Anomalous Semileptonic B Decays and New Flavor Physics

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Semi-leptonic B decays: Experiment vs. Standard Model

- The BABAR reported values are:

$$R^{\rm exp}(D) = \frac{\mathcal{BR}(B \to D\tau\nu)}{\mathcal{BR}(B \to Dl\nu)} = 0.440 \pm 0.072$$
$$R^{\rm exp}(D^*) = \frac{\mathcal{BR}(B \to D^*\tau\nu)}{\mathcal{BR}(B \to D^*l\nu)} = 0.332 \pm 0.030$$

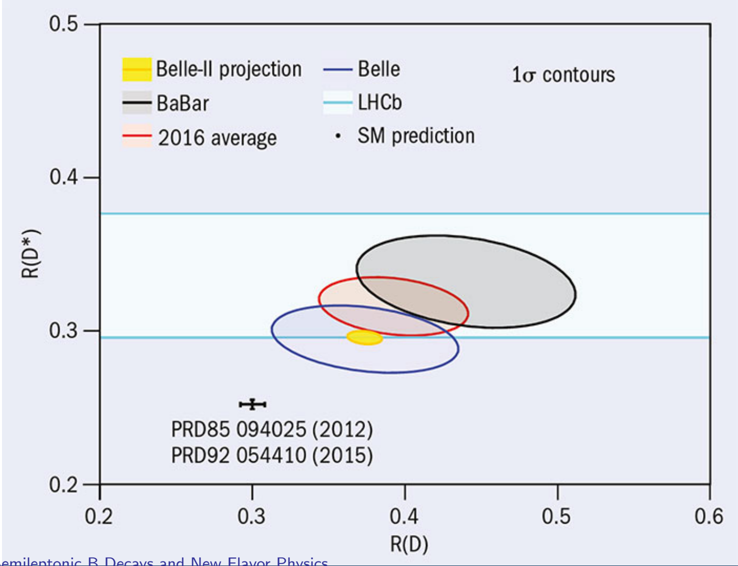
- Belle collaboration find :
  $R(D) = 0.375 \pm 0.069, R(D^*) = 0.293 \pm 0.04$
- LHCb find $R(D^*) = 0.336 \pm 0.042$
- Belle collaboration rate for the $B \to \tau\nu$ decay is

$$\mathcal{BR}(B \to \tau\nu) = (1.25 \pm 0.4) \times 10^{-4}.$$

- The expected SM values are:

$$R^{\rm SM}(D) = 0.297 \pm 0.017$$
$$R^{\rm SM}(D^*) = 0.252 \pm 0.003$$
$$\mathcal{BR}(B \to \tau\nu)^{\rm SM} = (0.753 \pm 0.1) \times 10^{-4}$$

Experimental situation and the future at Belle II)

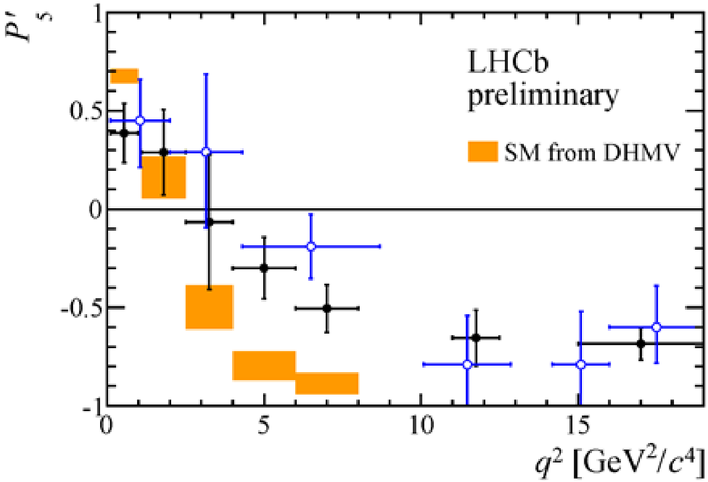


New results on $R(J/\psi)$at LHCb

Using data from Run 1 LHCb has measured:
$R(J/\psi) = Br(B_c \to J/\psi\tau\nu)/Br(B_c \to J/\psi\mu\nu) =$
$0.71 \pm 0.17 \pm 0.18$
Best theory estimates are $0.25 - 0.28$
This is 2σ deviation further confirming enhancement in $b \to c\tau\nu$ reaction.

