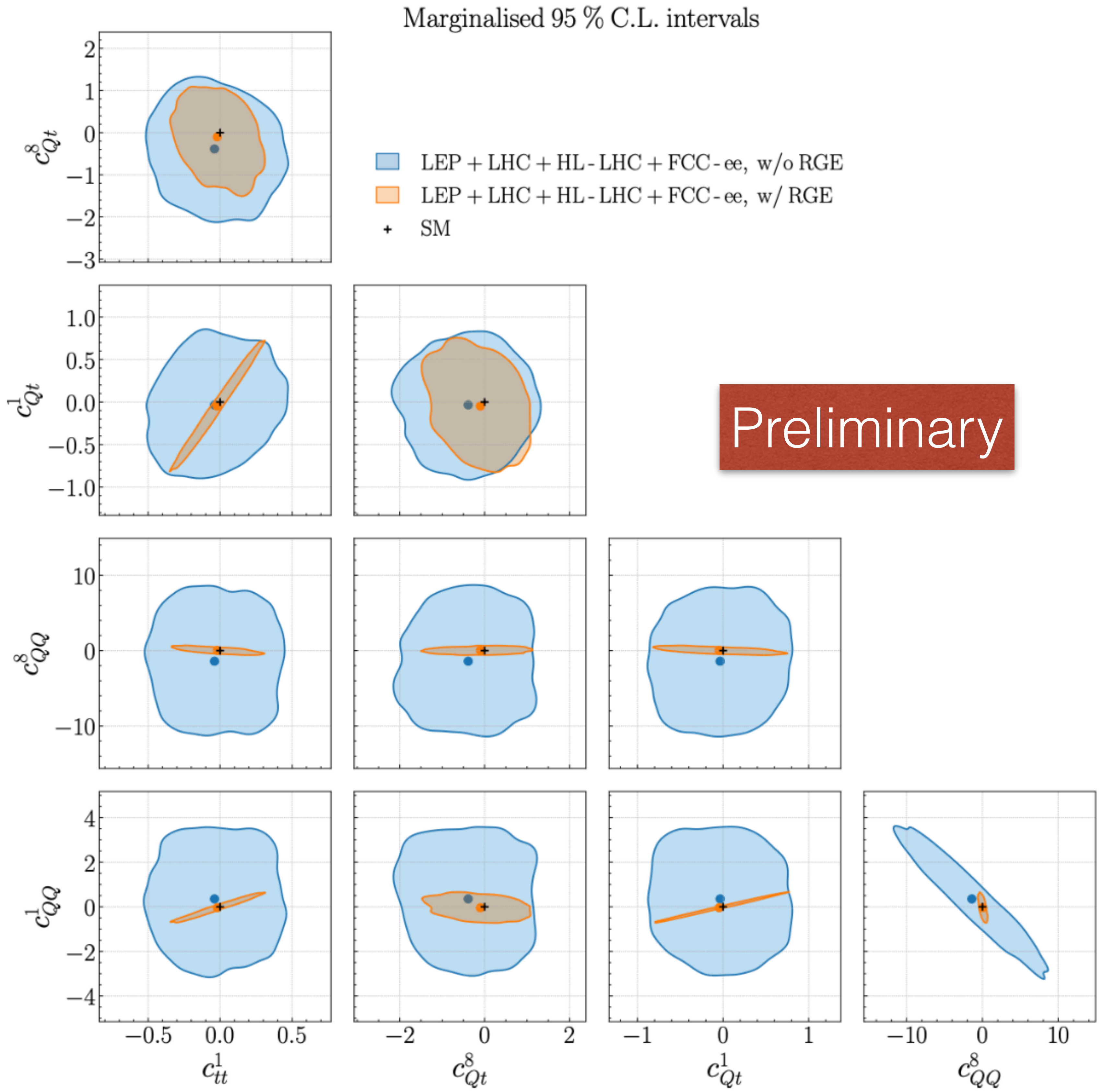
When can the RGE matter?

