Charmless hadronic beauty decays at LHCb

Tim Williams on behalf of the LHCb collaboration

QFTHEP 2017

30/06/2017
Decays of $b$-hadrons to charmless hadronic final states typically proceed via either:
- $b \to u$ tree level diagrams
- $b \to s, d$ penguin loop diagrams

Tree level decays involve factor $V_{ub}$:
- Often similar amplitude to penguin decays, good for CP violation searches!
- Charmless $b$ decays are generally rare, $B \sim \mathcal{O}(10^{-5} - 10^{-8})$ - experimental challenges.
Physics Motivation

- Two main routes to new physics with charmless $b$ decays.

**Measure Branching Fractions**
- Presence of new physics in virtual loops could alter rate of decay process
- Tree decay often forbidden or similar amplitude - sensitivity to loop processes.

**Measure CPV observables**
- New physics participants could introduce significant levels of CPV.
- Measure both time dependent and independent CPV observables.

- Any significant discrepancies wrt. the standard model could be evidence for new physics.
- All measurements provide vital tests/input for QCD.
• Acceptance: $2 < \eta < 5$, 25% of $b\bar{b}$ pairs within acceptance

• 2 RICH sub detectors provide excellent PID ability, $\varepsilon(K) \sim 95\%$ with misID($\pi^- \rightarrow K^-$) $\sim 5\%$

• Dedicated vertex locator (VELO) close to beam pipe - finds secondary vertices, impact parameter resolution: $(15 \pm 29 \rho_T) \mu m$


The LHCb Detector at the LHC [JINST 3 (2008) S08005]
Luminosity Levelling at LHCb

- Luminosity kept $\sim$ constant throughout duration of LHC fill by detuning beams.
  - 2012 LHCb mean interactions per bunch crossing = 2.5 c.f ATLAS mean interactions per bunch crossing $\sim$ 40.
  - Lower detector occupancy allows precision hardware to be used - make precision measurements.
Recent Charmless Hadronic Beauty Decay Results

**Discussed in this Talk**

- Updated branching fraction measurements of $B_{(s)}^{0} \rightarrow K_{S}^{0} hh'$ decays [LHCb-PAPER-2017-010]
- Observation of charmless baryonic decays $B_{(s)}^{0} \rightarrow p \bar{p} h^{+} h^{-}$ [arXiv:1704.08497]
- Search for the $B_{s}^{0} \rightarrow \phi \eta'$ decay. [JHEP 05 (2017) 158]
- Observation of the decay $\Xi_{b}^{-} \rightarrow p K^{-} K^{-}$. [Phys. Rev. Lett. 118 (2017) 071801]
- First observation of a baryonic $B_{s}^{0}$ decay [arxiv:1704.07908]

- Evidence for the two-body charmless baryonic decay $B^{+} \rightarrow p \bar{\Lambda}$ [JHEP 04 (2017) 162]
- Observation of the decay $B_{s}^{0} \rightarrow \phi \pi^{+} \pi^{-}$ and evidence for $B^{0} \rightarrow \phi \pi^{+} \pi^{-}$ [Phys. Rev. D 95 (2017) 012006]
- Observation of the annihilation mode decay $B^{0} \rightarrow K^{+} K^{-}$ [Phys. Rev. Lett. 118 (2017) 081801]
- Measurement of time-dependent CP-violating asymmetries in $B^{0} \rightarrow \pi^{+} \pi^{-}$ and $B_{s}^{0} \rightarrow K^{+} K^{-}$ decays at LHCb. [LHCb-CONF-2016-018]
Search for $B^0_{s} \rightarrow K^0_S K^+ K^-$ and Updated $B^0_{(s)} \rightarrow K^0_S hh'$ Branching Fraction Measurements

[LHCb-PAPER-2017-010] NEW!
Motivation

Long Term Goals

- Possible to measure the weak phase of $B^0$ meson mixing in $b\rightarrow q\bar{q}s$ ($q=s,d,u$) transitions through the decays $B^0 \rightarrow K^0_S\pi^+\pi^-$ and $B^0 \rightarrow K^0_S K^+ K^-$. 

- Several extensions to the standard model introduce additional weak phases only present in $b\rightarrow q\bar{q}s$ decays - compare to weak phase extracted from $b\rightarrow c\bar{c}s$ decays - search for new physics.

