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News on new physics in B decays

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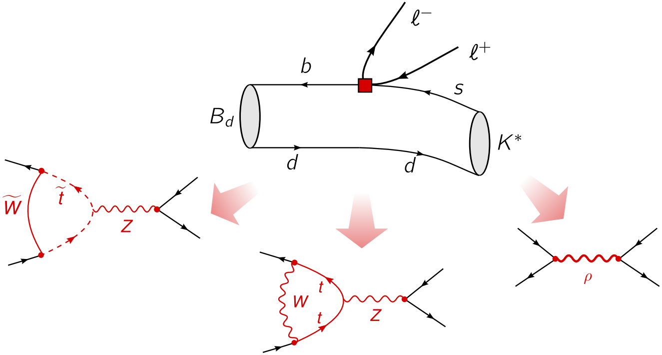
Outline

1. Anomalies in B decays?

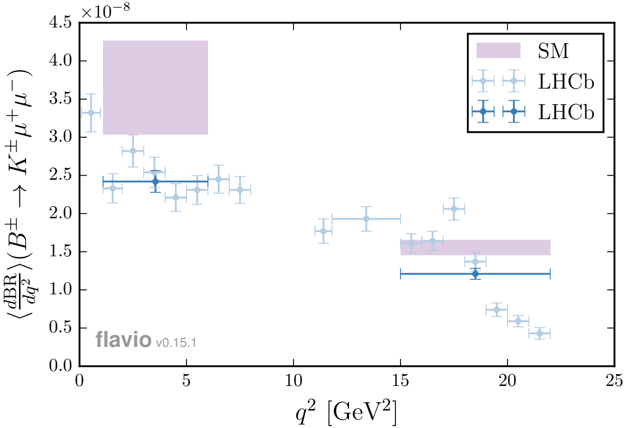
2. NP in radiative B decays

$b \to s$ FCNC decays

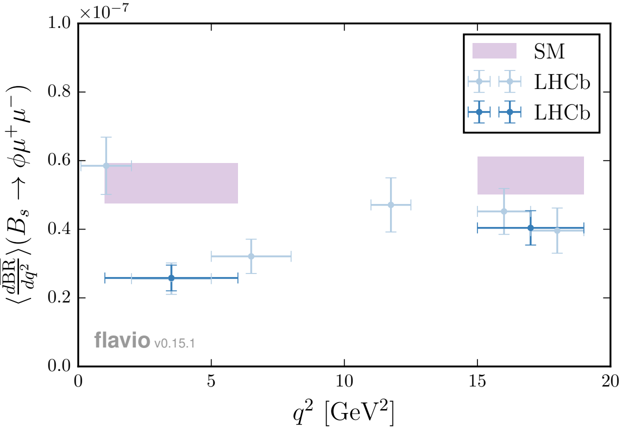
Loop- & CKM-suppressed $\Rightarrow$ sensitive to new physics



