New Physics searches in EW physics

David Marzocca

Les Rencontres de Physique de la Vallée d'Aoste, 1/03/2018
Outline

- Introduction

- Which EW processes @LHC offer the best sensitivity to New Physics?
  - Diboson production
  - Dilepton production (Drell-Yan)

- Present bounds, EFT validity, prospects.

- Application to neutral-current B-physics anomalies
Indirect searches of New Physics

Precision measurements of SM processes can allow to test New Physics at scales not reachable by direct searches.

The SM EFT allows to describe the low-energy effects of heavy New Physics

\[ E, m_Z \ll \Lambda \]

\[ \mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots \]
Indirect searches of New Physics

Precision measurements of SM processes can allow to test New Physics at scales not reachable by direct searches.

The SM EFT allows to describe the low-energy effects of heavy New Physics

SM + heavy New Physics

\[ E, m_Z \ll \Lambda \quad \mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots \]

For example:

- constraint on custodial symmetry violation,
- heavy states coupled to Higgs and/or fermion currents,
- deviations in Higgs couplings to SM gauge bosons,
- …
Indirect searches of New Physics

Precision measurements of SM processes can allow to test New Physics at scales not reachable by direct searches.

The SM EFT allows to describe the low-energy effects of heavy New Physics

**SM + heavy New Physics**

\[ E, m_Z \ll \Lambda \]

\[ \mathcal{L}^{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)} + \ldots \]

What are the electroweak processes at the LHC which offer the best sensitivity to such heavy New Physics?
New Physics @ LHC

Excluding direct searches and flavour physics

Two broad strategies for looking for deviations from the SM

1) Deviations in on-shell* couplings between SM particles

2) Deviations in the tails of differential distributions

\[ \frac{d\sigma}{d\xi} \]

\[ A_{BSM} / A_{SM} \sim E^2 \]
New Physics @ LHC

Excluding direct searches and flavour physics

1) **Z(W)-pole observables, Higgs couplings,** ...

\[ c_i \sim g_i^2 \quad \delta_{\text{pole}} \sim \mathcal{O} \left( g_i^2 \frac{m_Z^2}{\Lambda^2} \right) \]

\[ \text{LEP-I: } \delta_{\text{pole}} \lesssim 10^{-3} \quad g_* \sim 1 \quad \Lambda \gtrsim 3 \text{ TeV} \]

At LHC these measurements are limited by systematic (incl. theory) uncertainties.

Not much room for improvement beyond \( \sim \) (few) % level
[few exceptions, e.g. \( m_W \)]
New Physics @ LHC

Excluding direct searches and flavour physics

2) Deviations in the tails of $2 \to 2$ processes

$$\delta_{\text{tail}} \sim \mathcal{O} \left( g^2 \frac{p^2}{\Lambda^2} \right)$$

$$\delta_{\text{tail}} \lesssim 10^{-1} \quad \frac{p}{g^*} \sim 2 \text{ TeV}$$

$$\Lambda \gtrsim 6 \text{ TeV}$$

'Energy helps accuracy' [see e.g. Farina et al. 1609.08157]
New Physics @ LHC

Excluding direct searches and flavour physics

2) Deviations in the tails of $2 \to 2$ processes

$$\delta_{\text{tail}} \sim \mathcal{O} \left( g^2 \frac{p^2}{\Lambda^2} \right)$$

$$\delta_{\text{tail}} \lesssim 10^{-1} \quad \frac{p \sim 2 \text{ TeV}}{g^* \sim 1} \quad \Lambda \gtrsim 6 \text{ TeV}$$

'Energy helps accuracy' [see e.g. Farina et al. 1609.08157]

Less precise measurements at high energy can be competitive with very precise ones at low energy.
New Physics @ LHC

Excluding direct searches and flavour physics

2) **Deviations in the tails of $2 \rightarrow 2$ processes**

\[
\delta_{\text{tail}} \sim O \left( g^2 \frac{p^2}{\Lambda^2} \right)
\]

\[
\delta_{\text{tail}} \lesssim 10^{-1} \quad p \sim 2 \text{ TeV} \quad \Lambda \gtrsim 6 \text{ TeV}
\]

‘Energy helps accuracy’ [see e.g. Farina et al. 1609.08157]

Less precise measurements at high energy can be competitive with very precise ones at low energy.

