Enhanced CP asymmetries in $B \to K\mu^+\mu^-$

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in collaboration with

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EPJC 80, 940 (2020)
(ArXiv:2008.090649)

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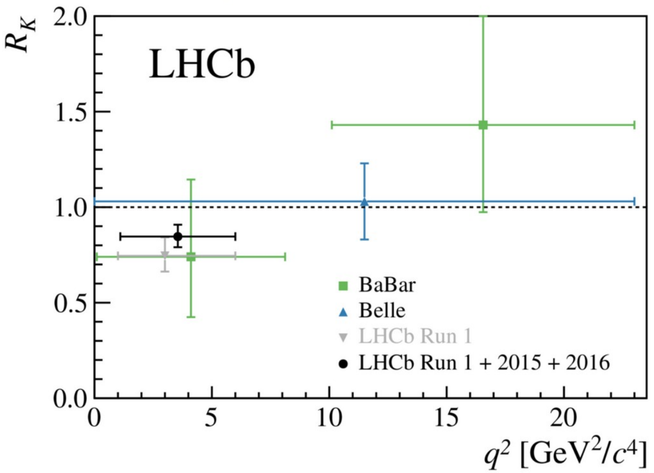
LFUV recap

$$R_{K^{(*)}} = \frac{\mathcal{B}'(B \to K^{(*)}\mu\mu)}{\mathcal{B}'(B \to K^{(*)}ee)}$$

In the SM: $R_{K^{(*)}} = 1.00(1)$

M. Bordone, G. Isidori, and A. Pattori,
Eur. Phys. J. C 76, 440 (2016)



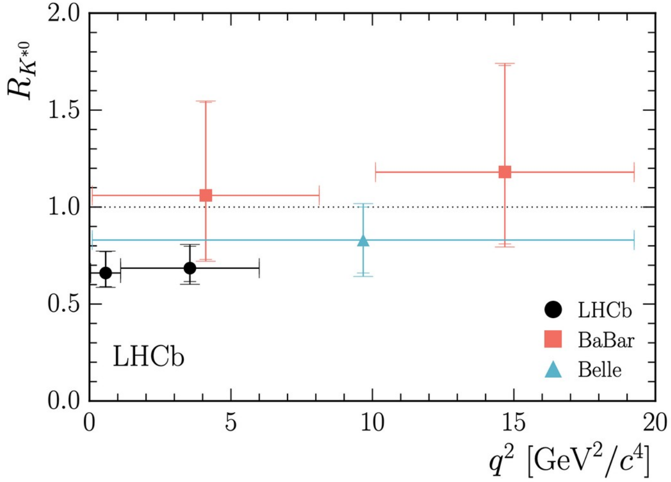
For $q^2 \in [1.1, 6]\,\mathrm{GeV}^2$:

$$R_K = 0.846^{+0.062}_{-0.056}$$

(LHCb), Phys. Rev. Lett. 113, 151601 (2014)
(LHCb), Phys. Rev. Lett. 122, 191801 (2019)

$$R_{K^*} = 0.69^{+0.12}_{-0.09}$$

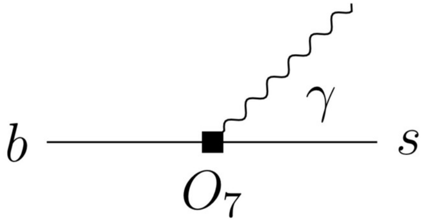
(LHCb), JHEP 08, 055 (2017)



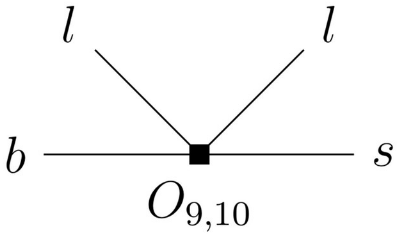
EFT approach

$$\mathcal{H}_{\text{eff}}^{b\to s\ell\ell} = -\frac{4G_F V_{tb}V_{ts}^*}{\sqrt{2}} \sum_{i=7,9,10} C_i(\mu)\mathcal{O}_i(\mu)$$

$$\mathcal{O}_7 = \frac{e m_b}{4\pi}(\bar{s}_R \sigma_{\mu\nu} b_R) F^{\mu\nu}$$



$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2}(\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu(\gamma^5)\ell)$$



Usual assumption: $C_9 = C_9^{\text{SM}} + \delta C_9$ with $\delta C_9 \in \mathbb{R}$

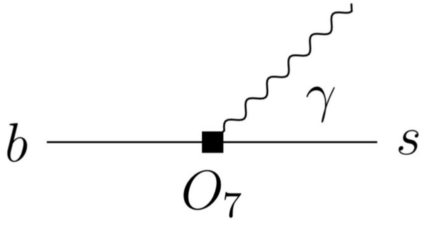
or

$\delta C_9 = -\delta C_{10} \in \mathbb{R}$

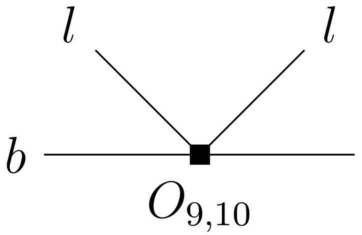
EFT approach

$$\mathcal{H}_{\text{eff}}^{b\to s\ell\ell} = -\frac{4G_F V_{tb}V_{ts}^*}{\sqrt{2}} \sum_{i=7,9,10} C_i(\mu)\mathcal{O}_i(\mu)$$

$$\mathcal{O}_7 = \frac{em_b}{4\pi}(\bar{s}_R\sigma_{\mu\nu}b_R)F^{\mu\nu}$$



$$\mathcal{O}_{9(10)} = \frac{e^2}{(4\pi)^2}(\bar{s}_L\gamma_\mu b_L)(\bar{\ell}\gamma^\mu(\gamma^5)\ell)$$



We consider $C_9 = C_9^{\text{SM}} + \delta C_9$ with $\delta C_9 \in \mathbb{C}$

or

$\delta C_9 = -\delta C_{10} \in \mathbb{C}$

New source of Weak phases?

