Flavour anomalies motivated LHC bounds on U_1 Leptoquark model

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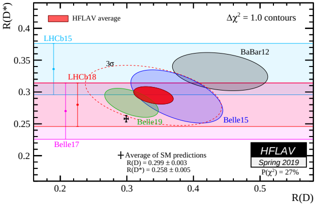
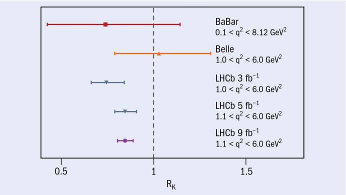
Flavour Anomalies



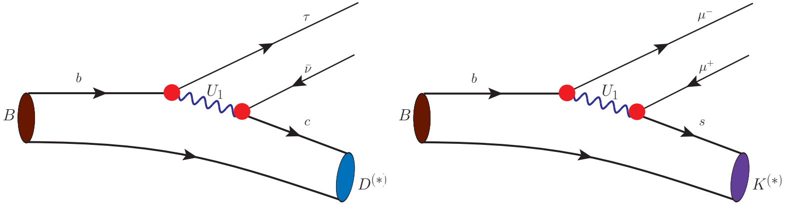


$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\hat{\ell}\bar{\nu})}$$

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu^+\mu^-)}{\mathcal{B}(B \to K^{(*)}e^+e^-)}$$

- Lepton Flavour Universality (LFU) violated, hint of new physics ??

Leptoquarks as a viable solution



- A U_1 vector LQ with charge $2/3$, a proposed model to explain both the B-anomalies simultaneously.
- It is color triplet, weakly singlet and has non-zero baryon and lepton numbers.

U_1 model

$$\mathcal{L} \supset x_{1\,ij}^{LL}\, \bar{Q}^i \gamma_\mu U_1^\mu P_L L^j + x_{1\,ij}^{RR}\, \bar{d}_R^i \gamma_\mu U_1^\mu P_R \ell_R^j + \mathrm{H.c.},$$

- $x_{1\,ij}^{LL}$ and $x_{1\,ij}^{RR}$ are 3×3 matrices in flavour space.
- The couplings are real. We consider those couplings which contribute to $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies.

$$x_1^{LL} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{22}^L & \lambda_{23}^L \\ 0 & \lambda_{32}^L & \lambda_{33}^L \end{pmatrix} \qquad x_1^{RR} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & \lambda_{22}^R & 0 \\ 0 & \lambda_{32}^R & \lambda_{33}^R \end{pmatrix}$$

- We have considered the above flavor ansatz for simplicity.
- Red ones contribute to $R_{K^{(*)}}$ and black ones to $R_{D^{(*)}}$.

$R_{D^{(*)}}$ anomalies

- For the $b \to c\tau\bar{\nu}$ transitions,

  $\mathcal{L} \supset -\frac{4G_F}{\sqrt{2}} V_{cb} \left[\left(1 + \mathcal{C}_{V_L}\right) \mathcal{O}_{V_L} + \mathcal{C}_{S_L} \mathcal{O}_{S_L}\right]$

- U_1 can contribute to $b \to c\tau\bar{\nu}$ transitions through the modified Wilson coefficients,

$$\mathcal{C}_{V_L}^{U_1} = \frac{1}{2\sqrt{2} G_F V_{cb}} \frac{\lambda_{c\nu}^L \left(\lambda_{b\tau}^L\right)^*}{M_{U_1}^2}; \quad \mathcal{C}_{S_L}^{U_1} = -\frac{1}{2\sqrt{2} G_F V_{cb}} \frac{2\lambda_{c\nu}^L \left(\lambda_{b\tau}^R\right)^*}{M_{U_1}^2}$$

$R_{D^{(*)}}$ scenarios	$\lambda_{c\nu}^L$	$\lambda_{b\tau}^L$	$\lambda_{b\tau}^R$
RD1A	λ_{23}^L	$V_{cb}^*\lambda_{23}^L$	–
RD1B	$V_{cb}\lambda_{33}^L$	λ_{33}^L	–
RD2A	$V_{cs}\lambda_{23}^L + V_{cb}\lambda_{33}^L$	λ_{33}^L	–
RD2B	$V_{cs}\lambda_{23}^L$	–	λ_{33}^R

