Global analysis of the *minimal* MFV SMEFT

MPA Summer School 2023

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MPA
MAINZ PHYSICS ACADEMY

Outline

MPA MAINZ PHYSICS ACADEMY

1. **Introduction**
   - Why going beyond the Standard Model (SM)?
   - The Standard Model Effective Field Theory (SMEFT)
2. **Symmetry assumption on New Physics (NP)**
   - $U(3)^5$ symmetry in SMEFT
   - Flavour symmetric operators
3. **The global fit**
   - The relevance of global fits
   - Observables constraints in SMEFT and unbounded operators
   - Dijets vs Dijets+γ
4. **Results and conclusion**

Introduction

The Standard Model

The Standard Model of particle physics has proven to be highly successful in describing elementary particles and their interactions.

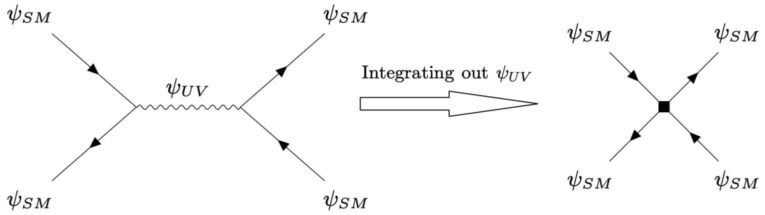
However:

- **Naturalness problems**
  - Higgs hierarchy problem
  - Strong CP problem
- **Cosmological observations**
  - Dark Matter
  - Baryon asymmetry
- **Flavour sector**
  - Fermion masses generation, including ν
  - Origin of flavour mixing

SM Effective Field Theory (SMEFT)

NP emerging at a scale Λ can be described at energies $E \ll \Lambda$ by non-renormalizable $SU(3)_c \times SU(2)_L \times U(1)_Y$ invariant operators.

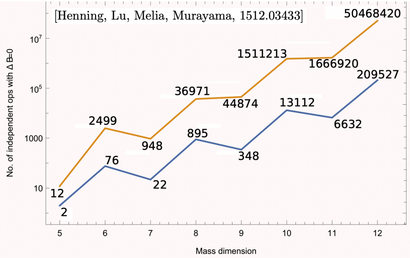
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{d>4} \sum_{i} \frac{C_i^{(d)}}{\Lambda^{d-4}} Q_i^{(d)}$$

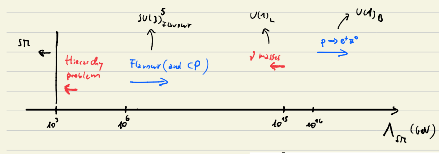


Symmetry assumption on New Physics (NP)

Model independent vs model agnostic

In SMEFT different manifestations of NP are well separated by present bounds.





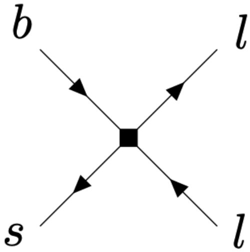
[Di Luzio, AT Unipd]

This allows us to specify a model within SMEFT, remaining agnostic on the particular features of a UV model.

$U(3)^5$ symmetry in dim 6 SMEFT

We assume NP to be flavour symmetric, reducing the number of operators to 41.

$$U(3)^5 = U(3)_\ell \times U(3)_q \times U(3)_e \times U(3)_u \times U(3)_d$$



No flavour changing neutral currents are generated at tree level.

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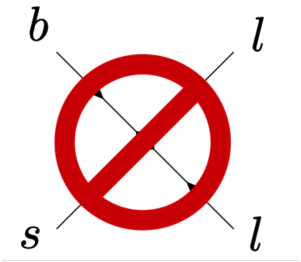

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$U(3)^5$ symmetry in dim 6 SMEFT

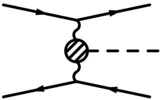
$1: X^3$		$2: H^6$		$3: H^4 D^2$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_H	$(H^\dagger H)^3$	$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$			Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

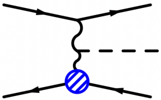
$4: X^2 H^2$		$7: \psi^2 H^2 D$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$	$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_p)$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_p)$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_p)$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_p)$
		$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_p)$
		Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_p)$
		Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_p)$

