Non-LHC EFT inputs

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- Introduction
- On the bounds on four-fermion operators
- Flavor symmetries in the SMEFT
- Conclusions

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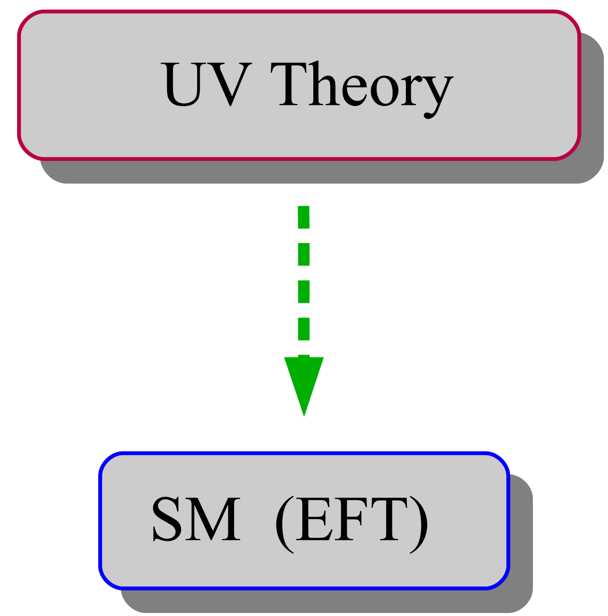
▶ <u>*Introduction*</u> [*general considerations the EFT approach to BSM physics*]

When dealing with EFTs there are two conceptually different approaches:

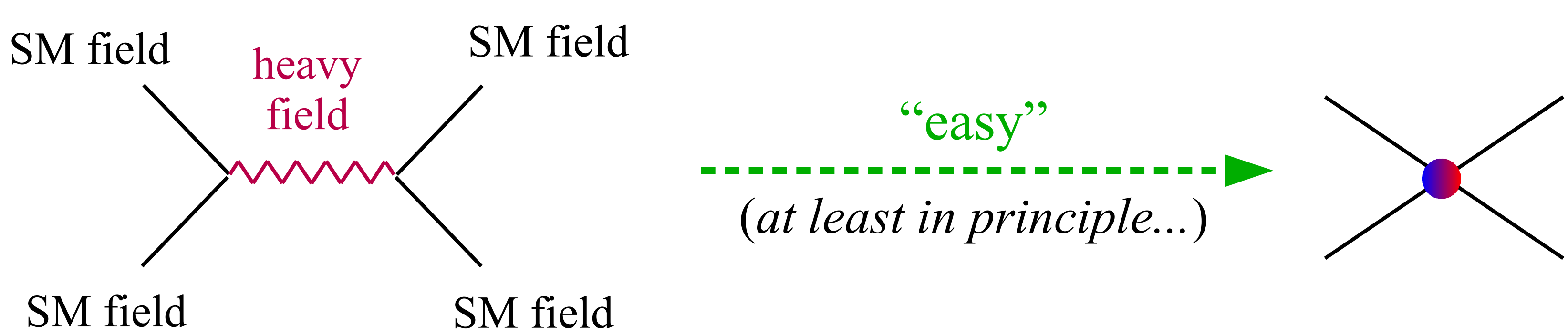
- top ⟶ down (UV theory known)

<u>low-energy “projection”</u>

“integrate out” heavy degrees of freedom



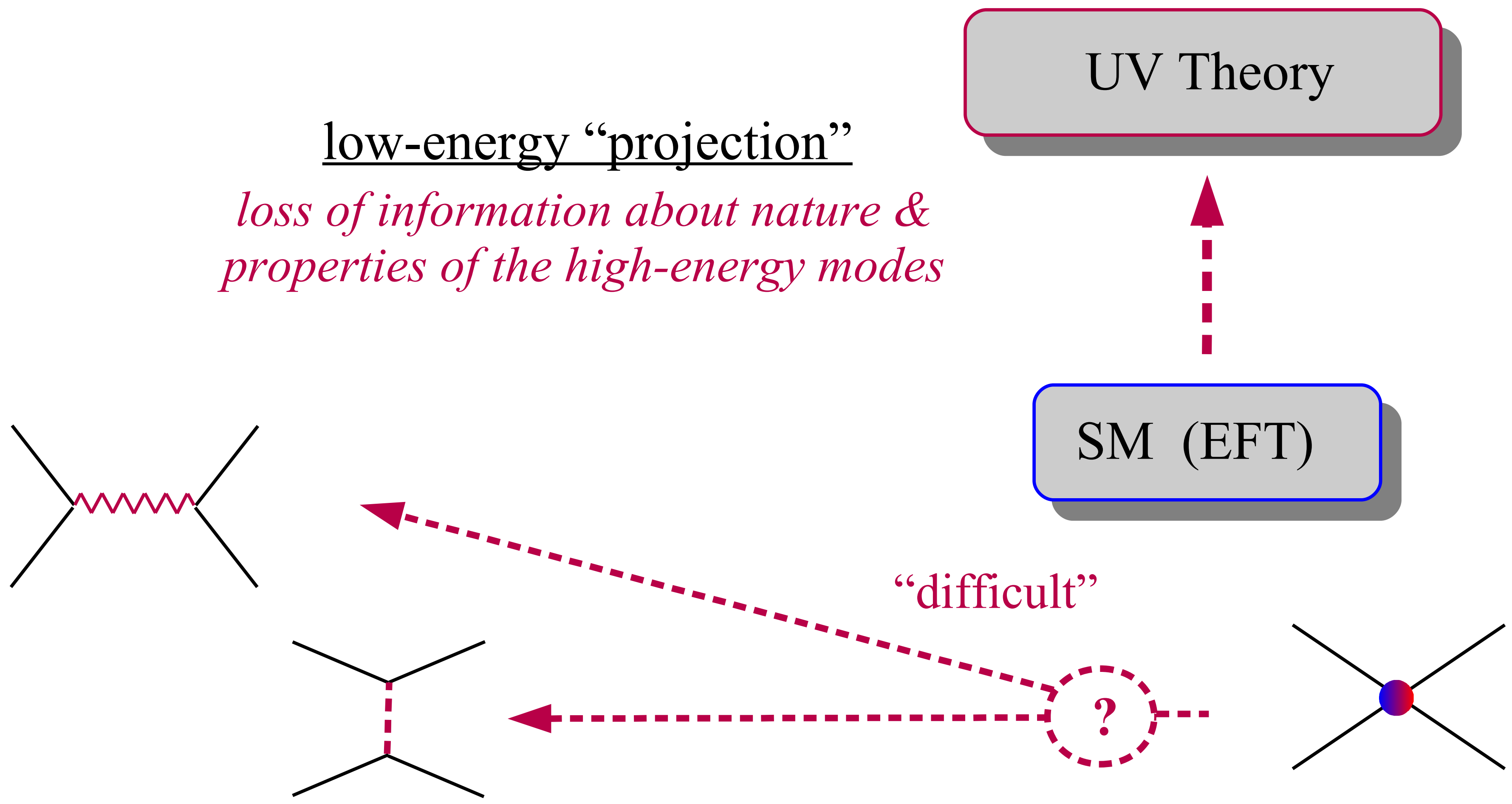
Depending on the UV Theory, conceivable to concentrate on specific sub-sectors of the EFT



Introduction [*general considerations the EFT approach to BSM physics*]

When dealing with EFTs there are two conceptually different approaches:

- top $\longrightarrow$ down (UV theory known)
- bottom $\rightarrow$ up (UV theory unknown)

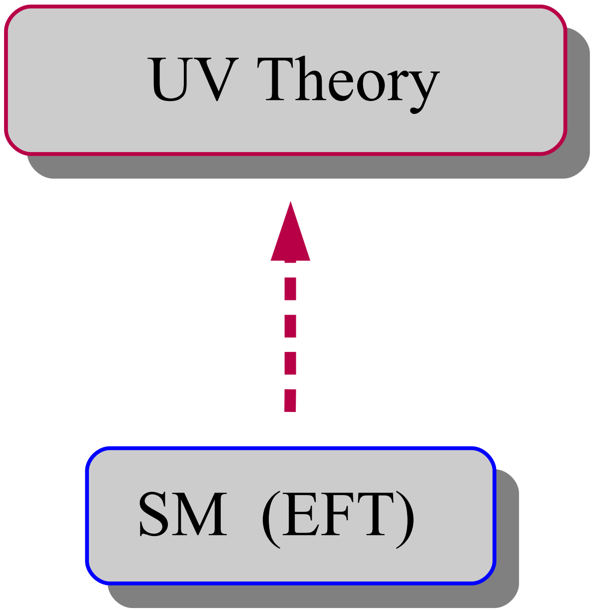


Introduction [*general considerations the EFT approach to BSM physics*]

