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Charmless (baryonic) decays of *B* mesons at LHCb

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(on behalf of the LHCb Collaboration)

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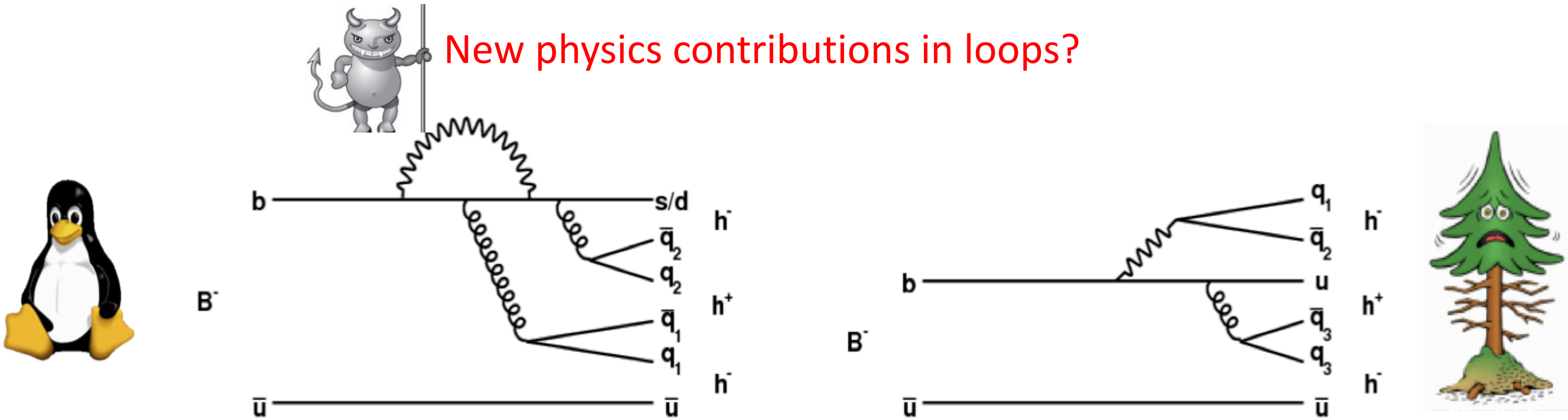
Overview

- Introduction
  - Charmless decays of b-hadrons
  - The LHCb experiment
- Recent results from LHCb:
  - Baryonic B decays
    - $B_s^0 \to p\overline{\Lambda}K^-$
    - $B \to p\bar{p}h^+h^-$
    - $B^0 \to p\bar{p}$
  - $B_{(s)}^0 \to K_S^0 h^+ h^-$
- Concluding remarks

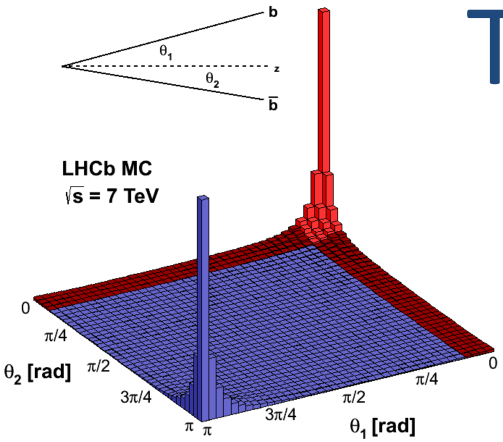
NB: $h \in \{\pi, K\}$

Rich physics of charmless decays



- Contributions from both loop (penguin) and tree decay diagrams
- Have comparable magnitude and a relative weak phase (= γ in SM)
- Interference can therefore give rise to *CP* violation
- Important to test the SM by comparing with tree-dominated decays
- Multi-body decays also possess rich resonance structure
- Provides important information for refining models of hadronisation
- Can also lead to very interesting variation of CPV over the phase space, e.g. as seen in $B^+ \to h^+h^-h'^+$ [Phys. Rev. D 90 (2014) 112004]

