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

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Alejo N. Rossia

Dipartimento di Fisica e Astronomia, Università degli Studi di Padova

Instituto Nazionale di Fisica Nucleare INFN Sezione di Padova

Based on:

[2502.20453] JHEP06 (2025) 125 Connecting Scales: RGE Effects in the SMEFT at the LHC and Future Colliders (w/ J. ter Hoeve, L. Mantani, J. Rojo, and E. Vryonidou)

[2504.05974] The Higgs Trilinear coupling in the SMEFT at the HL-LHC and the FCC-ee (w/ J. ter Hoeve, L. Mantani, J. Rojo, and E. Vryonidou)

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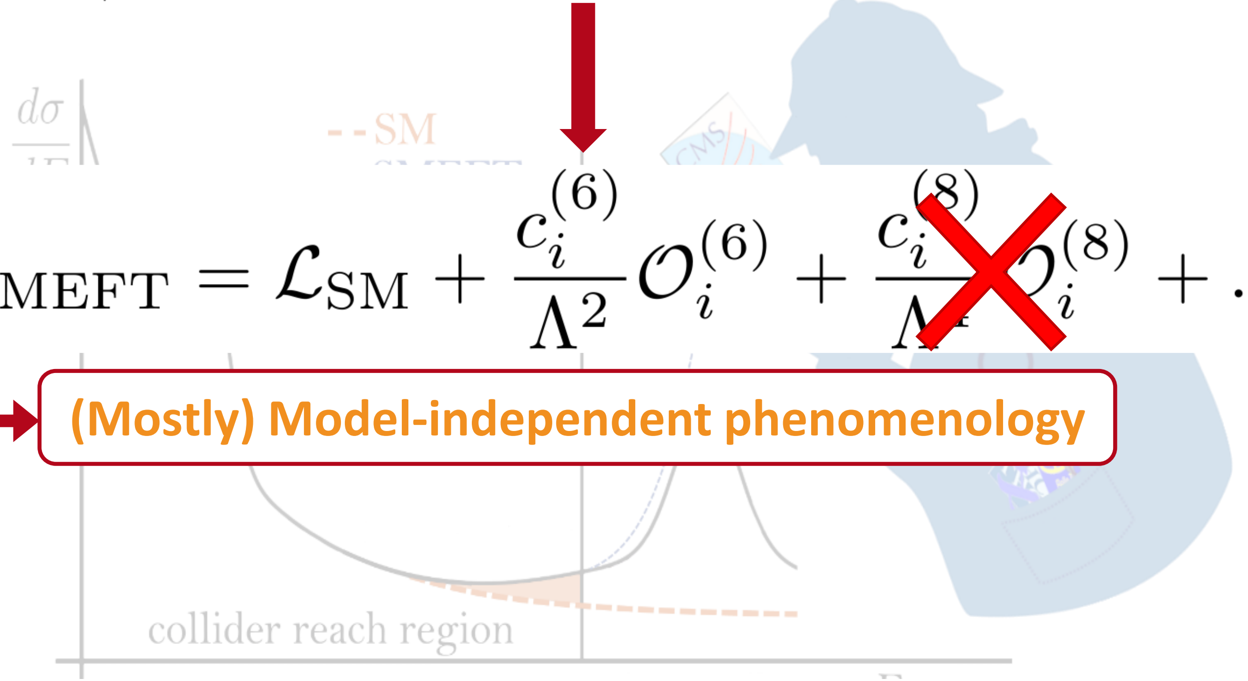
EFT approach to BSM physics

E

$$\psi_{UV} = ? \quad \mathcal{L}_{UV} = ? \quad G_{UV} = ?$$



Λ

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)} + \cancel{\frac{c_i^{(8)}}{\Lambda^4}\mathcal{O}_i^{(8)}} + \dots$$

(Mostly) Model-independent phenomenology

RGE Effects

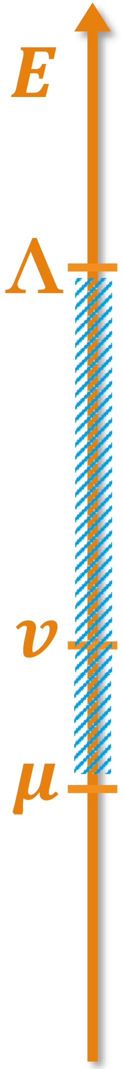
v

$$\sigma = |\mathcal{M}_{SM}|^2 + 2\text{Re}\left(\mathcal{M}_{SM}\mathcal{M}^*_{BSM}\right) + |\mathcal{M}_{BSM}|^2$$

$$\propto \mathcal{C}_i^{(6)}/\Lambda^2 \qquad \propto \left(\mathcal{C}_i^{(6)}/\Lambda^2\right)^2$$

The Renormalization Group Equations (RGEs)

RGE evolution improves perturbative convergence across scale gaps



$$c_i\left(\Lambda\right)$$

$$\left\{c_1\left(\mu\right),\ldots,c_i\left(\mu\right),\ldots,c_n\left(\mu\right)\right\}$$

$$\mathcal{M}\left(\mu\right)=\mathcal{M}_{\mathrm{SM}}\left(\mu\right)+\frac{c_i\left(\mu\right)}{\Lambda^2}\mathcal{M}^i_{1/\Lambda^2}\left(\mu\right)$$

Known fully at 1-loop order

Jenkins, Manohar, Trott, Alonso [1308.2627] [1310.4838] [1312.2014]

$$\frac{dc_i\left(\mu\right)}{d\log\left(\mu\right)}=\sum_j \gamma^{(6)}_{ij}\left(\bar{g}\right)\,c_j\left(\mu\right)$$

- Operator mixing
- Observable scale dependence
- Resums logarithms

SMEFiT In a nutshell

v. 2.0: Giani et al [2302.06660]
v. 3.0: Celada, ANR et al [2404.12809]

A Python software for global interpretation of particle physics data in SMEFT

THEORY

SM: (N)NLO QCD + NLO EW
SMEFT: NLO QCD, quadratic in WCs
56 WCs + 1-loop SMEFT RGEs!

+ wilson
Aebischer, et al [1804.05033]

DATA

LEP+SLD: EWPOs, WW, BrW…
LHC: Higgs, top, VV... Mostly Run-2
446 data points!
HL-LHC, CEPC and FCCee projections

UV models

Matched to SMEFT up to 1-loop

+ match2fit
Carmona, et al [2112.10787]
ter Hoeve, ANR, et al [2309.04523]

SMEFiT

METHOD

Bayesian **Nested Sampling**

TOOLS

PCA, Fisher, closure tests, documentation.

$$p\left(c_i|D\right)$$

Posterior on WCs

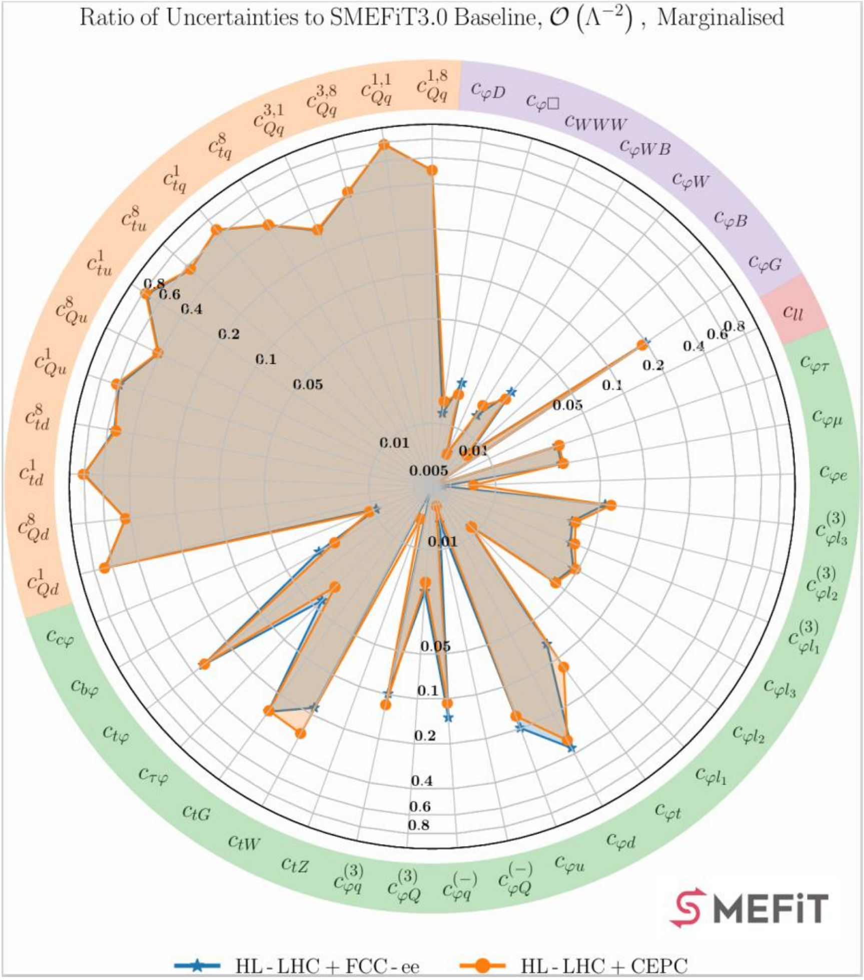
For more, see E. Celada's talk on Wednesday

