Discussion on B-anomalies

GGI Workshop - 24.08.2018

Luca Di Luzio
Outline

1. Review of “B-anomalies”
   - charged currents
   - neutral currents

2. Combined explanations
   - EFT
     - Simplified models
     - UV completions
BSM Flavour

- Almost all the “oddities” of the SM related to the Higgs

\[ \mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{gauge}} + (y_{ij} \bar{\psi}_i \psi_j H + \text{h.c.}) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda_{cc}^4 \]

- Flavour puzzle

1. Is there a dynamics behind the pattern fermion masses and mixings?
BSM Flavour

- Almost all the “oddities” of the SM related to the Higgs

\[
\mathcal{L}_{SM} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{gauge}} + (y_{ij}\bar{\psi}_i \psi_j H + \text{h.c.}) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda_{cc}^4
\]

- Flavour puzzle

1. Is there a dynamics behind the pattern fermion masses and mixings? 
2. How is possible to reconcile TeV-scale NP with the absence of indirect signals?

Figure 2.1: Massless neutrinos in the SM

[Strumia, Vissani]
Almost all the “oddities” of the SM related to the Higgs

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{gauge}} + (y_{ij} \overline{\psi}_i \psi_j H + \text{h.c.}) - \lambda |H|^4 + \mu^2 |H|^2 - \Lambda_{cc}^4$$

Flavour puzzle

1. Is there a dynamics behind the pattern fermion masses and mixings?
2. How is possible to reconcile TeV-scale NP with the absence of indirect signals?

pre-LHC scenario:

exciting NP at ATLAS/CMS, boring flavour physics at LHCb protected by MFV

data suggest instead unexpected flavour anomalies
Part-I

Review of “B-anomalies”
“B-anomalies”

- A seemingly coherent pattern of SM deviations building up since ~ 2012

<table>
<thead>
<tr>
<th></th>
<th>$b \to c\tau\nu$</th>
<th>$b \to s\mu\mu$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lepton Universality</strong></td>
<td>$R(D), R(D^*), R(J/\psi)$</td>
<td>$R(K), R(K^*)$</td>
</tr>
<tr>
<td><strong>Angular Distributions</strong></td>
<td></td>
<td>$B \to K^*\mu\mu ~ (P_S')$</td>
</tr>
<tr>
<td><strong>Differential BR</strong></td>
<td>$(d\Gamma/dq^2)$</td>
<td>$B \to K^{(*)}\mu\mu$</td>
</tr>
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<td></td>
<td></td>
<td>$B_s \to \phi\mu\mu$</td>
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<tr>
<td></td>
<td></td>
<td>$\Lambda_b \to \Lambda\mu\mu$</td>
</tr>
</tbody>
</table>
Charged current anomalies

\[ R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \rightarrow D^{(*)} + \tau \nu)}{\mathcal{B}(B^0 \rightarrow D^{(*)} + \ell \nu)} \]

\[ \ell = \mu, e \]

- SM prediction reasonably robust [lot of recent activity - HFLAV 2018]
- Deviation seen in 3 exp. in a consistent way, combined significance \(\sim 3.7\sigma\)
- \(R(D)\) and \(R(D^*)\) point to constructive interference (+15%) with SM amplitude
Charged current anomalies

\[ R(D^{(*)}) \equiv \frac{\mathcal{B}(B^0 \to D^{(*)} + \tau \nu)}{\mathcal{B}(B^0 \to D^{(*)} + \ell \nu)} \]

• As of Sept 2017:

\[ R(J/\psi) = \frac{\mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)}{\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu)} \sim 2\sigma \text{ above the SM} \]

clearly, a **systematic** effect!
Charged current anomalies

- BSM fit favours NP in LH tau operators (SM interference)*

$$\mathcal{H}_{SM} = \frac{4G_F}{\sqrt{2}} V_{cb}(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau)$$

$$\mathcal{L}_{BSM} = \frac{2c}{\Lambda^2}(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_\tau)$$

*Freytsis, Ligeti, Ruderman, 1506.08896 Azatov at al, 1805.03209
Charged current anomalies

- BSM fit favours NP in LH tau operators (SM interference)\(^*\)

\[
\mathcal{H}_{SM} = \frac{4G_F}{\sqrt{2}} V_{cb} (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_\tau)
\]

\[
\mathcal{L}_{BSM} = \frac{2c}{\Lambda^2} (\bar{c}_L \gamma_\mu b_L) (\bar{\tau}_L \gamma^\mu \nu_\tau)
\]

- What is the scale of NP?

\[\text{No suppression: } c = 1 \quad \Lambda = 3.4 \text{ TeV}\]

\[\text{MFV: } c = V_{cb} \quad \Lambda = 0.7 \text{ TeV}\]

\[\text{MFV + loop: } c = V_{cb} / 4\pi \quad \Lambda = 0.1 \text{ TeV}\]

\(*\text{Exception: } < 100 \text{ MeV sterile neutrino (no SM interference, relaxes bounds from SU(2)_L)}\)

\[
\mathcal{L}_{BSM}^{b \to c\tau\nu} = \frac{c_{RD}}{\Lambda^2} (\bar{c}_R \gamma_\mu b_R) (\bar{\tau}_R \gamma^\mu N_R)
\]

\[
\Lambda / \sqrt{c_{RD}} = (1.27^{+0.09}_{-0.07}) \text{ TeV}
\]

\[\text{[Freytsis, Ligeti, Ruderman, 1506.08896 Azatov et al, 1805.03209]}\]
Neutral current anomalies

- Angular distributions $B \rightarrow (K^* \rightarrow K\pi)\mu\mu$

Challenging SM prediction

- LFU ratios $R(K^{(*)}) = \frac{B(B \rightarrow K^{(*)}\mu\bar{\mu})}{B(B \rightarrow K^{(*)}e\bar{e})}$

Very clean SM prediction

Combined $R(K^{(*)})$ significance $\sim 4\sigma$
Neutral current anomalies

- Well-described by NP in $b \to s \mu \mu$ (explains also angular distributions)
- RH currents in quark sector disfavoured (predict wrong correlation)
- Significance of global fits $> 4\sigma$

![Graph showing deviations from the SM value](image)

$O_9 \propto (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}_L \gamma_\mu \ell)$

$O_{10} \propto (\bar{s}_L \gamma_\mu b_L)(\ell_L \gamma_\mu \gamma_5 \ell)$
Neutral current anomalies

- Well-described by NP in $b \to s\mu\mu$ (explains also angular distributions)
- RH currents in quark sector disfavoured (predict wrong correlation)
- Significance of global fits $> 4\sigma$
- What is the scale of NP?

\[ \mathcal{L}_{\text{BSM}} = \frac{c}{\Lambda^2} (\bar{s}_L \gamma_\alpha b_L) (\bar{\mu}_L \gamma^\alpha \mu_L) \]

No suppression: $c = 1$ \hspace{1cm} $\Lambda = 31$ TeV

MFV: $c = V_{ts}$ \hspace{1cm} $\Lambda = 6$ TeV

MFV + loop: $c = V_{ts}/4\pi$ \hspace{1cm} $\Lambda = 0.5$ TeV
**Future prospects**

- LHCb + Belle-II have the potential to fully establish NP in B-anomalies

[Albrecht et al, 1709.10308]

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**Table 1: The luminosity scenarios considered along with the estimated number of $b\bar{b}$-pairs produced inside the acceptance of the experiments are given. The LHCb cross sections are taken from Ref. [25] assuming an increase in $b\bar{b}$-production cross section with LHC beam energy. For Belle II only $e^+e^-\rightarrow B\bar{B}$ data sets are estimated.**

