Leptoquarks and recent anomalies in the Flavour Sector

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Based on: S. Sahoo and RM, PRD 91, 094019 (2015);
S. Sahoo and RM, PRD 93, 114001 (2016);
S. Sahoo, RM an A. Giri, PRD 95, 035027 (2017).

Candles of Darkness - 2017 ICTS, Bengaluru 07/06/2017

Outline

- Observed anomalies in the B sector

a. **$b \to s\, l^+ l^-$** (Neutral Current)

- $B_s \to \mu^+\mu^-$: Recent result and its Implications
- $B \to K^*\mu^+\mu^-$ measurements and anomalies
- $B_s \to \phi\mu^+\mu^-$ measurement

b. $b \to c\, \tau\nu$ (Charged Current)

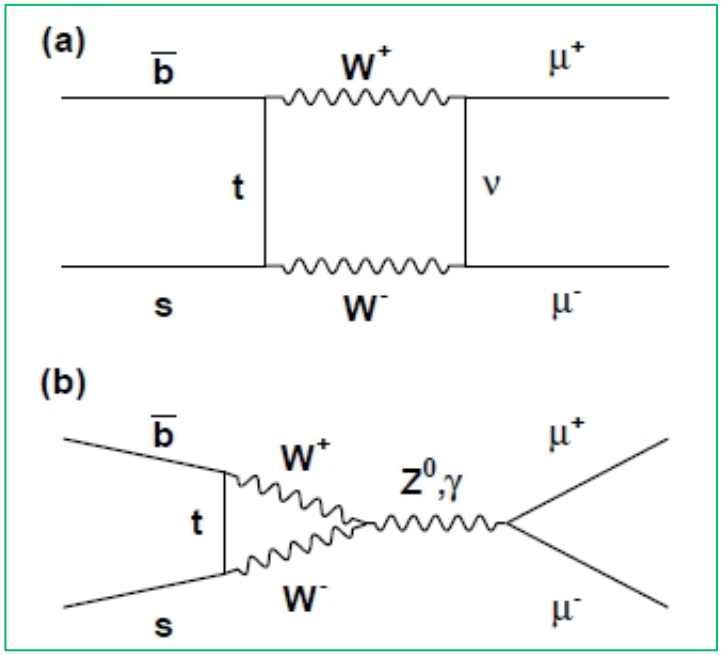
- $B \to D^{(*)}\, \tau\nu$ processes

- LQ model as a possible NP candidate

- Conclusion

$b \to s\, l^+ l^-$ transitions

- Rare B decays mediated by FCNC $b \to s$ are sensitive probe for NP
- These decays occur via box or penguin diagrams in the SM (loop suppressed)
- CKM suppressed ($\propto V_{tb} V_{ts}^*$)
- New Physics can possibly be seen at the same level of SM
- Allow indirect search for new particles

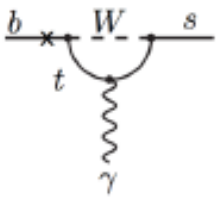


Effective Hamiltonian for b → s transition

- The most general effective Hamiltonian describing b → s transition in OPE is

$$H_{eff} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \left[C_i(\mu) O_i(\mu) + C_i'(\mu) O_i'(\mu) \right] \rightarrow$$

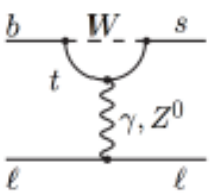
RH suppresed in SM



Electromagnetic penguin

$$Q_7^{(\prime)} = \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_{R(L)} b) F^{\mu\nu}$$

$b \rightarrow s l^+ l^-$

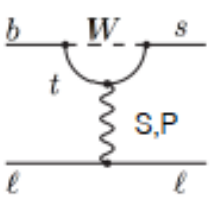


Semi-leptonic vector current

$$Q_9^{(\prime)} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu l)$$

Semi-leptonic A-V current

$$Q_{10}^{(\prime)} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_{L(R)} b)(\bar{l}\gamma^\mu \gamma_5 l)$$



Scalar

$$Q_S^{(\prime)} = \frac{e^2}{16\pi^2} (\bar{s}_{L(R)} b_{R(L)})(\bar{l}l)$$

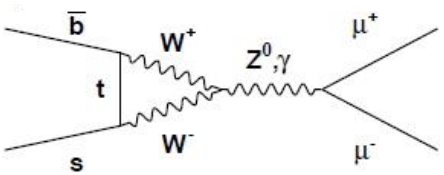
Pseudo-scalar

$$Q_P^{(\prime)} = \frac{e^2}{16\pi^2} (\bar{s}_{L(R)} b_{R(L)})(\bar{l}\gamma_5 l)$$

$B^0_{(s)} \rightarrow l^+ l^-$

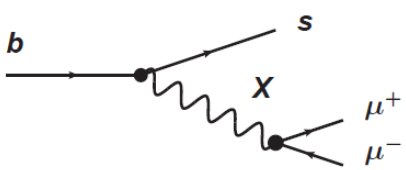
*four quark operators $Q_{1...6}$ only contribute through operator mixing.

Sensitivity to New Physics



$$\sim \frac{g^2}{16\pi^2}\frac{1}{M_W^2}V_{tb}V_{ts}^*$$

SM Amplitude is loop suppressed and CKM suppressed



$$\sim \frac{1}{\Lambda_{NP}^2}$$

Generic NP contributions not necessarily suppressed

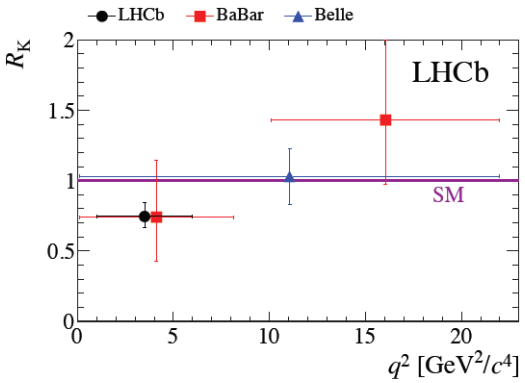
$$\Lambda_{NP} \sim \frac{M_W}{g^2}\sqrt{\frac{16\pi^2}{|V_{tb}V_{ts}^*|}} \sim 10 \text{ TeV}$$

Rare B decays can probe high scales, potentially sensitive to NP, beyond the direct search at LHC.

I. Lepton Flavour Universality Violation (LFUV)

LHCb : R_K= BR(B → K μμ)/BR(B → K ee)
in low q^2 region (1-6) GeV^2

$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$



R_K = 1.0003 ±0.0001
There is 2.6 σ deficit from SM prediction

$$\text{Br}(B^+ \to K^+\mu\mu)|_{[1-6]} = (1.19 \pm 0.07) \cdot 10^{-7}$$

$$\text{Br}(B^+ \to K^+\mu\mu)|^{SM}_{[1-6]} = (1.75^{+0.60}_{-0.29}) \cdot 10^{-7}$$

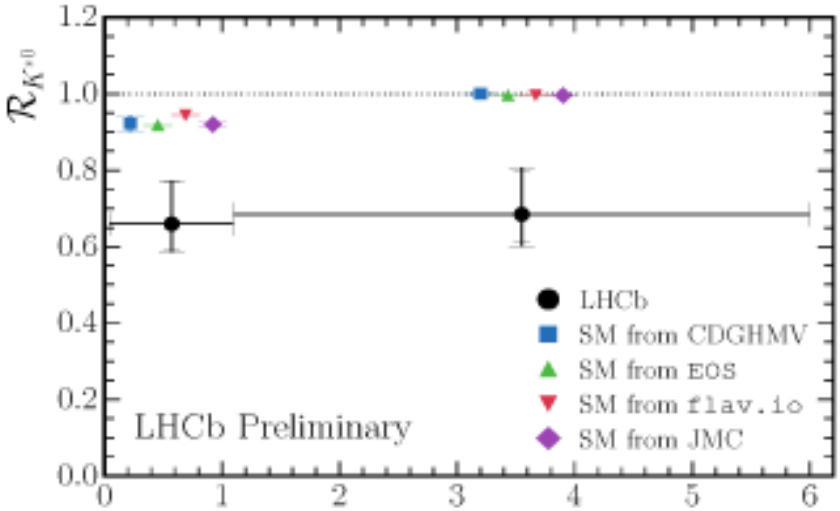
- BR(B^+ →K^+ ee) in agreement with SM
- Can be explained if possible NP contributes to b → s μμ not to b → s ee.

II. R_{K^*}= BR(B → K*μμ)/BR(B → K*ee)

- In April 2017, LHCb reported the measurement of R_{K^*} in two bins

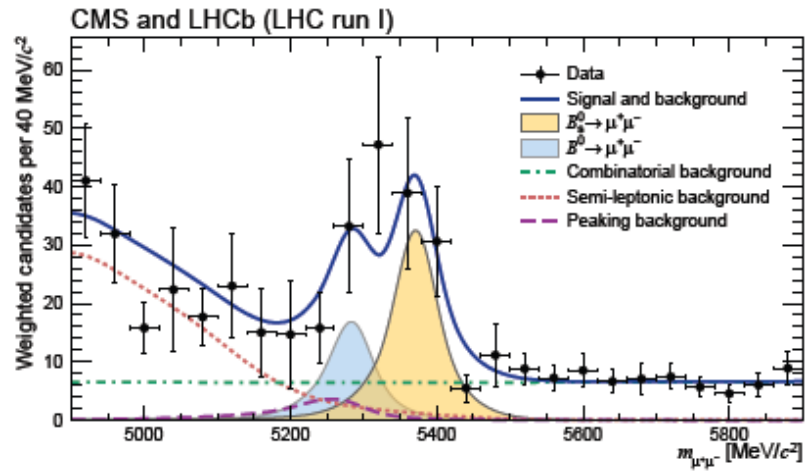
$$R_{K^*}^{\mathrm{LHCb}} = 0.660^{+0.110}_{-0.070} \pm 0.024, \qquad q^2 \in [0.045, 1.1]\ \mathrm{GeV}^2 \qquad \boxed{2.2\sigma}$$

$$R_{K^*}^{\mathrm{LHCb}} = 0.685^{+0.113}_{-0.069} \pm 0.047, \qquad q^2 \in [1.1, 6]\ \mathrm{GeV}^2 \qquad \boxed{2.4\sigma}$$



