Charmless hadronic beauty decays at LHCb

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Introduction

- 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, $\mathcal{B} \sim \mathcal{O}(10^{-5} - 10^{-8})$ - 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.

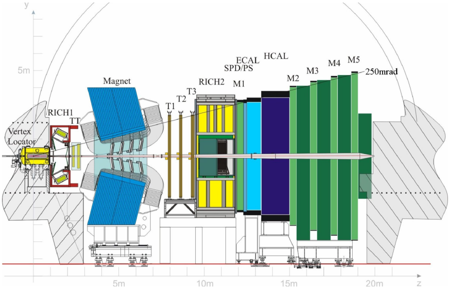
Measure CPV observables

- 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.

LHCb Detector

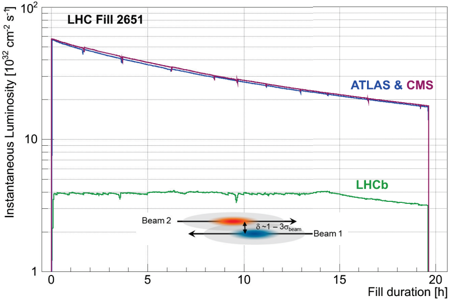
- Acceptance: $2 < \eta < 5$, 25% of $b\overline{b}$ pairs within acceptance
- 2 RICH sub detectors provide excellent PID ability, $\varepsilon(K) \sim 95\%$ with misID$(\pi^- \to K^-) \sim 5\%$
- Dedicated vertex locator (VELO) close to beam pipe - finds secondary vertices, impact parameter resolution: $(15 \pm \frac{29}{p_{\mathrm{T}}})\,\mu\mathrm{m}$



Detector Performance [Int. J. Mod. Phys. A 30 (2015) 1530022]

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

Luminosity Levelling at LHCb



- Luminosity kept ∼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 ∼ 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 $B^0_{(s)} \to K^0_S h h'$ decays [LHCb-PAPER-2017-010]
- Observation of charmless baryonic decays $B^0_{(s)} \to p\overline{p}h^+h^-$ [arXiv:1704.08497]
- Search for the $B^0_s \to \phi\eta'$ decay. [JHEP 05 (2017) 158]
- Observation of the decay $\Xi^-_b \to pK^-K^-$. [Phys. Rev. Lett. 118 (2017) 071801]
- First observation of a baryonic B^0_s decay [arxiv:1704.07908]
- Measurement of matter-antimatter differences in beauty baryon decays [Nature Physics 13 (2017) 391]

- Evidence for the two-body charmless baryonic decay $B^+ \to p\overline{\Lambda}$ [JHEP 04 (2017) 162]
- Observation of the decay $B^0_s \to \phi\pi^+\pi^-$ and evidence for $B^0 \to \phi\pi^+\pi^-$ [Phys. Rev. D 95 (2017) 012006]
- Observation of the annihilation mode decay $B^0 \to K^+K^-$ [Phys. Rev. Lett. 118 (2017) 081801]
- Measurement of time-dependent CP-violating asymmetries in $B^0 \to \pi^+\pi^-$ and $B^0_s \to K^+K^-$ decays at LHCb. [LHCb-CONF-2016-018]

Search for $B_s^0 \to K_S^0 K^+ K^-$ and Updated $B_{(s)}^0 \to K_S^0 hh'$ Branching Fraction Measurements

[LHCb-PAPER-2017-010] NEW!

Long Term Goals

- Possible to measure the weak phase of B^0 meson mixing in $b \to q\bar{q}s$ (q=s,d,u) transitions through the decays $B^0 \to K^0_S \pi^+ \pi^-$ and $B^0 \to K^0_S K^+ K^-$.
- Several extensions to the standard model introduce additional weak phases only present in $b \to q\bar{q}s$ decays - compare to weak phase extracted from $b \to c\bar{c}s$ decays - search for new physics.
- Possible to determine the CKM angle γ with input from the amplitude analysis of $B^0_s \to K^0_S \pi^+ \pi^-$ decays - theoretically clean [Phys. Lett. B645 (2007) 201].

First steps

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

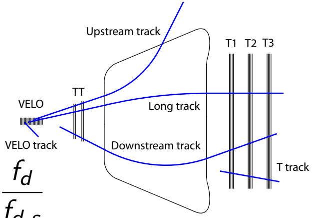
- Previous LHCb analysis using only $1\,\text{fb}^{-1}$ of 2011 data made first observation of the $B_s^0 \to K_S^0 K^\pm \pi^\mp$, $B_s^0 \to K_S^0 \pi^+ \pi^-$ decays and confirmed the $B^0 \to K_S^0 K^\pm \pi^\mp$. [JHEP 10 (2013) 143]
- No significant evidence for the $B_s^0 \to K_S^0 K^+ K^-$ decay - still unobserved.

