MANCHESTER 1824

The University of Manchester

The Automation of SMEFT-Assisted constraints on UV-complete models

Multi-Boson Interactions 2024

Toulouse, France

27 September 2024

Alejo N. Rossia

On behalf of the SMEFiT Collaboration

Department of Physics and Astronomy

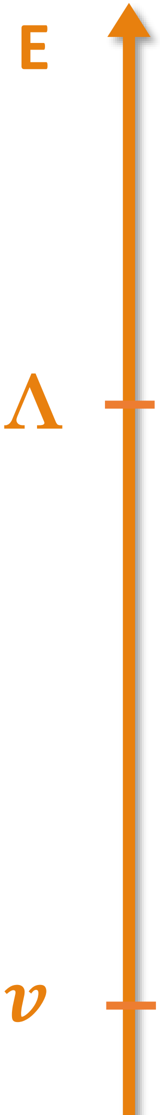
The University of Manchester

Based on:

[2309.04523] JHEP 01 (2024) 179 (w/ J. ter Hoeve, G. Magni, J. Rojo, and E. Vryonidou)

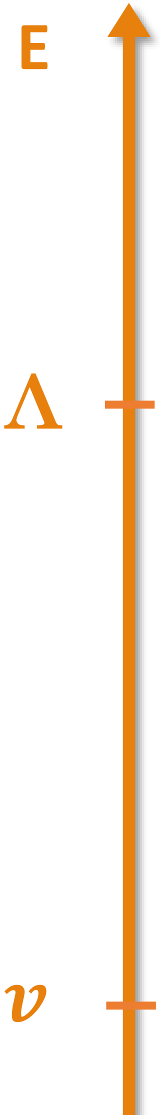
[2404.12809] JHEP 09 (2024) 091 (w/ E. Celada, T. Giani, J. ter Hoeve, L. Mantani, J. Rojo, M. Thomas and E. Vryonidou)

The Standard Model EFT (SMEFT)



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

The Standard Model EFT (SMEFT)



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

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

$$G_{\text{SMEFT}} = \text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$$
$$\psi_{\text{SMEFT}} = \psi_{\text{SM}}$$

The Standard Model EFT (SMEFT)

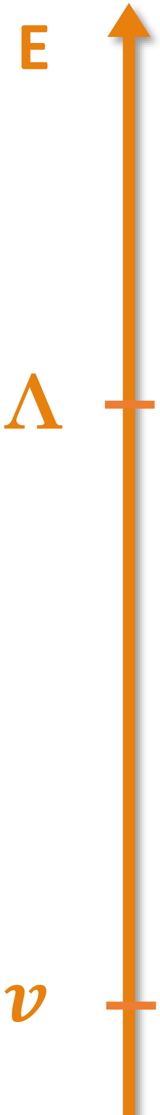
$$\psi_{UV} = ? \qquad \mathcal{L}_{UV} = ? \qquad G_{UV} = ?$$

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

$$G_{\mathrm{SMEFT}} = \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$$
$$\psi_{\mathrm{SMEFT}} = \psi_{\mathrm{SM}}$$

(Mostly) Model-independent phenomenology

The Standard Model EFT (SMEFT)



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

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

$$G_{\rm SMEFT} = {\rm SU}(3) \times {\rm SU}(2) \times {\rm U}(1)$$
$$\psi_{\rm SMEFT} = \psi_{\rm SM}$$

(Mostly) Model-independent phenomenology

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\rm SM} + \frac{c_i^{(6)}}{\Lambda^2} d\sigma^i_{\rm int.} + \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} d\sigma^{i,j}_{\rm EFT}$$

The Standard Model EFT (SMEFT)

E

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

Λ

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

$$G_{\rm SMEFT} = \mathrm{SU}(3) \times \mathrm{SU}(2) \times \mathrm{U}(1)$$
$$\psi_{\rm SMEFT} = \psi_{\rm SM}$$

(Mostly) Model-independent phenomenology

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\rm SM} + \frac{c_i^{(6)}}{\Lambda^2} d\sigma^i_{\rm int.} + \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} d\sigma^{i,j}_{\rm EFT}$$

v

Experimental measurement

The Standard Model EFT (SMEFT)

E

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

Λ

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

$$G_{\rm SMEFT} = {\rm SU}(3) \times {\rm SU}(2) \times {\rm U}(1)$$

$$\psi_{\rm SMEFT} = \psi_{\rm SM}$$

(Mostly) Model-independent phenomenology

$$d\sigma = d\sigma_{\rm SM} + \frac{c_i^{(6)}}{\Lambda^2} d\sigma^i_{\rm int.} + \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} d\sigma^{i,j}_{\rm EFT}$$

SM prediction

Experimental measurement

v

The Standard Model EFT (SMEFT)

E

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

Λ

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

$$G_{\text{SMEFT}} = \text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$$

$$\psi_{\text{SMEFT}} = \psi_{\text{SM}}$$

(Mostly) Model-independent phenomenology

$$\mathrm{d}\sigma = \mathrm{d}\sigma_{\text{SM}} + \frac{c_i^{(6)}}{\Lambda^2} d\sigma^i_{\text{int.}} + \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} d\sigma^{i,j}_{\text{EFT}}$$

SMEFT prediction

SM prediction

v

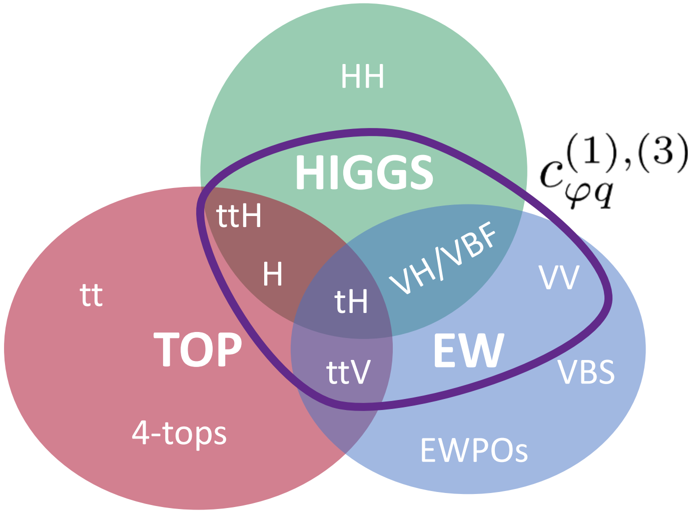
Experimental measurement

Global fits

Correlations, correlations everywhere…

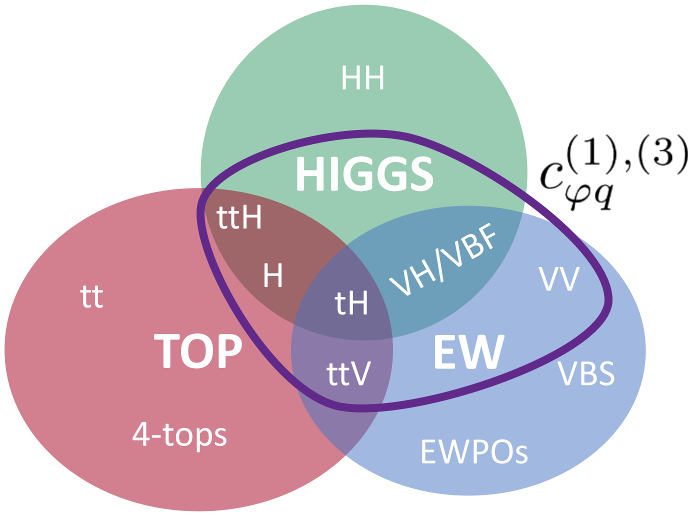
Global fits

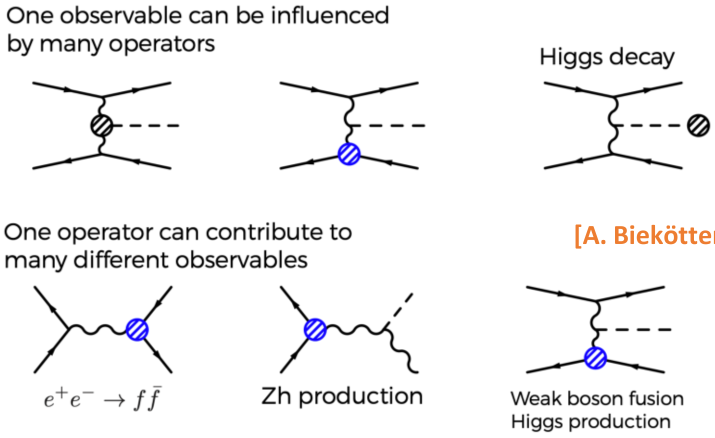
Correlations, correlations everywhere…



Global fits

Correlations, correlations everywhere…

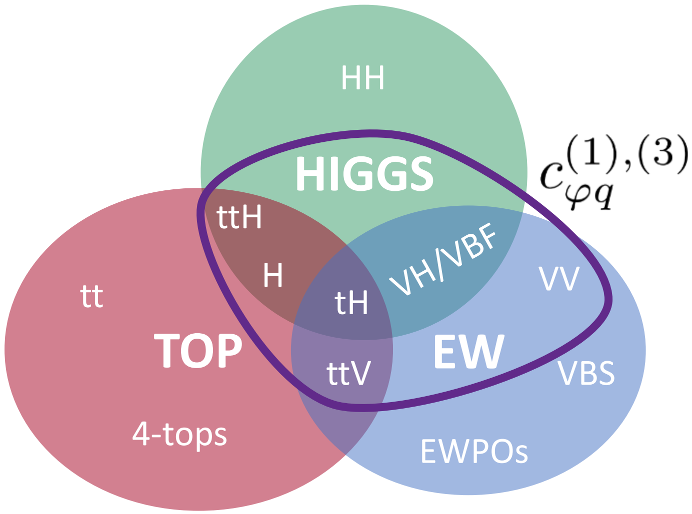


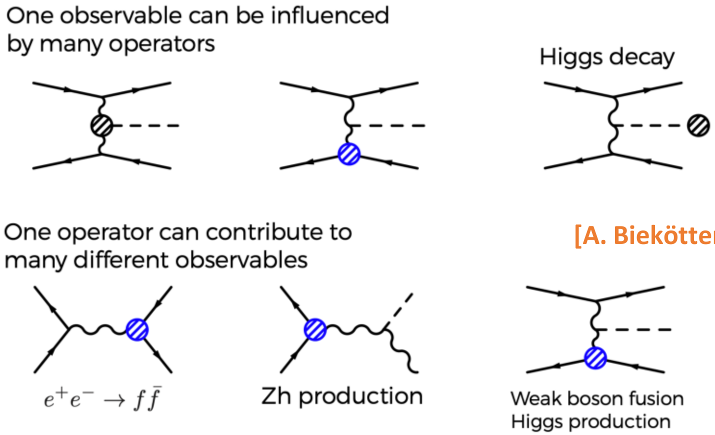


[A. Biekötter's seminar]

Global fits

Correlations, correlations everywhere...



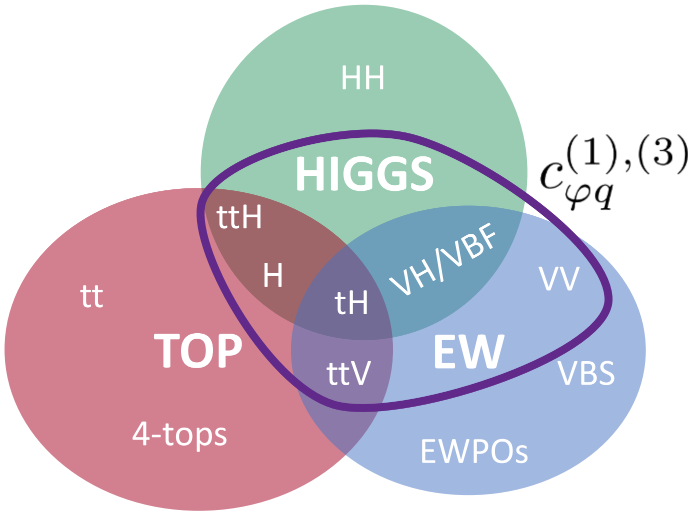


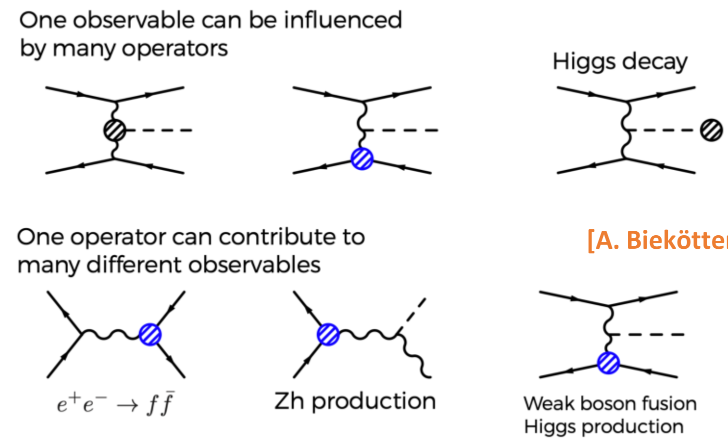
[A. Biekötter's seminar]

The choices in the fitter's way

Global fits

Correlations, correlations everywhere…





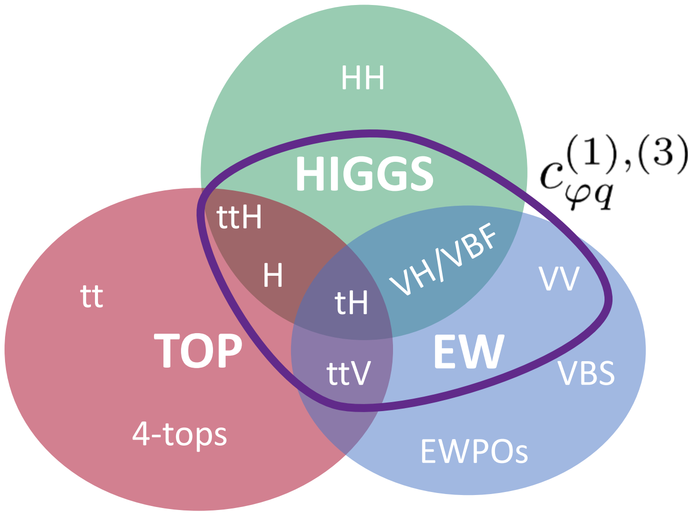
[A. Biekötter's seminar]

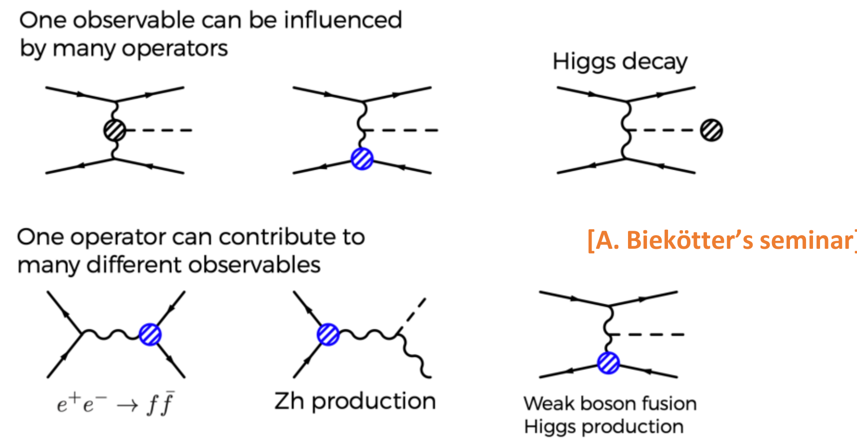
The choices in the fitter's way

- **Dataset**

Global fits

Correlations, correlations everywhere…



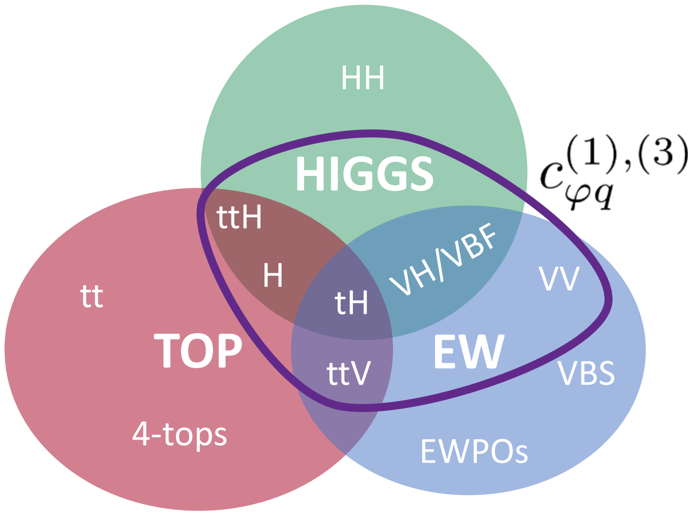


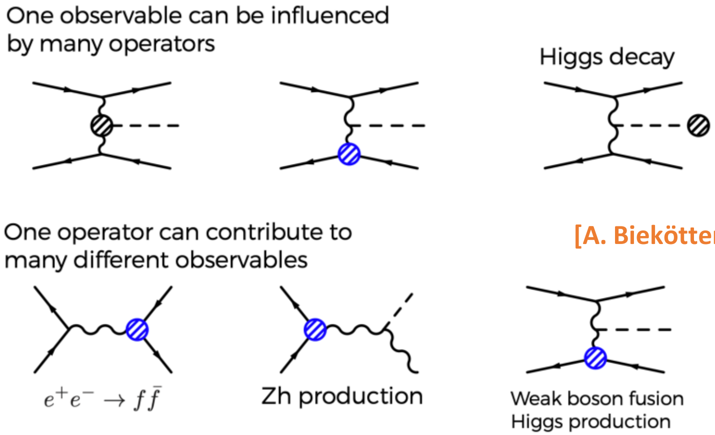
The choices in the fitter's way

- **Dataset**
- **Likelihoods**

Global fits

Correlations, correlations everywhere…





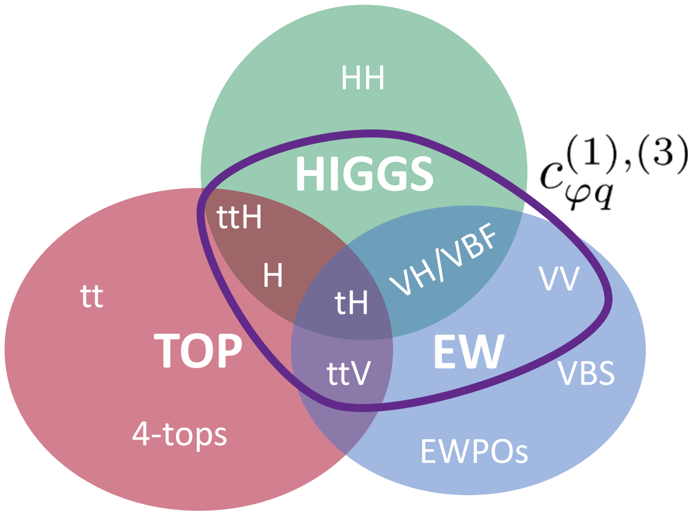
[A. Biekötter's seminar]

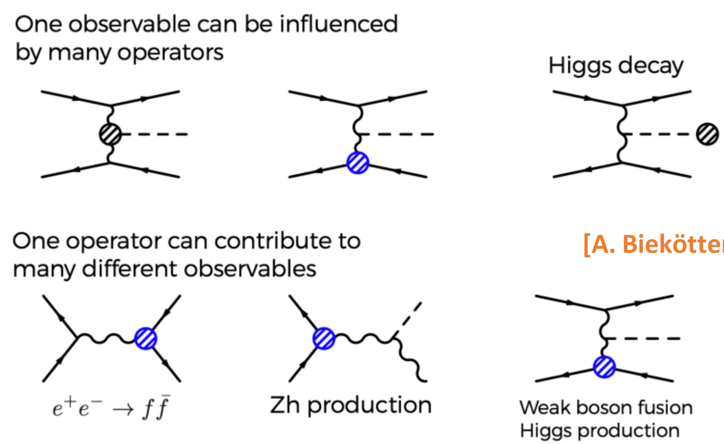
The choices in the fitter's way

- **Dataset**
- **Likelihoods**
- **QCD/EW Pert. Order**

Global fits

Correlations, correlations everywhere…





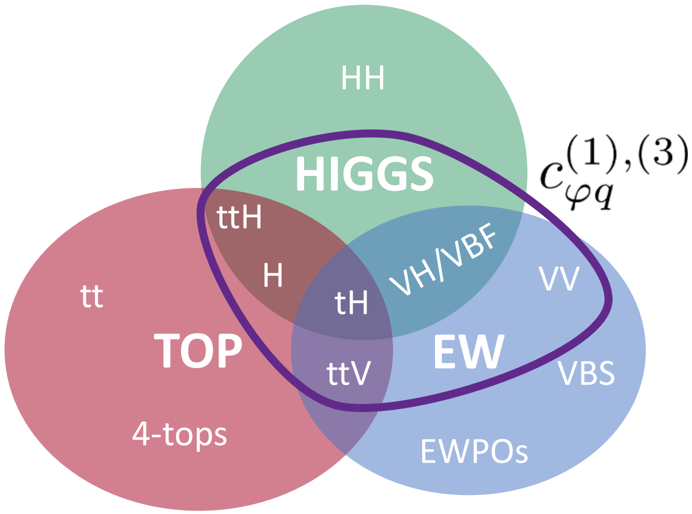
[A. Biekötter's seminar]

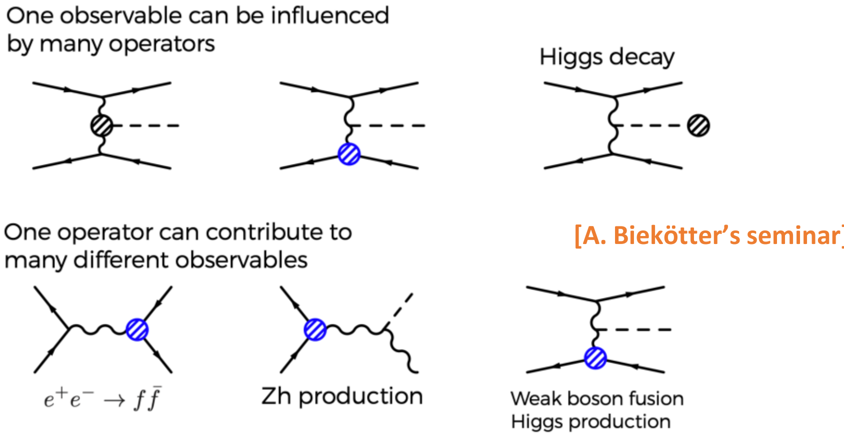
The choices in the fitter's way

- Dataset
- Likelihoods
- QCD/EW Pert. Order
- EFT Order

Global fits

Correlations, correlations everywhere...



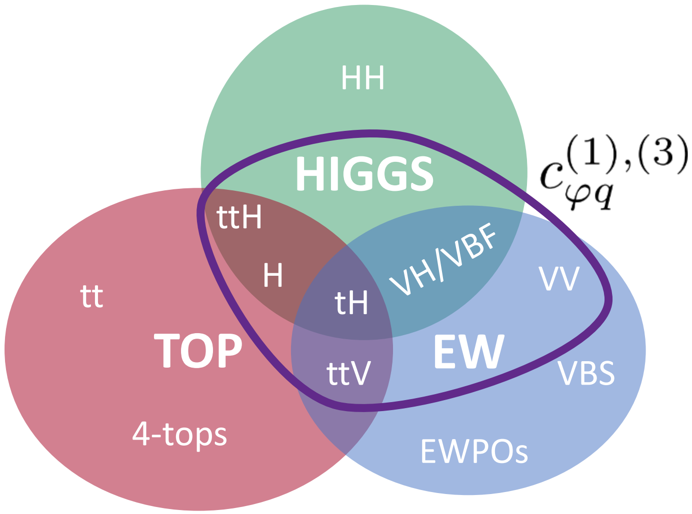


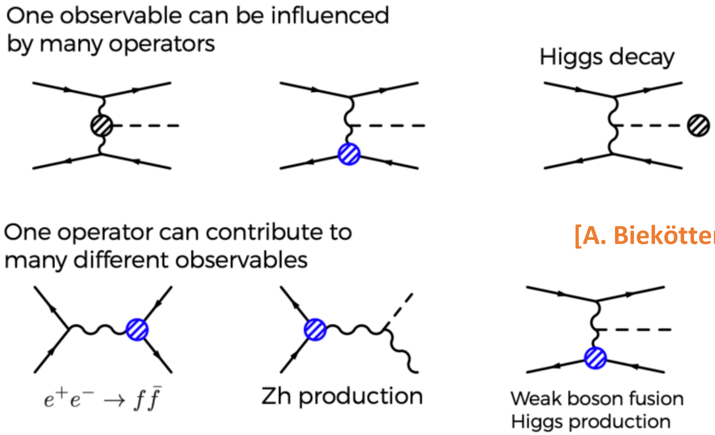
The choices in the fitter's way

- **Dataset**
- **Likelihoods**
- **QCD/EW Pert. Order**
- **EFT Order**
- **EFT Flavour Assump.**

Global fits

Correlations, correlations everywhere…





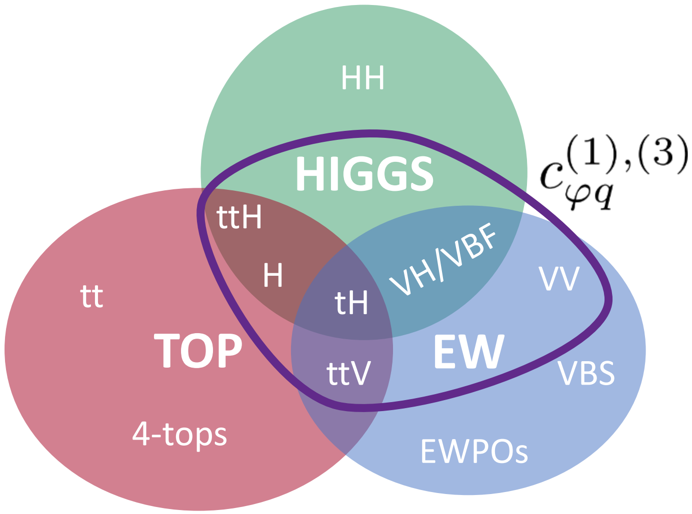
[A. Biekötter's seminar]

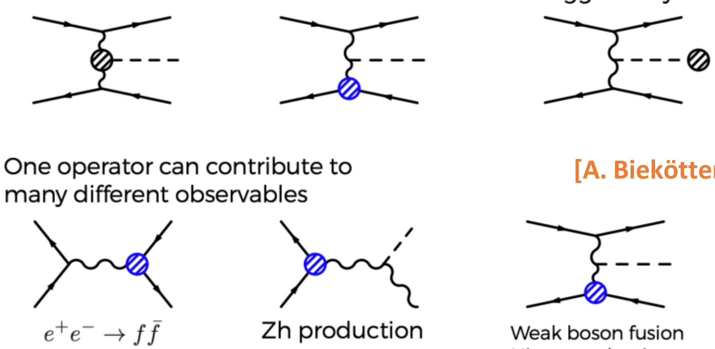
The choices in the fitter's way

- Dataset
- Likelihoods
- QCD/EW Pert. Order
- Fitting and stat. method
- EFT Order
- EFT Flavour Assump.

Global fits

Correlations, correlations everywhere…





[A. Biekötter's seminar]

The choices in the fitter's way

- Dataset
- Likelihoods
- QCD/EW Pert. Order
- Fitting and stat. method
- EFT Order
- EFT Flavour Assump.

Fitmaker [2012. 02779]

HEPfit [1910.14012]

SMEFiT [2302.06660]

SFitter [2208. 08454]

…

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

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
50 WCs!

↓

SMEFiT

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
50 WCs!

DATA

LEP+SLD: EWPOs, WW, BrW…
LHC: Higgs, top, VV… Mostly Run-2
445 data points!

→ SMEFiT

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
50 WCs!