<table>
<thead>
<tr>
<th>Year</th>
<th>Milestone I</th>
<th>Milestone II</th>
<th>Milestone III</th>
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<tbody>
<tr>
<td>2017</td>
<td>2018</td>
<td>2019</td>
<td>2020</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>LHCb</td>
<td>Start of Data taking period</td>
<td>Run 2</td>
<td>~ 8 fb$^{-1}$</td>
</tr>
<tr>
<td>Belle II</td>
<td>~ 5 ab$^{-1}$</td>
<td>Milestone I</td>
<td></td>
</tr>
<tr>
<td>2022</td>
<td>2023</td>
<td>2024</td>
<td>2025</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>LHCb</td>
<td>Run 3</td>
<td>~ 22 fb$^{-1}$</td>
<td>LHC Shutdown</td>
</tr>
<tr>
<td>Belle II</td>
<td>~ 50 ab$^{-1}$</td>
<td>End of Data taking period</td>
<td></td>
</tr>
<tr>
<td>2027</td>
<td>2028</td>
<td>2029</td>
<td>2030</td>
</tr>
<tr>
<td>Q1</td>
<td>Q2</td>
<td>Q3</td>
<td>Q4</td>
</tr>
<tr>
<td>LHCb</td>
<td>Run 4</td>
<td>~ 50 fb$^{-1}$</td>
<td>LHC Shutdown</td>
</tr>
</tbody>
</table>
• LHCb + Belle-II have the potential to fully establish NP in B-anomalies

Belle II  
5 ab$^{-1}$ 50 ab$^{-1}$ 8 fb$^{-1}$

LHCb  
22 fb$^{-1}$ 50 fb$^{-1}$

2020 2024 2019 2024 2030  

[Albrecht et al, 1709.10308]

Future prospects

- LHCb will measure R(K) and R(K*) at $> 5\sigma$ by 2019 and $\sim 15\sigma$ by 2030
- Belle-II will reach $\sim 7\sigma$ by 2024

+ LHCb will measure R(D)
Combined explanations
Bottom-up approach

Theoretical input / bias

UV completions
simplified models
EFT
Experimental input

new signatures
on-shell
tails

\[ \Lambda_{RD} = 3.4 \text{ TeV} \]

\[ \Lambda_{RK} = 31 \text{ TeV} \]
EFT [general considerations]

• SU(2)_L triplet operator (neutral+charged currents in SMEFT)

\[ \frac{\lambda^q_{ij} \lambda^\ell_{kl}}{\Lambda^2} (\overline{Q}_L \sigma^a \gamma_\mu Q^j_L)(\overline{L}_L \sigma^a \gamma_\mu L^i_L) \]

\[ Q^i_L = \left( \begin{array}{c} (V^\dagger_{\text{CKM}} u_L)^i \\ d_L^i \end{array} \right) \]

\[ L^k_L = \left( \begin{array}{c} \nu^k_L \\ e_L^k \end{array} \right) \]

[Bhattacharya et al 1412.7164
Alonso, Grinstein, Camalich 1505.05164,
Greljo, Isidori, Marzocca 1506.01705,
Calibbi, Crivellin, Ota 1506.02661, ... ]
EFT [general considerations]

- SU(2)_L triplet operator

\[
\frac{\lambda^q_{ij} \lambda^l_{kl}}{\Lambda^2} (\bar{Q}^i_L \sigma^a \gamma_\mu Q^j_L)(\bar{L}^k_L \sigma^a \gamma_\mu L^l_L) \supset -\frac{1}{\Lambda^2_{RD}} 2 \bar{c}_L \gamma_\mu b_L \bar{\tau}_L \gamma_\mu \nu_L + \frac{1}{\Lambda^2_{RK}} \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma_\mu \mu_L
\]

Λ_{RD} = 3.4 \text{ TeV} \quad \ll \quad Λ_{RK} = 31 \text{ TeV}

- What is the scale of NP?

Measured “Fermi constant” of the anomaly

\[
\frac{1}{\Lambda^2} = \frac{C}{M^2}
\]

model dependent part

\(C = \text{(loops)} \times \text{(couplings)} \times \text{(flavour)}\)

on-shell effects @ colliders
EFT [general considerations]

- SU(2)$_L$ triplet operator

\[
\frac{\lambda^q_{ij} \lambda^\ell_{kl}}{\Lambda^2} (\bar{Q}^i_L \sigma^a \gamma_\mu Q^j_L) (\bar{\ell}^k_L \sigma^a \gamma_\mu \ell^l_L) \supset -\frac{1}{\Lambda^2_{RD}} 2\bar{c}_L \gamma^\mu b_L \bar{\tau}_L \gamma_\mu \nu_L + \frac{1}{\Lambda^2_{RK}} \bar{s}_L \gamma^\mu b_L \bar{\mu}_L \gamma_\mu \mu_L
\]

\[
\Lambda_{RD} = 3.4 \text{ TeV} \ll \Lambda_{RK} = 31 \text{ TeV}
\]

- Perturbative unitarity bound from 2 $\rightarrow$ 2 fermion scatterings (worse case scenario)

\[
\sqrt{s}_{RD} < 9.2 \text{ TeV} \quad \quad \quad \quad \quad \quad \sqrt{s}_{RK} < 84 \text{ TeV}
\]

no-loose theorem for HL/HE-LHC? [LDL, Nardecchia 1706.01868]
EFT [general considerations]

• SU(2)_L triplet operator

\[
\frac{\lambda^q \lambda^\ell}{\Lambda^2}(Q^i_L)\sigma^a\gamma_\mu Q^j_L)(\bar{L}^k_L)\sigma^a\gamma_\mu L^l_L \supset -\frac{1}{\Lambda^2_{RD}}\bar{c}_L\gamma_\mu b_L\bar{\tau}_L\gamma_\mu \nu_L + \frac{1}{\Lambda^2_{RK}}\bar{s}_L\gamma_\mu b_L\bar{\mu}_L\gamma_\mu \mu_L
\]

• Flavour structure:

1. large couplings in taus (SM tree level)
2. sizable couplings in muons (SM one loop)
3. negligible couplings in electrons (well tested, not much room)

\[
\lambda^q_{ij} = \delta_{i3}\delta_{j3} + \text{corrections} \quad U(2)_q \times U(2)_\ell \quad \text{approx flavor symmetry}
\]

[Barbieri et al 1105.2296, 1512.01560]

link to SM Yukawa pattern?

\[
\bar{Q}_3 Q_3 \rightarrow V_{cb} \bar{c}_L b_L \quad \text{(pure mixing scenario)}
\]
**EFT [general considerations]**

- SU(2)$_L$ triplet operator

\[ \frac{\lambda_{ij}^q \lambda_{kl}^e}{\Lambda^2} (Q^i_L \sigma^a \gamma_\mu Q^j_L) (\bar{L}^k_L \sigma^a \gamma_\mu L^l_L) \]

- Tree-level mediators:

![Diagram](attachment:diagram.png)
EFT [problems]

- Three main problems mainly driven by R(D) [in the pure mixing scenario]

I. High-$p_T$ constraints

$$\overline{Q}_3Q_3 \rightarrow V_{cb} \overline{c}_L b_L$$

$$\Lambda_{33} = \Lambda_{R_D} V_{cb} = 0.7 \text{ TeV}$$

Diagram:

Vector LQ exclusion

[Faroughy, Greljo, Kamenik 1609.07138]
EFT [problems]

- Three main problems mainly driven by R(D) [in the pure mixing scenario]

1. High-$p_T$ constraints
2. Radiative constraints

\[ \overline{Q}_3 Q_3 \rightarrow V_{cb} \overline{c}_L b_L \]

\[ \Lambda_{33} \equiv \Lambda_{R_D} V_{cb} = 0.7 \text{ TeV} \]