Anomalies in $B \to K^* \mu^+ \mu^-$ Decay

- LHCb analysis of 3 fb^{-1} data confirms 3 σ anomaly in two large K^*-recoil bins of angular observable P_5'.
- The observable $R_K = Br(B \to K\mu^+\mu^-)/Br(B \to Ke^+e^-)$ measured at LHCb in data in dilepton mass range 1 to 6 GeV^2 is $0.742^{+.09}_{-.074} \pm .036$ corresponding to 2.6σ deviation from SM value of 1
- Analysis of New Physics requires (based on Descotes-Genon,Hofer,Matias and Virto arXiv: 1605.06059)
  (a) $C_9^{NP} = -1.09$ or
  (b) $C_9^{NP} = -C_{10}^{NP} = -0.68$ or
  (c) $C_9^{NP} = -C_{9'}^{NP} = -1.06$
  all with almost same pull of 4.2 to 4.8



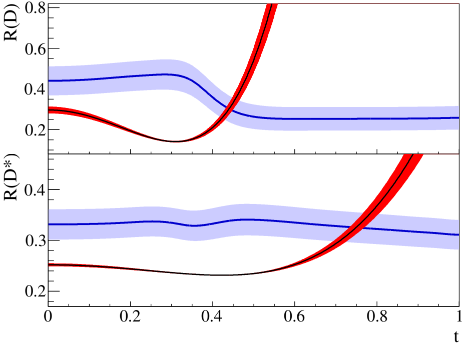
P'_5
1
0.5
0
-0.5
-1
0
5
10
15
q^2 [GeV^2/c^4]
LHCb
preliminary
SM from DHMV

Charged Higgs Contributions to the Semi-leptonic Decays

$$t = t_\beta / m_{H^+} (GeV^{-1})$$

$$R = R_{SM}(1 + 1.5 m_\tau \mathrm{Re}(g_{S_R} + g_{S_L}) + m_\tau^2 |g_{S_R} + g_{S_L}|^2)$$

$$R^* = R^*_{SM}(1 + 0.12 m_\tau \mathrm{Re}(g_{S_R} - g_{S_L}) + 0.05 m_\tau^2 |g_{S_R} - g_{S_L}|^2)$$



Scalar interactions are Inconsistent with B_c Lifetime: Alonso, Grinstein and Camalich

$$L = -[\frac{(4G_F V_{cb})}{\sqrt{2}}][(1+\epsilon_L)\bar{\tau}\gamma_\mu P_L \nu_\tau \bar{c}\gamma^\mu P_L b + \epsilon_P \bar{\tau} P_L \nu \bar{c}(\gamma_5/2)b]$$

$$\Gamma(B_c \to \tau\nu) = \frac{m_{B_c} m_\tau^2 f_{B_c}^2 G_F^2 |V_{cb}|^2}{8\pi}(1 - m_\tau^2/m_{B_c}^2)^2 \times [1 + 2\epsilon_L + \epsilon_P \frac{m_{B_c}^2}{m_\tau(m_b+m_c)}]$$

Experimentally $\tau_{B_c} = 0.507(8)ps$ while theoretically $\tau_{B_c} = 0.52 \pm 0.15ps$ by summing $b \to s$ and $c \to s$ decays.
Imposing $BR(B_c \to \tau\nu) \leq 0.30$ leads to $\epsilon_P \leq 0.61$
$R^{expt}(D^*) = 0.316(20)$ regires $\epsilon_P = 1.48(34)$(inconsistent !!.)

Tighter bounds on $B_c \to \tau\nu$ branching ratio: Akeroyd and Chen

From LEP search for b quark to $\tau\nu$ where both B_u and B_c contribute we have:
$BR_{eff} \leq 5.7 \times 10^{-4}$
we also know $BR(B_u \to \tau\nu) = 1.06 \times 10^{-4}$
From this we get :
$BR(B_c \to \tau\nu) = (f_u/f_c) \times [BR_{eff} - BR(B_u \to \tau\nu)]$
where f_c and f_u are fragementation functions that can be determined at Tevatron and LHCb.
$f_c/f_u \approx 1 \times 10^{-2}$
Result is $BR(B_c \to \tau\nu) \leq 10\%$
Therefore now:
Bound on $\epsilon_P \leq 0.3$ which cannot explain $B \to D^*\tau\nu$ data.