We focus on **operators** whose interfering amplitude with the SM grows quadratically with the energy.
EFT validity

Any experimental limit in the EFT approach will be on the combination

\[ c_i \sim g_*^2 \]

\[ \nu^2 \frac{c}{\Lambda^2} < \delta_{\text{prec.}} \]

\[
\begin{align*}
    c &< \frac{\Lambda^2}{\nu} \delta_{\text{prec.}} \\
    c &< 4 \delta_{\text{exp.}} \\
    \Lambda &\gg c_{\text{exp.}}
\end{align*}
\]
EFT validity

Any experimental limit in the EFT approach will be on the combination

\[ v^2 \frac{c_i}{\Lambda^2} < \delta_{\text{prec}}. \]

Bad precision at high energy could mean that no scenario is being probed consistently with the EFT.

Increasing the precision enlarges the size of the triangle, accessing more weakly coupled models.

This region is possibly excluded by same search, but using a ‘direct search’ approach.
2 → 2 processes at high-$p_T$

In this talk I will focus on:

Diboson (and VH) production

Constraints on $qqHD_\mu H$ operators.

or anomalous triple-gauge couplings (aTGC)

Dilepton production at high $m_{\ell\ell}$

Constraints on $qq\ell\ell$ four-fermion operators
Diboson production

The only SM-BSM interference term growing as \( E^2 \) is in longitu"dinal gauge bosons

\[
q \bar{q} \rightarrow V_L V_L \text{ (i.e. } H H) \]

[Azatov et al. 1607.05236, Falkowski et al. 1609.06312, Franceschini et al 1712.01310]

eg:

\[
\delta A(\bar{q}q' \rightarrow WZ) \sim a_q^{(3)} E^2
\]
Diboson production

The only SM-BSM interference term growing as $E^2$ is in **longitudinal gauge bosons**

$q \bar{q} \rightarrow V_L V_L$ (i.e. $H H$)

[Azatov et al. 1607.05236, Falkowski et al. 1609.06312, Franceschini et al 1712.01310]

eg: $\delta A(\bar{q}q' \rightarrow WZ) \sim a_q^{(3)} E^2$

Due to:

$$\frac{c_q^1}{\Lambda^2} (\bar{q} \gamma^\mu q) (H^\dagger \leftrightarrow D_\mu H)$$

$$\frac{c_q^3}{\Lambda^2} (\bar{q}_L \gamma^\mu \sigma^a q_L) (H^\dagger \sigma^a \leftrightarrow D_\mu H)$$

Assuming **universal new physics**, these correspond to combinations of $\text{aTGC}$ and oblique parameters:

$$a_q^{(3)} = -\frac{g^2}{m_W^2} \left( c_{\theta_W}^2 \delta g_1^Z + W \right), \quad a_q^{(1)} = \frac{g'^2}{3m_W^2} \left( \hat{S} - \delta \kappa_\gamma + c_{\theta_W}^2 \delta g_1^Z - Y \right)$$
Controlling the EFT (I)

Falkowski, Gonzalez-Alonso, Greljo, D.M., Son [1609.06312]

Perform a fit keeping only low-energy events (below some cut)

\[ m_{VV} < m_{VV}^{\text{max}} \]

We fit a selection of 8 TeV (20fb\(^{-1}\)) +13 TeV (3.2fb\(^{-1}\)) ATLAS and CMS WW and WZ data

Fits saturate at \( m_{VV}^{\text{max}} \sim 1\text{TeV} \): typical energy scale of the measurement.
Limits and prospects

[Franceschini, Panico, Pomarol, Riva, Wulzer 1712.01310]

Only from the leptonic WZ

\[ \alpha_q^{(3)} = -\frac{g^2}{m_W^2} \left( c_{\theta_W}^2 \delta g_1^Z + W \right) \]
Limits and prospects

[Franceschini, Panico, Pomarol, Riva, Wulzer 1712.01310]

Only from the leptonic WZ

The HL-LHC prospect corresponds to:

\[
\alpha_q^{(3)} = - \frac{g^2}{m_W^2} \left( c_{\theta_W}^2 \delta g_1^Z + W \right)
\]

Particularly relevant for states with strong coupling to SM fermions and Higgs currents.
Dilepton production

\[ q \rightarrow \ell^+ \ell^- \]

\[ \bar{q} \rightarrow \ell^+ \ell^- \]
The new frontier of 'precision': Drell-Yan @ LHC