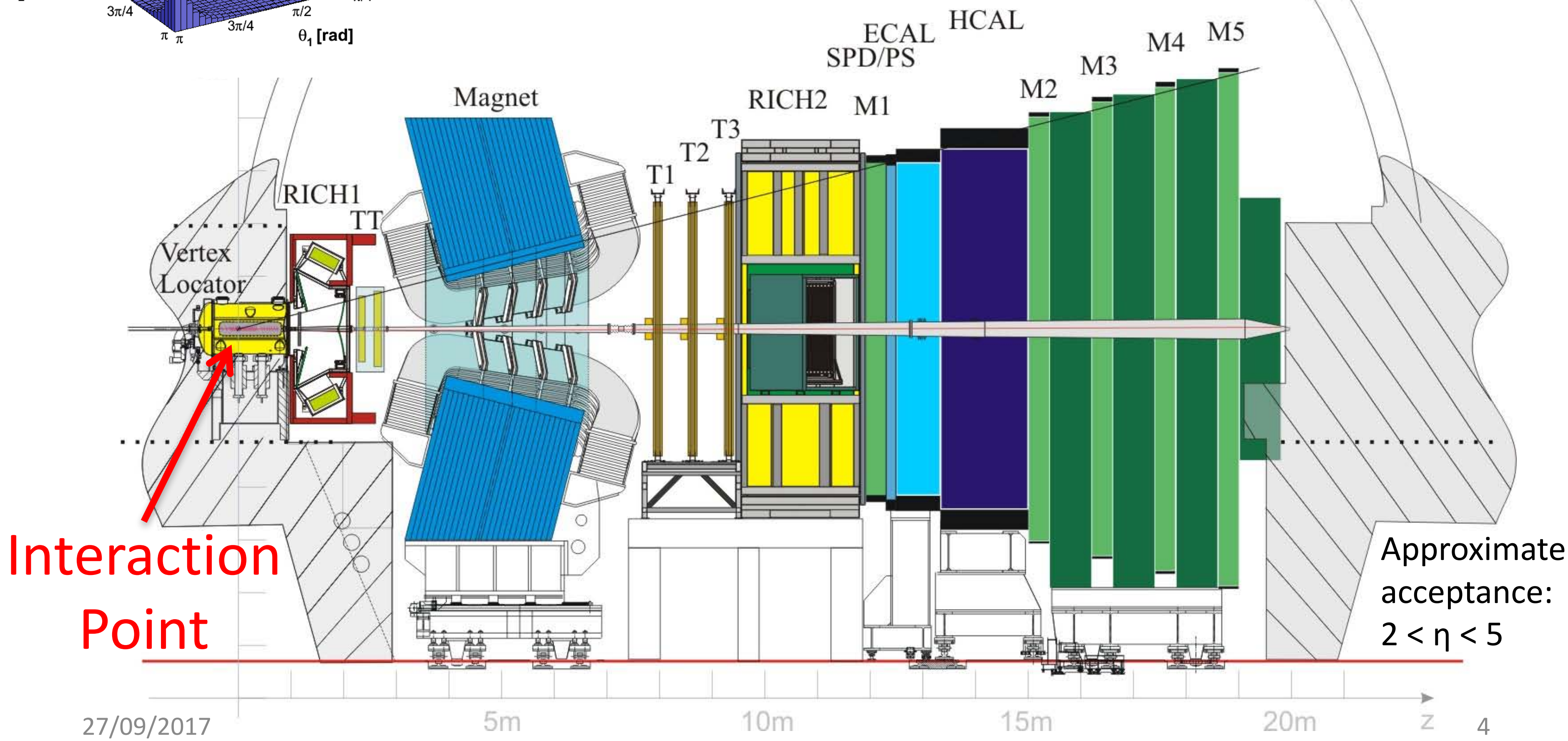
The LHCb detector



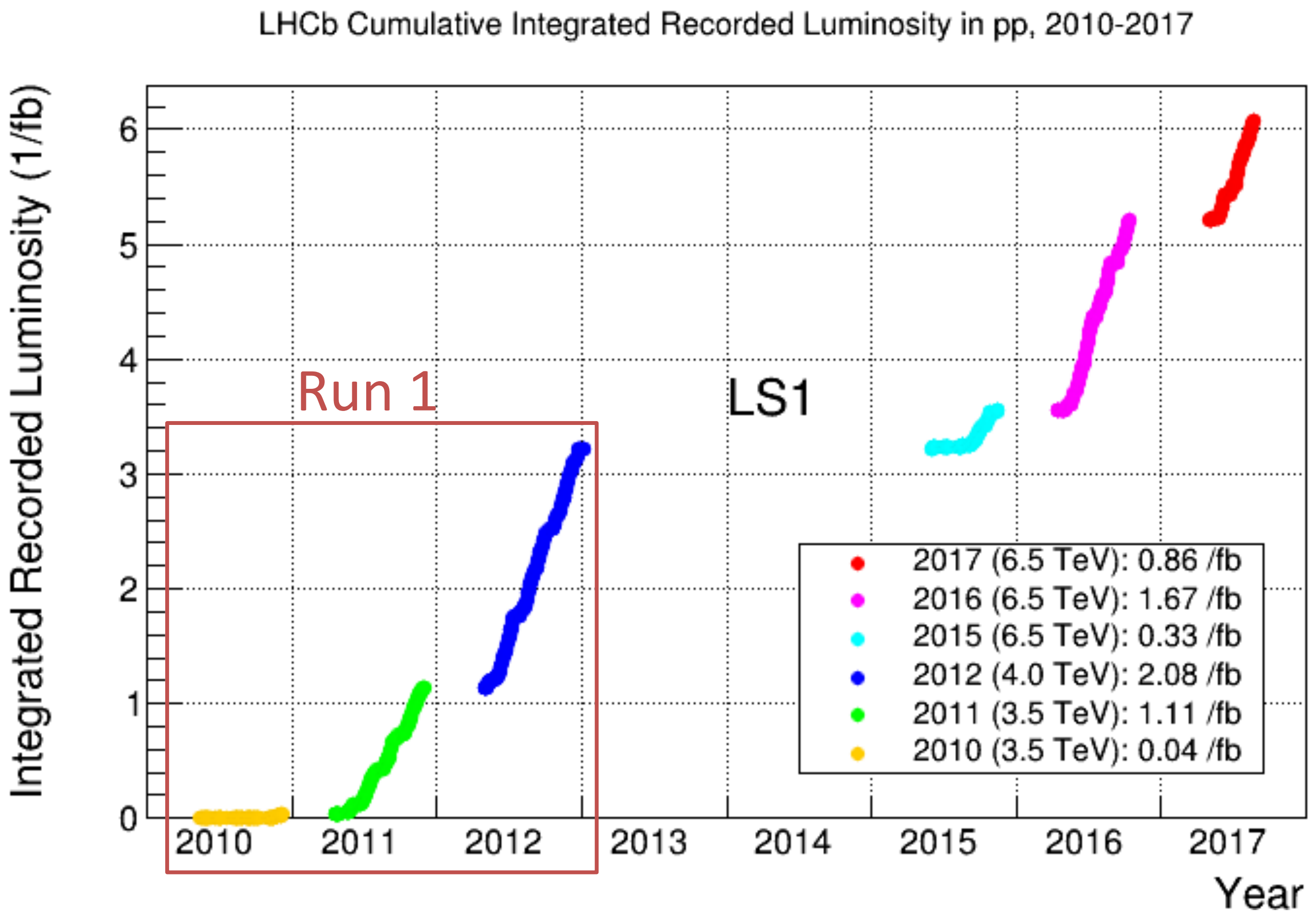
LHCb $\sigma(pp \rightarrow H_b X)$ @ 7 TeV = (72.0 ± 0.3 ± 6.8) μb

LHCb $\sigma(pp \rightarrow H_b X)$ @ 13 TeV = (154.3 ± 1.5 ± 14.3) μb

[Phys. Rev. Lett. 118 (2017) 052002]



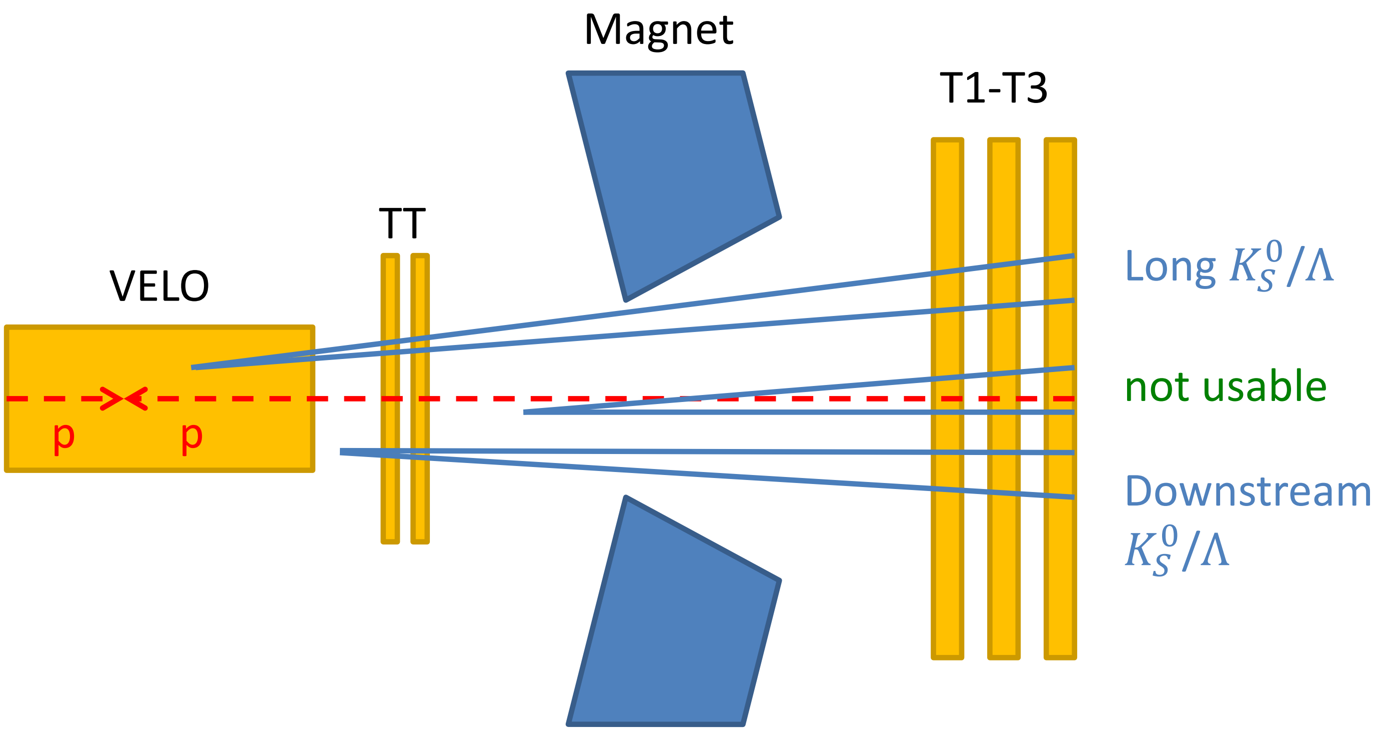
Data Sample



2011 + 2012 data set (3 fb^{-1}) used in analyses discussed today

K_S^0/Λ reconstruction

- $K_S^0 \to \pi^+\pi^-$ and $\Lambda \to p\pi^-$ decays reconstructed in two categories:
  - Long: pion/proton tracks have hits in the vertex detector (VELO)
  - Downstream: pion/proton tracks have no VELO hits
- Trigger efficiency varies, particularly for Downstream category, over data-taking period – much improved in latter part of 2012



Baryonic *B* meson decays

Baryonic B meson decays

- Baryonic decays expected to account for approximately 7% of the B meson decay width
  - Very few exclusive measurements – hence most decays still to be observed

- There are also a few quirks that have been seen in the decays so far observed
  - The hierarchy of 2-body $\ll$ 3-body $\lesssim$ many-body BFs is rather different from equivalent mesonic decays, which are more democratic
  - Enhancements are seen at di-baryon threshold in almost all multi-body decays

- Interesting to carry out CPV measurements in these decays in the future to compare with similar mesonic modes

Study of $B^0_{(s)} \to p\bar{\Lambda}h^-$ decays

- Search performed for the decays $B^0_s \to p\bar{\Lambda}K^-$ and $B^0_s \to \bar{p}\Lambda K^+$
- Sum of their BFs measured relative to topologically similar and previously established decay $B^0 \to p\bar{\Lambda}\pi^-$

$$\mathcal{B}(B^0_s \to p\bar{\Lambda}K^-) + \mathcal{B}(B^0_s \to \bar{p}\Lambda K^+) =$$

$$\frac{N(B^0_s \to p\bar{\Lambda}K^-)}{N(B^0 \to p\bar{\Lambda}\pi^-)} \frac{\varepsilon(B^0 \to p\bar{\Lambda}\pi^-)}{\varepsilon(B^0_s \to p\bar{\Lambda}K^-)} \frac{f_d}{f_s} \mathcal{B}(B^0 \to p\bar{\Lambda}\pi^-)$$

- Yields of signal and normalisation decays are obtained from fits to data
- Efficiencies are obtained from simulation, with corrections for known differences between data and simulation (PID, hardware trigger, tracking)
- Ratio of hadronisation fractions taken from previous LHCb measurement [JHEP 04 (2013) 001, LHCb-CONF-2013-011]
- Branching fraction of normalisation channel from average of B factory measurements [Phys. Rev. D79 (2009) 112009, Phys. Rev. D76 (2007) 052004]

