R_K and CP asymmetry in $B \to K\mu\mu$

Aleks Smolkovič

Advisor: Nejc Košnik

Jožef Stefan Institute

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Introduction: why $b \to sl^+l^-$?

Clean theoretical prediction for R_K, R_{K^*} ratios

$$R^{\text{SM}}_{K^{(*)}} = \frac{\Gamma(B \to K^{(*)}\mu^+\mu^-)}{\Gamma(B \to K^{(*)}e^+e^-)} = 1.00 \pm 0.01.$$

M. Bordone et al., Eur. Phys. J. C76, 440 (2016)

Experimentally for $1.1\ \text{GeV}^2 < q^2 < 6.0\ \text{GeV}^2$

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036,$$

R. Aaij et al. (LHCb), Phys. Rev. Lett. 113 (2014)

$$R_{K^*} = 0.69^{+0.11}_{-0.07} \pm 0.05.$$

R. Aaij et al. (LHCb), JHEP 1708 (2017)

Effective Hamiltonian

For $b \to sl^+l^-$ transitions:

$$\mathcal{H}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i(\mu) O_i(\mu),$$

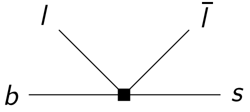
O_i - dim. 6 operators
C_i - Wilson coefficients $\to$ real in SM
in SM $i = 1, \ldots, 10$

Vector operator:

$$O_9 = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu l)$$

Axial vector operator:

$$O_{10} = \frac{e^2}{(4\pi)^2} (\bar{s}\gamma_\mu P_L b)(\bar{l}\gamma^\mu \gamma_5 l)$$



NP: $O'_{7,8,9,10}$, $O^{(\prime)}_{S,P}$

Invariant amplitude for $B \to Kl^+l^-$:

$$\mathcal{M} = \langle Kl^+l^-| - i\mathcal{H}_{\text{eff}}|B\rangle$$

Hadronic matrix elements:

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

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

form factors from lattice QCD

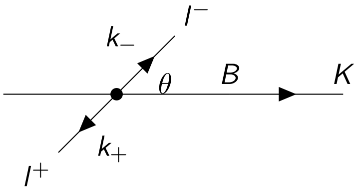
C. Bouchard et al. (HPQCD Collaboration), Phys. Rev. D88 (2013)

from here $\Gamma_l = \Gamma(B \to Kl^+l^-)$.

Decay width parametrization:

$$\frac{d^2\Gamma_l(q^2, \cos\theta)}{dq^2 d\cos\theta} = a_l(q^2) + b_l(q^2)\cos\theta + c_l(q^2)\cos^2\theta.$$

D. Bečirević, N. Košnik et al., Phys. Rev. D86 (2012)



with $q^2 = (k_+ + k_-)^2$

CP asymmetry $\to$ additional amplitude?

1. Introduction: $b \to sl^+l^-$
2. Contribution of vector resonances in $B \to K\mu^+\mu^-$
3. CP asymmetries in $B \to K\mu^+\mu^-$

$$B \to KV \to K\mu^+\mu^-$$

LHCb collaboration:

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

R. Aaij et al. (LHCb), Eur. Phys. J. C77 (2017)

with

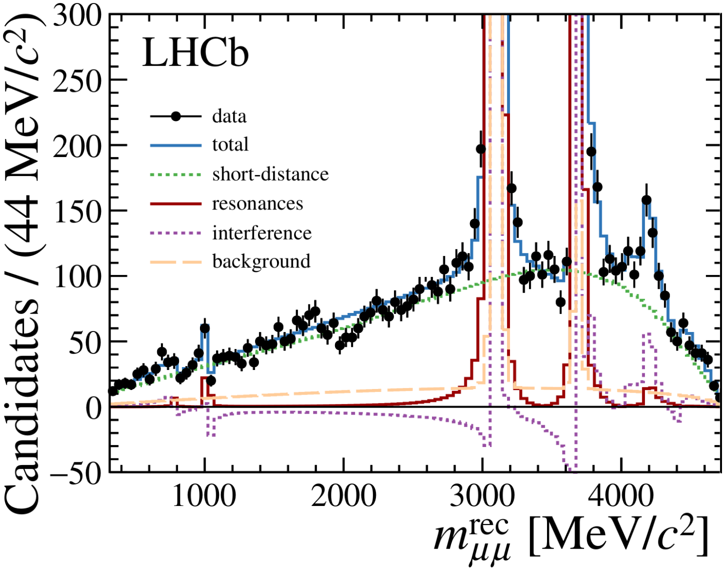
$$A_j^{\mathrm{res}}(q^2) = \frac{m_{0j}\Gamma_{0\,j}}{(m_{0j}^2 - q^2) - i m_{0j}\Gamma_j(q^2)},$$