Parametrisation of the amplitude

Neglecting chirality-flipping terms (Yukawa suppressed)

\[ \mathcal{A}(q^i_{p_1} \bar{q}^j_{p_2} \rightarrow \ell^-_{p_1'} \ell^+_{p_2'}) = i \sum_{q_L, q_R} \sum_{\ell_L, \ell_R} (\bar{q}^i \gamma^\mu q^j) (\bar{\ell} \gamma^\mu \ell) F_{q\ell}(p^2) \]

\[ F_{q\ell}(p^2) = \delta_{i,j} \frac{e^2 Q_q Q_\ell}{p^2} + \delta_{i,j} \frac{g^{q}_{Z} g^{\ell}_{Z}}{p^2 - m^2_{Z} + im_{Z} \Gamma_{Z}} + \frac{\varepsilon^{q\ell}_{ij}}{v^2} \]

Local interactions, i.e. 4-fermion operators.
The new frontier of 'precision':
Drell-Yan @ LHC

Parametrization of the amplitude

Neglecting chirality-flipping terms (Yukawa suppressed)

[Greljo, D.M. 1704.09015]

\[ \mathcal{A}(q^i_{p_1} q^j_{p_2} \rightarrow \ell^-_{p_1'} \ell^+_{p_2'}) = i \sum_{q_L,q_R} \sum_{q,M} (\overline{q}^j \gamma_\mu q^i) (\overline{\ell} \gamma_\mu \ell) F_{q\ell}(p^2) \]

\[ F_{q\ell}(p^2) = \delta^{ij} \frac{e^2 Q_q Q_\ell}{p^2} + \delta^{ij} \frac{g^q_{Z}g^\ell_{Z}}{p^2 - m_Z^2 + im_Z \Gamma_Z} + \frac{\epsilon_{ij}^{q\ell}}{v^2} \]

Convoluted with parton lumi:

\[ \frac{d\sigma}{d\tau} = \left( \frac{d\sigma}{d\tau} \right)_{SM} \times \frac{\sum_{q,\ell} \mathcal{L}_{q\bar{q}}(\tau, \mu_F) |F_{q\ell}(\tau s_0)|^2}{\sum_{q,\ell} \mathcal{L}_{q\bar{q}}(\tau, \mu_F) |F_{q\ell}^{SM}(\tau s_0)|^2} \]

Local interactions, i.e. 4-fermion operators.
Lepton Flavour Universality ratio

Differential LFU ratio

\[ R_{\mu^+\mu^-/e^+e^-}(m_{\ell\ell}) \equiv \frac{d\sigma_{\mu\mu}}{dm_{\ell\ell}} / \frac{d\sigma_{ee}}{dm_{\ell\ell}} = \frac{\sum_{q,\mu} \mathcal{L}_{q\bar{q}}(m_{\ell\ell}^2/s_0, \mu_F) |F_{q\mu}(m_{\ell\ell}^2)|^2}{\sum_{q,e} \mathcal{L}_{q\bar{q}}(m_{\ell\ell}^2/s_0, \mu_F) |F_{qe}(m_{\ell\ell}^2)|^2} \]

[Grelio, D.M. 1704.09015]

QCD and EW corrections are flavour universal: such ratios will reduce theory uncertainties in the SM prediction.

Tests of LFU are strongly motivated by the B-physics anomalies.
LEP-2 $\bar{f}f$ data

The $Z$ (or $\gamma$) is off-shell

This bounds four-fermion operators

Assuming “universality” (i.e. only $Z,W$ propagators are affected)

<table>
<thead>
<tr>
<th>Universal form factor ($\mathcal{L}$)</th>
<th>Contact operator ($\mathcal{L}'$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$W$</td>
<td>$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$</td>
</tr>
<tr>
<td>$Y$</td>
<td>$-\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$</td>
</tr>
</tbody>
</table>

$W$ and $Y$ parameters of [Barbieri et al. hep-ph/0405040]

$\sim 10^{-3}$ precision from LEP

---

David Marzocca

La Thuile, 01.03.2018
Assuming Universality

[Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer 1609.08157]

All 4-fermion operators aligned with the W and B currents:

\[- \frac{g^2_W}{2m^2_W} J_L^a \gamma_\mu J_L^a - \frac{g_Y^2}{2m^2_W} J_Y^\mu J_Y^\mu\]

Limits from LHC are already competitive/better than those from LEP and will improve even more with more data.

\(pp \to \ell \nu\) has also potential to provide strong bounds!
Limits on 36 4-fermion operators

[Greljo, D.M. 1704.09015]

Limits in the Warsaw basis, shown here one operator at a time. We have the complete Likelihood function and checked: no sizable correlations since different operators do not interfere (different flavours and chirality).

