Scalar Leptoquarks at Low and High Energies

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Outline

- Motivation;
- Low-energy constraints
- LQ at high energies;
- Leptoquarks and GUT;
- Leptoquarks at LHC;
- Summary.

Based on
D. Bečirević, SF, N. Košnik, Phys.Rev D 92 (2015) 014016;
I.Doršner, S.F.,J.F.Kamenik, N.Košnik, I. Nisandžić, JHEP 1506 (2015) 108;
I.Doršner, S.F and A. Greljo, JHEP 1410 (2014) 154;
I.Doršner, S.F., N.Košnik, I. Nisandžić, JHEP 1311 (2013) 084;
S.F. J.F. Kamenik and Nisandžić, Phys.Rev. D85 (2012) 094025;
I.Doršner, S.F., N.Košnik, Phys.Rev. D86 (2012) 015013;
We need Beyond Standard Model Physics;

Many proposals and searches of new non-SM particles at LHC;

Leptoquarks are present in GUT theories;

Scalar LQ might modify mass matrices;

Intensive searches of LQ at LHC

Explanation of anomalous events at low energies by LQ
Why Beyond SM Physics?

1) Naturalness

Comment: all others SM particles get logarithmic corrections!

2) Neutrinos have masses: does it come from BSM?

3) What is the nature of dark matter?

4) We need more CP violation to understand baryon – antibaryon asymmetry in the universe!
**ATLAS Exotics Searches** - 95% CL Exclusion

**Status:** July 2015

\[
\int \mathcal{L} dt = (4.7 - 20.3) \text{ fb}^{-1}
\]

\[\sqrt{s} = 7, 8 \text{ TeV}\]

| Model | \(\ell, \gamma\) | Jets | \(E_{\text{T}}^{\text{miss}}\) | \(\int \mathcal{L} dt [\text{fb}^{-1}]\) | Limit | Reference |
|-------|----------------|------|----------------|-----------------|-------|-----------|
| ADD \(g_{\ell\ell} + g/q\) | \(-\) | \(\geq 1\) | Yes | 20.3 | \(M_{\ell}\) | 5.25 TeV | \(n = 2\) | 1502.01518 |
| ADD non-resonant \(\ell\ell\) | \(2e, \mu\) | \(-\) | \(-\) | 20.3 | \(M_{\ell}\) | 4.7 TeV | \(n = 7\) | 1407.2410 |
| ADD QBH | \(e, \mu\) | \(1\) | \(-\) | 20.3 | \(M_{\ell}\) | 5.2 TeV | \(n = 6\) | 1311.2006 |
| ADD QBH | \(-\) | \(2\) | \(-\) | 20.3 | \(M_{\ell}\) | 5.82 TeV | \(n = 6\) | 1407.1736 |
| ADD BH high \(N_{\ell\ell}\) | \(2\mu\) (SS) | \(-\) | \(-\) | 20.3 | \(M_{\ell}\) | 4.7 TeV | \(n = 6\) | 1308.4675 |
| ADD BH high \(S_{\ell\ell}\) | \(\geq 1\) | \(\geq 2\) | \(-\) | 20.3 | \(M_{\ell}\) | 5.8 TeV | \(n = 6\) | 1405.2425 |
| ADD BH high \(S_{\ell\ell}\) | \(\geq 2\) | \(-\) | \(-\) | 20.3 | \(M_{\ell}\) | 5.8 TeV | \(n = 6\) | 1503.08988 |
| RS | \(2\mu\) | \(-\) | \(-\) | 20.3 | \(M_{\ell}\) | 2.68 TeV | \(k/M_{\ell} = 0.1\) | 1405.4123 |
| RS | \(2\gamma\) | \(-\) | \(-\) | 20.3 | \(M_{\ell}\) | 2.66 TeV | \(k/M_{\ell} = 1.0\) | 1504.05511 |
| Bulk RS \(g_{\ell\ell} \rightarrow ZZ \rightarrow q\bar{q}W\) | \(2\mu\) | \(1\) | \(-\) | 20.3 | \(M_{\ell}\) | 740 GeV | \(k/M_{\ell} = 1.0\) | 1504.16190 |
| Bulk RS \(g_{\ell\ell} \rightarrow WW \rightarrow q\bar{q}\gamma\) | \(1\) | \(1\) | \(-\) | 20.3 | \(M_{\ell}\) | 760 GeV | \(k/M_{\ell} = 1.0\) | 1503.04677 |
| Bulk RS \(g_{\ell\ell} \rightarrow HH \rightarrow b\bar{b}b\bar{b}\) | \(4\beta\) | \(-\) | \(-\) | 19.5 | \(M_{\ell}\) | 500-720 GeV | BR = 0.925 | 1505.07018 |
| Bulk RS \(g_{\ell\ell} \rightarrow \ell\ell\) | \(1\) | \(1\) | \(-\) | 20.3 | \(M_{\ell}\) | 2.2 TeV | \(|C_{\text{LL}}| = 1\) | 1504.06405 |
| 2UED / RPP | \(2\) | \(\geq 1\) | \(-\) | 20.3 | \(M_{\ell}\) | 960 GeV | \(|C_{\text{LL}}| = 1\) | 1405.4123 |
| SSM \(Z \rightarrow \ell\ell\) | \(2\mu\) | \(-\) | \(-\) | 20.3 | \(Z\) mass | 2.9 TeV | at 90% CL for \(M_{\ell} < 100\) GeV | 1502.07177 |
| SSM \(Z \rightarrow \ell\ell\) | \(2\tau\) | \(-\) | \(-\) | 19.5 | \(Z\) mass | 2.02 TeV | at 90% CL for \(M_{\ell} < 100\) GeV | 1407.7494 |
| SSM \(W \rightarrow \ell\nu\) | \(1\) | \(-\) | \(-\) | 20.3 | \(W\) mass | 3.24 TeV | Preliminary | 1406.4456 |
| EGM \(W \rightarrow W \rightarrow \ell\nu\) | \(3\mu\) | \(-\) | \(-\) | 20.3 | \(W\) mass | 1.52 TeV | Preliminary | 1406.4456 |
| EGM \(W \rightarrow W \

