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Complementary test of lepton flavor universality violation in $B_s \to f_2'(1525)\,(\to K^+ K^-)\,\mu^+ \mu^-$ decays

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Introduction

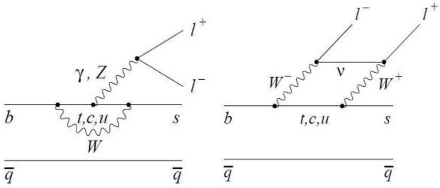
- Quarks come in six flavors - up, down, charm, strange, top and bottom..
- Weak interactions allow quarks to swap their flavors for another.
- The swapping process of the quark flavors occur in two ways (FCCC & FCNC).
- In SM, the flavor changing processes inherits a fundamental property/ symmetry called the lepton flavor universality (LFU).
- In SM, couplings of the gauge bosons to leptons are independent of lepton flavor.
- Any sign of the lepton flavour non-universality would be a direct sign for the New Physics.

LFU violation

- The evidence of the violation of the LFU have been observed both in the FCCC and FCNC quark level transitions.
- The significant deviations have been reported in various flavor observables such as
  - R_K, R_{K^*}, P_5' in $B \to K^{(*)} l^+ l^-$ decays;
  - The branching ratio of $\mathcal{B}(B_s \to \phi \mu^+ \mu^-)$;
  - R_D, R_{D^*}, $P_{D^*}^{\tau}$, $F_L^{D^*}$ in $B \to D^{(*)} l \nu$ decays;
  - $R_{J/\Psi}$ in $B_c \to J/\Psi l \nu$ decays.
- Various extensions to the SM have addressed the underlying discrepancies.
- We discuss the opportunities to look for NP associated with the similar $b \to s l^+ l^-$ transitions.

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

- The SM does not allow tree level contribution to the $b \to s\, l^+ \, l^-$ decays and hence they are highly suppressed.



- There are other possibilities as well: including Z' and LQ.
- Hence, these neutral decays provide an increased sensitivity to the possible existence of new physics.

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

- The SM predictions come with the large hadronic uncertainties.
- The hadronic uncertainties are reduced in some theoretically clean observables such as the ratio of branching ratio R_{H_s}:

$$R_{H_s} = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma}{dq^2}(H_b \to H_s \mu^+ \mu^-) dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\Gamma}{dq^2}(H_b \to H_s e^+ e^-) dq^2}$$

- The angular analysis allow us to construct set of optimized observables P_i's with reduced form factor dependency.

$$\langle P_5' \rangle = \frac{\int_{bin} dq^2 I_5}{2\sqrt{-\int_{bin} dq^2 I_2^c \int_{bin} dq^2 I_2^s}}$$

Motivation - Anomalies

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

	q^2 bins	Theoretical predictions	Experimental measurements	Deviation
R_K	[1.0, 6.0]	1 ± 0.01 Hiller et al., PRD 69, 074020 (2004), Bordone et al., EPJ. C 76,8,440 (2016)	$0.846^{+0.060}_{-0.054}$ (stat) $^{+0.016}_{-0.014}$ (syst) [LHCb] PRL 122, no.19,191801 (2019)	$\sim 2.5\sigma$
R_{K^*}	[0.045, 1.1]	1 ± 0.01 1 ± 0.01 Hiller et al., PRD 69, 074020 (2004) Bordone et al., EPJ. C 76,8,440 (2016)	$0.660^{+0.110}_{-0.070}$ (stat) ± 0.024 (syst) [LHCb] JHEP 08, 055 (2017) $0.52^{+0.36}_{-0.26}$ (stat) ± 0.05 (syst) [Belle], arXiv:1904.02440	$\sim 2.1 - 2.5\sigma$
	[1.1, 6.0]	1 ± 0.01 1 ± 0.01 Hiller et al., PRD 69, 074020 (2004), Bordone et al., EPJ. C 76,8,440 (2016)	$0.685^{+0.113}_{-0.069}$ (stat) ± 0.047 (syst) [LHCb] JHEP 08, 055 (2017) $0.96^{+0.45}_{-0.29}$ (stat) ± 0.11 (syst) [Belle], arXiv:1904.02440	

- The ratio R_K is measured by LHCb (Run 1 + Run 2)in the q^2 bin of [1, 6] GeV^2.
- This R_K measurement is consistent with SM expectations at the level of 2.5σ.
- The ratio R_{K*} is measured by LHCb and Belle in the two q^2 bins: [0.045, 1.1] and [1.1, 6] GeV^2.
- This R_{K*} measurement is consistent with SM expectations at the level of $2.1 - 2.3\sigma$ (low) and $2.4 - 2.5\sigma$ (central).