CP asymmetry

$$\mathcal{A}_{\mathrm{CP}}^{K^{(*)}} = \frac{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\mu\mu) - \mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(\overline{B} \to \overline{K}^{(*)}\mu\mu) + \mathcal{B}(B \to K^{(*)}\mu\mu)}$$

In the SM the effect is tiny

$$\mathrm{Im}C_9^{\mathrm{SM}} \approx 0 \qquad \mathrm{Im}V_{tb}V_{ts}^* \approx 0 \qquad (\mathcal{A}_{\mathrm{CP}}^{K^{(*)}})_{\mathrm{SM}} \approx 0$$

C. Bobeth et al. JHEP 07, 106 (2008)

C. Bobeth et al. JHEP 07, 067 (2011)

A. K. Alok et al. JHEP 11, 122 (2011)

D. Becirevic et al. Phys. Rev. D 86, 034034 (2012)

A. K. Alok et al. Phys. Rev. D 96, 015034(2017)

R. Fleischer et al. Eur. Phys. J. C 78, 1 (2018)

LHCb measured:

$$\mathcal{A}_{\mathrm{CP}}^{K^+} = 0.012(17)(1) \qquad \mathcal{A}_{\mathrm{CP}}^{K^{0*}} = -0.035(24)$$

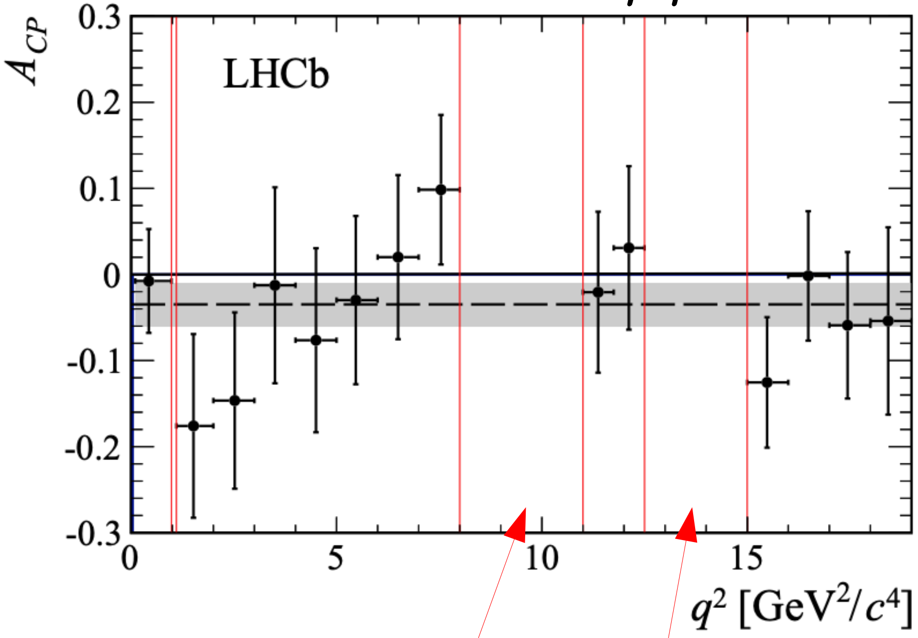
(LHCb), JHEP 09, 177 (2014)

Also bin-by-bin results are provided...

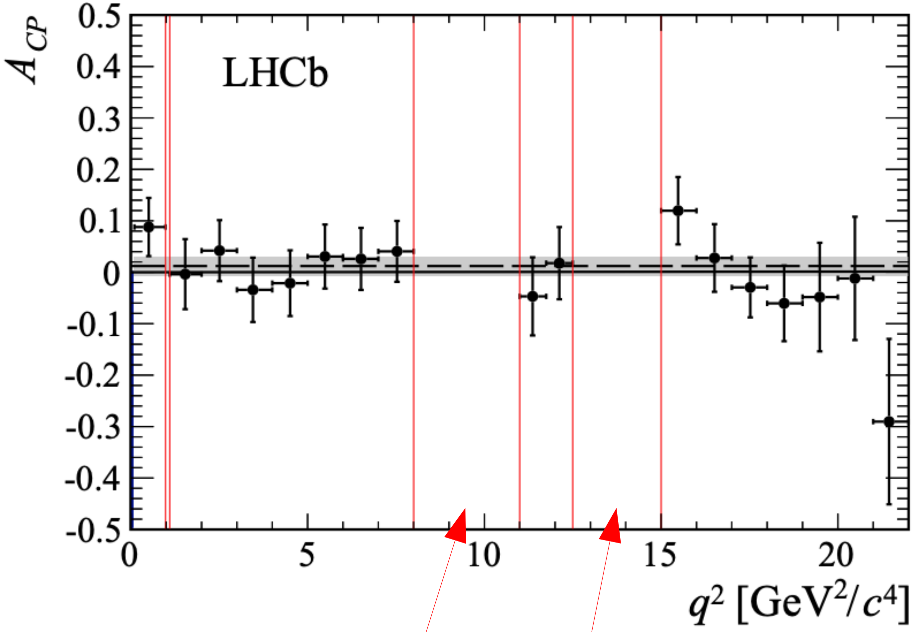
CP asymmetry

$B \to K^* \mu\mu$

(LHCb), JHEP 09, 177 (2014)