III. $B_s \to \mu\mu$

- Highly suppressed in SM, (CKM & Helicity suppressed)
- Very clean experimental signature, involve only f_B



$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (3.66 \pm 0.23) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (1.06 \pm 0.09) \times 10^{-10}$$

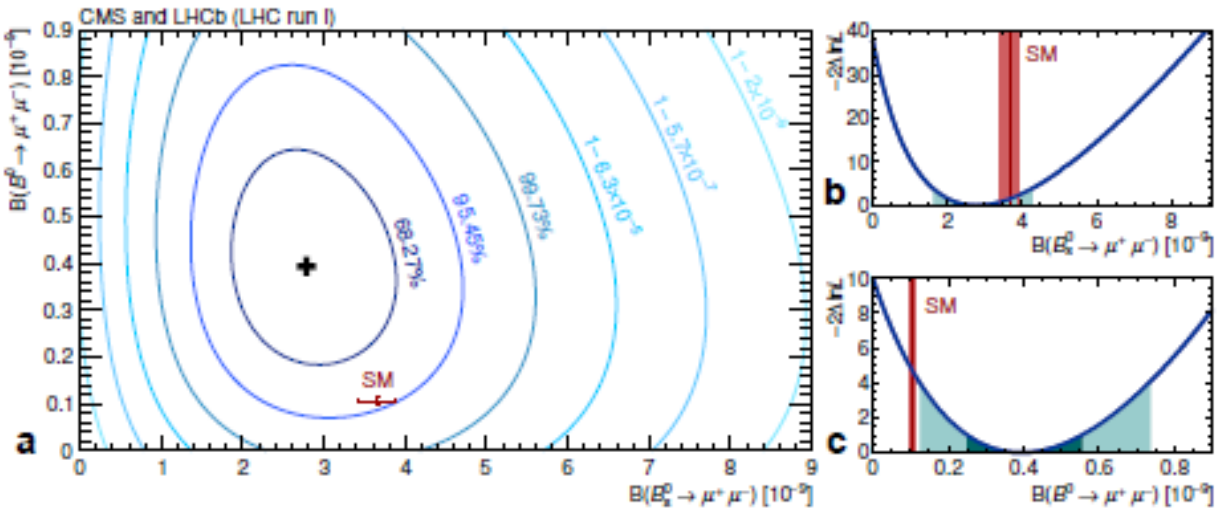
Precise SM predictions, Bobeth et al, PRL 112, 101801 (2014)
Updated in 1702.05498

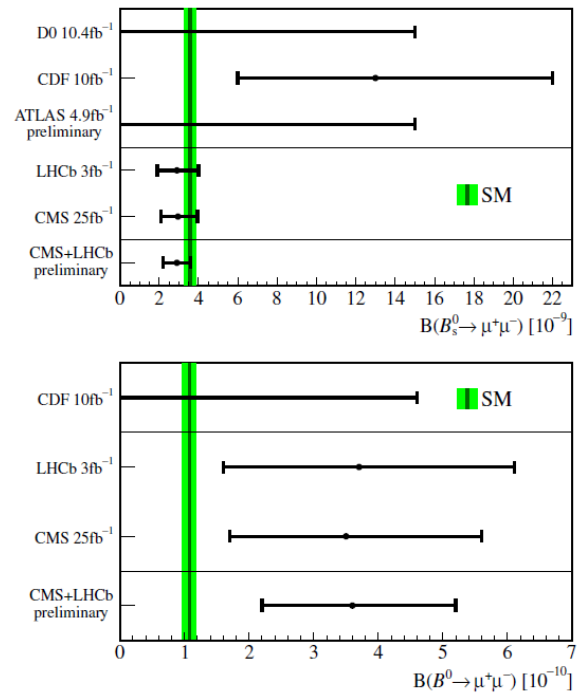
$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) = (2.8\,^{+0.7}_{-0.6}) \times 10^{-9}$$
$$\mathcal{B}(B^0 \to \mu^+\mu^-) = (3.9\,^{+1.6}_{-1.4}) \times 10^{-10}$$

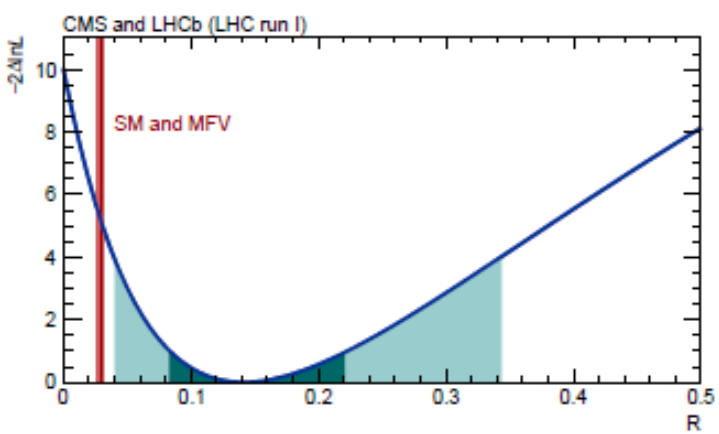
Combined LHCb and CMS data

- Observation of $B_s \to \mu\mu$ at 6.2 σ (Compatible with SM at 1.2 σ)
- Observation of $B_d \to \mu\mu$, excess events at 3 σ (Compatible with SM at 2.2 σ)

III. $B_s \to \mu\mu$



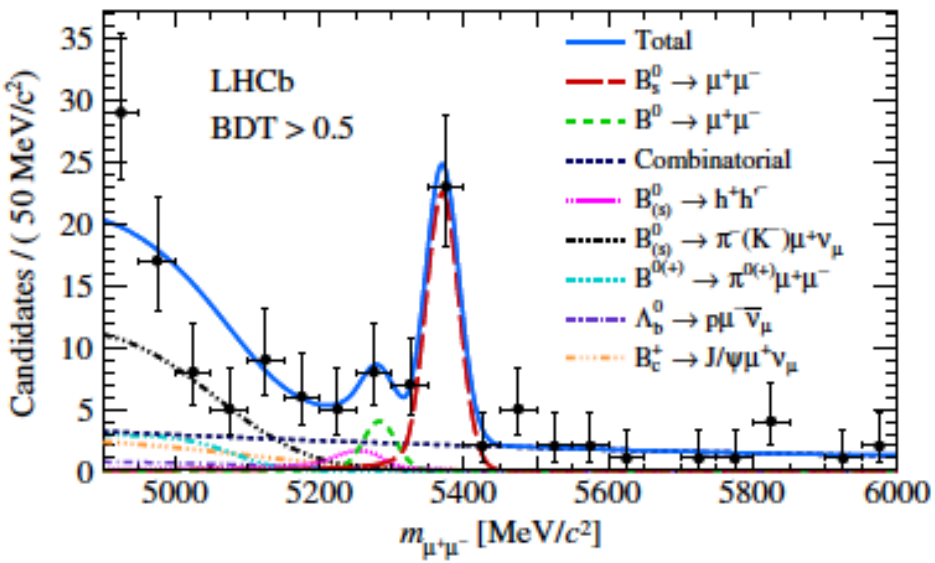




Compatible with SM at 2.3 σ

$$\mathcal{R} \equiv \mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-).$$

LHCb Run I + Run II

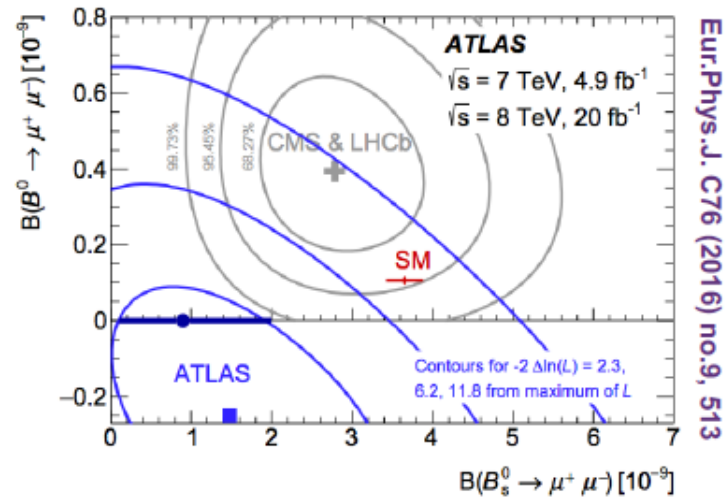


$$\mathcal{B}(B_s \to \mu^+\mu^-) = (3.0 \pm 0.6^{+0.3}_{-0.2}) \times 10^{-9}$$

$$\mathcal{B}(B_d \to \mu^+\mu^-) < 3.4 \times 10^{-10}$$

$B_s \to \mu\mu$ (7.8σ) and $B_d \to \mu\mu$ (1.6σ)

