B-anomalies: status and implications

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IFT- Workshop

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IFAE

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Outline & Questions

1. Diagnosis of anomalies: Where we stand?
2. A comparative study of Pre and Post Moriond
   - -Are now all the global significances smaller?
   - -Are new emerging hypothesis?
   - -Brief Comparison with other analysis.
3. Lepton Flavour Universal (LFU) New Physics
   - -Two kinds of New Physics? Maybe two scales?
4. Linking charge, neutral and LFU New Physics.
5. Solutions proposed to the anomalies
6. What's next? Q_5
7. Conclusions

Diagnosis of anomalies in $b \to s\ell\ell$

Model independent approach to $b \to s\ell\ell$

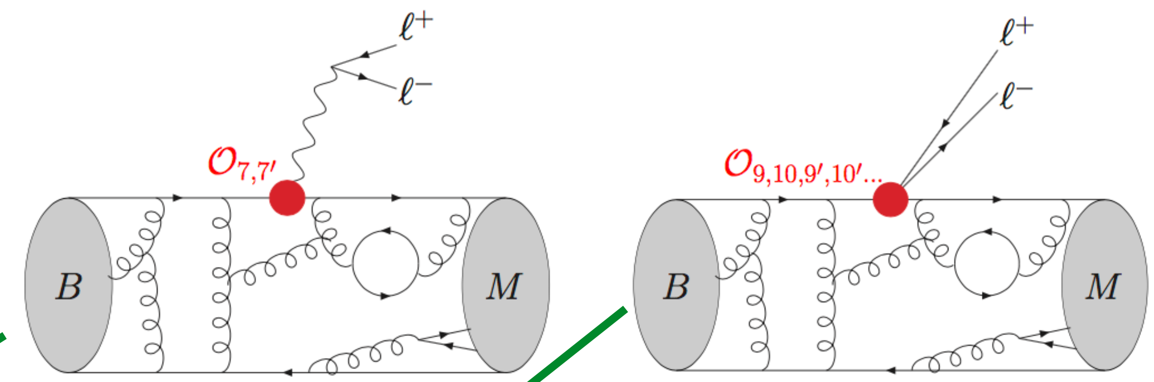
$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

$$\left.\begin{aligned}
\mathcal{O}_7 &= \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu}, \\
\mathcal{O}_{7'} &= \frac{e}{16\pi^2} m_b (\bar{s}\sigma_{\mu\nu} P_L b) F^{\mu\nu},
\end{aligned}\right\}$$

$$\left.\begin{aligned}
\mathcal{O}_{9\ell} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell), \\
\mathcal{O}_{9\ell'} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \ell), \\
\mathcal{O}_{10\ell} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell), \\
\mathcal{O}_{10\ell'} &= \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_R b)(\bar{\ell}\gamma^\mu \gamma_5 \ell),
\end{aligned}\right\}$$

At the $\mu_b = 4.8$ GeV scale:

$\mathcal{C}_7^{\rm SM} = -0.29$, $\mathcal{C}_9^{\rm SM} = 4.1$, $\mathcal{C}_{10}^{\rm SM} = -4.3$



Interesting Directions:

$\mathcal{C}_9 = -\mathcal{C}_{10} \quad \Rightarrow \quad L_q \otimes L_\ell$

$\mathcal{C}_{9'} = -\mathcal{C}_{10'} \quad \Rightarrow \quad R_q \otimes L_\ell$

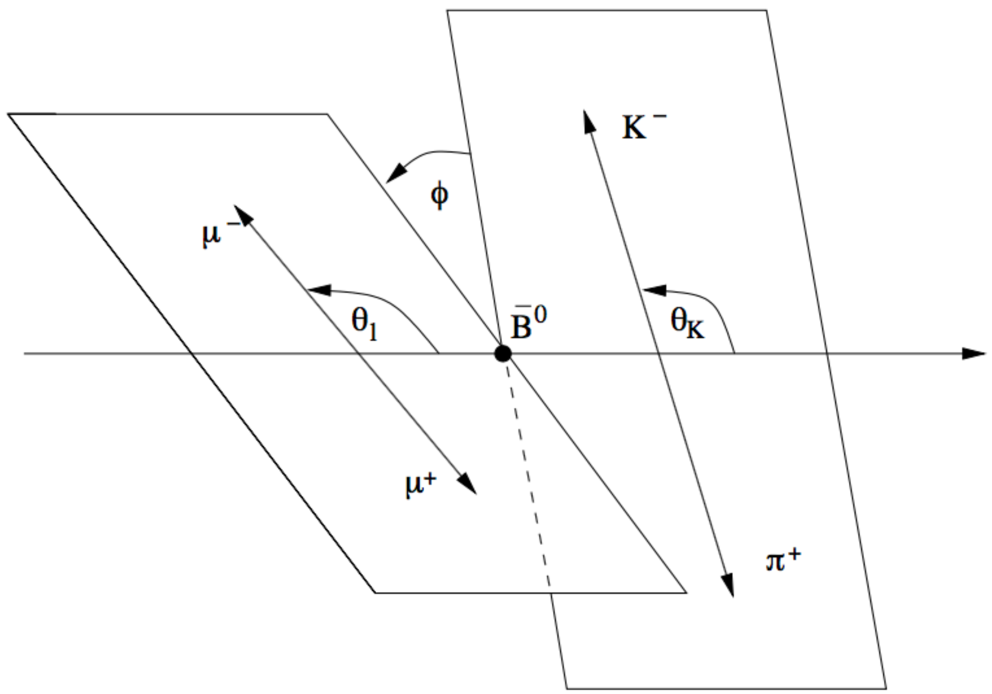
$\mathcal{C}_9 = -\mathcal{C}_{9'} \quad \Rightarrow \quad A_q \otimes V_\ell$

We explore not only directions BUT new BASIS

=>standard muon and electron basis
=> new LFUV and LFU basis

The starting point: Angular distribution

4-body angular distribution $\bar{\mathbf{B}}_{\mathbf{d}} \to \bar{\mathbf{K}}^{*\mathbf{0}}(\to \mathbf{K}^-\pi^+)\mathbf{l}^+\mathbf{l}^-$ with three angles, invariant mass of lepton-pair q^2.



θ_ℓ: Angle of emission between $\bar{K}^{*0}$ and μ^- in di-lepton rest frame.
$\theta_{\mathbf{K}}$: Angle of emission between $\bar{K}^{*0}$ and K^- in di-meson rest frame.
ϕ: Angle between the two planes.

$\mathbf{q^2}$: dilepton invariant mass square.

$$\frac{d^4\Gamma(\bar{B}_d)}{dq^2\, d\cos\theta_\ell\, d\cos\theta_K\, d\phi} = \frac{9}{32\pi} \sum_i J_i(q^2) f_i(\theta_\ell, \theta_K, \phi)$$

$J_i(q^2)$ function of transversity (helicity) amplitudes of K*: $A^{L,R}_{\perp,\|,0}$ but also A_t, A_S

$A^{L,R}_{\perp,\|,0} = \mathcal{C}_i$ (short) $\times$ Hadronic quantities (long)

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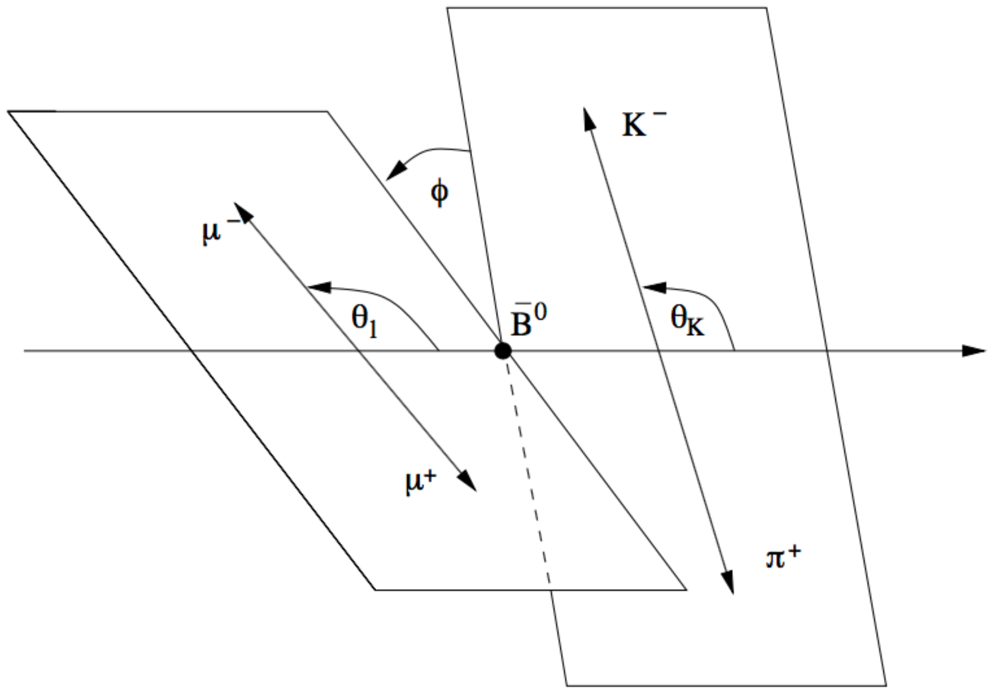

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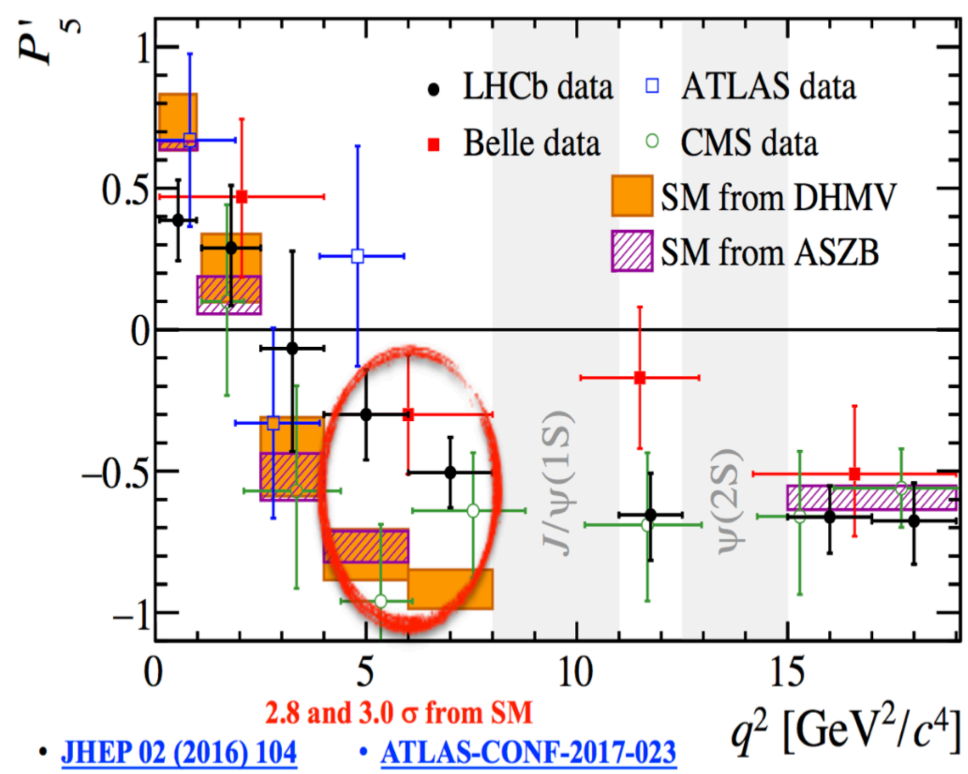
$$\frac{1}{\Gamma'_{full}} \frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\left[\frac{3}{4}\mathbf{F_T}\sin^2\theta_K + \mathbf{F_L}\cos^2\theta_K + (\frac{1}{4}\mathbf{F_T}\sin^2\theta_K - \mathbf{F_L}\cos^2\theta_K)\cos 2\theta_l\right.$$
$$+\sqrt{\mathbf{F_T}\mathbf{F_L}}\left(\frac{1}{2}\mathbf{P}'_4\sin 2\theta_K \sin 2\theta_l \cos\phi + \mathbf{P}'_5 \sin 2\theta_K \sin\theta_l \cos\phi\right) + 2\mathbf{P_2}\mathbf{F_T}\sin^2\theta_K\cos\theta_l + \frac{1}{2}\mathbf{P_1}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_l\cos 2\phi$$
$$\left.-\sqrt{\mathbf{F_T}\mathbf{F_L}}\left(\mathbf{P}'_6\sin 2\theta_K\sin\theta_l\sin\phi - \frac{1}{2}\mathbf{P}'_8\sin 2\theta_K\sin 2\theta_l\sin\phi\right) - \mathbf{P_3}\mathbf{F_T}\sin^2\theta_K\sin^2\theta_l\sin 2\phi\right](1-\mathbf{F_S}) + \frac{1}{\Gamma'_{full}}\mathbf{W_S}$$

P_5' anomaly: Lepton Flavour Dependent

[SDG,JM,JV,1207.2753]

- Angular optimized observables

$$P'_5 = J_5/2\sqrt{-J_{2s}J_{2c}} = P_5^\infty\left(1+\mathcal{O}(\alpha_s\xi_\perp)+\text{p.c.}\right)$$



Theory: I-QCDF+SFF+KMPW+p.c.

Improved QCDF

soft form factors and large recoil symmetry relations.

QCD LCSR with B-meson DA including power corrections

Impact of an improvement on KMPW-FF errors (50%):

- Optimized observable P'_5 (% present error size)

$$P'_{5[4,6]} = -0.82 \pm 0.08(\mathbf{10\%}) \to 0.06(\mathbf{8\%})$$

$\longrightarrow$ interestingly BSZ-FF+full-FF approach finds 0.05

- Non-optimized observable S_5

$$S_{5[4,6]} = -0.35 \pm 0.12(\mathbf{34\%}) \to 0.06(\mathbf{17\%})$$

LHCb: 1/fb with 3.7σ and
3/fb 2 bins with 3σ each
Belle consistent with LHCb [4,8]
ATLAS observed the tension.

CMS compatible with our SM-prediction

(Suggestions: extract correlations of F_L and P_1, P_5' from same PDF;
Use analytical integration of 3D PDFs instead of numerical with RooFit)

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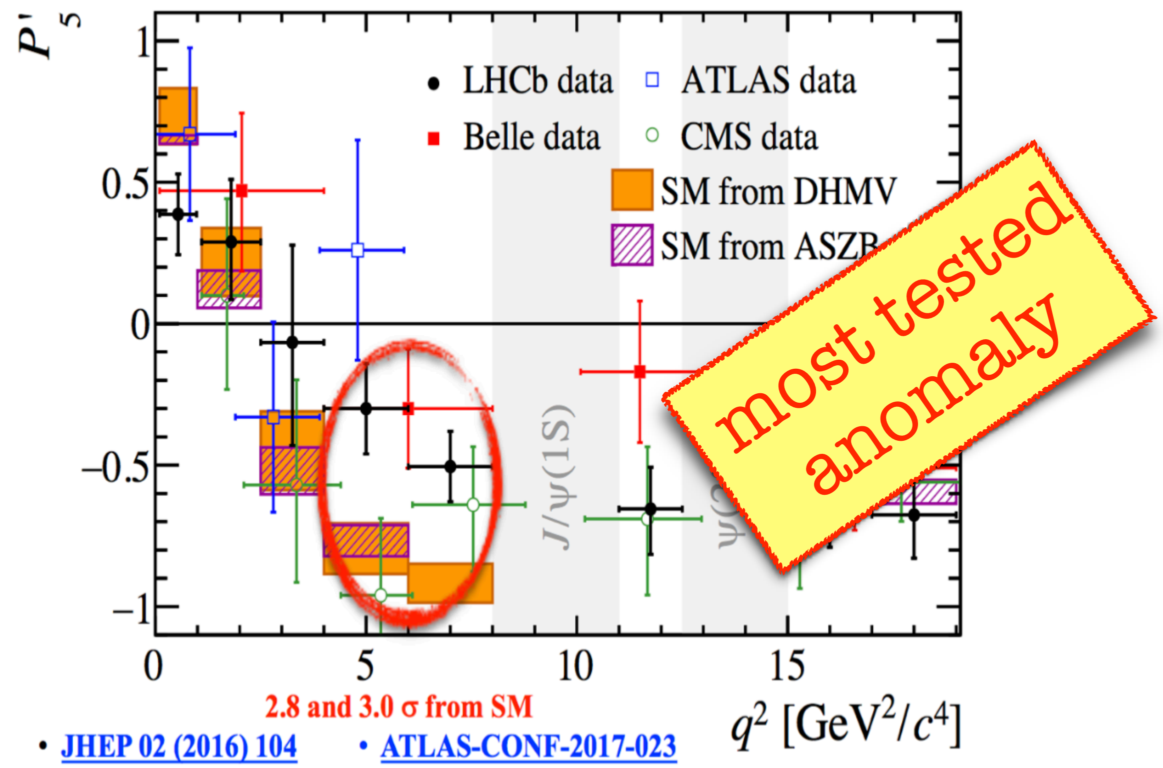

- JHEP 02 (2016) 104
- PRL 118 (2017)
- ATLAS-CONF-2017-023
- CMS-PAS-BPH-15-008

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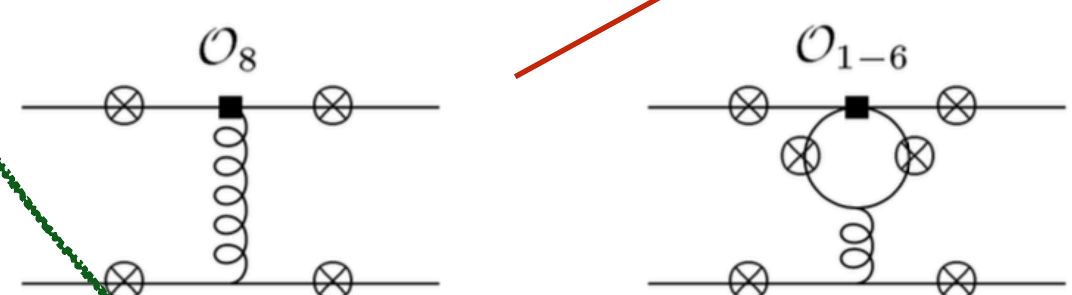
Factorizable & non-Factorizable perturbative corrections in α_s

Theoretical framework: QCDF/SCET+**robust large-recoil symmetries** +breaking (pert+non-pert)
$\hookrightarrow$ independent of LCSR details

$$\mathcal{T}_a = \xi_a \left(C_a^{(0)} + \frac{\alpha_s C_F}{4\pi} C_a^{(1)} \right) + \frac{\pi^2}{N_c} \frac{f_B f_{K^*,a}}{M_B} \Sigma_a \sum_{\pm} \int \frac{d\omega}{\omega} \Phi_{B,\pm}(\omega) \int_0^1 du \Phi_{K^*,a}(u) T_{a,\pm}(u,\omega). \quad a = \perp, \parallel$$

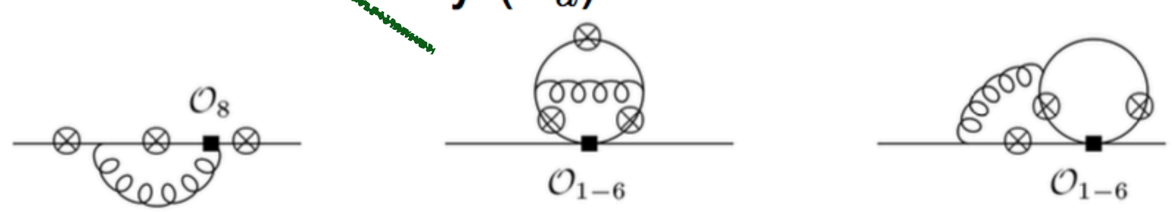
ξ_a (soft FF) . $C_i = 1 + \mathcal{O}(\alpha_s)$ hard-vertex renormalization and T_i hard-scattering kernels computed in α_s-expansion. Φ_i light-cone wave functions. Two types of non-factorizable contributions:

- Hard spectator scattering (T_a): matrix elements of 4-quark op. and the chromomagnetic O_8 operator



(a) (b)

- Diagrams involving the $b \to s$ transition only (C_a)



(c) (d) (e)

Perturbative and non-perturbative charm

Problem: Charm-loop yields a (most likely) q^2- and process-dependent contribution with $O_{7,9}$ structures that may (**in a local analysis of data**) mimic New Physics.