DATA

LEP+SLD: EWPOs, WW, BrW…
LHC: Higgs, top, VV… Mostly Run-2
445 data points!

METHOD

Bayesian **Nested Sampling**

SMEFiT

SMEFiT In a nutshell

v. 2.0: [2302.06660]
v. 3.0: [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
50 WCs!

DATA

LEP+SLD: EWPOs, WW, BrW…
LHC: Higgs, top, VV… Mostly Run-2
445 data points!

METHOD

Bayesian **Nested Sampling**

SMEFiT

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

Posterior on WCs

SMEFiT In a nutshell

v. 2.0: [2302.06660]
v. 3.0: [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
50 WCs!

DATA

LEP+SLD: EWPOs, WW, BrW…
LHC: Higgs, top, VV… Mostly Run-2
445 data points!

METHOD

Bayesian **Nested Sampling**

SMEFiT

TOOLS

PCA, Fisher, closure tests, documentation.

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

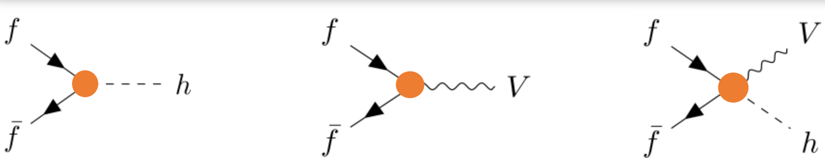
Posterior on WCs

MANCHESTER 1824
The University of Manchester

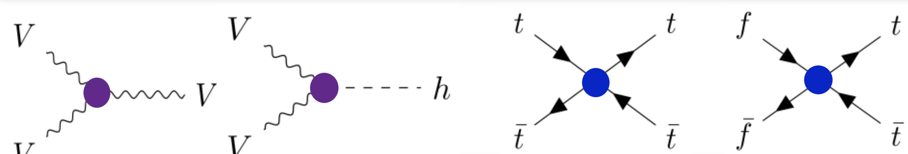
Operator basis

- **Warsaw basis with rotations.**
- **Flavour sym.: $U(2)_q \times U(3)_d \times U(2)_u \times (U(1)_l \times U(1)_e)^3 + y^{SM}_{b,c,\tau} + c_{\varphi(b,c,\tau)}$**

Operator	Coefficient	Definition	Operator	Coefficient	Definition
		3rd generation quarks			
$\mathcal{O}^{(1)}_{\varphi Q}$	$c^{(1)}_{\varphi Q}$ (*)	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{Q}\gamma^\mu Q)$	$\mathcal{O}_{tW}$	c_{tW}	$i(\bar{Q}\tau^{\mu\nu}\tau_I t)\tilde{\varphi}W^I_{\mu\nu} + \text{h.c.}$
$\mathcal{O}^{(3)}_{\varphi Q}$	$c^{(3)}_{\varphi Q}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I \varphi)(\bar{Q}\gamma^\mu \tau^I Q)$	$\mathcal{O}_{tB}$	c_{tB} (*)	$i(\bar{Q}\tau^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{\varphi t}$	$c_{\varphi t}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{t}\gamma^\mu t)$	$\mathcal{O}_{tG}$	c_{tG}	$ig_S(\bar{Q}\tau^{\mu\nu}T_A t)\tilde{\varphi}G^A_{\mu\nu} + \text{h.c.}$
$\mathcal{O}_{t\varphi}$	$c_{t\varphi}$	$(\varphi^\dagger\varphi)\bar{Q}t\tilde{\varphi} + \text{h.c.}$	$\mathcal{O}_{b\varphi}$	$c_{b\varphi}$	$(\varphi^\dagger\varphi)\bar{Q}b\varphi + \text{h.c.}$
		1st, 2nd generation quarks			
$\mathcal{O}^{(1)}_{\varphi q}$	$c^{(1)}_{\varphi q}$ (*)	$\sum_{i=1,2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{q}_i\gamma^\mu q_i)$	$\mathcal{O}_{\varphi d}$	$c_{\varphi d}$	$\sum_{i=1,2,3} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{d}_i\gamma^\mu d_i)$
$\mathcal{O}^{(3)}_{\varphi q}$	$c^{(3)}_{\varphi q}$	$\sum_{i=1,2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I\varphi)(\bar{q}_i\gamma^\mu \tau^I q_i)$	$\mathcal{O}_{c\varphi}$	$c_{c\varphi}$	$(\varphi^\dagger\varphi)\bar{q}_2 c\tilde{\varphi} + \text{h.c.}$
$\mathcal{O}_{\varphi u}$	$c_{\varphi u}$	$\sum_{i=1,2} i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{u}_i\gamma^\mu u_i)$			
		two-leptons			
$\mathcal{O}_{\varphi \ell_i}$	$c_{\varphi \ell_i}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{\ell}_i\gamma^\mu \ell_i)$	$\mathcal{O}_{\varphi\mu}$	$c_{\varphi\mu}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{\mu}\gamma^\mu \mu)$
$\mathcal{O}^{(3)}_{\varphi \ell_i}$	$c^{(3)}_{\varphi \ell_i}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \tau_I\varphi)(\bar{\ell}_i\gamma^\mu \tau^I \ell_i)$	$\mathcal{O}_{\varphi\tau}$	$c_{\varphi\tau}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{\tau}\gamma^\mu \tau)$
$\mathcal{O}_{\varphi e}$	$c_{\varphi e}$	$i(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi)(\bar{e}\gamma^\mu e)$	$\mathcal{O}_{\tau\varphi}$	$c_{\tau\varphi}$	$(\varphi^\dagger\varphi)\bar{\ell}_3\tau\varphi + \text{h.c.}$
		four-leptons			
$\mathcal{O}_{\ell\ell}$	$c_{\ell\ell}$	$(\bar{\ell}_1\gamma_\mu\ell_2)(\bar{\ell}_2\gamma^\mu\ell_1)$			



Operator	Coefficient	Definition	Operator	Coefficient	Definition
$\mathcal{O}_{\varphi G}$	$c_{\varphi G}$	$(\varphi^\dagger\varphi)G^{\mu\nu}_A G^A_{\mu\nu}$	$\mathcal{O}_{\varphi\Box}$	$c_{\varphi\Box}$	$\partial_\mu(\varphi^\dagger\varphi)\partial^\mu(\varphi^\dagger\varphi)$
$\mathcal{O}_{\varphi B}$	$c_{\varphi B}$	$(\varphi^\dagger\varphi)B^{\mu\nu}B_{\mu\nu}$	$\mathcal{O}_{\varphi D}$	$c_{\varphi D}$	$(\varphi^\dagger D^\mu\varphi)^\dagger(\varphi^\dagger D_\mu\varphi)$
$\mathcal{O}_{\varphi W}$	$c_{\varphi W}$	$(\varphi^\dagger\varphi)W^{\mu\nu}_I W^I_{\mu\nu}$	$\mathcal{O}_W$	c_{WWW}	$\epsilon_{IJK}W^I_{\mu\nu}W^{J,\nu\rho}W^{K,\mu}_\rho$
$\mathcal{O}_{\varphi WB}$	$c_{\varphi WB}$	$(\varphi^\dagger\tau_I\varphi)B^{\mu\nu}W^I_{\mu\nu}$			

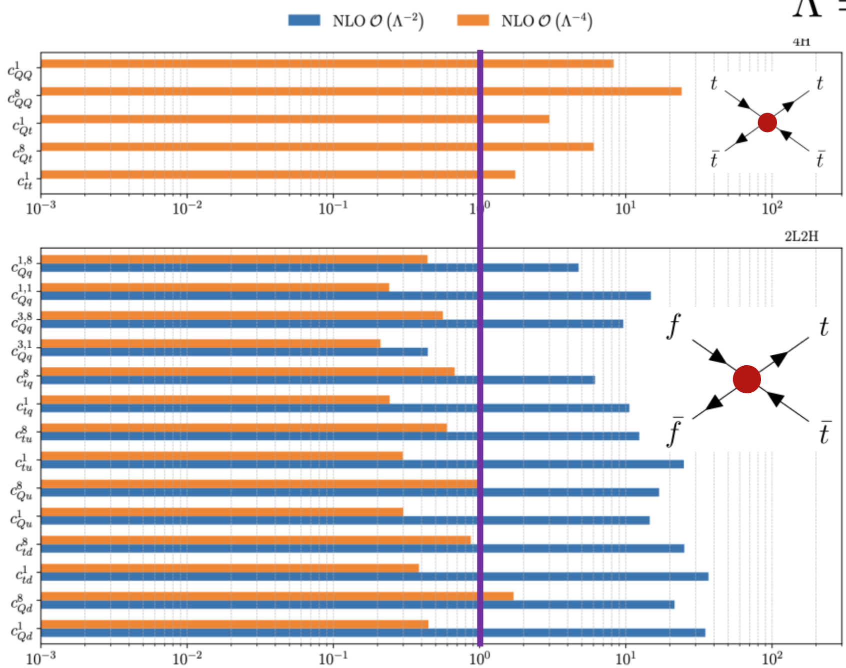


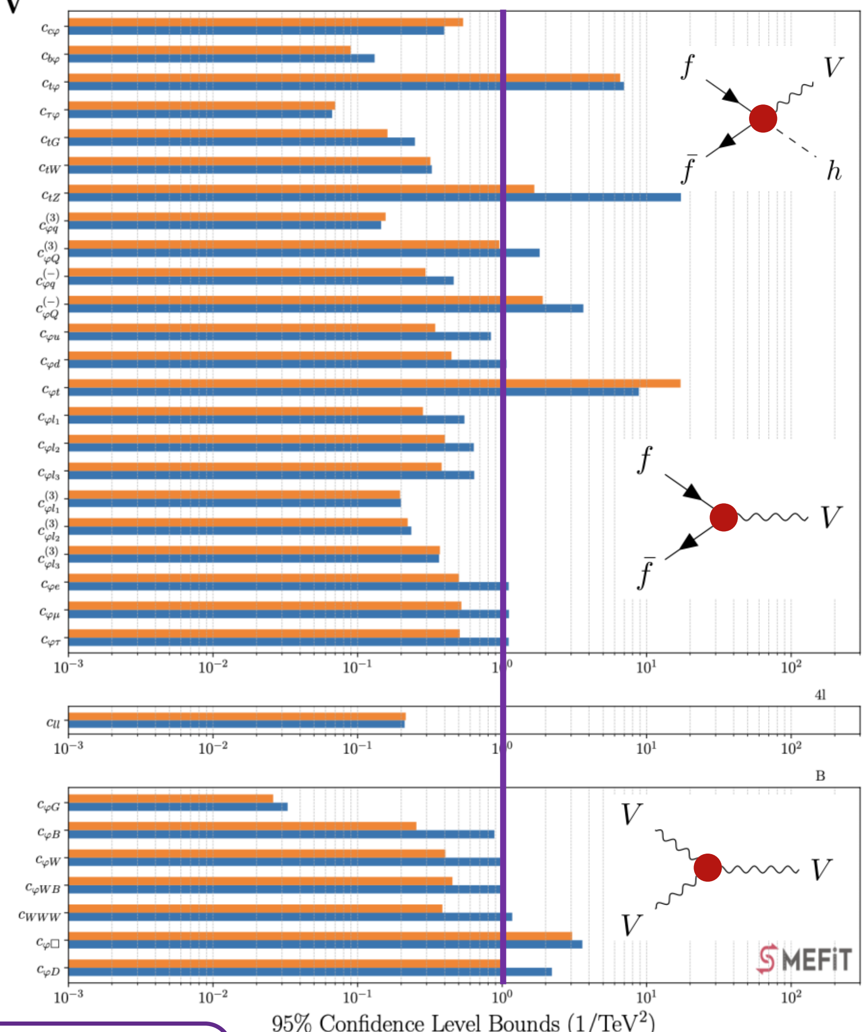
DoF	Definition (in Warsaw basis notation)	DoF	Definition (in Warsaw basis notation)
c^1_{QQ}	$2c^{1(3333)}_{qq} - \frac{2}{3}c^{3(3333)}_{qq}$	c^8_{QQ}	$8c^{3(3333)}_{qq}$
c^1_{Qt}	$c^{1(3333)}_{qu}$	c^8_{Qt}	$c^{8(3333)}_{qu}$
$c^{1,8}_{Qq}$	$c^{1(i33i)}_{qq} + 3c^{3(i33i)}_{qq}$	$c^{1,1}_{Qq}$	$c^{1(ii33)}_{qq} + \frac{1}{6}c^{1(i33i)}_{qq} + \frac{1}{2}c^{3(i33i)}_{qq}$
$c^{3,8}_{Qq}$	$c^{1(i33i)}_{qq} - c^{3(i33i)}_{qq}$	$c^{3,1}_{Qq}$	$c^{3(ii33)}_{qq} + \frac{1}{6}(c^{1(i33i)}_{qq} - c^{3(i33i)}_{qq})$
c^8_{tq}	$c^{8(ii33)}_{qu}$	c^1_{tq}	$c^{1(ii33)}_{qu}$
c^8_{tu}	$2c^{(i33i)}_{uu}$	c^1_{tu}	$c^{(ii33)}_{uu} + \frac{1}{3}c^{(i33i)}_{uu}$
c^8_{Qu}	$c^{8(33ii)}_{qu}$	c^1_{Qu}	$c^{1(33ii)}_{qu}$
c^8_{td}	$c^{8(33jj)}_{ud}$	c^1_{td}	$c^{1(33jj)}_{ud}$
c^8_{Qd}	$c^{8(33jj)}_{qd}$	c^1_{Qd}	$c^{1(33jj)}_{qd}$

Fit of 45 (50) WCs at the linear (quadratic) level

SMEFiT 3.0 results

$\Lambda = 1\,\mathrm{TeV}$





- Marginalised fit
- LEP + LHC

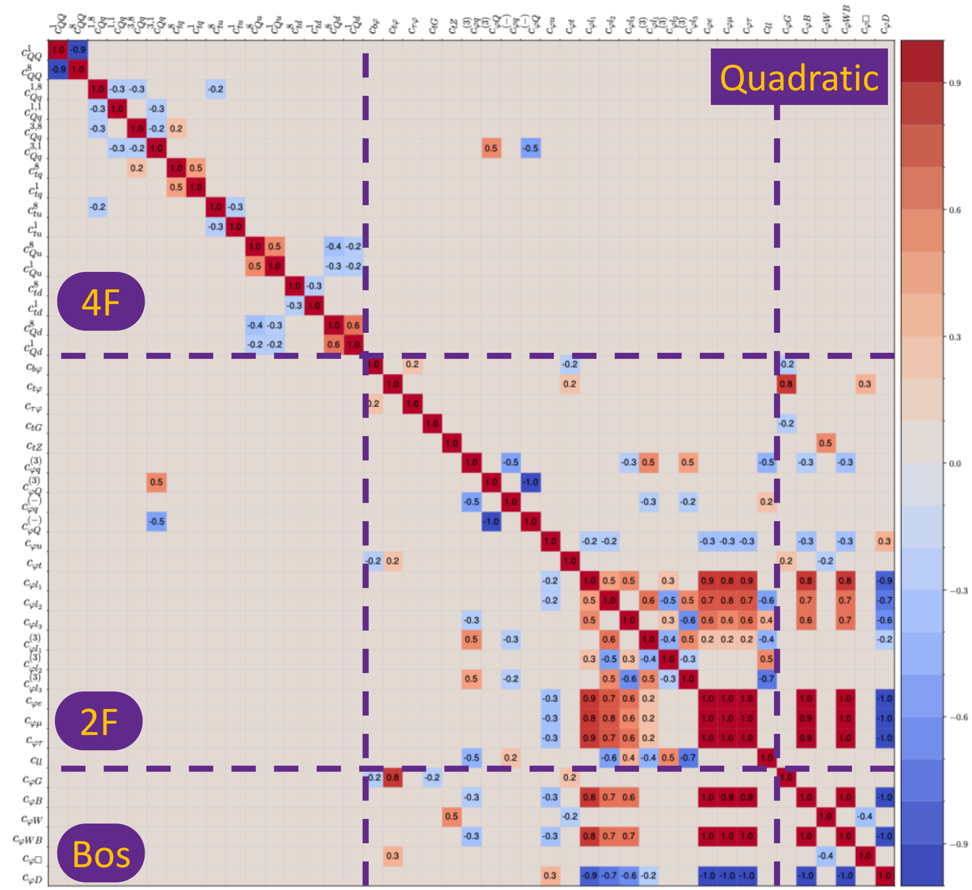
Linear in EFT

Quadratic in EFT

Many bounds dominated by quadratic contributions

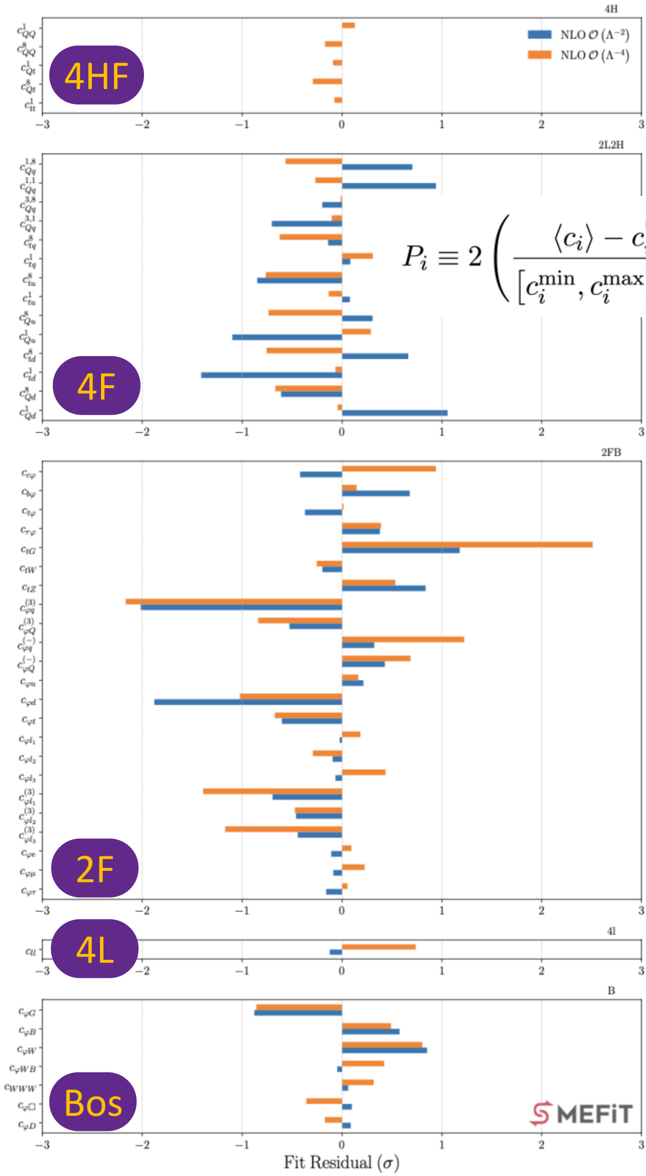
Pulls and correlations

No large correlations



Correlation: NLO $\mathcal{O}\left(\Lambda^{-4}\right)$

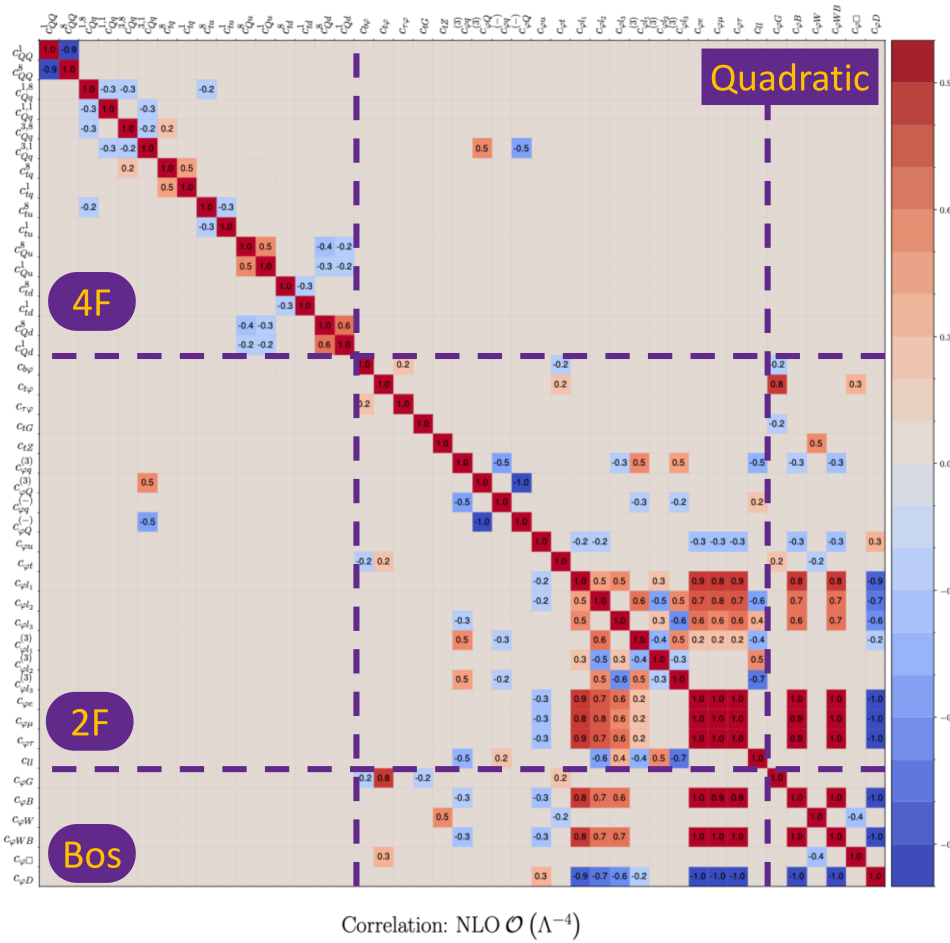
Pulls and correlations



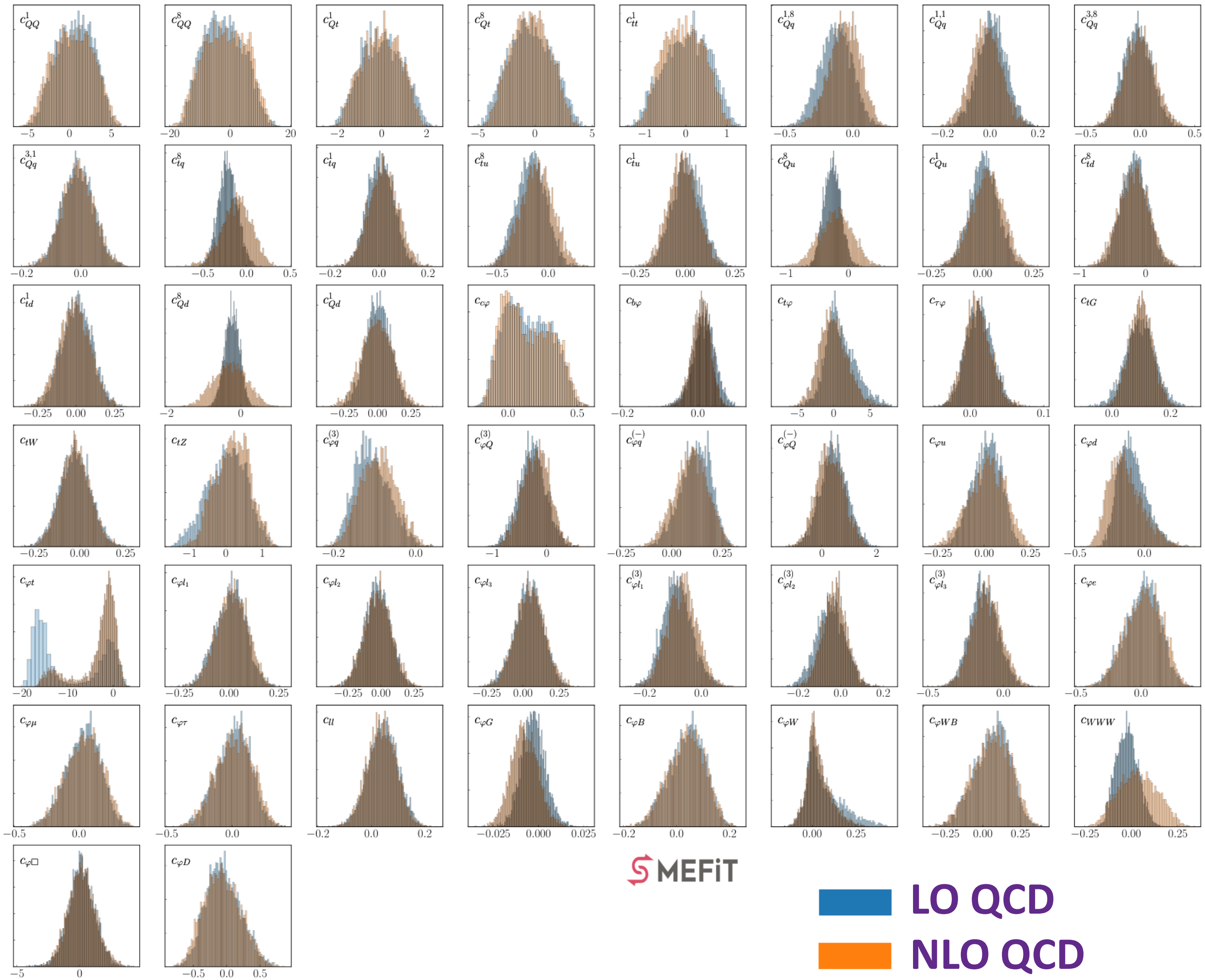
$$P_i \equiv 2\left(\frac{\langle c_i\rangle - c_i^{(\mathrm{SM})}}{\left[c_i^{\min}, c_i^{\max}\right]^{68\%\ \mathrm{CI}}}\right)$$

Fit residuals (pulls) largely SM compatible

No large correlations



NLO QCD in the EFT effects



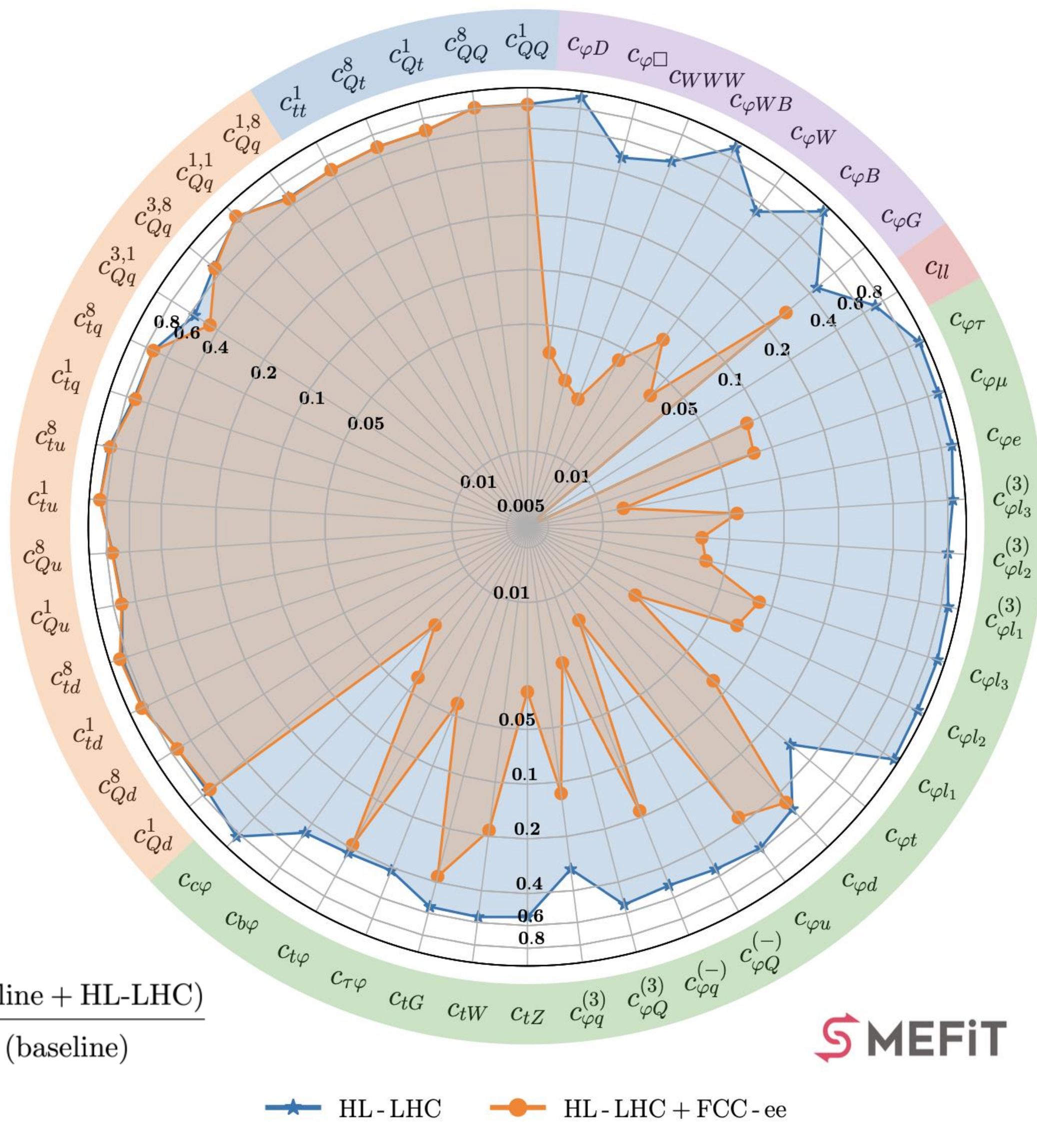
MANCHESTER 1824 The University of Manchester

