MIAPP discussion session, 14 November 2016

Radiative B decays

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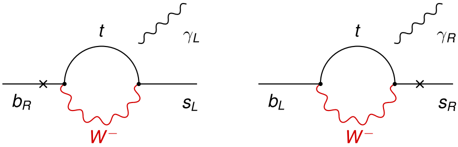
- Disclaimer: talk prepared at short notice
- Most plots from arXiv:1608.02556 with Ayan Paul

The $b \to s\gamma$ transition

- Chirality-changing FCNC



$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \left(\sum_{i=1}^{8} C_i Q_i + \sum_{i=7}^{8} C_i' Q_i' \right)$$

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

$$C_7^{\text{eff, SM}}(\mu = m_b) = -0.2915 \qquad C_7'^{\,\text{SM}} = \frac{m_s}{m_b} C_7^{\text{SM}}$$

Strongest constraint: inclusive decay

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

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

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

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

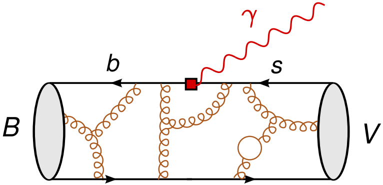
Misiak 1503.01789, Amhis 1412.7515

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

Exclusive decays

- $B \to V\gamma$ decays
  - $B^0 \to K^{*0}\gamma$
  - $B^+ \to K^{*+}\gamma$
  - $B_s \to \varphi\gamma$
- While semi-leptonic decays based on $b \to s\ell^+\ell^-$ are also sensitive to $C_7^{(\prime)}$, they also depend on operators of the form $(\bar{s}\Gamma b)(\ell\Gamma\ell)$ and on more diverse hadronic effects
  - Exception: $B \to K^* e^+e^-$ at very low $q^2_{e^+e^-}$ close to the photon pole

Form factors



- Prediction of $B \to V\gamma$ (and $B \to V\ell^+\ell^-$) decays require knowledge of $B \to V$ form factors

$$q^\nu \langle V(k,\varepsilon)|\bar{s}\sigma_{\mu\nu}b|B(p)\rangle = 2\,T_1(q^2)\,\varepsilon_{\mu\rho\tau\sigma}\varepsilon^{*\rho}p^\tau k^\sigma$$

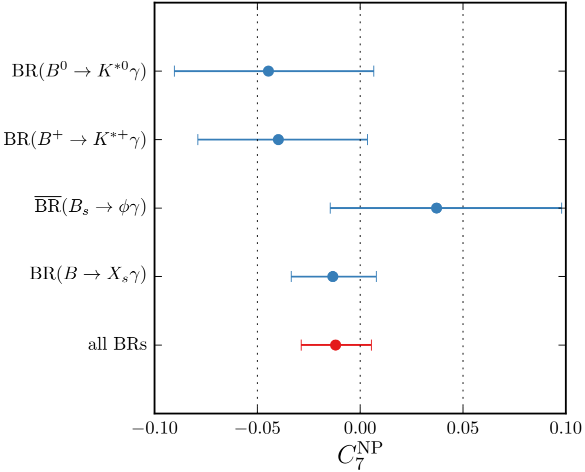
- inherently non-perturbative
- lattice QCD not applicable at low q^2 because relative momentum between hadrons too large
- most precise method: QCD sum rules on the light cone (LCSR)
  - recent update Bharucha et al. 1503.05534

Exclusive branching ratios vs. form factors

Observable	SM prediction	Measurement
$10^4 \times \text{BR}(B \to X_s\gamma)_{E_\gamma > 1.6\,\text{GeV}}$	3.36 ± 0.23	3.43 ± 0.22
$10^5 \times \text{BR}(B^+ \to K^*\gamma)$	3.43 ± 0.84	4.21 ± 0.18
$10^5 \times \text{BR}(B^0 \to K^*\gamma)$	3.48 ± 0.81	4.33 ± 0.15
$10^5 \times \overline{\text{BR}}(B_s \to \varphi\gamma)$	4.31 ± 0.86	3.5 ± 0.4

- Form factors have ~10% uncertainty $\Rightarrow$ ~20% uncertainty on exclusive BRs not competitive with inclusive