*Only a selection of the available mass limits on new states or phenomena is shown.*
Some of proposals of Physics beyond Standard Model contain Leptoquarks

Color triplet bosons (scalars or vectors) with renormalizable couplings to the SM fermions

\[ |Q| = 2/3 \quad \text{Charge} \quad |Q| = 1/3 \]

If LQ is a weak doublet then left down-quark fields “communicate” with up-quark fields through the CKM matrix (the same for leptons – PMNS matrix)
### Leptoquark candidates

| $(SU(3), \, SU(2))_Y$ | spin | LQ couplings                                                                 | $3B$ | $L$   |
|------------------------|------|------------------------------------------------------------------------------|------|------|
| $(3, 2)_{1/6}$         | 0    | $\overline{Q} \nu_R, \overline{d}_R L$                                    | $+1$ | $-1$ |
| $(3, 2)_{7/6}$         | 0    | $\overline{Q} \ell_R, \overline{u}_R L$                                  | $+1$ | $-1$ |
| $(3, 1)_{-1/3}$        | 0    | $\overline{Q} i \tau^2 L^C, \overline{d}_R \nu^C_R, \overline{u}_R \ell^C_R$ |      |      |
| $(3, 3)_{-1/3}$        | 0    | $\overline{Q} T^i i \tau^2 L^C$                                          |      |      |
| $(3, 1)_{2/3}$         | 1    | $\overline{u}_R \gamma_\mu \nu_R, \overline{Q} \gamma^\mu L$             | $+1$ | $-1$ |
| $(3, 3)_{2/3}$         | 1    | $\overline{Q} T^i \gamma_\mu L$                                          | $+1$ | $-1$ |
| $(3, 2)_{1/6}$         | 1    | $\overline{u}_R \gamma_\mu i \tau^2 L^C, \overline{Q} \gamma_\mu \nu^C_R$ | $+1$ | $-1$ |
| $(3, 2)_{5/6}$         | 1    | $\overline{Q} \gamma^\mu \ell^C_R, \overline{d}_R i \tau^2 \gamma_\mu L^C$| $+1$ | $-1$ |

- $(3,2)_{7/6}$ and $(3,2)_{1/6}$ proper candidates among scalar LQ

- Might destabilize proton ID, SF, NK 1204.0674
- We do not consider these states

**Q** = $I_3 + Y$
Most famous role of leptoquarks: proton destabilization

Experimental bound

$$\tau(p \rightarrow e^+ \pi^0) > 1.3 \times 10^{34} \text{ years}$$
Low energy constraints on leptoquark couplings

Scalar LQ might explain small deviation:
Experimental result

\[ \sim 2-3 \sigma \]