An eye on the future

Implemented in SMEFiT

Improvements at HL-LHC and FCC-ee

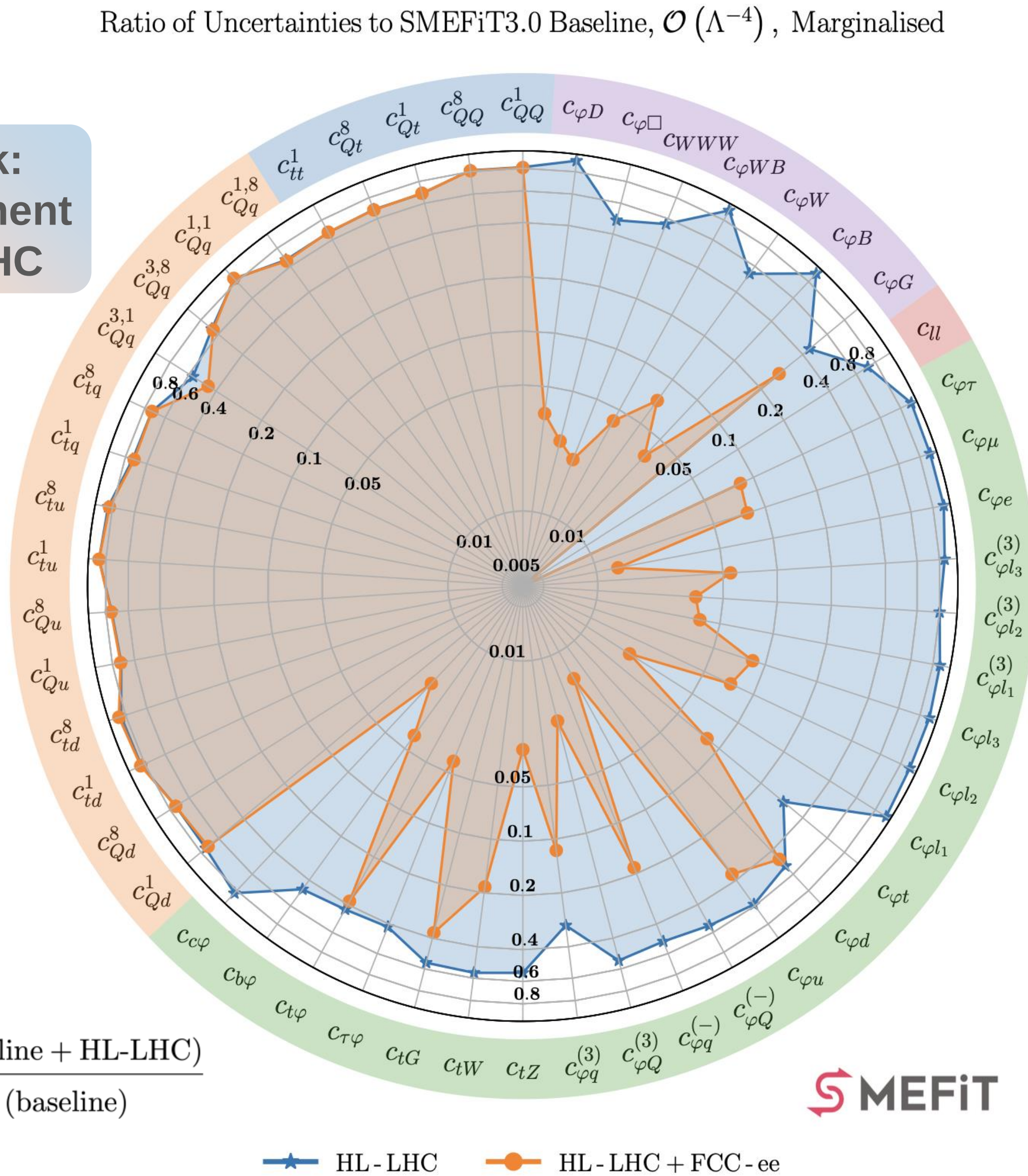
Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}\left(\Lambda^{-4}\right)$, Marginalised



$$R_{\delta c_i} = \frac{\left[c_i^{\min}, c_i^{\max}\right]^{95\%\ \mathrm{CL}}\ (\text{baseline} + \text{HL-LHC})}{\left[c_i^{\min}, c_i^{\max}\right]^{95\%\ \mathrm{CL}}\ (\text{baseline})}$$

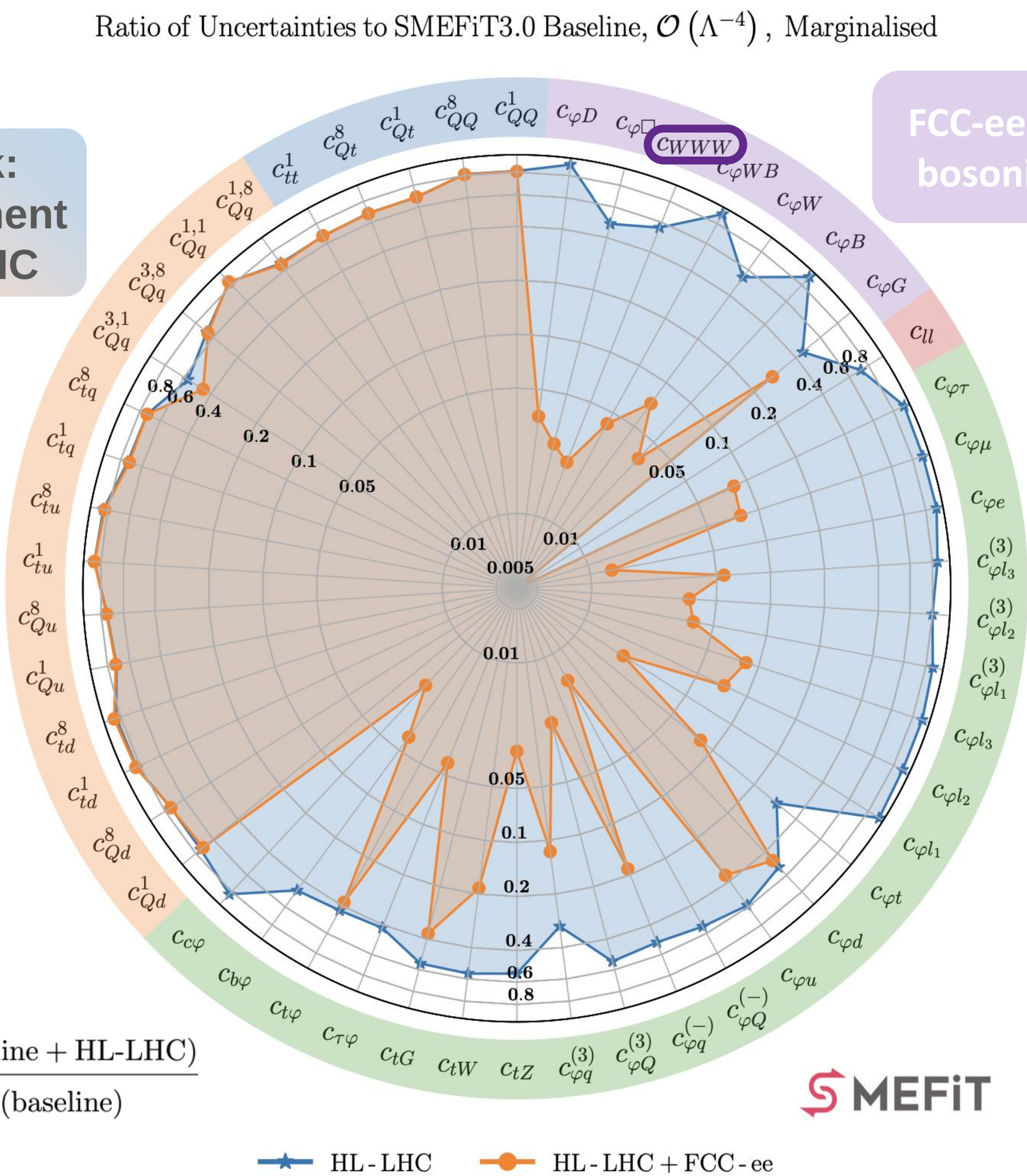
Improvements at HL-LHC and FCC-ee

4-quark: improvement at HL-LHC



$$R_{\delta c_i} = \frac{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CL}}\ (\text{baseline} + \text{HL-LHC})}{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CL}}\ (\text{baseline})}$$

Improvements at HL-LHC and FCC-ee



4-quark: improvement at HL-LHC

FCC-ee probes well bosonic operators

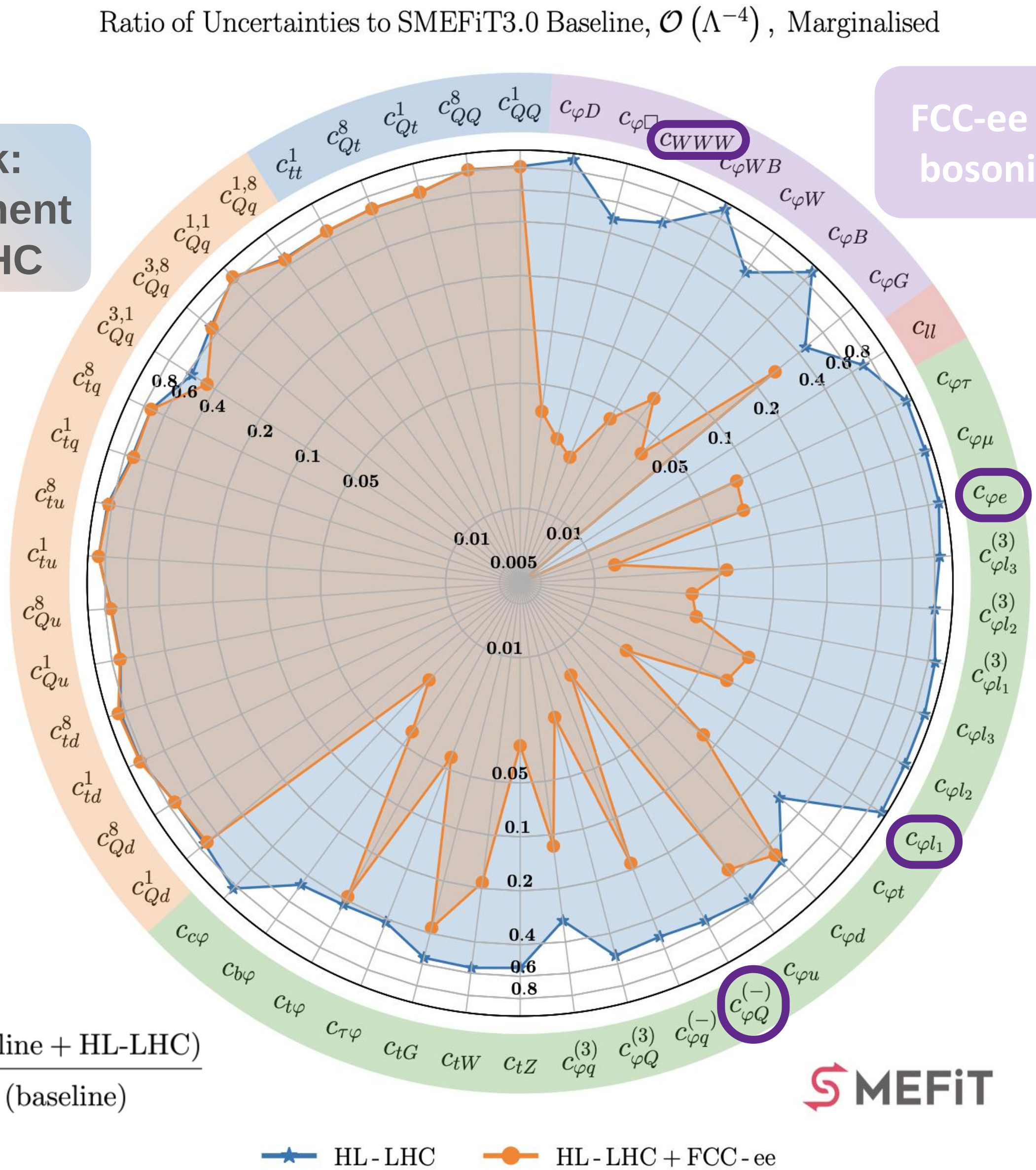
$$R_{\delta c_i} = \frac{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CL}}\ (\text{baseline} + \text{HL-LHC})}{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CL}}\ (\text{baseline})}$$

SMEFiT

MANCHESTER 1824 The University of Manchester

Improvements at HL-LHC and FCC-ee

4-quark: improvement at HL-LHC



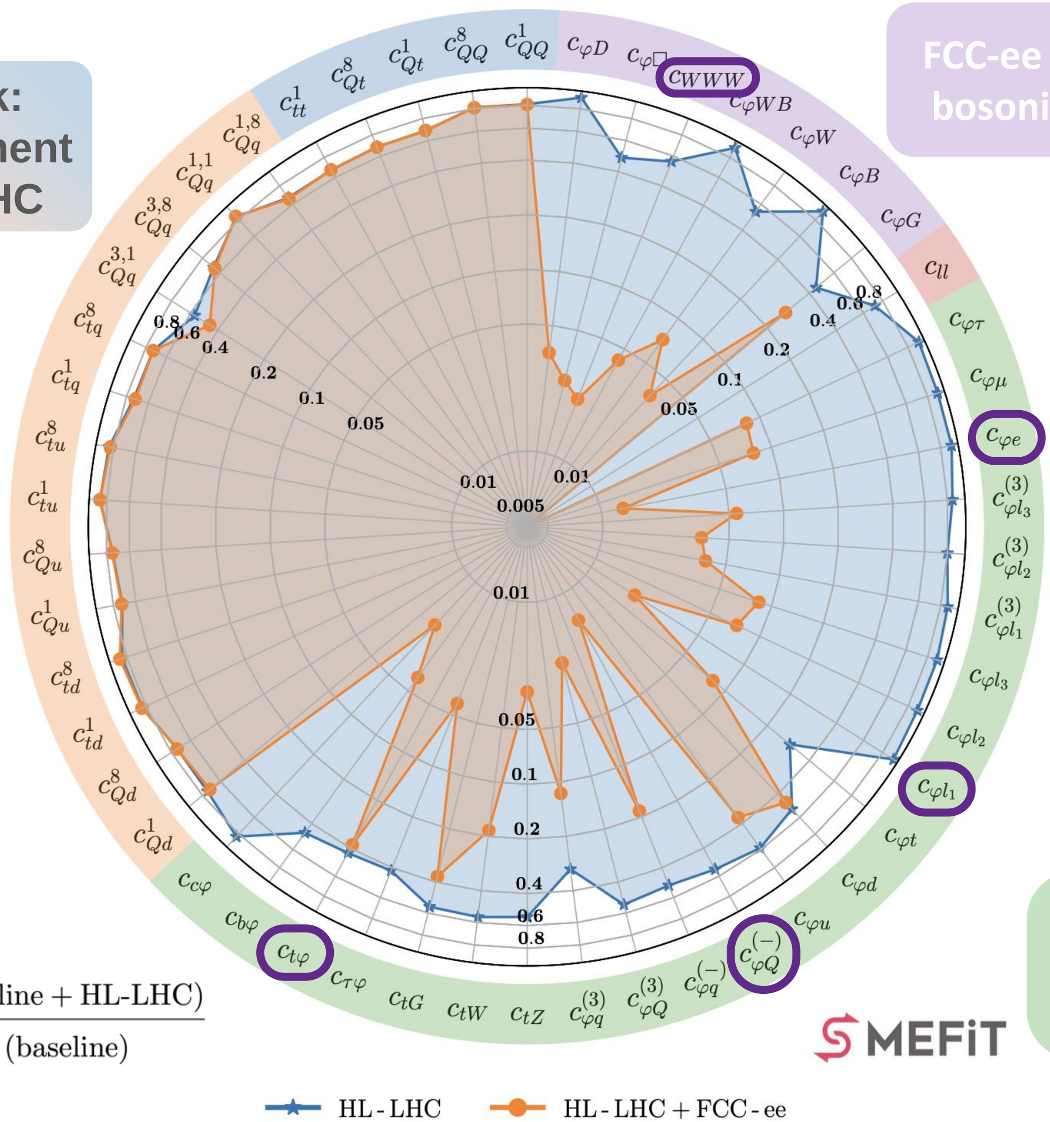
FCC-ee probes well bosonic operators

And several 2-fermion operators!

$$R_{\delta c_i} = \frac{\left[c_i^{\min}, c_i^{\max}\right]^{95\%\ \mathrm{CL}}\ (\text{baseline} + \text{HL-LHC})}{\left[c_i^{\min}, c_i^{\max}\right]^{95\%\ \mathrm{CL}}\ (\text{baseline})}$$

Improvements at HL-LHC and FCC-ee

Ratio of Uncertainties to SMEFiT3.0 Baseline, $\mathcal{O}(\Lambda^{-4})$, Marginalised



4-quark: improvement at HL-LHC

FCC-ee probes well bosonic operators

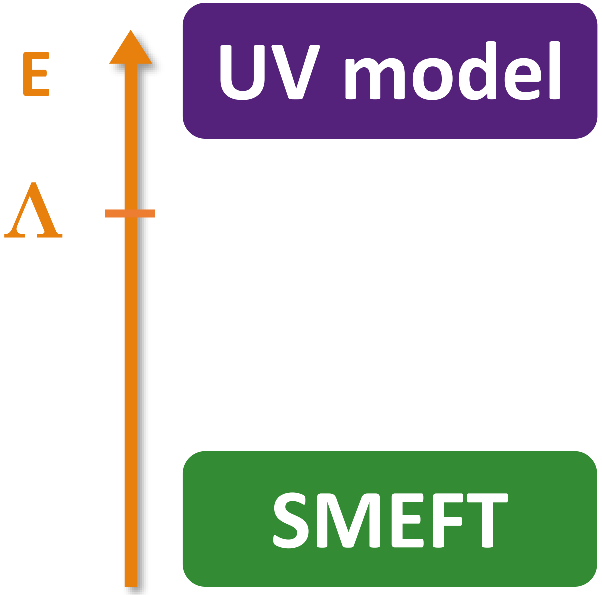
And several 2-fermion operators!

Top Yukawa only at HL-LHC

$$R_{\delta c_i} = \frac{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CL}}\ (\mathrm{baseline} + \mathrm{HL\text{-}LHC})}{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CL}}\ (\mathrm{baseline})}$$

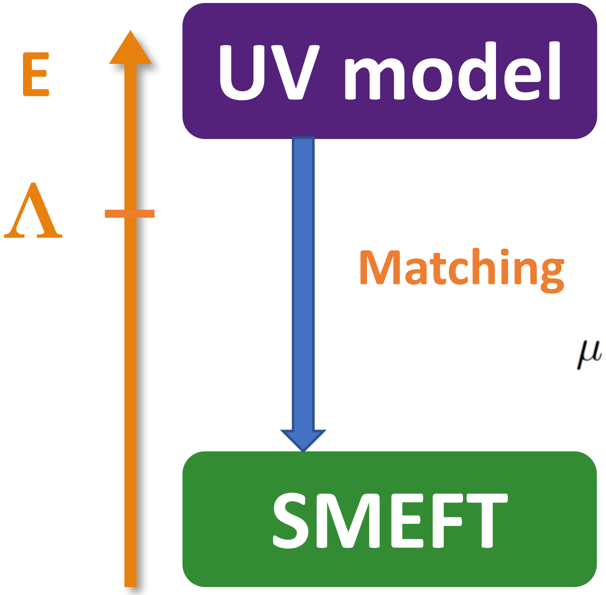
SMEFiT

UV perspective



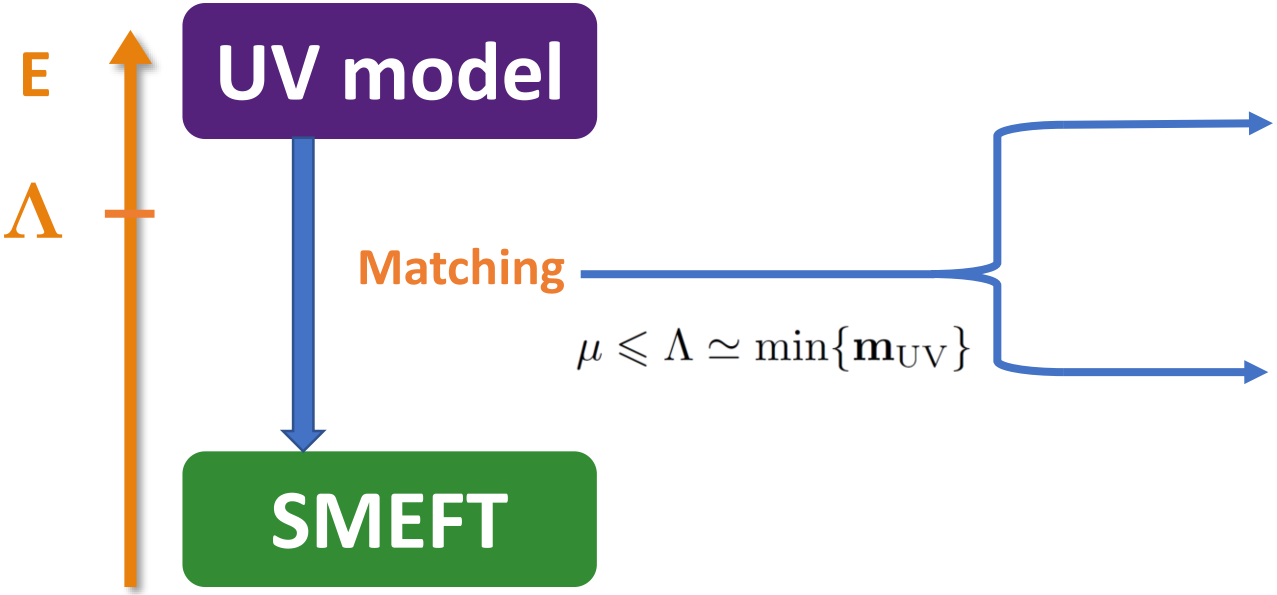
MANCHESTER 1824
The University of Manchester

UV perspective

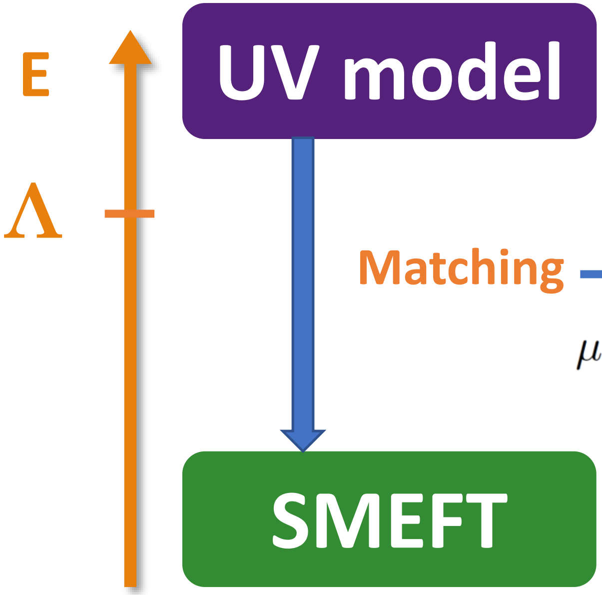


$$\mu \leqslant \Lambda \simeq \min\{\mathbf{m}_{\mathrm{UV}}\}$$

UV perspective



UV perspective



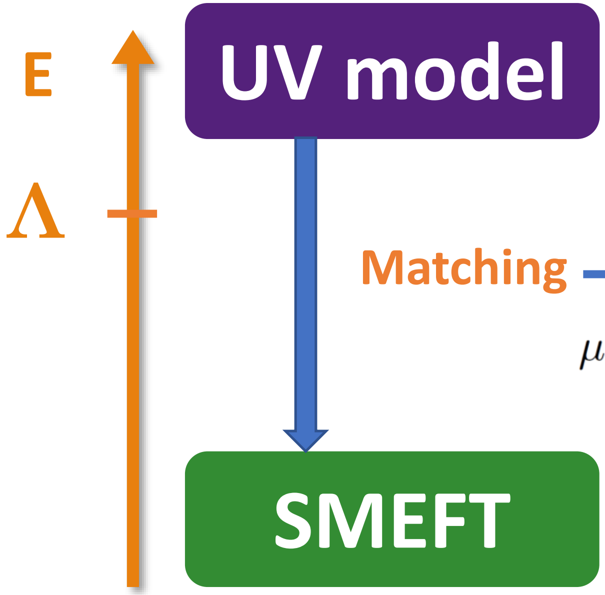
Matching

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

Functional

$$\Gamma_{\mathrm{1LPI,\,UV}}[\phi_{\mathrm{IR}}] = \Gamma_{\mathrm{EFT}}[\phi_{\mathrm{IR}}] + \mathcal{O}\left(\Lambda^{-(n+1)}\right)$$

UV perspective



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

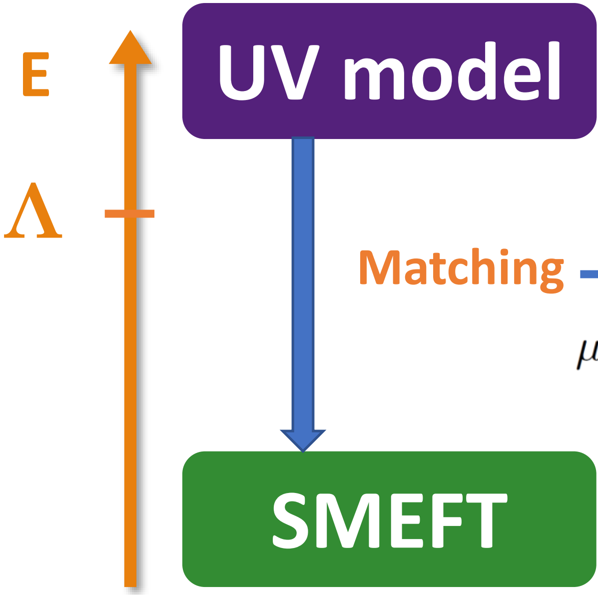
Functional

$$\Gamma_{1\mathrm{LPI,\ UV}}[\phi_{\mathrm{IR}}] = \Gamma_{\mathrm{EFT}}[\phi_{\mathrm{IR}}] + \mathcal{O}\left(\Lambda^{-(n+1)}\right)$$