When dealing with EFTs there are two conceptually different approaches:

- top $\longrightarrow$ down (UV theory known)
- bottom $\rightarrow$ up (UV theory unknown)

In this perspective, it is crucial trying to collect all the available information on the coeff. of the EFT operators (= *minimize the loss of information*)



→ Essential to put together low- and high-pT constraints

To do this in a consistent way we need to make extra assumptions on the structure of the EFT:

→ Key role of flavor and other global symmetries

Global symmetries → organize the EFT in sub-sectors that talk each others at a well-defined level of accuracy

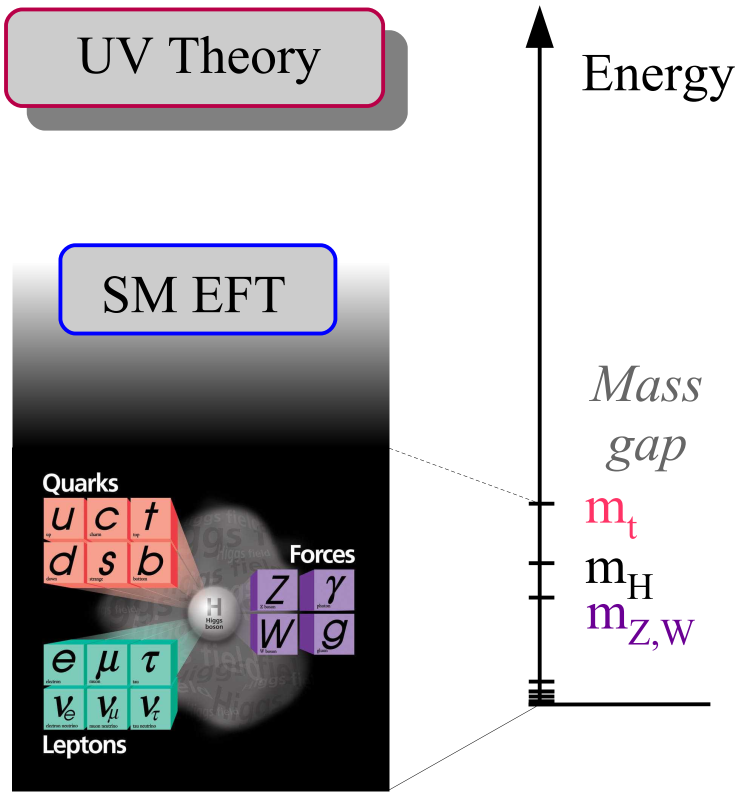
Introduction [*general considerations the EFT approach to BSM physics*]

When we build an EFT we need to specify:

- Number and species of "light" *matter fields* → $[Q_L\,, u_R, d_R, L_L, e_R\,] + H$

SM EFT

- The nature of *gauge* interactions → SU(3)×SU(2)×U(1)



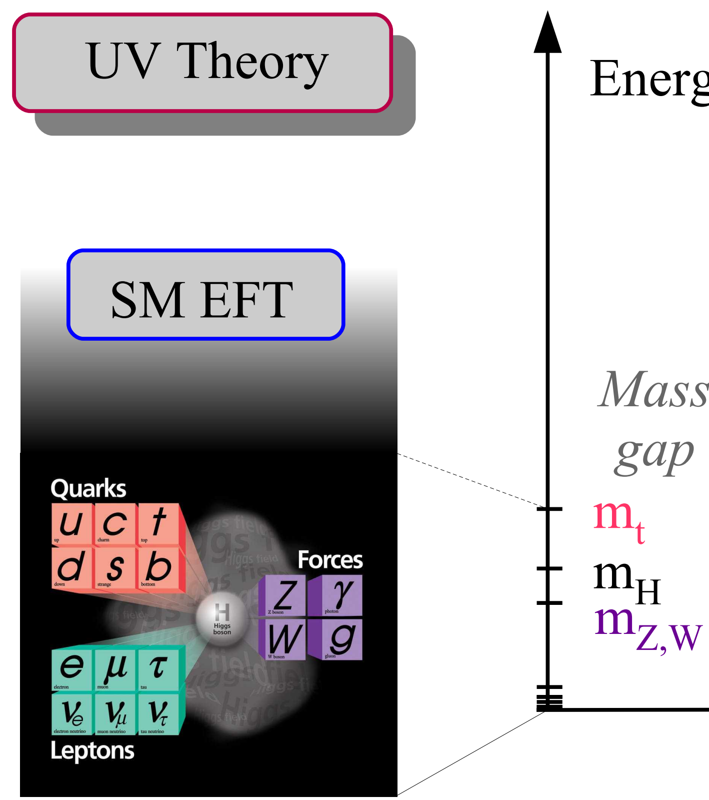
<u>*Introduction*</u> [*general considerations the EFT approach to BSM physics*]

When we build an EFT we need to specify:

- Number and species of "light" <u>*matter fields*</u> → $[Q_L\,,\, u_R,\, d_R,\, L_L,\, e_R\,] + \mathrm{H}$
- SM EFT
- The nature of <u>*gauge*</u> interactions → $SU(3)\times SU(2)\times U(1)$
- Possible <u>global symmetries</u> and <u>symmetry breaking terms</u>

↓

<u>*Different versions of the SM EFT*</u>



NB:

I. Flavor symmetries do not need to be "fundamental" symmetries in the UV (*possible accidental/dynamical effects*)

II. Assumptions on flavor symmetries necessary for a <u>consistent</u> EFT with BSM effects within LHC reach

▶ *Introduction* [*general considerations the EFT approach to BSM physics*]

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \underbrace{\mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}}^{\text{Non-trivial UV imprints}}$$

"trivial" low-energy projection

Structure fully dictated by

- Number of light fields
- Their gauge quantum numbers (= *charges under long-range interactions*)

Introduction [*general considerations the EFT approach to BSM physics*]

Non-trivial UV imprints

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \underbrace{\mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}}$$

"trivial" low-energy projection

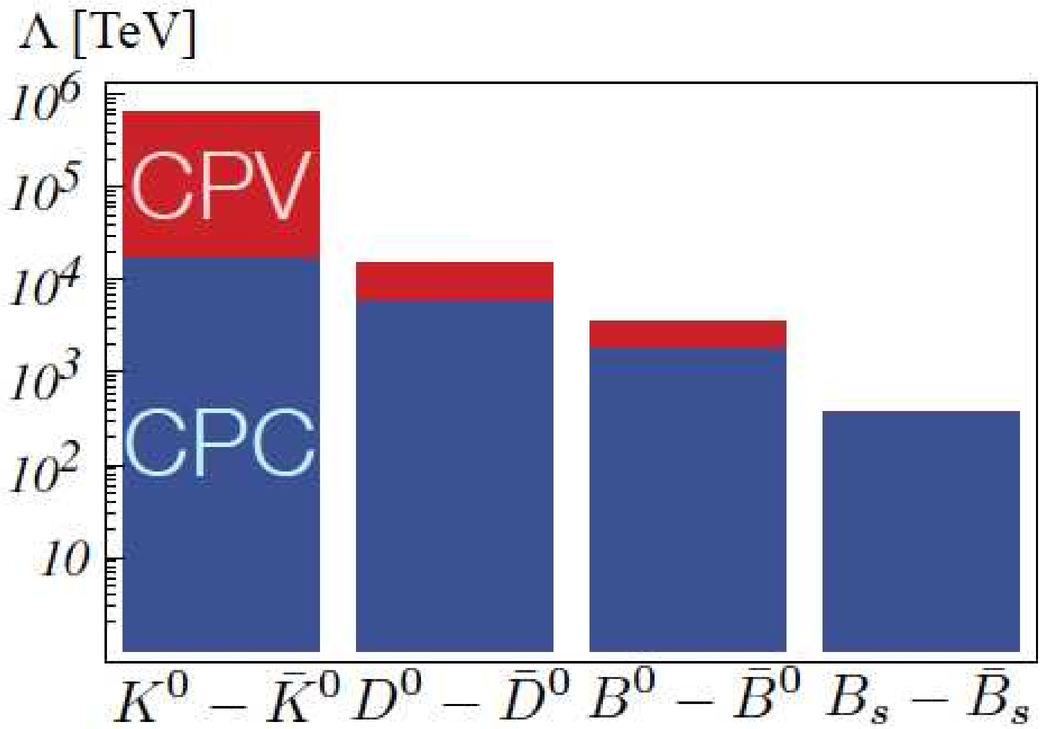
$y_{ij}\, \psi_i \psi_j H$

$\Lambda_{\text{Flavor}} > 10^2 - 10^5$ TeV

- In the absence of symmetries, we would expect $y_{ij} \sim O(1)$, while we know this is NOT the case

