$b \to s$ anomalies	$b \to c$ anomalies
Found by LHCb (and perhaps hinted by Belle)	Found by several experiments (LHCb, BaBar and Belle)
Many observables: global pattern	Two observables: R(D) and R(D*)
Neutral current	Charged current
1-loop (and CKM-suppressed) in the SM	Tree-level in the SM
The New Physics can be heavy	The New Physics must be light

The $b \to s$ anomalies

The $b \to s$ anomalies

[LHCb, 2014]
arXiv:1406.6482

Episode V: LHCb strikes back

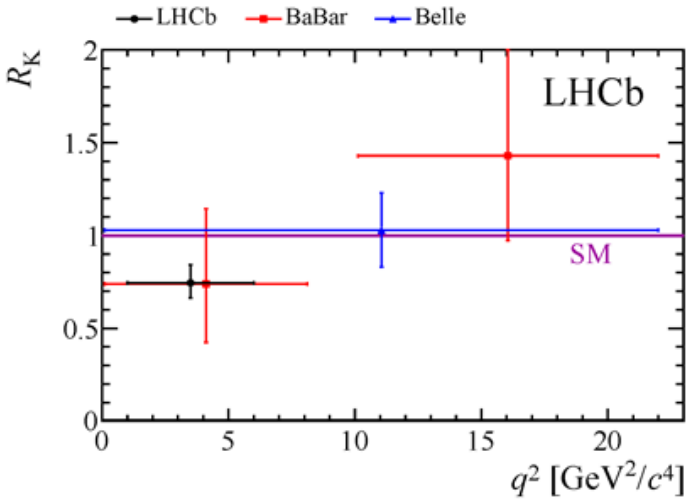
2014 : Lepton universality violation

Obtained with 3 fb^{-1}

$$R_K = [R_K]_{[1,6]} = \left.\frac{\text{BR}(B \to K\mu^+\mu^-)}{\text{BR}(B \to Ke^+e^-)}\right|_{q^2 \in [1,6]\text{GeV}^2} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$R_K^{\text{SM}} \sim 1.00 \pm 0.01$$

2.6σ away from the SM



The $b \to s$ anomalies

LHCb measurement

$$[R_K]_{[1,6]} = 0.745^{+0.090}_{-0.074} \pm 0.036$$

$$[R_{K^*}]_{[0.045,1.1]} = 0.660^{+0.110}_{-0.070} \pm 0.024$$

$$[R_{K^*}]_{[1.1,6]} = 0.685^{+0.113}_{-0.069} \pm 0.047$$

SM prediction

$$[R_K]^{\rm SM}_{[1,6]} = 1.00 \pm 0.01 \qquad \textbf{2.6 σ}$$

$$[R_{K^*}]^{\rm SM}_{[0.045,1.1]} = 0.92 \pm 0.02 \qquad \textbf{2.2 σ}$$

$$[R_{K^*}]^{\rm SM}_{[1.1,6]} = 1.00 \pm 0.01 \qquad \textbf{2.4 σ}$$

Important: LFUV ratios are clean observables, free from hadronic uncertainties

If confirmed: dramatic implications for New Physics

Run-2 update eagerly awaited

The $b \to c$ anomalies

The $b \to c$ anomalies

$$\mathcal{R}(D^{(*)}) \equiv \frac{\mathrm{BR}(B \to D^{(*)}\tau\nu)}{\mathrm{BR}(B \to D^{(*)}\ell\nu)},$$

$$\mathcal{R}(D^*)_{\mathrm{BABAR}} = 0.332 \pm 0.024 \pm 0.018,$$
$$\mathcal{R}(D^*)_{\mathrm{BELLE}} = 0.293 \pm 0.038 \pm 0.015,$$
$$\mathcal{R}(D^*)_{\mathrm{LHCb}} = 0.336 \pm 0.027 \pm 0.030.$$