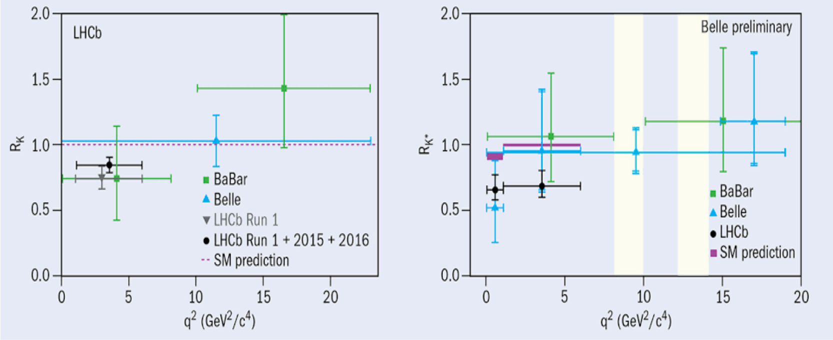
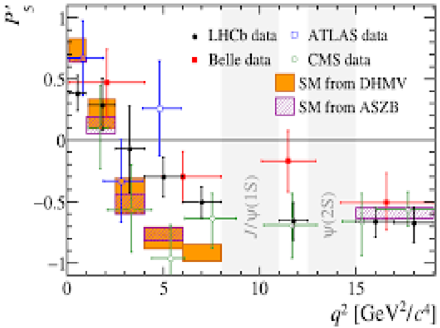


Fig credits: Symmetry magazine

P_5' anomaly

	q^2 bins	Theoretical predictions	Experimental measurements	Deviation
P_5'	[4.0, 6.0]	-0.757 ± 0.074 Sebastien et al., JHEP 05, 137 (2013)	-0.21 ± 0.15 [LHCb] JHEP 02,104 (2016), [ATLAS],JHEP 10, 047 (2018)	$\sim 3.3\sigma$
	[4.3, 6.0]	$-0.774^{+0.0.061+0.087}_{-0.059-0.093}$ Sebastien et al., JHEP 01, 048 (2013)	$-0.96^{+0.22}_{-0.21}$ (stat) ± 0.16 (syst) CMS-PAS-BPH-15-008	$\sim 1.0\sigma$
	[4.0, 8.0]	-0.881 ± 0.082 Sebastien et al., JHEP 12, 125 (2014)	$-0.267^{+0.275}_{-0.269}$ (stat) ± 0.049 (syst) BELLE-CONF-1603	$\sim 2.1\sigma$



- P_5': the angular distributions of $B \to K^* \mu^+ \mu^-$
- The P_5' measured by ATLAS and LHCb in the bin $q^2 \in [4, 6]$ GeV^2
- These measurements differ by $\sim 3.3\sigma$ from the SM expectations
- The P_5' measured by CMS in $q^2 \in [4.3, 6]$ GeV^2 differ by 1σ from the SM expectations
- The P_5' measured by Belle in $q^2 \in [4, 8]$ GeV^2 differ by 2.1σ from the SM expectations.

B_s^ϕ anomaly

	q^2 bins	Theoretical predictions	Experimental measurements	Deviation
$\mathcal{B}(B_s \to \phi\,\mu^+\,\mu^-)$	[1.0, 6.0]	$(5.39 \pm 0.66) \times 10^{-8}$ CDF Collaboration, CDF-NOTE-10894	$(2.57 \pm 0.37) \times 10^{-8}$ [LHCb] JHEP 09(2015) 179	$\sim 3.7\sigma$

- $\mathcal{B}(B_s \to \phi\,\mu^+\,\mu^-)$ is measured by LHCb.
- The measured value is found to deviate at the level of $\sim 3.7\sigma$ from the SM expectations.

