Analyzing semileptonic $b \to u$ transitions with vector and scalar leptoquarks

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Contents

Introduction and Motivation

Flavor Changing Charged Current ($b \to c$)

- With no concrete direct evidence for New Physics (NP) in the experimental sector, indirect channels can be a prominent way to look for NP.
- B sector anomalies have hinted at NP presence.
- Experimental values of $R(D)$ and $R(D^*)$ in $b \to c\ell\nu_\ell$ transitions exhibit discrepancies at 1.5σ and 2.5σ, respectively from Standard Model (SM) predictions [1]

	Experimental value	SM value
$R(D)$	0.342 ± 0.026	0.298 ± 0.004
$R(D^*)$	0.287 ± 0.012	0.254 ± 0.005

where

$$R(D^{(*)}) = \frac{Br(B \to D^{(*)}\tau\nu_\tau)}{Br(B \to D^{(*)}l\nu_l)}$$

- The $b \to c$ sector is a well-explored sector.

[1] https://hflav-eos.web.cern.ch/hflav-eos/semi/moriond24/html/RDsDsstar/RDRDs.html

Flavor Changing Charged Current ($b \to u$)

- $b \to u \ell \nu_\ell$ sector is not extensively probed for NP. We examine the decay channel $B_c \to D \ell \nu_\ell$ in this work.
- LHCb future upgrade is expected to measure these modes with sufficient accuracy [2].
- Lattice QCD calculations for form factors [3] pertaining to these modes are also available.
- For $b \to u$ transitions, only two decay channels (for $\ell = \tau$) are experimentally observed.

	Experimental value[4]	Calculated SM value
$B \to \tau \nu_\tau$	$1.09 \pm 0.24 \times 10^{-4}$	$0.89 \pm 0.14 \times 10^{-4}$
$B \to \pi \tau \nu_\tau$	$< 2.5 \times 10^{-4}$	$1.14 \pm 0.18 \times 10^{-4}$

- Does not have sufficient number of observables to constrain NP. Existing constraints are also not reliable.

[2] R. Aaij et al. (LHCb Collaboration), arXiv:1808.08865

[3] Cooper, Laurence J. and Davies, Christine T. H. and Wingate, Matthew, Phys. Rev. D 105, 014503 (2022)

[4] S. Navas et al. (Particle Data Group), to be published in Phys. Rev. D 110, 030001 (2024)

Motivation to correlate

- Unreliability on existing constraints motivates us to correlate Wilson coefficients of $b \to u$ to properly observed $b \to c$ transitions.
- Model dependent approach can be used to correlate and analyze.
- Here, we explore $B_c \to D\tau\nu_\tau$ channel within two Leptoquark Models (U_1 and S_1).

Theoretical Framework

Effective Hamiltonian

Including NP contributions, the effective Hamiltonian for $b \to q\ell\nu_\ell$ transitions can be written as

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{qb}[(1 + C_{V_L})\mathcal{O}_{V_L} + C_{V_R}\mathcal{O}_{V_R} + C_{S_L}\mathcal{O}_{S_L} + C_{S_R}\mathcal{O}_{S_R} + C_T\mathcal{O}_T],$$

where $q = u$ or c; C_{V_L} C_{V_R}, C_{S_L}, C_{S_R} and C_T are the vector, scalar and tensor Wilson coefficients, and

$$\begin{aligned}
\mathcal{O}_{V_L} &= (\bar{q}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma^\mu \nu_{\ell L}) \\
\mathcal{O}_{V_R} &= (\bar{q}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma^\mu \nu_{\ell L}) \\
\mathcal{O}_{S_L} &= (\bar{q}_R b_L)(\bar{\tau}_R \nu_{\ell L}) \\
\mathcal{O}_{S_R} &= (\bar{q}_L b_R)(\bar{\tau}_R \nu_{\ell L}) \\
\mathcal{O}_T &= (\bar{q}_R\sigma^{\mu\nu} b_L)(\bar{\tau}_R\sigma^{\mu\nu} \nu_{\ell L})
\end{aligned}$$

are the four-fermion operators.