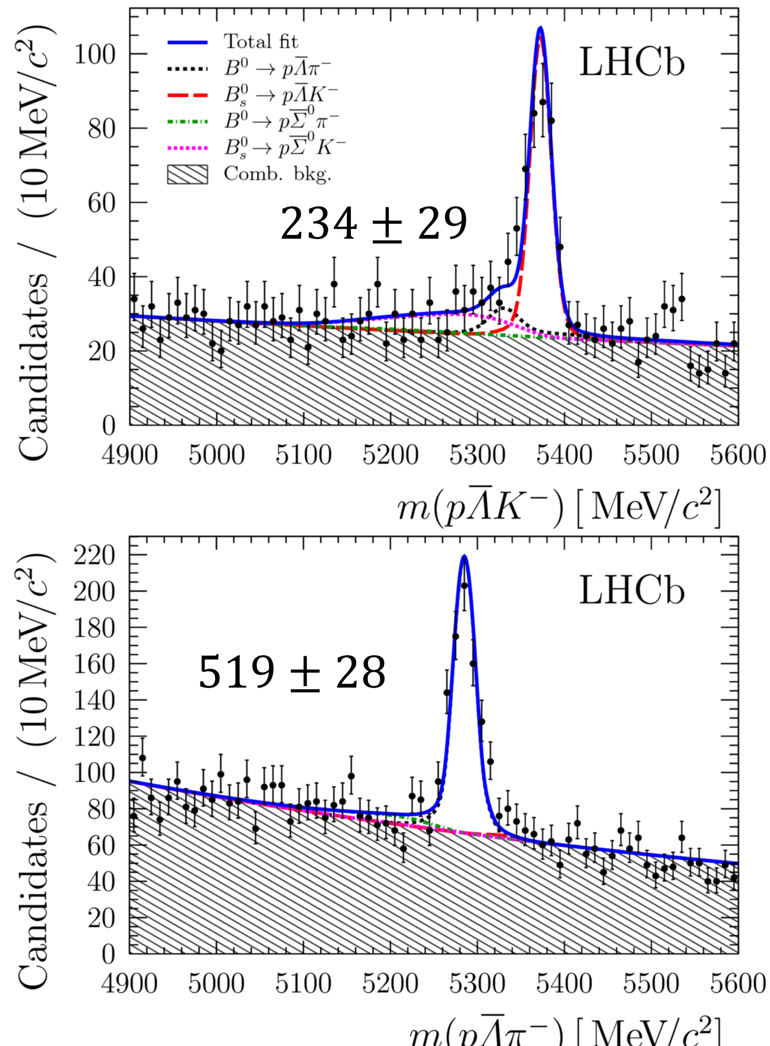
Phys. Rev. Lett. 119 (2017) 041802

First observation of a baryonic decay of the B_s^0 meson

- Simultaneous fit to 8 categories: 2011 & 2012, Long & Downstream, and $p\bar{\Lambda}K^-$ & $p\bar{\Lambda}\pi^-$ final states
- Signal is observed with significance in excess of 15 standard deviations
- Systematic uncertainties dominated by fit model, in particular the backgrounds from $B^0_{(s)} \to p\bar{\Sigma}^0 h^-$ decays

$$\mathcal{B}(B_s^0 \to p\bar{\Lambda}K^-) + \mathcal{B}(B_s^0 \to \bar{p}\Lambda K^+) =$$

$$[5.46 \pm 0.61 \pm 0.57 \pm 0.50(\mathcal{B}) \pm 0.32(f_s/f_d)] \times 10^{-6}$$

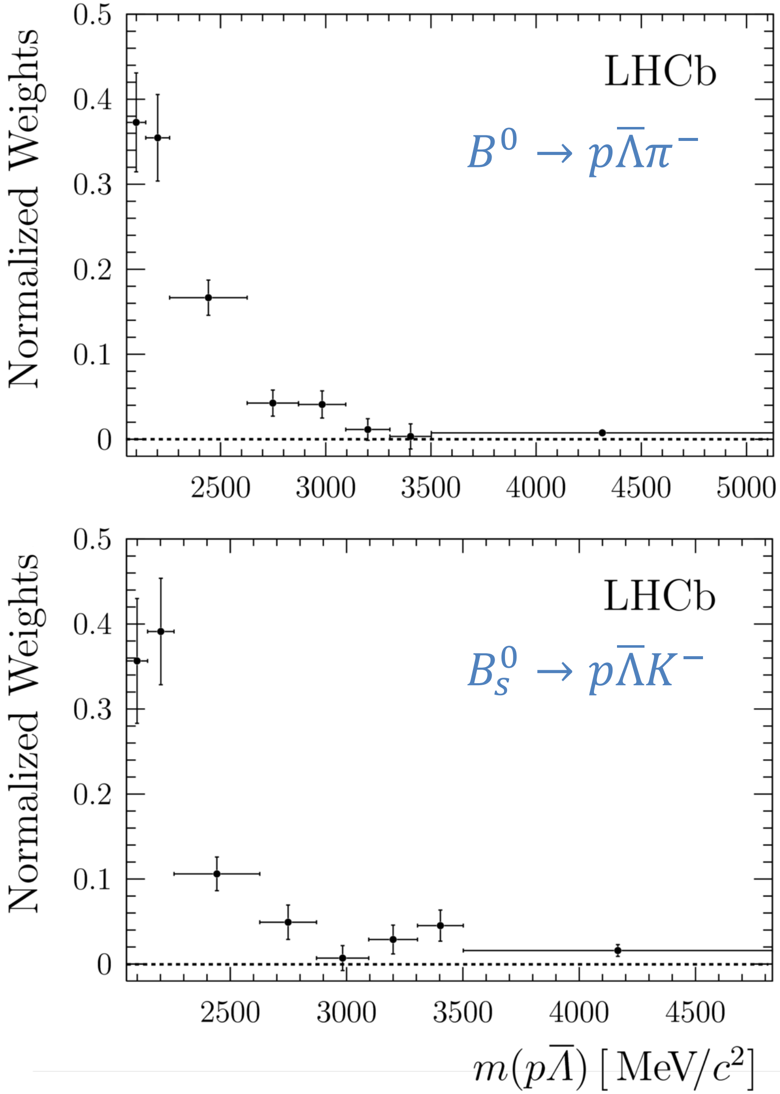


Phys. Rev. Lett. 119 (2017) 041802

Threshold enhancement in $B^0_{(s)} \to p\bar{\Lambda}h^-$

- Both the newly observed B^0_s decay and the normalisation channel exhibit pronounced threshold enhancements in the $p\bar{\Lambda}$ invariant mass

- Plots on right show efficiency-corrected and background-subtracted distributions



arXiv:1704.08497 [hep-ex]

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

- Similar analysis strategy as $B^0_{(s)} \to p\bar{\Lambda}h^-$ analysis, but using $B^0 \to J/\psi(\to p\bar{p})K^{*0}(\to K^+\pi^-)$ as the normalisation channel

- Only the $B^0 \to p\bar{p}K^{*0}$ decay was previously observed by the *B*-factories [Phys. Rev. D76 (2007) 092004, Phys. Rev. Lett. 100 (2008) 251801], with world average $\mathcal{B} = (1.24^{+0.28}_{-0.25})\times 10^{-6}$
- Search for all 6 decays in the LHCb data

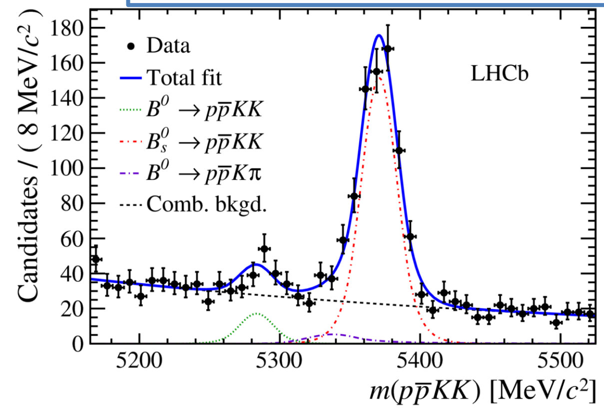
- These 4-body decays are an interesting prospect for future CPV searches using triple-product asymmetries

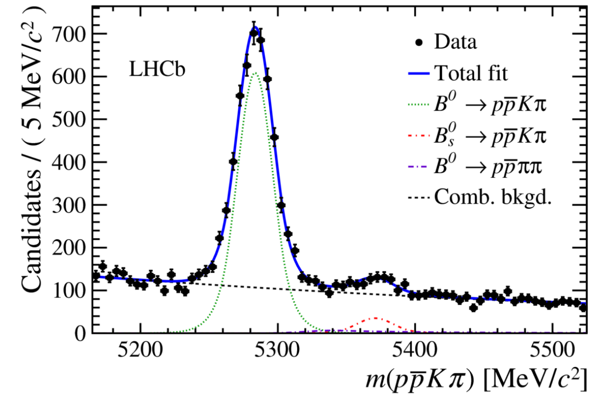
arXiv:1704.08497 [hep-ex]

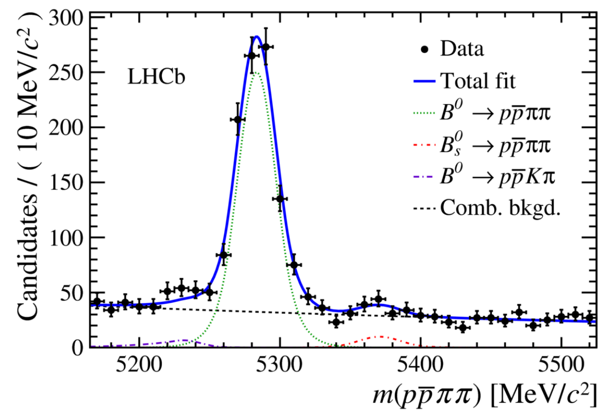
$B^0_{(s)} \to p\bar{p}h^+h'^-$ fit results

- Four decays observed with significance $> 5\sigma$, three for the first time
- Evidence for $B^0 \to p\bar{p}K^+K^-$ with 4.1σ significance

Decay channel	Yield $\mathcal{N}$	Significance $[\sigma]$
$B^0 \to p\bar{p}KK$	68 ± 17	4.1
$B^0 \to p\bar{p}K\pi$	4155 ± 83	> 25
$B^0 \to p\bar{p}\pi\pi$	902 ± 35	> 25
$B^0_s \to p\bar{p}KK$	635 ± 32	> 25
$B^0_s \to p\bar{p}K\pi$	246 ± 39	6.5
$B^0_s \to p\bar{p}\pi\pi$	39 ± 16	2.6
$B^0 \to J/\psi K^*(892)^0$	1216 ± 45	–



