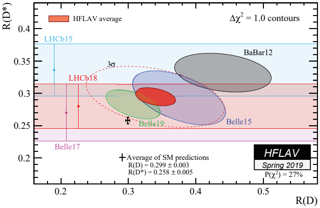
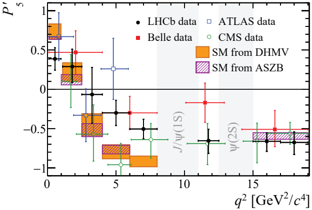
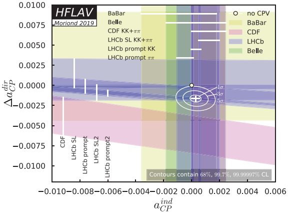
Flavour Anomalies

Antonio Pich

IFIC, U. Valencia – CSIC





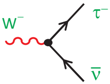


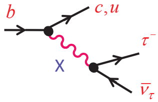
4th Red LHC Workshop, 4–6 November 2020

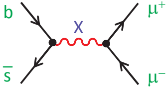
Many Interesting Flavour Anomalies

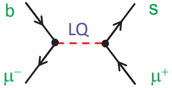
$b \to c\tau\nu$, $b \to s\,\mu^+\mu^-$, $(g-2)_{\mu,e}$, $\tau^\pm \to \pi^\pm K_S \nu$, $\Delta a_{\rm CP}$, V_{ub} , V_{ud} , $\cdots$

Some already gone: $B \to \tau\nu$, $W \to \tau\nu$, $\varepsilon'_K/\varepsilon_K$, ε_K , V_{cb} , $\cdots$









- Evidence for New Physics
- Statistical fluctuation
- Underestimated systematics
- Incorrect SM prediction or measurement

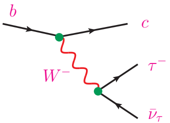
?

Not easy common explanation (within appealing BSM models)

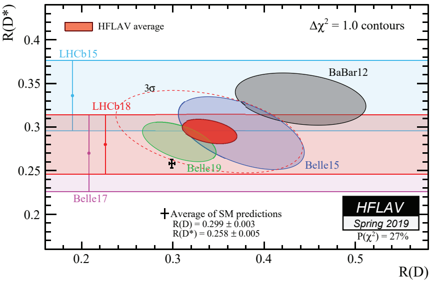
Separate analyses are (perhaps) more enlightening

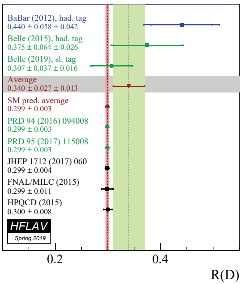
$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

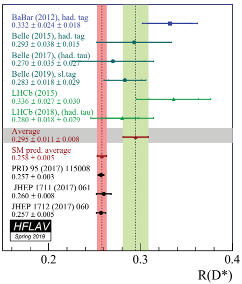
Tree-level process



3.08 σ discrepancy (3.2 σ with more recent predictions)







LHCb, 1711.05623: $\mathcal{R}_{J/\psi} \equiv \frac{\mathcal{B}(B_c \to J/\psi\tau\bar{\nu}_\tau)}{\mathcal{B}(B_c \to J/\psi\mu\bar{\nu}_\mu)} = 0.71 \pm 0.17 \pm 0.18$ (1.7 σ) $\mathcal{R}^{\mathrm{SM}}_{J/\psi} \approx 0.26 - 0.28$

Belle, 1903.03102: $F_L^{D^*} = 0.60 \pm 0.08 \pm 0.04$ (1.6 σ) $F^{D^*}_{L,\mathrm{SM}} = 0.455 \pm 0.003$

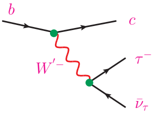
Belle, 1612.00529: $\mathcal{P}_\tau^{D^*} = -0.38 \pm 0.51^{+0.21}_{-0.16}$ $\mathcal{P}^{D^*}_{\tau,\mathrm{SM}} = -0.499 \pm 0.003$

Effective Field Theory

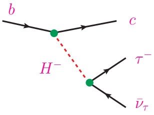
$C_{AB}^X\big|^{\mathrm{SM}} = 0$

$$\mathcal{H}_{\mathrm{eff}}^{b\to c\tau\nu} = \frac{4G_F}{\sqrt{2}} V_{cb} \left\{ \mathcal{O}_{LL}^V + \sum_{A,B=L,R} \left[C_{AB}^V \mathcal{O}_{AB}^V + C_{AB}^S \mathcal{O}_{AB}^S + C_{AB}^T \mathcal{O}_{AB}^T \right] + \text{h.c.} \right\}$$

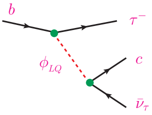
$$\mathcal{O}_{AB}^V = (\bar c\, \gamma^\mu \mathcal{P}_A b)\, (\bar\tau \gamma_\mu \mathcal{P}_B \nu)\,, \qquad \mathcal{O}_{AB}^S = (\bar c\, \mathcal{P}_A b)\, (\bar\tau \mathcal{P}_B \nu)\,, \qquad \mathcal{O}_{AB}^T = \delta_{AB}\, (\bar c\, \sigma^{\mu\nu} \mathcal{P}_A b)\, (\bar\tau \sigma_{\mu\nu} \mathcal{P}_A \nu)$$



