THE UNIVERSITY of EDINBURGH

Connecting Scales: RGE Effects in the SMEFT at the LHC and Future Colliders

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

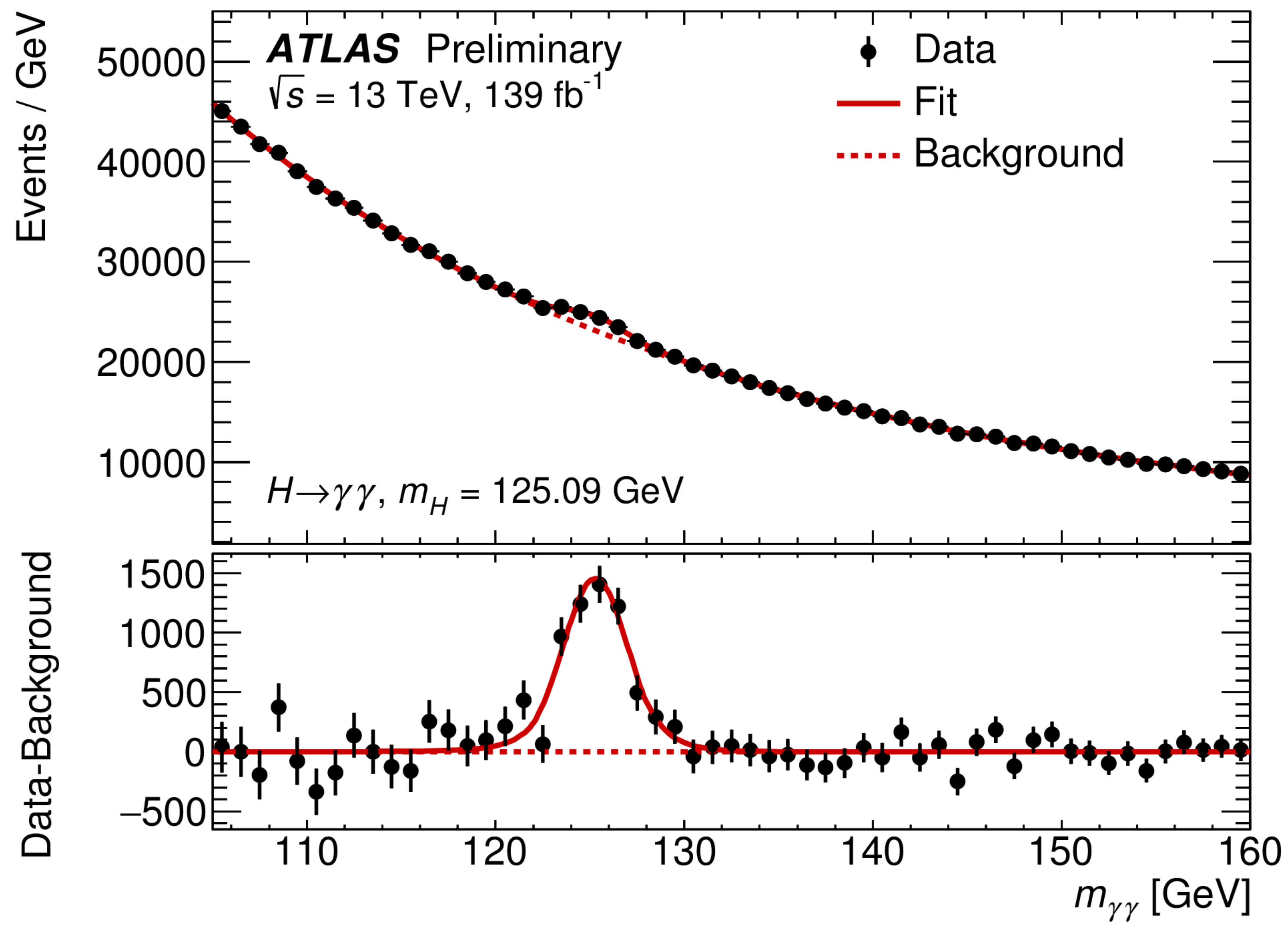
Jaco ter Hoeve
09/07/2025

Based on arXiv: 2502.20453, 2504.05974
JHEP 06 (2025) 125

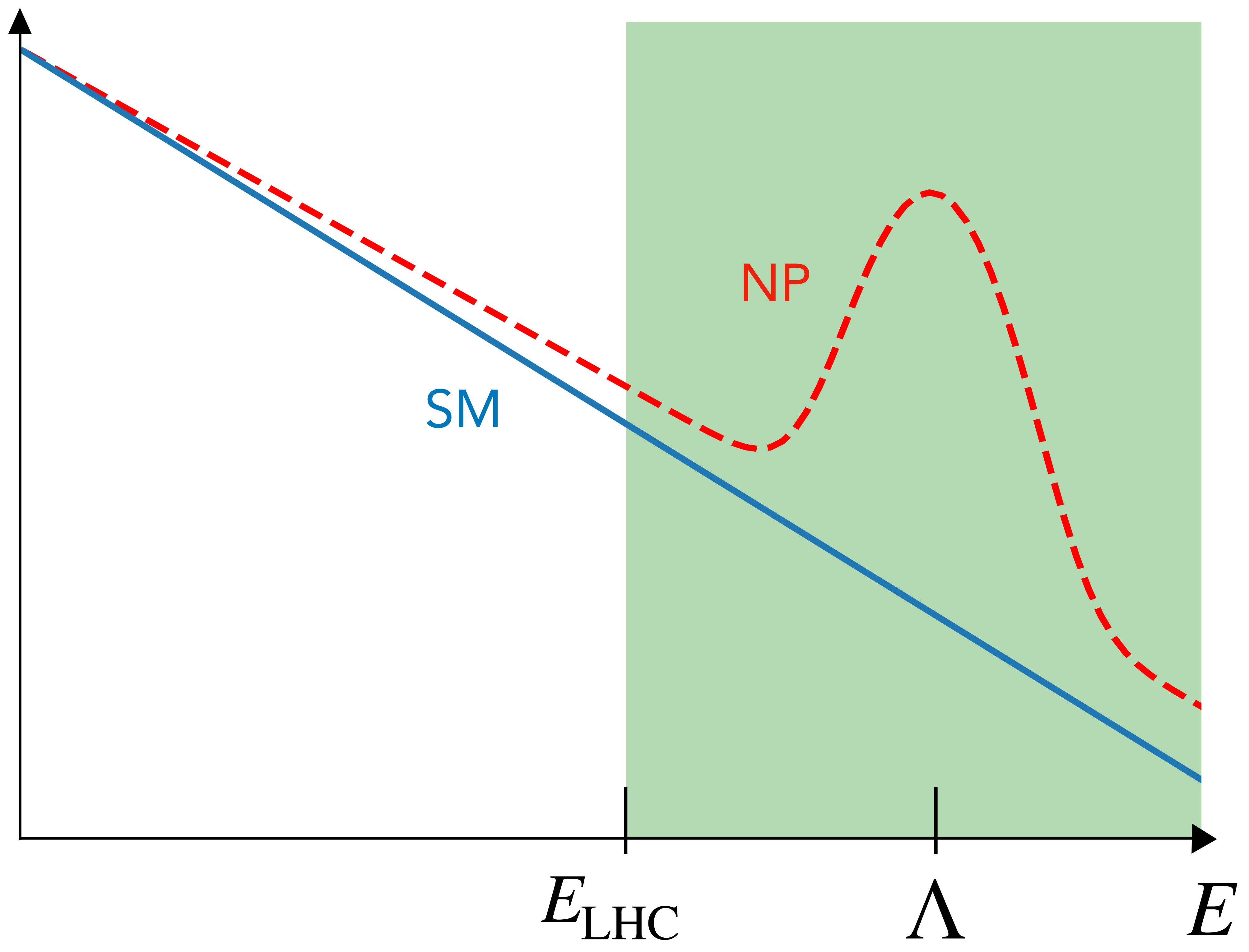
CENTRE FOR THEORETICAL PHYSICS Higgs

How to look for New Physics

1. Directly: bump hunting



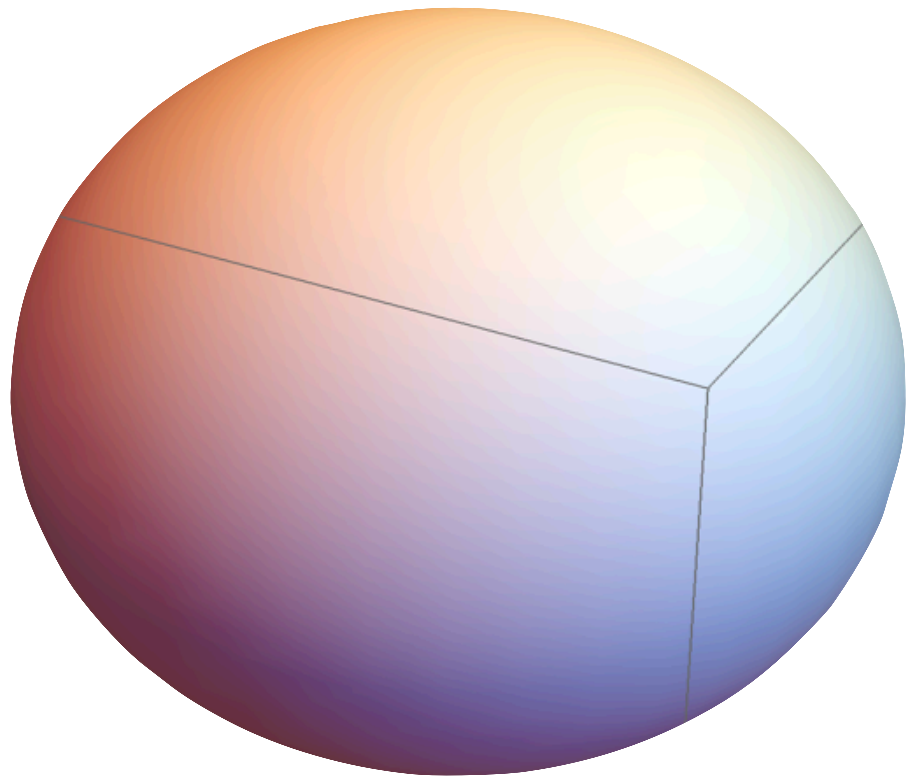
2. Indirectly: tiny deviations in tails



The Standard Model Effective Field Theory

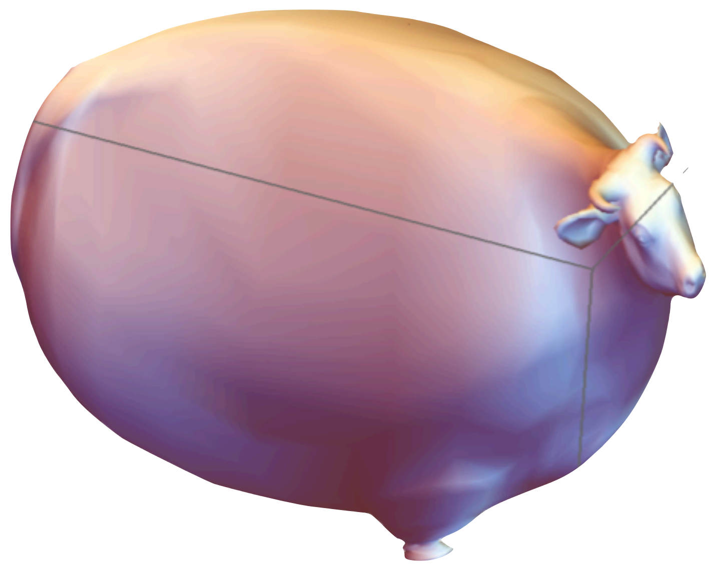
Brivio, Trott, arXiv: 1706.08945

The SM



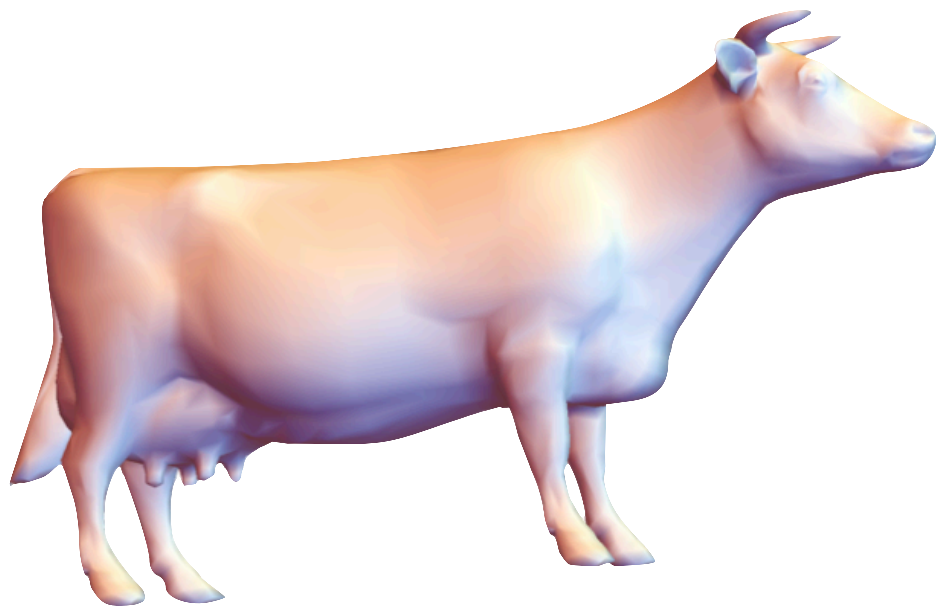
$+ \quad c \cdot$

EFT



$\approx$

New Physics

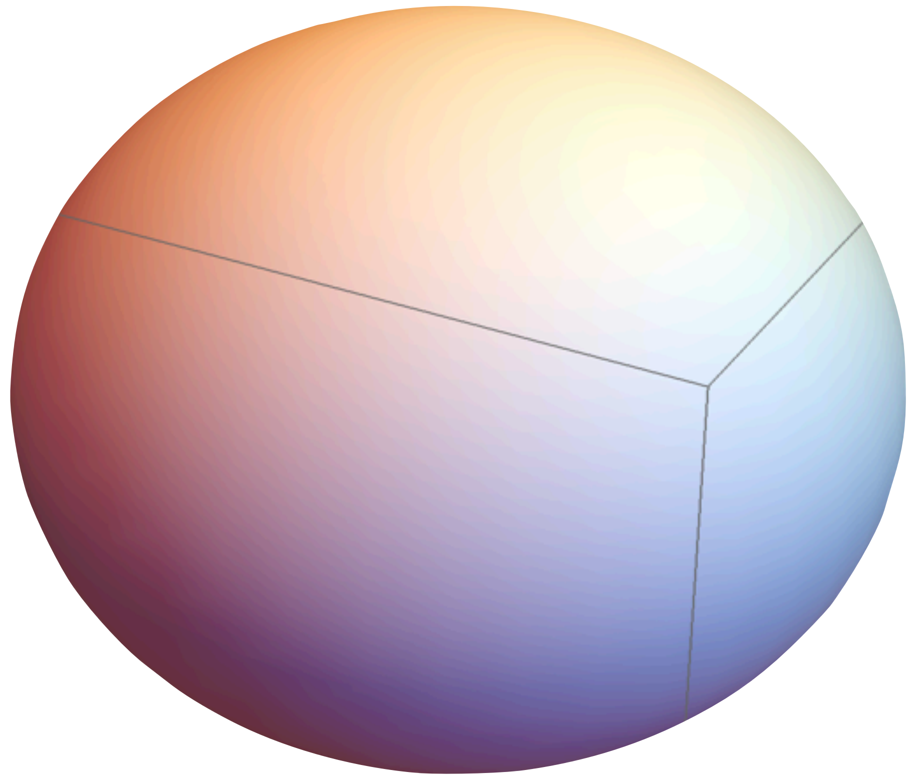


Goal: find the value of c, and precisely!