- Possible to determine the CKM angle $\gamma$ with input from the amplitude analysis of $B^0_s \rightarrow K^0_S\pi^+\pi^-$ decays - theoretically clean [Phys. Lett. B645 (2007) 201].

First steps

- Observe all $B^0_{(s)} \rightarrow K^0_S hh'$ signal modes and measure branching fractions
Current Status

- Previous LHCb analysis using only 1 fb\(^{-1}\) of 2011 data made first observation of the \(B_s^0 \rightarrow K_S^0 K^{\pm} \pi^\mp\), \(B_s^0 \rightarrow K_S^0 \pi^+ \pi^-\) decays and confirmed the \(B^0 \rightarrow K_S^0 K^{\pm} \pi^\mp\). [JHEP 10 (2013) 143]

- No significant evidence for the \(B_s^0 \rightarrow K_S^0 K^+ K^-\) decay - still unobserved.

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**Previous Branching Fraction Results (val\(\pm\)stat\(\pm\)syst\(\pm\)\(\sigma\)(\(\mathcal{B}(K_S^0 \pi^+ \pi^-)\)))**

\[
\begin{align*}
\mathcal{B}(B^0 \rightarrow K_S^0 K^{\pm} \pi^\mp) &= (6.4 \pm 0.9 \pm 0.4 \pm 0.3) \times 10^{-6} \\
\mathcal{B}(B^0 \rightarrow K_S^0 K^+ K^-) &= (19.1 \pm 1.5 \pm 1.1 \pm 0.8) \times 10^{-6} \\
\mathcal{B}(B_s^0 \rightarrow K_S^0 \pi^+ \pi^-) &= (14.3 \pm 2.8 \pm 1.8 \pm 0.6) \times 10^{-6} \\
\mathcal{B}(B_s^0 \rightarrow K_S^0 K^{\pm} \pi^\mp) &= (73.6 \pm 5.7 \pm 6.9 \pm 3.0) \times 10^{-6} \\
\mathcal{B}(B_s^0 \rightarrow K_S^0 K^+ K^-) &\in [0.2 - 3.4] \times 10^{-6}\;; \text{at 90\% CL}
\end{align*}
\]

- New analysis using 3 fb\(^{-1}\) 2012+2011 LHCb data aims to observe \(\mathcal{B}(B_s^0 \rightarrow K_S^0 K^+ K^-)\) mode.
Strategy and Event Selection

- Separate reconstruction categories for $K^0_S$ candidates with/without hits in the VELO - labelled Long/Downstream.

$$\frac{\mathcal{B}(B^0_{(s)} \to K^0_S hh')} {\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)} = \frac{\varepsilon^{sel}_{B^0 \to K^0_S \pi^+ \pi^-} N_{B^0_{(s)} \to K^0_S hh'}} {\varepsilon^{sel}_{B^0 \to K^0_S hh'} N_{B^0 \to K^0_S \pi^+ \pi^-}} \frac{f_d}{f_d,s}$$

- BDT classifier trained to remove combinatorial background.
  - Only use topological variables to avoid significant variation in efficiency over phase-space.
  - Separate optimisations for suppressed/favoured modes - two separate selections for each final state.

- PID requirements used to remove mis-ID backgrounds e.g $\Lambda^0_b \to K^0_S p\pi^-$. 
Mass Fits

- $B^0$ Signal, $B^0_s$ Signal, Partially Reconstructed Background, Mis-ID Background, Mis-ID Background.

### Favoured Optimisation

- $K^0_S K^+ K^-$
- $K^0_S K^\pm \pi^\mp$

### Suppressed Optimisation

- $K^0_S K^+ K^-$
- $K^0_S \pi^+ \pi^-$
- $K^0_S K^\pm \pi^\mp$
Unobserved $B_s^0 \rightarrow K_s^0 K^+ K^-$ channel Mass Fit

[Suppressed Optimisation]

- $12 \pm 6/7 \pm 4$ signal events seen in the long/downstream reconstruction category.
- Still only $2.5\sigma$ significance for $B_s^0 \rightarrow K_s^0 K^+ K^-$. 

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30/06/2017 12/43
Results and Conclusions

- Using world average value of $\mathcal{B}(B^0 \to K^0_s\pi^+\pi^-) = 4.96 \pm 0.20 \times 10^{-6}$ with previous LHCb result omitted.

