Physics Beyond the SM(EFT)

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Based on 2111.07421 [C. Burgess, S. Hamoudou, JK, D. London]

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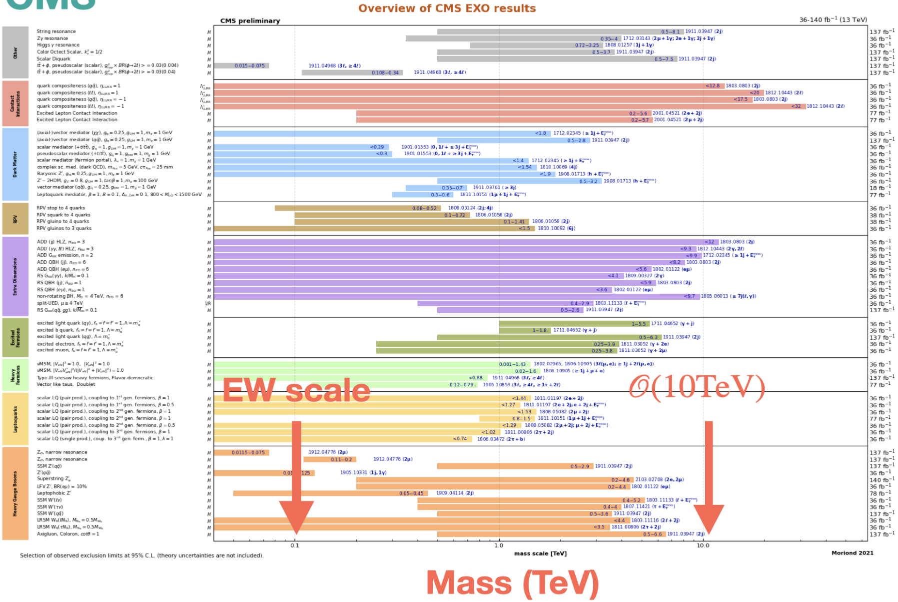
Outline

1. Status of New physics (NP) searches: scale gap
2. Modern Effective Field Theories (WET/SMEFT..)
3. Beyond SMEFT
4. Low energy phenomenology with non-SMEFT operators
5. Summary and conclusions

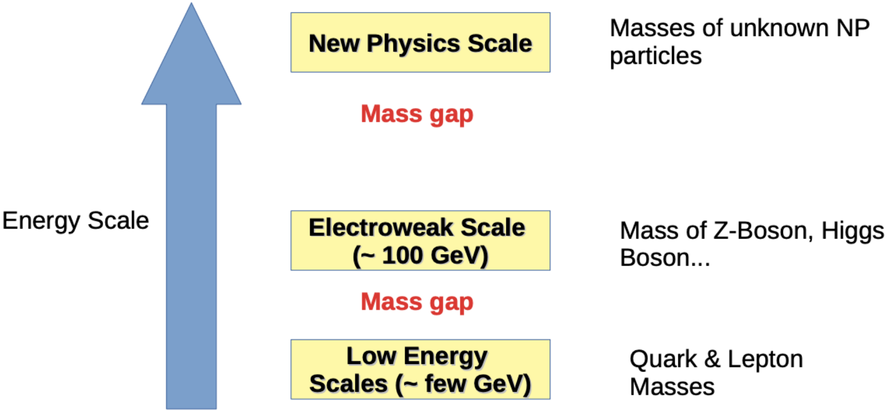
Outline

Experimental status of NP searches

CMS



Scale gap between the NP and the EW scale



The mass gap allows us to construct an Effective field theory (EFT) which can represent the effects of NP in a model independent fashion!