Diagrammatic

$$\mathcal{M}_{1\mathrm{LPI,\ UV}}[p_i] = \mathcal{M}_{\mathrm{EFT}}[p_i] + \mathcal{O}\left(\Lambda^{-(n+1)}\right)$$

UV perspective



Matching

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

Functional

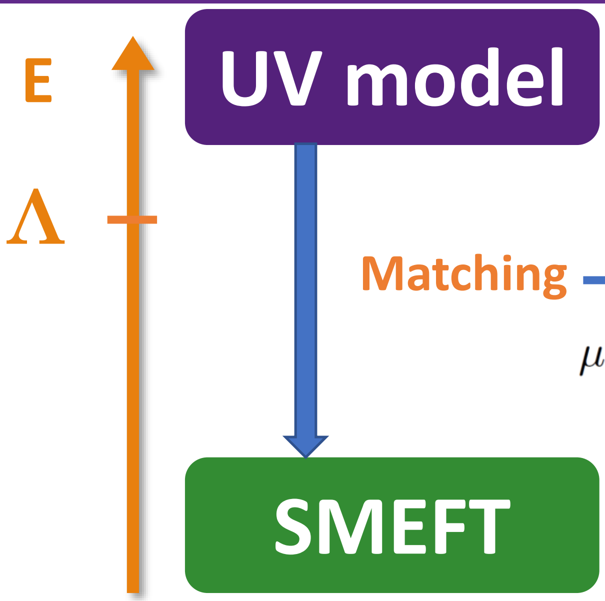
$$\Gamma_{\mathrm{1LPI,\ UV}}[\phi_{\mathrm{IR}}] = \Gamma_{\mathrm{EFT}}[\phi_{\mathrm{IR}}] + \mathcal{O}\left(\Lambda^{-(n+1)}\right)$$

Diagrammatic

$$\mathcal{M}_{\mathrm{1LPI,\ UV}}[p_i] = \mathcal{M}_{\mathrm{EFT}}[p_i] + \mathcal{O}\left(\Lambda^{-(n+1)}\right)$$

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

UV perspective



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

Functional

$$\Gamma_{\mathrm{1LPI,\,UV}}[\phi_{\mathrm{IR}}] = \Gamma_{\mathrm{EFT}}[\phi_{\mathrm{IR}}] + \mathcal{O}\left(\Lambda^{-(n+1)}\right)$$

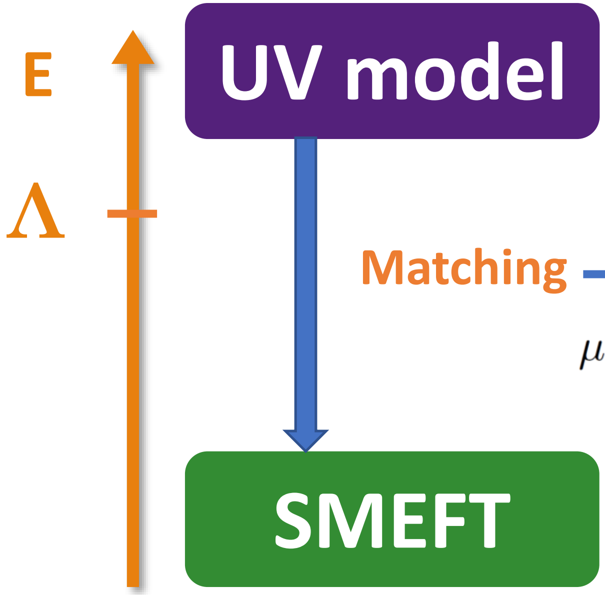
Diagrammatic

$$\mathcal{M}_{\mathrm{1LPI,\,UV}}[p_i] = \mathcal{M}_{\mathrm{EFT}}[p_i] + \mathcal{O}\left(\Lambda^{-(n+1)}\right)$$

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

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

UV perspective



Matching

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

Functional

$$\Gamma_{\text{1LPI, UV}}[\phi_{\text{IR}}] = \Gamma_{\text{EFT}}[\phi_{\text{IR}}] + \mathcal{O}\left(\Lambda^{-(n+1)}\right)$$

Diagrammatic

$$\mathcal{M}_{\text{1LPI, UV}}[p_i] = \mathcal{M}_{\text{EFT}}[p_i] + \mathcal{O}\left(\Lambda^{-(n+1)}\right)$$

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

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

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

The state of matching affairs

Automated 1-loop matching*

***Only up to tree level for heavy spin-1 bosons.**

The state of matching affairs

Automated 1-loop matching*

- **Diagrammatic** — MEFT [2112.10787] Updated to v.1.1.3
- **Functional** — MATCHETE [2212. 04510] Updated to v.0.2.0; CO [1808. 04403]

*Only up to tree level for heavy spin-1 bosons.

The state of matching affairs

Automated 1-loop matching*

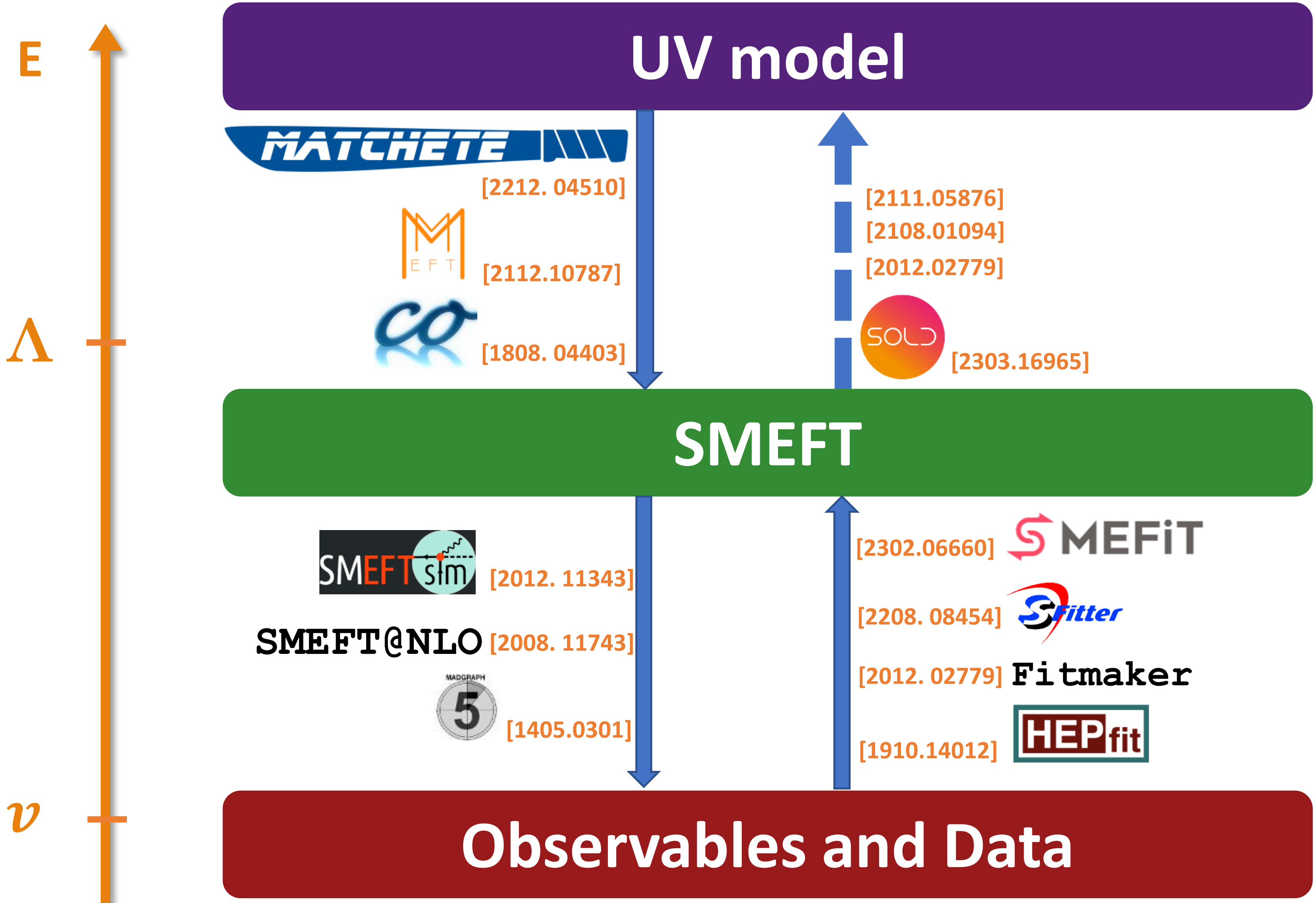
- **Diagrammatic** — MEFT [2112.10787] Updated to v.1.1.3
- **Functional** — MATCHETE [2212. 04510] Updated to v.0.2.0; CO [1808. 04403]

- **On-shell matching techniques** [2308.00035] [F. Vilches@Planck24] [J. López Miras@HEFT2024]
- **Matching with Spontaneous Symmetry Breaking** [2404.11640]
- **Functional matching for dim. >6** [2306.09103] [2308.03849] [2311.12757]
- **1-loop dictionaries** [2303.16965] [P. Olgoso@HEFT2024] [J. Gargalionis@Planck24]
- **2-loop matching** [2311.13630] [J. Fuentes-Martín@HEFT2024]

Disclaimer: incomplete list.

*Only up to tree level for heavy spin-1 bosons.

Automation across scales



Apologies for not including all tools/codes due to space restrictions.

Bridging the gap

Automating the reuse of SMEFT predictions and global fits to bound UV models

Constrains on WCs from UV matching

Tree-level matching

$$\frac{\left(c_{qd}^{(1)}\right)_{3333}}{\Lambda^2} = -\frac{\left(y_\phi^d\right)_{33}^2}{6\,m_\phi^2}, \quad \frac{\left(c_{qd}^{(8)}\right)_{3333}}{\Lambda^2} = -\frac{\left(y_\phi^d\right)_{33}^2}{m_\phi^2}, \quad \frac{(c_{d\varphi})_{33}}{\Lambda^2} = \frac{\lambda_\phi \left(y_\phi^d\right)_{33}}{m_\phi^2}, \quad \frac{c_\varphi}{\Lambda^2} = \frac{\lambda_\phi^2}{m_\phi^2}$$

Constrains on WCs from UV matching

Tree-level matching

$$\frac{\left(c_{qd}^{(1)}\right)_{3333}}{\Lambda^2} = -\frac{\left(y_\phi^d\right)_{33}^2}{6\,m_\phi^2}, \quad \frac{\left(c_{qd}^{(8)}\right)_{3333}}{\Lambda^2} = -\frac{\left(y_\phi^d\right)_{33}^2}{m_\phi^2}, \quad \frac{(c_{d\varphi})_{33}}{\Lambda^2} = \frac{\lambda_\phi \left(y_\phi^d\right)_{33}}{m_\phi^2}, \quad \frac{c_\varphi}{\Lambda^2} = \frac{\lambda_\phi^2}{m_\phi^2}$$

One-loop level matching

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

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

$$-\left(12\lambda_\varphi^{\rm SM} + \left(y_b^{\rm SM}\right)^2 - 11\left(y_t^{\rm SM}\right)^2\right)\frac{y_t^{\rm SM}}{64\pi^2}\frac{\left(y_\phi^u\right)_{33}^2}{m_\phi^2} + \frac{3}{128\pi^2}\frac{\lambda_\phi \left(y_\phi^u\right)_{33}^3}{m_\phi^2},$$

Constrains on WCs from UV matching

Tree-level matching

$$\frac{\left(c_{qd}^{(1)}\right)_{3333}}{\Lambda^2} = -\frac{\left(y_\phi^d\right)_{33}^2}{6\, m_\phi^2}, \quad \frac{\left(c_{qd}^{(8)}\right)_{3333}}{\Lambda^2} = -\frac{\left(y_\phi^d\right)_{33}^2}{m_\phi^2}, \quad \frac{(c_{d\varphi})_{33}}{\Lambda^2} = \frac{\lambda_\phi \left(y_\phi^d\right)_{33}}{m_\phi^2}, \quad \frac{c_\varphi}{\Lambda^2} = \frac{\lambda_\phi^2}{m_\phi^2}$$

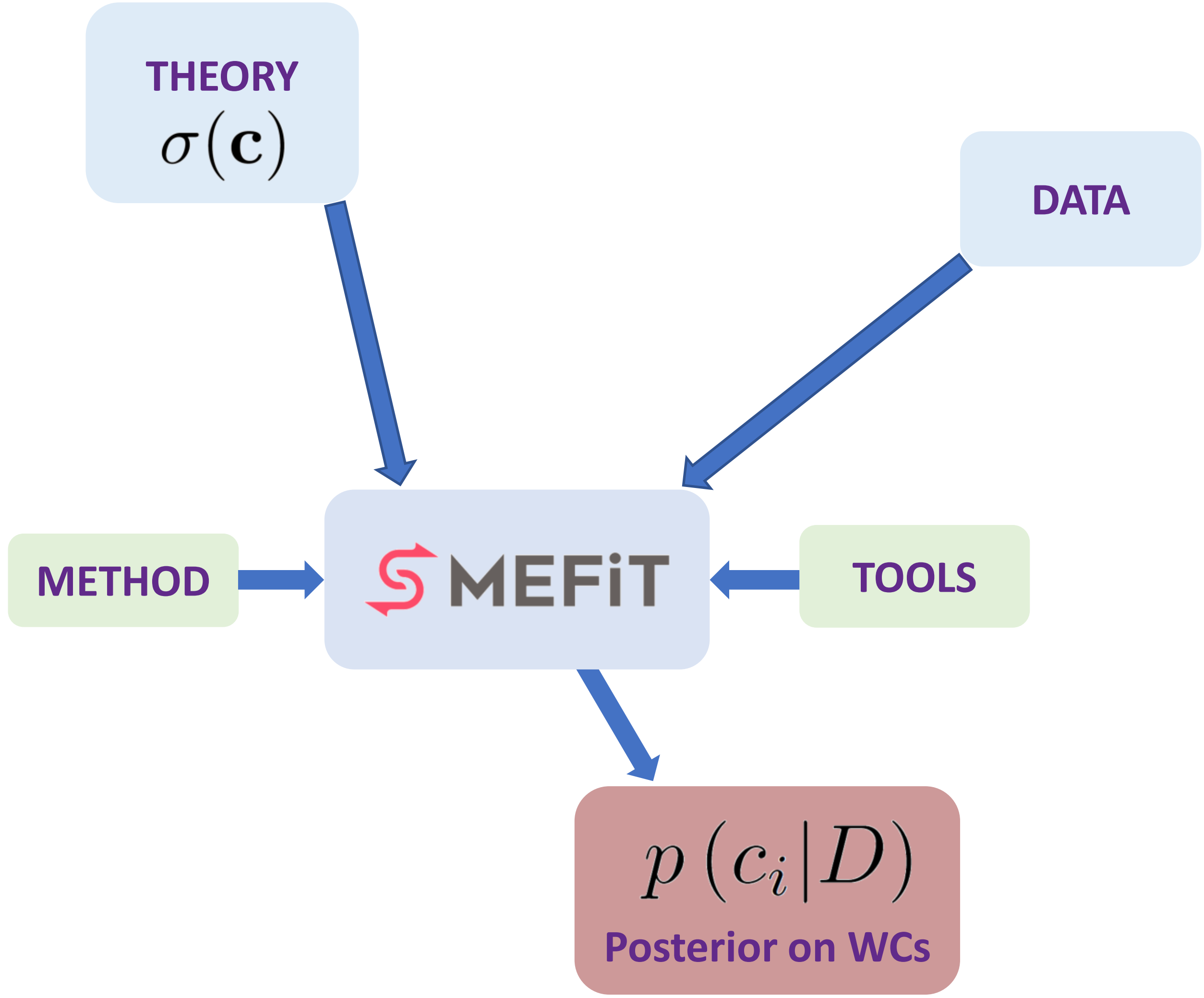
One-loop level matching

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

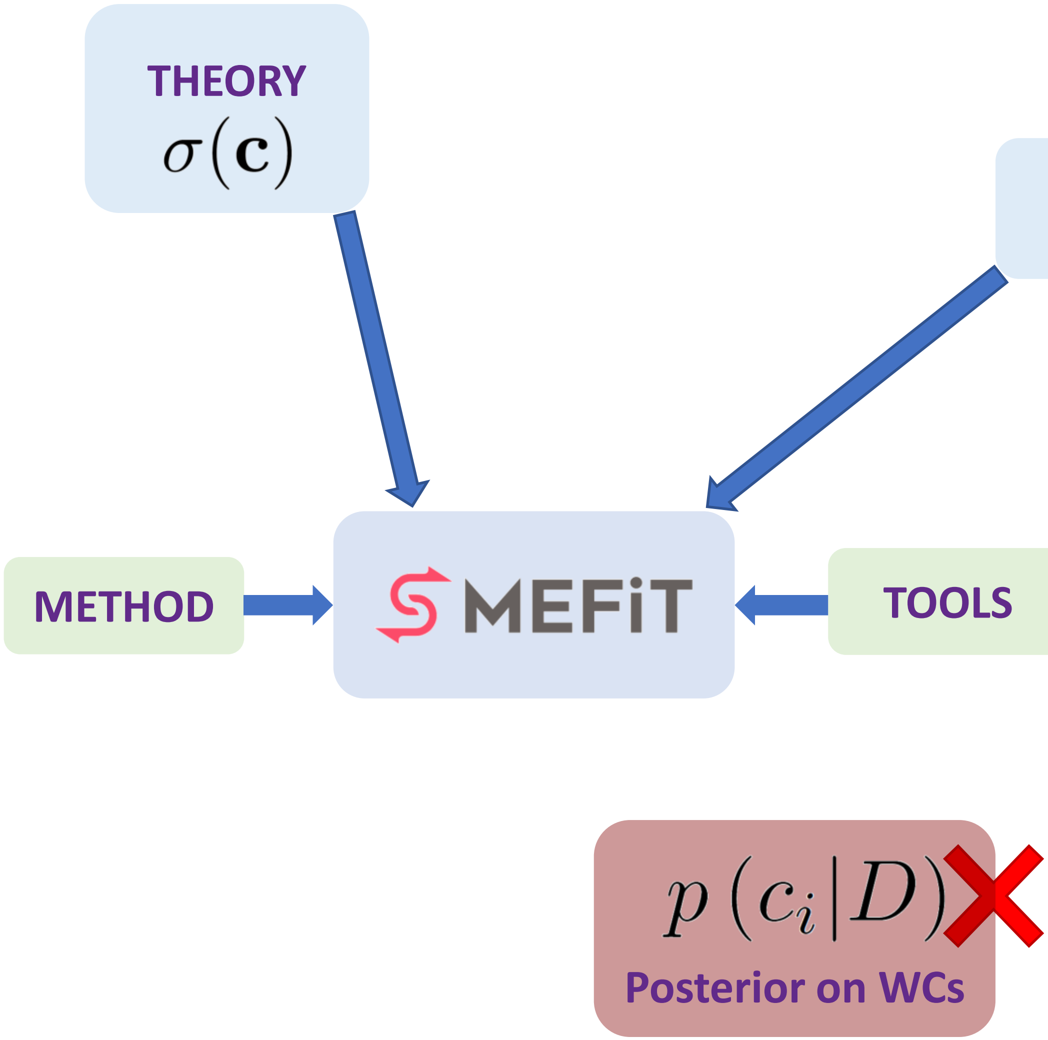
$$\frac{c_{t\varphi}}{\Lambda^2} = -\frac{\lambda_\phi \left(y_\phi^u\right)_{33}}{m_\phi^2} - \frac{g_2^4 y_t^{SM}}{3840\pi^2}\frac{1}{m_\phi^2} + \frac{y_t^{SM}}{16\pi^2}\frac{\lambda_\phi^2}{m_\phi^2} + \frac{\left(4\left(y_b^{SM}\right)^2 - 13\left(y_t^{SM}\right)^2\right)}{64\pi^2}\frac{\lambda_\phi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