CEPC vs FCCee

CEPC and FCCee give qualitatively equal results

(based on Snowmass and FCC Mid-Term Feas. Rep.)

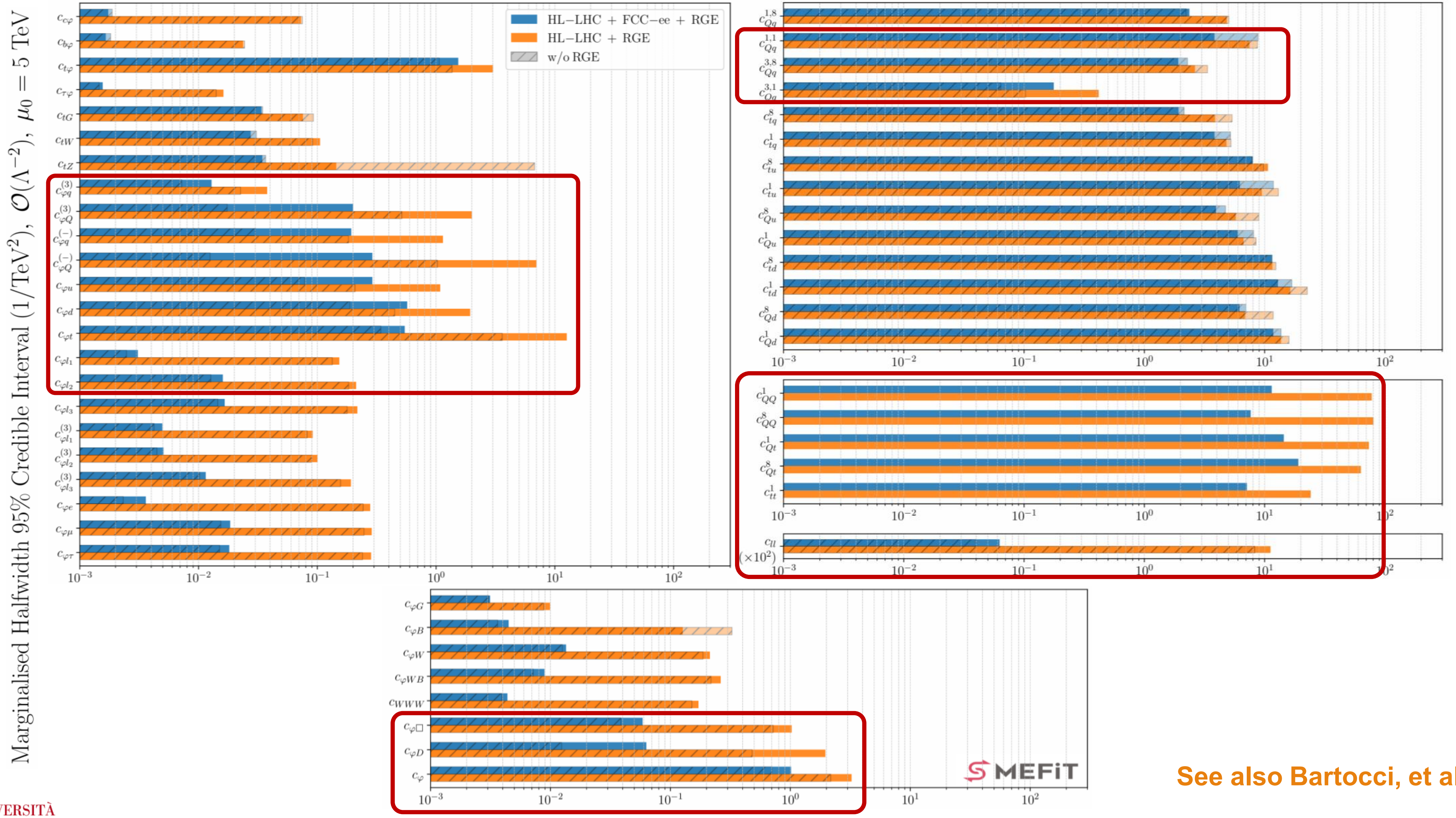
Energy ($\sqrt{s}$)	$\mathcal{L}_{\text{int}}$ (Run time) FCC-ee (4 IPs)	CEPC (2 IPs)
91 GeV (Z-pole)	300 ab^{-1} (4 years)	100 ab^{-1} (2 years)
161 GeV ($2\,m_W$)	20 ab^{-1} (2 years)	6 ab^{-1} (1 year)
240 GeV	10 ab^{-1} (3 years)	20 ab^{-1} (10 years)
350 GeV	0.4 ab^{-1} (1 year)	0.2 ab^{-1}
365 GeV ($2\,m_t$)	3 ab^{-1} (4 years)	1 ab^{-1} (5 years)



For details, see E. Celada's talk on Wednesday

Celada, ANR, et al [2404.12809]

RGE effects in the linear fit

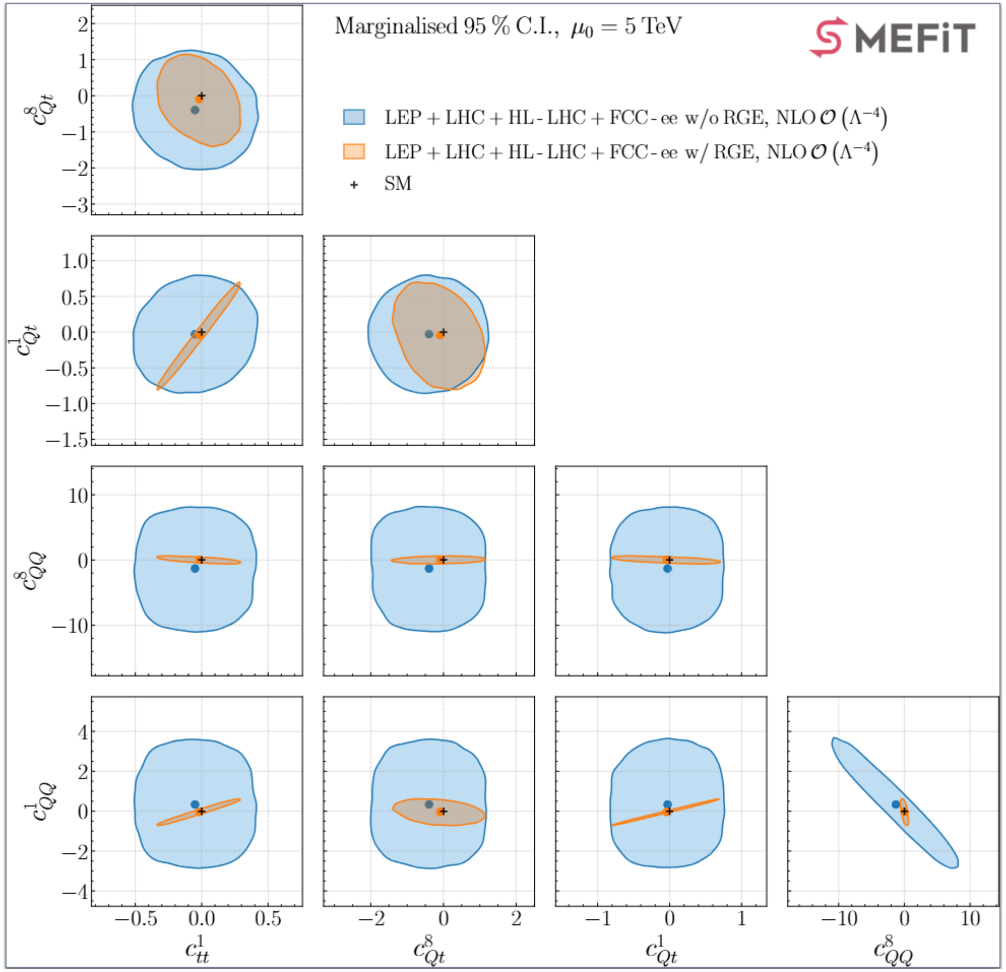


See also Bartocci, et al [2412.09674]

