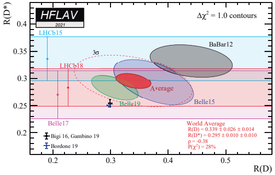
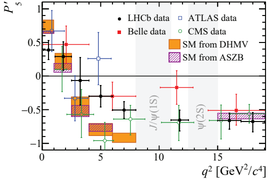
Flavour Anomalies

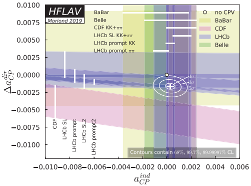
Hints of new non-universal interactions?

Antonio Pich

IFIC, U. Valencia – CSIC



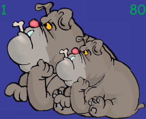




XLIX International Meeting on Fundamental Physics (IMPF22), Benasque (Spain), 5–10 September 2022

Table of Elementary Particles

Matter (Fermions , $J = \frac{1}{2}$) | Forces

Quarks		Leptons		Bosons
Q = 2/3	Q = -1/3	Q = 0	Q = -1	J = 1
0.002  up (u)	0.005  down (d)	< 0.000000001  neutrino e (ν_e)	0.0005  electron (e)	0  Photon; 0  gluons
1.3  charm (c)	0.1  strange (s)	< 0.000000001  neutrino μ (ν_μ)	0.105  muon (μ)	91 80  Z^0 $W^\pm$
173  top (t)	4.2  beauty (b)	< 0.000000001  neutrino τ (ν_τ)	1.777  tau (τ)	J = 0; 125  Higgs

Standard Model of the Fundamental Interactions

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$$

1. **Interactions determined by gauge symmetries. Flavour Universality**
2. **Gauge symmetries require all elementary particles to be massless**
3. **Masses generated through the interaction with the Higgs doublet**

$$\mathcal{L}_Y = -\sum_{jk} \left\{ \left(\bar{u}_j, \bar{d}'_j\right)_L \left[c_{jk}^{(d)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} d'_{kR} + c_{jk}^{(u)} \begin{pmatrix} \phi^{(0)*} \\ -\phi^{(-)} \end{pmatrix} u_{kR} \right] + \left(\bar{\nu}_j, \bar{\ell}'_j\right)_L c_{jk}^{(l)} \begin{pmatrix} \phi^{(+)} \\ \phi^{(0)} \end{pmatrix} \ell'_{kR} \right\}$$

Mass is the only difference among the three fermion families

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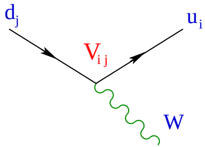
4. **Fermion mass eigenstates** $\neq$ **weak eigenstates**

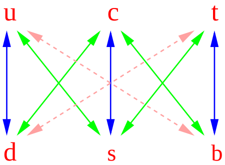
→ **Flavour Mixing:** $d'_i = V_{ij}\, d_j \quad , \quad V^\dagger V = V\, V^\dagger = I$

CP violation (if $N_G \geq 3$)

Flavour-Changing Charged Currents

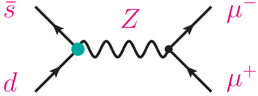
$$\mathcal{L}_{CC} = -\frac{g}{2\sqrt{2}}\, W_\mu^\dagger \left\{ \sum_{ij} \bar{u}_i \gamma^\mu (1-\gamma_5)\, V_{ij}\, d_j + \sum_{ij} \bar{\nu}_i \gamma^\mu (1-\gamma_5)\, U_{ij}^\dagger\, \ell_j \right\} + \text{h.c.}$$





Flavour-Conserving Neutral Currents (GIM)

NO

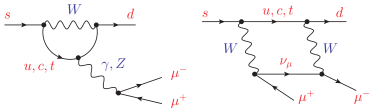


LHCb 2001.10354

$\mathrm{Br}(K_S \to \mu^+\mu^-) < 2.1 \times 10^{-10}$

(90% CL)

Successful Description of Flavour & CP



Rare Decays

$$\mathrm{Br}(K_L^0 \to \mu^+\mu^-) = 6.8 \times 10^{-9}$$

$$\mathrm{Br}(B_s^0 \to \mu^+\mu^-) = 3.0 \times 10^{-9}$$

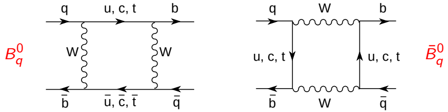
$$\mathrm{Br}(\bar{b} \to \bar{s}\gamma) = 3.1 \times 10^{-4}$$