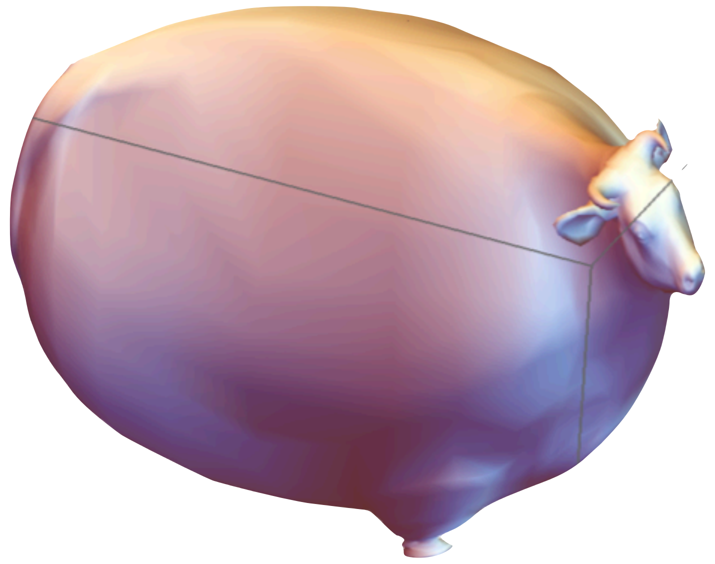
The Standard Model Effective Field Theory

Brivio, Trott, arXiv: 1706.08945

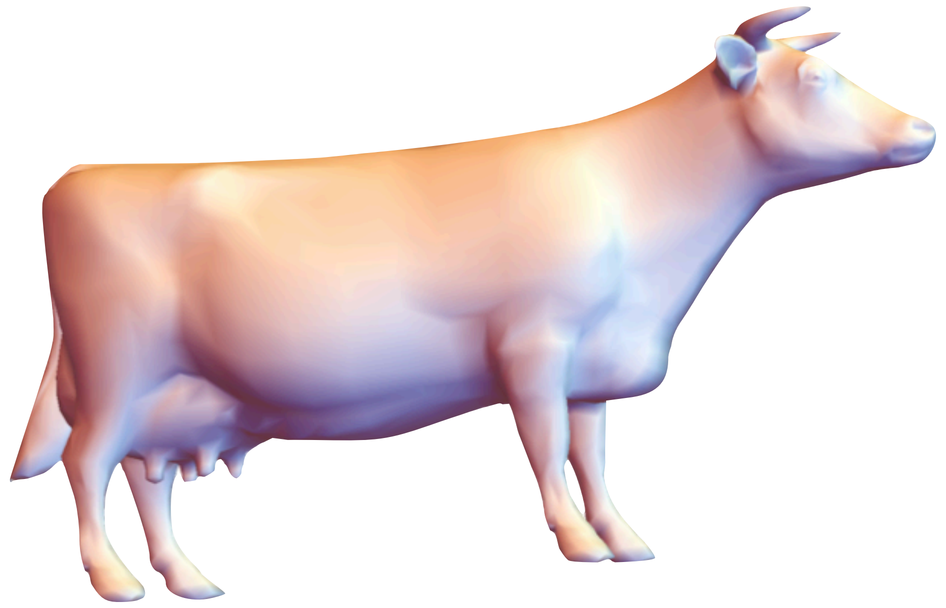
The SM | EFT | New Physics



$+ \; c \, \cdot$

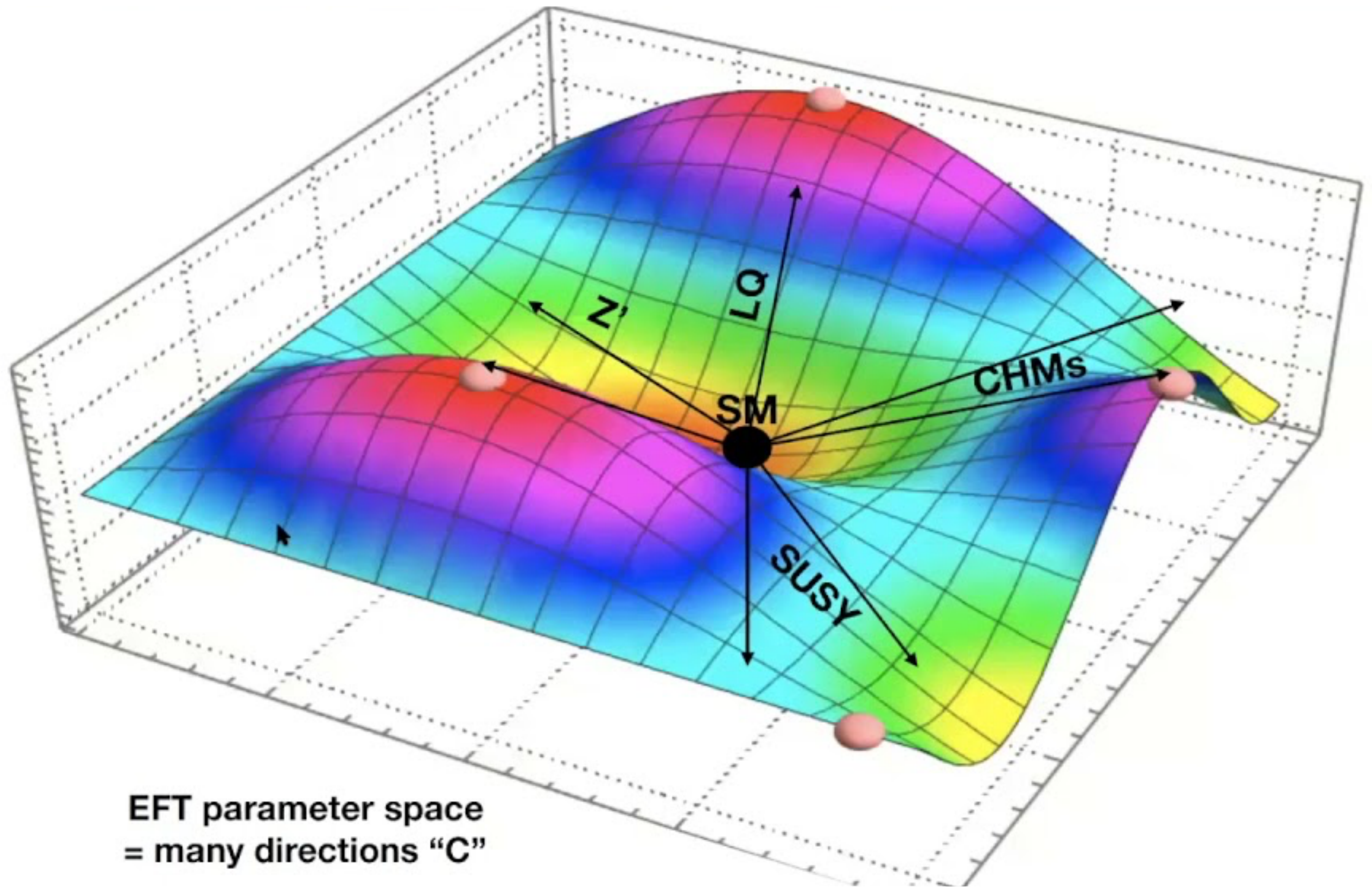


$\approx$



Goal: find the value of c, and precisely!

SMEFT predictions



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

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

State of the art SM predictions

Linear EFT corrections: interference with SM, computed with SMEFT@NLO

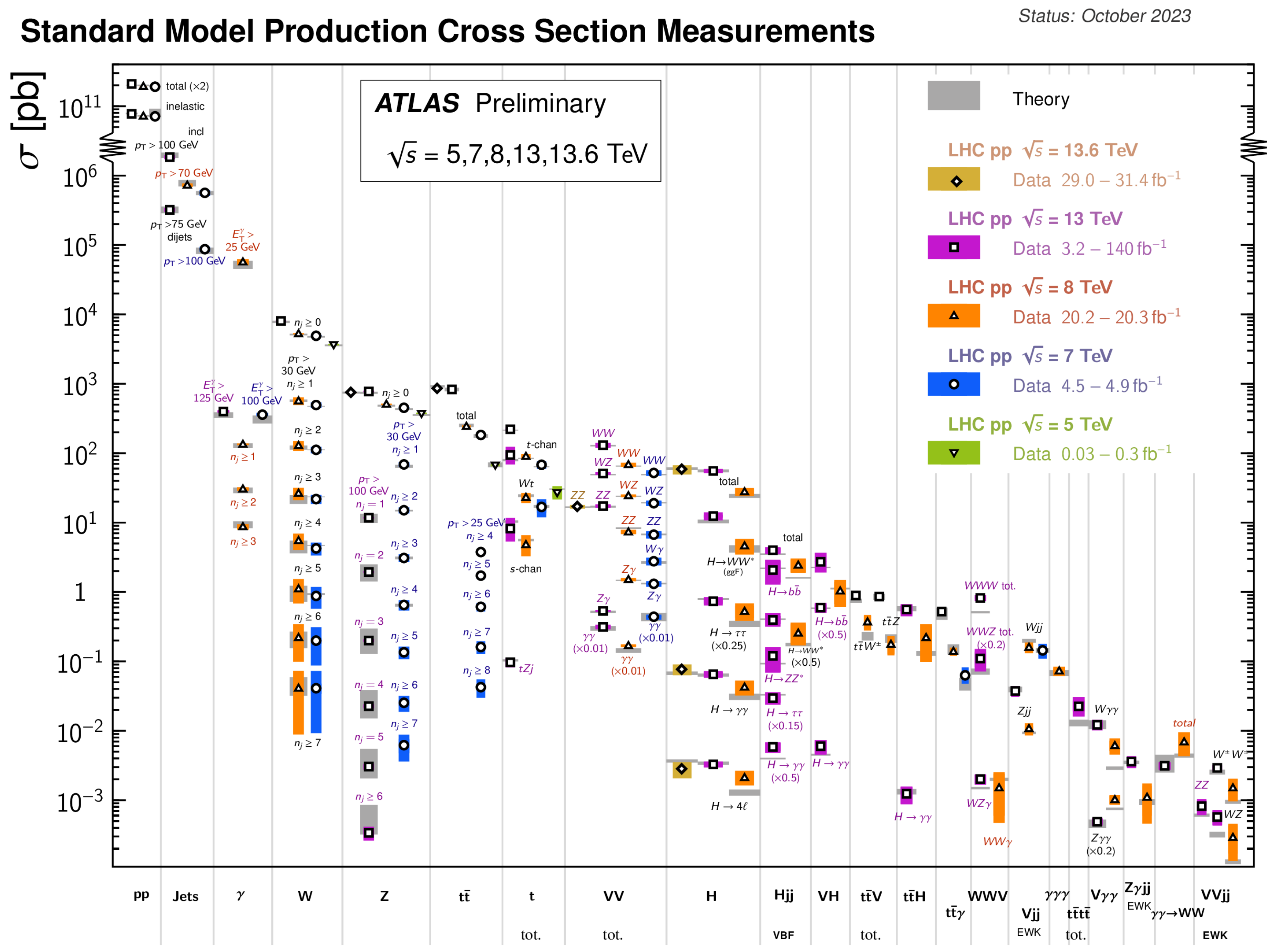
Quadratic EFT corrections, computed with SMEFT@NLO

Degrande et al, arXiv: 2008.11743

Building the likelihood

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

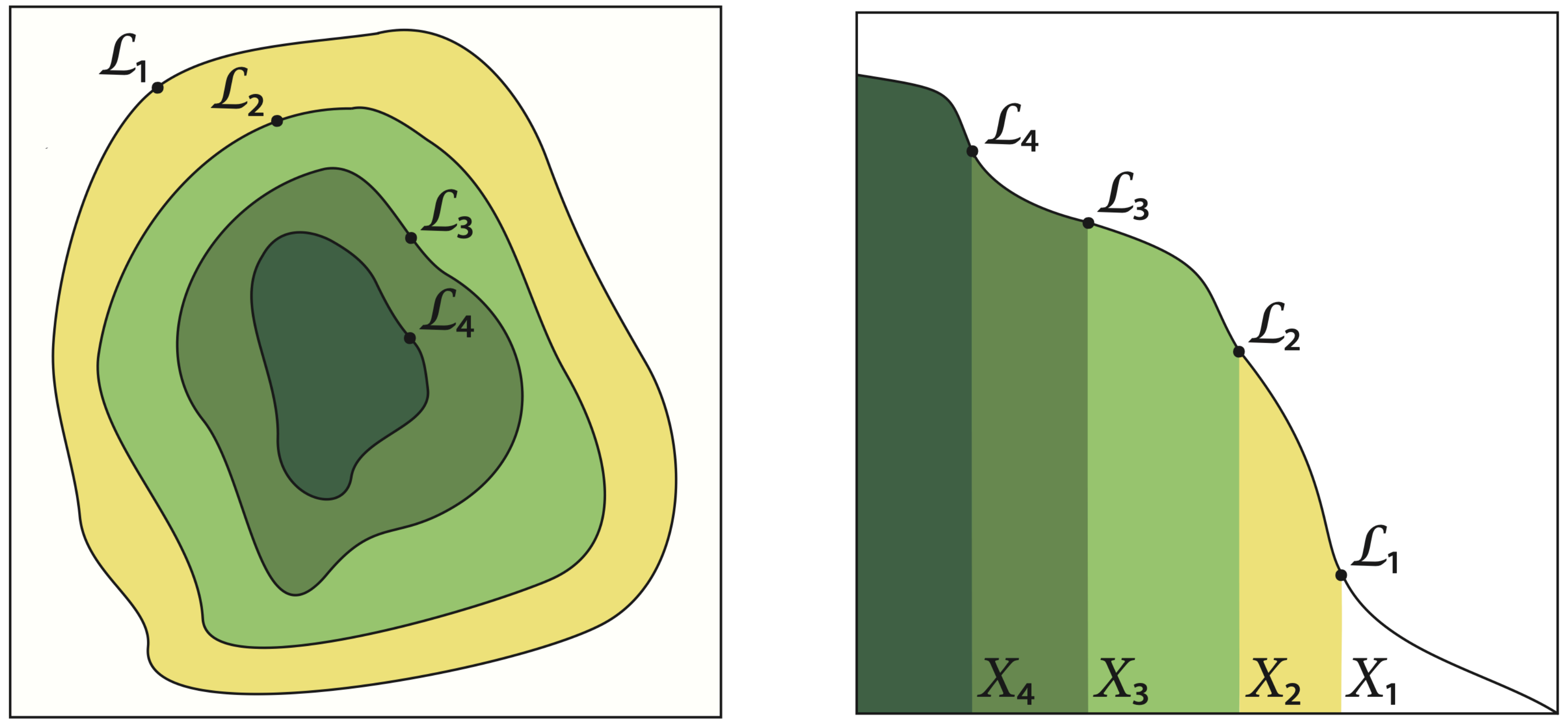
[ATL-PHYS-PUB-2023-039]



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

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]

SMEFiT

smefit.science

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**

Projections

HL-LHC, FCCee, CEPC

+ Automatic projection module

UV models *[2309.04523]*

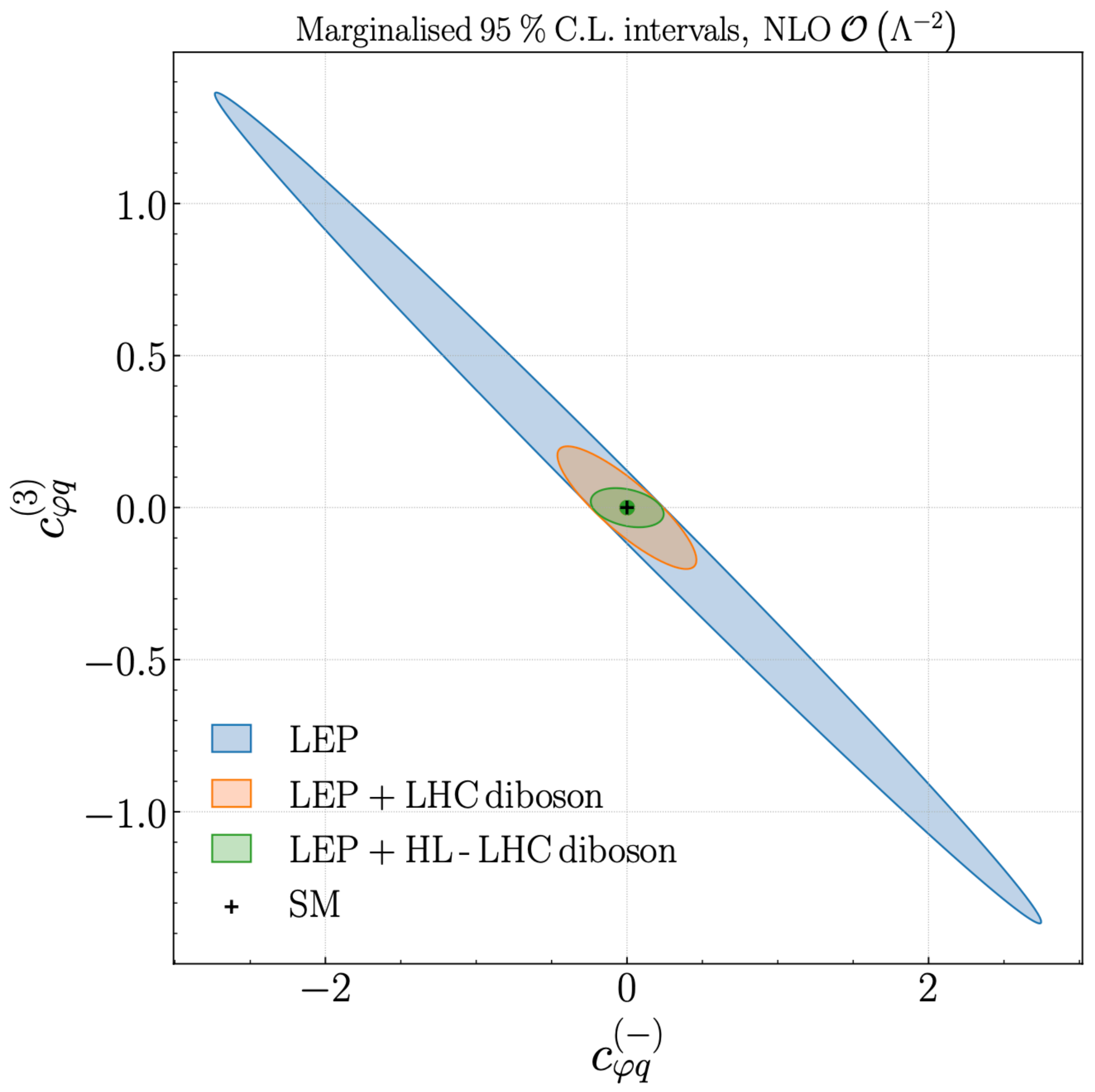
Automatised interface using **`Match2fit`** and **`Matchmakereft`**