Milder effects in the quadratic fit

Effects on operator subsets

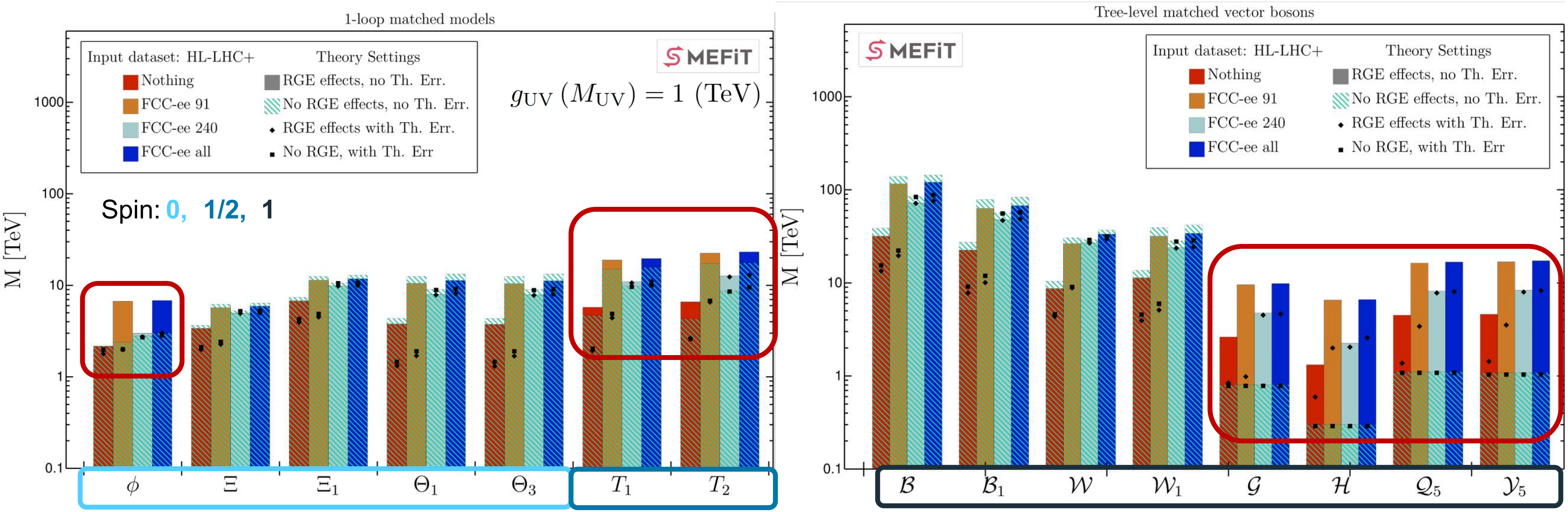
Enhanced effects in fits to small subsets of operators…



…so what will happen with UV-complete models?