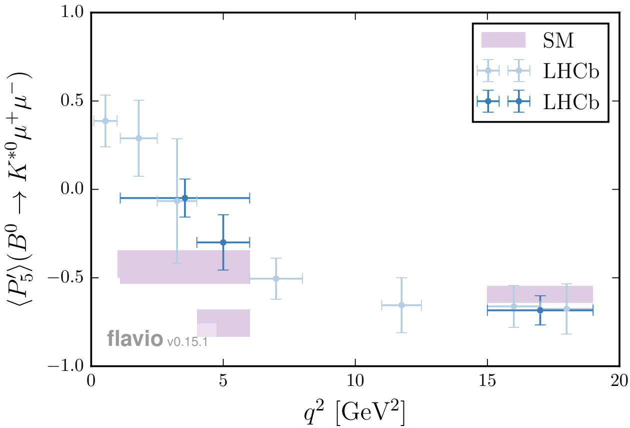
$B^+ \to K^+\mu^+\mu^-$ branching ratio



$B_s \to \varphi\mu^+\mu^-$ branching ratio



$B^0 \to K^* \mu^+ \mu^-$ angular observables



Significance of tensions

Mode	Observable	Bin	Pull
$B^0 \to K^* \mu^+ \mu^-$	P_5'	4–6	$-\mathbf{2.6}\boldsymbol{\sigma}$
$B_s \to \varphi \mu^+ \mu^-$	BR	1–6	$-\mathbf{3.3}\boldsymbol{\sigma}$
$B^+ \to K^+ \mu^+ \mu^-$	BR	1–6	$-\mathbf{2.0}\boldsymbol{\sigma}$
$B^+ \to K^+ \mu^+ \mu^-$	BR	15–22	$-\mathbf{2.6}\boldsymbol{\sigma}$

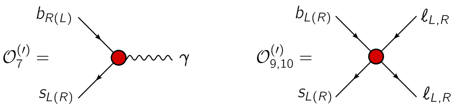
Suspects: New physics? Underestimated theory uncertainties?

(flavio v0.13.1 using combined LCSR+LQCD FFs for $B \to V$ FFs Bharucha et al. 1503.05534 and FNAL/MILC $B \to K$ FFs Bailey et al. 1509.06235; hadronic unc. estimated as in Altmannshofer and Straub 1411.3161)

New physics?

NP effects model-independently described by modification of Wilson coefficients of dim.-6 operators

$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}}\frac{e^2}{16\pi^2} V_{tb}V_{ts}^* \sum_i C_i O_i + \text{h.c.}$$



$$O_7^{(\prime)} = \frac{m_b}{e}(\bar{s}\sigma_{\mu\nu}P_{R(L)}b)F^{\mu\nu}$$

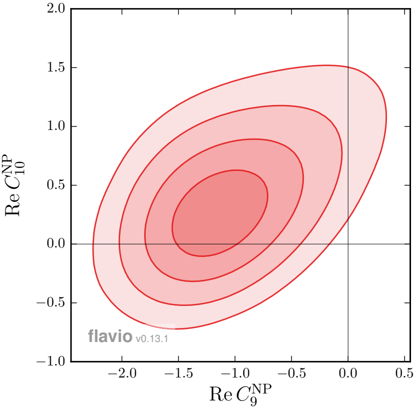
$$O_9^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\ell) \qquad O_{10}^{(\prime)} = (\bar{s}\gamma_\mu P_{L(R)}b)(\bar{\ell}\gamma^\mu\gamma_5\ell)$$

Global constraints on C_9 & C_{10}

- Global fit including also 3 fb^{-1} LHCb measurements of $\mathrm{BR}(B^0 \to K^* \mu^+ \mu^-)$ (2016) and $B_s \to \varphi \mu^+ \mu^-$ (2015), updated $B \to V$ FFs from v2 of

  Bharucha et al. 1503.05534
- Best fit point: **4.5σ pull** from SM

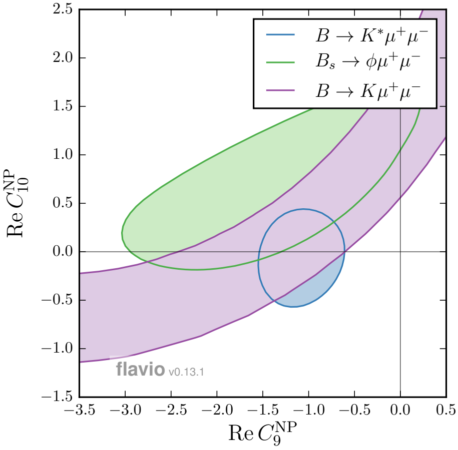
see also Altmannshofer and Straub 1411.3161, Descotes-Genon et al. 1510.04239, Hurth et al. 1603.00865



A closer look

Pulls for individual modes:

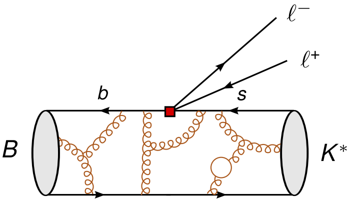
- $B \to K^* \mu^+ \mu^-$: **2.7σ**
- $B_s \to \varphi \mu^+ \mu^-$: **3.4σ**
- $B \to K \mu^+ \mu^-$: **2.6σ**



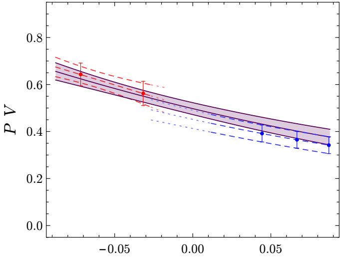
Comment on “flavour sigmas”

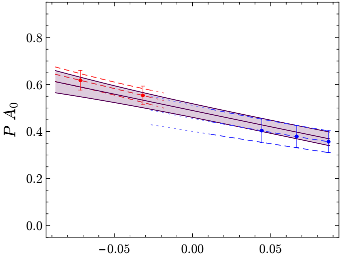
- Clearly crucial to understand the source of these tensions
- In my opinion, we (theorists) should not give in to the temptation of inflating errors just because of “tensions” with data. Might be statistical fluctuations, experimental problems, new physics!
- Nevertheless, use tensions as opportunity to scrutinize whether uncertainties have been estimated conservatively enough

Scrutinizing uncertainties: form factors?

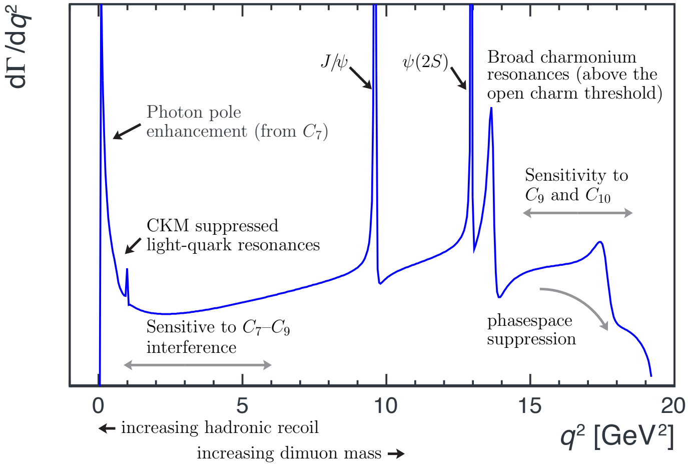


- Complementary light-cone sum rule & lattice results for $B \to (K^*, \varphi)$ show good agreement Bharucha et al. 1503.05534, Horgan et al. 1501.00367





Cartoon: q^2 dependence of $B \to K^* \ell^+ \ell^-$



Blake et al. 1606.00016

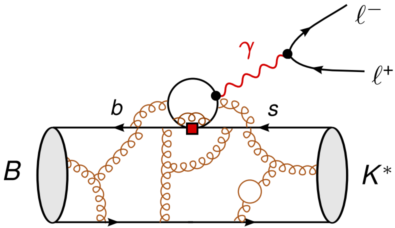
Scrutinizing uncertainties: charm loops?

- Culprit: matrix element of $O_{1,2}$

$$\langle \bar{K}^* | T\{j^\mu_{\rm em}(x) C_{1,2} O_{1,2}(0)\} | \bar{B} \rangle$$

$$O_2 = (\bar{s}_L \gamma_\mu c_L)(\bar{c}_L \gamma^\mu b_L)$$

- Since $O_9 \propto \bar{\ell}\gamma^\mu \ell$, h_λ could mimic a new phyiscs effect in C_9
- can be parametrised as q^2-dependent effective shift of C_9: $\Delta C_9^{+,-,0}(q^2)$ for the 3 helicity amplitudes

