Exploring an alternative model of the long-distance contributions to $\bar{B}^0 \rightarrow \bar{K}^{0*} \mu^+ \mu^-$ transitions 1709.03921.

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Present an empirical model of the long-distance contributions to $\bar{B}^0 \to \bar{K}^{0*} \mu^+ \mu^-$ transitions.

Simple approach that allows to extract short-distance components while capturing resonant structures across the full dimuon mass spectrum.

- Our model of long-distance effects is not meant as a formal prediction for various hadronic contributions.

- Interference between short- and long-distance amplitudes could mimic New Physics.
Modeling short- and long-distance contributions

- The differential decay rate of $\bar{B}^0 \rightarrow \bar{K}^{0*}(892)\mu^+\mu^-$ transitions depends on 6 complex amplitudes, $A_0^{L,R}, A_{||}^{L,R}, A_{\perp}^{L,R}$.

\[
A_0^{L,R}(q^2) = -8N\frac{m_B m_{K^*}}{\sqrt{q^2}} \left\{ \left( C_{9\,0}^{\text{eff}} \mp C_{10}^{\text{eff}} \right) A_{12}(q^2) + \frac{m_b}{m_B + m_{K^*}} C_7 T_{23}(q^2) \right\},
\]

\[
A_{||}^{L,R}(q^2) = -N\sqrt{2}(m_B^2 - m_{K^*}^2) \left\{ \left( C_{9\,||}^{\text{eff}} \mp C_{10}^{\text{eff}} \right) \frac{A_1(q^2)}{m_B - m_{K^*}} + \frac{2m_b}{q^2} C_7 T_2(q^2) \right\},
\]

\[
A_{\perp}^{L,R}(q^2) = N\sqrt{2\lambda} \left\{ \left( C_{9\,\perp}^{\text{eff}} \mp C_{10}^{\text{eff}} \right) \frac{V(q^2)}{m_B + m_{K^*}} + \frac{2m_b}{q^2} C_7 T_1(q^2) \right\},
\]

- Form Factors are taken from a combination of Light Cone Sum Rules (LCSM) and Lattice QCD (LQCD) results given in, Straub et al, JHEP08(2016)098.
Long distance contributions

- Empirical model using relativistic Breit-Wigners to model resonant contributions (a similar approach as $B \rightarrow K^+ \mu^+ \mu^-$, PAPER-2016-045).
- Incorporate many hadronic contributions: $J/\psi, \psi(2S), \rho(770), \phi(1020), \psi(3770), \psi(4040), \psi(4160)$.
- We group the resonant contributions into the Wilson Coefficient $C_9$

$$\Delta C_9^{\text{had}}(q^2) = \sum_j \eta_j^\lambda e^{i \theta_j} A_j^{\text{res}}(q^2),$$

Magnitude and phase of each resonant amplitude relative to $C_9$
Analyses of $B \to VK^*$ decays from LHCb, Belle and BaBar constrain the overall sizes of the magnitudes $\eta_0, \perp, \parallel$ and phases $\theta_\parallel, \theta_\perp$.

The phase, $\theta_0$ is an unknown parameter for each resonance.

No analyses exist for the $\psi(3770), \psi(4040)$ and $\psi(4160)$.

- Estimate from $B \to K^* J/\psi$ results and scaling of measurements from $B^+ \to VK^+$. 

\[
\Delta C^\text{had}_{9,\lambda}(q^2) = \sum_j \eta_j^\lambda e^{i\theta_j} A_j^\text{res}(q^2),
\] 

Magnitude and phase of each resonant amplitude relative to $C_9$.
Include long-distance contributions entering $\Delta C_{7\lambda}^{\text{had}}$. Parameters $\zeta_0, \perp, \parallel$ and $\omega_0, \perp, \parallel$ need to be determined from fit to $B^0 \rightarrow K^{*0} \mu^+ \mu^-$ data.