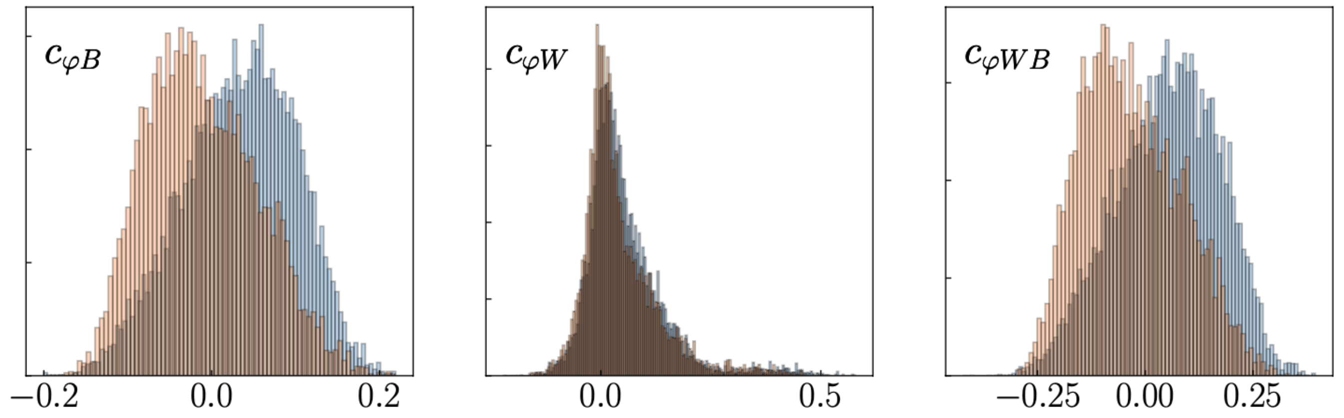
SMEFiT


```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}
}
```

```yaml
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
```