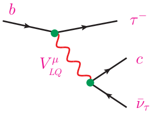
C_{LL}^V



$C_{LL}^S,\ C_{RL}^S \quad (C_{LL}^T)$



$C_{LL}^V,\ C_{LL}^S,\ C_{LL}^T$



$C_{LL}^V,\ C_{RL}^S$

Many analyses (usually with single operator/mediator and partial data information)

Freytsis et al, Bardhan et al, Cai et al, Hu et al, Celis et al, Datta et al, Bhattacharya et al, Alonso et al, . . .

Global fit to all data: (q^2 distributions included)

ν_L Murgui-Peñuelas-Jung-Pich, 1904.09311

ν_R Mandal-Murgui-Peñuelas-Pich, 2004.06726

Assumptions

- $C_{AB}^X \neq 0$ for 3rd fermion generation only
- EWSB linearly realized ➔ $C_{RL}^V = 0$
- CP symmetry ➔ Real Wilson coefficients

Global fit to all data: ν_L

Murgui-Penüelas-Jung-Pich, 1904.09311

$F_L^{D^*}$, $\mathcal{B}_{10}$	Min 1	Min 2
χ^2/d.o.f.	37.4/54	40.4/54
C_{LL}^V	$0.09\,^{+\,0.13}_{-\,0.12}$	$0.34\,^{+\,0.05}_{-\,0.07}$
C_{RL}^S	$0.09\,^{+\,0.12}_{-\,0.61}$	$-1.10\,^{+\,0.48}_{-\,0.07}$
C_{LL}^S	$-0.14\,^{+\,0.52}_{-\,0.07}$	$-0.30\,^{+\,0.11}_{-\,0.50}$
C_{LL}^T	$0.008\,^{+\,0.046}_{-\,0.044}$	$0.093\,^{+\,0.029}_{-\,0.030}$

$\mathcal{B}(B_c \to \tau\bar{\nu}) < 10\%$

$F_L^{D^*}$ included

- **Strong preference for New Physics** $(\chi^2_{\mathrm{SM}} - \chi^2 = 31.4)$
- **No clear preference for a particular Wilson coefficient in the global minimum**
- **Min 1 compatible with a global modification of the SM**
  (Fitting only C_{LL}^V just increases χ^2 by 1.4)
- **Min 2 is further away from the SM & involves large scalar contributions**
- **$F_L^{D^*}$ difficult to accommodate at 1σ**
- Complex C_{AL}^X do not improve the χ^2, but open many more solutions
- Including C_{RL}^V slightly improves the agreement with data $(\chi^2/\mathrm{d.o.f.} = 32.5/53)$.
  Two additional fine-tuned solutions with $C_{LL}^V \sim -0.9$

Global Fit within ν_R Scenarios

Mandal-Murgui-Peñuelas-Pich, 2004.06726

Sc 1: $\mathcal{O}^V_{LR}$, $\mathcal{O}^V_{RR}$, $\mathcal{O}^S_{LR}$, $\mathcal{O}^S_{RR}$, $\mathcal{O}^T_{RR}$, $\mathcal{O}^V_{LL}$

Sc 2: $\mathcal{O}^V_{LR}$, $\mathcal{O}^V_{RR}$, $\mathcal{O}^S_{LR}$, $\mathcal{O}^S_{RR}$, $\mathcal{O}^T_{RR}$

Sc 3, V^μ: $\mathcal{O}^V_{RR}$

Sc 4, Φ: $\mathcal{O}^S_{LR}$, $\mathcal{O}^S_{RR}$ [b: + $\mathcal{O}^S_{LL}$, $\mathcal{O}^S_{RL}$]

Sc 5, U_1^μ: $\mathcal{O}^V_{RR}$, $\mathcal{O}^S_{LR}$ [b: + $\mathcal{O}^V_{LL}$, $\mathcal{O}^S_{RL}$]

Sc 6, $\tilde{R}_2$: $\mathcal{O}^S_{RR}$, $\mathcal{O}^T_{RR}$

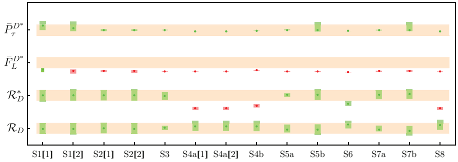
Sc 7, S_1: $\mathcal{O}^V_{RR}$, $\mathcal{O}^S_{RR}$, $\mathcal{O}^T_{RR}$ [b: + $\mathcal{O}^V_{LL}$, $\mathcal{O}^S_{LL}$, $\mathcal{O}^T_{LL}$]

