Flavour Anomalies

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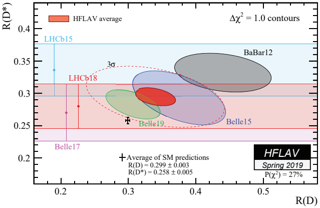
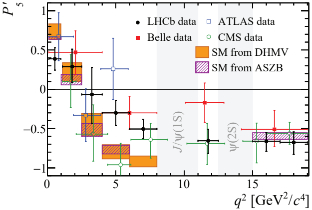
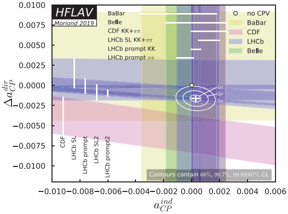




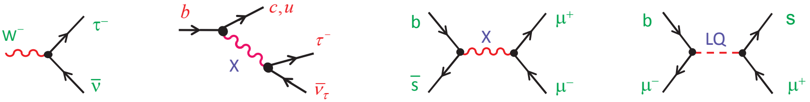


Wien on-line seminar, 12 January 2021

Many Interesting Flavour Anomalies

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

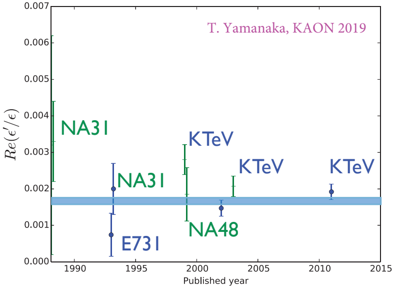
CP Violation in $K \to \pi\pi$

$$\eta_{00} \equiv \frac{\mathcal{M}(K_L^0 \to \pi^0\pi^0)}{\mathcal{M}(K_S^0 \to \pi^0\pi^0)} \equiv \varepsilon - 2\varepsilon' \qquad , \qquad \eta_{+-} \equiv \frac{\mathcal{M}(K_L^0 \to \pi^+\pi^-)}{\mathcal{M}(K_S^0 \to \pi^+\pi^-)} \equiv \varepsilon + \varepsilon'$$

- **Indirect $\not{C}\not{P}$:** $\quad |\varepsilon| = \frac{1}{3}\,|\eta_{00} + 2\,\eta_{+-}| = (2.228 \pm 0.011) \cdot 10^{-3}$
- **Direct $\not{C}\not{P}$:** $\quad \mathrm{Re}(\varepsilon'/\varepsilon) = \frac{1}{3}\left(1 - \left|\frac{\eta_{00}}{\eta_{+-}}\right|\right) = (16.6 \pm 2.3) \cdot 10^{-4}$

First evidence in 1988 by NA31

Time evolution of ε'/ε measurements



Time evolution of ε'/ε predictions: 10^{-3} units

- 1983	SD (Q_6), LO	~ 2	Gilman-Hagelin
- 1990-2000	SD, large m_t (Q_8), NLO	$\sim \mathrm{few} \cdot 10^{-1}$	Munich, Rome
	+ models of LD contributions	$\sim \mathcal{O}(1)$	Dortmund, Trieste
- 1999-2001	SD + LD (χPT) at NLO	1.7 ± 0.9	Scimemi-Pallante-Pich
- 2000-2003	models of LD contributions	$\sim \mathcal{O}(1)$	Lund, Marseille
- 2003	NLO isospin breaking in χPT	1.9 ± 1.0	Cirigliano-Ecker-Neufeld-Pich
- 2015	Lattice	0.14 ± 0.70	RBC-UKQCD
- 2015-2017	Dual QCD, Lattice input	0.19 ± 0.45	Munich
- 2017	NLO χPT re-analysis	1.5 ± 0.7	Gisbert-Pich
- 2019	χPT re-analysis of NLO IB	1.4 ± 0.5	Cirigliano-Gisbert-Pich-Rodríguez
- 2020 (April)	Lattice re-analysis (no IB)	2.17 ± 0.84	RBC-UKQCD
- 2020 (May)	Lattice input + χPT IB	1.74 ± 0.61	Munich
	Lattice input + naive IB	1.39 ± 0.52	

Empirical Evidence

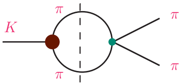
$$A[K^0 \to \pi^+\pi^-] = A_0\, e^{i\delta_0} + \frac{1}{\sqrt{2}} A_2\, e^{i\delta_2} \equiv \mathcal{A}_{1/2} + \frac{1}{\sqrt{2}} \mathcal{A}_{3/2}$$

$$A[K^0 \to \pi^0\pi^0] = A_0\, e^{i\delta_0} - \sqrt{2}\, A_2\, e^{i\delta_2} \equiv \mathcal{A}_{1/2} - \sqrt{2}\, \mathcal{A}_{3/2}$$

$$A[K^+ \to \pi^+\pi^0] = \frac{3}{2} A_2\, e^{i\delta_2} \equiv \frac{3}{2} \mathcal{A}_{3/2}$$

1. **$\Delta I = 1/2$ Rule:** $\omega \equiv \mathrm{Re}(A_2)/\mathrm{Re}(A_0) \approx 1/22$
2. **Strong Final-State Interactions:** $\delta_0 - \delta_2 \approx 45°$

- **Unitarity:** $\delta_0 = (39.2 \pm 1.5)°$ ➔ $A_0 \approx 1.3 \times \mathrm{Dis}(\mathcal{A}_0)$



$$A_I = \mathrm{Dis}(\mathcal{A}_I)\, \sqrt{1 + \tan^2\delta_I} \qquad \tan\delta_I = \frac{\mathrm{Abs}(\mathcal{A}_I)}{\mathrm{Dis}(\mathcal{A}_I)}$$