[Calibbi, Crivellin, Ota, '15]

[Greljo, GI, Marzocca '15]

[Impact of one-loop-triggered constraints when addressing the]

[Feruglio, Paradisi, Pattori 1606.00524, 1705.00929]
EFT [problems]

• Three main problems mainly driven by R(D)

1. High-\(p_T\) constraints
2. Radiative constraints
3. Flavour bounds

(absent at tree-level with LQ) (consequence of SU(2)\(_L\) invariance)
• Tension gets drastically alleviated if

1. Triplet + Singlet operator (more freedom in SU(2)_L structure)

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2} \lambda_{ij}^{q} \lambda_{\alpha\beta}^{l} \left[ C_T (\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j) (\bar{L}_L^\alpha \gamma_\mu \sigma^a L_L^\beta) + C_S (\bar{Q}_L^i \gamma_\mu Q_L^j) (\bar{L}_L^\alpha \gamma_\mu L_L^\beta) \right] \]
EFT [solutions]

- Tension gets drastically alleviated if

1. Triplet + Singlet operator (more freedom in SU(2)_L structure)

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2} \lambda_{ij}^{q} \lambda_{\alpha\beta}^l \left[ C_T (\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j) (\bar{L}_L^\alpha \gamma_\mu \sigma^a L_L^\beta) + C_S (\bar{Q}_L^i \gamma_\mu Q_L^j) (\bar{L}_L^\alpha \gamma_\mu L_L^\beta) \right] \]

2. Deviation from pure-mixing scenario

\[ \bar{Q}^i \lambda_{ij}^q Q^j = (\bar{u}^k V_{ki} \quad \bar{d}^i) \lambda_{ij}^q \left( V_{jl}^\dagger u^j \right) \supset \bar{c} (V_{cb} \lambda_{bb}^q + V_{cs} \lambda_{sb}^q + \ldots) b \]

\[ R_{D(\ast)}^{\tau\ell} \approx 1 + 2C_T \left( 1 - \lambda_{sb}^q \frac{V_{tb}^*}{V_{ts}^*} \right) \quad \xrightarrow{\lambda_{sb}^q > \mathcal{O}(V_{cb})} \text{ allows for larger NP scale} \]
1. Triplet + Singlet operator (more freedom in SU(2)_L structure)

\[ \mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2} \lambda_{ij}^q \lambda_{i\alpha}^\ell \left[ C_T (\bar{Q}_L^i \gamma_\mu \sigma^a Q_L^j)(\bar{L}_R^\alpha \gamma_\mu \sigma^a L_R^\beta) + C_S (\bar{Q}_L^i \gamma_\mu Q_L^j)(\bar{L}_R^\alpha \gamma_\mu L_R^\beta) \right] \]

2. Deviation from pure-mixing scenario

\[ |\lambda_{sb}^q| > \mathcal{O}(V_{cb}) \] allows for larger NP scale

[Zürich’s guide for combined explanations, 1706.07808]
Simplified models

- Finite list of tree-level mediators

<table>
<thead>
<tr>
<th>Simplified Model</th>
<th>Spin</th>
<th>SM irrep</th>
<th>$C_S/C_T$</th>
<th>$R_{D(*)}$</th>
<th>$R_{K(*)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z'$</td>
<td>1</td>
<td>(1, 1, 0)</td>
<td>$\infty$</td>
<td>$\times$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$V'$</td>
<td>1</td>
<td>(1, 3, 0)</td>
<td>0</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$S_1$</td>
<td>0</td>
<td>$\overline{(3, 1, 1/3)}$</td>
<td>$-1$</td>
<td>$\checkmark$</td>
<td>$\times$</td>
</tr>
<tr>
<td>$S_3$</td>
<td>0</td>
<td>$(3, 3, 1/3)$</td>
<td>3</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$U_1$</td>
<td>1</td>
<td>$(3, 1, 2/3)$</td>
<td>1</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
<tr>
<td>$U_3$</td>
<td>1</td>
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<td>$-3$</td>
<td>$\checkmark$</td>
<td>$\checkmark$</td>
</tr>
</tbody>
</table>

$$B(B \rightarrow K^*\nu\nu) \propto (C_T - C_S)$$

A clear winner: $U_1$  \[\rightarrow\]  $C_T = C_S$ (at threshold)

Linear combinations also possible (e.g. $S_1 + S_3$ or $Z' + V'$)  \[\rightarrow\]  tuning required
UV completion: $U_1 \sim (3,1,2/3)$

- Massive vectors point to UV dynamics at the TeV scale

  - Composite resonance of a new strong dynamics
  - Gauge boson of an extended gauge sector
UV completion: $U_1 \sim (3,1,2/3)$

- Massive vectors point to UV dynamics at the TeV scale

  
  composite resonance of a new strong dynamics

\[
G = \frac{SU(4) \times SO(5) \times U(1)_X}{SU(4) \times SO(5) \times U(1)_X}
\]

- pNGB Higgs + $U_1$ as composite state of $G$

  😊 conceptual link with the naturalness issue of EW scale

  😞 light LQ lowers the whole resonances’ spectrum (direct searches + EWPTs)

  😞 intrinsically non-calculable (divergent loop observables)

[Barbieri, Isidori, Pattori, Senia 1502.01560
Barbieri, Murphy, Senia 1611.0493
Buttazzo et al, 1706.07808
Barbieri,Tesi 1712.06844]
UV completion: $U_1 \sim (3,1,2/3)$

- An interesting option: minimal Pati-Salam (PS)

\[ G_{PS} = SU(4)_{PS} \times SU(2)_L \times SU(2)_R \]
\[ G_{PS}/G_{SM} = U_1 + Z' + W_R \]

👍 hinted by SM chiral structure + everything’s calculable

😢 $M_{U_1} \gtrsim 86$ TeV from $K_L^0, B^0, B_s \rightarrow \ell \ell'$ decays (L x R couplings)

\[ \mathcal{L}_{PS} \supset \frac{g_4}{\sqrt{2}} \left( \overline{d}_L^i \delta_{ij} \gamma_\mu e_j^i_L + \overline{d}_R^i \delta_{ij} \gamma_\mu e_j^i_R \right) U_1^\mu \]

\[ \beta_{L,R}^{L,R} = U_{d_{L,R}}^\dagger U_{e_{L,R}} \] (unitary matrices)

\[ \rightarrow \frac{g_4}{\sqrt{2}} \left( \overline{d}_L^i \beta_{ij}^L \gamma_\mu e_j^i_L + \overline{d}_R^i \beta_{ij}^R \gamma_\mu e_j^i_R \right) U_1^\mu \]

gauge boson of an extended gauge sector

[Kutuznetsov et al 1203.0196 + update from A. D. Smirnov 1801.02895]
UV completion: $U_1 \sim (3,1,2/3)$

- An interesting option: minimal Pati-Salam (PS)

\[ G_{PS} = SU(4)_{PS} \times SU(2)_L \times SU(2)_R \]

\[ G_{PS}/G_{SM} = U_1 + Z' + W_R \]

|- hinted by SM chiral structure + everything’s calculable

|- $M_{U_1} \gtrsim 86$ TeV from $K^0_L, B^0, B_s \to \ell \ell'$ decays (L x R couplings)

|- $Z'$ direct searches ($M_{U_1} \sim M_{Z'} \sim$ TeV + O(g_s) $Z'$ couplings to valence quarks)

|- neutrino masses also suggest $M_{U_1} \gg$ TeV ($y_{top} \sim y_{\nu_3}$-Dirac)