$R_{K^{(*)}}$ anomalies

- For the $b \to s\mu^+\mu^-$ transitions,

$$\mathcal{L} \supset \frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_{i=9,10,S,P} \left(\mathcal{C}_i \mathcal{O}_i + \mathcal{C}'_i \mathcal{O}'_i \right)$$

- The U_1 modified Wilson coefficients are given as,

$$\mathcal{C}_9^{U_1} = -\mathcal{C}_{10}^{U_1} = \frac{\pi}{\sqrt{2} G_F V_{tb} V_{ts}^*} \frac{\lambda_{s\mu}^L (\lambda_{b\mu}^L)^*}{M_{U_1}^2}; \; \mathcal{C}_9'^{\,U_1} = \mathcal{C}_{10}'^{\,U_1} = \frac{\pi}{\sqrt{2} G_F V_{tb} V_{ts}^*} \frac{\lambda_{s\mu}^R (\lambda_{b\mu}^{R*})}{M_{U_1}^2}$$

$$\mathcal{C}_S^{U_1} = -\mathcal{C}_P^{U_1} = \frac{\sqrt{2}\pi}{G_F V_{tb} V_{ts}^*} \frac{\lambda_{s\mu}^L (\lambda_{b\mu}^R)^*}{M_{U_1}^2}; \qquad \mathcal{C}_S'^{\,U_1} = \mathcal{C}_P'^{\,U_1} = \frac{\sqrt{2}\pi}{G_F V_{tb} V_{ts}^*} \frac{\lambda_{s\mu}^R (\lambda_{b\mu}^{L*})}{M_{U_1}^2}$$

$R_{K^{(*)}}$ Scenarios

$R_{K^{(*)}}$ scenarios	$\lambda^L_{s\mu}$	$\lambda^L_{b\mu}$	$\lambda^R_{s\mu}$	$\lambda^R_{b\mu}$
RK1A	$V^*_{cs}\lambda^L_{22}$	$V^*_{cb}\lambda^L_{22}$	—	—
RK1B	$V^*_{ts}\lambda^L_{32}$	$V^*_{tb}\lambda^L_{32}$	—	—
RK1C	—	—	$V_{cs}\lambda^R_{22}$	$V_{cb}\lambda^R_{22}$
RK1D	—	—	$V_{ts}\lambda^R_{32}$	$V_{tb}\lambda^R_{32}$
RK2A	λ^L_{22}	λ^L_{32}	—	—
RK2B	λ^L_{22}	—	—	λ^R_{32}
RK2C	—	λ^L_{32}	λ^R_{22}	—
RK2D	—	—	λ^R_{22}	λ^R_{32}

LHC phenomenology: Variety of final states

(Scenario RD1A: $\lambda^L_{23} = 1$)

$$pp \to \left\{ \begin{array}{l} U_1 U_1 \to s\tau\, s\tau \equiv \tau\tau + 2j \\ U_1 U_1 \to s\tau\, c\nu \equiv \tau + \not{E}_T + 2j \\ U_1 U_1 \to c\nu\, c\nu \equiv \not{E}_T + 2j \end{array} \right\}$$

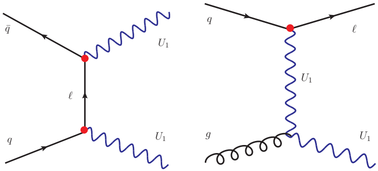
(Scenario RD1B: $\lambda^L_{33} = 1$)

$$pp \to \left\{ \begin{array}{l} U_1 U_1 \to b\tau\, b\tau \equiv \tau\tau + 2j \\ U_1 U_1 \to b\tau\, t\nu \equiv \tau + \not{E}_T + j_t + j \\ U_1 U_1 \to t\nu\, t\nu \equiv \not{E}_T + 2j_t \end{array} \right\}$$

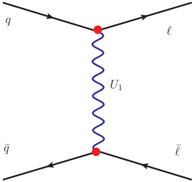
- Considering $R_{D^{(*)}}$ and $R_{K^{(*)}}$ scenarios gives us different signatures to look for at the LHC.