- **Analyticity:** $\Delta\, \mathrm{Dis}(\mathcal{A}_I)[s] = \frac{1}{\pi} \int dt\, \frac{\mathrm{Abs}(\mathcal{A}_I)[t]}{t - s - i\epsilon} + \text{subtractions}$

Large δ_0 ➔ Large $\mathrm{Abs}(\mathcal{A}_0)$ ➔ Large correction to $\mathrm{Dis}(\mathcal{A}_0)$

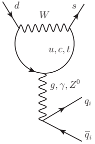
Claims of an ε'/ε anomaly originate in incorrect treatments of the $\pi\pi$ cut

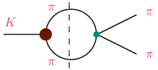
SM Prediction of ε'/ε

Cirigliano, Gisbert, Pich, Rodríguez-Sánchez, 1911.01359

Effective Field Theory

M_W	W, Z, γ, g; τ, μ, e, ν_i; t, b, c, s, d, u	Standard Model
	↓ OPE	
$\lesssim m_c$	γ, g ; μ, e, ν_i; s, d, u	$\mathcal{L}_{\rm QCD}^{(n_f=3)}$, $\mathcal{L}_{\rm eff}^{\Delta S=1,2}$
	↓ $N_C \to \infty$	
M_K	γ ; μ, e, ν_i; π, K, η	χPT





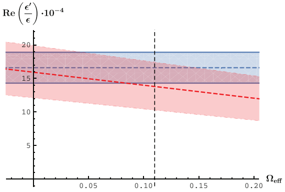
$$\mathcal{L}_{\rm eff}^{\Delta S=1} \sim \sum_i C_i(\mu) Q_i(\mu)$$

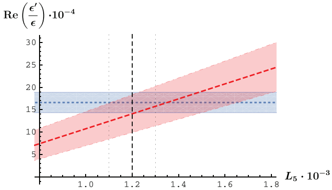
Large logarithms:

OPE: $\alpha_s^k(\mu)\log^n(M_W/\mu)$

χPT: $\log(\mu/m_\pi)$

$$\text{Re}\,(\varepsilon'/\varepsilon)_{\rm SM} \;=\; (14 \pm 5)\cdot 10^{-4}$$

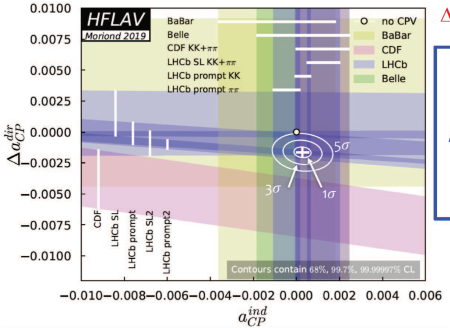




$$\text{Re}\,(\varepsilon'/\varepsilon)_{\rm SM} \;=\; \left(13.8\,^{+0.5}_{-0.4}\,{}_{m_s}\;^{+1.7}_{-1.3}\,{}_{\mu}\;^{+3.1}_{-3.2}\,{}_{\nu_\chi} \pm 1.3_{\gamma_5} \pm 2.1_{L_{5,8}} \pm 1.3_{L_7} \pm 0.2_{K_i} \pm 0.3_{X_i}\right)\cdot 10^{-4}$$

First evidence of $\not{C}\not{P}$ in charm decays $(5.3\,\sigma)$

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



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

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: $5{\times}10^{-8}$

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

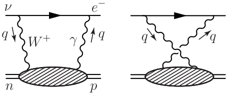
Large uncertainty in SM prediction:

- 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

V_{ud}: Superallowed $(0^+ \to 0^+)$ nuclear β transitions

$f_+(0) = 1 + \mathcal{O}[(m_u - m_d)^2]$ $\longrightarrow$ $$|V_{ud}|^2 = \frac{\pi^3 \log 2}{ft\, G_F^2 m_e^5 (1+\delta_{\mathrm{RC}})} = \frac{(2984.48 \pm 0.05)\ \mathrm{s}}{ft\,(1+\delta_{\mathrm{RC}})}$$

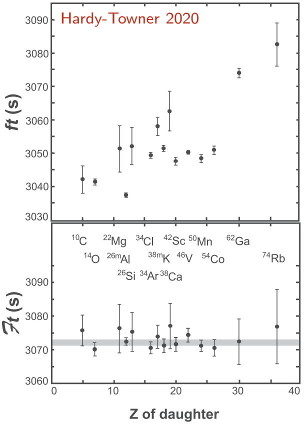
$$\delta_{\mathrm{RC}} = \Delta_R^V + \Delta_{\mathrm{Nucl}} \quad , \quad \mathcal{F}t = ft\,(1+\Delta_{\mathrm{Nucl}})$$



Nucleus-independent radiative corrections

$$\Delta_R^V = \begin{cases} 0.02361\ (38) & \text{Marciano-Sirlin 2006} \\ 0.02467\ (22) & \text{Seng et al, 1807.10197} \\ 0.02426\ (32) & \text{Czarnecki et al, 1907.06737} \end{cases}$$

$\longrightarrow$ $$|V_{ud}| = \begin{cases} 0.97420\ (21) & \text{PDG 2018} \\ 0.97370\ (14) & \text{PDG 2020} \\ 0.97373\ (31) & \text{Hardy-Towner 2020} \end{cases}$$



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

PDG 2020 $\longrightarrow$

$$1 - \sum_i |V_{ui}|^2 = \begin{cases} 0.00212\ (41) & 5.1\,\sigma \\ 0.00149\ (45) & 3.3\,\sigma \end{cases}$$