General R-Parity Violating SUSY

- General Superpotential:

$$W_{\mathrm{RPV}} = \mu_i L_i H_u + \frac{1}{2}\lambda_{ijk} L_i L_j E_k + \lambda'_{ijk} L_i Q_j D_k + \frac{1}{2}\lambda''_{ijk} U_i D_j D_k$$

- Imposing Z_3^B baryon symmetry leads to a proton stability and in the physical H_d basis

$$W = W_{\mathrm{MSSM}} + \frac{1}{2}\hat{\lambda}_{ijk}\hat{L}_i\hat{L}_j\hat{E}^c_k + \hat{\lambda}'_{ijk}\hat{E}_i\hat{Q}_j\hat{D}^c_k$$

- Keeping only λ' term which is sufficient to explain the anomaly and has the correct structure to explain the q^2 distribution :

$$L = \lambda'_{ijk}\left[\tilde{\nu}^i_L \bar{d}^k_R d^j_L + \tilde{d}^j_L \bar{d}^k_R \nu^i_L + \tilde{d}^{k*}_R \bar{\nu}^{ci}_L d^j_L - \tilde{l}^i_L \bar{d}^k_R u^j_L - \tilde{u}^j_L \bar{d}^k_R l^i_L - \tilde{d}^{k*}_R \bar{l}^{ci}_L u^j_L\right] ,$$

Interactions of squark $\tilde{d}_R^k$ that lead to Semileptonic Decays

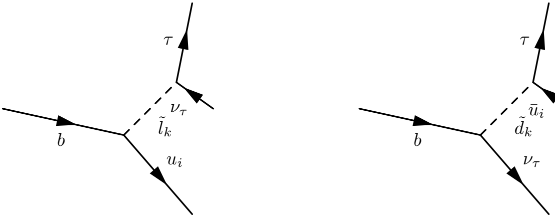
We assume that lefthanded up sqarks and down squarks are much much heavier. The model is then equivalent to single leptoquark. In SUSY there are three right-handed d squarks, but we shall assume that only one is involved in enhancement of B decays. Working in the basis where down quarks are in their mass eigenstates, $Q^T = (V^{KM\dagger} u_L, d_l)$, one replaces u_L^j in the above by $(V^{KM\dagger} u_L)^j$. The leptons are in the weak basis.

$$\mathcal{L}_{eff} = \frac{\lambda'_{ijk}\lambda'^{*}_{i'j'k}}{2m^2_{\tilde{d}_R^k}} \Big[\bar{\nu}_L^{i'}\gamma^\mu \nu_L^i \bar{d}_L^{j'}\gamma_\mu d_L^j + \bar{e}_L^{i'}\gamma^\mu e_L^i (\bar{u}_L V^{KM})^{j'}\gamma_\mu (V^{KM\dagger} u_L)^j$$
$$-\nu_L^{i'}\gamma^\mu e_L^i \bar{d}_L^{j'}\gamma_\mu (V^{KM\dagger} u_L)^j - \bar{e}_L^{i'}\gamma^\mu \nu_L^i (\bar{u}_L V^{KM})^{j'}\gamma_\mu d_L^j \,\Big]$$

It is tempting to assume flavor hierarchy for λ'_{ijk}

- We assume λ' for third generation is the largest because effects are more pronounced for third generation.
- We assume smaller λ' associated with second generation smaller but not vanishing because there are anomalies in B decays into muons
- We assume λ' associated with first generation are vanishingly small because constraints are sufficiently strong for the first generation.
- To explain all anomalies we are lead to $\lambda'_{333} \geq \lambda'_{233} \gg \lambda'_{323} \approx \lambda'_{223}$. These are the four couplings allowed

Illustration of λ and λ' induced b-quark decays



A Simple Model

- Keeping only λ'_{333} for illustration we get

$$\mathcal{L}_{4f} \quad \subset \quad -V^{\mathrm{KM}*}_{3m} \left[\left(\frac{\lambda'_{333}\lambda'^{*}_{333}}{m^2_{\tilde{d}_3}} \right) (\bar{\tau}\gamma^{\mu} P_L \nu_{\tau})(\bar{u}_m \gamma_{\mu} P_L b) \right] + \mathrm{h.c.}$$