Different production Modes and Decays

Resonant Production processes

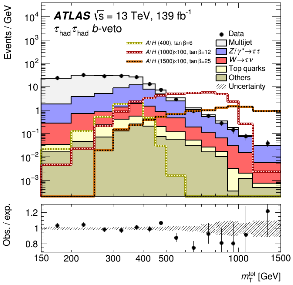


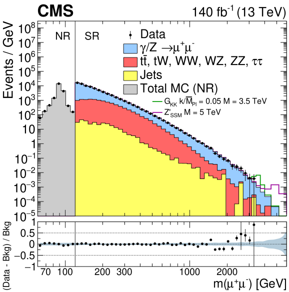
Non-resonant Production processes



- The non-resonant production interferes with the SM backgrounds process of $pp \to \gamma/Z(W) \to \ell^+\ell^-$.
- The interference and t-channel U_1 exchange are independent of the branching ratio.
- The non-resonant production methods contribute significantly for large values of the couplings.

ATLAS $\tau\tau$ search 139 fb^{-1} and CMS $\mu\mu$ search 140 fb^{-1}





- All the production modes result in dileptons in the final state.
- The t channel process interferes destructively with the SM process. This leads to a reduction in the number of events.

Recasting the LHC data

- Chi-square test is performed, with the test statistic:

$$\chi^2 = \sum_i \left[\frac{N_T^i - N_D^i}{\Delta N^i}\right]^2$$

Events are combined as follows:

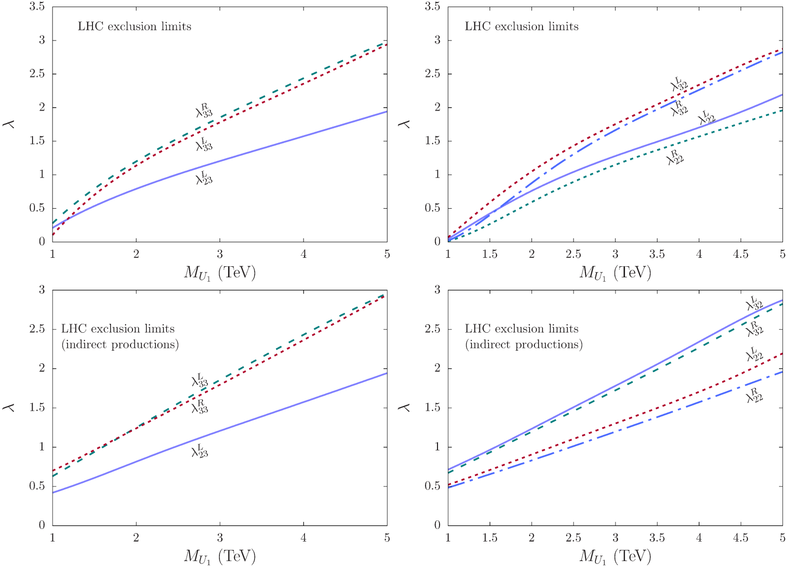
$$\begin{aligned} N_T^i &= N_{\mathcal{S}_1}^i + N_{BG}^i \\ &= \left[N_p + N_s^{incl} + N_t - N_\times\right]^i + N_{BG}^i \end{aligned}$$