Minimal PS cannot explain B-anomalies
Beyond minimal PS

• We look for something like

\[
\begin{align*}
\beta^L & \sim \begin{pmatrix}
\epsilon & \epsilon & \epsilon \\
\epsilon & 0.01 & 0.2 \\
\epsilon & 0.05 & 1 \\
\end{pmatrix} \\
\beta^R & \sim \epsilon \\
\end{align*}
\]  
\( (\beta^t \beta \neq 1) \)}
Beyond minimal PS

• We look for something like

\[
\beta^L \sim \begin{pmatrix}
\epsilon & \epsilon & \epsilon \\
\epsilon & 0.01 & 0.2 \\
\epsilon & 0.05 & 1
\end{pmatrix} \quad \beta^R \sim \epsilon \quad (\beta^\dagger \beta \neq 1)
\]

1) non-minimal matter content (mixing with heavy fermions) [Calibbi, Crivellin, Li 1709.00692]

\[
\frac{g_A}{\sqrt{2}} \bar{D}^A \hat{\beta}_{AB} \gamma_\mu \mathcal{E}^B U^\mu_1 \quad \hat{\beta} = \begin{pmatrix}
\beta_{LL} & \beta_{LH} \\
\beta_{HL} & \beta_{HH}
\end{pmatrix} \quad \hat{\beta}^\dagger \hat{\beta} = 1 \quad \beta_{LL} \beta_{LL} \neq 1
\]

☆ Z’ direct searches

☆ neutrino masses
Beyond minimal PS

• We look for something like

\[
\beta^L \sim \begin{pmatrix}
\epsilon & \epsilon & \epsilon \\
\epsilon & 0.01 & 0.2 \\
\epsilon & 0.05 & 1
\end{pmatrix}
\]

\[
\beta^R \sim \epsilon
\]

\[
(\beta^L\beta^R) \neq 1
\]

1): non-minimal matter content (mixing with heavy fermions)  
[Calibbi, Crivellin, Li 1709.00692]

2): non-universal gauge interactions  
[Bordone, Cornella, Fuentes-Martin, Isidori 1712.01368]

\[
(422)^3 \sum_{i=1,2,3} \frac{g_i^4}{\sqrt{2}} Q^i \gamma^\mu L^i U^i_{\mu} \quad m_{U_1} \gg m_{U_2} \gg m_{U_3} \quad \beta^{LO} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}
\]

😊 flavour hierarchies

😢 neutrino masses  
[Greljo, Stefanek 1802.04274]
Beyond minimal PS

- We look for something like

\[
\begin{pmatrix}
\epsilon & \epsilon & \epsilon \\
\epsilon & 0.01 & 0.2 \\
\epsilon & 0.05 & 1
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\]

\[
\beta^L \sim (\epsilon \ 0.01 \ 0.2) \quad \beta^R \sim \epsilon \quad (\beta^\dagger \beta \neq 1)
\]

1): non-minimal matter content (mixing with heavy fermions) [Calibbi, Crivellin, Li 1709.00692]


3): non-minimal matter and gauge content (4321 model)

\[
G = SU(4) \times SU(3)' \times SU(2)_L \times U(1)' + \text{heavy fermions}
\]

[LDL, Greljo, Nardecchia 1708.08450, See also Diaz, Schmaltz, Zhong 1706.05033, for a similar constructions]
The ‘4321’ model

\[ SU(4) \times SU(3)' \times SU(2)_L \times U(1)' \]
The ‘4321’ model

\[ G_{4321}/G_{\text{SM}} = U + Z' + g' \]

\[ M_{g'} \simeq \sqrt{2} M_U \quad M_{Z'} \simeq \frac{1}{\sqrt{2}} M_U \]

Three TeV-scale massive vectors

\[ g_s = \frac{g_4 g_3}{\sqrt{g_4^2 + g_3^2}} \simeq g_3 \]

\[ g_Y = \frac{g_4 g_1}{\sqrt{g_4^2 + \frac{2}{3} g_1^2}} \simeq g_1 \]
The ‘4321’ model

\[ G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y \]

Matter content:

<table>
<thead>
<tr>
<th>Field</th>
<th>( SU(4) )</th>
<th>( SU(3)' )</th>
<th>( SU(2)_L )</th>
<th>( U(1)' )</th>
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<tr>
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<td>2</td>
<td>1/6</td>
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<tr>
<td>( u^R_R )</td>
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<td>3</td>
<td>1</td>
<td>2/3</td>
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<td>( d^R_R )</td>
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<td>−1/3</td>
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<td>2</td>
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<td>( \Omega_1 )</td>
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<td>1</td>
<td>1</td>
<td>−1/2</td>
</tr>
</tbody>
</table>

Would-be SM fields

Vector-like fermions (Q'+L')

mix after SSB

SSB
The ‘4321’ model

\[ G_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y \]

Field | \(SU(4)\) | \(SU(3)'\) | \(SU(2)_L\) | \(U(1)'\) \\
--- | --- | --- | --- | --- \\
\(q_L^i\) | 1 | 3 | 2 | 1/6 \\
\(u_R^i\) | 1 | 3 | 1 | 2/3 \\
\(d_R^i\) | 1 | 3 | 1 | 1/3 \\
\(e_L^i\) | 1 | 1 | 2 | -1/3 \\
\(\ell_L^i\) | 1 | 1 | 1 | -1/2 \\
\(\Psi_L^i\) | 4 | 1 | 2 | 0 \\
\(\Psi_R^i\) | 1 | 1 | 1 | 0 \\
\(H\) | 1 | 1 | 2 | 1/2 \\
\(\Omega_3\) | 1/4 | 3 | 1 | 1/6 \\
\(\Omega_1\) | 1/4 | 1 | 1 | -1/2 \\

LQ dominantly couples to 3rd generation LH fields
[can satisfy Zürich’s EFT criteria]
1. Introduction

The mixing among the left-handed SM-like and vector-like fermions is described by the leptoquark directly. In order to induce the required leptoquark interactions to SM fermions, they come in three copies of flavour. Being doublet field transforming as $G_{SU_3}$ gauge group the 4321 model and conclude. A thorough discussion of several more technical aspects of scale in order to escape direct detection. In Sect.

1. Large quark-lepton transitions in 3-2 sector [mainly driven by $R(D^*)$)]

2. Severe constraints from quark-quark transitions [$\Delta F = 2$, … ]

3. Severe constraints from lepton-lepton transitions [LFV, … ]

4. Absence of signals in direct searches @ high-pT
Flavour structure

- Pick-up a basis exploiting $U(3)^7$ symmetry of kinetic term

$$\mathcal{L}_{\text{SM-like}} = -\bar{q}_L' Y_d H d'_R - \bar{q}_L' V^\dagger Y_u \tilde{H} u'_R - \tilde{\ell}_L' \tilde{Y}_e H e'_R$$

$$\mathcal{L}_{\text{mix}} = -\bar{q}_L \lambda_q \Omega_3^T \Psi_R - \tilde{\ell}_L' \lambda_\ell \Omega_1^T \Psi_R - \bar{\Psi}_L \hat{M} \Psi_R$$

<table>
<thead>
<tr>
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<th>$SU(2)_L$</th>
<th>$U(1)'$</th>
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<td>$\Omega_1$</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>-1/2</td>
</tr>
</tbody>
</table>

$$\Psi = \begin{pmatrix} Q' \\ L' \end{pmatrix}$$
Flavour structure

- $\mathcal{L}_{\text{mix}} \rightarrow 0$

$$\mathcal{L}_{\text{SM-like}} = -\bar{q}_L \hat{Y}_d H d'_R - \bar{q}_L V^\dagger \hat{Y}_u H u'_R - \bar{\ell}_L \hat{Y}_e H e'_R$$

- A well-known story:
  - $Y_u \rightarrow 0$: $U(1)_d \times U(1)_s \times U(1)_b$
  - $Y_d \rightarrow 0$: $U(1)_u \times U(1)_c \times U(1)_t$
Flavour structure