ATLAS

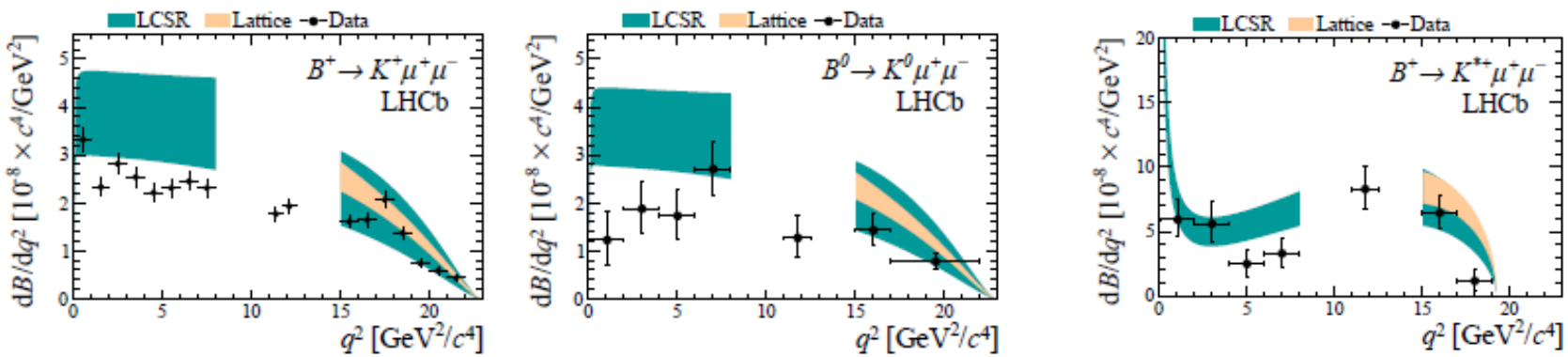


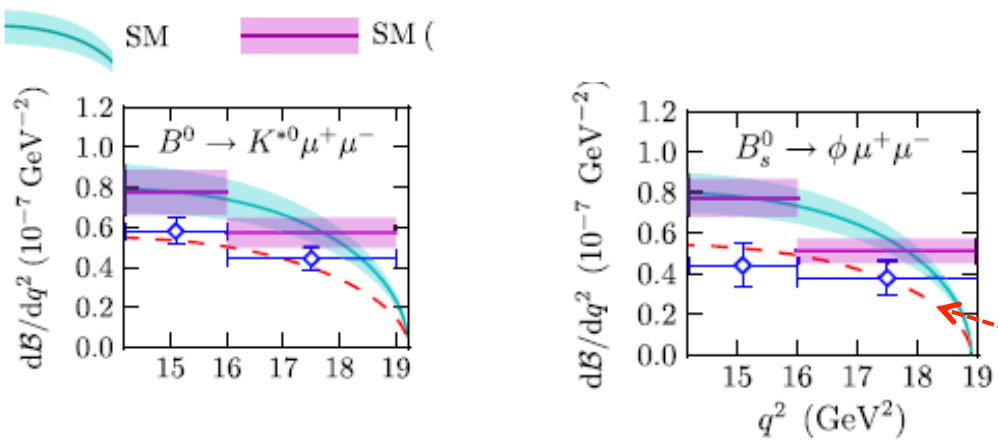
Eur.Phys.J. C76 (2016) no.9, 513

$$\mathcal{BR}(B_s \to \mu^+\mu^-) = 0.9^{+1.1}_{-0.8} \times 10^{-9}\ (2\sigma)$$

$$\mathcal{BR}(B_d \to \mu^+\mu^-) < 4.2 \times 10^{-10} (95\% CL)$$

IV. Results on b → s μμ branching fractions





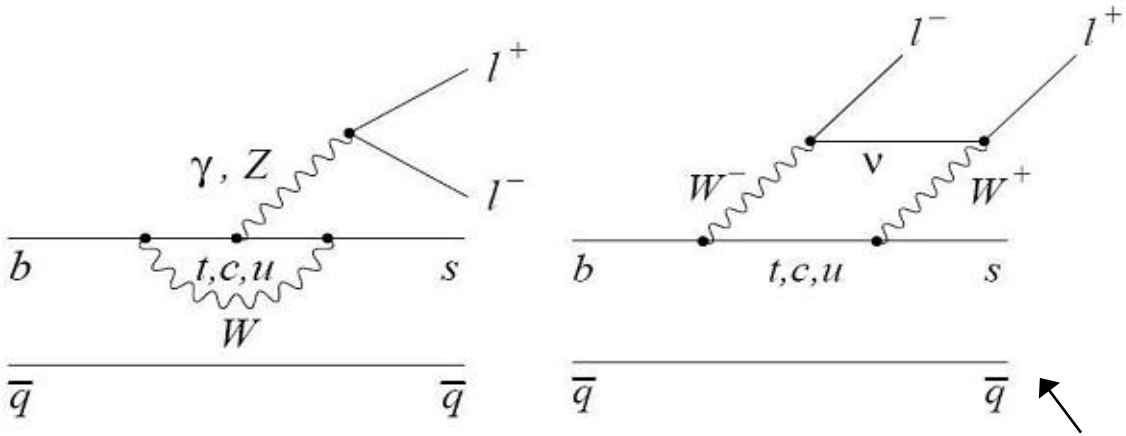
Data is average of LHCb, CMS, ATLAS and CDF.

$C_9 = C_9^{SM} - 1.0$
$C_9' = 1.2$

Branching ratio tend to lie below SM predictions
Horgan et al., PRL 112, 212003 (2014)

V. Results from $B_d \to K^*\mu^+\mu^-$

- The decay $B \to K^*(\to K\pi)\mu^+\mu^-$ plays a special role
- Ang dist. of the 4-body final state gives numerous observables sensitive to NP.



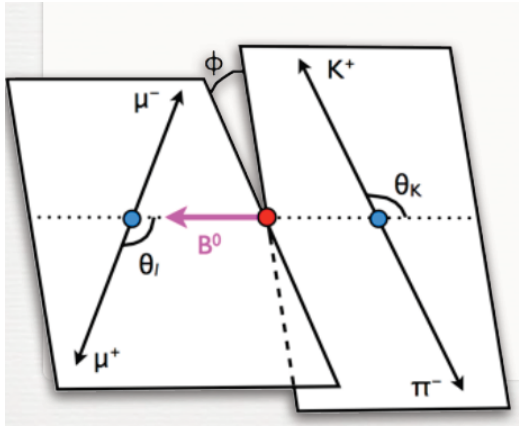
- Forbidden at tree level
- Penguin and Box diagrams

- Assortment of measurables whose dependence on $\mu^+\mu^-$ mass can reveal NP

- Angular distributions: Forward-Backward asymmetry and its zero point

- The decay distribution of B^0

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi}\Big[I_1^s \sin^2\theta_K + I_1^c \cos^2\theta_K + I_2^s \sin^2\theta_K \cos 2\theta_\ell + I_2^c \cos^2\theta_K \cos 2\theta_\ell + I_3 \sin^2\theta_K \sin^2\theta_\ell \cos 2\phi + I_4 \sin 2\theta_K \sin 2\theta_\ell \cos\phi + I_5 \sin 2\theta_K \sin\theta_\ell \cos\phi + I_6 \sin^2\theta_K \cos\theta_\ell + I_7 \sin 2\theta_K \sin\theta_\ell \sin\phi + I_8 \sin 2\theta_K \sin 2\theta_\ell \sin\phi + I_9 \sin^2\theta_K \sin^2\theta_\ell \sin 2\phi \Big],$$



- Combining B^0 and $\overline{B}^0$ decays,

CP Avg. $S_j = (I_j + \bar{I}_j) \Big/ \frac{d\Gamma}{dq^2}$ or $A_j = (I_j - \bar{I}_j) \Big/ \frac{d\Gamma}{dq^2}$. CP Asymmetry

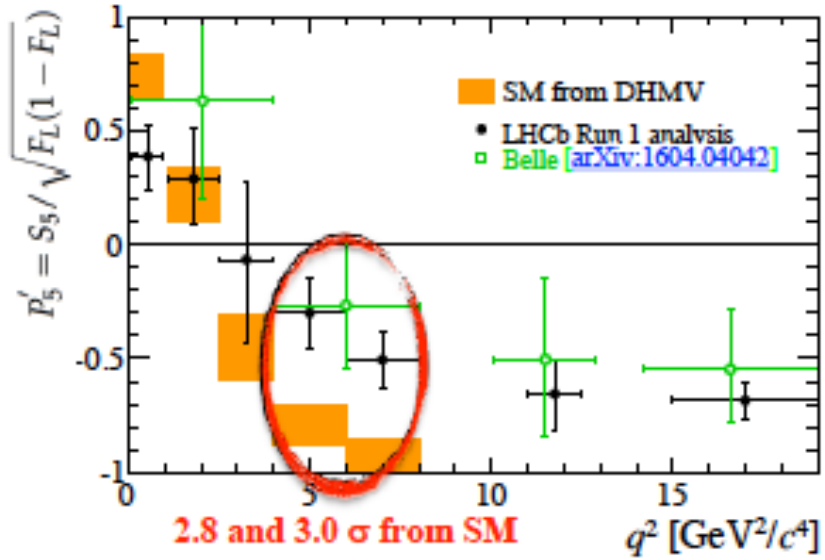
S_7, S_8 and S_9 depend on combinations $\mathrm{Im}(\mathcal{A}_m \mathcal{A}_n^*)$

- Supressed by small size of strong phase and are expected to be zero for the full q^2 (A_7, A_8 and A_9 are not)

Result on P_5'

Less form-factor dependent observable:
(smaller theoretical uncertainties)

$$P_5' = \frac{S_5}{\sqrt{F_L(1-F_L))}}$$



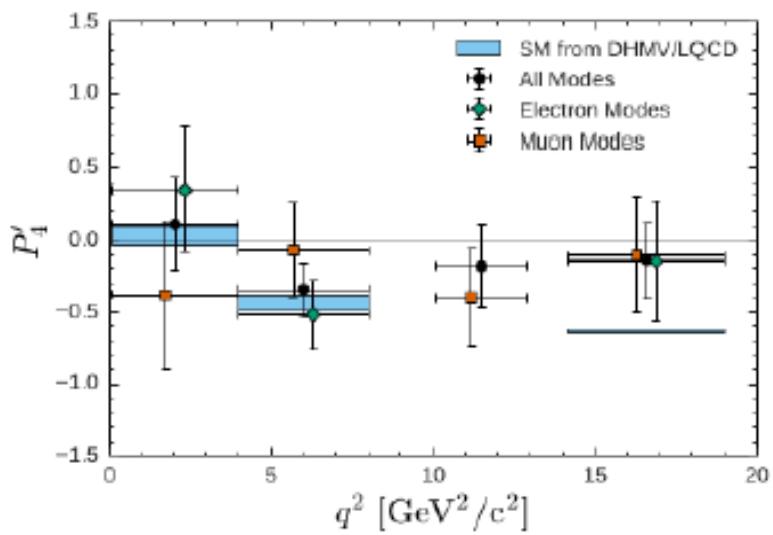
[Descotes-Genon et al, JHEP 05 (2013) 137]

