Single particle extensions at FCC-ee

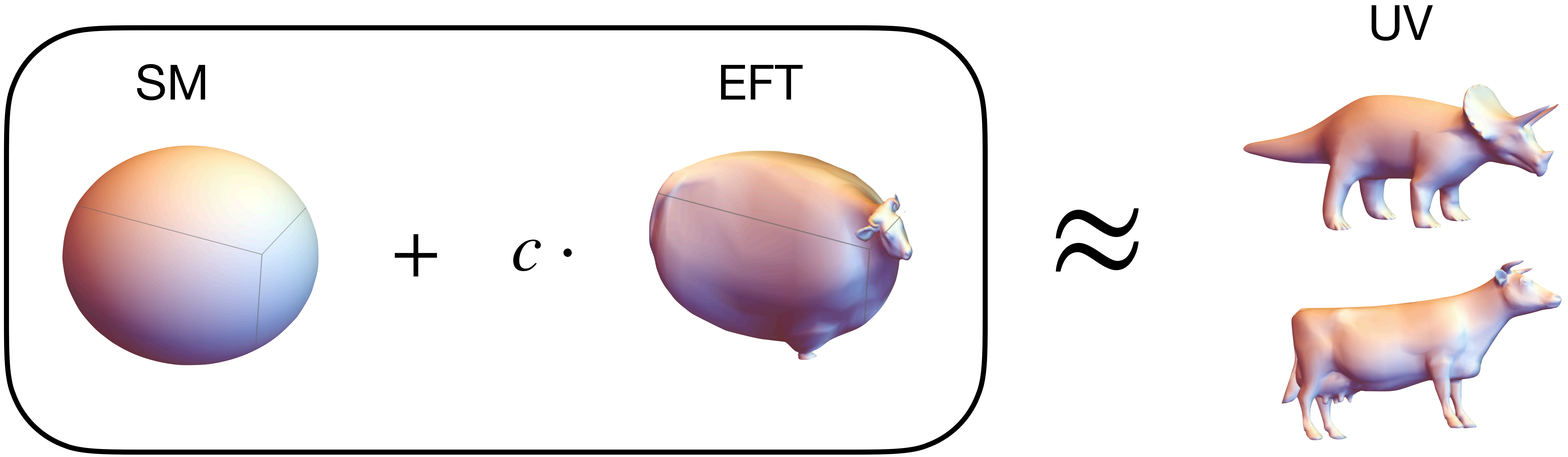
From a global SMEFT fit

In collaboration with L. Mantani, J. Rojo, A.N. Rossia, E. Vryonidou

Jaco ter Hoeve
14/01/25

THE UNIVERSITY of EDINBURGH

Scanning the UV with the SMEFT



- The ultimate goal of the EFT program is to bridge the gap to UV models
- Bypasses the need to recompute predictions for different UV models
- Benefits from correlating a wide range of observables

This talk

Heavy fermions

- Tree level
- One loop
- RG effects
- Theory errors

“Granada dictionary” [1711.10391]

Scalar	$\mathcal{S}$ $(1,1)_0$	$\mathcal{S}_1$ $(1,1)_1$	$\mathcal{S}_2$ $(1,1)_2$	φ $(1,2)_{\frac{1}{2}}$	Ξ $(1,3)_0$	Ξ_1 $(1,3)_1$	Θ_1 $(1,4)_{\frac{1}{2}}$	Θ_3 $(1,4)_{\frac{3}{2}}$
	ω_1 $(3,1)_{-\frac{1}{3}}$	ω_2 $(3,1)_{\frac{2}{3}}$	ω_4 $(3,1)_{-\frac{4}{3}}$	Π_1 $(3,2)_{\frac{1}{6}}$	Π_7 $(3,2)_{\frac{7}{6}}$	ζ $(3,3)_{-\frac{1}{3}}$		
	Ω_1 $(6,1)_{\frac{1}{3}}$	Ω_2 $(6,1)_{-\frac{2}{3}}$	Ω_4 $(6,1)_{\frac{4}{3}}$	Υ $(6,3)_{\frac{1}{3}}$	Φ $(8,2)_{\frac{1}{2}}$			
Fermion	N $(1,1)_0$	E $(1,1)_{-1}$	Δ_1 $(1,2)_{-\frac{1}{2}}$	Δ_3 $(1,2)_{-\frac{3}{2}}$	Σ $(1,3)_0$	Σ_1 $(1,3)_{-1}$		
	U $(3,1)_{\frac{2}{3}}$	D $(3,1)_{-\frac{1}{3}}$	Q_1 $(3,2)_{\frac{1}{6}}$	Q_5 $(3,2)_{-\frac{5}{6}}$	Q_7 $(3,2)_{\frac{7}{6}}$	T_1 $(3,3)_{-\frac{1}{3}}$	T_2 $(3,3)_{\frac{2}{3}}$	
Vector	$\mathcal{B}$ $(1,1)_0$	$\mathcal{B}_1$ $(1,1)_1$	$\mathcal{W}$ $(1,3)_0$	$\mathcal{W}_1$ $(1,3)_1$	$\mathcal{G}$ $(8,1)_0$	$\mathcal{G}_1$ $(8,1)_1$	$\mathcal{H}$ $(8,3)_0$	$\mathcal{L}_1$ $(1,2)_{\frac{1}{2}}$
	$\mathcal{L}_3$ $(1,2)_{-\frac{3}{2}}$	$\mathcal{U}_2$ $(3,1)_{\frac{2}{3}}$	$\mathcal{U}_5$ $(3,1)_{\frac{5}{3}}$	$\mathcal{Q}_1$ $(3,2)_{\frac{1}{6}}$	$\mathcal{Q}_5$ $(3,2)_{-\frac{5}{6}}$	$\mathcal{X}$ $(3,3)_{\frac{2}{3}}$	$\mathcal{Y}_1$ $(\bar{6},2)_{\frac{1}{6}}$	$\mathcal{Y}_5$ $(\bar{6},2)_{-\frac{5}{6}}$

Special focus on

- Impact of separate FCC-ee runs
- The EW quadruplet model
- Impact of NLO EW corrections
- 1-loop RG and matching effects

This talk

Heavy fermions

- Tree level
- One loop
- RG effects
- Theory errors

Heavy vector bosons

- Tree level
- RG effects
- Theory errors

“Granada dictionary” [1711.10391]

Scalar	$\mathcal{S}$ $(1,1)_0$	$\mathcal{S}_1$ $(1,1)_1$	$\mathcal{S}_2$ $(1,1)_2$	φ $(1,2)_{\frac{1}{2}}$	Ξ $(1,3)_0$	Ξ_1 $(1,3)_1$	Θ_1 $(1,4)_{\frac{1}{2}}$	Θ_3 $(1,4)_{\frac{3}{2}}$
	ω_1 $(3,1)_{-\frac{1}{3}}$	ω_2 $(3,1)_{\frac{2}{3}}$	ω_4 $(3,1)_{-\frac{4}{3}}$	Π_1 $(3,2)_{\frac{1}{6}}$	Π_7 $(3,2)_{\frac{7}{6}}$	ζ $(3,3)_{-\frac{1}{3}}$		
	Ω_1 $(6,1)_{\frac{1}{3}}$	Ω_2 $(6,1)_{-\frac{2}{3}}$	Ω_4 $(6,1)_{\frac{4}{3}}$	Υ $(6,3)_{\frac{1}{3}}$	Φ $(8,2)_{\frac{1}{2}}$			
Fermion	N $(1,1)_0$	E $(1,1)_{-1}$	Δ_1 $(1,2)_{-\frac{1}{2}}$	Δ_3 $(1,2)_{-\frac{3}{2}}$	Σ $(1,3)_0$	Σ_1 $(1,3)_{-1}$		
	U $(3,1)_{\frac{2}{3}}$	D $(3,1)_{-\frac{1}{3}}$	Q_1 $(3,2)_{\frac{1}{6}}$	Q_5 $(3,2)_{-\frac{5}{6}}$	Q_7 $(3,2)_{\frac{7}{6}}$	T_1 $(3,3)_{-\frac{1}{3}}$	T_2 $(3,3)_{\frac{2}{3}}$	
Vector	$\mathcal{B}$ $(1,1)_0$	$\mathcal{B}_1$ $(1,1)_1$	$\mathcal{W}$ $(1,3)_0$	$\mathcal{W}_1$ $(1,3)_1$	$\mathcal{G}$ $(8,1)_0$	$\mathcal{G}_1$ $(8,1)_1$	$\mathcal{H}$ $(8,3)_0$	$\mathcal{L}_1$ $(1,2)_{\frac{1}{2}}$
	$\mathcal{L}_3$ $(1,2)_{-\frac{3}{2}}$	$\mathcal{U}_2$ $(3,1)_{\frac{2}{3}}$	$\mathcal{U}_5$ $(3,1)_{\frac{5}{3}}$	$\mathcal{Q}_1$ $(3,2)_{\frac{1}{6}}$	$\mathcal{Q}_5$ $(3,2)_{-\frac{5}{6}}$	$\mathcal{X}$ $(3,3)_{\frac{2}{3}}$	$\mathcal{Y}_1$ $(\bar{6},2)_{\frac{1}{6}}$	$\mathcal{Y}_5$ $(\bar{6},2)_{-\frac{5}{6}}$