$B \to K \mu\mu$



Regions around $q^2 \approx m^2_{J/\psi,\psi(2S)}$ not measured

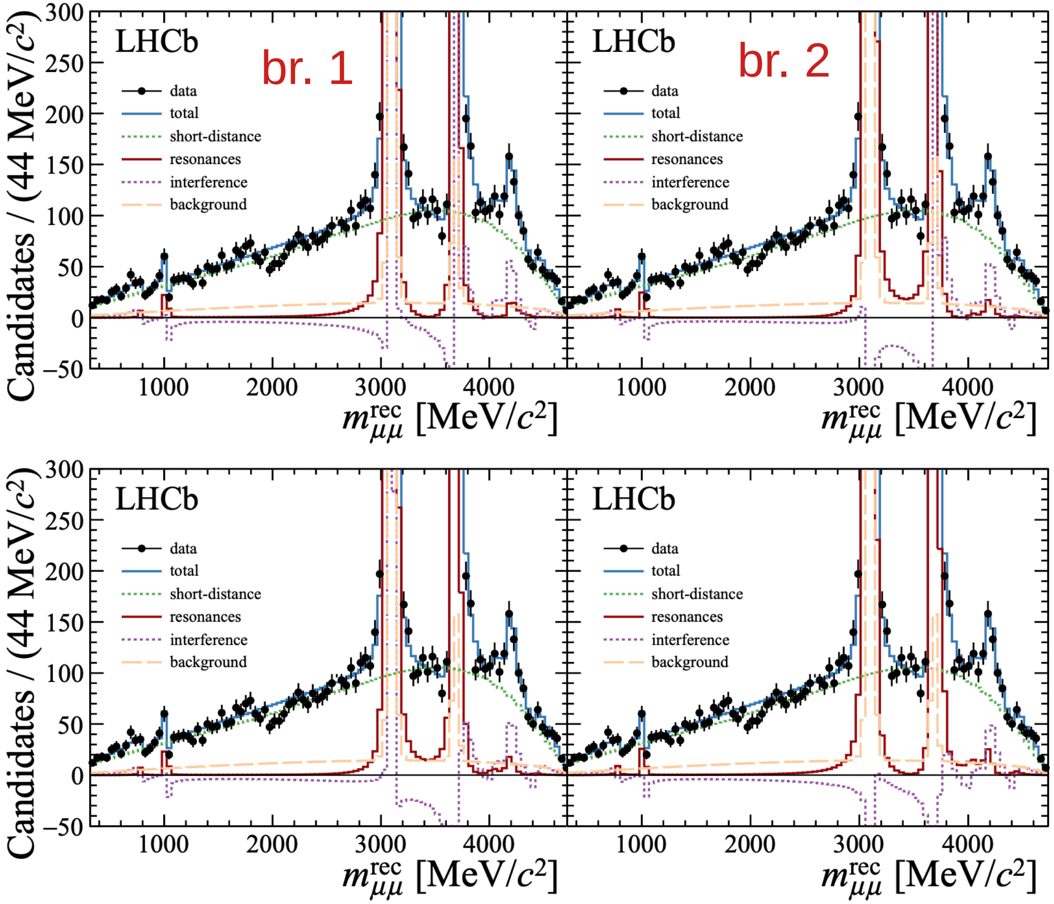
How to handle the complicated resonant regions?

LHCb provides a fit to CP-averaged spectrum:

(LHCb), Eur. Phys. J. C 77, 161 (2017)

$$C_9^{\mathrm{eff}}(q^2) = C_9 + C_9^{\mathrm{res}}(q^2) = C_9 + \sum_j \frac{m_j\,\Gamma_j\,\eta_j\,e^{i\delta_j}}{m_j^2 - q^2 - i\,m_j\Gamma_j(q^2)}$$

$j \in \{J/\psi, \psi(2S), \psi(3770), \psi(4040), \psi(4160), \psi(4415)\}$



- η_j and δ_j extracted
- Fourfold ambiguity in signs of $\delta_{J/\psi}$ and $\delta_{\psi(2S)}$

Source of strong phases

Combined constraints

Using $$C_9^{\rm eff}(q^2) = C_9^{\rm SM} + \delta C_9 + \sum_j \frac{m_j\,\Gamma_j\,\eta_j\,e^{i\delta_j}}{m_j^2 - q^2 - i\,m_j\Gamma_j(q^2)}$$ (LHCb), Eur. Phys. J. C 77, 161 (2017)