using total uncertainity,

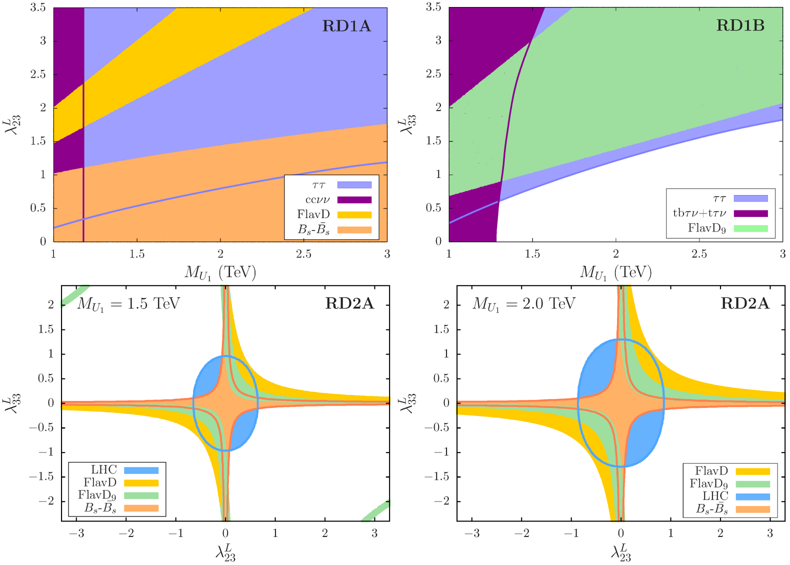
$$\Delta N^i = \sqrt{\left(\Delta N_{Stat}^i\right)^2 + \left(\Delta N_{Syst}^i\right)^2}$$

where, $\Delta N_{stat}^i = \sqrt{N_D^i}$ and we assume $\Delta N_{sys}^i = \delta^i \times N_D^i$