Special focus on

- Impact of separate FCC-ee runs
- The EW quadruplet model
- Impact of NLO EW corrections
- 1-loop RG and matching effects

This talk

Heavy scalars

- Tree level
- One loop
- RG effects
- Theory errors

Heavy vector bosons

- Tree level
- RG effects
- Theory errors

Heavy fermions

- Tree level
- One loop
- RG effects
- Theory errors

"Granada dictionary" [1711.10391]

Scalar	$\mathcal{S}$ $(1,1)_0$	$\mathcal{S}_1$ $(1,1)_1$	$\mathcal{S}_2$ $(1,1)_2$	φ $(1,2)_{\frac{1}{2}}$	Ξ $(1,3)_0$	Ξ_1 $(1,3)_1$	Θ_1 $(1,4)_{\frac{1}{2}}$	Θ_3 $(1,4)_{\frac{3}{2}}$
	ω_1 $(3,1)_{-\frac{1}{3}}$	ω_2 $(3,1)_{\frac{2}{3}}$	ω_4 $(3,1)_{-\frac{4}{3}}$	Π_1 $(3,2)_{\frac{1}{6}}$	Π_7 $(3,2)_{\frac{7}{6}}$	ζ $(3,3)_{-\frac{1}{3}}$		
	Ω_1 $(6,1)_{\frac{1}{3}}$	Ω_2 $(6,1)_{-\frac{2}{3}}$	Ω_4 $(6,1)_{\frac{4}{3}}$	Υ $(6,3)_{\frac{1}{3}}$	Φ $(8,2)_{\frac{1}{2}}$			
Fermion	N $(1,1)_0$	E $(1,1)_{-1}$	Δ_1 $(1,2)_{-\frac{1}{2}}$	Δ_3 $(1,2)_{-\frac{3}{2}}$	Σ $(1,3)_0$	Σ_1 $(1,3)_{-1}$		
	U $(3,1)_{\frac{2}{3}}$	D $(3,1)_{-\frac{1}{3}}$	Q_1 $(3,2)_{\frac{1}{6}}$	Q_5 $(3,2)_{-\frac{5}{6}}$	Q_7 $(3,2)_{\frac{7}{6}}$	T_1 $(3,3)_{-\frac{1}{3}}$	T_2 $(3,3)_{\frac{2}{3}}$	
Vector	$\mathcal{B}$ $(1,1)_0$	$\mathcal{B}_1$ $(1,1)_1$	$\mathcal{W}$ $(1,3)_0$	$\mathcal{W}_1$ $(1,3)_1$	$\mathcal{G}$ $(8,1)_0$	$\mathcal{G}_1$ $(8,1)_1$	$\mathcal{H}$ $(8,3)_0$	$\mathcal{L}_1$ $(1,2)_{\frac{1}{2}}$
	$\mathcal{L}_3$ $(1,2)_{-\frac{3}{2}}$	$\mathcal{U}_2$ $(3,1)_{\frac{2}{3}}$	$\mathcal{U}_5$ $(3,1)_{\frac{5}{3}}$	$\mathcal{Q}_1$ $(3,2)_{\frac{1}{6}}$	$\mathcal{Q}_5$ $(3,2)_{-\frac{5}{6}}$	$\mathcal{X}$ $(3,3)_{\frac{2}{3}}$	$\mathcal{Y}_1$ $(\bar{6},2)_{\frac{1}{6}}$	$\mathcal{Y}_5$ $(\bar{6},2)_{-\frac{5}{6}}$

Special focus on

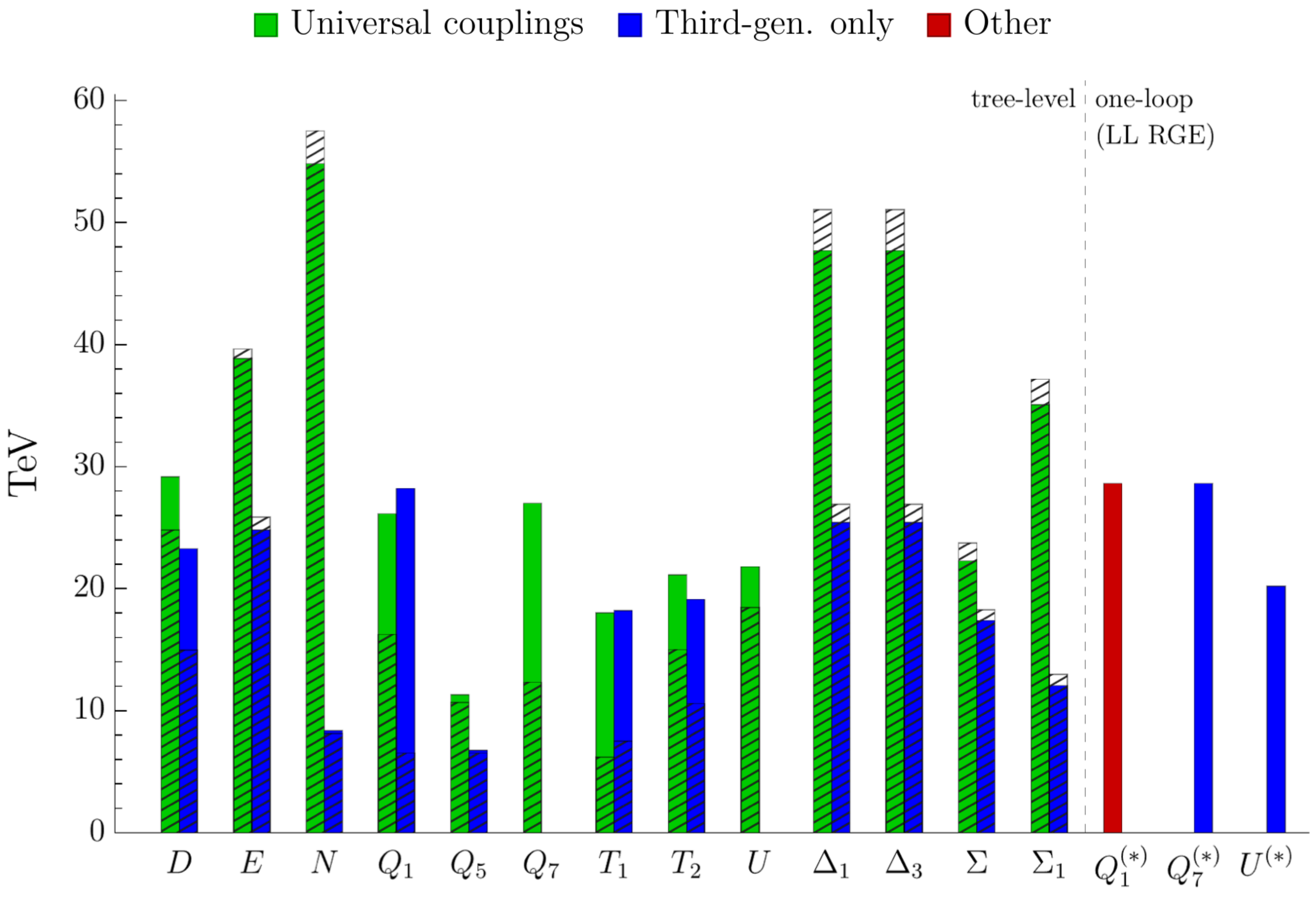
- Impact of separate FCC-ee runs
- The EW quadruplet model
- Impact of NLO EW corrections
- 1-loop RG and matching effects