For unconstrained operators RGE can offer new sensitivity

Example: 4-heavy 4-fermion coefficients

Significant improvement of bounds due to impact on EWPO at FCC

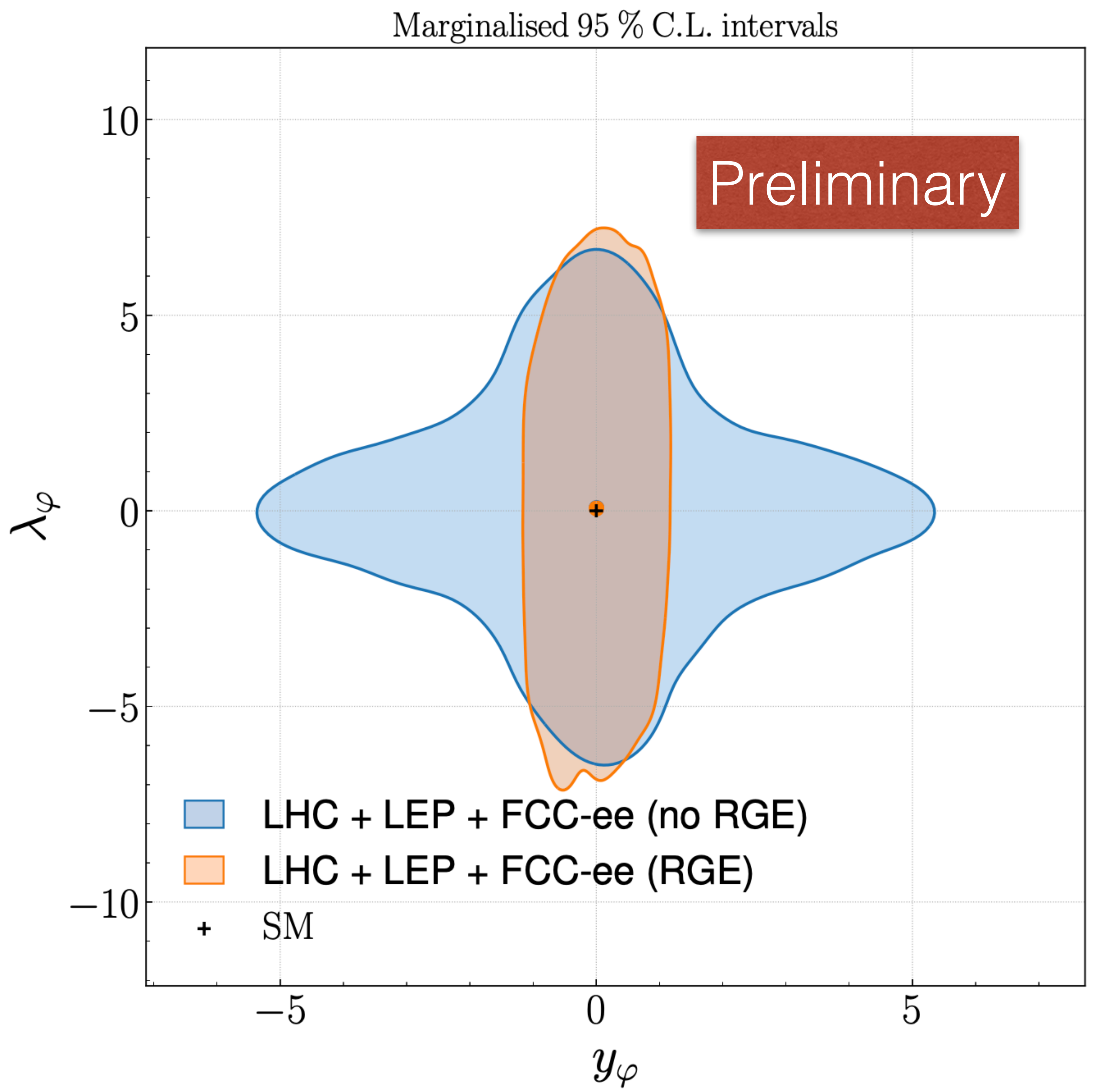




ter Hoeve, Mantani, Rojo, Rossia, EV in preparation

How about particular UV complete models?