$$\Gamma_j(q^2) = \frac{p}{p_{0j}} \frac{m_{0j}}{\sqrt{q^2}} \Gamma_{0j},$$

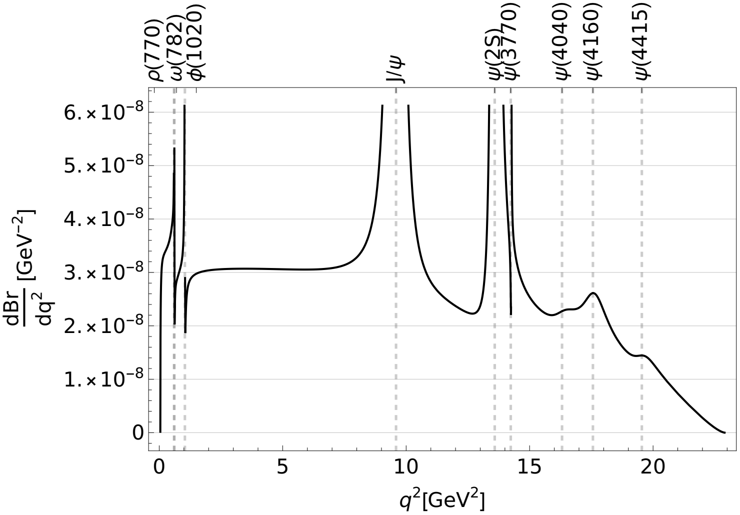
$$\Gamma_{\psi(3770)}(q^2) = \frac{p}{p_{0\,j}} \frac{m_{0\,j}}{\sqrt{q^2}} \left[\Gamma_1 + \Gamma_2 \sqrt{\frac{1 - (4m_D^2/q^2)}{1 - (4m_D^2/q_0^2)}} \right] .$$

Fit to the dimuon mass distribution $\to$ parameters η_j and δ_j for $j = \rho$, ω, ϕ, J/ψ, $\psi(2S)$, $\psi(3770)$, $\psi(4040)$, $\psi(4160)$ in $\psi(4415)$.

R. Aaij et al. (LHCb), Eur. Phys. J. C77 (2017)

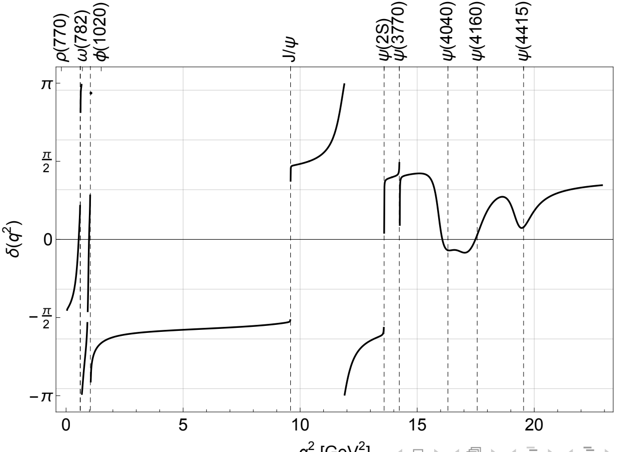


Branching fraction



The resonance amplitude is the source of the strong phase

$$\delta(q^2) = \arg \sum_j \eta_j e^{i\delta_j} A_j^{\mathrm{res}}(q^2)$$



Potential CP asymmetry

CP asymmetry:

- interference of two amplitudes ✓
- difference strong phase ✓
- difference in weak phases?