- In the absence of symmetries, we expect similar size for all the d=6 ops → flavor bounds implies very heavy NP scale → <u>no chance to see NP effects in genuine EW processes & high-pT observables</u>

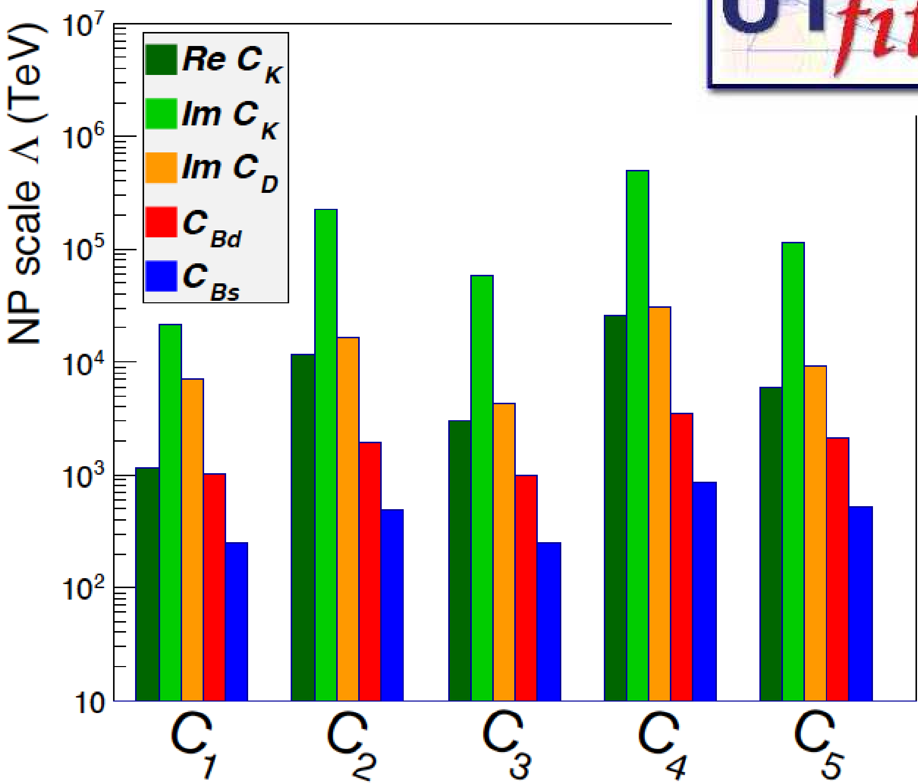
On the bounds on
four-fermion operators



On the bounds on four-fermion operators [*a brief overview*]

The prototype of relevant non-LHC bounds on SMEFT operators are the bounds from meson-antimeson mixing processes.

Since a long time it is know that these processes set very strong bounds on dimension-6 |ΔF|=2 operators:



← bounds on the limited set of 5 ops. with non-vanishing <u>tree-level</u> contrib. (*for each quark-pair*):

$$
\begin{aligned}
Q_1^{q_i q_j} &= \bar{q}^{\alpha}_{jL}\gamma_\mu q^{\alpha}_{iL}\bar{q}^{\beta}_{jL}\gamma^\mu q^{\beta}_{iL}\,,\\
Q_2^{q_i q_j} &= \bar{q}^{\alpha}_{jR} q^{\alpha}_{iL}\bar{q}^{\beta}_{jR} q^{\beta}_{iL}\,,\\
Q_3^{q_i q_j} &= \bar{q}^{\alpha}_{jR} q^{\beta}_{iL}\bar{q}^{\beta}_{jR} q^{\alpha}_{iL}\,,\\
Q_4^{q_i q_j} &= \bar{q}^{\alpha}_{jR} q^{\alpha}_{iL}\bar{q}^{\beta}_{jL} q^{\beta}_{iR}\,,\\
Q_5^{q_i q_j} &= \bar{q}^{\alpha}_{jR} q^{\beta}_{iL}\bar{q}^{\beta}_{jL} q^{\alpha}_{iR}\,.
\end{aligned}
$$

On the bounds on four-fermion operators [*a brief overview*]

The prototype of relevant non-LHC bounds on SMEFT operators are the bounds from meson-antimeson mixing processes.

What is maybe less known, is that is a key constraint on the whole SM EFT, once we take into RGE effects [Silvestrini & Valli, 2019]:

	$C_{ij}^{HQ^{(1,3)}}$ [TeV^{-2}]	
ij	Y_D diag	Y_U diag
11	$\varnothing$	$4.1^{\square}\ 10^{-3}$
12	$(8.9^{\square}, 3.8^{\square})\ 10^{-4}$	$(9.9^{\square}, 3.8^{\square})\ 10^{-4}$
13	$(7.4^{\triangle}, 6.3^{\triangle})\ 10^{-3}$	$(7.6^{\triangle}, 6.4^{\triangle})\ 10^{-3}$
22	$\varnothing$	$4.1^{\square}\ 10^{-3}$
23	$(3.0^{\triangledown}, 1.0^{\triangledown})\ 10^{-2}$	$(3.1^{\triangledown}, 1.0^{\triangledown})\ 10^{-2}$
33	$\varnothing$	$7.3^{\triangle}\ 10^{-1}$

← Bounds on the following |ΔF|=1 operators:

$$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$$

$$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$$

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33	$\varnothing$	$7.3^{\triangle}\ 10^{-1}$

$ijkl$	C_{ijkl}^{LeQu} [TeV^{-2}] Y_D diag	C_{ijkl}^{LedQ} [TeV^{-2}] Y_U diag
2221	$(5.1^{\diamond}, 1.6^{\diamond})\ 10^{-1}$	$(4.2^{\square}, 0.13^{\square})\ 10^{-1}$
2222	$(22^{\diamond}, 6.8^{\diamond})\ 10^{-1}$	$(18^{\square}, 0.58^{\square})\ 10^{-1}$
2223	$(\varnothing, \varnothing)$	$(4.3^{\square}, 1.6^{\square})$
3321	$(3.0^{\diamond}, 0.93^{\diamond})\ 10^{-2}$	$(24^{\square}, 0.8^{\square})\ 10^{-3}$
3322	$(1.3^{\diamond}, 0.4^{\diamond})\ 10^{-1}$	$(10^{\square}, 0.34^{\square})\ 10^{-2}$
3323	$(3.1^{\diamond}, 3.6^{\diamond})$	$(2.5^{\square}, 0.9^{\square})\ 10^{-1}$
3331	$(\varnothing, 9.5^{\diamond})$	$(8.5^{\triangle}, 11^{\triangle})$
3332	$(\varnothing, \varnothing)$	$(\varnothing, 8.9^{\triangledown})$