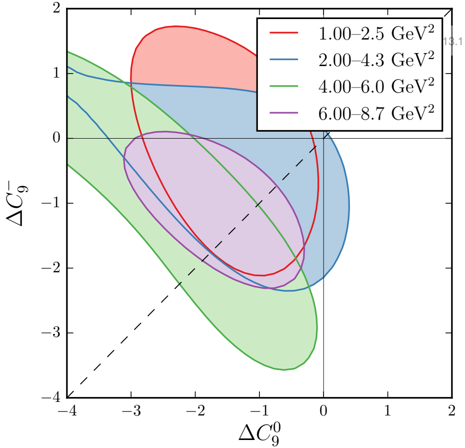


see e.g. Khodjamirian et al. 1006.4945, Lyon and Zwicky 1406.0566

q^2 dependence of ΔC_9^λ

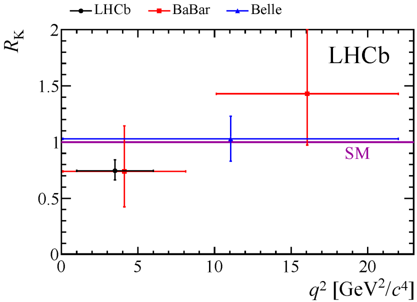
- Bin-by-bin fit of ΔC_9^0 vs. ΔC_9^- from low-q^2 $B \to K^* \mu^+ \mu^-$ data
- New physics: expect $\Delta C_9^0 = \Delta C_9^-$ equal for all bins

Current data **not precise enough** to exclude new physics hypothesis!



see also Altmannshofer and Straub 1503.06199,

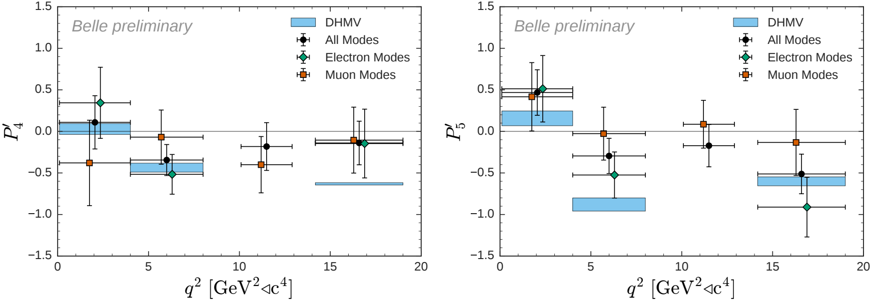
Violation of lepton flavour universality?



$$R_K = \frac{\text{BR}(B \to K\mu^+\mu^-)_{[1,6]}}{\text{BR}(B \to Ke^+e^-)_{[1,6]}}$$
$$= 0.745^{+0.090}_{-0.074} \pm 0.036$$
$$R_K^{\text{SM}} \simeq 1.00$$

- 2.6σ deviation from lepton flavour universality (LFU)
- This cannot be explained by a hadronic effect!

The plot thickens ...



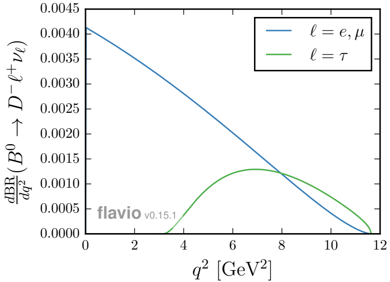
- Belle measurement of $B \to K^* ee$ vs. $\mu\mu$ angular observables
- 2.6σ tension in $\mu\mu$, 1.1σ agreement in ee

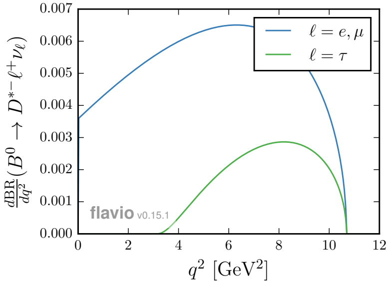
(S. Wehle @ CKM 2016, Mumbai, November 30)