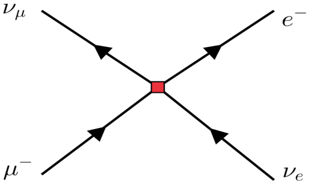
Outline

Fermi theory: an EFT for the SM

Muon-decay

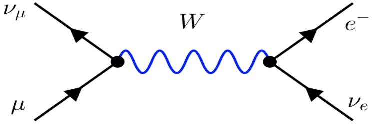
$$\mu \to \mathbf{e}^- + \bar{\nu}_\mathbf{e} + \nu_\mu$$

Fermi-theory (1933) :



$$[\bar{\nu}_\mu \gamma_\mu (\mathbf{1} - \gamma_5) \mu] \; [\bar{\mathbf{e}} \gamma^\mu (\mathbf{1} - \gamma_5) \nu_\mathbf{e}]$$

W-boson discovery (1983)



$$\mathbf{p^2 << m_W^2}$$

$$\frac{1}{p^2 - m_W^2} \sim -\frac{1}{m_W^2} + \mathcal{O}\left(\frac{p^2}{m_W^4}\right)$$

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$$\mathcal{L} = \mathcal{L}_{\rm SM}(d=4) + \mathcal{L}_{\rm eff}(d>4)$$

$$\mathcal{L}_{\rm eff}(d>4) = \sum_{d=5,6,..} C_I Q_I + h.c.$$

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- It's an EFT for which the full theory can be the SM or SMEFT after integrating out the W/Z/Higgs and top quark.
- Power counting parameter $\delta = p^2/m_W^2$.
- From last several decades WET has been used to parameterize and test the SM effects for low-energy processes such as flavour violating transitions, lepton flavour violating decays etc.

WET Lagrangian

μ_{EW}

Scale

$SU(3)_c \otimes U(1)_{\text{em}}$

$$\frac{1}{m_W^2}(\overline{\psi}\Gamma_1\psi)(\overline{\psi}\Gamma_2\psi)$$

μ_{low}

Field Content:

Quarks u_L, d_L, u_R, d_R Leptons e_L, e_R, ν_L Photon $F_{\mu\nu}$ Gluons $G_{\mu\nu}$

Symmetries: $SU(3)_c \otimes U(1)_{\text{em}}$

Power counting: $\frac{p^2}{m_W^2}$

Full Basis by:
[Jenkins, Manohar, Stoffer 2017]

Four-fermion operators in WET

$(\overline{L}L)(\overline{L}L)$

$\mathcal{O}_{\nu\nu}^{V,LL}$	$(\bar\nu_{Lp}\gamma^\mu\nu_{Lr})(\bar\nu_{Ls}\gamma_\mu\nu_{Lt})$
$\mathcal{O}_{ee}^{V,LL}$	$(\bar e_{Lp}\gamma^\mu e_{Lr})(\bar e_{Ls}\gamma_\mu e_{Lt})$
$\mathcal{O}_{\nu e}^{V,LL}$	$(\bar\nu_{Lp}\gamma^\mu\nu_{Lr})(\bar e_{Ls}\gamma_\mu e_{Lt})$
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$(\overline{R}R)(\overline{R}R)$

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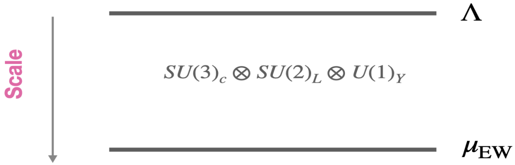
- An EFT constructed by integrating out the heavy NP particles for which the full theory can be UV completion which is currently unknown!
- Power counting parameter $\delta = p^2/\Lambda^2$, where $\Lambda \gtrsim$ a few TeV.
- SMEFT has become quite popular in last couple of years and has been used to parameterize and test the NP effects for low-energy processes such as flavour violating transitions, lepton flavour violating decays etc.