$8: (\bar{L}L)(\bar{L}L)$		$8: (\bar{R}R)(\bar{R}R)$		$8: (\bar{L}L)(\bar{R}R)$	
$Q_{\ell\ell}$	$(\bar{l}_p \gamma_\mu l_p)(\bar{l}_s \gamma^\mu l_s)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_p)(\bar{e}_s \gamma^\mu e_s)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_p)(\bar{e}_s \gamma^\mu e_s)$
$Q_{\ell\ell}'$	$(\bar{l}_p \gamma_\mu l_s)(\bar{l}_s \gamma^\mu l_p)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_p)(\bar{u}_s \gamma^\mu u_s)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_p)(\bar{u}_s \gamma^\mu u_s)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_p)(\bar{q}_s \gamma^\mu q_s)$	Q_{uu}'	$(\bar{u}_p \gamma_\mu u_s)(\bar{u}_s \gamma^\mu u_p)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_p)(\bar{d}_s \gamma^\mu d_s)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_p)(\bar{q}_s \gamma^\mu \tau^I q_s)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_p)(\bar{d}_s \gamma^\mu d_s)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_p)(\bar{e}_s \gamma^\mu e_s)$
$Q_{qq}^{(1)\prime}$	$(\bar{q}_p \gamma_\mu q_p)(\bar{q}_s \gamma^\mu q_s)$	Q_{dd}'	$(\bar{d}_p \gamma_\mu d_s)(\bar{d}_s \gamma^\mu d_p)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_p)(\bar{u}_s \gamma^\mu u_s)$
$Q_{qq}^{(3)\prime}$	$(\bar{q}_p \gamma_\mu \tau^I q_s)(\bar{q}_s \gamma^\mu \tau^I q_p)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_p)(\bar{u}_s \gamma^\mu u_s)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_p)(\bar{u}_s \gamma^\mu T^A u_s)$
$Q_{\ell q}^{(1)}$	$(\bar{l}_p \gamma_\mu l_p)(\bar{q}_s \gamma^\mu q_s)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_p)(\bar{d}_s \gamma^\mu d_s)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_p)(\bar{d}_s \gamma^\mu d_s)$
$Q_{\ell q}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_p)(\bar{q}_s \gamma^\mu \tau^I q_s)$	$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_p)(\bar{d}_s \gamma^\mu d_s)$	$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_p)(\bar{d}_s \gamma^\mu T^A d_s)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_p)(\bar{d}_s \gamma^\mu T^A d_s)$		

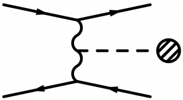
The global fit

One observable can be influenced by many operators:

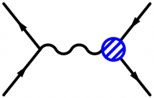




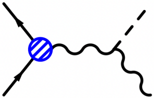
Higgs decay



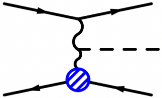
One operator can contribute to many different observables:



$e^+e^- \to f\bar{f}$



Zh production



Weak boson fusion
Higgs production

[Biekötter, Invisibles]

Leading order SMEFT constraints

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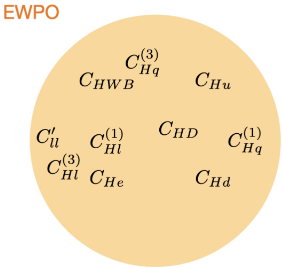
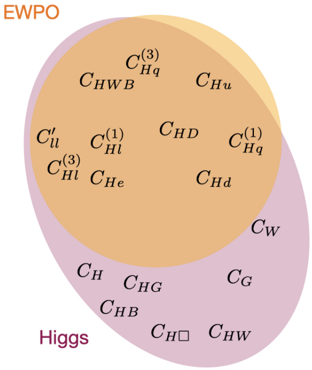
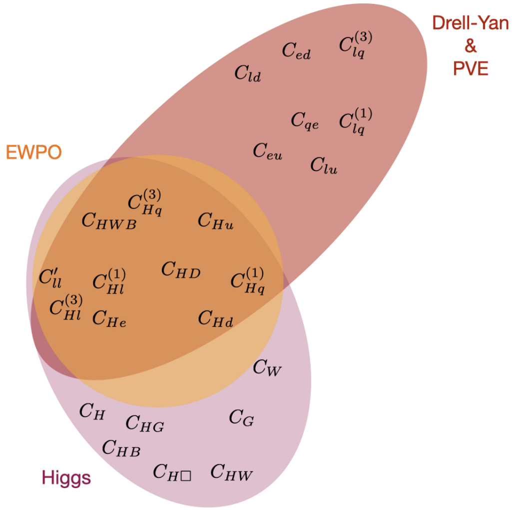