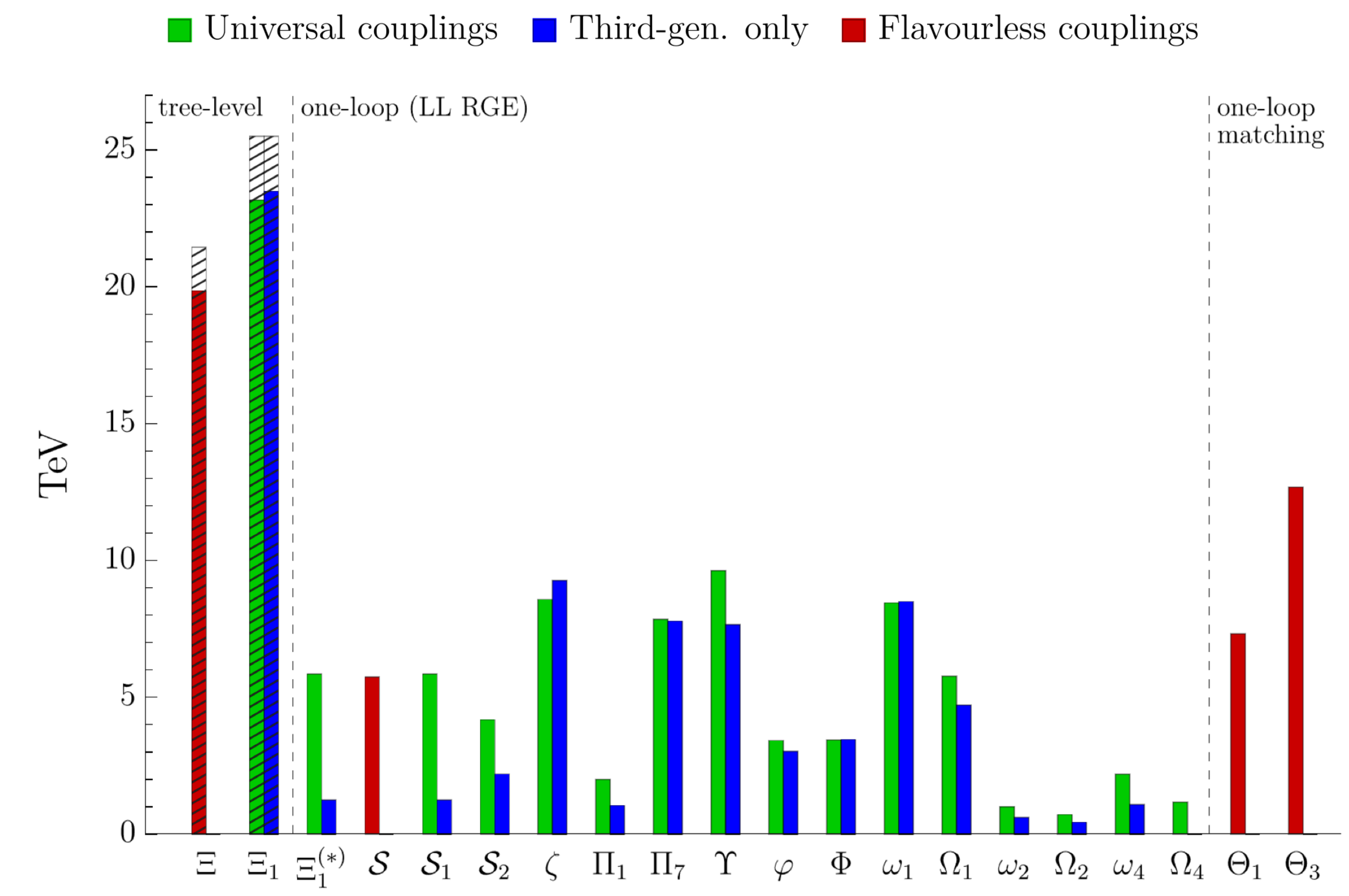
Allwicher, McCullough, Renner [2408.03992]

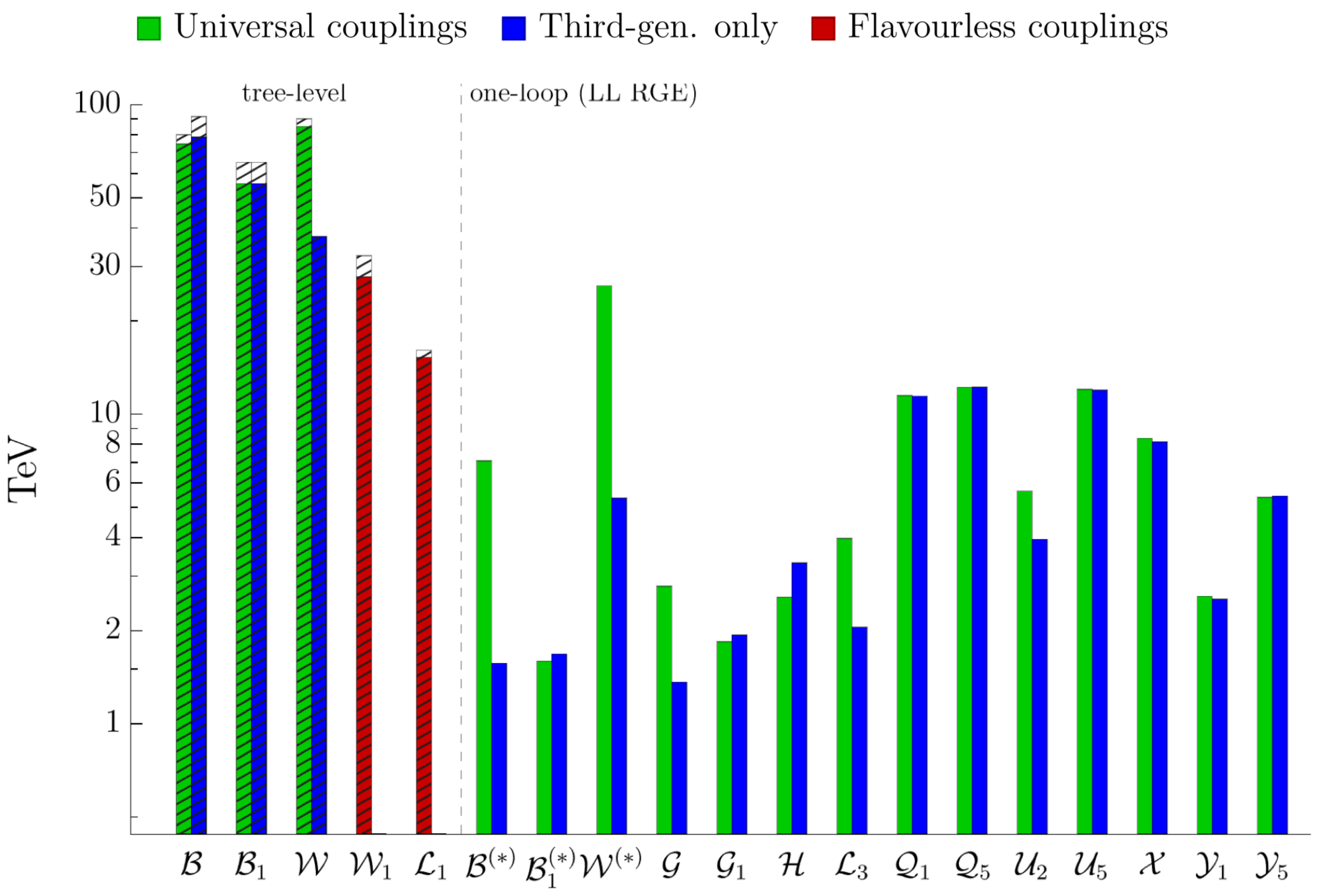
RG at Tera-Z

- Almost all particles matched at tree level induce operators that flow into EWPOs at tera-Z!

See Matthew's plenary from Monday







Methodology

[1901.05965], [2101.03180], [2105.00006], [2302.06660], [2309.04523], [2404.12809]

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

SMEFiT

Methodology

Linear: **Analytical solution** (fast!)
Quadratic: **Nested Sampling**

Output

Automatised fit reports that include
Posterior distributions, PCA, Fisher info, closure tests,..