SMEFT Lagrangian



Field Content:

Quarks $q = (u_L, d_L)^T, u_R, d_R$ Leptons $\ell = (\nu_L, e_L)^T, e_R$

Gauge fields: $B_{\mu\nu}, W_{\mu\nu}, G_{\mu\nu}$ Higgs doublet: $H = (H^+, H^0)^T$

Symmetries: $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$

Buchmuller, Wyler 1986

Grzadkowski, Iskrzynski, Misiak, Rosiek 2010

(Dimension-8 SMEFT) C. Murphy 2020

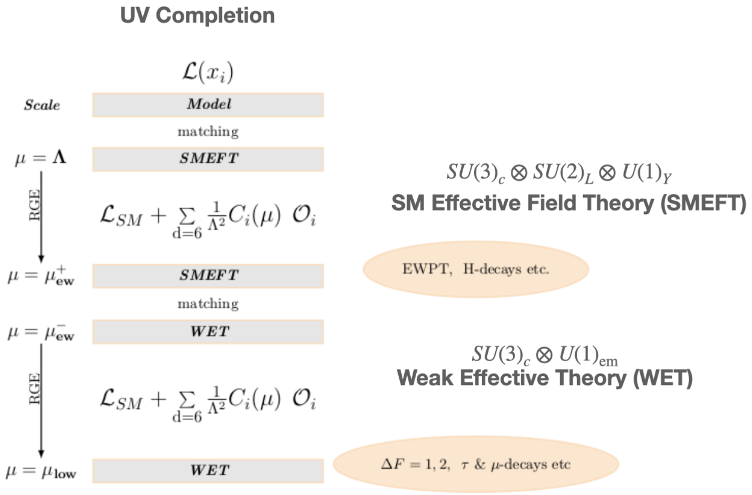
Four-fermion operators in SMEFT

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
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}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$		

Table 3: Four-fermion operators.

SMEFT Strategy



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Outline

Beyond SMEFT

Due to a larger symmetry group, SMEFT [$SU(2)_L \times U(1)_Y$] puts certain restrictions on the LEFT [$U(1)_Q$].

- Some of the LEFT operators can not be generated from SMEFT at the leading order.
- SMEFT impose relations between the LEFT Wilson coefficients.

The implications of these restrictions on the low-energy phenomenology can shed some light on the *physics beyond the SMEFT framework!*

Non-SMEFT operators

The LEFT operators absent in SMEFT at the leading order.

$$O_{ed}^{S,RR} = (\bar{e}P_R e)(\bar{d}P_R d)$$

Symmetries

Electric charge: **+1 -1 +1/3 -1/3 = 0** $U(1)_Q$

$Y_{e_L} = -1, \ \ Y_{e_R} = -2, \ \ Y_{d_L} = +1/3, \ \ Y_{d_R} = -2/3$ $U(1)_Y$ ✗

Hypercharge: **+1 -2 -1/3 -2/3 = -2 $\neq$ 0 !**

$Q = T_3 + Y/2$ $SU(2)_L$ ✗

- Such Hypercharge(isospin) violating operators can be termed as *non-SMEFT* operators.

Complete list of non-SMEFT operators

There are 10 such operators in LEFT (suppressing flavour structure).

$$O_{\nu edu}^{V,LR} : \quad (\overline{\nu}_{Lp}\gamma^{\mu} e_{Lr})(\overline{d}_{Rs}\gamma_{\mu} u_{Rt}) + h.c$$
$$O_{ed}^{S,RR} : \quad (\overline{e}_{Lp} e_{Rr})(\overline{d}_{Ls} d_{Rt})$$
$$O_{ed}^{T,RR} : \quad (\overline{e}_{Lp}\sigma^{\mu\nu} e_{Rr})(\overline{d}_{Ls}\sigma_{\mu\nu} d_{Rt})$$

$$O_{ee}^{S,RR} : \quad (\overline{e}_{Lp} e_{Rr})(\overline{e}_{Ls} e_{Rt})$$

$$O_{uddu}^{V1,LR} : \quad (\overline{u}_{Lp}\gamma^{\mu} d_{Lr})(\overline{d}_{Rs}\gamma_{\mu} u_{Rt}) + h.c$$
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Generating such operators within SMEFT

$$O^{V,LR}_{\nu edu} = (\bar{\nu}\gamma_\mu P_L e)(\bar{d}\gamma^\mu P_R u)$$

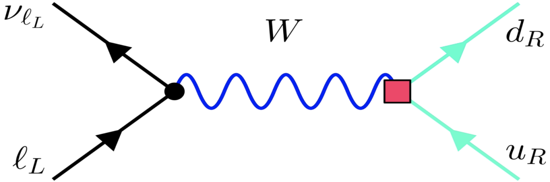
Symmetries

Electric charge: **-1 +1/3 +2/3 = 0** $U(1)_Q$

$Y_{\nu_L} = -1,\ \ Y_{e_L} = -1,\ \ Y_{d_R} = -2/3,\ \ Y_{u_R} = +4/3$ $U(1)_Y$ ✘