- In this context, we perform an angular study of $B_s \to f_2'(\to K^+K^-)\mu^+\mu^-$ decays and provide a complementary information on the lepton flavor universality violation.
- This analysis is well motivated since,
  - This decay has received less attention so far.
  - Not many experimental results on electroweak penguin decays involving spin 2 particles.
  - This decay can be detected easily at the LHCb detector.

Theory

- The SM extension of the effective Hamiltonian by allowing the NP contributions:

$$\mathcal{H}_{eff} = -\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^{*} \frac{\alpha_e}{4\pi}\Big(C_9^{eff}\mathcal{O}_9 + C_{10}^{eff}\mathcal{O}_{10} - \frac{2\,m_b}{q^2} C_7^{eff}\mathcal{O}_7 + C_9^{NP}\mathcal{O}_9^{NP} + C_{10}^{NP}\mathcal{O}_{10}^{NP} + C_9'\mathcal{O}_9' + C_{10}'\mathcal{O}_{10}'\Big)$$

$$\mathcal{O}_9 = [\bar{s}\,\gamma^{\mu}\,P_L\,b\,\bar{l}\,\gamma_{\mu}\,l\,]; \qquad \mathcal{O}_{10} = [\bar{s}\,\gamma^{\mu}\,P_L\,b\,\bar{l}\,\gamma_{\mu}\,\gamma_5\,l\,];$$

$$\mathcal{O}_7 = [\bar{s}\,i\,q_{\nu}\,\sigma^{\mu\nu}\,P_R\,b\,\bar{l}\,\gamma_{\mu}\,l\,];$$

$$\mathcal{O}_9^{NP} = [\bar{s}\,\gamma^{\mu}\,P_L\,b\,\bar{l}\,\gamma_{\mu}\,l\,]; \qquad \mathcal{O}_{10}^{NP} = [\bar{s}\,\gamma^{\mu}\,P_L\,b\,\bar{l}\,\gamma_{\mu}\,\gamma_5\,l\,];$$

$$\mathcal{O}_9' = [\bar{s}\,\gamma^{\mu}\,P_R\,b\,\bar{l}\,\gamma_{\mu}\,l\,]; \qquad \mathcal{O}_{10}' = [\bar{s}\,\gamma^{\mu}\,P_R\,b\,\bar{l}\,\gamma_{\mu}\,\gamma_5\,l\,].$$

- The values for each WC obtained are in the leading logarithmic approximation at the energy scale $\mu = m_{b,pole}$. A. J. Buras et al.,PRD 52, 186-195 (1995).

- Similarly, the values for each new WC are considered from the global fits. A. K. Alok et al.,JHEP 06, 089 (2019)

Theory

- We consider in total 7 (1D→4 & 2D→3) NP scenarios A. K. Alok et al.,JHEP 06, 089 (2019)

WCs	C_9^{NP}	C_{10}^{NP}	$C_9^{NP} = -C_{10}^{NP}$	$C_9^{NP} = -C_9'$	(C_9^{NP}, C_{10}^{NP})	$(C_9^{NP} = -C_9')$	$(C_9^{NP} = -C_{10}')$
Best fits	-1.07	$+0.78$	-0.52	-1.11	$(-0.94, +0.23)$	$(-1.27, +0.68)$	$(-1.36, -0.46)$

- The $B_s \to f_2'$ hadronic matrix elements are obtained using the perturbative QCD approach (pQCD) R. H. Li et al.,PRD 83, 034034 (2011).
- Using the helicity amplitude techniques, we get partial decay width: R. H. Li et al.,PRD 83, 034034 (2011)

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{3}{8}\left[|\mathcal{M}_b|^2\right]$$

- where, $|\mathcal{M}_b|^2$ is decomposed into 11 angular coefficients I_i's
- The differential decay rate is given by

$$\frac{d\,\Gamma}{d\,q^2} = \frac{1}{4}\left[3I_1^c + 6I_1^s - I_2^c - 2I_2^s\right]$$