<table>
<thead>
<tr>
<th>$C_i$</th>
<th>ATLAS 36.1 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
<th>$C_i$</th>
<th>ATLAS 36.1 fb$^{-1}$</th>
<th>3000 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{Q^1 L^1}^{(1)}$</td>
<td>[-0.0, 1.75] $\times 10^{-3}$</td>
<td>[-1.01, 1.13] $\times 10^{-4}$</td>
<td>$C_{Q^1 L^2}^{(1)}$</td>
<td>[-5.73, 14.2] $\times 10^{-4}$</td>
<td>[-1.30, 1.51] $\times 10^{-4}$</td>
</tr>
<tr>
<td>$C_{Q^1 L^1}^{(3)}$</td>
<td>[-8.92, -0.54] $\times 10^{-4}$</td>
<td>[-3.99, 3.93] $\times 10^{-5}$</td>
<td>$C_{Q^1 L^2}^{(3)}$</td>
<td>[-7.11, 2.84] $\times 10^{-4}$</td>
<td>[-5.25, 5.25] $\times 10^{-5}$</td>
</tr>
<tr>
<td>$C_{u_R L^1}$</td>
<td>[-0.19, 1.92] $\times 10^{-3}$</td>
<td>[-1.56, 1.92] $\times 10^{-4}$</td>
<td>$C_{u_R L^2}$</td>
<td>[-0.84, 1.61] $\times 10^{-3}$</td>
<td>[-2.00, 2.66] $\times 10^{-4}$</td>
</tr>
<tr>
<td>$C_{u_R L^1}$</td>
<td>[0.15, 2.06] $\times 10^{-3}$</td>
<td>[-7.89, 8.23] $\times 10^{-5}$</td>
<td>$C_{u_R L^2}$</td>
<td>[-0.52, 1.36] $\times 10^{-3}$</td>
<td>[-1.04, 1.08] $\times 10^{-4}$</td>
</tr>
<tr>
<td>$C_{Q^2 e_R}$</td>
<td>[-0.40, 1.37] $\times 10^{-3}$</td>
<td>[-1.8, 2.85] $\times 10^{-4}$</td>
<td>$C_{Q^2 L^1}$</td>
<td>[-0.82, 1.27] $\times 10^{-3}$</td>
<td>[-2.25, 4.10] $\times 10^{-4}$</td>
</tr>
<tr>
<td>$C_{d_R L^1}$</td>
<td>[-2.1, 1.04] $\times 10^{-3}$</td>
<td>[-7.59, 4.23] $\times 10^{-4}$</td>
<td>$C_{d_R L^2}$</td>
<td>[-2.13, 1.61] $\times 10^{-3}$</td>
<td>[-8.98, 5.11] $\times 10^{-4}$</td>
</tr>
<tr>
<td>$C_{d_R L^1}$</td>
<td>[-2.55, 0.46] $\times 10^{-3}$</td>
<td>[-3.37, 2.59] $\times 10^{-4}$</td>
<td>$C_{d_R L^2}$</td>
<td>[-2.31, 1.34] $\times 10^{-3}$</td>
<td>[-4.89, 3.33] $\times 10^{-4}$</td>
</tr>
<tr>
<td>$C_{L^1 L^1}$</td>
<td>[-6.62, 4.36] $\times 10^{-3}$</td>
<td>[-3.31, 1.92] $\times 10^{-3}$</td>
<td>$C_{L^2 L^2}$</td>
<td>[-8.84, 7.35] $\times 10^{-3}$</td>
<td>[-3.83, 2.39] $\times 10^{-3}$</td>
</tr>
<tr>
<td>$C_{Q^2 e_R}$</td>
<td>[-4.67, 6.34] $\times 10^{-3}$</td>
<td>[-2.11, 3.30] $\times 10^{-3}$</td>
<td>$C_{Q^2 L^1}$</td>
<td>[-9.75, 5.56] $\times 10^{-3}$</td>
<td>[-1.43, 1.15] $\times 10^{-3}$</td>
</tr>
<tr>
<td>$C_{Q^2 L^1}$</td>
<td>[-7.4, 5.9] $\times 10^{-3}$</td>
<td>[-3.96, 2.8] $\times 10^{-3}$</td>
<td>$C_{Q^2 L^2}$</td>
<td>[-7.53, 8.67] $\times 10^{-3}$</td>
<td>[-2.58, 3.73] $\times 10^{-3}$</td>
</tr>
<tr>
<td>$C_{Q^2 L^1}$</td>
<td>[-8.17, 5.06] $\times 10^{-3}$</td>
<td>[-3.82, 2.13] $\times 10^{-3}$</td>
<td>$C_{Q^2 L^2}$</td>
<td>[-1.04, 0.93] $\times 10^{-2}$</td>
<td>[-4.42, 3.33] $\times 10^{-3}$</td>
</tr>
<tr>
<td>$C_{c_R L^1}$</td>
<td>[-0.83, 1.13] $\times 10^{-2}$</td>
<td>[-3.74, 5.77] $\times 10^{-3}$</td>
<td>$C_{c_R L^2}$</td>
<td>[-1.09, 0.87] $\times 10^{-2}$</td>
<td>[-4.67, 2.73] $\times 10^{-3}$</td>
</tr>
<tr>
<td>$C_{c_R L^1}$</td>
<td>[-0.67, 1.27] $\times 10^{-2}$</td>
<td>[-2.59, 4.17] $\times 10^{-3}$</td>
<td>$C_{c_R L^2}$</td>
<td>[-1.33, 1.52] $\times 10^{-2}$</td>
<td>[-4.58, 6.54] $\times 10^{-3}$</td>
</tr>
<tr>
<td>$C_{b_R L^1}$</td>
<td>[-1.93, 1.19] $\times 10^{-2}$</td>
<td>[-8.62, 4.82] $\times 10^{-3}$</td>
<td>$C_{b_R L^2}$</td>
<td>[-1.21, 1.62] $\times 10^{-2}$</td>
<td>[-3.48, 6.32] $\times 10^{-3}$</td>
</tr>
<tr>
<td>$C_{b_R L^1}$</td>
<td>[-1.47, 1.67] $\times 10^{-2}$</td>
<td>[-7.29, 8.99] $\times 10^{-3}$</td>
<td>$C_{b_R L^2}$</td>
<td>[-2.61, 2.07] $\times 10^{-2}$</td>
<td>[-11.1, 6.33] $\times 10^{-3}$</td>
</tr>
<tr>
<td>$C_{b_R L^1}$</td>
<td>[-1.65, 1.49] $\times 10^{-2}$</td>
<td>[-8.86, 7.48] $\times 10^{-3}$</td>
<td>$C_{b_R L^2}$</td>
<td>[-2.41, 2.29] $\times 10^{-2}$</td>
<td>[-9.90, 8.68] $\times 10^{-3}$</td>
</tr>
<tr>
<td>$C_{b_R L^1}$</td>
<td>[-1.73, 1.40] $\times 10^{-2}$</td>
<td>[-9.38, 6.63] $\times 10^{-3}$</td>
<td>$C_{b_R L^2}$</td>
<td>[-2.47, 2.23] $\times 10^{-2}$</td>
<td>[-10.5, 7.97] $\times 10^{-3}$</td>
</tr>
</tbody>
</table>

