Highlights of LHCb measurement in rare decays and discovery of first pentaquark states with Run1 data

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(National Centre for Nuclear Research)
on behalf of the LHCb Collaboration
Outline

• Introduction
  ⊳ Why are we interested in flavour physics?

• The selected measurements in the LHCb
  ⊳ Exotic spectroscopy of $X(3872)$, $Z(4430)$ and pentaquark states $P_c(4380), P_c(4450)$
  ⊳ Very rare and rare decays:
    $B^0 \rightarrow \mu^+\mu^-$, $B^0 \rightarrow K^{*0} \mu^+\mu^-$, $B^+ \rightarrow K^+ \mu^+\mu^-$, $B^0_s \rightarrow \phi \mu^+\mu^-$, $\Lambda_b \rightarrow \Lambda \mu^+\mu^-$
  ⊳ Probes of lepton universality – ratios of branching fractions:
    $B^+ \rightarrow K^+\mu^+\mu^- / B^+ \rightarrow K^+e^+e^-$, $B^0 \rightarrow D^{(*)}\tau\nu / B^0 \rightarrow D^{(*)}\mu\nu$

• Summary
Why are we interested in flavour physics?

- The Standard Model (SM) is a theory which describes well existed data, but there are many phenomena which are not understood:
  - known value of CPV in the SM is too small to explain the observed size of matter domination over antimatter in the Universe

- The main goal of particle physics is to search for physics beyond the SM

There are two ways of searches for New Physics:

- **direct searches** for produced new objects (Atlas and CMS)

- **indirect searches** via testing the SM in precise measurements of known processes, finding disagreement will be indirect indication of new phenomena existence (BaBar, Belle, LHCb,...)
Why are we interested in flavour physics?

- The new particles can be exchanged in the loops

![Diagram showing Standard Model and New Physics](image)

In particular, we are interested in:

- **CP symmetry violation** in B and D sectors (see A. Obłąkowska-Mucha’s talk)
  - so far, there is no observation of CPV in charm sector, the SM predictions are very small

- **very rare decays** of B (this talk)
  - predicted highly supressed in SM

- as well as test of QCD models (quarkonia spectroscopy is an area where these tests can be performed)
Hadronic b decays

Introduction

Measuring $\gamma$ $\gamma$

Combination $\Box$ $\Box$ $\Box$

$\Box$

CP in $B^{\pm} \rightarrow D^{0} h$

$\Lambda_{b} \rightarrow \pi K p h$

$\Box$

Conclusions

C. Fitzpatrick

March 24, 2014

LHCb – precision detector

The single-arm forward spectrometer (a new concept for HEP experiments)

$\sigma(b\bar{b}) = 284 \pm 53 \mu b$ [PLB 694 (2010) 209] $10 < \theta < 300$ mrad ($2<\eta<5$)

$\sigma(c\bar{c}) \approx 20 \times \sigma(b\bar{b})$ [LHCb-CONF-2010-013]

(at $\sqrt{s}=7$TeV)

Run 1:

For each 1/fb:
~28k $B_{s}^{0} \rightarrow J/\psi(\mu\mu) \phi(K^{+}K^{-})$
~2M $D^{*\pm} \rightarrow D^{0}(\rightarrow K^{-}K^{+})\pi^{\pm}$

- VELO – precision primary and secondary vertex measurements,
  resolution of IP: 20 $\mu$m, decay lifetime resolution $\sim 45$ fs: $0.1 \tau(D^{0})$
- Excellent tracking resolution: $\Delta p/p = 0.4\%$ at 5 GeV to 0.6$\%$ at 100 GeV
- RICH – very good particle identification for $\pi$ and K
Observation of the $X(3872)$ resonance:

- First observed by Belle (2003)
  
  

- It has now been seen by 6 experiments (Belle, BaBar, CDF, D0, LHCb, CMS) in B decays and prompt production

- LHCb determined quantum numbers $J^{PC} = 1^{++}$ via angular analysis of $B \rightarrow X(J/\psi \pi \pi)K$
  
  

- Nature is still unclear; compatible with tetraquark, molecule or $\chi_{c1}(2^{3}P_{1})$ hypotheses (possibly mixed); it excludes any other charmonium state
Observation of the $Z(4430)\pm$:
- First seen by Belle (2008)
- Among all tetraquark candidates the $Z(4430)\pm$ is special; being charged it cannot be a $c$ anti-$c$ state
- LHCb sees 125k $B\to\psi(2S)K\pi$ decays