Total long distance contribution $= \Delta C_{9\lambda}^{\text{had}} + \Delta C_{7\lambda}^{\text{had}}$. 
Model 1:

- The model does not account for strong phases.
- Ignoring all phases gives a good agreement. But when we introduce the measured relative phases, no value of $\theta_0$ can describe the amplitudes simultaneously.
Model 2

- Compare to model by D. van Dyk et al,1707.07305 as presented earlier.
- For a given choice of phase, there is nice agreement.
- Discrepancy for the imaginary part is understood and comes setting $\omega_\lambda = \pi$. A complex value of $\Delta C_7^{\text{had}}$ provides a better agreement.
$$\bar{B}^0 \rightarrow \bar{K}^{0*} \mu^+ \mu^-$$ angular observables

**CP—averaged observables**

- Our model for $\Delta C_9^{\text{total}}$ can be used to provide predictions for $\bar{B}^0 \rightarrow \bar{K}^{0*} \mu^+ \mu^-$ angular observables in the SM.

- For each observable scan over all possible combinations of $\theta_0$ for each of the resonances.

- Bands are formed for each phase combination, by the $B \rightarrow K^*$ form factor uncertainties which are from combining light cone sum rules and lattice QCD calculations.
Distributions of the angular observables as function of $q^2$, for different phases (cyan), above (right) and below (left) the open charm threshold for regions below.

Observe $S_7$ being extremely sensitive to the choice of phases.
Exploring possible $CP$—violation

Since we have a model for the strong phases, we can now explore the impact of $CP$ violation by introducing weak phases.

A similar method has been done in $D \rightarrow P l^+ l^-$ decays PhysRevD.87.054026.

Determine subset of particularly sensitive $CP$—odd observables.

Set the relative (strong) phase $\theta_j^0$ for all long distant contributions to $-\frac{\pi}{2}, 0, \pi, \frac{\pi}{2}$.


1. $C^\text{NP}_9 = -1.0 - 1.0i$
2. $C^\text{NP}_7 = -0.03i$ and $C^\text{NP}_9 = -1$
Depending on the free phase, $\theta_j^0$, one can enhance $CP$ violation.
Predicted experimental precision

- Generate Monte Carlo equivalent to expected yields in Run 2.
- Include S-wave amplitudes for the $J/\psi$ and $\psi(2S)$, others are minute and so ignored.
- As dealing with narrow hadronic contributions we include detector resolution effects in $q^2$, applied in both generating and fitting.
- Perform a 4-dimensional fit in $q^2, \cos(\theta_L), \cos(\theta_K)$ and $\phi$.
- Float all resonant amplitudes including the Wilson Coefficients $C_9, C_{10}$.
- Form Factors fixed in the fit but introduced later as a systematic uncertainty.
Predictions of the observables $P_5'$ and $A_{FB}$ using the resulting precision from a fit to the model introducing long-distance contributions to $\bar{B}^0 \to \bar{K}^{0*} \mu^+ \mu^-$. LHCb data can help pin down the phases $\theta_{0,||,\perp}$ for each resonance.
Long-distance effects in tests of lepton universality

- If $C_9$ is not universal, hadronic effects do not cancel and observables such as $R_K$ and $R_K^*$ cannot be calculated precisely in the SM.
- Predictions for $R_K$ uses long-distance model and has been measured by PAPER-2016-045.
- Consider full variation of $\theta_0$ for each resonance to assess residual dependence of $R_K^*$ on hadronic effects.
- Effect on $R_K^*$ is small but dominates over residual form factor uncertainties (cf Form Factor choice from Capdevila et al:1704.05340).

### Table

<table>
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<tr>
<th>$C_{9NP}$</th>
<th>$R_K^*$: $1.1 &lt; q^2 &lt; 6.0 \text{ GeV}^2/c^4$</th>
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### Diagram

- $R_K^*$ vs $C_{9NP}$ for different $q^2$ ranges.
Our model will allow a simultaneous measurement of Wilson Coefficients and of multiple strong phases across the whole $q^2$ region.

Knowledge of strong phases enables an optimised measurement of $CP$ violating effects.

The residual dependence of $R_K$ and $R_K^*$ on hadronic effects in the presence of NP was found to be small.
Backup
Values of the Wilson Coefficients used.

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<thead>
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