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

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

- New analysis using $3\,\text{fb}^{-1}$ 2012+2011 LHCb data aims to observe $\mathcal{B}(B_s^0 \to K_S^0 K^+ K^-)$ mode.

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



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

- 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 $\Lambda_b^0\to K^0_\mathrm{S} p\pi^-$.

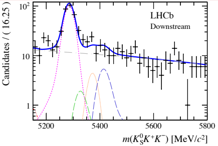
Mass Fits

[LHCb-PAPER-2017-010]

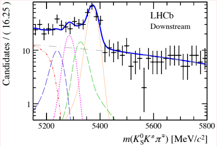
- B^0 Signal, B^0_s Signal, Partially Reconstructed Background, Mis-ID Background, Mis-ID Background.

Favoured Optmisation

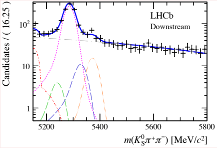
$K^0_S\ K^+\ K^-$



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

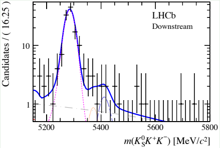


$K^0_S\ \pi^+\ \pi^-$

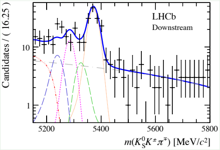


Suppressed Optimisation

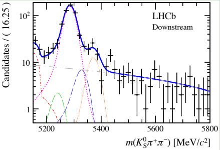
$K^0_S\ K^+\ K^-$



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



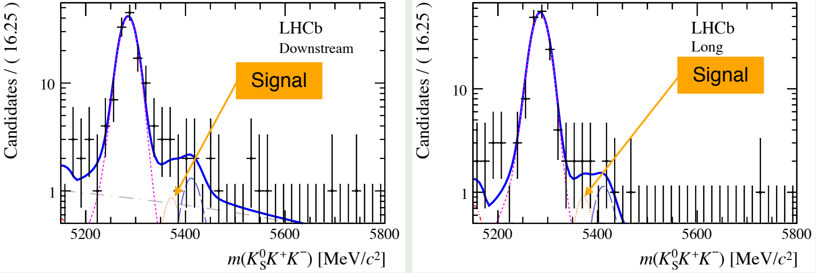
$K^0_S\ \pi^+\ \pi^-$



Unobserved $B_s^0 \to K_S^0 K^+ K^-$ channel Mass Fit

[LHCb-PAPER-2017-010]

Suppressed Optimisation



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

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 (val±stat±syst±$\sigma(\mathcal{B}(K^0_S \pi^+ \pi^-))$

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

- 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 $B_s^0 \to p\overline{\Lambda}K^-$

[arxiv:1704.07908]

Introduction & Motivation

- 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)
- $\mathcal{B}(B_s^0 \to p\overline{\Lambda}K^-)$ predicted to be $\mathcal{O}(10^{-6})$.
- Perform blind search for $B_s^0 \to p\overline{\Lambda}K^-$ using $3\,\text{fb}^{-1}$ Run I dataset.
  - Optimise selection on MC, Data not viewed until selection and mass fit frozen.
- Threshold enhancement in baryon-antibaryon system observed in other decays [Eur. Phys. J. C74 (2014) 3026].

Analysis Strategy & Selection [arxiv:1704.07908]

Strategy

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

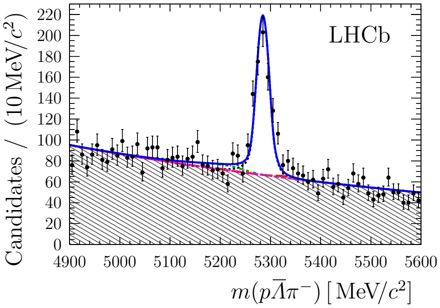
$$\mathcal{B}(B_s^0 \to p\overline{\Lambda}K^-) + \mathcal{B}(B_s^0 \to p\overline{\Lambda}K^-) = \frac{f_d}{f_s} \frac{N(B_s^0 \to p\overline{\Lambda}K^-)}{N(B^0 \to p\overline{\Lambda}\pi^-)} \frac{\varepsilon_{B^0 \to p\overline{\Lambda}\pi^-}}{\varepsilon_{B_s^0 \to p\overline{\Lambda}K^-}} \mathcal{B}(B^0 \to p\overline{\Lambda}\pi^-)$$