Hypercharge: **+1 -1 +2/3 +4/3 = 2 $\neq$ 0 !**

$Q = T_3 + Y/2$ $SU(2)_L$ ✘

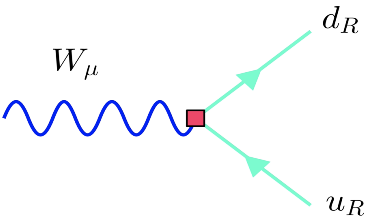


Generating $\bar{d}_R \gamma_\mu u_R W^\mu$ vertex

SMEFT $[O_{\phi ud}]_{ij} = (\tilde{\phi}^\dagger i D_\mu \phi)(\bar{u}_i \gamma^\mu d_j)$ $y_\phi = +1$

Electroweak symmetry breaking

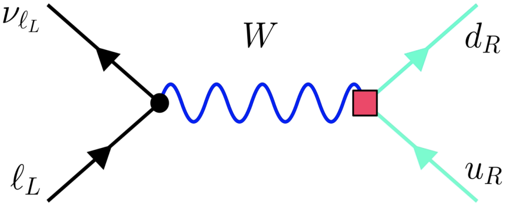
$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}$$



$$-\frac{v^2}{2}[C_{\phi ud}]_{ij}$$

Restrictions imposed by SMEFT

The W-boson couples universally to all three lepton generations:



$$(\bar{\nu}_e\gamma_\mu P_L e)(\bar{d}\gamma^\mu P_R u) = (\bar{\nu}_\mu\gamma_\mu P_L \mu)(\bar{d}\gamma^\mu P_R u) = (\bar{\nu}_\tau\gamma_\mu P_L \tau)(\bar{d}\gamma^\mu P_R u)$$

In SMEFT $O^{V,LR}_{\nu edu}$ is lepton flavour universal!

Is there a way to get a non-universal contribution to $(\bar{\nu}_\ell \gamma_\mu P_L \ell)(\bar{c}\gamma^\mu P_R b)$ within the SMEFT?

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Yes, but at dimension-eight level.

Dimension-8 SMEFT For the complete list [C. Murphy 2020]

$$\frac{C_8}{\Lambda^4}(\bar{\ell} d H)(\tilde{H}^\dagger \bar{u} \ell)$$

EW symmetry breaking + Fierz transformation generates:

$$(\bar{\nu}\gamma_\mu P_L e)(\bar{d}\gamma^\mu P_R u)$$

But:

$$C_{\nu e d u}^{V,LR} \propto \frac{v^2}{\Lambda^4} C_8$$

So, the non-SMEFT operators bear an extra suppression.

Typical suppression within SMEFT

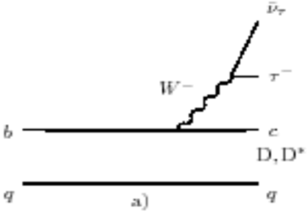
- Assuming the NP scale to be $\mathcal{O}(5\text{TeV})$.
- Using LEFT power counting $C_{\nu edu}^{V,LR} \sim \frac{1}{\Lambda^2} \sim 4 \times 10^{-2}\ \mathrm{TeV}^{-2}$.
- In SMEFT $C_{\nu edu}^{V,LR} \sim \frac{v^2}{\Lambda^4} \sim 10^{-3}\ \mathrm{TeV}^{-2}$.

So by experimentally extracting the value of $C_{\nu edu}^{V,LR}$, one can know if a non-SMEFT like NP is needed or not.