$$\mathcal{R}(D^*)_{\mathrm{SM}} = 0.252 \pm 0.003,$$

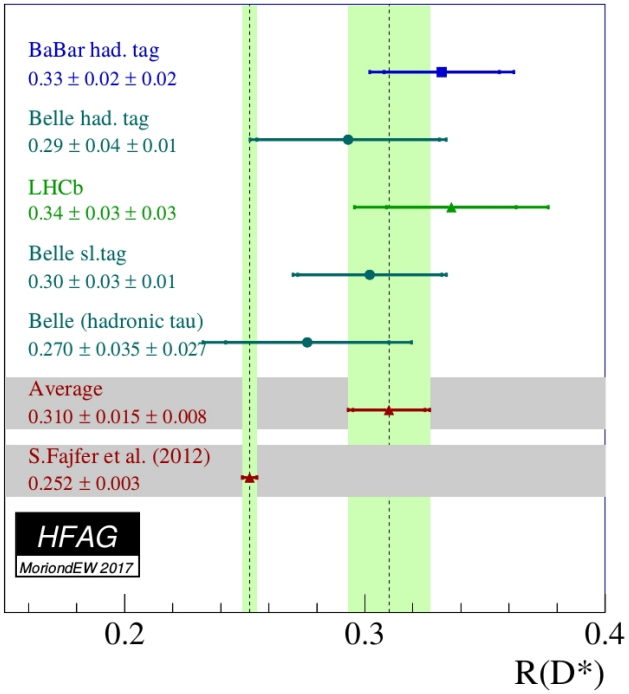
$$\mathcal{R}(D^*)_{\mathrm{exp}} = 0.321 \pm 0.021.$$

$$\mathcal{R}(D)_{\mathrm{BABAR}} = 0.440 \pm 0.058 \pm 0.042,$$
$$\mathcal{R}(D)_{\mathrm{BELLE}} = 0.375 \pm 0.064 \pm 0.026,$$