Recent updates

SMEFiT3.0

- UV models (tree and 1-loop matching)
- External likelihoods
  - Going beyond the Gaussian approximation
  - Allows easy interface to external tools

Matchmakereft

[2112.10787]

match2fit

[2309.04523]

SMEFiT

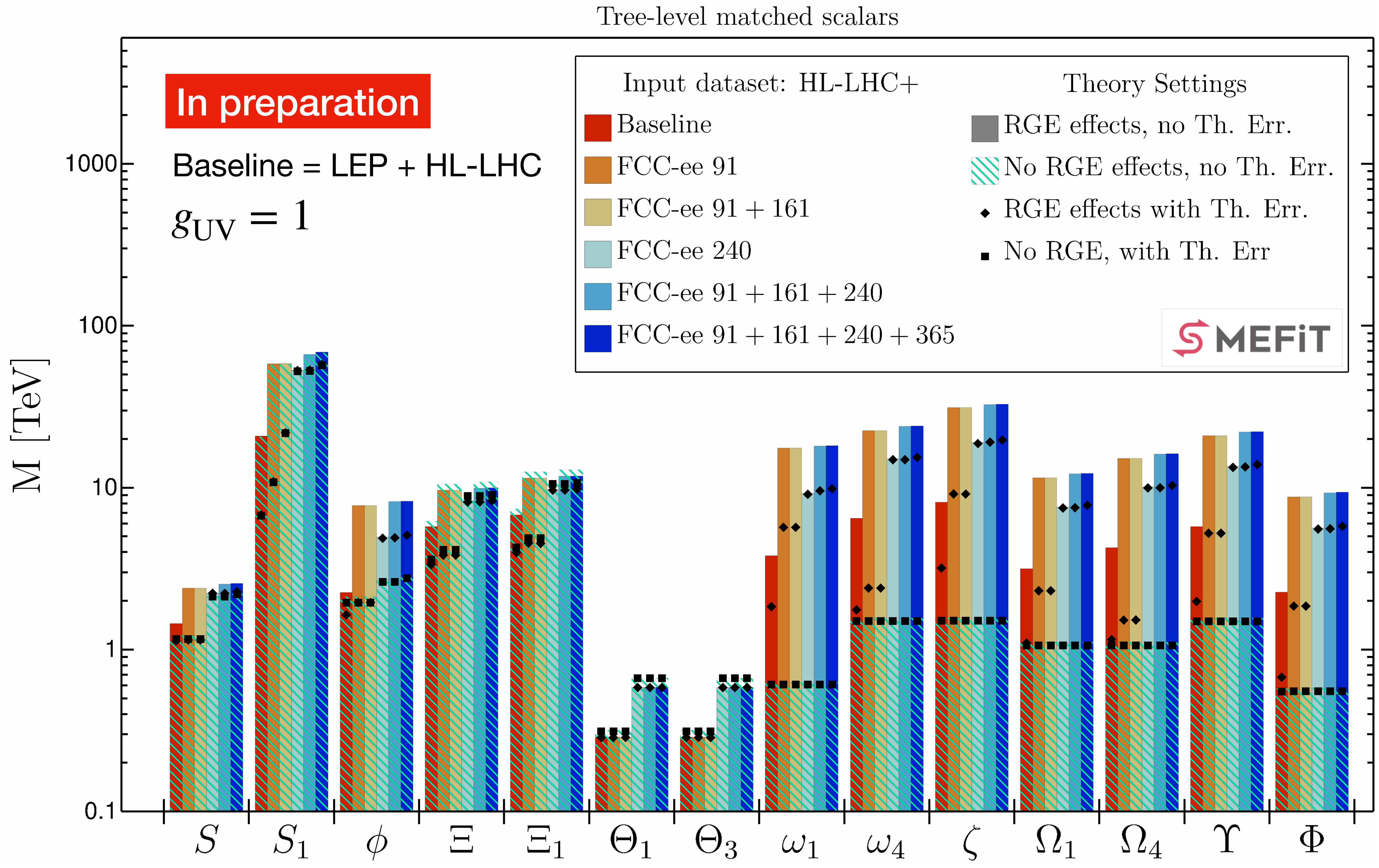
[2302.06660]

- RGE running: interface to Wilson with matrix evolution approximation

[1804.05033]

- JAX-enhanced: fast matrix calculations and GPU acceleration

Heavy scalars

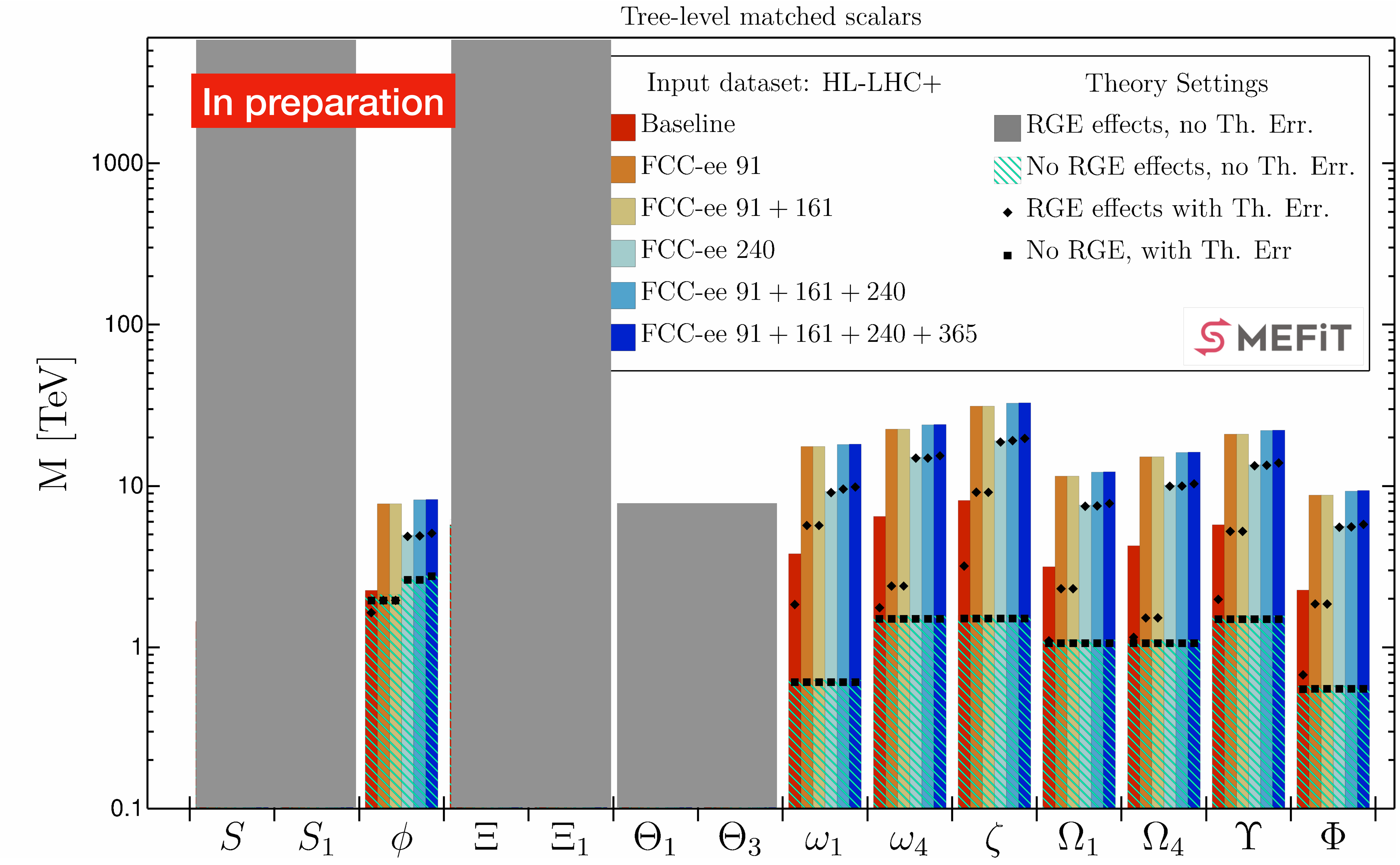


L.Mantani, J.Rojo, A. Rossia, E. Vryonidou, **JtH** [2501.xxxx]

General takeaways

- Tera Z dominates most bounds
- Indirect mass reach as high as **6 times HL-LHC**
- RGE effects are **crucial** for most models
- Reach reduced by a factor ~2 upon inclusion of **theory errors**