EWPO
$C_{Hq}^{(3)}$
C_{HWB}
C_{Hu}
C'_{ll}
$C_{Hl}^{(1)}$
C_{HD}
$C_{Hq}^{(1)}$
$C_{Hl}^{(3)}$
C_{He}
C_{Hd}
C_W
C_H
C_{HG}
C_G
C_{HB}
Higgs
$C_{H\Box}$
C_{HW}

Leading order SMEFT constraints



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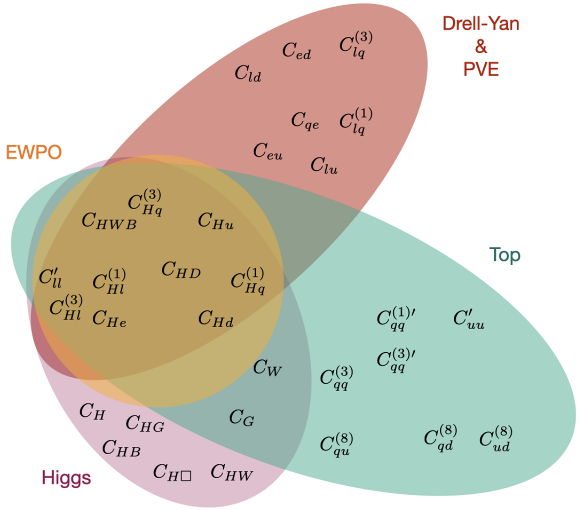

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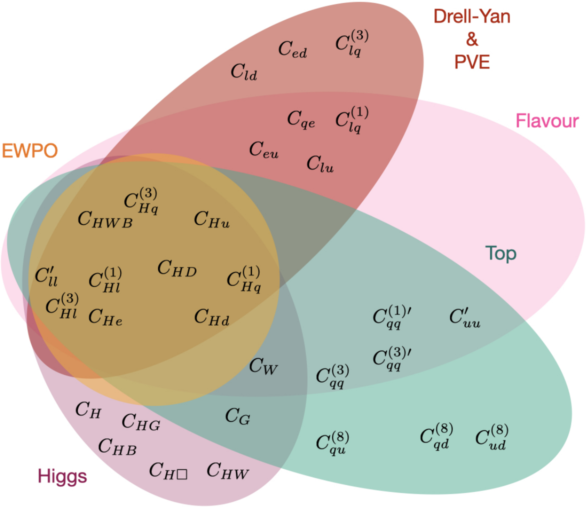

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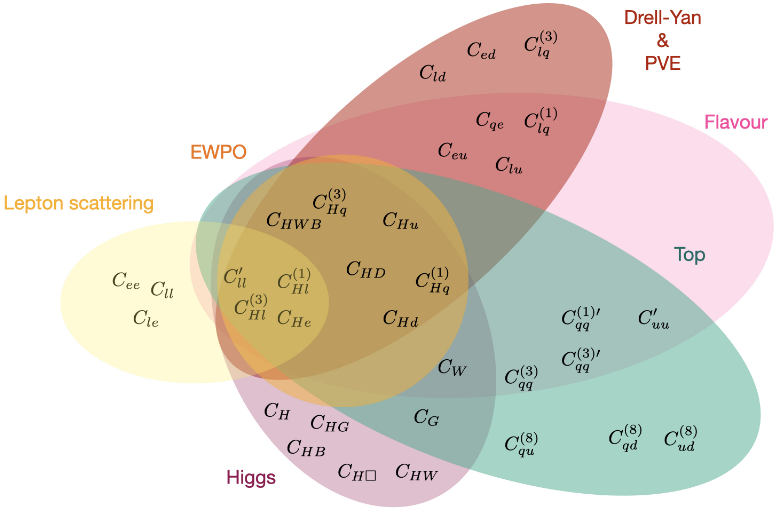

Unconstrained operators in SMEFT

Leading order observables are not enough to constrain significantly the following operators:

$$\{C_{qq}^{(1)}, C_{qu}^{(1)}, C_{ud}^{(1)}, C_{qd}^{(1)}, C_{dd}, C'_{dd}, C_{uu}\}$$

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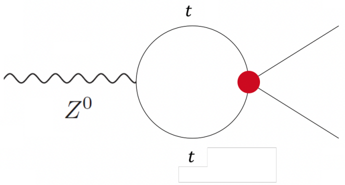

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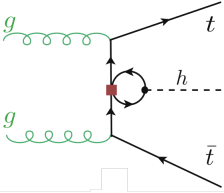

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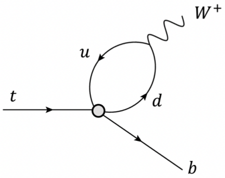

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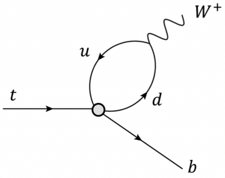
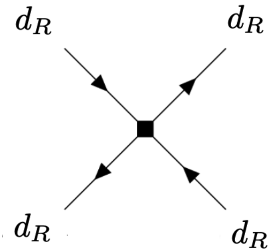


NLO top, Higgs and EW data are not sufficient to constrain these seven operators.