$$\mathcal{R}(D)_{\mathrm{SM}} = 0.297 \pm 0.017,$$

$$\mathcal{R}(D)_{\mathrm{exp}} = 0.388 \pm 0.047,$$

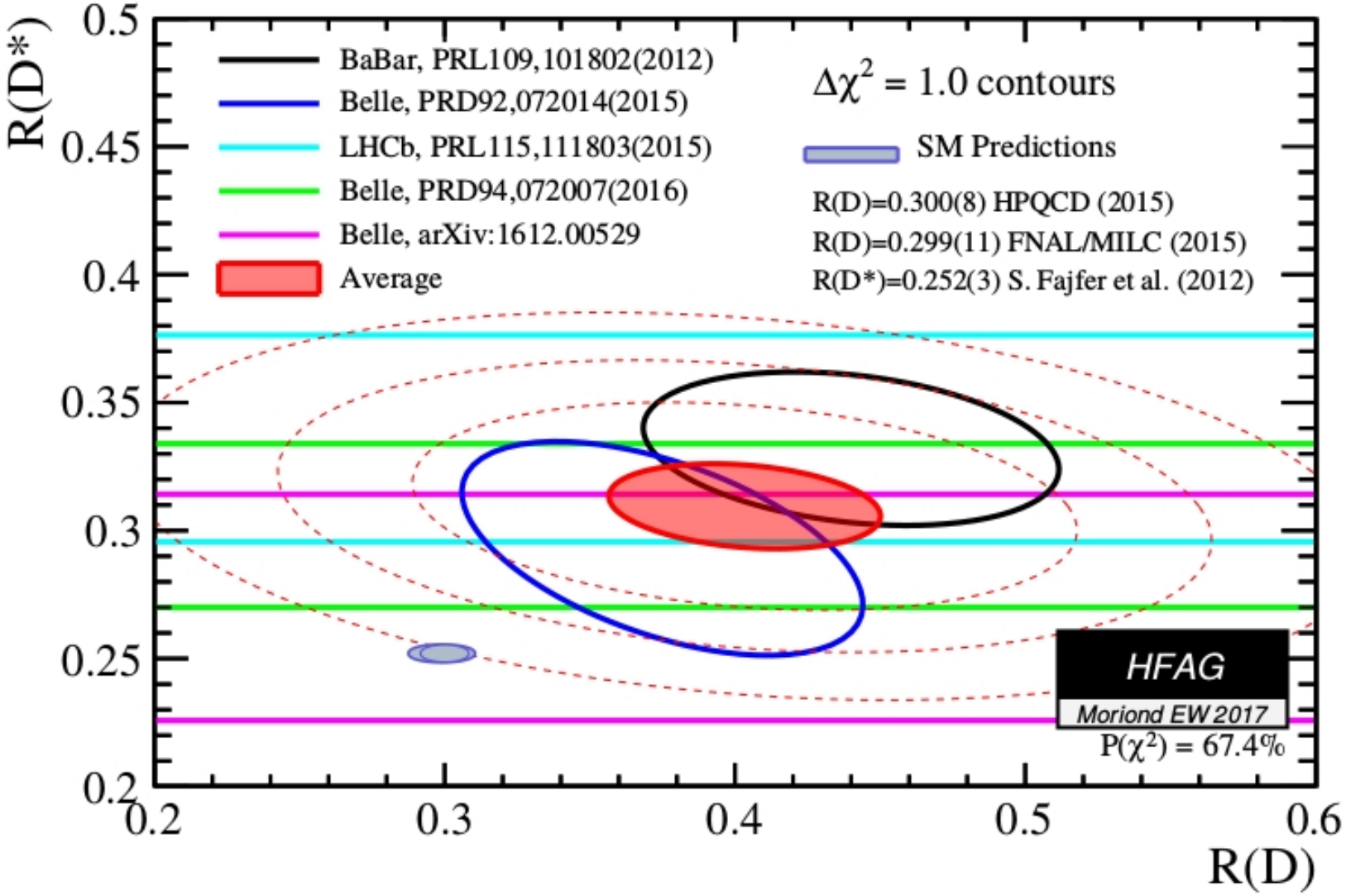
BaBar + Belle + LHCb



Another hint of lepton universality violation?

Deviation from the SM at the 4 σ level

The $b \to c$ anomalies



New Physics explanations

New Physics explanations

R_{K,K^*} ⇒ **Neutral current**

Z' boson, leptoquarks, compositeness, RPV loops

$R(D^{(*)})$ ⇒ **Charged current**

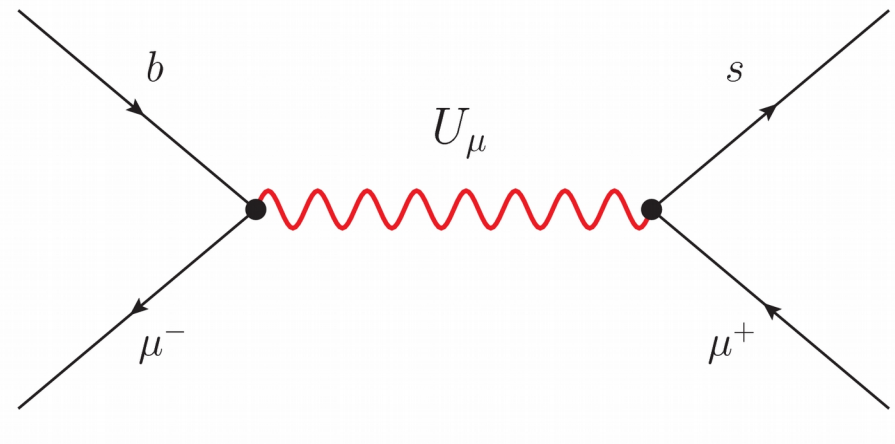
Charged Higgs, leptoquarks, compositeness, W' boson, RPV sfermions

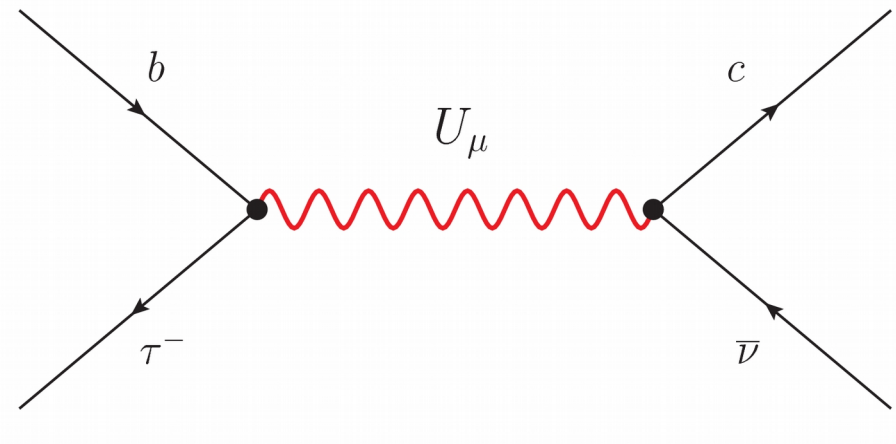
Leptoquarks

Simultaneous explanation of both puzzles: leptoquarks?