V_{ud}: Superallowed $(0^+ \to 0^+)$ nuclear β transitions

$f_+(0) = 1 + \mathcal{O}[(m_u - m_d)^2]$ ➡ $$|V_{ud}|^2 = \frac{\pi^3 \log 2}{ft\, G_F^2 m_e^5 (1+\delta_{\rm RC})} = \frac{(2984.48 \pm 0.05)\ {\rm s}}{ft\,(1+\delta_{\rm RC})}$$

$$\delta_{\rm RC} = \Delta_R^V + \Delta_{\rm Nucl} \quad , \quad \mathcal{F}t = ft\,(1+\Delta_{\rm Nucl}) \quad , \quad \Delta_{\rm Nucl} = \delta_R' + \delta_{\rm NS} - \delta_C$$

Hardy-Towner 2020:

$$\Delta_R^V = 0.02454\ (19)$$

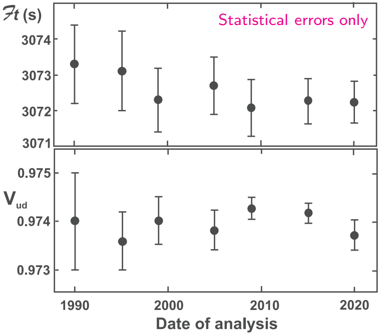
$$\mathcal{F}t = (3072.24 \pm 0.57_{\rm stat} \pm 0.36_{\delta_R'} \pm 1.73_{\delta_{\rm NS}})\ {\rm s}$$
$$= (3072.24 \pm 1.85)\ {\rm s}$$

$\mathcal{F}t$ error 2.6 larger than in 2015 ($\delta_{\rm NS}$)

Seng et al, Gorchtein

⬇

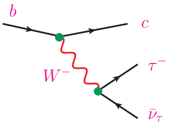
$$|V_{ud}| = 0.97373\ (31)$$



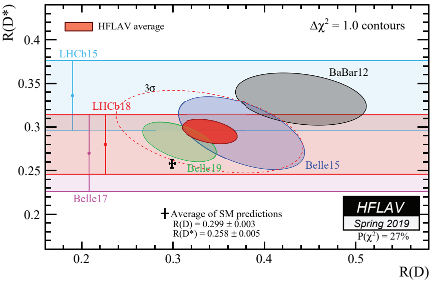
➡ $$1 - \sum_i |V_{ui}|^2 = \begin{cases} 0.00206\ (68)_{K\to\pi\ell\nu} & 3.0\,\sigma \\ 0.00144\ (70)_{K\to\ell\nu,\pi\ell\nu} & 2.0\,\sigma \end{cases}$$

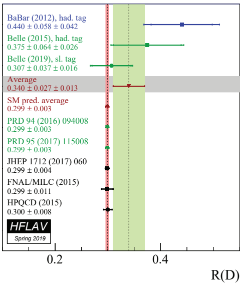
$$\mathcal{R}_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)} \tau^- \bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)} \ell^- \bar{\nu}_\ell)}$$

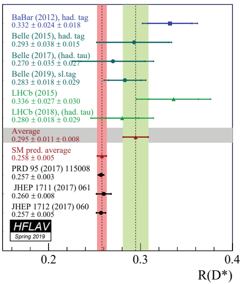
Tree-level process



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

Possible Caveats / Constraints:

1 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**

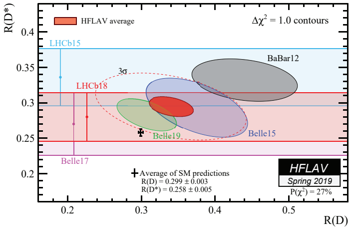
  $\mathcal{B}(B \to X_c\ell\nu) = (10.65 \pm 0.16)\%$ ➔ $\mathcal{B}(B \to X_c\tau\nu) = (2.36 \pm 0.08)\%$

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

2 $b \to c\tau\nu$ ⟷ $b\bar{c} \to \tau\nu$**:** $\mathcal{B}(B_c \to \tau\nu) < 10\%$ (30%) Akeroyd-Chen Alonso et al, Celis et al

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

4 Time evolution of data:

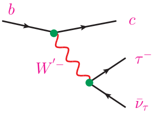


Effective Field Theory

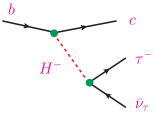
$C^X_{AB}\big|^{\rm SM} = 0$

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

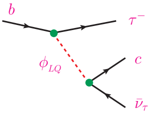
$$\mathcal{O}^V_{AB} = (\bar c\, \gamma^\mu \mathcal{P}_A b)\,(\bar\tau \gamma_\mu \mathcal{P}_B \nu)\,, \qquad \mathcal{O}^S_{AB} = (\bar c\, \mathcal{P}_A b)\,(\bar\tau \mathcal{P}_B \nu)\,, \qquad \mathcal{O}^T_{AB} = \delta_{AB}\; (\bar c\, \sigma^{\mu\nu} \mathcal{P}_A b)\,(\bar\tau \sigma_{\mu\nu}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



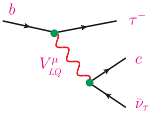
C^V_{LL}



$C^S_{LL},\; C^S_{RL} \quad (C^T_{LL})$



$C^V_{LL},\; C^S_{LL},\; C^T_{LL}$



$C^V_{LL},\; C^S_{RL}$

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

- $C^X_{AB} \neq 0$ for 3rd fermion generation only
- EWSB linearly realized ➔ $C^V_{RL} = 0$
- 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** $(\chi^2_{\rm SM} - \chi^2 = 31.4)$
- **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^μ_1: $\mathcal{O}^V_{RR}$, $\mathcal{O}^S_{LR}$ [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, $\tilde{V}^\mu_2$: $\mathcal{O}^S_{LR}$