Meson-Antimeson Mixing

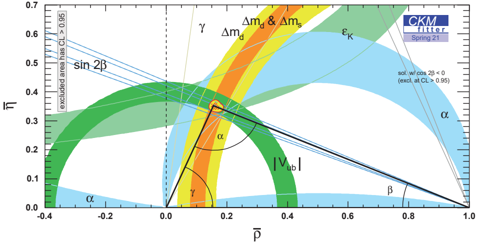
$$\Delta M_{K^0}/M_{K^0} = 7.0 \times 10^{-15}$$

$$\Delta M_{B_d^0}/M_{B_d^0} = 6.3 \times 10^{-14}$$

$$\Delta M_{B_s^0}/M_{B_s^0} = 2.2 \times 10^{-12}$$

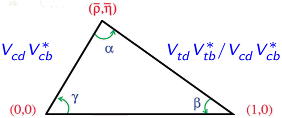


$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$



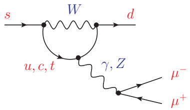
CKM Unitarity

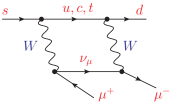
$V_{ud}V_{ub}^*/V_{cd}V_{cb}^*$



$V_{td}V_{tb}^*/V_{cd}V_{cb}^*$

Successful Description of Flavour & CP





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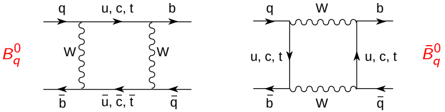
Sensitivity to (virtual) heavy scales

Meson-Antimeson Mixing

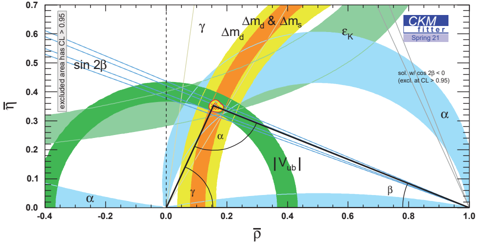
$\Delta M_{K^0} / M_{K^0} = 7.0 \times 10^{-15}$ ➡ m_c

$\Delta M_{B_d^0} / M_{B_d^0} = 6.3 \times 10^{-14}$ ➡ m_t

$\Delta M_{B_s^0} / M_{B_s^0} = 2.2 \times 10^{-12}$ ➡ m_t



$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$



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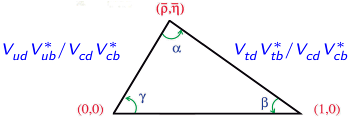
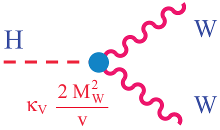
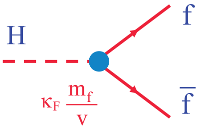
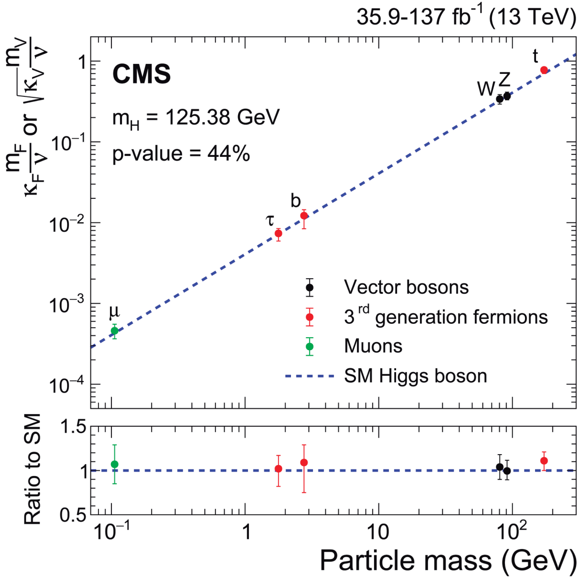


A Higgs field indeed

Interaction proportional to mass



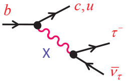


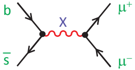


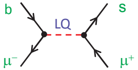
Many Interesting Flavour Anomalies

$b \to c\tau\nu$, $b \to s\,\mu^+\mu^-$, $(g-2)_{\mu,e}$, $\tau^\pm \to \pi^\pm K_S \nu$, $a_{\rm CP}^{D^0\to\pi\pi}$, V_{ub} , V_{ud} , $\cdots$