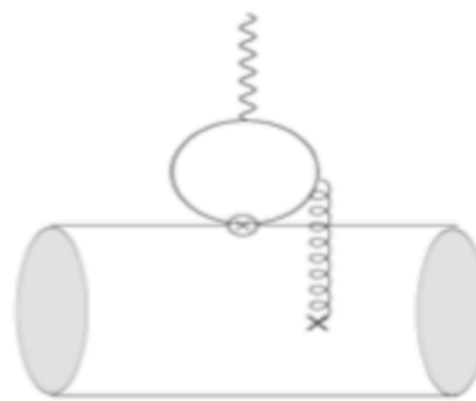
$$C_{9i}^{\rm eff}(q^2) = \mathbf{C_{9\,\rm SMpert}} + C_9^{\rm NP} + \mathbf{s_i \delta C_{9i}^{c\bar{c}LD}(q^2)}. \qquad \mathbf{i} = \perp, \|, \mathbf{0}$$

Perturbative: $\mathbf{C_{9\,\rm SMpert}} = C_9^{\rm SM} + Y(q^2)$
with $Y(q^2)$ stemming from one-loop matrix elements of 4-quark operators O_{1-6}.
...$\mathcal{O}(\alpha_s)$ corrections to $C_{7,9}^{\rm eff}$ of $Y(q^2)$ included via $C_{\perp,\|}^{1\,(\rm nf)}$ but only $O_{1,2}$ (previous slide)

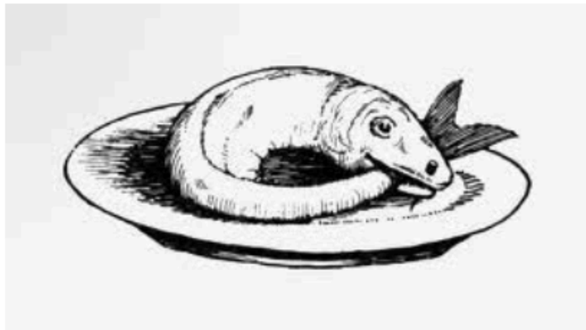
Non-perturbative: $\delta \mathbf{C_{9i}^{c\bar{c}LD}(q^2)}$

More difficult to make progress here:

1. Use LCSR to estimate long-distance contribution with soft-gluon exchange. $\Rightarrow$



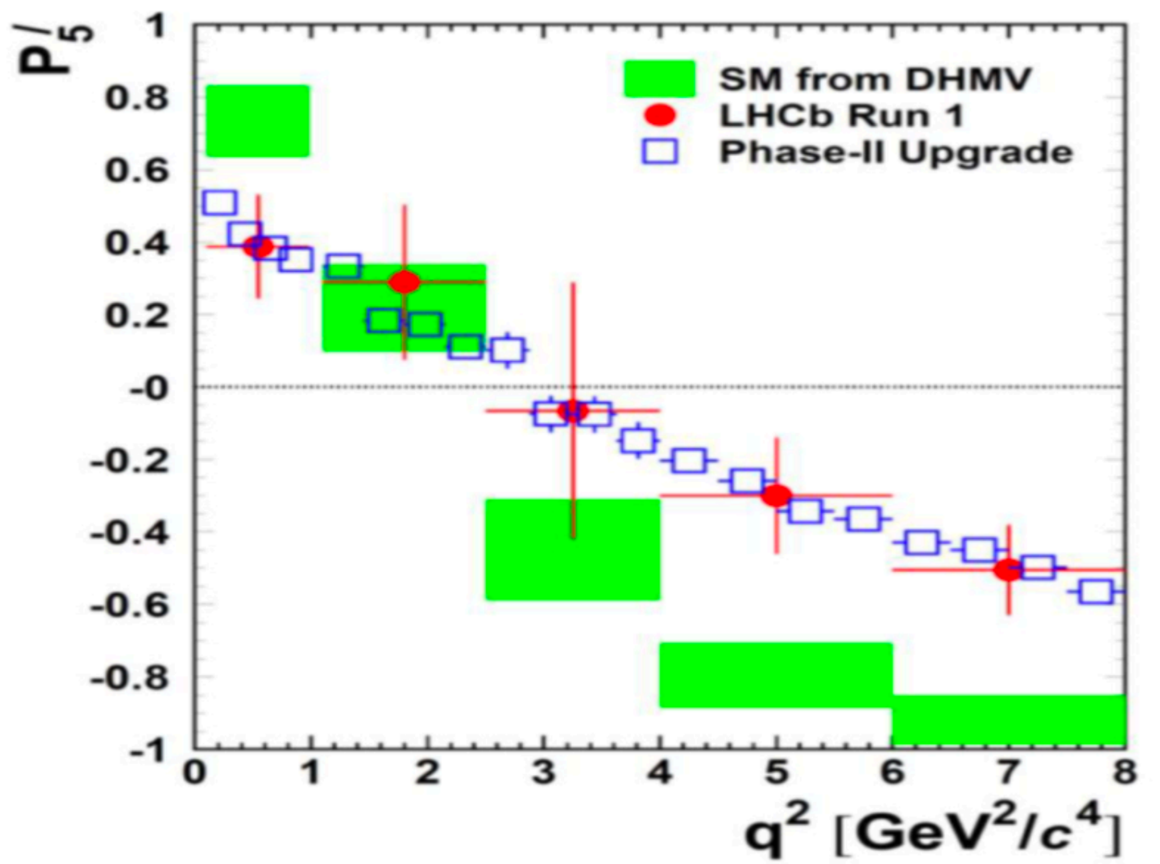
2. Or use fits to the same data you want to explain [Ciuchini, Silvestrini et al.] $\Rightarrow$

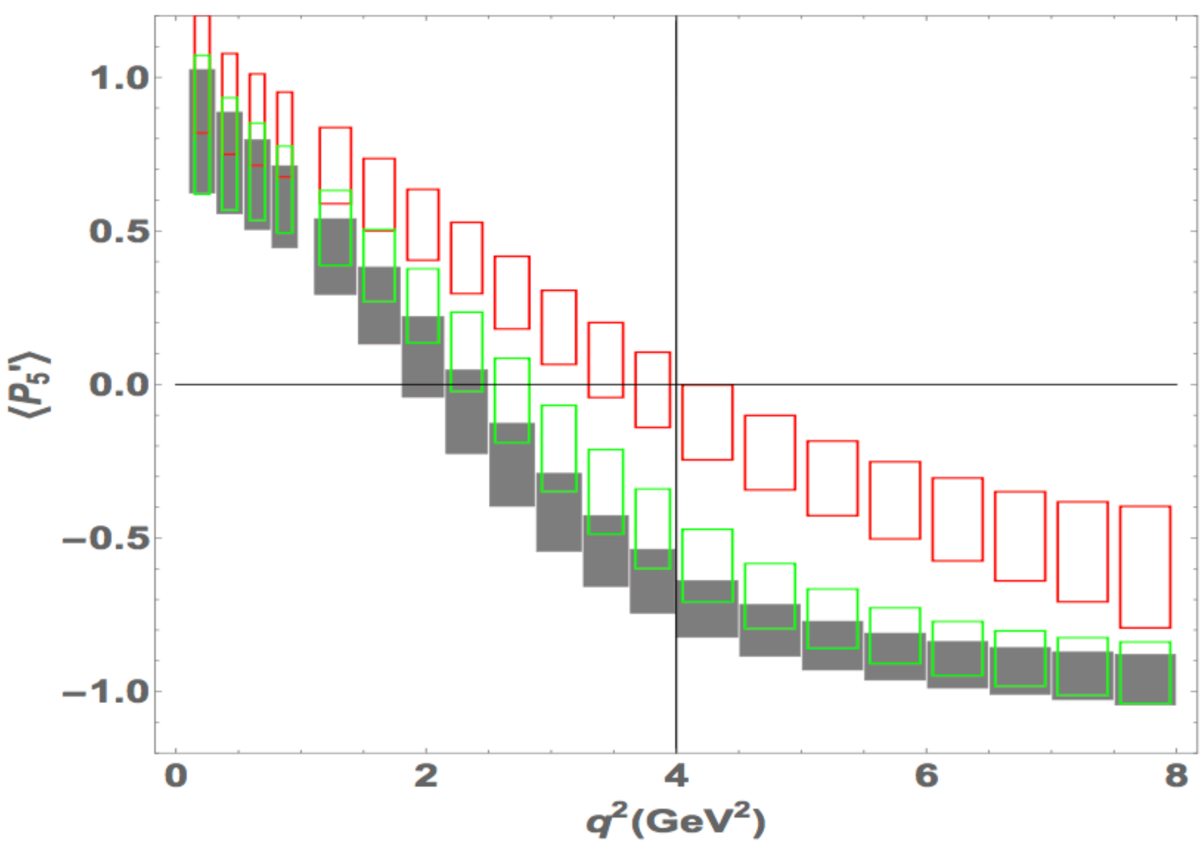


A bright future: LHCb ultimate precision expected in RUNII

Projections from LHCb for P_5' in Phase-II Upgrade.

Green (Sc1): $C_9^{\rm NP} = -C_{10}^{\rm NP} = -0.66$,
Red (Sc2): $C_9^{\rm NP} = -1.76$





A large number of small bins open the window in P_5' for another observable: zero of P_5'.

At LO:

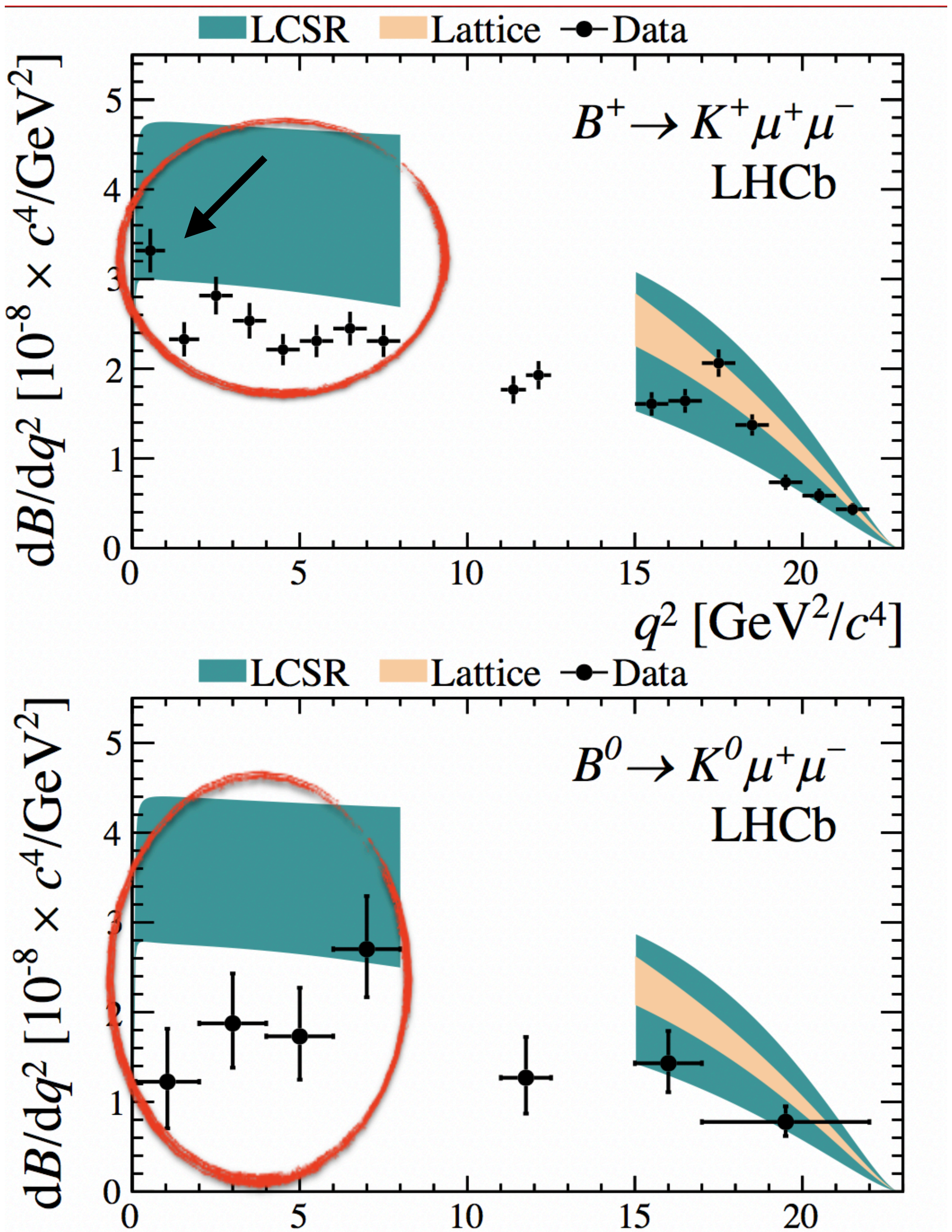
$$q_0^2 = -\frac{m_b m_B^2 C_7^{\rm eff}}{m_b C_7^{\rm eff} + m_B C_9^{\rm eff}(q_0^2)}$$

zero not sensitive to C_{10} (at LO).

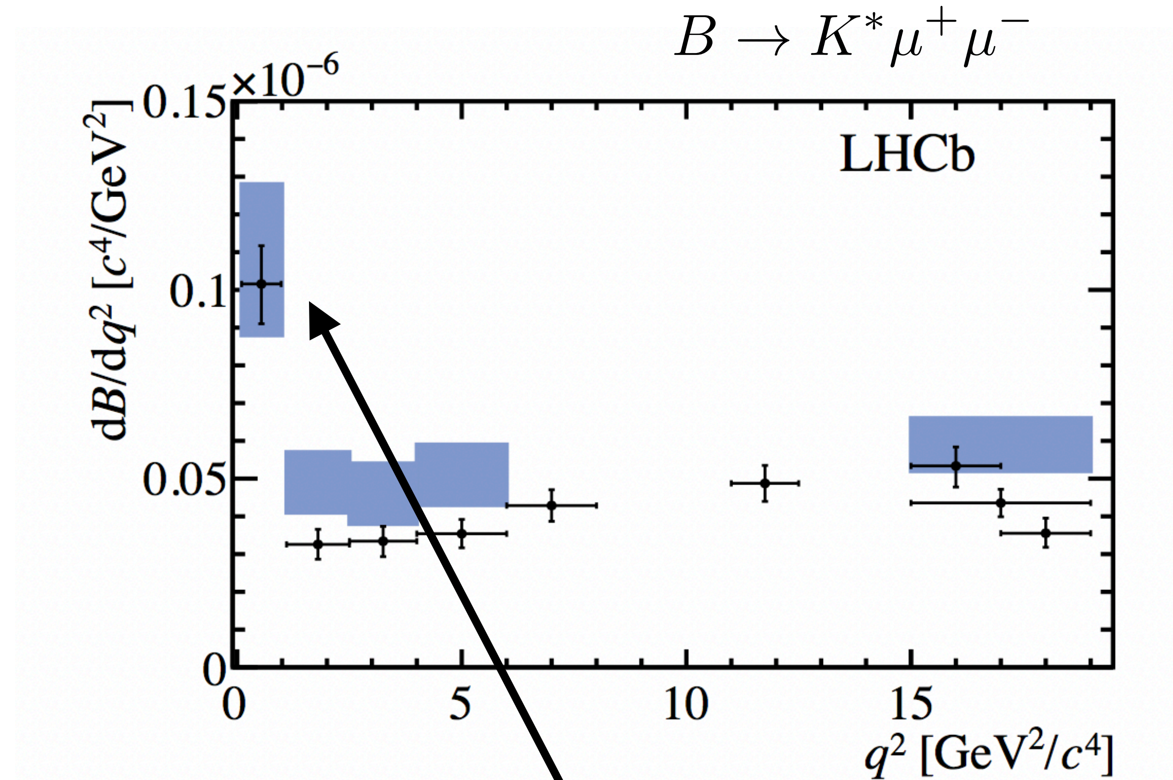
At NLO:

- Large shift of zero of P_5' from $q_0^{2SM} \simeq 2$ GeV² to $q_0^{C_9^{\rm NP}=-1.76} \simeq 3.8$ GeV².

Diff. Branching Ratios: Lepton Flavour Dependent



JHEP 06 (2014) 133



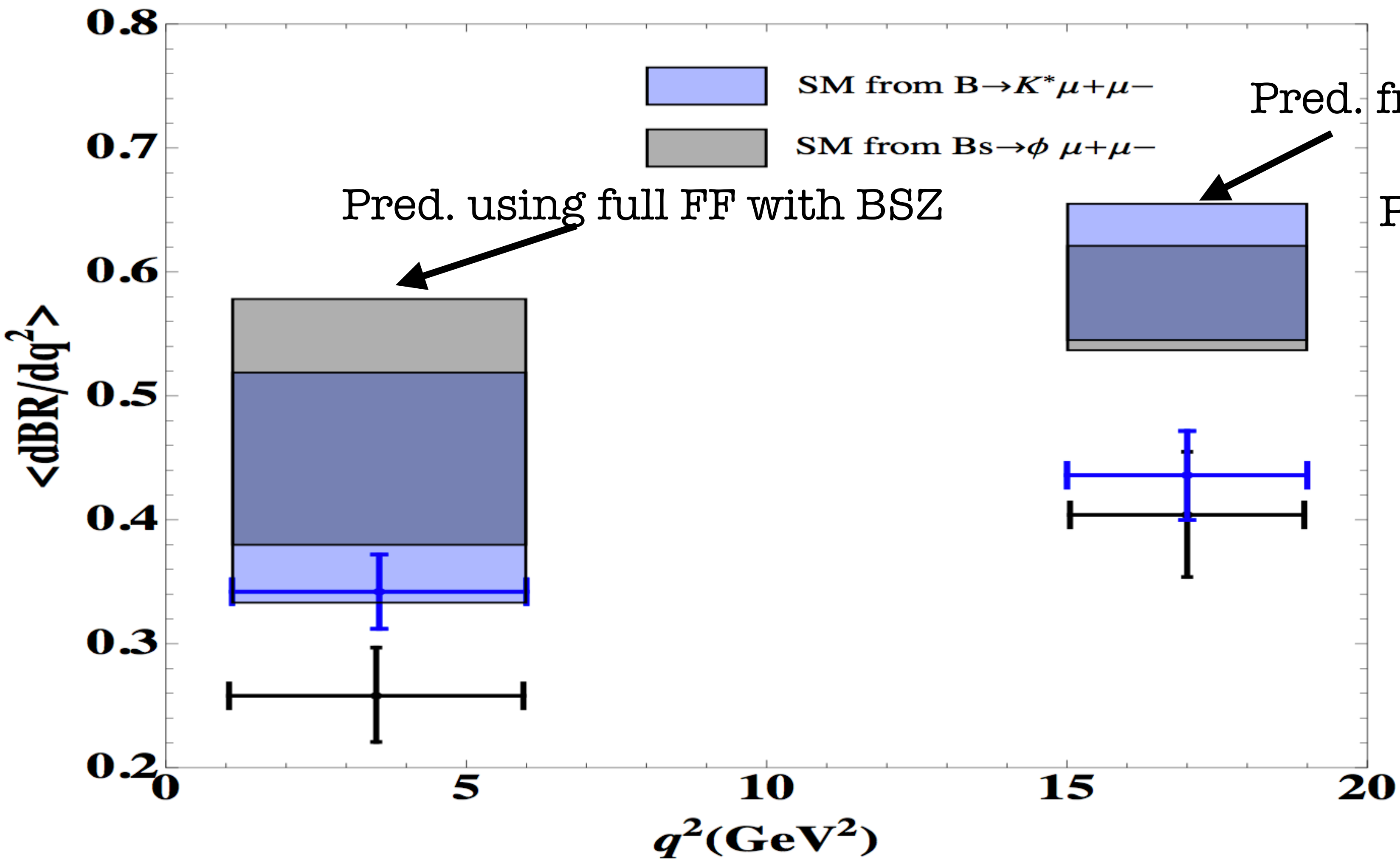
Systematic deficit in muonic channels at large and low-recoil

Possible caveat: In some muonic channels first bin is SM-like

This is **OK** if also electronic channel is SM-like (C_7 dominated). Radiative constraints are tight.

also 1st bins of opt. obs. in mild tension

$B_s \to \phi\mu\mu$ vs $B \to K^*\mu\mu$: Lepton Flavour Dependent



Tension at large and low recoil of

$B(B_s \to \phi\mu\mu) \times 10^7$

Pred. using our approach with BSZ-FF:

	SM	EXP	PULL
[0.1,2]	1.55±0.34	1.11±0.16	+1.2
[2,5]	1.55±0.33	0.77±0.14	+2.2
[5,8]	1.88±0.39	0.96±0.15	+2.2
[15,19]	2.20±0.17	1.62±0.20	+2.2

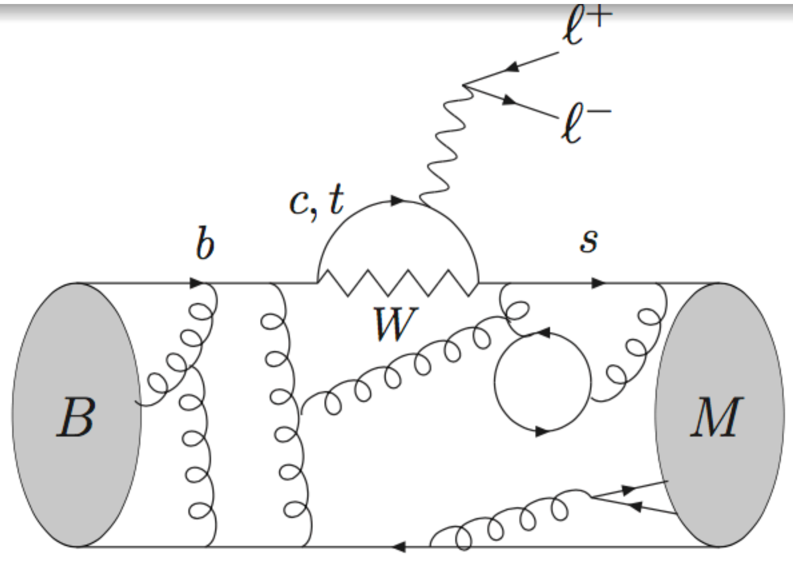
with corrected BSZ FF

Not yet significant: FF at low-q^2 for $B_s \to \phi$ (BSZ) larger than $B \to K^*$, while data is reversed. Ok at high-q^2. **BSZ problem or statistical fluctuation**?
Our prediction for $B \to K^*$ with KMPW has larger errors so **no problem in our case**.

More data will clarify it....