We consider

1) $\delta C_9 \in \mathbb{C}$

2) $\delta C_9 = -\delta C_{10} \in \mathbb{C}$

Included constraints:

$$R_K = 0.846^{+0.062}_{-0.056}$$ (LHCb), Phys. Rev. Lett. 113, 151601 (2014)
(LHCb), Phys. Rev. Lett. 122, 191801 (2019)

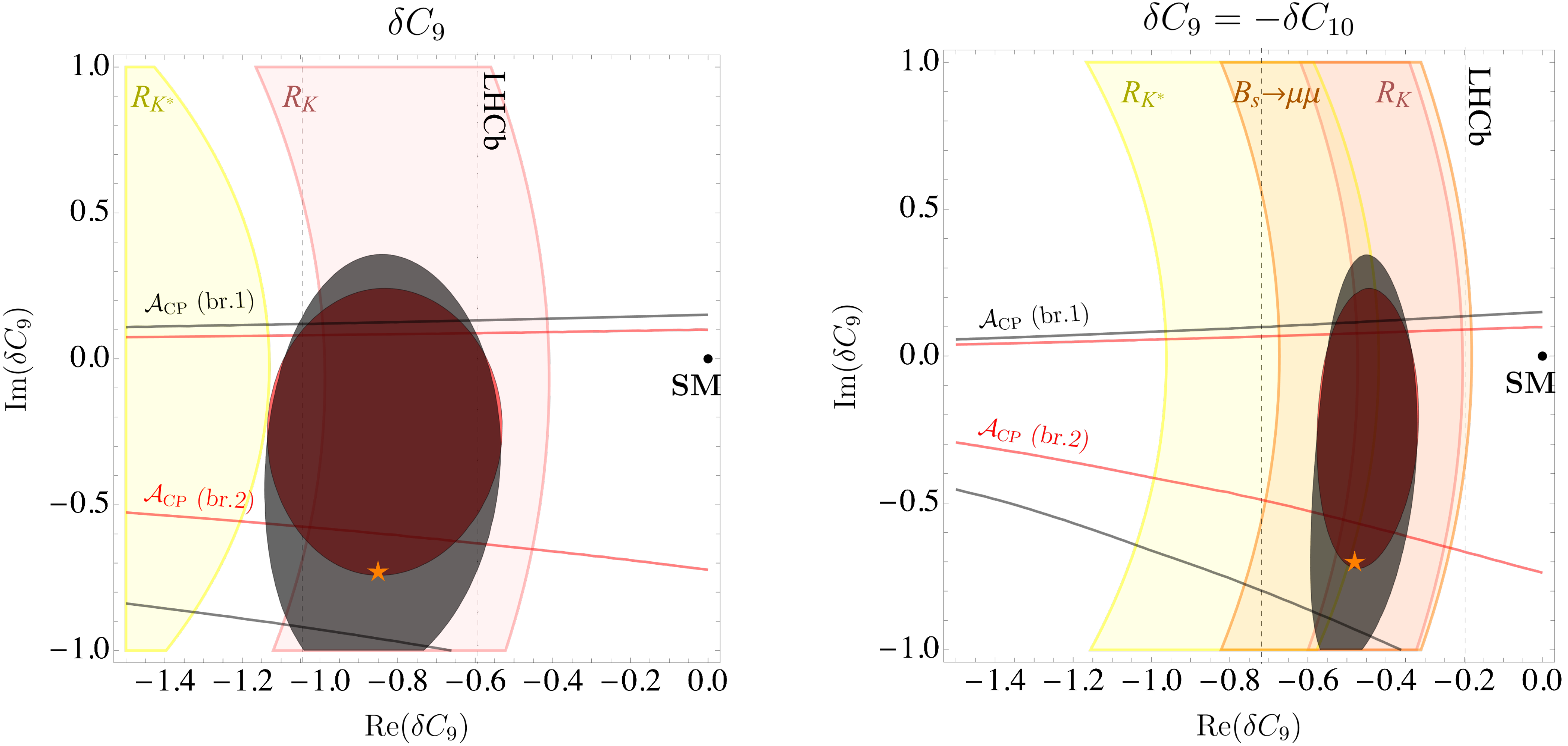
$$R_{K^*} = 0.69^{+0.12}_{-0.09}$$ (LHCb), JHEP 08, 055 (2017)

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\rm exp} = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$ Tech. Rep. LHCb-CONF-2020-002. CERN-LHCb- CONF-2020-002, CERN, Geneva (2020)

$\mathcal{A}_{\rm CP}^K$ from 6 bins with $q^2 \in [2,8]$ GeV^2 (LHCb), JHEP 09, 177 (2014)

Fit to C_9 and C_{10} by LHCb (LHCb), Eur. Phys. J. C 77, 161 (2017)

Combined constraints



A case for resonant regions

Considering q^2 region close to one isolated resonance:

$$C_9^{\rm res}(q^2) \approx \frac{m_j \Gamma_j \eta_j e^{i\delta_j}}{m_j^2 - q^2 - i m_j \Gamma_j}$$

$$\boxed{\mathcal{A}_{\rm CP} = {\rm Im}(\delta C_9)\,\frac{2\eta_j\left(\cos\delta_j - x\sin\delta_j\right)}{\eta_j^2 - 2\eta_j B\left[\sin\delta_j + x\cos\delta_j\right] + A\left[1+x^2\right]}}$$