SM prediction

- \[ B \to D^{(*)} \tau \nu_\tau \]
- \[ B \to K^* l^+ l^- \]
- \[ Z \to b\bar{b} \]
- \[ (g - 2)_\mu \]
- \[ \mu \to e\gamma \]
- \[ \tau \to \mu\gamma \]
- \[ R_K \]
- \[ h \to \tau \mu \ (?) \]
Current status of flavor anomalies (subjective)

- Some would be unambiguous NP signals
- Except for theoretically cleanest modes, cross-checks needed to build robust case
- Measurements of related observables
- Independent theory / lattice calc.

\[ f \text{ (theoretical cleanliness)} \]

\[ h \to \tau \mu \]

\[ B \to K^+ e^- / B \to K^+ \mu^- \mu^- \]

- Dimuon CP asym

\[ B \to D^{(*)} \tau \nu \]

\[ B \to K^* \mu^+ \mu^- \text{ angular} \]

- \( |V_{cb}| \) incl/excl
- \( |V_{ub}| \) incl/excl

\[ B_s \to \phi \mu^+ \mu^- \]

- \( \epsilon'/\epsilon \)

- \( g-2 \)

From Z. Ligeti, LP 2015, Ljubljana
In ratios there is no dependence on CKM matrix elements:

\[
R_{\tau/\ell}^* \equiv \frac{\mathcal{B}(B \to D^{*}\tau\nu)}{\mathcal{B}(B \to D^{*}\ell\nu)} = 0.332 \pm 0.030
\]

\[
R_{\tau/\ell} \equiv \frac{\mathcal{B}(B \to D\tau\nu)}{\mathcal{B}(B \to D\ell\nu)} = 0.440 \pm 0.072
\]

|       | \(R(D)\)                  | \(R(D^*)\)                 |
|-------|---------------------------|-----------------------------|
| BaBar | \(0.440 \pm 0.058 \pm 0.042\) | \(0.332 \pm 0.024 \pm 0.018\) |
| Belle | \(0.375 \pm 0.064 \pm 0.026\) | \(0.293 \pm 0.038 \pm 0.015\) |
| LHCb  | \(0.336 \pm 0.027 \pm 0.030\) | \         |
| Average | \(0.391 \pm 0.050\)          | \(0.322 \pm 0.022\)                  |
| SM expectation | \(0.300 \pm 0.010\)          | \(0.252 \pm 0.005\)                  |
| Belle II, 50/ab | \(\pm 0.010\)               | \(\pm 0.005\)                  |
The B* decay rates

- BaBar, PRL109,101802(2012)
- Belle, arXiv:1507.03233
- LHCb, arXiv:1506.08614
- Average

Δχ^2 = 1.0

Combined 3.4σ larger than SM

Standard Model

\[
\begin{align*}
R_{\tau/\ell}^{*,\text{SM}} &= 0.252(3) \\
R_{\tau/\ell}^{\text{SM}} &= 0.296(16)
\end{align*}
\]
Leptoquark contribution in $b \rightarrow c \tau \nu_\tau$

Scalar and vector leptoquark that trigger $b \rightarrow c l u$, I.Doršner, S.F., N. Košnik, (2013)

Color triplet bosons (scalars or vectors) with renormalizable couplings to the SM fermions

Charge

\[
\begin{align*}
|Q| &= 2/3 \\
|Q| &= 1/3
\end{align*}
\]

If LQ is a weak doublet then left down-quark fields “communicate” with up-quark fields through the CKM matrix (the same for leptons – PMNS matrix)
Can observed effects be explained within SM?

New form-factors show up in \[ B \rightarrow D^{(*)} \tau \nu_\tau \]

How well do we know all form-factors?

Lattice improvements?

Lepton flavor universality violation in B semileptonic decays?

S.F. J.F. Kamenik, I. Nišandžić, J. Zupan, 1206.1872

Many proposals of NP:

P. Ko et al., 1212.4607;
A. Celis et al, 1210.8443;
D. Bečirević et al. 1206.4977;
A. Crivelin et al., 1206.2634;
P. Biancofiore et al., 1302.1042,
Interactions of $\Delta = (3,2,7/6)$ state

\[
\mathcal{L} = \bar{\ell}_R Y \Delta^\dagger Q + \bar{u}_R Z \tilde{\Delta}^\dagger L + \text{H.c.}
\]

Fields are in the weak base. We use a basis in which all rotations are assigned to neutrinos and up-like quarks.