Heavy scalars

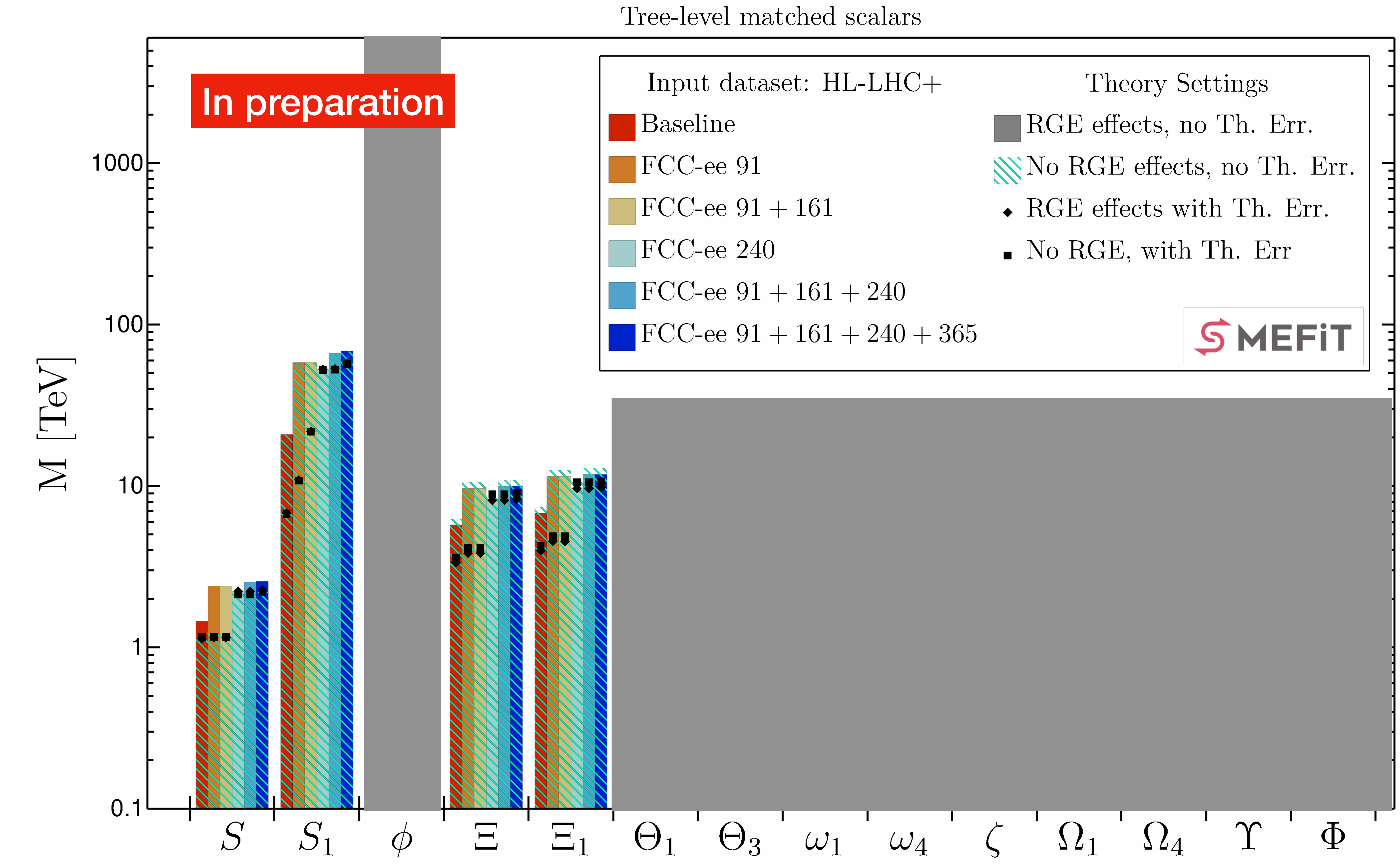


L.Mantani, J.Rojo, A. Rossia, E. Vryonidou, **JtH** [2501.xxxx]

- **RGE effects matter**
  4 quark operators flow into operators sensitive to EWPOs

	Heavy Scalars											
	$\mathcal{S}$	$\mathcal{S}_1$	ϕ	Ξ	Ξ_1	ω_1	ω_4	ζ	Ω_1	Ω_4	Υ	Φ
$c_{\varphi\Box}$	✓			✓	✓							
$c_{\varphi D}$				✓	✓							
$c_{\tau\varphi}$				✓	✓							
$c_{b\varphi}$				✓	✓							
$c_{t\varphi}$			✓	✓	✓							
$c_{\ell\ell}$		✓										
c^1_{Qt}			✓									✓
c^8_{Qt}			✓									✓
c^1_{QQ}						✓		✓	✓		✓	
c^8_{QQ}						✓		✓	✓		✓	
c^1_{tt}							✓			✓		

Heavy scalars



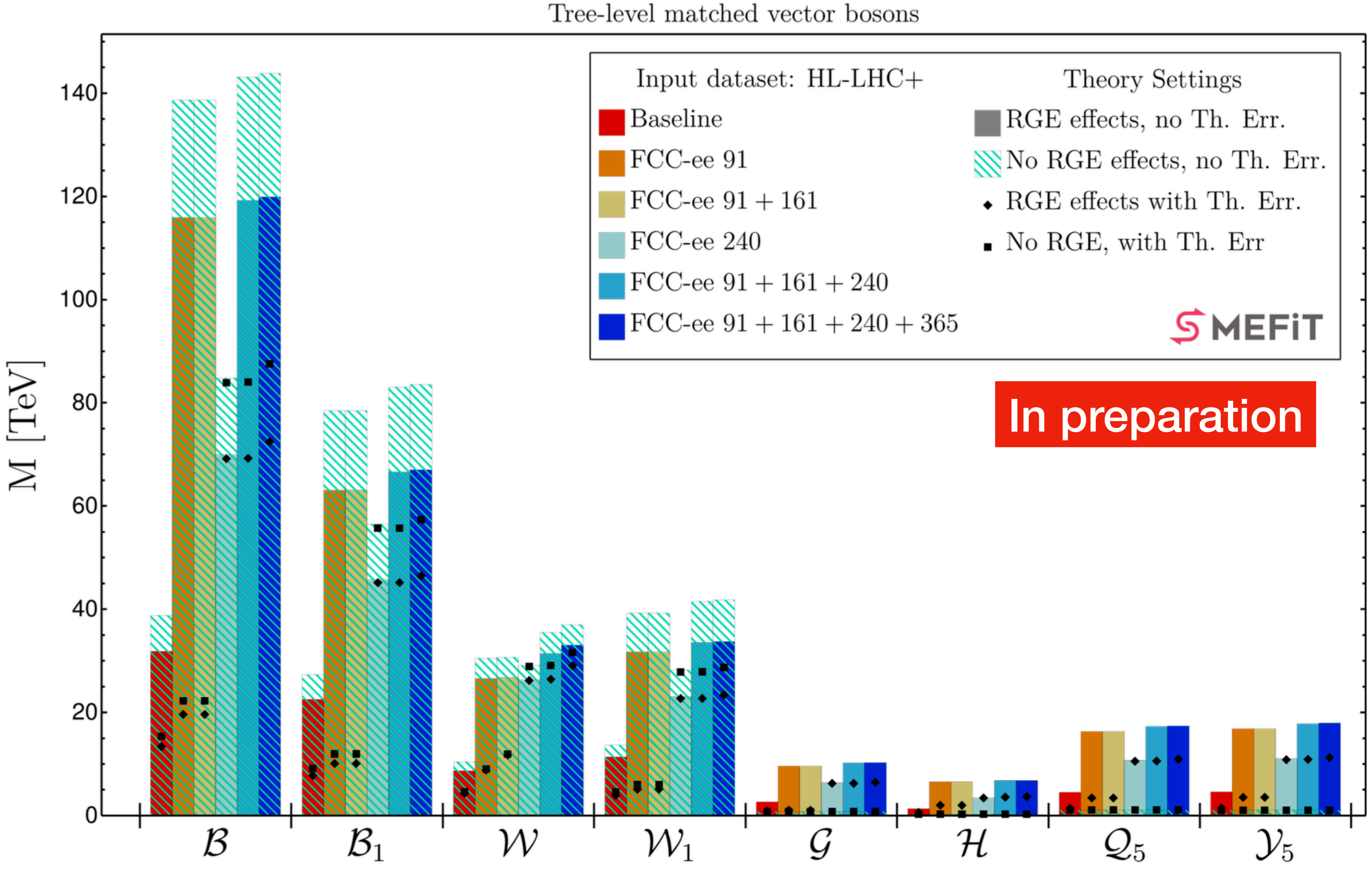
L.Mantani, J.Rojo, A. Rossia, E. Vryonidou, **JtH** [2501.xxxx]