LFU in $B \to D^{(*)}\ell\nu$

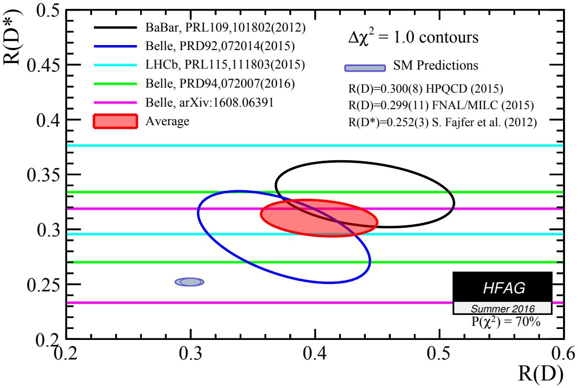
Charged-current decays $B \to D^{(*)}\ell\nu$:

- with $\ell = e, \mu$ used to measure CKM element V_{cb}
- $B \to D^{(*)}\tau\nu$ known in SM up to form factor uncertainties





Violation of μ-τ universality?



- 3.9σ combined tension with SM (HFAG)
- Note that SM (FF) uncertainties are insignificant for the tension

EFT analysis

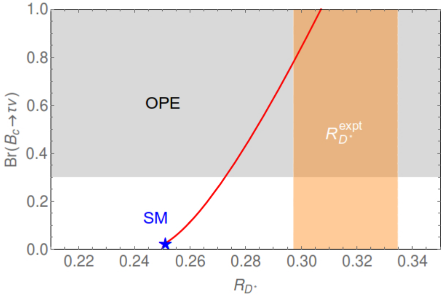
$$\mathcal{H}_{\text{eff}} = -\frac{4\,G_F}{\sqrt{2}} V_{cb} \sum_i C_i O_i + \text{h.c.}$$

$$O_V^{(\prime)} = (\bar{c}_{L(R)}\gamma_\mu b_{L(R)})(\bar{\tau}_L\gamma^\mu \nu_L) \qquad O_S^{(\prime)} = (\bar{c}_{L(R)}\gamma_\mu b_{R(L)})(\bar{\tau}_{L(R)}\gamma^\mu \nu_L)$$

$$O_T = (\bar{c}_R\sigma_{\mu\nu} b_L)(\bar{\tau}_R\sigma^{\mu\nu}\nu_L)$$

$B_c \to \tau\nu$ constraint

- Not a single B_c branching ratio has been measured – but its lifetime!
- Even with conservative assumptions, scalar operators cannot explain R_D^*



see Li et al. 1605.09308, plot from Alonso et al. 1611.06676

The $R_K - P_5' - R_D^{(*)}$ connection

- The operators

$$O_9 - O_{10} \propto (\bar{s}_L \gamma^\mu b_L)(\ell_L \gamma_\mu \ell_L)$$
$$O_V = (\bar{c}_L \gamma^\mu b_L)(\ell_L \gamma_\mu \nu_L)$$

can explain all "anomalies"

- they could arise from a common source at short distance:

$$Q_{ql}^{(3)} = (\bar{Q}_L \gamma^\mu \sigma^i Q_L)(L_L \gamma_\mu \sigma_i L_L)$$

- especially compelling when NP couples dominantly to 3rd generation

Bhattacharya et al. 1412.7164, Greljo et al. 1506.01705

Unified “one-particle” models

Spin	$SU(3)_c$	$SU(2)_L$	Name	Suggested
1	1	3	W', Z'	Greljo et al. 1506.01705
0	3	1	S_1	Bauer and Neubert 1511.01900
0	3	3	S_3	Medeiros Varzielas and Hiller 1503.01084
1	3	1	U_1	Barbieri et al. 1512.01560
1	3	3	U_3	Fajfer and Košnik 1511.06024