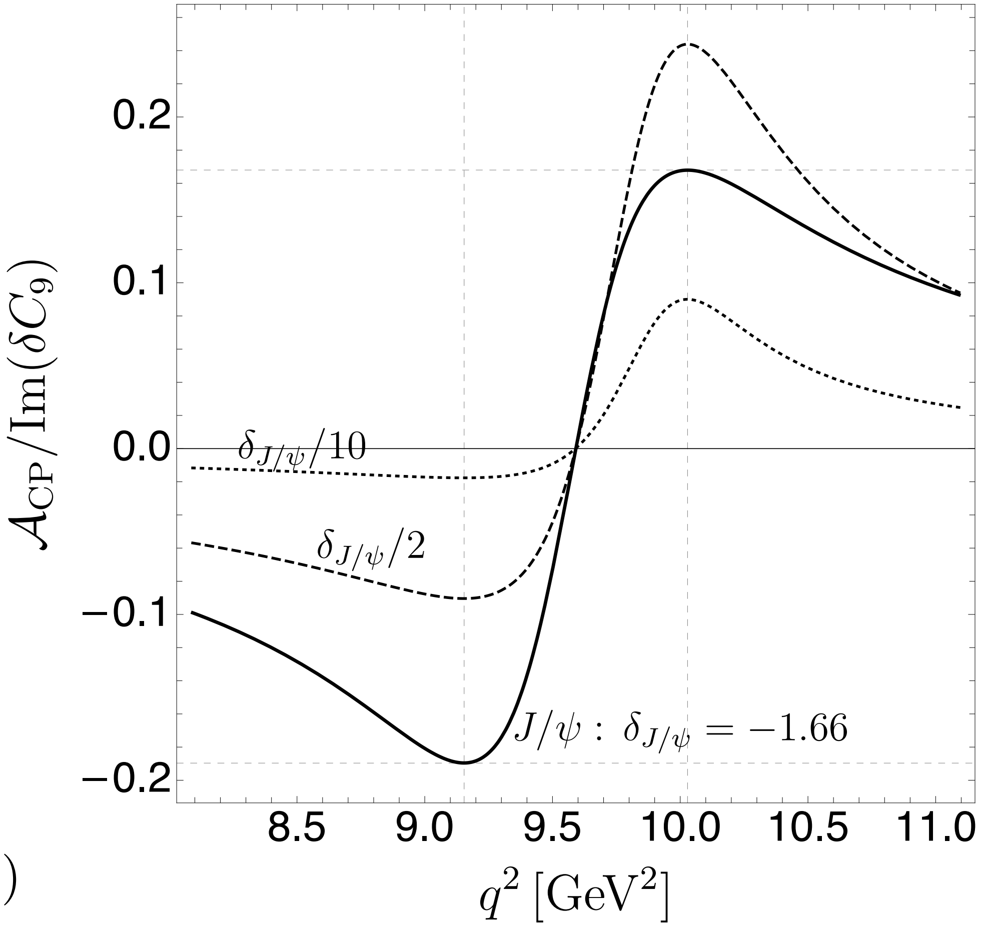
$$x \equiv (q^2 - m_j^2)/(m_j\Gamma_j)$$

For J/ψ and $\psi(2S)$ we take the $\delta_j \to \frac{\pi}{2}$ and large η_j limit...

$$\mathcal{A}_{\rm CP} = {\rm Im}(\delta C_9)\,\frac{2\eta_j\left(\cos\delta_j - x\sin\delta_j\right)}{\eta_j^2 - 2\eta_j B\left[\sin\delta_j + x\cos\delta_j\right] + A\left[1+x^2\right]}$$

For J/ψ and $\psi(2S)$:

- Large η_j and δ_j
- $\mathcal{A}_{\rm CP}$: - suppressed at resonant peak
  - enhanced away from peak
  - antisymmetric wrt. peak