$C_x \equiv \frac{v^2}{\Lambda^2} c_x$
Limits on 36 4-fermion operators

[Greljo, D.M. 1704.09015]

Limits in the Warsaw basis, shown here one operator at a time. We have the complete Likelihood function and checked: no sizable correlations since different operators do not interfere (different flavours and chirality).

\[ C = \frac{g_x^2 v^2}{\Lambda^2} \quad g_x \approx 1 \quad \Rightarrow \quad M \gtrsim 8 \text{ TeV} \]

\[ C_x \equiv \frac{v^2}{\Lambda^2} c_x \]

<table>
<thead>
<tr>
<th>( C_i )</th>
<th>ATLAS 36.1 fb(^{-1} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C_{Q^1 L^1}^{(1)} )</td>
<td>([-0.0, 1.75] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{Q^1 L^1}^{(3)} )</td>
<td>([-8.92, -0.54] \times 10^{-4} )</td>
</tr>
<tr>
<td>( C_{uR L^1} )</td>
<td>([-0.19, 1.92] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{uRE} )</td>
<td>([0.15, 2.06] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{Q^3 e_R} )</td>
<td>([-0.40, 1.37] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{dR L^1} )</td>
<td>([-2.1, 1.04] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{dRE} )</td>
<td>([-2.55, 0.46] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{Q^1 e_R} )</td>
<td>([-6.62, 4.36] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{Q^2 L^1} )</td>
<td>([-8.24, 2.05] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{Q^2 e_R} )</td>
<td>([-4.67, 6.34] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{sQL^1} )</td>
<td>([-7.4, 5.9] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{sRE} )</td>
<td>([-8.17, 5.06] \times 10^{-3} )</td>
</tr>
<tr>
<td>( C_{cR L^1} )</td>
<td>([-0.83, 1.13] \times 10^{-2} )</td>
</tr>
<tr>
<td>( C_{cRE} )</td>
<td>([-0.67, 1.27] \times 10^{-2} )</td>
</tr>
<tr>
<td>( C_{b_L L^1} )</td>
<td>([-1.93, 1.19] \times 10^{-2} )</td>
</tr>
<tr>
<td>( C_{b_L e_R} )</td>
<td>([-1.47, 1.67] \times 10^{-2} )</td>
</tr>
<tr>
<td>( C_{b_R L^1} )</td>
<td>([-1.65, 1.49] \times 10^{-2} )</td>
</tr>
<tr>
<td>( C_{b_R e_R} )</td>
<td>([-1.73, 1.40] \times 10^{-2} )</td>
</tr>
</tbody>
</table>