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	$C^{Qd^{(1)}}_{ijkl}$ [TeV^{-2}]		$C^{Qd^{(8)}}_{ijkl}$ [TeV^{-2}]		$C^{Qu^{(1)}}_{ijkl}$ [TeV^{-2}]		$C^{Qu^{(8)}}_{ijkl}$ [TeV^{-2}]	
ijkl	Y_D diag	Y_U diag	Y_D diag	Y_U diag	Y_D diag	Y_U diag	Y_D diag	Y_U diag
1111	$11^{\square}$	$8.2^{\square}\ 10^{-4}$	$3.3^{\square}$	$1.7^{\square}\ 10^{-4}$	$3.7^{\diamond}\ 10^{-1}$	$\varnothing$	$2.2^{\diamond}$	$\varnothing$
1112	$(1.9^{\square}, 0.81^{\square})\ 10^{-5}$	$(64^{\square}, 0.29^{\square})\ 10^{-9}$	$(5.5^{\square}, 2.3^{\square})\ 10^{-6}$	$(14^{\square}, 0.062^{\square})\ 10^{-9}$	$(6.0^{\diamond}, 0.18^{\diamond})\ 10^{-7}$	$(5.0^{\diamond}, 4.9^{\diamond})$	$(14^{\diamond}, 0.45^{\diamond})\ 10^{-8}$	$(1.4^{\diamond}, 1.4^{\diamond})$
1113	$(2.2^{\triangle}, 2.1^{\triangle})\ 10^{-3}$	$(7.7^{\triangle}, 0.77^{\square})\ 10^{-5}$	$(1.1^{\triangle}, 0.81^{\triangle})\ 10^{-3}$	$(3.4^{\triangle}, 0.16^{\square})\ 10^{-5}$	$(3.9^{\diamond}, 0.12^{\diamond})\ 10^{-2}$	$(\varnothing, 1.8^{\square})$	$(24^{\diamond}, 0.74^{\diamond})\ 10^{-2}$	$(\varnothing, 5.5^{\square})$
1122	$12^{\square}$	$8.2^{\square}\ 10^{-4}$	$3.3^{\square}$	$1.7^{\square}\ 10^{-4}$	$1.9^{\diamond}\ 10^{-1}$	$\varnothing$	$1.4^{\diamond}\ 10^{-1}$	$\varnothing$
1123	$(\varnothing, \varnothing)$	$(1.9^{\square}, 0.75^{\square})\ 10^{-3}$	$(7.4^{\square}, 7.4^{\square})$	$(4.0^{\square}, 1.6^{\square})\ 10^{-4}$	$(7.9^{\diamond}, 6.5^{\diamond})\ 10^{-3}$	$(4.8^{\square}, 11^{\square})\ 10^{-2}$	$(5.9^{\diamond}, 4.9^{\diamond})\ 10^{-3}$	$(1.4^{\square}, 3.2^{\square})\ 10^{-1}$
1133	$\varnothing$	$\varnothing$	$\varnothing$	$10^{\square}$	$\varnothing$	$4.1^{\square}\ 10^{-3}$	$\varnothing$	$1.2^{\square}\ 10^{-2}$
1211	$(1.8^{\square}, 0.76^{\square})\ 10^{-4}$	$(2.0^{\square}, 0.76^{\square})\ 10^{-4}$	$(3.8^{\square}, 1.6^{\square})\ 10^{-5}$	$(4.3^{\square}, 1.6^{\square})\ 10^{-5}$	$(9.1^{\diamond}, 2.5^{\diamond})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(5.4^{\diamond}, 1.5^{\diamond})\ 10^{-1}$	$(\varnothing, \varnothing)$
1212	$(140^{\square}, 0.63^{\square})\ 10^{-10}$	$(150^{\square}, 0.67^{\square})\ 10^{-10}$	$(30^{\square}, 0.14^{\square})\ 10^{-10}$	$(32^{\square}, 0.14^{\square})\ 10^{-10}$	$(14^{\diamond}, 0.43^{\diamond})\ 10^{-8}$	$(13^{\diamond}, 0.40^{\diamond})\ 10^{-8}$	$(3.3^{\diamond}, 0.1^{\diamond})\ 10^{-8}$	$(32^{\diamond}, 0.98^{\diamond})\ 10^{-9}$
1213	$(9.2^{\square}, 0.17^{\square})\ 10^{-5}$	$(6.4^{\triangle}, 1.8^{\square})\ 10^{-6}$	$(20^{\square}, 0.36^{\square})\ 10^{-6}$	$(36^{\triangle}, 3.8^{\triangle})\ 10^{-7}$	$(9.1^{\diamond}, 0.28^{\diamond})\ 10^{-3}$	$(\varnothing, 4.4^{\diamond})\ 10^{-1}$	$(5.5^{\diamond}, 0.17^{\diamond})\ 10^{-2}$	$(\varnothing, 5.2^{\diamond})\ 10^{-1}$
1221	$(1.2^{\square}, 1.2^{\square})$	$(28^{\square}, 0.13^{\square})\ 10^{-8}$	$(2.5^{\square}, 2.7^{\square})\ 10^{-1}$	$(60^{\square}, 0.27^{\square})\ 10^{-9}$	$(26^{\diamond}, 0.8^{\square})\ 10^{-7}$	$(\varnothing, \varnothing)$	$(6.2^{\diamond}, 0.19^{\diamond})\ 10^{-7}$	$(\varnothing, \varnothing)$
1222	$(1.8^{\square}, 0.76^{\square})\ 10^{-4}$	$(2.0^{\square}, 0.77^{\square})\ 10^{-4}$	$(3.9^{\square}, 1.6^{\square})\ 10^{-5}$	$(4.3^{\square}, 1.6^{\square})\ 10^{-5}$	$(4.5^{\diamond}, 1.3^{\diamond})\ 10^{-2}$	$(\varnothing, 4.5^{\diamond})\ 10^{-2}$	$(3.4^{\diamond}, 0.95^{\diamond})\ 10^{-2}$	$(\varnothing, 1.3^{\diamond})\ 10^{-1}$
1223	$(4.6^{\square}, 2.1^{\square})$	$(7.3^{\triangledown}, 2.5^{\triangledown})\ 10^{-4}$	$(9.8^{\square}, 4.4^{\square})\ 10^{-1}$	$(4.6^{\triangledown}, 1.6^{\triangledown})\ 10^{-4}$	$(3.4^{\diamond}, 2.8^{\diamond})\ 10^{-2}$	$(120^{\square}, 0.38^{\square})\ 10^{-2}$	$(2.6^{\diamond}, 2.1^{\diamond})\ 10^{-2}$	$(37^{\square}, 0.11^{\square})\ 10^{-1}$
1231	$(\varnothing, \varnothing)$	$(3.3^{\triangle}, 0.33^{\square})\ 10^{-4}$	$(\varnothing, \varnothing)$	$(15^{\triangle}, 0.71^{\square})\ 10^{-5}$	$(4.8^{\square}, 0.53^{\diamond})\ 10^{-2}$	$(\varnothing, \varnothing)$	$(14^{\square}, 3.2^{\diamond})\ 10^{-2}$	$(\varnothing, \varnothing)$
1232	$(4.1^{\square}, 1.7^{\square})\ 10^{-4}$	$(4.3^{\square}, 1.7^{\square})\ 10^{-4}$	$(8.7^{\square}, 3.6^{\square})\ 10^{-5}$	$(9.2^{\square}, 3.7^{\square})\ 10^{-5}$	$(3.8^{\diamond}, 1.1^{\diamond})\ 10^{-3}$	$(12^{\square}, 4.4^{\square})\ 10^{-3}$	$(2.8^{\diamond}, 0.82^{\diamond})\ 10^{-3}$	$(3.5^{\square}, 1.3^{\square})\ 10^{-2}$
1233	$(10^{\square}, 4.5^{\square})$	$(12^{\square}, 4.3^{\square})$	$(2.2^{\square}, 0.95^{\square})$	$(2.5^{\square}, 0.95^{\square})$	$(2.5^{\square}, 1.0^{\square})\ 10^{-1}$	$(9.9^{\square}, 3.8^{\square})\ 10^{-4}$	$(7.6^{\square}, 3.1^{\square})\ 10^{-1}$	$(3.0^{\square}, 1.1^{\square})\ 10^{-3}$
1311	$(1.8^{\square}, 0.80^{\square})\ 10^{-1}$	$(4.7^{\square}, 1.8^{\square})\ 10^{-3}$	$(3.0^{\square}, 1.4^{\square})\ 10^{-2}$	$(10^{\square}, 4.0^{\square})\ 10^{-4}$	$(1.8^{\diamond}, 0.6^{\diamond})$	$(\varnothing, \varnothing)$	$(11^{\diamond}, 3.5^{\diamond})$	$(\varnothing, \varnothing)$
1312	$(36^{\square}, 0.65^{\square})\ 10^{-7}$	$(8.6^{\square}, 0.16^{\square})\ 10^{-8}$	$(6.1^{\square}, 0.11^{\square})\ 10^{-7}$	$(18^{\square}, 0.34^{\square})\ 10^{-9}$	$(31^{\diamond}, 0.96^{\diamond})\ 10^{-7}$	$(3.6^{\diamond}, 0.11^{\diamond})\ 10^{-1}$	$(7.5^{\diamond}, 0.23^{\diamond})\ 10^{-7}$	$(9.4^{\diamond}, 0.29^{\diamond})\ 10^{-2}$
1313	$(2.6^{\triangle}, 2.5^{\triangle})\ 10^{-7}$	$(2.7^{\triangle}, 2.6^{\triangle})\ 10^{-7}$	$(1.5^{\triangle}, 1.1^{\triangle})\ 10^{-7}$	$(1.6^{\triangle}, 1.2^{\triangle})\ 10^{-7}$	$(20^{\diamond}, 0.63^{\diamond})\ 10^{-2}$	$(8.5^{\triangle}, 7.1^{\triangle})$	$(12^{\diamond}, 0.38^{\diamond})\ 10^{-1}$	$(\varnothing, \varnothing)$
1321	$(5.2^{\square}, 5.2^{\square})\ 10^{-2}$	$(8.6^{\square}, 3.5^{\square})\ 10^{-8}$	$(1.1^{\square}, 1.1^{\square})\ 10^{-2}$	$(1.8^{\square}, 0.75^{\square})\ 10^{-8}$	$(5.2^{\diamond}, 12^{\diamond})\ 10^{-6}$	$(\varnothing, \varnothing)$	[illegible]	$(\varnothing, \varnothing)$
1322	$(1.8^{\square}, 0.8^{\square})\ 10^{-1}$	$(4.7^{\square}, 1.8^{\square})\ 10^{-3}$	$(3.0^{\square}, 1.4^{\square})\ 10^{-2}$	$(10^{\square}, 4.0^{\square})\ 10^{-4}$	$(9.2^{\diamond}, 3.0^{\diamond})\ 10^{-1}$	[illegible]	[illegible]	[illegible]
1323	$(3.2^{\triangle}, 3.1^{\triangle})\ 10^{-1}$	$(3.1^{\triangledown}, 1.1^{\triangledown})\ 10^{-5}$	$(1.8^{\triangle}, 1.4^{\triangle})\ 10^{-1}$	$(2.0^{\triangledown}, 0.67^{\triangledown})\ 10^{-5}$	$(7.4^{\triangle}, 6.2^{\triangle})\ 10^{-2}$	[illegible]	[illegible]	[illegible]
1331	$(8.9^{\triangle}, 8.7^{\triangle})$	$(2.2^{\square}, 0.94^{\square})\ 10^{-3}$	$(4.0^{\triangle}, 4.0^{\triangle})$	$(4.7^{\square}, 2.0^{\square})\ 10^{-4}$	$(3.5^{\diamond}, 6.7^{\triangle})\ 10^{-1}$	[illegible]	[illegible]	[illegible]
1332	$(4.0^{\square}, 2.7^{\square})\ 10^{-1}$	$(4.2^{\square}, 0.25^{\square})\ 10^{-3}$	$(6.9^{\square}, 3.0^{\square})\ 10^{-2}$	$(15^{\square}, 2.2^{\square})\ 10^{-4}$	$(15^{\diamond}, 4.7^{\diamond})\ 10^{-5}$	[illegible]	[illegible]	[illegible]
1333	$(7.0^{\triangle}, 7.0^{\triangle})\ 10^{-1}$	$(7.1^{\triangle}, 2.8^{\triangledown})\ 10^{-1}$	$(4.0^{\triangle}, 3.0^{\triangle})\ 10^{-1}$	$(3.8^{\triangle}, 1.8^{\triangledown})\ 10^{-1}$	$(7.4^{\triangle}, 6.3^{\triangle})\ 10^{-3}$	$(7.6^{\triangle}, 6.4^{\triangle})\ 10^{-3}$	$(2.2^{\triangle}, 1.9^{\triangle})\ 10^{-2}$	$(2.3^{\triangle}, 2.0^{\triangle})\ 10^{-2}$