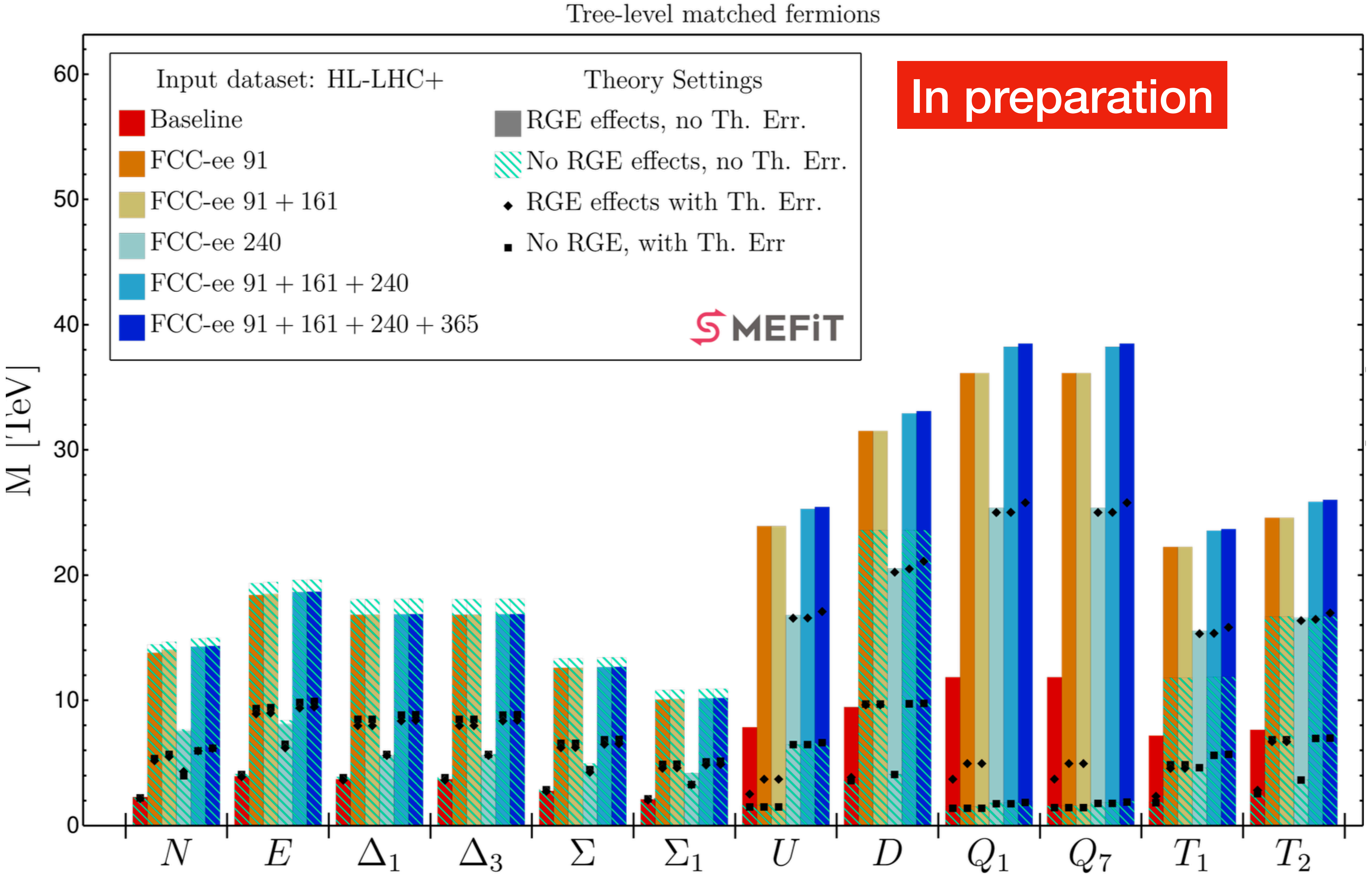
RGE effects subdominant

- Some models induce operators sensitive to EWPOs at tree-level and reduce impact of RG effects

	Heavy Scalars											
	$\mathcal{S}$	$\mathcal{S}_1$	ϕ	Ξ	Ξ_1	ω_1	ω_4	ζ	Ω_1	Ω_4	Υ	Φ
$c_{\varphi\Box}$	✓			✓	✓							
$c_{\varphi D}$				✓	✓							
$c_{\tau\varphi}$				✓	✓							
$c_{b\varphi}$				✓	✓							
$c_{t\varphi}$			✓	✓	✓							
$c_{\ell\ell}$		✓										
c_{Qt}^{1}			✓									✓
c_{Qt}^{8}			✓									✓
c_{QQ}^{1}						✓		✓	✓		✓	
c_{QQ}^{8}						✓		✓	✓		✓	
c_{tt}^{1}							✓			✓		

Vector bosons & fermions





Indirect searches can reach much higher scales than direct searches, as high as $\mathcal{O}(100)\,\mathrm{TeV}$

The EW quadruplet model

[2408.03992]
[2209.00666]

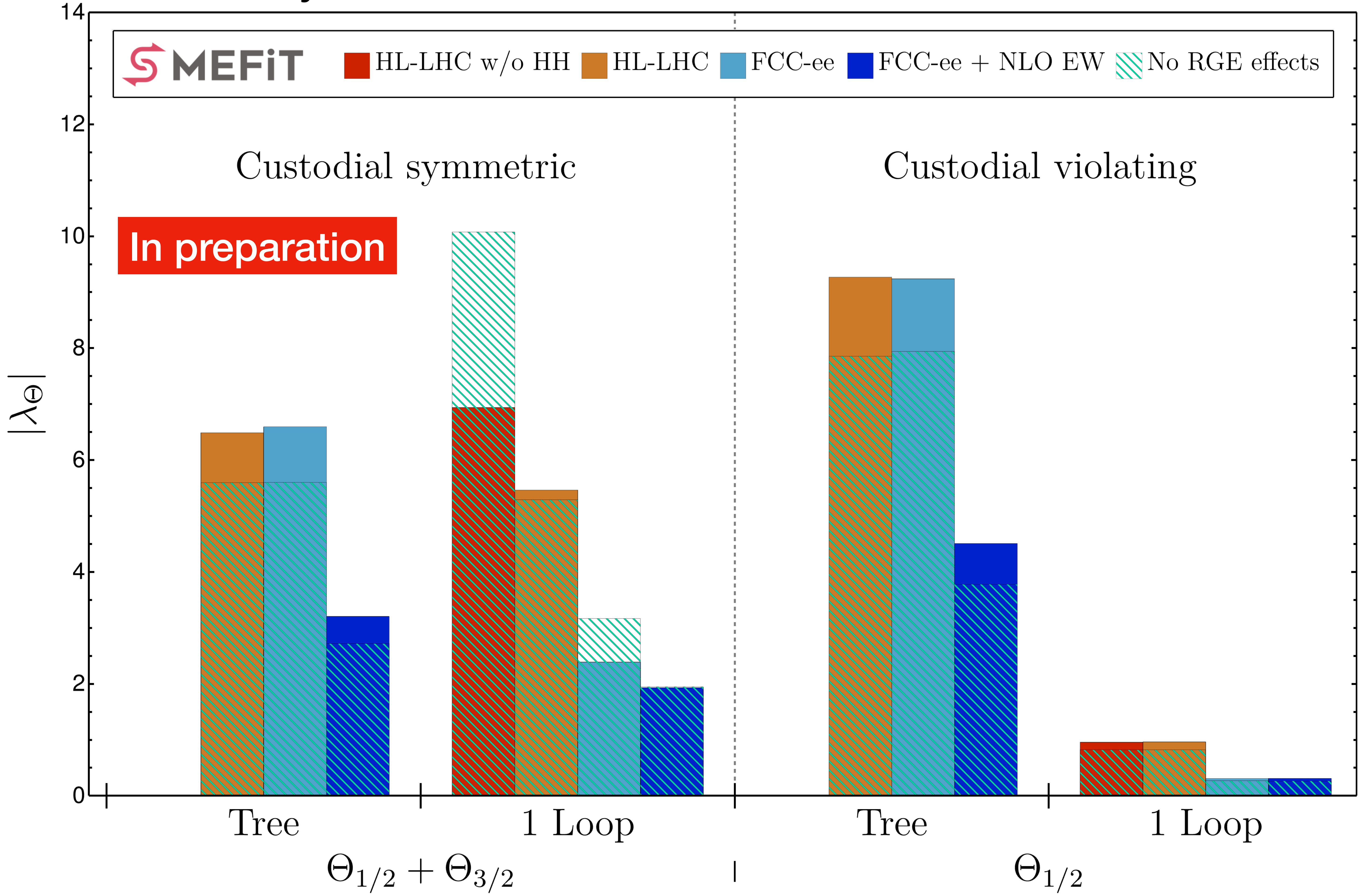
$$\mathcal{L}_{UV} \supset -\lambda_\Theta\, \varphi^* \varphi^* \left(\varepsilon \varphi\right) \Theta_{1/2} - \frac{\lambda_\Theta}{\sqrt{3}} \varphi^* \varphi^* \varphi^* \Theta_{3/2} + \mathrm{h.c.}\,.$$

- Interesting phenomenologically as it generates only $\mathcal{O}_\varphi$ at tree-level
- Can explain potential large deviations in the Higgs self coupling without affecting other couplings
- Each quadruplet violates custodial symmetry at one-loop, i.e. $O_{\varphi D}$ is induced
- **Solution**: 2 quadruplets with equals masses remove the contribution to $O_{\varphi D}$ at one-loop