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





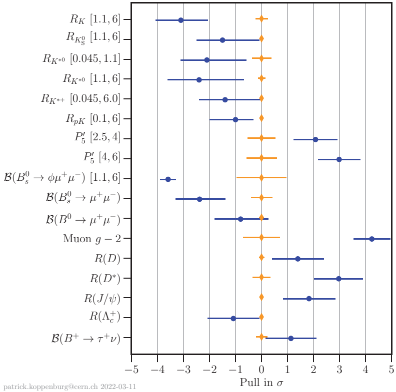


- Evidence for New Physics
- Statistical fluctuation
- Underestimated systematics
- Incorrect SM prediction or measurement

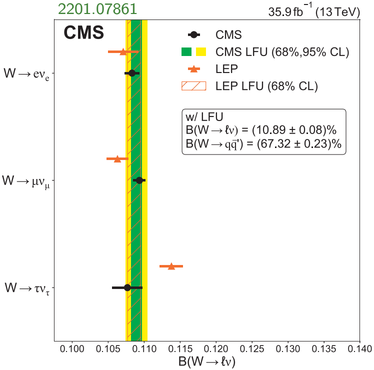
?

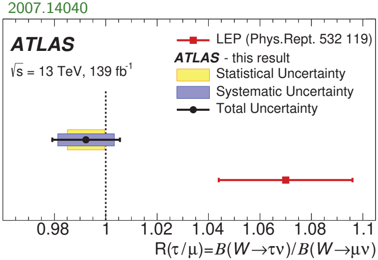
Not easy common explanation

(within appealing BSM models)



Lepton Flavour Universality in W Decays



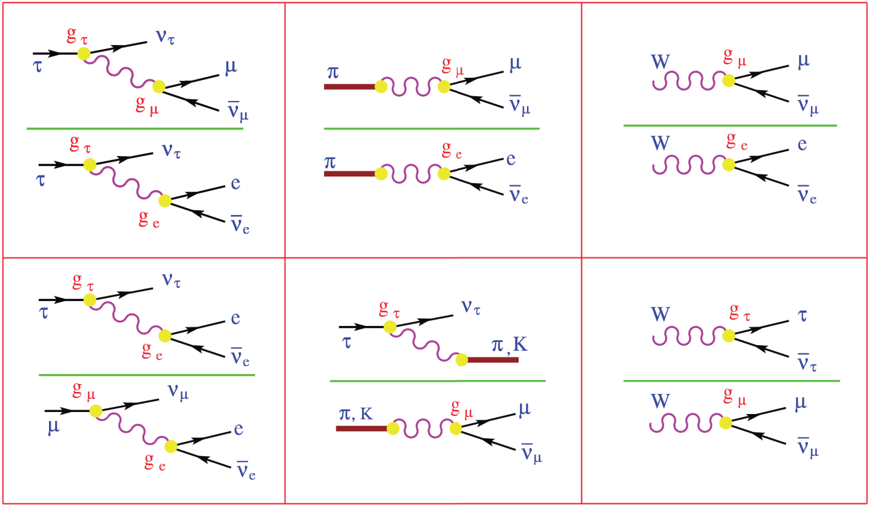


	CMS	LEP	ATLAS	LHCb	CDF	D0
$R_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$R_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	—	—	—	—
$R_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	—	—	—
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	—	—	—	—

LEPTON UNIVERSALITY

$\frac{g_\mu}{g_e}$

$\frac{g_\tau}{g_\mu}$



CHARGED CURRENT UNIVERSALITY

A. Pich, arXiv:2012.07099
(updated)

$|g_\mu / g_e|$

$B_{\tau\to\mu} / B_{\tau\to e}$	1.0017 ± 0.0016
$B_{\pi\to\mu} / B_{\pi\to e}$	1.0010 ± 0.0009
$B_{K\to\mu} / B_{K\to e}$	0.9978 ± 0.0018
$B_{K\to\pi\mu} / B_{K\to\pi e}$	1.0010 ± 0.0025
$B_{W\to\mu} / B_{W\to e}$	1.001 ± 0.003