Updated Branching Fraction Results ($\text{val} \pm \text{stat} \pm \text{syst} \pm \sigma(\mathcal{B}(K^0_s\pi^+\pi^-))$)

- $\mathcal{B}(B^0 \to K^0_s K^{\pm}\pi^\mp) = (6.1 \pm 0.5 \pm 0.7 \pm 0.3) \times 10^{-6}$
- $\mathcal{B}(B^0 \to K^0_s K^+K^-) = (27.2 \pm 0.9 \pm 1.6 \pm 1.1) \times 10^{-6}$
- $\mathcal{B}(B^0_s \to K^0_s \pi^+\pi^-) = (9.5 \pm 1.3 \pm 1.5 \pm 0.4) \times 10^{-6}$
- $\mathcal{B}(B^0_s \to K^0_s K^{\pm}\pi^\mp) = (84.3 \pm 3.5 \pm 7.4 \pm 3.4) \times 10^{-6}$
- $\mathcal{B}(B^0_s \to K^0 K^+K^-) \in [0.4 - 2.5] \times 10^{-6}$; at 90% C.L.

- Precision improved but still consistent with previous LHCb results. [JHEP 10 (2013) 143]

- $B^0_s \to K^0_s K^K$ still not observed - have to wait for inclusion of LHC Run II data.

- Work underway to perform Dalitz-plot analyses of dominant decay modes - $B^0 \to K^0_s\pi^+\pi^-$, $B^0_s \to K^0_s K^{\pm}\pi^\mp$, and $B^0 \to K^0_s K^+K^-$. 
Search for the decay $B_s^0 \rightarrow p \Lambda \bar{K}^-$
Inclusive branching fraction to baryonic final states $\sim 7\%$ of total $B$ width!
- Most decay modes still unobserved/unstudied

Baryonic decay of $B_s^0$ meson never previously observed.

$\mathcal{B}$(Multi-body baryonic $B$ decays) > $\mathcal{B}$(two-body baryonic $B$ decays)

$\mathcal{B}(B_s^0 \rightarrow p\Lambda K^-)$ predicted to be $\mathcal{O}(10^{-6})$.

Perform blind search for $B_s^0 \rightarrow p\Lambda K^-$ using 3 fb$^{-1}$ Run I dataset.
- Optimise selection on MC, Data not viewed until selection and mass fit frozen.

Strategy

- Measure $\mathcal{B}(B_s^0 \rightarrow p\Lambda K^-) + \mathcal{B}(\bar{B}_s^0 \rightarrow p\Lambda K^-)$ because of identical final states.
- Topologically very similar decay $B^0 \rightarrow p\Lambda\pi^-$ used as normalisation channel.

\[
\mathcal{B}(B_s^0 \rightarrow p\Lambda K^-) + \mathcal{B}(\bar{B}_s^0 \rightarrow p\Lambda K^-) = \frac{f_d}{f_s} \frac{N(B_s^0 \rightarrow p\Lambda K^-)}{N(B^0 \rightarrow p\Lambda\pi^-)} \frac{\epsilon_{B_s^0 \rightarrow p\Lambda K^-}}{\epsilon_{B^0 \rightarrow p\Lambda\pi^-}} \mathcal{B}(B^0 \rightarrow p\Lambda\pi^-)
\]

- Yield of control channel and ratio of branching fractions determined with simultaneous fit to all data samples.
  - Ratio of efficiencies included as Gaussian constraint.

Selection

- MLP classifier used to remove combinatorial background and PID requirements on $p$ and $K^-/\pi^-$ to remove mis-ID background.
Mass Fits

![Graphs showing mass distributions for $B^0 \rightarrow p \Lambda \pi^-$ and $B^0_s \rightarrow p \Lambda K^-$](image)

**Fit Results**

- $N(B^0 \rightarrow p \Lambda \pi^-) = 519 \pm 28$
- $N(B^0_s \rightarrow p \Lambda K^-) = 234 \pm 29$, significance $>15\sigma$, first observation!
- $\mathcal{B}(B^0_s \rightarrow p \Lambda K^-) + \mathcal{B}(\bar{B}^0_s \rightarrow p \Lambda K^-) = 5.46 \pm 0.61 \pm 0.57 \pm 0.50(\mathcal{B}) \pm 0.32(\frac{f_s}{f_d}) \times 10^{-6}$
Normalised, background subtracted and efficiency corrected $M(p \, \overline{\Lambda})$ distributions shown.