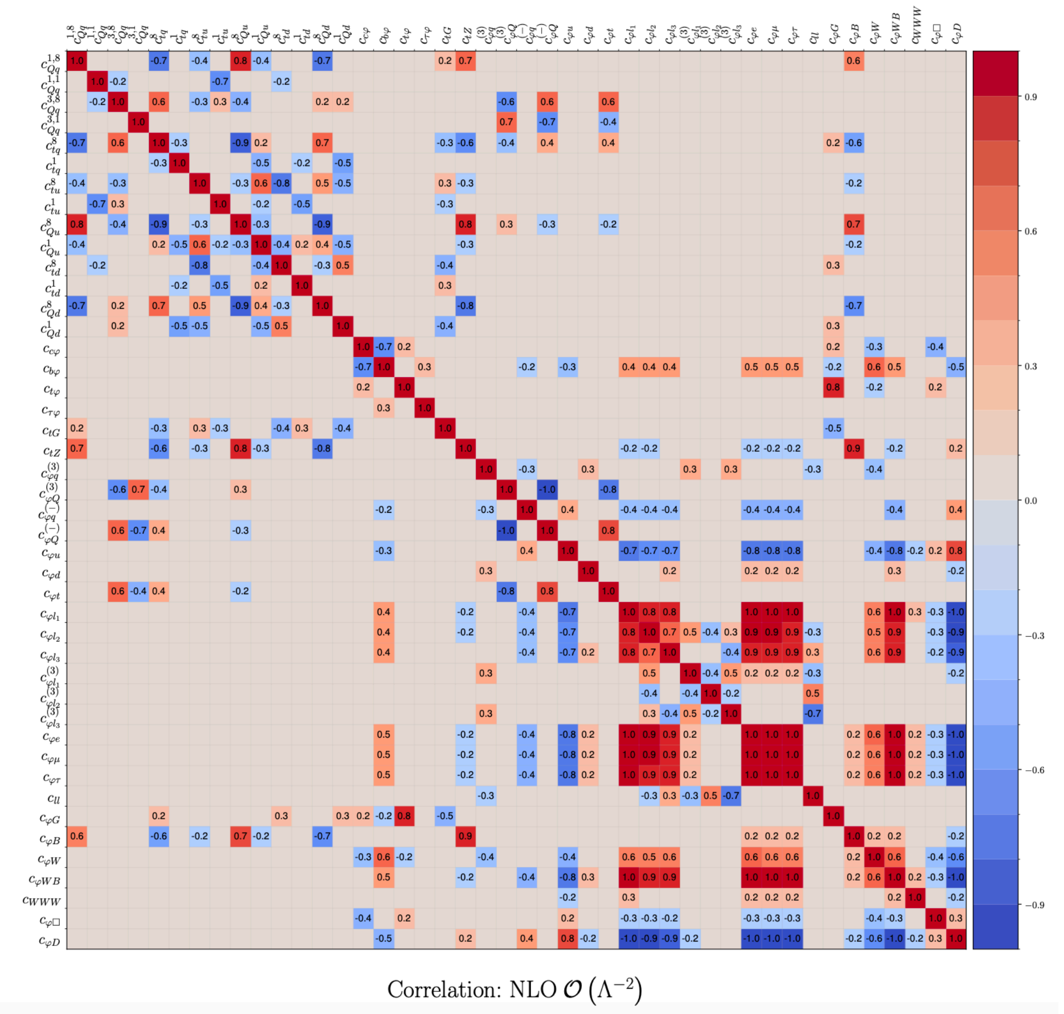
Analysis tools

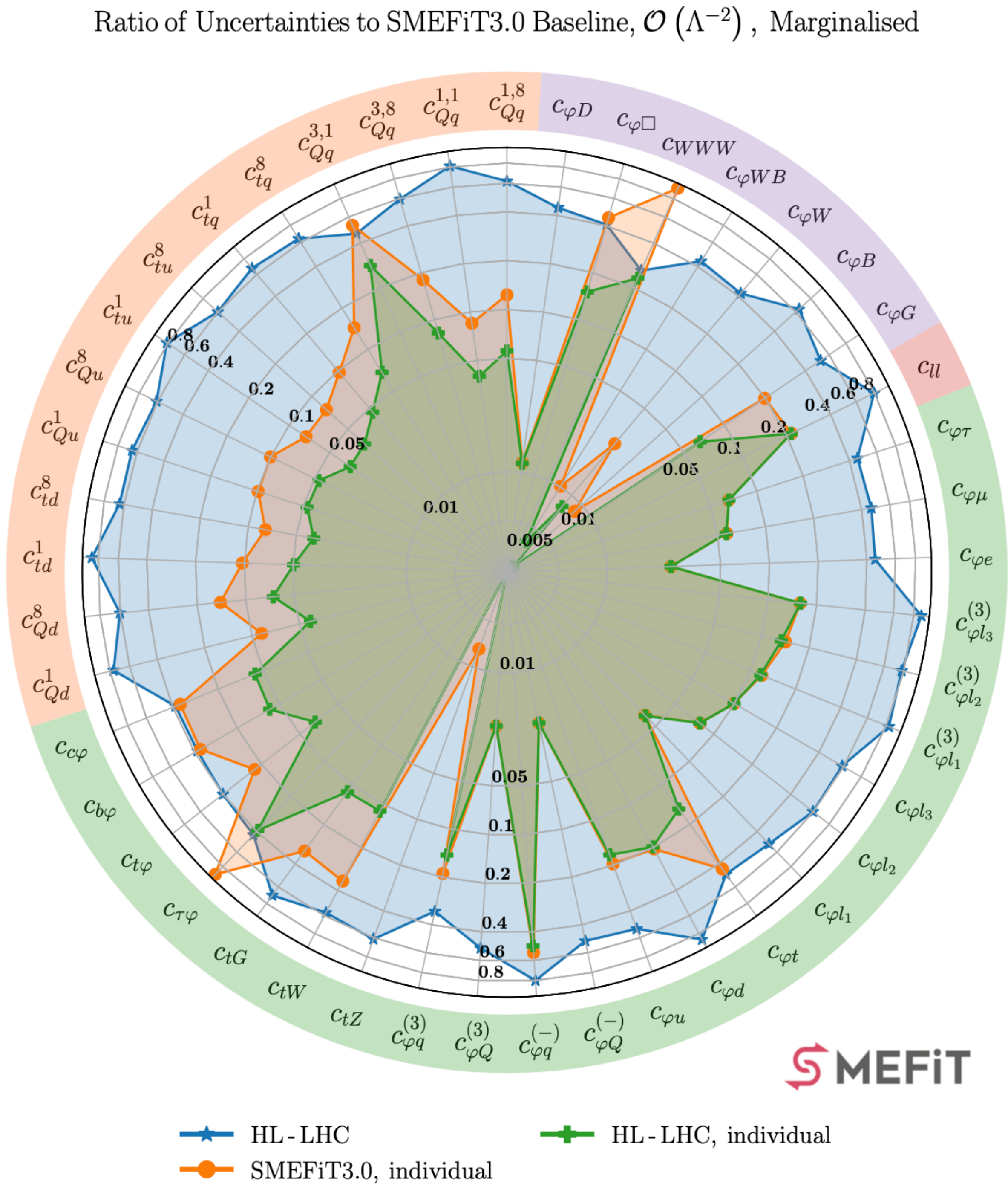


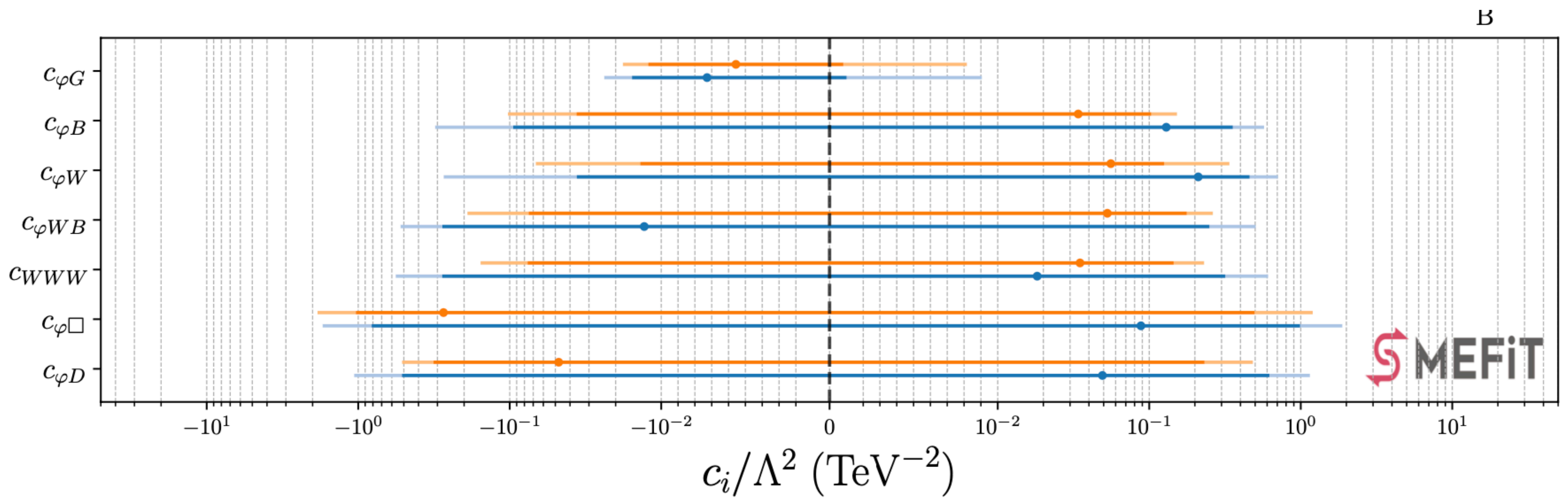


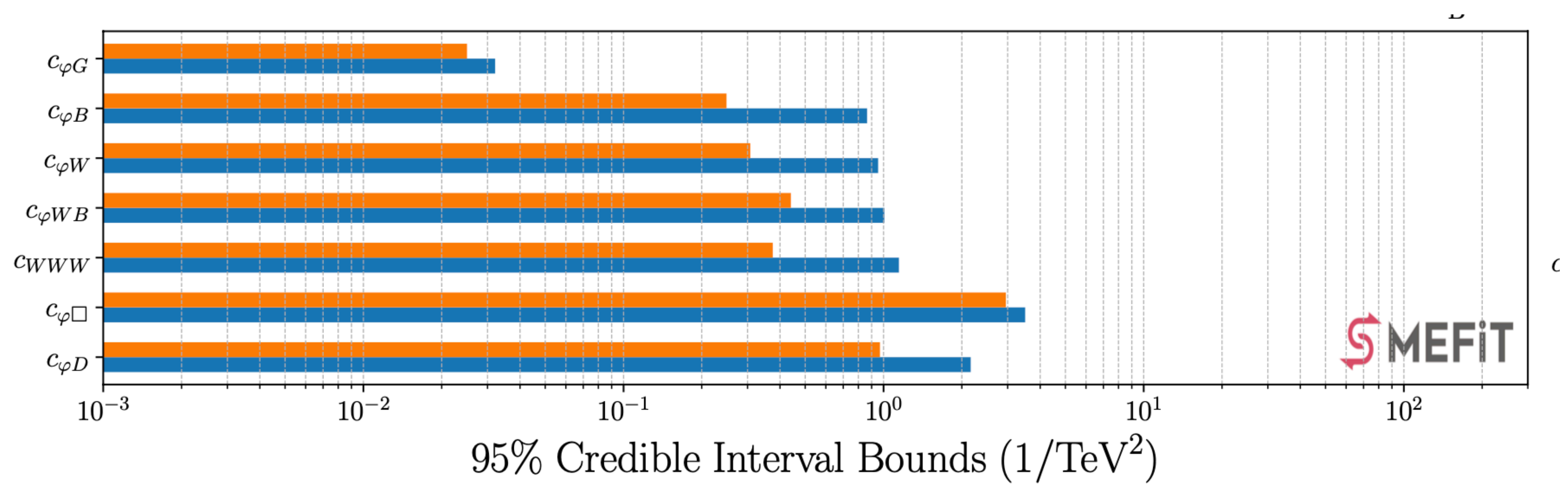
Report module

Automatised fit reports that analyse the SMEFiT results





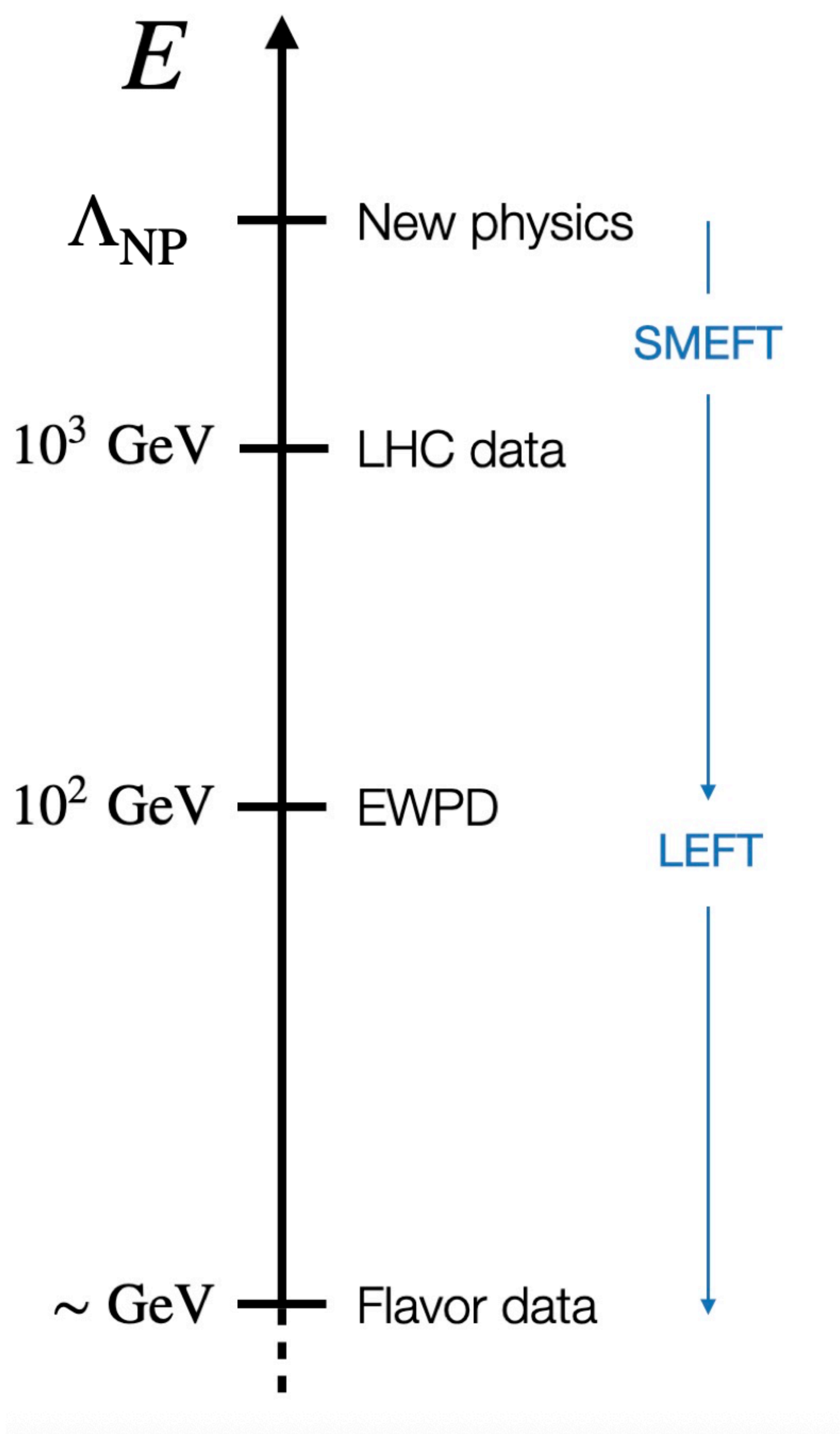




RGE effects in the SMEFT

Scale differences

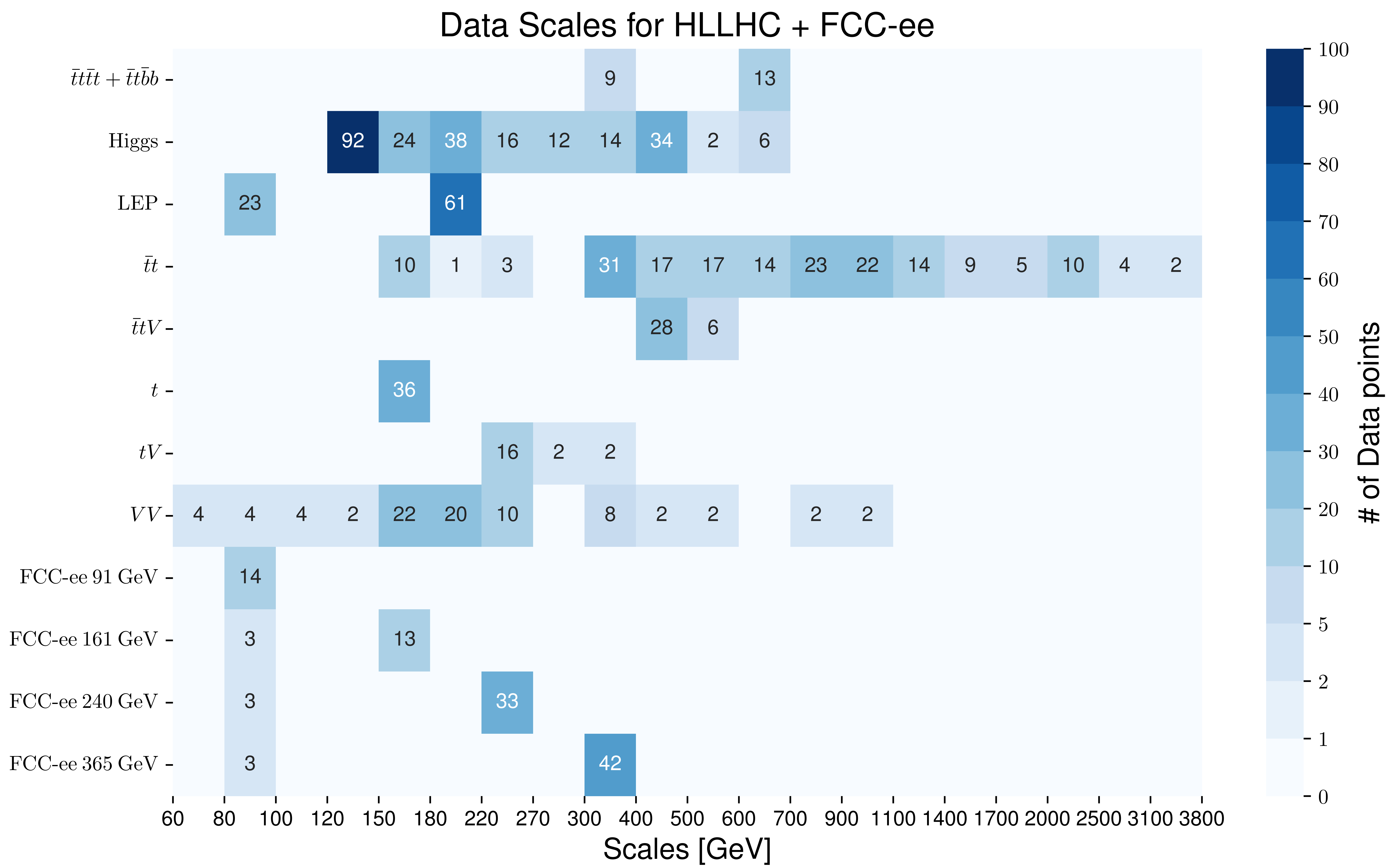
- Experimental input to global fits spans **a wide range of energy scales,** from m_Z at LEP to $m_{t\bar{t}} \sim 3\,\mathrm{TeV}$ in tails at LHC
- Scale differences become even more marked when including **flavour data** $Q \sim m_b$
- as well as projections at the FCC-ee around the Z pole



B. Stefanek, 3rd ECFA workshop

Assuming all measurements entering a global SMEFT fit to correspond to the same energy scale is in general **not well justified!**

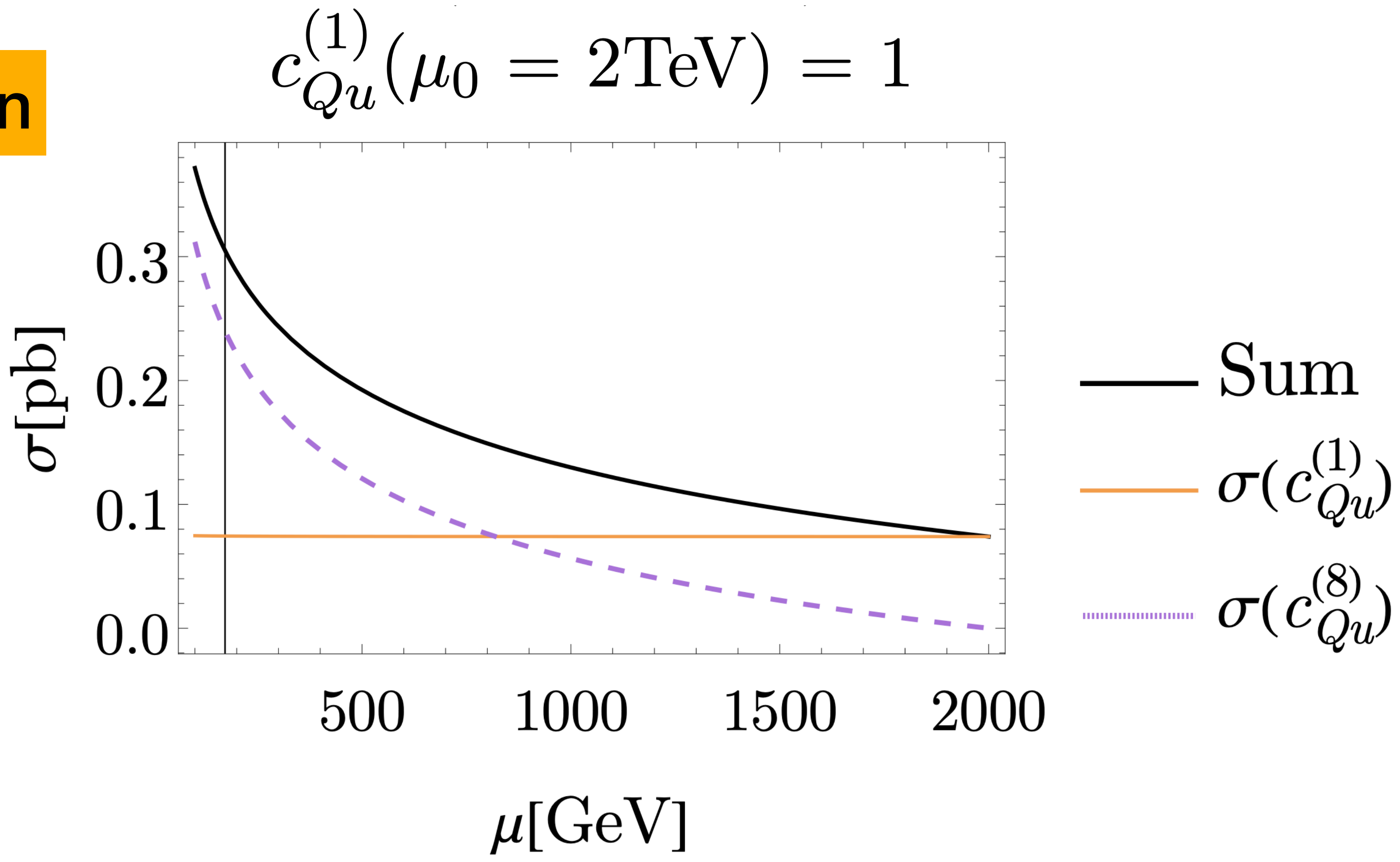
Scale differences



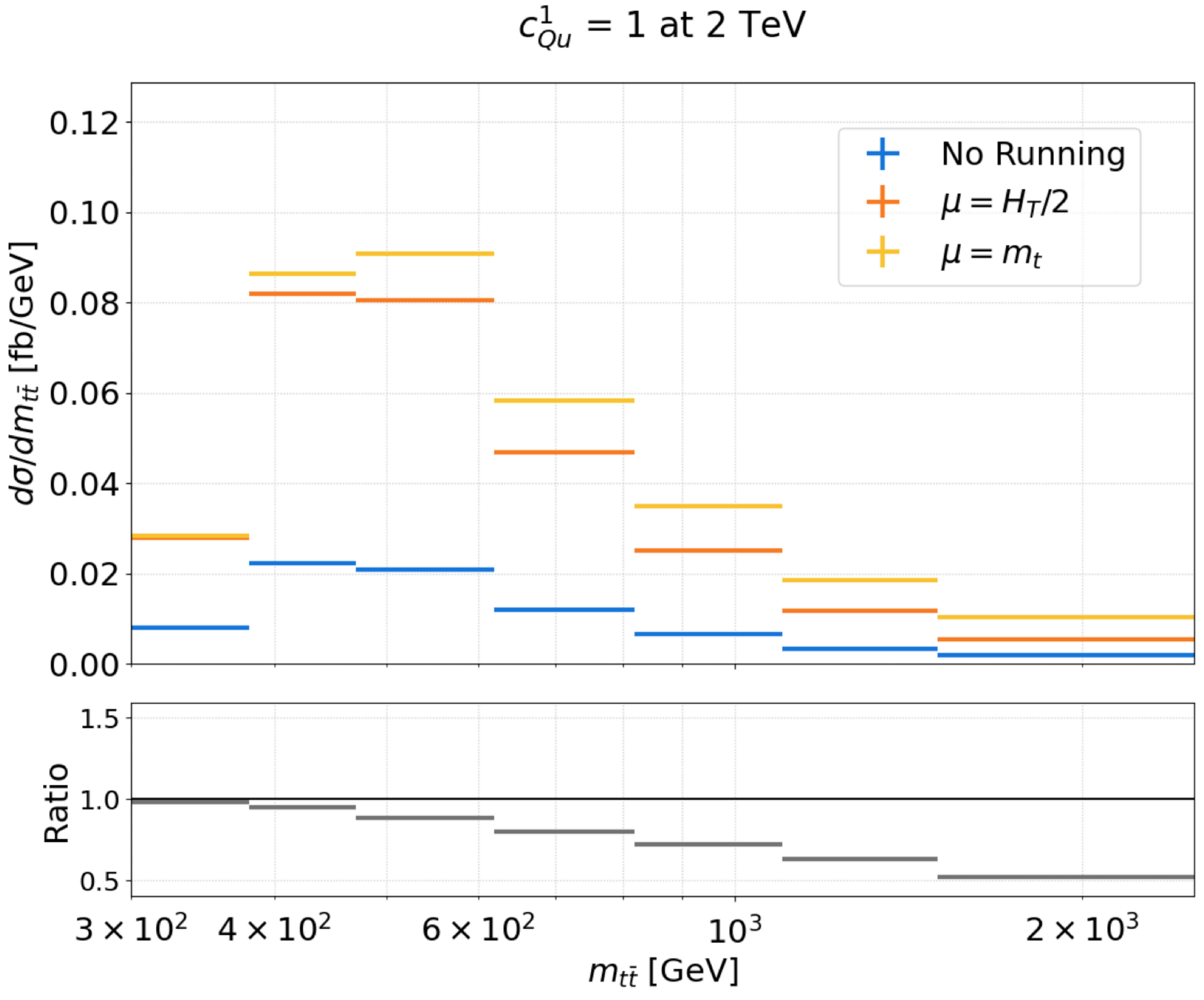
Mantani, Rojo, Rossia, Vryonidou,
JtH, *arXiv: 2502.20453*

RGE in SMEFT phenomenology

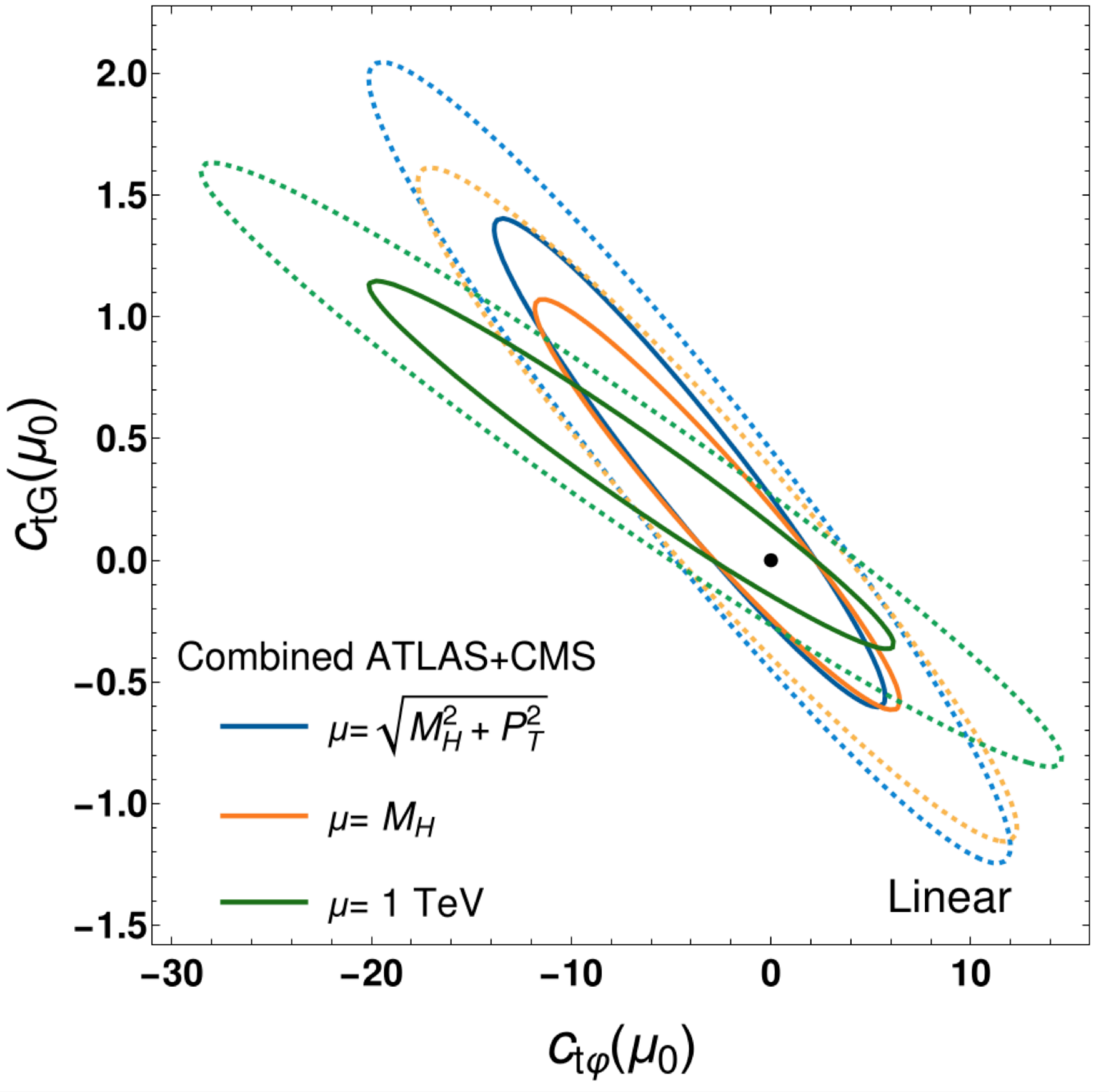
Top pair production



Aoude et al.
arXiv: 2212.05067



Higgs production

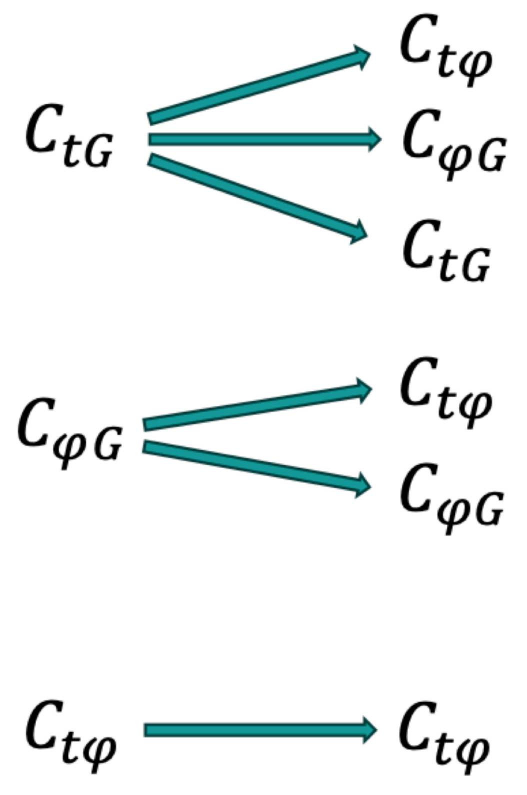


Maltoni, Ventura, Vryonidou
arXiv: 2406.06670

RGE in SMEFiT

Solution: promote the Wilson coefficient to carry scale dependence

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



- Wilson coefficients run and mix with energy through the anomalous dimension

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

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

- Implemented in several codes

wilson — *[1804.05033] Aebischer et al*

DsixTools — *[2010.16341] Fuentes-Martin et al*

RGESolver — *[2210.06838] Di Noi et al*

RGE in SMEFiT

We include RG effects in the **Matrix Evolution Approximation** interfaced to Wilson