Observables I

- **Differential Branching Fraction**

$$\frac{dBr}{dq^2}(B \to P\ell\nu_\ell) = \tau_B \frac{G_F^2|V_{ub}|^2}{192\pi^3 M_B^3} q^2 \sqrt{\lambda_P(q^2)}(1-\frac{m_\ell^2}{q^2})^2 \times$$
$$\Bigg\{|1+C_{V_L}+C_{V_R}|^2\left[\left(1+\frac{m_\ell^2}{2q^2}\right)H_{V,0}^2+\frac{3}{2}\frac{m_\ell^2}{q^2}H_{V,t}^2\right]$$
$$+\frac{3}{2}|C_{S_L}+C_{S_R}|^2 H_S^2 + 8|C_T|^2\left(1+\frac{2m_\ell^2}{q^2}\right)H_T^2$$
$$+3\mathrm{Re}[(1+C_{V_L}+C_{V_R})(C_{S_L}^*+C_{S_R}^*)]\frac{m_\ell}{\sqrt{q^2}}H_S H_{V,t}$$
$$-12\mathrm{Re}[(1+C_{V_L}+C_{V_R})C_T^*]\frac{m_\ell}{\sqrt{q^2}}H_T H_{V,0}\Bigg\},$$

Observables II

where

$$
\begin{aligned}
H_{V,0}(q^2) &= \sqrt{\frac{\lambda_P(q^2)}{q^2}}\, f_+(q^2), \\
H_{V,t}(q^2) &= \frac{M_B^2 - M_P^2}{\sqrt{q^2}}\, f_0(q^2) \\
H_S(q^2) &= \frac{M_B^2 - M_P^2}{m_b - m_u}\, f_0(q^2) \\
H_T(q^2) &= \frac{\sqrt{\lambda_P(q^2)}}{M_B + M_P}\, f_T(q^2)
\end{aligned}
$$

are helicity amplitudes and $f_0(q^2)$, $f_+(q^2)$ and $f_T(q^2)$ are the scalar, vector and tensor form factors.

Also, $\lambda_P(q^2) = ((M_B - M_P)^2 - q^2)((M_B + M_P)^2 - q^2)$.

Observables III

- **Lepton Flavor Universality (LFU) Ratio**

$$R = \frac{Br(B_c \to D\tau\nu_\tau)}{Br(B_c \to Dl\nu_l)}$$

- **Forward-Backward Asymmetry (A_{FB})**

$$A_{FB} = \frac{\int_0^1 \frac{d^2\Gamma}{dq^2 d\cos\theta}\, d\cos\theta - \int_{-1}^0 \frac{d^2\Gamma}{dq^2 d\cos\theta}\, d\cos\theta}{d\Gamma/dq^2} = \frac{b_\theta(q^2)}{d\Gamma/dq^2}$$

where the angular decay distribution with respect to q^2 and θ is given by

$$\frac{d^2\Gamma}{dq^2 d\cos\theta}(B \to P\ell\nu_\ell) = a_\theta(q^2) + b_\theta(q^2)\cos\theta + c_\theta(q^2)\cos^2\theta,$$

and b_θ determines the lepton forward-backward asymmetry.