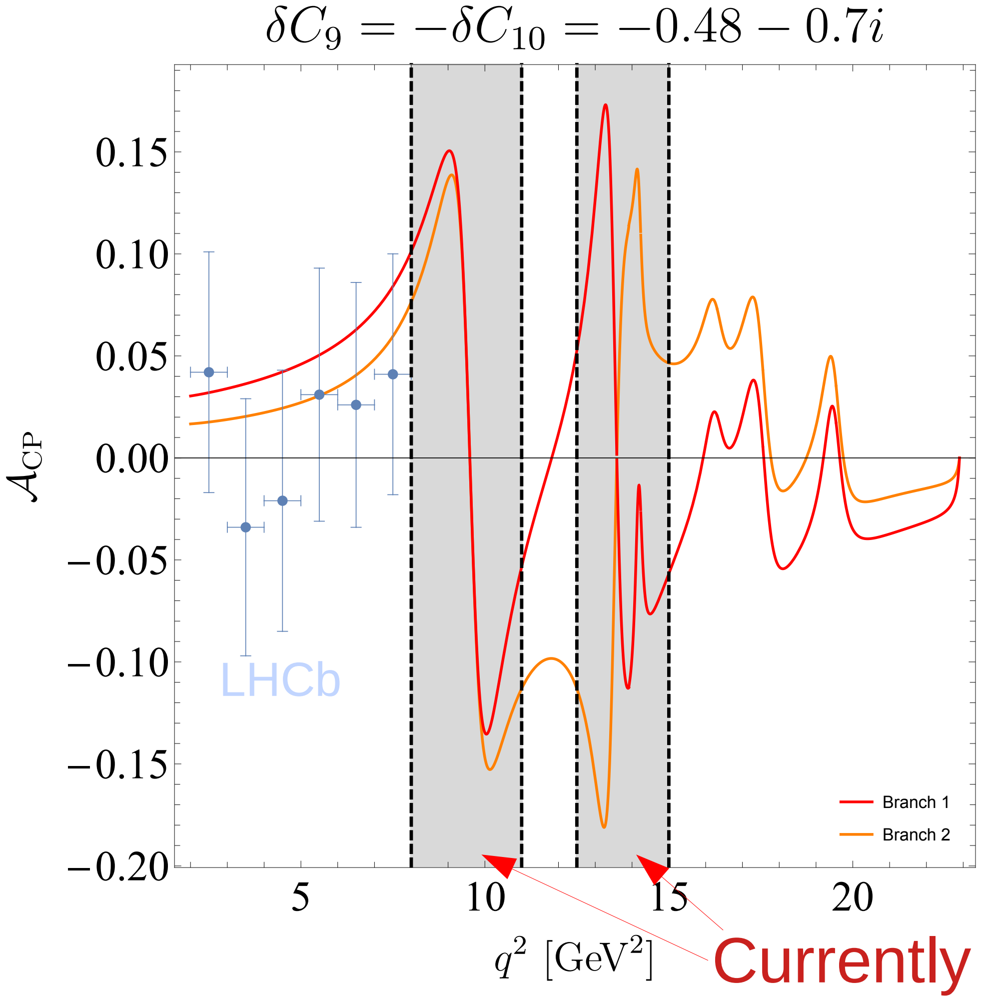


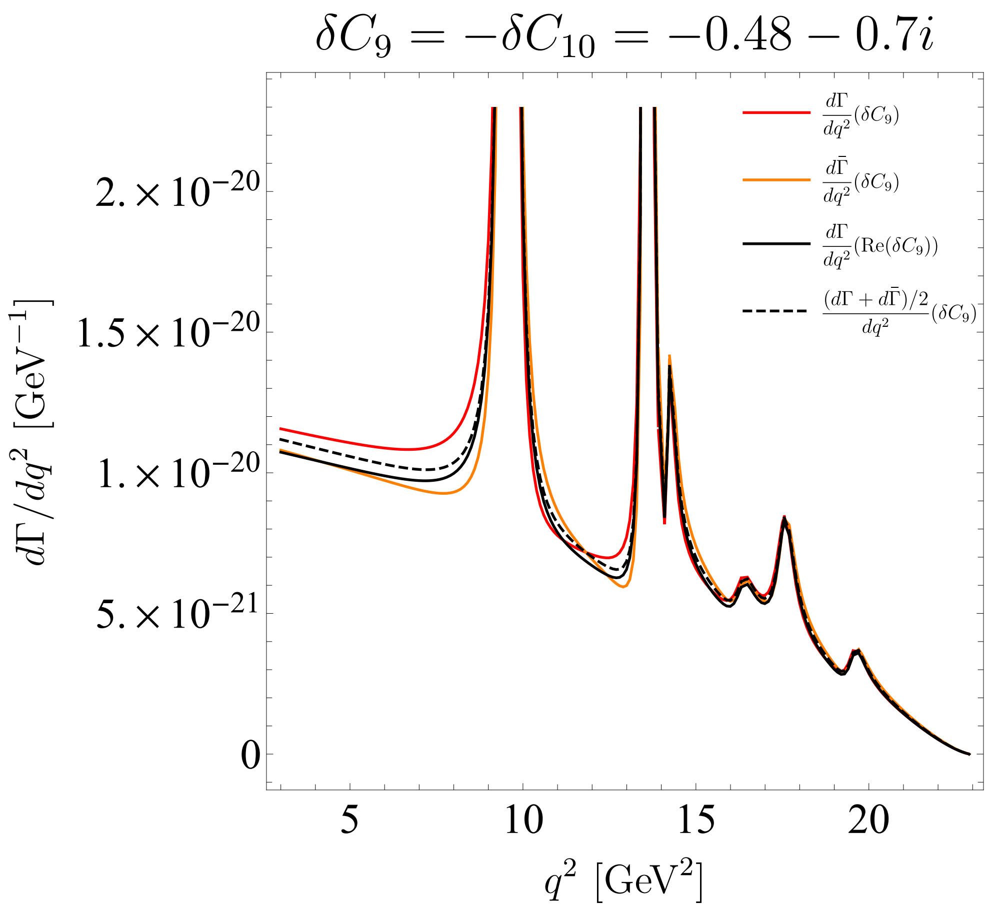
Maximal asymmetry:

$$q^2_{1,2} = m_j^2 \pm m_j\Gamma_j\left(\frac{\eta_j}{\sqrt{A}} + \frac{B}{\sqrt{A}\sin\delta_j}\right) + m_j\Gamma_j\cot\delta_j + \mathcal{O}(1/\eta_j)$$

$$\mathcal{A}_{\rm CP}\left(q^2_{1,2}\right) = {\rm Im}(\delta C_9)\,\frac{\sin\delta_j}{\pm\sqrt{A} + B\cos\delta_j} + \mathcal{O}(1/\eta_j)$$