- $\mathcal{L}_{\text{mix}} \rightarrow 0$

\[ \mathcal{L}_{\text{SM-like}} = -\bar{q}'_L \hat{Y}_d H d'_R - \bar{q}'_L V^\dagger \hat{Y}_u \tilde{H} u'_R - \bar{\ell}'_L \hat{Y}_e H e'_R \]

- A well-known story:
  - $Y_u \rightarrow 0$: $U(1)_d \times U(1)_s \times U(1)_b$
  - $Y_d \rightarrow 0$: $U(1)_u \times U(1)_c \times U(1)_t$

\[ \underbrace{SU(2)_L}_{U(1)_{d+u} \times U(1)_{s+c} \times U(1)_{b+t}} \rightarrow U(1)_B \]

- Collective breaking in the SM ensures:
  1. No FCNC in either up or down sector [forbidden by the two $U(1)^3$ in isolation]
  2. FCCC from up/down misalignment [due to CKM $\neq 1$]
Flavour structure

- We assume: 
  \[ \mathcal{L}_{\text{SM-like}} = -\bar{q}_L' \hat{Y}_d H d_R' - \bar{q}_L' V^\dagger \hat{Y}_u \tilde{H} u_R' - \bar{\ell}_L' \hat{Y}_e H e_R' \]
  \[ \mathcal{L}_{\text{mix}} = -\bar{q}_L' \lambda_q \Omega_3^T \Psi_R - \bar{\ell}_L' \lambda_\ell \Omega_3^T \Psi_R - \bar{\Psi}_L \hat{M} \Psi_R \]

  \[ \lambda_q = \text{diag}(\lambda_{12}^q, \lambda_{12}^q, \lambda_3^q) \]

  \[ \lambda_\ell = \text{diag}(\lambda_1^\ell, \lambda_2^\ell, \lambda_3^\ell) \quad W = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{LQ} & \sin \theta_{LQ} \\ 0 & -\sin \theta_{LQ} & \cos \theta_{LQ} \end{pmatrix} \quad \hat{M} \propto \mathbb{1} \]
Flavour structure

- We assume:
  \[ \mathcal{L}_{\text{SM-like}} = -q'_L \hat{Y}_d H d'_R - q'_L V^\dagger \hat{Y}_u \hat{H} u'_R - \ell'_L \hat{Y}_e H e'_R \]
  \[ \mathcal{L}_{\text{mix}} = -q'_L \lambda_q \Omega^T_3 \Psi_R - \ell'_L \lambda_\ell \Omega^T_1 \Psi_R - \overline{\Psi}_L \hat{M} \Psi_R \]

  \[ \lambda_q = \text{diag}(\lambda^q_{12}, \lambda^q_{12}, \lambda^q_3) \]
  \[ \lambda_\ell = \text{diag}(\lambda^\ell_1, \lambda^\ell_2, \lambda^\ell_3) \]
  \[ W = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{LQ} & \sin \theta_{LQ} \\ 0 & -\sin \theta_{LQ} & \cos \theta_{LQ} \end{pmatrix} \]
  \[ \hat{M} \propto 1 \]

- \( \lambda_\ell \to 0 \)

  \[ G_Q = U(2)_{q'} + \Psi \times U(1)_{q''} + \Psi_3 \quad \text{[promoting approximate } U(2)_{q'} \text{ of SM to NP]} \]

1. No tree-level FCNC in the down sector (\( \lambda_q \) and \( Y_d \) diagonal in the same basis)
2. CKM-induced tree-level FCNC in the up sector (D-mixing) protected by \( U(2)_{q'} \)
Flavour structure

**We assume:**

\[
\mathcal{L}_{\text{SM-like}} = -\bar{q}_L' \hat{Y}_d \, H \, d'_R - \bar{q}_L' \, V^\dagger \hat{Y}_u \, \hat{H} u'_R - \bar{\ell}_L' \, \hat{Y}_e \, H e'_R
\]

\[
\mathcal{L}_{\text{mix}} = -\bar{q}_L' \lambda_q \Omega_3^T \Psi_R - \bar{\ell}_L' \lambda_\ell \Omega_1^T \Psi_R - \bar{\Psi}_L \hat{M} \Psi_R
\]

\[
\lambda_q = \text{diag} (\lambda_{q1}^2, \lambda_{q1}^2, \lambda_3^q)
\]

\[
\lambda_\ell = \text{diag} (\lambda_1^\ell, \lambda_2^\ell, \lambda_3^\ell) \, W \quad W = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{LQ} & \sin \theta_{LQ} \\ 0 & -\sin \theta_{LQ} & \cos \theta_{LQ} \end{pmatrix} \quad \hat{M} \propto 1
\]

**\( \lambda_q \rightarrow 0 \)**

\[
G_L = U(1)_{\ell_1'} \times \bar{\Psi}_1 \times U(1)_{\ell_2'} \times \bar{\Psi}_2 \times U(1)_{\ell_3'} \times \bar{\Psi}_3 \quad [\bar{\Psi} = W \Psi]
\]

1. No tree-level FCNC in the lepton sector (\( \lambda_\ell \) and \( Y_e \) diagonal in the same basis)

2. \( W \) is unphysical
Flavour structure

- We assume:

\[ \mathcal{L}_{\text{SM-like}} = -\bar{q}'_L \hat{Y}_d H d'_R - \bar{q}'_L V^\dagger \hat{Y}_u \hat{H} u'_R - \bar{l}'_L \hat{Y}_e H e'_R \]

\[ \mathcal{L}_{\text{mix}} = -\bar{q}'_L \lambda_q \Omega^T_3 \Psi_R - \bar{l}'_L \lambda_\ell \Omega^T_1 \Psi_R - \overline{\Psi}_L \hat{M} \Psi_R \]

\[ \lambda_q = \text{diag} (\lambda_{12}^q, \lambda_{12}^q, \lambda_3^q) \]

\[ \lambda_\ell = \text{diag} (\lambda_1^\ell, \lambda_2^\ell, \lambda_3^\ell) \]

\[ W = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta_{LQ} & \sin \theta_{LQ} \\ 0 & -\sin \theta_{LQ} & \cos \theta_{LQ} \end{pmatrix} \]

\[ \hat{M} \propto 1 \]

- Collective breaking:

\[ \mathcal{G}_Q \cap \mathcal{G}_L \xrightarrow{SU(4)+W} U(1)_{q'_1+e'_1+\Psi_1} \times U(1)_{q'_1+e'_1+\Psi_1} \]

1. \( \lambda_1^\ell = 0 \):

\[ U(1)_{q'_1+e'_1+\Psi_1} \rightarrow U(1)_{q'_1+\Psi_1} \times U(1)_{e'_1+\Psi_1} \] [no FV involving down and electrons]

2. Large effects in 3-2 lepto-quark transitions via \( W \):

\[ i \overline{\Psi}_L \gamma^\mu D_\mu \Psi_L \supset \frac{g_4}{\sqrt{2}} U_\mu \overline{Q}_L \gamma^\mu W L_L \]
An suggestive analogy*