What's wrong with C_{dd} and C'_{dd}?

$$Q_{dd} = (\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$$



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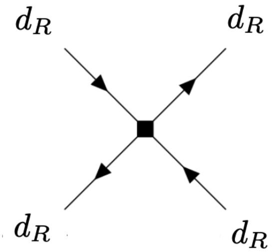

- **4-quark operator** { No TL observables

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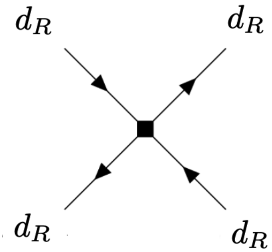
$$Q_{dd} = (\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$$



- **4-quark operator** { No TL observables
- **Down type** { No Top; Loop suppression

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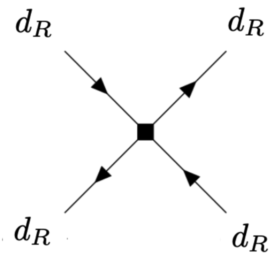
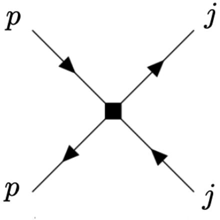


- **4-quark operator** { No TL observables
- **Down type** { No Top, Loop suppression
- **Right handed** { Flavour excluded

Dijets constraints

Two jets production at LHC looks the perfect choice to constrain the unconstrained operators.

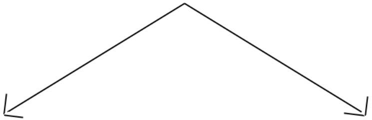


Dijets constraints

Two jets production at LHC looks the perfect choice to constrain the unconstrained operators.

But:

Trigger threshold for jets at the LHC restricts the testable kinematic to multi-TeV invariant masses.



Validity of Effective Theory? Dominant quadratic terms

In SMEFT every cross section has the form:

$$\sigma \propto |\mathcal{A}|^2 = \underbrace{|\mathcal{A}_{\rm SM}|^2}_{\text{SM background}} + \underbrace{\frac{2C_6}{\Lambda^2}\,{\rm Re}(\mathcal{A}_{\rm d6}\mathcal{A}^*_{\rm SM})}_{\text{signal}} + \underbrace{\frac{C_6^2}{\Lambda^4}|\mathcal{A}_{\rm d6}|^2 + \frac{2C_8}{\Lambda^4}\,{\rm Re}(\mathcal{A}_{\rm d8}\mathcal{A}^*_{\rm SM})}_{\text{theoretical uncertainty}} + \ldots$$

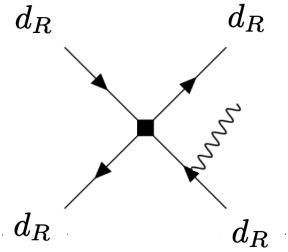
for 4-quark operators we have:

$$\sigma \propto \frac{|C_{dd}|^2}{\Lambda^4} s$$

If one cannot neglect $1/\Lambda^4$ terms, dimension 8 operators enter the game.

Dijets+γ solution

Considering instead the production of two jets in association with a photon enables us to probe lower dijet invariant-mass ranges $m_{jj} < 1.1$ TeV and circumvent this issue.

