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
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Status of New physics (NP) searches: scale gap

Overview of CMS EXO results

EW scale

Mass (TeV)
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!
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Fermi theory: an EFT for the SM

Muon-decay

$$\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Fermi-theory (1933):

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

W-boson discovery (1983):

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

$$p^2 \ll m_W^2$$
Given the **present situation** one can construct EFTs for parameterizing the NP effects in a model independent fashion.
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In this regard, the EFTs such as **LEFT, SMEFT, $\nu$SMEFT, HEFT** have become quite popular and have become standard **testing grounds for the physics beyond the Standard Model**:
Effective Field Theories for NP

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$$\mathcal{L} = \mathcal{L}_{\text{SM}}(d = 4) + \mathcal{L}_{\text{eff}}(d > 4)$$
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In this regard, the EFTs such as LEFT, SMEFT, $\nu$SMEFT, HEFT have become quite popular and have become standard **testing grounds for the physics beyond the Standard Model**:

\[ \mathcal{L} = \mathcal{L}_{SM}(d = 4) + \mathcal{L}_{eff}(d > 4) \]

\[ \mathcal{L}_{eff}(d > 4) = \sum_{d=5,6,\ldots} C_l Q_l + h.c. \]
WET: a generalized Fermi Theory

- It’s a general version of Fermi theory to parameterize *the low energy observables such as the muon decay.*
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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.
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- Power counting parameter $\delta = \frac{p^2}{m_W^2}$.

- 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

\[ \mu_{EW} \]

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

\[ \mu_{low} \]

**Field Content:**
- Quarks: \( u_L, d_L, u_R, d_R \)
- Leptons: \( e_L, e_R, \nu_L \)
- Photon: \( F_{\mu\nu} \)
- Gluons: \( G_{\mu\nu} \)

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

**Power counting:** \( \frac{p^2}{m_W^2} \)

**Full Basis by:** [Jenkins, Manohar, Stoffer 2017]
### Four-fermion operators in WET

<table>
<thead>
<tr>
<th></th>
<th>((\bar{L}L)(\bar{L}L))</th>
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</tr>
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<tbody>
<tr>
<td>(O_{\nu \nu}^{V,LL})</td>
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\(O_{\nu \nu}^{V,LL} \) (\(\bar{L}L\))(\(\bar{L}L\)) \(O_{\nu \nu}^{V,LR} \) (\(\bar{L}L\))(\(\bar{R}R\)) \(O_{\nu \nu}^{V,RR} \) (\(\bar{L}R\))(\(\bar{R}L\))
SMEFT

- A model independent framework to parameterize the *NP effects above the EW scale.*
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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!
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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 $\delta = \frac{p^2}{\Lambda^2}$, where $\Lambda \gtrsim$ a few TeV.
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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 $\delta = \frac{p^2}{\Lambda^2}$, 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**

\[ \Lambda \]

\[ SU(3)_c \otimes SU(2)_L \otimes U(1)_Y \]

\[ \mu_{EW} \]

**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

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<td>$Q_{ll}$</td>
<td>$Q_{ee}$</td>
<td>$Q_{le}$</td>
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<td>$(\bar{l}<em>p \gamma</em>\mu l_r)(\bar{l}_s \gamma^\mu l_t)$</td>
<td>$(\bar{e}<em>p \gamma</em>\mu e_r)(\bar{e}_s \gamma^\mu e_t)$</td>
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<td>$Q_{qq}^{(1)}$</td>
<td>$Q_{wu}$</td>
<td>$Q_{lu}$</td>
</tr>
<tr>
<td>$(\bar{q}<em>p \gamma</em>\mu q_r)(\bar{q}_s \gamma^\mu q_t)$</td>
<td>$(\bar{u}<em>p \gamma</em>\mu u_r)(\bar{u}_s \gamma^\mu u_t)$</td>
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<td>$Q_{qq}^{(3)}$</td>
<td>$Q_{dd}$</td>
<td>$Q_{ld}$</td>
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<td>$(\bar{q}<em>p \gamma</em>\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$</td>
<td>$(\bar{d}<em>p \gamma</em>\mu d_r)(\bar{d}_s \gamma^\mu d_t)$</td>
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<td>$Q_{lq}^{(1)}$</td>
<td>$Q_{le}$</td>
<td>$Q_{qu}$</td>
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<td>$Q_{dd}$</td>
<td>$Q_{qu}^{(8)}$</td>
</tr>
<tr>
<td>$(\bar{l}<em>p \gamma</em>\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$</td>
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<tr>
<td>$Q_{ud}^{(1)}$</td>
<td>$Q_{ge}$</td>
<td>$Q_{qu}^{(1)}$</td>
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<tr>
<th>$\langle \bar{L}R \rangle(\bar{R}L)$ and $\langle \bar{L}R \rangle(\bar{R} \bar{L})$</th>
<th>$B$-violating</th>
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<td>$Q_{duq}$</td>
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<tr>
<td>$(\bar{l}<em>p \gamma</em>\mu e_r)(\bar{d}_s q_t^j)$</td>
<td>$\varepsilon^{\alpha \beta \gamma} \varepsilon_{j k} \left[ (d_p^\alpha)^T C u_r^\beta \right] \left[ (q_s^j)^T C l_t^\gamma \right]$</td>
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<td>$Q_{quqd}^{(8)}$</td>
<td>$Q_{qqu}$</td>
</tr>
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<td>$(\bar{q}<em>p^j u_r)(\varepsilon</em>{jk} (\bar{q}_s^j d_t))$</td>
<td>$\varepsilon^{\alpha \beta \gamma} \varepsilon_{j k} \left[ (q_p^{\alpha j})^T C q_r^{\beta k} \right] \left[ (u_s^\gamma)^T C e_t \right]$</td>
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<td>$\varepsilon^{\alpha \beta \gamma} \varepsilon_{j n} \varepsilon_{k m} \left[ (q_p^{\alpha j})^T C q_r^{\beta k} \right] \left[ (q_s^{\gamma m})^T C l_t^\gamma \right]$</td>
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<td>$Q_{lequ}^{(1)}$</td>
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<td>$(\bar{l}<em>p \gamma</em>\mu e_r)(\varepsilon_{jk} (\bar{q}_s^j u_t))$</td>
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| $Q_{lequ}^{(3)}$                  |               |