R_K: Lepton Flavour Universality Violation

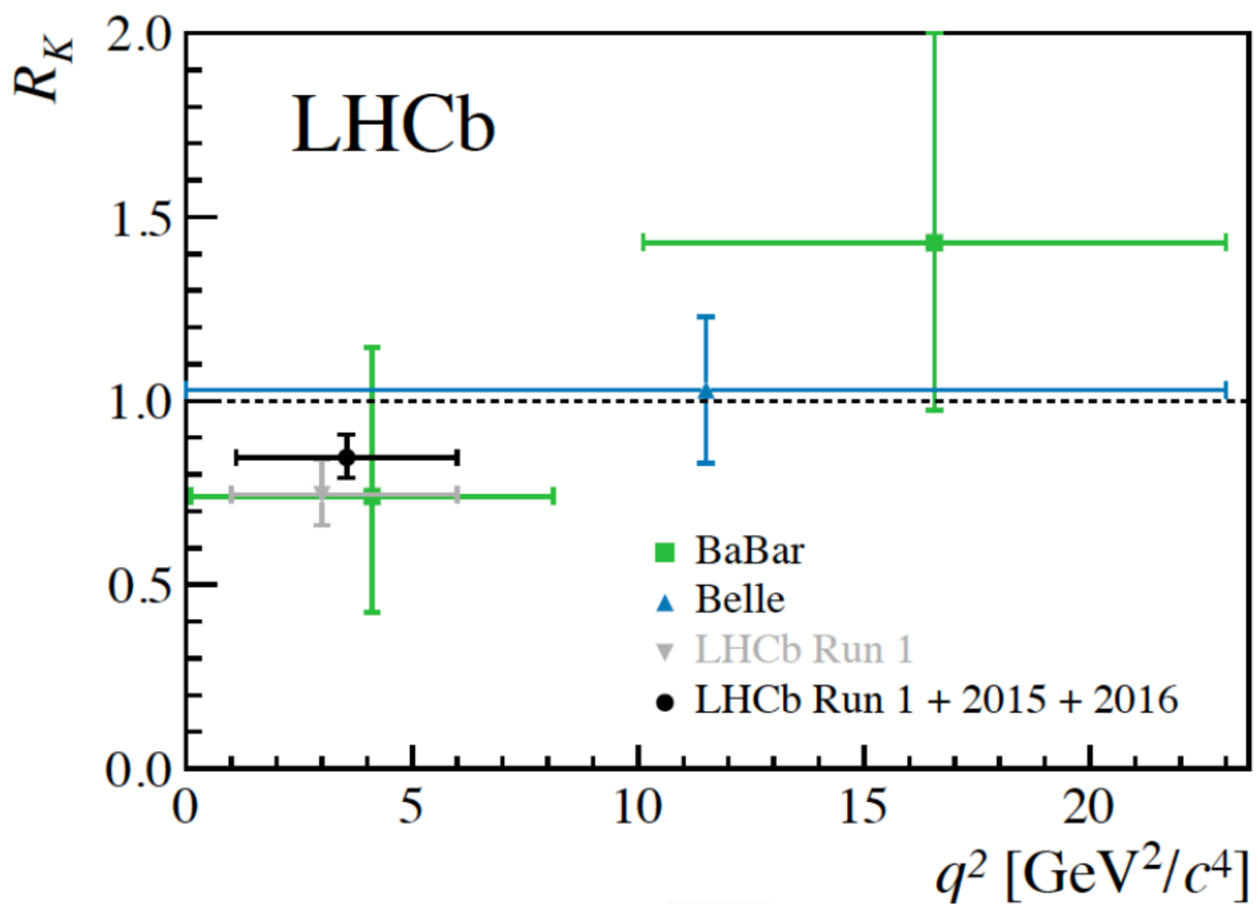
FCNC, **test of universality** of lepton coupling, potential high sensitivity to NP contributions.



First possible signal of LFUV … after LHCb update

$$R_K^{[1.1,6]} = \frac{\mathcal{B}(B \to K\mu^+\mu^-)}{\mathcal{B}(B \to Ke^+e^-)} = 0.846^{+0.060\,+0.016}_{-0.054\,-0.014}$$

still at 2.5σ from SM



Simple structure of BR: $f_{+,0,T} \to f_+$

dominates while the other two suppressed by lepton mass or C_7.

=> **Good observable in presence NP**

=> tensions cannot be explained by FF or charm. Electromagnetic small.

[Isidori et al.]

Does a more SM-like central value imply a reduction in significance?

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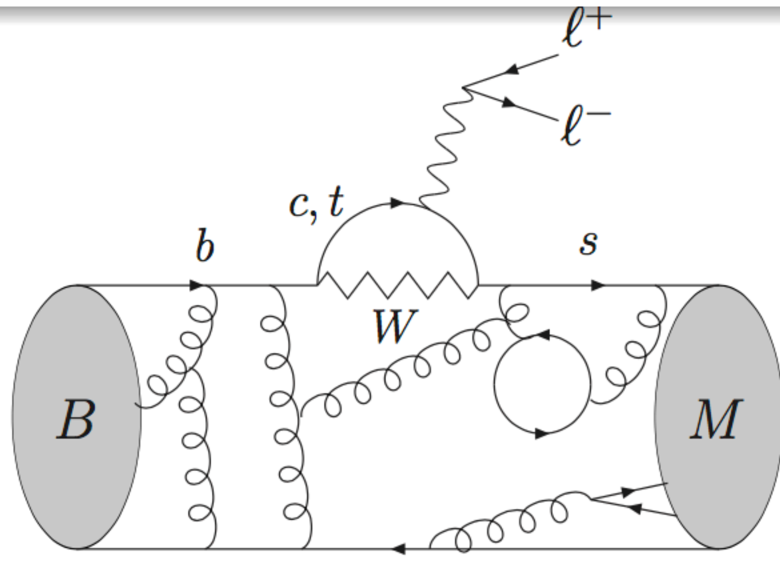

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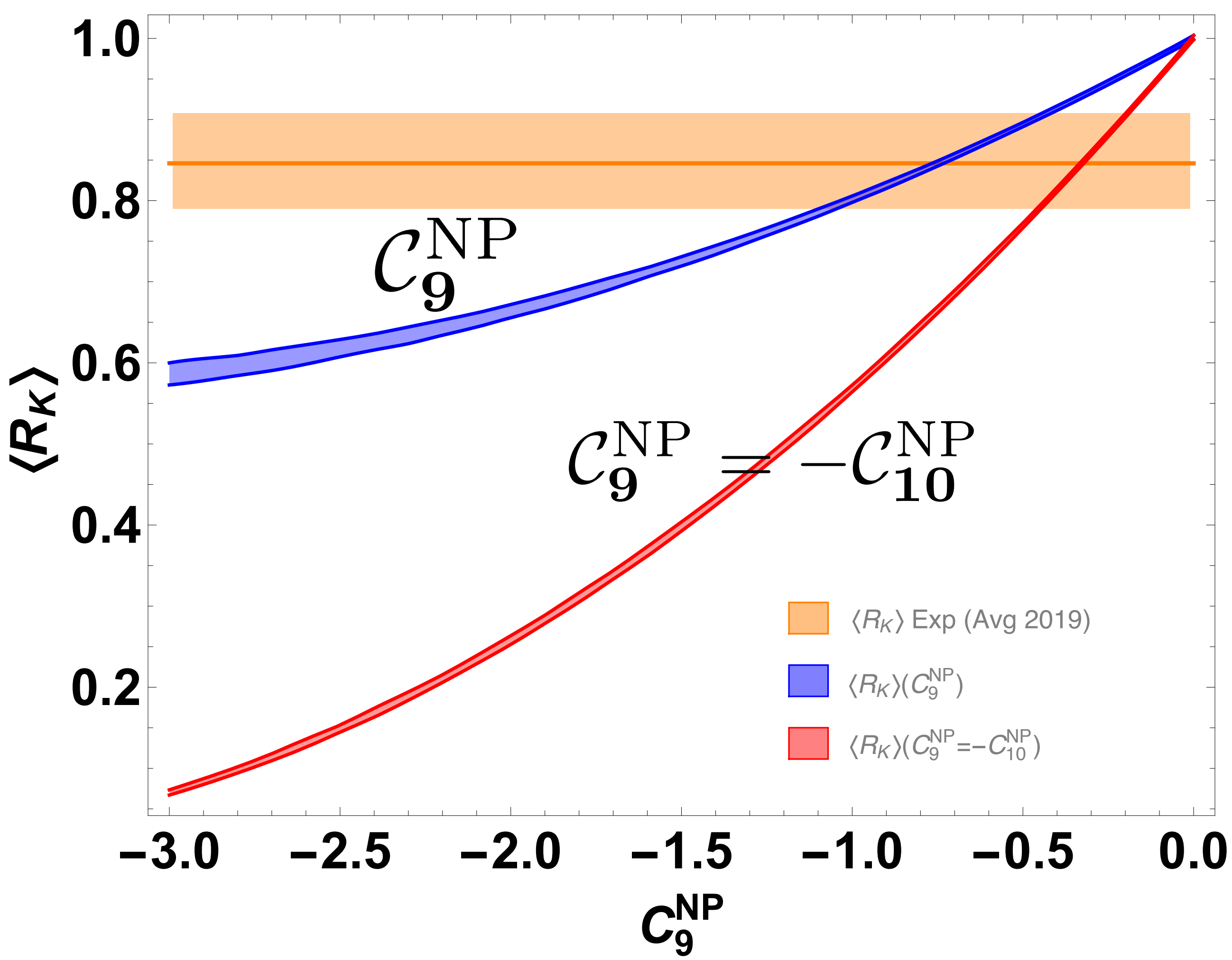

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R_{K^*}: Lepton Flavour Universality Violation

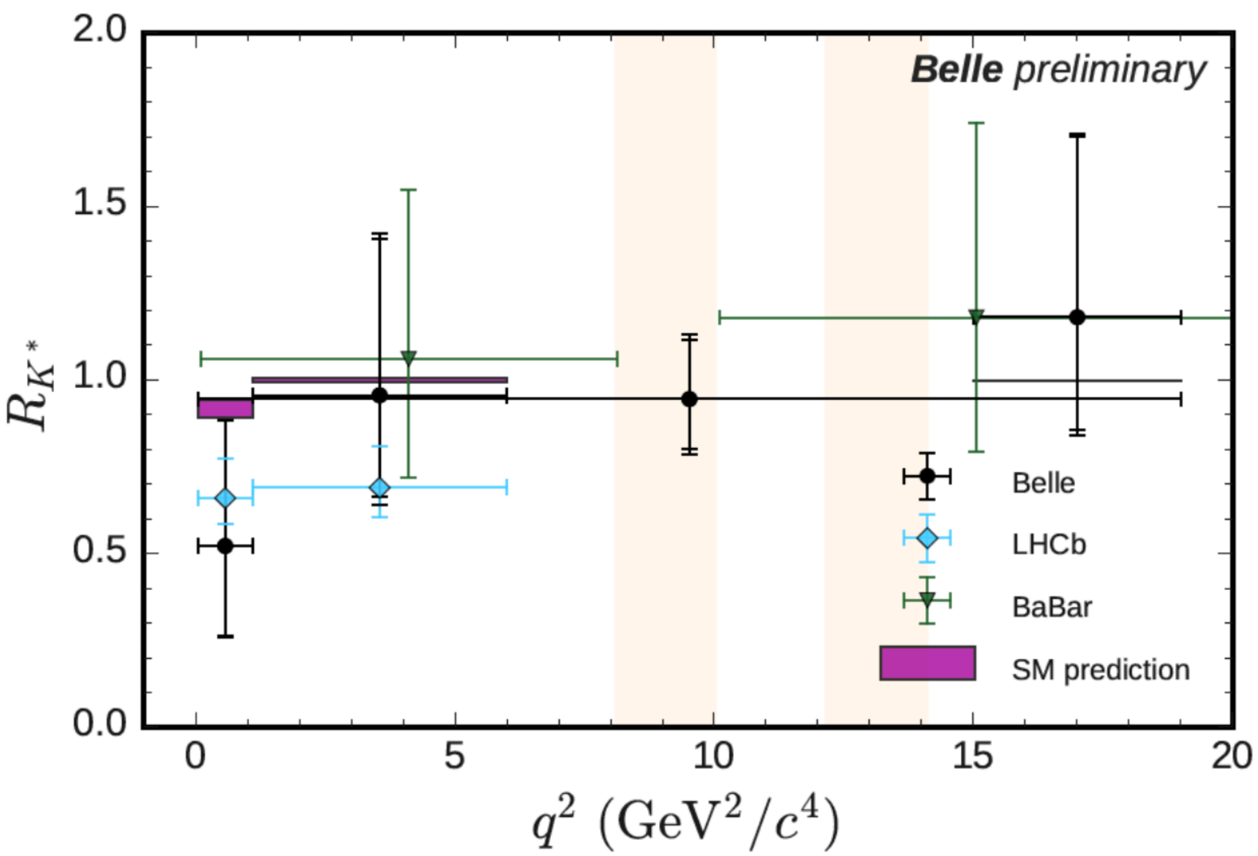
FCNC, second **test of universality** of lepton coupling.

$$R_{K^*} = \frac{Br(B^0 \to K^{*0}\mu^+\mu^-)}{Br(B^0 \to K^{*0}e^+e^-)}$$

different mechanisms?

LHCb:

pulls	$R_{K^*}^{[0.045,1.1]}$	$R_{K^*}^{[1.1,6]}$
Exp.	$0.66^{+0.113}_{-0.074}$	$0.685^{+0.122}_{-0.083}$
SM	0.92 ± 0.02	1.00 ± 0.01



Belle combined data on charged and neutral channels:

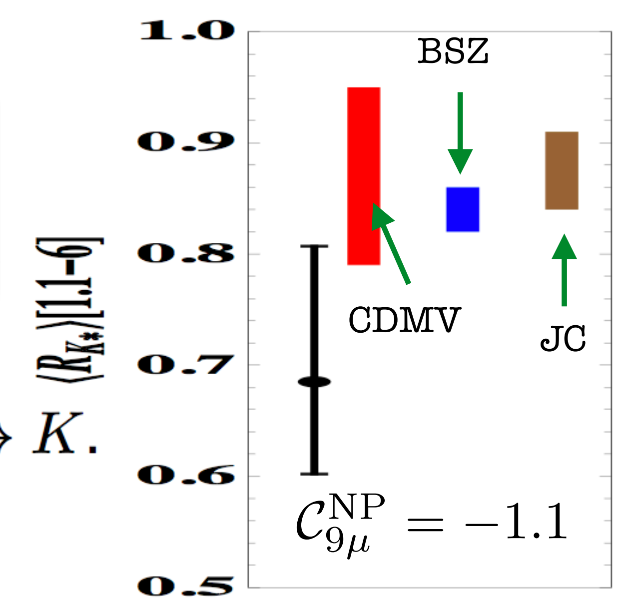
$$R_{K^*}^{[0.045,1.1]} = 0.52^{+0.36}_{-0.26} \pm 0.05$$

$$R_{K^*}^{[1.1,6]} = 0.96^{+0.45}_{-0.29} \pm 0.11$$

$$R_{K^*}^{[15,19]} = 1.18^{+0.52}_{-0.32} \pm 0.10$$

Th: **Nuisance parameter required**

Example of NP:



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.**

Updated global analysis of $b \to s\ell\ell$

2017 → [JHEP 1801(2018) 093]

2019 → [1903.09578]

... hopefully now the race for the right pattern

include additional interesting horses than just the old guys: C_9 and C_9=-C_{10} !

Global analysis of $b \to s\ell\ell$

178 observables from (LHCb, Belle, ATLAS and CMS, no CP-violating obs)

- $B \to K^*\mu\mu$ ($P_{1,2}, P'_{4,5,6,8}, F_L$ in 5 large-recoil bins + 1 low-recoil bin)+available electronic obs.

  ...latest update $\mathrm{Br}(B \to K^*\mu\mu)$ in small bins.

  ...LHCb results on R_{K^*}

- $B_s \to \phi\mu\mu$ ($P_1, P'_{4,6}, F_L$ in 3 large-recoil bins + 1 low-recoil bin)
- $B^+ \to K^+\mu\mu$, $B^0 \to K^0\ell\ell$ (BR) ($\ell = e, \mu$) (new average $R_K = 0.846^{+0.060+0.016}_{-0.054-0.014}$)
- $B \to X_s\gamma$, $B \to X_s\mu\mu$, $B_s \to \mu\mu$ (BR).
- Radiative decays: $B^0 \to K^{*0}\gamma$ (A_I and $S_{K^*\gamma}$), $B^+ \to K^{*+}\gamma$, $B_s \to \phi\gamma$

▶ Belle measurements for the isospin-averaged but lepton-flavour dependent ($Q_{4,5} = P'^{\mu}_{4,5} - P'^{e}_{4,5}$):

[3rd test of LFUV]

$$P'^{\ell}_i = \sigma_+ \, P'^{\ell}_i(B^+) + (1-\sigma_+)\, P'^{\ell}_i(\bar{B}^0) \qquad \sigma_+ = 0.5 \pm 0.5$$

similar treatment of new Belle isospin-averaged result on R_{K^*} (3-bins)

▶ ATLAS measurement of whole basis of P_i and CMS measurements of P_1 and P'_5.

▶ ATLAS update of $B_s \to \mu\mu$ (averaged with LHCb & CMS) and latest f_{B_s} lattice update.

Implications of the new updates on R_K, R_{K^*}, $B_s \to \mu\mu$

$Pull_{SM}$: $\chi^2_{SM}(C_i=0)-\chi^2_{min}(C_i^{HIP})$ considering N_{dof}

2017

1D Hyp.	All: Best fit	All: 1 σ	All: 2 σ	All: $Pull_{SM}$	All: p-value	LFUV: Best fit	LFUV: 1 σ	LFUV: 2 σ	LFUV: $Pull_{SM}$	LFUV: p-value
$\mathcal{C}_{9\mu}^{NP}$	-1.11	$[-1.28, -0.94]$	$[-1.45, -0.75]$	5.8	68	-1.76	$[-2.36, -1.23]$	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$	-0.62	$[-0.75, -0.49]$	$[-0.88, -0.37]$	5.3	58	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}'_{9\mu}$	-1.01	$[-1.18, -0.84]$	$[-1.34, -0.65]$	5.4	61	-1.64	$[-2.13, -1.05]$	$[-2.52, -0.49]$	3.2	32
$\mathcal{C}_{9\mu}^{NP} = -3\mathcal{C}_{9e}^{NP}$	-1.07	[-1.24,-0.90]	[-1.40,-0.72]	5.8	70	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	72

2019

1D Hyp.	All: Best fit	All: 1 σ/2 σ	All: $Pull_{SM}$	All: p-value	LFUV: Best fit	LFUV: 1 σ/ 2 σ	LFUV: $Pull_{SM}$	LFUV: p-value
$\mathcal{C}_{9\mu}^{NP}$	-1.02	$[-1.18, -0.85]$ $[-1.34, -0.68]$	5.8	65.1 %	-1.02	$[-1.38, -0.69]$ $[-1.80, -0.40]$	3.5	50.6 %
$\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}$	-0.49	$[-0.59, -0.40]$ $[-0.69, -0.30]$	5.4	55.5 %	-0.44	$[-0.55, -0.32]$ $[-0.68, -0.21]$	4.0	74.0 %
$\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{9'\mu}$	-1.02	$[-1.18, -0.85]$ $[-1.33, -0.67]$	5.7	61.3 %	-1.66	$[-2.15, -1.05]$ $[-2.54, -0.47]$	3.1	35.4 %
$\mathcal{C}_{9\mu}^{NP} = -3\mathcal{C}_{9e}^{NP}$	-0.92	$[-1.08, -0.76]$ $[-1.23, -0.60]$	5.7	62.7 %	-0.76	$[-1.02, -0.52]$ $[-1.30, -0.30]$	3.5	50.8 %

- Hierarchy remains invariant except $C_{9\mu} = -C_{9'\mu}$ scenario ($R_K \approx 1$)
  - Scenario $C_{9\mu}$ preferred in "All" fit
    Scenario $C_{9\mu} = -C_{10\mu}$ preferred in "LFUV" fit.

- Best fit points for All and LFUV fits in scen. $C_{9\mu}$ in nice agreement
- Scenario $C_{10\mu}$ stays at a significance of ≈4σ for All and LFUV fits.

Implications of the new updates on R_K, R_{K^*}, $B_s \to \mu\mu$

Interesting surprises in 2D updates...

2017

2D Hyp.	All Best fit	All Pull_{SM}	All p-value	LFUV Best fit	LFUV Pull_{SM}	LFUV p-value
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{10\mu}^{NP})$	(-1.01,0.29)	5.7	72	(-1.30,0.36)	3.7	75
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{7}')$	(-1.13,0.01)	5.5	69	(-1.85,-0.04)	3.6	66
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9'\mu})$	(-1.15,0.41)	5.6	71	(-1.99,0.93)	3.7	72
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{10'\mu})$	(-1.22,-0.22)	5.7	72	(-2.22,-0.41)	3.9	85
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9e}^{NP})$	(-1.00,0.42)	5.5	68	(-1.36,0.46)	3.5	65
Hyp. 1	(-1.16,0.38)	5.7	73	(-1.68,0.60)	3.8	78
Hyp. 2	(-1.15, 0.01)	5.0	57	(-2.16,0.41)	3.0	37
Hyp. 3	(-0.67,-0.10)	5.0	57	(0.61,2.48)	3.7	73
Hyp. 4	(-0.70,0.28)	5.0	57	(-0.74,0.43)	3.7	72

2019

2D Hyp.	All Best fit	All Pull_{SM}	All p-value	LFUV Best fit	LFUV Pull_{SM}	LFUV p-value
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{10\mu}^{NP})$	(-0.95,0.20)	5.7	69.5 %	(-0.30,0.52)	3.6	74.5 %
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{7}')$	(-1.03,0.02)	5.6	68.2 %	(-1.03,-0.04)	3.1	53.7 %
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9'\mu})$	(-1.13,0.54)	5.9	74.5 %	(-1.88,1.14)	3.6	75.7 %
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{10'\mu})$	(-1.17,-0.34)	6.1	78.1 %	(-2.07,-0.63)	4.0	92.8 %
$(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9e}^{NP})$	(-1.04,-0.11)	5.5	65.3 %	(-0.76,0.25)	3.1	50.8 %
Hyp. 1	(-1.09,0.28)	6.0	75.8 %	(-1.69,0.32)	3.6	77.1 %
Hyp. 2	(-1.00,0.09)	5.4	63.9 %	(-2.00,0.26)	3.3	61.2 %
Hyp. 3	(-0.50,0.08)	5.1	55.8 %	(-0.43,-0.09)	3.6	74.5 %
Hyp. 4	(-0.52,0.11)	5.2	58.7 %	(-0.50,0.15)	3.7	81.9 %
Hyp. 5	(-1.17,0.24)	6.1	78.2 %	(-2.20,0.52)	4.1	93.8 %

- **Increase in significance in scenarios with RHC**
- R_K more SM-like better described if $C_{9'\mu}>0$ and $C_{10'\mu}<0$
- A $R_q \otimes L_\ell$ structure for primed operators prefers a V over a L_ℓ structure for leptons.
- Hyp.1 is SM-like for $B_s \to \mu\mu$ but perfect for R_K!