UV constraints on the WC space are highly non trivial

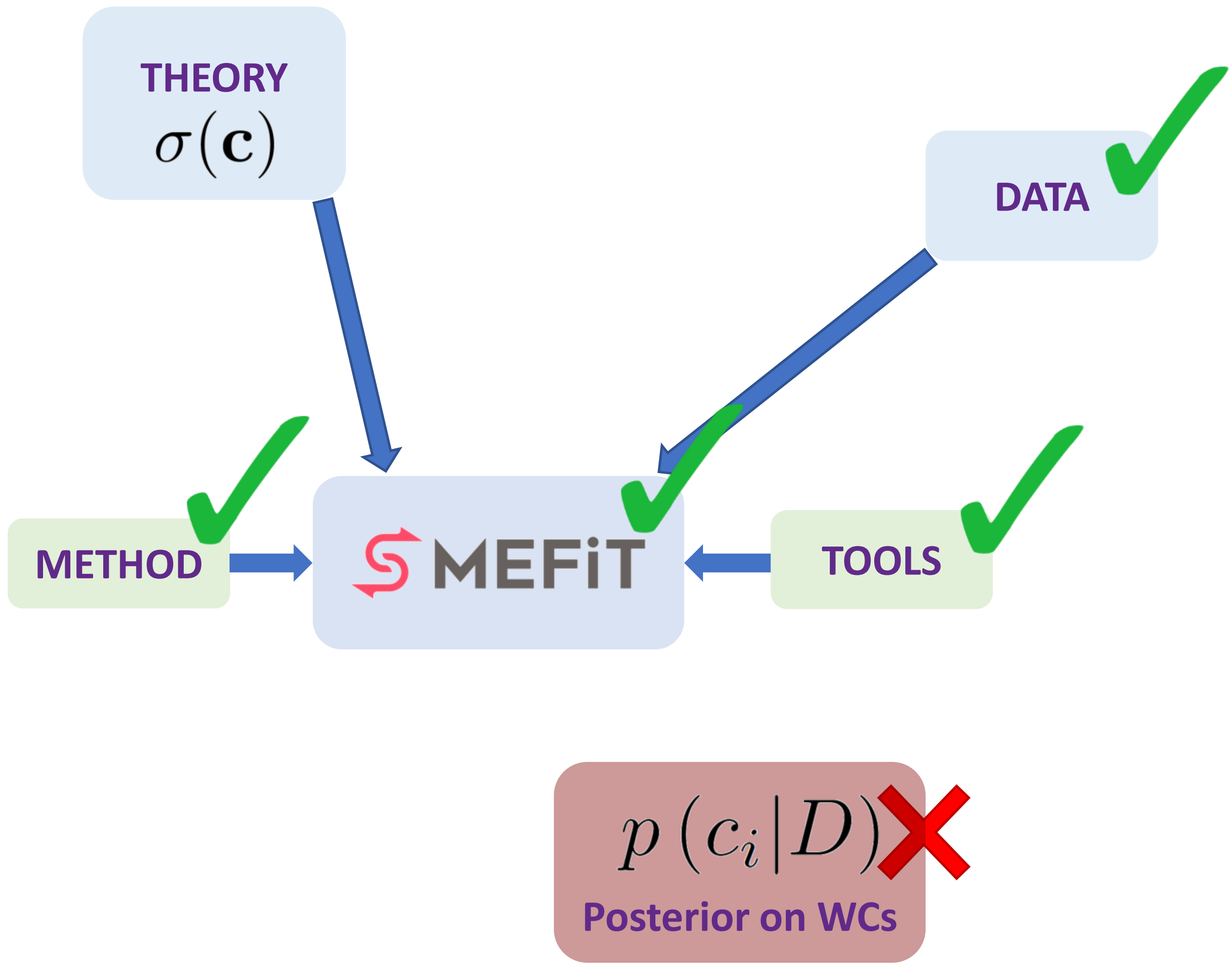
Reusing EFT global fits for the UV



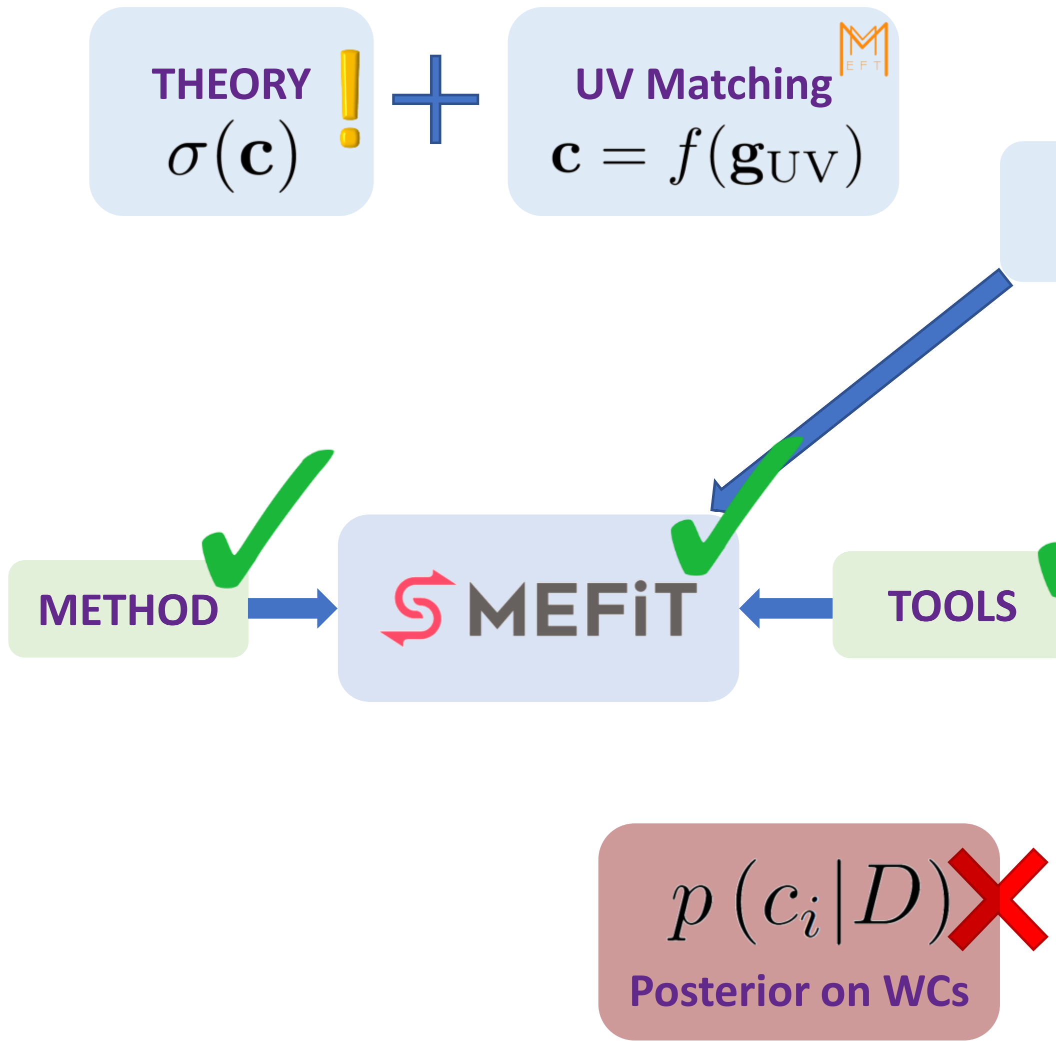
Reusing EFT global fits for the UV



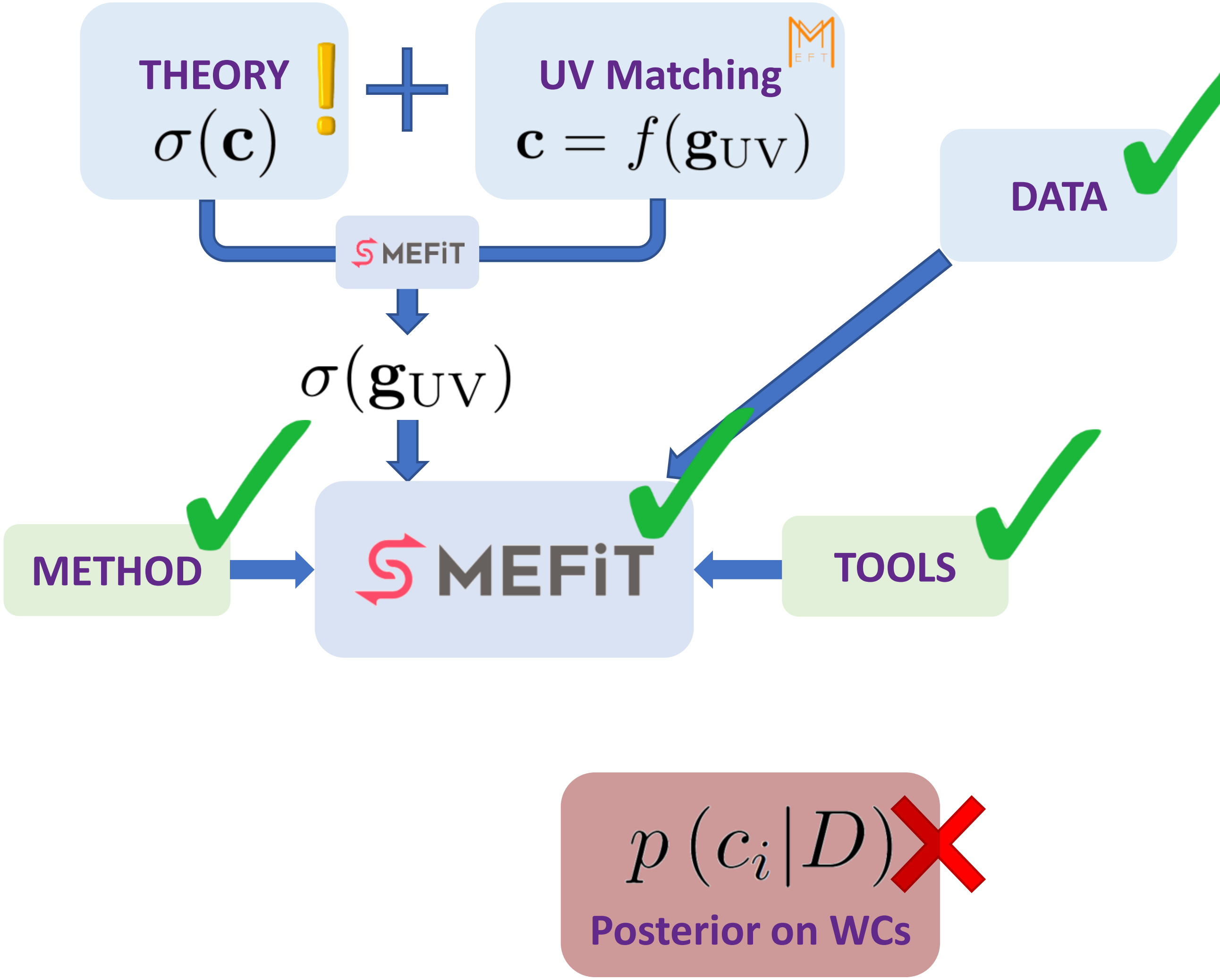
Reusing EFT global fits for the UV



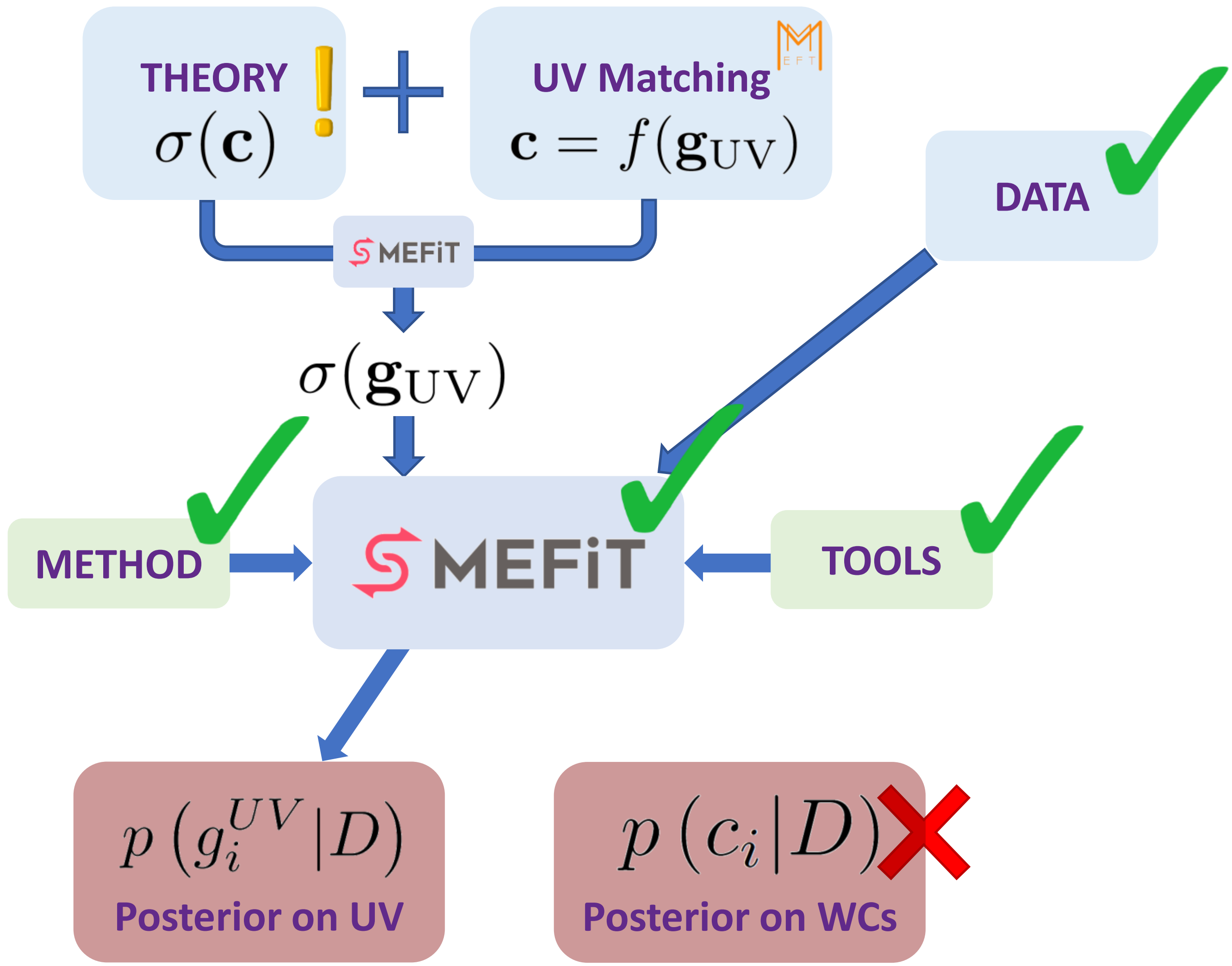
Reusing EFT global fits for the UV



Reusing EFT global fits for the UV



Reusing EFT global fits for the UV



match2fit

- A Wolfram Mathematica™ package, fully documented.
- Reads results from `Matchmakereft` and produces run cards that can be fed into `smefit` to perform a fit .
- Uses the same WC basis than SMEFiT.

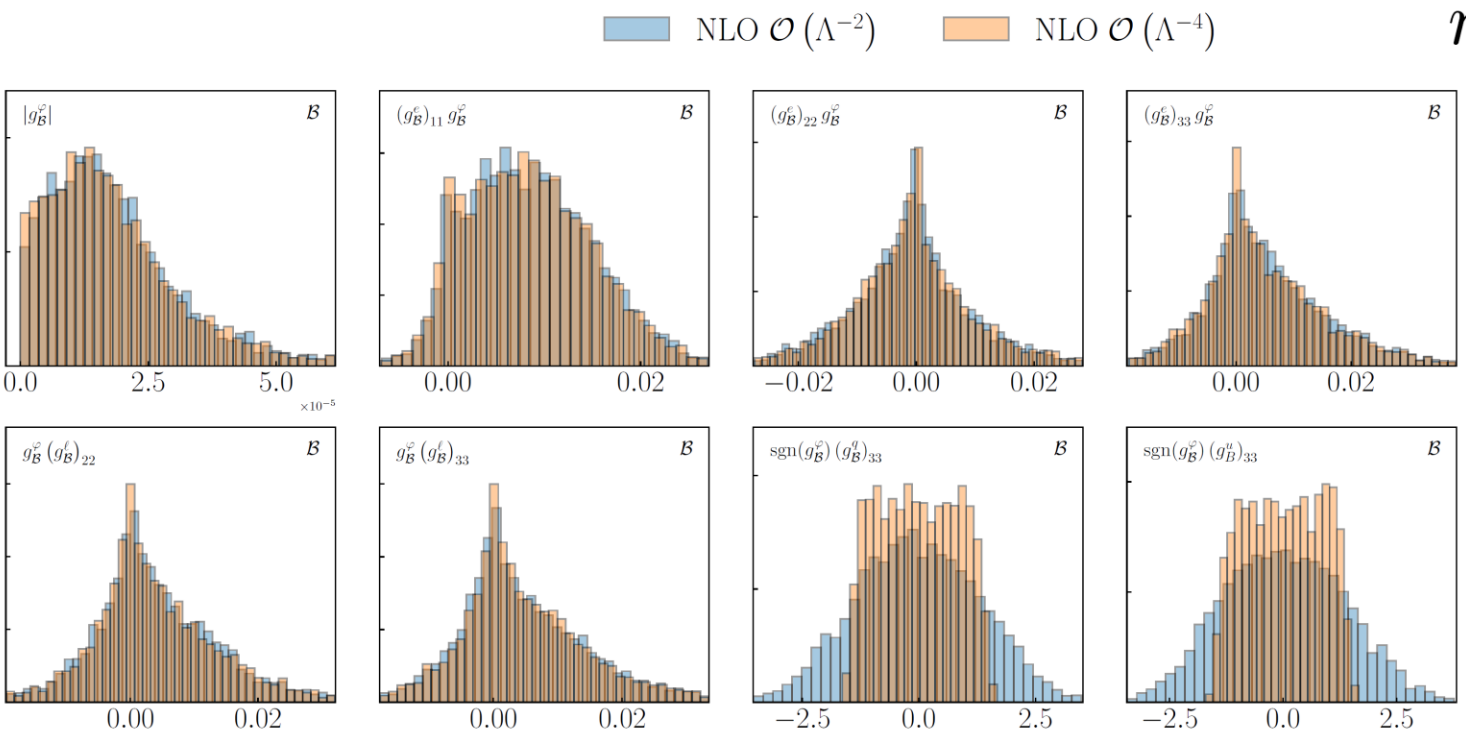
$$\mathrm{U}(2)_q \times \mathrm{U}(3)_d \times \mathrm{U}(2)_u \times \left(\mathrm{U}(1)_\ell \times \mathrm{U}(1)_e\right)^3 + c_{b\varphi},\, c_{\tau\varphi},\, c_{c\varphi}$$

- It can impose UV flavor assumptions and evaluates the masses.
- It can run Matchmakereft to perform the matching and translation at once.

It supports 1-loop matching results.

One-part. models at tree level

$m_{\mathcal{B}} = 1\ \text{TeV}$



Spin 1

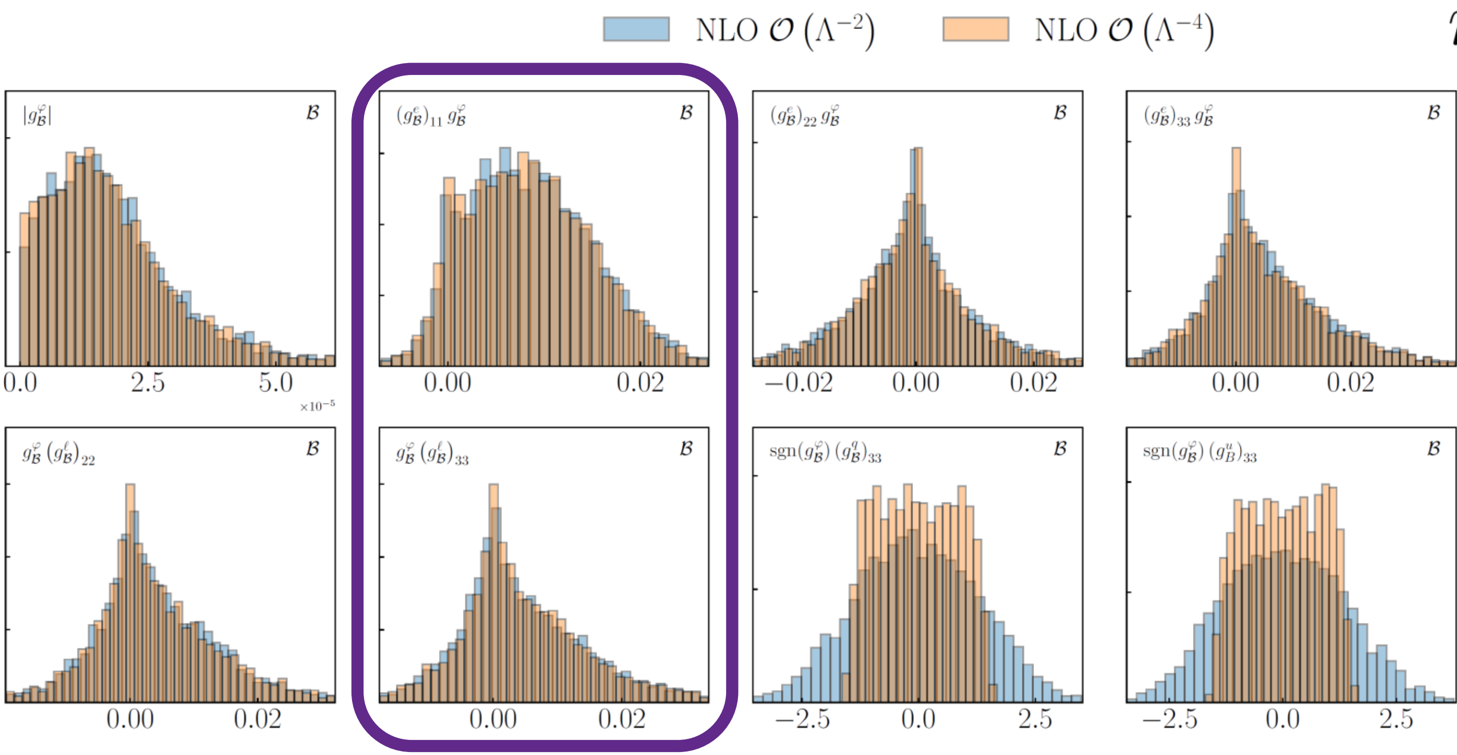
$\mathcal{B} \sim (1,1)_0$

$(\text{SU}(3)_c, \text{SU}(2)_L)_{\text{U}(1)_Y}$

Dataset: SMEFiT 2.0 + EWPOs

One-part. models at tree level

$m_{\mathcal{B}} = 1\ \text{TeV}$



Spin 1

$\mathcal{B} \sim (1, 1)_0$

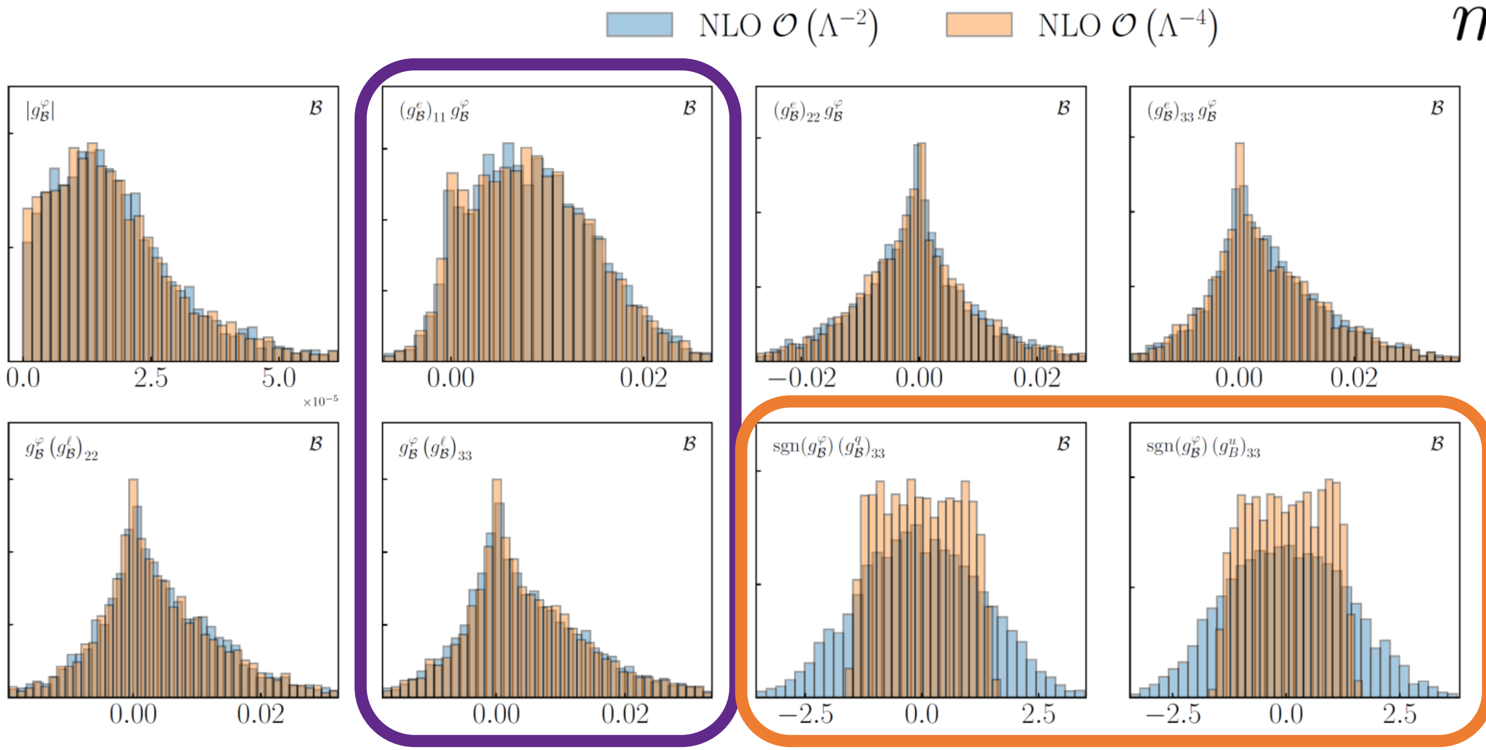
$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_{\mathrm{U}(1)_Y}$

Sensitivity to the sign of UV couplings

Dataset: SMEFiT 2.0 + EWPOs

One-part. models at tree level

$m_{\mathcal{B}} = 1$ TeV



Spin 1

$\mathcal{B} \sim (1,1)_0$

$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_{\mathrm{U}(1)_Y}$

Sensitivity to the sign of UV couplings

Top couplings sensitive to quadratic-in-WCs pieces

Dataset: SMEFiT 2.0 + EWPOs

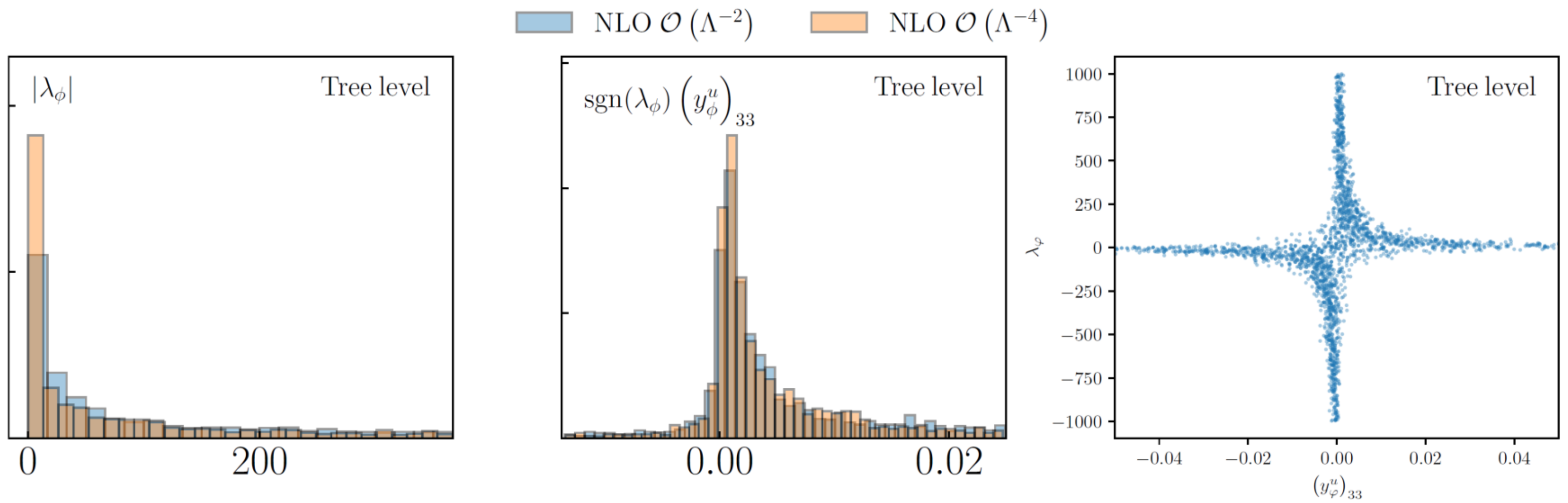
One-loop matching makes a difference

$\phi \sim (1,2)_{1/2}$ $\mathcal{L}_{\text{UV}} \supset -\left(y_\phi^u\right)_{33} \phi^\dagger i\sigma_2 \bar{q}_L^{T,3} u_R^3 - \lambda_\phi \phi^\dagger H |H|^2 + \text{h.c.}$ $m_\phi = 1 \text{ TeV}$

Dataset: SMEFiT 2.0 + EWPOs

One-loop matching makes a difference

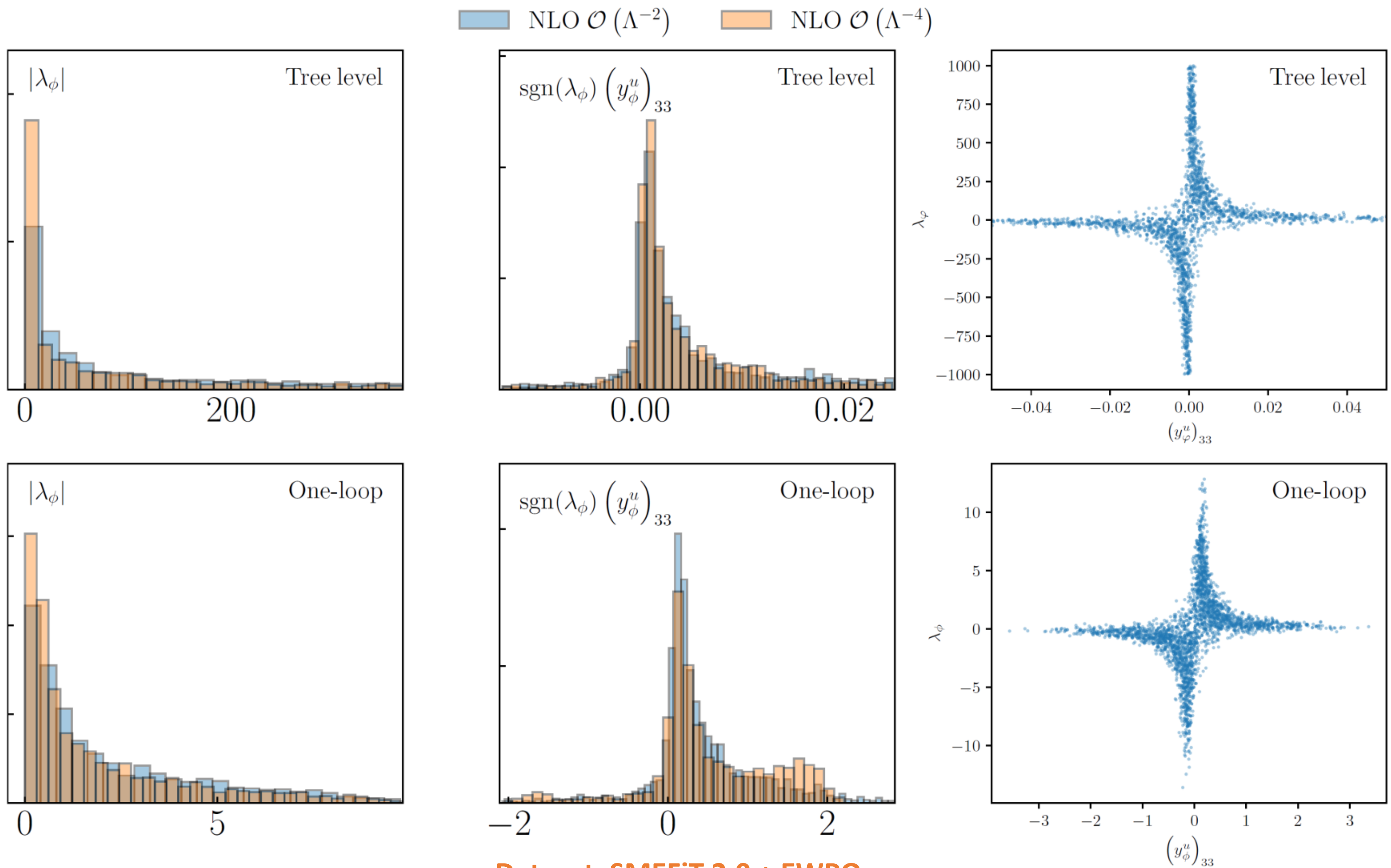
$\phi \sim (1,2)_{1/2}$ $\mathcal{L}_{\rm UV} \supset -\left(y_\phi^u\right)_{33} \phi^\dagger i\sigma_2 \bar{q}_L^{T,3} u_R^3 - \lambda_\phi \phi^\dagger H |H|^2 + \text{h.c.}$ $m_\phi = 1$ TeV