**No $Z(4430)$ p-value $\sim 10^{-6}$**

**Fit with $Z(4430)$ p-value $\sim 12\%$**

**The spin is confirmed to be $1^+$**
Pentaquarks

- Predicted by Gell-Mann (64), Zweig (64), other later in context of specific QCD models: Jafee (76), Högaasen & Sorba (78), Strottman (79)

M.Gell-Mann (Phys.Lett.8(1964)214-215): "Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q anti-q), etc., while mesons are made out of (q anti-q), (q q anti-q anti-q), etc.”

- No convincing states for 51 years

- Previous observations have been refuted
The $\Lambda_b \to J/\psi p K$ decays

- The decay $\Lambda_b \to J/\psi p K$ was first used by LHCb to make a precision measurements of the $\Lambda_b$ lifetime
- Results shown here use the full Run 1 data set, 3(fb)

![Plot with the three-body decay](image_url)

The three-body decay make a Dalitz plot, which showed an unusual feature
The prospect of hadrons with more than the minimal quark content (\(J/\psi p K\))

The solid (red) curve is the expectation from phase space. The background has been subtracted.

Figure 2: Invariant mass of (a) spectrum shown in Fig. 2(b).

An unexpected peaking structure was observed in the \(J/\psi p\) system.
No pentaquark

The amplitude analysis is performed. Fits with all known $\Lambda^*$ resonances but no pentaquark amplitudes fail to describe the data.

Also tried adding: all $\Sigma^*$ (isospin-violating) decays; two new $\Lambda^*$ resonances with free $M, \Gamma$; 4 non-resonant $\Lambda^*$ amplitudes. All fail to describe the data.
With pentaquark

One pentaquark

Two pentaquarks

Adding one pentaquark state improves the description but still fails to fully describe the data

Two pentaquarks (p_c = 4380MeV, 4450MeV) describe data

Best fit has J^P = 3/2^- (lower mass) and 5/2^+ (higher mass), also (3/2^+,5/2^-) & (5/2^+,3/2^-) are preferred

They have spin 3/2 & 5/2 & opposite parity
Are there resonances?

- The Argand diagram shows the typical phase motion of a resonance.
- Clear resonant-like behavior of the $P_{c}(4450)$; uncertainties too large to make conclusive statement about $P_{c}(4380)$.

LHCb has observed two states decaying into $J/\psi p$ consistent with pentaquark content of $(c \text{ anti-}c \ u \ u \ d)$

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$P_{c}(4380)^+$</th>
<th>$P_{c}(4450)^+$</th>
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<tbody>
<tr>
<td>$3^-_{2}</td>
<td>4380 \pm 8 \pm 29</td>
<td>4449.8 \pm 1.7 \pm 2.5</td>
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<td>Mass [MeV/c^2]</td>
<td></td>
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<td>Width [MeV]</td>
<td>205 \pm 18 \pm 86</td>
<td>39 \pm 5 \pm 19</td>
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<td>Significance</td>
<td>$9\sigma$</td>
<td>$12\sigma$</td>
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</table>
Rare decays as indirect probes for BSM physics

- Rare flavour changing neutral current (FCNC) decays (proceeds via a b- to s-quark) are forbidden at tree level in the SM
- It only occurs via electroweak penguin and box processes
- New heavy particles in SM extensions can enter in competing processes and can significantly change the branching fraction of the decay

Today:
- $B^0_{(s)} \rightarrow \mu^+\mu^-$
- $B^0 \rightarrow K^*\mu^+\mu^-$
- $B^{0,+} \rightarrow K^{0,+,*+}\mu^+\mu^-$
- $B^0_s \rightarrow \phi\mu^+\mu^-$
- $\Lambda_b \rightarrow \Lambda\mu^+\mu^-$
Very rare $B^0_{(s)} \rightarrow \mu^+ \mu^-$ decays

- Purely leptonic final state: theoretically and experimentally very clean
- Very sensitive to NP
- SM predictions (accounting for $\Delta \Gamma_s \neq 0$):
  \[
  \mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (3.66 \pm 0.23) \times 10^{-9}
  \]
  \[
  \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (1.06 \pm 0.09) \times 10^{-10}
  \]