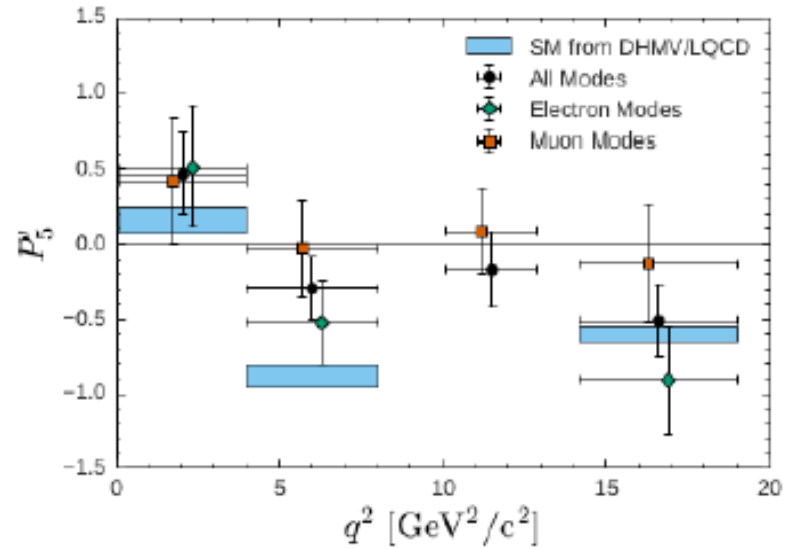
- Two bins each show local deviations of ~3 σ

(LHCb: 3 fb^{-1} data, 3.4 sigma deviation 1512.04442)

New Belle result consistent with LHCb

Belle Results on $P'_{4,5}$

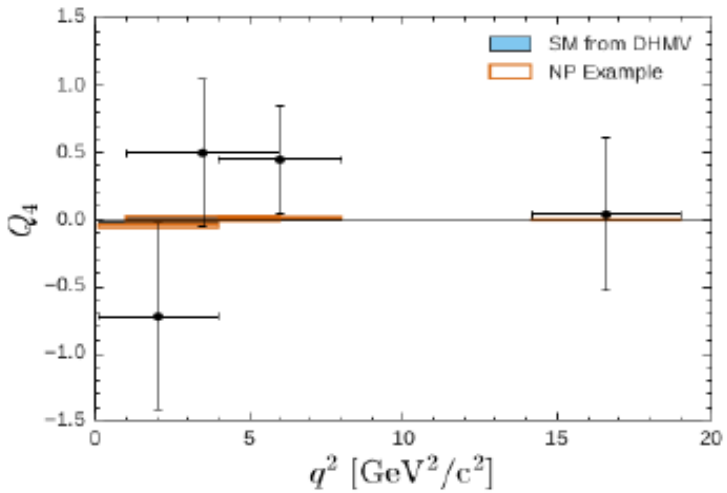


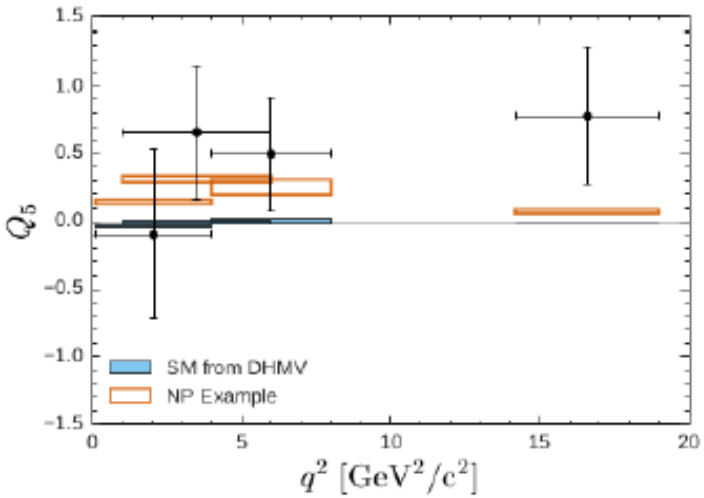


Includes $B^0 \to K^{*0}\mu^+\mu^-$, $B^+ \to K^{*+}\mu^+\mu^-$, $B^0 \to K^{*0}e^+e^-$, and $B^+ \to K^{*+}e^+e^-$

1612.05014

$Q_{4,5}$ Observables: $Q_i = P_i'^{\mu} - P_i'^{e}$





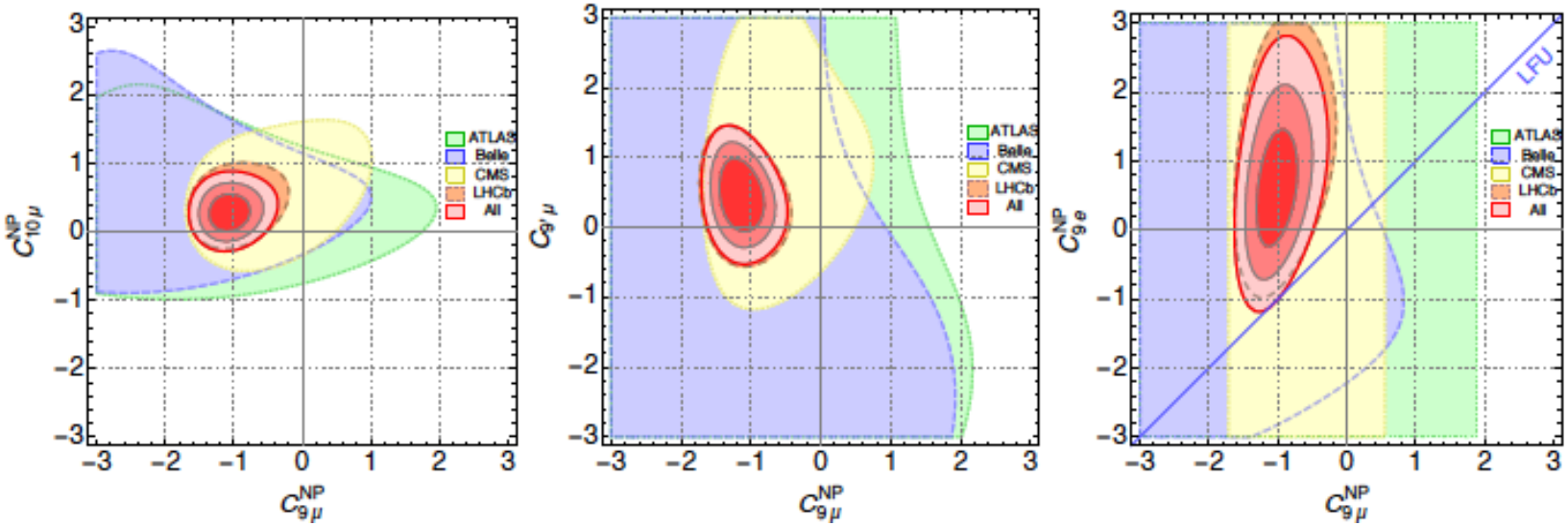
NP Scenario: $C_{9\mu}^{\mathrm{NP}} = -1.1$ (1612.15014)

b → s μμ Anomalies

Decay	obs.	q^2 bin	SM pred.	measurement		pull
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[2, 4.3]$	0.81 ± 0.02	0.26 ± 0.19	ATLAS	$+2.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	F_L	$[4, 6]$	0.74 ± 0.04	0.61 ± 0.06	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	S_5	$[4, 6]$	-0.33 ± 0.03	-0.15 ± 0.08	LHCb	-2.2
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[1.1, 6]$	-0.44 ± 0.08	-0.05 ± 0.11	LHCb	-2.9
$\bar{B}^0 \to \bar{K}^{*0}\mu^+\mu^-$	P_5'	$[4, 6]$	-0.77 ± 0.06	-0.30 ± 0.16	LHCb	-2.8
$B^- \to K^{*-}\mu^+\mu^-$	$10^7 \frac{d\mathrm{BR}}{dq^2}$	$[4, 6]$	0.54 ± 0.08	0.26 ± 0.10	LHCb	$+2.1$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{d\mathrm{BR}}{dq^2}$	$[0.1, 2]$	2.71 ± 0.50	1.26 ± 0.56	LHCb	$+1.9$
$\bar{B}^0 \to \bar{K}^0\mu^+\mu^-$	$10^8 \frac{d\mathrm{BR}}{dq^2}$	$[16, 23]$	0.93 ± 0.12	0.37 ± 0.22	CDF	$+2.2$
$B_s \to \phi\mu^+\mu^-$	$10^7 \frac{d\mathrm{BR}}{dq^2}$	$[1, 6]$	0.48 ± 0.06	0.23 ± 0.05	LHCb	$+3.1$

arXiv:1503.06199

Best fit Results (arXiv: 1704.05340)



Global fit: $C_{9\mu}^{\rm NP} = -1.1$

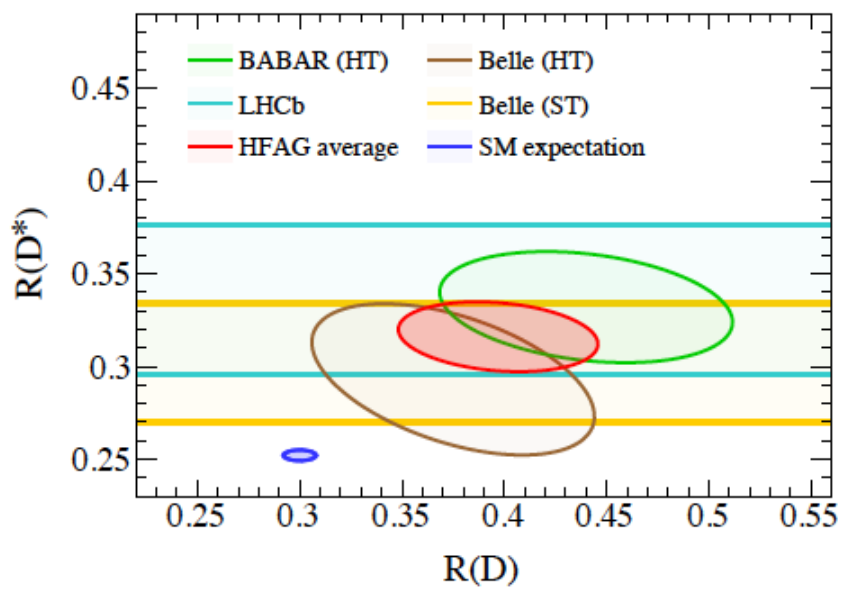
Other coefficients play a secondary role: C_9^{NP}, $C_9^{NP} = -C_{10}^{NP}$, $C_9^{NP} = -C_{9'}^{NP}$