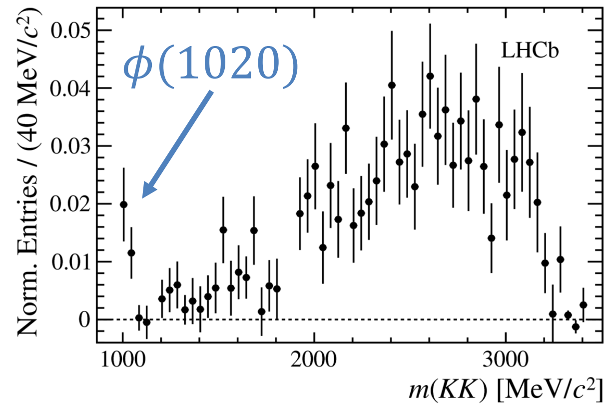


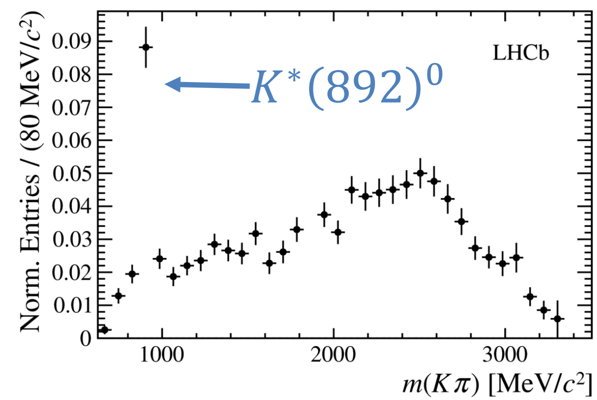


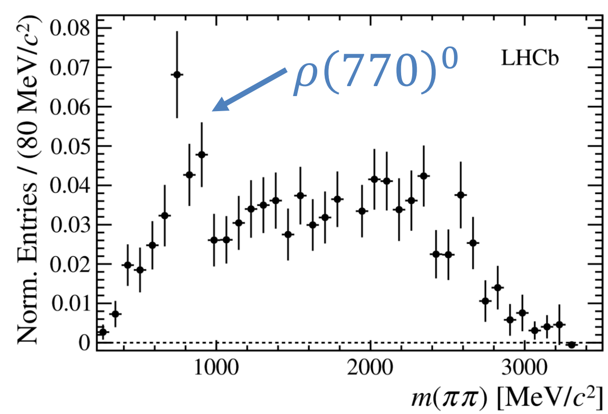
arXiv:1704.08497 [hep-ex]

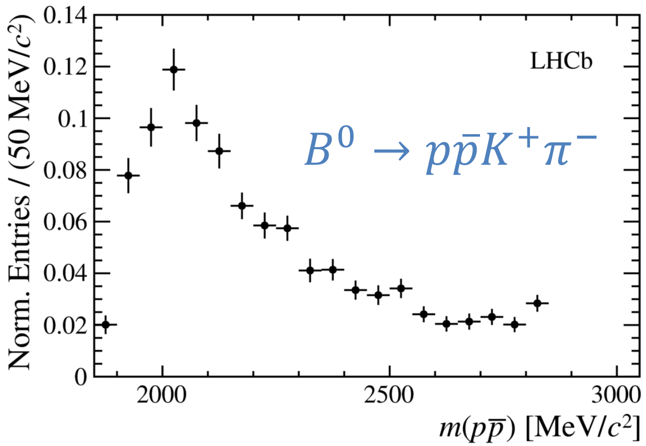
Structure in phase space

- Efficiency-corrected and background-subtracted distributions
- Prominent vector meson resonances in each $h^+h'^-$ spectrum
- Threshold enhancement clear in $m(p\bar{p})$ in all decays









arXiv:1704.08497 [hep-ex]

Branching fractions

- Branching fractions in region $m(p\bar{p}) < 2.86$ GeV determined wrt $B^0 \to J/\psi K^{*0}$ normalisation channel

Decay channel	Branching fraction / 10^{-6}				
$B^0 \to p\bar{p}KK$	0.113	± 0.028	± 0.011	± 0.008	
$B^0 \to p\bar{p}K\pi$	5.9	± 0.3	± 0.3	± 0.4	
$B^0 \to p\bar{p}\pi\pi$	2.7	± 0.1	± 0.1	± 0.2	
$B^0_s \to p\bar{p}KK$	4.2	± 0.3	± 0.2	± 0.3	± 0.2
$B^0_s \to p\bar{p}K\pi$	1.30	± 0.21	± 0.11	± 0.09	± 0.08
$B^0_s \to p\bar{p}\pi\pi$	0.41	± 0.17	± 0.04	± 0.03	± 0.02
Uncertainties:		stat.,	syst.,	norm. BF,	f_s/f_d

- Upper limit on $B^0_s \to p\bar{p}\pi^+\pi^-$ determined to be:

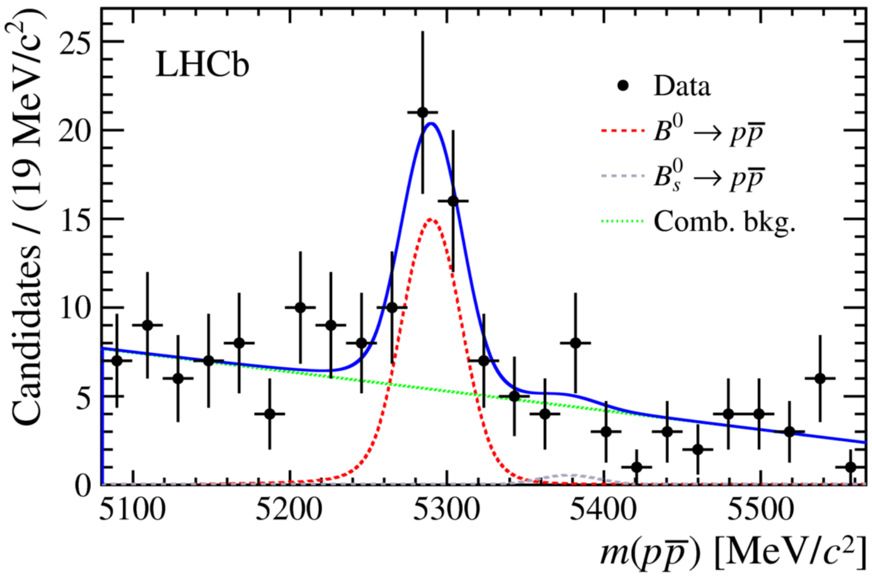
$$\mathcal{B}(B^0_s \to p\bar{p}\pi^+\pi^-) < 7.3\times10^{-7} \text{ at 90\% CL}$$

Search for $B^0 \to p\bar{p}$

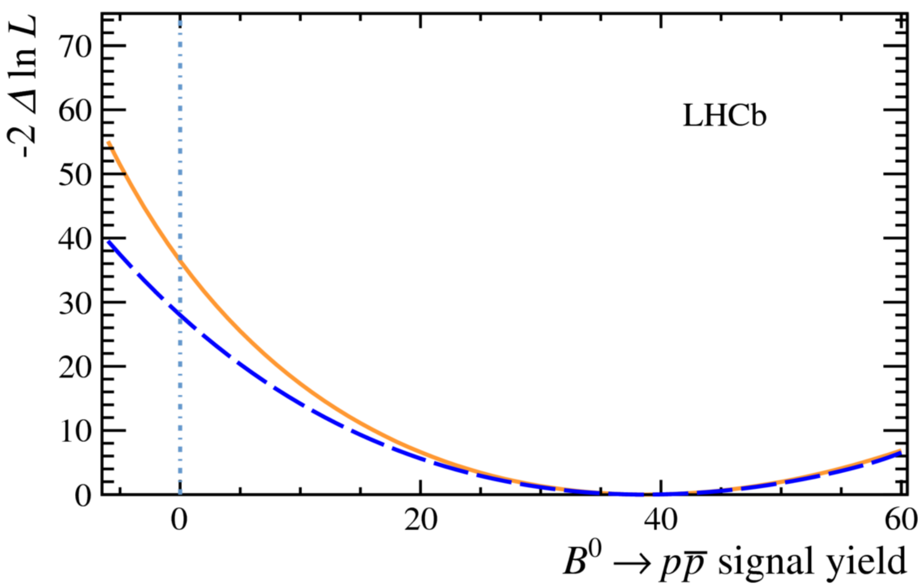
- Decay not seen at B factories, first evidence came from LHCb analysis of 2011 data [JHEP 10 (2013) 005]
- Central value determined there ($\sim 10^{-8}$) was much smaller than most theoretical calculations at the time
- More recent theoretical work has been able to accommodate the small BF of this mode, see e.g. [Phys. Rev. D 91 (2015) 077501, Phys. Rev. D 91 (2015) 036003]
- Important to improve knowledge of such rare hadronic decays

arXiv:1709.01156 [hep-ex]

First observation of $B^0 \to p\bar{p}$



- Clear B^0 signal peak, with yield of 39 ± 8
- No significant signal from corresponding B_s^0 decay: 2 ± 4