First observation of $B^0_s \rightarrow \mu^+ \mu^-$ with 6.2$\sigma$ significance:
  \[
  \mathcal{B}(B^0_s \rightarrow \mu^+ \mu^-) = (2.8^{+0.7}_{-0.6}) \times 10^{-9}
  \]

First evidence of $B^0 \rightarrow \mu^+ \mu^-$ with 3.0$\sigma$ significance:
  \[
  \mathcal{B}(B^0 \rightarrow \mu^+ \mu^-) = (3.9^{+1.6}_{-1.4}) \times 10^{-10}
  \]

Both compatible with SM
The ratio \( R = \frac{\text{BF}(B^0 \rightarrow \mu\mu)}{\text{BF}(B^0_s \rightarrow \mu\mu)} \)

\[
R_{\text{SM}} = 0.0295^{+0.0028}_{-0.0025} \\
R = 0.14^{+0.08}_{-0.06} \text{ compatible at 2.3 } \sigma
\]

More details (including future plans): Hannah Mary Evans
Rare \(B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-)\ \mu^+\mu^-\) decays

The final state of the decay can be fully described by three angles and \(q^2 = m_{\mu\mu}^2\).

The CP-averaged angular distribution of the decay:

\[
\frac{1}{d(G + \bar{G})/dq^2} \frac{d^3(G + \bar{G})}{d\Omega} = \frac{9}{32\pi} \left[ \frac{3}{4} (1 - F_L) \sin^2 \theta_K + F_L \cos^2 \theta_K + \frac{1}{4} (1 - F_L) \sin^2 \theta_K \cos 2\theta_\ell \right.
\]

\[
- F_L \cos^2 \theta_K \cos 2\theta_\ell + S_3 \sin^2 \theta_K \sin^2 \theta_\ell \cos 2\phi + S_4 \sin 2\theta_K \sin 2\theta_\ell \cos \phi + S_5 \sin 2\theta_K \sin \theta_\ell \cos \phi
\]

\[
+ \frac{4}{3} A_{FB} \sin^2 \theta_K \cos \theta_\ell + S_7 \sin 2\theta_K \sin \theta_\ell \sin \phi
\]

\[
+ S_8 \sin 2\theta_K \sin 2\theta_\ell \sin \phi + S_9 \sin^2 \theta_K \sin^2 \theta_\ell \sin 2\phi \]

\(S_j\) – CP-averaged observables (relationships reduce the number of observable)

\(F_L (= S_1)\) – the longitudinal polarisation fraction of the \(K^{*0}\)

\(A_{FB} (= 3/4 \ S_6)\) – the forward-backward asymmetry of the dimuon system
Rare $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-) \mu^+\mu^-$ decays

LHCb 3/fb, 2011+2012, $2398 \pm 57$ events

Example in one $q^2$ bin

The CP-averaged observables $F_L$, $A_{FB}$ and $S_j$ are determined from a simultaneous unbinned maximum likelihood fit to three angles and invariant mass distributions in $q^2$ bins.

Good agreement of the fitted function with the data is observed.
Rare $B^0 \rightarrow K^{*0} (\rightarrow K^+ \pi^-) \mu^+ \mu^-$ decays

The $q^2$ at zero of $A_{FB}$ is a good probe of New Physics. 

The zero-crossing point of $A_{FB}$ is determined to be $3.7^{+0.8}_{-1.1}$ GeV$^2$, which is in good agreement with the SM prediction.
Rare $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-) \mu^+\mu^-$ decays

The measured CP-averaged observables $F_L$, $S_3$, $S_4$, $S_5$ (LHCb-PAPER-2015-051)

![Graphs showing the measured CP-averaged observables $F_L$, $S_3$, $S_4$, $S_5$ as a function of $q^2$ (GeV$^2$/c$^4$).]
Rare $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-) \mu^+\mu^-$ decays

Perform ratios of angular observables where form factors cancel at leading order

$$P'_5 = \frac{S_5}{\sqrt{F_L(1 - F_L)}}$$

A naïve combination of the deviations in two bins of $P'_5$: $4 < q^2 < 8 \text{ GeV}^2$ give a significance of $3.7\sigma$ agreement with the SM prediction
The decays: $B^{0,+} \rightarrow K^{0,+,*+} \mu^+\mu^-$