R_{D^*} Anomaly in $B \to D^{(*)} l \nu$ (Tree level)

- Belle/BaBar/LHCb: $R_{D^{(*)}} = \frac{\Gamma(B \to D^{(*)} \tau \bar{\nu})}{\Gamma(B \to D^{(*)} l \bar{\nu})}$

$R_D = 0.397 \pm 0.049$ (World Ave.)
$= 0.30 \pm 0.01$ (SM)

$R_{D^*} = 0.316 \pm 0.016$ (World Ave)
$= 0.252 \pm 0.005$ (SM)



$\sim 4\sigma$ deviation from SM predictions

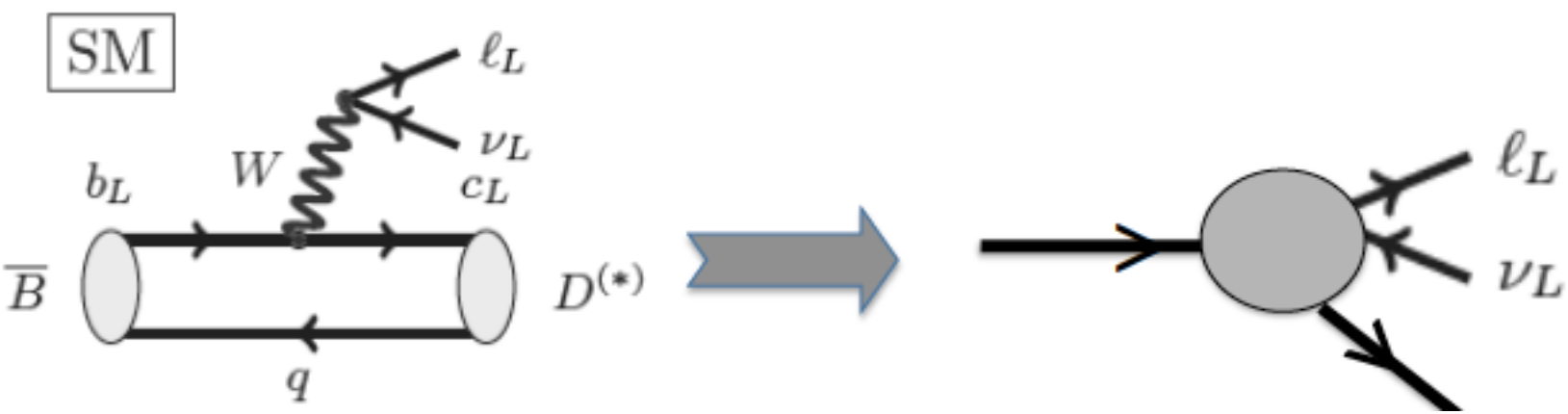
NP competing with SM at tree level

Effective Hamitonian for b →c τ ν

$$\mathcal{H}_{\rm eff} = \frac{4G_F}{\sqrt{2}} V_{cb} \Big[\left(\delta_{l\tau} + C^l_{V_1}\right) \mathcal{O}^l_{V_1} + C^l_{V_2}\mathcal{O}^l_{V_2} + C^l_{S_1}\mathcal{O}^l_{S_1} + C^l_{S_2}\mathcal{O}^l_{S_2} \Big],$$

where the operators are

$$\mathcal{O}^l_{V_1} = (\bar{c}_L\gamma^\mu b_L)(\bar{\tau}_L\gamma_\mu\nu_{lL}), \qquad \mathcal{O}^l_{V_2} = (\bar{c}_R\gamma^\mu b_R)(\bar{\tau}_L\gamma_\mu\nu_{lL}),$$
$$\mathcal{O}^l_{S_1} = (\bar{c}_L b_R)(\bar{\tau}_R\nu_{lL}), \qquad \mathcal{O}^l_{S_2} = (\bar{c}_R b_L)(\bar{\tau}_R\nu_{lL}).$$



Leptoquarks

- LQs are color triplet bosons
- Coupled to Quarks and Lepton simultaneously
- Classified by F = 3B + L, F= 0,2
- Spin=0,1
- Naturally emerge in many extensions of SM
- |Q|=1/3, 2/3, 4/3, 5/3
- Representation under SM Gauge group:

  Triplet under SU(3): as Q(triplet) and L(singlet)

  Singet, Doublet, Triplet under SU(2): As LH quarks and leptons are doublets and RH are singlets

  Y is characterized by the charge $Q = T_3+Y$
- Intergenerational mixing is severely restricted by FCNC data

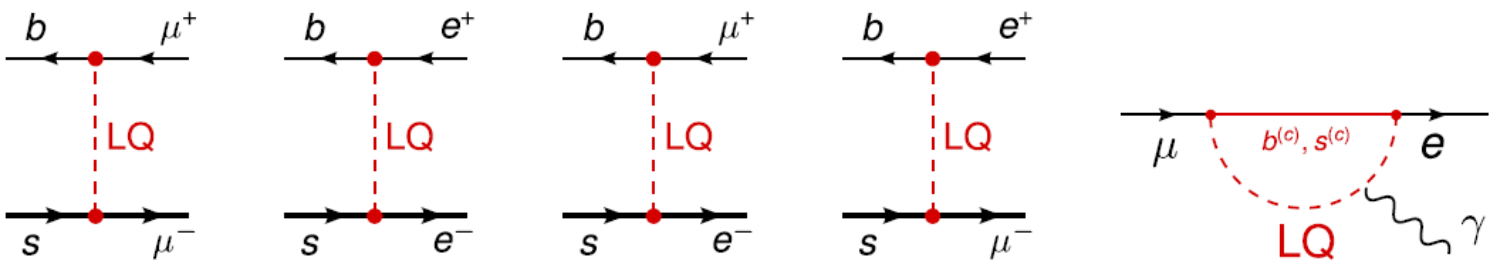
List of Scalar and Vector LQs (1603.04993)

$(SU(3), SU(2), U(1))$	Spin	Symbol	Type	F
$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	0	S_3	$LL\,(S_1^L)$	-2
$(\mathbf{3}, \mathbf{2}, 7/6)$	0	R_2	$RL\,(S_{1/2}^L)$, $LR\,(S_{1/2}^R)$	0
$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\tilde{R}_2$	$RL\,(\tilde{S}_{1/2}^L)$, $\overline{LR}\,(\tilde{S}_{1/2}^{\overline{L}})$	0
$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\tilde{S}_1$	$RR\,(\tilde{S}_0^R)$	-2
$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	0	S_1	$LL\,(S_0^L)$, $RR\,(S_0^R)$, $\overline{RR}\,(S_0^{\overline{R}})$	-2
$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	0	$\bar{S}_1$	$\overline{RR}\,(\bar{S}_0^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{3}, 2/3)$	1	U_3	$LL\,(V_1^L)$	0
$(\overline{\mathbf{3}}, \mathbf{2}, 5/6)$	1	V_2	$RL\,(V_{1/2}^L)$, $LR\,(V_{1/2}^R)$	-2
$(\overline{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\tilde{V}_2$	$RL\,(\tilde{V}_{1/2}^L)$, $\overline{LR}\,(\tilde{V}_{1/2}^{\overline{R}})$	-2
$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\tilde{U}_1$	$RR\,(\tilde{V}_0^R)$	0
$(\mathbf{3}, \mathbf{1}, 2/3)$	1	U_1	$LL\,(V_0^L)$, $RR\,(V_0^R)$, $\overline{RR}\,(V_0^{\overline{R}})$	0
$(\mathbf{3}, \mathbf{1}, -1/3)$	1	$\bar{U}_1$	$\overline{RR}\,(\bar{V}_0^{\overline{R}})$	0

Leptoquark Model

Wise et al, PRD 88,035009 (2013)

- $|F|$ can be either 0 or 2 depending on whether LQ couples to fermion-antifermion pair or fermion-fermion pair
- F = 0 interaction between leptoquark and quark-lepton pair due to a scalar doublet: X = (3, 2, 7/6) and X = (3, 2, 1/6) or vector U^3_μ (3, 3, 2/3) or singlets U^1_μ (3, 1, 2/3).
- Couplings are not lepton flavour universal or conserving



Scalar LQs and b → s processes

- Models with scalar leptoquarks can modify the $\mathbf{H}_{\text{eff}}$
- Minimal renormalizable scalar LQ model with *B* and *L* conserving couplings which do not allow proton decay
- X = (3, 2, 7/6) and X = (3, 2, 1/6) under the SU(3)×SU(2)×U(1)
- Interaction Lagrangian for the scalar leptoquark X = (3, 2, 7/6)

$$\mathcal{L} = -\lambda_u^{ij}\bar{u}_R^i X^T \epsilon L_L^j - \lambda_e^{ij}\bar{e}_R^i X^\dagger Q_L^j + h.c.,$$

$$X = \begin{pmatrix} V_\alpha \\ Y_\alpha \end{pmatrix}, \quad \epsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$$

- After expanding the SU(2) indices and Fierz transformation,

$$\mathcal{H}_{LQ} = \frac{\lambda_\mu^{32}\lambda_\mu^{22*}}{8M_Y^2}\left[\bar{s}\gamma^\mu(1-\gamma_5)b\right]\left[\bar{\mu}\gamma_\mu(1+\gamma_5)\mu\right] = \frac{\lambda_\mu^{32}\lambda_\mu^{22*}}{4M_Y^2}\left(\mathcal{O}_9 + \mathcal{O}_{10}\right),$$

- One obtains the new Wilson coefficients

$$C_9^{NP} = C_{10}^{NP} = -\frac{\pi}{2\sqrt{2}G_f \alpha V_{tb} V_{ts}^*} \frac{\lambda_\mu^{32} \lambda_\mu^{22*}}{M_Y^2}.$$