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

wilson

[1804.05033] Aebischer, Kumar, Straub

to express the theory predictions at a common reference scale μ_0 = 5 TeV

$$T_{\rm EFT}(\boldsymbol{c}(\mu)/\Lambda^2) = T_{\rm SM} + \sum_{i=1}^{n_{\rm op}} \kappa_i \frac{c_i(\mu)}{\Lambda^2} + \sum_{i,j=1}^{n_{\rm op}} \widetilde{\kappa}_{ij} \frac{c_i(\mu)c_j(\mu)}{\Lambda^4}$$

$$= T_{\rm SM} + \sum_{i,j=1}^{n_{\rm op}} \kappa_i \Gamma_{ij} \frac{c_j(\mu_0)}{\Lambda^2} + \sum_{i,j,k,\ell=1}^{n_{\rm op}} \widetilde{\kappa}_{ij} \Gamma_{ik} \Gamma_{j\ell} \frac{c_k(\mu_0)c_\ell(\mu_0)}{\Lambda^4}$$

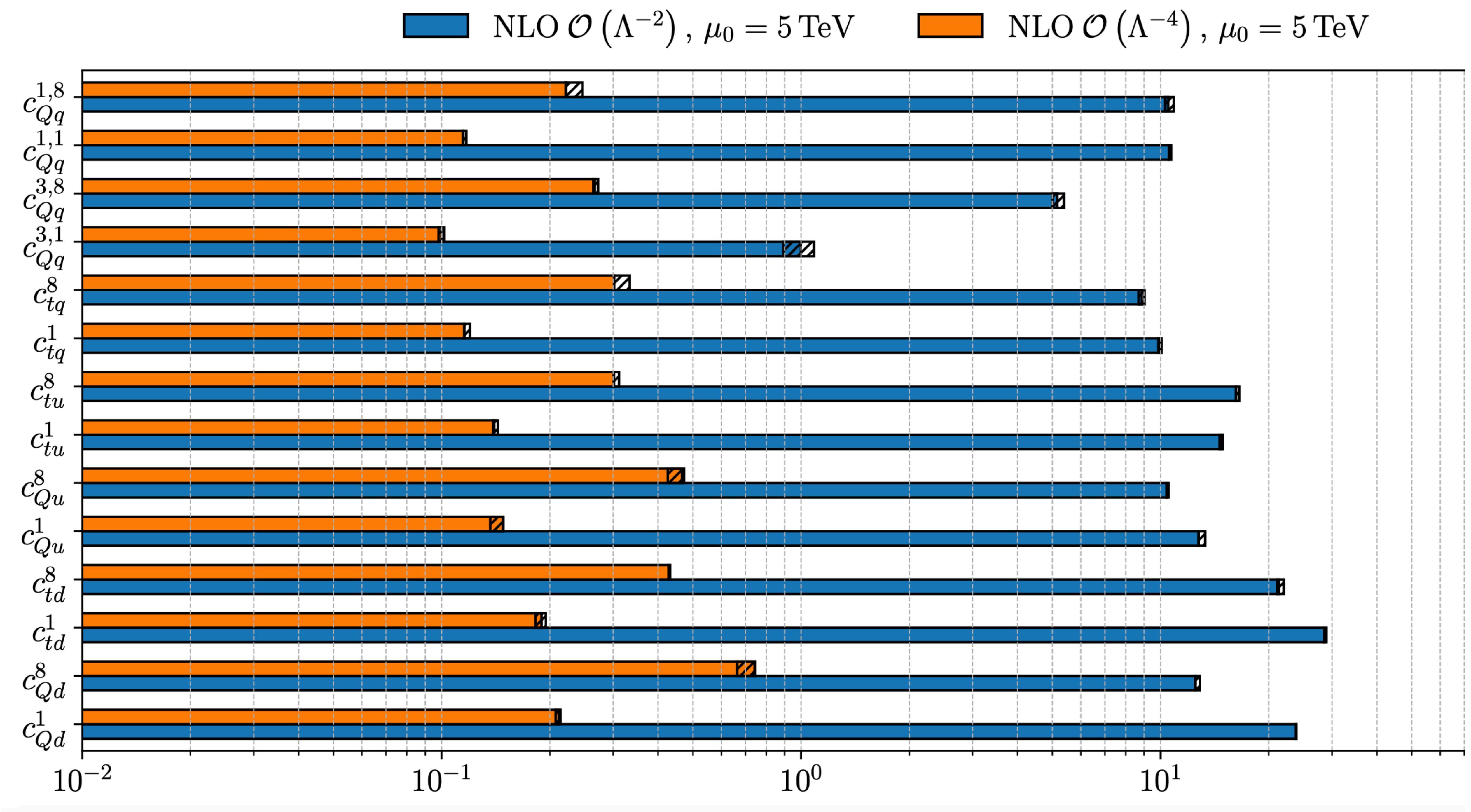
$$= T_{\rm SM} + \sum_{j=1}^{n_{\rm op}} \kappa'_j \frac{c_j(\mu_0)}{\Lambda^2} + \sum_{k,\ell=1}^{n_{\rm op}} \widetilde{\kappa}'_{k\ell} \frac{c_k(\mu_0)c_\ell(\mu_0)}{\Lambda^4}$$

Theory predictions keep the same form!

Scale variations

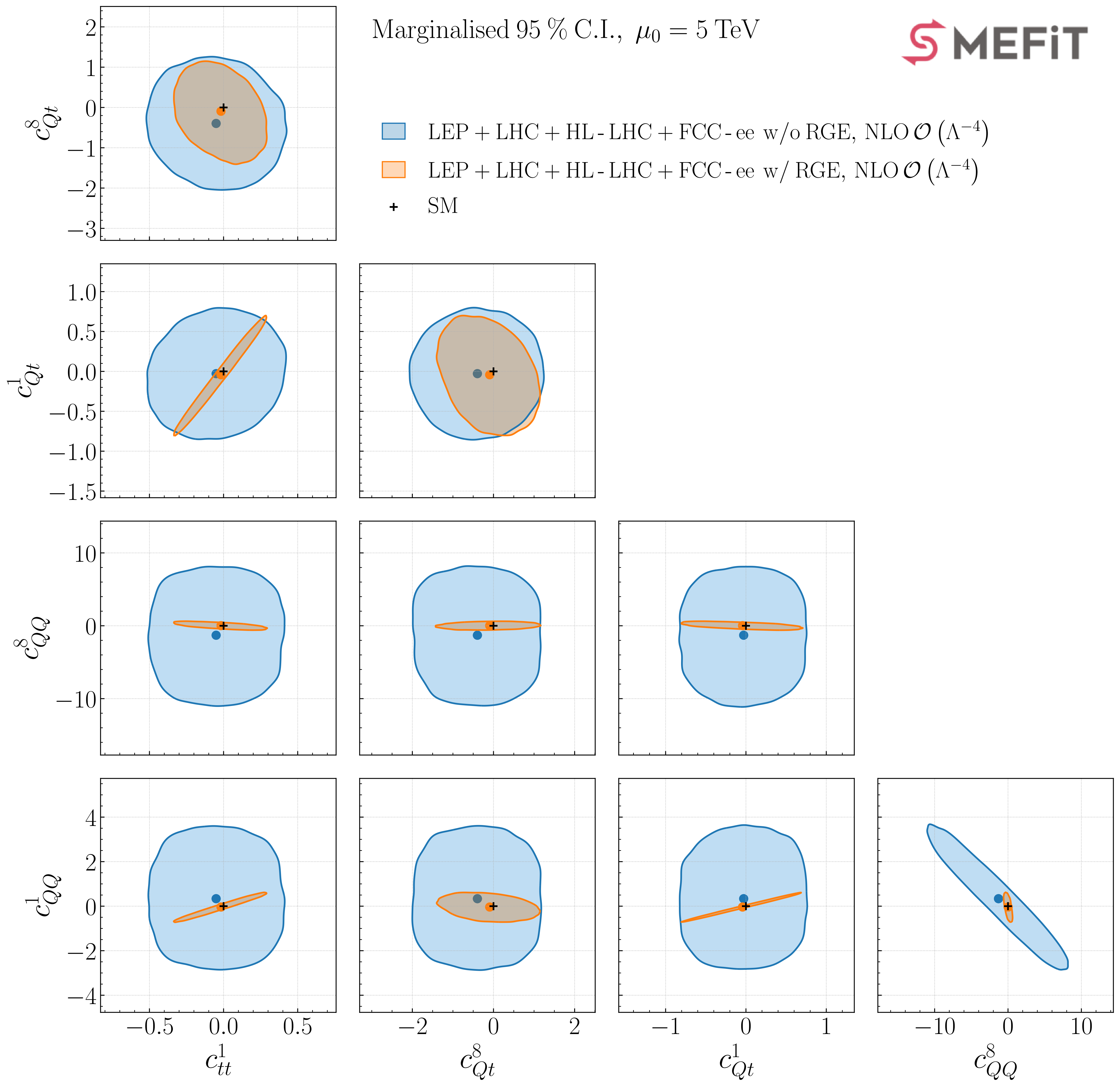
We associate a fixed characteristic scale choice μ to **each bin**, but this is choice is not unique!

Study scale variations $\mu \to \tilde{\mu} = \kappa\mu$

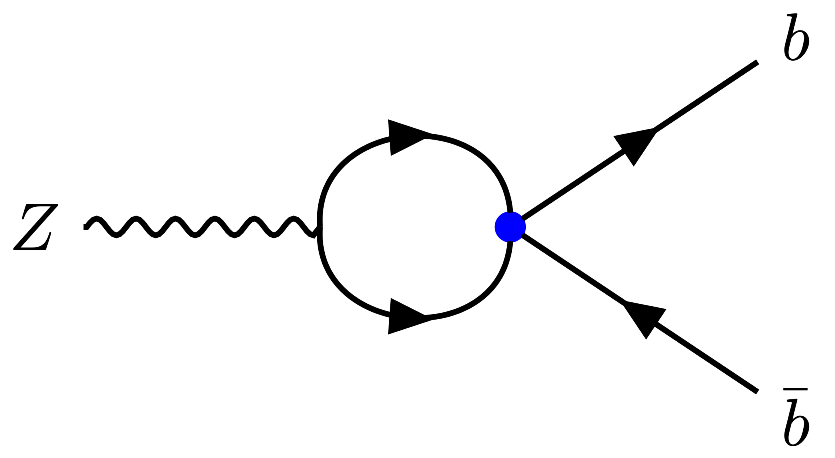


Process	**Scale Choice** μ	**Process**	**Scale Choice** μ
Higgs (ggF)	$\sqrt{m_H^2 + (p_T^H)^2}$	$t\bar{t}b\bar{b}$	$2m_t$
Higgs (VBF)	$\sqrt{m_H^2 + (p_T^H)^2}$	$t\bar{t}V$	$\sqrt{(2m_t + m_V)^2 + (p_T^V)^2}$
VH	$\sqrt{(m_V + m_H)^2 + (p_T^V)^2}$	tV	$m_t + m_V$ or $\sqrt{(m_t + m_V)^2 + (p_T^t)^2}$
$t\bar{t}H$	$\sqrt{(2m_t + m_H)^2 + (p_T^H)^2}$	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	$2m_H$	$e^+e^- \to ZH$	$\sqrt{s}$

Example



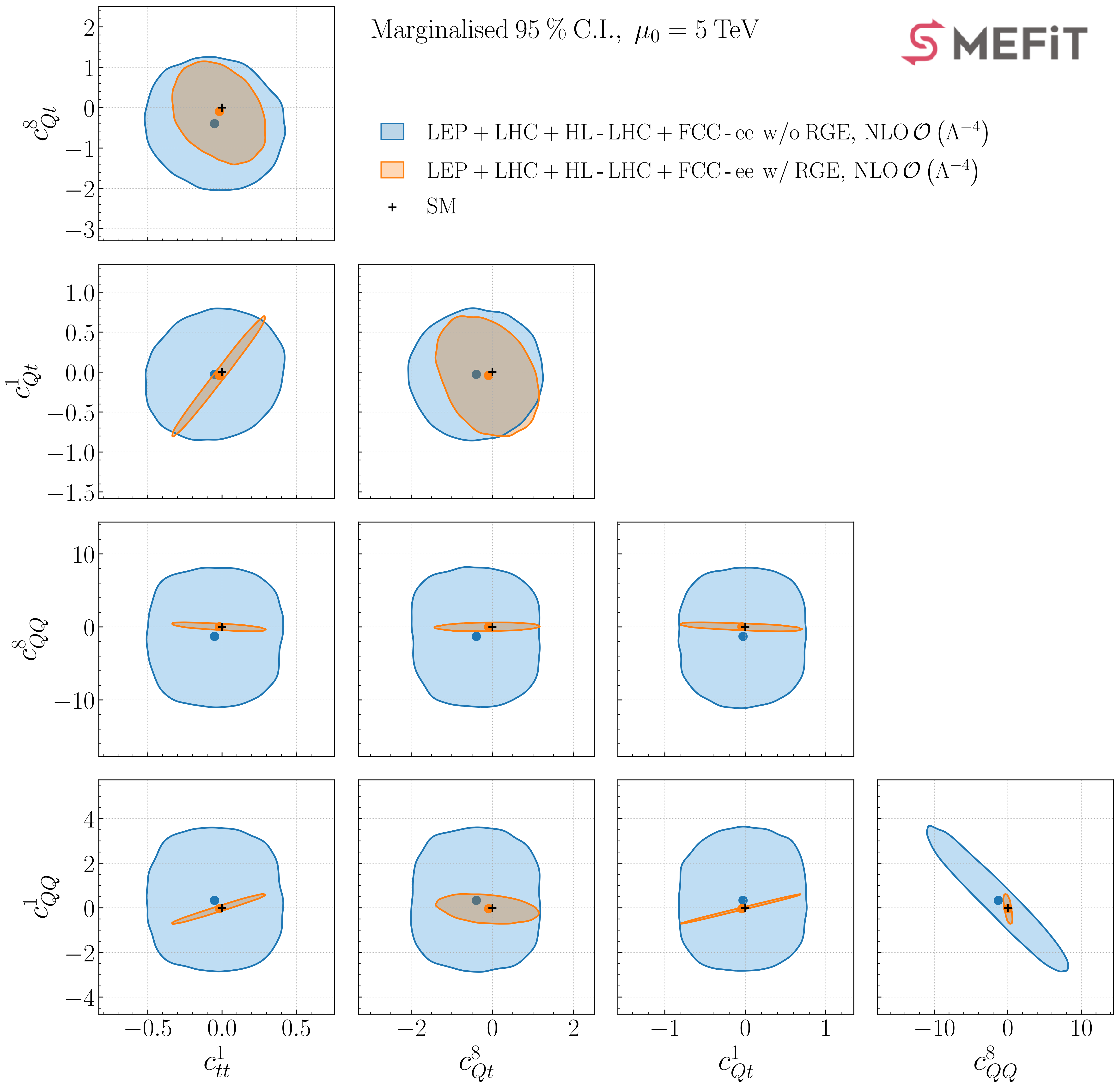
4 heavy operators flow into operators sensitive to the EWPOs at low energy:



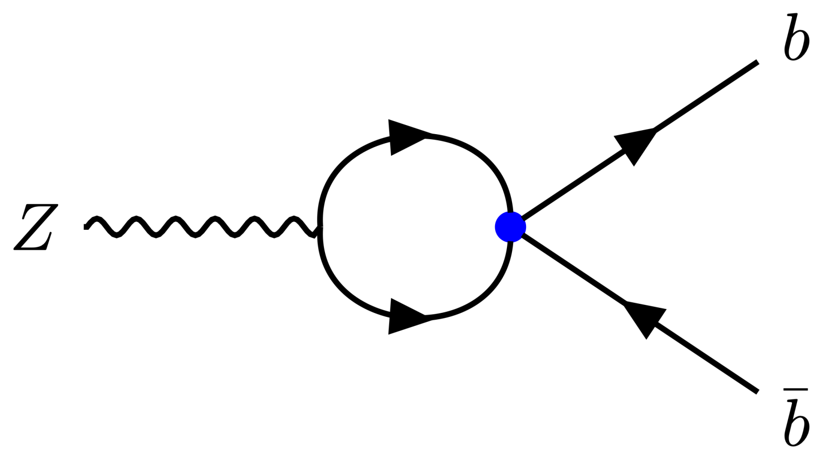
	$t\bar{t}t\bar{t} + t\bar{t}b\bar{b}$	Higgs	LEP	$t\bar{t}$	$t\bar{t}V$	t	tV	VV	FCC − ee 91 GeV	FCC − ee 161 GeV	FCC − ee 240 GeV	FCC − ee 365 GeV
c_{QQ}^1	100.0 / 0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.0	16.1	0.0	78.2	5.3
c_{QQ}^8	100.0 / 0.0	0.0 / 0.0	0.2	0.0	0.0	0.0	0.0	0.0	1.5	0.0	91.2	7.0
c_{Qt}^1	100.0 / 0.0	0.0	0.3	0.0	0.0	0.0	0.0	0.0	5.7	0.0	88.1	5.9
c_{Qt}^8	100.0 / 7.8	0.0 / 27.7	0.2	1.0	1.4	0.0	0.0	0.0	6.6	0.0	47.2	8.1
c_{tt}^1	100.0 / 0.0	0.0	0.2	0.0	0.0		0.0	0.0	0.4	0.0	93.0	6.3