- Due to $\Delta = \frac{\sqrt{2}}{4G_f} \frac{|\lambda'_{333}|^2}{2m^2_{\tilde{d}_3}}$ the enhancement to b decays is

$$L_{\mathrm{EFF}} = -\frac{4G_f}{\sqrt{2}} \sum_{m=1,2} V^{\mathrm{KM}}_{3m} \left[1 + \Delta\right] (\bar{u}_m \gamma^{\mu} P_L b)(\bar{\tau}\gamma^{\mu} P_L \nu_{\tau})$$

Consequences of the simple model

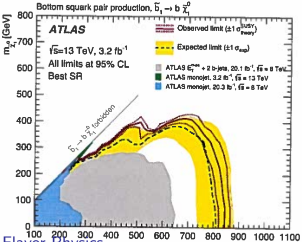
$$-\left[\frac{4G_f}{\sqrt{2}}\right]^{-1} L_{\rm EFF} = V_{bc}^{\rm KM}\left[1+\Delta\right](\bar{c}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$
$$+V_{bu}^{\rm KM}\left[1+\Delta\right](\bar{u}\gamma^\mu P_L b)(\bar{\tau}\gamma^\mu P_L \nu_\tau)$$

- $R(D, D^*) = Br(\bar{B} \to D\tau\bar{\nu})/Br(\bar{B} \to D\tau\bar{\nu})_{SM}$
  $= Br(\bar{B} \to D^*\tau\bar{\nu})/Br(\bar{B} \to D^*\tau\bar{\nu})_{SM} \approx 1 + 2\Delta.$
- $R(\rho, \pi) = Br(\bar{B} \to \rho\tau\bar{\nu})/Br(\bar{B} \to \rho\tau\bar{\nu})_{SM}$
  $= Br(\bar{B} \to \pi\tau\bar{\nu})/Br(\bar{B} \to \pi\tau\bar{\nu})_{SM}$
  $= Br(\bar{B} \to \tau\bar{\nu})/Br(\bar{B} \to \tau\bar{\nu})_{SM} \approx 1 + 2\Delta.$

Bound on Mass of $\tilde{d}$ squark

If we take enhancement Δ to be 15%
Then we get the most general expression:
$\Delta = [\sqrt{2}/8G_F](1/m_{\tilde{d}}^2) \times \lambda'_{333}[\lambda'_{333} + \lambda'_{323}/V_{bc}]$
If we impose the condition $\lambda'_{333} \leq (4\pi)^{1/2}$ we get a bound on mass of $\tilde{d}$ squark:
$m_{\tilde{d}} \leq 1$ TeV.
Note the product $\lambda'_{333}.\lambda'_{323} \leq 0.08$ from constraint on $B \to K\nu\bar{\nu}$.

ATLAS 13 TeV limit on bottom squark



Loop Contributions to $b \to s\mu^+\mu^-$ From New Physics

New physics contributes to $b \to s l\bar{l}$ can be parametrized as $H_{eff}^{NP} = \sum C_i^{NP} O_i$.
Some of the most studied operators O_i are

$$O_9 = \frac{\alpha}{4\pi}\bar{s}\gamma^\mu P_L b\bar{\mu}\gamma_\mu\mu \ , \qquad O_9' = \frac{\alpha}{4\pi}\bar{s}\gamma^\mu P_R b\bar{\mu}\gamma_\mu\mu \ ,$$
$$O_{10} = \frac{\alpha}{4\pi}\bar{s}\gamma^\mu P_L b\bar{\mu}\gamma_\mu\gamma_5\mu \ , \quad O_{10}' = \frac{\alpha}{4\pi}\bar{s}\gamma^\mu P_R b\bar{\mu}\gamma_\mu\gamma_5\mu \ , \tag{1}$$

where $P_{L,R} = (1 \mp \gamma_5)/2$.
The SM predictions are $C_9^{SM} \approx -C_{10}^{SM} = 4.1$.