~10\(^{-3}\) - 10\(^{-2}\) precision now

a 5-10-fold improvement at HL-LHC

David Marzocca
La Thuile, 01.03.2018
How do the limits vary when using only events with \( m_{ll} < \Lambda_{\text{cut}} \)?

**Limits saturate at \( \Lambda_{\text{cut}} \sim 2-3 \text{ TeV at 13TeV}.**

(more luminosity \( \rightarrow \) more events at high energy)
The plots in Fig. scenarios with NP in one individual Wilson coefficients to be SM-like.

TABLE I. Best-fit values and pulls for scenarios with NP in Flavio v0.21

Re C

10

flavio v0.21

LFU observables

b ! sμµ global fit

3 2 1 0 1 2 3

Re C

9

2

1

0

1

2

Re C

9

flavio v0.21

RK

R⇤

K

LFU observables

b ! sμµ global fit

Required EFT operator

\[ \mathcal{L} \supset \frac{C_{bs\mu}}{v^2} (\bar{b}_L \gamma_\mu s_L) (\bar{\mu}_L \gamma^\mu \mu_L) + h.c. \]

\[ C_{bs\mu} = \frac{\alpha}{\pi} V_{tb} V_{ts}^* \Delta C^\mu_9 \simeq 9.3 \times 10^{-5} \Delta C^\mu_9 \]

\[ \Delta C^\mu_9 = -\Delta C^\mu_{10} = -0.61 \pm 0.12 \]

This is a ‘measurement’ of non-zero \( C_{bs\mu} \).

The result of the fit is compatible with the observed anomaly in \( P'_5 \).
Application to B anomalies

Required EFT operator

\[ \mathcal{L} \supset \frac{C_{bs\mu}}{v^2} (\bar{b}_L \gamma_\mu s_L)(\bar{\mu}_L \gamma_\mu \mu_L) + h.c. \]

\[ C_{bs\mu} = \frac{\alpha}{\pi} V_{tb} V_{ts}^* \Delta C_9^{\mu} \approx 9.3 \times 10^{-5} \Delta C_9^{\mu} \]

\[ \Delta C_9^{\mu} = - \Delta C_{10}^{\mu} = -0.61 \pm 0.12 \]

The result of the fit is compatible with the observed anomaly in P'\_5.

This is a ‘measurement’ of non-zero \( C_{bs\mu} \).

In the SM EFT at the EW scale:

\[ C_T \left( \bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j \right) \left( \bar{L}_L^\alpha \gamma_\mu \sigma^a L_L^\beta \right) + C_S \left( \bar{Q}_L^i \gamma_\mu Q_L^j \right) \left( \bar{L}_L^\alpha \gamma_\mu L_L^\beta \right) \]
Flavor in dimuon tails?

The present (future) direct bound on $\Delta C^{9\mu}$ from ATLAS dimuon search

$$|\Delta C^{9\mu}| = \left| \frac{\pi}{\alpha V_{tb} V_{ts}^*} C_{bs\mu} \right| < 100 \ (39)$$

No sensitivity.
Flavor in dimuon tails?

The present (future) direct bound on $\Delta C_{9\mu}$ from ATLAS dimuon search

$$|\Delta C_{9\mu}| = \left| \frac{\pi}{\alpha V_{tb} V_{ts}^*} C_{bs\mu} \right| < 100 \quad (39)$$

No sensitivity.

In a complete flavour model, such a flavour-violating operator will be related to the flavour-conserving ones:

$$\mathcal{L}^{\text{eff}} \supset \frac{C_{ij}^{U\mu}}{v^2} (\bar{u}_L^{i} \gamma_{\mu} u_L^{j})(\bar{\mu}_L \gamma_{\mu} \mu_L) + \frac{C_{ij}^{D\mu}}{v^2} (\bar{d}_L^{i} \gamma_{\mu} d_L^{j})(\bar{\mu}_L \gamma_{\mu} \mu_L)$$

$$C_{ij}^{U\mu} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \quad C_{ij}^{D\mu} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C_{bs\mu}^* \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$

This structure is predicted in a given model.

$$\lambda_{bs}^q \equiv C_{bs\mu} / C_{q\mu} \rightarrow \sim \text{fixed in a model,}$$

$$\sim V_{ts} \text{ in MFV}$$
Flavor in dimuon tails?