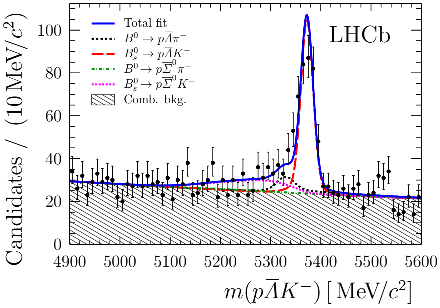
- Yield of control channel and ratio of branching fractions determined with simultaneous fit to all data samples.
    - Ratio of efficiencies included as Gaussian constraint.

Selection

- MLP classifier used to remove combinatorial background and PID requirements on p and K^-/π^- to remove mis-ID background.

Mass Fits

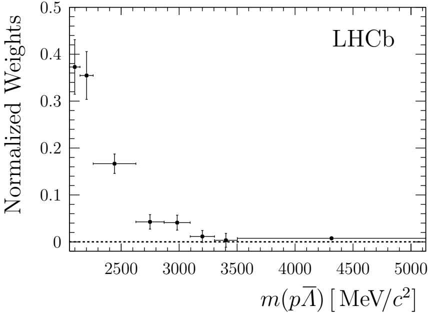


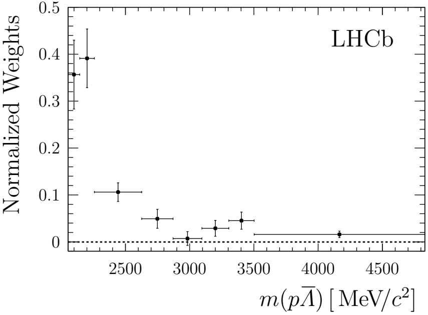


Fit Results

- $N(B^0 \to p\overline{\Lambda}\pi^-) = 519 \pm 28$
- $N(B^0_s \to p\overline{\Lambda}K^-) = 234 \pm 29$, significance $>15\sigma$, first observation!
- $\mathcal{B}(B^0_s \to p\overline{\Lambda}K^-) + \mathcal{B}(\overline{B}^0_s \to p\overline{\Lambda}K^-) = \left[5.46 \pm 0.61 \pm 0.57 \pm 0.50(\mathcal{B}) \pm 0.32(\frac{f_s}{f_d})\right] \times 10^{-6}$

Threshold enhancement in M($p\ \overline{\Lambda}$) [arxiv:1704.07908]





- Normalised, background subtracted and efficiency corrected M($p\ \overline{\Lambda}$) distributions shown.
- Clear threshold enhancement can be seen.

Search for $B^0_{(s)} \to p\bar{p}h^+h^-$ decays

[arXiv:1704.08497]

Motivation and Strategy

[arXiv:1704.08497]

- No four body charmless baryonic B_s^0 decay has been observed.
- Search performed for $B_{(s)}^0 \to p\overline{p}h^+h^-$ (h=K or π) decays using $3\,\mathrm{fb}^{-1}$ data from LHCb Run I.
  - m($p\ \overline{p}$) $<2.85\,\mathrm{GeV}$ and Λ_c^+ and D^0 resonances vetoed.
- $B^0 \to (J/\psi \to p\overline{p})(K^{*0} \to K^+\pi^-)$ 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($p\ \overline{p}\ K\ \pi$), M($p\ \overline{p}\ K\ K$), M($p\ \overline{p}\ \pi\ \pi$)).
- 3D Fit to M($p\ \overline{p}\ K\ \pi$), M($p\ \overline{p}$) and M($K\ \pi$) used to extract normalisation yield.

Signal Channel Fit Results

[arXiv:1704.08497]

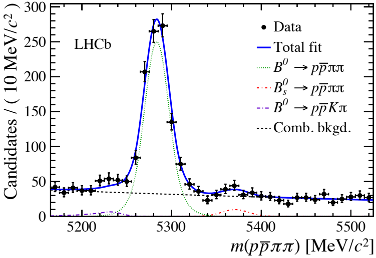
Signal Yields

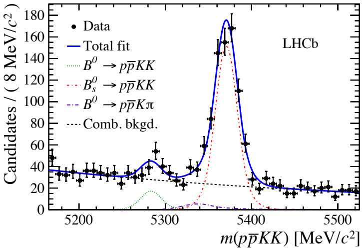
$N^{p\bar{p}KK}_{B^0} = 68 \pm 17$ $N^{p\bar{p}KK}_{B^0_s} = 635 \pm 32$