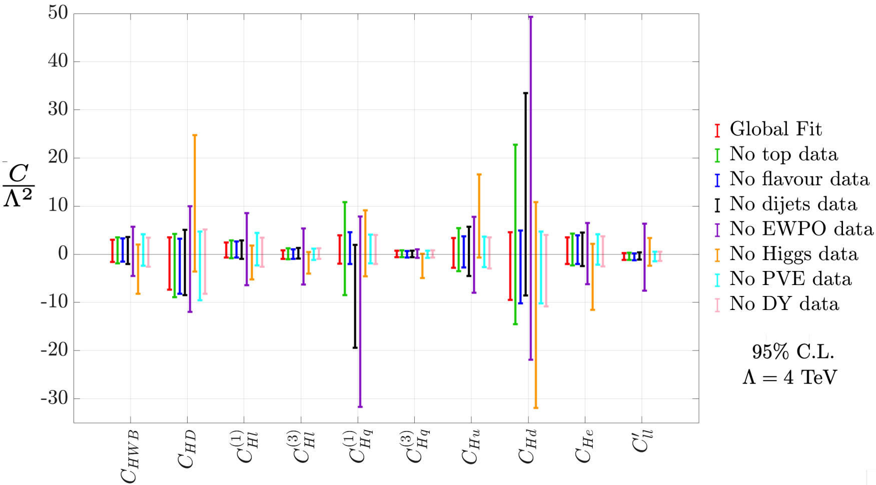


Dijet mass range: 225 GeV–1.1 TeV [ATLAS, 1901.10917]

We evaluated cross sections for this process with Madgraph and implemented the relevant cuts in a Rivet analysis for the event selection.

Results and conclusion

Global fit results



Conclusion

Summary:

- SM needs an extension to address fundamental problems;
- SMEFT is the framework to study NP in a model agnostic way;
- Global fits are needed to map all directions of NP;
- We employed 8 different data sets in order to constrain all the flavour symmetric coefficients;
- Some coefficients are really hard to constrain due to their structure;
- Dijets+γ provides a consistent solution to constrain 4-quark operators.

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Summary:

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THANK YOU FOR YOUR ATTENTION!

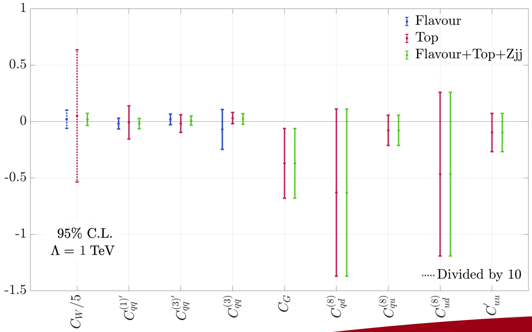
Backup slides

$U(3)^5$ symmetry in dim 6 SMEFT

We assume NP to be flavour symmetric, reducing the number of operators to 41.

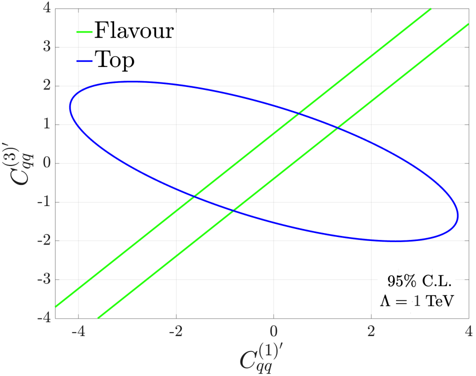
$$U(3)^5 = U(3)_\ell \times U(3)_q \times U(3)_e \times U(3)_u \times U(3)_d$$

Even if NP is $U(3)^5$ symmetric, Yukawa couplings break the symmetry. In the RGE we generate flavour violating operators.



Correlations between Flavour and Top

Not only flavour constraints can be better than Top constraints but they also constrain different directions:



Warsaw basis

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				
$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

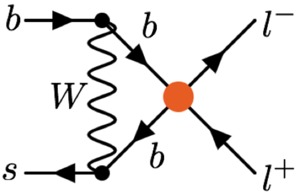
Warsaw basis

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

FCNC at 1 loop under $U(3)^5$

Even if the SMEFT operator is flavour symmetric, we generate FCNC thanks to the SM flavour violating couplings:



Primed vs unprimed coefficients

Some 4−fermion operators can be made flavour symmetric in two different ways.

$$Q_{ll} = (\bar{l}_i \gamma_\mu l_j)(\bar{l}_k \gamma^\mu l_l)$$

$$C_{ll}\,\delta_{ij}\delta_{lk} \qquad \text{and} \qquad C'_{ll}\,\delta_{ik}\delta_{jl}$$

Both contractions are $U(3)^5$ symmetric but only the two different operators enter differently in the observables.

Relevance of global fits

One parameter bounds seem to push the NP scale far above the EW scale. However, no UV models provide matching on single operators.

$$\text{Single parameter bound on } C_{qe} \rightarrow \Lambda > 11.1\,\text{TeV}$$
$$\text{Global parameter bound on } C_{qe} \rightarrow \Lambda > 1.3\,\text{TeV}$$

In addition, also correlations clearly present in 2D fits can be erased in the global analysis.