$|g_\tau / g_\mu|$

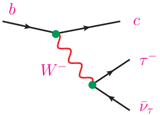
$B_{\tau\to e} \; \tau_\mu / \tau_\tau$	1.0011 ± 0.0014
$\Gamma_{\tau\to\pi} / \Gamma_{\pi\to\mu}$	0.9964 ± 0.0038
$\Gamma_{\tau\to K} / \Gamma_{K\to\mu}$	0.986 ± 0.008
$B_{W\to\tau} / B_{W\to\mu}$	1.001 ± 0.010

$|g_\tau / g_e|$

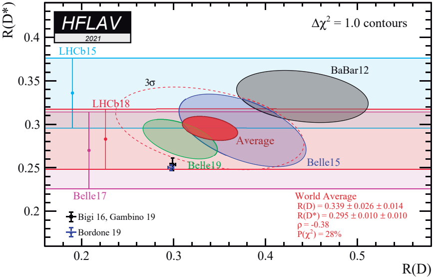
$B_{\tau\to\mu} \; \tau_\mu / \tau_\tau$	1.0028 ± 0.0015
$B_{W\to\tau} / B_{W\to e}$	1.008 ± 0.012

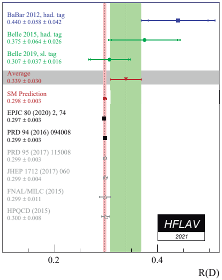
$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)} \ell^- \bar{\nu}_\ell)}$$

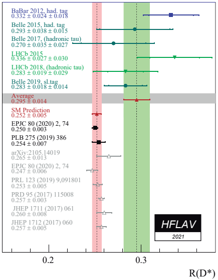
Tree-level process



3.4 σ discrepancy







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) $\mathcal{R}^{\mathrm{SM}}_{J/\psi} \approx 0.26 - 0.28$

LHCb, 2201.03497: $\mathcal{R}_{\Lambda_b^0 \to \Lambda_c^+} = 0.242 \pm 0.026 \pm 0.040 \pm 0.059$ $\mathcal{R}^{\mathrm{SM}}_{\Lambda_b^0 \to \Lambda_c^+} \approx 0.324 \pm 0.004$

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

Possible Caveats / Constraints:

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

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

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

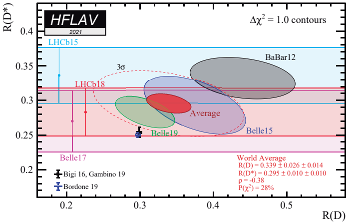
  $\mathcal{B}(B \to X_c\ell\nu) = (10.65 \pm 0.16)\%$ ➡ $\mathcal{B}(B \to X_c\tau\nu) = (2.36 \pm 0.08)\%$

- 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:

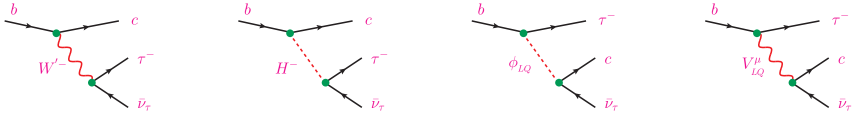


Effective Field Theory

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

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

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



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-Penũelas-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, $\tilde{R}_2$: $\mathcal{O}^S_{RR}$, $\mathcal{O}^T_{RR}$

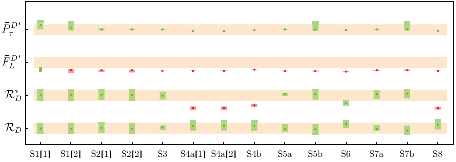
Sc 7, S_1: $\mathcal{O}^V_{RR}$, $\mathcal{O}^S_{RR}$, $\mathcal{O}^T_{RR}$ [b: + $\mathcal{O}^V_{LL}$, $\mathcal{O}^S_{LL}$, $\mathcal{O}^T_{LL}$]

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$_{SM}$			Pull$_{SM}$	p-value
			$\bar{\mathcal{P}}_\tau^{D^*}$, $F_L^{D^*}$	$\mathcal{R}_{D,D^*}$	$d\Gamma/dq^2$		
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%