Transition to a mass base:

\[
\begin{align*}
\mathcal{L}^{(2/3)} &= (\bar{\ell}_R Y d_L) \Delta^{(2/3)*} + (\bar{u}_R [Z V_{\text{PMNS}}] \nu_L) \Delta^{(2/3)} + \text{H.c.} \\
\mathcal{L}^{(5/3)} &= (\bar{\ell}_R [Y V^\dagger_{\text{CKM}}] u_L) \Delta^{(5/3)*} - (\bar{u}_R Z \ell_L) \Delta^{(5/3)} + \text{H.c.}
\end{align*}
\]

Requirements:

- to explain deviation of SM prediction in $b \rightarrow c \tau \nu_\tau$
- no contributions in $b \rightarrow c l \nu_l, \ l = e, \mu$
We impose: $b$ couples to $\tau$ only and $c$ quark to neutrinos

$$\Delta^{(2/3)}$$ couplings

$$\mathcal{L}^{(2/3)} = (\bar{\ell}_R Y d_L) \Delta^{(2/3)*} + (\bar{u}_R [Z V_{PMNS}] \nu_L) \Delta^{(2/3)} + \text{H.c.}$$

$$Y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & y_{33} \end{pmatrix}, \quad Z V_{PMNS} = \begin{pmatrix} 0 & 0 & 0 \\ z_{21} & z_{22} & z_{23} \\ 0 & 0 & 0 \end{pmatrix}$$

$$\Delta^{(5/3)}$$ couplings

$$\mathcal{L}^{(5/3)} = (\bar{\ell}_R [Y V^{\dagger}_{CKM}] u_L) \Delta^{(5/3)*} - (\bar{u}_R Z \ell_L) \Delta^{(5/3)} + \text{H.c.}$$

$$Y V^{\dagger}_{CKM} = y_{33} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ V^*_{ub} & V^*_{cb} & V^*_{tb} \end{pmatrix}, \quad Z = \begin{pmatrix} 0 & 0 & 0 \\ \tilde{z}_{21} & \tilde{z}_{22} & \tilde{z}_{23} \\ 0 & 0 & 0 \end{pmatrix}$$
Effective hamiltonian for $b \rightarrow c T \nu_\tau$ transition induced by LQ transition

\[ \mathcal{H}^{(2/3)} = \frac{y_{33} z_{23}}{2m_\Delta^2} \left[ (\bar{\tau}_R \nu_{iL})(\bar{c}_R b_L) + \frac{1}{4}(\bar{\tau}_R \sigma_{\mu\nu} \nu_{iL})(\bar{c}_R \sigma_{\mu\nu} b_L) \right] \]

(Fierz’s transformation are used)

SM + NP operators

\[ \mathcal{H} = \frac{4G_F}{\sqrt{2}} V_{cb} \left[ (\bar{\tau}_L \gamma^\mu \nu_L)(\bar{c}_L \gamma_\mu b_L) + g_S(\bar{\tau}_R \nu_L)(\bar{c}_R b_L) + g_T(\bar{\tau}_R \sigma_{\mu\nu} \nu_L)(\bar{c}_R \sigma_{\mu\nu} b_L) \right] \]

\[ g_S(m_\Delta) = 4g_T(m_\Delta) \equiv \frac{1}{4} \frac{y_{33} z_{23}}{2m_\Delta^2} \frac{\sqrt{2}}{G_F V_{cb}}. \]

this relation holds on the mass scale of $\Delta$
scalar and tensor operators have anomalous dimension contrary to V and A currents

\[ g_T(m_b) \approx 0.14 g_S(m_b) \]
Lepton electromagnetic current

\[-ie \bar{u}_\ell(p + q) \gamma^\mu u_\ell(p)\]

Muon anomalous magnetic moment

\[\Delta^{(5/3)} \text{ enters loop functions} \]

charm quark in the loop

\[ \delta a_\mu \equiv F_M^\mu(q^2 = 0) = -\frac{N_c |\tilde{z}_{22}|^2 m_\mu^2}{16\pi^2 m_\Delta^2} \left[ Q_c F_q(x) + Q_{\Delta} F_{\Delta}(x) \right] \]
$Z \rightarrow b\bar{b}$

- is not affected due to -1/3 charge of quarks and 2/3 charge of the LQ;

$(g - 2)_\mu$

- muon and tau in the loop – negligible modification of the $g_L$ coupling

Is GUT possible with such extension?

