Discussion: LFUV, what's next?

Joaquim Matias

Universitat Autònoma de Barcelona

$b \to s\ell\ell$ **2018 Workshop**

A New Generation of LFUV Observables

⇒ Assume Nature violates lepton flavour universality (muons vs electrons).

Types: Ratios of BR, based on angular observables, ...

$$\langle R_X \rangle = \frac{\langle B \to X\mu^+\mu^- \rangle}{\langle B \to Xe^+e^- \rangle} \quad \langle Q_i \rangle = \langle P_i^\mu \rangle - \langle P_i^e \rangle \quad \langle B_k \rangle = \frac{\langle J_k^\mu \rangle}{\langle J_k^e \rangle} - 1, \quad k = 5, 6s \quad \ldots$$

Properties: LFUV observables fulfill the following criteria:

- All LFUV are EXCELLENT DISCOVERY probes: $R_{X=K,K^*,\phi}$, Q_i, B_i, T_i,...
- Sensitivity only to the short distance part of C_9 (**charm free** in the SM).
  → only QED corrections naively $\frac{\alpha}{\pi}\log^2(\frac{m_\ell^2}{q^2})$ maybe relevant but controlled [Bordone, Isidori, Pattori]
- Sensitivity to Wilson coefficients other than C_9.
- In presence of New Physics can be classified according to their hadronic uncertainty sensitivity:

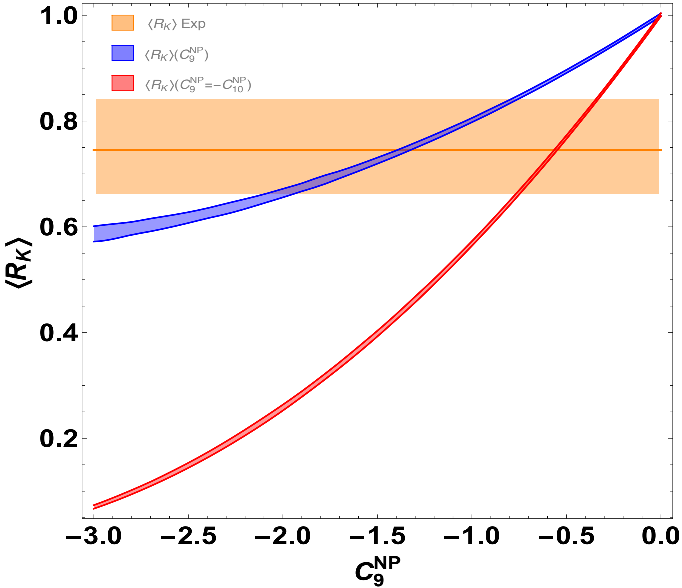
Reminder: $\delta \mathbf{BR} \propto \delta\xi_{\perp,\|}$ + sensitivity to charm (known and unknown $(\delta C_9^{c\bar{c}})^2$)+ p.c.

... crucial dependence on form factor error estimate $\Rightarrow \mathbf{R_X}$

$\delta \mathbf{P_i}$, $\delta \mathbf{J^\mu_{i=5,6s}}/\mathbf{J^e_{i=5,6s}} \propto \alpha_s \delta\xi_{\perp,\|}$ + sensitivity to charm + p.c. $\Rightarrow \mathbf{Q_i}, \mathbf{B_i}$

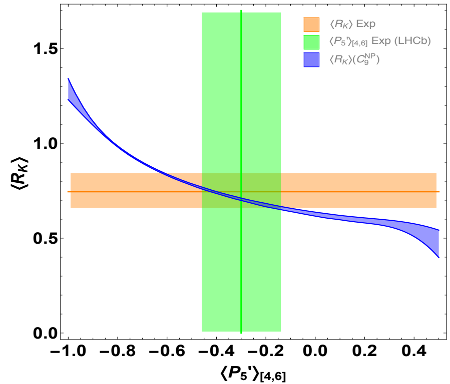
Classification according to sensitivity to hadronic uncertainties in presence of New Physics: Ratios of BR, R_K

$\mathbf{R_K}$: Simple structure: $f_{+,0,T} \to$ one SFF (f_+) at large-recoil.
$\to f_0$ lepton mass suppressed or arises in the presence of (pseudo)scalar while f_T suppressed by $C_7^{\rm eff}$.