Clear threshold enhancement can be seen.
Search for $B^0_{(s)} \rightarrow p\bar{p}h^+h^-$ decays

[arXiv:1704.08497]
Motivation and Strategy

- No four body charmless baryonic $B_s^0$ decay has been observed.
- Search performed for $B_{(s)}^0 \rightarrow p\bar{p}h^+h^-$ ($h=K$ or $\pi$) decays using 3 fb$^{-1}$ data from LHCb Run I.
  - $m(p \bar{p}) < 2.85$ GeV and $\Lambda_c^+$ and $D^0$ resonances vetoed.
- $B^0 \rightarrow (J/\psi \rightarrow p\bar{p})(K^{*0} \rightarrow K^+\pi^-)$ used as normalisation channel.
- BDT used to reduce combinatorial background and particle identification requirements remove mis-ID background.
- Simultaneous fit to invariant mass of 3 final states used to extract signal yields ($M(p \bar{p} K \pi)$, $M(p \bar{p} K K)$, $M(p \bar{p} \pi \pi)$).
- 3D Fit to $M(p \bar{p} K \pi)$, $M(p \bar{p})$ and $M(K \pi)$ used to extract normalisation yield.
Signal Channel Fit Results

Signal Yields

\[
\begin{align*}
N_{B^0}^{p\bar{p}KK} &= 68 \pm 17 \\
N_{B^0}^{p\bar{p}K\pi} &= 4155 \pm 83 \\
N_{B^0}^{p\bar{p}\pi\pi} &= 902 \pm 35 \\
N_{B_s}^{p\bar{p}KK} &= 635 \pm 32 \\
N_{B_s}^{p\bar{p}K\pi} &= 246 \pm 39 \\
N_{B_s}^{p\bar{p}\pi\pi} &= 39 \pm 16
\end{align*}
\]

First observation, Strong Evidence

![Invariant mass distributions for various signal modes](image)

- Data
- Total fit
- \(B^0 \to p\bar{p}\pi\pi\)
- \(B^0_s \to p\bar{p}\pi\pi\)
- \(B^0 \to p\bar{p}K\pi\)
- \(B^0_s \to p\bar{p}K\pi\)
- Comb. bkgd.
<table>
<thead>
<tr>
<th>Decay Channel</th>
<th>Significance/$\sigma$</th>
<th>Branching Fraction/10^{-6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow p\bar{p}K^+K^-$</td>
<td>4.1</td>
<td>$0.113 \pm 0.028 \pm 0.011 \pm 0.008$</td>
</tr>
<tr>
<td>$B^0 \rightarrow p\bar{p}K^+\pi^-$</td>
<td>$&gt; 25$</td>
<td>$5.9 \pm 0.3 \pm 0.3 \pm 0.4$</td>
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<td>$B_s^0 \rightarrow p\bar{p}K^+\pi^-$</td>
<td>6.5</td>
<td>$1.3 \pm 0.21 \pm 0.11 \pm 0.09 \pm 0.08$</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow p\bar{p}\pi^+\pi^-$</td>
<td>2.6</td>
<td>$&lt; 0.66$ at 90% CL</td>
</tr>
</tbody>
</table>

- Results presented as $val \pm stat \pm sys \pm \sigma(normB) \pm \sigma(f_s/f_d)$
- Limit set on $B_s^0 \rightarrow p\bar{p}\pi^+\pi^-$ by integrating likelihood in physical region.
Normalised background subtracted and efficiency corrected $M(h^+h^-)$ distributions shown.

Vector mesons, $\phi$, $\rho^0$, $K^{*0}$ clearly present.

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Threshold enhancement in $M(p\bar{p})$

- Normalised background subtracted and efficiency corrected $M(p\bar{p})$ distributions shown.
- Clear threshold enhancement

$B_s^0 \to p\bar{p}K^+K^-$

$B^0 \to p\bar{p}\pi^+\pi^-$

$B^0 \to p\bar{p}K^+\pi^-$
Search for the decay $B_s^0 \rightarrow \phi \eta'$

[JHEP 05 (2017) 158]
**Motivation**

- $B_s^0 \rightarrow \phi \eta'$ proceeds predominantly through a $b \rightarrow s$ gluonic penguin diagram.