The small $\tilde{z}_{12} \sim 10^{-5}$ coupling implies vev of representation 45 $v_{45}$ to be large!
\[ a_\mu^{\exp} = 1.16592080(63) \times 10^{-3} \]
\[ a_\mu^{\text{SM}} = 1.16591793(68) \times 10^{-3} \]

\[ \delta a_\mu = a_\mu^{\exp} - a_\mu^{\text{SM}} = (2.87 \pm 0.93) \times 10^{-9} \]

MEG experiment result on muon BR for LFV decay is much stronger then for bound on tau LFV decay rate. The \( \mu \) lifetime and the strong bound on LFV compensate for a helicity suppression.
Is our low-energy Yukawa ansatz compatible with the idea of GUT?

GUT models contain such a state in an extended SU(5), SO(10).

Georgi-Glashow (1974) proposed $SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$

Two problems:

- Minimal SU(5) GUT fails!
- $M_E \approx M_D$ at GUT scale
(3,2)_{7/6} in GUT

(3,2)_{7/6} can be found in representations 45 and 50 of SU(5)

has both couplings Z and Y

In SO(10) scenario: 120 and 126

- anti-symmetric couplings to matter
- symmetric couplings to matter fields
Our assumption: \((3,2)_{7/6}\) in 45 of SU(5)

\[
\begin{align*}
\text{without 45: } M_E &\approx M_D \text{ at GUT scale} \\
\text{with 45: } M_E &= -3 M_D \text{ at GUT scale}
\end{align*}
\]

Representation 45 with its vev modifies mass relation for down-like quarks and charged leptons

\[
2M_D^{\text{diag}} D_R^T = -2Y_1 v_{45} - Y_3 v_5
\]

\[
2E_R M_E^{\text{diag}} = 6Y_1 v_{45} - Y_3 v_5
\]

We assume that \(D_R, U_R, E_R\) are real!

\[
M_D^{\text{diag}} D_R^T - E_R M_E^{\text{diag}} = 4U_R Z v_{45}
\]

this equation should be satisfied at GUT scale!

11 parameters and 9 equations only parameter \(\xi\) can not be fixed!

\[
\tilde{z}_{21} : \tilde{z}_{22} : \tilde{z}_{23} = 0.024 : 0.32 : 1
\]
1σ region allowed by existing data

couplings remain perturbative all the way to the GUT scale

2σ allowed region:

\[ 0.74 < |y_{33}| < 0.80 \]

\[ 0.021 < |\tilde{z}_{22}| < 0.032 \]

\[ f_{\text{RGE}} \ 5.0 \text{ GeV} < v_{45} < f_{\text{RGE}} \ 7.6 \text{ GeV} \quad (f_{\text{RGE}} \in [1.1, 3.7]) \]
Proton decay amplitude depends on one parameter!

necessary to know:
- all unitary transformations in the charged fermion sector;
- masses of all proton mediated gauge bosons and
- a gauge coupling constant;

In our approach proton decay prediction depend on:
\[ m_{GUT}, \ \alpha_{GUT}, \ \xi \]

In some part of parameter space \( p \rightarrow \pi^0 e^+ \) is suppressed in comparison with
\( p \rightarrow K^+ \bar{\nu}, \ p \rightarrow K^0 e^+ \)
Predictions

\[ BR_{SM+LQ}(B_c \to \tau \nu_\tau) \approx \begin{cases} 
0.36 BR_{SM}(B_c \to \tau \nu_\tau) \\
84 BR_{SM}(B_c \to \tau \nu_\tau) 
\end{cases} \]

\[ g_S = -0.37 \]

\[ g_S \simeq 1.8 \pm 0.4i \]

SM: \[ \mathcal{B}(B_c \to \tau \nu) = 0.0194(18) \]

generate \[ t \to c \tau^+ \tau^- \text{ and } \bar{D}^0 \to \tau^- e^+ \]

\[ BR_{LQ}(t \to c \tau^+ \tau^-) \sim 10^{-8} \]

\[ BR_{LQ}(\bar{D}^0 \to \tau^- e^+) \sim 10^{-14} \]
G. Hiller and F. Kruger, hep-ph/0310219 suggested to measure

\[ R_K = \frac{\mathcal{B}(B \rightarrow K \mu^+ \mu^-)_{q^2 \in [1,6]} \text{ GeV}^2}{\mathcal{B}(B \rightarrow K e^+ e^-)_{q^2 \in [1,6]} \text{ GeV}^2} \]

\[ R_{K}^{LHCb} = 0.745 \pm 0.090 \pm 0.036 \quad R_{K}^{SM} = 1.0003 \pm 0.0001 \]
This decay modes give useful constraints on NP!