$U_1 = (3,1)_{2/3}$ leptoquark model I

- Lagrangian[5] $\Longrightarrow \mathcal{L} \supset x_{ij}^{LL}\bar{Q}^i\gamma_\mu U_1^\mu P_L L^j + x_{ij}^{RR}\bar{d}_R^i\gamma_\mu U_1^\mu P_R l_R^j$
- Couplings in matrix form

$$x_{ij}^{LL(RR)} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} e & \mu & \tau \end{array} \\ \begin{pmatrix} \lambda_{11}^{L(R)} & \lambda_{12}^{L(R)} & \lambda_{13}^{L(R)} \\ \lambda_{21}^{L(R)} & \lambda_{22}^{L(R)} & \lambda_{23}^{L(R)} \\ \lambda_{31}^{L(R)} & \lambda_{32}^{L(R)} & \lambda_{33}^{L(R)} \end{pmatrix} \end{array}$$

- Expanding in the mass basis and assuming rotation in the up-type quark sector, we have

$$\mathcal{L} = [(\lambda_{13}^L V_{ud} + \lambda_{23}^L V_{us} + \lambda_{33}^L V_{ub})\bar{u}\gamma_\mu\nu_\tau + (\lambda_{13}^L V_{cd} + \lambda_{23}^L V_{cs} + \lambda_{33}^L V_{cb})\bar{c}\gamma_\mu\nu_\tau + \lambda_{33}^L\bar{b}_L\gamma_\mu\tau_L + \lambda_{33}^R\bar{b}_R\gamma_\mu\tau_R]U_1^\mu$$

[5] Arvind Bhaskar, Diganta Das, Tanumoy Mandal, Subhadip Mitra, and Cyrin Neeraj Phys. Rev. D 104, 035016 (2022)

$U_1 = (3,1)_{2/3}$ leptoquark model I

- Only C_{V_L} and C_{S_R} can be generated in U_1 leptoquark model

$$C_{V_L}(\mu_{LQ}) = \frac{1}{2\sqrt{2}G_F V_{qb}} \frac{\lambda^L_{q\nu}(\lambda^L_{b\tau})^*}{M^2_{U_1}}$$

$$C_{S_R}(\mu_{LQ}) = -\frac{1}{\sqrt{2}G_F V_{qb}} \frac{\lambda^L_{q\nu}(\lambda^R_{b\tau})^*}{M^2_{U_1}}$$

$U_1 = (3, 1)_{2/3}$ leptoquark model I

For $b \to u$ transition

$$C_{V_L}(\mu_{LQ}) = \frac{1}{2\sqrt{2}G_F V_{13}} \frac{\sum_{i=1}^{3} V_{1i}\lambda_{i3}^{L}\lambda_{33}^{L}}{M_{U_1}^2}$$

$$C_{S_R}(\mu_{LQ}) = -\frac{1}{\sqrt{2}G_F V_{13}} \frac{\sum_{i=1}^{3} V_{1i}\lambda_{i3}^{L}\lambda_{33}^{R}}{M_{U_1}^2}$$

For $b \to c$ transition

$$C_{V_L}(\mu_{LQ}) = \frac{1}{2\sqrt{2}G_F V_{23}} \frac{\sum_{i=1}^{3} V_{2i}\lambda_{i3}^{L}\lambda_{33}^{L}}{M_{U_1}^2}$$

$$C_{S_R}(\mu_{LQ}) = -\frac{1}{\sqrt{2}G_F V_{23}} \frac{\sum_{i=1}^{3} V_{2i}\lambda_{i3}^{L}\lambda_{33}^{R}}{M_{U_1}^2}$$

$S_1 = (\bar{3}, 1)_{1/3}$ leptoquark model

- Lagrangian[6] $\Longrightarrow \mathcal{L} \supset [g^L_{ij} \bar{Q}^c_i (i\tau_2) L_j + g^R_{ij} \bar{u}^c_i \ell_{R_j}] S^\dagger_1$
- Couplings in matrix form

$$g^{L(R)}_{ij} = \begin{array}{c} \\ u \\ c \\ t \end{array} \begin{array}{c} \begin{array}{ccc} e & \mu & \tau \end{array} \\ \begin{pmatrix} g^{L(R)}_{11} & g^{L(R)}_{12} & g^{L(R)}_{13} \\ g^{L(R)}_{21} & g^{L(R)}_{22} & g^{L(R)}_{23} \\ g^{L(R)}_{31} & g^{L(R)}_{32} & g^{L(R)}_{33} \end{pmatrix} \end{array}$$