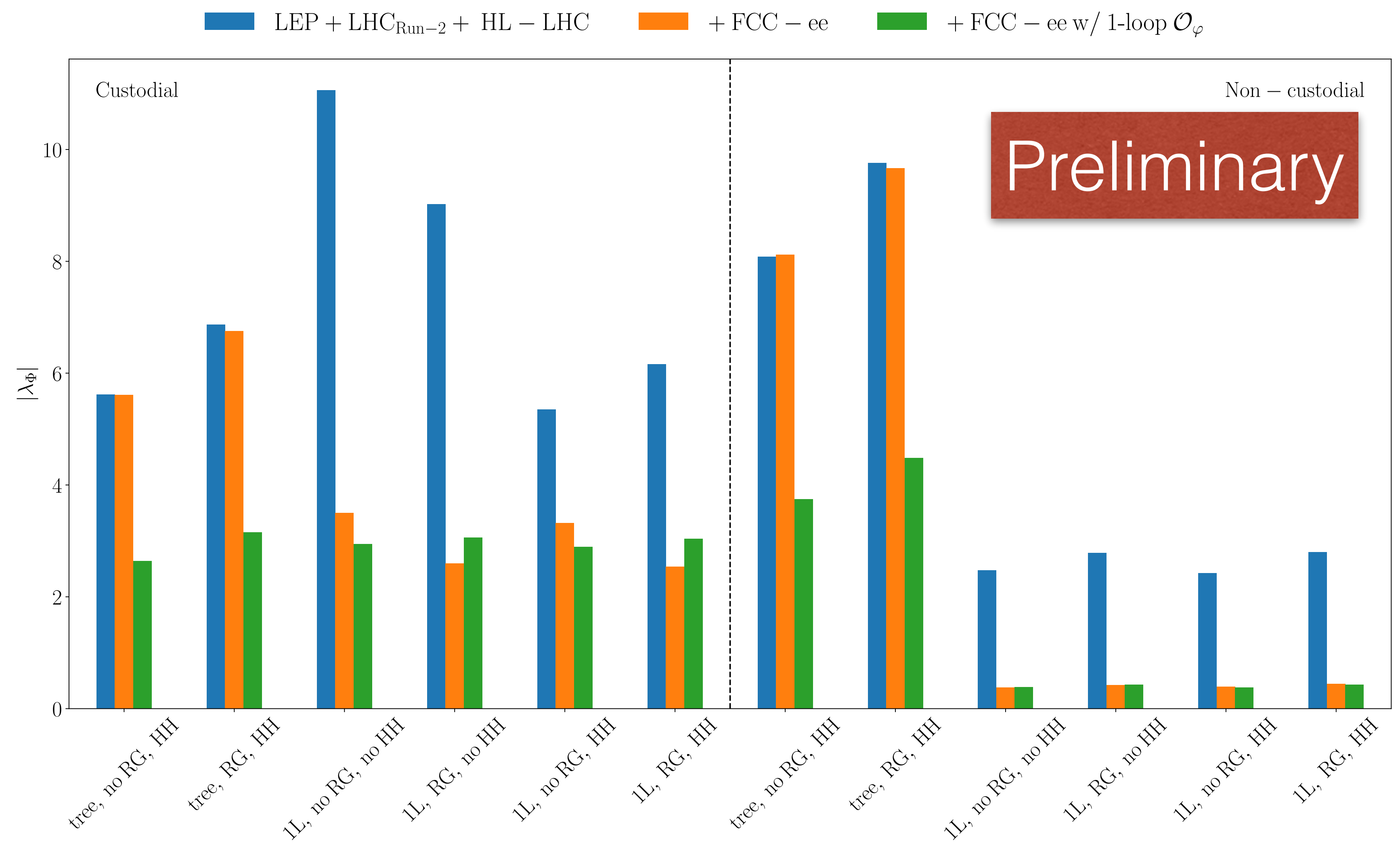
2HDM in decoupling limit



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

2-scalar EW quadruplet model

UV matching in SMEFit: ter Hoeve, Magni, Rojo, Rossia, EV arXiv: 2309.04523



Matchmakereft [2112.10787]
↓
match2fit [2309.04523]
↓
SMEFiT [2302.06660]

$$\mathcal{L}_{\mathrm{UV}} \supset -\lambda_\Phi H^* H^* (\varepsilon H)\Phi - \lambda_{\widetilde{\Phi}} H^* H^* H^* \widetilde{\Phi}/\sqrt{3} + \text{h.c.}\,,$$