Sc 8, $\tilde{V}_2^\mu$: $\mathcal{O}^S_{LR}$

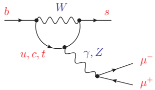
Scenario	$\mathcal{B}(B_c \to \tau\bar\nu)$	χ^2/d.o.f	Pull$_{SM}$: $\bar{\mathcal{P}}_\tau^{D^*}$, $F_L^{D^*}$	Pull$_{SM}$: $\mathcal{R}_{D,D^*}$	Pull$_{SM}$: $d\Gamma/dq^2$	Pull$_{SM}$	p-value
SM	2.16%	52.87/59					69.95%
Scenario 1, Min 1	< 10%	37.26/53	0.007	2.08	0.0414	2.4	95.02%
Scenario 1, Min 2	< 10%	38.86/53	0.001 ✗	2.08	0.0006	2.2	92.68%
Scenario 1, Min 1	< 30%	36.42/53	0.022	2.08	0.0866	2.5	96.00%
Scenario 1, Min 2	< 30%	38.54/53	0.011	2.08	0.000	2.2	93.21%
Scenario 2, Min 1	< 10%	38.54/54	0.006 ✗	2.32	0.0113	2.5	93.20%
Scenario 2, Min 2	< 10%	39.05/54	0.004 ✗	2.32	0.0003	2.4	93.73%
Scenario 2, Min 1	< 30%	38.33/54	0.035 ✗	2.32	0.0023	2.5	94.73%
Scenario 2, Min 2	< 30%	38.80/54	0.025 ✗	2.32	0*	2.4	94.09%
Scenario 3	< 10%	39.50/58	0.150 ✗	3.65	0.0835	3.7 ✓	97.00%
Scenario 4a, Min 1	< 10%	49.93/57	0.079 ✗	2.34 ✗	0*	1.2	73.52%
Scenario 4a, Min 2	< 10%	49.93/57	0.079 ✗	2.34 ✗	0*	1.2	73.52%
Scenario 4a, Min 1	< 30%	44.49/57	0.311 ✗	2.66 ✗	0*	2.4	88.62%
Scenario 4a, Min 2	< 30%	44.49/57	0.311 ✗	2.66 ✗	0*	2.4	88.62%
Scenario 4b	< 10%	43.56/55	0.054 ✗	2.07 ✗	0*	1.9	86.70%
Scenario 4b	< 30%	40.03/55	0.218	2.52	0*	2.5	93.54%
Scenario 5a	< 10%	39.39/57	0* ✗	3.22	0.0981	3.2 ✓	96.36%
Scenario 5b	< 10%	39.37/55	0* ✗	3.34	0.0060	2.6	94.47%
Scenario 6	< 10%	44.20/58	0* ✗	3.34	0*	2.9	90.93%
Scenario 7a	< 10%	39.21/57	0.126 ✗	3.22	0.0616	3.3 ✓	96.53%
Scenario 7b	< 10%	39.06/55	0.014 ✗	2.56	0.0112	2.7	94.87%
Scenario 8	< 10%	47.32/57	0.259 ✗	2.56 ✗	0*	1.9	81.60%

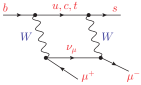
- $F_L^{D^*}$ difficult to fit at 1σ

  Only possible in Sc 1 and 4b ($< 30\%$)
- Scalar solution ➔ larger $\mathrm{Br}(B_c \to \tau\bar\nu)$
- Higher pulls: V^μ, S_1, U_1^μ



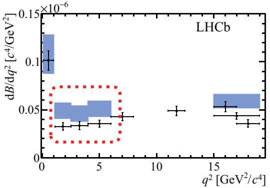
$b \to s\,\mu^+\mu^-$



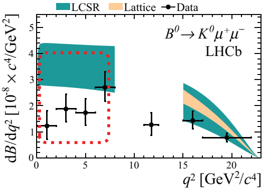


SM loop process

LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



Data below SM predictions

$B^0 \to K^{(*)0}\mu^+\mu^-$, $B^+ \to K^{(*)+}\mu^+\mu^-$,

$B^0_s \to \phi\mu^+\mu^-$, $\Lambda_b \to \Lambda\mu^+\mu^-$, . . .

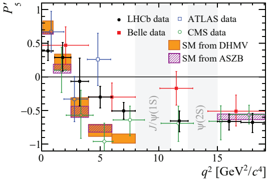
(1-3 σ tensions)

Large hadronic uncertainties

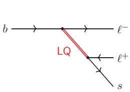
Optimized observables

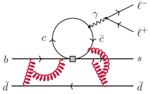
(angular distribution)

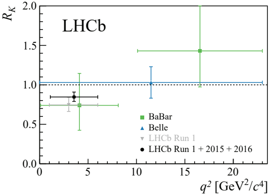
Descotes-Genon et al, 1207.2753

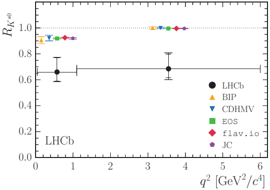


New Physics or SM $\bar{c}c$ loop?