+ many other similar tables

On the bounds on four-fermion operators [*a brief overview*]

The prototype of relevant non-LHC bounds on SMEFT operators are the bounds from meson-antimeson mixing processes.

What is maybe less known, is that is a key constraint on the whole SM EFT, once we take into RGE effects [Silvestrini & Valli, 2019]:

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← Bounds on the following |ΔF|=1 operators:

$$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$$
$$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$$

- taking into account 1-loop RGE effects from m_W to 1 TeV,
- assuming down- or up-type alignment of the quark doublets,
- barring accidental cancellations among different ops.

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13	$\cancel{(7.4^{\triangle}, 6.3^{\triangle})\ 10^{-3}}$	$\cancel{(7.6^{\triangle}, 6.4^{\triangle})\ 10^{-3}}$
22	$\varnothing$	$4.1^{\square}\ 10^{-3}$
23	$\cancel{(3.0^{\triangledown}, 1.0^{\triangledown})\ 10^{-2}}$	$\cancel{(3.1^{\triangledown}, 1.0^{\triangledown})\ 10^{-2}}$
33	$\varnothing$	$7.3^{\triangle}\ 10^{-1}$

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$$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$$
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- taking into account 1-loop RGE effects from m_W to 1 TeV,
- assuming down- or up-type alignment of the quark doublets,

Not relevant if we assume MFV or U(2)^5

some (different) effects survive in MFV & U(2)^5 → Non-trivial implications for top-quark physics

On the bounds on four-fermion operators [*a brief overview*]

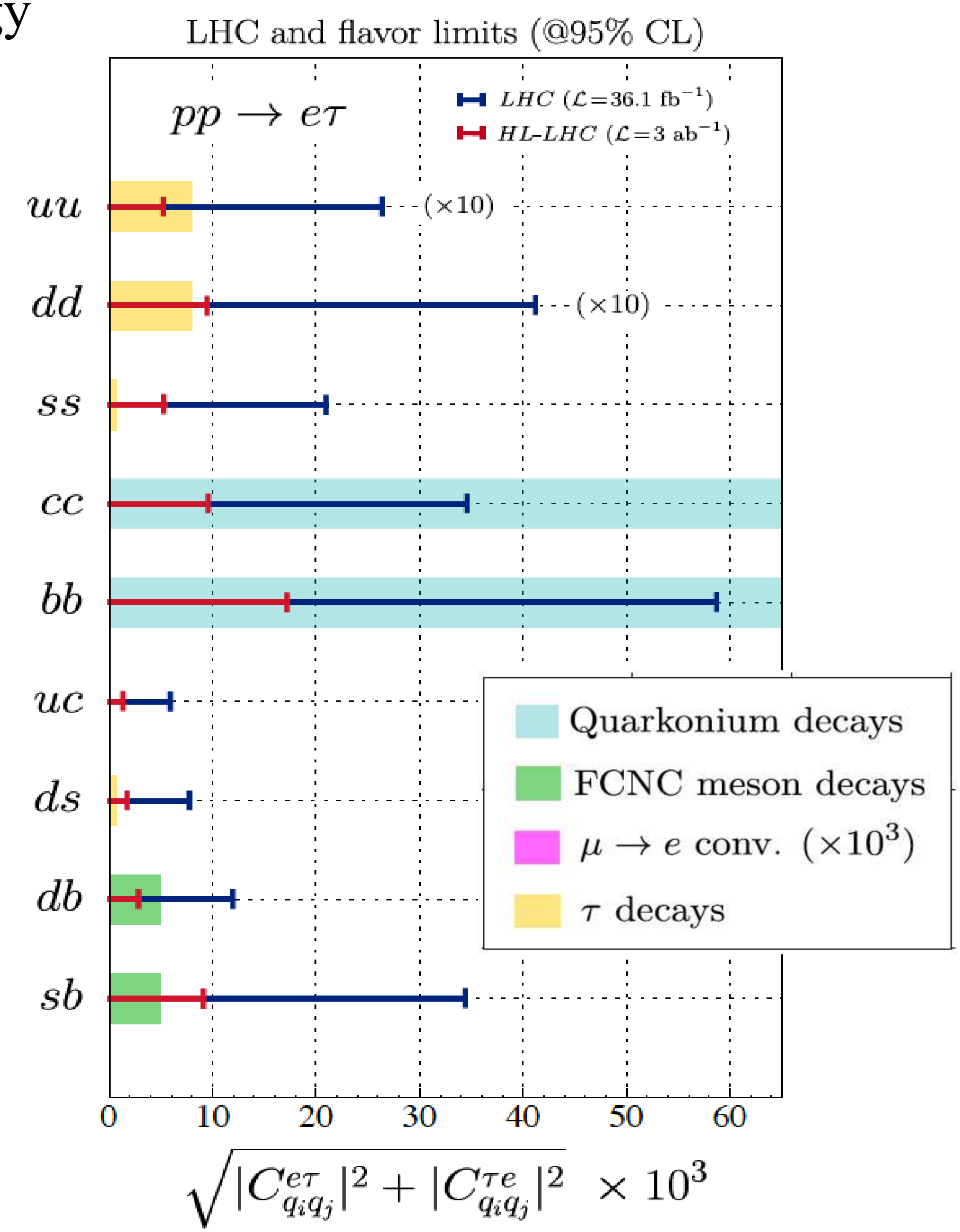
On the other hand, not always low-energy flavor-violating process "win" in constraining four-fermion operators