Hyp. 1: $(\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{NP} = \mathcal{C}_{10'\mu})$,
Hyp. 2: $(\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{9'\mu}, \mathcal{C}_{10\mu}^{NP} = -\mathcal{C}_{10'\mu})$,
Hyp. 3: $(\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}, \mathcal{C}_{9'\mu} = \mathcal{C}_{10'\mu})$,
Hyp. 4: $(\mathcal{C}_{9\mu}^{NP} = -\mathcal{C}_{10\mu}^{NP}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$
Hyp. 5: $(\mathcal{C}_{9\mu}^{NP}, \mathcal{C}_{9'\mu} = -\mathcal{C}_{10'\mu})$.

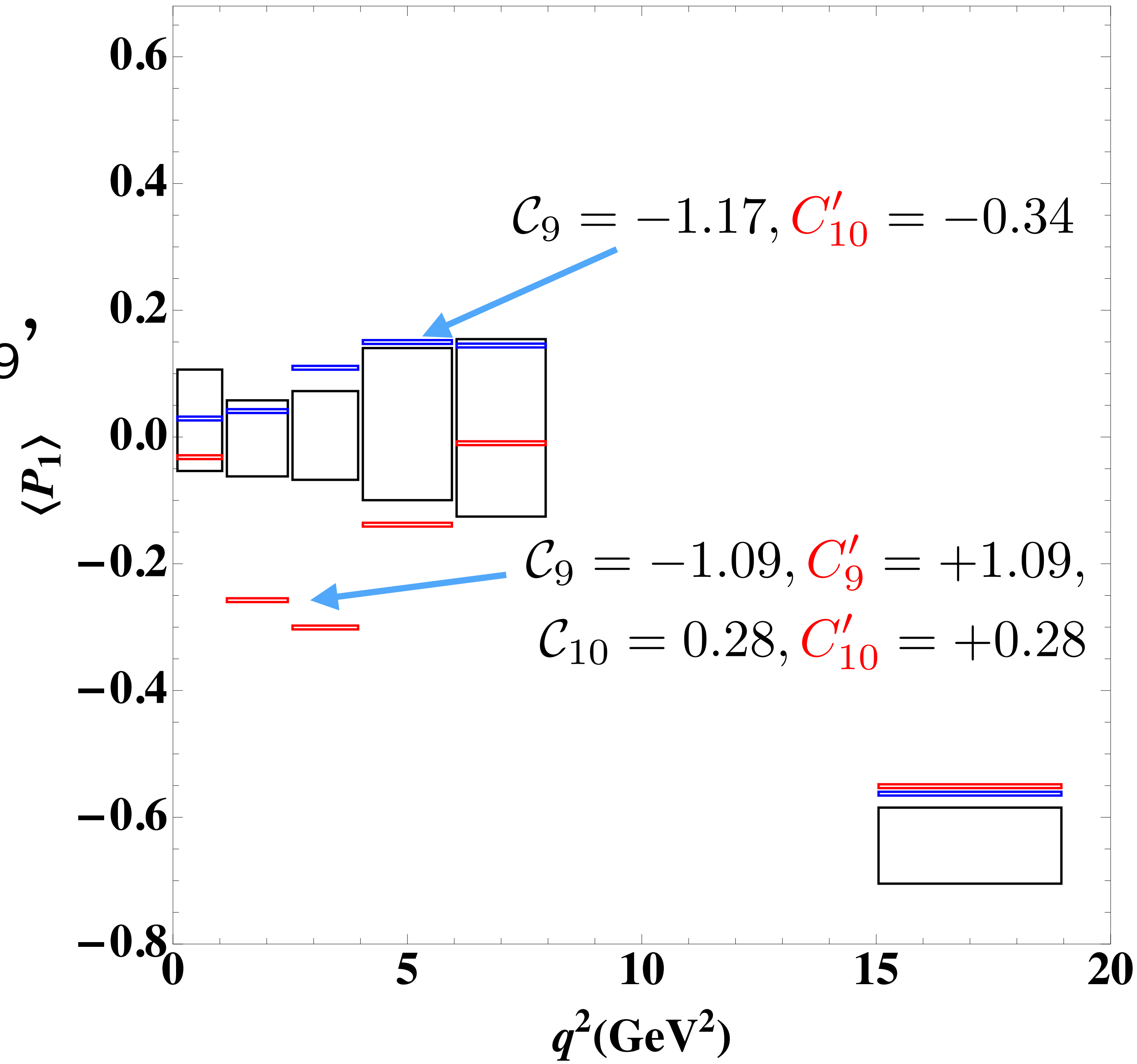
How can we test the presence of RHC (C_9' and C_{10}')?

An accurate measurement:

Observable P_1 in two bins

$P_{1\,[1.1,2.5]} \sim -0.16\, C_{10}' - 0.20\, C_9'$

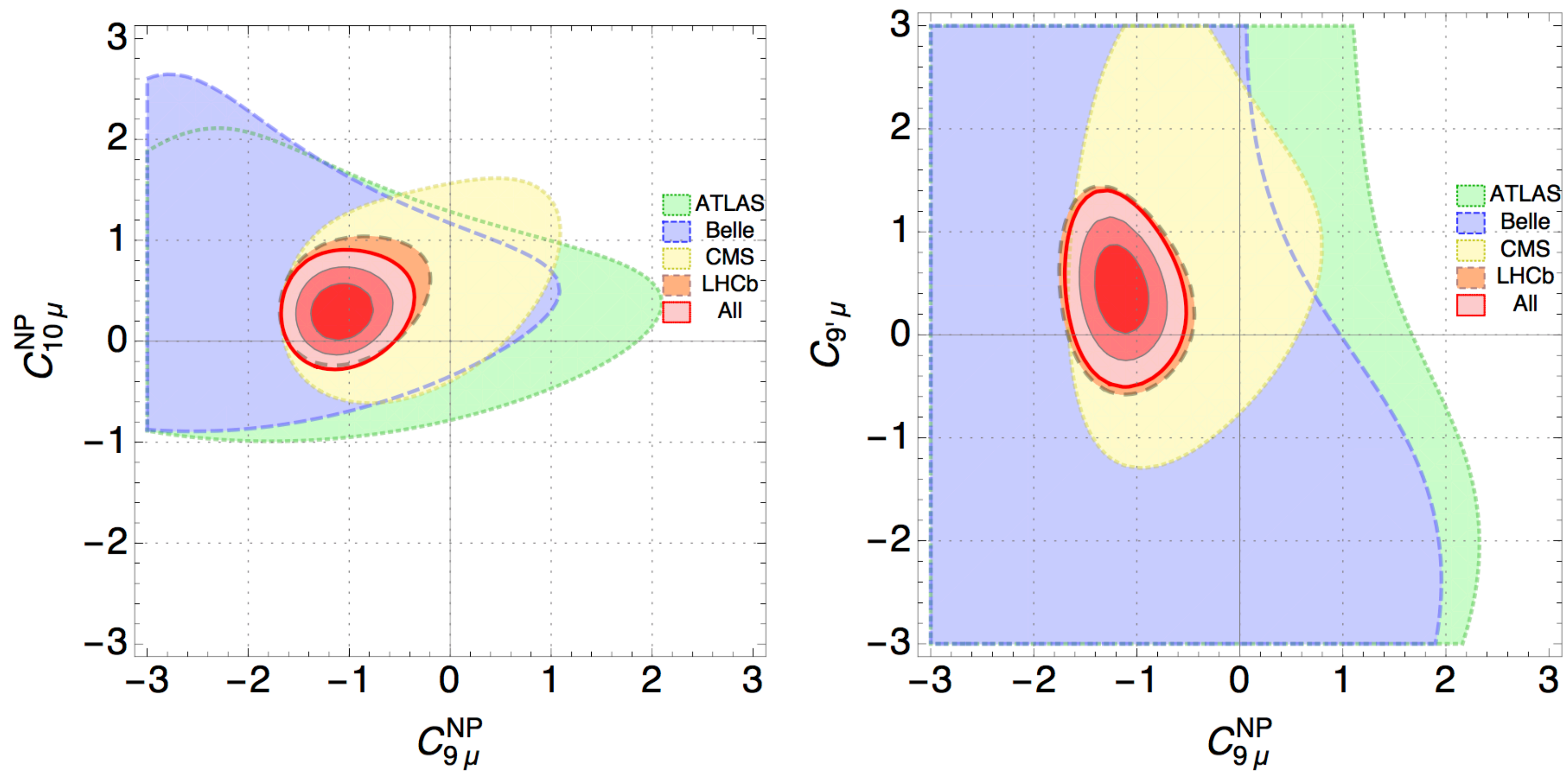
$P_{1\,[4,6]} \sim -0.40\, C_{10}' + 0.07\, C_9' + 0.09\, C_9\, C_9'$



$C_{10}' > 0$ and $C_9' > 0 \Rightarrow P_1 < 0$

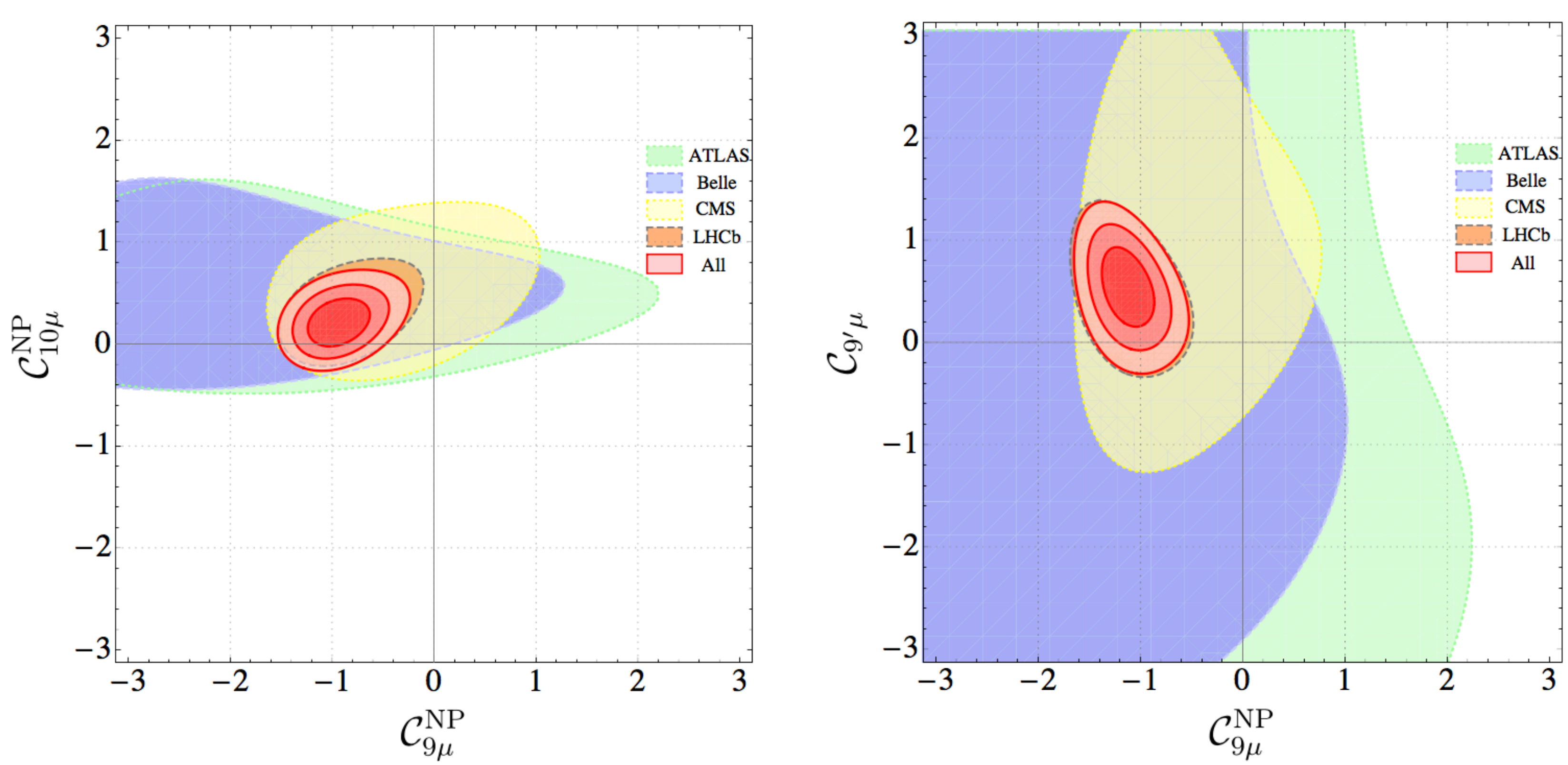
$C_{10}' < 0 \Rightarrow P_1 > 0$

Implications of the new updates on R_K, R_{K^*}, $B_s \to \mu\mu$



2017

-Differences among the 2D scenarios pre and after Moriond are very tiny.



2019

-A $C_{9'}$>0 gets slightly more significant after Moriond.

Implications of the new updates on R_K, R_{K^*}, $B_s \to \mu\mu$

Let's check how the 6D fit has evolved:

2017	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Best fit	+0.03	-1.12	+0.31	+0.03	+0.38	+0.02
1 σ	[−0.01, +0.05]	[−1.34, −0.88]	[+0.10, +0.57]	[+0.00, +0.06]	[−0.17, +1.04]	[−0.28, +0.36]
2 σ	[−0.03, +0.07]	[−1.54, −0.63]	[−0.08, +0.84]	[−0.02, +0.08]	[−0.59, +1.58]	[−0.54, +0.68]

2019	$\mathcal{C}_7^{\rm NP}$	$\mathcal{C}_{9\mu}^{\rm NP}$	$\mathcal{C}_{10\mu}^{\rm NP}$	$\mathcal{C}_{7'}$	$\mathcal{C}_{9'\mu}$	$\mathcal{C}_{10'\mu}$
Best fit	+0.02	-1.13	+0.21	+0.02	+0.39	-0.12
1 σ	[−0.01, +0.05]	[−1.28, −0.91]	[+0.04, +0.42]	[+0.00, +0.04]	[−0.09, +0.96]	[−0.40, +0.17]
2 σ	[−0.03, +0.06]	[−1.48, −0.71]	[−0.12, +0.61]	[−0.02, +0.06]	[−0.56, +1.14]	[−0.57, +0.34]

$C_{10\mu}$-$C'_{10\mu}$ stays the same

- Again **same picture**,

  -except change in sign of bfp of $C_{10'\mu}$

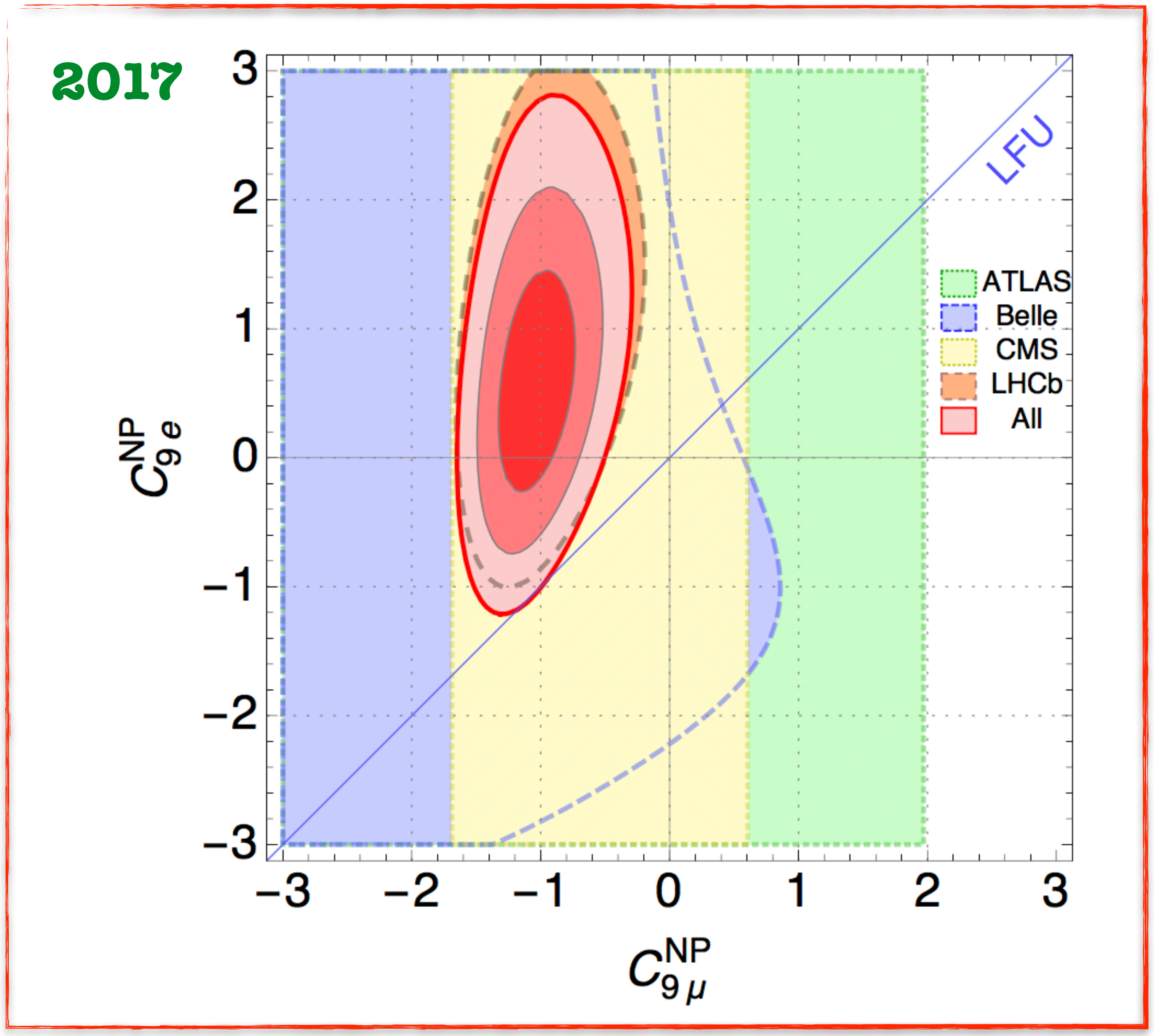
  -except significance 5.0σ→**5.3σ**

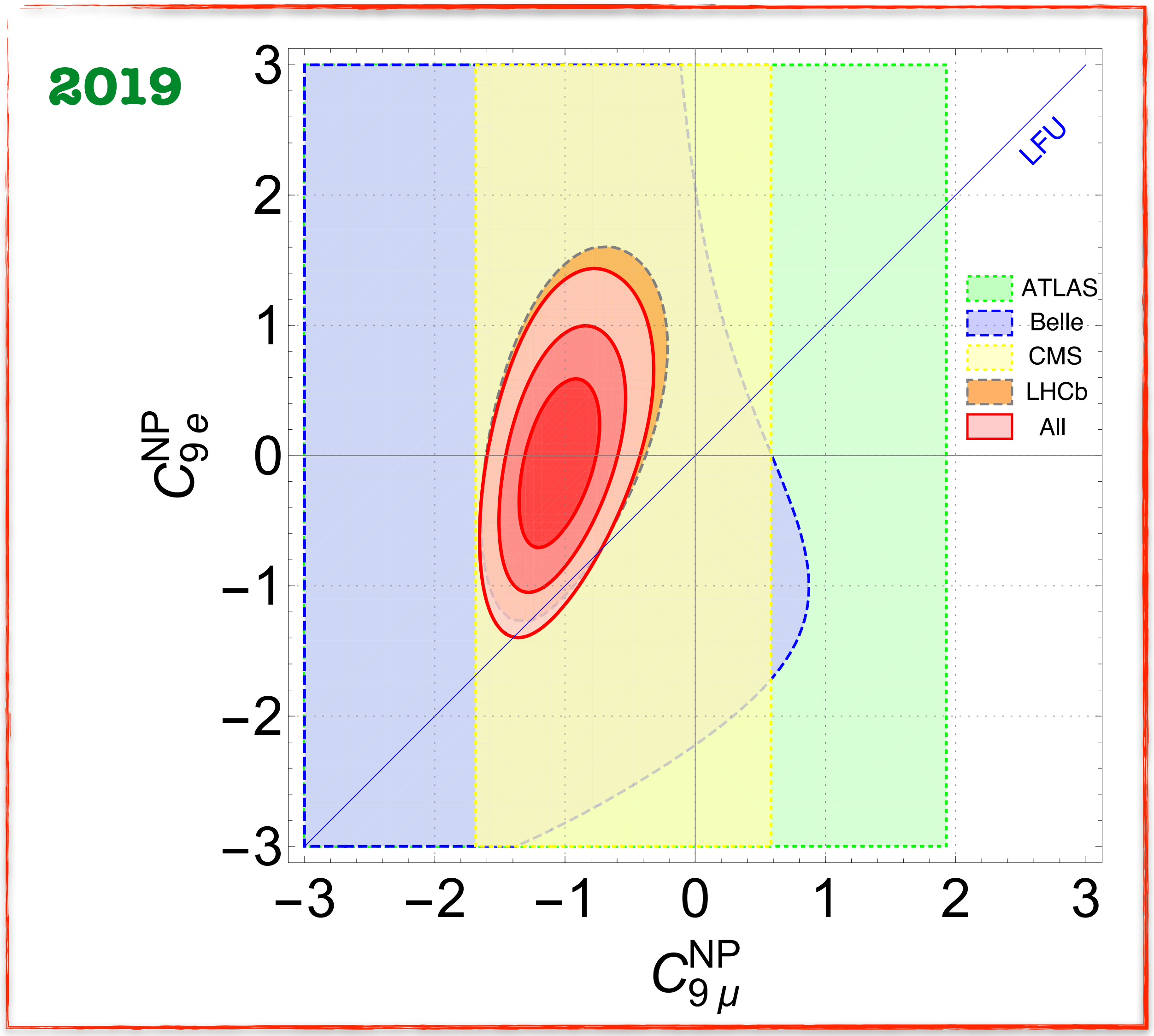
Implications of the new updates on R_K, R_{K^*}, $B_s \to \mu\mu$

New Physics in electrons slightly more compatible with zero.