Branching ratio constraints on C_7



Observables not/less sensitive to form factors

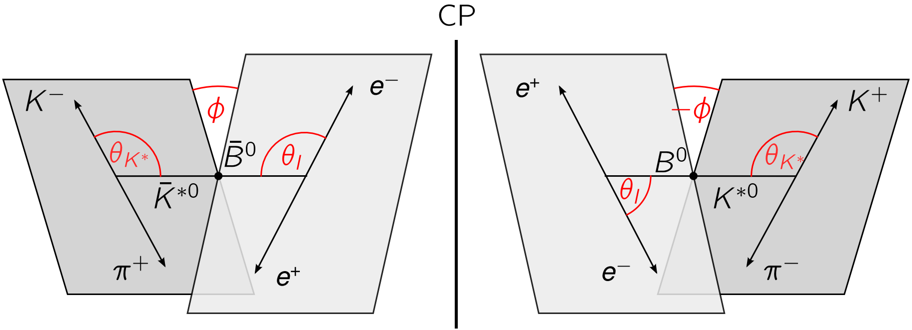
- Time-dependent decay rate of B_q ($q = d$ or s) and $\bar{B}_q$ mesons to a CP eigenstate f

$$\Gamma_{\bar{B}_q \to f}(t) = \frac{e^{-t/\tau}}{4\tau}\left[\cosh(\tfrac{\Delta\Gamma_q t}{2}) + S\sin(\Delta M_q t) - C\cos(\Delta M_q t) - A_{\Delta\Gamma}\sinh(\tfrac{\Delta\Gamma_q t}{2})\right]$$

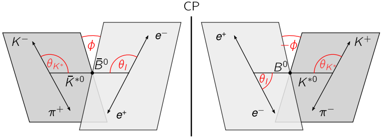
$$\Gamma_{B_q \to f}(t) = \frac{e^{-t/\tau}}{4\tau}\left[\cosh(\tfrac{\Delta\Gamma_q t}{2}) - S\sin(\Delta M_q t) + C\cos(\Delta M_q t) - A_{\Delta\Gamma}\sinh(\tfrac{\Delta\Gamma_q t}{2})\right]$$

- Special cases:
  - $B_d \to K^*\gamma$: $\Delta\Gamma_d \ll \Delta M_d$ can be neglected $\Rightarrow A_{\Delta\Gamma}$ not measureable
  - $B_d \to K^*\gamma$: C coincides with the time-integrate CP asymmetry: $C = A_{\text{CP}}$
  - $B_s \to \varphi\gamma$: B_s and $\bar{B}_s$ decays cannot be distinguished $\Rightarrow S$ and C not measurable

$B \to K^* e^+ e^-$ angular distribution



$B \to K^* e^+ e^-$ angular distribution



- One-dimensional projections:

$$\frac{d(\Gamma+\bar{\Gamma})}{d\theta_{K^*}\,dq^2} \Big/ \frac{d(\Gamma+\bar{\Gamma})}{dq^2} = \frac{3}{4} F_L \left(3\cos^2\theta_{K^*} - 1\right) + \frac{3}{4}\left(1 + \cos^2\theta_{K^*}\right)$$

$$\frac{d(\Gamma+\bar{\Gamma})}{d\varphi\,dq^2} \Big/ \frac{d(\Gamma+\bar{\Gamma})}{dq^2} = \frac{1}{2\pi}\left[1 + S_3\cos(2\varphi) - A_9\sin(2\varphi)\right]$$

- F_L: K^* longitudinal polarization fraction
- $P_1 = 2S_3/(1-F_L)$ CP-averaged angular observable
- $A_T^{\text{Im}} = 2A_9/(1-F_L)$ angular CP asymmetry