<table>
<thead>
<tr>
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<th>4321</th>
</tr>
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<tbody>
<tr>
<td>(\theta_C)</td>
<td>(\theta_{LQ})</td>
</tr>
<tr>
<td>(V)</td>
<td>(W)</td>
</tr>
<tr>
<td>(W^\mu)</td>
<td>(U^\mu)</td>
</tr>
<tr>
<td>(q_L = \begin{pmatrix} u_L \ V d_L \end{pmatrix})</td>
<td>(\Psi_L = \begin{pmatrix} Q_L \ W L_L \end{pmatrix})</td>
</tr>
<tr>
<td>(Y_u, Y_d)</td>
<td>(\lambda_q, \lambda_\ell)</td>
</tr>
<tr>
<td>(SU(2)_L)</td>
<td>(SU(4))</td>
</tr>
<tr>
<td>(U(1)_u \times U(1)_c \times U(1)_t)</td>
<td>(U(2)<em>{q' + \Psi} \times U(1)</em>{q'_3 + \Psi_3})</td>
</tr>
<tr>
<td>(U(1)_d \times U(1)_s \times U(1)_b)</td>
<td>(U(1)_{\ell'<em>1 + \Psi_1} \times U(1)</em>{\ell'<em>2 + \Psi_2} \times U(1)</em>{\ell'_3 + \bar{\Psi}_3})</td>
</tr>
<tr>
<td>(U(1)_B)</td>
<td>(U(1)_{q'_1 + \ell'<em>1 + \Psi_1} \times U(1)</em>{q' + \ell' + \Psi})</td>
</tr>
<tr>
<td>(u \rightarrow d) tree level</td>
<td>(Q \rightarrow L) tree level</td>
</tr>
<tr>
<td>(u_i \rightarrow u_j) loop level</td>
<td>(Q_i \rightarrow Q_j) loop level</td>
</tr>
<tr>
<td>(d_i \rightarrow d_j) loop level</td>
<td>(L_i \rightarrow L_j) loop level</td>
</tr>
</tbody>
</table>

* symmetries in 321 **accidental**, in 4321 **imposed** (still, helpful for understanding pheno)
Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector

\[ \mathcal{L}_U \supset \frac{g_4}{\sqrt{2}} \beta_{ij} \bar{q}_L^i \gamma^\mu \ell_L^j U_\mu \]

\[ \beta = \begin{pmatrix} 0 & 0 & 0 \\ 0 & c_{\theta_{LQ}} s_{12} s_{\mu_L} & s_{\theta_{LQ}} s_{12} s_{\tau_L} \\ 0 & -s_{\theta_{LQ}} s_{b_L} s_{\mu_L} & c_{\theta_{LQ}} s_{b_L} s_{\tau_L} \end{pmatrix} \]

\[ \Delta R_{D^{(*)}} = \frac{g_4^2 v^2}{2 M_U^2} \beta_{b\tau} \left( \beta_{b\tau} - \beta_{s\tau} \frac{V_{tb}^*}{V_{ts}^*} \right) \]
Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector

\[ \mathcal{L}_U \supset \frac{g_4}{\sqrt{2}} \beta_{ij} \bar{q}_L^i \gamma^\mu \ell_L^j U_\mu \]

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\[ \Delta R_{D^{(*)}} = \frac{g_4^2 v^2}{2 M_U^2} \beta_{b\tau} \left( \beta_{b\tau} - \beta_{s\tau} \frac{V_{tb}^*}{V_{ts}^*} \right) \]

\[ \beta_{s\tau} > V_{ts} \sim 0.04 \quad \text{allows to raise the LQ mass scale} \]

we need: \( \theta_{LQ} \sim \pi/4 \quad \theta_{\tau L} \sim \pi/2 \quad \theta_{bL} \sim \pi/2 \quad \theta_{12} \sim \mathcal{O}(1) \)
Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector

2. Tree-level FCNC involving down quarks and leptons are absent

3. Tree-level FCNC involving up quarks are U(2) protected

\[ C_1^D \propto (V_{cb}V_{ub}^*)^2 \sim 10^{-8} \]
1. Large quark-lepton transitions in 3-2 sector

2. Tree-level FCNC involving down quarks and leptons are absent

3. Tree-level FCNC involving up quarks are $U(2)$ protected

4. FCNC @ 1-loop under control

\[
\mathcal{H}_{\text{eff}}^{\text{NP}} = -\frac{g_4^4}{128\pi^2 m_U^2} \left( \bar{b} L \gamma^\mu s_L \right) \left( \bar{b} L \gamma_\mu s_L \right) \sum_{\alpha, \beta} \lambda_\alpha \lambda_\beta F(x_\alpha, x_\beta)
\]

\[
\lambda_\alpha = (\mathcal{V}^\dagger)_{ab}^* \mathcal{V}_{a\alpha} \quad x_\alpha = \frac{m_\alpha^2}{M_U^2}
\]

\[\sum_{\alpha} \lambda_\alpha = 0 \quad \text{ensures cancellation of quadratic divergencies + GIM-like suppression}\]

\[F(x_\alpha, x_\beta) \simeq x_\alpha + x_\beta + \ldots \quad \text{light lepton partners welcomed!}\]
Key phenomenological features
Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector
2. Tree-level FCNC involving down quarks and leptons are absent
3. Tree-level FCNC involving up quarks are U(2) protected
4. FCNC @ 1-loop under control
5. Suppressed $Z'$ and $g'$ couplings to light generations

\[ \mathcal{L}_L = \frac{g_4}{\sqrt{2}} Q'_L \gamma^\mu L'_L U^a_\mu + \text{h.c.} \]
\[ + g_s \left( \frac{g_4}{g_3} Q'_L \gamma^\mu T^a Q'_L - \frac{g_3}{g_4} q'_L \gamma^\mu T^a q'_L \right) g^a_\mu \]
\[ + \frac{1}{6} \sqrt{\frac{3}{2}} g_Y \left( \frac{g_4}{g_1} Q'_L \gamma^\mu Q'_L - \frac{2}{3} \frac{g_1}{g_4} q'_L \gamma^\mu q'_L \right) Z'_\mu \]
\[ - \frac{1}{2} \sqrt{\frac{3}{2}} g_Y \left( \frac{g_4}{g_1} L'_L \gamma^\mu L'_L - \frac{2}{3} \frac{g_1}{g_4} \ell'_L \gamma^\mu \ell'_L \right) Z'_\mu \]
Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector
2. Tree-level FCNC involving down quarks and leptons are absent
3. Tree-level FCNC involving up quarks are $U(2)$ protected
4. FCNC @ 1-loop under control
5. Suppressed $Z'$ and $g'$ couplings to light generations

\[ \mathcal{L}_L = \frac{g_4}{\sqrt{2}} Q_L' \gamma^\mu L_L' U_\mu + \text{h.c.} \]
\[ + g_s \left( \frac{g_4}{g_3} Q_L' \gamma^\mu T^a Q_L' - \frac{g_3}{g_4} q_L' \gamma^\mu T^a q_L' \right) g_\mu^a \]
\[ + \frac{1}{6} \sqrt{\frac{3}{2}} g_Y \left( \frac{g_4}{g_1} Q_L' \gamma^\mu Q_L' - \frac{2}{3} \frac{g_1}{g_4} q_L' \gamma^\mu q_L' \right) Z_\mu' \]
\[ - \frac{1}{2} \sqrt{\frac{3}{2}} g_Y \left( \frac{g_4}{g_1} \ell_L' \gamma^\mu \ell_L' - \frac{2}{3} \frac{g_1}{g_4} \ell_L' \gamma^\mu \ell_L' \right) Z_\mu' \]

requires the phenomenological limit
\[ g_4 \gg g_3 \approx g_s \gg g_1 \approx g_Y \]
Key phenomenological features

1. Large quark-lepton transitions in 3-2 sector

2. Tree-level FCNC involving down quarks and leptons are absent

3. Tree-level FCNC involving up quarks are U(2) protected

4. FCNC @ 1-loop under control

5. Suppressed $Z'$ and $g'$ couplings to light generations

6. B and L accidental global symmetries as in the SM ($m_\nu = 0$)

\[ O_5 = \frac{1}{\Lambda_L} \ell' \ell' H H \quad \Lambda_L \gg v \]
High-\(p_T\) searches

