Charm-loop contribution from data

Patrick Owen,
on behalf of the LHCb collaboration

24/09/19

2nd Hadronic Contributions to New Physics (HC2NP) workshop
Tensions

Something is interfering with $b\rightarrow sll$ decays.
What am I talking about?

Theoretically difficult to calculate

Could it be causing the tensions in previous slide?
Checks with data

- Can bin global fit in $q^2$.

![Diagram showing $C^\text{NP}_9$ vs. $q^2$ with shaded regions and dashed line]

- No significance dependence seen with $q^2$. 

The importance of an amplitude analysis

- Observables integrated in q^2 bins largely theory independent.
- However, important information in q^2 spectrum lost.
  - Useful to determine long-distance contributions.
  - Can also improve sensitivity to semileptonic part.

- Will discuss two approaches today:


Chrzaszcz et al, arxiv:1805.06378
Isobar approach

- The idea that the J/ψ phase can have a large effect at low q² was first discussed in [1].

![Graph showing C_{J/ψ} vs q²](image)

- By modelling the resonances with Breit-Wigner functions, can determine these phases with the data.

Main issue to deal with is the narrow J/psi and psi(2S) widths of 90 KeV and 300 KeV.

Resolution 100 times larger than that.

The other issue is that we have ~1M candidates at the J/psi peak.

Phase sensitivity from its tail, where resolution is complicated.

- Calculate $q^2$ after B-mass constrained kinematic fit.
- Float resolution parameters when fitting for phase.
- Validate fit with two different resolution approaches.
Fit model (Kµµ)

\[ \frac{d\Gamma}{dq^2} = \frac{G_F^2 c^2 |V_{tb} V_{ts}^*|^2}{27 \pi^5} |k| \beta_+ \left\{ \frac{2}{3} |k|\beta_+^2 |C_{10}^{\text{eff}} f_+(q^2)|^2 + \frac{m_b^2 (M_B^2 - M_K^2)^2}{q^2 M_B^2} |C_{10}^{\text{eff}} f_0(q^2)|^2 \right\} \]

\[ + |k|^2 \left[ 1 - \frac{1}{3} \beta_+^2 \right] \left| C_9^{\text{eff}} f_+(q^2) + 2 C_7^{\text{eff}} \frac{m_b + m_s}{M_B + M_K} f_T(q^2) \right|^2 \]

(2.10)

Add resonances here.

Replace \( Y(q^2) \) term with sum of Breit-Wigner functions.

Continuum of broad states above \( q^2_{\text{max}} \) neglected.
• Fit to data reveals that the J/ψ has little impact outside the region.

![Graph showing LHCb data and analysis results](image)

• Analysis substantially improves precision on J/ψ contribution.

• Non-resonant branching fraction \(~3\sigma\) below SM …
Other contributions

• There are several things we don’t currently account for:
  
  • Broad continuum of heavy cc states
  
  • Heavier states than the $\phi$
  
  • Other non-resonant contributions (?)

See C. Cornella’s talk later in this session.

<table>
<thead>
<tr>
<th>Decay</th>
<th>% of $B^+ \to K^+ \mu^+ \mu^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penguin</td>
<td>0.6 %</td>
</tr>
<tr>
<td>$B^+ \to \rho K^+$</td>
<td>0.0003 %</td>
</tr>
<tr>
<td>$B^+ \to \omega K^+$</td>
<td>0.0006 %</td>
</tr>
<tr>
<td>$B^+ \to \phi K^+$</td>
<td>0.003 %</td>
</tr>
<tr>
<td>$B^+ \to J/\psi K^+$</td>
<td>92 %</td>
</tr>
<tr>
<td>$B^+ \to \psi(2S) K^+$</td>
<td>7.3 %</td>
</tr>
<tr>
<td>$B^+ \to \psi(3770) K^+$</td>
<td>0.007 %</td>
</tr>
<tr>
<td>$B^+ \to \psi(4040) K^+$</td>
<td>$\sim 0$ %</td>
</tr>
<tr>
<td>$B^+ \to \psi(4160) K^+$</td>
<td>0.005 %</td>
</tr>
<tr>
<td>$B^+ \to \psi(4415) K^+$</td>
<td>$\sim 0$ %</td>
</tr>
</tbody>
</table>
Two useful checks

- For $m_{\mu\mu}^{\text{rec}}$ in MeV/c^2:
  - Data
  - Total
  - Short-distance
  - Resonances
  - Interference
  - Background

- For form factor value b_i:
  - Prior
  - Posterior

- For $q^2$ in (GeV^2/c^4):
  - Re$(\Delta C_{9,1})$
  - Re$(\Delta C_{9,2})$
  - Re$(\Delta C_{9,3})$

References:
What about $K^*\mu\mu$?

- $K^*\mu\mu$ angular observables can also discriminate between different phases.

- With the right phase, $J/\psi$ can explain half the effect in $P_5'$

- Very important to measure these in the data.