We measure also the differential branching fractions

$B^0 \rightarrow K^0 \mu^+\mu^-$

$LHCb$

$176 \pm 17$

$B^+ \rightarrow K^{*+} \mu^+\mu^-$

$LHCb$

$162 \pm 16$

$LHCb$

$B^+ \rightarrow K^{*+} \mu^+\mu^-$

$LHCb$

$B^0 \rightarrow K^0 \mu^+\mu^-$

$LHCb$

$4746 \pm 81$

$LHCb$

$B^+ \rightarrow K^{*+} \mu^+\mu^-$

$LHCb$

$162 \pm 16$

$LHCb$

Trend to be below SM prediction at low $q^2$?
**Rare $B^0_s \rightarrow \phi (\rightarrow K^+ K^-) \mu^+ \mu^-$ decays**

**LHCb 3/fb, 2011+2012, $432 \pm 24$ events**

- Dominant $b \rightarrow s \mu^+ \mu^-$ decay for $B^0_s$, analogous to the decay $B^0 \rightarrow K^*(0) (\rightarrow K^+ \pi^-) \mu^+ \mu^-$
- Full angular analysis performed, measure also differential branching fraction

![Graph showing differential branching fraction](image1)

For the $q^2$ region $1 < q^2 < 6$ GeV$^2$ the differential branching fraction of

$$\left(2.58^{+0.33}_{-0.31} \pm 0.08 \pm 0.19\right) \times 10^{-8} \text{ GeV}^{-2}$$

is $3.3\sigma$ below the SM prediction of $(4.81 \pm 0.56) \times 10^{-8}$ GeV$^{-2}$

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**JHEP09 (2015) 179**

Rare $B^0_s \rightarrow \phi(\rightarrow K^+K^-) \mu^+\mu^-$ decays

All angular observables consistent with the Standard Model

JHEP09 (2015) 179

Highlights of LHCb

Rare $\Lambda_b \rightarrow \Lambda \mu^+\mu^-$ decays

LHCb 3/fb, 2011+2012:

- $1.1<q^2<6$ GeV$^2$: 9.4 ± 6.3 candidates (1.7 significance)
- $15<q^2<20$ GeV$^2$: 276 ± 20 candidates (21 significance)

Similar tension with SM prediction for branching fraction at low $q^2$

Statistics still low for angular analysis
Probes of lepton universality

• Lepton flavour universality and conservation are accidental in the Standard Model.

• Any evidence of lepton flavour violation will point directly to new physics.

• Despite countless searches in many experiments no evidence of lepton flavour violation (apart from neutrinos...).

• Today:

  ➢ $B^+ \rightarrow K^+\mu^+\mu^- / B^+ \rightarrow K^+e^+e^-$

  ➢ $B^0 \rightarrow D^{(*)}\tau\nu / B^0 \rightarrow D^{(*)}\mu\nu$

  \[
  \overline{B}\left\{ \begin{array}{c}
  b \\
  q \\
  \end{array} \right\} \rightarrow W^- / H^- \rightarrow \tau^- \overline{\nu}_\tau \rightarrow D^{(*)}
  \]
Lepton universality using $B^+ \rightarrow K^+\ell^+\ell^-$

- The deficit of $B^+\rightarrow K^+\mu^+\mu^-$ compared to expectation in the differential branching fraction at low $q^2$ could be seen in $K^+\mu^+\mu^-/K^+e^+e^-$ ratio ($R_K$)
- SM prediction is $R_K = 1$ with an uncertainty of $O(10^{-3})$

Example mass fit for $K^+e^+e^-$

Note huge tail due to energy loss

Only $2.6\sigma$ from SM but suggestive
The decays $B^0 \to D^{(*)}\tau\nu$, $B^0 \to D^{(*)}\mu\nu$

We count decays with B, once in the final state there is heavy lepton ($\tau$) and once light ($\mu$)

\[ R(D^*) \equiv \frac{B(\bar{B}^0 \to D^{*+}\tau^-(\mu^-\overline{\nu}_\mu\nu_\tau)\overline{\nu}_\tau)}{B(\bar{B}^0 \to D^{*+}\mu^-\overline{\nu}_\mu)} \]

- Powerful channel to test lepton universality
- Sensitive to New Physics
- Measurements form BaBar and Belle hint of lepton universality violation