Lepton Flavour Violations

$\mu^+\mu^-$ versus e^+e^-

Not confirmed/refuted by Belle

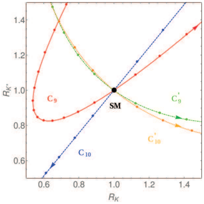
Global 2D Fits: $C_{9,\mu}^{\rm NP} \sim -0.2\, C_{9,\mu}^{\rm SM}$

$$\mathcal{H}_{\rm eff}^{b\to s\ell\ell} = -\frac{4G_F}{\sqrt{2}}\, V_{tb} V_{ts}^* \,\frac{\alpha}{4\pi} \sum_i C_i\, O_i + \text{h.c.}$$

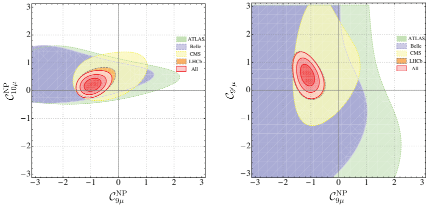
$$O_9 = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell) \quad , \quad O_9' = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu \ell)$$

$$O_{10} = (\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \quad , \quad O_{10}' = (\bar{s}_R\gamma_\mu b_R)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

Geng et al, 1704.05446



Algueró et al, 1903.09578



$C_{9,\mu}^{\rm NP} \sim -0.95$

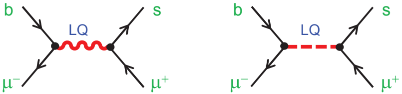
$C_{10,\mu}^{\rm NP} \sim 0.20$

(5.7σ pull)

- $B_s^0 \to \mu^+\mu^-$ strongly constrains pseudoscalar operators and bounds $C_{10,\mu}^{\rm NP}$
- Preferred solutions: $C_{9,\mu}^{\rm NP} \neq 0$ or $C_{9,\mu}^{\rm NP} \approx -C_{10,\mu}^{\rm NP} \neq 0$
- Slight tension ($2\,\sigma$) in current $B_s^0 \to \mu^+\mu^-$ world average favours $C_{9,\mu}^{\rm NP} - C_{10,\mu}^{\rm NP}$
- Recent data allow more space for right-handed currents
- Additional solutions with LFU components (Algueró et al, 1809.08447)
- SMEFT: $b \to c\tau\nu$ and $b \to s\ell\ell$ anomalies ➔ Large $b \to s\tau\tau$

$$(\bar{Q}_2\gamma^\mu Q_3)(\bar{L}_3\gamma_\mu L_3) + (\bar{Q}_2\gamma^\mu \sigma^I Q_3)(\bar{L}_3\gamma_\mu \sigma^I L_3) \;\approx\; 2\left[(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu \nu_{\tau L}) + (\bar{s}_L\gamma_\mu b_L))(\bar{\tau}_L\gamma^\mu \tau_L)\right]$$

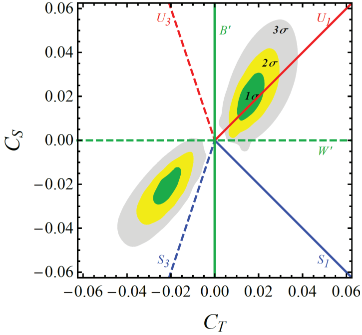
Leptoquark Solutions



$$\mathcal{L}_{\rm eff} = -\frac{1}{v^2}\lambda^q_{ij}\lambda^\ell_{\alpha\beta}\left[C_T\,(\bar{Q}^i_L\gamma_\mu\sigma^a Q^j_L)(\bar{L}^\alpha_L\gamma^\mu\sigma^a L^\beta_L) + C_S\,(\bar{Q}^i_L\gamma_\mu Q^j_L)(\bar{L}^\alpha_L\gamma^\mu L^\beta_L)\right]$$

$U(2)_q \otimes U(2)_\ell$ Family Symmetry

Buttazzo et al, 1706.07808



Angelescu et al, 1808.08179

Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗*	✗*
$R_2 = (3, 2, 7/6)$	✓	✗*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

Possible UV completions:

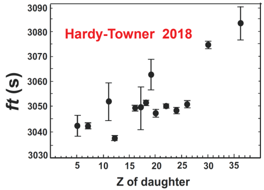
- 4321 model — Di Luzio et al
- (Pati-Salam)^3 — Bordone et al
- PS + VLF — Calibbi et al
- Warped PS — Blanke-Crivellin
- SU(5) GUT (R_2 & S_3) — Becirevic et al
- S_1 & S_3 — Crivellin et al, Buttazzo et al, Marzocca
- …

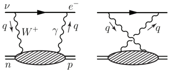
Superallowed Nuclear β Transitions $(0^+ \to 0^+)$

$$|V_{ud}|^2 = \frac{\pi^3 \ln 2}{ft\, G_F^2 m_e^5\, (1+\delta_{RC})} = \frac{(2984.48 \pm 0.05)\ \mathrm{s}}{ft\,(1+\delta_{RC})}$$

$f_+(0) = 1 + O[(m_u - m_d)^2]$

$$\delta_{RC} = \Delta_R^V + \Delta_{Nucl} \quad , \quad \mathcal{F}t = ft\,(1+\Delta_{Nucl}) = 3072.27\,(72)\ \mathrm{s}$$