- LQ pair production via QCD

- 3rd generation final states (fixed by anomaly and \(SU(2)_L\) invariance)

\[
\begin{align*}
U & \rightarrow b\tau^+, \quad \text{BR} = 50\% \\
U & \rightarrow t\bar{\nu}, \quad \text{BR} = 50\%
\end{align*}
\]

\[m_U \gtrsim 1.5 \text{ TeV}\]

LQ mass sets the overall scale: 
\[M_{g'} \simeq \sqrt{2} M_U \quad M_{Z'} \simeq \frac{1}{\sqrt{2}} M_U\]

[CMS search for spin-0, 1703.03995 recast for spin-1 1706.01868 (see also 1706.05033) + Moriond EW update]
High-$p_T$ searches

- LQ pair production via QCD

- $Z'$ Drell-Yan production naturally suppressed

\[
\sin \theta_{Z'} = \sqrt{\frac{3}{2}} \frac{g_Y}{g_4} \approx 0.09 \quad \text{requires} \quad g_4 \gtrsim 3
\]

- $g'$ resonant di-jet searches [ATLAS, 1703.09127]

\[
\sin \theta_{g'} = \frac{g_s}{g_4} \approx 0.3 \quad \text{2 TeV coloron naively excluded}
\]
High-p$_T$ searches

[LDL, Fuentes-Martin, Greljo, Nardecchia, Renner 1808.00942]

Figure 11: (Top panel) Contributions to the $pp \rightarrow jj$ (left panel) and $pp \rightarrow tt$ (right panel) invariant mass spectrum for two representative benchmark points. (Bottom panel) Coloron exclusion limits in the mass-total width plane for $jj$ and $tt$ for several representative $s_{q2}$ benchmarks.

The model. Here we provide a catalog of promising topologies and estimate their potential future impact.

5.3.1 Coloron searches in $tt$ and $bb$ final states

The dominant production mechanism of the colour octet $g_0$ in $pp$ collisions is resonant production from a quark-antiquark pair, $qq \rightarrow g_0$. There is no tree-level coupling between $g_0$ and a $gg$ pair, see App. A.8. Due to the flavour structure of the model, the couplings to light quarks are suppressed, however the PDF enhancement of valence quarks relative to third generation quarks in the proton ensures that this channel is nevertheless dominant. The interesting regimes of the model are when the width is rather large (but still calculable) or the resonance is narrow but rather heavy.

Existing analyses which are most sensitive to the coloron are an ATLAS $tt$ invariant mass measurement \cite{106}, an ATLAS dijet resonance search \cite{107}, and an ATLAS dijet resonance search.
Conclusions

1. We will know much more by ~ 2020 (LHCb + Belle II)

2. Early speculations point to TeV-scale vector leptoquark (R(D)+R(K) explanation)

   who ordered that?

3. In the meantime, lesson from UV complete models

   unexpected experimental signatures (coloron, vector-like leptons, …) + playground to compute correlations
Backup slides
In the following, we review some well-known frameworks: In order to create a link between the fermions of the third generation. For example, when considering the channel related to the ones. This implies that a stronger unitary bound can be derived from 2 operators involving fermions of the third family are enhanced compared to flavour violating for FCNC. In models with motivated flavour structures, it is natural to expect sizable electric transitions involving the third and second generation, respectively

Anomaly $\mathcal{O}$ $|V_{cb}|$ $|V_{ts}|$ $\Lambda_A[\text{TeV}]$ $\Lambda_D[\text{TeV}]$ $\Lambda_U[\text{TeV}]$ $M_\ast[\text{TeV}]$ $\Lambda_D[\text{TeV}]$

| $b \rightarrow c\tau\bar{\nu}$ | $Q_{23}L_{33}$ | 1 | 1 | 3.4 | 3.4 | 9.2 | 43 |
| $b \rightarrow c\tau\bar{\nu}$ | $Q_{33}L_{33}$ | $|V_{cb}|$ | 1 | 3.4 | 0.7 | 1.9 | 8.7 |
| $b \rightarrow s\mu\bar{\nu}$ | $Q_{22}L_{22}$ | 1 | 1 | 31 | 31 | 84 | 390 |
| $b \rightarrow s\mu\bar{\nu}$ | $Q_{33}L_{22}$ | $|V_{ts}|$ | 1 | 31 | 6.2 | 17 | 78 |
| $b \rightarrow s\mu\bar{\nu}$ | $Q_{33}L_{33}$ | $|V_{ts}|$ | $|m_\mu/m_\tau|$ | 31 | 1.5 | 4.1 | 19 |
| $b \rightarrow s\mu\bar{\nu}$ | $Q_{33}L_{33}$ | $|V_{ts}|$ | $(m_\mu/m_\tau)^2$ | 31 | 0.4 | 1.0 | 4.7 |

A tale of scales

[LDL, Nardecchia 1706.01868]

• “Fermi constant” of the process $[\text{SU}(3)_C \times U(1)_{\text{EM}}$ invariant EFT]

$$\mathcal{L}_{\text{eff}} \supset -\frac{1}{\Lambda_{RD}^2} 2\bar{c}_L \gamma_\mu b_L \bar{\tau}_L \gamma^\mu \nu_L + \frac{1}{\Lambda_{RK}^2} \bar{s}_L \gamma_\mu b_L \bar{\mu}_L \gamma^\mu \mu_L$$

- fixed by anomaly
A tale of scales

| Anomaly | $O$ | $F_{S_Q}$ | $F_{S_L}$ | $\Lambda_A$ [TeV] | $|\Lambda_O| / [TeV]$ | $\Lambda_U$ [TeV] | $M_*$ [TeV] |
|---------|-----|-------------|-------------|-----------------|----------------|----------------|----------|
| $b \rightarrow c\tau\bar{\nu}$ | $Q_{23}L_{33}$ | 1 | 1 | 3.4 | 3.4 | 9.2 | 43 |
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[LDL, Nardecchia 1706.01868]

- Scale of the SMEFT operator $[SU(3)_C \times SU(2)_L \times U(1)_{EM}$ invariant EFT]

$$\mathcal{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda_{Q ij L_{kl}}^2} \left( \bar{Q}_i \gamma^\mu \sigma^A Q_j \right) \left( \bar{L}_k \gamma^\mu \sigma^A L_l \right)$$

- can be effectively reduced by flavour structure, e.g.

$$Q^i = \left( \left(V_{\text{CKM}}^T u_L\right)^i \right) \quad \bar{Q}_3 Q_3 \rightarrow V_{cb} \bar{L}_L b_L \quad \Lambda_{Q_{33}L_{33}} / \sqrt{|V_{cb}|} = \Lambda_{R_{D(*)}}$$
This motivates an interesting interplay of the flavour anomalies with direct searches, which is the values of the four di

As we will discuss in detail in Sect.