… and many more studies in the last 2 years

* See Bečirević et al. 1608.08501 for a LQ model with RH neutrinos

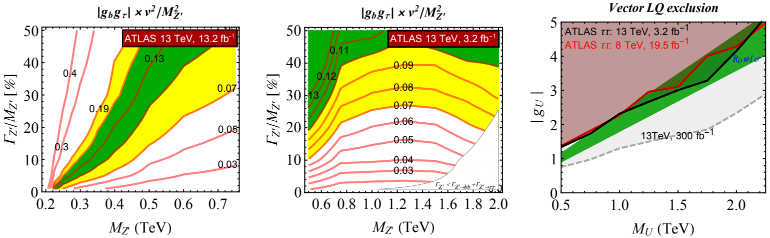
Indirect constraints

- U_3, S_3: strong constraint from $B \to K\nu_\tau\bar{\nu}_\mu$ cf. Buras et al. 1409.4557
- S_1:
  - $b \to s\mu^+\mu^-$ generated at 1-loop level Bauer and Neubert 1511.01900
  - Problem with μ/e non-universality in $B \to D\ell\nu$ Bečirević et al. 1608.07583
- RG effects lead to purely leptonic LFV ($\tau \to \mu\ell\ell$, ...)

  Feruglio et al. 1606.00524

Direct constraints

- Strong constraints from $b\bar{b} \to \tau^+\tau^-$ searches at ATLAS/CMS
  Greljo et al. 1506.01705, Faroughy et al. 1609.07138
  - both Z' (s-channel) and LQ (t-channel)

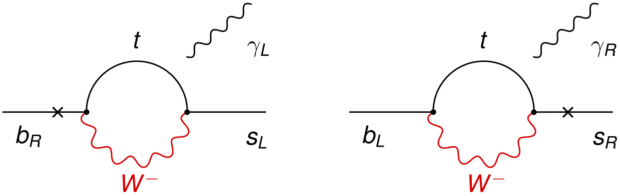


- U_1 LQ on the verge of being excluded
- W'/Z' only allowed if light ($M < 500$ GeV) or broad ($\Gamma/M > 30\%$)

1. Anomalies in B decays?

2. NP in radiative B decays

The $b \to s\gamma$ transition



$$Q_7 = \frac{e}{16\pi^2} m_b (\bar{s}_L \sigma_{\mu\nu} b_R) F^{\mu\nu} \qquad Q_7' = \frac{e}{16\pi^2} m_b (\bar{s}_R \sigma_{\mu\nu} b_L) F^{\mu\nu}$$

Strongest constraint: inclusive decay

$$\text{BR}(B \to X_s \gamma) \sim \text{BR}(b \to s\gamma) + O\left(\frac{\Lambda^2}{m_b^2}\right) + \delta_{\text{nonp.}}$$

$$\text{BR}(b \to s\gamma)_{\text{LO}} \propto |C_7^{\text{eff}}|^2 + |C_7'|^2$$

$$\text{BR}(B \to X_s \gamma)^{\text{SM}}_{E_\gamma > 1.6\,\text{GeV}} = (3.36 \pm 0.23) \times 10^{-4}$$

$$\text{BR}(B \to X_s \gamma)^{\text{exp}}_{E_\gamma > 1.6\,\text{GeV}} = (3.43 \pm 0.22) \times 10^{-4}$$

Misiak et al. 1503.01789, Amhis et al. 1412.7515

- Excellent agreement, but no information on $\text{Im}\, C_7^{(\prime)}$ or C_7'/C_7

Probing C_7'

- Exclusive decays
  - $B^0 \to K^{*0}\gamma$
  - $B^+ \to K^{*+}\gamma$
  - $B_s \to \varphi\gamma$
  - $B \to K^* e^+ e^-$ at very low $q^2_{e^+e^-}$ (close to the photon pole)
- challenge: form factors
  - consider observables where FFs drop out!
- hadronic uncertainties beyond FFs: less problematic than in SL

Observables less sensitive to form factors

- Mixing-induced CP asymmetry in $B^0 \to K^*(\to K_S\pi)\gamma$

$$\Gamma_{\bar{B}\to K_S\pi\gamma}(t) - \Gamma_{\bar{B}\to K_S\pi\gamma}(t) = \frac{e^{-t/\tau}}{2\tau}\left[S\sin(\Delta M_q t) - C\cos(\Delta M_q t)\right]$$