Durieux, McCullough, Salvioni arXiv:2209.00666

Impact of RGE and 1-loop matching
Significant improvement of reach due to impact on EWPO at FCC

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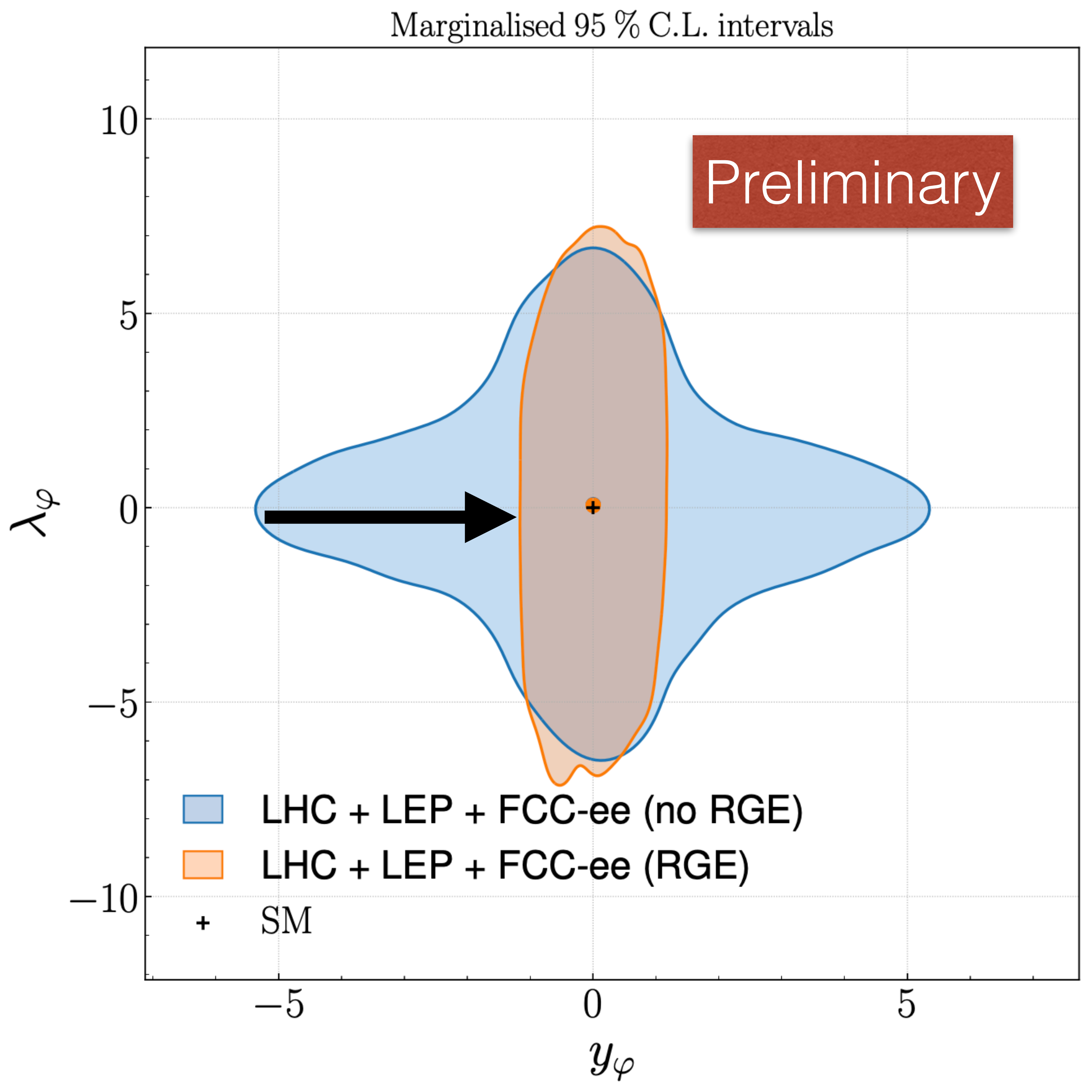