Impact on UV-complete toy models

Large effects for models that interact with the top quark

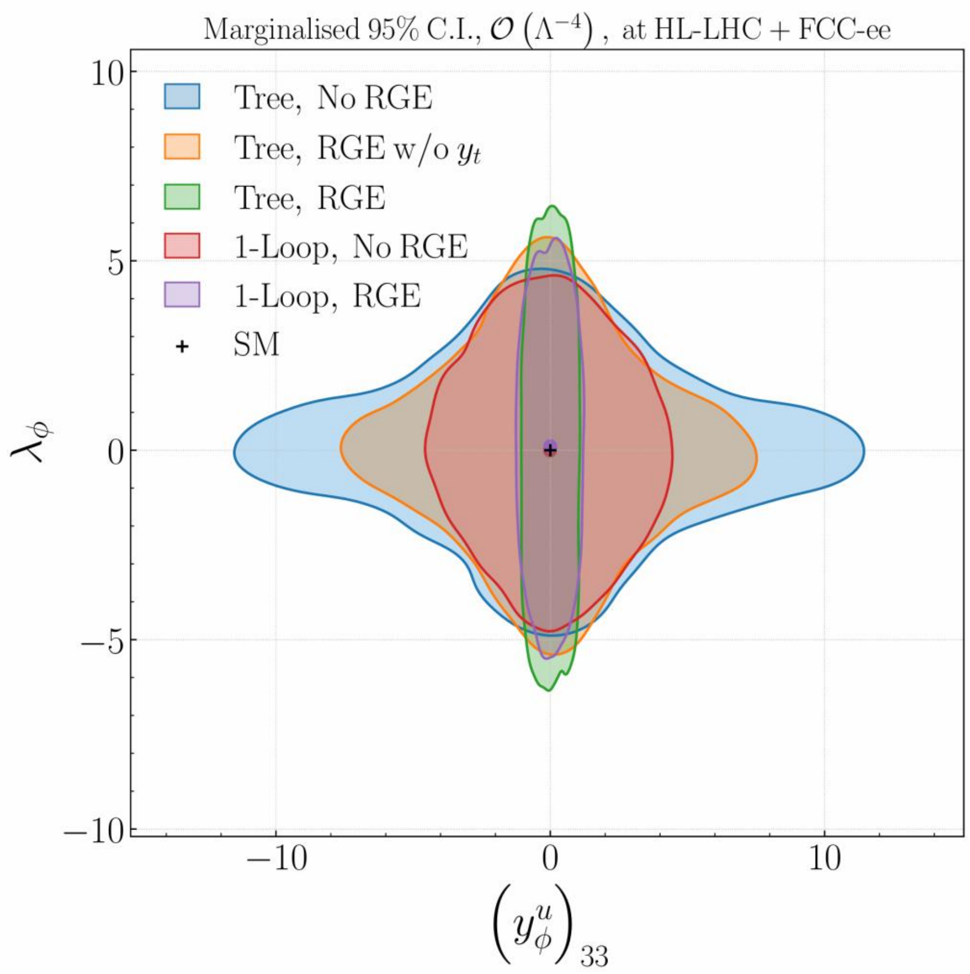


Theoretical uncertainties on the Z-pole have a huge impact

Impact on UV-complete toy models

The top Yukawa running can be very important

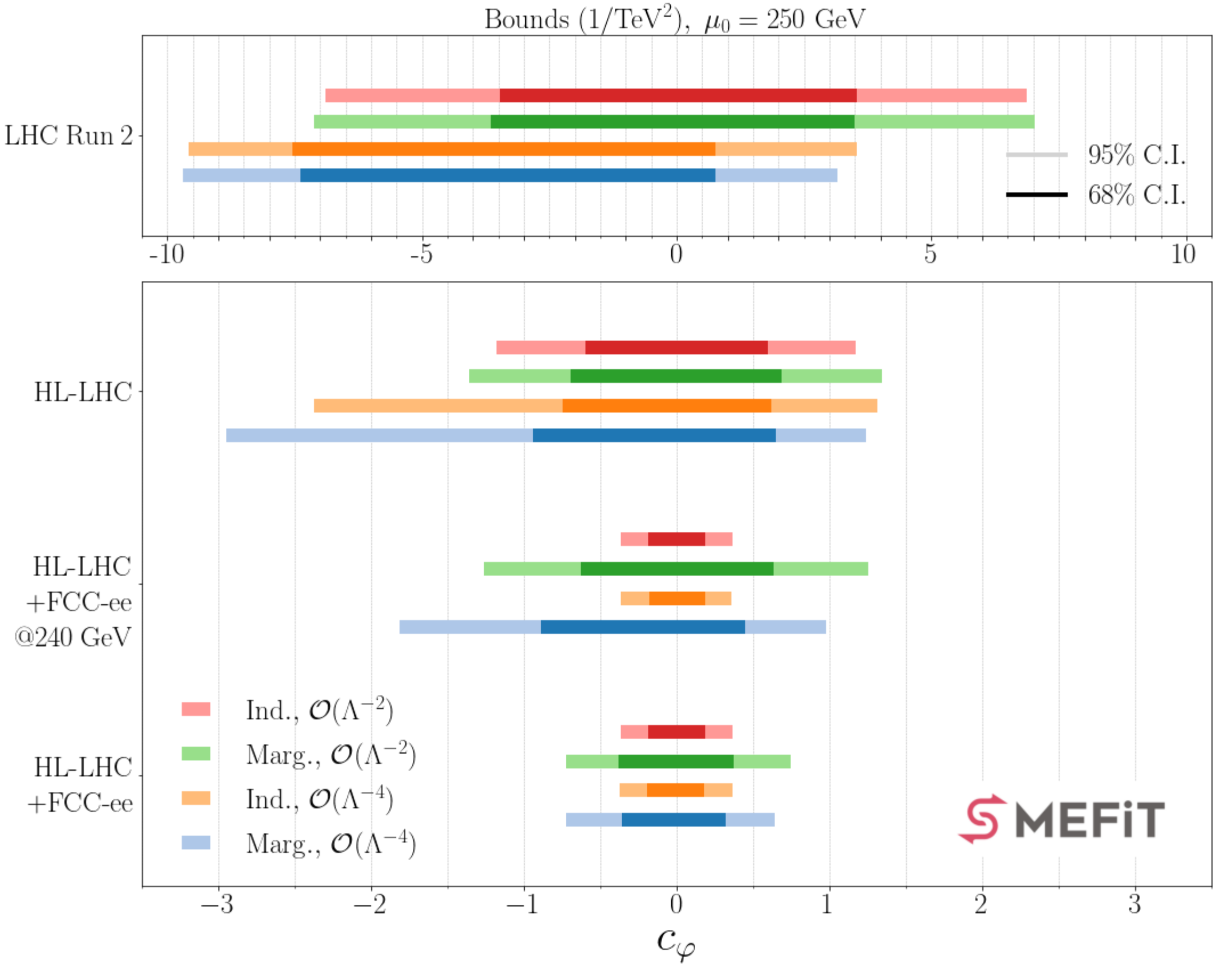
$$\mathcal{L}_{\text{UV}} \supset -\left(y_\phi^u\right)_{33} \phi^\dagger i\sigma_2 \bar{q}_L^{T,3} u_R^3 - \lambda_\phi \phi^\dagger H |H|^2 + \text{h.c.}$$
$$M_\phi = 8\,\text{TeV}$$

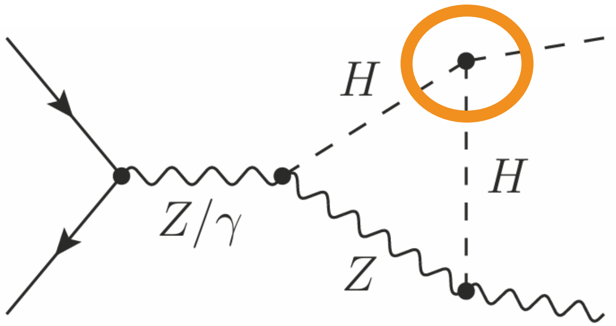


Bonus: The Higgs trilinear coupling

FCCee/CEPC could improve significantly on HL-LHC

$$\mathcal{O}_\varphi = \left(\varphi^\dagger\varphi - \frac{v^2}{2}\right)^3 \supset v^3h^3 + \frac{3}{2}v^2h^4$$





Asteriadis, et al [2409.11466]

Conclusions

- The inclusion of RGE effects is key to seize on the advantages of using (SM)EFTs.
- Crucial for low-energy lepton colliders exploring heavy New Physics.
- We included the full effects of 1-loop RGEs.
- Larger RGE effects in linear fits and with restricted operator sets.
- Quadratic global fits yield milder RGE effects.
- Simple UV-complete models of colored particles show large RGE effects.
- Z-pole theory uncertainties seriously harm our sensitivity to NP.
- FCC-ee (CEPC?) offers great sensitivity to the Higgs self-coupling with the price of correlations.

Thank you for your attention!

Alejo N. Rossia
Theoretical Physics at the Energy Frontier Group
Dipartimento di Fisica e Astronomia “Galileo Galilei”
Università degli Studi di Padova
E-mail: alejonahuel dot rossia at unipd dot it
http://www.dfa.unipd.it/