Physical observables

$$DBR(q^2) = \frac{d\Gamma/dq^2}{\Gamma_{Total}}$$

$$A_{FB}(q^2) = \frac{3I_6}{3I_1^c + 6I_1^s - I_2^c - 2I_2^s}$$

$$F_L(q^2) = \frac{3I_1^c - I_2^c}{3I_1^c + 6I_1^s - I_2^c - 2I_2^s}$$

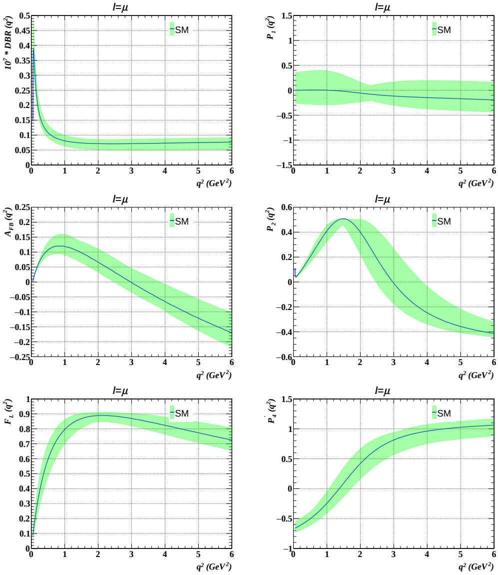
$$R_{f_2'}(q^2) = \frac{d\Gamma/dq^2(B_s \to f_2' \mu^+ \mu^-)}{d\Gamma/dq^2(B_s \to f_2' e^+ e^-)}$$

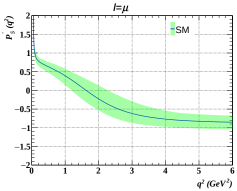
$$\langle P_1 \rangle = \frac{1}{2}\frac{\int_{bin} dq^2 I_3}{\int_{bin} dq^2 I_2^s}, \langle P_2 \rangle = \frac{1}{8}\frac{\int_{bin} dq^2 I_6}{\int_{bin} dq^2 I_2^s}$$

$$\langle P_4' \rangle = \frac{\int_{bin} dq^2 I_4}{\sqrt{-\int_{bin} dq^2 I_2^c \int_{bin} dq^2 I_2^s}}$$
$$\langle P_5' \rangle = \frac{\int_{bin} dq^2 I_5}{2\sqrt{-\int_{bin} dq^2 I_2^c \int_{bin} dq^2 I_2^s}}$$

$$\langle Q_{F_L} \rangle = \langle {F_L}^{\mu} \rangle - \langle {F_L}^{e} \rangle,$$
$$\langle Q_{A_{FB}} \rangle = \langle {A_{FB}}^{\mu} \rangle - \langle {A_{FB}}^{e} \rangle,$$
$$\langle Q_i^{(\prime)} \rangle = \langle P_i^{(\prime)\mu} \rangle - \langle P_i^{(\prime)e} \rangle$$