[JHEP 1801(2018) 093]

[1903.09578]





It is then natural to expect some impact in the significance of LFUV+LFU scenarios

Scale of New Physics

Flavour observables are sensitive to higher scales than direct searches at colliders

... if NP affects flavour it is not surprising that we detect it first.

What is the scale of NP for $b \to s\ell\ell$? Reescaling the Hamiltonian by $H_{eff}^{\rm NP} = \sum \frac{\mathcal{O}_i}{\Lambda_i^2}$

- Tree-level induced (semi-leptonic) with $\mathcal{O}(1)$ couplings ($\times\sqrt{g_{bs}\, g_{\mu\mu}}$):

$$\Lambda_i^{\rm Tree} = \frac{4\pi v}{s_w g} \frac{1}{\sqrt{2|V_{tb}V_{ts}^*|}} \frac{1}{|C_i^{\rm NP}|^{1/2}} \sim \frac{\mathbf{35}\,\rm TeV}{|C_i^{\rm NP}|^{1/2}}$$

- Loop level-induced (semi-leptonic) with $\mathcal{O}(1)$ couplings:

$$\Lambda_i^{\rm Loop} \sim \frac{35\rm TeV}{4\pi |C_i^{\rm NP}|^{1/2}} = \frac{\mathbf{2.8}\,\rm TeV}{|C_i^{\rm NP}|^{1/2}}$$

- MFV with CKM-SM, suppression $\sqrt{|V_{tb}V_{ts}^*|} \sim 1/5$: Tree level: $\frac{\mathbf{7\ TeV}}{|C_i^{\rm NP}|^{1/2}}$ and Loop: $\frac{\mathbf{0.6\ TeV}}{|C_i^{\rm NP}|^{1/2}}$

Solution $C_9^{\rm NP} \sim -1.1$ (scale is $\sim$ numerator) or $C_9^{\rm NP} = -C_{10}^{\rm NP} \sim -0.6$ (30 % higher scale).

Similar exercise for $b \to c\tau\nu$ taking a 15% enhancement over SM:

$$\Lambda^{\rm NP} \sim 1/(\sqrt{2} G_F |V_{cb}| 0.15)^{1/2} \sim \mathbf{3.2}\,\rm TeV$$

Are we overlooking Lepton Flavour Universal NP?

[Algueró, Capdevila, SDG, Masjuan, JM, PRD'19]

Hypothesis: Lepton Flavour Universality

[Algueró, Capdevila, SDG, Masjuan, JM, PRD'19]

We traded the usual controversy:

Is this New Physics or long-distance charm?

by a more constructive question:

Are we observing two kinds of New Physics?

$$\mathcal{C}_{i\ell}^{NP} = \mathcal{C}_{i\ell}^{V} + \mathcal{C}_{i}^{U} \quad \text{with} \quad i = 9, 10 \quad \ell = e, \mu$$

$$\mathcal{C}_{ie}^{V} = 0$$

$\mathcal{C}_{i}^{U}$ ↔ Lepton Flavour **Universal** NP

$\mathcal{C}_{i\ell}^{V}$ ↔ Lepton Flavour Universal **Violating** NP

....extended to primed operators in [Addendum: 1903.09578v3]

Motivation:

- We have LFUV and LFD observables, then it is natural to split:

  LFUV ↔ $\mathcal{C}_{i\ell}^{V}$ LFD ↔ $\mathcal{C}_{i\ell}^{V} + \mathcal{C}_{i}^{U}$

- New mechanism to fulfill $B_s \to \mu\mu$

Is this the same as adding NP in electrons?

Many previous works already included NP in electrons:

Mahmoudi et al. (large and low recoil data)

London et al. (large and low recoil data)

Ciuchini et al. (only large recoil data)

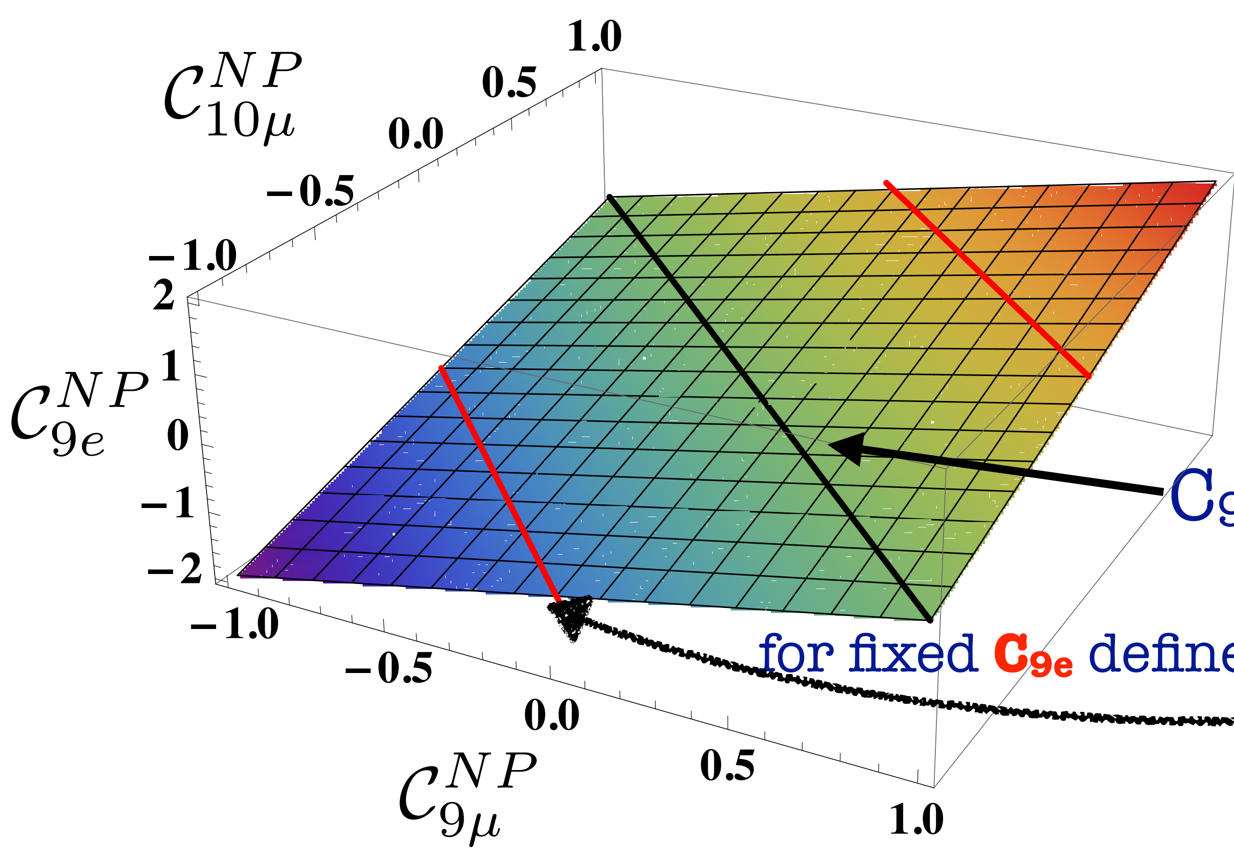
....

Which is the difference with our proposal?

All previous analyses explored directions within 2D planes in coordinates

$(C_{9\mu},C_{10\mu})$ and (C_{9e},C_{10e})

instead the plane in coordinates (C_9^V,C_{10}^V) in presence for instance of C_9^U LFU can translate in a tilted plane in $(C_{9\mu},C_{10\mu},C_{9e})$ coordinates



$C_{9\mu} = -C_{10\mu}$

for fixed C_{9e} define new directions

Example:

$C_{9\mu}^V = -C_{10\mu}^V$ with C_9^U

implies in the old language

$C_{9\mu} = -C_{10\mu} + \mathbf{C_{9e}}$

... in summary this is NOT simply a reparametrization

LFU updates 2019

1809.08447		Best-fit point	1 σ	Pull_{SM}	p-value
Sc. 5	$\mathcal{C}^{\text{V}}_{9\mu}$	-0.16	$[-0.94, +0.46]$	5.8	78 %
	$\mathcal{C}^{\text{V}}_{10\mu}$	$+1.00$	$[+0.18, +1.59]$		
	$\mathcal{C}^{\text{U}}_{9} = \mathcal{C}^{\text{U}}_{10}$	-0.87	$[-1.43, -0.14]$		
Sc. 6	$\mathcal{C}^{\text{V}}_{9\mu} = -\mathcal{C}^{\text{V}}_{10\mu}$	-0.64	$[-0.77, -0.51]$	6.0	79 %
	$\mathcal{C}^{\text{U}}_{9} = \mathcal{C}^{\text{U}}_{10}$	-0.44	$[-0.58, -0.29]$		
Sc. 7	$\mathcal{C}^{\text{V}}_{9\mu}$	-1.57	$[-2.14, -1.06]$	5.7	72 %
	$\mathcal{C}^{\text{U}}_{9}$	$+0.56$	$[+0.01, +1.15]$		
Sc. 8	$\mathcal{C}^{\text{V}}_{9\mu} = -\mathcal{C}^{\text{V}}_{10\mu}$	-0.42	$[-0.57, -0.27]$	5.8	74 %
	$\mathcal{C}^{\text{U}}_{9}$	-0.67	$[-0.90, -0.42]$		

2019		Best-fit point	1 σ	Pull_{SM}	p-value
Sc. 5	$\mathcal{C}^{\text{V}}_{9\mu}$	-0.34	$[-0.93, +0.19]$	5.5	72 %
	$\mathcal{C}^{\text{V}}_{10\mu}$	$+0.69$	$[+0.21, +1.12]$		
	$\mathcal{C}^{\text{U}}_{9} = \mathcal{C}^{\text{U}}_{10}$	-0.50	$[-0.92, +0.02]$		
Sc. 6	$\mathcal{C}^{\text{V}}_{9\mu} = -\mathcal{C}^{\text{V}}_{10\mu}$	-0.52	$[-0.64, -0.41]$	5.8	71 %
	$\mathcal{C}^{\text{U}}_{9} = \mathcal{C}^{\text{U}}_{10}$	-0.37	$[-0.52, -0.22]$		
Sc. 7	$\mathcal{C}^{\text{V}}_{9\mu}$	-0.91	$[-1.25, -0.58]$	5.5	65 %
	$\mathcal{C}^{\text{U}}_{9}$	-0.08	$[-0.46, +0.31]$		
Sc. 8	$\mathcal{C}^{\text{V}}_{9\mu} = -\mathcal{C}^{\text{V}}_{10\mu}$	-0.33	$[-0.45, -0.22]$	5.9	74 %
	$\mathcal{C}^{\text{U}}_{9}$	-0.72	$[-0.93, -0.47]$		

Changed

Sc. 7: If only V-NP (C_9) now preference for LFUV-C_9

$$\mathcal{C}^{V}_{9\mu} + \mathcal{C}^{U}_{9} = -0.98$$

Unchanged

Sc. 8: A LFUV left-handed lepton struc. (C_9^V=-C_{10}^V) **yields a better description** with LFU-NP in C_9.

Still

Sc. 6: A LFUV V-A struc. (C_9^V=-C_{10}^V) and a LFU V+A struc. provides a good description of data.

- **LFU-NP is quite dependent on structure of LFUV-NP**

LFU updates 2019

[1903.09578]

Scenario		Best-fit point	1 σ	$\mathrm{Pull}_{\mathrm{SM}}$	p-value
Sc. 9	$\mathcal{C}_{9\mu}^{\mathrm{V}} = -\mathcal{C}_{10\mu}^{\mathrm{V}}$	-0.63	$[-0.79, -0.47]$	5.3	73.4 %
	$\mathcal{C}_{10}^{\mathrm{U}}$	-0.39	$[-0.65, -0.13]$		
Sc. 10	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-0.99	$[-1.17, -0.80]$	5.7	69.7 %
	$\mathcal{C}_{10}^{\mathrm{U}}$	$+0.29$	$[0.10, 0.48]$		
Sc. 11	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-1.07	$[-1.25, -0.88]$	5.9	73.9 %
	$\mathcal{C}_{10'}^{\mathrm{U}}$	-0.31	$[-0.48, -0.13]$		
Sc. 12	$\mathcal{C}_{9'\mu}^{\mathrm{V}}$	-0.05	$[-0.23, 0.14]$	1.7	13.1 %
	$\mathcal{C}_{10}^{\mathrm{U}}$	$+0.43$	$[0.22, 0.65]$		
Sc. 13	$\mathcal{C}_{9\mu}^{\mathrm{V}}$	-1.12	$[-1.29, -0.94]$	5.6	78.7 %
	$\mathcal{C}_{9'\mu}^{\mathrm{V}}$	$+0.48$	$[0.19, 0.85]$		
	$\mathcal{C}_{10}^{\mathrm{U}}$	$+0.26$	$[0.01, 0.50]$		
	$\mathcal{C}_{10'}^{\mathrm{U}}$	-0.05	$[-0.28, 0.18]$		

- Sc. 9 versus Sc.10 preference of C_9^V versus $C_9^V=-C_{10}^V$ in presence of C_{10}^U, opposite to the case of C_9^U (sc.7-8).

- **Sc. 10 versus Sc.11 shows a slight preference of $C_{10'}^U$ over C_{10}^U.**

- Sc.12 irrelevance of RHC without C_9^V.If $C_{10}^U \to C_9^U$ then 4σ

Changed

Sc. 7: If only V-NP (C_9) now preference for LFUV-C_9

$$\mathcal{C}_{9\mu}^{V} + \mathcal{C}_{9}^{U} = -0.98$$

Unchanged

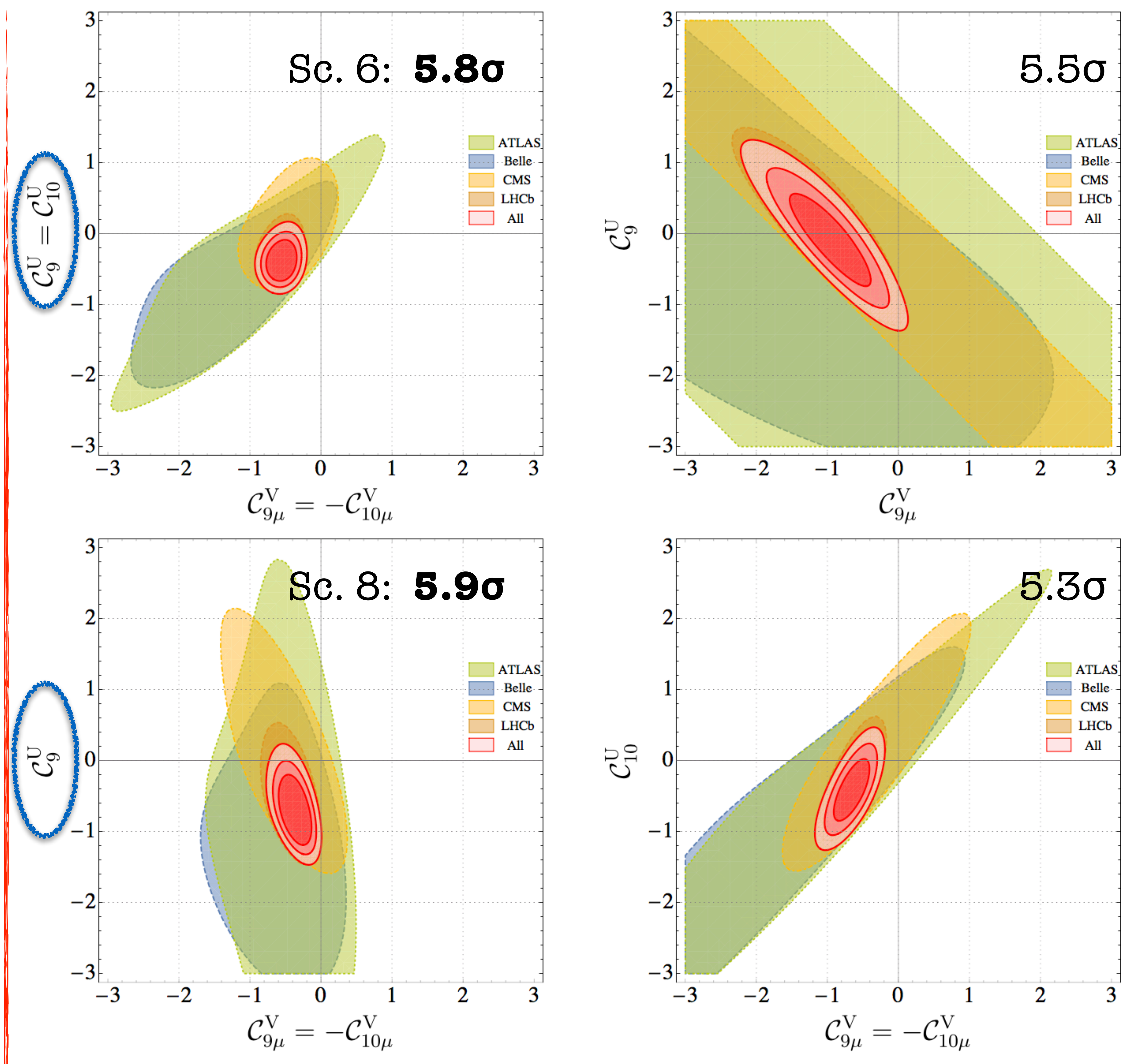
Sc. 8: A LFUV left-handed lepton struc. ($C_9^V=-C_{10}^V$) **yields a better description** with LFU-NP in C_9.

New

Sc.9-13: We extend the universal contribution also to **primed universal coefficients** associated to models.

- **Sc.7-10 show LFU-NP is quite dependent on structure of LFUV-NP**

LFU updates 2019



Assuming loop-level scale of NP and no MFV

$$\Lambda_i^L \sim \frac{v}{s_w g} \frac{1}{\sqrt{2|V_{tb}V_{ts}^*|}} \frac{1}{|C_i^{\rm NP}|^{1/2}}$$

Mild preference

Scenario 6: $\mathcal{C}_{9\mu}^{V} = -\mathcal{C}_{10\mu}^{V}$, $\mathcal{C}_9^{U} = \mathcal{C}_{10}^{U}$

LFUV-NP $L_q \otimes L_\ell$

$\Lambda_i^{\rm LFUV} \sim$ 3.9 TeV

LFU-NP $L_q \otimes R_\ell$

$\Lambda_i^{\rm LFU} \sim$ 4.6 TeV

Scenario 8: $\mathcal{C}_{9\mu}^{V} = -\mathcal{C}_{10\mu}^{V}$, $\mathcal{C}_9^{U}$

LFUV-NP $L_q \otimes L_\ell$

$\Lambda_i^{\rm LFUV} \sim$ 4.6 TeV

LFU-NP $L_q \otimes V_\ell$

$\Lambda_i^{\rm LFU} \sim$ 3.3 TeV

- If we are in presence of two types and scales of NP, their hierarchy depend on the LFU

Results from other analysis

[Aebischer, Altmannshofer, Guadagnoli, Reboud, Stangl, Straub]

Similar results in general terms **but** 1D differences. Why?