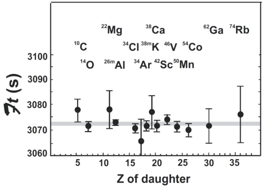


Nucleus-independent radiative correction

$$\Delta_R^V = \begin{cases} 0.02361\,(38) & \text{Marciano-Sirlin, 2006} \\ 0.02467\,(22) & \text{Seng et al, 1807.10197} \end{cases}$$

$$|V_{ud}| = \begin{cases} \mathbf{0.97420\ (21)} & \text{Marciano-Sirlin} \\ \mathbf{0.97366\ (15)} & \text{Seng et al} \end{cases}$$

Independent check needed!



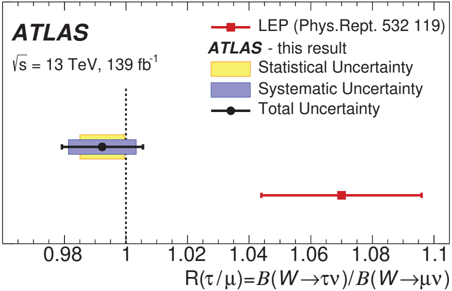
PDG 2020: $|V_{ud}| = 0.97370\ (14)$

$$|V_{us}| = \begin{cases} 0.2231\ (7) & (K \to \pi \ell \nu) \\ 0.2245\ (8) & (K \to \ell\nu, \pi\ell\nu) \end{cases}$$

$$\rightarrow \quad 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = \begin{cases} 0.00212\ (41) & 5.1\,\sigma \\ 0.00149\ (45) & 3.3\,\sigma \end{cases}$$

Lepton Flavour Universality in W Decays

2007.14040



$$\left|\frac{g_\tau}{g_\mu}\right| = \begin{cases} 0.996 \pm 0.007 & \text{ATLAS} \\ 1.034 \pm 0.013 & \text{LEP} \\ 1.004 \pm 0.016 & \text{Average} \end{cases}$$

Summary

- Flavour structure and $\not{\mathcal{CP}}$ are major pending questions
- Related to SSB ➡ Scalar Sector (Higgs)
- Important cosmological implications (Baryogenesis)
- Sensitive to New Physics: Flavour Anomalies!

Intriguing signals **(Most anomalies related to 3^{rd} family)**

Many questions. Higher statistics & better systematics (QCD) needed

Eagerly awaiting new experimental results

Backup


4th Red LHC Workshop
4 - 6 November 2020 (virtual)
Organizers:
J.A. Aguilar-Saavedra
B. Álvarez González
C. Escobar Ibáñez
S. Heinemeyer
C. Santamaría Ríos
https://indico.cern.ch/e/redlhc4

Possible Caveats / Constraints:

❶ **Saturation of inclusive width:** $\mathcal{B}(B \to D^{**}\tau\nu) > 0.5\%$ Freytsis et al, 1506.08896

- $\mathcal{R}_{D^{(*)}}$ ➡ $\mathcal{B}(B \to D\tau\nu) + \mathcal{B}(B \to D^*\tau\nu) = (2.39 \pm 0.13)\%$

- $\left.\frac{\mathcal{B}(B \to X_c\tau\nu)}{\mathcal{B}(B \to X_c e\nu)}\right|_{\rm OPE} = (0.222 \pm 0.007)$ **Not a problem of form factors**

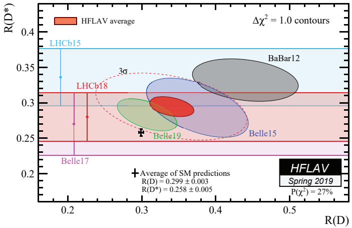
  $\mathcal{B}(B \to X_c\ell\nu) = (10.65 \pm 0.16)\%$ ➡ $\mathcal{B}(B \to X_c\tau\nu) = (2.36 \pm 0.08)\%$

- LEP: $\mathcal{B}(b \to X_c\tau\nu) = (2.41 \pm 0.23)\%$

❷ $b \to c\tau\nu$ ⟷ $b\bar{c} \to \tau\nu$: $\mathcal{B}(B_c \to \tau\nu) < 10\%$ (30%) Akeroyd-Chen, Alonso et al, Celis et al

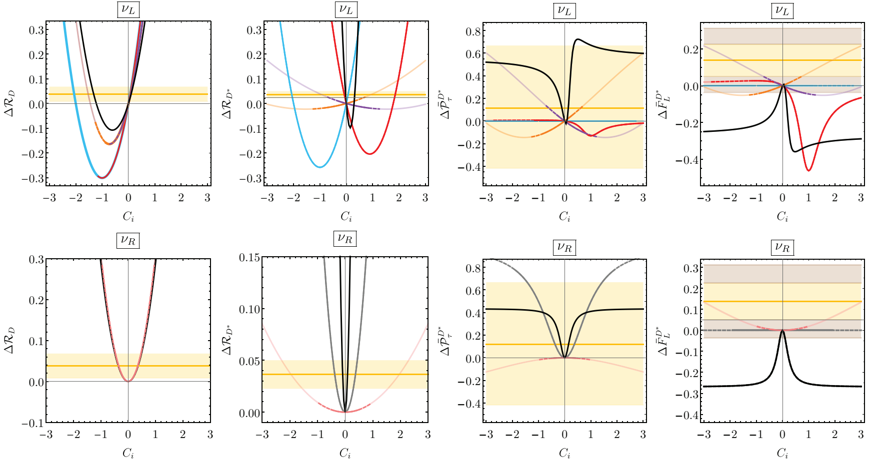
❸ **Differential distributions. Polarizations:** **Data self-consistency**