BLUE $C_9^{\rm NP}$, RED $C_9^{\rm NP} = -C_{10}^{\rm NP}$

- $C_9^{\rm NP} < 0$ and $C_{10}^{\rm NP} > 0$ same weight adds coherently.
- Central value of R_K prefers a large negative contrib. to $C_9^{\rm NP}$ in excellent agreement with P_5' anomaly.

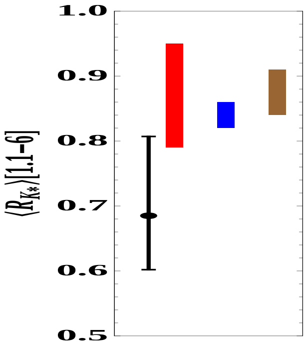


Classification according to sensitivity to hadronic uncertainties in presence of New Physics: Ratios of BR, R_{K^*}

$\mathbf{R_{K^*}}$: More complex structure, 6-8 Amplitudes and 7 form factors.

Impact of long-distance charm from KMPW on $B \to K^*$ larger than on $B \to K$.

- In presence of NP or for $q^2 < 1$ GeV^2 **hadronic uncertainties return.**
- The largest the NP $\to$ the largest the uncertainty: $\delta R_{K^*} \propto (C_i^\mu - C_i^e)\delta FF$



Predictions R_{K^*}			
Bins	$[0.045, 1.1]$	$[1.1, 6.]$	$[15., 19.]$
Standard Model	0.916 ± 0.025	1.000 ± 0.006	0.998 ± 0.001
$C_{9\mu}^{\rm NP} = -1.1$	0.897 ± 0.044	0.867 ± 0.076	0.788 ± 0.005
$C_{9\mu}^{\rm NP} = -1.76$	0.897 ± 0.084	0.832 ± 0.141	0.698 ± 0.009
$C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.62$	0.866 ± 0.057	0.751 ± 0.027	0.714 ± 0.006

- 1st bin is expected to be SM-like.
- $C_9 < 0$ gets near saturation at large-recoil and $C_9 < 0$ $C_{10} > 0$ adds coherently.

At the point $C_{9\mu}^{\rm NP} = -1.1$, $C_{9e}^{\rm NP} = 0$:

KMPW-sch.1: $\xi_\perp = \mathbf{0.31^{+0.20}_{-0.10}}$, $\xi_\| = \mathbf{0.10^{+0.03}_{-0.02}}$

BSZ-sch.1 $\xi_\perp = \mathbf{0.32 \pm 0.03}$, $\xi_\| = 0.12 \pm 0.02$

JC-sch.2 $\xi_\perp = \mathbf{0.31 \pm 0.04}$, $\xi_\| = 0.10 \pm 0.02$

Classification according to sensitivity to hadronic uncertainties in presence of New Physics: Different type of observables, Q_i, B_i, T_i

[CDMV'16]

Observables based on angular observables with cancelation of SFF at LO in presence of NP.

I) **Difference of Optimized observables**: $\mathbf{Q_i = P_i^{\mu} - P_i^{e}}$.

$\rightarrow$ *LFUV properties+ Inheritate the excellent properties of optimized observables in presence of NP*

II) **Ratios of coefficients** of angular distribution: $\mathbf{B_i = J_i^{\mu}/J_i^{e} - 1}$ with i=5,6s.

$\rightarrow$ *Linear sensitivity to δC_9 but* **kinematically suppressed**

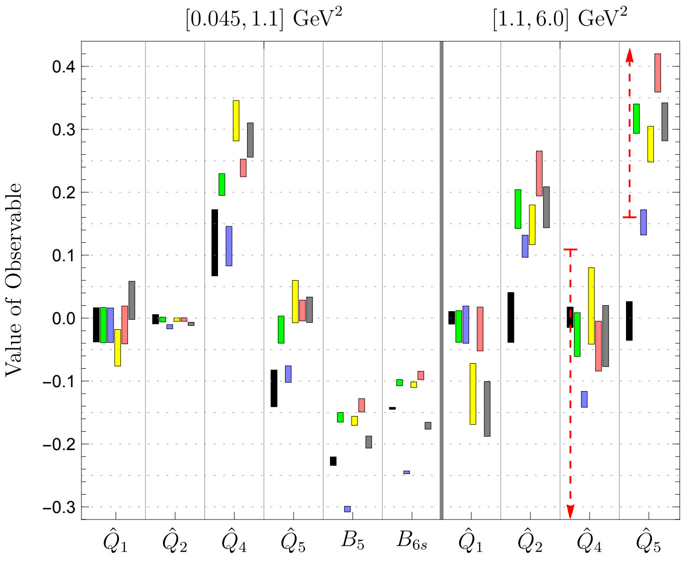
$\rightarrow$ *Sensitivity to δC_{10} at* **very low-q^2**