Summary: exclusive observables

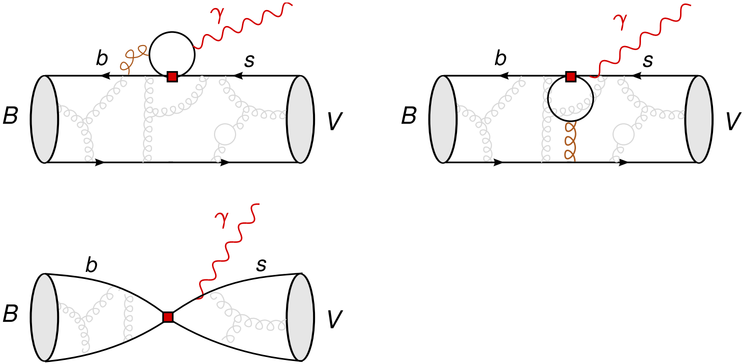
- Branching ratios of $B^{0,+} \to K^*\gamma$
- Branching ratio of $B_s \to \varphi\gamma$
- $S(B^0 \to K^*\gamma)$
- $A_{\text{CP}}(B^0 \to K^*\gamma)$
- $A_{\Delta\Gamma}(B_s \to \varphi\gamma)$
- $\langle P_1\rangle(B^0 \to K^*e^+e^-)$
- $\langle A_T^{\text{Im}}\rangle(B^0 \to K^*e^+e^-)$

Summary: exclusive observables

- Branching ratios of $B^{0,+} \to K^* \gamma$
- Branching ratio of $B_s \to \varphi\gamma$
- $S(B^0 \to K^* \gamma)$
- $A_{\rm CP}(B^0 \to K^* \gamma)$
- $A_{\Delta\Gamma}(B_s \to \varphi\gamma)$
- $\langle P_1 \rangle (B^0 \to K^* e^+ e^-)$
- $\langle A_T^{\rm Im} \rangle (B^0 \to K^* e^+ e^-)$

- News from experiment:
  - First angular analysis of $B^0 \to K^* e^+ e^-$: LHCb January 2015
  - First measurement of $A_{\Delta\Gamma}(B_s \to \varphi\gamma)$: LHCb August 2016

Form factors are not the whole story!



Vertex corrections, spectator scattering, weak annihilation, …
"non factorisable effects"

Exclusive "Wilson" coefficient

- Define:

$$\mathcal{C}_7 = C_7^{\text{eff}} + \Delta C_7$$

  - C_7^{eff} is the short-distance Wilson coefficient containing possible new physics contributions
  - ΔC_7 contains the "non-factorisable" hadronic contributions not contained in the form factors (i.e. Wilson coefficients and matrix elements of 4-quark operators and Q_8)

- Under CP:

$$\mathcal{C}_7 \overset{CP}{\to} \overline{\mathcal{C}}_7 = C_7^{\text{eff}*} + \Delta C_7$$

  - $\text{Im}(C_7)$ is odd under CP, $\text{Im}(\Delta C_7)$ is even

non-factorisable contributions: numerics

- Contributions to ΔC_7 in units of 10^{-2}

	$B^0 \to K^*\gamma$	$B^+ \to K^*\gamma$	$B_s \to \varphi\gamma$
Vertex corrections	$-(7.8 \pm 1.0) - (1.1 \pm 0.3)i$		
Spectator scattering Q_{1-6}	$-0.7 - 1.3i$	$-0.7 - 1.3i$	$-0.7 - 1.7i$
Spectator scattering Q_8	-0.3	-0.3	-0.4
Weak annihilation	-0.4	$+0.9$	-0.5

- Remaining effects assumed (based on existing estimates Ball et al. hep-ph/0612081, Khodjamirian et al. 1006.4945, Muheim et al. 0802.0876) to be $\lesssim 1.5 \times 10^{-2}$
- $\Delta C_7'$ estimated to be $\lesssim 0.4 \times 10^{-2}$

Observables in terms of $\mathcal{C}_7^{(\prime)}$

$$\text{Let } \mathcal{C}_7 = |\mathcal{C}_7| e^{i\varphi_7} e^{i\delta_7}, \qquad \mathcal{C}_7' = |\mathcal{C}_7'| e^{i\varphi_7'} e^{i\delta_7'}, \qquad \tan x \equiv \left| \frac{\mathcal{C}_7'}{\mathcal{C}_7} \right|$$

$$S(B^0 \to K^* \gamma) = \sin(2x)\ \sin(\varphi_7 + \varphi_7' - 2\beta - \varphi_d^\Delta - 2|\beta_s|) \cos(\delta_7 - \delta_7')$$

$$A_{\Delta\Gamma}(B_s \to \varphi\gamma) = \sin(2x)\ \cos(\varphi_7 + \varphi_7' - \varphi_s^\Delta) \cos(\delta_7 - \delta_7')$$