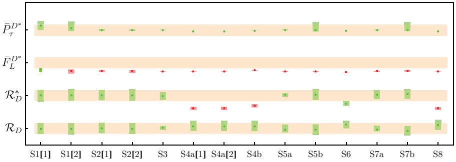
Scenario	$\mathcal{B}(B_c \to \tau\bar{\nu})$	χ^2/d.o.f	Pull$_{SM}$ $\bar{\mathcal{P}}^{D^*}_\tau$, $F^{D^*}_L$	Pull$_{SM}$ $\mathcal{R}_{D,D^*}$	Pull$_{SM}$ $d\Gamma/dq^2$	Pull$_{SM}$	p-value
SM	2.16%	52.87/59					69.95%
Scenario 1, Min 1	< 10%	37.26/53	0.007	2.08	0.0414	2.4	95.02%
Scenario 1, Min 2	< 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%

- $F^{D^*}_L$ difficult to fit at 1σ

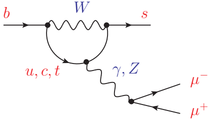
  Only possible in Sc 1 and 4b (< 30%)

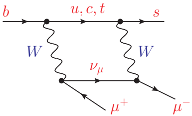
- Scalar solution ➡ larger $\mathrm{Br}(B_c \to \tau\bar{\nu})$

- Higher pulls: V^μ, S_1, U^μ_1



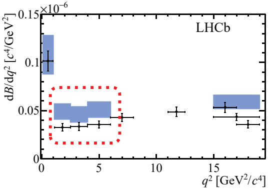
$b \to s\,\mu^+\mu^-$



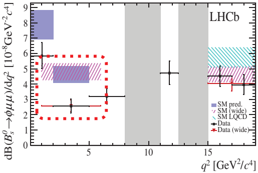


SM loop process

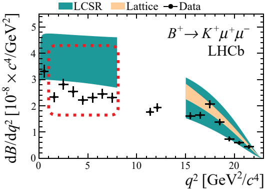
LHCb $B^0 \to K^{*0}\mu^+\mu^-$ [JHEP 11 (2016) 047]



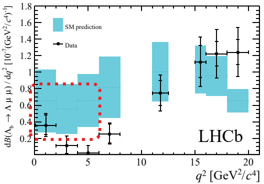
LHCb $B_s^0 \to \phi\mu^+\mu^-$ [JHEP 09 (2015) 179]



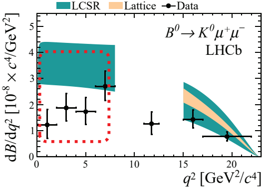
LHCb $B^+ \to K^+\mu^+\mu^-$ [JHEP 06 (2014) 133]



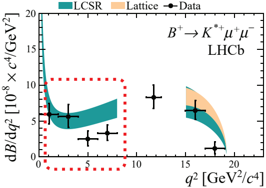
$\Lambda_b^0 \to \Lambda\mu^+\mu^-$ [JHEP 06 (2015) 115]



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)**

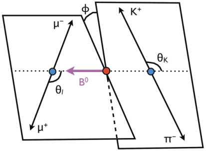
Large hadronic uncertainties

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

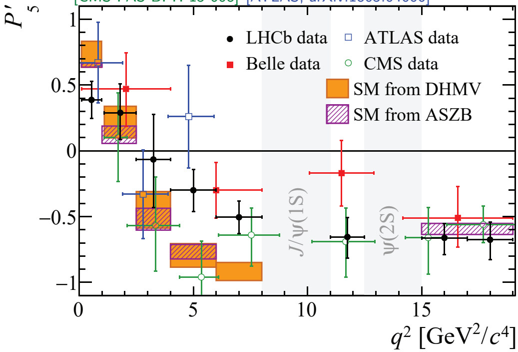
$$\frac{1}{\mathrm{d}\Gamma/\mathrm{d}q^2}\,\frac{\mathrm{d}^4\Gamma}{\mathrm{d}\cos\theta_\ell\,\mathrm{d}\cos\theta_K\,\mathrm{d}\phi\,\mathrm{d}q^2} = \frac{9}{32\pi}\Big[\frac{3}{4}(1-F_L)\sin^2\theta_K + F_L\cos^2\theta_K + \frac{1}{4}(1-F_L)\sin^2\theta_K\cos 2\theta_\ell$$
$$- F_L\cos^2\theta_K\cos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

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

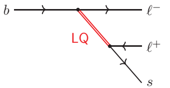
$$P'_{i=4,5,6,8} = \frac{S_{j=4,5,7,8}}{\sqrt{F_L(1-F_L)}}$$



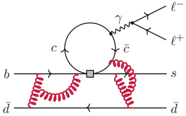
[LHCb, JHEP 02 (2016) 104] [Belle, PRL 118 (2017) 111801]
[CMS-PAS-BPH-15-008] [ATLAS, arXiv:1805.04000]



C. Langenbruch, LHC implications 2018



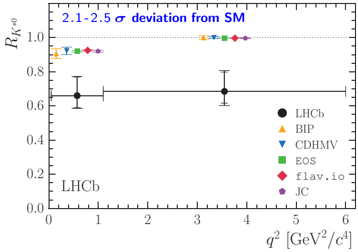
NP or SM $c\bar{c}$-loop?