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Appendix

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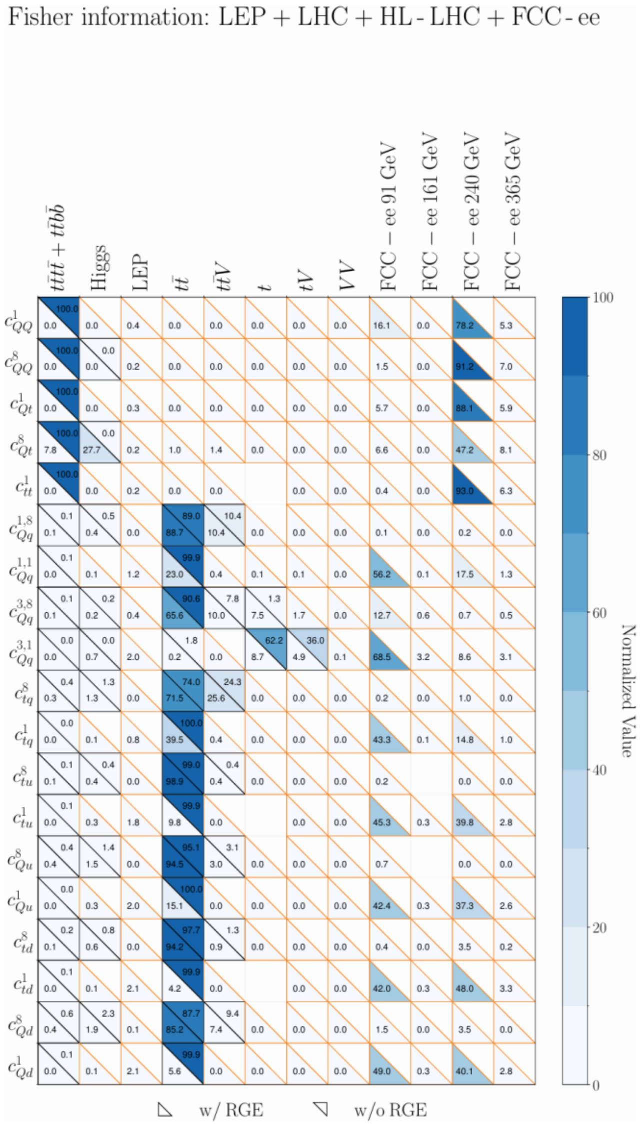
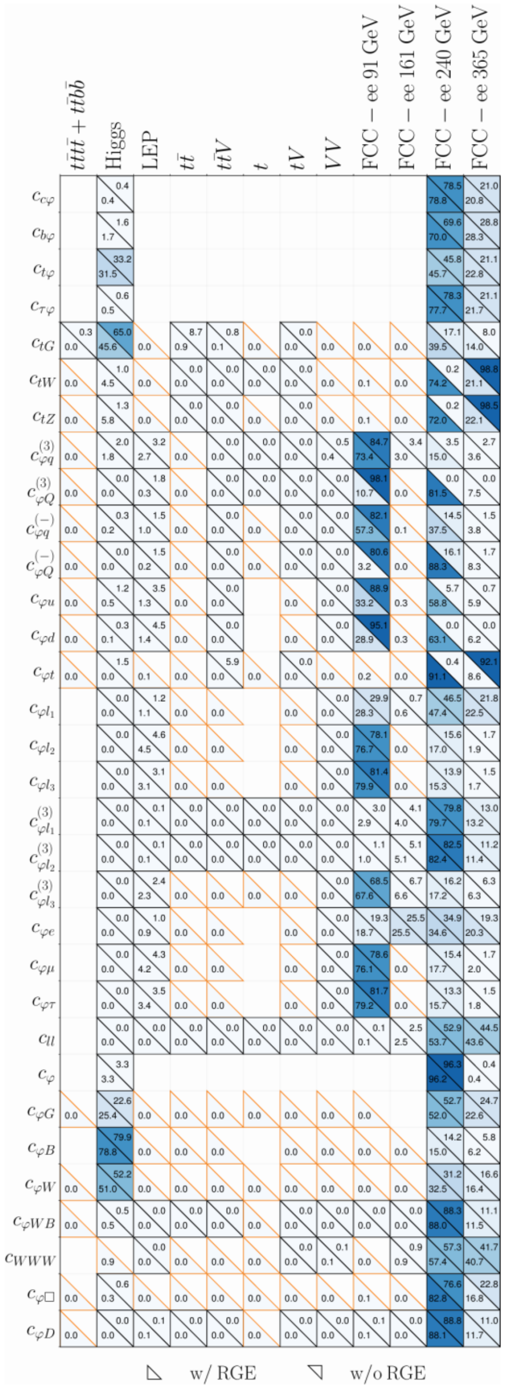
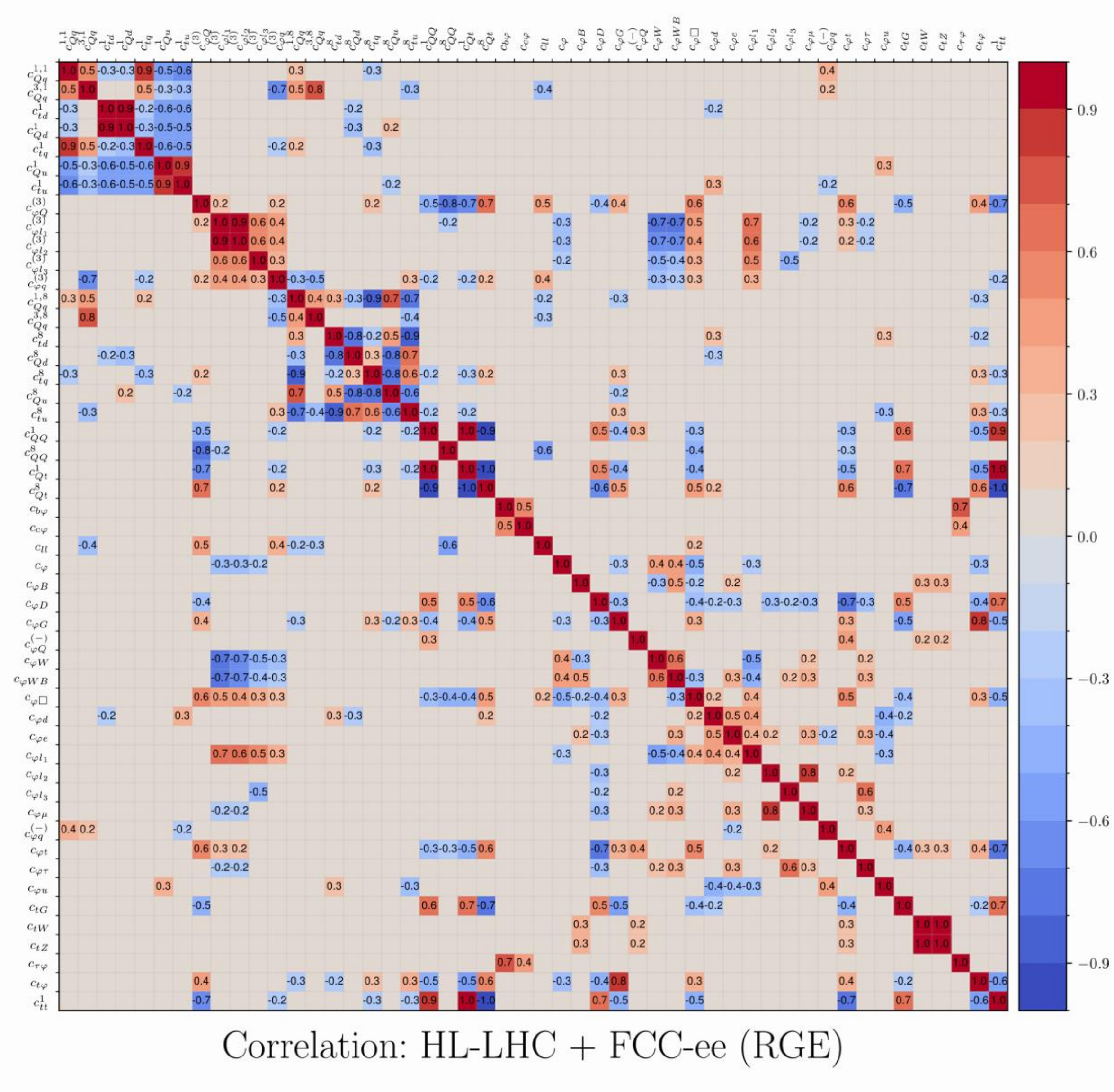
Fisher Information Matrix





Correlation matrix



Fitted operators

Operator	Coefficient
$\mathcal{O}_{\varphi G}$	$c_{\varphi G}$
$\mathcal{O}_{\varphi B}$	$c_{\varphi B}$
$\mathcal{O}_{\varphi W}$	$c_{\varphi W}$
$\mathcal{O}_{\varphi WB}$	$c_{\varphi WB}$
$\mathcal{O}_{\varphi\Box}$	$c_{\varphi\Box}$
$\mathcal{O}_{\varphi D}$	$c_{\varphi D}$
$\mathcal{O}_{W}$	c_{WWW}

$\mathcal{O}_{\varphi Q}^{(1)}$	$c_{\varphi Q}^{(1)}$ (*)
$\mathcal{O}_{\varphi Q}^{(3)}$	$c_{\varphi Q}^{(3)}$
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$
$\mathcal{O}_{\varphi q}^{(1)}$	$c_{\varphi q}^{(1)}$ (*)
$\mathcal{O}_{\varphi q}^{(3)}$	$c_{\varphi q}^{(3)}$
$\mathcal{O}_{\varphi u}$	$c_{\varphi u}$

$\mathcal{O}_{tW}$	c_{tW}
$\mathcal{O}_{tB}$	c_{tB} (*)
$\mathcal{O}_{tG}$	c_{tG}
$\mathcal{O}_{b\varphi}$	$c_{b\varphi}$
ation quarks	
$\mathcal{O}_{\varphi d}$	$c_{\varphi d}$
$\mathcal{O}_{c\varphi}$	$c_{c\varphi}$

$\mathcal{O}_{\varphi \ell_i}$	$c_{\varphi \ell_i}$
$\mathcal{O}_{\varphi \ell_i}^{(3)}$	$c_{\varphi \ell_i}^{(3)}$
$\mathcal{O}_{\varphi e}$	$c_{\varphi e}$
$\mathcal{O}_{\ell\ell}$	$c_{\ell\ell}$