Fisher information / sensitivity metric

Example



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

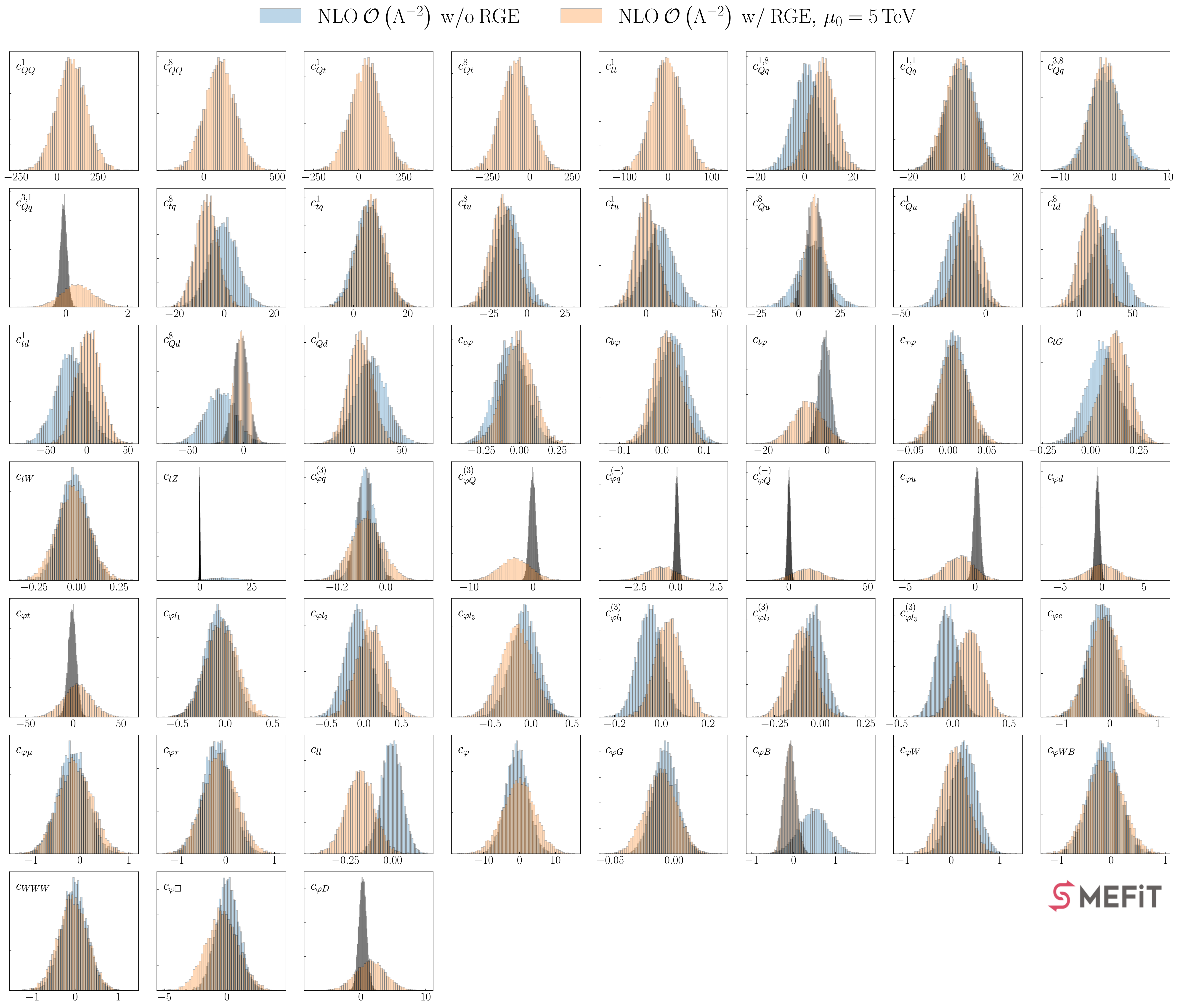


In general one may see two competing effects:

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

The global fit

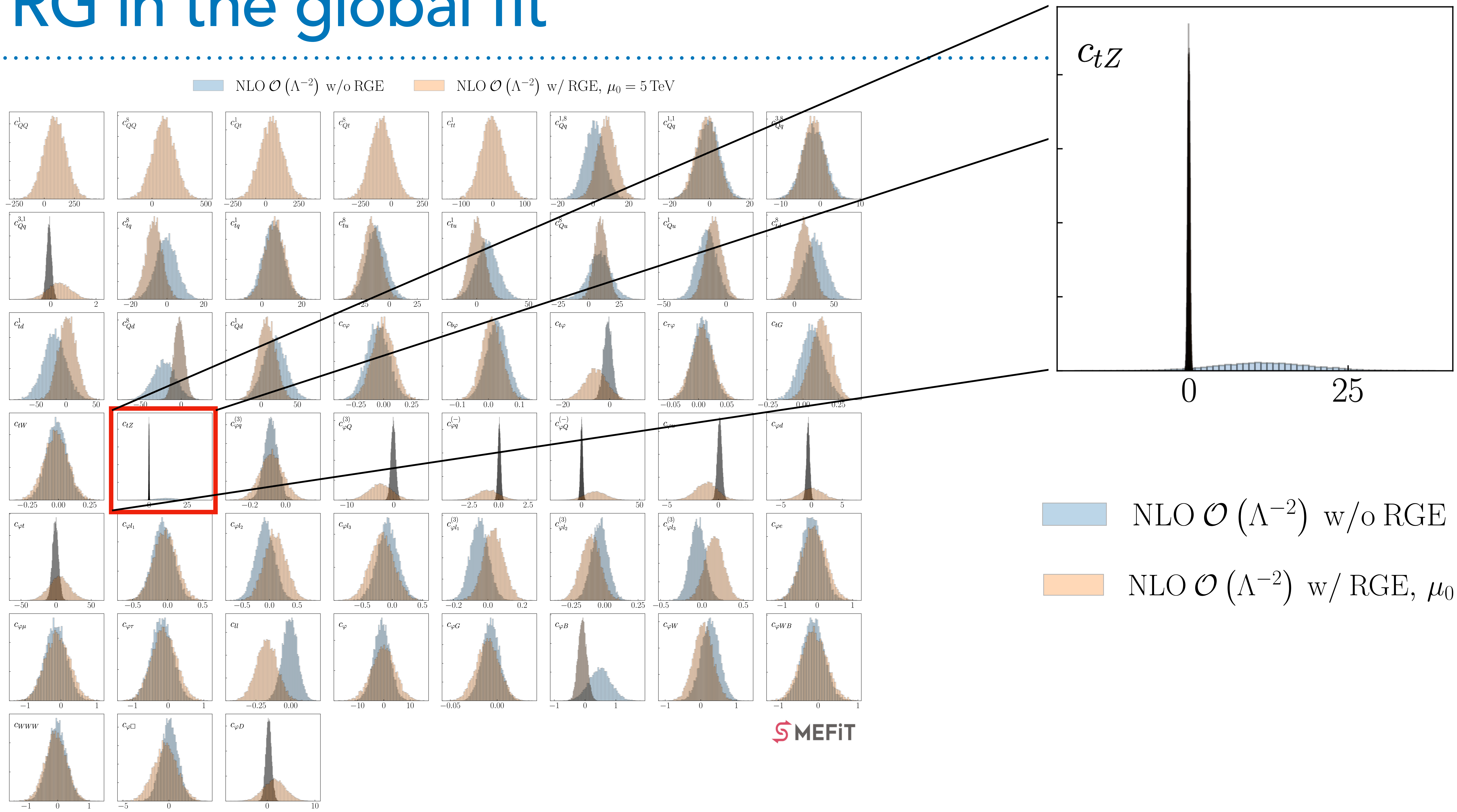
RG in the global fit



NLO $\mathcal{O}\left(\Lambda^{-2}\right)$ w/o RGE

NLO $\mathcal{O}\left(\Lambda^{-2}\right)$ w/ RGE, $\mu_0 = 5\,\text{TeV}$

RG in the global fit

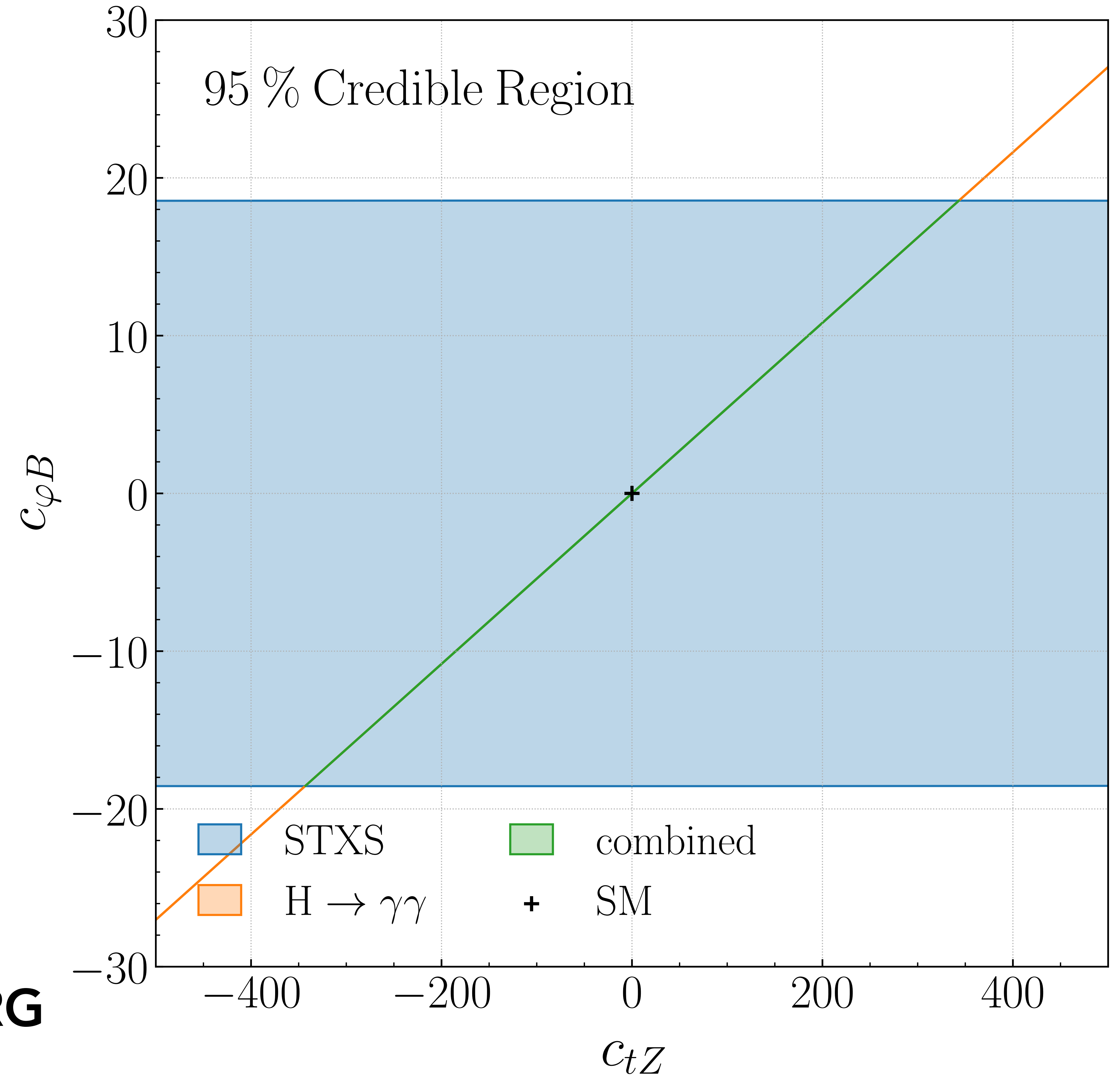


NLO $\mathcal{O}(\Lambda^{-2})$ w/o RGE

NLO $\mathcal{O}(\Lambda^{-2})$ w/ RGE, $\mu_0 = 5\,\text{TeV}$

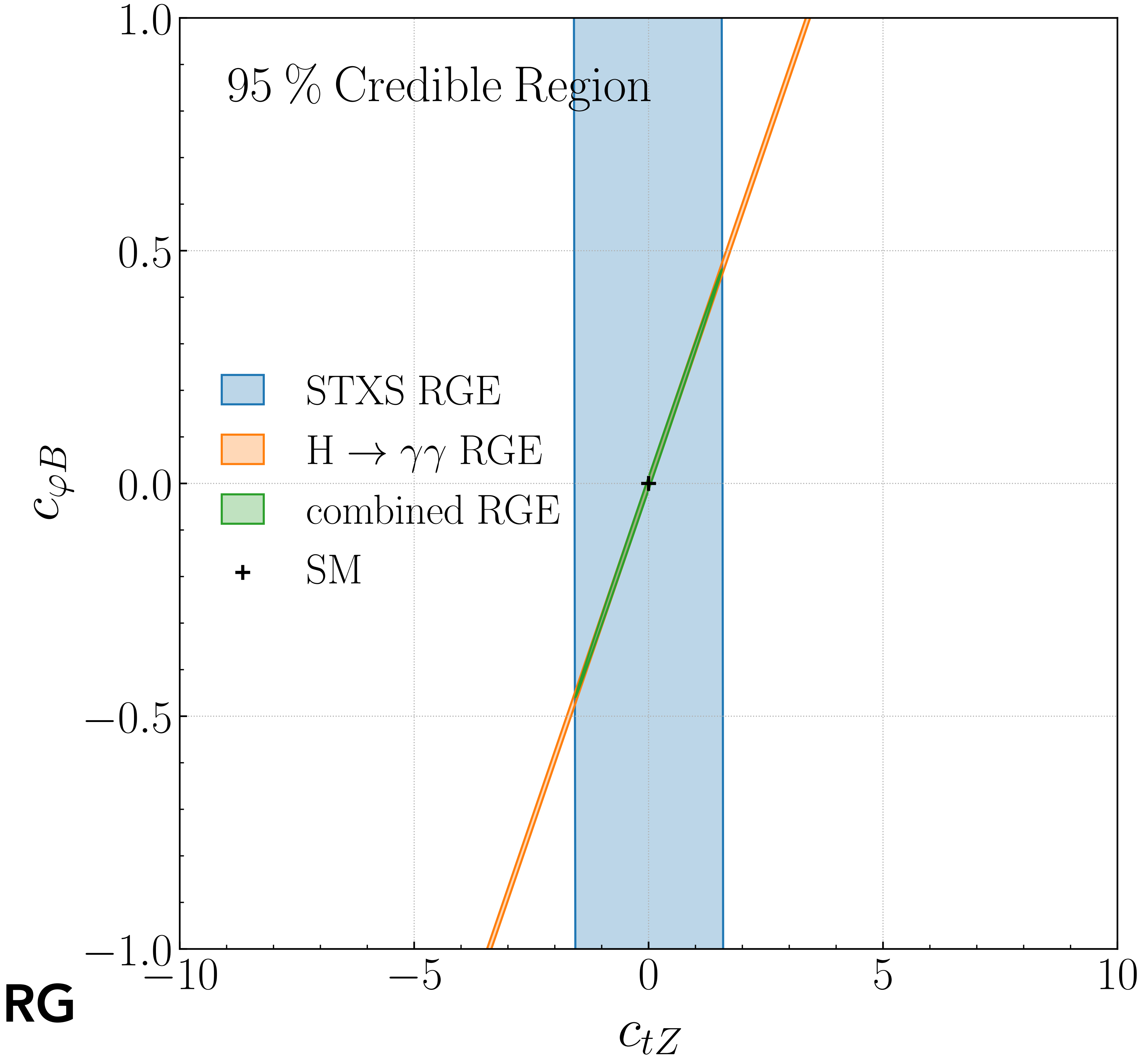
RG in the global fit

Global fits neglecting RGE effects can severely underestimate bounds!