The present (future) direct bound on $\Delta C_{9\mu}$ from ATLAS dimuon search:

$$|\Delta C_{9\mu}| = \left| \frac{\pi}{\alpha V_{tb} V_{ts}^*} C_{bs\mu} \right| < 100 \quad (39)$$

No sensitivity.

In a complete flavour model, such a flavour-violating operator will be related to the flavour-conserving ones:

$$\mathcal{L}_{\text{eff}} \supset \frac{C_{ij}^{U\mu}}{v^2} (\bar{u}_L^i \gamma_\mu u_L^j) (\bar{\mu}_L \gamma_\mu \mu_L) + \frac{C_{ij}^{D\mu}}{v^2} (\bar{d}_L^i \gamma_\mu d_L^j) (\bar{\mu}_L \gamma_\mu \mu_L)$$

$$C_{ij}^{U\mu} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \quad C_{ij}^{D\mu} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C_{bs\mu}^* \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$

This structure is predicted in a given model.

$$\lambda_{bs}^q \equiv C_{bs\mu} / C_{q\mu} \rightarrow \sim \text{fixed in a model,}$$

$$\sim V_{ts} \text{ in MFV}$$

We might test the flavour-diagonal ones.
Minimal Flavour Violation

Assumption: The only breaking of the SU(3)$^5$ flavour symmetry is via the SM Yukawas.

$$C_{ij}^{U\mu} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \quad C_{ij}^{D\mu} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C_{bs\mu}^* \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$

$$C_{u\mu} = C_{c\mu} = C_{t\mu} \equiv C_{U\mu}$$
$$C_{d\mu} = C_{s\mu} = C_{b\mu} \equiv C_{D\mu}$$

$$|C_{bs\mu}| \sim |V_{tb}V_{ts}y_t^2 C_{D\mu}|$$

We get a prediction for $C_{D\mu}$ (which is tested by LHC)

$$|C_{D\mu}| \sim 1.4 \times 10^{-3}$$
Minimal Flavour Violation

Assumption: The only breaking of the SU(3)$^5$ flavour symmetry is via the SM Yukawas.

$$C_{ij}^{U} = \begin{pmatrix} C_{u\mu} & 0 & 0 \\ 0 & C_{c\mu} & 0 \\ 0 & 0 & C_{t\mu} \end{pmatrix}, \quad C_{ij}^{D} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C_{bs\mu}^{*} \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$

MFV case – 95% CL limits

We get a prediction for $C_{D\mu}$ (which is tested by LHC)

$$|C_{D\mu}| \sim 1.4 \times 10^{-3}$$

$qq\mu\mu$ operators with valence quarks are tested better than per-mille level.

The MFV solution is already in strong tension with LHC.
Compare to explicit model

Model with a spin-1 singlet: $Z'$.

\[
\frac{C}{\nu^2} = -\frac{g^2_{\ast}}{M_{Z'}^2}
\]
Compare to explicit model

Model with a spin-1 singlet: $Z'$. 

\[ \frac{\mathcal{C}}{\mathcal{V}^2} = -\frac{g_{\#}^2}{M_{Z'}^2} \]

95% CL limits on MFV $Z'$ from $p p \rightarrow \mu^+ \mu^-$

Such an explanation of the anomalies is excluded for any mass.

For $M_{Z'} \approx 4-5$ TeV the EFT expansion is OK (still weak coupling).
Compare to explicit model

Model with a spin-1 singlet: $Z'$. 

\[
\mathcal{C} = -\frac{g^2}{M_{Z'}^2}
\]

95% CL limits on MFV $Z'$ from $p p \rightarrow \mu^+ \mu^-$

For $M_{Z'} \gtrsim 4$-5 TeV the EFT expansion is OK (still weak coupling).

Such an explanation of the anomalies is excluded for any mass.

Limit from on-shell production searches

Limit in the model

EFT limit

ATLAS 13 TeV, 36.1 fb$^{-1}$

$R(K^{(*)}) @ 2\sigma$
Conclusions

- LHC measurements of high-$p_T$ tails of $2 \rightarrow 2$ processes offer strong probes of new physics, complementing (and often surpassing) limits derived from LEP.