\[
\begin{aligned}
B & \rightarrow K^* l^+ l^- \\
B & \rightarrow K l^+ l^- \\
B & \rightarrow X_s l^+ l^- \\
B_s & \rightarrow l^+ l^-
\end{aligned}
\]

In our study we use:

\[
\begin{aligned}
BR(B_s \rightarrow \mu^+ \mu^-)_{LHCb} &= (2.9^{+1.1}_{-1.0}) \times 10^{-9} \\
BR(B_s \rightarrow \mu^+ \mu^-)_{CMS} &= (3.0^{+1.0}_{-0.9}) \times 10^{-9} \\
BR(B_s \rightarrow \mu^+ \mu^-)_{SM} &= (3.23 \pm 0.23) \times 10^{-9}
\end{aligned}
\]

Experimental results 2013
Effective Hamiltonian for $b \to s \mu^+ \mu^-$

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}}V_{tb}V_{ts}^* \left[ \sum_{i=1}^{6} C_i(\mu)\mathcal{O}_i(\mu) + \sum_{i=7,\ldots,10} (C_i(\mu)\mathcal{O}_i(\mu) + C'_i(\mu)\mathcal{O}'_i(\mu)) \right]$$

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu},$$

$$\mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell),$$

$$\mathcal{O}_8 = \frac{1}{g} m_b (\bar{s}\sigma_{\mu\nu} G^{\mu\nu} P_R b),$$

$$\mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell).$$

$$P_{L/R} = (1 \mp \gamma_5)/2$$

Wilson coefficients mix under QCD renormalisation- effective Wilson coefficients are used!
Our explanation of $R_K$ anomaly (D. Bečirević, SF, N. Košnik, 1503.09024)

NP in

$$C'_9 = -C'_{10}$$

$$R_K(C'_{10}) = 1.001(1) - 0.46 \, \text{Re}[C'_{10}] - 0.094(3) \, \text{Im}[C'_{10}] + 0.057(1)|C'_{10}|^2.$$  

in agreement with exp. results for at $1\sigma$

$$B \rightarrow K \mu^+ \mu^-$$

$R_K^{\text{pred.}} = 0.88 \pm 0.08.$
G. Hiller & M. Schmaltz: observed $R_K$ can be explained by LQ which fulfill

\[ C'_9 = -C'_{10} \]

\[ \mathcal{L} = Y_{ij} \bar{L}_i i \tau^2 \Delta^* d_{Rj} + h.c. \]

\[ = Y_{ij} \left( -\bar{\ell}_L i d_{Rj} \Delta^{(2/3)*} + \bar{\nu}_{Lk} (V_{PMNS})_{ki}^\dagger d_{Rj} \Delta^{(-1/3)*} \right) + h.c. \]

\[ C'_{10} = -C'_9 = \frac{-\pi}{2\sqrt{2}G_F V_{tb} V_{ts}^* \alpha} \frac{Y_{\mu b} Y_{\mu s}^*}{m_\Delta^2} \]

However, it can contribute to

\[ B_s - \bar{B}_s \]

\[ C_{6LQ}^{LQ}(m_\Delta) = -\frac{Y_{\mu b}^* Y_{\mu s}^2}{64\pi^2 m_\Delta^2} \]

With value $C_{10}'$, one can get very loose bound on $m_\Delta \sim 100 \text{ TeV}$. 
Here which is in excellent agreement with the measured

With the current values for

\[ q^2 \in [1,6] \text{ GeV}^2 \]

in this case stands for the invariant mass of the neutrino pair. Notice that the above expression, for
cients at next-to-leading order in QCD is

\[ \frac{\Gamma(B \to K^{*}\mu^+\mu^-)}{\Gamma(B \to K^{*}e^+e^-)} q^2 \in [1,6] \text{ GeV}^2 \]

is expected to be small. To be more specific, we fully rely on quark-hadron duality since we avoid the region in which

pairs coming from

comparison, in the same plot we also show

\[ 0.4 \leq \frac{\Gamma(B \to K^{*}\mu^+\mu^-)}{\Gamma(B \to K^{*}e^+e^-)} q^2 \leq 0.8 \]

for a broad scalar state \[ \mathcal{O}(22) \text{ GeV} \], we found that in the SM the

ratio of forward-backward asymmetries is then simply,

\[ A^{\ell}_{fb[4-6]} = \frac{3}{4} \frac{\int_4^{6} \text{ GeV}^2 I_6^e(q^2) dq^2}{\Gamma(B \to K^{*}\ell^+\ell^-)} q^2 \in [4,6] \text{ GeV}^2 \]