- Lagrangian for the coupling of scalar leptoquark X = (3, 2, 1/6)

$$\mathcal{L} = -\lambda_d^{ij} \bar{d}_R^i X^T \epsilon L_L^j + h.c.,$$

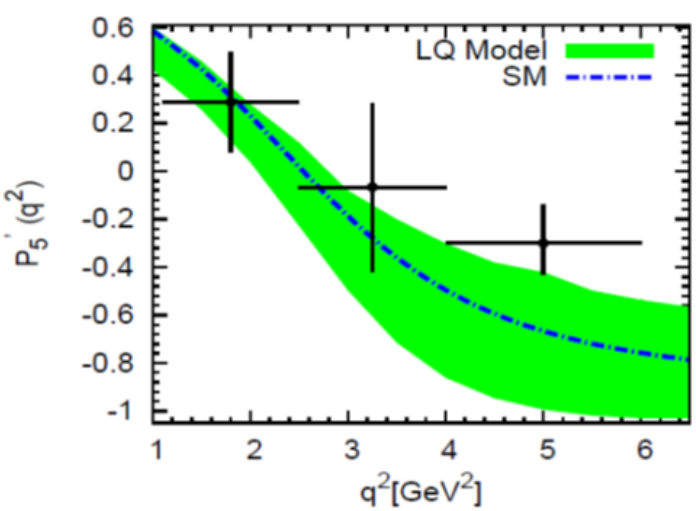
- Which after expansion gives

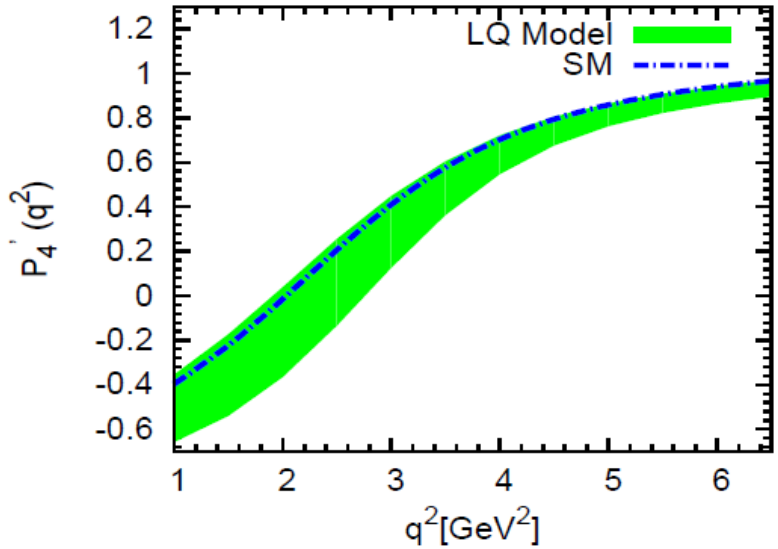
$$\mathcal{H}_{LQ} = \frac{\lambda_s^{22} \lambda_b^{32*}}{8M_V^2} \left[\bar{s}\gamma^\mu(1+\gamma_5)b\right] \left[\bar{\mu}\gamma_\mu(1-\gamma_5)\mu\right] = \frac{\lambda_s^{22} \lambda_b^{32*}}{4M_V^2} \left(\mathcal{O}_9' - \mathcal{O}_{10}'\right),$$

$$C_9'^{NP} = -C_{10}'^{NP} = \frac{\pi}{2\sqrt{2}G_f \alpha V_{tb} V_{ts}^*} \frac{\lambda_s^{22} \lambda_b^{32*}}{M_V^2}.$$

LQ Parameter space: $B_s \to l^+ l^-$ B_s,- B_s mixing $B \to X_s l^+ l^-$ both at high q^2 and low q^2

P_4' and P_5'





S. Sahoo & RM, PRD 93, 034018 (2016)

This simple model can explain most of the anomalies

Lepton Flavour Universality

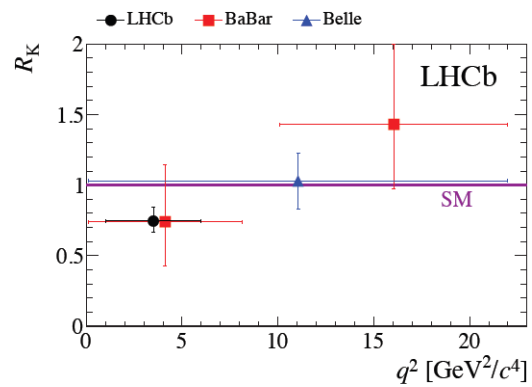
Recently LHCb measured the ratio of decay rates B → K μμ and B → K ee in low q^2 region

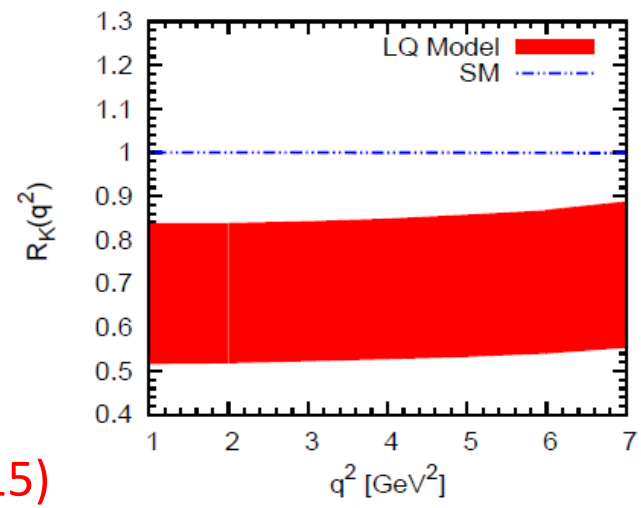
$$R_K = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{syst})$$

This ratio is expected to be 1 in the SM with uncertainty less than 1%.
There is 2.6 σ deficit from SM prediction

- This result can be accommodated in the scalar LQ model with predicted value

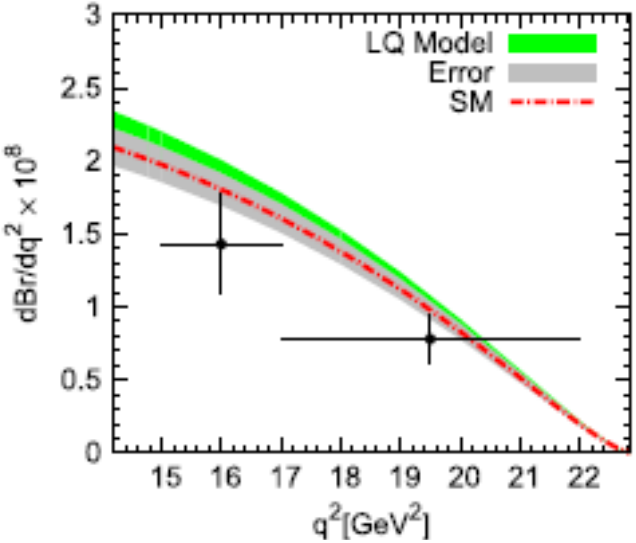
$$R_K = 0.62 - 0.96$$

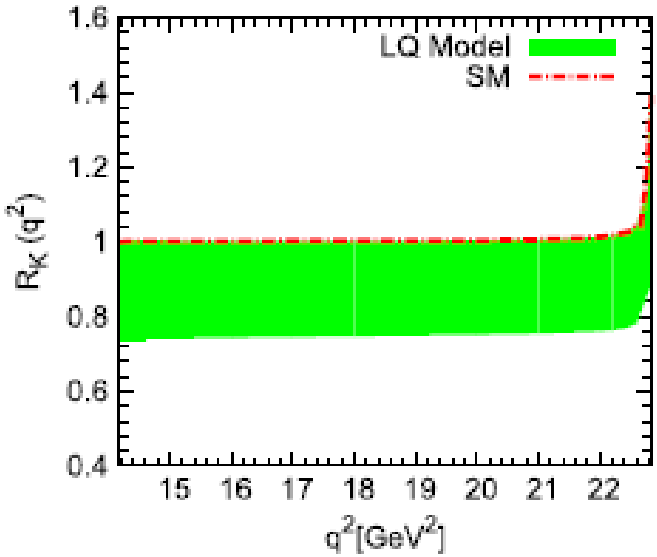




S Sahoo and R. Mohanta, PRD 094019 (2015)

$B \to K \mu\mu$ in high q^2





Variation of differential BR and RK in high q^2 region

S. Sahoo and R Mohanta, NJP 18, 013032 (2016)

Explanation to R_K and $R_{D(*)}$ with scalar LQ

- (3,2,1/6) can explain both these anomalies for RH neutrinos (two states with Q = 2/3, -1/3)

$$\mathcal{L}_Y = - x_{ij}\bar{d}^i_R e^j_L \tilde{R}_2^{2/3} + (xV_{\rm PMNS})_{ij}\bar{d}^i_R \nu^j_L \tilde{R}_2^{-1/3} + (V_{\rm CKM}y)_{ij}\bar{u}^i_L \nu^j_R \tilde{R}_2^{2/3} + y_{ij}\bar{d}^i_L \nu^j_R \tilde{R}_2^{-1/3} + \text{h.c.}$$

R_K: $C_9' = - C_{10}'$

- Since LQ couples to RH neutrinos there will be no inteference with SM

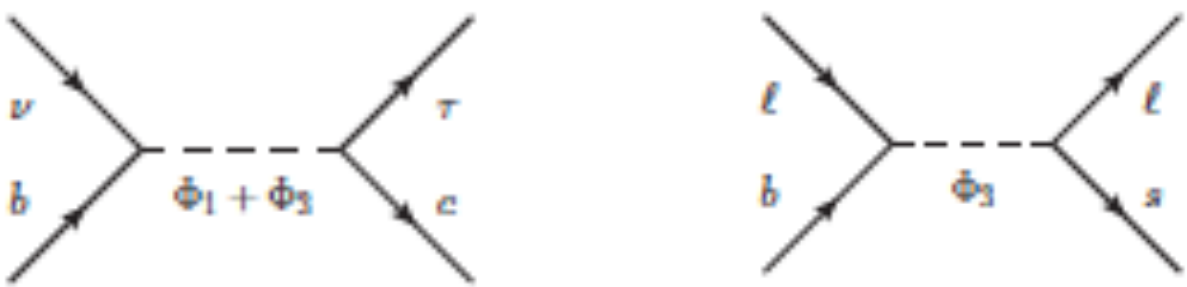
$$|\mathcal{M}(B \to D^{(*)}\ell\nu)|^2 = |\mathcal{M}_{\rm SM}|^2 + |\mathcal{M}_{\rm NP}|^2$$