Example I:

Bounds on helicity conserving 4-fermion Lepton Flavor Violating semi-leptonic ops.:

$$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{Lk}\gamma^\mu \ell_{Ll})$$

$\left(\mathcal{O}_{lq}^{(1)}, \mathcal{O}_{lq}^{(3)} \right.$ in the SMEFT basis $\left. \right)$



Angelescu, Faroughi, Sumensari, '20

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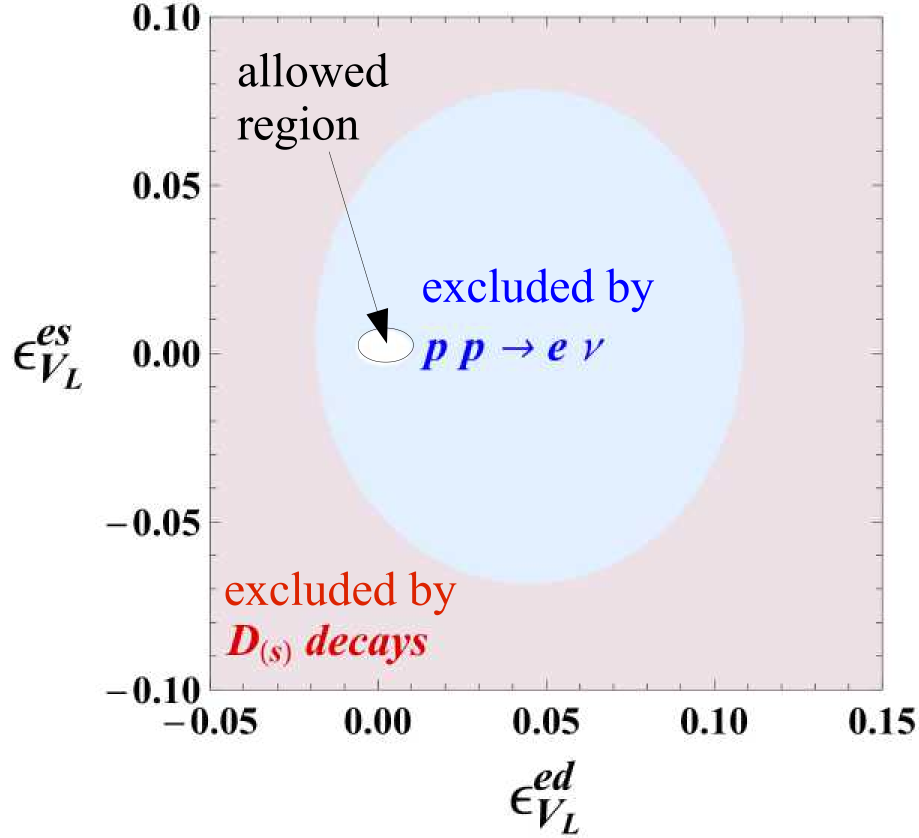
Example II:

Bounds on helicity conserving 4-fermion Quark Flavor Violating (|ΔC|=1, |ΔL|=0) semi-leptonic ops.:

$$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{Lk}\gamma^\mu \ell_{Ll})$$

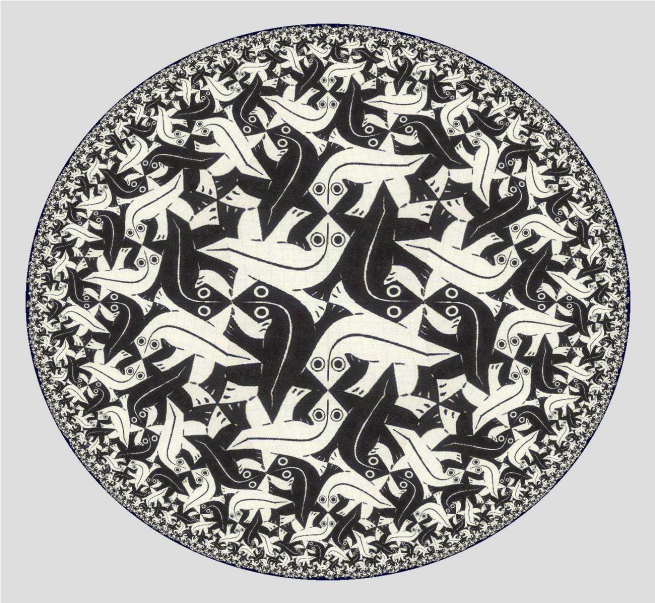
$\mathcal{O}_{lq}^{(1)}, \mathcal{O}_{lq}^{(3)}$ in the SMEFT basis



$$-\frac{4G_F}{\sqrt{2}}V_{ci}\;\epsilon_{V_L}^{(6)}\;(\bar{e}_L^\alpha\gamma_\mu\nu_L^\alpha)(\bar{c}_L\gamma^\mu d_L^i)$$

Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez, '20

Flavor symmetries in the SMEFT



based on:
Faorughi, GI, Wilsch, Yamamoto, 2005.05366

Flavor symmetries in the SMEFT

$$\mathscr{L}_{\text{SM-EFT}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Higgs}} + \Sigma_i \frac{1}{\Lambda_i^{d-4}} O_i^{d\geq 5}$$

"trivial" low-energy projection

$y_{ij}\, \psi_i \psi_j H$

$\Lambda_{\text{Flavor}} > 10^2 - 10^5$ TeV

- In the absence of symmetries,
  - we would expect $y_{ij} \sim O(1)$, while we know this is NOT the case
  - flavor bounds implies very heavy NP scale → no visible NP effects at LHC

- Imposing a global *flavor symmetry* + a *set of symmetry breaking terms* allows us to organize the large number of free parameter in a consistent way (*well-defined power-counting compatible with RGE structure of the EFT*)

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Relevant figures concerning d=6 operators in the SMEFT:

- Indep. coupl. for 1 family: 53+23 = 76
- Independent couplings for 3 families:

Exact U(3)^5: 41+6 = 47

↓ *flavor* !