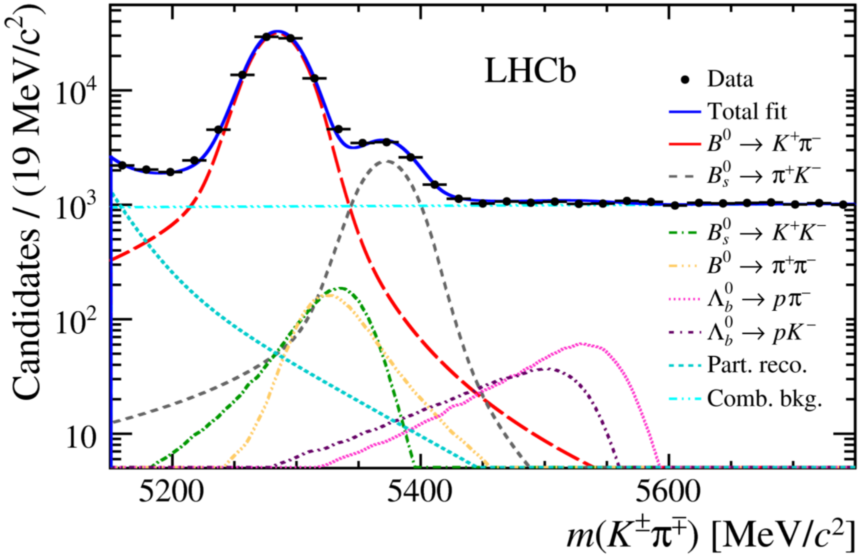


- Significance of $B^0 \to p\bar{p}$ determined to be 5.3σ including effect of systematic uncertainties
- Constitutes first observation of the decay!

arXiv:1709.01156 [hep-ex]

Branching fraction of $B^0 \to p\bar{p}$

- Branching fractions determined relative to $B^0 \to K^+\pi^-$ decay, very clean sample with around 89k signal candidates



$$\mathcal{B}(B^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18)\times 10^{-8}$$

$$\mathcal{B}(B_s^0 \to p\bar{p}) < 1.5\times 10^{-8} \text{ at 90\% CL}$$

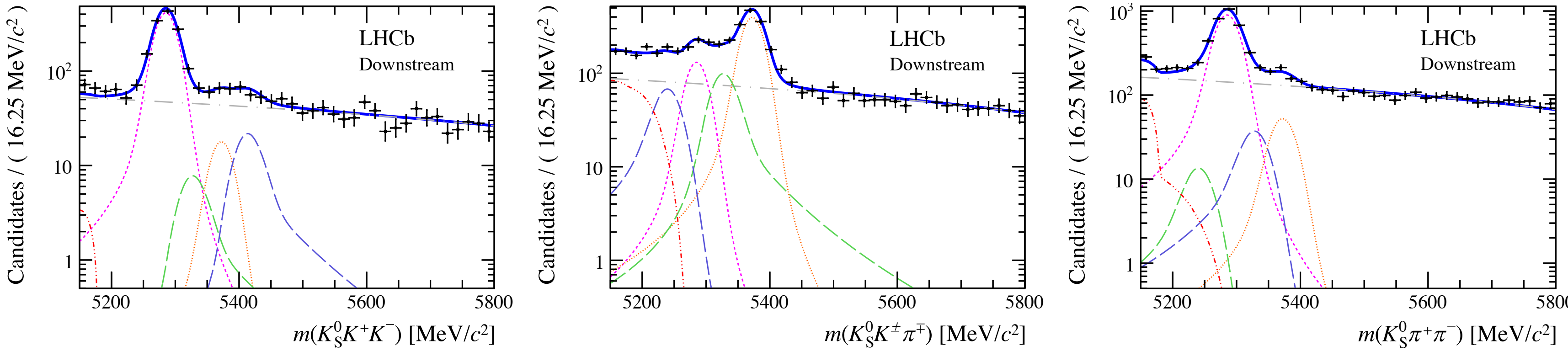
- Rarest hadronic B decay ever observed!

3-body B decays

BFs of $B^0_{(s)} \to K^0_S h^+ h'^-$ decays

- Family of decays with extensive physics potential
  - Measurements of *CP*-violating phases from flavour-tagged time-dependent Dalitz-plot (DP) analyses
  - Very rich resonance structure
- Update of previous LHCb analysis of 2011 data [JHEP 10 (2013) 143]
- Aim to:
  - Update BF measurements of all modes
  - Hope to observe $B^0_s \to K^0_S K^+ K^-$ for first time
  - Define optimised selection for forthcoming DP analyses of favoured decays
- Simultaneous fits performed to 24 categories:
  - 4 final states, 2 K^0_S reconstruction categories, 3 data-taking periods
  - Allows better control of cross-feed backgrounds due to particle mis-ID
  - Also reduces systematic uncertainties from fit model parameters
- Two such fits performed for two different optimisations of the selection:
  - One for favoured mode and one for suppressed mode in each final state

Fit results (favoured mode selection)



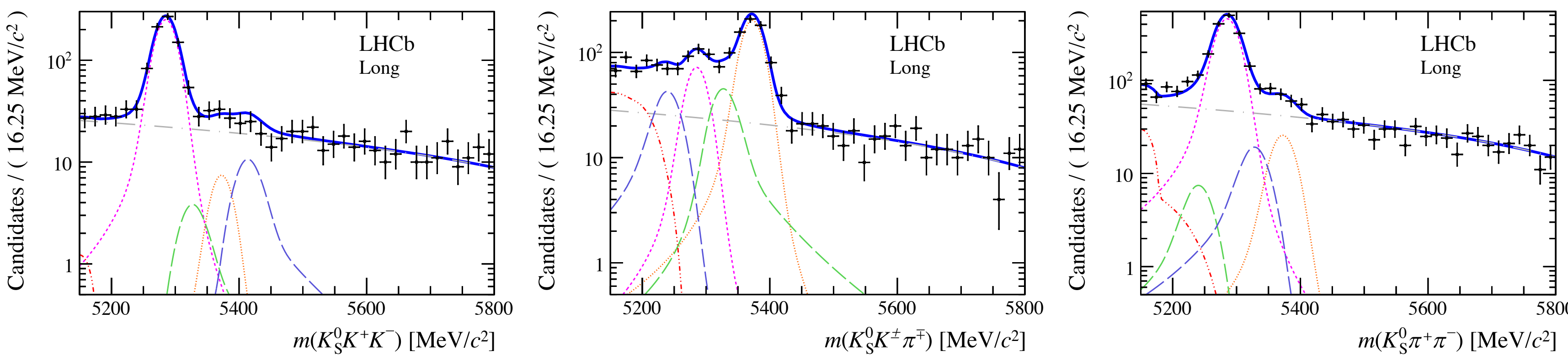
B^0 signal

B^0_s signal

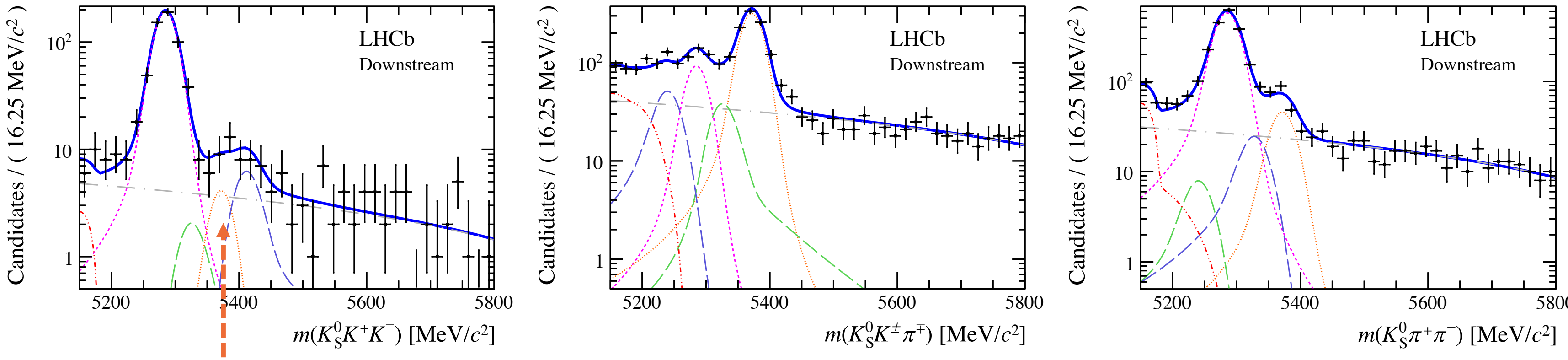
Cross-feed backgrounds

Partially-reconstructed backgrounds

Combinatorial background



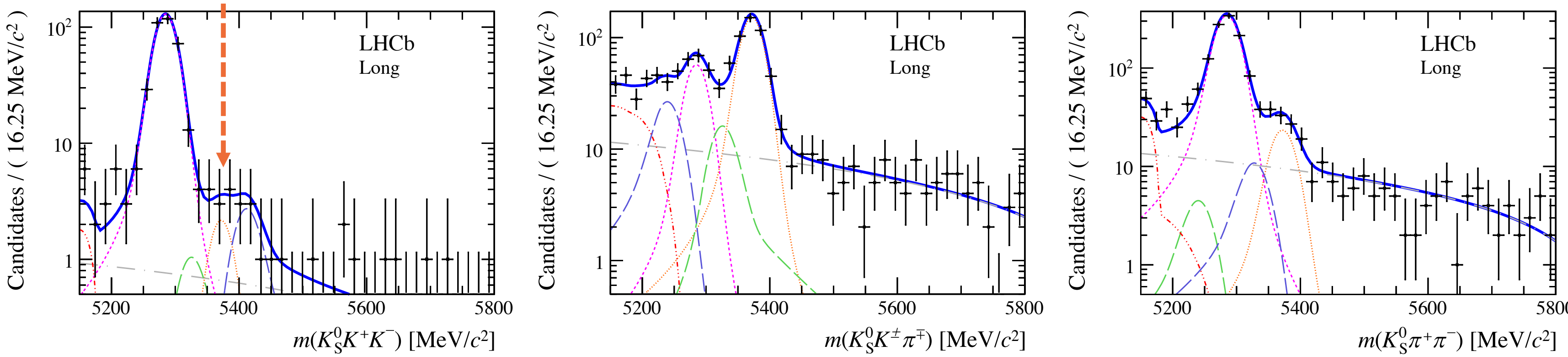
Fit results (suppressed mode selection)