In order to create a link between the di

In models with motivated flavour structures, it is natural to expect sizable e

transitions involving the third and second generation, respectively

The MFV hypothesis \([\text{FS}^a]\) states that the strength of new physics e

Anomaly

<table>
<thead>
<tr>
<th>Anomaly</th>
<th>(\mathcal{O})</th>
<th>(\text{FS}_Q)</th>
<th>(\text{FS}_L)</th>
<th>(\Lambda_A [\text{TeV}])</th>
<th>(\Lambda_D [\text{TeV}])</th>
<th>(\Lambda_U [\text{TeV}])</th>
<th>(M_* [\text{TeV}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>(b \rightarrow c \tau \bar{\nu})</td>
<td>(Q_{23} L_{33})</td>
<td>1</td>
<td>1</td>
<td>3.4</td>
<td>3.4</td>
<td>9.2</td>
<td>43</td>
</tr>
<tr>
<td>(b \rightarrow c \tau \bar{\nu})</td>
<td>(Q_{33} L_{33})</td>
<td>(</td>
<td>V_{cb}</td>
<td>)</td>
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<td>(b \rightarrow s \mu \bar{\nu})</td>
<td>(Q_{23} L_{22})</td>
<td>1</td>
<td>1</td>
<td>31</td>
<td>31</td>
<td>84</td>
<td>390</td>
</tr>
<tr>
<td>(b \rightarrow s \mu \bar{\nu})</td>
<td>(Q_{33} L_{22})</td>
<td>(</td>
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<td>)</td>
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<td>)</td>
<td>(\frac{2m_{\mu}}{m_{\tau}})</td>
<td>31</td>
<td>1.5</td>
</tr>
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<td>(b \rightarrow s \mu \bar{\nu})</td>
<td>(Q_{33} L_{33})</td>
<td>(</td>
<td>V_{ts}</td>
<td>)</td>
<td>(\frac{1}{2}(m_{\mu}/m_{\tau})^2)</td>
<td>31</td>
<td>0.4</td>
</tr>
</tbody>
</table>

A tale of scales

[LDL, Nardecchia 1706.01868]

- Scale of unitarity violation (\(\sqrt{s} = \Lambda_U\) saturates pert. unitarity criterium)

\[
\Lambda_U = \sqrt[3]{\frac{4\pi}{\Lambda_{Q_{ij} L_{kl}}}}
\]

- strongest bound from leading op. (effectively rescale by \(\sqrt{\text{FS}_Q \times \text{FS}_L}\) )

- correlation of the partial wave in SM-group space strengthens the bound by \(~2\)
A tale of scales

| Anomaly | $O$ | $FS_Q$ | $FS_L$ | $\Lambda_A$ [TeV] | $|\Lambda_O|$ [TeV] | $\Lambda_U$ [TeV] | $M_*$ [TeV] |
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[LDL, Nardecchia 1706.01868]

- NDA mass scale in the strongly-coupled regime $|g_*| = 4\pi$ [Manohar, Georgi NPB234 (1984)]

$$\frac{1}{|\Lambda_O|} = \frac{4\pi}{M_*}$$

- unitarity bound sets in earlier!

$$[\mathcal{L}] = [\hbar]/L^4$$

$$[M_*] = L^{-1}$$

$$[g_*] = [\hbar^{-1}]$$

$$\mathcal{L}_{\text{EFT}} = \frac{M_*^4}{g_*^2} \mathcal{L}_{\text{tree}} \left[ \frac{\partial}{M_*}, \frac{g_* \Phi}{M_*}, \frac{g_* \Psi}{M_*^{3/2}} \right] + \frac{g_*^2 \hbar}{16\pi^2} \frac{M_*^4}{g_*^2} \mathcal{L}_{\text{1-loop}} \left[ \frac{\partial}{M_*}, \frac{g_* \Phi}{M_*}, \frac{g_* \Psi}{M_*^{3/2}} \right] + \cdots$$
A tale of scales

| Anomaly | $\mathcal{O}$ | $FS_Q$ | $FS_L$ | $\Lambda_A$ [TeV] | $|\Lambda_0|$ [TeV] | $\Lambda_U$ [TeV] | $M_*$ [TeV] |
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| $b \to s\mu\bar{\nu}$ | $Q_{33}L_{33}$ | $|V_{ts}|$ | $*(m_\mu/m_\tau)^2$ | 31 | 0.4 | 1.0 | 4.7 |

[LDL, Nardecchia 1706.01868]

- Most conservative unitarity bounds (no flavour enhancement)

\[ \sqrt{s_{RD}} < 9.2 \text{ TeV} \quad \sqrt{s_{RK}} < 84 \text{ TeV} \]

no-loose theorem for HL/HE-LHC?
- 4 parameters fit: $C_S, C_T, \lambda_{bs}^q, \lambda_{\mu\mu}^\ell$ ($\lambda_{bb}^q = \lambda_{\tau\tau}^\ell = 1$) [Zürich’s guide for combined explanations, 1706.07808]

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} - \frac{1}{v^2} \lambda_{ij}^q \lambda_{\alpha\beta}^\ell \left[ C_T (\bar{Q}^i_L \gamma_{\mu} \sigma^a Q^j_L)(\bar{L}^\alpha_L \gamma_{\mu} \sigma^a L^\beta_L) + C_S (\bar{Q}^i_L \gamma_{\mu} Q^j_L)(\bar{L}^\alpha_L \gamma_{\mu} L^\beta_L) \right]$$

<table>
<thead>
<tr>
<th>Observable</th>
<th>Experimental bound</th>
<th>Linearised expression</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{D(\ast)}^\tau\ell$</td>
<td>$1.237 \pm 0.053$</td>
<td>$1 + 2C_T (1 - \lambda_{sb}^q V_{tb}^* / V_{ts}^*) (1 - \lambda_{\mu\mu}^\ell / 2)$</td>
</tr>
<tr>
<td>$\Delta C_9^{\mu} = -\Delta C_{10}^{\mu}$</td>
<td>$-0.61 \pm 0.12$ [36]</td>
<td>$- \frac{\pi}{\alpha_{\text{em}}} V_{tb} V_{ts}^{\ast} \lambda_{\mu\mu}^\ell \lambda_{sb}^q (C_T + C_S)$</td>
</tr>
<tr>
<td>$R_{b \to c}^{\mu\epsilon}$</td>
<td>$0.00 \pm 0.02$</td>
<td>$2C_T (1 - \lambda_{sb}^q V_{tb}^* / V_{ts}^*) \lambda_{\mu\mu}^\ell$</td>
</tr>
<tr>
<td>$B_{K(\ast)\nu\bar{\nu}}$</td>
<td>$0.0 \pm 2.6$</td>
<td>$1 + \frac{2}{3} \frac{\pi}{\alpha_{\text{em}} V_{tb} V_{ts}^{\ast} C_{\mu\mu}^{\text{SM}}} (C_T - C_S) \lambda_{sb}^q (1 + \lambda_{\mu\mu}^\ell) - 0.033 C_T - 0.043 C_S$</td>
</tr>
<tr>
<td>$\delta g_{\tau L}^Z$</td>
<td>$-0.0002 \pm 0.0006$</td>
<td>$- 0.033 C_T - 0.043 C_S$</td>
</tr>
<tr>
<td>$\delta g_{\nu_{\tau}}^Z$</td>
<td>$-0.0040 \pm 0.0021$</td>
<td>$1 - 0.084 C_T$</td>
</tr>
<tr>
<td>$</td>
<td>g_{\tau}^W / g_{\ell}^W</td>
<td>$</td>
</tr>
<tr>
<td>$B(\tau \to 3\mu)$</td>
<td>$(0.0 \pm 0.6) \times 10^{-8}$</td>
<td></td>
</tr>
</tbody>
</table>
- 4 parameters fit: $C_S, C_T, \lambda_{bs}^q, \lambda_{\mu\mu}^\ell$ ($\lambda_{bb}^q = \lambda_{TT}^\ell = 1$)

![Plots showing the fit to the semi-leptonic and purely leptonic (radiatively generated) observables in Table 1, in the framework of the triplet and singlet $V_A$ operators (see Eq. (1)), imposing $|q_{sb}| < 5 |V_{cb}|$. In green, yellow, and gray, we show the $2 \sigma, 2.3 \sigma (1)$, $6.2 \sigma (2)$, and $11.8 \sigma (3)$ regions, respectively, after marginalising over all other parameters. In the bottom-right plot we fix $C_T = C_S$ and perform a fit with and without the radiatively induced observables.]