- Mass-eigenstate rate asymmetry in $B_s \to \varphi\gamma$

$$\Gamma_{B_s\to\varphi\gamma}(t) + \Gamma_{B_s\to\varphi\gamma}(t) = \frac{e^{-t/\tau}}{2\tau}\left[\cosh(\frac{\Delta\Gamma_q t}{2}) - A_{\Delta\Gamma}\sinh(\frac{\Delta\Gamma_q t}{2})\right]$$

- $B \to K^* e^+ e^-$ angular observables P_1, A_T^{Im}

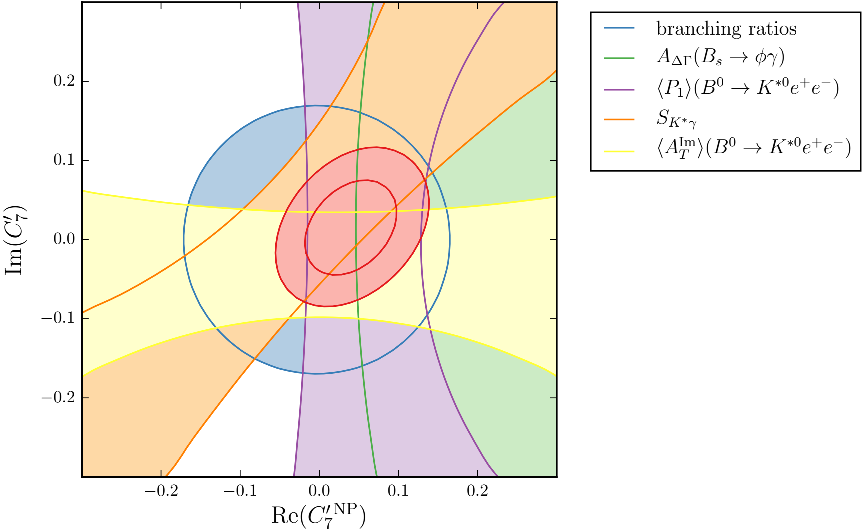
All these observables directly probe C_7'!

Measurements

Observable	SM prediction	Measurement	
$S(B^0 \to K^* \gamma)$	-0.023 ± 0.015	-0.16 ± 0.22	
$A_{\Delta\Gamma}(B_s \to \varphi\gamma)$	0.031 ± 0.021	-1.0 ± 0.5	2
$\langle P_1 \rangle (B^0 \to K^* e^+ e^-)_{[0.002,1.12]}$	0.04 ± 0.02	-0.23 ± 0.24	1
$\langle A_T^{\mathrm{Im}} \rangle (B^0 \to K^* e^+ e^-)_{[0.002,1.12]}$	0.0003 ± 0.0002	0.14 ± 0.23	1

- [1] LHCb 2015
- [2] LHCb 2016

Global constraints on C_7' Paul and Straub 1608.02556



flavio

- a Python package for flavour phenomenology in the SM & beyond
  - repository: `http://github.com/flav-io/flavio`
  - documentation: `http://flav-io.github.io`
- Features
  - SM predictions with uncertainties
  - NP predictions for arbitrary Wilson coefficients
  - Fitting SM parameters and Wilson coefficients to data
- Click on logo in slides to reproduce plots!

Conclusions

- Anomalies in $b \to s\mu^+\mu^-$ and $b \to c\tau\nu$
  - Model-independent NP explanation possible
  - Could be due to conspiracy of underestimated hadronic effects & underestimated exp. systematics
  - Simultaneous explanations increasingly challenged, even by direct searches
- NP in radiatie B decays
  - exclusive decays constrain C_7'
  - new observables measured by LHCb
  - clean null tests – excellent future prospects for improvement (LHCb & Belle-II)