12 ± 6

No evidence for decay $B_s^0 \rightarrow K_S^0 K^+ K^-$, significance of 2.5$\sigma$

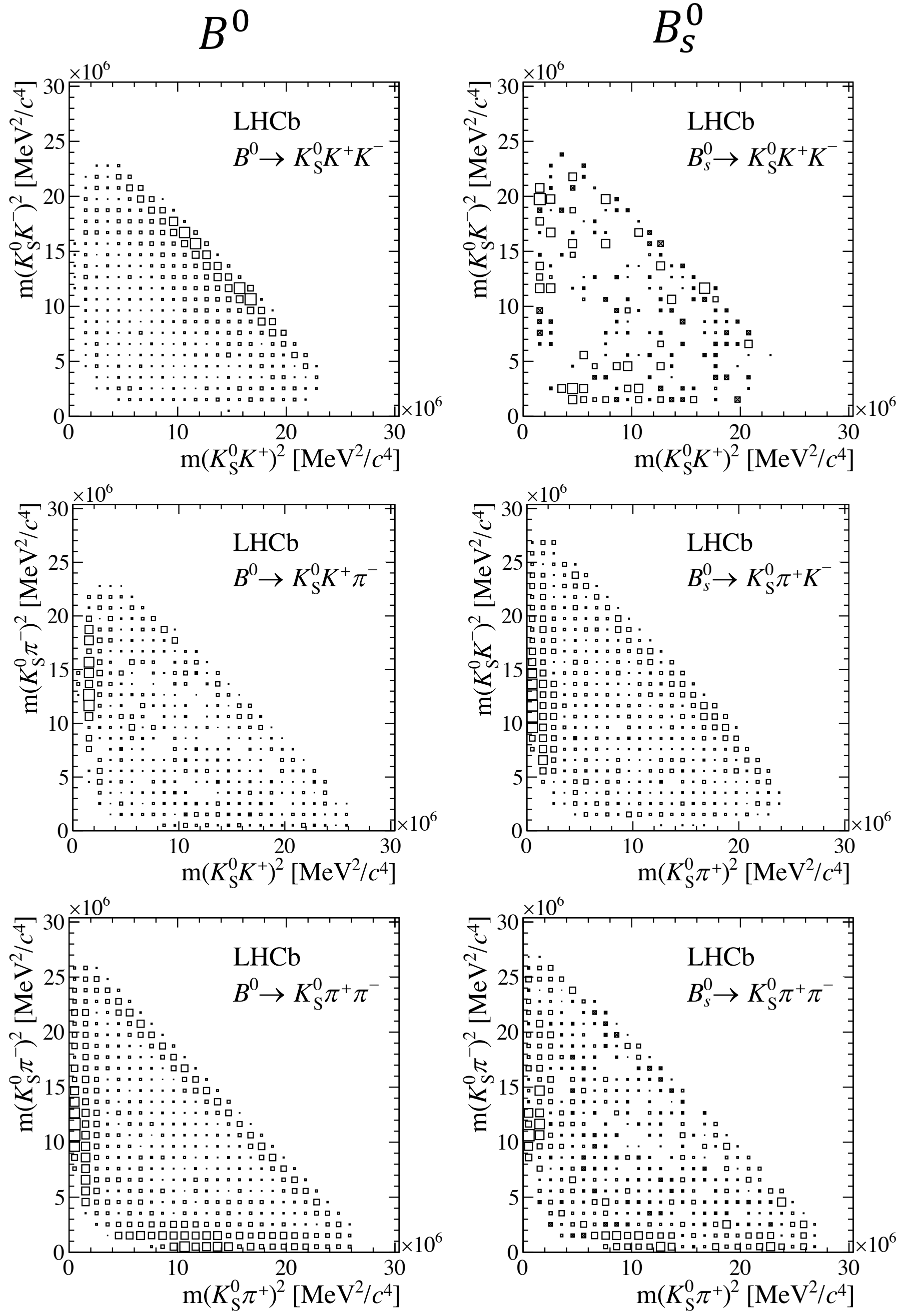
7 ± 4



arXiv:1707.01665 [hep-ex]

Dalitz plots

- Background-subtracted Dalitz-plot distributions
- Used, together with maps describing the efficiency variation, to calculate the BFs
- Very interesting also to inspect the dominant contributions to the amplitudes
- Dalitz-plot analyses of the three dominant modes underway



arXiv:1707.01665 [hep-ex]

Branching fractions

- Branching fractions measured relative to $B^0 \to K_S^0 \pi^+ \pi^-$
- Upper limit on BF of $B_s^0 \to K_S^0 K^+ K^-$ determined using Feldman-Cousins method

$$\frac{\mathcal{B}(B^0 \to K_S^0 K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K_S^0 \pi^+ \pi^-)} = 0.123 \pm 0.009 \text{ (stat) } \pm 0.015 \text{ (syst)},$$

$$\frac{\mathcal{B}(B^0 \to K_S^0 K^+ K^-)}{\mathcal{B}(B^0 \to K_S^0 \pi^+ \pi^-)} = 0.549 \pm 0.018 \text{ (stat) } \pm 0.033 \text{ (syst)},$$

$$\frac{\mathcal{B}(B_s^0 \to K_S^0 \pi^+ \pi^-)}{\mathcal{B}(B^0 \to K_S^0 \pi^+ \pi^-)} = 0.191 \pm 0.027 \text{ (stat) } \pm 0.031 \text{ (syst) } \pm 0.011 \text{ } (f_s/f_d),$$

$$\frac{\mathcal{B}(B_s^0 \to K_S^0 K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K_S^0 \pi^+ \pi^-)} = 1.70 \pm 0.07 \text{ (stat) } \pm 0.11 \text{ (syst) } \pm 0.10 \text{ } (f_s/f_d),$$

$$\frac{\mathcal{B}(B_s^0 \to K_S^0 K^+ K^-)}{\mathcal{B}(B^0 \to K_S^0 \pi^+ \pi^-)} \in [0.008 - 0.051] \text{ at } 90\% \text{ C.L.}$$

- Absolute BFs calculated using world average value (omitting previous LHCb result):

$$\mathcal{B}(B^0 \to K^0 \pi^+ \pi^-) = (4.96 \pm 0.20) \times 10^{-5}$$

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

Concluding remarks

- A wealth of recent measurements of charmless b-hadron decays at LHCb, with many more ongoing
- Several first observations of baryonic decays of B mesons have been made, including:
  - First 3 baryonic decays of the B_s^0 meson: $p\overline{\Lambda}K^-$, $p\bar{p}K^+K^-$, $p\bar{p}K^\pm\pi^\mp$
  - The rarest hadronic B meson decay yet observed: $B^0 \to p\bar{p}$
- Branching fractions measurements of neutral B meson decays to $K_S^0 h^+ h'^-$ final states have been updated with improved precision, laying the groundwork for forthcoming amplitude analyses
- Great potential to search for *CP* violation (see talk in this session tomorrow at 16:45)
- The addition of Run 2 data and then that from the LHCb upgrade will bring much larger samples of charmless decays
- Excellent prospects for increasingly precise measurements, both in terms of *CP* violation observables and hadron physics phenomena

Backup Slides

arXiv:1704.08497 [hep-ex]

$B^0_{(s)} \to p\bar{p}h^+h'^-$ ratios of BFs

$\mathcal{B}(B^0 \to p\bar{p}KK)/\mathcal{B}(B^0 \to p\bar{p}K\pi)$	0.019	± 0.005	± 0.002	
$\mathcal{B}(B^0 \to p\bar{p}\pi\pi)/\mathcal{B}(B^0 \to p\bar{p}K\pi)$	0.46	± 0.02	± 0.02	
$\mathcal{B}(B^0_s \to p\bar{p}K\pi)/\mathcal{B}(B^0 \to p\bar{p}K\pi)$	0.22	± 0.04	± 0.02	± 0.01
$\mathcal{B}(B^0_s \to p\bar{p}K\pi)/\mathcal{B}(B^0_s \to p\bar{p}KK)$	0.31	± 0.05	± 0.02	

arXiv:1704.08497 [hep-ex]