Example: $U_\mu = \left(3, 1, \frac{2}{3}\right)$

Alonso, Grinstein, Martin-Camalich [1505.05164]
Barbieri, Isidori, Pattori, Senia [1512.01560]
... and others





Other leptoquarks have also been proposed

However: leptoquarks added to the models without a clear theoretical motivation... *ad-hoc*

Backup slides

The $b \to s$ anomalies

2013 - Episode IV: A new hope

2014 - Episode V: LHCb strikes back

2015 - Episode VI: Return of the anomalies

2016 - Episode I: The Belle menace

2017 - Episode II: Attack of R_K^*

2018 - Episode III: ???

The $b \to s$ anomalies

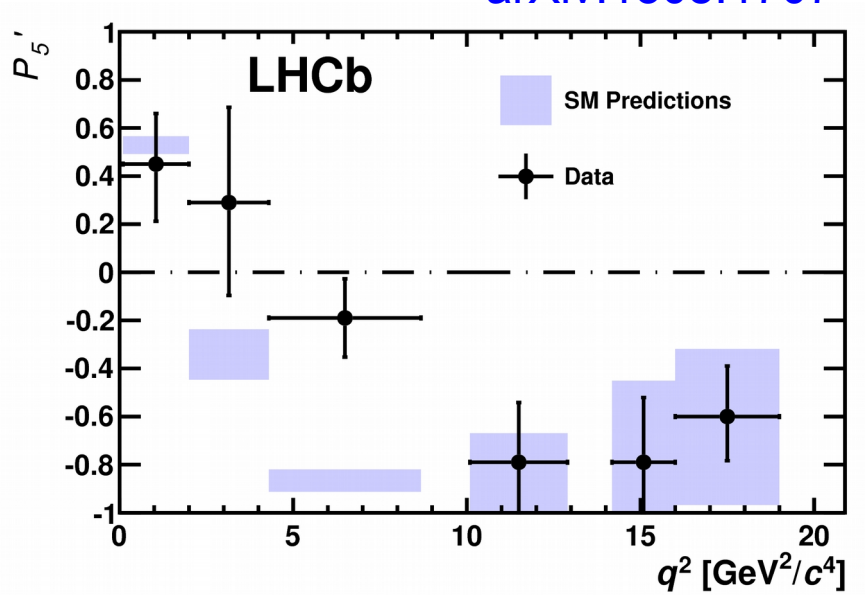
[LHCb, 2013]
1305.2168, 1308.1707, 1403.8044

Episode IV: A new hope

2013 : First anomalies found by LHCb

- Data collected: $1\ \mathrm{fb}^{-1}$ ($3\ \mathrm{fb}^{-1}$ in some observables)
- Decrease (w.r.t. the SM) in several branching ratios
- Several anomalies in angular observables