III) **Ratios of non-optimized observables:** $\mathbf{T_i = \frac{S_i^{\mu} - S_i^{e}}{S_i^{\mu} + S_i^{e}}}$

$\rightarrow$ *Reduced but not perfect cancellation*

Q_i observables: Differences of Optimized observables (long bin)

[1-GREEN]: $C_{9\mu}^{\rm NP} = -1.1$, [2-BLUE]: $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.61$, [3-YELLOW]: $C_{9\mu}^{\rm NP} = -C'_{9\mu} = -1.01$, [4-ORANGE]: $C_{9\mu}^{\rm NP} = -3C_{9e}^{\rm NP} = -1.06$, [5-GRAY]: The b.f.p in the 6D. SM-[BLACK] and dashed-red [BELLE]



$$Q_i = P_i^\mu - P_i^e$$

1st bin of Q_i (not much sensitivity):

- $Q_{1,2}$ control observables.
- Q_4 only exception of sc.3 (no R_K) and sc. 6

2nd bin of Q_i:

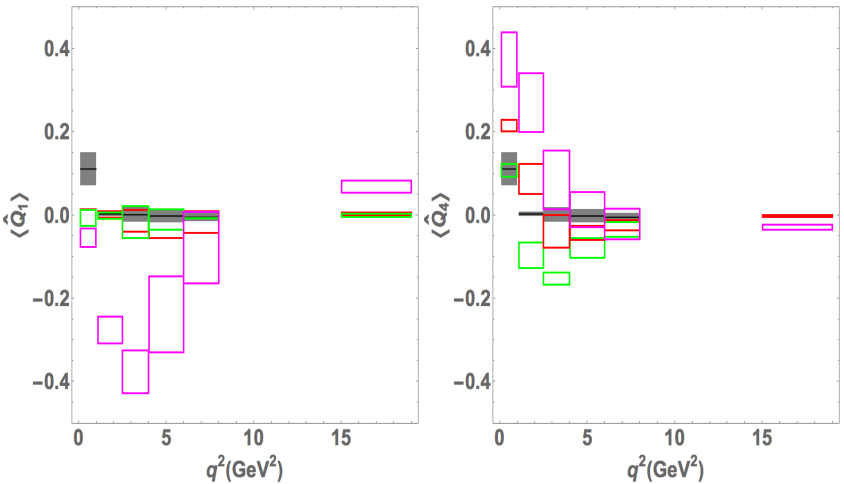
- Q_2 useful to signal LFUV, ...not discriminating power.
- Q_5 largest discriminating power: sc. 1 & 2. $C_{10}^{\rm NP}$ subleading, sc. 1 & 2 reversed w.r.t. R_{K^*}.

1st bin of $B_{5,6s}$ promising to disentangle C_9 from $C_9 = -C_{10}$

Probing right-handed currents (RHC) with Q_i (short bins): Different information of short versus long bins

SM predictions (grey boxes),
NP: $C_{9,\mu}^{\rm NP} = -1.11$ & $C_{9,\mu}^{\rm NP} = -C_{10,\mu}^{\rm NP} = -0.65$ & $C_{9,\mu}^{\rm NP} = -C_{9,\mu}^{\prime\rm NP} = -1.18$ & $C_{10,\mu}^{\rm NP} = C_{10,\mu}^{\prime\rm NP} = 0.38$.

with $\delta C_i = C_{i,\mu} - C_{i,e}$ (and $C_{i,e}$ SM)



$Q_1 = P_1^\mu - P_1^e$ $\qquad$ $Q_4 = P_4^{\prime\mu} - P_4^{\prime e}$

⇒ $Q_{1,4}$ provide excellent opportunities to probe RHC in $C'_{9,\mu}$ & $C'_{10,\mu}$.