- Sensitive to phase $\phi_s$ but yet to be observed.

- Wide range of theory predictions and large uncertainties partly due to limited knowledge of $B_s^0 \rightarrow \phi$ form factors.

<table>
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<th>Theory Approach</th>
<th>$\mathcal{B}(10^{-6})$</th>
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<td>$0.05^{+1.18}_{-0.19}$</td>
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Blind search performed using full LHCb Run I data set.

- $B^+ \rightarrow K^+ \eta'$ used as normalisation channel - high yield, minimal background and precisely known $\mathcal{B}(B^+ \rightarrow K^+ \eta') = (70.6 \pm 2.5) \times 10^{-6}$
- $\eta'$ reconstructed in decay $\eta' \rightarrow \pi^+ \pi^- \gamma$ and $\phi$ reconstructed in decay $\phi \rightarrow K^+ K^-$. 

Optimise similar selection for signal and control channel:
- Multivariate classifier (BDT) with 9 variables used to reject majority of background
- Particle identification requirements on both hadrons and photons.
- $2D(M_{\eta'K^+(K^-)}, M_{\pi^+\pi^-\gamma})$ simultaneous fit to both $B_s^0 \rightarrow \phi \eta'$ and $B^+ \rightarrow K^+ \eta'$ to extract yields
Fit Components:

**Signal**

\[ B_s^0 \rightarrow \phi(\phi \rightarrow \pi^+ \pi^- \pi^0) \]

background

Combinatorial background with true \( \eta' \)

Combinatorial background without true \( \eta' \)
Small bias correction due to $B_s^0 \rightarrow \phi (\phi \rightarrow \pi^+ \pi^- \pi^0)$ component (1.3 $\pm$ 0.7) events.

**Fit Results**

- $N(B_s^0 \rightarrow \phi \eta') = -1.9_{-3.8}^{+5.0} (\text{stat}) \pm 1.1 (\text{syst})$
- $\frac{N(B_s^0 \rightarrow \phi \eta')}{N(B^+ \rightarrow K^+ \eta')} = (-1.73_{-3.45}^{+4.54} (\text{stat}) \pm 0.99 (\text{syst})) \times 10^{-4}$

Upper limit set on branching fraction using bayesian method with uniform prior.

**Branching Fraction Limit**

$\mathcal{B}(B_s^0 \rightarrow \phi \eta') < 0.82(1.01) \times 10^{-6}$ at 90%(95%) CL
Comparison to Theoretical Predictions

Motivation
\(B^0_s \to \pi^0\) proceeds predominantly through a \(b \to s\) gluonic penguin diagram.

- Theory Approach
- \(B(10^{-6})\)
- Reference

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- 4 out of 7 presented theory predictions are ruled out at 95% confidence level!
Search for $\Xi_b^-, \Omega_b^- \rightarrow p h^- h'^-$ decays

The decay of a \( \Xi_b^- \) or \( \Omega_b^- \) to a charmless final state has never been observed.

Interference between CKM suppressed tree and loop diagrams may lead to CP-violation effects.

First search for these decays performed using \( 3 \text{ fb}^{-1} \) LHCb Run I data.
### Analysis Strategy

#### Selection

- Neural network used to separate signal and combinatorial background
- Tight Particle-ID requirement on proton to remove background from $B^- \rightarrow K^- h^- h'^-$ decays.
- Pion and Kaon Particle-ID requirements optimised and chosen to ensure each candidate is only assigned to one of three possible final states ($p K^- K^-$, $p K^- \pi^-$, $p \pi^- \pi^-$).

#### Fit Strategy

- Fit performed to all three $p h^+ h'^-$ mass distributions simultaneously, constrain cross-feed between channels to expected rate.
- Separate fit to $B^- \rightarrow K^+ K^- K^-$ control channel.
Mass Fits

LHCb

Candidates / ( 20 MeV/c² )

m(pK^-K^-) [MeV/c²]

Data
Total fit
Ξ_b^- Signal
Ω_b^- Signal
Cross-feed bkgd.
Part. rec. bkgd.
Comb. bkgd.

LHCb

Candidates / ( 20 MeV/c² )

m(pπ^-π^-) [MeV/c²]

Data
Total fit
Ξ_b^- Signal
Ω_b^- Signal
Cross-feed bkgd.
Part. rec. bkgd.
Comb. bkgd.