Loop Contributions to C_9 from box diagrams with squark and W boson and two squarks

We assume $m_d = 1\text{TeV}$

$$C_9^{NP} = C_9^{NP(a)} + C_9^{NP(b)}$$

Contribution from W exchange is always positive definite:

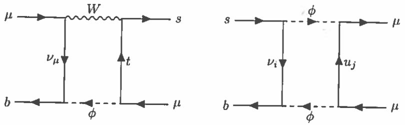
$$C_9^{NP(a)} = (0.157\lambda'_{l3k}\lambda'^{*}_{l'3k})$$

Contribution from two squarks is:

$$C_9^{NP(b)} = (2.0\lambda'_{l3k}\lambda'^{*}_{l'3k})(\lambda'_{23k}\lambda'^{*}_{22k} + \lambda'_{33k}\lambda'^{*}_{32k})$$

The contribution from second bracket has to be negative and fairly large. We show that low energy constraints make that impossible

Loop Contributions to C_9 from box diagrams with squark and W boson and two squarks



Constraint on λ' from $D^0 \to \mu\mu$ Decay

$$H_{eff} = -\frac{1}{2m^2_{\tilde{d}^k_R}} C^k_{D\mu\mu} \mu_L \gamma_\mu \mu_L \bar{u}_L \gamma^\mu c_L \ ,$$

$$C^k_{D\mu\mu} = \lambda'_{2jk} \lambda'^*_{2j'k} V_{1j'} V^*_{2j}$$
$$= (\lambda'_{21k} V^*_{21} + \lambda'_{22k} V^*_{22} + \lambda'_{23k} V^*_{23})(\lambda'^*_{21k} V_{11} + \lambda'^*_{22k} V_{12} + \lambda'^*_{23k} V_{13}) \ .$$

λ'_{23k} is only very loosely constrained from $D^0 \to \mu + \mu^-$. If just λ'_{21k} or λ'_{22k} is non-zero, they are constrained as

$$\lambda'_{21k} \lambda'^*_{21k} \frac{(1\text{TeV})^2}{m^2_{\tilde{d}^k_R}}, \lambda'_{22k} \lambda'^*_{22k} \frac{(1\text{TeV})^2}{m^2_{\tilde{d}^k_R}} < 0.28 \ .$$

Constraint on λ' from $K \to \pi\nu\nu$ and $B \to K\nu\nu$ Decays

The contribution is given by the interaction:

$$\frac{\lambda'_{ijk}\lambda'^{*}_{i'j'k}}{2m^2_{\tilde{d}^k_R}}\bar{\nu}^{i'}_L\gamma^\mu\nu^i_L\bar{d}^{j'}_L\gamma_\mu d^j_L$$

For $K \to \pi\nu\bar{\nu}$, the ratio of $R_{K\to\pi\nu\bar{\nu}} = \Gamma_{RPV}/\Gamma_{SM}$ is given by:

$$R_{K\to\pi\nu\bar{\nu}} = \sum_{i=,e,\mu,\tau}\frac{1}{3}\left|1+\frac{\Delta^{RPV}_{\nu_i\bar{\nu}_i}}{X_0(x_t)V_{ts}V^*_{td}}\right|^2 + \frac{1}{3}\sum_{i\neq i'}\left|\frac{\Delta^{RPV}_{\nu_i\bar{\nu}_{i'}}}{X_0(x_t)V_{ts}V^*_{td}}\right|^2 ,$$

$$\Delta^{RPV}_{\nu_i\bar{\nu}_{i'}} = \frac{\pi s^2_W}{\sqrt{2}G_F\alpha}\left|\frac{\lambda'_{i2k}\lambda'^{*}_{i'1k}}{2m^2_{\tilde{d}^k_R}}\right|^2 , X_0(x) = \frac{x(2+x)}{8(x-1)} + \frac{3x(x-2)}{8(x-1)^2}\ln x ,$$

where $x_t = m_t^2/m_W^2$.

Constraint on λ' from $K \to \pi\nu\nu$ and $B \to K\nu\nu$ Decays continued

Using $Br(K \to \pi\nu\nu) = (1.7 \pm 1.1) \times 10^{-10}$, at 2σ level:
we find $\lambda'_{i2k}\lambda'^{*}_{i'1k} \leq 10^{-3}(m^2_{d^k_R}/(1\text{TeV})^2)$.

We will set $\lambda'^{*}_{i1k} = 0$, so that this process is not affected at tree level.
The expressions for $R_{\bar{B}\to\pi\nu\bar{\nu}}$ and $R_{\bar{B}\to K(K^*)\nu\bar{\nu}}$ of $\bar{B} \to \pi\nu\bar{\nu}$ and $\bar{B} \to K(K^*)\nu\bar{\nu}$ can be obtained f by replacing $V_{ts}V^*_{td}$ to $V_{tb}V^*_{td}$ and $V_{tb}V^*_{ts}$, respectively.
From $B \to K\nu\nu$ we find experimentally $\Gamma_{RPV}/\Gamma_{SM} \leq 4.3$
we find $\lambda'_{33k}\lambda'_{32k} \leq 0.07$
We will impose this constraint.