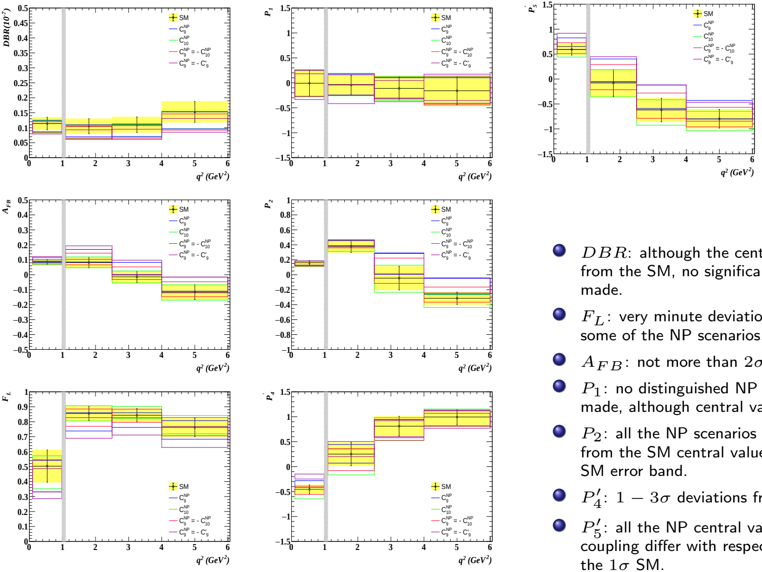
SM predictions





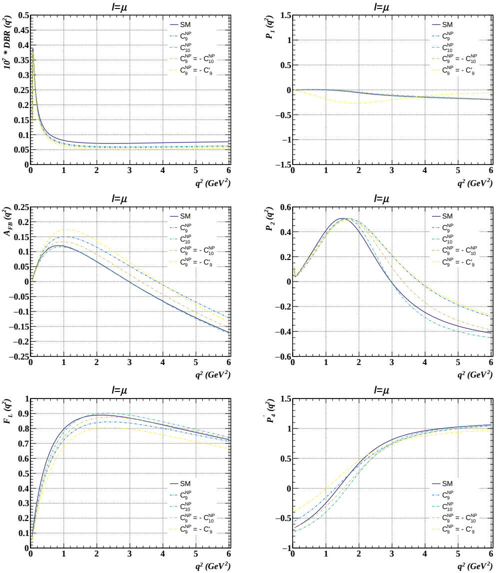
- In SM, we assume all the new vector and the axial vector NP WCs $C_{9,10}^{NP}$ and $C'_{9,10}$ to be zero.
- $A_{FB}(q^2)$, $P_2(q^2)$, $P'_4(q^2)$, and $P'_5(q^2)$ make intersections with the zero line.
- $A_{FB}(q^2)$ and $P_2(q^2)$ have same zero crossing points at $q^2 \sim 3$ GeV^2.
- $P'_4(q^2)$ and $P'_5(q^2)$ have the zero crossings at $q^2 \sim 1.4$ GeV^2 and $q^2 \sim 1.6$ GeV^2.
- $P_1(q^2)$ is almost zero in the low q^2
- $R_{f'_2}(q^2)$ is constant and equal to ~ 1.
- The uncertainty in $R_{f'_2}(q^2)$ is almost negligible.

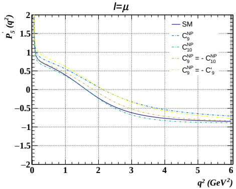
New Physics 1D (bin wise)



- DBR: although the central values differ slightly from the SM, no significant observations can be made.
- F_L: very minute deviations are found in the some of the NP scenarios.
- A_{FB}: not more than 2σ deviations observed.
- P_1: no distinguished NP discussions can be made, although central values differ.
- P_2: all the NP scenarios although differ slightly from the SM central values but lie within the 1σ SM error band.
- P_4': $1-3\sigma$ deviations from SM are observed.
- P_5': all the NP central values in each NP coupling differ with respect to SM but lie within the 1σ SM.

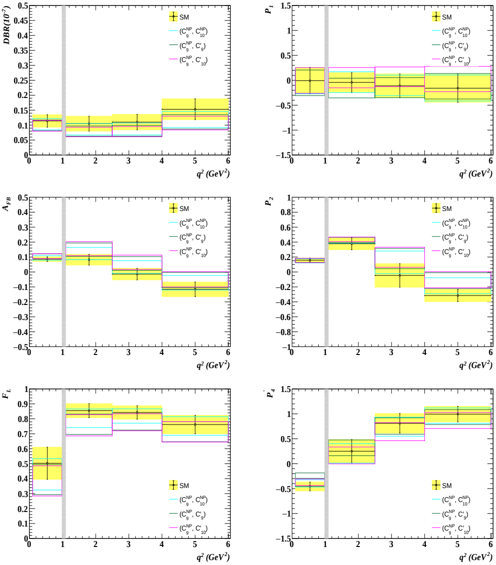
New Physics 1D (q^2 distribution)

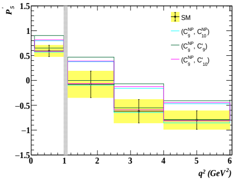




- The observables: $A_{FB}(q^2)$, $P_2(q^2)$, $P'_4(q^2)$ and $P'_5(q^2)$ make the zero crossings (ZC).
- The ZC point for $A_{FB}(q^2)$ in SM is at $q^2 \sim 3$ GeV^2 and the C_9^{NP} is overlapping with the SM.
- The ZC for $C_9^{NP} = -C_{10}^{NP}$ is at ~ 3.4 GeV^2 and for C_{10}^{NP} and $C_9^{NP} = -C'_9$ is at ~ 3.8 GeV^2.
- The similar observations are made in the case of $P_2(q^2)$.
- For $P'_4(q^2)$, the ZC for SM is found at $q^2 \sim 1.4$ GeV^2 and C_{10}^{NP} is overlapping with SM. C_9^{NP} and $C_9^{NP} = -C_{10}^{NP}$ at ~ 1.8 GeV^2 and $C_9^{NP} = -C'_9$ at ~ 1 GeV^2.
- $P'_5(q^2)$, ZC for SM and the C_9^{NP} is found at around $q^2 \sim 1.6$ GeV^2. For the $C_9^{NP} = -C_{10}^{NP}$ at ~ 1.8 GeV^2 and for the C_{10}^{NP} and $C_9^{NP} = -C'_9$ at ~ 2.2 GeV^2.