Dataset: SMEFiT 2.0 + EWPOs

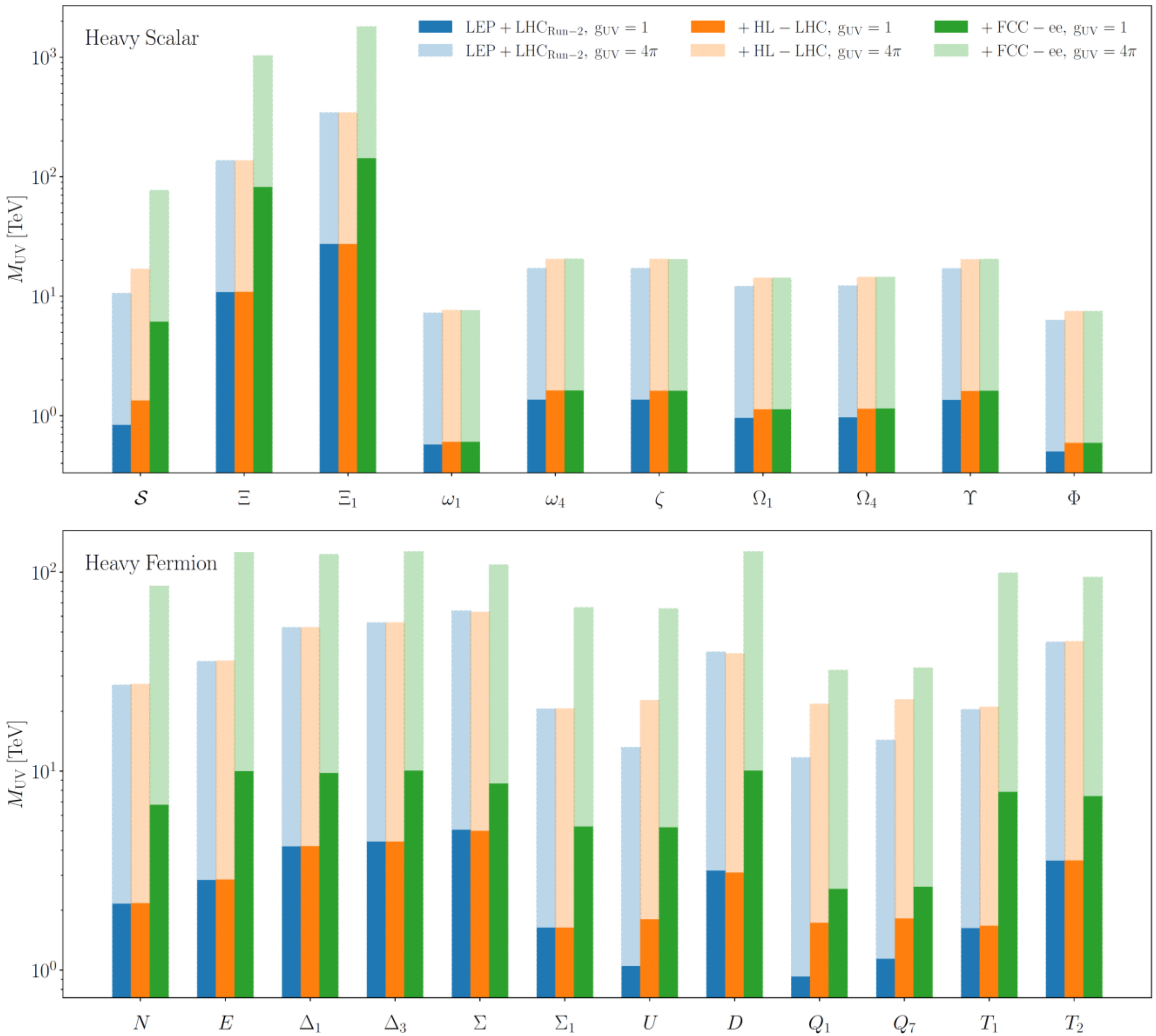
One-loop matching makes a difference

$\phi \sim (1,2)_{1/2}$ $\mathcal{L}_{\text{UV}} \supset -\left(y_\phi^u\right)_{33} \phi^\dagger i\sigma_2 \bar{q}_L^{T,3} u_R^3 - \lambda_\phi \phi^\dagger H |H|^2 + \text{h.c.}$ $m_\phi = 1\ \text{TeV}$



Dataset: SMEFiT 2.0 + EWPOs

Projections for the future: simple models



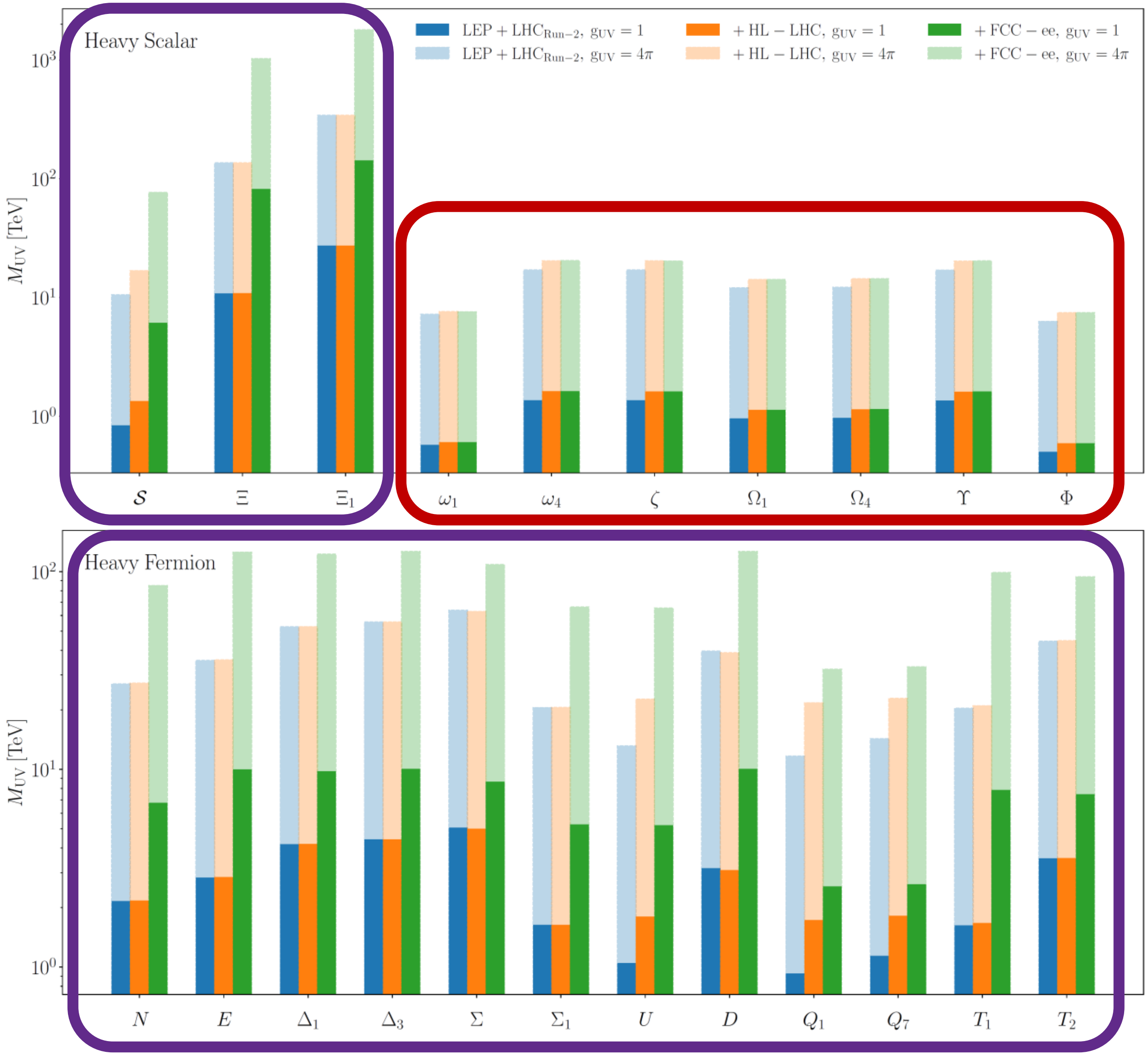
Tree-level matching

Projections for the future: simple models

Driven by heavy 4-quark operators

Tree-level matching

Projections for the future: simple models

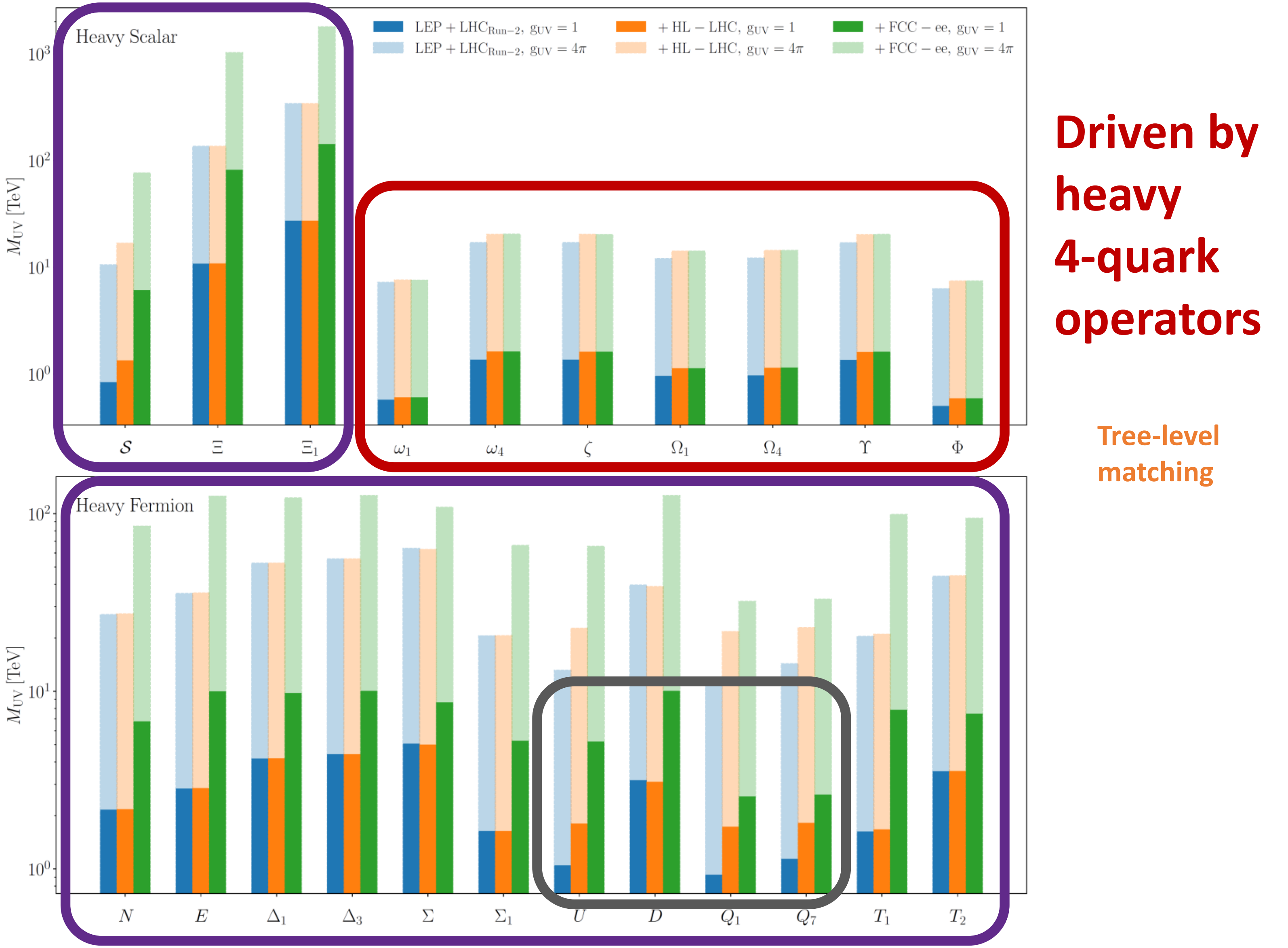


Driven by heavy 4-quark operators

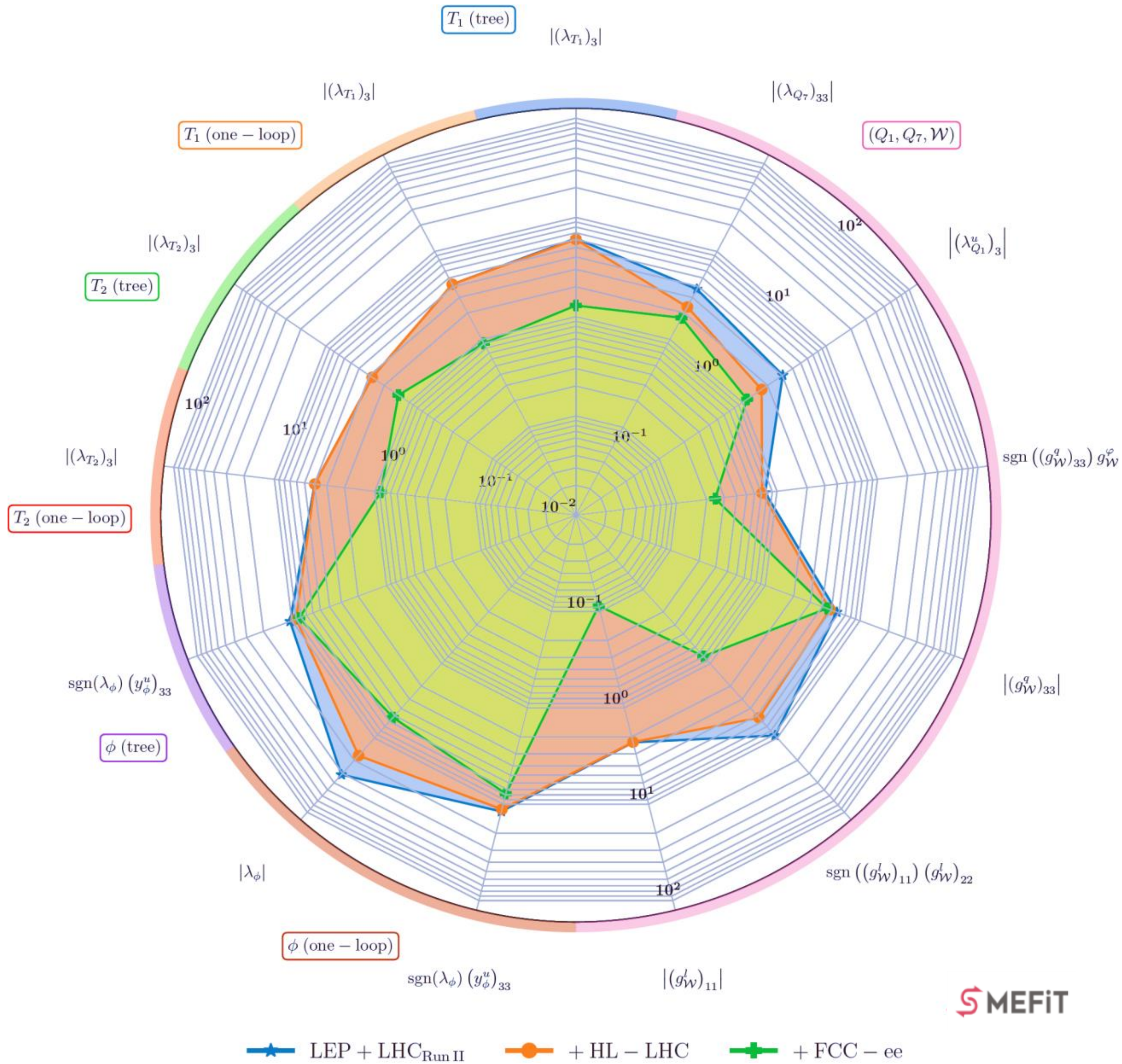
Tree-level matching

Driven by EWPOs

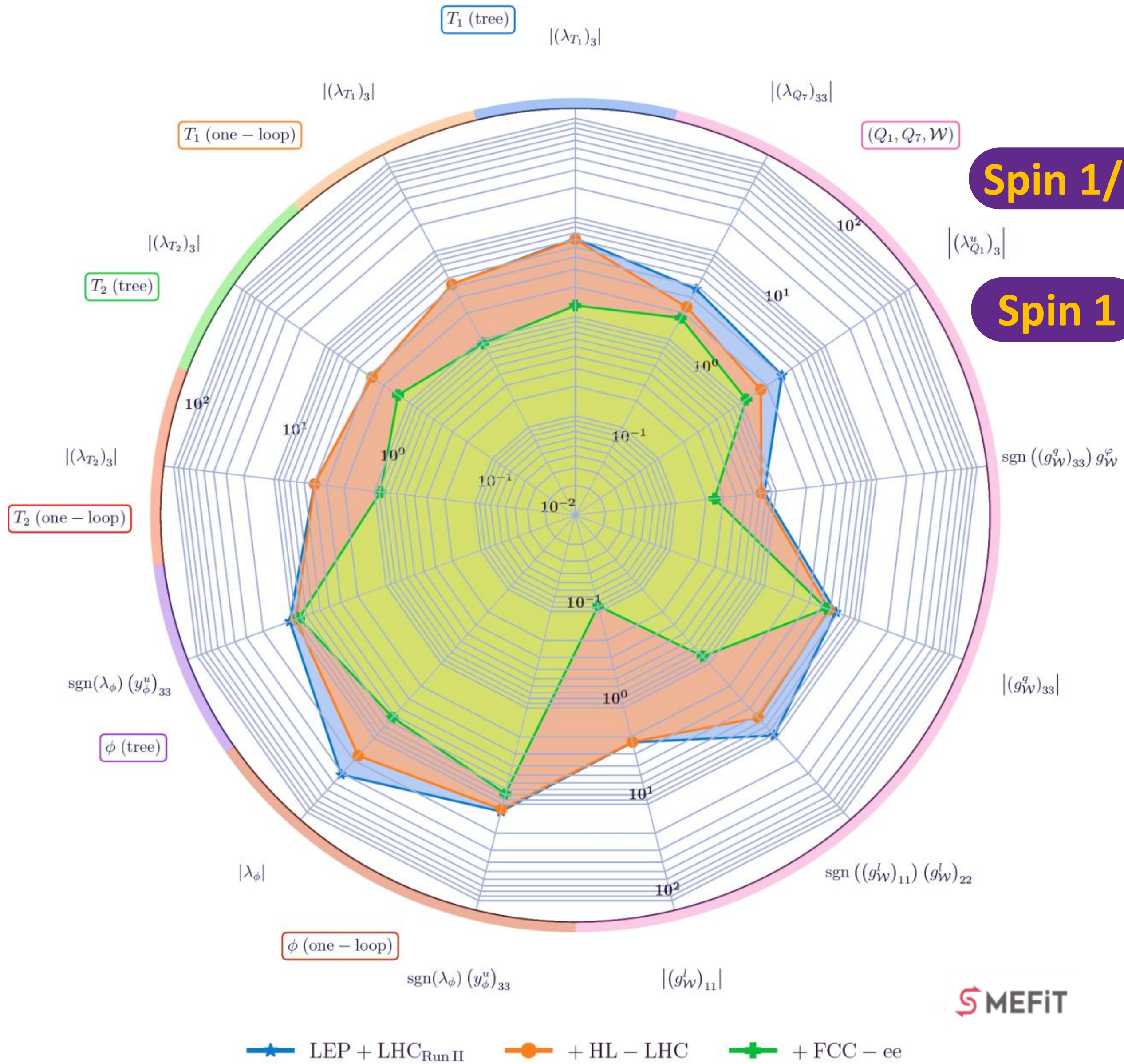
Projections for the future: simple models



Projections for the future: complex models



Projections for the future: complex models



Spin 1/2

$Q_1 \sim (3,2)_{1/6}$

$Q_7 \sim (3,2)_{7/6}$

Spin 1

$\mathcal{W} \sim (1,3)_0$

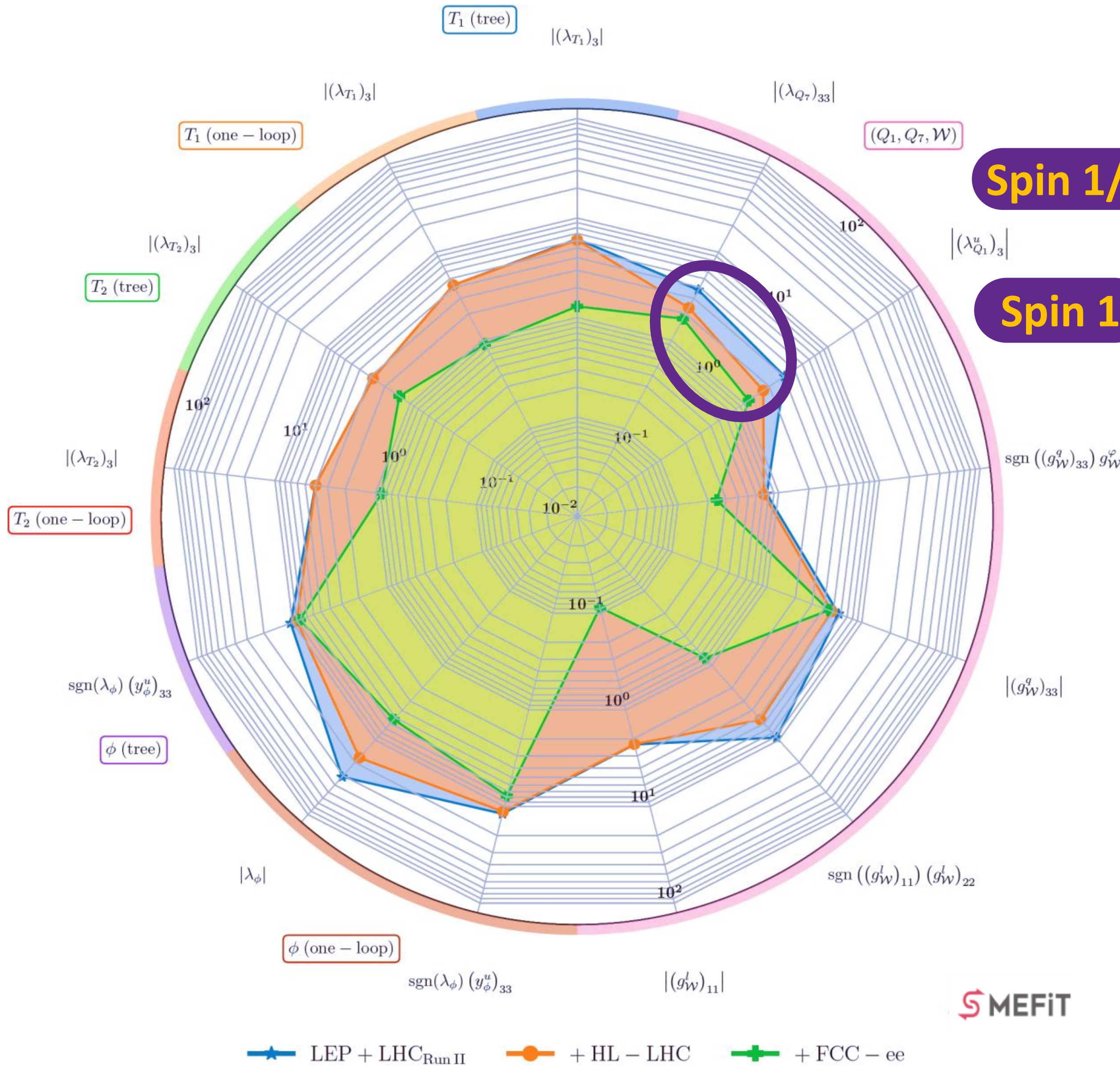
$(\mathrm{SU(3)_c, SU(2)_L)_{U(1)_Y}}$

$m_{Q_1} = 3$ TeV

$m_{Q_7} = 4.5$ TeV

$m_{\mathcal{W}} = 2.5$TeV

Projections for the future: complex models



Spin 1/2
$Q_1 \sim (3,2)_{1/6}$
$Q_7 \sim (3,2)_{7/6}$

Spin 1
$\mathcal{W} \sim (1,3)_0$

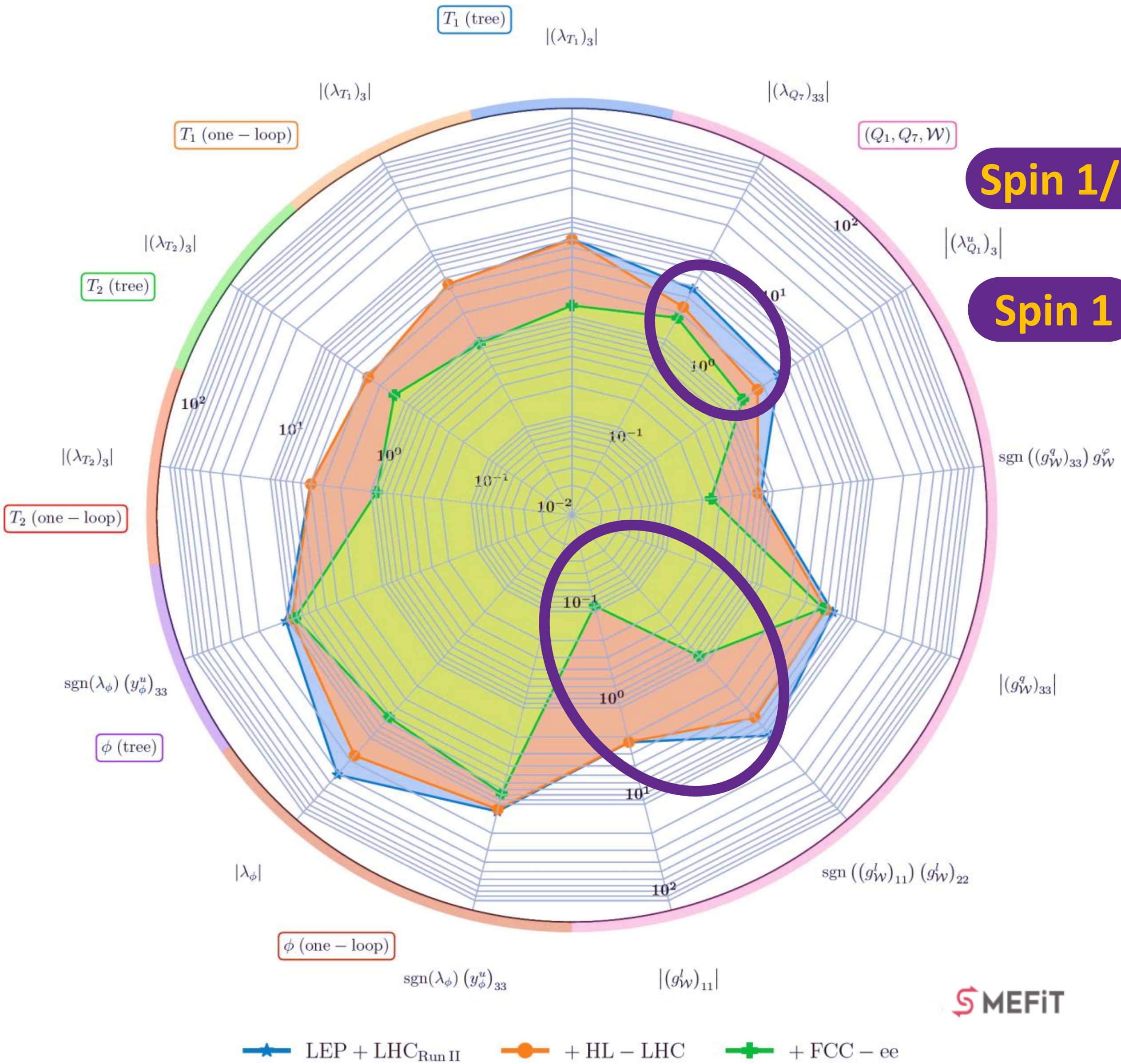
$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_{U(1)_Y}$

$m_{Q_1} = 3$ TeV

$m_{Q_7} = 4.5$ TeV

$m_{\mathcal{W}} = 2.5$TeV

Projections for the future: complex models



Spin 1/2 $\begin{cases} Q_1 \sim (3,2)_{1/6} \\ Q_7 \sim (3,2)_{7/6} \end{cases}$