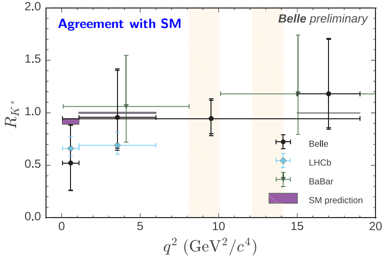
Violations of Lepton Flavour Universality

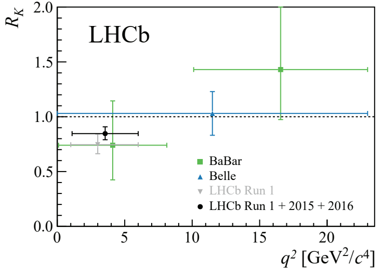
$$\frac{\Gamma(B \to K^* \mu^+ \mu^-)}{\Gamma(B \to K^* e^+ e^-)}$$

LHCb 1705.05802



Belle 1904.02440





LHCb, 1903.09252 $\qquad q^2 \in [1.1, 6.0]\ \text{GeV}^2$

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

2.5 σ below the SM

Not confirmed/refuted by Belle 1908.01848

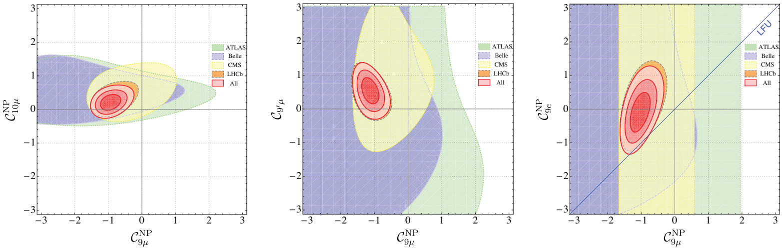
$$R_K = \begin{cases} 1.03\,^{+0.28}_{-0.24} \pm 0.01 & q^2 \in [1, 6]\ \text{GeV}^2 \\ 1.10\,^{+0.16}_{-0.15} \pm 0.02 & \forall q^2 \end{cases}$$

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

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

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

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

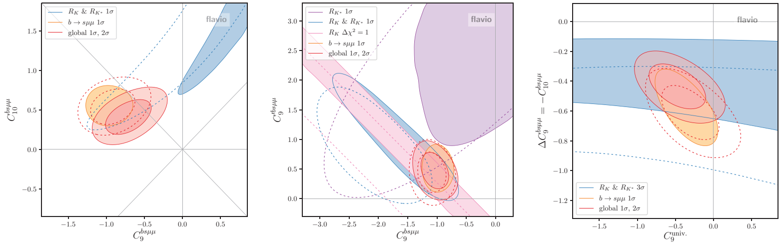


Algueró et al 1903.09578

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

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

(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)

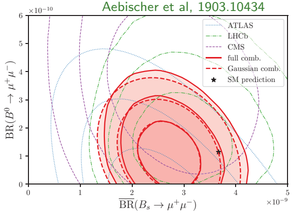
Global 2D Fits: $C^{\rm NP}_{9,\mu} \sim -0.2\; C^{\rm SM}_{9,\mu}$

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

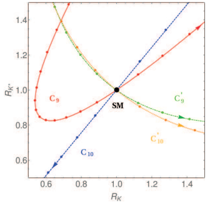
$$O_9 = (\bar s_L \gamma_\mu b_L)(\bar\ell\gamma^\mu \ell) \quad , \quad O_9' = (\bar s_R \gamma_\mu b_R)(\bar\ell\gamma^\mu \ell)$$

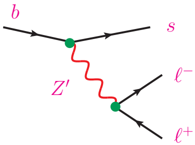
$$O_{10} = (\bar s_L \gamma_\mu b_L)(\bar\ell\gamma^\mu \gamma_5 \ell) \quad , \quad O_{10}' = (\bar s_R \gamma_\mu b_R)(\bar\ell\gamma^\mu \gamma_5 \ell)$$

Aebischer et al, 1903.10434



Geng et al, 1704.05446

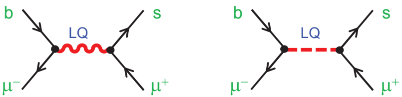




- $B_s^0 \to \mu^+\mu^-$ strongly constrains pseudoscalar operators and bounds $C^{\rm NP}_{10,\mu}$
- Preferred solutions: $C^{\rm NP}_{9,\mu} \neq 0$ or $C^{\rm NP}_{9,\mu} \approx -C^{\rm NP}_{10,\mu} \neq 0$
- Slight tension $(2\,\sigma)$ in current $B_s^0 \to \mu^+\mu^-$ world average favours $C^{\rm NP}_{9,\mu} - C^{\rm NP}_{10,\mu}$
- 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 $b\to s\tau\tau$

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

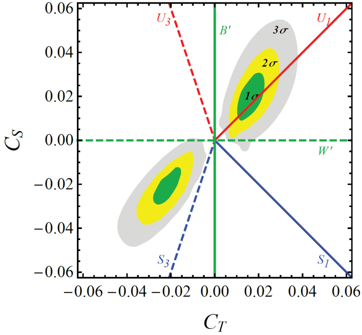
Leptoquark Solutions



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

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

Buttazzo et al, 1706.07808



Angelescu et al, 1808.08179

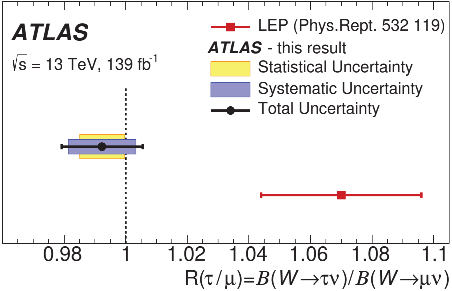
Model	$R_{D^{(*)}}$	$R_{K^{(*)}}$	$R_{D^{(*)}}$ & $R_{K^{(*)}}$
$S_1 = (\bar{3}, 1, 1/3)$	✓	✗*	✗*
$R_2 = (3, 2, 7/6)$	✓	✗*	✗
$S_3 = (\bar{3}, 3, 1/3)$	✗	✓	✗
$U_1 = (3, 1, 2/3)$	✓	✓	✓
$U_3 = (3, 3, 2/3)$	✗	✓	✗