- Expanding in the mass basis and assuming rotation in the up-type quark sector, we have

$$\begin{aligned} \mathcal{L} \;=\; & \{[g^L_{13}(V^*_{ud}\bar{u}^c + V^*_{cd}\bar{c}^c) + g^L_{23}(V^*_{us}\bar{u}^c + V^*_{cs}\bar{c}^c) + g^L_{33}(V^*_{ub}\bar{u}^c + V^*_{cb}\bar{c}^c)]\tau_L \\ & -g^L_{33}\bar{b}^c\nu_L + [g^R_{13}(V^*_{ud}\bar{u}^c + V^*_{cd}\bar{c}^c) + g^R_{23}(V^*_{us}\bar{u}^c + V^*_{cs}\bar{c}^c) \\ & +g^R_{33}(V^*_{ub}\bar{u}^c + V^*_{cb}\bar{c}^c)]\tau_R\} S^\dagger_1 \end{aligned}$$

[6] Ufuk Aydemir, Tanumoy Mandal and Subhadip Mitra, Phys. Rev. D 101, 015011 (2020)

$S_1 = (\bar{3}, 1)_{1/3}$ leptoquark model

- Only C_{V_L}, C_{S_L} and C_T can be generated in the S_1 leptoquark model

For $b \to u$ transition

$$\mathsf{C}_{V_L}(\mu_{LQ}) = \frac{1}{2\sqrt{2} G_F V_{13}} \frac{\sum_{i=1}^{3} V_{1i} g_{i3}^{L} g_{33}^{L}}{2 M_{S_1}^2}$$

$$\mathsf{C}_{S_L}(\mu_{LQ}) = -\frac{1}{2\sqrt{2} G_F V_{13}} \frac{\sum_{i=1}^{3} V_{1i} g_{i3}^{R} g_{33}^{L}}{2 M_{S_1}^2}$$

$$C_T(\mu_{LQ}) = -\frac{1}{4} C_{S_L}(\mu_{LQ})$$

For $b \to c$ transition

$$\mathsf{C}_{V_L}(\mu_{LQ}) = \frac{1}{2\sqrt{2} G_F V_{23}} \frac{\sum_{i=1}^{3} V_{1i} g_{i3}^{L} g_{33}^{L}}{2 M_{S_1}^2}$$

$$\mathsf{C}_{S_L}(\mu_{LQ}) = -\frac{1}{2\sqrt{2} G_F V_{23}} \frac{\sum_{i=1}^{3} V_{1i} g_{i3}^{L} g_{33}^{L}}{2 M_{S_1}^2}$$

$$C_T(\mu_{LQ}) = -\frac{1}{4} C_{S_L}(\mu_{LQ})$$

Renormalization-Group Equations (RGE)

Wilson coefficients at the Leptoquark scale (μ_{LQ}) scale are evolved to the μ_b using RGE [7]

$$\begin{pmatrix} C_{V_L}(\mu_b) \\ C_{V_R}(\mu_b) \\ C_{S_L}(\mu_b) \\ C_{S_R}(\mu_b) \\ C_T(\mu_b) \end{pmatrix} \equiv \begin{pmatrix} 1.12 & 0 & 0 & 0 & 0 \\ 0 & 1.07 & 0 & 0 & 0 \\ 0 & 0 & 1.91 & 0 & -0.38 \\ 0 & 0 & 0 & 2.00 & 0 \\ 0 & 0 & 0 & 0 & 0.89 \end{pmatrix} \begin{pmatrix} C_{V_L}(\mu_{LQ}) \\ C_{V_R}(\mu_{LQ}) \\ C_{S_L}(\mu_{LQ}) \\ C_{S_R}(\mu_{LQ}) \\ C_T(\mu_{LQ}) \end{pmatrix}$$