Spin 1 $\{\ \mathcal{W} \sim (1,3)_0$

$(\mathrm{SU(3)_c, SU(2)_L)_{U(1)_Y}}$

$m_{Q_1} = 3$ TeV

$m_{Q_7} = 4.5$ TeV

$m_{\mathcal{W}} = 2.5$TeV

Projections for the future: complex models

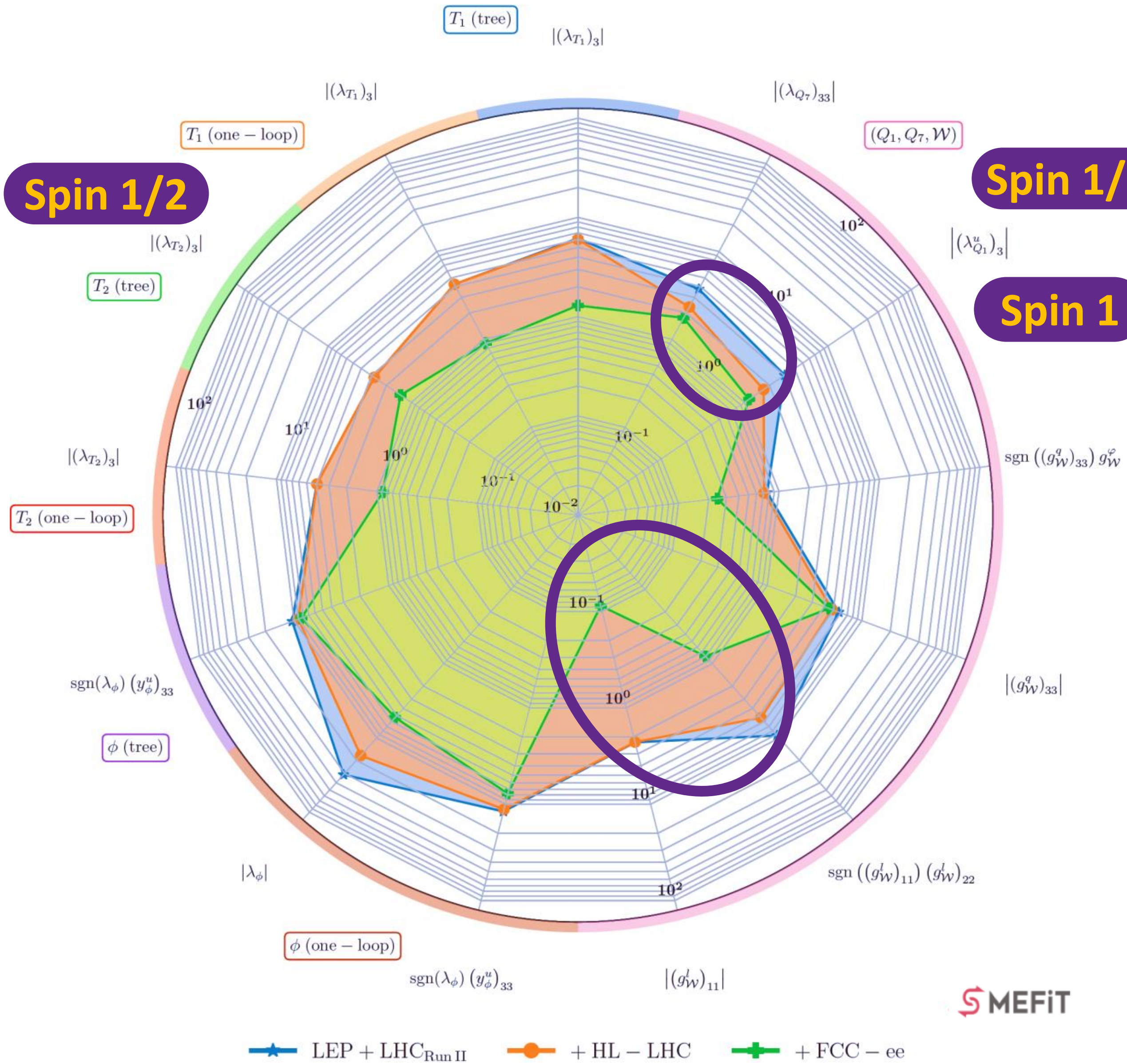
$T_1 \sim (3,3)_{-1/2}$

$T_2 \sim (3,3)_{2/3}$

Spin 1/2

$m_{T_1} = 10$ TeV

$m_{T_2} = 10$ TeV



Spin 1/2

$Q_1 \sim (3,2)_{1/6}$

$Q_7 \sim (3,2)_{7/6}$

Spin 1

$\mathcal{W} \sim (1,3)_0$

$(\text{SU}(3)_c, \text{SU}(2)_L)_{U(1)_Y}$

$m_{Q_1} = 3$ TeV

$m_{Q_7} = 4.5$ TeV

$m_{\mathcal{W}} = 2.5$TeV

Projections for the future: complex models

$T_1 \sim (3,3)_{-1/2}$

$T_2 \sim (3,3)_{2/3}$

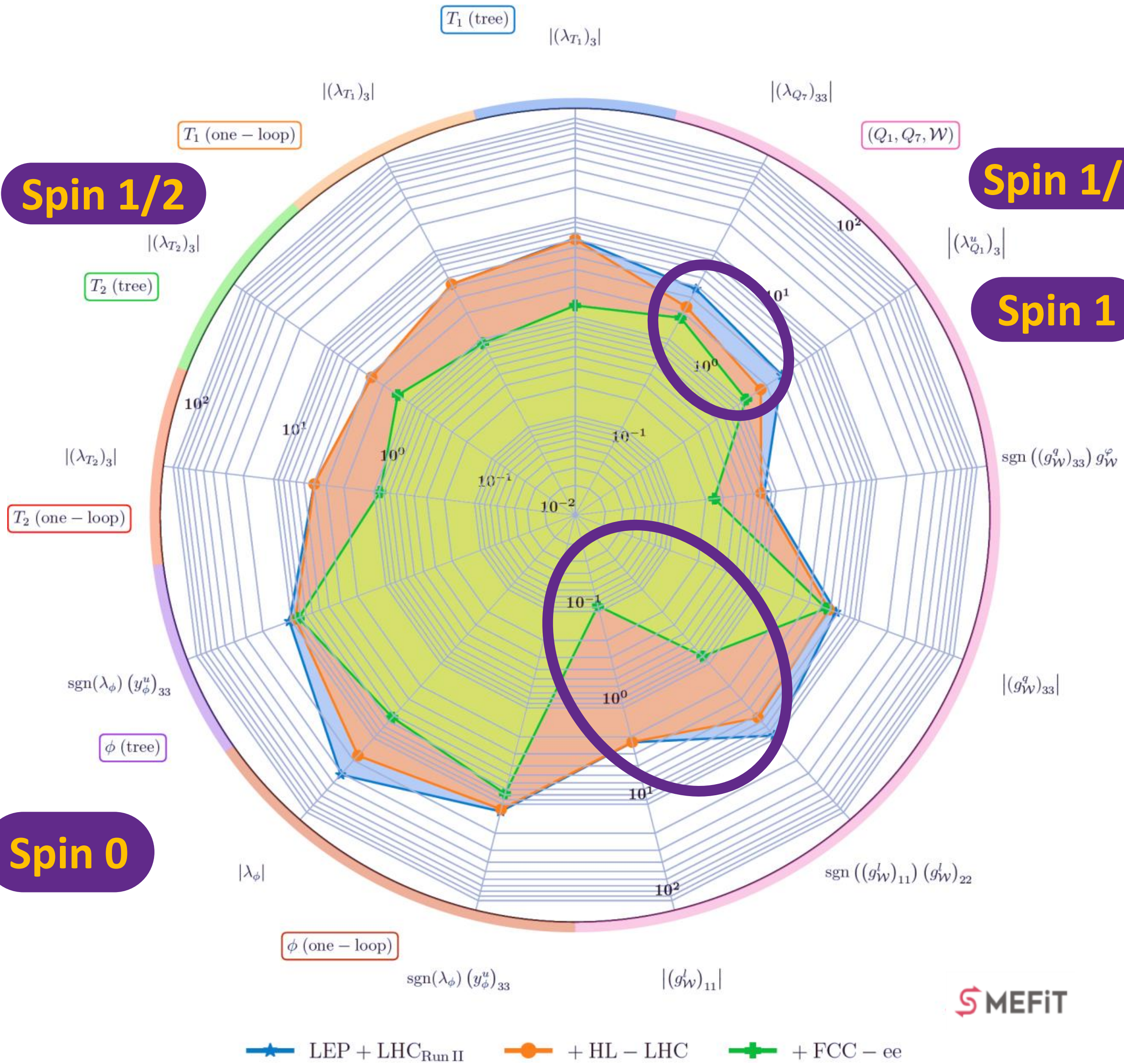
Spin 1/2

$m_{T_1} = 10$ TeV

$m_{T_2} = 10$ TeV

$\phi \sim (1,2)_{1/2}$ **Spin 0**

$m_\phi = 5$ TeV



$Q_1 \sim (3,2)_{1/6}$

$Q_7 \sim (3,2)_{7/6}$

Spin 1/2

Spin 1 $\mathcal{W} \sim (1,3)_0$

$(\mathrm{SU(3)_c, SU(2)_L)_{U(1)_Y}}$

$m_{Q_1} = 3$ TeV

$m_{Q_7} = 4.5$ TeV

$m_{\mathcal{W}} = 2.5$TeV

Projections for the future: complex models

$T_1 \sim (3,3)_{-1/2}$

$T_2 \sim (3,3)_{2/3}$

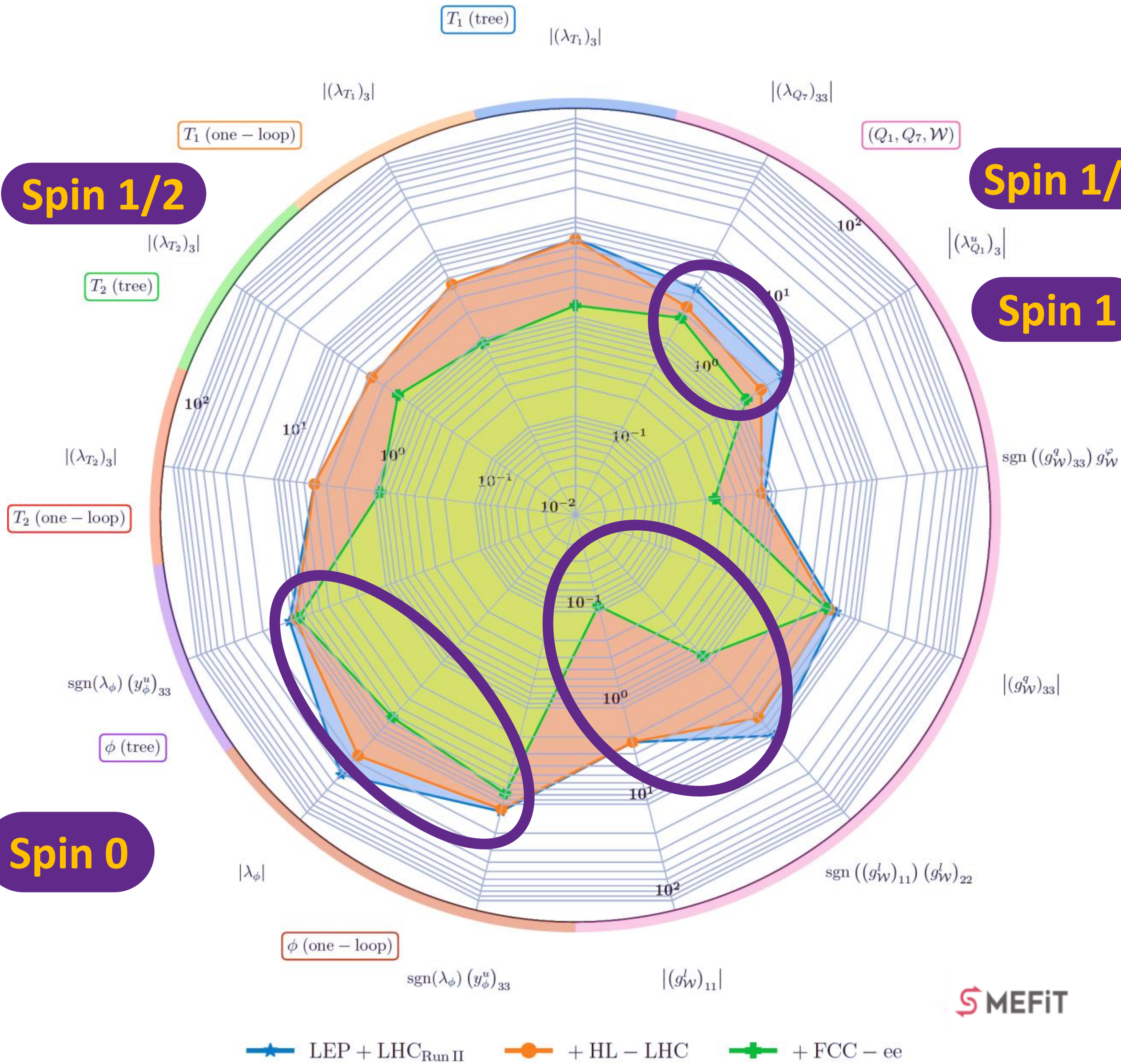
Spin 1/2

$m_{T_1} = 10$ TeV

$m_{T_2} = 10$ TeV

$\phi \sim (1,2)_{1/2}$ **Spin 0**

$m_\phi = 5$ TeV



$(\mathrm{SU(3)_c, SU(2)_L)_{U(1)_Y}}$

Spin 1/2

$Q_1 \sim (3,2)_{1/6}$

$Q_7 \sim (3,2)_{7/6}$

Spin 1

$\mathcal{W} \sim (1,3)_0$

$m_{Q_1} = 3$ TeV

$m_{Q_7} = 4.5$ TeV

$m_{\mathcal{W}} = 2.5$TeV

Conclusions

- We have the tools for the full cycle of the EFT program for BSM Physics.
- SMEFiT allows to interpret LHC data at the EFT and UV model levels from one set of predictions.
- Match2fit provides a simple and flexible SMEFiT-MMEFT interface.
- LHC Run 2 data shows an impressive constrain power.
- We can understand the impact of future colliders at SMEFT and UV level.
- Several improvement possibilities: interfacing more codes, flavor data, RGE effects, more general flavor symmetries…

Thanks for your attention!

Contact:

Alejo N. Rossia

HEP Theory Group – Dept. Of Physics and Astronomy

E-mail: alejo dot rossia at manchester dot ac dot uk

Thanks to M. Thomas, E. Celada, V. Miralles and H. el Faham for ideas for the slides and discussions.

Appendix

UV invariants

We are sensitive only to combinations of UV couplings that enter the WCs.

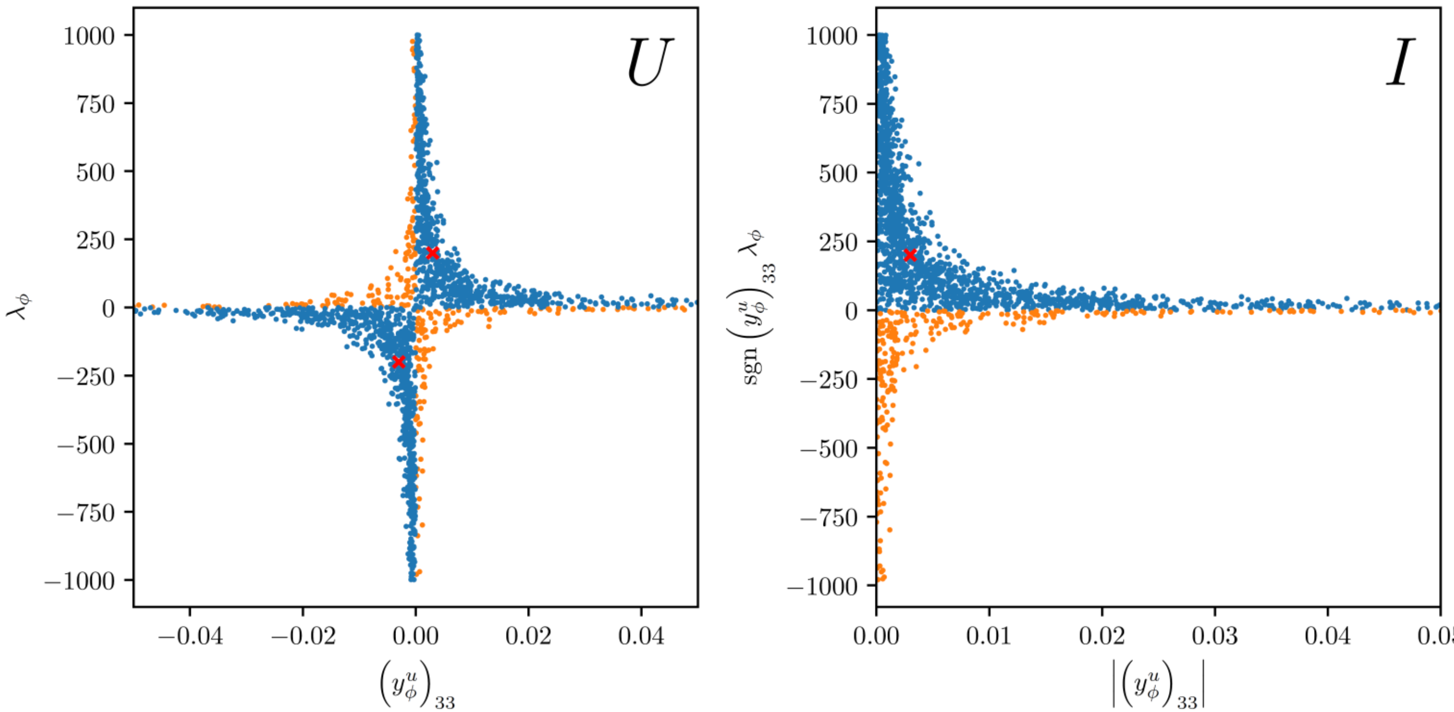
$$h : U \to I$$

"UV invariants"

$$\mathbf{c} = f(\mathbf{g}_{\mathrm{UV}})$$

$$f\,(h(g)) = f(h(g')) \iff h(g) = h(g')$$

$$\mathbf{c} = f(h(\mathbf{g}_{\mathrm{UV}}))$$



Not necessary to do the fit, but useful to understand the results.

Restrictions from EFT flavor symmetry

- Your model produces an operator that should vanish and does not enter in any fitted process.
  - The bounds from the fit might be suboptimal with respect to bounds from other processes.

- Your model produces an operator that should vanish and enters some processes in the dataset.
  - The bounds from the fit might not be trustworthy and suboptimal.

- The symmetry assumes two WCs to be equal but your model produces them with different values.
  - Match2fit will take only one of those values and ignore the other. Unless the difference is small, the bounds from the fit are not trustworthy.

How to forecast

(3 ab^{-1})

- Take SMEFiT 3.0 **LHC datasets with highest int. luminosity**
- Pseudodata fluctuated around SM
- **Rescale uncertainties:**
  - Statistical $\longrightarrow \mathcal{L}$
  - Systematics $\longrightarrow \frac{1}{2}$
- **No HL-LHC optimization**

- **Snowmass + FCC midterm Feas. Rep.**
- **Z-pole+161+240+350/365 GeV**
  - **EWPOs**
  - $f\bar{f}$ **production**
  - $ZH + \nu\bar{\nu}H$ **+ all** H **decays.**
  - $W^+W^- + t\bar{t}$ **with Optim. Obs.**

Additional technicalities

SMEFiT supports relations among fit parameters like:

$$\sum_i a_i \left(c_1\right)^{n_{1,i}} \ldots \left(c_N\right)^{n_{N,i}} = 0$$

The exponents can be rational numbers of any sign.
This imposes restrictions on the supported matching relations.

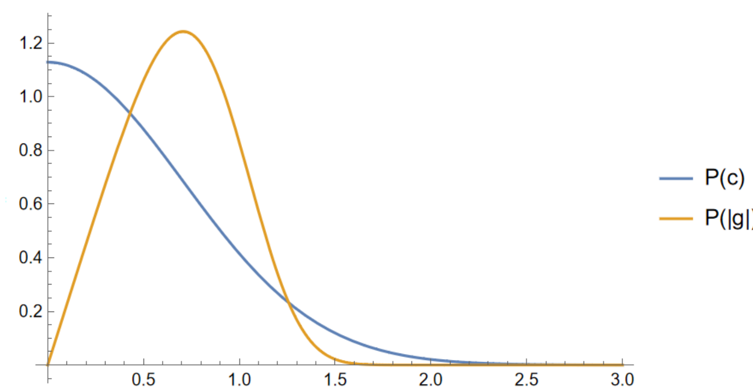
Probability in UV and WC spaces

The relation between PDFs in WC and UV space can be misleading.

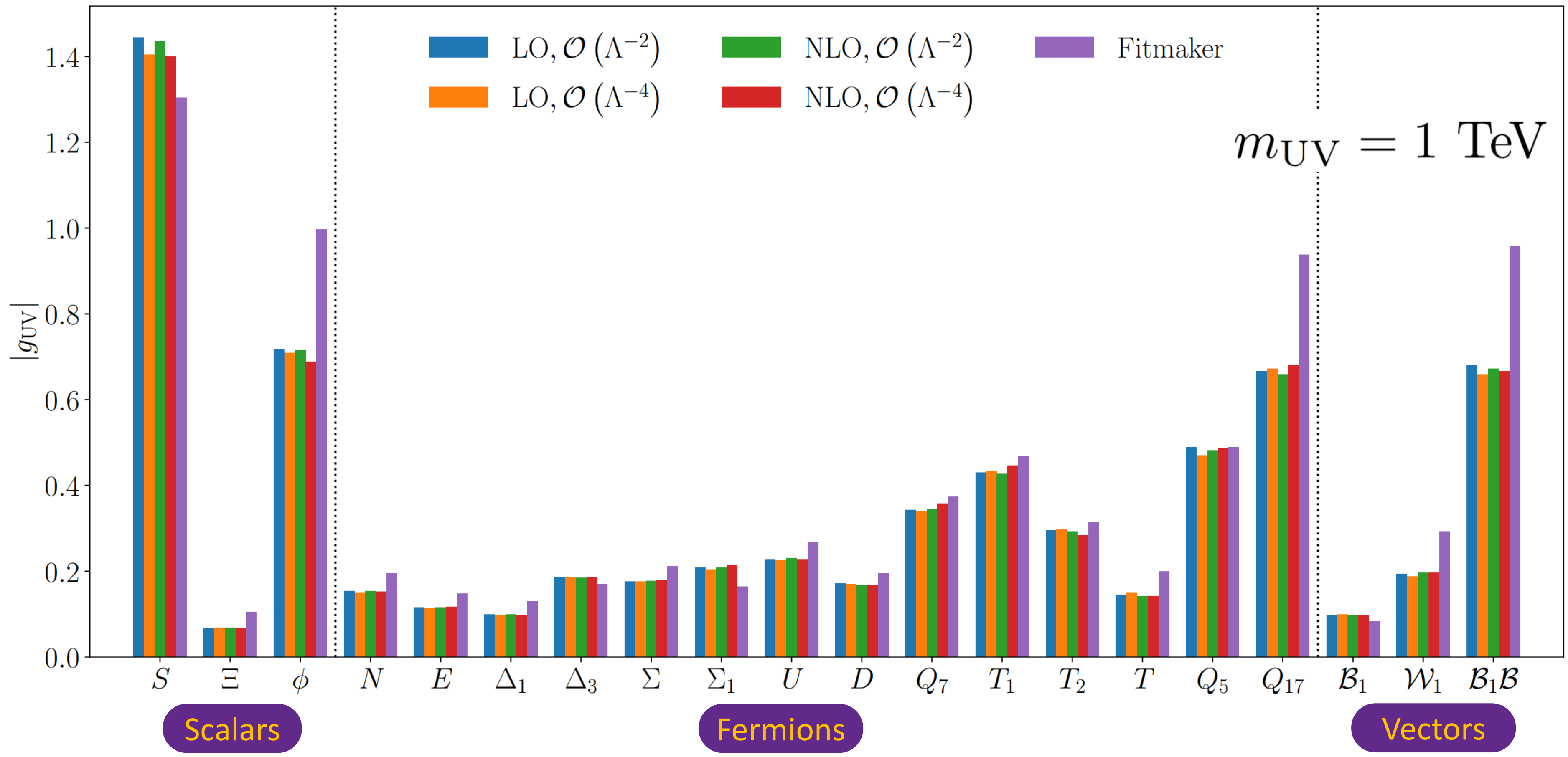
$$P(c) = \frac{2}{\sqrt{\pi}} e^{-c^2}\,, \qquad \int_0^\infty dc\, P(c) = 1$$

$$\downarrow \; c = g^2$$

$$P(|g|) = \frac{4}{\sqrt{\pi}} |g| e^{-|g|^4}\,, \qquad \int_0^\infty d|g|\, P(|g|) = 1$$



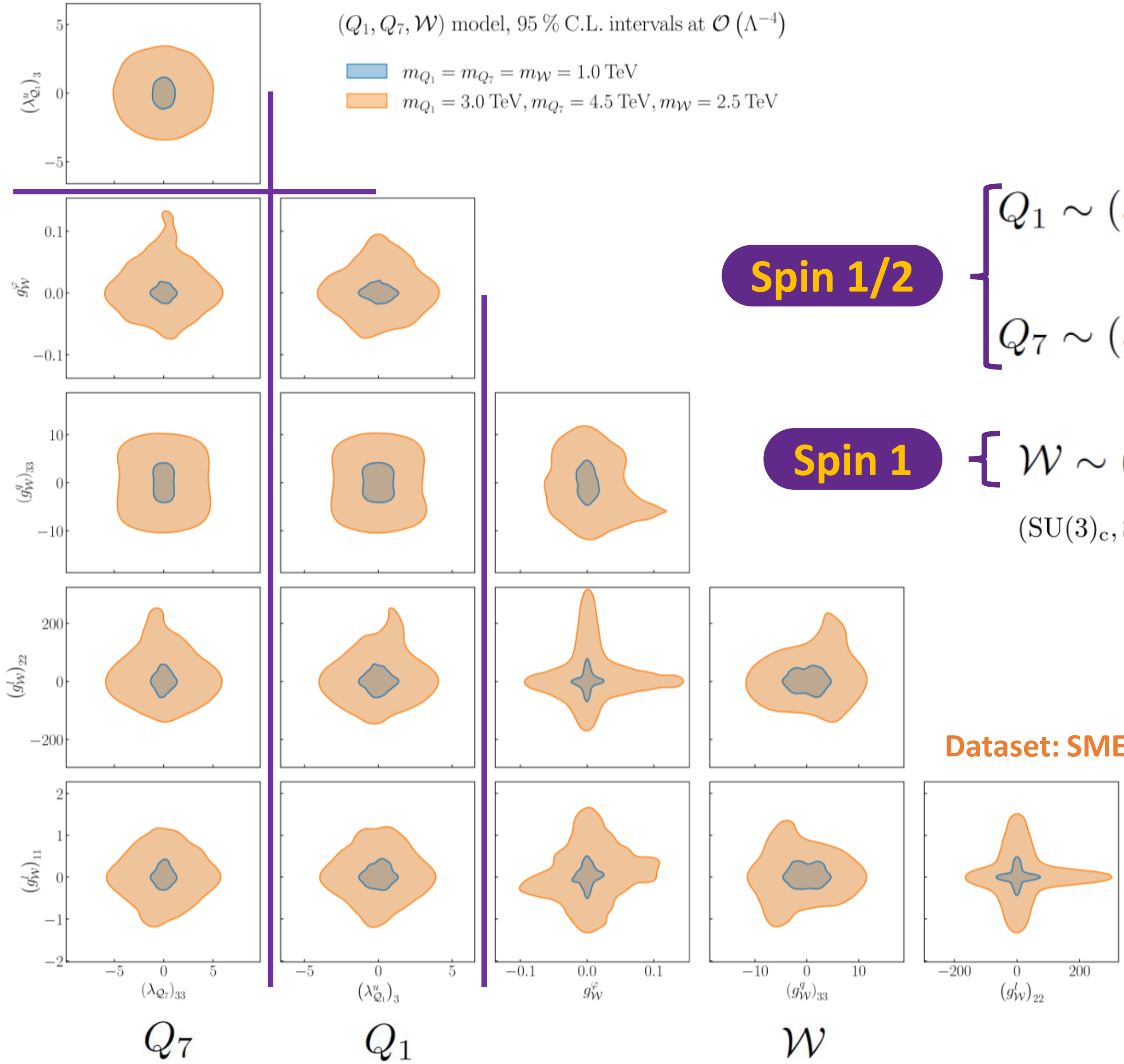
One-part. models at tree level



Good agreement with the Fitmaker results

Dataset: SMEFiT 2.0 + EWPOs

Multi-particle models at tree level



Spin 1/2

$\mathcal{Q}_1 \sim (3,2)_{1/6}$

$\mathcal{Q}_7 \sim (3,2)_{7/6}$

Spin 1

$\mathcal{W} \sim (1,3)_0$

$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_{U(1)_Y}$

Dataset: SMEFiT 2.0 + EWPOs

List of models

Scalars		Fermions		Vectors	
Particle	Irrep	Particle	Irrep	Particle	Irrep
$\mathcal{S}$	$(1,1)_0$	N	$(1,1)_0$	$\mathcal{B}$	$(1,1)_0$
$\mathcal{S}_1$	$(1,1)_1$	E	$(1,1)_{-1}$	$\mathcal{B}_1$	$(1,1)_1$
ϕ	$(1,2)_{1/2}$	Δ_1	$(1,2)_{-1/2}$	$\mathcal{W}$	$(1,3)_0$
Ξ	$(1,3)_0$	Δ_3	$(1,2)_{-3/2}$	$\mathcal{W}_1$	$(1,3)_1$
Ξ_1	$(1,3)_1$	Σ	$(1,3)_0$	$\mathcal{G}$	$(8,1)_0$
ω_1	$(3,1)_{-1/3}$	Σ_1	$(1,3)_{-1}$	$\mathcal{H}$	$(8,3)_0$
ω_4	$(3,1)_{-4/3}$	U	$(3,1)_{2/3}$	$\mathcal{Q}_5$	$(8,3)_0$
ζ	$(3,3)_{-1/3}$	D	$(3,1)_{-1/3}$	$\mathcal{Y}_5$	$(\bar{6},2)_{-5/6}$
Ω_1	$(6,1)_{1/3}$	Q_1	$(3,2)_{1/6}$		
Ω_4	$(6,1)_{4/3}$	Q_7	$(3,2)_{7/6}$		
Υ	$(6,3)_{1/3}$	T_1	$(3,3)_{-1/3}$		
Φ	$(8,2)_{1/2}$	T_2	$(3,3)_{2/3}$		
		Q_5	$(3,2)_{-5/6}$		