- Q_1 shows significant deviations in presence of RHC. If $C'_7 = 0$ at LO

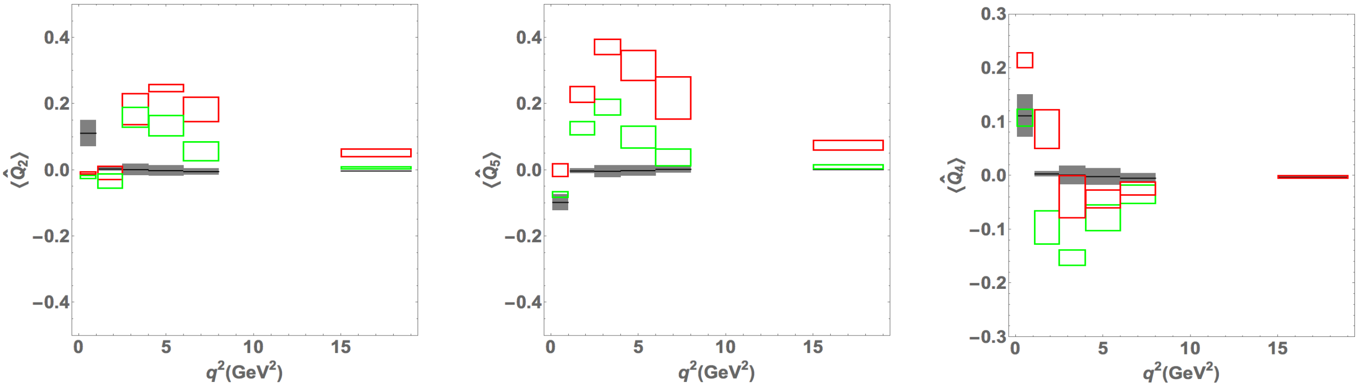
$$s_0^{LO} = -2\frac{C_7\delta C'_9 m_b M_B}{C_{10,\mu}\delta C'_{10} + {\rm Re}C_{9,\mu}\delta C'_9}$$

no zero (except $s = 0$) if $\delta C'_9 = 0$.
no sensitivity to C_i if $C'_i = 0$.

- Q_4 at low-q^2 exhibits deviations for $C'_{9,10,\mu}$ when accurate precision in measurements is achieved.

Probing NP in $C_{9,10}$ with Q_i (short bins)

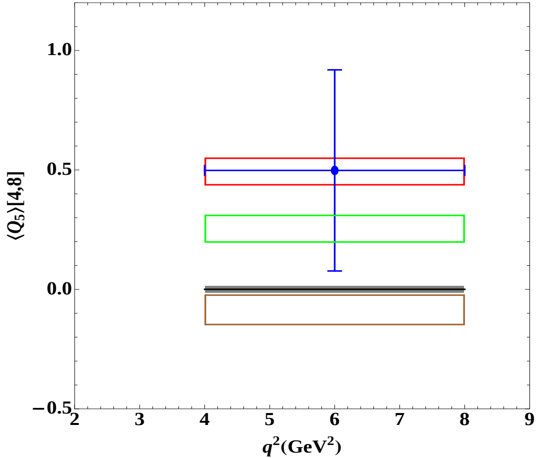
SM predictions (grey boxes),
NP: $C^{\rm NP}_{9,\mu} = -1.11$ (scenario1) & $C^{\rm NP}_{9,\mu} = -C^{\rm NP}_{10,\mu} = -0.65$ (scenario 2) with $\delta C_i = C_{i,\mu} - C_{i,e}$ (and $C_{i,e}$ SM)

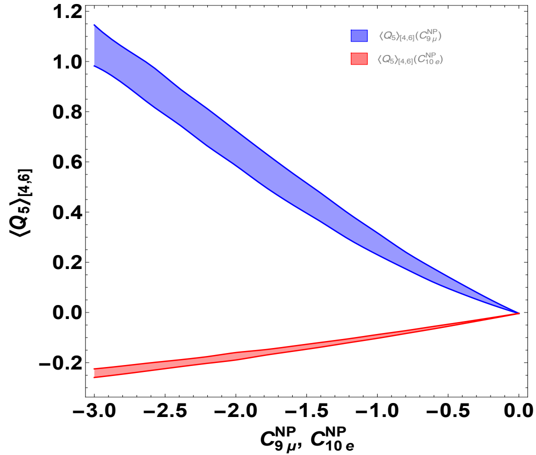


$Q_2 = P_2^\mu - P_2^e$ $\quad$ $Q_5 = P_5'^\mu - P_5'^e$ $\quad$ $Q_4 = P_4'^\mu - P_4'^e$

$\Rightarrow$ Q_2, Q_4 & Q_5 show distinctive signatures for the two NP scenarios considered.

- Differences in the high-q^2 bins of the large recoil region of Q_2 & Q_5 are quite significant. Lack of difference between scenario 2 and SM same reason why P_5' in scenario 2 is worst than scenario 1.
- Q_4 at very low-q^2 (second bin) is very promising to disentangle scenario 1 from 2.