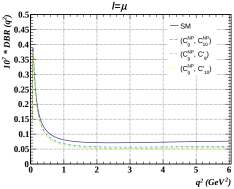
New Physics 2D (bin wise)

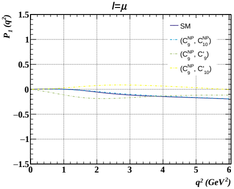


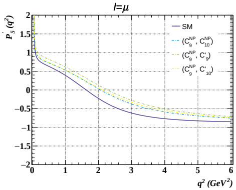


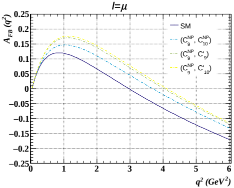
- DBR: quite more deviations from the SM expectation is observed.
- F_L: around $1-1.5\sigma$ deviations found from the SM.
- A_{FB}: Not more than 2σ deviations observed.
- P_1: there are slight variations in the central values, lie within the SM 1σ.
- P_2: except in [0.045, 0.98] and [1.1, 2.5], quite significant deviation of around $1.5-2.5\sigma$ are found.
- P_4': around 2σ deviation found in [0.045, 0.98] due to (C_9^{NP}, C_9'), other lie within the 1σ.
- P_5': central values differ in each NP scenarios but are consistant within the 1σ of the SM error bar.

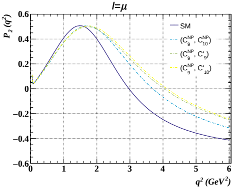
New Physics 2D (q^2 distribution)

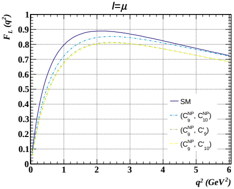


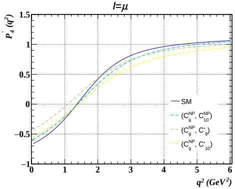






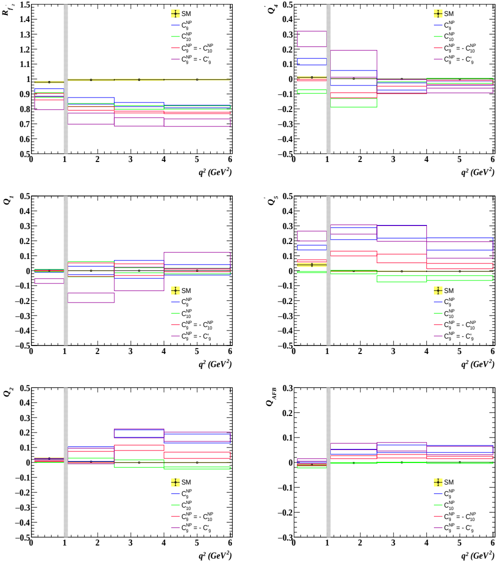


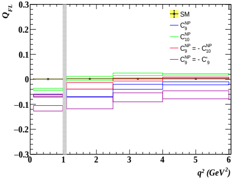




- We do observe the interesting zero crossing (ZC) behaviors in the similar observables: $A_{FB}(q^2)$, $P_2(q^2)$, $P_4'(q^2)$ and $P_5'(q^2)$.
- The ZC for $A_{FB}(q^2)$ is found at $q^2 \sim 3.6$ GeV^2 due to (C_9^{NP}, C_9') and at ~ 4 GeV^2 due to (C_9^{NP}, C_{10}^{NP}) and (C_9^{NP}, C_{10}').
- Similar observations are made in $P_2(q^2)$ as well.
- For $P_4'(q^2)$, ZC for SM, (C_9^{NP}, C_9') and (C_9^{NP}, C_{10}') are found at $q^2 \sim 1.4$ GeV^2 whereas, for (C_9^{NP}, C_{10}^{NP}) at ~ 1.2 GeV^2.
- In the case of $P_5'(q^2)$, all the 2D NP scenarios exhibit distinct distribution from the SM. The ZC for all the scenarios approximately lie between $q^2 \sim 2 - 2.2$ GeV^2.
- All the values are found to be distinct from SM as well as 1D scenarios.