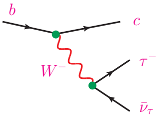
- $F_L^{D^*}$ difficult to fit at 1σ

  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

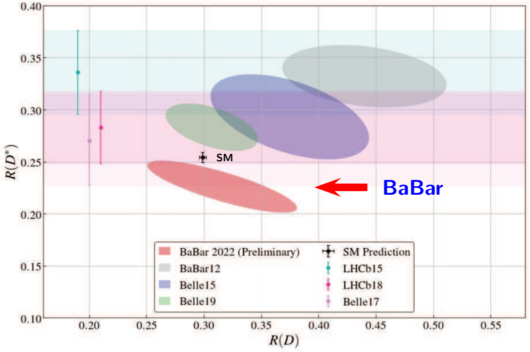


$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)}$$

Tree-level process



New (non official) analysis of BaBar data:

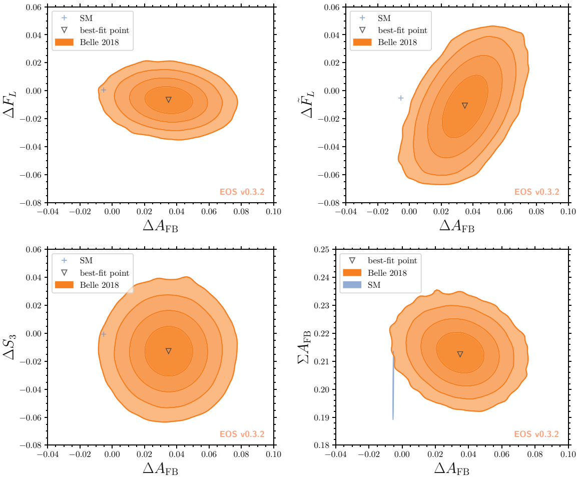


BaBar

Yunxuan Li
Ph.D. thesis
Caltech, May 2022

Advisors: D.G. Hitlin, F.C. Porter

$e-\mu$ anomaly in $B \to D^*\ell\nu$ Belle data (1809.03290)



Bobeth et al, 2104.02094

4σ discrepancy in $\Delta A_{\rm FB}$

$$\Delta O \equiv O^{\mu} - O^{e}$$

$$\frac{d\widehat{\Gamma}^{(\ell)}}{dw} \equiv \frac{1}{2}\frac{d(\Gamma^{(\ell)}+\bar{\Gamma}^{(\ell)})}{dw}\,,$$

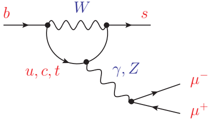
$$\frac{1}{\widehat{\Gamma}^{(\ell)}}\frac{d\widehat{\Gamma}^{(\ell)}}{d\cos\theta_\ell} = \frac{1}{2} + \langle A_{\rm FB}^{(\ell)}\rangle\cos\theta_\ell + \frac{1}{4}\left(1-3\,\langle\widetilde{F}_L^{(\ell)}\rangle\right)\frac{3\cos^2\theta_\ell - 1}{2}\,,$$

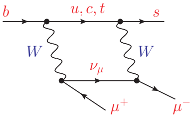
$$\frac{1}{\widehat{\Gamma}^{(\ell)}}\frac{d\widehat{\Gamma}^{(\ell)}}{d\cos\theta_D} = \frac{3}{4}\left(1-\langle F_L^{(\ell)}\rangle\right)\sin^2\theta_D + \frac{3}{2}\,\langle F_L^{(\ell)}\rangle\cos^2\theta_D\,,$$

$$\frac{1}{\widehat{\Gamma}^{(\ell)}}\frac{d\widehat{\Gamma}^{(\ell)}}{d\chi} = \frac{1}{2\pi} + \frac{2}{3\pi}\,\langle S_3^{(\ell)}\rangle\cos 2\chi + \frac{2}{3\pi}\,\langle S_9^{(\ell)}\rangle\sin 2\chi\,,$$