- Blue (option 1) $C_{9\mu}^{\rm NP} < 0$, $C_{9e}^{\rm NP} = 0$ predicts $Q_5 > 0$.
- Red (option 2) $C_{10e}^{\rm NP} < 0$, $C_{9\mu}^{\rm NP} = 0$ predicts $Q_5 < 0$.

BLUE Belle data.

- Green $C_{9\mu}^{\rm NP} = -1.1$, $C_{9e}^{\rm NP} = 0$ predicts Q_5 positive and very large.
- Red $C_{9\mu}^{\rm NP} = -1.76$, $C_{9e}^{\rm NP} = 0$ predicts Q_5 positive and large.
- Brown $C_{10e} < 0$, predicts Q_5 negative.

If no RHC $0 \lesssim Q_5 \lesssim 0.2$ favours mechanisms with NP in $C_{9\mu} = -C_{10\mu} < 0$ or $C_{9\mu} < 0$ while $Q_5 \geq 0.2$ favours mechanisms with $C_{9\mu} < 0$, explains $P_5^{\prime\mu}$ and excludes h_λ^i explanation,

on the contrary

$Q_5 < 0$ would favour the solution $C_{10e} < 0$ and require $h_\lambda^i \neq 0$ to explain P_5'.

B_5 & B_{6s} Observables (unique properties)

Idea: Combine J_i^μ & J_i^e to build combinations sensitive to some C_i, with controlled sensitivitiy to long-distance charm.

$$\beta_\ell J_5 - 2iJ_8 = 8\beta_\ell^2 N^2 m_B^2 (1-\hat{s})^3 \frac{\hat{m}_{K^*}}{\hat{s}\sqrt{\hat{s}}} C_{10}^\ell \left[C_7 \hat{m}_b (1+\hat{s}) + \hat{\mathbf{s}} C_9^\ell\right] \xi_\perp \xi_{||} + \ldots$$

$$\beta_\ell J_{6s} - 2iJ_9 = 16\beta_\ell^2 N^2 m_B^2 \frac{(1-\hat{s})^2}{\hat{s}} C_{10}^\ell \left[2C_7 \hat{m}_b + \hat{\mathbf{s}} C_9^\ell\right] \xi_\perp^2 + \ldots$$

Assuming real NP & maximal LFUV μ vs e, natural combinations are

$$B_5 = \frac{J_5^\mu}{J_5^e} - 1 \quad B_{6s} = \frac{J_{6s}^\mu}{J_{6s}^e} - 1$$

- Full charm insensitive in the SM.
- Linear sensitivity to δC_9 **kinematically suppressed**.

In the large-recoil limit and in absence of RHC currents [CDMV'16]:

$$B_5 = \frac{J_5^\mu - J_5^e}{J_5^e} = \frac{\beta_\mu^2 - \beta_e^2}{\beta_e^2} + \frac{\beta_\mu^2}{\beta_e^2}\frac{\delta C_{10}}{C_{10}} + \frac{\beta_\mu^2}{\beta_e^2}\frac{2(C_{10}+\delta C_{10})\delta C_9 \hat{\mathbf{s}}}{C_{10}\left(2C_7\hat{m}_b(1+\hat{s}) + (2C_9 + \triangle C_{9,0} + \triangle C_{9,\perp})\hat{\mathbf{s}}\right)} + \ldots$$

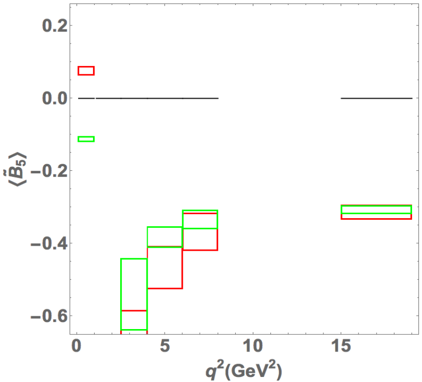
$$B_{6s} = \frac{J_{6s}^\mu - J_{6s}^e}{J_{6s}^e} = \frac{\beta_\mu^2 - \beta_e^2}{\beta_e^2} + \frac{\beta_\mu^2}{\beta_e^2}\frac{\delta C_{10}}{C_{10}} + \frac{\beta_\mu^2}{\beta_e^2}\frac{2(C_{10}+\delta C_{10})\delta C_9 \hat{\mathbf{s}}}{C_{10}\left(4C_7\hat{m}_b + (2C_9 + \triangle C_{9,\perp} + \triangle C_{9,||})\hat{\mathbf{s}}\right)} + \ldots$$