Best Fit Values for non vanishing λ' and predictions

Assume $m_{\tilde{d}} = 1\,TeV$
$\lambda'_{22k} = -0.0068$
$\lambda'_{23k} = 6.3, \quad \lambda'_{32k} = -0.0068\,, \quad \lambda'_{33k} = 6.3\,.$

With this set of values, we have
$r(\bar{B} \to D^{(*)}\nu\bar{\tau})_{ave} = 1.48\,, \quad C_9^{NP} = -0.68\,,$
$r(\bar{B} \to \tau\bar{\nu}) = 1.48 = r(\bar{B} \to \rho\bar{\tau}\nu)\,,$
$R_{\bar{B}\to K(K^*)\nu\bar{\nu}} = 4.238\,, \quad R_\mu^{SM}(c) = 2.9$.!!!!
The large value of r and $R_\mu^{SM}(c)$ make this solution unacceptable.Value of λ's also exceed unitarity bound

Here
$r(\bar{B} \to D^{(*)}\nu\bar{\tau})_{ave} = Br(B \to D^{(*)}\nu\tau)_{EXPT}/Br(B \to D^*\nu\tau)_{SM}$
and similarly for $r(\bar{B} \to \rho\nu\bar{\tau})$
$R_\mu^{SM}(c) = Br(B \to D^{(*)}\mu\nu)/Br_{SM}(B \to D^*\mu\nu)$

$B_s - \bar{B}_s$ mixing and $b \to s\gamma$

$$C_{B_s} = \frac{\langle B_s | H_{eff}^{NP} | \bar{B}_s \rangle}{\langle B_s | H_{eff}^{SM} | \bar{B}_s \rangle}$$

$$= 1 + \frac{s_W^2}{\sqrt{2}\pi\alpha G_F S_0(x_t)} \frac{m_W^2}{m_{\tilde{d}_R^k}^2} \left(\frac{\lambda'_{23k}\lambda'^{*}_{22k} + \lambda'_{33k}\lambda'^{*}_{32k}}{V_{tb}V_{ts}^{*}} \right)^2 = 2.0\ ,$$

$$C_{7\gamma} = C_{7\gamma}^{SM} + \left(\frac{v}{12 m_{\tilde{d}_R^k}} \right)^2 \frac{\lambda'_{23k}\lambda'^{*}_{22k} + \lambda'_{33k}\lambda'^{*}_{32k}}{V_{tb}V_{ts}^{*}} = C_{7\gamma}^{SM} - 0.006$$

The R-parity violating contribution to $C_{7\gamma}$ is small and can be neglected. The contribution to C_{B_s} is however too large and therefore unacceptable.

Conclusion of single leptoqark scenario

We conclude that there is no choice of of RPV couplings that can reconcile both $R(D^{(*)})$ and $b \to s\mu^+\mu^-$ anomalies. We can however choose parameters such that we can explain $R(D^{(*)})$ anomalies provided we set all λ except λ_{33k} equal to zero. Then we have:

- $r(\rho, \pi) = Br(\bar{B} \to \rho\tau\bar{\nu})/Br_{SM}(\bar{B} \to \rho\tau\bar{\nu}) = Br(\bar{B} \to \pi\tau\bar{\nu})/Br_{SM}(\bar{B} \to \pi\tau\bar{\nu}) = Br(\bar{B} \to \tau\bar{\nu})/Br_{SM}(\bar{B} \to \tau\bar{\nu}) \approx 1.27$.
- The model requires $\tilde{d}_R^k$ squark should have a mass not much larger than 1 TeV. Such a low mass should be able to be detected at the LHC soon.

Beyond a single lepto-quark

- A lepto-quark model with a scalar doublet Δ with hyper charge Y= 7/6 proposed by Beciervic and Sumensari. Loop diagram with W and Δ exchange is able to generate a negative contribution to C_9. See also Chauhan, Kendra and Narang for applications to $(g-2)_\mu$ and IceCube events.
- A leptoquark model with vector lepto-quark has also been proposed by Beciervic et al.