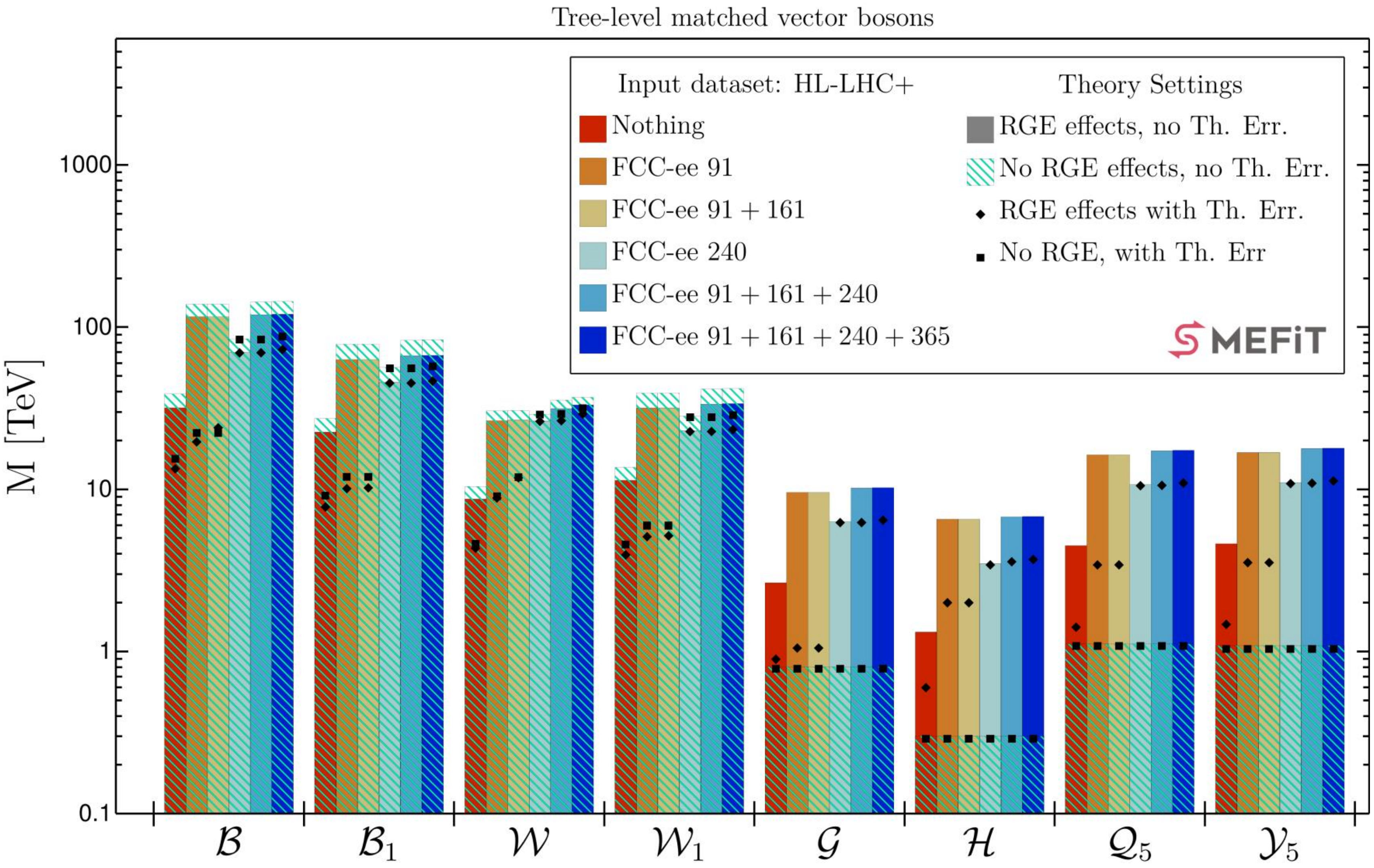
$\mathcal{O}_{\varphi\mu}$	$c_{\varphi\mu}$
$\mathcal{O}_{\varphi\tau}$	$c_{\varphi\tau}$
$\mathcal{O}_{\tau\varphi}$	$c_{\tau\varphi}$

$c_{\varphi Q}^{(-)}$	$c_{\varphi Q}^{(1)} - c_{\varphi Q}^{(3)}$
c_{tZ}	$-s_\theta\, c_{tB} + c_\theta\, c_{tW}$
$c_{\varphi q}^{(-)}$	$c_{\varphi q}^{(1)} - c_{\varphi q}^{(3)}$

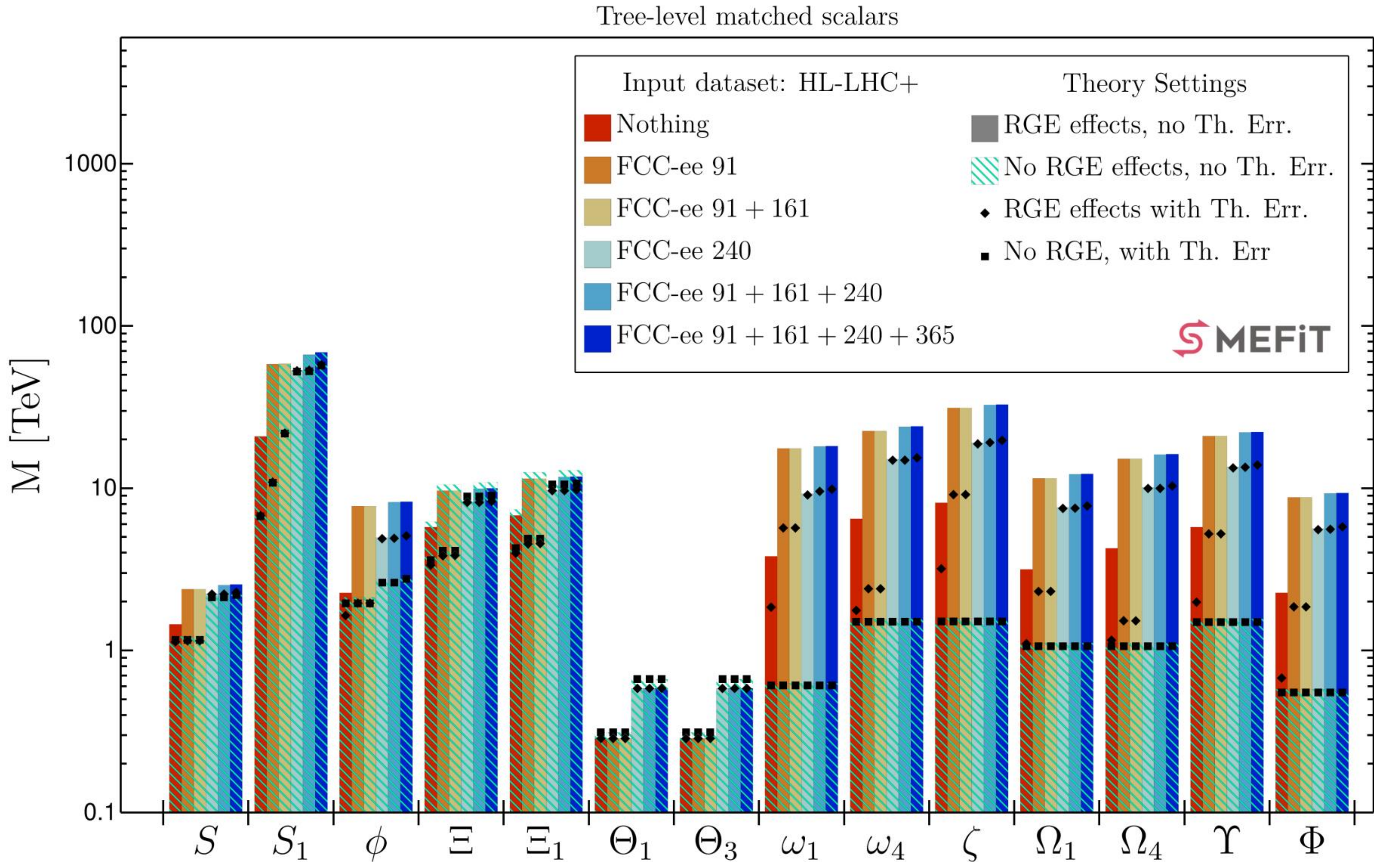
$$\mathcal{O}_{te},\ \mathcal{O}_{t\ell},\ \mathcal{O}_{Qe},\ \mathcal{O}_{Q\ell}^{(-)};\ \mathcal{O}_{\varphi}$$

c_{QQ}^{1}	$2c_{qq}^{1(3333)} - \frac{2}{3}c_{qq}^{3(3333)}$	c_{QQ}^{8}	$8c_{qq}^{3(3333)}$
c_{Qt}^{1}	$c_{qu}^{1(3333)}$	c_{Qt}^{8}	$c_{qu}^{8(3333)}$
$c_{Qq}^{1,8}$	$c_{qq}^{1(i33i)} + 3c_{qq}^{3(i33i)}$	$c_{Qq}^{1,1}$	$c_{qq}^{1(ii33)} + \frac{1}{6}c_{qq}^{1(i33i)} + \frac{1}{2}c_{qq}^{3(i33i)}$
$c_{Qq}^{3,8}$	$c_{qq}^{1(i33i)} - c_{qq}^{3(i33i)}$	$c_{Qq}^{3,1}$	$c_{qq}^{3(ii33)} + \frac{1}{6}(c_{qq}^{1(i33i)} - c_{qq}^{3(i33i)})$
c_{tq}^{8}	$c_{qu}^{8(ii33)}$	c_{tq}^{1}	$c_{qu}^{1(ii33)}$
c_{tu}^{8}	$2c_{uu}^{(i33i)}$	c_{tu}^{1}	$c_{uu}^{(ii33)} + \frac{1}{3}c_{uu}^{(i33i)}$
c_{Qu}^{8}	$c_{qu}^{8(33ii)}$	c_{Qu}^{1}	$c_{qu}^{1(33ii)}$
c_{td}^{8}	$c_{ud}^{8(33jj)}$	c_{td}^{1}	$c_{ud}^{1(33jj)}$
c_{Qd}^{8}	$c_{qd}^{8(33jj)}$	c_{Qd}^{1}	$c_{qd}^{1(33jj)}$