Without RG

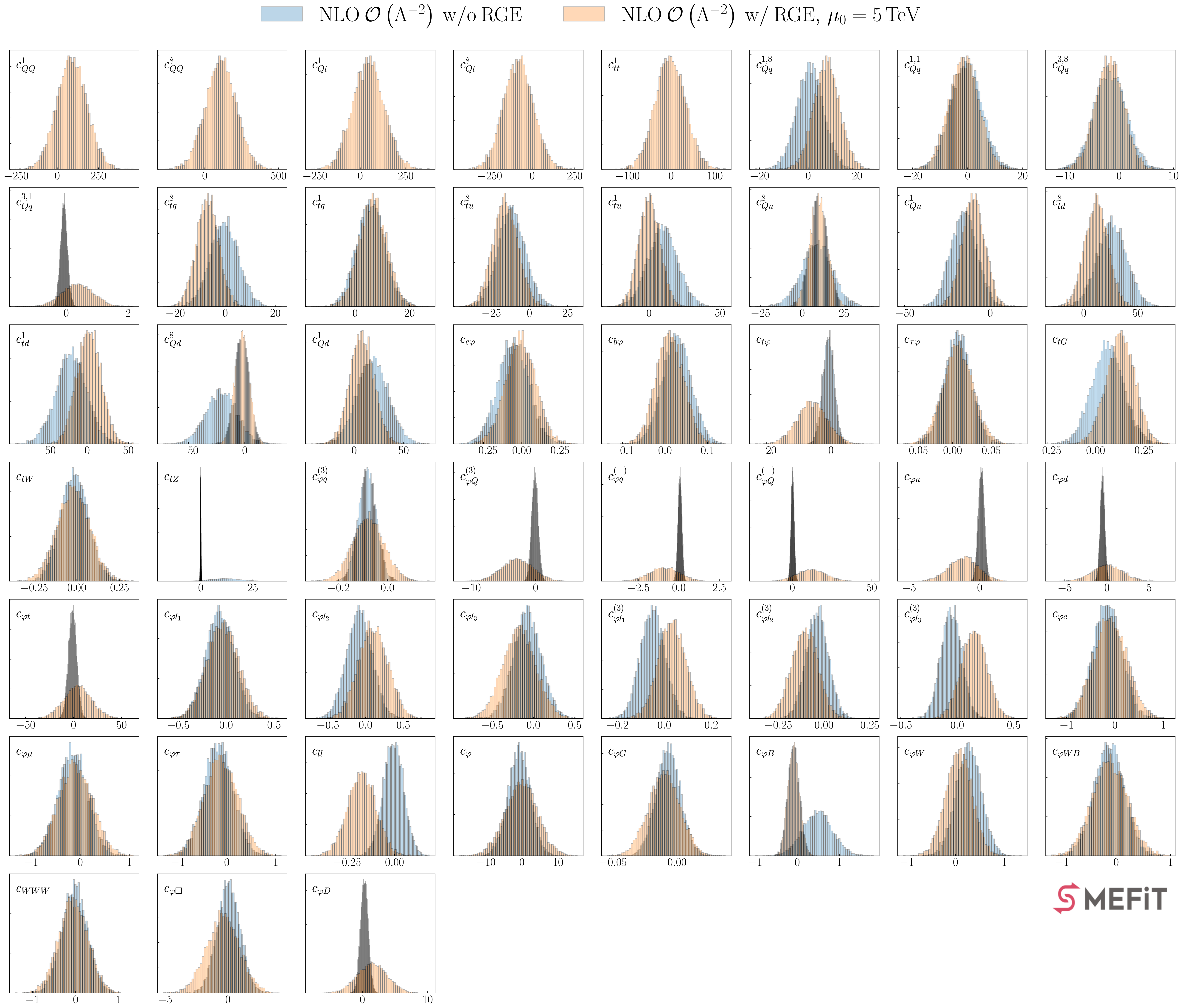
Remains mostly constrained by top



With RG

Also constrained by Higgs through $O_{\varphi B}$ and $O_{\varphi WB}$

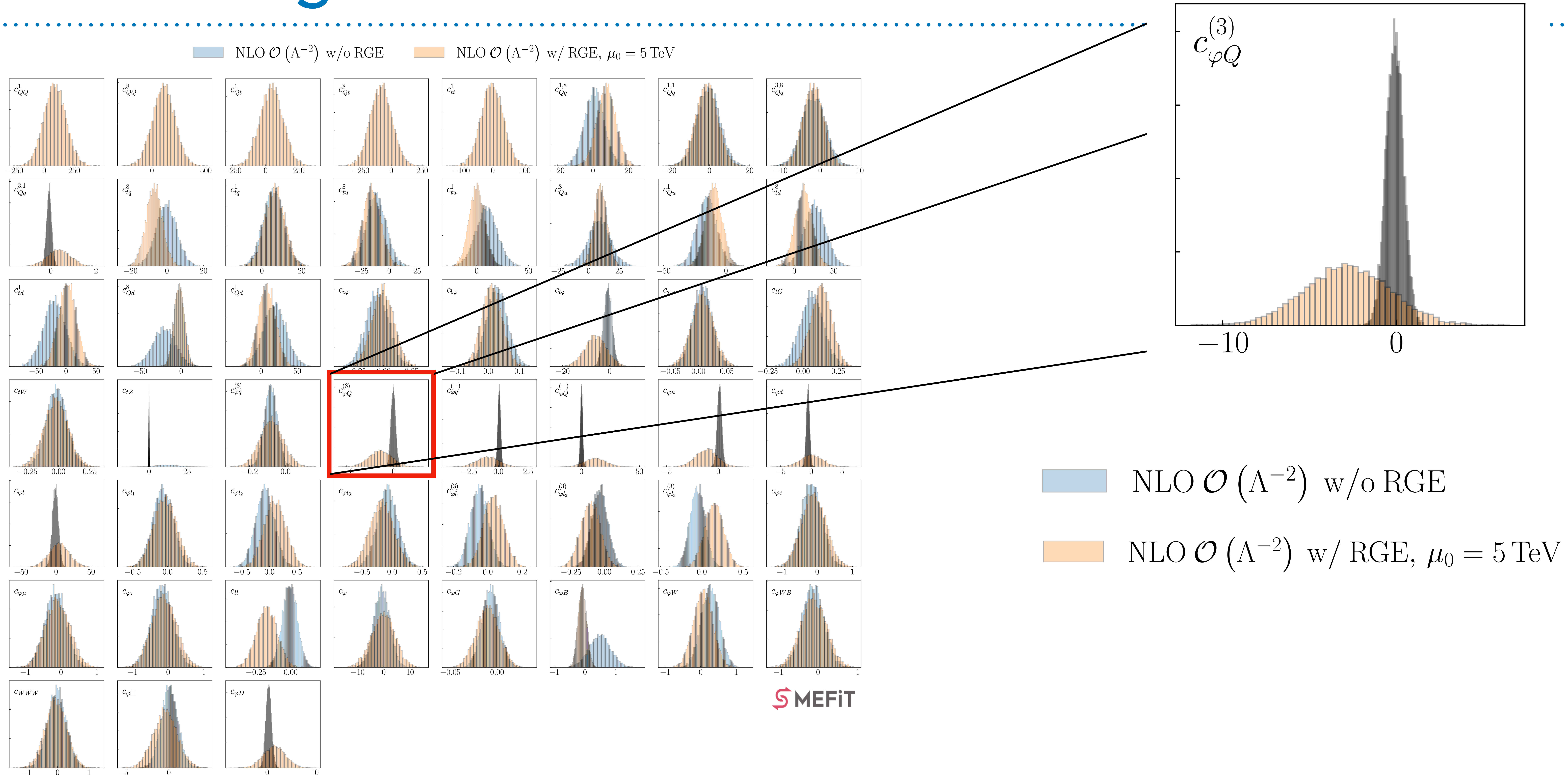
RG in the global fit



NLO $\mathcal{O}\left(\Lambda^{-2}\right)$ w/o RGE

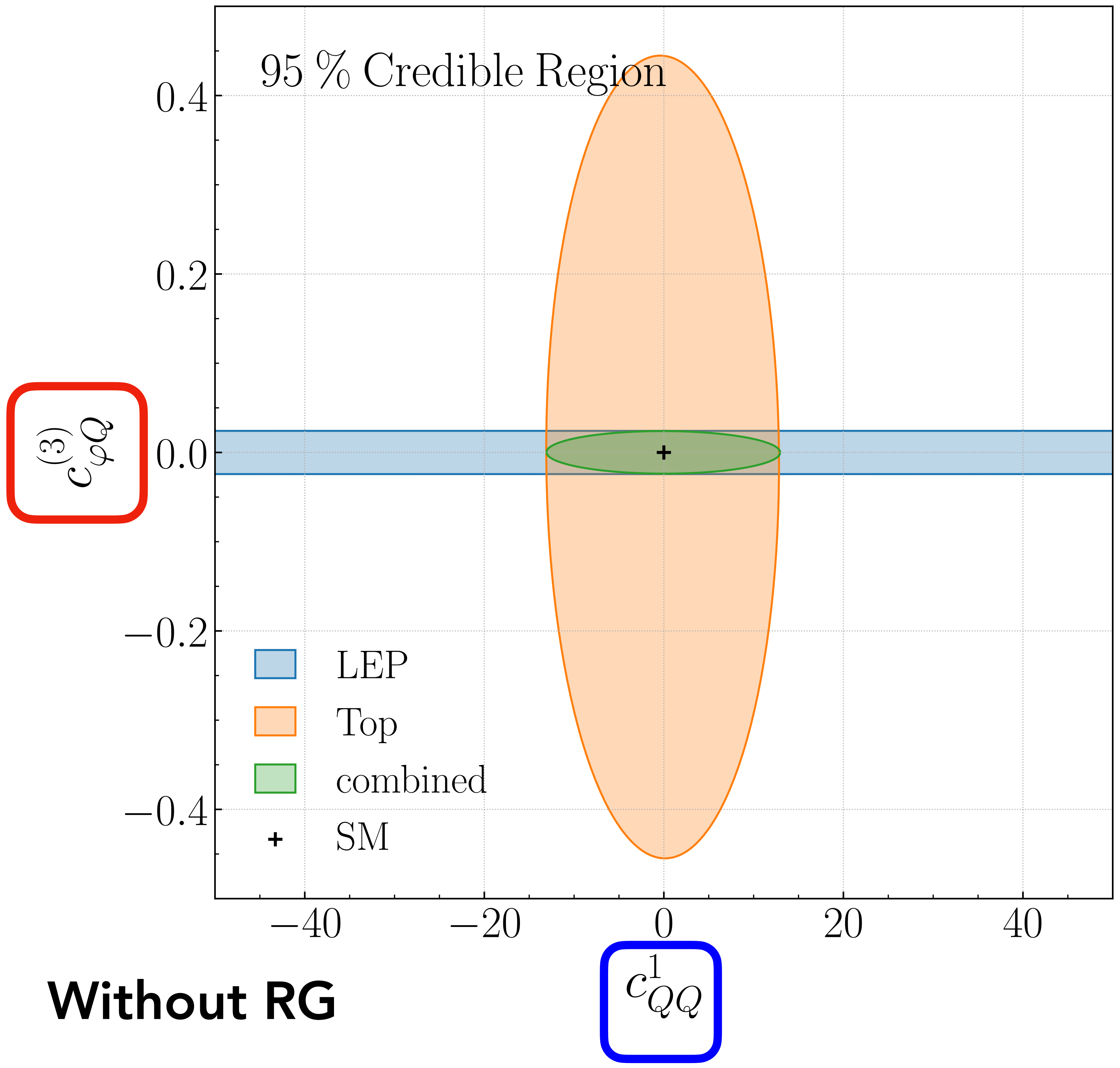
NLO $\mathcal{O}\left(\Lambda^{-2}\right)$ w/ RGE, $\mu_0 = 5\,\text{TeV}$

RG in the global fit

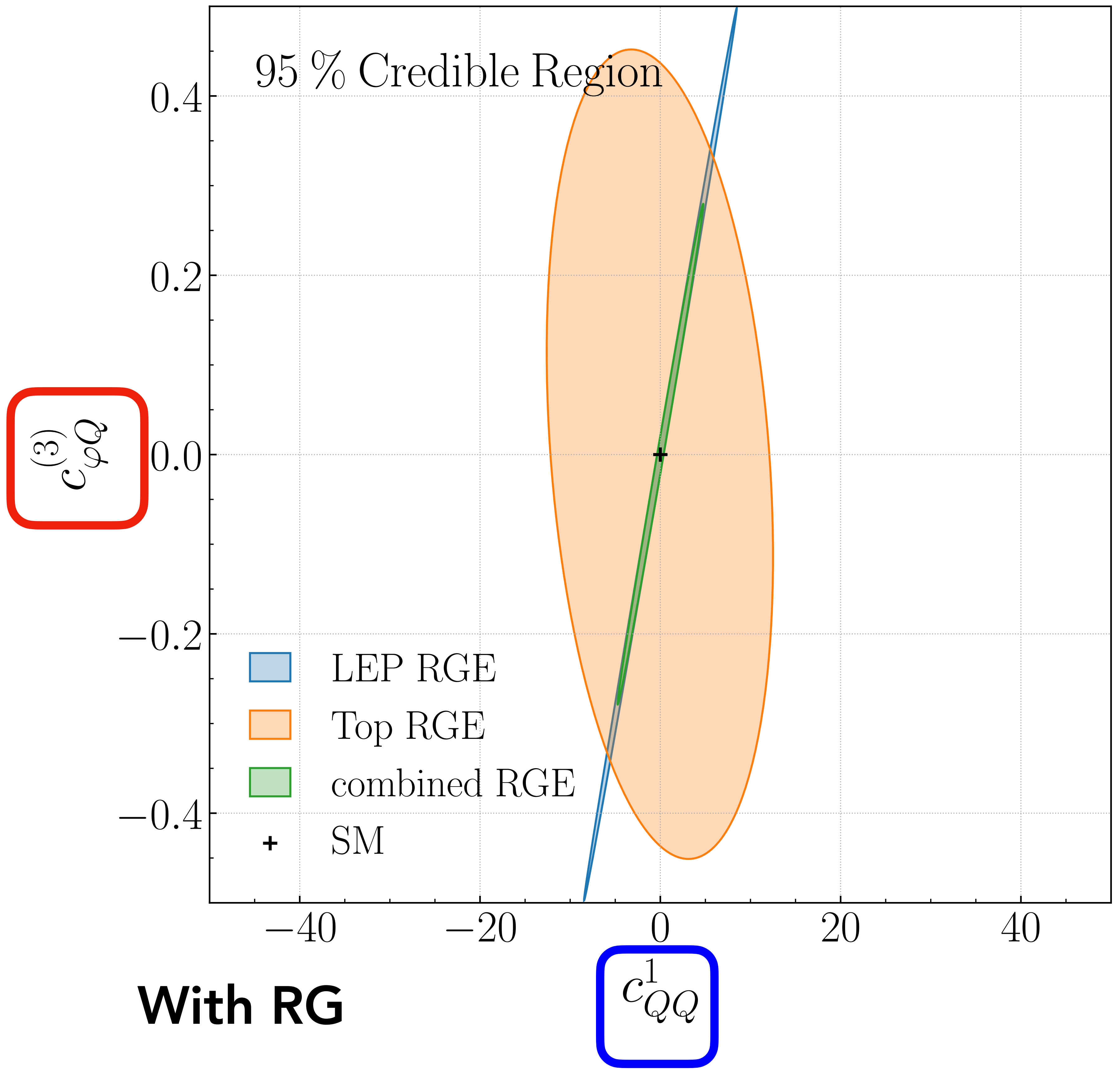


RG in the global fit

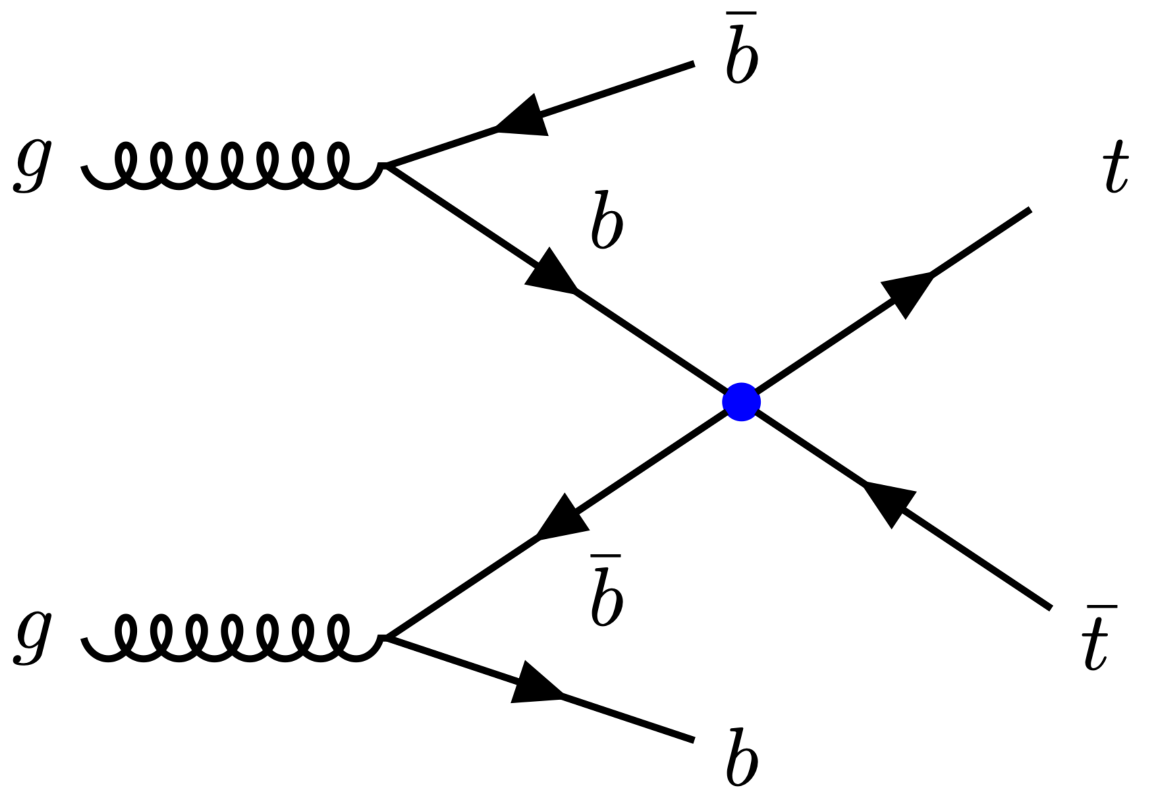
....or severely overestimate bounds!