Fajfer etal 1503.09024

Combination of two scalar LQs

- One can consider two LQs with same mass (one singlet and other triplet under SU(2))

$$L = \lambda^{1L}_{fi}\overline{Q^c_f}i\tau_2 L_i \Phi_1^\dagger + \lambda^{3L}_{fi}\overline{Q^c_f}i\tau_2(\tau\cdot\Phi_3)^\dagger L_i + \text{h.c.}\,.$$



Crivellin et al: 1703.09226

Vector LQ and B anomalies

- We consider the LQs $U_1(3,1,2/3)$, $U_3(3,3,2/3)$, which can mediate $b \to c\, l\, \nu$ and $b \to s\, ll$
- Conserve baryon number, avoid rapid proton decay
- L_{int} of $U_{1,3}$ LQs with SM fermion bilinear is

$$\mathcal{L}^{LQ} = \left(h_{1L}^{ij}\bar{Q}_{iL}\gamma^{\mu}L_{jL} + h_{1R}^{ij}\bar{d}_{iR}\gamma^{\mu}l_{jR}\right)U_{1\mu} + h_{3L}^{ij}\bar{Q}_{iL}\boldsymbol{\sigma}\gamma^{\mu}L_{jL}\mathbf{U}_{3\mu}$$

- Int. Lagrangian gives additional contributions to b →c τ ν:

$$C_{V_1}^{LQ} = \frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3} \left[\frac{h_{1L}^{2l} h_{1L}^{k3*}}{M^2_{U_1^{2/3}}} - \frac{h_{3L}^{2l} h_{3L}^{k3*}}{M^2_{U_3^{2/3}}} \right],$$

$$C_{V_2}^{LQ} = 0, \qquad C_{S_1}^{LQ} = -\frac{1}{2\sqrt{2}G_F V_{cb}} \sum_{k=1}^{3} V_{k3} \frac{2 h_{1L}^{2l} h_{1R}^{k3*}}{M^2_{U_1^{2/3}}}.$$

- It also gives additional contributions to b →s ll

$$C_9^{\rm NP} = -C_{10}^{\rm NP} = \frac{\pi}{\sqrt{2}G_F V_{tb} V_{ts}^* \alpha} \left[\frac{h_{1L}^{2l} h_{1L}^{k3*}}{M^2_{U_1^{2/3}}} + \frac{h_{3L}^{2l} h_{3L}^{k3*}}{M^2_{U_3^{2/3}}} \right],$$

$$C_9'^{\rm NP} = C_{10}'^{\rm NP} = \frac{\pi}{\sqrt{2}G_F V_{tb} V_{ts}^* \alpha} \frac{h_{1R}^{2l} h_{1R}^{k3*}}{M^2_{U_1^{2/3}}},$$

$$-C_P^{\rm NP} = C_S^{\rm NP} = \frac{\sqrt{2}\pi}{G_F V_{tb} V_{ts}^* \alpha} \frac{h_{1L}^{2l} h_{1R}^{k3*}}{M^2_{U_1^{2/3}}},$$

$$C_P'^{\rm NP} = C_S'^{\rm NP} = \frac{\sqrt{2}\pi}{G_F V_{tb} V_{ts}^* \alpha} \frac{h_{1R}^{2l} h_{1L}^{k3*}}{M^2_{U_1^{2/3}}},$$

LQ parameter space constrained from:

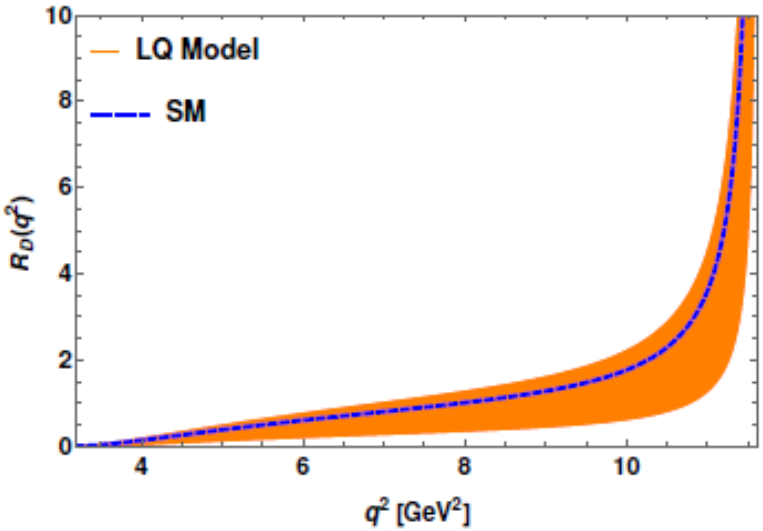
$B_s \to l^+ l^-$

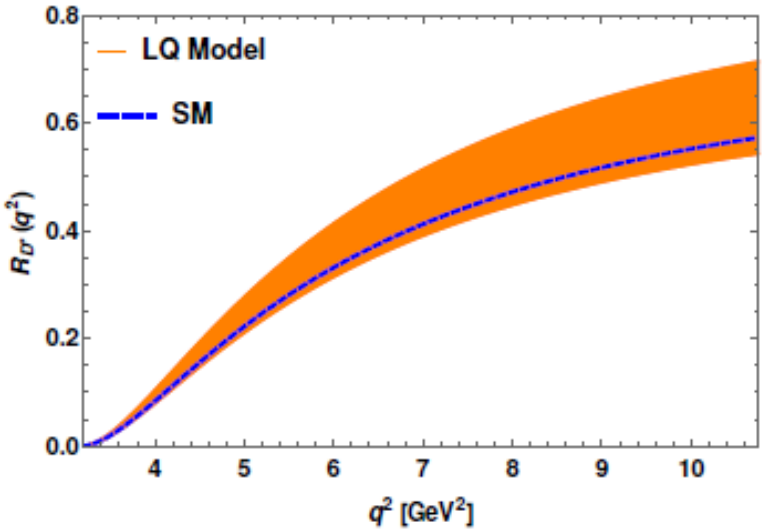
$B \to X_s \nu\nu$

$B \to X_s l^+ l^-$ both at high q^2 and low q^2

Muon (g-2)

Results: $R_{D(*)}$

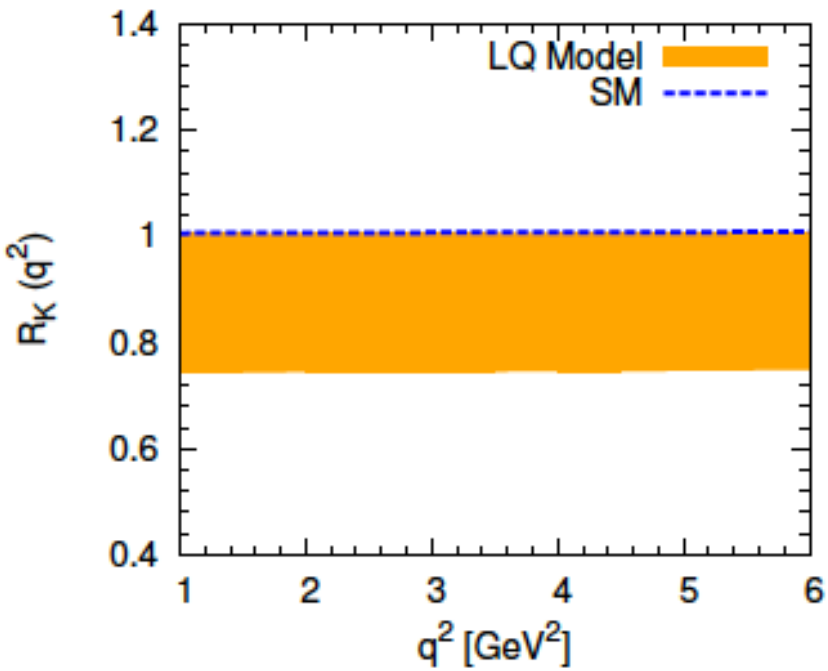


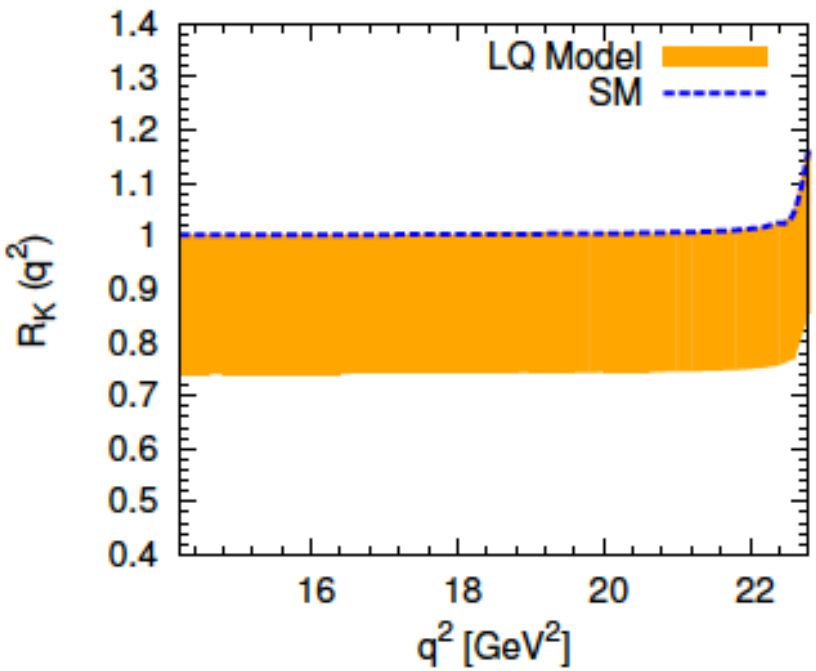


Observables	SM Predictions	Values in LQ Model	Experimental Limit
R_D	0.31	$0.11 - 0.386$	$0.397 \pm 0.040 \pm 0.028$
R_{D^*}	0.26	$0.243 - 0.32$	$0.316 \pm 0.016 \pm 0.010$