Signal Yields

\[ \Xi_b^- \rightarrow pK^-K^- \] \quad 82.9 \pm 10.4 \quad 8.7 \sigma

\[ \Xi_b^- \rightarrow pK^-\pi^- \] \quad 59.6 \pm 16.0 \quad 3.4 \sigma

\[ \Xi_b^- \rightarrow p\pi^-\pi^- \] \quad 33.2 \pm 17.9 \quad < 2 \sigma

\[ \Omega_b^- \rightarrow pK^-K^- \] \quad -2.8 \pm 2.5 \quad < 2 \sigma

\[ \Omega_b^- \rightarrow pK^-\pi^- \] \quad -7.6 \pm 9.2 \quad < 2 \sigma

\[ \Omega_b^- \rightarrow p\pi^-\pi^- \] \quad 20.1 \pm 13.8 \quad < 2 \sigma
\[ R_{phh'} = \frac{f_\Xi}{f_d} \times \frac{\mathcal{B}(\Xi^- \rightarrow p h^- h'^-)}{\mathcal{B}(B^- \rightarrow K^+ K^- K^-)} = \frac{N(\Xi^- \rightarrow p h^- h'^-)}{N(B^- \rightarrow K^+ K^- K^-)} \frac{\varepsilon(B^- \rightarrow K^+ K^- K^-)}{\varepsilon(\Xi^- \rightarrow p h^- h'^-)} \]

- \( \Xi_b^- , \Omega_b^- \) fragmentation fractions not measured, measure \( \frac{f_\Xi}{f_d} \times \mathcal{B} \)
- Efficiencies corrected for variation over phase-space.
- For channels with < 3\( \sigma \) significance, limit set by integrating likelihood in physical region, 90% confidence levels shown.

**\( R_{phh'} \) Results (10^{-5})**

\[ R_{phh'}(\Xi_b^- \rightarrow p K^- K^-) = 265 \pm 35 \pm 47 \]
\[ R_{phh'}(\Xi_b^- \rightarrow p K^- \pi^-) = 259 \pm 64 \pm 49 \]
\[ R_{phh'}(\Xi_b^- \rightarrow p \pi^- \pi^-) < 147 \]
\[ R_{phh'}(\Omega_b^- \rightarrow p K^- K^-) < 18 \]
\[ R_{phh'}(\Omega_b^- p K^- \pi^-) < 51 \]
\[ R_{phh'}(\Omega_b^- p \pi^- \pi^-) < 109 \]

- No evidence for \( \Omega_b^- \) decays, hierarchy of \( \Xi_b^- \) decays as expected.
Background subtracted using sPlot method.

- Efficiency corrected $M(pK^-)_{min}$ distribution shows a rich resonant structure which appears to be consistent with known states such as the $\Lambda(1520)$, $\Lambda(1670)$ and $\Lambda(1690)$.

<table>
<thead>
<tr>
<th>Mode</th>
<th>Yield</th>
</tr>
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<tbody>
<tr>
<td>$\Lambda(1520)$</td>
<td>3000</td>
</tr>
<tr>
<td>$\Lambda(1670)$ &amp; $\Lambda(1690)$</td>
<td>2500</td>
</tr>
<tr>
<td>$\Xi(1500)$</td>
<td>2000</td>
</tr>
<tr>
<td>$\Xi(1670)$</td>
<td>1500</td>
</tr>
<tr>
<td>$\Xi(1690)$</td>
<td>1000</td>
</tr>
</tbody>
</table>

Upper limits are quoted at 90 (95) % confidence level for modes with signal significance less than 3σ.
Search for CP Violation in $\Lambda_b^0 \rightarrow p\pi^- \pi^+ \pi^-$ decays

Nature Physics 13 (2017) 391
Motivation

- **5σ evidence for CP violation in a b-baryon has never been observed.**

- Cabibbo suppressed tree diagram (left) and loop diagram (right) have similar amplitudes-CPV could arise from the interference of the two amplitudes.

- LHCb looks to exploit copious $\Lambda_b^0$ production at the LHC, nearly 20% of all $b$ hadrons produced.
Study asymmetries in the $\hat{T}$ operator - unitary operator that reverses both momentum and spin three-vectors.