LQ \((3,2,1/6)\) in suggested observables leads to:

\[ R_K = 0.88 \pm 0.08 \]

\[ R_K^* = 1.11 \pm 0.08 \]

\[ X_K = 0.27 \pm 0.19 \]

\[ R_{fb} = 0.84 \pm 0.12 \]

It can give increase of the rate for \[ B \to K \nu \bar{\nu} \]
at the order of 5%
Lepton flavor violating decay $h \rightarrow \tau \mu$

CMS result (assuming SM Higgs production)

\[ B(h \rightarrow \tau \mu) = (0.84^{+0.39}_{-0.37}) \% \]

After EWSB

\[ \mathcal{L}_{Y\ell}^{\text{eff.}} = -m_{\tau} \delta_{ij} \bar{\ell}_{L}^{i} \ell_{R}^{j} - y_{ij} \left( \bar{\ell}_{L}^{i} \ell_{R}^{j} \right) h + \ldots + h.c. \]

\[ B(h \rightarrow \tau \mu) = \frac{m_{h}}{8\pi \Gamma_{h}} \left( |y_{\tau\mu}|^2 + |y_{\mu\tau}|^2 \right) \]

\[ 0.0019(0.0008) < \sqrt{|y_{\tau\mu}|^2 + |y_{\mu\tau}|^2} < 0.0032(0.0036) \text{ at 68\% (95\%) C.L.} \]

We considered low energy bounds and found that if CMS result holds the at Belle II $\tau \rightarrow \mu \gamma$ should be observed!
LQ candidates: \( \Delta_1 = (3, 1, -1/3) \), 
\[ \Delta_2 = (3, 2, 7/6) \]

\[
\mathcal{L}_{\Delta_1} = y_{ij}^L \bar{Q}^{i,a} \Delta_1 \epsilon^{ab} L^C j,b + y_{ij}^R \bar{U}^i \Delta_1 E^C j + h.c.,
\]

\[
\frac{\mathcal{B}(h \rightarrow \mu)}{\mathcal{B}(h \rightarrow \tau)} \propto \left( |y_{ij}^L y_{ir}^R|^2 + |y_{ir}^L y_{ij}^R|^2 \right)^{1/2}
\]

\[
\frac{\mathcal{B}(\mu \rightarrow \tau \gamma)}{\mathcal{B}(\tau \rightarrow \mu \gamma)} \propto \left( |y_{ij}^L y_{ir}^R|^2 + |y_{ir}^L y_{ij}^R|^2 \right)^{1/2}
\]
LQ alone cannot explain LFV rate of Higgs and make sensible prediction for $\tau \rightarrow \mu \gamma$ rate. We suggested LQ+ vector-like T quark.
(I.Doršner, S.F., J.F.Kamenik, N.Košnik, I. Nisandžić, 1502.07784)
What do we achieve obtaining bounds from low energy phenomenology?

- If leptoquarks are relatively light (mass ~ 1 TeV) one might check whether unification is possible within SU(5) and SO(10)!

- ATLAS and CMS search for LQ. Are these bounds relevant for their searches?
Experimental searches for LQ

Tevatron (CDF, D0)  ATLAS  CMS

Search for LQ of only one generation (in majority of models LQ couples to all three generations of quarks and leptons)

CMS

ATLAS

| LQ                        | ATLAS Searches                                                                 |
|---------------------------|-------------------------------------------------------------------------------|
| Scalar LQ 1st gen         | 2 e  ≥ 2 j  – 20.3                                                           |
| Scalar LQ 2nd gen         | 2 μ  ≥ 2 j  – 20.3                                                           |
| Scalar LQ 3rd gen         | 1 e, μ  ≥ 1 b, ≥ 3 j  Yes 20.3                                               |

Leptoquarks

- LQ1(ej) x2
- LQ1(ej)+LQ1(vj)
- LQ2(μj) x2
- LQ2(μj)+LQ2(vj)
- LQ3(vb) x2
- LQ3(tb) x2
- LQ3(ττ) x2
- LQ3(ντ) x2
- Single LQ1 (λ=1)
- Single LQ2 (λ=1)

Mass scale [TeV]:

- Scalar LQ 1st gen: 1.05 TeV
- Scalar LQ 2nd gen: 1.0 TeV
- Scalar LQ 3rd gen: 640 GeV
- Sizable Yukawa couplings of LQ with SM fermions could influence pair production at LHC;
- For small Yukawas LQ production is the same as within QCD.
Search of LQ(3,2,1/6) at LHC

For simplicity we assume only diagonal couplings in the search for LQ at LHC!