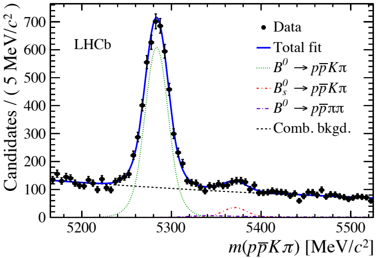
$N^{p\bar{p}K\pi}_{B^0} = 4155 \pm 83$ $N^{p\bar{p}K\pi}_{B^0_s} = 246 \pm 39$

$N^{p\bar{p}\pi\pi}_{B^0} = 902 \pm 35$ $N^{p\bar{p}\pi\pi}_{B^0_s} = 39 \pm 16$

First observation, Strong Evidence







Results

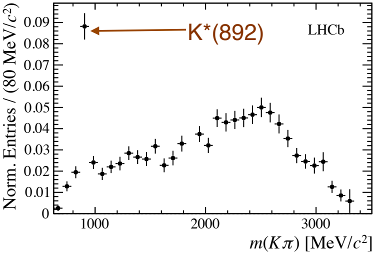
Decay Channel	Significance/σ	Branching Fraction/10^{-6}
$B^0 \to p\bar{p}K^+K^-$	4.1	$0.113 \pm 0.028 \pm 0.011 \pm 0.008$
$B^0 \to p\bar{p}K^+\pi^-$	> 25	$5.9 \pm 0.3 \pm 0.3 \pm 0.4$
$B^0 \to p\bar{p}\pi^+\pi^-$	> 25	$2.7 \pm 0.1 \pm 0.1 \pm 0.2$
$B_s^0 \to p\bar{p}K^+K^-$	> 25	$4.2 \pm 0.3 \pm 0.2 \pm 0.3 \pm 0.3$
$B_s^0 \to p\bar{p}K^+\pi^-$	6.5	$1.3 \pm 0.21 \pm 0.11 \pm 0.09 \pm 0.08$
$B_s^0 \to p\bar{p}\pi^+\pi^-$	2.6	< 0.66 at 90% CL

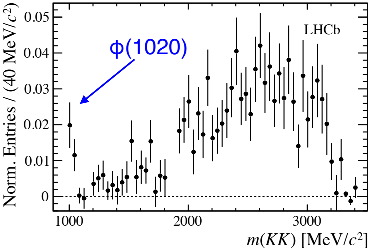
- Results presented as $val \pm stat \pm sys \pm \sigma(norm\mathcal{B}) \pm \sigma(\frac{f_s}{f_d})$
- Limit set on $B_s^0 \to p\bar{p}\pi^+\pi^-$ by integrating likelihood in physical region.

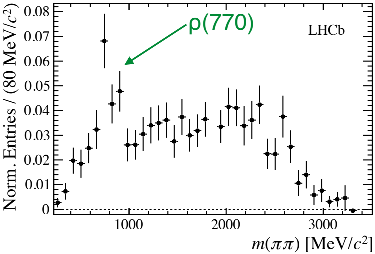
$M(h^+h^-)$ Substructures

[arXiv:1704.08497]

- Normalised background subtracted and efficiency corrected $M(h^+h^-)$ distributions shown.
- Vector mesons, ϕ, ρ^0, K^{*0} clearly present



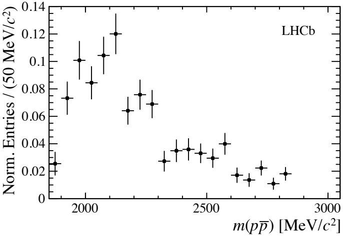




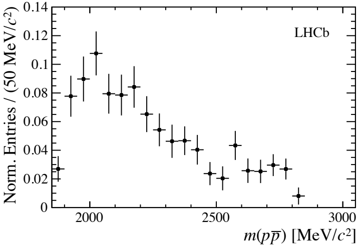
Threshold enhancement in M($p\ \overline{p}$)

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

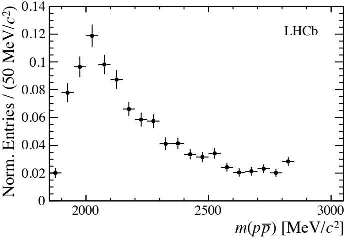
$B^0 \to p\overline{p}\pi^+\pi^-$



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



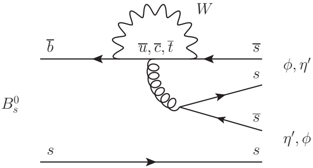
$B^0 \to p\overline{p}K^+\pi^-$



Search for the decay $B_s^0 \to \phi\eta'$

[JHEP 05 (2017) 158]