The EW quadruplet model

No theory errors

UV coupling



L.Mantani, J.Rojo, A. Rossia, E. Vryonidou, **JtH** [2501.xxxx]

Tree level matching

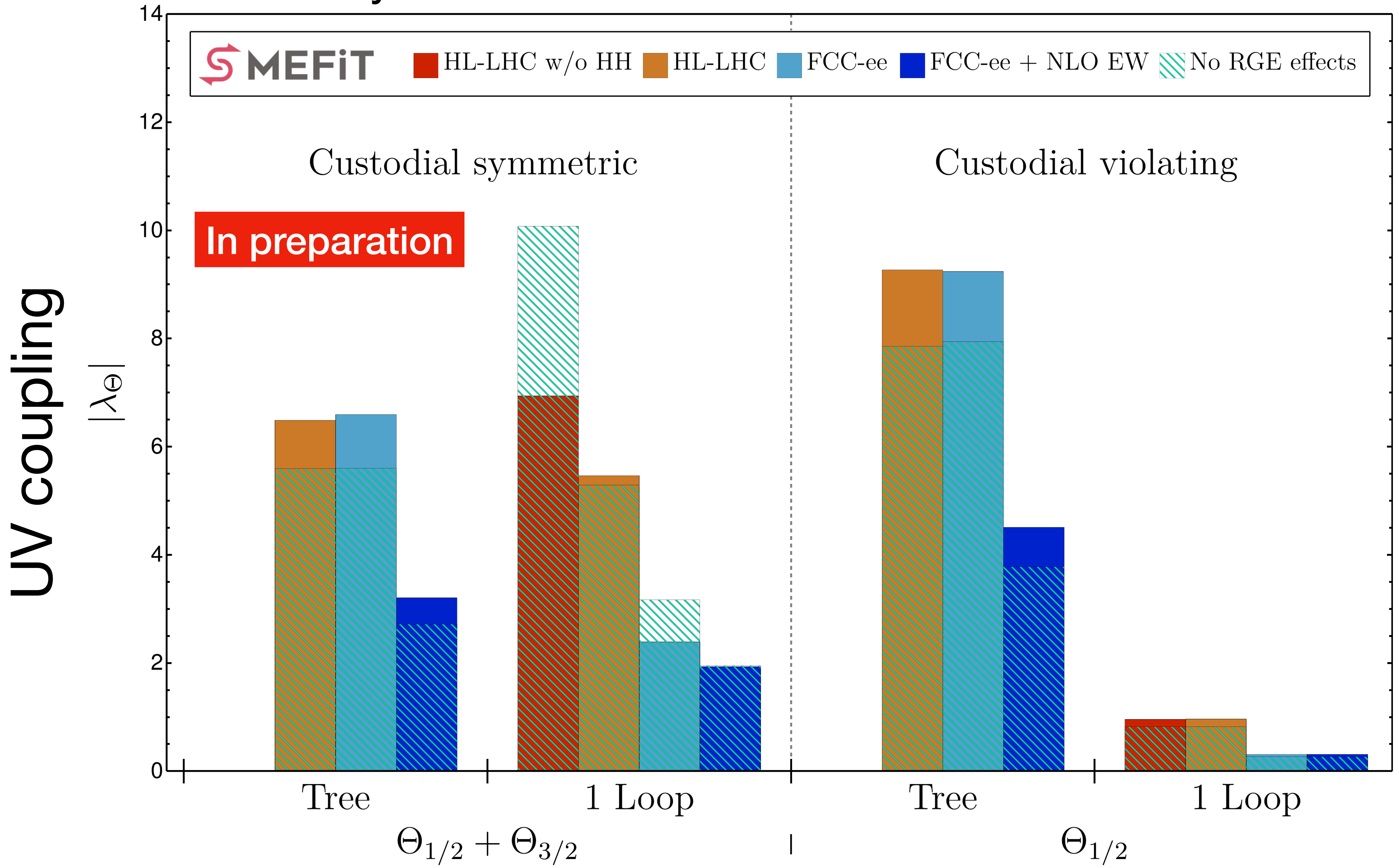
- Sensitivity only from HH @ HL-LHC and NLO-EW ZH @ FCC-ee
- Precision makes NLO EW ZH relevant : bound improves by a factor ~2

  Asteriadis, Dawson, Giardino, Szafron [2409.11466]

- Ignoring RG effects overestimates the bounds: sensitivity to $\mathcal{O}_\varphi$ decreases when lowering the scale

The EW quadruplet model

No theory errors

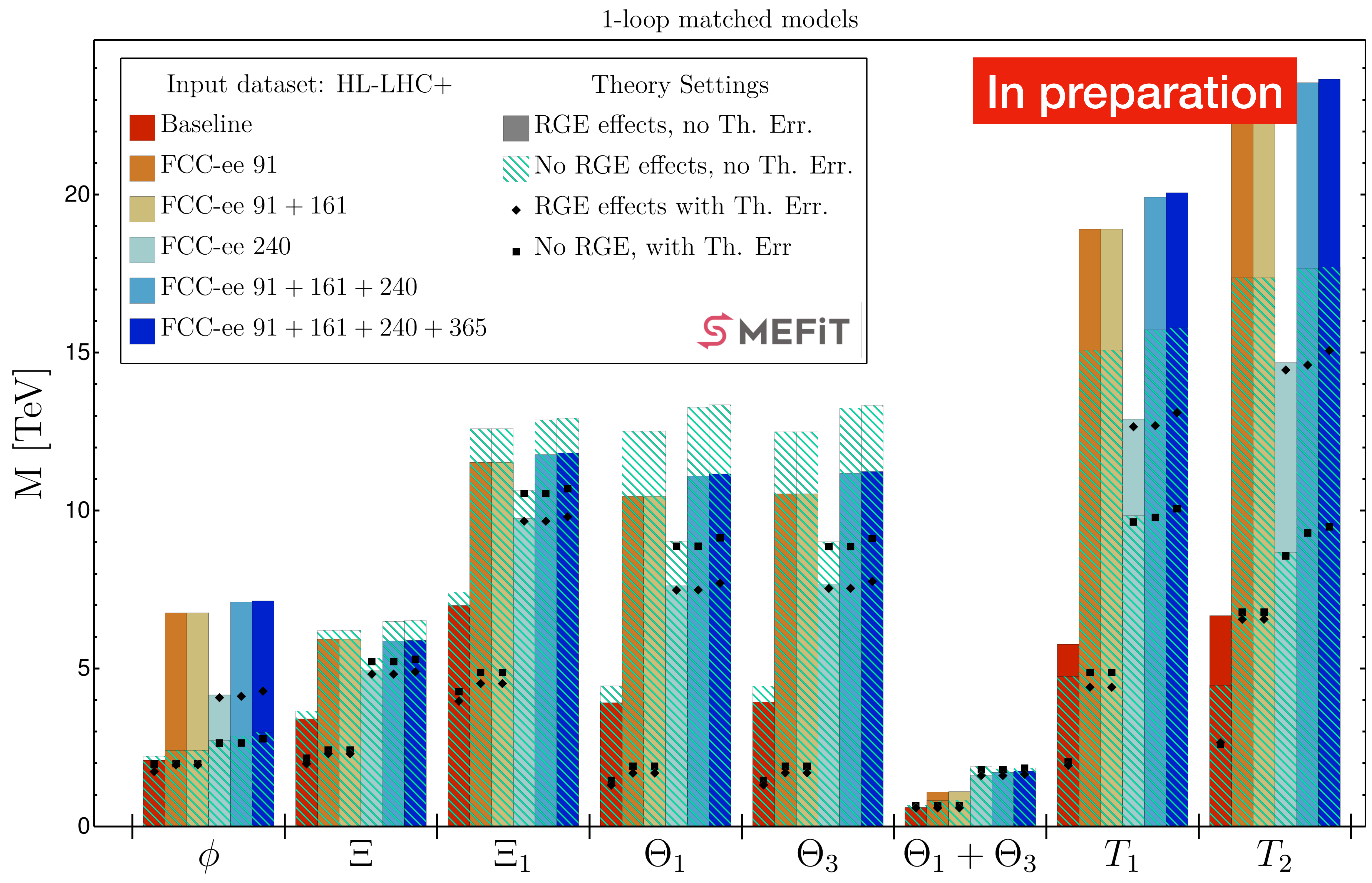


L.Mantani, J.Rojo, A. Rossia, E. Vryonidou, **JtH** [2501.xxxx]