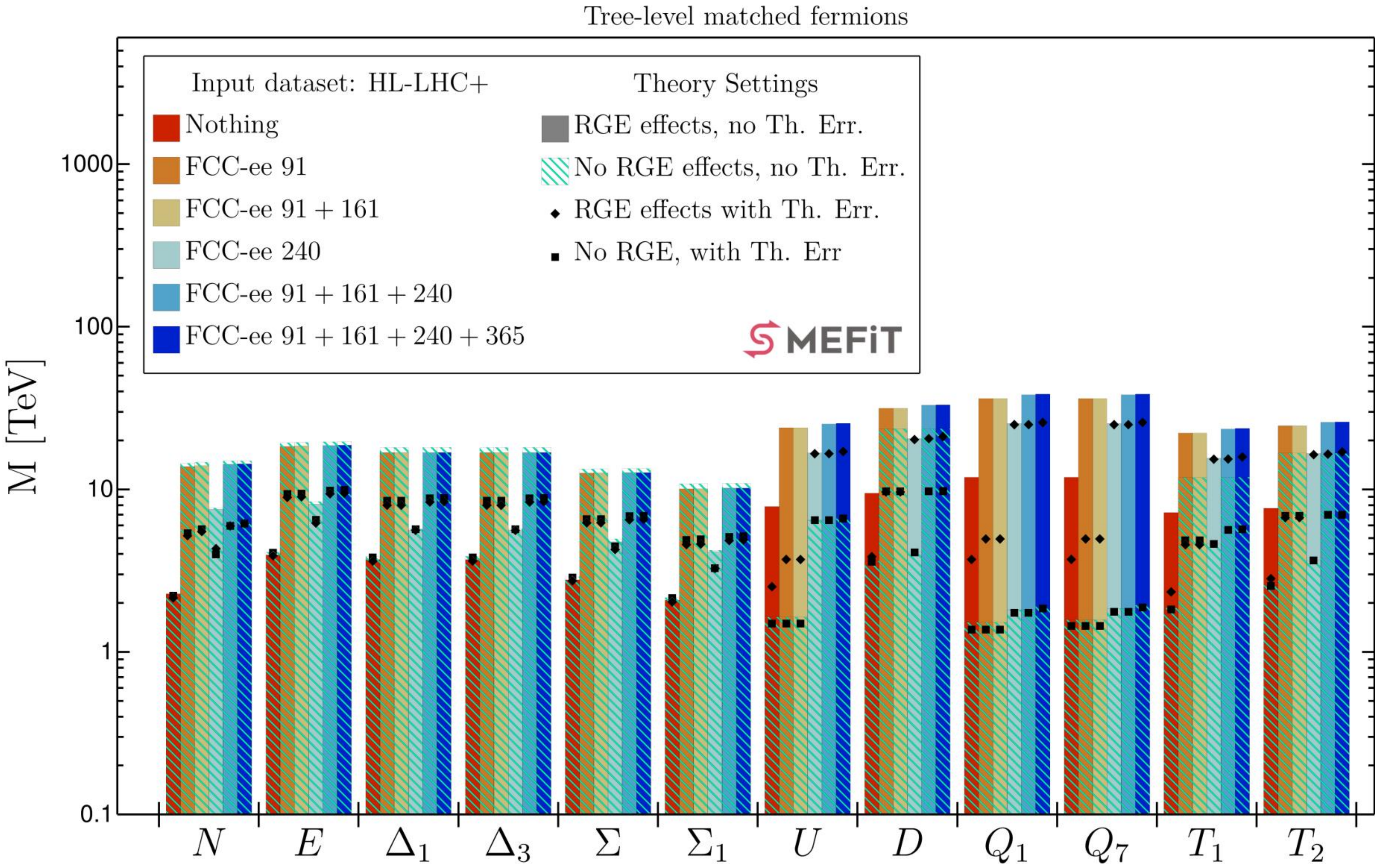
More results



More results



More results



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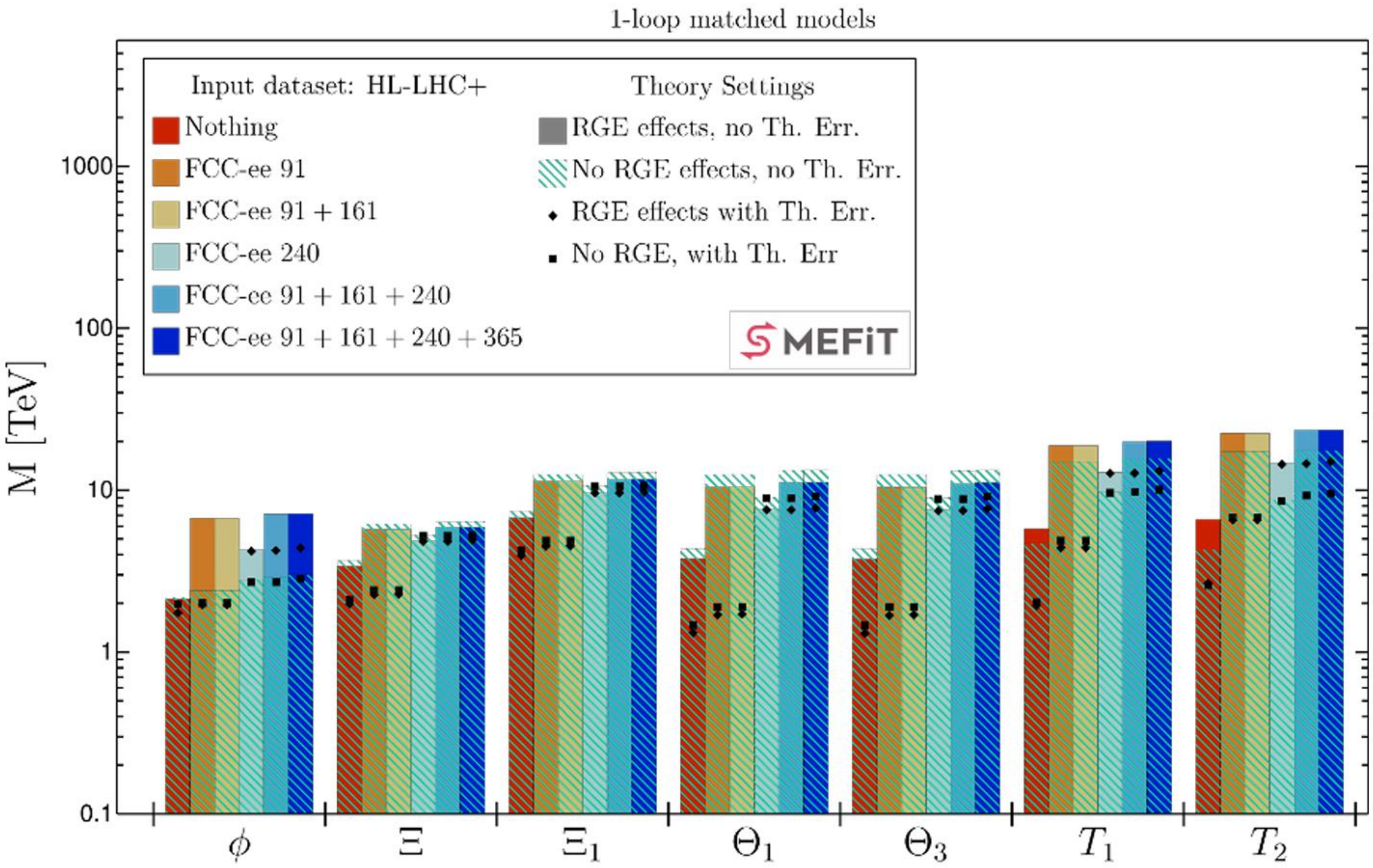