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
- …

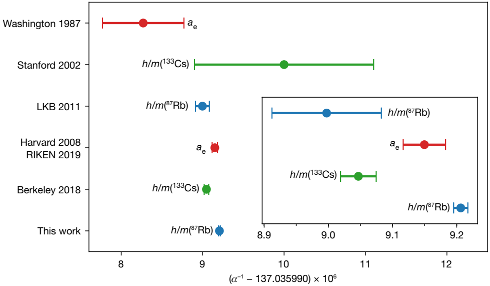
Lepton Flavour Universality in W Decays

2007.14040



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

Electron Anomalous Magnetic Moment



Morel et al, Nature 588 (2020) 61

New measurement of α

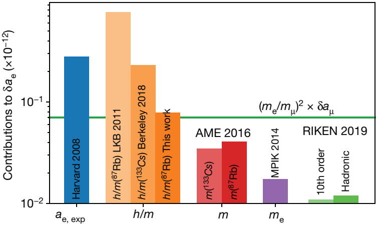
$\alpha^{-1}(\mathrm{Rb}) = 137.035\,999\,206\ (11)$

8.1×10^{-11} accuracy

$5.8\,\sigma$ discrepancy with Cs experiment

$$\Delta a_e \equiv a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}}$$

$$= \begin{cases} (-8.8 \pm 3.6) \cdot 10^{-13} & (\mathrm{Cs},\ -2.4\sigma) \\ (+4.8 \pm 3.0) \cdot 10^{-13} & (\mathrm{Rb},\ +1.6\sigma) \end{cases}$$



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

Anatomy of ε'/ε calculation

$$\mathrm{Re}\left(\frac{\varepsilon'}{\varepsilon}\right) = -\frac{\omega_+}{\sqrt{2}|\varepsilon|}\left\{\frac{\mathrm{Im}\, A_0^{(0)}}{\mathrm{Re}\, A_0^{(0)}}\,(1-\Omega_{\mathrm{eff}}) - \frac{\mathrm{Im}\, A_2^{\mathrm{emp}}}{\mathrm{Re}\, A_2^{(0)}}\right\}$$

$$\mathcal{A}_n^{(X)} = a_n^{(X)}\left[1 + \Delta_L\,\mathcal{A}_n^{(X)} + \Delta_C\,\mathcal{A}_n^{(X)}\right]$$

Cirigliano-Gisbert-Pich-Rodríguez 2019

❶ $O(p^4)$ χ**PT Loops: Large correction** (NLO in $1/N_C$) FSI

$$\Delta_L\,\mathcal{A}_{1/2}^{(8)} = 0.27 + 0.47\,i \quad ; \quad \Delta_L\,\mathcal{A}_{3/2}^{(g)} = -0.50 - 0.21\,i$$

❷ $O(p^4)$ **LECs fixed at $N_C \to \infty$: Small correction**

$$\Delta_C\,[\mathcal{A}_{1/2}^{(8)}]^- = 0.10 \pm 0.05 \quad ; \quad \Delta_C\,[\mathcal{A}_{3/2}^{(g)}]^- = -0.19 \pm 0.19$$

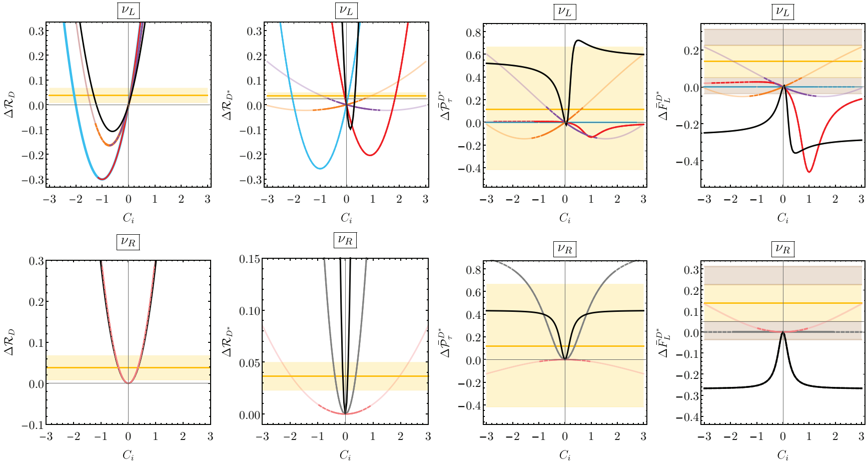
❸ **Isospin Breaking** $O\left[(m_u - m_d)\,p^2, e^2 p^2\right]$**: Sizeable correction**

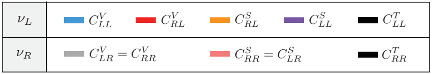
$$\Omega_{\mathrm{eff}} = 0.11 \pm 0.09$$

❹ **$\mathrm{Re}(g_8)$, $\mathrm{Re}(g_{27})$, $\chi_0 - \chi_2$ fitted to data**