Observables in terms of $\mathcal{C}_7^{(\prime)}$

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$$A_{\Delta\Gamma}(B_s \to \varphi\gamma) = \sin(2x)\, \cos(\varphi_7 + \varphi_7' - \varphi_s^\Delta) \cos(\delta_7 - \delta_7')$$

- For $q^2 \to 0$, P_1 and $A_T^{(\mathrm{Im})}$ only depend on the helicity amplitudes with transverse K^*

$$\lim_{q^2 \to 0} P_1 = \sin(2x)\, \cos(\varphi_7 - \varphi_7') \cos(\delta_7 - \delta_7')$$

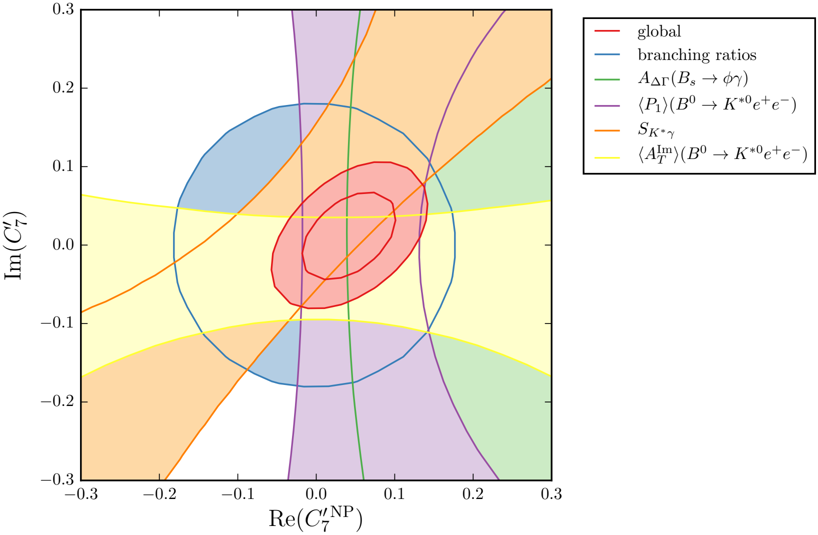
$$\lim_{q^2 \to 0} A_T^{(\mathrm{Im})} = \sin(2x)\, \sin(\varphi_7 - \varphi_7') \cos(\delta_7 - \delta_7')$$

Measurements

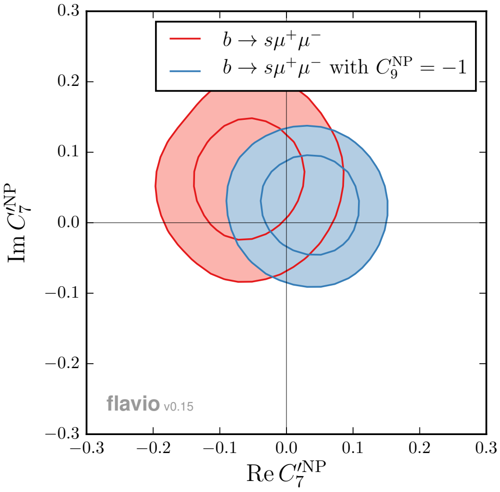
Observable	SM prediction	Measurement	
$S(B^0 \to K^* \gamma)$	-0.023 ± 0.015	-0.16 ± 0.22	
$A_{\mathrm{CP}}(B^0 \to K^* \gamma)$	0.003 ± 0.001	-0.002 ± 0.015	
$A_{\Delta\Gamma}(B_s \to \varphi \gamma)$	0.031 ± 0.021	-1.0 ± 0.5	2
$\langle P_1 \rangle (B^0 \to K^* e^+ e^-)_{[0.002,1.12]}$	0.04 ± 0.02	-0.23 ± 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'