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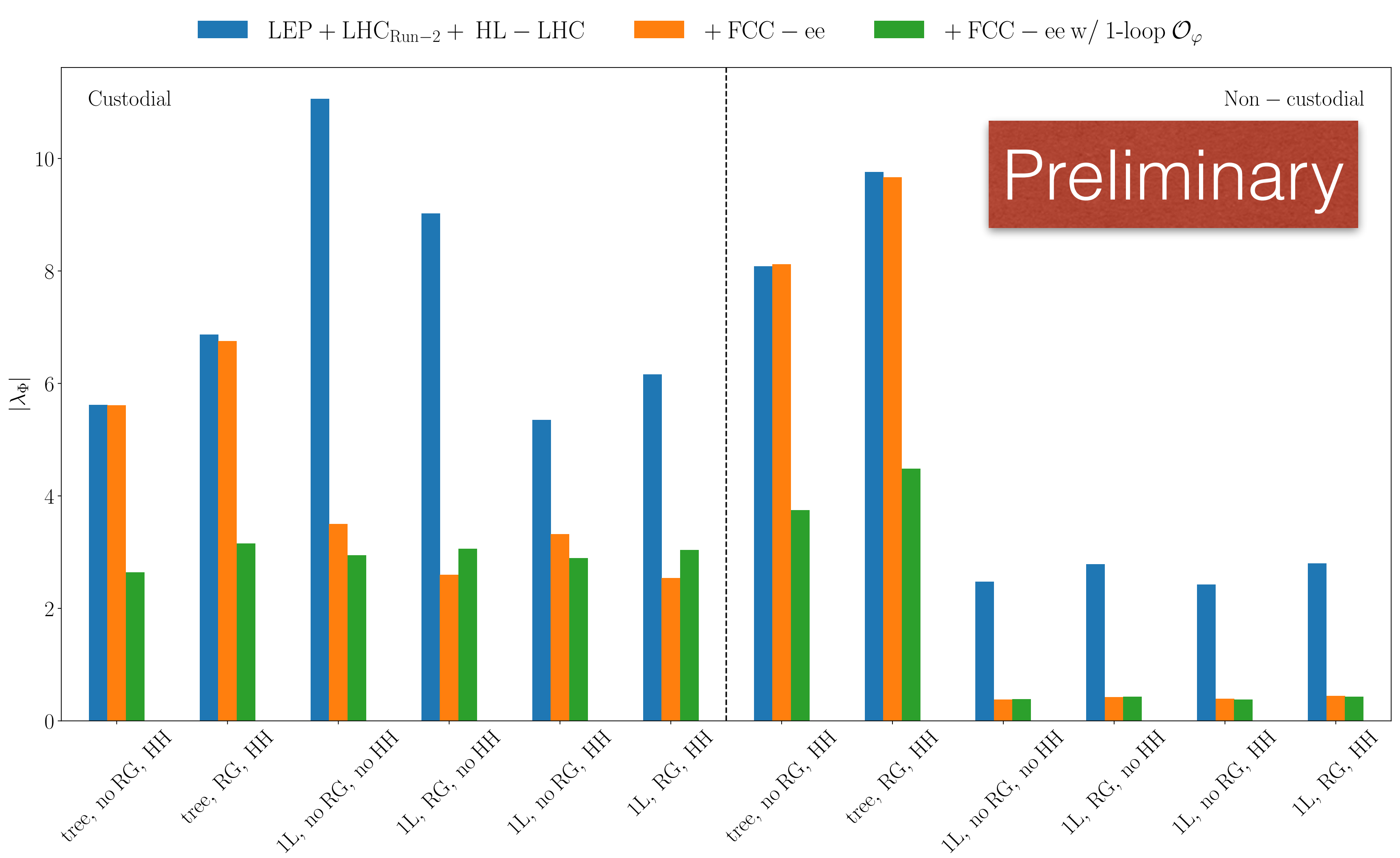