Sensitivity to individual Wilson coefficients

Mandal-Murgui-Peñuelas-Pich, 2004.06726



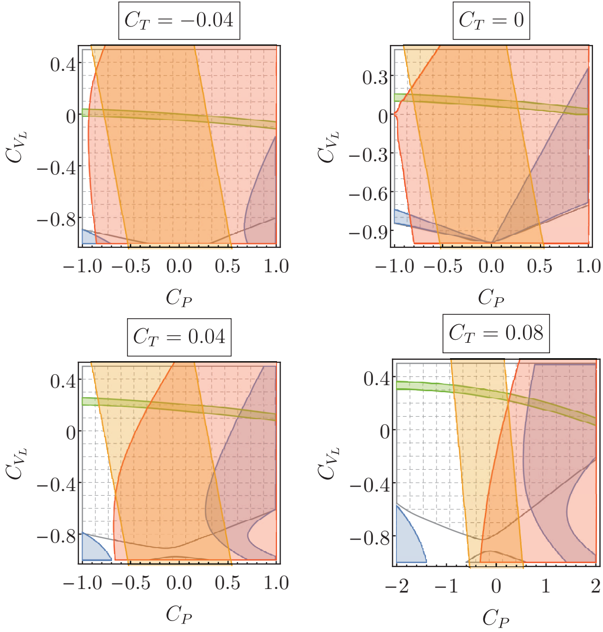


$F_L^{D^*}$ always below the exp. 1σ region

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

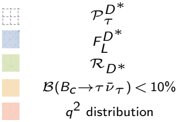
D^* Observables

Murgui-Peñuelas-Jung-Pich, 1904.09311



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

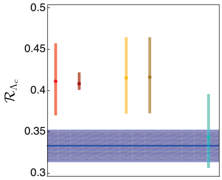
$C_P \equiv C_{S_R} - C_{S_L}$

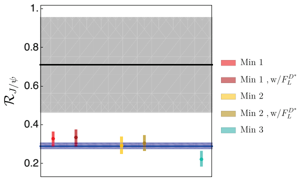


Predictions from global fit:

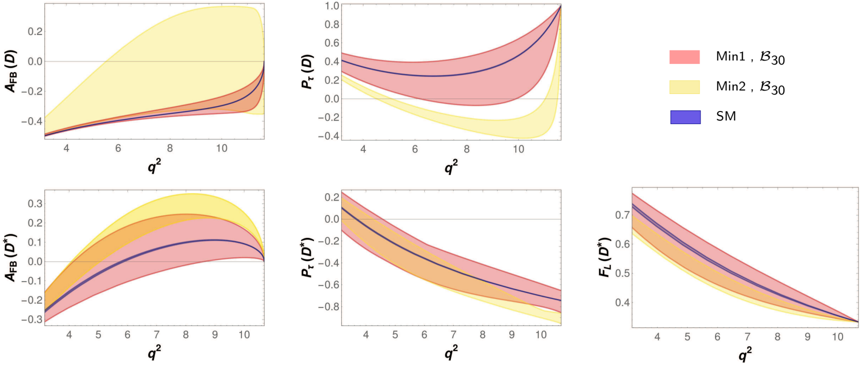
Murgui-Peñuelas-Jung-Pich, 1904.09311

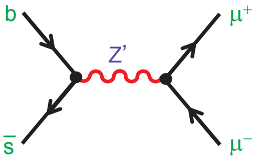
$$\frac{\mathcal{B}(\Lambda_b \to \Lambda_c \tau \bar{\nu}_\tau)}{\mathcal{B}(\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell)}$$





$$\frac{\mathcal{B}(B_c \to J\psi \tau \bar{\nu}_\tau)}{\mathcal{B}(B_c \to J\psi \ell \bar{\nu}_\ell)}$$



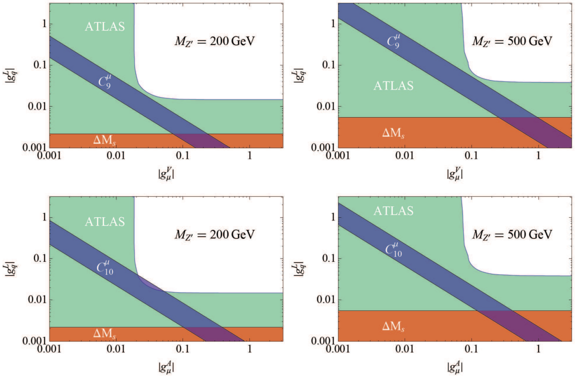


$$\mathcal{L} \supset \frac{g_2}{2c_W} Z'_\alpha \left\{ \left[\bar{s}\gamma^\alpha (g_L^Q P_L + g_R^Q P_R) b + h.c. \right] + \bar{\ell}\gamma^\alpha (g_V^\ell + \gamma_5 g_A^\ell)\ell \right\}$$

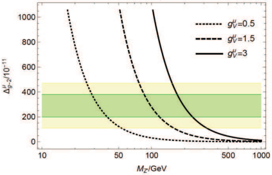
$$\Downarrow$$

$$\frac{e^2}{16\pi^2} V_{tb} V_{ts}^* \cdot \left\{ C_9^\ell,\, C_{10}^\ell \right\} = \frac{M_Z^2}{2m_{Z'}^2} \cdot \left\{ g_L^Q g_V^\ell,\, g_L^Q g_A^\ell \right\}$$

Di Chiara et al, 1704.06200



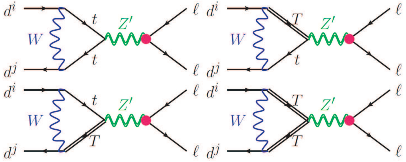
$(g-2)_\mu$



Many possibilities:

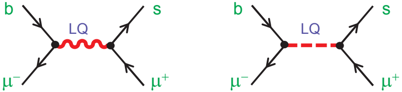
- L_μ-L_τ Altmannshofer et al, …
- Z’ + VLQ Kamenik et al
- Fermiophobic Falkowski et al
- Horizon. Sym. Guadagnoli et al
- … Faisel-Tandeam, …

More possibilities…



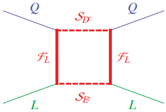
Flavour conserving Z'

Kamenik et al, 1704.06005



Leptoquarks

Hiller-Schmaltz, 1408.1627; Bauer et al, 1511.01900; Hiller- Nisandzic, 1704.05444; D'Amico et al, 1704.05438; Becirevic-Sumensari, 1704.05835; …



New Fermions and Scalars

D'Amico et al, 1704.05438; …

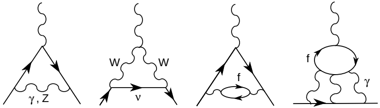
LFUV ➡ LFV

Glashow-Guadagnoli-Lane, 1411.0565

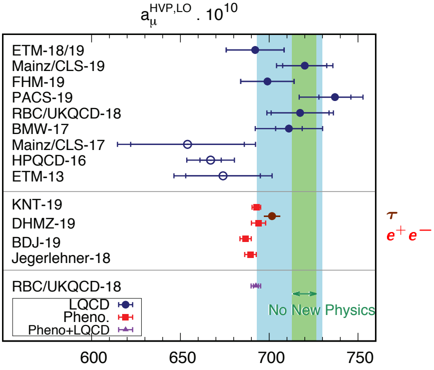
$$\mathcal{H}_{NP} = G\, \bar{b}'_L \gamma^\lambda b'_L\, \bar{\tau}'_L \gamma_\lambda \tau'_L \qquad b'_L = \sum_{i=1}^{3} U^d_{L3i}\, d_{Li}\,, \qquad \tau'_L = \sum_{i=1}^{3} U^\ell_{L3i}\, \ell_{Li}$$

$$\mathcal{B}(B^+ \to K^+ \mu^\pm e^\mp) \cong 2\rho^2_{NP} \left|\frac{U^\ell_{L31}}{U^\ell_{L32}}\right|^2 \mathcal{B}(B^+ \to K^+ \mu^+ \mu^-) = \left(2.16^{+2.54}_{-1.50}\right) \left|\frac{U^\ell_{L31}}{U^\ell_{L32}}\right|^2 \times 10^{-8}$$

μ Anomalous Magnetic Moment



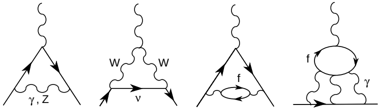
Aoyama et al, 2006.04822



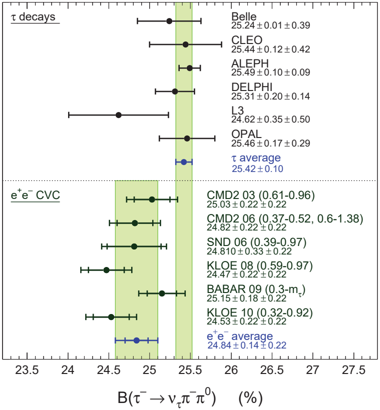
$$\Delta a_\mu \equiv a_\mu^{\rm exp} - a_\mu^{\rm SM} = (279 \pm 76) \cdot 10^{-11} \qquad (3.7\sigma)$$

New a_μ measurement eagerly expected

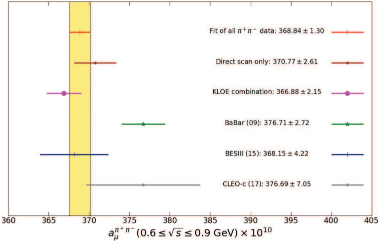
μ Anomalous Magnetic Moment



Davier et al, 0906.5443



Keshavarzi et al, 1911.00367



CP Asymmetry

$$A_\tau \equiv \frac{\Gamma\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) - \Gamma\left(\tau^- \to \pi^- K_S \nu_\tau\right)}{\Gamma\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) + \Gamma\left(\tau^- \to \pi^- K_S \nu_\tau\right)} = \left(-3.6 \pm 2.3 \pm 1.1\right)\cdot 10^{-3}$$

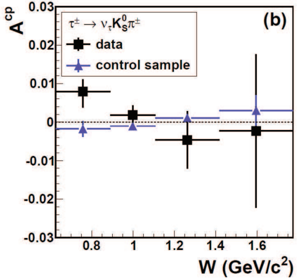
BaBar'11 $\left(\geq 0\, \pi^0\right)$

$$A_\tau^{SM}\left(\tau^+ \to \pi^+ K_S \bar{\nu}_\tau\right) = \left(3.6 \pm 0.1\right)\cdot 10^{-3}$$

Bigi-Sanda, Grossman-Nir

2.8 σ discrepancy

Belle does not see any asymmetry at the 10^{-2} level



$$A_i^{CP} \simeq \langle \cos\beta \cos\psi \rangle_i^{\tau^-} - \langle \cos\beta \cos\psi \rangle_i^{\tau^+}$$

bins (i) of $W = \sqrt{Q^2}$

$\beta = K_S$ direction in hadronic rest frame

$\psi = \tau$ direction

BaBar signal incompatible (with EFT) with other sets of flavour data

Cirigliano-Crivellin-Hoferichter, 1712.06595

Rendón-Roig-Toledo, 1902.08143