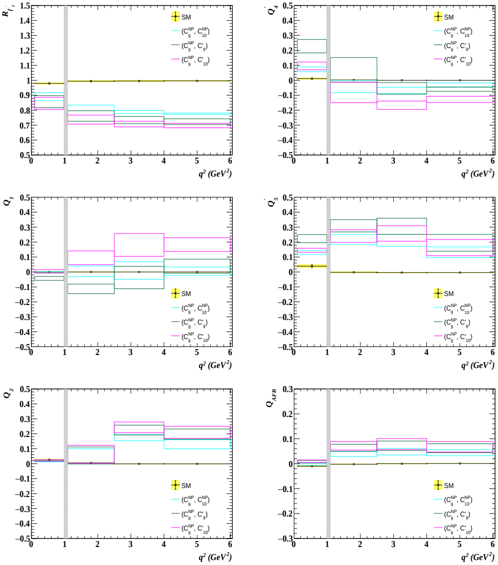
LFUV sensitivity in 1D (bin wise)

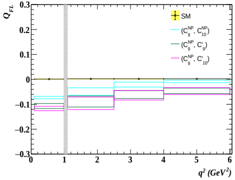




- Uncertainties are reduced in these observable.
- $R_{f_2'}$: all the NP scenarios exhibit very distinct nature (with $> 3\sigma$ deviation).
- Q_1: interesting due to $C_9^{NP} = -C'_9$ in the bins [0.045, 0.98] and [1.1, 2.5].
- Q_2: [1.1, 2.5] no major deviations, $> 5\sigma$ in [2.5, 4.0] and [4.0, 6.0] in some NP.
- Q'_4: $> 5\sigma$ deviation in [1.1, 2.5], $> 3\sigma$ deviation in $C_9^{NP} = -C'_9$ in [4.0, 6.0].
- Q'_5: C_{10}^{NP} is SM like and other deviate $> 5\sigma$ in [1.1, 2.5]. Some deviations found due to all in the rest of the bins.
- Q_{AFB}: in bins [1.1, 2.5] and [2.5, 4.0] $> 4\sigma$ deviation except C_{10}^{NP}, in the last bin all deviate at $> 1\sigma$
- Q_{F_L}: C_{10}^{NP}, $C_9^{NP} = -C_{10}^{NP}$ similar to SM (2nd& 3rd), major deviations in 1st and last.

LFUV sensitivity in 2D (bin wise)





- $R_{f_2'}$: very significant deviations found in all the scenarios.
- Q_1: In the bins [0.045, 0.98] and [1.1, 2.5], no deviations found due to (C_9^{NP}, C_{10}^{NP}), (C_9^{NP}, C_{10}') deviate at $> 2\sigma$.
- Q_2: No significant deviations found in the bin [1.1, 2.5], $> 5\sigma$ deviations found in the rest.
- Q_4', in [1.1, 2.5] all lie near 1σ, quite more deviations found in the rest.
- Q_5': we do observe significant deviations to some extent in all scenarios.
- $Q_{A_{FB}}$: $> 3\sigma$ deviations found in all the bins.
- Q_{F_L}: $> 3\sigma$ deviations found in all the bins.

Conclusion

- The branching ratio of $B_s \to f_2' \, \mu^+ \, \mu^-$ of order of $\mathcal{O}(10^{-7})$ in SM.
- The branching ratio is reduced at all q^2 for most of NP cases.
- In all the cases except for C_9^{NP}, the zero crossing for $A_{FB}(q^2)$ is shifted to the higher q^2 values.
- In the case of F_L, the peak seems to be reduced and shifted to the higher values of q^2 in comparison to the SM.
- $R_{f_2'}$ and Q's observe significant deviations from SM in most of the NP scenarios.
- It is worth to mention that the zero crossing for $A_{FB}(q^2)$ is quite interesting and can be measured to check the LFUV.
- Measurements of various observables for this decay mode in future can shed more light to identify the possible NP.

....................Thank you for your patience.......................