arXiv:1308.1707

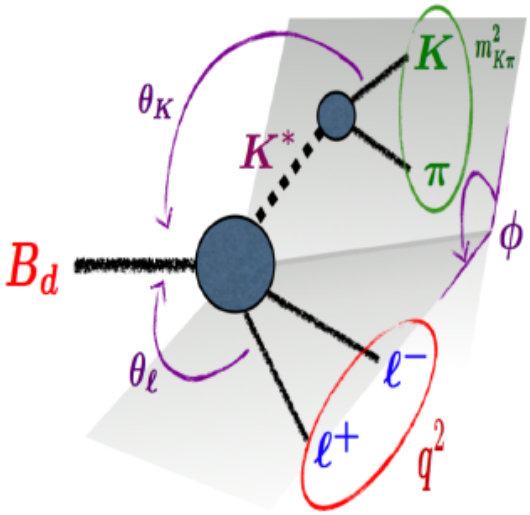


Popular example: P_5' in $B \to K^* \mu^+ \mu^-$

The $b \to s$ anomalies

$B \to K^* (\to K\pi)\ \mu^+\mu^-$ differential angular distribution

$$\frac{d^4\Gamma}{dq^2\, d\cos\theta_K\, d\cos\theta_l\, d\phi} = \frac{9}{32\pi}\Big[J_{1s}\sin^2\theta_K + J_{1c}\cos^2\theta_K + (J_{2s}\sin^2\theta_K + J_{2c}\cos^2\theta_K)\cos 2\theta_l$$
$$+J_3\sin^2\theta_K\sin^2\theta_l\cos 2\phi + J_4\sin 2\theta_K\sin 2\theta_l\cos\phi + J_5\sin 2\theta_K\sin\theta_l\cos\phi$$
$$+(J_{6s}\sin^2\theta_K + J_{6c}\cos^2\theta_K)\cos\theta_l + J_7\sin 2\theta_K\sin\theta_l\sin\phi$$
$$+J_8\sin 2\theta_K\sin 2\theta_l\sin\phi + J_9\sin^2\theta_K\sin^2\theta_l\sin 2\phi\Big]$$



[Figure borrowed from Javier Virto]

J_i : functions of q^2, C_i, FF

Optimized observables
[Descotes-Genon et al, 2012, 2013]

$$P_5' = \frac{J_5}{2\sqrt{-J_{2s}J_{2c}}}$$

The $b \to s$ anomalies

[LHCb, 2015]
1512.04442

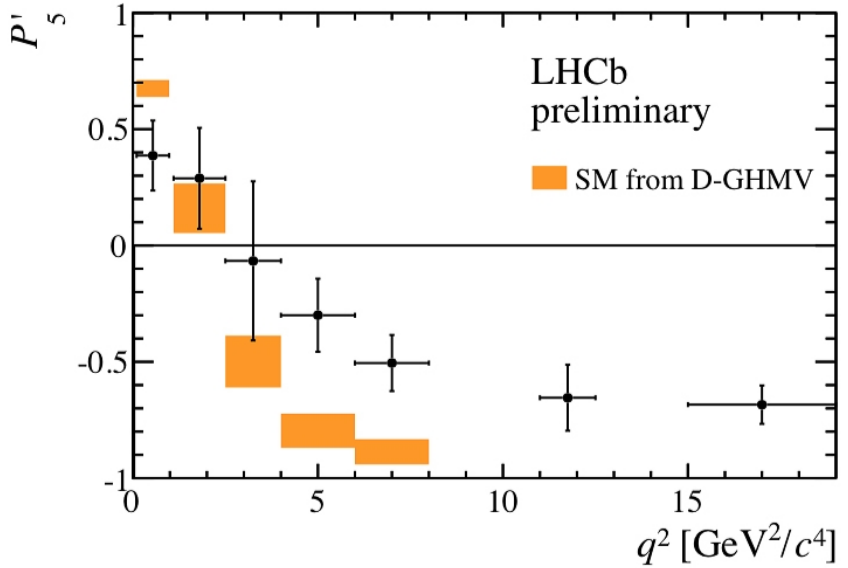
Episode VI: Return of the anomalies

2015 : LHCb confirms first anomalies

All observables updated to 3 fb^{-1}

[Complete LHC Run I dataset]