Constraints from $b \to s\mu\mu$



$\mathrm{Im}\, C_7$ and A_{CP}

- Non-zero direct CP asymmetry requires interference of two amplitudes with non-zero strong and weak phases

$$A_{\mathrm{CP}}(B^0 \to K^*\gamma) \times \mathrm{BR}(B^0 \to K^*\gamma) = 2\,\mathrm{Im}\,C_7^{\mathrm{eff}}\,\mathrm{Im}\,\Delta C_7 + 2\,\mathrm{Im}\,C_7'\,\mathrm{Im}\,\Delta C_7' + \ldots$$

- Calculable non-factorisable effects imply sizable strong phase $\Rightarrow$ strong bound on $\mathrm{Im}\,C_7$

$$\mathrm{Im}\,C_7^{\mathrm{NP}}(\mu_b) \in [-0.064, 0.094] \times \left[\frac{-0.027}{\mathrm{Im}\,\Delta C_7}\right] \qquad @\ 95\%\ \mathrm{C.L.}$$

- **but** proportional to $\mathrm{Im}\,\Delta C_7$ that is not theoretically clean

Comment on $A_{\text{CP}}(B^0 \to K^*\gamma)$

- the **time-integrated** $A_{\text{CP}}(B^0 \to K^*\gamma)$ is measured precisely; HFAG:

$$A_{\text{CP}}(B^0 \to K^*\gamma) = -0.002 \pm 0.015$$

- to be compared with **TCPV** in $B^0 \to K^*(\to K_S\pi^0)\gamma$:

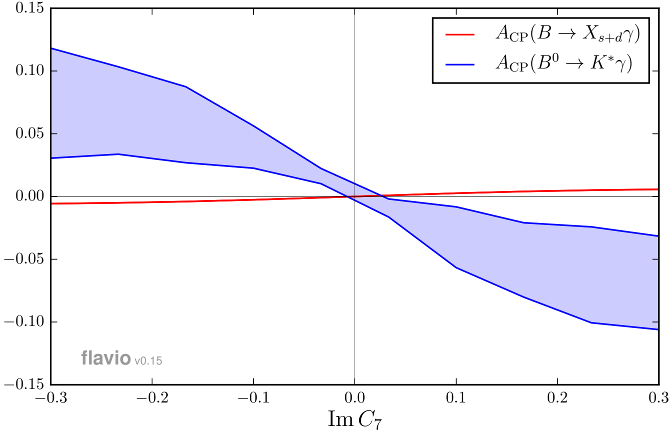
$$A_{\text{CP}}(B^0 \to K^*\gamma) = -0.04 \pm 0.14$$

$A_{CP}(B \to X\gamma)$

- $A_{CP}(B \to X_s\gamma)$ is dominated by poorly known long-distance contribution ("resolved photons")
- $\Delta A_{X_s\gamma} = A_{CP}(B^- \to X_s\gamma) - A_{CP}(\bar{B}^0 \to X_s\gamma)$ vanishes in the SM and probes the relative phase of C_7 and C_8
- $A_{CP}(B \to X_{s+d}\gamma)$ vanishes the SM and is free from "resolved photon" contributions

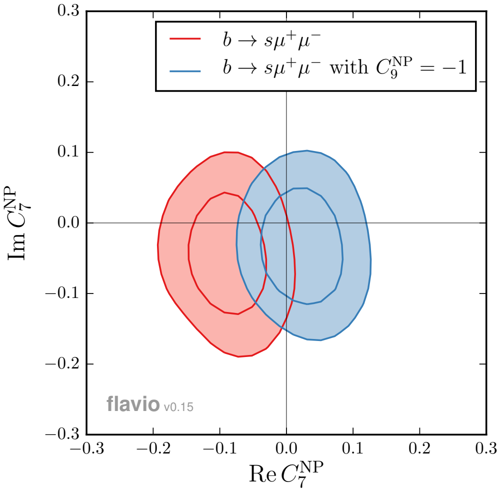
Benzke et al. 1012.3167

A_{CP}: sensitivity inclusive vs. exclusive



(very preliminary; uncertainties in $A_{\mathrm{CP}}(B \to X_s\gamma)$ underestimated)

Constraints from $b \to s\mu\mu$



T-odd CP asymmetries $A_{7,8}$ exclude large effects in $\mathrm{Im}(C_7)$