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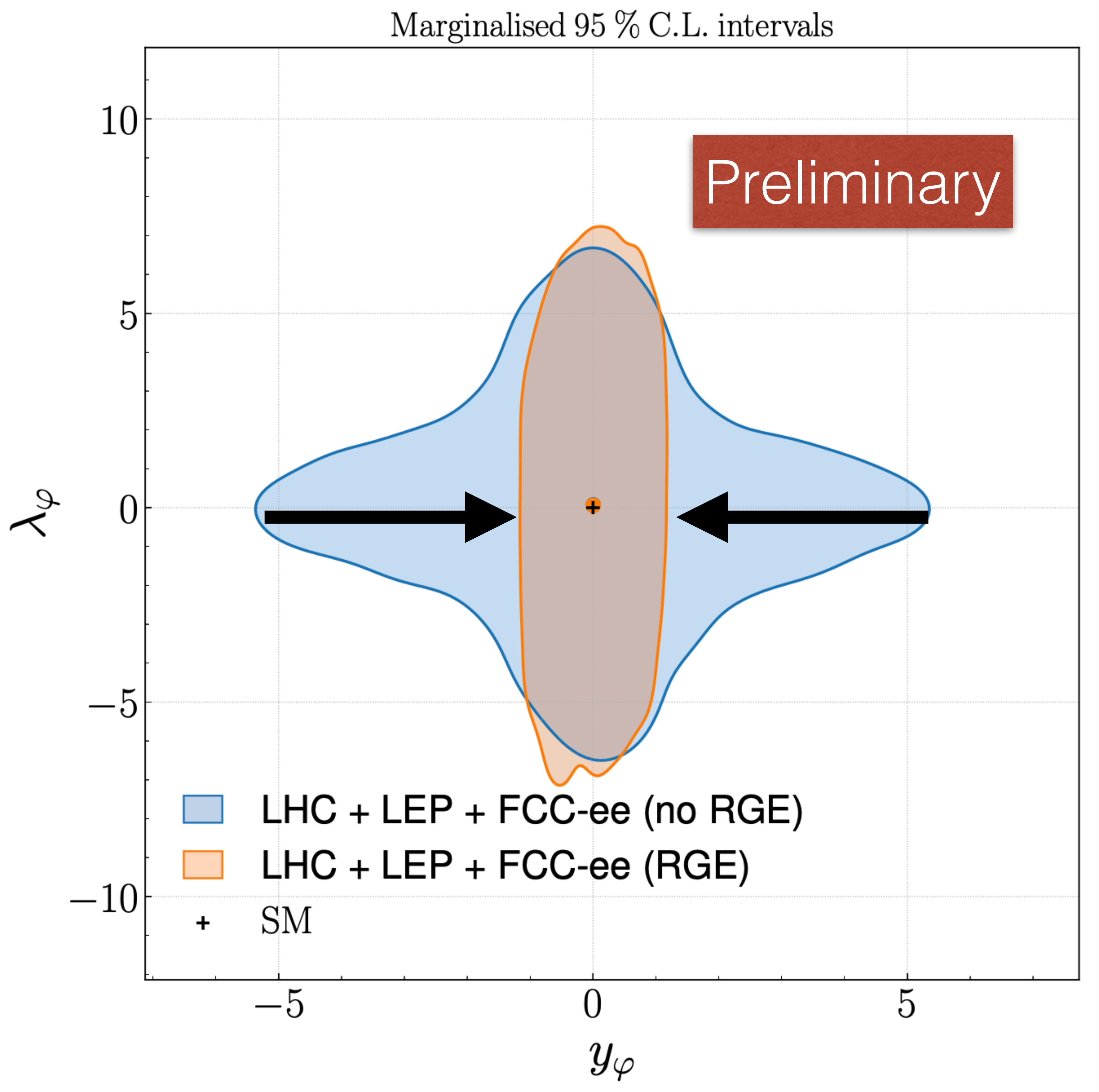
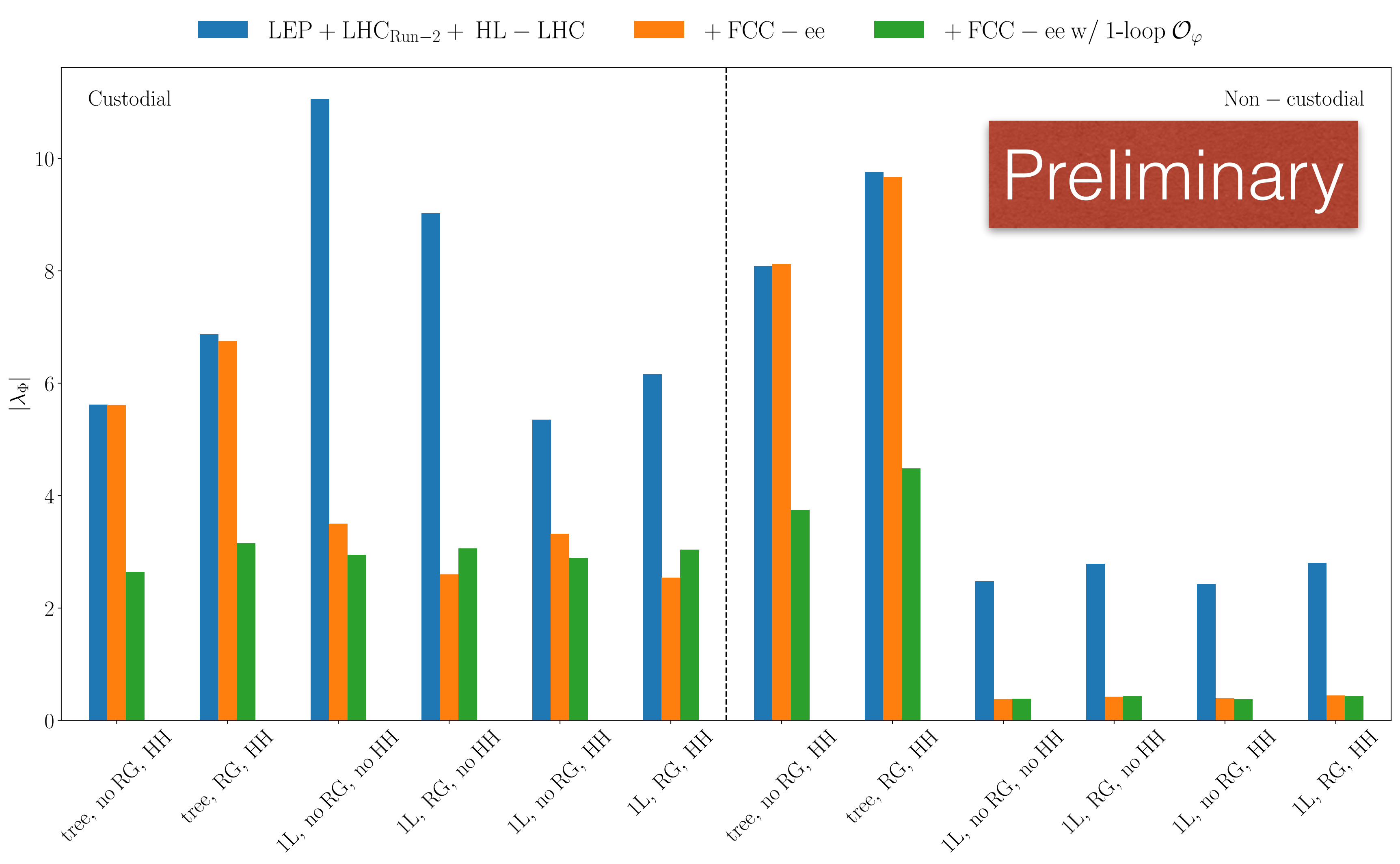
2HDM in decoupling limit



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

2-scalar EW quadruplet model

UV matching in SMEFit: ter Hoeve, Magni, Rojo, Rossia, EV arXiv: 2309.04523



Matchmakereft [2112.10787]
match2fit [2309.04523]
SMEFiT [2302.06660]

$$\mathscr{L}_{\rm UV} \supset -\lambda_\Phi H^* H^* (\varepsilon H)\Phi - \lambda_{\widetilde{\Phi}} H^* H^* H^* \widetilde{\Phi}/\sqrt{3} + \text{h.c.},$$

Durieux, McCullough, Salvioni arXiv:2209.00666

Impact of RGE and 1-loop matching
Significant improvement of reach due to impact on EWPO at FCC

ter Hoeve, Mantani, Rojo, Rossia, EV in preparation

Summary

Global fit results affected by the precision of EFT predictions

Aim to include more and more precise theory predictions in the fits

Inclusion of RGE effects in predictions is necessary, and can significantly affect constraints

Particularly important for poorly constrained operators and in the constraints on UV complete models