Some inconsistencies identified in the data

$B^0_{s,d} \to \mu^+\mu^-$

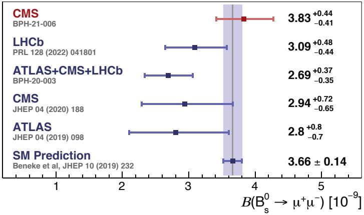


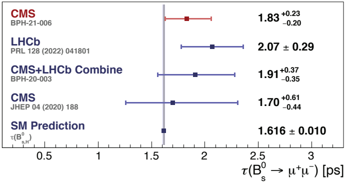


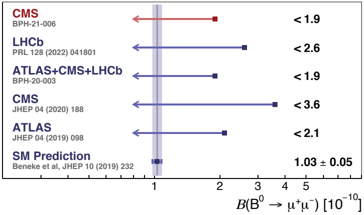
SM loop process

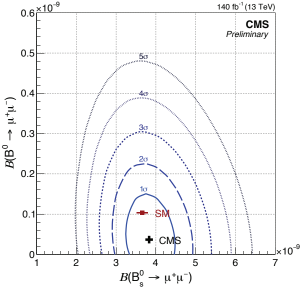
Sensitive to (pseudo) scalar contributions: $W^\pm \leftrightarrow H^\pm$, $Z \leftrightarrow H^0, A^0$

D. Kovalskyi, ICHEP 2022

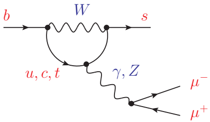


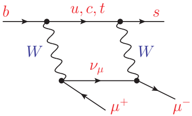






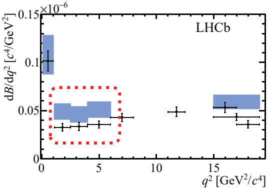
$b \to s\,\mu^+\mu^-$



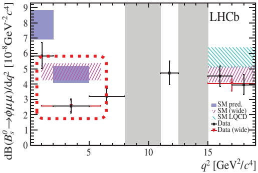


SM loop process

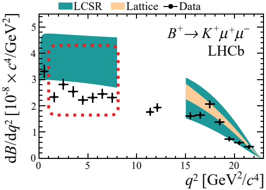
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



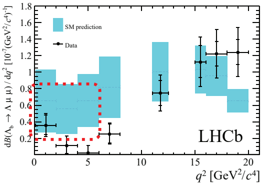
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



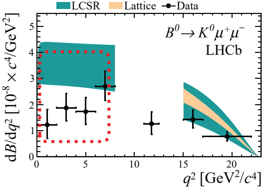
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



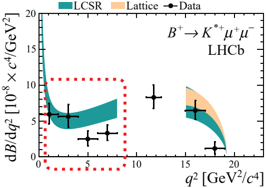
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



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)**

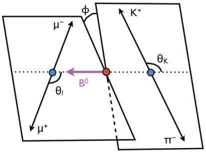
Large hadronic uncertainties

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

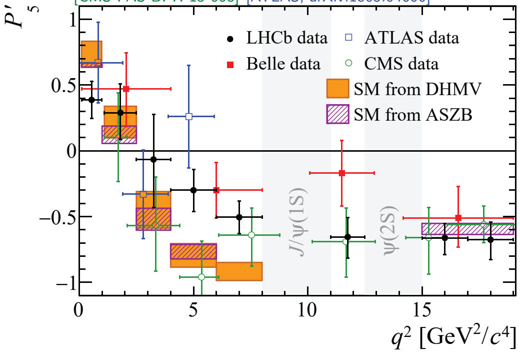
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\,\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos 2\theta_\ell + S_3\sin^2\theta_K\sin^2\theta_\ell\cos 2\phi + S_4\sin 2\theta_K\sin 2\theta_\ell\cos\phi$$
$$+ S_5\sin 2\theta_K\sin\theta_\ell\cos\phi + S_6\sin^2\theta_K\cos\theta_\ell + S_7\sin 2\theta_K\sin\theta_\ell\sin\phi$$
$$+ S_8\sin 2\theta_K\sin 2\theta_\ell\sin\phi + S_9\sin^2\theta_K\sin^2\theta_\ell\sin 2\phi\Big]$$

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

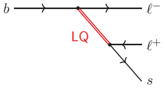
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$



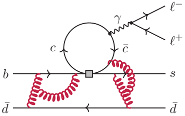
[LHCb, JHEP 02 (2016) 104] [Belle, PRL 118 (2017) 111801]
[CMS-PAS-BPH-15-008] [ATLAS, arXiv:1805.04000]



C. Langenbruch, LHC implications 2018



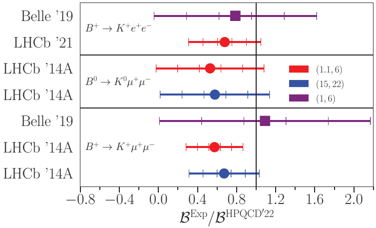
NP or SM $c\bar{c}$-loop?