A case for resonant regions

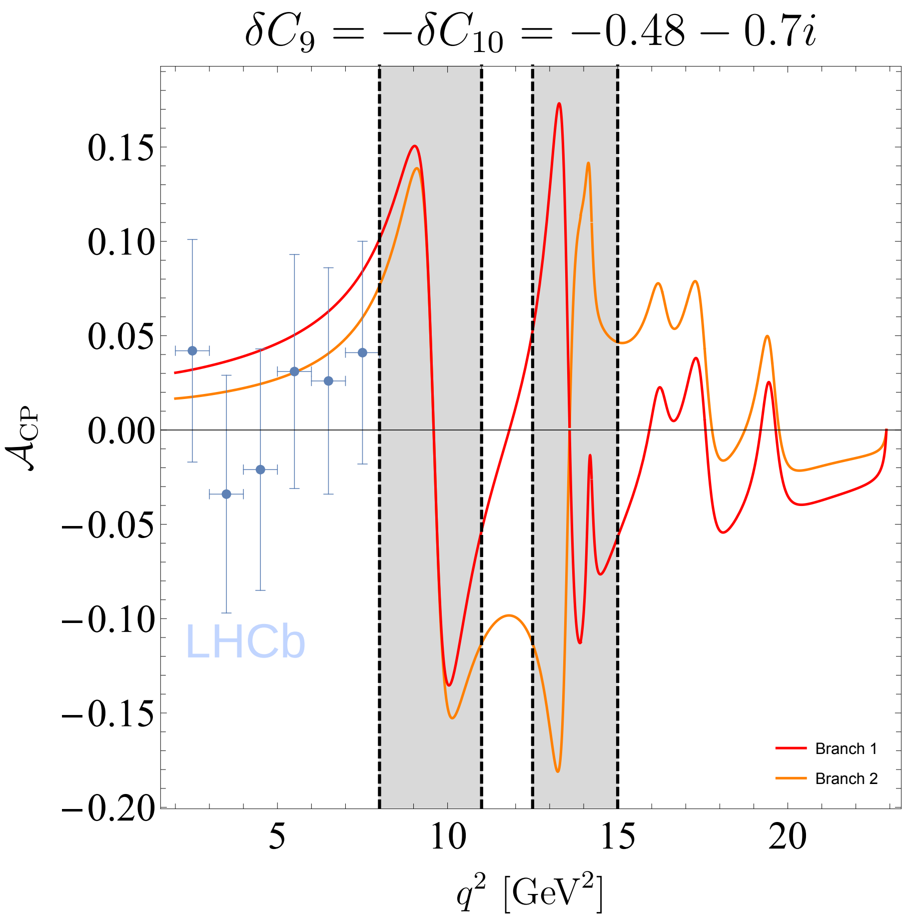




Currently not measured!

Conclusion

- The $\delta C_9 \in \mathbb{R}$ assumption should be experimentally scrutinized
- We show that $\delta C_9 \in \mathbb{C}$ still offers an explanation for $R_{K^{(*)}}$
- We include the current measurements of $\mathcal{A}_{\rm CP}$ and show $\mathrm{Im}\delta C_9 \sim 0.5$ viable
- Arguably the most interesting regions around $q^2 \approx m^2_{J/\psi,\psi(2S)}$ are currently cut out of analyses
- CP asymmetries are enhanced in those regions, it might be worth to include them!



Additional slides

$B \to K\mu^+\mu^-$ decay width

C. Bobeth, G. Hiller, and G. Piranishvili, JHEP 07, 106 (2008)

$$\frac{d\Gamma}{dq^2} = 2\mathcal{N}(q^2)\left[\frac{1}{6}\left(1+\frac{2m_\ell^2}{q^2}\right)\lambda(q^2)\left(|F_V|^2+|F_A|^2\right) + 4m_\ell^2 m_B^2|F_A|^2 - q^2|F_P|^2 + 2m_\ell(m_B^2-m_K^2-q^2)\mathrm{Re}\left(F_P F_A^*\right)\right]$$

$$\begin{aligned} F_V &= C_9\, f_+(q^2) + \frac{2m_b}{m_B+m_K} C_7\, f_T(q^2) \\ F_A &= C_{10}\, f_+(q^2) \\ F_P &= C_{10}\, m_\ell\left[f_+(q^2) - \frac{m_B^2-m_K^2}{q^2}\left(f_0(q^2)-f_+(q^2)\right)\right] \end{aligned}$$

$$\mathcal{N}(q^2) = \frac{G_F^2\alpha^2|V_{tb}V_{ts}^*|^2}{512\pi^5 m_B^3}\sqrt{\lambda(q^2)}\sqrt{1-\frac{4m_\ell^2}{q^2}}$$

$$\langle K(k)|\bar{s}\gamma_\mu b|B(p)\rangle = \left[(p+k)_\mu - \frac{m_B^2-m_K^2}{q^2}q_\mu\right]f_+(q^2) + \frac{m_B^2-m_K^2}{q^2}q_\mu f_0(q^2)$$

$$\langle K(k)|\bar{s}\sigma_{\mu\nu} b|B(p)\rangle = -i\left(p_\mu k_\nu - p_\nu k_\mu\right)\frac{2f_T(q^2)}{m_B+m_K}$$