S. Sahoo, R. Mohanta and A. K. Giri, PRD, 95, 035027 (2017).

Results: R_K

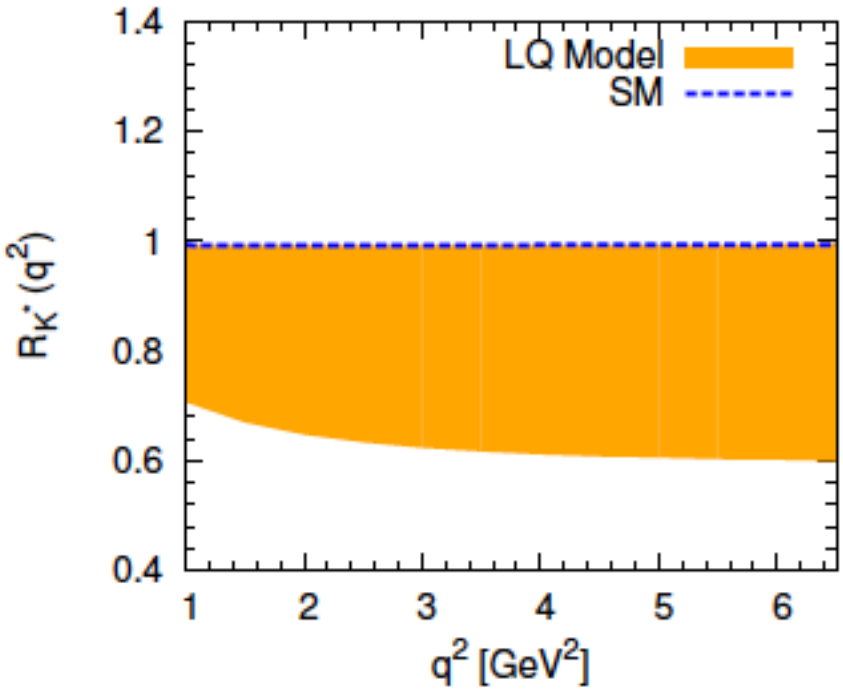


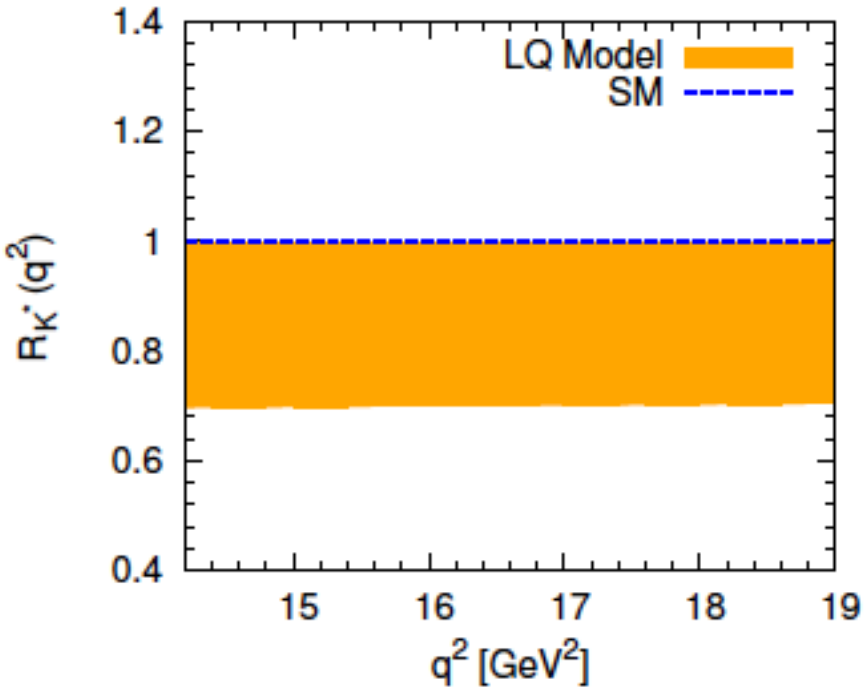


Observables	SM Predictions	Values in LQ Model	Experimental Limit
$R_{K^{\mu e}_{q^2\in[1,6]}}$	1.006	$0.75 - 1.006$	$0.745^{+0.090}_{-0.074} \pm 0.036$
$R_{K^{\mu e}_{q^2\geq 14.18}}$	1.004	$0.74 - 1.004$	...

S. Sahoo, R. Mohanta and A. K. Giri, PRD, 95, 035027 (2017).

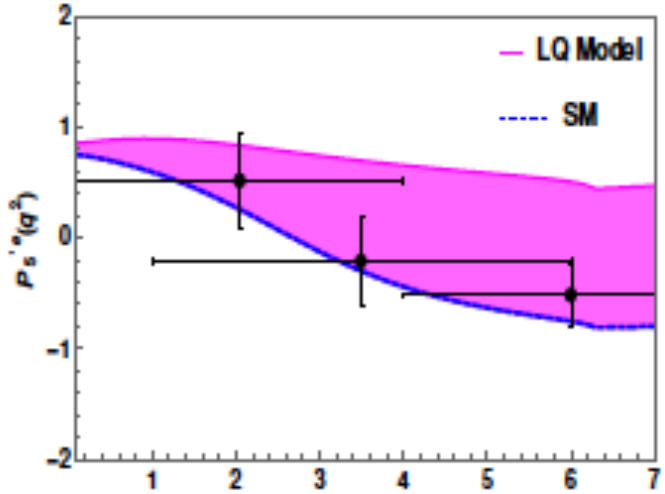
R_{K^*}

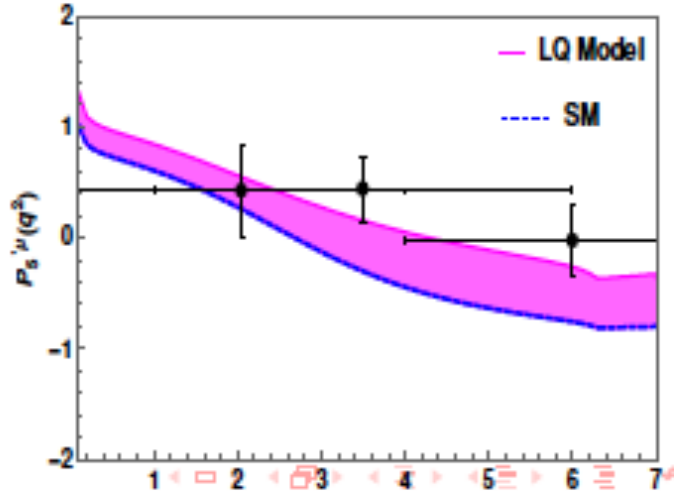




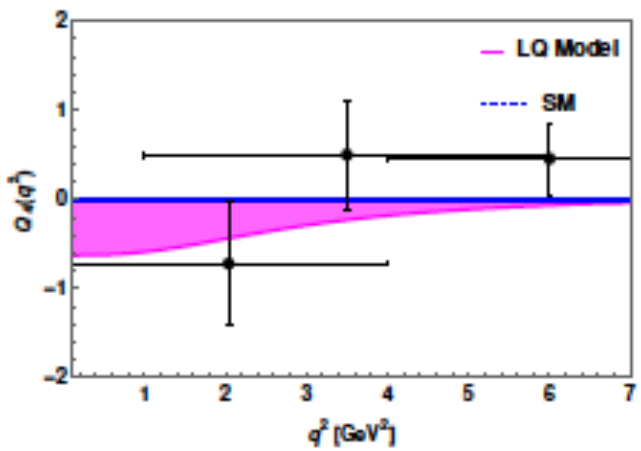
Observables	SM Predictions	Values in LQ Model
$R_{K^*}{}^{\mu e}_{q^2\in[0.045,1.1]}$	0.996	0.725 – 0.996
$R_{K^*}{}^{\mu e}_{q^2\in[1.1,6]}$	0.996	0.725 – 0.996
$R_{K^*}{}^{\mu e}_{q^2\geq 14.18}$	0.999	0.816 – 0.999

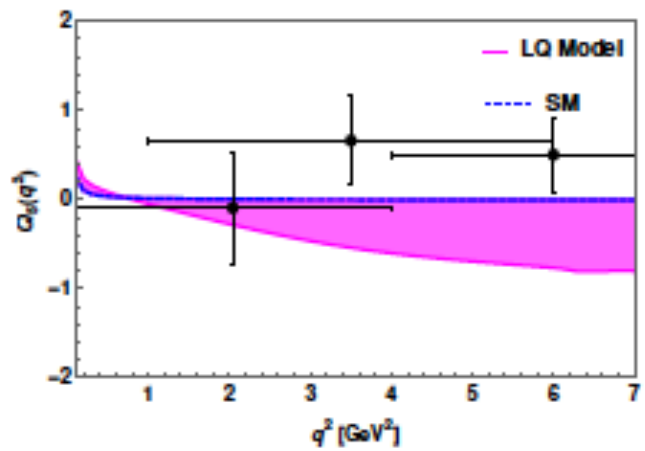
P_5'


LQ Model
SM
$P_5'^{e}(q^2)$


LQ Model
SM
$P_5'^{\mu}(q^2)$

$Q_{4,5}$


LQ Model
SM
$Q_4(q^2)$
q^2 [GeV^2]


LQ Model
SM
$Q_5(q^2)$
q^2 [GeV^2]

Summary

- There exist some mild discrepancies in the rare decays involving $b \to s$ processes.
- Intriguing hints for Lepton Flavour Universality violating New Physics
- It is not yet confirmed whether these are the smoking gun signals of some NP or just the statistical fluctuations.
- Scalar/Vector LQ models can accommodate these anomalies.
- Hopefully future results from the Flavour Factories will settle these issues and/or provide the new direction to High Energy Physics.

THANK YOU