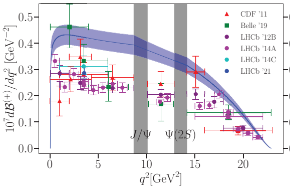


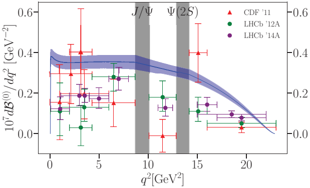
Discrepancy confirmed in recent lattice analyses

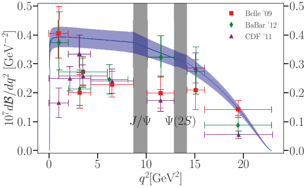
$B \to K \ell^+ \ell^-$

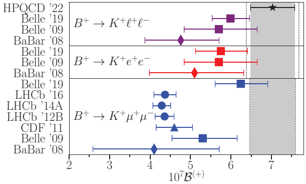
HPQCD 2207.13371

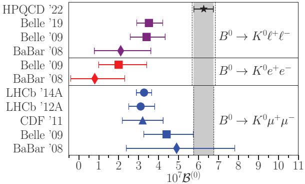


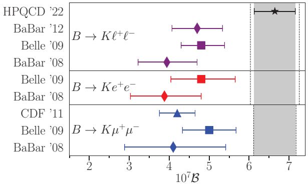




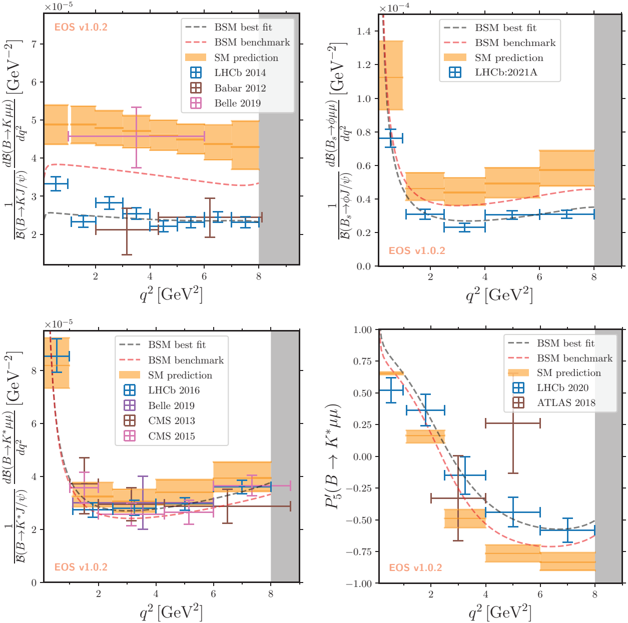








Inclusion of non-local (long-distance) contributions



Gubernari-Reboud-van Dyk-Virto

2206.03797

Increased errors
but
anomaly remains

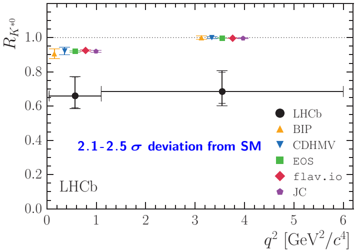
Violations of Lepton Flavour Universality

$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B\to H\,\mu^+\mu^-)}{dq^2}\, dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B\to H\,e^+e^-)}{dq^2}\, dq^2} \overset{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