Define scalar triple products:

$$C_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{\pi^-} \times \vec{p}_{\pi^+}), \quad \bar{C}_{\hat{T}} = \vec{p}_p \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$$

Define asymmetries as:

$$A_{\hat{T}}(C_{\hat{T}}) = \frac{\mathcal{N}(C_{\hat{T}}>0) - \mathcal{N}(C_{\hat{T}}<0)}{\mathcal{N}(C_{\hat{T}}>0) + \mathcal{N}(C_{\hat{T}}<0)} \quad \bar{A}_{\hat{T}}(\bar{C}_{\hat{T}}) = \frac{\bar{\mathcal{N}}(-\bar{C}_{\hat{T}}>0) - \bar{\mathcal{N}}(-\bar{C}_{\hat{T}}<0)}{\bar{\mathcal{N}}(-\bar{C}_{\hat{T}}>0) + \bar{\mathcal{N}}(-\bar{C}_{\hat{T}}<0)}$$

where CPV and PV observables then defined as:

$$a_{\hat{T} - odd}^{CP} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}), \quad a_{\hat{T} - odd}^{p} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$$

A significant deviation from zero in this observable would signal CPV.
Observation of $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$

- $\Lambda_b^0 \rightarrow p\pi^+\pi^-\pi^+$ yet to be observed - first step is to observe it!
- Selection makes use of BDT classifier and LHCb particle ID requirements.
- Signal yield extracted with unbinned extended maximum likelihood fit.

Yield Results

- 6646 ± 105 Signal events
- First observation of $\Lambda_b^0 \rightarrow p\pi^-\pi^+\pi^-$
Sample split into 4 categories according to $\Lambda_b^0$ or $\bar{\Lambda}_b^0$ and $C$ or $\bar{C}$ - simultaneous extended maximum likelihood fit to extract asymmetries.

CP asymmetries may vary over phase space of four body decay due to resonant contributions - phase-space integrated asymmetries could cancel.

Measure $a_{CP}^{\hat{T}-odd}$ and $a_p^{\hat{T}-odd}$ in bins of phase-space - two separate binning schemes used.

Binning scheme A - use two body invariant masses - designed to exploit strong resonant structure e.g. $\Delta(1232)^{++} \rightarrow p\pi^+$

Binning scheme B - use angle between $p\pi_{fast}^-$ and $\pi^+\pi_-\text{slow}$ decay planes $\Phi$ - exploit interference of contributions.
CPV results

\[ \chi^2 \] test used to determine compatibility of each binning scheme with the null hypothesis of CP symmetry.

- p-values indicate 2.0\(\sigma\) and 3.4\(\sigma\) evidence for CP violation in binning schemes A and B respectively.

- Combined significance = 3.3\(\sigma\) obtained using permutation test. First evidence for CP-violation in a \(b\)-baryon decay!
Summary & Conclusions

- Wide and interesting range of charmless $b$-hadron decays are studied at LHCb.
- Stringent upper limit set on $\mathcal{B}(B_s^0 \rightarrow \phi \eta') < 0.82(1.01) \times 10^{-6}$ at 90%(95%) confidence level.
- First observation of the baryonic $B_s^0$ decay, $B_s^0 \rightarrow p \bar{\Lambda} K^-$.
- First observations of $B^0 \rightarrow p \bar{p} \pi^+ \pi^-$, $B_s^0 \rightarrow p \bar{p} K^+ \pi^-$, $B_s^0 \rightarrow p \bar{p} K^+ K^-$ decays and strong evidence for $B^0 \rightarrow p \bar{p} K^+ K^-$ decay.
- Updated branching fraction measurements for all $B_{d,s}^0 \rightarrow K_S^0 h^\pm h'^\mp$ decays.
- 8.4$\sigma$ observation of $\Xi_b^- \rightarrow p K^- K^-$, no evidence seen for $\Omega_b^- \rightarrow p K^- K^-$
- 3.3$\sigma$ evidence for CP violation seen in $\Lambda_b^0 \rightarrow p \pi^- \pi^+ \pi^-$, first evidence for CP violation in a $b$-baryon decay!
Particle Identification

The power of the RICH PID can be appreciated by considering the Cherenkov angle as a function of momentum. Figure 40 shows the Cherenkov angle as a function of track momentum and for different ranges of transverse momentum, demonstrating the kaon efficiency (kaons identified as kaons) and showing that more than 90% of the protons are misidentified as pions. Figure 41 demonstrates the kaon efficiency (kaons identified as kaons in the interaction point or in the calorimeter shower) and shows that the misidentification rate is reduced for higher momenta.