- Care must be taken to understand the typical energy scale of the experiment and making sure that, at the interpretation level,

$$E_{\text{exp}} \ll \Lambda_{NP}$$

- This allows us to probe mass scales often higher than the reach of direct searches.

- The limits are already relevant for models addressing B-anomalies.

Thank you!
Backup
We study BSM effects in the SMEFT (for the moment at LO). Dimension-6 operators can contribute in many ways:

The only physical (basis indep.) quantity is the total on-shell amplitude

\[ \text{aTGC} \]

I take Z(W)-pole bounds and approximate:
fix those SMEFT directions as SM-like.

Note that this is a basis-independent statement.
Indeed, in our work we use both SILH and Warsaw bases.
SMEFT contributions

After imposing Z(W)-pole limits, **Three unconstrained combinations** of SMEFT coefficients contribute to the process:

\[
\delta g_{1, z} = -\frac{v^2}{\Lambda^2} \frac{g_L^2 + g_Y^2}{2(g_L^2 - g_Y^2)} \left( 4 \frac{g_Y}{g_L} w_{\phi WB} + w_{\phi D} - [w_{\ell \ell}]_{1221} + 2 [w_{\phi \ell}^{(3)}]_{11} + 2 [w_{\phi \ell}^{(3)}]_{22} \right)
\]

**Warsaw basis:**

\[
\delta \kappa_\gamma = \frac{v^2}{\Lambda^2} \frac{g_L}{g_Y} w_{\phi WB} , \quad \lambda_z = -\frac{v^2}{\Lambda^2} \frac{3}{2} g_L w_W ,
\]

**SILH basis:**

\[
\delta g_{1z} = -\frac{g_L^2 + g_Y^2}{g_L^2 - g_Y^2} \left[ \frac{g_L^2 - g_Y^2}{g_L^2} \tilde{c}_{HW} + \tilde{c}_W + \tilde{c}_{2W} + \frac{g_Y}{g_L^2} \tilde{c}_B + \frac{g_Y^2}{g_L^2} \tilde{c}_{2B} - \frac{1}{2} c_T \right]
\]

\[
\delta \kappa_\gamma = -\tilde{c}_{HW} - \tilde{c}_{HB} , \quad \lambda_z = -6 g_L^2 \tilde{c}_{3W} ,
\]

Falkowski, Gonzalez-Alonso, Greljo, D.M., Son JHEP [1609.06312]

Not only 3 operators contribute to diboson production, but the independent, unconstrained, combinations are 3 (in any basis).

Let us call them:

\[
\delta g_{1, z}, \ \delta \kappa_\gamma, \ \lambda_z \sim c^{(6)} \frac{m_W^2}{\Lambda^2}
\]
Applications & Validity

Model with a vector triplet + singlet. No vertex corrections, at low energy

\[ \delta g_{1,z} = -\kappa_H^2 \frac{m_W^2}{2 s_\theta^2 m_V^2} \]

EFT Limits (no high-E cut) from CMS WW @ 8TeV.

Limits directly from the model (different benchmarks points with same low energy EFT)

1) For \( M_V \gtrsim 3\, \text{TeV} \) the EFT approximates well the model.
2) For lower masses, the EFT gives conservative bounds (in this case).
Universal Scenario

i.e. oblique corrections

Assuming that New Physics is “universal” — affects only gauge boson self-energies

\[ \Pi_V(q^2) \simeq \Pi_V(0) + q^2 \Pi'_V(0) + \frac{(q^2)^2}{2!} \Pi''_V(0) + \cdots \]

\[ \langle V_\mu(-q)V_\nu'(q) \rangle \propto \Pi_{VV'}(q^2) \]

[Altarelli and Barbieri ’91, Peskin and Takeuchi ’92, Barbieri et al. hep-ph/0405040]

At dim-6 in SM EFT only these are generated:

\[ g^{-2} \hat{S} = \Pi'_{W3B}(0) \]
\[ g^{-2} M_W^2 \hat{T} = \Pi_{W3W3}(0) - \Pi_{W+W-}(0) \]
\[ 2g'^{-2} M_W^{-2} \hat{Y} = \Pi''_{BB}(0) \]
\[ 2g^{-2} M_W^{-2} \hat{W} = \Pi''_{W3W3}(0) \]

\[ S = 4s_W^2 \hat{S}/\alpha \approx 119 \hat{S}, \quad T = \hat{T}/\alpha \approx 129 \hat{T} \]

\[ \sim 10^{-3} \text{ precision} \]