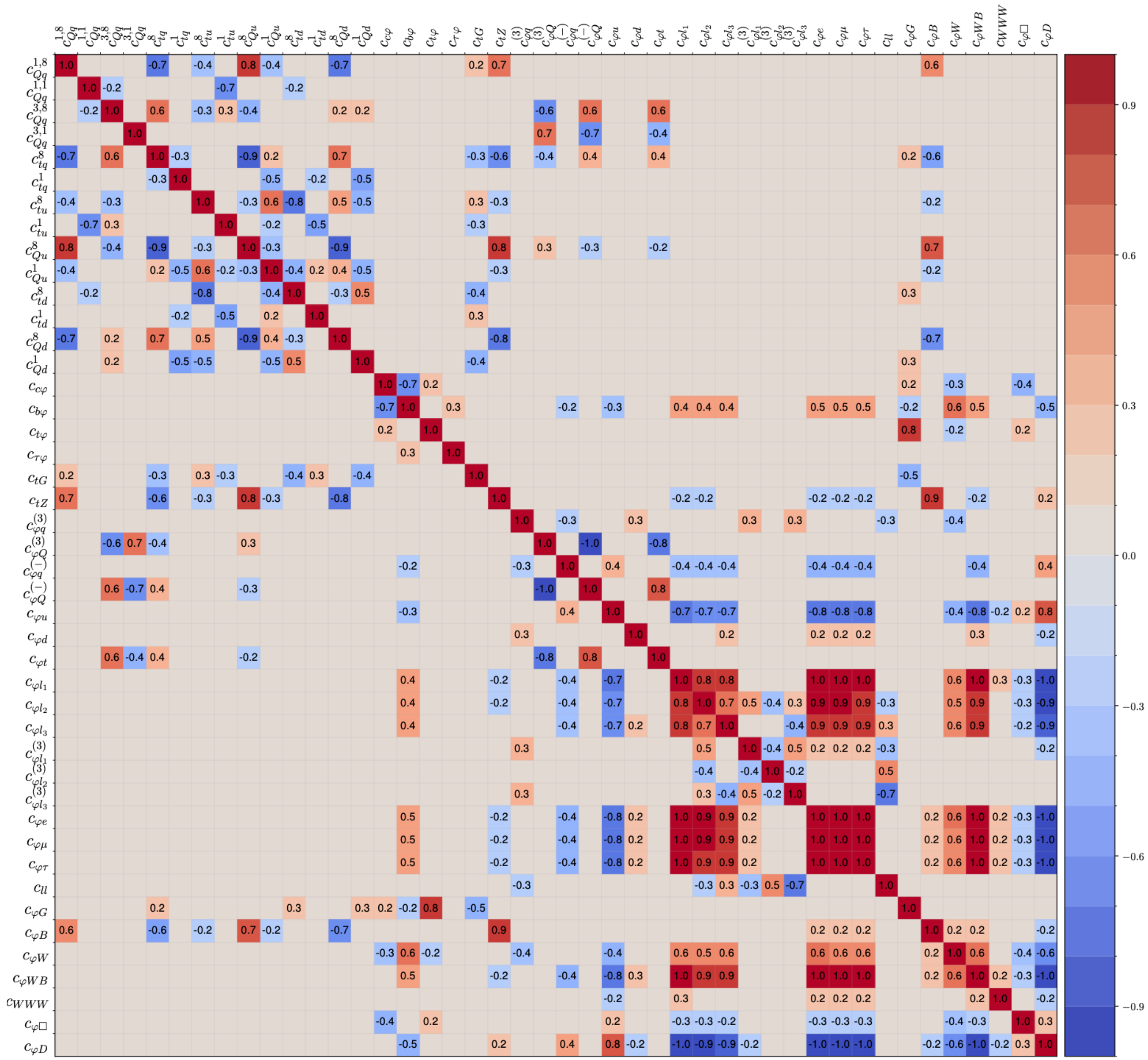
UV Couplings

Scalars		Fermions		Vectors	
Model	UV couplings	Model	UV couplings	Model	UV couplings
$\mathcal{S}$	$\kappa_{\mathcal{S}}$	N	$(\lambda_N^e)_3$	$\mathcal{B}$	$(g_B^u)_{33}$, $(g_B^q)_{33}$, g_B^φ,
ϕ	λ_ϕ, $(y_\phi^u)_{33}$	E	$(\lambda_E)_3$		$(g_B^e)_{11}$, $(g_B^e)_{22}$, $(g_B^e)_{33}$,
Ξ	κ_Ξ	Δ_1	$(\lambda_{\Delta_1})_3$		$\left(g_B^\ell\right)_{22}$, $\left(g_B^\ell\right)_{33}$
Ξ_1	κ_{Ξ_1}	Δ_3	$(\lambda_{\Delta_3})_3$	$\mathcal{B}_1$	$g_{B_1}^\varphi$
ω_1	$(y_{\omega_1}^{qq})_{33}$	Σ	$(\lambda_\Sigma)_3$	$\mathcal{W}$	$\left(g_{\mathcal{W}}^l\right)_{11} = 2\left(g_{\mathcal{W}}^l\right)_{22}$, $\left(g_{\mathcal{W}}^l\right)_{33}$
ω_4	$(y_{\omega_4}^{uu})_{33}$	Σ_1	$(\lambda_{\Sigma_1})_3$		$g_{\mathcal{W}}^\varphi$, $(g_{\mathcal{W}}^q)_{33}$
ζ	$\left(y_\zeta^{qq}\right)_{33}$	U	$(\lambda_U)_3$	$\mathcal{W}_1$	$g_{\mathcal{W}_1}^\varphi$
Ω_1	$\left(y_{\Omega_1}^{qq}\right)_{33}$	D	$(\lambda_D)_3$	$\mathcal{G}$	$\left(g_{\mathcal{G}}^q\right)_{33}$, $(g_{\mathcal{G}}^u)_{33}$
Ω_4	$(y_{\Omega_4})_{33}$	Q_1	$\left(\lambda_{\mathcal{Q}_1}^u\right)_3$		
Υ	$(y_\Upsilon)_{33}$	Q_7	$(\lambda_{\mathcal{Q}_7})_3$	$\mathcal{H}$	$(g_{\mathcal{H}})_{33}$
Φ	$(y_\Phi^{qu})_{33}$	T_1	$(\lambda_{T_1})_3$	$\mathcal{Q}_5$	$\left(g_{\mathcal{Q}_5}^{uq}\right)_{33}$
		T_2	$(\lambda_{T_2})_3$	$\mathcal{Y}_5$	$(g_{\mathcal{Y}_5})_{33}$

Dataset

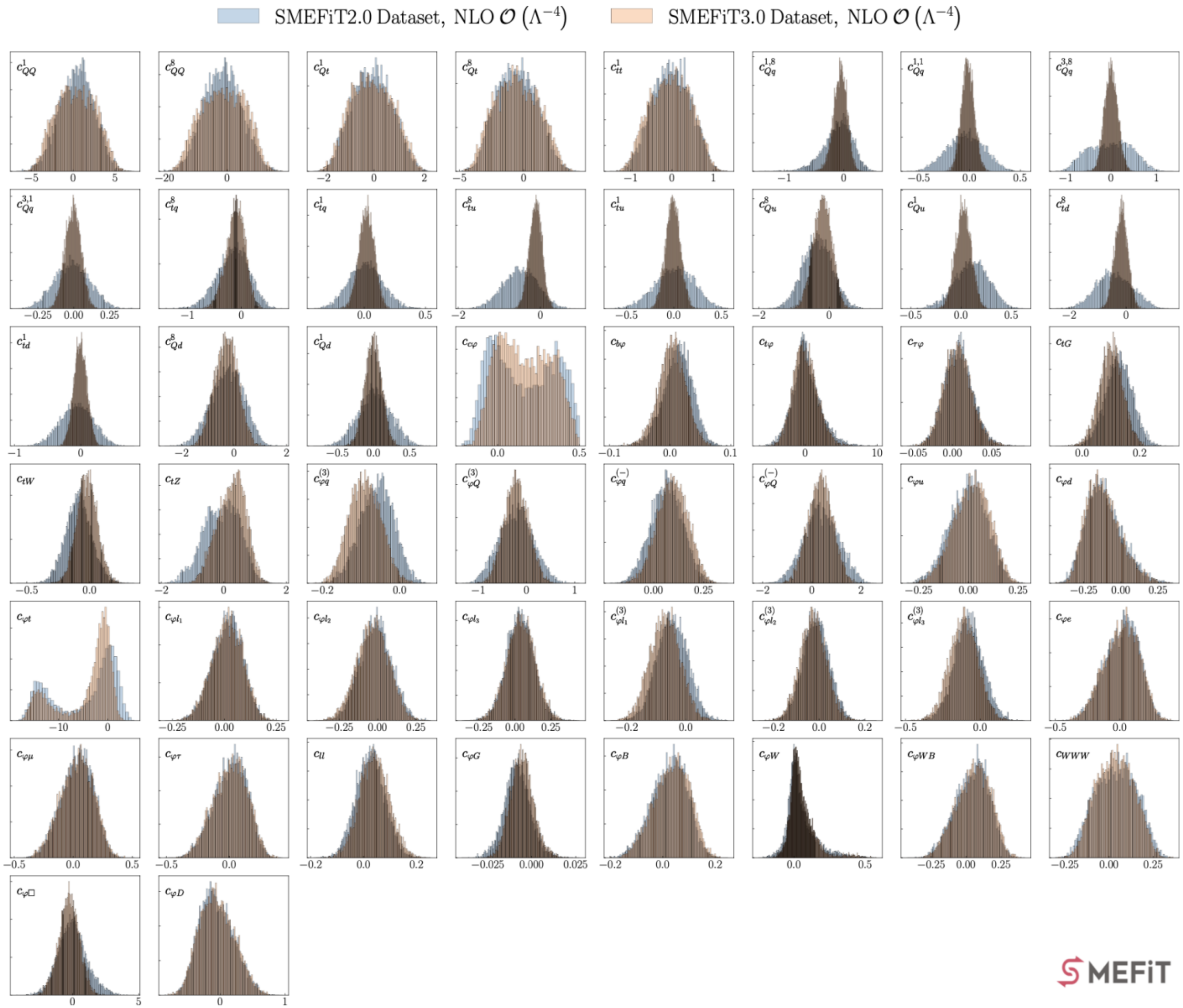
Category	Processes	$n_{\rm dat}$ SMEFiT2.0	$n_{\rm dat}$ SMEFiT3.0
Top quark production	$t\bar{t} + X$	94	115
	$t\bar{t}Z$, $t\bar{t}W$	14	21
	$t\bar{t}\gamma$	-	2
	single top (inclusive)	27	28
	tZ, tW	9	13
	$t\bar{t}t\bar{t}$, $t\bar{t}b\bar{b}$	6	12
	Total	**150**	**191**
Higgs production and decay	Run I signal strengths	22	22
	Run II signal strengths	40	36 (*)
	Run II, differential distributions & STXS	35	71
	Total	**97**	**129**
Diboson production	LEP-2	40	40
	LHC	30	41
	Total	**70**	**81**
EWPOs	LEP-2	-	44
Baseline dataset	**Total**	**317**	**445**

Correlations in linear fit



Correlation: NLO $\mathcal{O}\left(\Lambda^{-2}\right)$

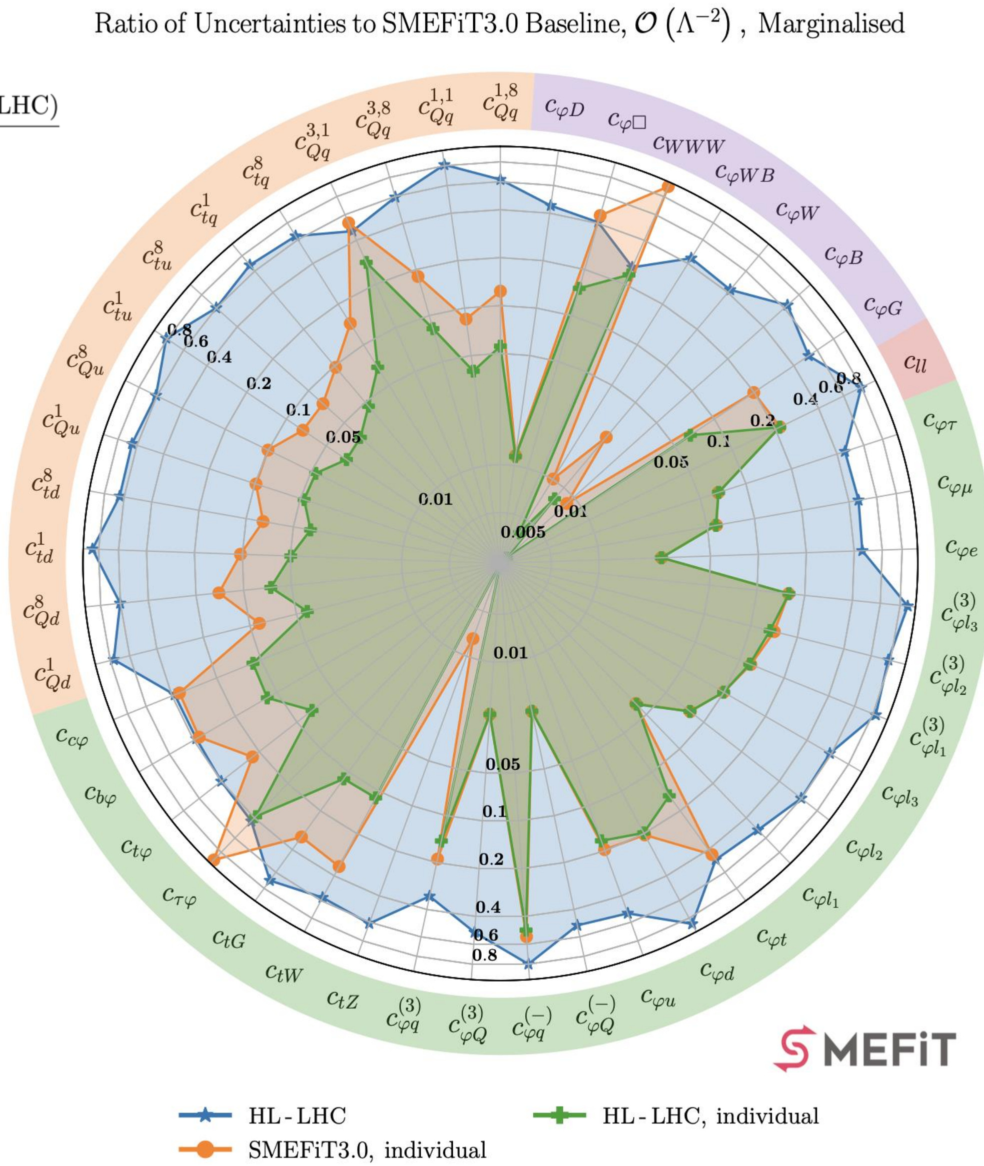
Impact of new LHC Run 2 data



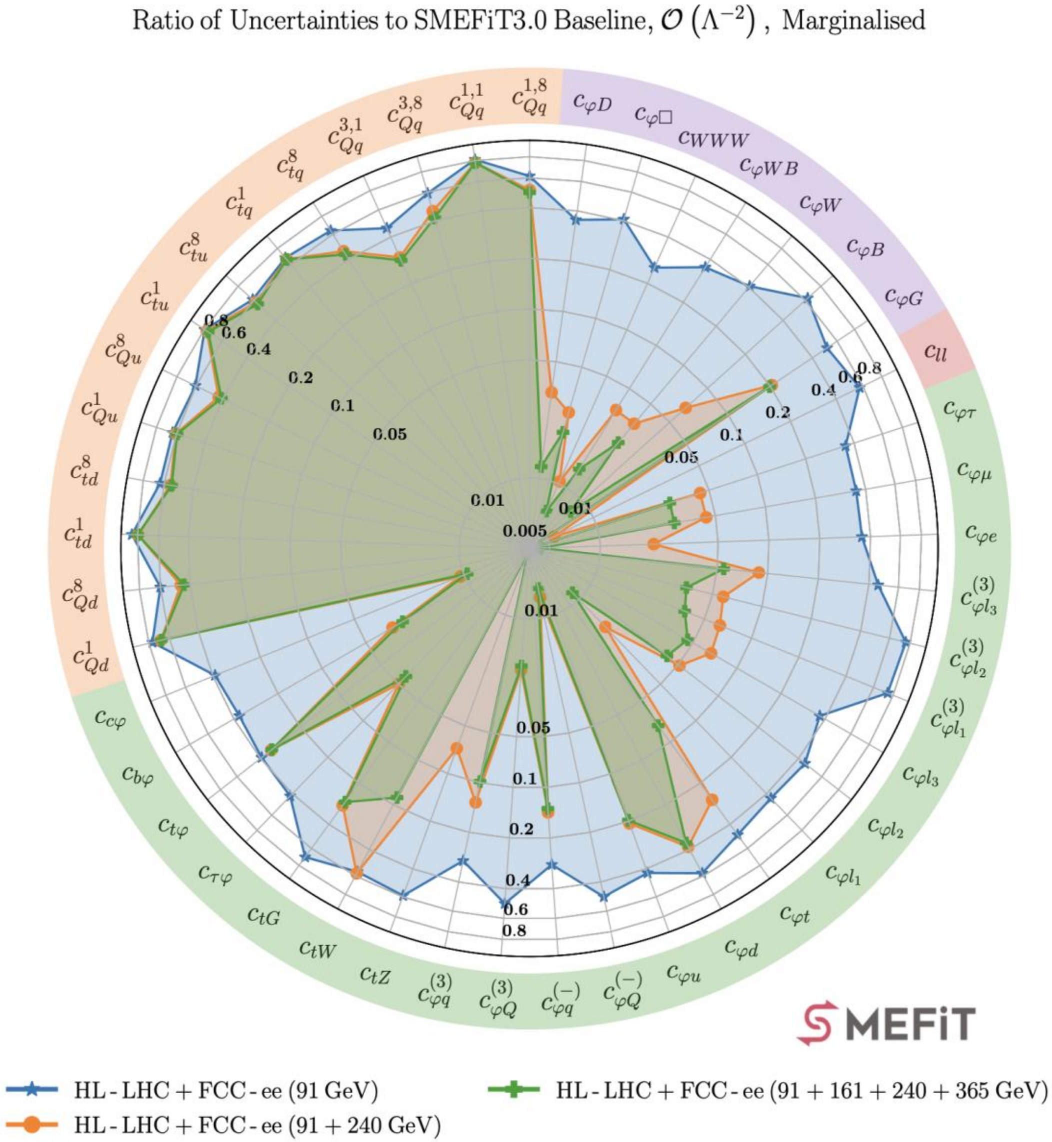
SMEFiT

HL-LHC impact in detail

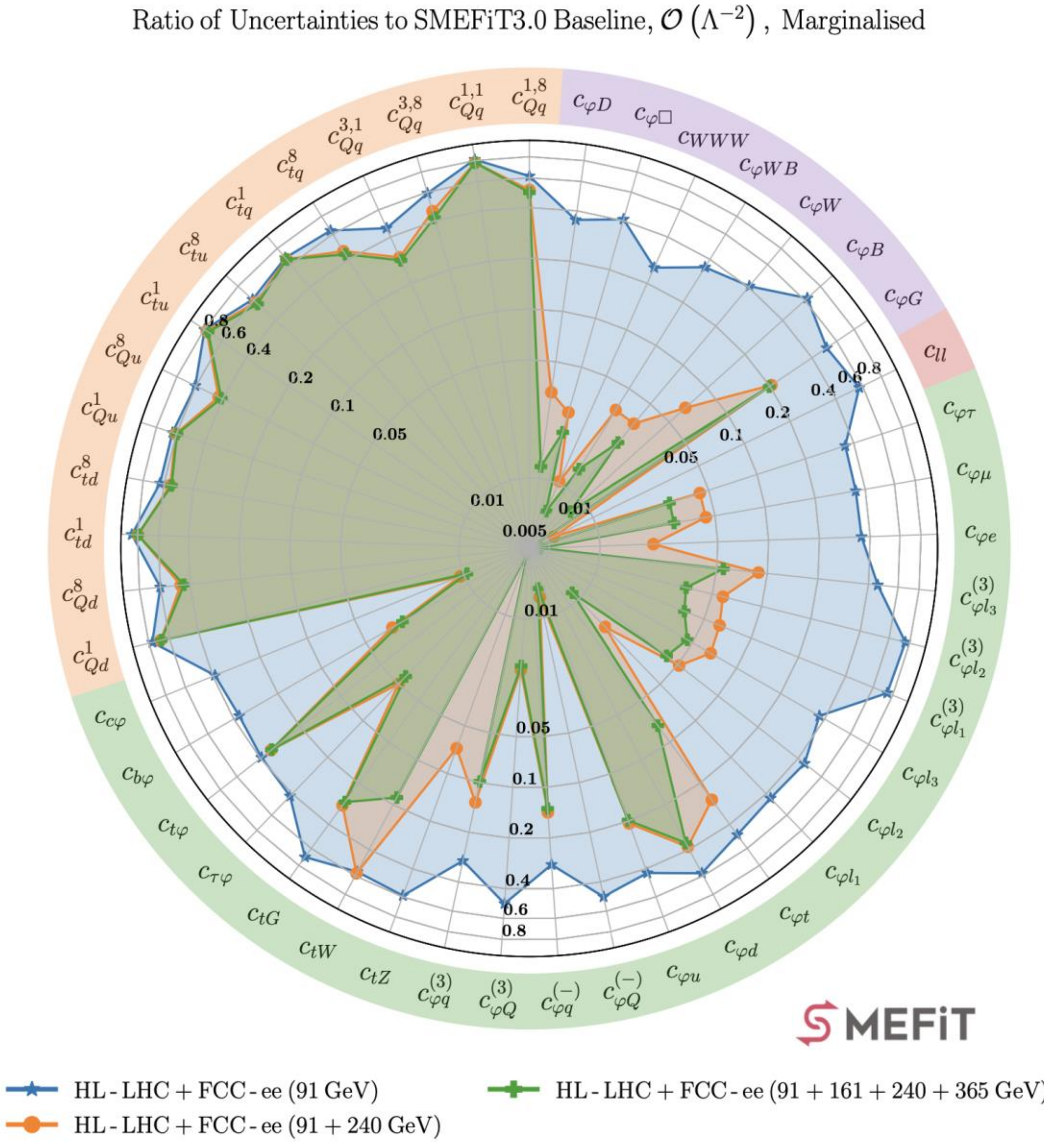
$$R_{\delta c_i} = \frac{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CL}}\ (\text{baseline} + \text{HL-LHC})}{[c_i^{\min}, c_i^{\max}]^{95\%\ \mathrm{CL}}\ (\text{baseline})}$$



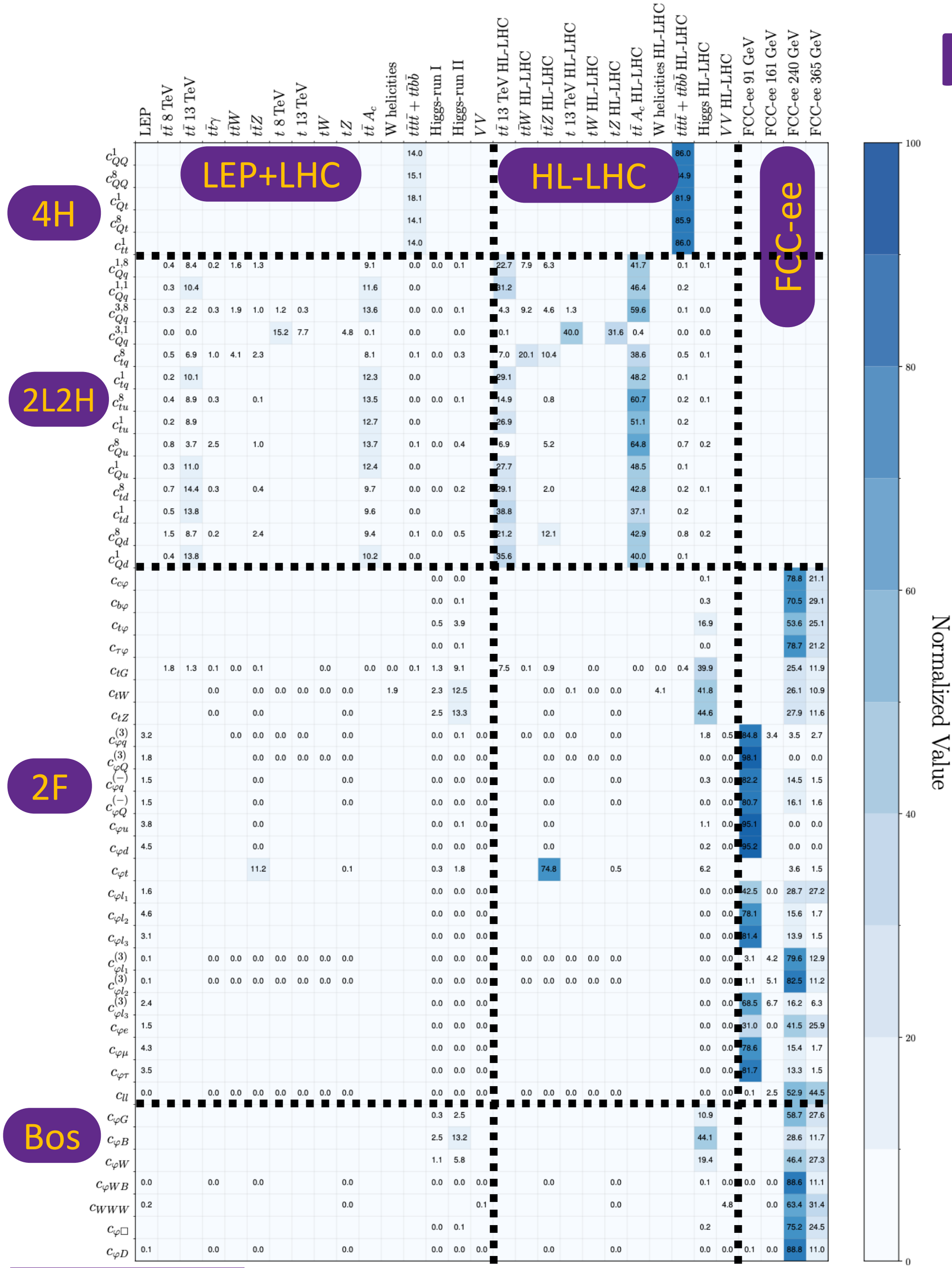
FCC-ee Energy runs



FCC-ee Energy runs



Fisher Information matrix



- Quantifies which datasets have more sensitivity to given operator
- Proxy for linear individual fit
- FCC-ee dominates nearly all operators except 4-quark operators, only accessible in pp collisions (tree level)
- Combination of 91 GeV and 240 GeV runs important to pin down 2-fermion and gauge operators
- FCC-ee run at 161 GeV is the least useful for the SMEFT

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

The power of multi(di)-boson