Coeff.	best fit	1σ	2σ	pull
$C_9^{bs\mu\mu}$	-0.95	$[-1.10, -0.79]$	$[-1.26, -0.63]$	5.8σ
$C_9'^{bs\mu\mu}$	$+0.09$	$[-0.07, +0.24]$	$[-0.23, +0.39]$	0.5σ
$C_{10}^{bs\mu\mu}$	$+0.73$	$[+0.59, +0.87]$	$[+0.46, +1.01]$	5.6σ
$C_{10}'^{bs\mu\mu}$	-0.19	$[-0.30, -0.07]$	$[-0.41, +0.04]$	1.6σ
$C_9^{bs\mu\mu} = C_{10}^{bs\mu\mu}$	$+0.20$	$[+0.05, +0.35]$	$[-0.09, +0.51]$	1.4σ
$C_9^{bs\mu\mu} = -C_{10}^{bs\mu\mu}$	-0.53	$[-0.62, -0.45]$	$[-0.70, -0.36]$	6.5σ

- Difference in observable sets:

$$BR(b \to s\ell\ell)\ (B, B_s, \Lambda_b)\ (BR, P_i),\ R_{K^{(*)}},\ b \to s\gamma$$

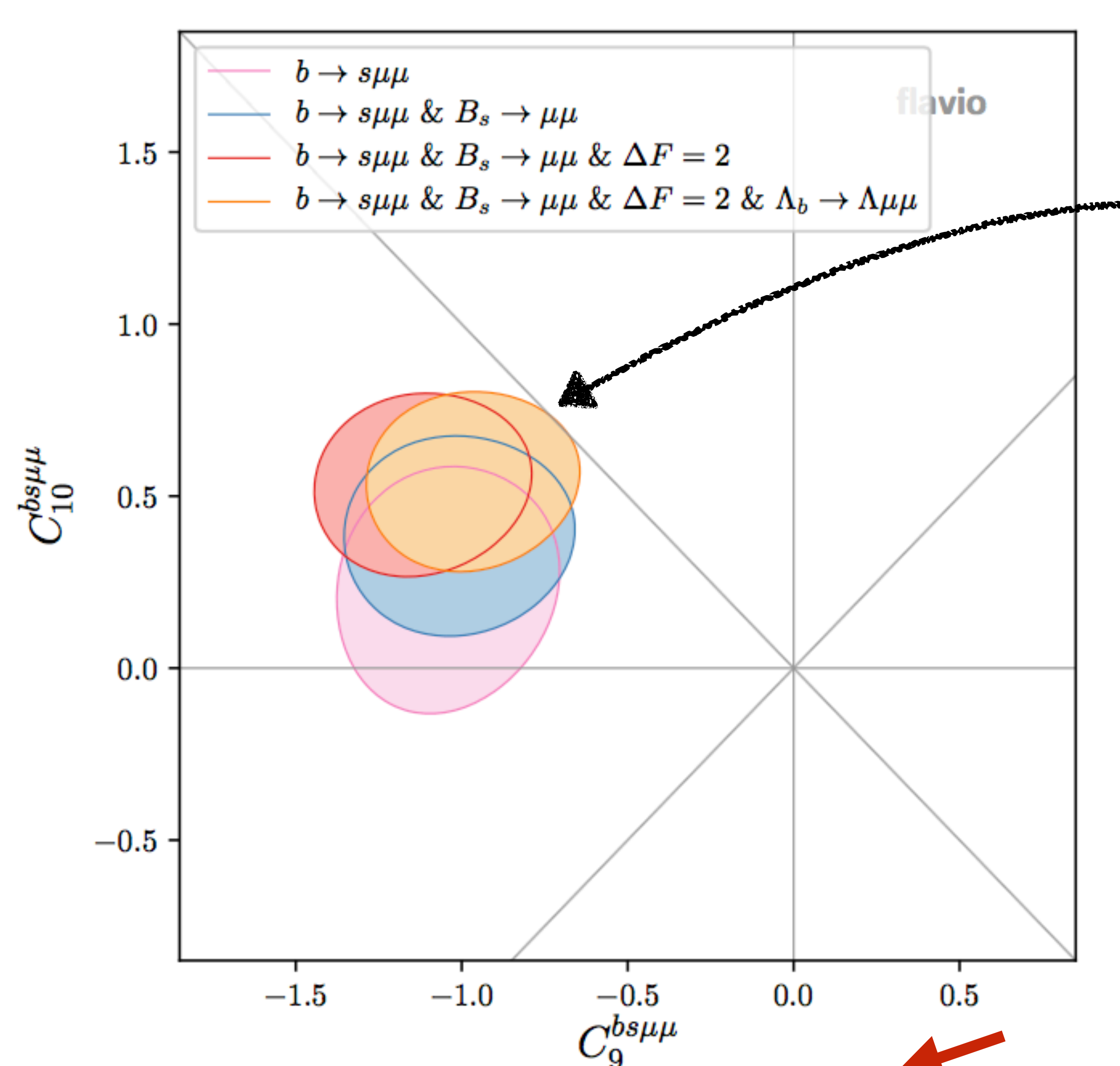
favours mildly $C_{9\mu} = -C_{10\mu}$

But latest Belle updates on P_5' and Q_5 are missing

- Extra assumption: no NP in $\Delta F=2$ observables

=> constraints inputs for $B_s \to \mu\mu\ (f_{B_s}, V_{tb} V_{ts}^* \ldots)$

Different question: Is there NP in b→sll assuming no NP in $\Delta F=2$



- Difference :

$BR(b \to s\ell\ell)$ (B, B_s, Λ_b) (BR, P_i), $R_{K^{(*)}}$, $b \to s\gamma$

favours mildly $C_{9\mu} = -C_{10\mu}$

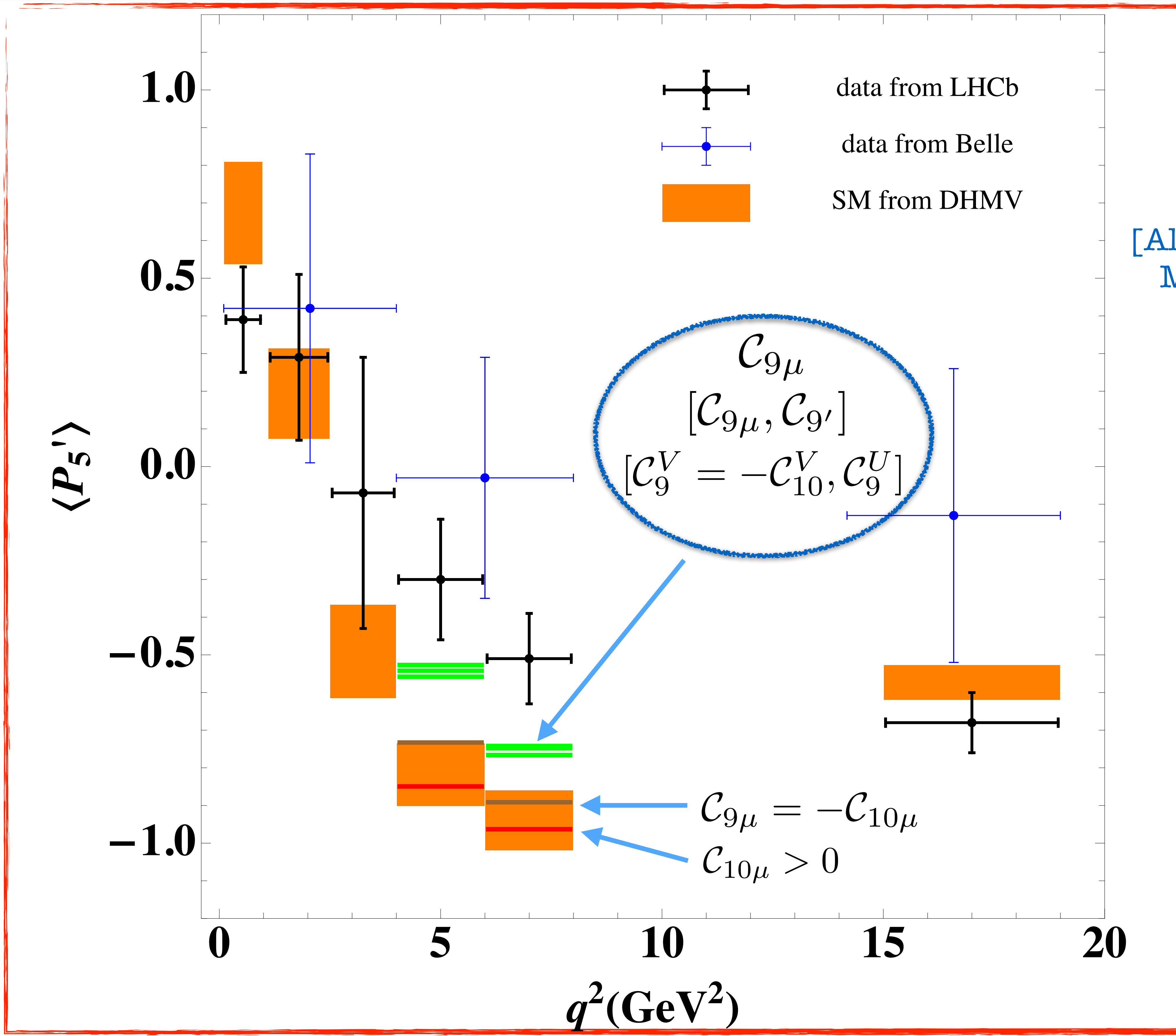
But latest Belle updates on P_5' and Q_5 are missing

- Extra assumption: no NP in ΔF=2 observables

  => constraints inputs for $B_s \to \mu\mu$ $(f_{B_s}, V_{tb}V_{ts}^* \ldots)$

Different question: Is there NP in b→sll assuming no NP in ΔF=2

P'$_5$ under different scenarios



In

[Algueró, Capdevila, SDG, Masjuan, JM, PRD'19]

it was found:

Only in presence of LFU-NP a scenario C_9^V=-C_{10}^V can work. True also for P_5'

for NP points (green, blue, red) only central values are depicted here

Results from other analysis

[Arbey, Hurth, Mahmoudi, Martinez Santos, Neshatpour]

Obs: $b \to s\ell\ell$ (B, B_s) (BR, S_i), $R_{K^{(*)}}$, $b \to s\gamma$
not included yet latest Belle's results on P_5'.
FF: light-meson LCSR+lattice

All observables ($\chi^2_{\rm SM} = 117.03$)			
	b.f. value	$\chi^2_{\rm min}$	Pull$_{\rm SM}$
δC_9	-1.01 ± 0.20	99.2	4.2σ
δC_9^μ	-0.93 ± 0.17	89.4	5.3σ
δC_9^e	0.78 ± 0.26	106.6	3.2σ
δC_{10}	0.25 ± 0.23	115.7	1.1σ
δC_{10}^μ	0.53 ± 0.17	105.8	3.3σ
δC_{10}^e	-0.73 ± 0.23	105.2	3.4σ
$\delta C_{\rm LL}^\mu$	-0.41 ± 0.10	96.6	4.5σ
$\delta C_{\rm LL}^e$	0.40 ± 0.13	105.8	3.3σ

Left-handed hypothesis considered.
... similar 1D and 2D results

Confirm our hierarchy of 1D scenarios

$$\delta C^\ell_{LL} = \delta C^\ell_9 = -\delta C^\ell_{10}$$

[Alok, Dighe, Gangal, Kumar]

122 **Obs**: $BR(b \to s\ell\ell)$ (B, B_s), P'_5 $R_{K^{(*)}}$ FF: light-meson LCSR+lattice

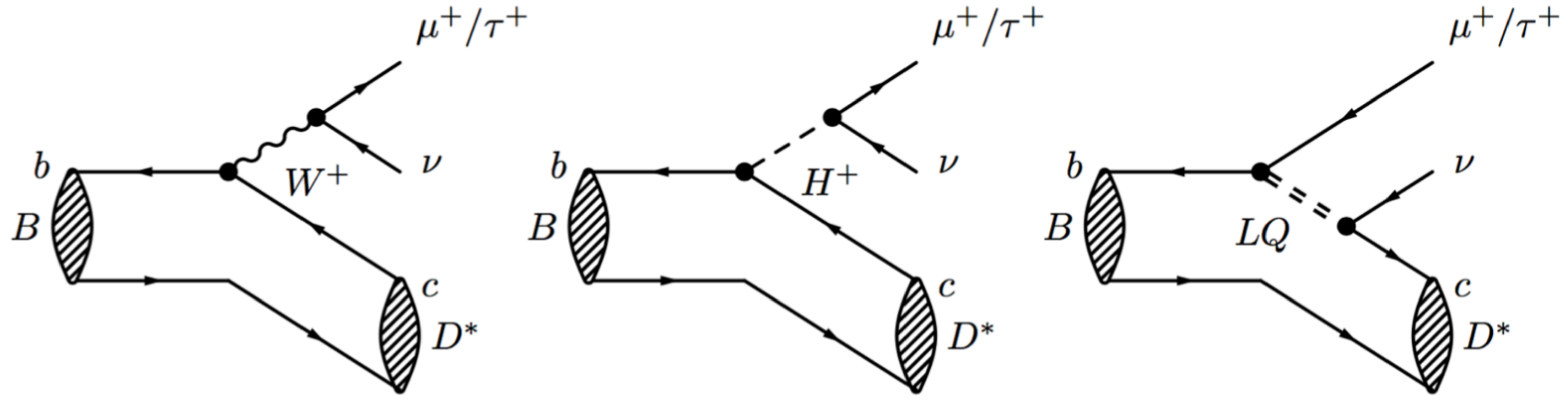
Flavio based analysis: slight decrease of SM pull for $(\mathcal{C}_{9\mu}, \mathcal{C}_{10\mu})$, at the same level as $(\mathcal{C}_{9\mu}, \mathcal{C}_{9'\mu})$ and $(\mathcal{C}_{9\mu}, \mathcal{C}_{10'\mu})$ ..very similar results to ours

[Ciuchini et al.]

Only large-recoil obs. considered, but latest Belle results on P_5' incl.
Flavio based analysis for FF. Bayesian approach. OK: RHC and not C_{10}.

Linking charge and neutral anomalies and LFU NP

LFUV for charged anomalies b→cτν



SM NP

Semi-tauonic B decays are charged current processes that can probe also New Physics.
Experimentally (in analogy to R_{K,K^*}) a LFUV ratio:

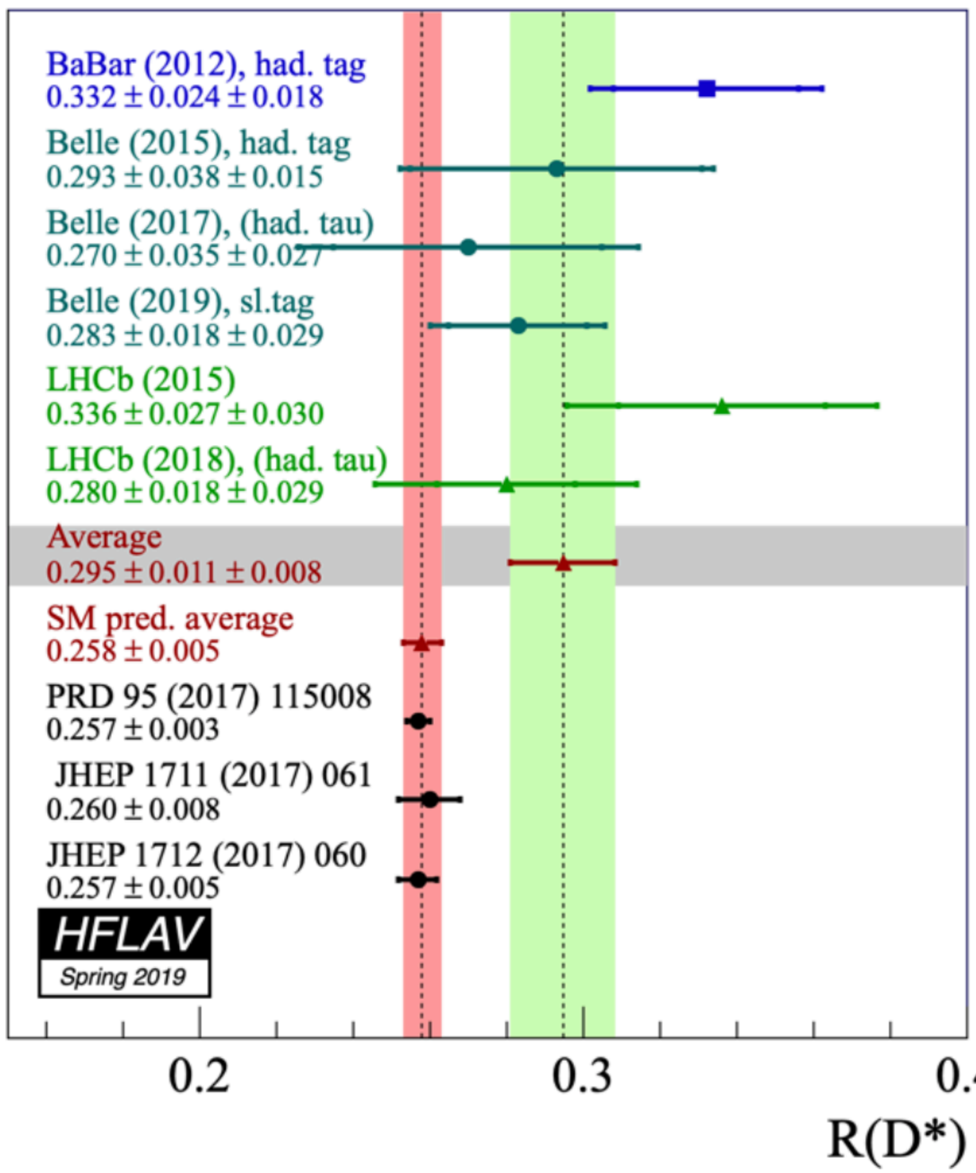
$$R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

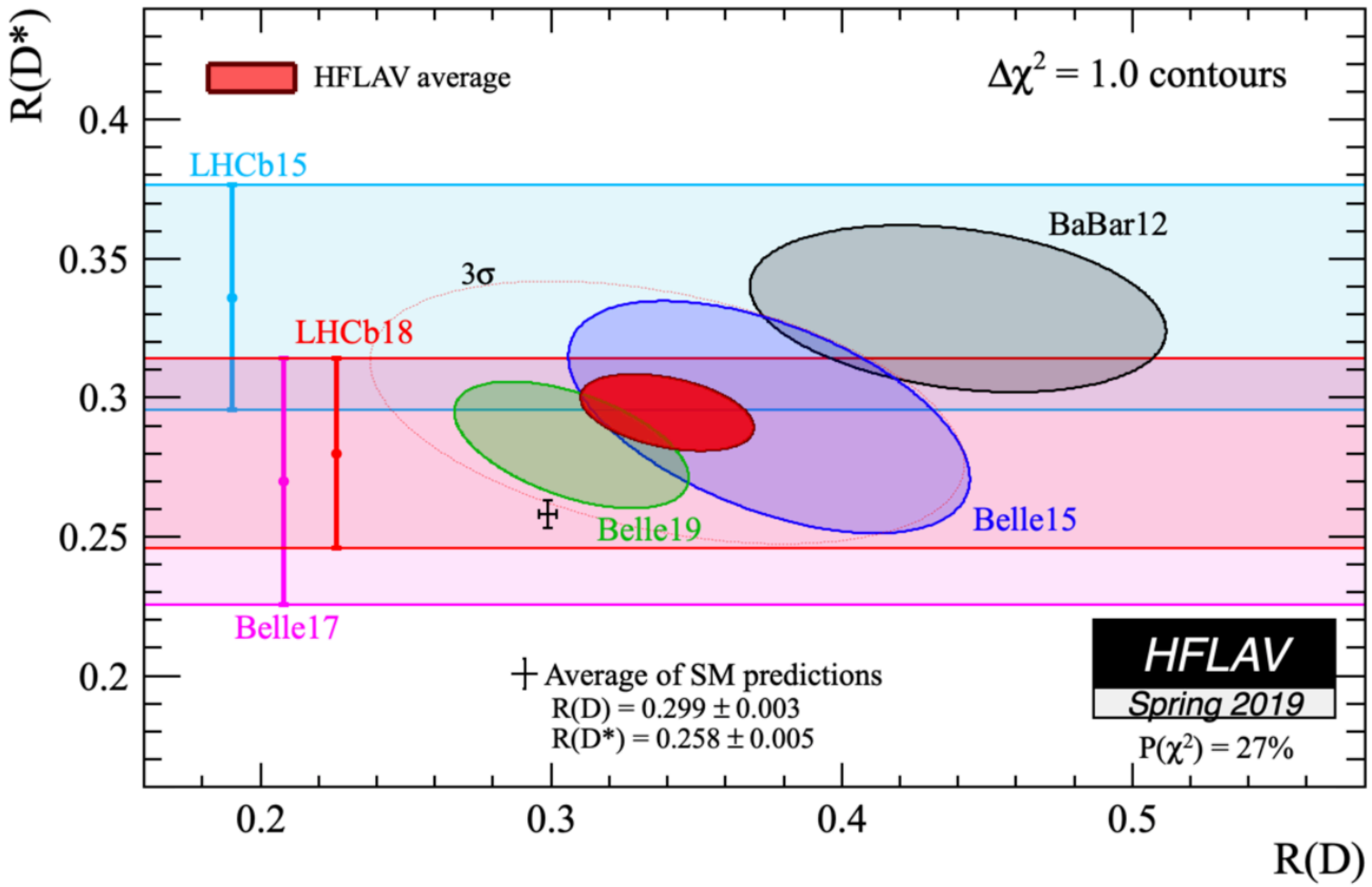
The ratio:

- differs in lepton mass: τ versus $\ell = \mu, e$ mass.
- cancels: form factors, V_{cb}, experimental systematics

R(D) and R(D*) combination

[From Julian Garcia Pardiñas, UZH]





New R(D) and R(D*) measurement by Belle.
[arXiv:1904.08794]

New world average for R(D) and R(D*) at 3.1σ from the SM

Linking charged and neutral anomalies (step 1)

Let's move to SMEFT ($\Lambda_{NP} >> m_{t,W,Z}$) [Grzadkowski, Iskrzynski, Misiak, Rosiek; Alonso, Grinstein, Camalich]

- **NP contribution to** : $[\bar{c}\gamma^\mu \mathbf{P_L b}][\bar{\tau}\gamma_\mu \mathbf{P_L}\nu_\tau]$ ⟶ $R_{J/\psi}/R^{SM}_{J/\psi} = R_D/R^{SM}_D = R_{D^*}/R^{SM}_{D^*}$

  G_F rescaling

BUT who order that (at high energy)? Only Two $SU(2)_L$ invariant operators in SMEFT @ 1st order

$$\mathcal{O}^{(1)}_{ijkl} = [\bar{Q}_i\gamma_\mu Q_j][\bar{L}_k\gamma^\mu L_l], \qquad \mathcal{O}^{(3)}_{ijkl} = [\bar{Q}_i\gamma_\mu\sigma^I Q_j][\bar{L}_k\gamma^\mu\sigma^I L_l],$$

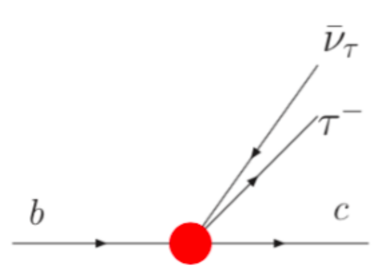
After EWSB i=2, j=k=l=3 **if $C^{(1)}=C^{(3)}$** [Capdevila, Crivellin, SDG, Hofer, JM]

b→c **b→s**

Accommodate charged $R_{D(*)}$.