[7] Syuhei Iguro, Teppei Kitahara, Ryoutaro Watanabe, arXiv:2210.10751

Analysis

Constraints for the new couplings C_i

We use the following observables to constrain the new couplings :

- $b \to c$ sector

  $\Longrightarrow R(D)$, $R(D^*)$, $P_\tau^{D^*}$ and $Br(B_c \to \tau\nu_\tau)$

- $b \to u$ sector

  $\Longrightarrow Br(B \to \tau\nu_\tau)$, $Br(B \to \pi\tau\nu_\tau)$ and R_π^l
  where

$$R_\pi^l = \frac{Br(B \to \tau\nu_\tau)}{Br(B \to \pi l \nu_l)}$$

Observables	Experimental values
$R(D)$[1]	0.342 ± 0.026
$R(D^*)$[1]	0.287 ± 0.012
$P_\tau^{D^*}$[8]	$0.38^{-0.53}_{+0.55}$
$Br(B_c \to \tau\nu_\tau)$	$< 30\%$
$Br(B \to \tau\nu_\tau)$[4]	$1.09 \pm 0.24 \times 10^{-4}$
$Br(B \to \pi\tau\nu_\tau)$[4]	$< 2.5 \times 10^{-4}$
R_π^l[4]	0.727 ± 0.224

Table: Numerical values of observables

[8] S. Hirose et al. (Belle Collaboration) Phys. Rev. Lett. 118, 211801

- Predicted range for various couplings :

Table: U_1 Leptoquark

Couplings	Range
$\lambda^L_{13}\lambda^L_{33}$	[-1.341 – 0.231]
$\lambda^L_{23}\lambda^L_{33}$	[0.271 – 0.833]
$\lambda^L_{33}\lambda^L_{33}$	[-1.991 – 1.642]
$\lambda^L_{13}\lambda^R_{33}$	[-0.011 – 0.089]
$\lambda^L_{23}\lambda^R_{33}$	[-0.261 – 0.059]
$\lambda^L_{33}\lambda^R_{33}$	[-0.321 – 1.972]
C_{V_L}	[-2.234 – 0.568]
C_{S_R}	[-0.131 – 0.039]

Table: S_1 Leptoquark

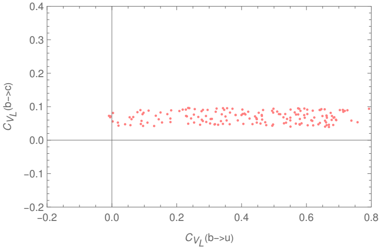
Couplings	Range
$g^L_{13}g^L_{33}$	[-0.193 – 0.083]
$g^L_{23}g^L_{33}$	[0.150 – 0.917]
$g^L_{33}g^L_{33}$	[-1.665 – 1.874]
$g^R_{13}g^L_{33}$	[-0.095 – 0.170]
$g^R_{23}g^L_{33}$	[-0.776 – 0.438]
$g^R_{33}g^L_{33}$	[-1.972 – 1.772]
C_{V_L}	[0.005 – 0.152]
C_{S_L}	[-0.011 – 0.046]
C_T	[-0.005 – 0.0012]

SM and LQ predictions for Br. Ratio, A_{FB} and LFU Ratio

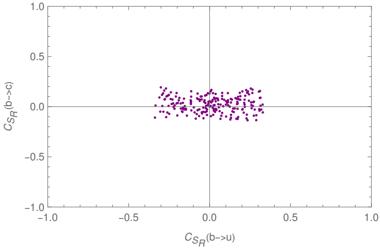
Observables	SM	U_1	S_1
$Br(B_c \to D\tau\nu_\tau)$	$(2.17 \pm 0.34) \times 10^{-5}$	$(2.21 - 4.93) \times 10^{-5}$	$(2.19 - 3.02) \times 10^{-5}$
A_{FB}	0.280	0.281 – 0.288	0.277 – 0.281
R	0.759	0.774 – 1.723	0.766 – 1.054