Errors shrunk...
... anomalies persist

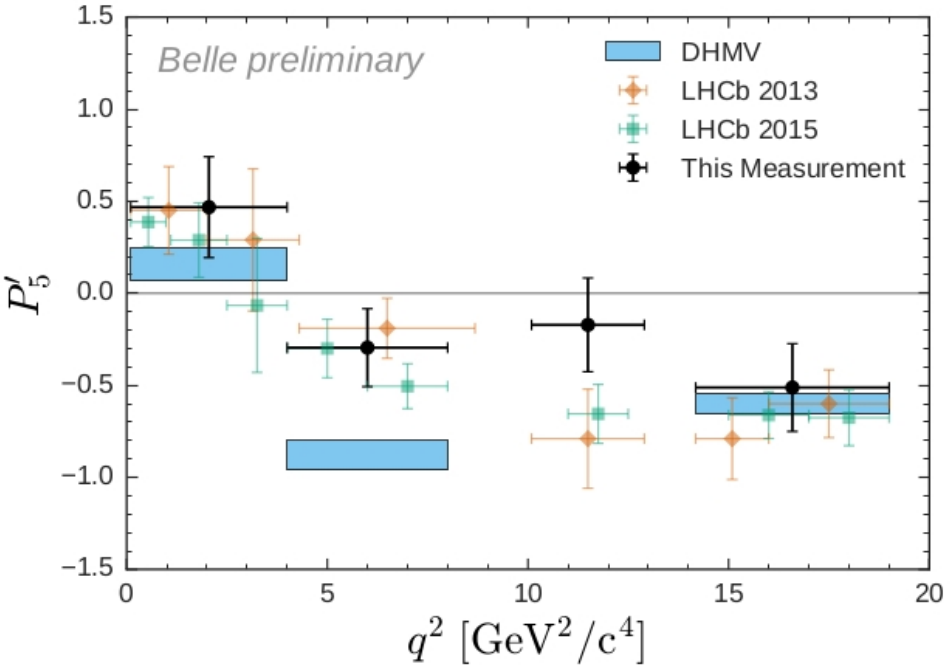


The $b \to s$ anomalies

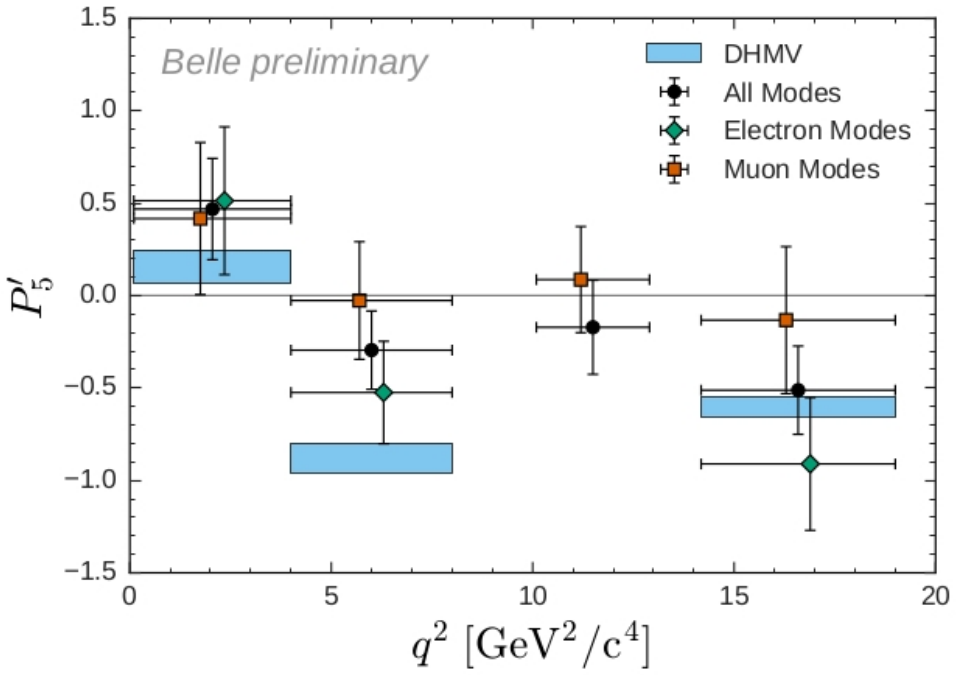
[Belle, 2016]
1612.05014

Episode I: The Belle menace

2016 : Belle finds additional hints



P_5' anomaly confirmed



Little LFVU indication

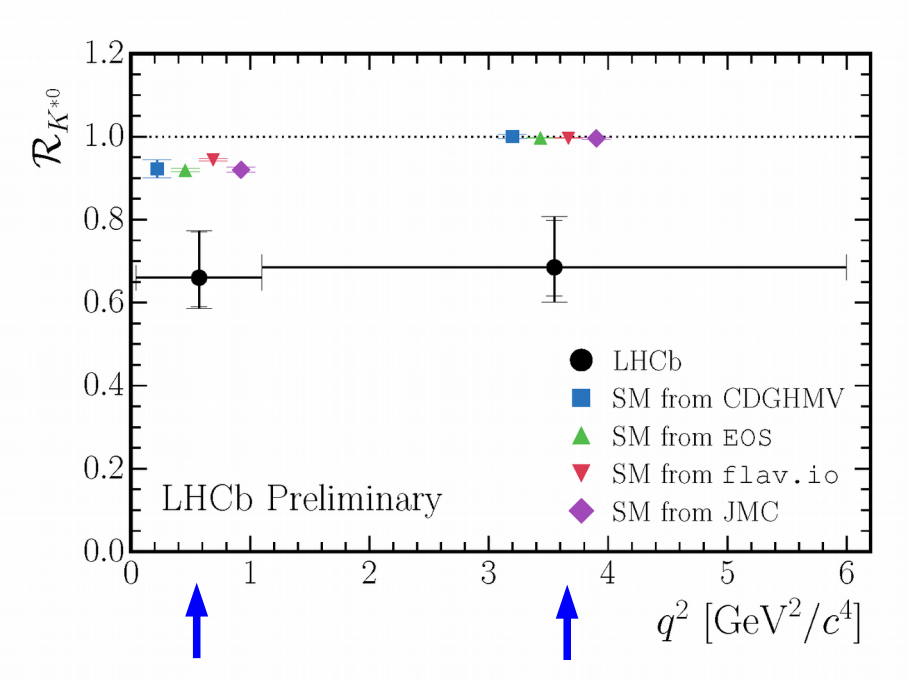
The $b \to s$ anomalies

[LHCb, 2017]
Talk by S. Bifani
April 18th
1705.05802

Episode II: Attack of R_{K^*}

2017 : More universality violation in LHCb

Obtained with 3 fb^{-1}



Interpreting the anomalies

$$\boxed{b \to s}$$

Effective hamiltonian

$$\mathcal{H}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{e^2}{16\pi^2} \sum_i (C_i\mathcal{O}_i + C_i'\mathcal{O}_i') + \text{h.c.}$$

C_i : Wilson coefficients $\qquad$ $\mathcal{O}_i$: Operators

$$\mathcal{O}_9 = (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma^\mu \ell) \qquad \mathcal{O}_9' = (\bar{s}\gamma_\mu P_R b)\ (\bar{\ell}\gamma^\mu \ell)$$

$$\mathcal{O}_{10} = (\bar{s}\gamma_\mu P_L b)\ (\bar{\ell}\gamma^\mu\gamma_5 \ell) \qquad \mathcal{O}_{10}' = (\bar{s}\gamma_\mu P_R b)\ (\bar{\ell}\gamma^\mu\gamma_5 \ell)$$