$B^0_{(s)} \to p\bar{p}h^+h'^-$ systematic uncertainties

	$B^0 \to p\overline{p}KK$	$B^0 \to p\overline{p}K\pi$	$B^0 \to p\overline{p}\pi\pi$	$B^0_s \to p\overline{p}KK$	$B^0_s \to p\overline{p}K\pi$	$B^0_s \to p\overline{p}\pi\pi$
MC statistics	3.0	1.7	2.1	1.9	4.7	4.1
Efficiency of hardware trigger	3.7	3.7	3.7	3.7	3.7	3.7
Tracking efficiency	1.1	1.1	1.1	1.1	1.1	1.1
Calibration of particle identification	1.9	1.7	1.4	2.0	1.7	1.4
Effect of B_s lifetime	-	-	-	2.6	2.5	2.7
Effect of charm vetoes	0.5	0.1	0.1	0.4	0.4	0.2
Shape fit components	1.8	0.3	0.5	0.4	0.5	1.9
Additional fit components	8.4	2.3	2.3	2.5	4.6	7.3
Normalisation of reflections in fit	0.2	0.0	0.1	0.4	0.7	1.7
Branching fraction of normalisation mode	6.9	6.9	6.9	6.9	6.9	6.9
f_d/f_s	-	-	-	5.8	5.8	5.8
Total systematic uncertainty	10.1	5.1	5.2	6.0	8.2	10.0
Statistical uncertainty	25.0	4.2	5.4	6.2	16.4	41.3

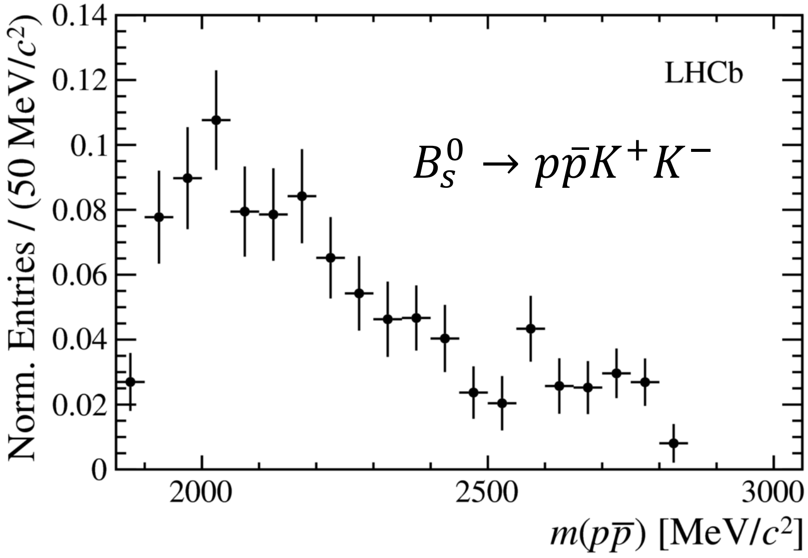
arXiv:1704.08497 [hep-ex]

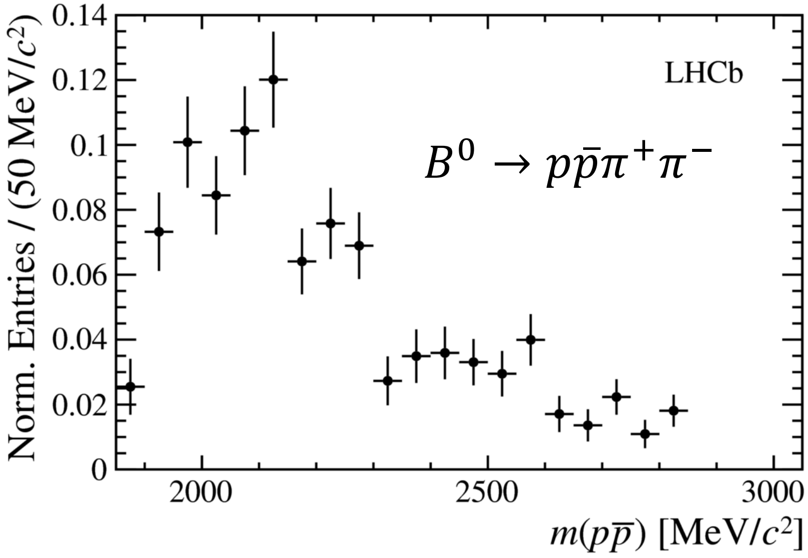
$B^0_{(s)} \to p\bar{p}h^+h'^-$ systematic uncertainties

	$\frac{\mathcal{B}(B^0\to p\bar{p}KK)}{\mathcal{B}(B^0\to p\bar{p}K\pi)}$	$\frac{\mathcal{B}(B^0\to p\bar{p}\pi\pi)}{\mathcal{B}(B^0\to p\bar{p}K\pi)}$	$\frac{\mathcal{B}(B^0_s\to p\bar{p}K\pi)}{\mathcal{B}(B^0\to p\bar{p}K\pi)}$	$\frac{\mathcal{B}(B^0_s\to p\bar{p}K\pi)}{\mathcal{B}(B^0_s\to p\bar{p}KK)}$
MC statistics	3.1	2.3	4.8	4.8
Efficiency of hardware trigger	3.7	3.7	3.7	3.7
Tracking efficiency	1.1	1.1	1.1	1.1
Calibration of particle identification	1.7	1.2	1.6	1.8
Effect of B_s lifetime	-	-	2.5	0.1
Effect of charm vetoes	0.5	0.1	0.4	0.5
Shape fit components	-	-	-	-
Additional fit components	8.2	0.8	4.0	4.2
Normalisation of reflections in fit	0.2	0.1	0.7	0.8
f_d/f_s	-	-	5.8	-
Total systematic uncertainty	-	-	-	-
Statistical uncertainty	24.8	4.5	16.3	17.0

arXiv:1704.08497 [hep-ex]

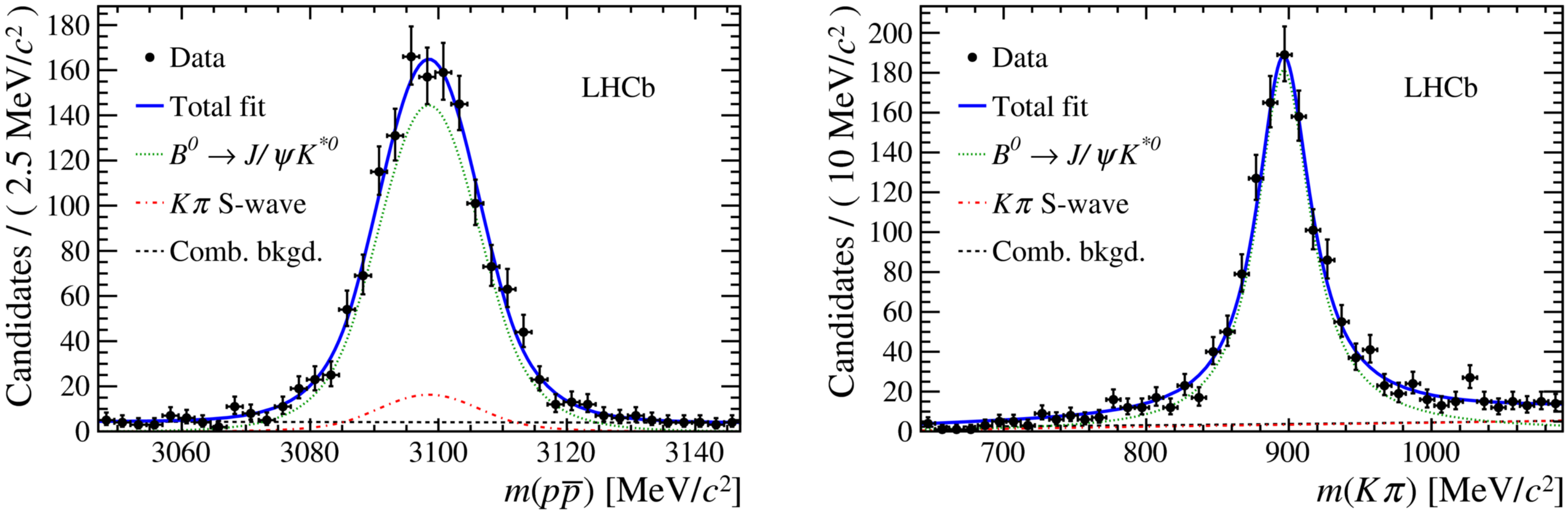
$B^0_{(s)} \to p\bar{p}h^+h'^-$ threshold enhancements





arXiv:1704.08497 [hep-ex]

$B^0 \to J/\psi(\to p\bar{p})K^*(892)^0(\to K^+\pi^-)$



arXiv:1709.01156 [hep-ex]

$B_{(s)}^0 \to p\bar{p}$ systematic uncertainties

Uncertainty origin	Value (%)	
	$B^0 \to p\bar{p}$	$B_s^0 \to p\bar{p}$
Trigger	3.1	3.1
Tracking	6.1	6.1
Selection	8.6	8.3
Particle identification	4.7	4.6
Mass fits	7.3	208
$B^0 \to K^+\pi^-$ branching fraction	2.6	2.6
f_s/f_d	–	5.8
Total systematic uncertainty	14.2	209
Statistical uncertainty	21.6	34.1

arXiv:1707.01665 [hep-ex]