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



  - Sensitive to phase ϕ_s but yet to be observed.
  - Wide range of theory predictions and large uncertainties partly due to limited knowledge of $B_s^0 \to \phi$ form factors

Theory Approach	$\mathcal{B}(10^{-6})$	Reference
QCD Factorisation	$0.05^{+1.18}_{-0.19}$	[Nucl.Phys. B 675 (2003) 333-415]
QCD Factorisation	$2.2^{+9.4}_{-3.1}$	[arXiv:hep-ph/0701146]
Perturbative QCD	$0.19^{+0.20}_{-0.13}$	[Phys.Rev. D 76 (2007) 074018]
Perturbative QCD	$20.0^{+16.3}_{-9.1}$	[Phys.Rev. D 80 (2009) 114026]
SCET	$4.3^{+5.2}_{-3.6}$	[Phys.Rev. D 78 (2008) 034011]
SU(3) flav. symm	5.5 ± 1.8	[Phys.Rev.D 91 (2014) 014011]
FAT	13.0 ± 1.6	[Eur. Phys. J. C (2017) 77: 125.]

Analysis Strategy

[JHEP 05 (2017) 158]

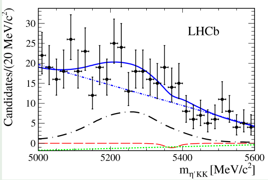
- Blind search performed using full LHCb Run I data set.
- $B^+ \to K^+ \eta'$ used as normalisation channel - high yield, minimal background and precisely known $\mathcal{B}(B^+ \to K^+ \eta') = (70.6 \pm 2.5) \times 10^{-6}$
- η' reconstructed in decay $\eta' \to \pi^+ \pi^- \gamma$ and ϕ reconstructed in decay $\phi \to K^+ K^-$.
- 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 $B_s^0 \to \phi \eta'$ and $B^+ \to K^+ \eta'$ to extract yields

Mass Fits

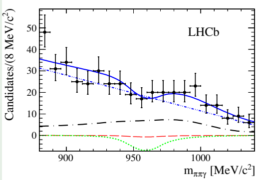
[JHEP 05 (2017) 158]

- Fit Components:
  Signal
  $B_s^0 \to \phi(\phi \to \pi^+\pi^-\pi^0)$ background
  Combinatorial background with true η'
  Combinatorial background without true η'

Signal Channel

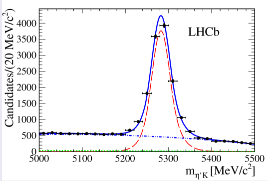


M(B_s^0)

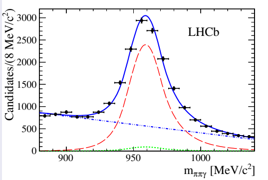


M(η')

Control Channel



M(B^+)



M(η')

Results

- Small bias correction due to $B_s^0 \to \phi(\phi \to \pi^+\pi^-\pi^0)$ component (1.3 ± 0.7) events.

Fit Results

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

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

Branching Fraction Limit

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

Comparison to Theoretical Predictions [JHEP 05 (2017) 158]

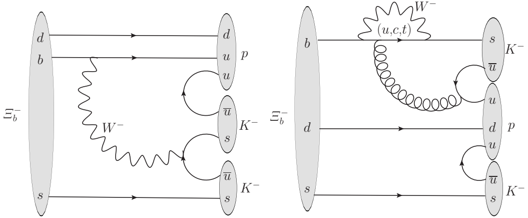
Theory Approach	$\mathcal{B}(10^{-6})$	Reference
QCD Factorisation	$0.05^{+1.18}_{-0.19}$	[Nucl.Phys. B 675 (2003) 333-415]
QCD Factorisation	$2.2^{+9.4}_{-3.1}$	[arXiv:hep-ph/0701146]
Perturbative QCD	$0.19^{+0.20}_{-0.13}$	[Phys.Rev. D 76 (2007) 074018]
~~Perturbative QCD~~	~~$20.0^{+16.3}_{-9.1}$~~	~~[Phys.Rev. D 80 (2009) 114026]~~
~~SCET~~	~~$4.3^{+5.2}_{-3.6}$~~	~~[Phys.Rev. D 78 (2008) 034011]~~
~~SU(3) flav. symm~~	~~5.5 ± 1.8~~	~~[Phys.Rev.D 91 (2014) 014011]~~
~~FAT~~	~~13.0 ± 1.6~~	~~[Eur. Phys. J. C (2017) 77: 125.]~~

- 4 out of 7 presented theory predictions are ruled out at 95% confidence level!