I generation couplings: best constraints come from atomic parity violation

$$\mathcal{L}_{\text{PV}} = \frac{G_F}{\sqrt{2}} \sum_{q=u,d} \left( C_{1q} \bar{e} \gamma^\mu \gamma_5 e \bar{q} \gamma^\mu \mu q + C_{2q} \bar{e} \gamma^\mu e \bar{q} \gamma^\mu \mu \gamma_5 q \right)$$

$$C_{1d} = C_{1d}^{\text{SM}} + \delta C_{1d}$$

$$\delta C_{1u(d)} = \frac{\sqrt{2} |y_{u(d)} e|^2}{G_F} \frac{8m_{LQ}^2}{8m_{LQ}^2} \left\{ \begin{array}{l}
|y_{de}| \leq 0.34 \left( \frac{m_{LQ}}{1 \text{ TeV}} \right) \\
|y_{ue}| \leq 0.36 \left( \frac{m_{LQ}}{1 \text{ TeV}} \right)
\end{array} \right. $$

Bounds on II generation LQ

$$\text{BR}(K_L \to \mu^\pm e^\mp) < 4.7 \times 10^{-12}$$

Experimental bound:

$$|y_{\mu e} y_{de}^*| < 2.1 \times 10^{-5} \left( \frac{m_{LQ}}{1 \text{ TeV}} \right)^2$$

The LQ of the first generation is fully constrained by APV, hence couplings of LQ to a down quark and an electron is very small.
If Yukawa couplings are large, one also needs to take into consideration a single leptoquark production and $t$-channel leptoquark pair production.
Summary

- (3,2,7/6) state introduced to explain R(D) and R(D*);
- scalar with charge 2/3 introduces scalar and tensor operator into effective Lagrangian;
- charge 5/3 state induces quark and lepton flavor changing processes;
- constraints from $Z \to b\bar{b}$, $(g - 2)_\mu$, $d_\tau$, $\tau \to \mu \gamma$, $\mu \to e\gamma$;
- Model with (3,2,7/6) LQ state can be accommodated with SU(5) GUT by adding 45 scalar representation.
- (3,2,1/6) can explain $R_K$ anomaly.
- LQ alone cannot explain LFV rate of Higgs and make sensible prediction for $\tau \to \mu \gamma$ rate.
- Searches of LQ at LHC do depend on LQ couplings to quark and lepton, for large Yukawa couplings a single leptoquark production and t-channel leptoquark pair production are important - IMPORTANCE OF FLAVOUR PHYSICS FOR LHC!
Global fit of NP contributions (S. Decotes-Genot et al., 1307.5683)

47 observables

\[ BR(B \to X_s \gamma), \quad BR(B \to X_s \mu^+ \mu^-)_{\text{Low } q^2} \]

\[ BR(B_s \to \mu^+ \mu^-), \quad A_l(B \to K^* \gamma), \quad S(B \to K^* \gamma) \]

\[ B \to K^* \mu^+ \mu^- : \langle P_1 \rangle, \langle P_2 \rangle, \langle P_4' \rangle, \langle P_5' \rangle, \langle P_6' \rangle, \langle P_8' \rangle, \langle A_{FB} \rangle \]

| Coefficient | 1σ | 2σ | 3σ |
|-------------|----|----|----|
| \( C_7^{NP} \) | \([-0.05, -0.01]\) | \([-0.06, 0.01]\) | \([-0.08, 0.03]\) |
| \( C_9^{NP} \) | \([-1.6, -0.9]\) | \([-1.8, -0.6]\) | \([-2.1, -0.2]\) |
| \( C_{10}^{NP} \) | \([-0.4, 1.0]\) | \([-1.2, 2.0]\) | \([-2.0, 3.0]\) |
| \( C_7'^{NP} \) | \([-0.04, 0.02]\) | \([-0.09, 0.06]\) | \([-0.14, 0.10]\) |
| \( C_9'^{NP} \) | \([-0.2, 0.8]\) | \([-0.8, 1.4]\) | \([-1.2, 1.8]\) |
| \( C_{10'}^{NP} \) | \([-0.4, 0.4]\) | \([-1.0, 0.8]\) | \([-1.4, 1.2]\) |
Most likely modifications of SM Wilson coefficients; confirmed also by Altmannshofer and Straub 1308.1501, Beujean, Bobeth, van Dyk 1310.2478, Horgan et al., 1310.3887