Table 3: Four-fermion operators.
**SMEFT Strategy**

UV Completion

\[ \mathcal{L}(x_i) \]

<table>
<thead>
<tr>
<th>Scale</th>
<th>Model</th>
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<tbody>
<tr>
<td>[ \mu = \Lambda ]</td>
<td><strong>SMEFT</strong></td>
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<td>[ \mu = \mu^+_{\text{ew}} ]</td>
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<td>[ \mu = \mu_{\text{low}} ]</td>
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**SM Effective Field Theory (SMEFT)**

\[ \text{SU}(3)_c \otimes \text{SU}(2)_L \otimes U(1)_Y \]

EWPT, H-decays etc.

**Weak Effective Theory (WET)**

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

\[ \Delta F = 1, 2, \tau \text{ & } \mu \text{-decays etc} \]
Outline

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2. Modern Effective Field Theories (WET/SMEFT..)
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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!*
Beyond SMEFT

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:**

\[ \begin{align*}
Y_{e_L} &= -1, \\
Y_{e_R} &= -2, \\
Y_{d_L} &= +1/3, \\
Y_{d_R} &= -2/3
\end{align*} \]

\[ +1 \quad -1 \quad +1/3 \quad -1/3 = 0 \]

\[ \text{Symmetry: } U(1)_Q \]

**Hypercharge:**

\[ \begin{align*}
Y_{e_L} &= -1, \\
Y_{e_R} &= -2, \\
Y_{d_L} &= +1/3, \\
Y_{d_R} &= -2/3
\end{align*} \]

\[ +1 \quad -2 \quad -1/3 \quad -2/3 = -2 \neq 0! \]

\[ Q = T_3 + Y/2 \]

\[ \text{Symmetry: } SU(2)_L \]

- 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).

\[
\begin{align*}
O_{\nu \text{edu}}^{V,LR} & : (\overline{\nu}_{Lp} \gamma^{\mu} e_{Lr})(\overline{d}_{Rs} \gamma_{\mu} u_{Rt}) + h.c \\
O_{\text{ed}}^{S,RR} & : (\overline{e}_{Lp} e_{Rr})(\overline{d}_{Ls} d_{Rt}) \\
O_{\text{ed}}^{T,RR} & : (\overline{e}_{Lp} \sigma^{\mu \nu} e_{Rr})(\overline{d}_{Ls} \sigma_{\mu \nu} d_{Rt}) \\
O_{\text{ee}}^{S,RR} & : (\overline{e}_{Lp} e_{Rr})(\overline{e}_{Ls} e_{Rt}) \\
O_{\text{uddu}}^{V1,LR} & : (\overline{u}_{Lp} \gamma^{\mu} d_{Lr})(\overline{d}_{Rs} \gamma_{\mu} u_{Rt}) + h.c \\
O_{\text{uddu}}^{V8,LR} & : (\overline{u}_{Lp} \gamma^{\mu} T^{A} d_{Lr})(\overline{d}_{Rs} \gamma_{\mu} T^{A} u_{Rt}) + h.c \\
O_{\text{uu}}^{S1,RR} & : (\overline{u}_{Lp} u_{Rr})(\overline{u}_{Ls} u_{Rt}) \\
O_{\text{uu}}^{S8,RR} & : (\overline{u}_{Lp} T^{A} u_{Rr})(\overline{u}_{Ls} T^{A} u_{Rt}) \\
O_{\text{dd}}^{S1,RR} & : (\overline{d}_{Lp} d_{Rr})(\overline{d}_{Ls} d_{Rt}) \\
O_{\text{dd}}^{S8,RR} & : (\overline{d}_{Lp} T^{A} d_{Rr})(\overline{d}_{Ls} T^{A} d_{Rt})
\end{align*}
\]
Generating such operators within SMEFT

\[ O_{\nu edu}^{V,LR} = (\bar{\nu} \gamma_\mu P_L e)(\bar{d} \gamma^\mu P_R u) \]