In SM: a very small CKM contribution

Proposal:
We allow complex NP couplings $\to$ difference in weak phases.

Wilson coefficients: $C_i = C_i^{\mathrm{SM}} + C_i^{\mathrm{NP}}$ where $C_i^{\mathrm{NP}} \in \mathbb{C}$

Experimental constraints

Experimentally for q^2 region without $\phi(1020)$, J/ψ and $\psi(2S)$:

$$A_{CP}(B^+ \to K^+\mu^+\mu^-) = 0.012 \pm 0.017 \pm 0.001.$$

R. Aaij et al. (LHCb), JHEP 09 (2014)

We also consider the $B_s \to \mu^+\mu^-$ branching fraction

$$\mathrm{Br}(B_s \to \mu^+\mu^-) = (2.4^{+0.9}_{-0.7}) \times 10^{-9}$$

C. Patrignani et al. (Particle Data Group), Chin. Phys. C40 (2016)

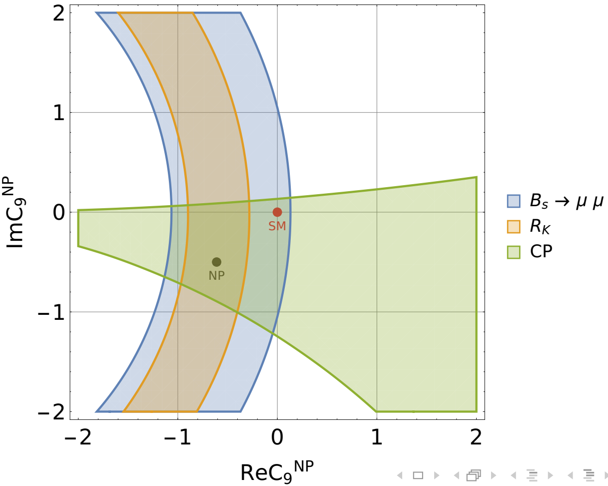
and R_K for $1.1\ \mathrm{GeV}^2 < q^2 < 6.0\ \mathrm{GeV}^2$:

$$R_K = 0.745^{+0.090}_{-0.074} \pm 0.036,$$

R. Aaij et al. (LHCb), Phys. Rev. Lett. 113 (2014)

$C_9^{\rm NP} = -C_{10}^{\rm NP}$ model

Preliminary results



Observables

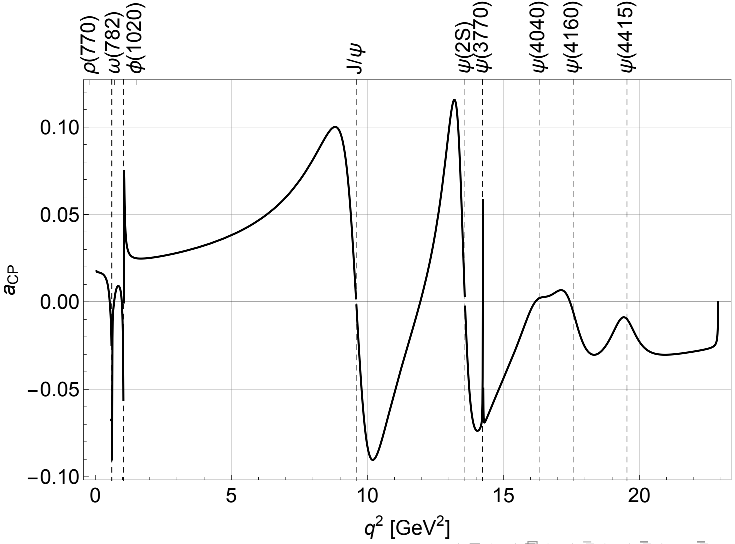
Partial CP asymmetry:

$$A_{CP}(q_1^2, q_2^2) = \frac{\Gamma_l(q_1^2, q_2^2) - \bar{\Gamma}_l(q_1^2, q_2^2)}{\Gamma_l(q_1^2, q_2^2) + \bar{\Gamma}_l(q_1^2, q_2^2)}$$