❹ **Time evolution of data:**



Sensitivity to individual Wilson coefficients

Mandal-Murgui-Peñuelas-Pich, 2004.06726



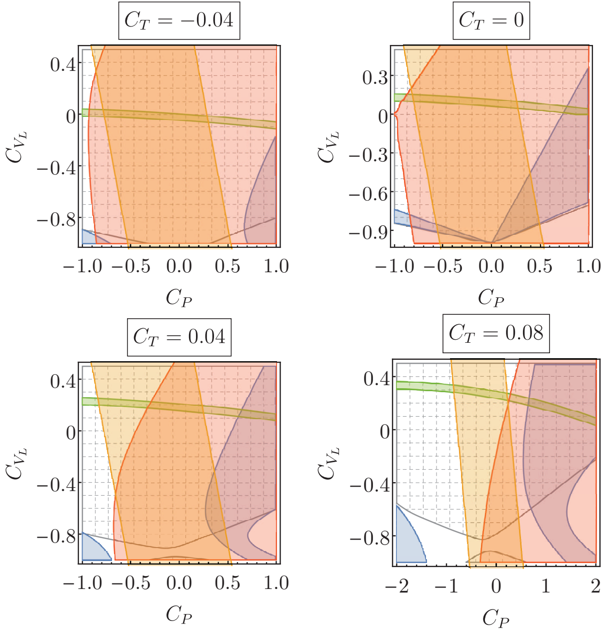
ν_L	C_{LL}^V	C_{RL}^V	C_{RL}^S	C_{LL}^S	C_{LL}^T
ν_R	$C_{LR}^V = C_{RR}^V$		$C_{RR}^S = C_{LR}^S$		C_{RR}^T

$F_L^{D^*}$ always below the exp. 1σ region

Solid (dashed) lines indicate ranges satisfying $\mathrm{Br}(B_c \to \tau\nu) < 10\%$ (30%). Fainted lines do not fulfil this constraint

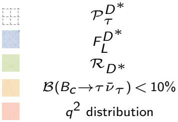
D^* Observables

Murgui-Peñuelas-Jung-Pich, 1904.09311

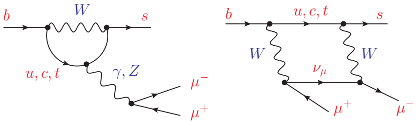


It is not possible to accommodate all D^* data at 1σ

$C_P \equiv C_{S_R} - C_{S_L}$

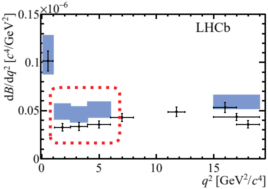


$b \to s\,\mu^+\mu^-$

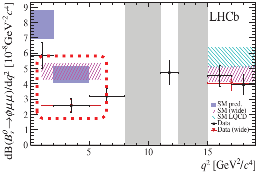


SM loop process

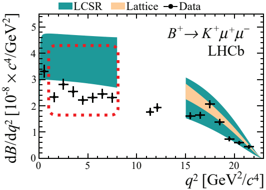
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



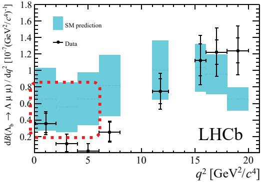
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



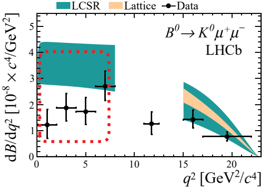
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



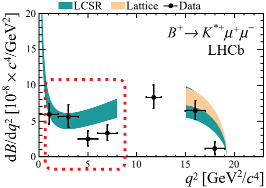
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



LHCb $B^0 \to K^0\mu^+\mu^-$ [JHEP 06 (2014) 133]



$B^+ \to K^{*+}\mu^+\mu^-$ [JHEP 06 (2014) 133]



C. Langenbruch, LHC implications 2018

Data consistently below SM predictions **(1-3 σ tensions)**

Large hadronic uncertainties

$B \to K^* \mu^+ \mu^- \to K\pi\, \mu^+ \mu^-$

$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\,\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$

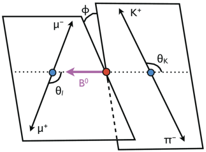
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$