**Symmetries**

**Electric charge:**
-1 \hspace{1cm} +1/3 \hspace{1cm} +2/3 = 0

**Hypercharge:**
+1 \hspace{1cm} -1 \hspace{1cm} +2/3 \hspace{1cm} +4/3 = 2 \neq 0

\[ Q = T_3 + Y/2 \]

- \[ Y_{\nu L} = -1, \ Y_{e L} = -1, \ Y_{d R} = -2/3, \ Y_{u R} = +4/3 \]

\[ U(1)_Q \]

\[ U(1)_Y \]

\[ SU(2)_L \]

Diagram:

- \( \nu_{\ell L} \)\rightarrow W \rightarrow d_{R} \rightarrow u_{R} \\ell_{L}
Generating $\bar{d}_R \gamma_\mu u_R W^\mu$ vertex

**SMEFT**

$$[O_{\phi ud}]_{ij} = (\bar{\phi}^* i D_\mu \phi)(\bar{u}_i \gamma^\mu d_j) \quad \gamma_\phi = +1$$

Electroweak symmetry breaking

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

$$W_\mu$$

$$d_R$$

$$u_R$$

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

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

$\nu_{\ell L} \rightarrow W \rightarrow d_R \ell_L$

$\ell_L \rightarrow W \rightarrow u_R \nu_{\ell L}$

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

In SMEFT $O^{V,LR}_{\text{vedu}}$ 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?
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?

Yes, but at dimension-eight level.
Dimension-8 SMEFT

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

EW symmetry breaking + Fierz transformation generates:

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

But:

\[ C_{\nu edu}^{V,LR} \propto \frac{v^2}{\Lambda^4} C_8 \]

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 $C_{\nu edu}^{V,LR} \sim \frac{1}{\Lambda^2} \sim 4 \times 10^{-2} \text{ TeV}^{-2}$.

- In SMEFT $C_{\nu edu}^{V,LR} \sim \frac{v^2}{\Lambda^4} \sim 10^{-3} \text{ TeV}^{-2}$.

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

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
**$b \rightarrow c \tau \bar{\nu}$ observables**

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

### Observables:

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

$$
F_L(D^*) \equiv \frac{\Gamma(B \rightarrow D_L^*\tau\nu)}{\Gamma(B \rightarrow D^*\tau\nu)}, \quad P_\tau(D^*) \equiv \frac{\Gamma^{+1/2} - \Gamma^{-1/2}}{\Gamma^{+1/2} + \Gamma^{-1/2}}
$$
Fit to $b \to c \tau \bar{\nu}$ data

$$\mathcal{H}_{\text{eff}} = \frac{4G_F}{\sqrt{2}} V_{cb} O_{LL}^{V} - \frac{C_{LL}^{V}}{\Lambda^2} O_{LL}^V - \frac{C_{LR}^{V}}{\Lambda^2} O_{LR}^V,$$

$$- \frac{C_{LL}^{S}}{\Lambda^2} O_{LL}^{S} - \frac{C_{LR}^{S}}{\Lambda^2} O_{LR}^{S} - \frac{C_{T}}{\Lambda^2} O_{T}.$$

Experimental measurements:

- $R(D) = 0.340 \pm 0.027 \pm 0.013$ \hspace{1cm} HFLAV Collaboration
- $R(D^*) = 0.295 \pm 0.011 \pm 0.008$
- $P_t(D^*) = -0.38 \pm 0.51 + 0.21 - 0.16$ \hspace{1cm} Belle Collaboration
- $R(J/\psi) = 0.71 \pm 0.17 \pm 0.18$ \hspace{1cm} LHCb Collaboration

Fit results:

$$\Lambda = 5 \text{ TeV}$$

<table>
<thead>
<tr>
<th>New-physics coeff.</th>
<th>Best fit</th>
<th>$p$ value (%)</th>
<th>pull$_{\text{SM}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{LL}^{V}$</td>
<td>$-3.1 \pm 0.7$</td>
<td>51</td>
<td>4.1</td>
</tr>
<tr>
<td>$C_{LR}^{V}$</td>
<td>$2.8 \pm 1.2$</td>
<td>0.3</td>
<td>2.3</td>
</tr>
<tr>
<td>$(C_{LL}^{V}, C_{LR}^{V})$</td>
<td>$(-3.0 \pm 0.8, 0.6 \pm 1.2)$</td>
<td>35</td>
<td>3.7</td>
</tr>
</tbody>
</table>
Low energy phenomenology with non-SMEFT operators

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

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

![Figure 1](image.png)

**FIG. 1:** (Correlated) allowed values of $C^{LL}_V$ and $C^{LR}_V$ at 1$\sigma$ (inner region) and 2$\sigma$ (outer region).
Outline

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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 $(\bar{\nu}\gamma_\mu P_L \ell)(\bar{c}\gamma^\mu P_R b)$. 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.