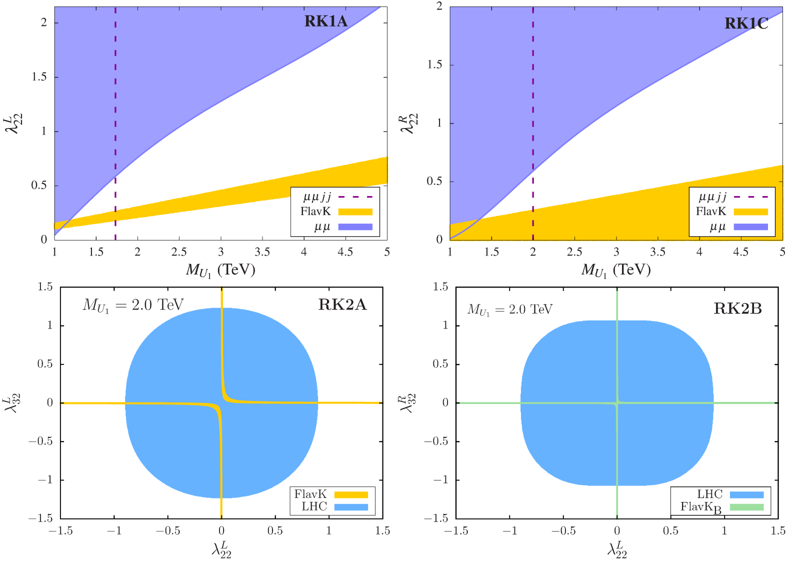
LHC Exclusion Limits



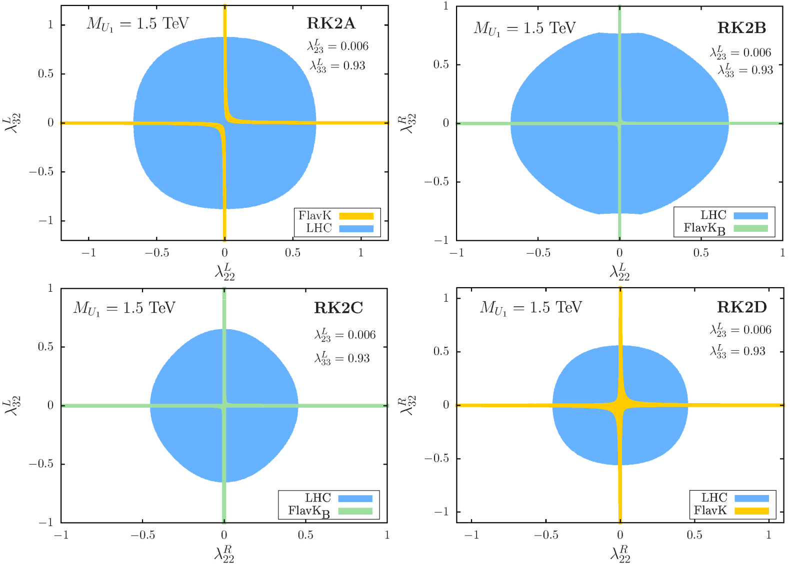
Bounds from LHC and $R_{D^{(*)}}$ data



Bounds from LHC and $R_{K^{(*)}}$ data



A 1.5 TeV U_1 can explain $R_{D^{(*)}}$ and $R_{K^{(*)}}$



Conclusions

- The $R_{D^{(*)}}$ and $R_{K^{(*)}}$ can lead to different signatures at the LHC. From an EFT approach the new couplings may appear same but decay modes of the LQ due to the couplings are different.
- At the low mass regions, the contributions from the resonant production are significant.
- The interference between the t-channel U_1 process and the SM is destructive.
- A 1.5 TeV LQ can explain $R_{D^{(*)}}$ and $R_{K^{(*)}}$ anomalies.
- For a detailed study, please refer to arxiv: 2101.12069

Cross-section Parametrization: Pair Production

Total cross section:

$$\sigma^{p}\left(M_{U_1},\lambda\right)=\sigma^{p_0}\left(M_{U_1}\right)+\sum_{i}^{n}\lambda_i^2\sigma_i^{p_2}\left(M_{U_1}\right)+\sum_{i\geq j}^{n}\lambda_i^2\lambda_j^2\sigma_{ij}^{p_4}\left(M_{U_1}\right)$$

No. of surviving events:

$$\mathcal{N}^{p}=\sigma^{p}\times\epsilon^{p}\left(M_{U_1},\lambda\right)\times\mathcal{B}^2(M_{U_1},\lambda)$$

$$=\left\{\sigma^{p_0}\times\epsilon^{p_0}+\sum_{i}^{n}\lambda_i^2\sigma_i^{p_2}\times\epsilon_i^{p_2}+\sum_{i\geq j}^{n}\lambda_i^2\lambda_j^2\sigma_{ij}^{p_4}\times\epsilon_{ij}^{p_4}\right\}\times\mathcal{B}^2(M_{U_1},\lambda)\times L$$

Cross-section Parametrization: Single Production

Total cross section:

$$\sigma^s(M,\lambda_i) = \sum_i^n \lambda_i^2 \sigma_i^{s_2}(M_{U_1}) + \sum_{i\geq j\geq k}^n \lambda_i^2 \lambda_j^2 \lambda_k^2 \sigma_{ijk}^{s_6}(M_{U_1})$$

No. of surviving events:

$$\mathcal{N}^s = \sigma^s \times \epsilon^s\,(M_{U_1},\lambda) \times \mathcal{B}(M_{U_1},\lambda) \times L$$

$$=$$

$$\left\{ \sum_i \lambda_i^2 \sigma_i^{s_2}(M_{U_1})\epsilon_i^{s_2}(M_{U_1}) + \sum_{i\geq j\geq k} \lambda_i^2 \lambda_j^2 \lambda_k^2 \sigma_{ijk}^{s_6}(M_{U_1})\epsilon_{ijk}^{s_6}(M_{U_1}) \right\} \cdot \mathcal{B}(M_{U_1},\lambda_i) \cdot L$$

Cross-section Parametrization: Non-resonant Production

Total cross section:

$$\sigma^{nr}(M_{U_1},\lambda) = \sum_{i}^{n} \lambda_i^2 \sigma_i^{nr_2}(M_{U_1}) + \sum_{i\geq j}^{n} \lambda_i^2 \lambda_j^2 \sigma_{ij}^{nr_4}(M_{U_1})$$

No. of surviving events:

$$\mathcal{N}^{nr} = \sigma^{nr} \times \epsilon^{nr}\ (M_{U_1},\lambda) \times L$$

$$= \left\{ \sum_{i}^{n} \lambda_i^2 \sigma_i^{nr_2}(M_{U_1}) \times \epsilon_i^{nr_2}(M_{U_1}) + \sum_{i\geq j}^{n} \lambda_i^2 \lambda_j^2 \sigma_{ij}^{nr_4}(M_{U_1}) \times \epsilon_{ij}^{nr_4}(M_{U_1}) \right\} \times L$$

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