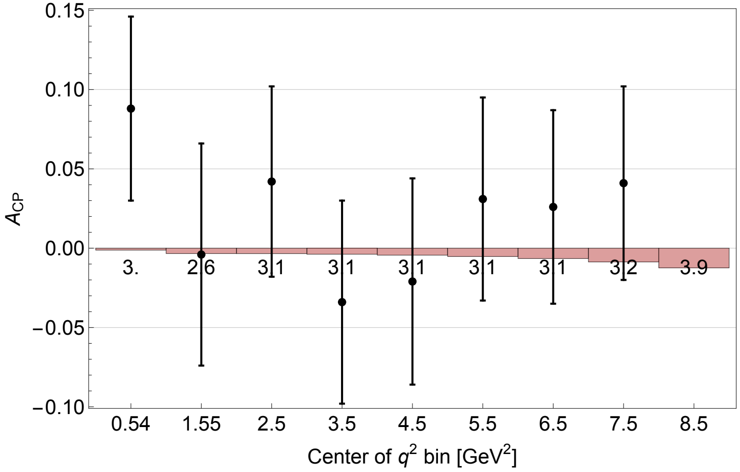
Differential CP asymmetry:

$$a_{CP}(q^2) = \frac{\frac{d\Gamma_l}{dq^2}(q^2) - \frac{d\bar{\Gamma}_l}{dq^2}(q^2)}{\frac{d\Gamma_l}{dq^2}(q^2) + \frac{d\bar{\Gamma}_l}{dq^2}(q^2)}$$

Differential CP asymmetry with $C_9^{\mathrm{NP}} = -C_{10}^{\mathrm{NP}} = -0.61 - 0.5\mathrm{i}$

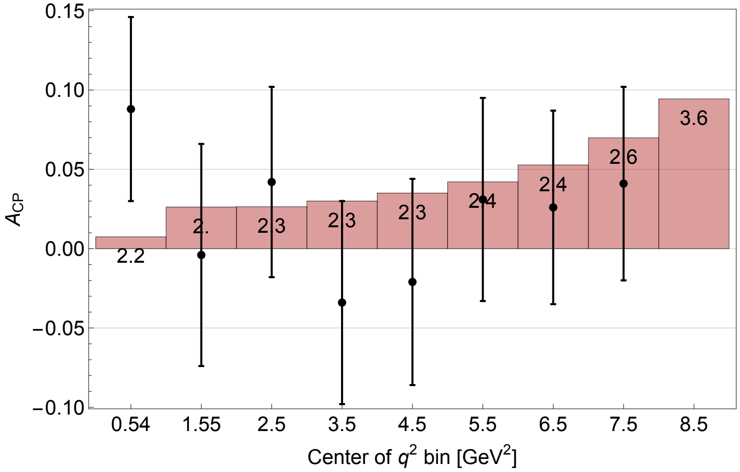


Partial CP asymmetry and branching fraction ($\times 10^8$) (SM)



Data from R. Aaij et al. (LHCb), JHEP 09 (2014)

$$C_9^{\rm NP} = -C_{10}^{\rm NP} = -0.61 - 0.5i$$



Data from R. Aaij et al. (LHCb), JHEP 09 (2014)

Conclusion

- Resonance contributions are the source of the strong phase
- NP Wilson coefficients can be the source of weak phases if allowed to be complex
- Large cancellations when measuring A_{CP} on whole q^2 region
- Large A_{CP} on smaller q^2 regions near narrow resonances gives clear NP signals
- Future analysis of $B \to K\tau\tau$ and $B \to K^*\mu\mu$