Wilson coefficients correlation (U_1)

Figure: Correlation between Wilson coefficients of $b \to u$ and $b \to c$ for U_1 leptoquark



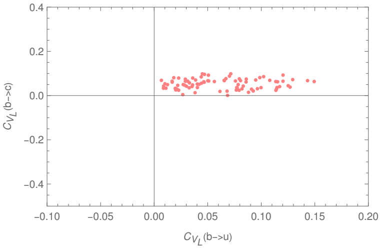
(a) C_{V_L}



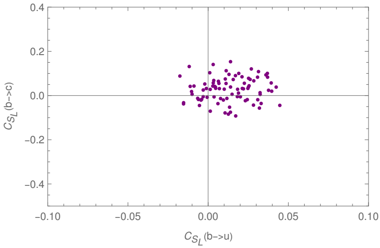
(b) C_{S_R}

Wilson coefficients correlation S_1

Figure: Correlation between Wilson coefficients of $b \to u$ and $b \to c$ for S_1 leptoquark



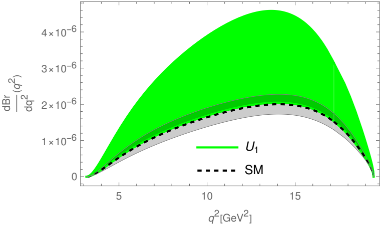
(a) C_{V_L}



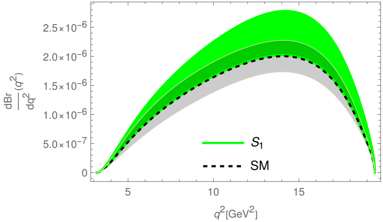
(b) C_{S_L}

Differential Branching Fraction

Figure: q^2-dependence of Differential Branching Fraction



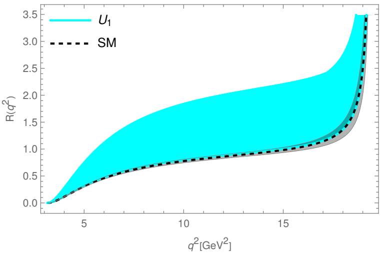
(a) U_1 Leptoquark



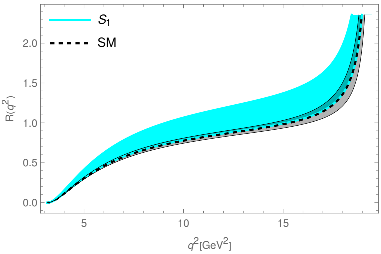
(b) S_1 Leptoquark

Lepton Flavor Universality Ratio

Figure: q^2-dependence of LFU ratio R



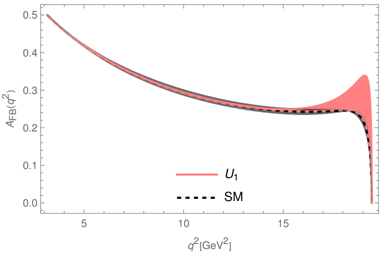
(a) U_1 Leptoquark



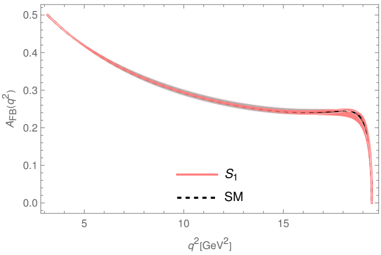
(b) S_1 Leptoquark

Forward-Backward Asymmetry

Figure: q^2-dependence of A_{FB}



(a) U_1 Leptoquark



(b) S_1 Leptoquark

Conclusion

Conclusion

- $B_c \to D\tau\nu_\tau$ decay mode is analysed within the SM and in the U_1 and S_1 Leptoquark models.
- NP couplings are constrained using available experimental measurements in the $b \to c$ and $b \to u$ sectors.
- Predictions of various observables, such as $dBr(B_c \to D\tau\nu_\tau)$, R and A_{FB} in SM as well as in U_1 and S_1 Leptoquark models are presented.
- The observables are found have more sensitivity in the presence of U_1 leptoquark compared to S_1 leptoquark.
- The LFU ratio can have large deviations from the SM and can be tested further to substantiate or rule out NP.