Outline

$b \to c\tau\bar{\nu}$ observables

- $O_{\nu edu}^{V,LR}$ give rise to $b \to c\tau\bar{\nu}$ transitions.



Observables:

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathcal{B}(B \to D^{(*)}\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}, \mathcal{R}(J/\psi) \equiv \frac{\mathcal{B}(B_c \to J/\psi\tau\nu)}{\mathcal{B}(B_c \to J/\psi\mu\nu)}$$

$$F_L(D^*) \equiv \frac{\Gamma(B \to D_L^*\tau\nu)}{\Gamma(B \to D^*\tau\nu)}, \; P_\tau(D^*) \equiv \frac{\Gamma^{+1/2} - \Gamma^{-1/2}}{\Gamma^{+1/2} + \Gamma^{-1/2}}$$

Fit to $b \to c\tau\bar{\nu}$ data

$$\mathcal{H}_{eff} = \frac{4G_F}{\sqrt{2}} V_{cb}\, O_V^{LL} - \boxed{\frac{C_V^{LL}}{\Lambda^2} O_V^{LL} - \frac{C_V^{LR}}{\Lambda^2} O_V^{LR}}, \\ - \frac{C_S^{LL}}{\Lambda^2} O_S^{LL} - \frac{C_S^{LR}}{\Lambda^2} O_S^{LR} - \frac{C_T}{\Lambda^2} O_T \ .$$

Experimental measurements:

$R(D) = 0.340 \pm 0.027 \pm 0.013$ — HFLAV Collaboration

$R(D^*) = 0.295 \pm 0.011 \pm 0.008$

$P_\tau(D^*) = -0.38 \pm 0.51 + 0.21 - 0.16$ — Belle Collaboration

$R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$ — LHCb Collaboration

Fit results:

$\Lambda = 5$ TeV

New-physics coeff.	Best fit	p value (%)	pull$_{\rm SM}$
C_V^{LL}	-3.1 ± 0.7	51	4.1
C_V^{LR}	2.8 ± 1.2	0.3	2.3
(C_V^{LL}, C_V^{LR})	$(-3.0 \pm 0.8, 0.6 \pm 1.2)$	35	3.7

Fit to $b \to c\tau\bar{\nu}$ data

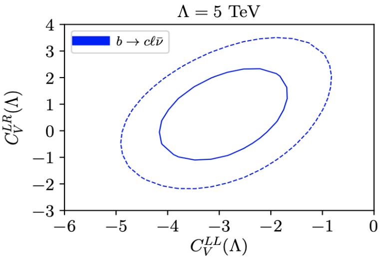


FIG. 1: (Correlated) allowed values of C_V^{LL} and C_V^{LR} at 1σ (inner region) and 2σ (outer region).

- Current data allows $\mathcal{O}(1)$ non-SMEFT like values for the Wilson coefficients.
- In future, the angular distributions $\overline{B} \to D^*(\to D\pi')\tau^-(\to \pi^-\nu_\tau)\nu_\tau$ will allow us to perform more general fits with multiple Wilson coefficients. [Bhattacharya, Datta, Kamali, London 2020]

Outline

Summary and conclusions

- The SM of particle physics seems to work pretty well. The LHC did not find any BSM particles yet, indicating a scale gap between the EW and NP scale.
- As a result one can construct EFTs to parameterize the NP effects in a model independent fashion. Modern EFTs: LEFT, SMEFT, νSMEFT, HEFT.
- The SMEFT puts certain restrictions on the structure of LEFT operators.
- There are total 10 non-SMEFT operators in LEFT. The SMEFT predicts suppression of these Wilson coefficients since they can only at the dimension-8 level.
- One such non-SMEFT operators is $(\bar{\nu}_\ell \gamma_\mu P_L \ell)(\bar{c}\gamma^\mu P_R b)$. The current data allows its size to be non-SMEFT like.
- The measurement of angular distributions would allow us extract simultaneously more than two Wilson coefficients.

Thanks for your attention.