Additional slides

Decay width

$$\frac{d^2\Gamma_l(q^2,\cos\theta)}{dq^2 d\cos\theta} = a_l(q^2) + b_l(q^2)\cos\theta + c_l(q^2)\cos^2\theta$$

$$\begin{aligned} a_l(q^2) = \mathcal{C}(q^2)\Big[& q^2\left(\beta_l^2(q^2)|F_S(q^2)|^2 + |F_P(q^2)|^2\right) \\ & + \frac{\lambda(q^2,m_B^2,m_K^2)}{4}\left(|F_A(q^2)|^2 + |F_V(q^2)|^2\right) + 4m_l^2 m_B^2 |F_A(q^2)|^2 \\ & + 2m_l\left(m_B^2 - m_K^2 + q^2\right)\mathrm{Re}\left(F_P(q^2)F_A^*(q^2)\right)\Big], \end{aligned}$$

$$b_l(q^2) = 2\,\mathcal{C}(q^2) m_l \sqrt{\lambda(q^2,m_B^2,m_K^2)}\beta_l(q^2)\mathrm{Re}\left(F_S(q^2)F_V^*(q^2)\right)\,,$$

$$c_l(q^2) = -\mathcal{C}(q^2)\frac{\lambda(q^2,m_B^2,m_K^2)}{4}\beta_l^2(q^2)\left(|F_A(q^2)|^2 + |F_V(q^2)|^2\right)\,.$$

$$\mathcal{C}(q^2) = \frac{G_F^2 \alpha^2 |V_{tb} V_{ts}^*|^2}{512 \pi^5 m_B^3} \beta_l(q^2) \sqrt{\lambda(q^2, m_B^2, m_K^2)}\,,$$
$$\lambda(x,y,z) = (x+y+z)^2 - 4(xy+yz+zx),$$
$$\beta_l(q^2) = \sqrt{1 - 4m_l^2/q^2},$$

$$F_V(q^2) = \left(C_9 + C_9'\right) f_+(q^2) + \frac{2m_b}{m_B + m_K} \left(C_7 + C_7'\right) f_T(q^2)\,,$$
$$F_A(q^2) = \left(C_{10} + C_{10}'\right) f_+(q^2)\,,$$
$$F_S(q^2) = \frac{m_B^2 - m_K^2}{2m_b} \left(C_S + C_S'\right) f_0(q^2)\,,$$
$$F_P(q^2) = \frac{m_B^2 - m_K^2}{2m_b} \left(C_P + C_P'\right) f_0(q^2) - m_l \left(C_{10} + C_{10}'\right) \left[f_+(q^2) - \frac{m_B^2 - m_K^2}{q^2} \left(f_0(q^2) - f_+(q^2)\right)\right]\,.$$

LHCb fit

Resonance	Phase [rad]	Branching fraction
$\rho(770)$	-0.35 ± 0.54	$(1.71 \pm 0.25) \times 10^{-10}$
$\omega(782)$	0.26 ± 0.39	$(4.93 \pm 0.59) \times 10^{-10}$
$\phi(1020)$	0.47 ± 0.39	$(2.53 \pm 0.26) \times 10^{-9}$
J/ψ	-1.66 ± 0.05	–
$\psi(2S)$	-1.93 ± 0.10	$(4.64 \pm 0.20) \times 10^{-6}$
$\psi(3770)$	-2.13 ± 0.42	$(1.38 \pm 0.54) \times 10^{-9}$
$\psi(4040)$	-2.52 ± 0.66	$(4.17 \pm 2.72) \times 10^{-10}$
$\psi(4160)$	-1.90 ± 0.64	$(2.61 \pm 0.84) \times 10^{-9}$
$\psi(4415)$	-2.52 ± 0.36	$(6.04 \pm 3.93) \times 10^{-10}$

$$\tau_B \frac{G_F^2 \alpha^2 |V_{tb} V_{ts}^*|^2}{128\pi^5} \int_{4m_\mu^2}^{(m_B - m_K)^2} |\mathbf{k}|^3 \left[\beta - \frac{1}{3}\beta^3\right] \left|f_+(q^2)\right|^2 \left|\eta_j\right|^2 \left|A_j^{\mathrm{res}}(q^2)\right|^2 dq^2$$