B_5 & $B_{6s} \to \widetilde{B}_5$ & $\widetilde{B}_{6s}$ Observables

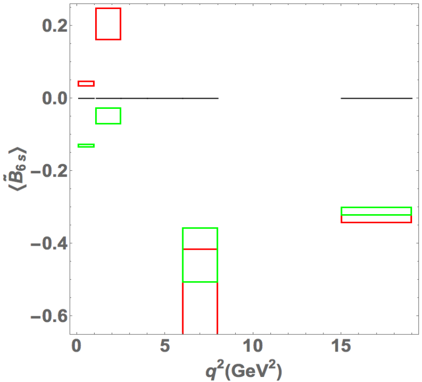
B_5 & B_{6s} are **not identically 0** in the SM.
Lepton mass differences generates a non-zero contribution mainly in the first bin.
$\Rightarrow$ If on an event-by-event basis experimentalist can measure $\langle J_i^\mu/\beta_\mu^2\rangle$:

$$\langle \widetilde{B}_5 \rangle = \frac{\langle J_5^\mu/\beta_\mu^2\rangle}{\langle J_5^e/\beta_e^2\rangle} - 1 \quad \langle \widetilde{B}_{6s} \rangle = \frac{\langle J_{6s}^\mu/\beta_\mu^2\rangle}{\langle J_{6s}^e/\beta_e^2\rangle} - 1$$

- SM Predictions: $\langle \widetilde{B}_i \rangle = 0.00 \pm 0.00$.
- All good properties of $B_{5,6s}$ + simpler structure $\beta_i \to 1$.



$\widetilde{B}_5$



$\widetilde{B}_{6s}$

- When $\hat{s} \to 0$,
  $\widetilde{B}_5 = \widetilde{B}_{6s} = \delta C_{10}/C_{10} \Rightarrow$
  Sensitivity to δC_{10}!
  Exactly as B_5, B_{6s} but simpler.
- 1st Bins: Capacity to distinguish $C_{9,\mu}^{\rm NP} = -1.11$ from $C_{9,\mu}^{\rm NP} = -C_{10,\mu}^{\rm NP} = -0.65$.

BACK-UP

How LFUV NP enter in Wilson coefficients?:

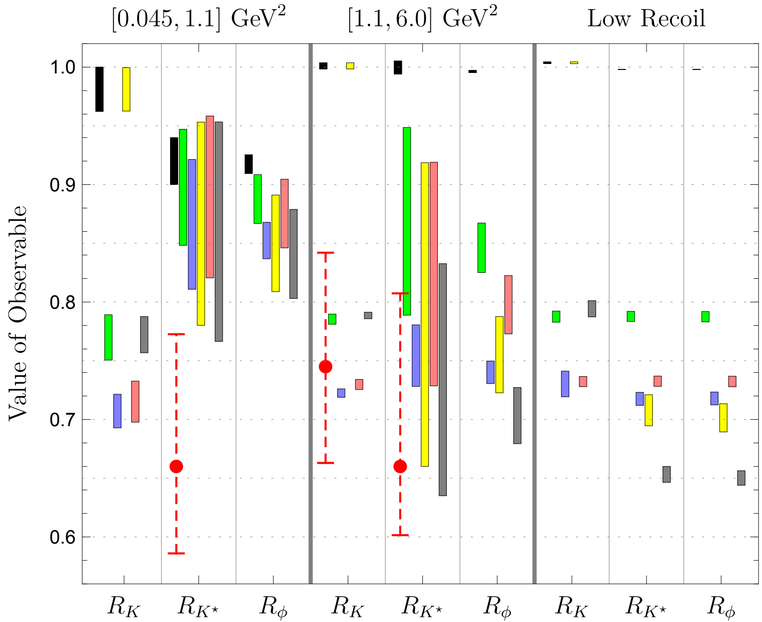
$$C_{i,\mu} = \begin{cases} C_i + \delta C_i, \; i = 10, 9', 10' \\ C_9 + \delta C_9 + \triangle C_9^{(j)} \end{cases} \qquad C_{i,e} = \begin{cases} C_i, \; i = 10, 9', 10' \\ C_9 + \triangle C_9^{(j)} \end{cases}$$

$$j = \perp, \|, 0$$

Notice $C_{7,7'}$ is obviously lepton-mass independent.