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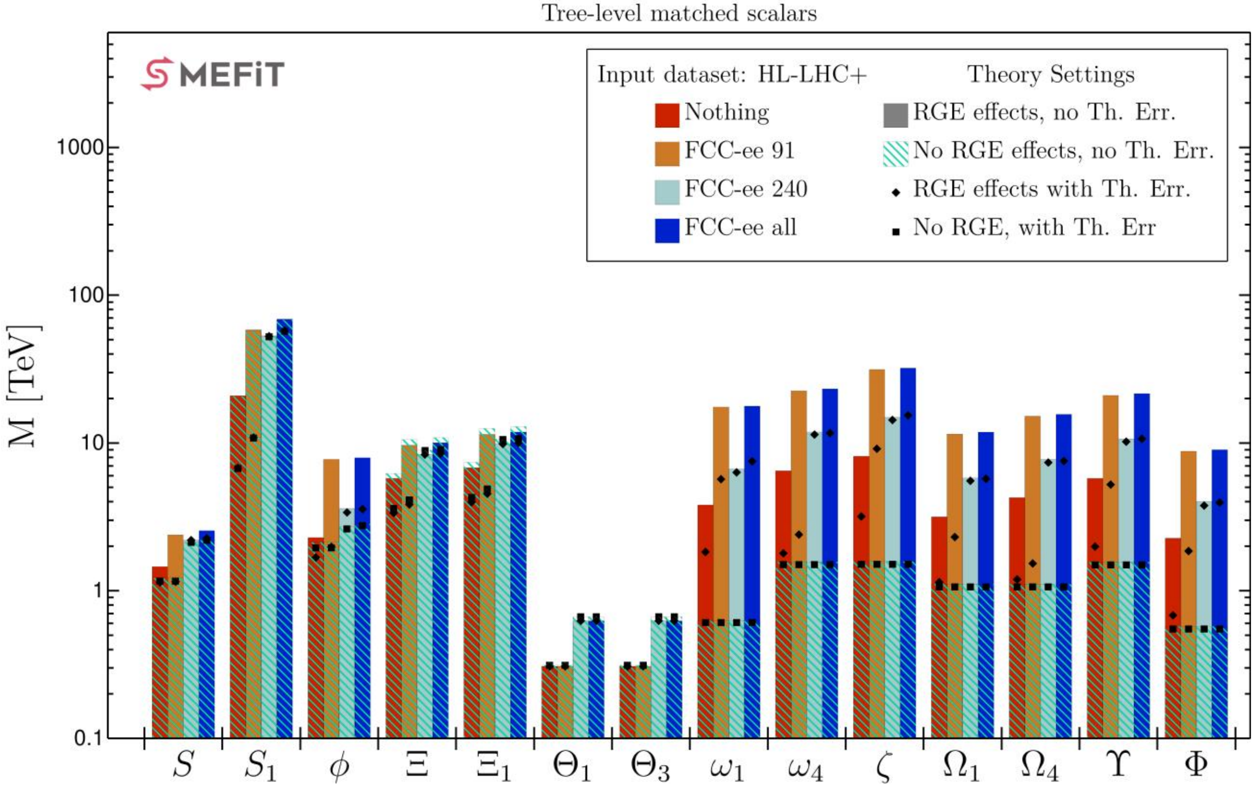

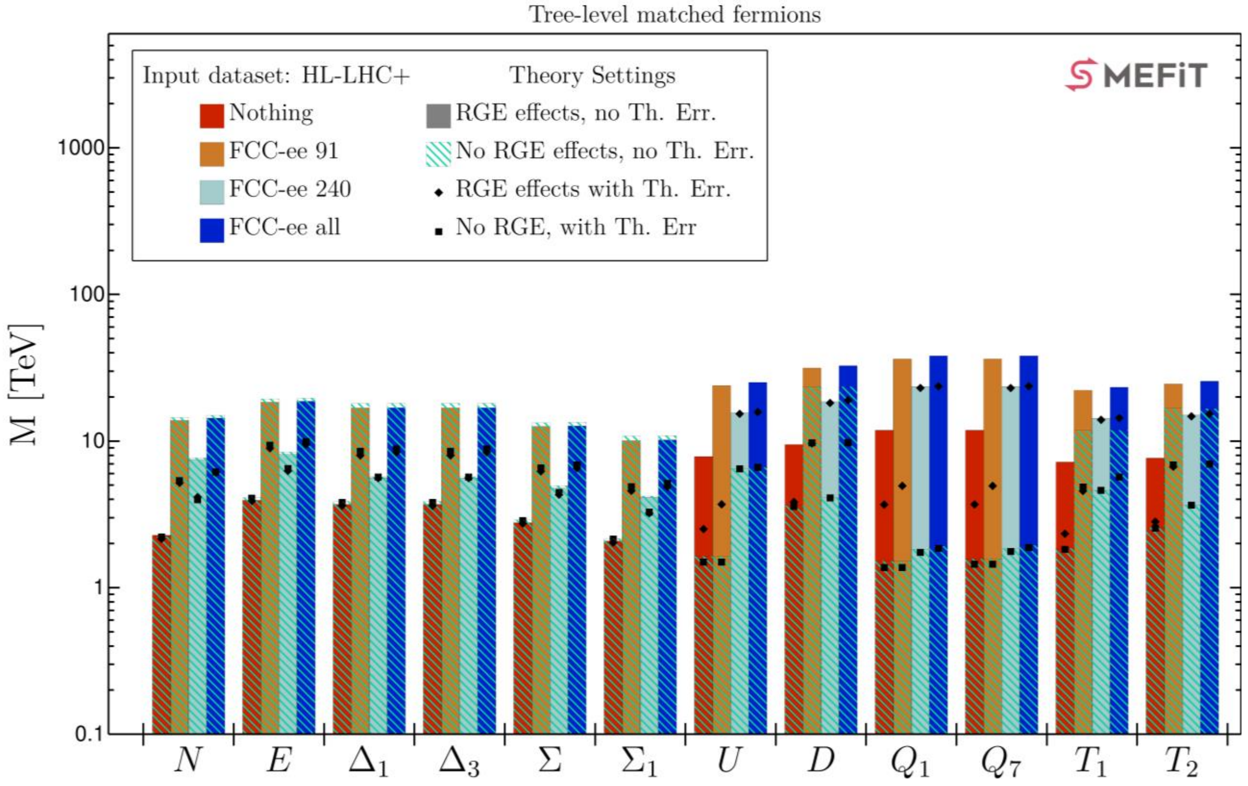

CEPC (& FCCee) projections

Celada, ANR, et al [2404.12809]

Energy ($\sqrt{s}$)	$\mathcal{L}_{\text{int}}$ (Run time) FCC-ee (4 IPs)	$\mathcal{L}_{\text{int}}$ (Run time) CEPC (2 IPs)	$\mathcal{L}_{\text{FCC-ee}}/\mathcal{L}_{\text{CEPC}}$
91 GeV (Z-pole)	300 ab^{-1} (4 years)	100 ab^{-1} (2 years)	3
161 GeV ($2\,m_W$)	20 ab^{-1} (2 years)	6 ab^{-1} (1 year)	3.3
240 GeV	10 ab^{-1} (3 years)	20 ab^{-1} (10 years)	0.5
350 GeV	0.4 ab^{-1} (1 year)	0.2 ab^{-1}	2
365 GeV ($2\,m_t$)	3 ab^{-1} (4 years)	1 ab^{-1} (5 years)	3

- **Z-pole EWPOs**
- **W-pole data**
- **ZH production (inc. and asym.)**
- **Light di-fermion production (inc. and asym.)**
- **WW and tt production via Optimal Observables**

Based on Snowmass 2022 (+ FCC Mid-Term Feas. Rep.)
Update to ESPPU26 coming out soon!

Armadillo, Celada, ANR, et al [25xx.yyyzz]