S. Aoki et al. (Flavour Lattice Averaging Group), Eur. Phys. J. C 80, 113 (2020)

J. A. Bailey et al., Phys. Rev. D 93, 025026 (2016)

C. Bouchard, G. Lepage, C. Monahan, H. Na, and J. Shigemitsu (HPQCD), Phys. Rev. D 88, 054509 (2013)

$B_s \to \mu^+\mu^-$ constraint

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\text{exp}} = (2.69^{+0.37}_{-0.35}) \times 10^{-9}$$

Tech. Rep. LHCb-CONF-2020-002. CERN-LHCb- CONF-2020-002, CERN, Geneva (2020)

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\text{SM}} = (3.66 \pm 0.11) \times 10^{-9}$$

M. Beneke, C. Bobeth, and R. Szafron, JHEP 10, 232 (2019)

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\text{th}} = \tau_{B_s} \frac{\alpha^2 G_F^2 m_{B_s}}{16\pi^3} \left|V_{tb} V_{ts}^*\right|^2 m_\mu^2 \sqrt{1 - \frac{4m_\mu^2}{m_{B_s}^2}} \left|C_{10}\right|^2 f_{B_s}^2$$

$$f_{B_s} = (230.3 \pm 1.3)\,\text{MeV}$$

S. Aoki et al. (Flavour Lattice Averaging Group), Eur. Phys. J. C 80, 113 (2020)

$B_s - \overline{B}_s$ oscillations:

$$\mathcal{B}(B_s \to \mu^+\mu^-)^{\text{exp}} \approx \frac{1}{1 - y_s} \mathcal{B}(B_s \to \mu^+\mu^-)^{\text{th}}$$

K. De Bruyn, R. Fleischer, R. Knegjens, P. Koppenburg, M. Merk, and N. Tuning, Phys. Rev. D 86, 014027 (2012)

$$y_s = \Delta\Gamma_{B_s}/(2\Gamma_{B_s}) = 0.061(7)$$

(LHCb), Phys. Rev. Lett. 114, 041801 (2015)

CP asymmetry at the resonance

$$\frac{d\bar{\Gamma}}{dq^2} - \frac{d\Gamma}{dq^2} = \frac{4\mathcal{N}\lambda}{3}\left[f_+(q^2)\right]^2 \,\mathrm{Im}(C_9^{\mathrm{res}}(q^2))\,\mathrm{Im}(\delta C_9)$$

$$C_9^{\mathrm{res}}(q^2) \approx \frac{m_j \Gamma_j \eta_j e^{i\delta_j}}{m_j^2 - q^2 - i m_j \Gamma_j}$$

$$\boxed{\mathcal{A}_{\mathrm{CP}} = \mathrm{Im}(\delta C_9)\,\frac{2\eta_j\,(\cos\delta_j - x\sin\delta_j)}{\eta_j^2 - 2\eta_j B\left[\sin\delta_j + x\cos\delta_j\right] + A\left[1 + x^2\right]}}$$

$$x \equiv (q^2 - m_j^2)/(m_j\Gamma_j)$$

$$B = C_9^{\mathrm{SM}} + \frac{2m_b}{m_B + m_K}\frac{f_T(q^2)}{f_+(q^2)}C_7^{\mathrm{SM}} \approx 3.8$$

$$A = (C_{10}^{\mathrm{SM}})^2 + B^2 \approx 31$$

CP asymmetry at the resonance

$$\mathcal{A}_{\rm CP} = {\rm Im}(\delta C_9)\,\frac{2\eta_j\left(\cos\delta_j - x\sin\delta_j\right)}{\eta_j^2 - 2\eta_j B\left[\sin\delta_j + x\cos\delta_j\right] + A\left[1+x^2\right]}$$

For $\delta_j \to 0$:

$$\mathcal{A}_{\rm CP}(x\to 0)\Big|_{\delta_j=0} = {\rm Im}(\delta C_9)\,\frac{2\eta_j}{\eta_j^2 + A}$$

$$\mathcal{A}_{\rm CP} = {\rm Im}(\delta C_9)\,\frac{2\eta_j\,(\cos\delta_j - x\sin\delta_j)}{\eta_j^2 - 2\eta_j B\,[\sin\delta_j + x\cos\delta_j] + A\,[1+x^2]}$$

For $\delta_j \to \frac{\pi}{2}$, large η_j (J/ψ and $\psi(2S)$):

$$\mathcal{A}_{\rm CP}(x\to 0)\Big|_{\delta_j=\frac{\pi}{2}} = 0$$

$$\mathcal{A}_{\rm CP}(|x|\to\infty) = {\rm Im}(\delta C_9)\,\frac{2\eta_j(\cos\delta_j - x\sin\delta_j)}{A\,x^2}$$

Extrema:

$$q^2_{1,2} = m_j^2 \pm m_j\Gamma_j\left(\frac{\eta_j}{\sqrt{A}} + \frac{B}{\sqrt{A}\sin\delta_j}\right) + m_j\Gamma_j\cot\delta_j + \mathcal{O}(1/\eta_j)$$

$$\mathcal{A}_{\rm CP}\left(q^2_{1,2}\right) = {\rm Im}(\delta C_9)\,\frac{\sin\delta_j}{\pm\sqrt{A} + B\cos\delta_j} + \mathcal{O}(1/\eta_j)$$