One-loop level matching

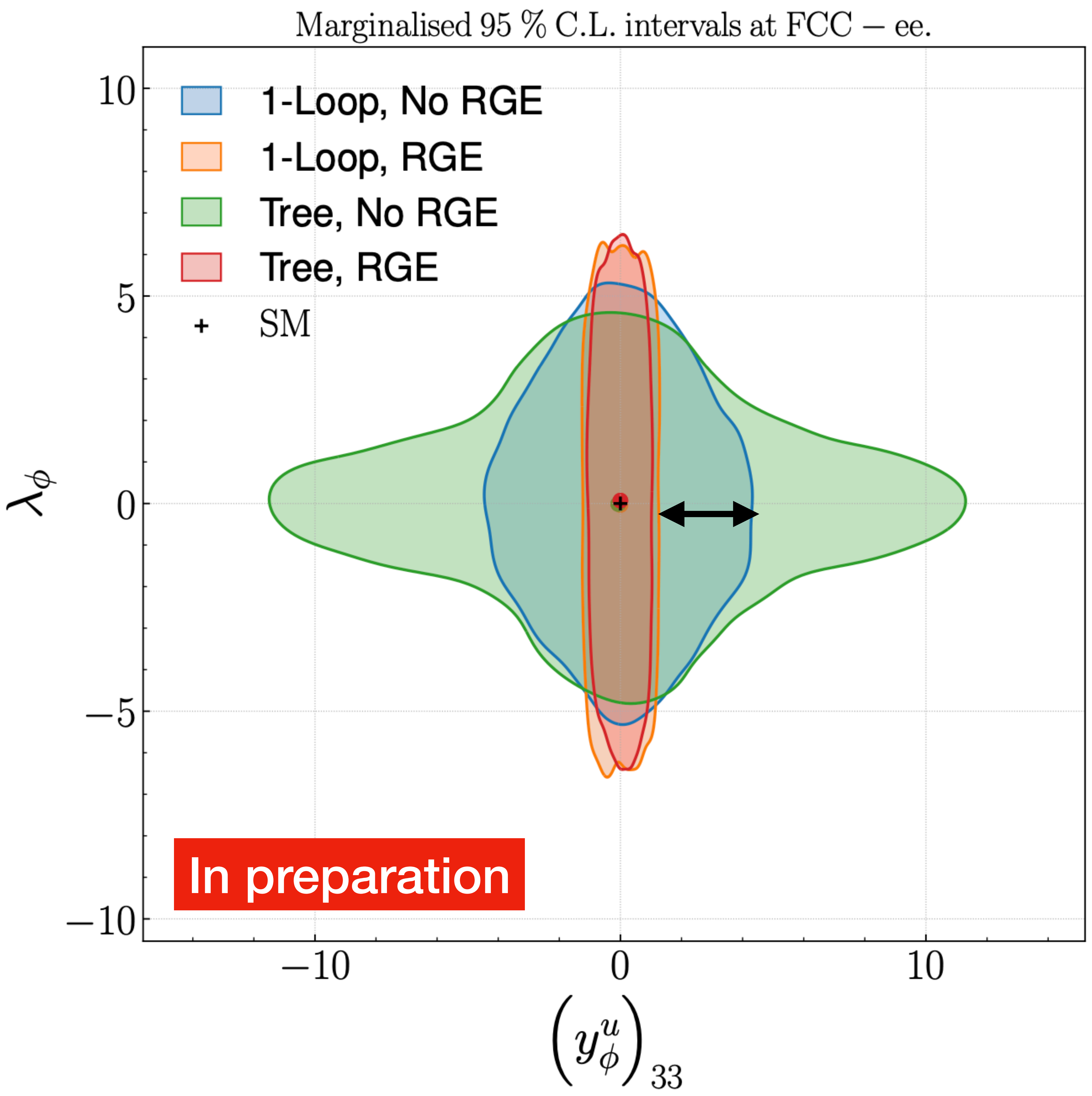
- Custodial violating: sensitivity driven by $c_{\varphi D}$
- Custodial symmetric:
  - Impact of $c_{\varphi D}$ reduced
  - sensitivity in ZH through $c_{\varphi\Box}$ and its running into $c_{\varphi D}$

One-loop matching and RGE



- 1-loop matching does not rule out important RG effects, e.g. T_1, T_2, ϕ
- So ideally one includes both

One-loop matching and RGE



Consider 2HDM in decoupling limit

$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + |D_\mu\phi|^2 - m_\phi^2\phi^\dagger\phi - \Big(y^e_{\phi,ij}\,\phi^\dagger\bar{e}^i_R\ell^j_L + y^d_{\phi,ij}\,\phi^\dagger\bar{d}^i_R q^j_L + y^u_{\phi,ij}\,\phi^\dagger i\sigma_2\bar{q}^{T,i}_L u^j_R + \lambda_\phi\,\phi^\dagger\varphi|\varphi|^2 + \text{h.c.}\Big)\,.$$

- RG effects bring in more sensitivity than 1-loop matching in some cases
- c_φ closes flat direction along λ_ϕ even at tree level

Summary and conclusion

- The unprecedented precision of FCC-ee puts indirect limits on the masses of new UV models up to $\mathcal{O}(100)\,\mathrm{TeV}$
- NLO-EW ZH corrections are key, especially for models generating $\mathcal{O}_\varphi$
- We need to keep theory errors under control
- RGE effects are not only necessary, but bring in additional sensitivity
- The different energy runs show beautifully the complementarity of the FCC-ee physics program

Summary and conclusion

- The unprecedented precision of FCC-ee puts indirect limits on the masses of new UV models up to $\mathcal{O}(100)\ \mathrm{TeV}$
- NLO-EW ZH corrections are key, especially for models generating $\mathcal{O}_{\varphi}$
- We need to keep theory errors under control
- RGE effects are not only necessary, but bring in additional sensitivity
- The different energy runs show beautifully the complementarity of the FCC-ee physics program

Thank you very much for your attention!

	Heavy Scalars											
	$\mathcal{S}$	$\mathcal{S}_1$	ϕ	Ξ	Ξ_1	ω_1	ω_4	ζ	Ω_1	Ω_4	Υ	Φ
$c_{\varphi\Box}$	✓			✓	✓							
$c_{\varphi D}$				✓	✓							
$c_{\tau\varphi}$				✓	✓							
$c_{b\varphi}$				✓	✓							
$c_{t\varphi}$			✓	✓	✓							
$c_{\ell\ell}$		✓										
c^1_{Qt}			✓									✓
c^8_{Qt}			✓									✓
c^1_{QQ}						✓		✓	✓		✓	
c^8_{QQ}						✓		✓	✓		✓	
c^1_{tt}							✓			✓		

	Heavy Fermions									
	N	E	Δ_1, Δ_3	Σ, Σ_1	U	D	Q_1	Q_5	Q_7	T_1, T_2
$c^{(3)}_{\varphi\ell_3}$	✓	✓		✓						
$c_{\varphi\ell_3}$	✓	✓		✓						
$c_{\varphi\tau}$			✓							
$c_{\tau\varphi}$		✓	✓	✓						
$c^{(3)}_{\varphi Q}$					✓	✓				✓
$c^{(-)}_{\varphi Q}$					✓					✓
$c_{\varphi t}$							✓		✓	
$c_{t\varphi}$					✓		✓		✓	✓
$c_{b\varphi}$						✓		✓		✓

	Heavy Vector Bosons							
	$\mathcal{B}$	$\mathcal{B}_1$	$\mathcal{W}$	$\mathcal{W}_1$	$\mathcal{G}$	$\mathcal{H}$	$\mathcal{Q}_5$	$\mathcal{Y}_5$
$c_{\varphi\Box}$	✓	✓	✓	✓				
$c_{\varphi D}$	✓	✓		✓				
$c_{\tau\varphi}$		✓	✓	✓				
$c_{b\varphi}$		✓	✓	✓				
$c_{t\varphi}$		✓	✓	✓				
$c^{(3)}_{\varphi l_{1,2,3}}$			✓					
$c^{(1)}_{\varphi l_{1,2,3}}$	✓							
$c_{\varphi(e,\mu,\tau)}$	✓							
$c^{(3)}_{\varphi Q}$			✓					
$c^{(-)}_{\varphi Q}$	✓		✓					
$c_{\varphi t}$	✓							
$c_{\ell\ell}$			✓					
c^1_{Qt}	✓						✓	✓
c^8_{Qt}					✓		✓	✓
c^1_{QQ}	✓		✓			✓		
c^8_{QQ}			✓		✓	✓		
c^1_{tt}	✓				✓			
$c_{\ell\ell_{1111}}$	✓		✓					