The background estimation and likelihood minimisation are performed to determine the background contribution for each HPD, as well as to maximise the efficiency of pions as muons. The same criterion is used to define the number of stations required to reject the background. The selection of such control samples must be performed to reconstruct, through a high polar angle and therefore fall outside of the high-occupancy part of the detector. Decays in flight are the dominant cause of misidentification, with any other ring from the same radiator.

The background contribution to the event likelihood is determined prior to the likelihood algorithm described in the next iterations. These modifications to the likelihood minimisation dramatically reduce the proton misidentification rate in the interval 300,400 GeV.

In addition to K/π separation, both p/π and p/Ks e p a r a t i o n a r ee q u a l l y v i t a l for a r g e large [Birmingham]
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<th>$B(10^{-6})$</th>
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Observation of annihilation mode decay $B^0 \rightarrow K^+ K^-$

[Phys. Rev. Lett. 118, 081801]
Large uncertainties still remain on the theoretical predictions of branching fractions for decays that are dominated by weak annihilation transitions, e.g. $B^0 \rightarrow K^+ K^-$ and $B_s^0 \rightarrow \pi^+ \pi^-$.

Measurement of $B^0 \rightarrow K^+ K^-$ and $B_s^0 \rightarrow \pi^+ \pi^-$ branching fractions provide vital input to understanding these decays.

The decay $B_s^0 \rightarrow \pi^+ \pi^-$ was observed for the first time by LHCb using fraction of Run I dataset. $\mathcal{B}(B_s^0 \rightarrow \pi^+ \pi^-) = (0.95^{+0.21}_{-0.17} \pm 0.13) \times 10^{-6}$.

No evidence previously existed for the decay $B^0 \rightarrow K^+ K^-$. 
Analysis Strategy

- Perform search for $B^0 \rightarrow K^+ K^-$ and improve measurement of $B_s^0 \rightarrow \pi^+ \pi^-$ using full Run I LHCb dataset.
- Well known decay $B^0 \rightarrow K^+ \pi^-$ used as control channel for both signal channels.
- Extract signal yields by fitting $K^+ K^-$ and $\pi^+ \pi^-$ final states simultaneously and constraining mis-ID crossfeed.

Selection

- LHCb PID system used to separate data into mutually exclusive subsamples corresponding to $K^+ \pi^-$, $\pi^+ \pi^-$ and $K^+ K^-$ final states.
- BDT classifier used to reduce combinatorial background.
- Two separate optimisations of BDT output and PID requirements for $K^+ K^-$ and $\pi^+ \pi^-$ final states, selections denoted $S_{K^+K^-}$ and $S_{\pi^+\pi^-}$. 
Mass Fit Results

Fit Results

- \( N(B^0 \rightarrow K^+ K^-) = 201 \pm 33 \pm 14 \)
- \( N(B_s^0 \rightarrow \pi^+ \pi^-) = 455 \pm 35 \pm 24 \)
- Statistical significance of \( B^0 \rightarrow K^+ K^- \) signal = 5.5\( \sigma \).
First observation of $B^0 \to K^+ K^-$!

Branching Fraction calculated as:

$$\frac{\mathcal{B}(B^0_x \to h^+ h^-)}{\mathcal{B}(B^0 \to K^+ \pi^-)} = \frac{N(B^0_x \to h^+ h^-)}{N(B^0 \to K^+ \pi^-)} \frac{\varepsilon(B^0 \to K^+ \pi^-)}{\varepsilon(B^0_x \to h^+ h^-)} \frac{f_d}{f_x}$$

Branching Fraction Results

- $\mathcal{B}(B^0 \to K^+ K^-) = (7.80 \pm 1.27 \pm 0.81 \pm 0.21) \times 10^{-8}$
- $\mathcal{B}(B^0 \to \pi^+ \pi^-) = (6.91 \pm 0.54 \pm 0.63 \pm 0.19 \pm 0.40) \times 10^{-7}$

Results presented as $val \pm stat \pm sys \pm \sigma(norm\mathcal{B}) \pm \sigma(fS/f_d)$