LHCb (PRL115(2015)112001):
- Agree with other measurements
- $2.1\sigma$ above SM:
  \[ R(D^*)^{SM} = 0.252 \pm 0.003 \]

Combined result from all measurements: $3.9\sigma$ above Standard Model
Summary

• The LHCb has performed **spectacularly well** in Run 1 (2011+2012, \(3/\text{fb}\)) confirming so far the robustness of the Standard Model

• For the first time, LHCb has observed **two resonant states in \(J/\psi p\)** consistent with pentaquarks: \(P_c(4380\text{MeV})\), \(P_c(4450\text{MeV})\)

• Rare decays are an excellent laboratory to search for BSM effects

• Several potential \(\sim 3\sigma\) hints of BSM effects to be explored further:
  - in rare \(B^0 \rightarrow K^0\mu^+\mu^-\) decays observable \(P'_5\) in \(4 < q^2 < 8 \text{ GeV}^2\) give a significance of \(3.7\sigma\) agreement with the SM
  - in rare \(B^0_s \rightarrow \phi\mu^+\mu^-\) decays in \(1<q^2<6 \text{ GeV}^2\) the differential branching fraction is \(3.3\sigma\) below the SM and this trend is seen in other decays
  - \(\mathcal{B}(D^*\tau\nu)/\mathcal{B}(D^*\mu\nu) = 0.336 \pm 0.027 \pm 0.030\) agree with SM (2.1\(\sigma\)), but combined result from all measurements is \(3.9\sigma\) above SM

• **First measurement of \(B \rightarrow X\tau\nu\) decay at a hadron collider performed by LHCb**

• Similar precision of previous \(B\) Factory measurements

• Demonstrate LHCb capabilities for high precision measurements in semileptonic decays

• Similar studies with hadronic tau decays ongoing
Prospects

Future:

• Data are being recorded, $2015-18 > 8/$fb at $\sqrt{s}=13$ TeV (Run 2)

• Move towards precision era for $B_s \rightarrow X \mu^+\mu^-$ decays

• Expand physics programme to more modes with electrons and taus:
  ⊘ not only $R_k (B \rightarrow K e^+ e^- / B \rightarrow K \mu^+ \mu^-)$ but similar ratios with different hadronic systems ($K^*, \phi, \Lambda$, etc.)
  ⊘ not only $D^* \tau \nu$, but also $D \tau \nu, D_s \tau \nu, \Lambda_c \tau \nu$, etc.

• LHCb upgrade (starting 2019) plans to collect $\sim 50/$fb data in 2022 and reach sensitivity which are comparable or better than theoretical uncertainties
## Prospects for rare decays in 2018 and beyond