$B^0_{(s)} \to K^0_S h^+ h'^-$ yields and efficiencies

Decay	downstream		long	
	Yield	Efficiency (%)	Yield	Efficiency (%)
$B^0 \to K^0_S\pi^+\pi^-$	2766 ± 66	0.0447 ± 0.0039	1411 ± 45	0.0168 ± 0.0015
$B^0 \to K^0_S K^\pm\pi^\mp$	261 ± 24	0.0340 ± 0.0031	160 ± 17	0.0120 ± 0.0012
$B^0 \to K^0_S K^+K^-$	1133 ± 39	0.0300 ± 0.0035	685 ± 29	0.0142 ± 0.0017
$B^0_s \to K^0_S\pi^+\pi^-$	146 ± 19	0.0359 ± 0.0030	74 ± 11	0.0127 ± 0.0011
$B^0_s \to K^0_S K^\pm\pi^\mp$	1100 ± 41	0.0387 ± 0.0035	568 ± 28	0.0146 ± 0.0013
$B^0_s \to K^0_S K^+K^-$	12 ± 6	0.0282 ± 0.0023	7 ± 4	0.0094 ± 0.0013

arXiv:1707.01665 [hep-ex]

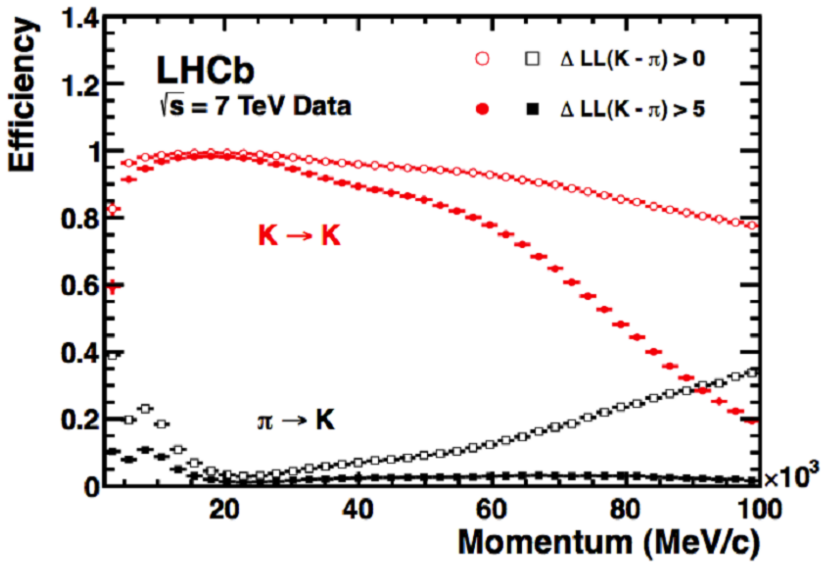
$B^0_{(s)} \to K^0_S h^+ h'^-$ systematic uncertainties

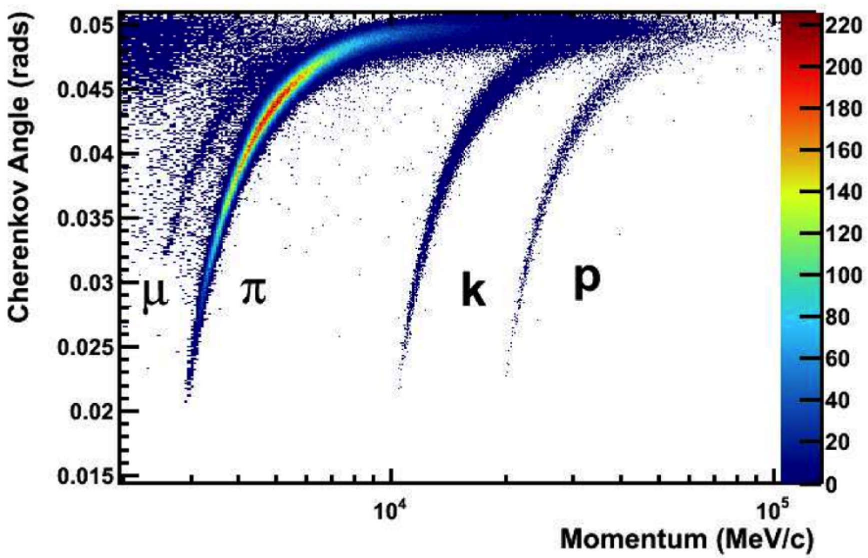
Relative $\mathcal{B}$		$\frac{\mathcal{B}(B^0 \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)}$	$\frac{\mathcal{B}(B^0 \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)}$	$\frac{\mathcal{B}(B^0_s \to K^0_S \pi^+ \pi^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)}$	$\frac{\mathcal{B}(B^0_s \to K^0_S K^\pm \pi^\mp)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)}$	$\frac{\mathcal{B}(B^0_s \to K^0_S K^+ K^-)}{\mathcal{B}(B^0 \to K^0_S \pi^+ \pi^-)}$
Fit model	[%]	9.7	2.1	13.5	4.7	18.5
Selection	[%]	3.8	1.9	3.3	2.4	6.7
Tracking	[%]	0.2	0.1	0.2	0.1	0.3
Trigger	[%]	3.2	5.0	6.8	3.5	12.6
PID	[%]	1.1	1.1	1.1	1.1	1.1
Total	[%]	12.2	6.0	16.2	6.5	26.9
f_s/f_d	[%]	...	...	5.8	5.8	5.8

Kaon/pion separation

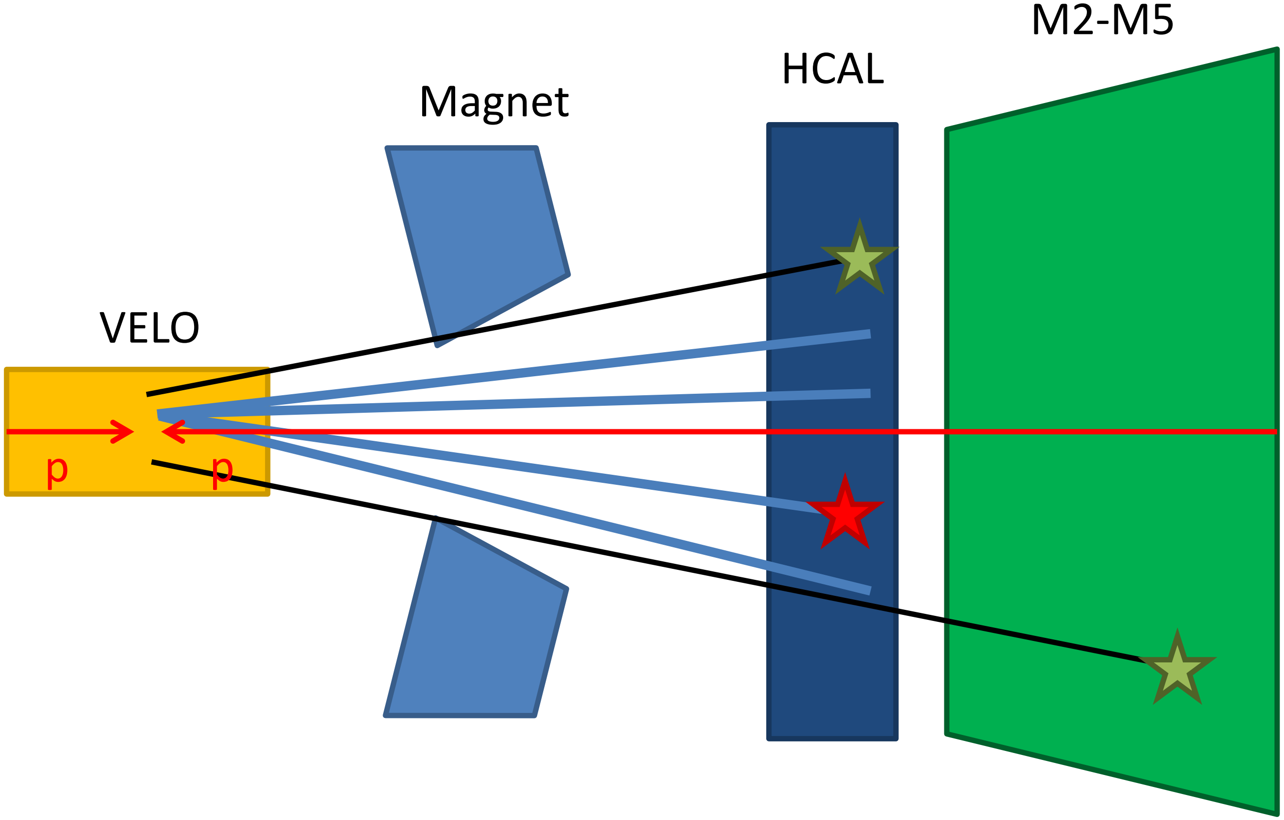
- Most particle identification information comes from the Ring Imaging Cherenkov detectors.
- Three different radiators provide separation over a wide momentum range.

$$\cos\theta = \frac{1}{\beta n}$$





Trigger categories



Trigger On Signal

- Particle from the signal decay fires a trigger line.
- Triggered by HCAL deposits.

Trigger Independent of Signal

- Particle from the rest of the event fires a trigger line.
- Triggered mostly by HCAL deposits or muons.

- Trigger Efficiencies:
  - ~30% efficient for multi-body hadronic
  - ~90% efficient for di-muons

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Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\mathrm{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities. Note that the current sensitivities do not include new results presented at ICHEP 2012 or CKM2012.

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [138]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [214]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [244, 258]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm CP violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

The Physics of the B Factories
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The Dalitz plot

A graphical representation of the 3-body phase space: M ⟶ a b c