$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$

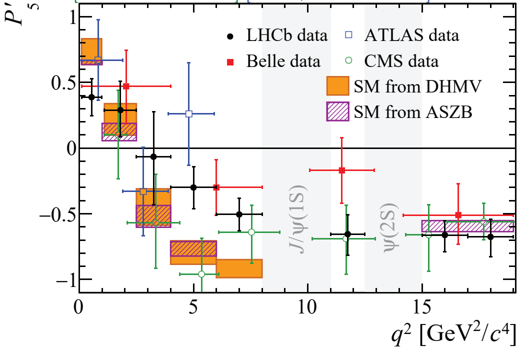
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

$$q^2 = s_{\mu\mu}$$

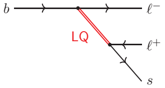
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$



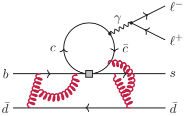
[LHCb, JHEP 02 (2016) 104] [Belle, PRL 118 (2017) 111801]
[CMS-PAS-BPH-15-008] [ATLAS, arXiv:1805.04000]



C. Langenbruch, LHC implications 2018

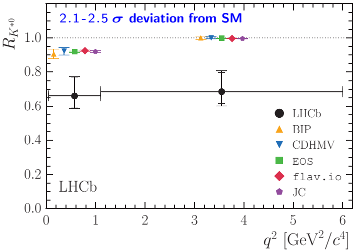


NP or SM $c\bar{c}$-loop?



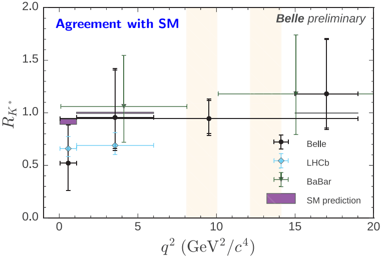
Violations of Lepton Flavour Universality

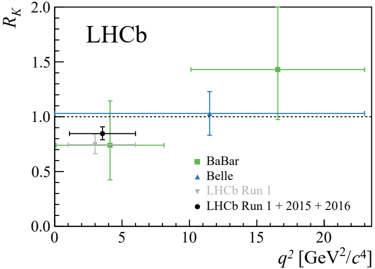
LHCb 1705.05802



$$\frac{\Gamma(B \to K^* \mu^+ \mu^-)}{\Gamma(B \to K^* e^+ e^-)}$$

Belle 1904.02440





LHCb, 1903.09252

$q^2 \in [1.1, 6.0]$ GeV^2

$$R_K \equiv \frac{\Gamma(B^+ \to K^+ \mu^+ \mu^-)}{\Gamma(B^+ \to K^+ e^+ e^-)} = 0.846 \,^{+0.060}_{-0.054} \,^{+0.016}_{-0.014}$$

2.5 σ below the SM

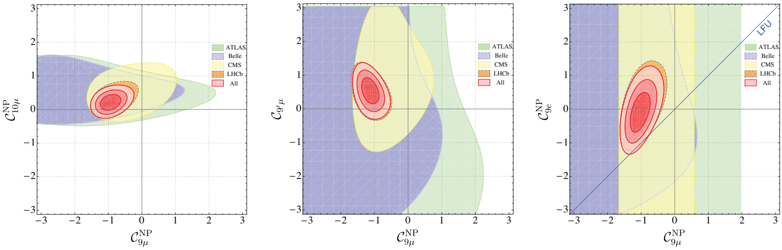
Not confirmed/refuted by Belle 1908.01848

Global 2D Fits: $C_{9,\mu}^{\rm NP} \sim -0.2\ C_{9,\mu}^{\rm SM}$

$$\mathcal{H}_{\rm eff}^{b\to s\ell\ell} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \frac{\alpha}{4\pi} \sum_i C_i\, O_i + \text{h.c.}$$

$$O_9 = (\bar{s}_L\gamma_\mu b_L)(\bar\ell\gamma^\mu\ell) \quad , \quad O_9' = (\bar{s}_R\gamma_\mu b_R)(\bar\ell\gamma^\mu\ell)$$

$$O_{10} = (\bar{s}_L\gamma_\mu b_L)(\bar\ell\gamma^\mu\gamma_5\ell) \quad , \quad O_{10}' = (\bar{s}_R\gamma_\mu b_R)(\bar\ell\gamma^\mu\gamma_5\ell)$$

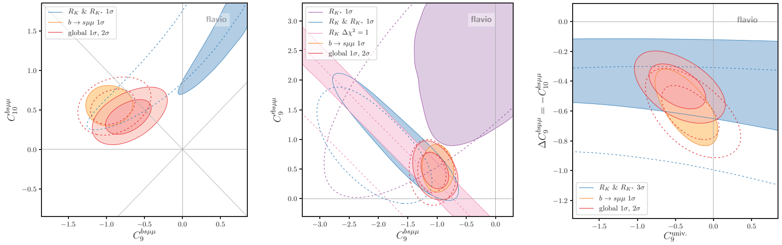


Algueró et al 1903.09578

$C_{9,\mu}^{\rm NP} \sim -0.95$

$C_{10,\mu}^{\rm NP} \sim 0.20$

(5.7 σ pull)