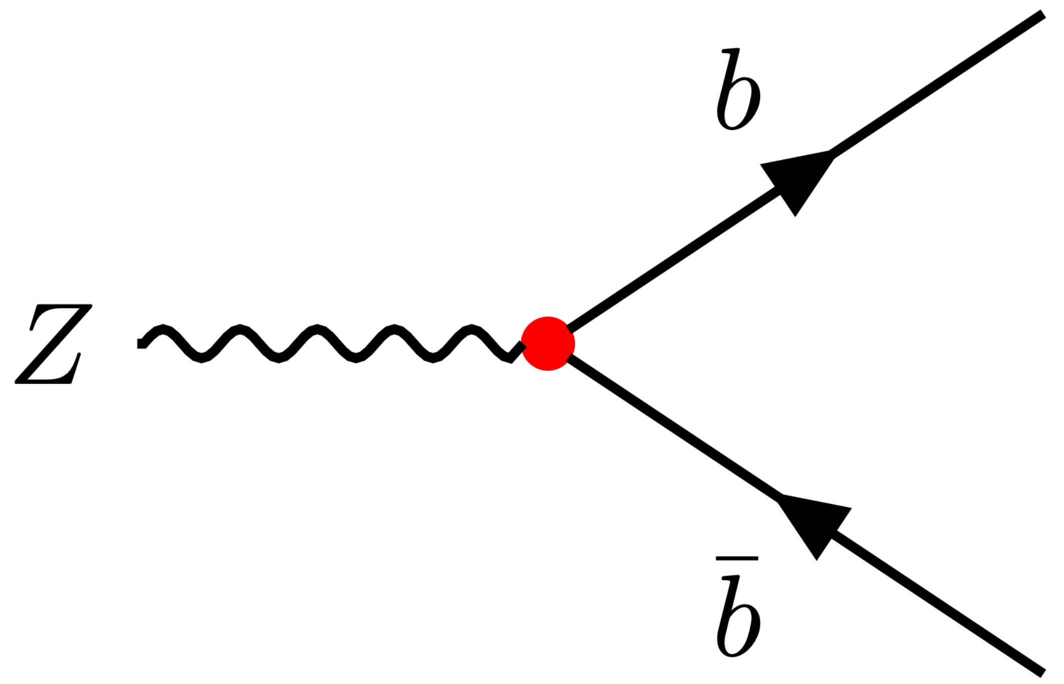


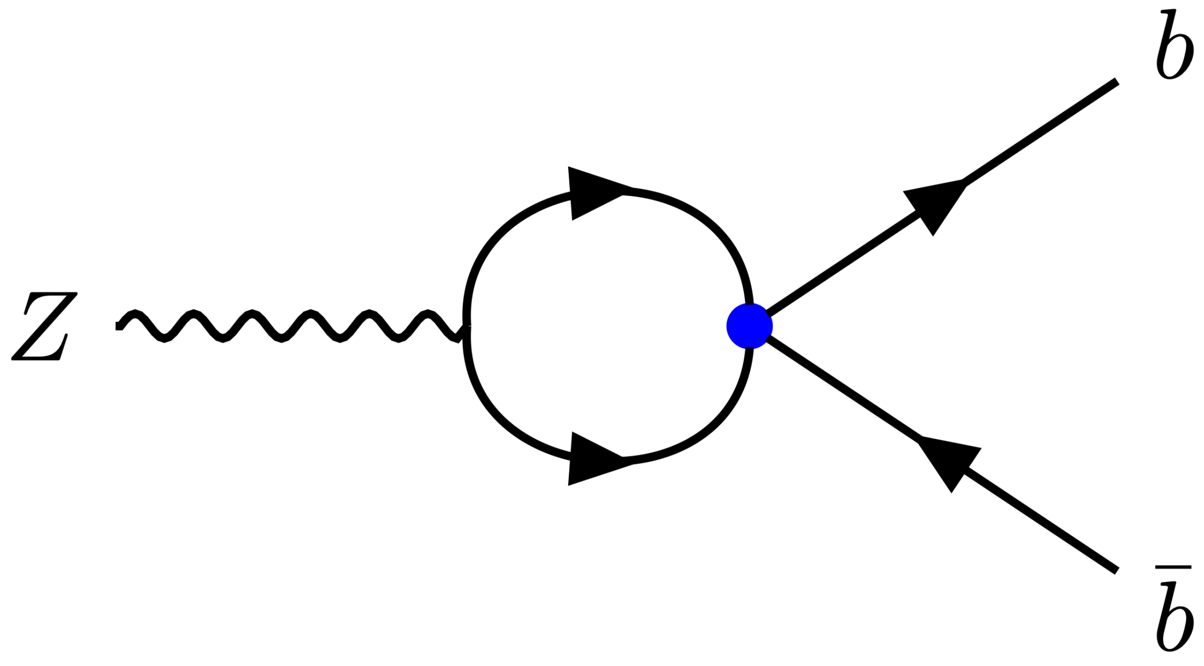
Without RG



With RG

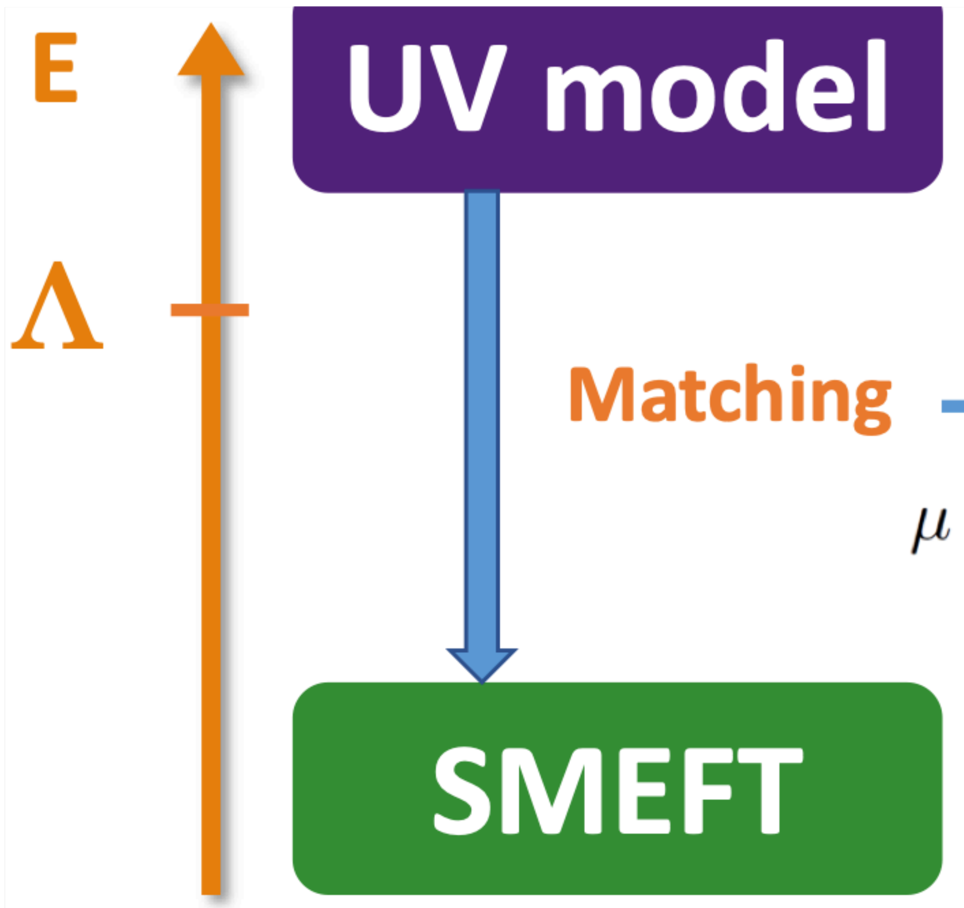






RG effects in UV models

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



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

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

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

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

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

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

Slide from A. Rossia at
SMEFT-tools 2025

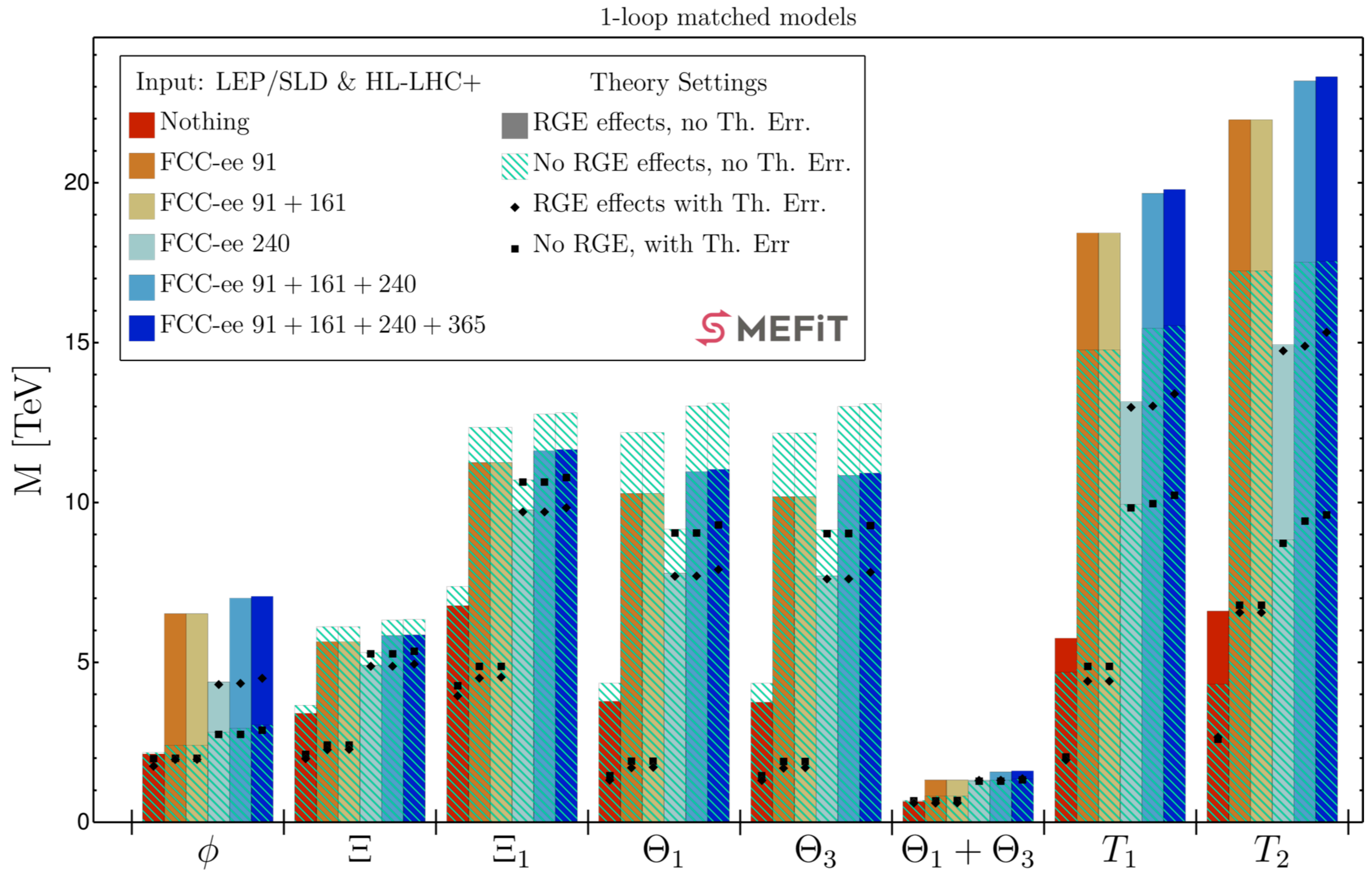
RG effects in UV models

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

RGE effects are **crucial** to harness the power of the FCC-ee to constrain extensions of the SM

Z pole run provides the dominant sensitivity *[2311.00020]*

Reduction of theory uncertainties on EWPO is essential for the FCC-ee

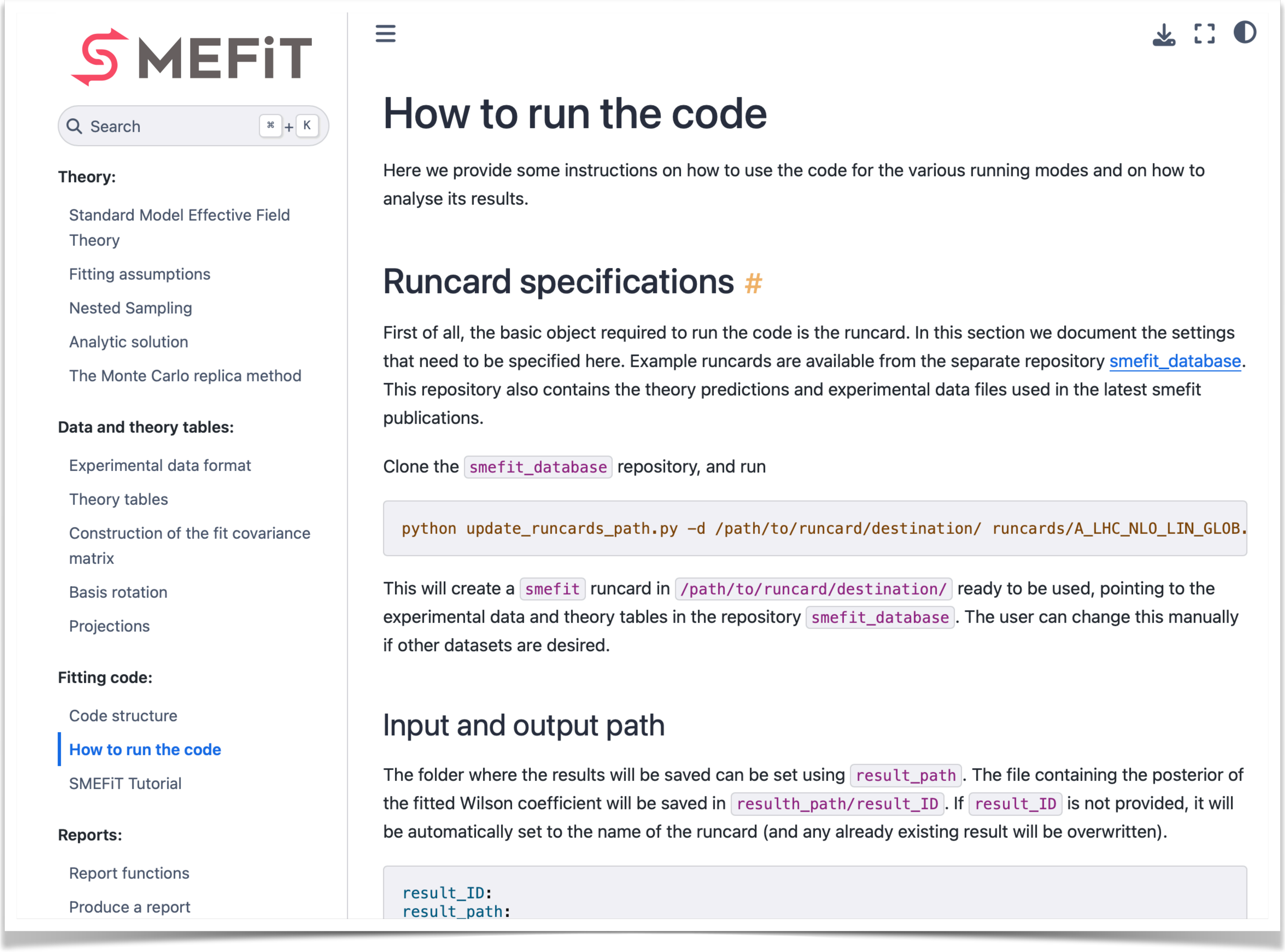


$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + |D_\mu \phi|^2 - m_\phi^2 \phi^\dagger \phi - \Big((y_\phi^e)_{ij}\, \phi^\dagger \bar{e}_R^i \ell_L^j + (y_\phi^d)_{ij}\, \phi^\dagger \bar{d}_R^i q_L^j$$
$$+ (y_\phi^u)_{ij}\, \phi^\dagger i\sigma_2 \bar{q}_L^{T,i} u_R^j + \lambda_\phi\, \phi^\dagger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

Open source

- Everything is **fully public**, including
  - Our EFT theory predictions
  - Dataset implementation
  - Code

smefit.science


SMEFiT

Search ⌘ + K

Theory:

Standard Model Effective Field Theory

Fitting assumptions

Nested Sampling

Analytic solution

The Monte Carlo replica method

Data and theory tables:

Experimental data format

Theory tables

Construction of the fit covariance matrix

Basis rotation

Projections

Fitting code:

Code structure

How to run the code

SMEFiT Tutorial

Reports:

Report functions

Produce a report

How to run the code

Here we provide some instructions on how to use the code for the various running modes and on how to analyse its results.

Runcard specifications

First of all, the basic object required to run the code is the runcard. In this section we document the settings that need to be specified here. Example runcards are available from the separate repository smefit_database. This repository also contains the theory predictions and experimental data files used in the latest smefit publications.

Clone the `smefit_database` repository, and run

```
python update_runcards_path.py -d /path/to/runcard/destination/ runcards/A_LHC_NLO_LIN_GLOB.
```

This will create a `smefit` runcard in `/path/to/runcard/destination/` ready to be used, pointing to the experimental data and theory tables in the repository `smefit_database`. The user can change this manually if other datasets are desired.

Input and output path

The folder where the results will be saved can be set using `result_path`. The file containing the posterior of the fitted Wilson coefficient will be saved in `resulth_path/result_ID`. If `result_ID` is not provided, it will be automatically set to the name of the runcard (and any already existing result will be overwritten).

```
result_ID:
result_path:
```

Summary and conclusion

- The SMEFT provides a convenient tool to search for new physics in a model agnostic way
- The impact of RGE effects on the SMEFT parameter space is essential to include in order to connect disparate energy scales
- RG effects drastically change the game for UV models, improving indirect bounds by several TeV

Summary and conclusion

- The SMEFT provides a convenient tool to search for new physics in a model agnostic way
- The impact of RGE effects on the SMEFT parameter space is essential to include in order to connect disparate energy scales
- RG effects drastically change the game for UV models, improving indirect bounds by several TeV

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

Backup

Dataset upgrade

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

Category	Processes	$n_{\rm dat}$ SMEFiT2.0	$n_{\rm dat}$ 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**

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