$$C_i = C_i^{\rm SM} + C_i^{\rm NP}$$

[analogous for primed operators]

Global fits

Table from Capdevila et al, 1704.05340

	All					LFUV				
1D Hyp.	Best fit	1 σ	2 σ	Pull_{SM}	p-value	Best fit	1 σ	2 σ	Pull_{SM}	p-value
$\mathcal{C}_{9\mu}^{\text{NP}}$	-1.10	$[-1.27, -0.92]$	$[-1.43, -0.74]$	5.7	72	-1.76	$[-2.36, -1.23]$	$[-3.04, -0.76]$	3.9	69
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{10\mu}^{\text{NP}}$	-0.61	$[-0.73, -0.48]$	$[-0.87, -0.36]$	5.2	61	-0.66	$[-0.84, -0.48]$	$[-1.04, -0.32]$	4.1	78
$\mathcal{C}_{9\mu}^{\text{NP}} = -\mathcal{C}_{9\mu}^{\prime}$	-1.01	$[-1.18, -0.84]$	$[-1.33, -0.65]$	5.4	66	-1.64	$[-2.12, -1.05]$	$[-2.52, -0.49]$	3.2	31
$\mathcal{C}_{9\mu}^{\text{NP}} = -3\mathcal{C}_{9e}^{\text{NP}}$	-1.06	[-1.23,-0.89]	[-1.39,-0.71]	5.8	74	-1.35	$[-1.82, -0.95]$	$[-2.38, -0.59]$	4.0	71

All observables
"clean" + "dirty"

Only LFUV observables
"clean"

New Physics hypothesis preferred over SM by more than 5 σ (4 σ if only LFUV)

The $C_{9\mu}$ coefficient seems to be crucial

Qualitatively similar results in
1704.05435 and 1704.05438