Search for $\Xi_b^-, \Omega_b^- \to p h^- h'^-$ decays

[Phys. Rev. Lett. 118 (2017) 071801]

- The decay of a Ξ_b^- or Ω_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

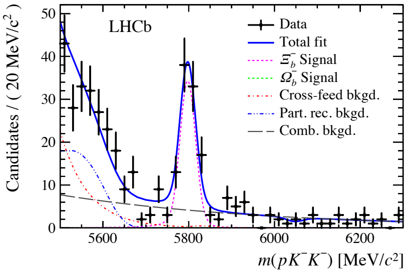
[Phys. Rev. Lett. 118 (2017) 071801]

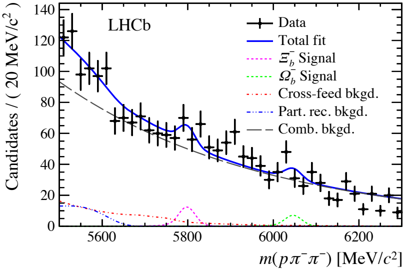
Selection

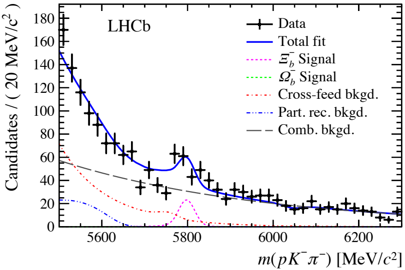
- Neural network used to separate signal and combinatorial background
- Tight Particle-ID requirement on proton to remove background from $B^- \to K^- h^- h'^-$ decays.
- Pion and Kaon Particle-ID requirements optimised and chosen to ensure each candidate is only assigned to one of three possible final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







Signal Yields

$\Xi_b^- \to pK^-K^-$	82.9 ± 10.4	8.7σ
$\Xi_b^- \to pK^-\pi^-$	59.6 ± 16.0	3.4σ
$\Xi_b^- \to p\pi^-\pi^-$	33.2 ± 17.9	$< 2\sigma$
$\Omega_b^- \to pK^-K^-$	-2.8 ± 2.5	$< 2\sigma$
$\Omega_b^- \to pK^-\pi^-$	-7.6 ± 9.2	$< 2\sigma$
$\Omega_b^- \to p\pi^-\pi^-$	20.1 ± 13.8	$< 2\sigma$

Branching Fraction Results

[Phys. Rev. Lett. 118 (2017) 071801]

- Ξ_b^-, Ω_b^- fragmentation fractions not measured, measure $\frac{f_\Xi}{f_d} \times \mathcal{B}$

$$R_{phh'} = \frac{f_\Xi}{f_d} \times \frac{\mathcal{B}(\Xi_b^- \to ph^- h'^-)}{\mathcal{B}(B^- \to K^+ K^- K^-)} = \frac{\mathcal{N}(\Xi_b^- \to ph^- h'^-)}{\mathcal{N}(B^- \to K^+ K^- K^-)} \frac{\varepsilon(B^- \to K^+ K^- K^-)}{\varepsilon(\Xi_b^- \to ph^- h'^-)}$$

- 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})

$R_{phh'}(\Xi_b^- \to pK^- K^-) = 265 \pm 35 \pm 47$ $\quad$ $R_{phh'}(\Omega_b^- \to pK^- K^-) < 18$

$R_{phh'}(\Xi_b^- \to pK^- \pi^-) = 259 \pm 64 \pm 49$ $\quad$ $R_{phh'}(\Omega_b^- p\ K^-\ \pi^-) < 51$

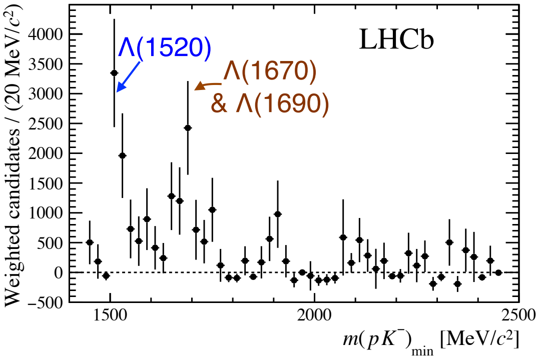
$R_{phh'}(\Xi_b^- \to p\pi^- \pi^-) < 147$ $\quad$ $R_{phh'}(\Omega_b^- \to p\pi^- \pi^-) < 109$

- No evidence for Ω_b^- decays, hierarchy of Ξ_b^- decays as expected.