Aebischer et al 1903.10434

$C_{9,\mu}^{\rm NP} \sim -0.72$

$C_{10,\mu}^{\rm NP} \sim 0.40$

(6.2 σ pull)

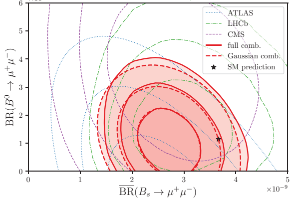
Global 2D Fits: $C_{9,\mu}^{\rm NP} \sim -0.2\, C_{9,\mu}^{\rm SM}$

$$\mathcal{H}_{\rm eff}^{b\to s\ell\ell} = -\frac{4G_F}{\sqrt{2}} V_{tb}V_{ts}^* \frac{\alpha}{4\pi} \sum_i C_i\, O_i + \text{h.c.}$$

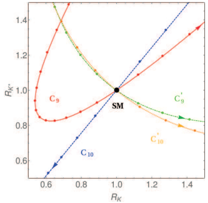
$$O_9 = (\bar s_L\gamma_\mu b_L)(\bar\ell\gamma^\mu\ell) \quad , \quad O_9' = (\bar s_R\gamma_\mu b_R)(\bar\ell\gamma^\mu\ell)$$

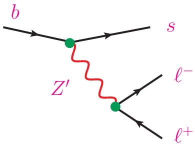
$$O_{10} = (\bar s_L\gamma_\mu b_L)(\bar\ell\gamma^\mu\gamma_5\ell) \quad , \quad O_{10}' = (\bar s_R\gamma_\mu b_R)(\bar\ell\gamma^\mu\gamma_5\ell)$$

Aebischer et al, 1903.10434



Geng et al, 1704.05446



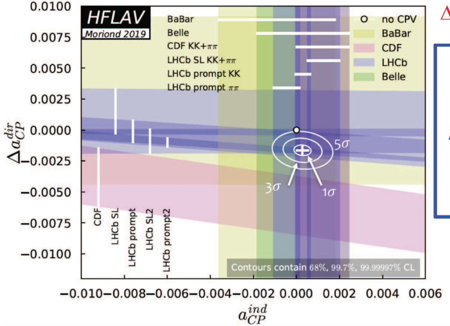


- $B_s^0\to\mu^+\mu^-$ strongly constrains pseudoscalar operators and bounds $C_{10,\mu}^{\rm NP}$
- Preferred solutions: $C_{9,\mu}^{\rm NP}\neq 0$ or $C_{9,\mu}^{\rm NP}\approx -C_{10,\mu}^{\rm NP}\neq 0$
- Slight tension $(2\,\sigma)$ in current $B_s^0\to\mu^+\mu^-$ world average favours $C_{9,\mu}^{\rm NP} - C_{10,\mu}^{\rm NP}$
- Moriond data allows more space for right-handed currents
- Additional solutions with LFU components (Algueró et al, 1809.08447)
- SMEFT: $b\to c\tau\nu$ and $b\to s\ell\ell$ anomalies ➡ Large $b\to s\tau\tau$

$$(\bar Q_2\gamma^\mu Q_3)(\bar L_3\gamma_\mu L_3) + (\bar Q_2\gamma^\mu\sigma^I Q_3)(\bar L_3\gamma_\mu\sigma^I L_3) \approx 2\,[(\bar c_L\gamma_\mu b_L)(\bar\tau_L\gamma^\mu\nu_{\tau L}) + (\bar s_L\gamma_\mu b_L))(\bar\tau_L\gamma^\mu\tau_L)]$$

First evidence of $\mathcal{C}\!\!\!/\mathcal{P}$ in charm decays $(5.3\,\sigma)$

LHCb 1903.08726 $\Delta a_{\mathcal{CP}} = (-15.4 \pm 2.9)\cdot 10^{-4}$, $\Delta a_{\mathcal{CP}}^{\rm dir} = (-15.7 \pm 2.9)\cdot 10^{-4}$



$\Delta a_{CP} = a_{CP}(K^+K^-) - a_{CP}(\pi^+\pi^-)$

HFLAV combination

$a_{CP}^{\rm ind} = (0.028 \pm 0.026)\%$

$\Delta a_{CP}^{\rm dir} = (-0.164 \pm 0.028)\%$

Consistency with NO CPV hypothesis: $5{\times}10^{-8}$

$$a_{CP} \equiv \frac{\Gamma\left(D^0 \to \mathrm{f}\right) - \Gamma\left(\bar{D}^0 \to \mathrm{f}\right)}{\Gamma\left(D^0 \to \mathrm{f}\right) + \Gamma\left(\bar{D}^0 \to \mathrm{f}\right)}$$

Large uncertainty in SM prediction:

- Naive perturbative QCD (+ LCSR) ➔ $|\Delta a_{\mathcal{CP}}^{\rm dir}| \le 3\cdot 10^{-4}$ Chala et al, 1903.10490
- Re-scattering: $\Delta a_{\mathcal{CP}}^{\rm dir}$ ➔ $\Delta U = 0$ rule in charm Grossman-Schacht, 1903.10952