OK **constraints**:

- Bc lifetime, q2 distributions, but also **B→K*$\nu\bar{\nu}$**, direct searches and EWP data.



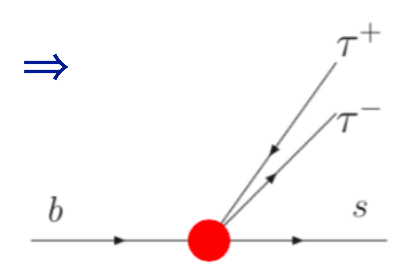
Contribution to neutral b→s ττ with a pattern: $C_{9(10)\tau} \simeq C^{SM}_{9,10} - (+)\Delta$

$$\Delta = 2\frac{\pi}{\alpha_{em}}\frac{V_{cb}}{V_{tb}V^*_{ts}}\left(\sqrt{\frac{R_X}{R_X^{SM}}} - 1\right) \simeq \mathcal{O}(100)$$

(40)

- 10% NP w.r.t. tree-level SM ⇒

  Huge contrib. w.r.t. loop-induced SM.

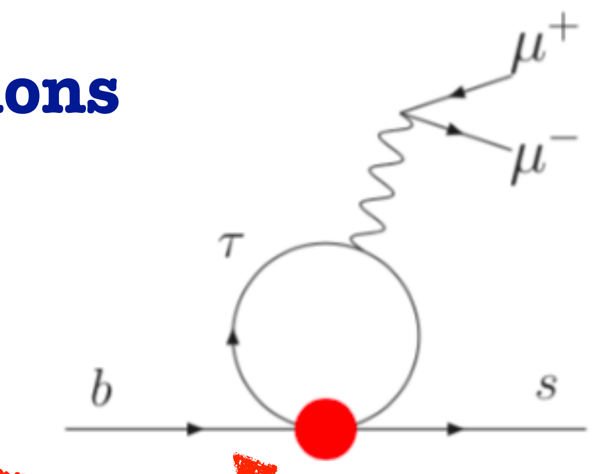


Linking anomalies with LFU NP (step 2)

Scenario 8 well motivated to link charged/neutral anomalies with LFU

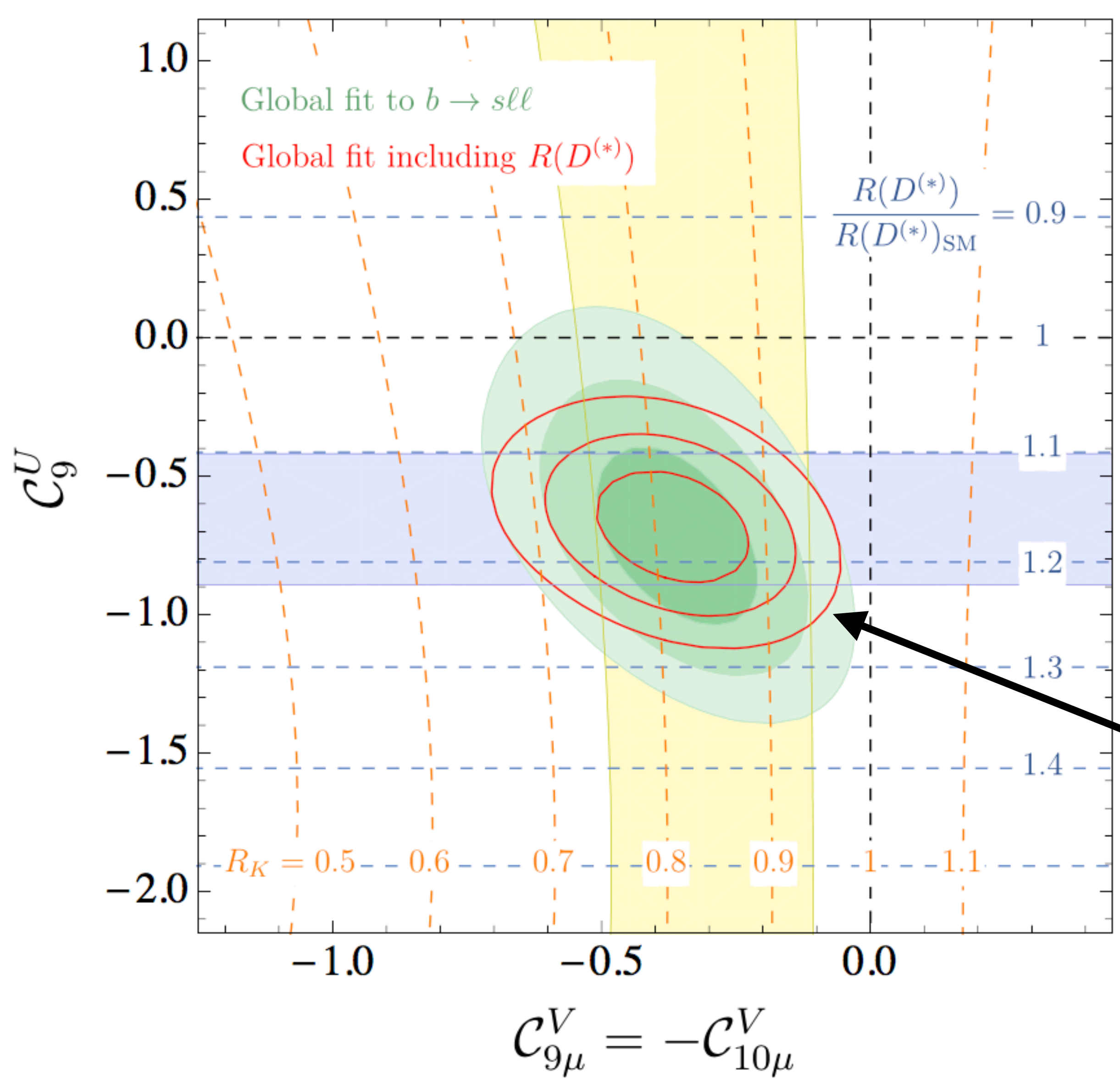
$\mathcal{C}^{V}_{9\mu} = -\mathcal{C}^{V}_{10\mu}$
$\mathcal{C}^{U}_{9}$

- LFUV: $C^V_9 = - C^V_{10}$ **from O_{2322}**
- LFU: C^U_9 **from radiative corrections with insertion of O_{2333}**



Assuming a generic flavour structure and NP at the scale Λ:

$$\mathcal{C}^{U}_{9} \approx 7.5\left(1-\sqrt{\frac{R_{D^{(*)}}}{R_{D^{(*)};SM}}}\right)\left(1+\frac{\log(\Lambda^2/(1\mathrm{TeV}^2))}{10.5}\right)$$



Agreement region including new $R_{D^{(*)}}$ from Belle, bs→ll LFUV and LFU-NP: NP hyp. 7σ

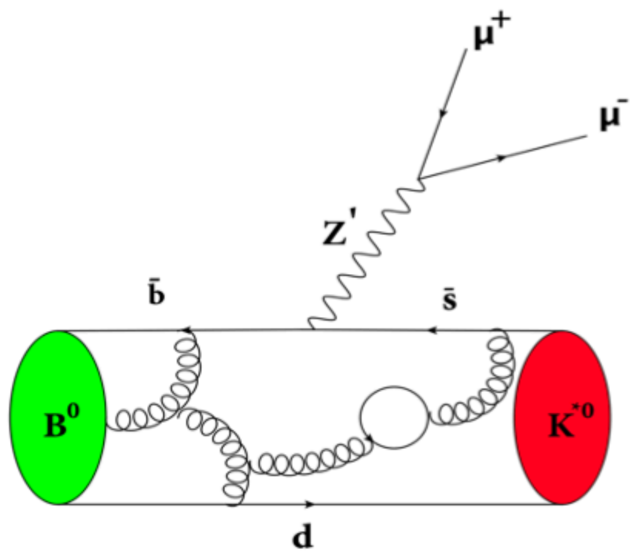
See G. Isidori for explicit UV realisations and A. Crivellin et al. PRL 2019.

Some Solutions to the anomalies

Solution to anomalies, generation of couplings

Colourless vector $SU(2)_L$ triplets (W', B') or $U(1)'$ singlet

$$G \equiv SU(3)_c \times SU(2)_L \times U(1)_Y \times G_E$$

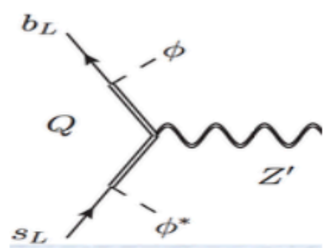


$G_E \equiv SU(2)_L$ could pot. explain anomalies ($R_K > 0.9$ & conflict with LHC searches)

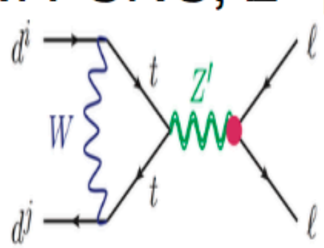
- $\bar{b}sZ'$ Quark FVC
- $Z'\ell\ell$ LFUV coupling

Generating Quark FV Coupling:

- Vector-like quarks: SM-VL couplings

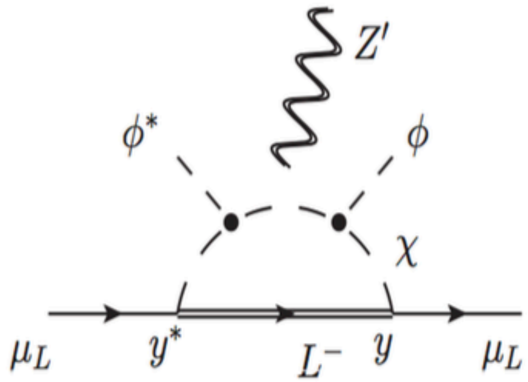


- Loop induced: SM FCNC, Z' penguins

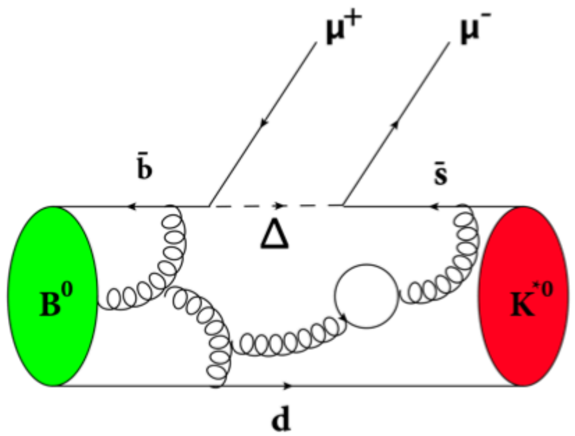


Generating Couplings to Leptons:

- Gauged $U(1)_{\mu-\tau}$ symmetry
- Loop induced with vector-like fermions



Solution to anomalies: leptoquarks



- Spin 1 (vector) $SU(2)_L$ singlet or triplet leptoquarks
- Spin 0 (scalar) $SU(2)_L$ singlet or triplet leptoquarks
- via loop....

They mainly point in all versions to $C_9 = -C_{10}$ (left-handed structure like in the SM)

Important constraints:

- $b \to s\nu\bar{\nu}$ (two scalars LQ can do the job)
- direct bounds (from 0.5-1 TeV)

Colour triplet

Scalar LQ:

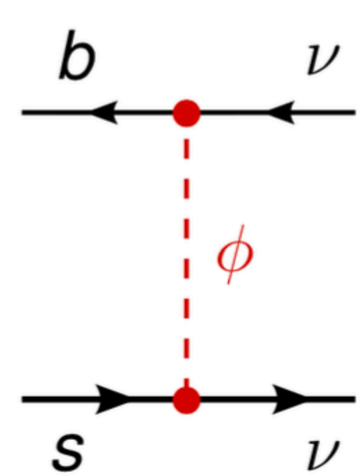
$S_1 \sim (\bar{3}, 1, 1/3)$

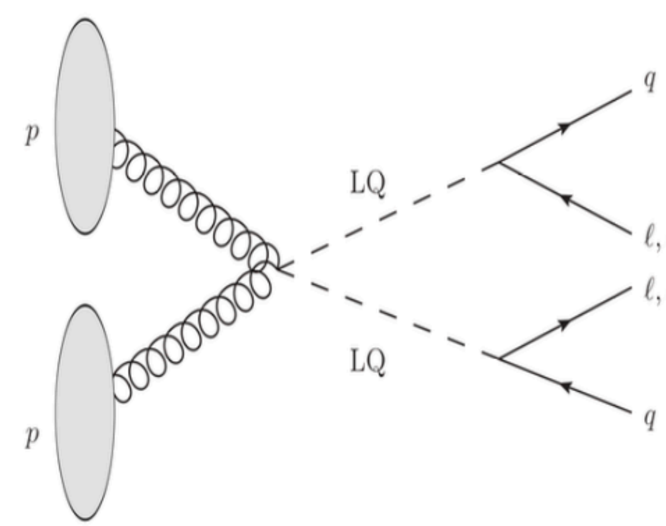
$S_3 \sim (\bar{3}, 3, 1/3)$

Vector LQ:

$U_1^\mu \sim (3, 1, 2/3)$

$U_3^\mu \sim (3, 3, 2/3)$





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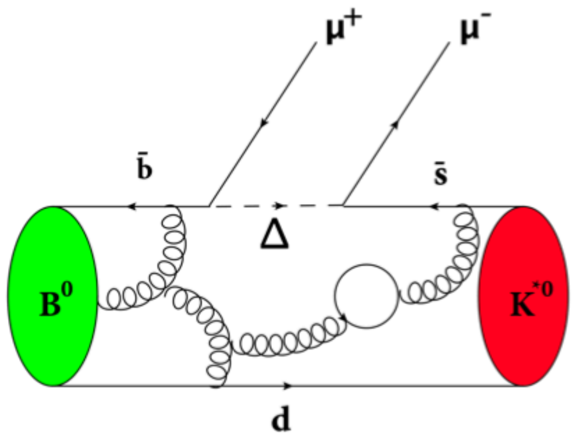

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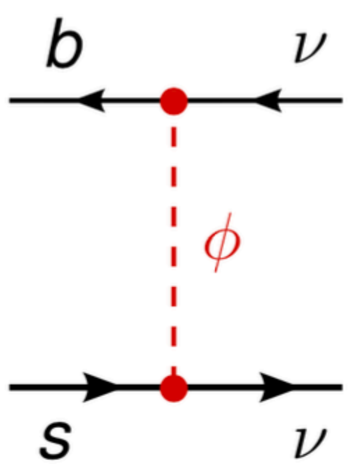
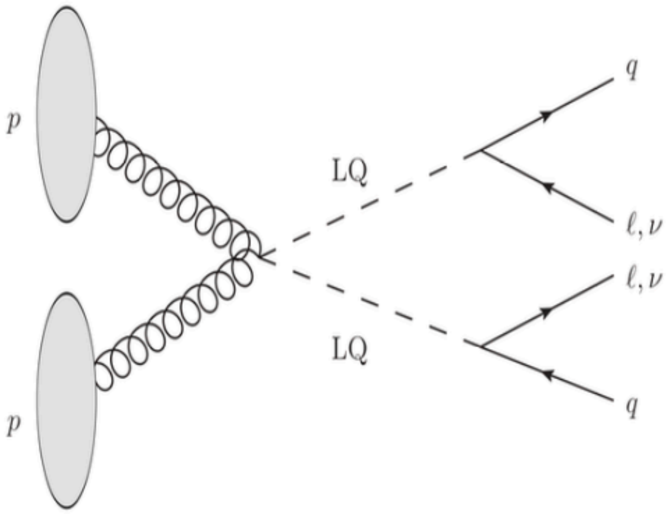




A possible successful candidate?

A very promising candidate is:

Vector leptoquark SU(2) singlet:
$U_1(3,1,2/3)$
Coupled mainly to 3rd generation

1. It can explain both charged and neutral anomalies
2. $C_9 = -C_{10}$ pattern in $b \to s\mu\mu$
3. No tree level effect for $b \to s\nu\nu$
4. No conflict with direct searches

Good solution, but challenging UV completion

Possible UV completions

- $SU(4)\times SU(3)'\times SU(2)_L\times U(1)_Y$ + Vector-like fermions

  L. Di Luzio, A. Greljo, M. Nardecchia, arXiv:1708.08450
- $SU(4)\times U(2)_L\times SU(2)_R$ + vector-like fermions

  L. Calibbi, AC, T. Li, arXiv:1709.00692
- $SU(4)\times SU(4)\times SU(4)$

  M. Bordone, C. Cornella, J. Fuentes-Martin, G. Isidori, arXiv:1712.01368
- $SU(4)\times U(2)_L\times SU(2)_R$ including scalar LQs and light right-handed neutrinos

  J. Heeck, D. Teresi, arXiv:1808.07492
- SU(8) might even explain ε'/ε

  S. Matsuzaki, K. Nishiwaki and K. Yamamoto, arXiv:1806.02312
- $SU(4)\times U(2)\times SU(2)_R$ in RS background

  M. Blanke, AC, arXiv:1801.07256

Good solution, but challenging UV completion

Pati-Salam LQ model

Original PS=SU(4) x SU(2)$_L$ x SU(2)$_R$

It does not work: tight bounds from couplings to light generation: $K_L \to \mu e$ and $K \to \pi \mu e$

... too heavy (Flavour-Blind) to work.

[M. Bordone et al.]

A recent proposal : $\mathrm{PS}^3 \equiv \mathrm{PS}_1 \times \mathrm{PS}_2 \times \mathrm{PS}_3$

$$\mathrm{PS}_i = \mathrm{SU}(4)_i \times [\mathrm{SU}(2)_\mathrm{L}]_i \times [\mathrm{SU}(2)_\mathrm{R}]_i$$

1. SSB decouple very heavy fields coupled to 1st & 2nd gen.
2. TeV-scale LQ associated to 3rd gen and LQ coupling to RH SM
3. Higgs of EWSB only on third generation site:

... yukawa hierarchies from hierarchy of breaking vevs

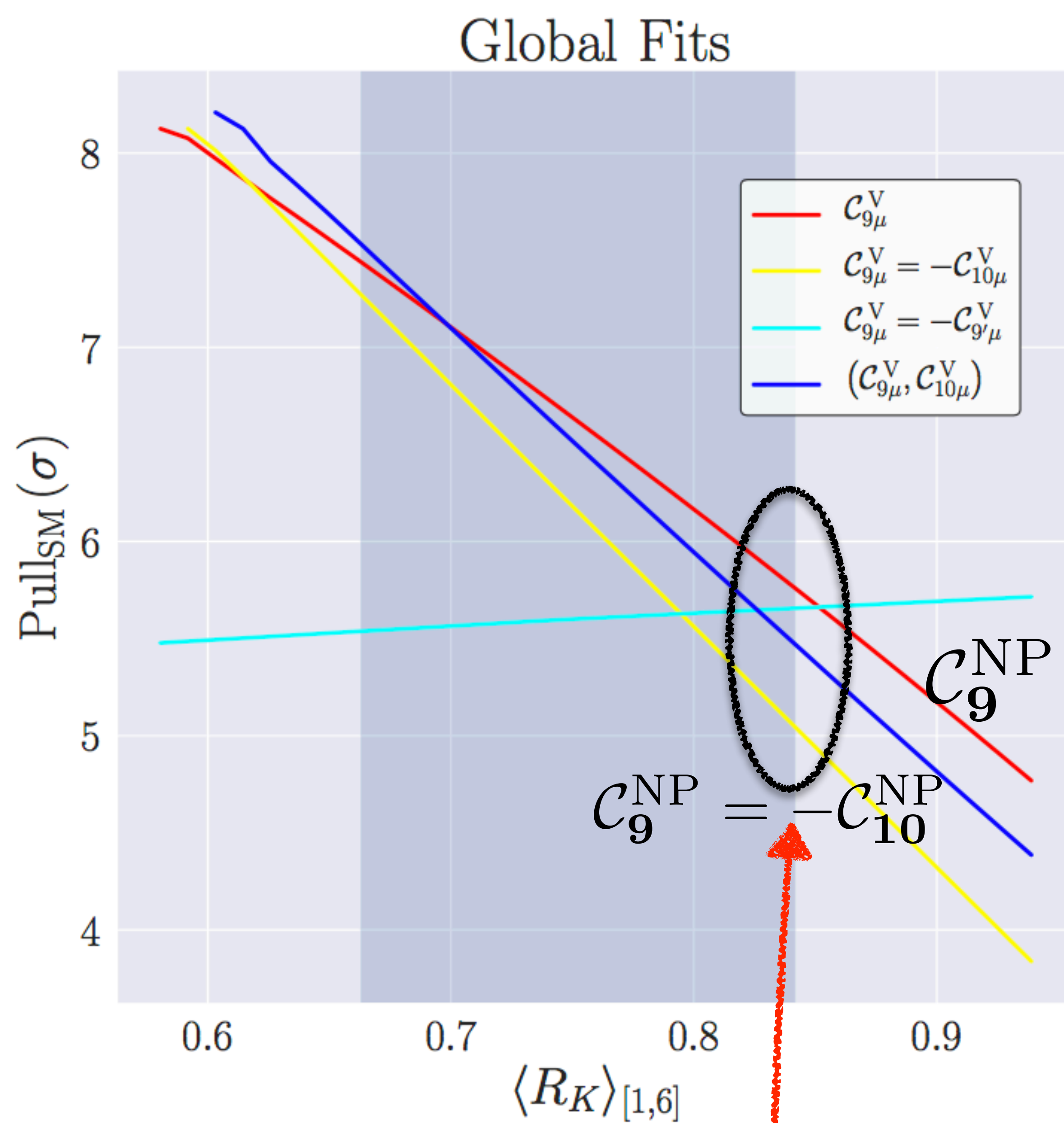
Near Future next test: $Q_5=P'_{5\mu}-P'_{5e}$

What can we learn?