$M(pK^-)$ Resonances in $\Xi_b^- \to pK^-K^-$

[Phys. Rev. Lett. 118 (2017) 071801]

- Background subtracted using sPlot method.

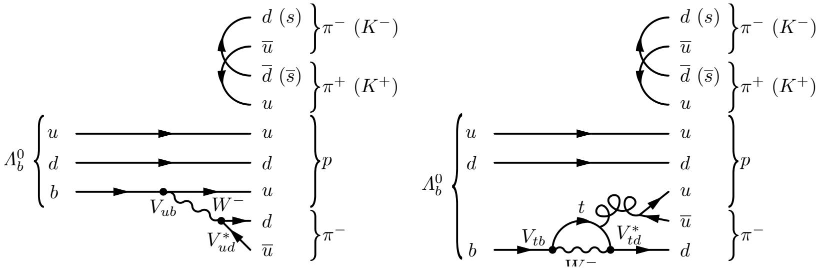


- Efficiency corrected $M(pK^-)_{min}$ distribution shows a rich resonant structure which appears to be consistent with known states such as the $\Lambda(1520)$, $\Lambda(1670)$ and $\Lambda(1690)$.

Search for CP Violation in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays

Nature Physics 13 (2017) 391

- 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 Λ_b^0 production at the LHC, nearly 20% of all b hadrons produced.

Strategy

- Study asymmetries in the $\hat{T}$ operator - unitary operator that reverses both momentum and spin three-vectors.
- Define scalar triple products:

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

- Define asymmetries as:

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

- where CPV and PV observables then defined as:

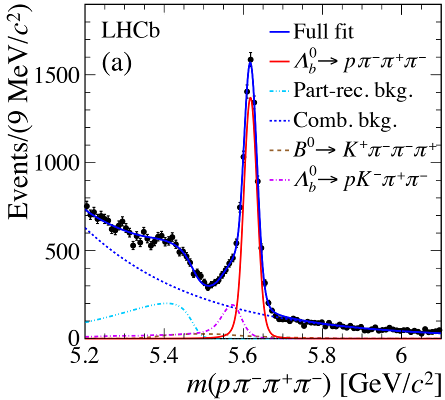
$$a_{CP}^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} - \bar{A}_{\hat{T}}), a_p^{\hat{T}-odd} = \frac{1}{2}(A_{\hat{T}} + \bar{A}_{\hat{T}})$$

- A significant deviation from zero in this observable would signal CPV.

Observation of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

Nature Physics 13 (2017) 391

- $\Lambda_b^0 \to p\pi^+\pi^-\pi^+$ 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

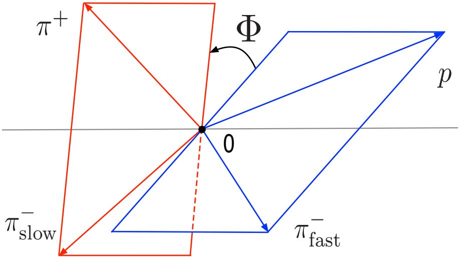
- 6646 ± 105 Signal events
- First observation of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$

CPV observable extraction

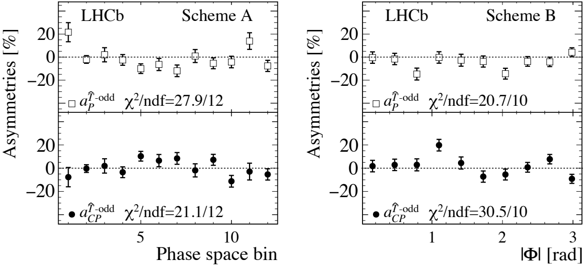
Nature Physics 13 (2017) 391

- Sample split into 4 categories according to Λ_b^0 or $\overline{\Lambda}_b^0$ and $C_{\hat{T}}$ or $\bar{C}_{\hat{T}}$ - 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 $\pi^{+}\pi^{-}_{slow}$ decay planes Φ - exploit interference of contributions.



CPV results



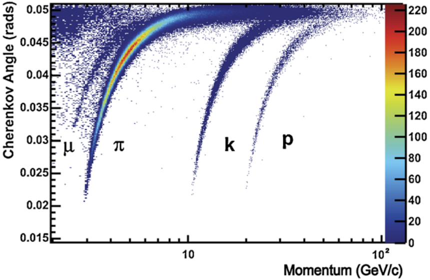
- χ^2 test used to determine compatibility of each binning scheme with the null hypothesis of CP symmetry.
- p-values indicate 2.0σ and 3.4σ evidence for CP violation in binning schemes A and B respectively.
- Combined significance = 3.3σ obtained using permutation test. First evidence for CP-violation in a *b*-baryon decay!