QED corrections

LHCb 1705.05802

$R_{K^{*0}}$

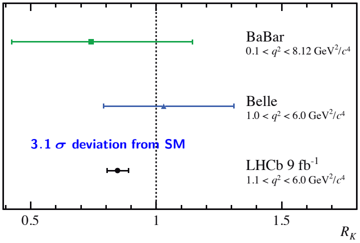


2.1-2.5 σ deviation from SM

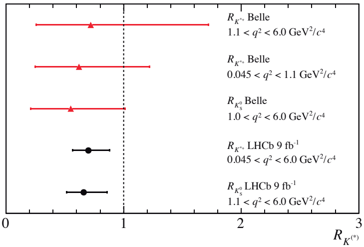
LHCb 2103.11769

R_{K^+,K^0_S}

R_{K^+}



3.1 σ deviation from SM



D. Lancierini, Moriond 2022

$R_{K^{*+}}$, $R_{K^0_S}$

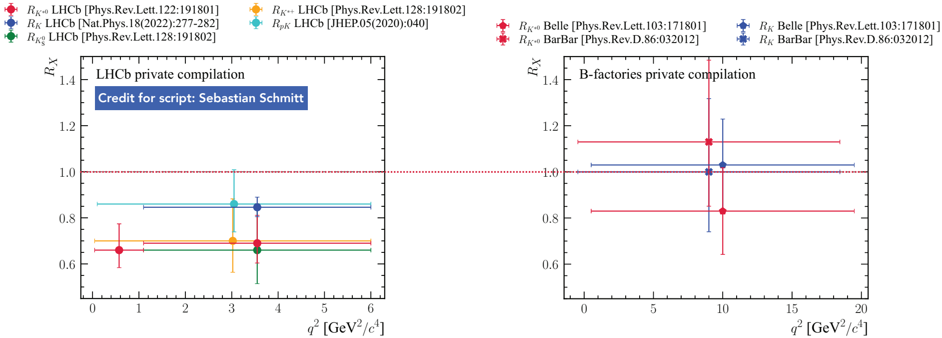
1.5-1.6 σ deviation from SM

Violations of Lepton Flavour Universality

$$R_H \equiv \frac{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B\to H\,\mu^+\mu^-)}{dq^2}\,dq^2}{\int_{q^2_{\min}}^{q^2_{\max}} \frac{d\Gamma(B\to H\,e^+e^-)}{dq^2}\,dq^2} \stackrel{\text{SM}}{=} 1 \pm \mathcal{O}(10^{-2})$$

QED corrections

V. Gligorov, ICHEP 2022



Precision dominated by LHCb, Belle 2 will be able to independently verify with ~10ab^{-1}.
Will be interesting to see the eventual impact of the parked CMS dataset.

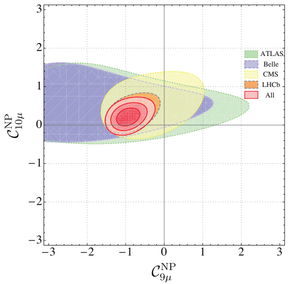
Global 2D Fits: $C_{9,\mu}^{\rm NP} \sim -0.2\; C_{9,\mu}^{\rm SM}$

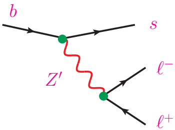
$$\mathcal{H}_{\rm eff}^{b\to s\ell\ell} = -\frac{4G_F}{\sqrt{2}}\, V_{tb} V_{ts}^* \,\frac{\alpha}{4\pi}\, \sum_i C_i\, O_i + \text{h.c.}$$

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

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

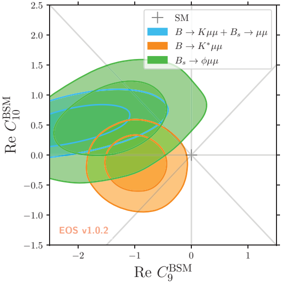
Algueró et al 1903.09578





5.7 σ pull

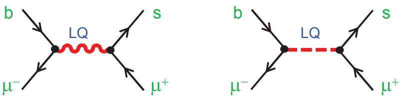
Gubernari et al 2206.03797



- $B_s^0 \to \mu^+\mu^-$ strongly constrains pseudoscalar operators and bounds $C_{10,\mu}^{\rm NP}$
- Preferred solutions: $C_{9,\mu}^{\rm NP} \neq 0$ or $C_{9,\mu}^{\rm NP} \approx -C_{10,\mu}^{\rm NP} \neq 0$
- Additional solutions with LFU components (Algueró et al, 1809.08447)
- SMEFT: $b\to c\tau\nu$ and $b \to s\ell\ell$ anomalies ➡ Large $b\to s\tau\tau$

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

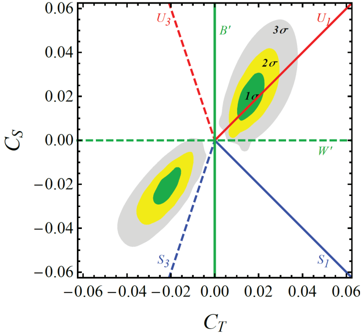
Leptoquark Solutions



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

$U(2)_q \otimes U(2)_\ell$ 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
- …