Q_5 can disentangle relevant scenarios?

R_K (if no-RHC are included) cannot distinguish among relevant scenarios.

[Algueró, Capdevila, SDG, Masjuan, JM: 1902.04900]



The main 1D scenarios with present value of R_K are still too packed within 0.5σ to disentangle the correct pattern.

Q_5 can disentangle relevant scenarios?

Only Belle has been able to measure Q_5 up to now: $Q_{5\,[1,6]}^{\mathrm{Belle}} = 0.656 \pm 0.496$

[S. Wehle et al. PRL118 (2017)]

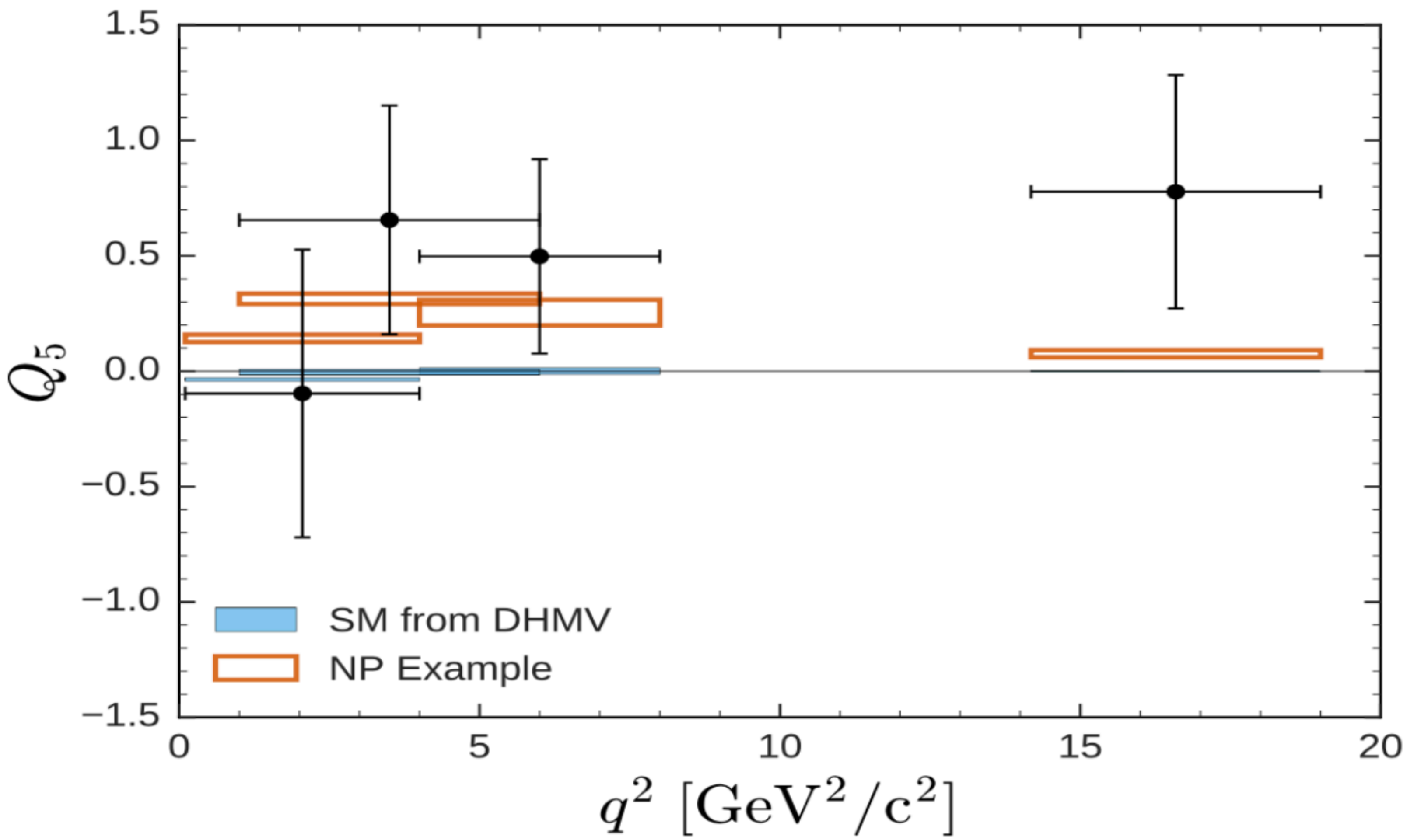
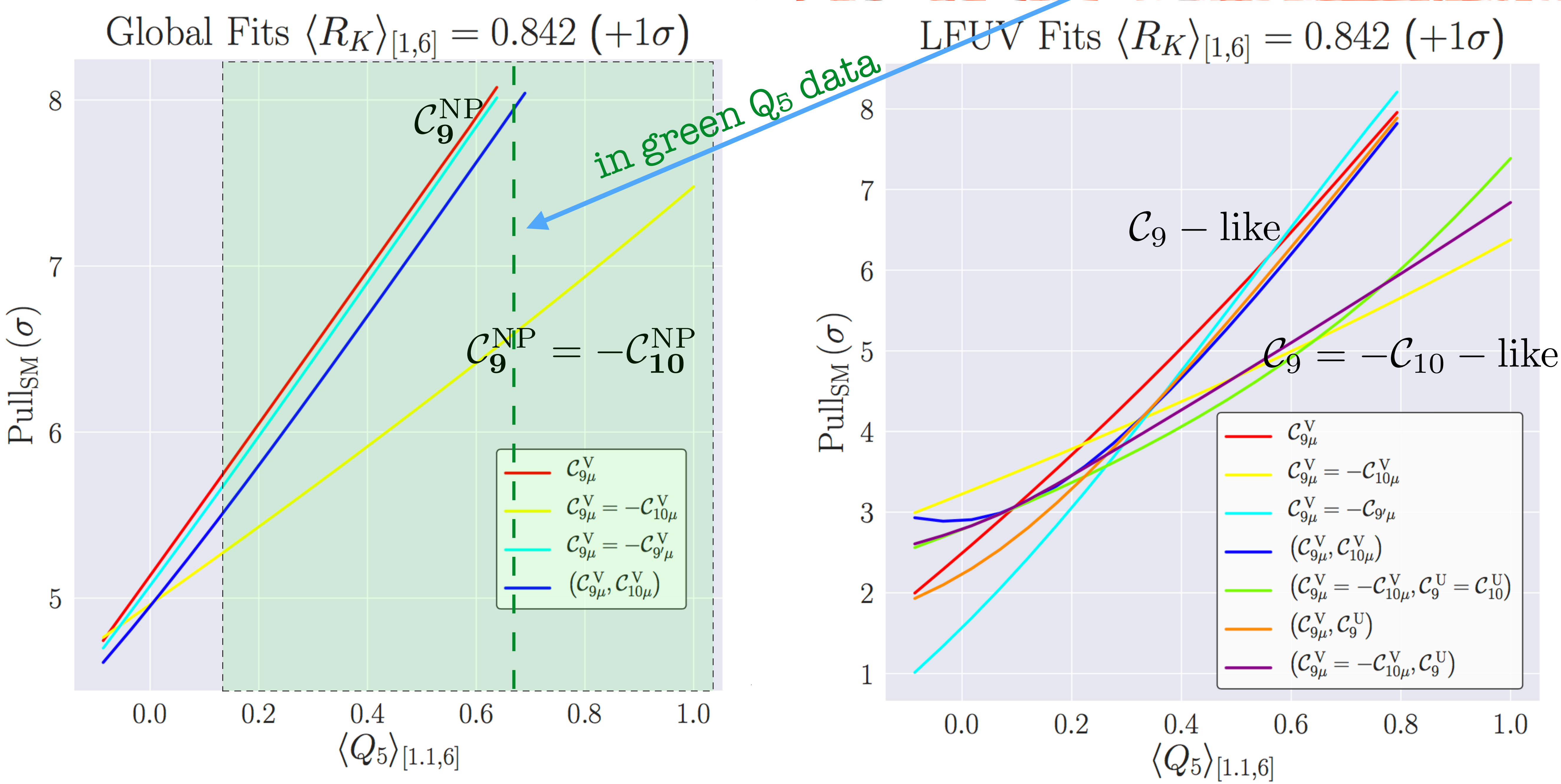


Table 2: Results for the lepton-flavor-universality-violating observables Q_4 and Q_5. The first uncertainty is statistical and the second systematic.

q^2 in GeV$^2/c^2$	Q_4	Q_5
[1.00, 6.00]	$0.498 \pm 0.527 \pm 0.166$	$0.656 \pm 0.485 \pm 0.103$
[0.10, 4.00]	$-0.723 \pm 0.676 \pm 0.163$	$-0.097 \pm 0.601 \pm 0.164$
[4.00, 8.00]	$0.448 \pm 0.392 \pm 0.076$	$0.498 \pm 0.410 \pm 0.095$
[14.18, 19.00]	$0.041 \pm 0.565 \pm 0.082$	$0.778 \pm 0.502 \pm 0.065$

Q_5 can disentangle relevant scenarios?

Instead Q_5 groups relevant scenarios differently. $Q_{5\,[1,6]}{}^{\text{Belle}} = 0.656 \pm 0.496$



All scenarios with C^V_9 **are packed** as well as those with $C^V_9 = - C^V_{10}$ **BUT in two different sets. Also:**

- * Q_5 **positive and large** would **favour** scenarios with $C_{9\mu} < -1$
- * $Q_5 < 0$ **or small** would **favour** scenarios with $C_{9\mu} = -C_{10\mu}$

Conclusions

- After the updates of R_K (LHCb), R_{K^*}(Belle) and $B_s \to \mu\mu$ we find:

  - **no dramatic changes** in the hierarchy of 1D hypothesis:

    C_9 and C_9=-C_9' preferred with All fit [178 obs] significance 5.8 (5.7) σ

    C_9=-C_{10} preferred with LFUV fit [20 obs] significance 4.0 σ

  - 2D **new emerging scenarios including RHC** with C_9'>0 & C_{10}'<0:

    ($C_{9\mu}$,$C'_{9\mu}$=-$C'_{10\mu}$) (6.1 σ)

- LFU-NP structure is **quite dependent** on LFUV-NP structure:
  A C_9^V=-C_{10}^V struct. provides a good description only in presence of C_9^U

- We have found a link of charged & neutral anomalies & LFU NP in scn 8.

- While R_K cannot disentangle scenarios, **a measurement of Q_5** such that:

  -Q_5 **positive and large** would **favour** scenarios with $C_{9\mu}$<-1

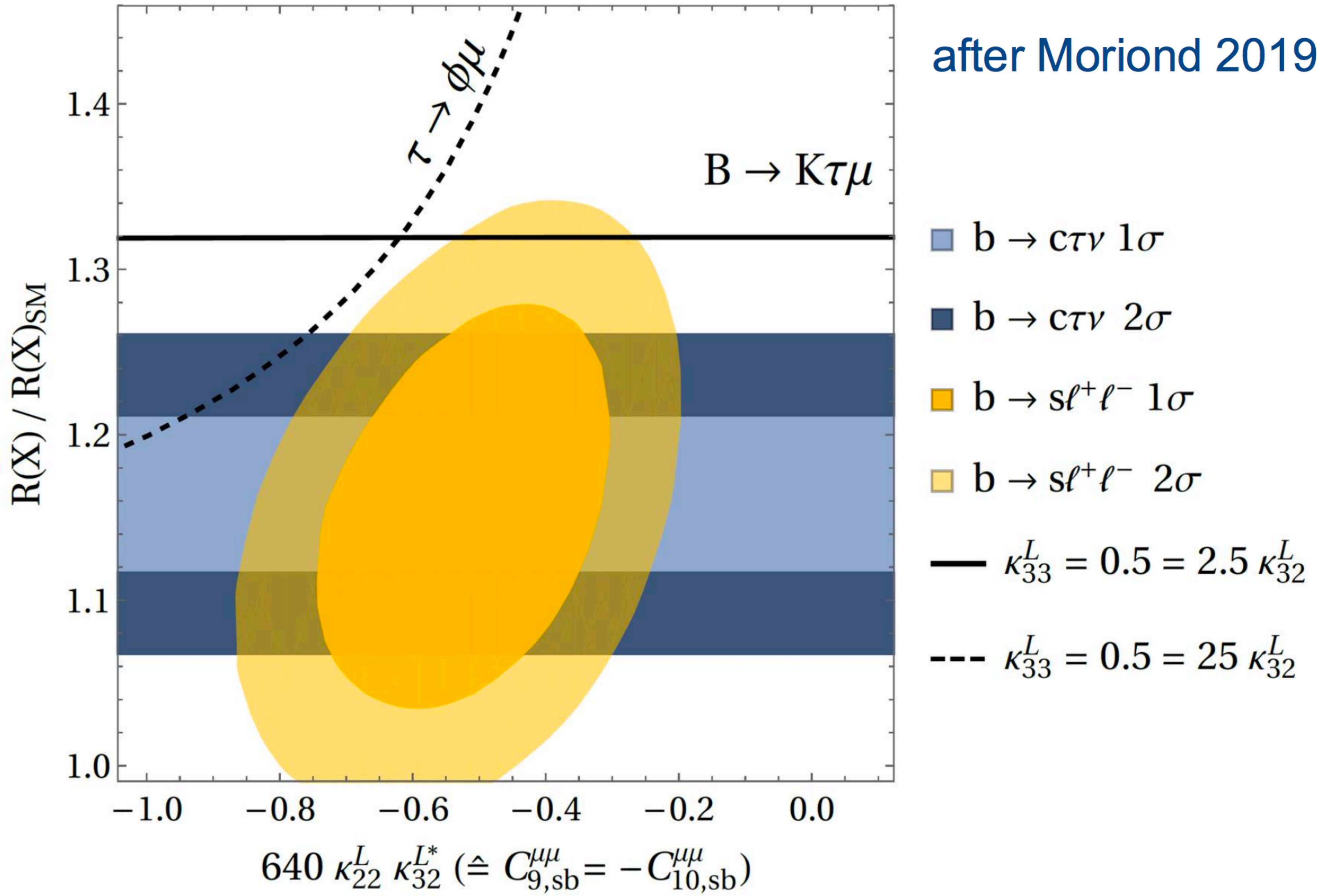
  -Q_5 < 0 or small would **favour** scenarios with $C_{9\mu}$=-$C_{10\mu}$

.... new data on Q_5, R_ϕ, updated optimized observables is essential.
Belle II inputs are also crucial.

BACK-UP

... in summary

[Courtesy of A. Crivellin]



Pati-Salam LQ can explain the flavour anomalies

P_5' anomaly: Lepton Flavour Dependent

- Different theory approaches to **estimate/predict** "LD charm":

Long distance non-factorizable :
LCSR by Khodjamirian
+ s_i const/destr interference.

Empirical model to determine the impact of resonances :
(amp. analysis+BW)
Blake et al. '17

LD effects from analyticity:
(fixes q^2 dep. up to pol. & systematic)
Bobeth et al.'18

In all theoretical estimates the anomaly remains.

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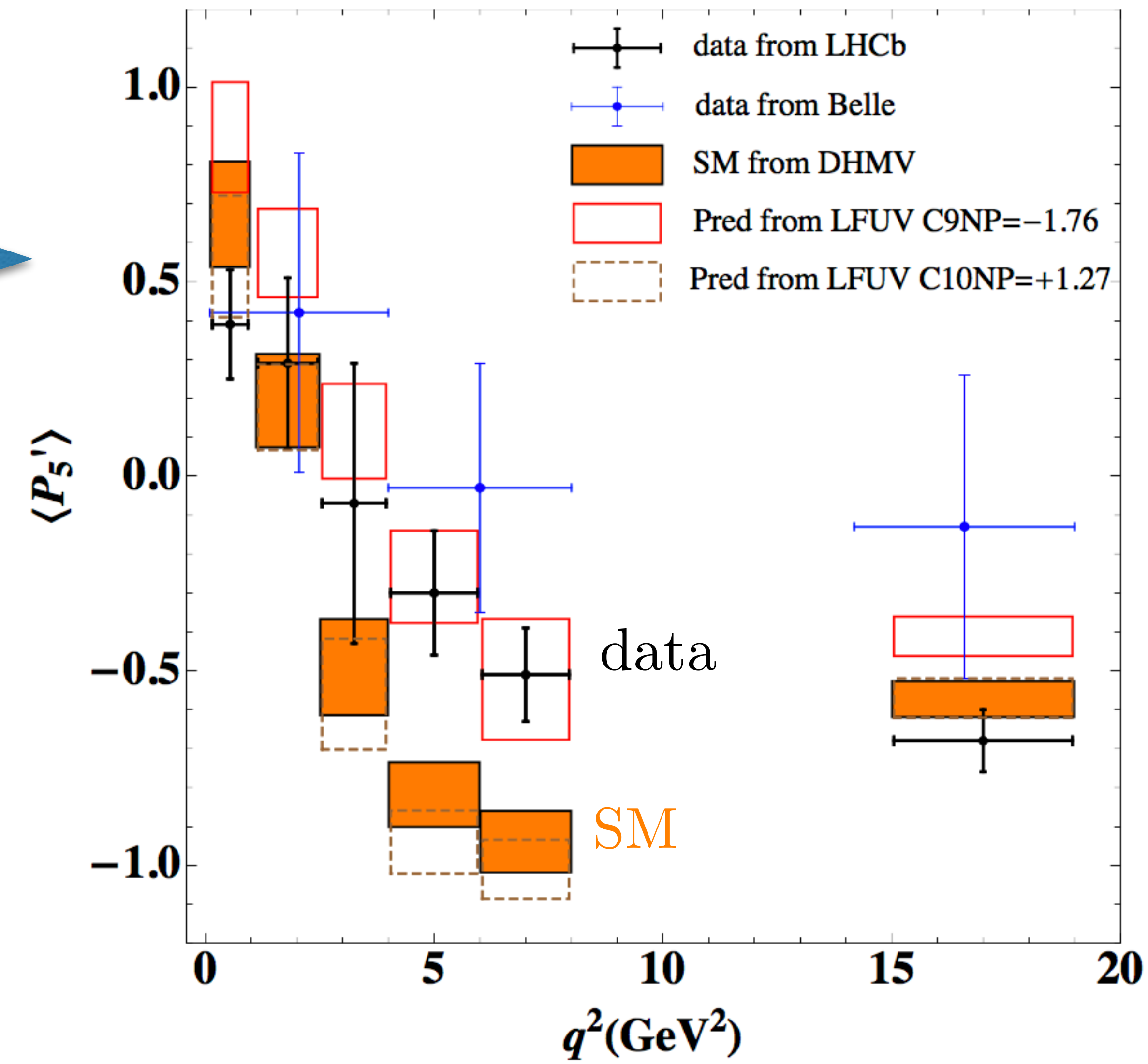

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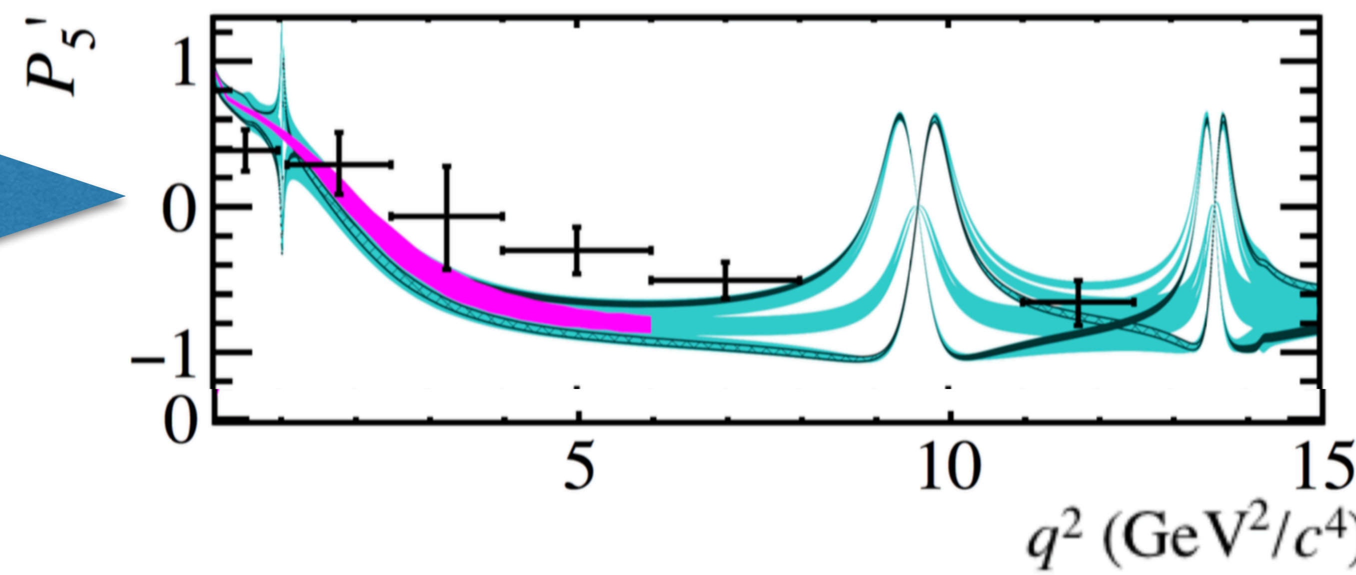

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