- A_{FB} has less sensitivity to the leptoquarks. A_{FB} in presence of U_1 leptoquark show deviations mainly at high q^2, where scalar coupling plays a dominating role.
- With future LHCb upgrade and precision measurements, these modes can be measured and tested for any NP sensitivity or constrain NP.

THANK YOU

BACK UP

Form factor I

Form factors can be parametrized as

$$f_(q^2) = P(q^2)^{-1} \sum_{n=0}^{N_n} c^{(n)} \hat{z}^{(n,N_n)}$$

where

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

and $c^{(n)}$ is defined in reference. We use the Bourreley-Caprini-Lellouch (BCL) parametrization.

For f_0

$$\hat{z}_0^{(n,N_n)} = z^n$$

For f_+

$$\hat{z}_+^{(n,N_n)} = z^n - \frac{n(-1)^{N_n+1-n}}{N_n + 1} z_{N_n+1}$$

Form factor II

$P(q^2)$ is given as

$$P(q^2) = 1 - \frac{q^2}{M_{res}^2}$$

and for f_0 and f_+ the value of M_{res} are

$m_{B(0^+)}$	5.627 GeV
$m_{B(1^-)}$	5.279 GeV

Results are derived from the Lattice QCD model. Details can be found in [9]

[9] Cooper, Laurence J. and Davies, Christine T. H. and Wingate, Matthew, Phys. Rev. D 105, 014503 (2022)

Decay Frame

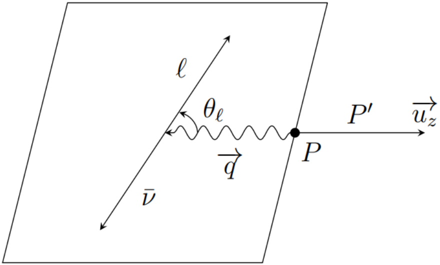
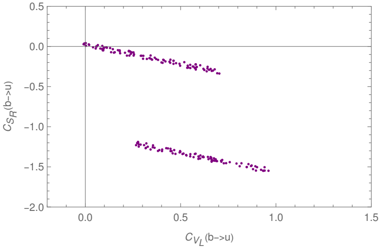


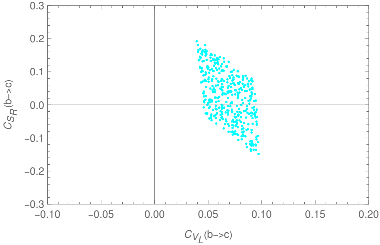
Figure: Angular convention for the process $P \to P' \tau \nu_t au$

U_1

Figure: Variation of Wilson coefficients C_{V_L} vs C_{S_R} for U_1 leptoquark



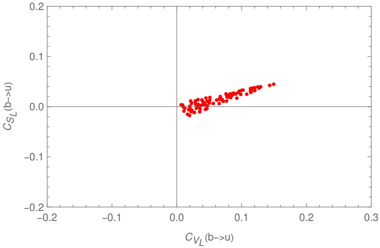
(a) For $b \to u$ transition



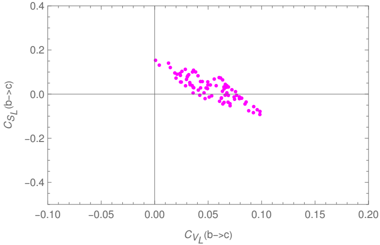
(b) For $b \to c$ transition

S_1

Figure: Variation of Wilson coefficients C_{V_L} vs C_{S_R} for S_1 leptoquark



(a) For $b \to u$ transition



(b) For $b \to c$ transition