- $\Rightarrow$ $\delta C_i = C_{i,\mu} - C_{i,e} \equiv$ amount of LFU violation.
- $\Rightarrow$ $C_i \equiv$ SM $+$ LFU NP.
- $\Rightarrow$ $\triangle C_9^{(j)} \equiv$ long-distance charm.Two types:
  - **Transversity Dependent**: $\triangle C_9^{\perp,\|,0}$ different.
  - **Transversity Independent**: $\triangle C_9^{\perp} = \triangle C_9^{\|} = \triangle C_9^{0}$.

Disentangling New Physics: Ratios of Branching Ratios



SM-[BLACK]

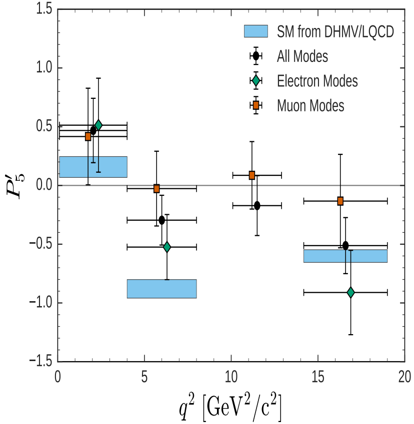
Five "good" scenarios:

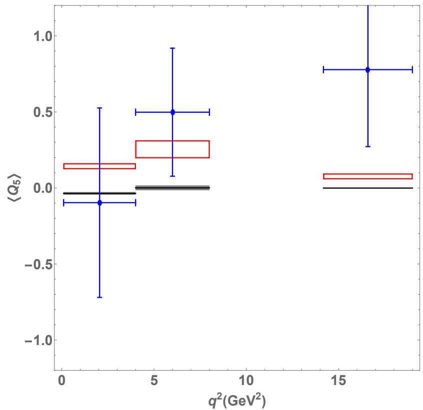
- Sc. 1 [GREEN]: $C_{9\mu}^{\rm NP} = -1.1$,
- Sc. 2 [BLUE]: $C_{9\mu}^{\rm NP} = -C_{10\mu}^{\rm NP} = -0.61$,
- Sc. 3 [YELLOW]: $C_{9\mu}^{\rm NP} = -C'_{9\mu} = -1.01$,
- Sc. 4 [ORANGE]: $C_{9\mu}^{\rm NP} = -3C_{9e}^{\rm NP} = -1.06$,
- Sc. 5:[GRAY]: The best fit point in the six-dimensional fit.

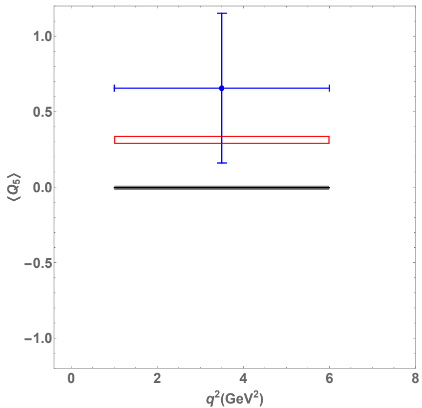
R_{K^*} is computed using very conservative KMPW-FF but R_ϕ using BSZ-FF (only available).

ATTENTION: In presence of NP $R_{K,K^*,\phi}$ are largely sensitive to FF choices

First hint from Belle?