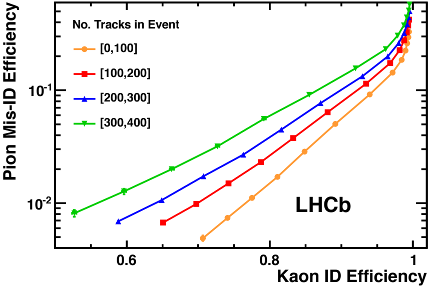
Summary & Conclusions

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

Backup

Particle Identification





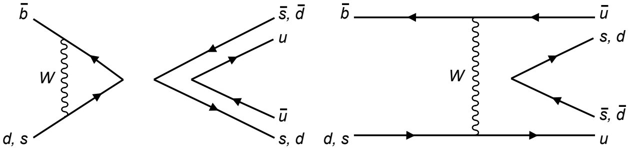
$B_s^0 \to \phi\eta'$ Theory Prediction Authors

$\mathcal{B}(10^{-6})$	Reference	Authors
QCD Factorisation	$0.05^{+1.18}_{-0.19}$	M. Beneke, M. Neubert
QCD Factorisation	$2.2^{+9.4}_{-3.1}$	X. Chen, D. Guo, Z. Xiao
Perturbative QCD	$0.19^{+0.20}_{-0.13}$	A. Ali, G. Kramer, Y. Li,
		C. Lu, Y. Shen, W. Wang, Y. Wang
Perturbative QCD	$20.0^{+16.3}_{-9.1}$	H. Cheng, C. Chua
SCET	$4.3^{+5.2}_{-3.6}$	W. Wang, Y. Wang, D. Yang, C. Lu
SU(3) flav. symm	5.5 ± 1.8	H. Cheng, C. Chiang, A. Kuo
FAT	13.0 ± 1.6	S. Zhou, Q. Zhang, W. Lyu,C. Lü

Observation of annhilation mode decay $B^0 \to K^+ K^-$

[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 $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$



- Measurement of $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$ branching fractions provide vital input to understanding these decays.
- The decay $B_s^0 \to \pi^+\pi^-$ was observed for the first time by LHCb using fraction of Run I dataset. $\mathcal{B}(B_s^0 \to \pi^+\pi^-) = (0.95^{+0.21}_{-0.17} \pm 0.13) \times 10^{-6}$.
- No evidence previously existed for the decay $B^0 \to K^+K^-$.

Strategy & Selection

[Phys. Rev. Lett. 118, 081801]

Analysis Strategy

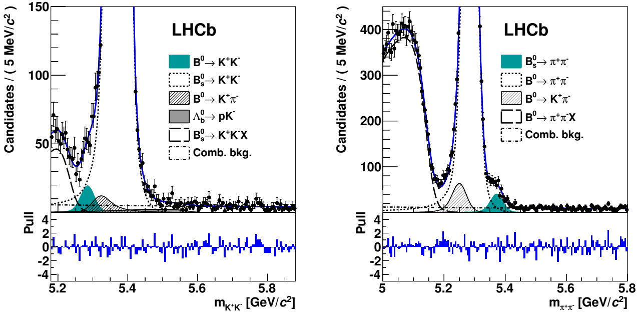
- Perform search for $B^0 \to K^+ K^-$ and improve measurement of $B_s^0 \to \pi^+ \pi^-$ using full Run I LHCb dataset.
- Well known decay $B^0 \to K^+ \pi^-$ used as control channel for both signal channels.
- Extract signal yields by fitting $K^+ K^-$ and $\pi^+ \pi^-$ final states simultaneously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

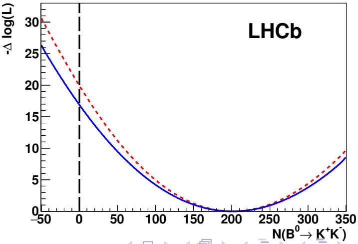
Mass Fit Results

[Phys. Rev. Lett. 118, 081801]



Fit Results

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



Branching Fraction Results

[Phys. Rev. Lett. 118, 081801]

- First observation of $B^0 \to K^+ K^-$!
- Branching Fraction calculated as:

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

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 $val \pm stat \pm sys \pm \sigma(norm\mathcal{B}) \pm \sigma(\frac{f_s}{f_d})$