Anarchic: 1350+1149 = 2499

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- Main drawback: *no unique choice...*

- However, if we require: compatibility with the SM gauge symmetry + "natural" Yukawa couplings + avoid most dangerous flavor constraints → very limited choice

Flavor symmetries in the SMEFT

$$\boxed{U(3)^5 = U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E}$$

- Largest flavor symmetry group compatible with the SM gauge symmetry
- MFV = minimal breaking of $U(3)^3$ via the (SM) Yukawa couplings only

virtues:

- Automatic GIM and CKM suppression as in the SM → *minimization of the flavor constraints at fixed NP scale*
- Minimal number of free parameters

drawbacks:

- *No explanation for Y hierarchies* (problem postponed to UV)
- *Enhanced hierarchy problem* due to the strong LHC bounds on "1st & 2nd gen. Partners"
- Cannot accommodate viable NP models with special role for 3rd gen.
- Flavor-violating and flavor-conserving (non-universal) processes are linked

Flavor symmetries in the SMEFT

SMEFT parameter counting in MFV:

		No symmetry				$U(3)^5$				[*]	
Class	Operators	3 Gen.		1 Gen.		Exact		$\mathcal{O}(Y^1_{e,d,u})$		$\mathcal{O}(Y^1_e, Y^1_d Y^2_u)$	
1–4	X^3, H^6, H^4D^2, X^2H^2	9	6	9	6	9	6	9	6	9	6
5	$\psi^2 H^3$	27	27	3	3	–	–	3	3	4	4
6	$\psi^2 XH$	72	72	8	8	–	–	8	8	11	11
7	$\psi^2 H^2 D$	51	30	8	1	7	–	7	–	11	1
	$(\bar{L}L)(\bar{L}L)$	171	126	5	–	8	–	8	–	14	–
	$(\bar{R}R)(\bar{R}R)$	255	195	7	–	9	–	9	–	14	–
8	$(\bar{L}L)(\bar{R}R)$	360	288	8	–	8	–	8	–	18	–
	$(\bar{L}R)(\bar{R}L)$	81	81	1	1	–	–	–	–	–	–
	$(\bar{L}R)(\bar{L}R)$	324	324	4	4	–	–	–	–	4	4
total:		1350	1149	53	23	41	6	52	17	85	26

[*] = Level of expansion in the breaking terms (=SM Yukawa coupl.) necessary to accommodate possible BSM effects in all the observed flavor-violating processes

$$\boxed{U(3)^5 = U(3)_Q \times U(3)_U \times U(3)_D \times U(3)_L \times U(3)_E}$$

- Largest flavor symmetry group compatible with the SM gauge symmetry
- MFV = minimal breaking of $U(3)^3$ by the Yukawa couplings

$$\boxed{U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D \times U(2)_L \times U(2)_E}$$

acting on 1^{st} & 2^{nd} generations

Barbieri, G.I., Jones-Perez, Lodone, Straub, '11

virtues:

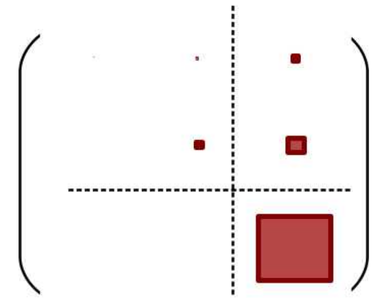
- The exact symmetry limit is good starting point for the SM quark spectrum ($m_u=m_d=m_s=m_c=0$, $V_{CKM}=1$) → we only need small breaking terms
- The small breaking ensures small effects in rare processes (as in MFV) but also decoupling of flavor-violating & flavor-conserving operators
- Allow us to describe models where NP couple dominantly to 3rd generations → reduced tension with hierarchy problem

problems: more free parameters, flavor basis not fully specified by SM Yukawas

Flavor symmetries in the SMEFT

The U(2)^5 symmetry in the up-quark sector:

$$\mathscr{L}_{\text{Yukawa}} = Q_L^{\,i}\, Y_U^{\,ij}\, U_R^{\,j}\, \phi + \ldots \qquad Y_U\,|_{\text{exp}} = V_{\text{CKM}}^{\,+}\, \text{diag}(y_u, y_c, y_t) =$$



$$\text{U}(2)^5 = \text{U}(2)_q \times \text{U}(2)_u \times \ldots$$

$$Y_U\,|_{\text{th}} = y_t \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \leftarrow \text{U}(2)_q$$

$\text{U}(2)_u$

unbroken symmetry

$$V_{\text{CKM}}\,|_{\text{th}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The exact symmetry limit is a
<u>good starting point for the SM spectrum</u>
($m_u = m_d = m_s = m_c = 0$, $V_{\text{CKM}} = 1$)

Flavor symmetries in the SMEFT

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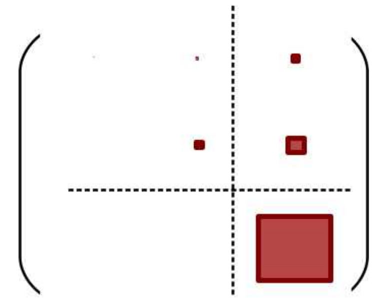

$$U(2)^5 = U(2)_q \times U(2)_u \times \ldots$$

$$Y_U\big|_{\rm th} = y_t \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right] \leftarrow U(2)_q$$

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unbroken symmetry

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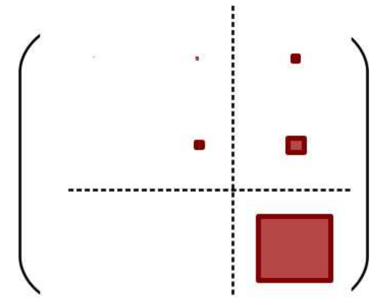

$$U(2)^5 = U(2)_q \times U(2)_u \times \ldots$$

$$Y_U|_{\rm th} = y_t \left[\begin{array}{c|c} 0 & 0 \\ \hline 0 & 1 \end{array}\right] \rightarrow \underbrace{\left[\begin{array}{c|c} 0 & V \\ \hline 0 & 1 \end{array}\right]}_{\textit{leading breaking}} \rightarrow \underbrace{\left[\begin{array}{c|c} \Delta & V \\ \hline 0 & 1 \end{array}\right]}_{\textit{final breaking}}$$

$$V_{\rm CKM}|_{\rm th} = \left[\begin{array}{c|c} 1 & V \\ \hline V^T & 1 \end{array}\right]$$

Minimal breaking necessary to reproduce SM Yukawa couplings:

$$|V| = O(|V_{ts}|) = 0.1$$

$$|\Delta| = O(y_c) = 0.01$$

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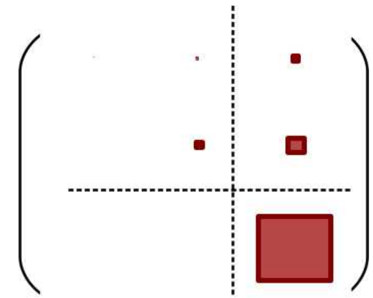

$$U(2)^5 = U(2)_q \times U(2)_u \times \ldots$$

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leading breaking   *final breaking*

Minimal breaking necessary to reproduce SM Yukawa couplings:

$$|V| = O(|V_{ts}|) = 0.1$$
$$|\Delta| = O(y_c) = 0.01$$

- The assumption of a single (CKM-like) leading breaking ensures a protection of FCNCs as in MFV
- But large NP effects for 3rd gen. now much less constrained

Flavor symmetries in the SMEFT

SMEFT parameter counting with $U(2)^5$:

	$U(2)^5$ [terms summed up to differer									
Operators	Exact		$\mathcal{O}(V^1)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^1,\Delta^1)$		$\mathcal{O}(V^2,\Delta^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6
$\psi^2 H^3$	3	3	6	6	6	6	9	9	9	9
$\psi^2 XH$	8	8	16	16	16	16	24	24	24	24
$\psi^2 H^2 D$	15	1	19	5	23	5	19	5	23	5
$(\bar{L}L)(\bar{L}L)$	23	–	40	17	67	24	40	17	67	24
$(\bar{R}R)(\bar{R}R)$	29	–	29	–	29	–	29	–	29	–
$(\bar{L}L)(\bar{R}R)$	32	–	48	16	64	16	53	21	69	21
$(\bar{L}R)(\bar{R}L)$	1	1	3	3	4	4	5	5	6	6
$(\bar{L}R)(\bar{L}R)$	4	4	12	12	16	16	24	24	28	28
total:	124	23	182	81	234	93	212	111	264	123

N. of parameters relevant in most collider observables
(*natural separation of flavor-violating and flavor-conserving ops.*)

Flavor symmetries in the SMEFT

SMEFT parameter counting with $U(2)^5$:

Taking into account the spurion size, eff. suppression of order:

Operators	Exact		$\mathcal{O}(V^1)$ [10^{-1}]		$\mathcal{O}(V^2)$ [10^{-2}]		$\mathcal{O}(V^1,\Delta^1)$ [10^{-3}]		$\mathcal{O}(V^2,\Delta^1)$ [10^{-4}]	
Class 1–4	9	6	9	6	9	6	9	6	9	6
$\psi^2 H^3$	3	3	6	6	6	6	9	9	9	9
$\psi^2 XH$	8	8	16	16	16	16	24	24	24	24
$\psi^2 H^2 D$	15	1	19	5	23	5	19	5	23	5
$(\bar{L}L)(\bar{L}L)$	23	–	40	17	67	24	40	17	67	24
$(\bar{R}R)(\bar{R}R)$	29	–	29	–	29	–	29	–	29	–
$(\bar{L}L)(\bar{R}R)$	32	–	48	16	64	16	53	21	69	21
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			[10^{-1}]		[10^{-2}]		[10^{-3}]		[10^{-4}]	
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$\psi^2 XH$	8	8	16	16	16	16	24	24	24	24
$\psi^2 H^2 D$	15	1	19	5	23	5	19	5	23	5
$(\bar{L}L)(\bar{L}L)$	23	–	40							
$(\bar{R}R)(\bar{R}R)$	29	–	29							
$(\bar{L}L)(\bar{R}R)$	32	–	48							
$(\bar{L}R)(\bar{R}L)$	1	1	3							
$(\bar{L}R)(\bar{L}R)$	4	4	12							
total:	124	23	182							

N.B.: Two angles (s_b & s_τ) controlling the alignment of the leading spurions in the mass-eigenstate basis of quark & leptons appears [↔ definition of what 3rd generation means for left-handed fields]

→ results must be given in terms of these free parameters

N. of parameters relevant in most collider observables
(*natural separation of flavor-violating and flavor-conserving ops.*)

Flavor symmetries in the SMEFT

E.g.:

$$\Lambda_{prst}\,(\bar{\ell}_p \Gamma \ell_r)(\bar{q}_s \tilde{\Gamma} q_t)$$

No symmetry: $45+36 = 81$

Exact $U(2)^5$: $4 + 0 = 4$

$O(V^1)$: $4 + 4 = 8$

$O(V^2)$: $6 + 2 = 8$

$|V| = 0.1$

	(11)	(12)	(13)	(21)	(22)	(23)	(31)	(32)	(33)
(11)	a_1				a_1 $c_3\epsilon_q^2$	$\beta_3\epsilon_q$		$\beta_3^*\epsilon_q$	a_2
(12)									
(13)									
(21)									
(22)	a_1 $c_1\epsilon_\ell^2$				a_1 $c_1\epsilon_\ell^2$ $c_3\epsilon_q^2$	$\beta_3\epsilon_q$		$\beta_3^*\epsilon_q$	a_2 $c_2\epsilon_\ell^2$
(23)	$\beta_1\epsilon_\ell$				$\beta_1\epsilon_\ell$	$\gamma_1\epsilon_\ell\epsilon_q$		$\gamma_2\epsilon_\ell\epsilon_q$	$\beta_2\epsilon_\ell$
(31)									
(32)	$\beta_1^*\epsilon_\ell$				$\beta_1^*\epsilon_\ell$	$\gamma_2^*\epsilon_\ell\epsilon_q$		$\gamma_1^*\epsilon_\ell\epsilon_q$	$\beta_2^*\epsilon_\ell$
(33)	a_3				a_3 $c_4\epsilon_q^2$	$\beta_4\epsilon_q$		$\beta_4^*\epsilon_q$	a_4

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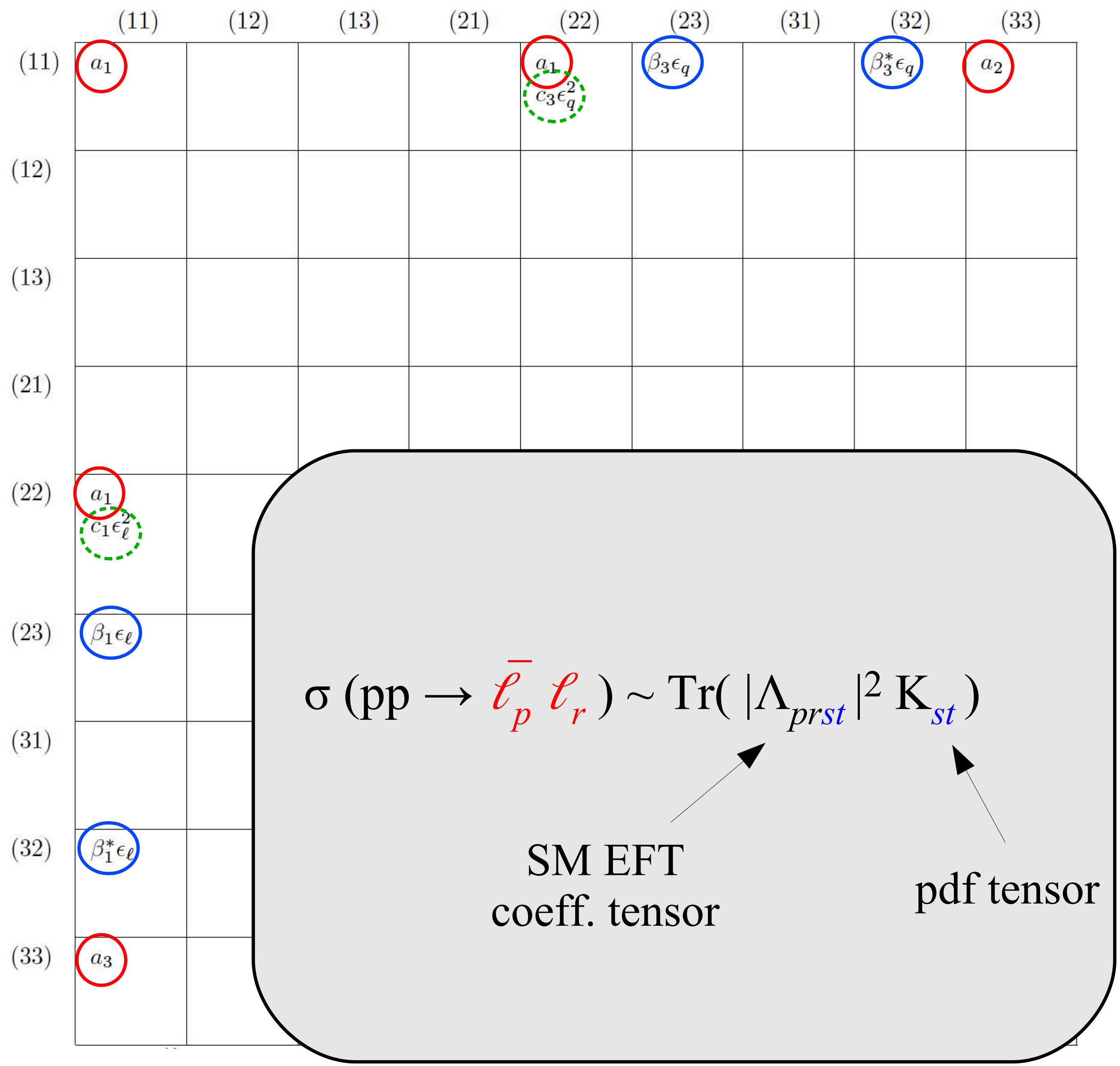
O(V^2): 6 + 2 = 8

This relatively small number of free parameters can all be well constrained (*lifting flat directions*) combining low & high-pT constraints [*work in prog.*]



Conclusions

- We cannot give up on extracting information on the "flavored" operators of the SM-EFT → precious source of information on the UV Theory

- Important and useful to combine low-energy flavor constraints and high-pT constraints (various cases of comparable sensitivity & mutual influence)

- We need an organizing principle to explain why some operators have very strong bounds → EFT consistency

We need to make assumptions about the flavor structure of the SMEFT

Conclusions

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- We need an organizing principle to explain why some operators have very strong bounds → EFT consistency

We need to make assumptions about the flavor structure of the SMEFT

No unique choice

but the $U(2)^5$ framework has several advantages both from the pheno/exp & the model-building point of view