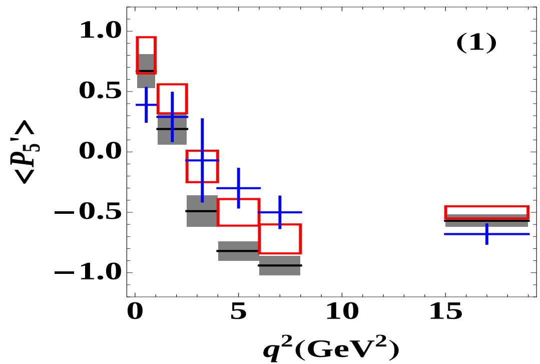


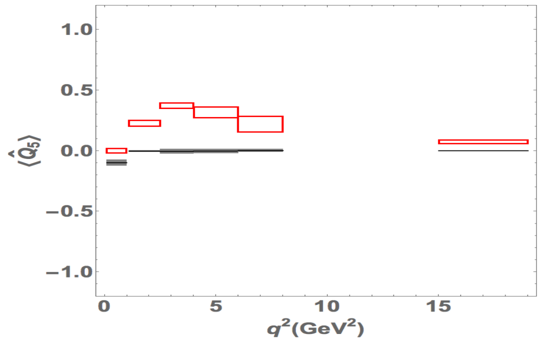
- different systematics than LHCb (combination of channels).
- Belle has found for $\langle P_5' \rangle^{\mu}_{[4,8]}$ a 2.6σ deviation while 1.3σ for $\langle P_5' \rangle^{e}_{[4,8]}$
- Q_5 points in the same direction as $C_{9\mu}^{\rm NP} = -1.1$ scenario (in red).

More data needed for confirmation...

Q_i observables. The example: P_5' versus $Q_5 = P_5'^{\mu} - P_5'^{e}$

Gray-SM, Red-NP $C_{9,\mu}^{\rm NP} = -1.11, C_{9,e}^{\rm NP} = 0$ and data



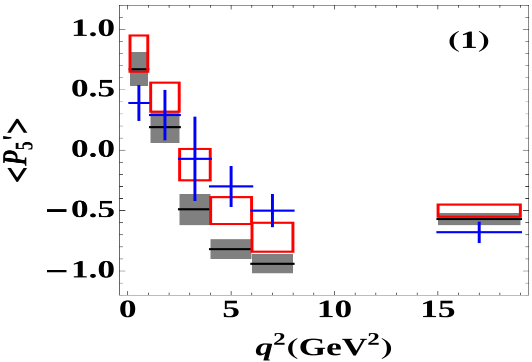


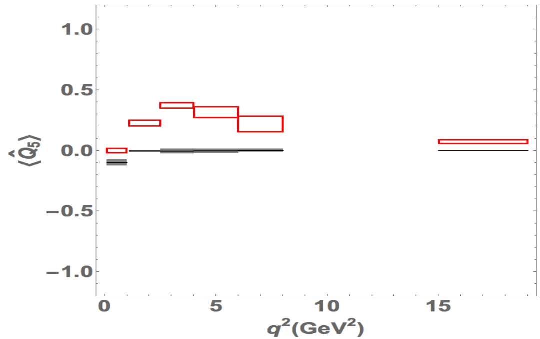
- Soft FF independent at LO exactly in SM
  Soft FF independent at LO exactly in NP.
- Large sensitivity to $C_{9,\mu}$. SM (DHMV'15):

$$\langle P_5' \rangle_{[4,6]} = -0.82 \pm 0.08$$
$$\langle P_5' \rangle_{[6,8]} = -0.94 \pm 0.08$$

- FF indep. at all orders in SM (up to $\triangle m_\ell^2/q^2$).
  Soft FF indep. at LO exactly in NP.
- Long-distance charm insensitive in the SM.
  Large sensitivity to $\delta C_9 = C_{9,\mu} - C_{9,e}$.
  (CDMV'16): ($< 10^{-3}$ without lepton mass)

$$\left\langle \hat{Q}_5 \right\rangle_{[4,6]} = -0.002 \pm 0.017$$
$$\left\langle \hat{Q}_5 \right\rangle_{[6,8]} = +0.002 \pm 0.010$$





Remark: In presence of NP hadronic uncertainties reemerge in $\hat{Q}_5$ ...

P_5'	Prediction $C_{9,\mu}^{\rm NP} = -1.1$	$\hat{Q}_5$	SM-Prediction	$\hat{Q}_5$	Prediction $\delta C_9 = -1.1$
$[0.1, 0.98]$	$+0.80 \pm 0.14$	$[0.1, 0.98]$	-0.097 ± 0.023	$[0.1, 0.98]$	0.000 ± 0.018
$[1.1, 2.5]$	$+0.43 \pm 0.12$	$[1.1, 2.5]$	-0.003 ± 0.007	$[1.1, 2.5]$	0.227 ± 0.023
$[2.5, 4]$	-0.12 ± 0.13	$[2.5, 4]$	-0.005 ± 0.017	$[2.5, 4]$	0.370 ± 0.021
$[4, 6]$	-0.50 ± 0.11	$[4, 6]$	-0.002 ± 0.017	$[4, 6]$	0.314 ± 0.046
$[6, 8]$	-0.73 ± 0.12	$[6, 8]$	$+0.002 \pm 0.010$	$[6, 8]$	0.216 ± 0.061

BUT, it only matters when discussing the **type** of NP we can see.