C. Langenbruch (Warwick), LIO 2015

<table>
<thead>
<tr>
<th>Type</th>
<th>Observable</th>
<th>LHC Run 1</th>
<th>LHCb 2018</th>
<th>LHCb upgrade</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_s^0$ mixing</td>
<td>$\phi_s(B_s^0 \to J/\psi \phi)$ (rad)</td>
<td>0.049</td>
<td>0.025</td>
<td>0.009</td>
<td>$\sim 0.003$</td>
</tr>
<tr>
<td></td>
<td>$\phi_s(B_s^0 \to J/\psi f_0(980))$ (rad)</td>
<td>0.068</td>
<td>0.035</td>
<td>0.012</td>
<td>$\sim 0.01$</td>
</tr>
<tr>
<td></td>
<td>$A_{sl}(B_s^0)$ ($10^{-3}$)</td>
<td>2.8</td>
<td>1.4</td>
<td>0.5</td>
<td>0.03</td>
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<tr>
<td>Gluonic</td>
<td>$\phi_{s eff}(B_s^0 \to \phi \phi)$ (rad)</td>
<td>0.15</td>
<td>0.10</td>
<td>0.018</td>
<td>0.02</td>
</tr>
<tr>
<td>penguin</td>
<td>$\phi_{s eff}(B_s^0 \to K^{*0}K^{*0})$ (rad)</td>
<td>0.19</td>
<td>0.13</td>
<td>0.023</td>
<td>$&lt; 0.02$</td>
</tr>
<tr>
<td></td>
<td>$2\beta_{eff}(B_s^0 \to \phi K_S^0)$ (rad)</td>
<td>0.30</td>
<td>0.20</td>
<td>0.036</td>
<td>0.02</td>
</tr>
<tr>
<td>Right-handed currents</td>
<td>$\phi_{s eff}(B_s^0 \to \phi \gamma)$ (rad)</td>
<td>0.20</td>
<td>0.13</td>
<td>0.025</td>
<td>$&lt; 0.01$</td>
</tr>
<tr>
<td></td>
<td>$\tau_{eff}(B_s^0 \to \phi \gamma)/\tau_{\tau_{s}}$</td>
<td>5%</td>
<td>3.2%</td>
<td>0.6%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Electroweak</td>
<td>$S_3(B_s^0 \to K^{*0} \mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.04</td>
<td>0.020</td>
<td>0.007</td>
<td>0.02</td>
</tr>
<tr>
<td>penguin</td>
<td>$q_0^2 A_{FB}(B_s^0 \to K^{*0} \mu^+\mu^-)$</td>
<td>10%</td>
<td>5%</td>
<td>1.9%</td>
<td>$\sim 7%$</td>
</tr>
<tr>
<td></td>
<td>$A_1(K\mu^+\mu^-; 1 &lt; q^2 &lt; 6 \text{ GeV}^2/c^4)$</td>
<td>0.09</td>
<td>0.05</td>
<td>0.017</td>
<td>$\sim 0.02$</td>
</tr>
<tr>
<td></td>
<td>$B(B^+ \to \pi^+\mu^+\mu^-)/B(B^+ \to K^{*+}\mu^+\mu^-)$</td>
<td>14%</td>
<td>7%</td>
<td>2.4%</td>
<td>$\sim 10%$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$B(B_s^0 \to \mu^+\mu^-)$ ($10^{-9}$)</td>
<td>1.0</td>
<td>0.5</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td>penguin</td>
<td>$B(B_s^0 \to \mu^+\mu^-)/B(B_s^0 \to \mu^+\mu^-)$</td>
<td>220%</td>
<td>110%</td>
<td>40%</td>
<td>$\sim 5%$</td>
</tr>
<tr>
<td>Unitarity</td>
<td>$\gamma(B \to D^{(<em>)}K^{(</em>)})$</td>
<td>7°</td>
<td>4°</td>
<td>0.9°</td>
<td>negligible</td>
</tr>
<tr>
<td>triangle</td>
<td>$\gamma(B_s^0 \to D_s^{(<em>)}K^{(</em>)})$</td>
<td>17°</td>
<td>11°</td>
<td>2.0°</td>
<td>negligible</td>
</tr>
<tr>
<td>angles</td>
<td>$\beta(B_s^0 \to J/\psi K_S^0)$</td>
<td>1.7°</td>
<td>0.8°</td>
<td>0.31°</td>
<td>negligible</td>
</tr>
<tr>
<td>Charm</td>
<td>$A_\Gamma(D_s^0 \to K^+K^-)$ ($10^{-4}$)</td>
<td>3.4</td>
<td>2.2</td>
<td>0.4</td>
<td>–</td>
</tr>
<tr>
<td>CP violation</td>
<td>$\Delta A_{CP}$ ($10^{-3}$)</td>
<td>0.8</td>
<td>0.5</td>
<td>0.1</td>
<td>–</td>
</tr>
</tbody>
</table>
The blue and purple histograms show the two states. Events are shown as (black) squares with error bars, while the (red) circles show the results of the fit.

**Figure 8:**

- **Such interference requires two states with opposite parity**
- **LHCb has observed two resonant states decaying into J/ψp consistent with pentaquark content of (c anti-c u u d)**

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$\Lambda_b^0 \rightarrow J/\psi \ p \ K^- \ candidate$
Rare $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-) \mu^+\mu^-$ decays

LHCb 3/fb, 2011+2012

Full $q^2$ range: $2398 \pm 57$ events
Rare $B^0 \to K^{*0}(\to K^+\pi^-) \mu^+\mu^-$ decays

LHCb-C充满2015-002

(A. Ukleja)

Highlights of LHCb

08/01/2016

A. Ukleja

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Rare $B^0 \rightarrow K^{*0}(\rightarrow K^+\pi^-) \mu^+\mu^-$ decays

LHCb-CONF-2015-002
Rare $B^0_s \rightarrow \phi(\rightarrow K^+K^-) \mu^+\mu^-$ decays

All angular asymmetries consistent with SM