- $S_7$ very sensitive.
Approach using $z$-parameterisation

- Calculate the inclusive charm contribution at negative $q^2$.
- Extrapolate using $z$-parameterised dispersion relation.

$$\mathcal{H}_\lambda(z) = \frac{1 - z z^{*}_{J/\psi}}{z - z_{J/\psi}} \frac{1 - z z^{*}_{\psi(2S)}}{z - z_{\psi(2S)}} \mathcal{H}_\lambda(z)$$

$$\hat{\mathcal{H}}_\lambda(z) = \left[ \sum_{k=0}^{K} \alpha_{k}^{(\lambda)} z^k \right] \mathcal{F}_\lambda(z)$$

- Fit polynomial to theory points.
- Use polynomial parameters as constraints in fit to data.
Truncation of the polynomial

- Issue reported at Implications ’17 by A. Mauri was that the sensitivity to $C_9$ was heavily dependent on the truncation of the series.

- $z$ is not that small and so far has no unitarity condition.

$$\sigma(C_9)\big|_{z^2 \text{ fit}} = 0.19 \quad \text{and} \quad \sigma(C_9)\big|_{z^3 \text{ fit}} = 0.69$$

• However, this was using a staged approached to the data.
Simultaneous fit

- Simultaneous fit significantly improves situation.

Heavily dependent on theory, but consensus is that these are reliable at negative $q^2$.

Chrzaszcz et al, arxiv:1805.06378

<table>
<thead>
<tr>
<th></th>
<th>LHCb Run2</th>
<th>LHCb Upgrade [50 fb$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Re $C^\text{NP}$ mean</td>
<td>Re $C^\text{NP}$ sigma</td>
</tr>
<tr>
<td>$z^2$ fit</td>
<td>-0.966 ± 0.006</td>
<td>0.120 ± 0.004</td>
</tr>
<tr>
<td>$z^3$ fit</td>
<td>-0.991 ± 0.011</td>
<td>0.217 ± 0.008</td>
</tr>
<tr>
<td>$z^4$ fit</td>
<td>-1.022 ± 0.011</td>
<td>0.229 ± 0.008</td>
</tr>
<tr>
<td>$z^5$ fit</td>
<td>-0.942 ± 0.016</td>
<td>0.293 ± 0.011</td>
</tr>
</tbody>
</table>
Improvements to external inputs

- Improvement in phase measurements of resonances also useful for high $q^2$ region.
- Need a consistent treatment of exotic states between rare/tree-level measurements (something much simpler for the $\phi$).

\[ C_{10} \text{ uncertainty also saturates quite soon due to form factor uncertainties.} \]
Plan

• Unbinned $K^{(*)}\mu\mu$ analyses useful to help disentangle NP from QCD.

• So far they have not shown any evidence for large charm-loop effects at low $q^2$.

• Following two approaches, hopefully they get the same value of $C_9$. 

• Challenge to make analyses reanalysable with model improvements.
• Obviously no charm uncertainty on LFU observables in the SM.

• But NP interpretation can be affected.

• Uncertainty not so bad if one can measure spectrum in muon mode.

Blake et al, arXiv:1709.03921
Analysis assumptions

- Resonances described by Breit-Wigner line shapes, apart from the ψ(3770).

\[
A_{j}^{\text{res}}(q^2) = \frac{m_{0,j} \Gamma_{0,j}}{(m_{0,j}^2 - q^2) - i m_{0,j} \Gamma_{j}(q^2)}
\]

\[
\Gamma_{j}(q^2) = \frac{p}{p_{0,j}} \frac{m_{0,j}}{\sqrt{q^2}} \Gamma_{0,j}.
\]

\[
\Gamma_{\psi(3770)}(q^2) = \Gamma_{1} + \Gamma_{2} \sqrt{\frac{1 - (4m_{D}^2/q^2)}{1 - (4m_{D}^2/q_{0}^2)}}
\]

- Wilson Coefficients assumed to be real and no right-handed current counterparts.

- Assume that form factor is common for short- and long-distance.

- No contributions from weak annihilation or resonances with mass > q^{2}_{\text{max}} included.

- No (pseudo-)scalar or exotic contributions considered.
Breit-Wigner

- The Breit-Wigner formulation arises from 3D scattering theory.

\[ f = \frac{e^{i\delta}(e^{i\delta} - e^{-i\delta})}{2i} = e^{i\delta} \sin \delta = \frac{1}{(\cot \delta - i)} \]

\[ \cot \delta(E) = \cot \delta(E_R) + (E - E_R) \left[ \frac{d}{dE} \cot \delta(E) \right]_{E=E_R} + \cdots \]

\[ \simeq -(E - E_R) \frac{2}{\Gamma}, \]

Provided \(|E - E_R| \approx \Gamma \ll E_R^\ast\)

- Perhaps Lattice can check the J/ψ as well.
- The broader resonances at high q^2 more affected, but less data there.
- We are really worried about tail of the tail.
Fully hadronic input

- Huge samples of $B \rightarrow D^{(*)}D^{(*)}K$ expected at Belle 2 and LHCb upgrade 2

- Can these help fill in the gaps of missing components?