Salamanca
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CP violation in B mesons and b-baryons at LHCb

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(on behalf of the LHCb Collaboration)

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THE UNIVERSITY OF WARWICK

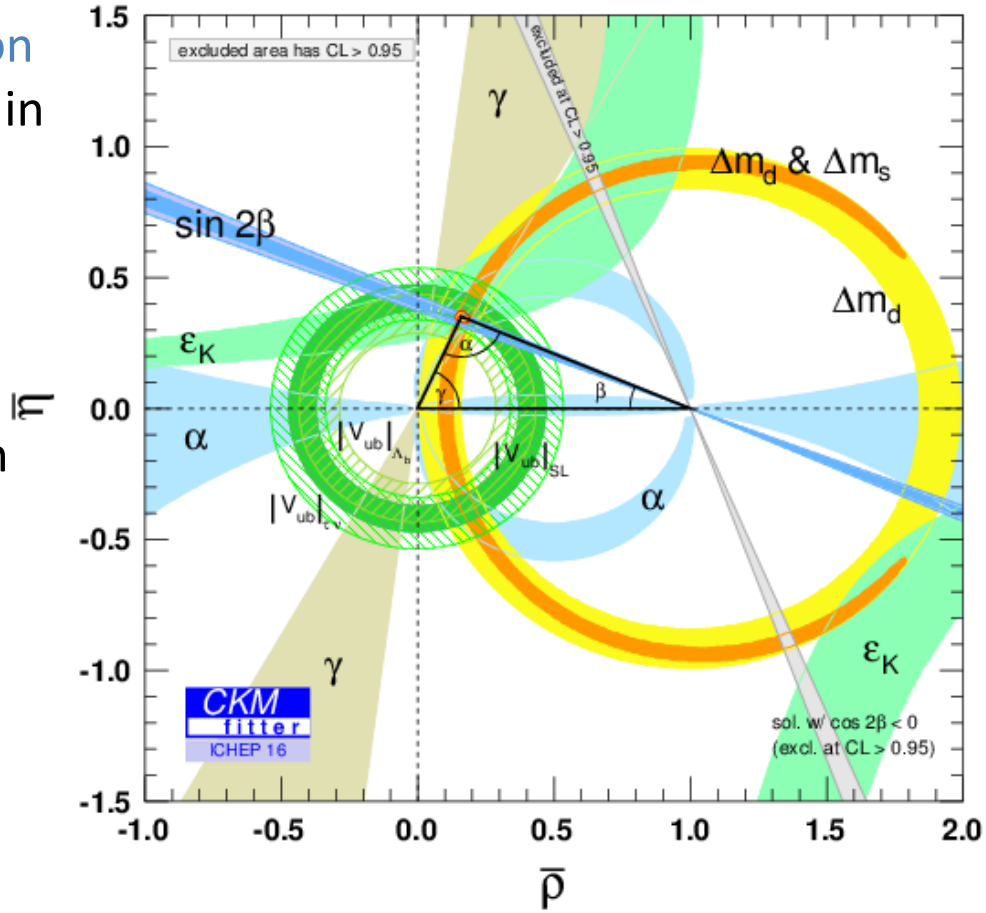
Overview

- Introduction
  - CP violation
  - The LHCb experiment
- Recent results from LHCb
  - Determination of CKM angle β from:
    - $B^0 \to (J/\psi \to e^+e^-)K_S^0$
    - $B^0 \to (\psi(2S) \to \mu^+\mu^-)K_S^0$
  - Search for CPV in $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^-K^+K^-$
- Concluding remarks

CKM mechanism and CP violation

- Standard Model description of quark coupling to weak interaction
- CPV arises due to complex phase in the mixing matrix
- Convenient representation for *b*-hadron physics is the Unitarity Triangle

- CKM mechanism agrees well with experiment
- But still plenty of room for new physics
- Vital to measure CP violating observables in as many different decay processes as possible
- Look for disagreements



Manifestations of CPV

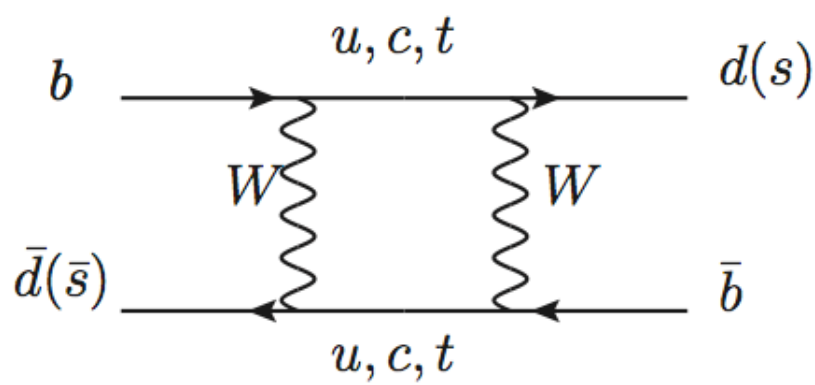
- **CPV in decay** $|\bar{A}_{\bar{f}}/A_f| \neq 1$
  - The ratio of the amplitudes for the decay of b and $\bar{b}$ hadrons to CP-conjugate final states is not of unit magnitude
  - Only form of CPV possible for B^+ mesons and b-baryons

- **Mixing-induced CPV** $\arg(\lambda_f) + \arg(\lambda_{\bar{f}}) \neq 0$
  - The ratio of the amplitudes for decays with and without mixing is not real
  - Investigated for both B^0 and B_s^0 decays
  - Requires time-dependent analyses (more on this later)

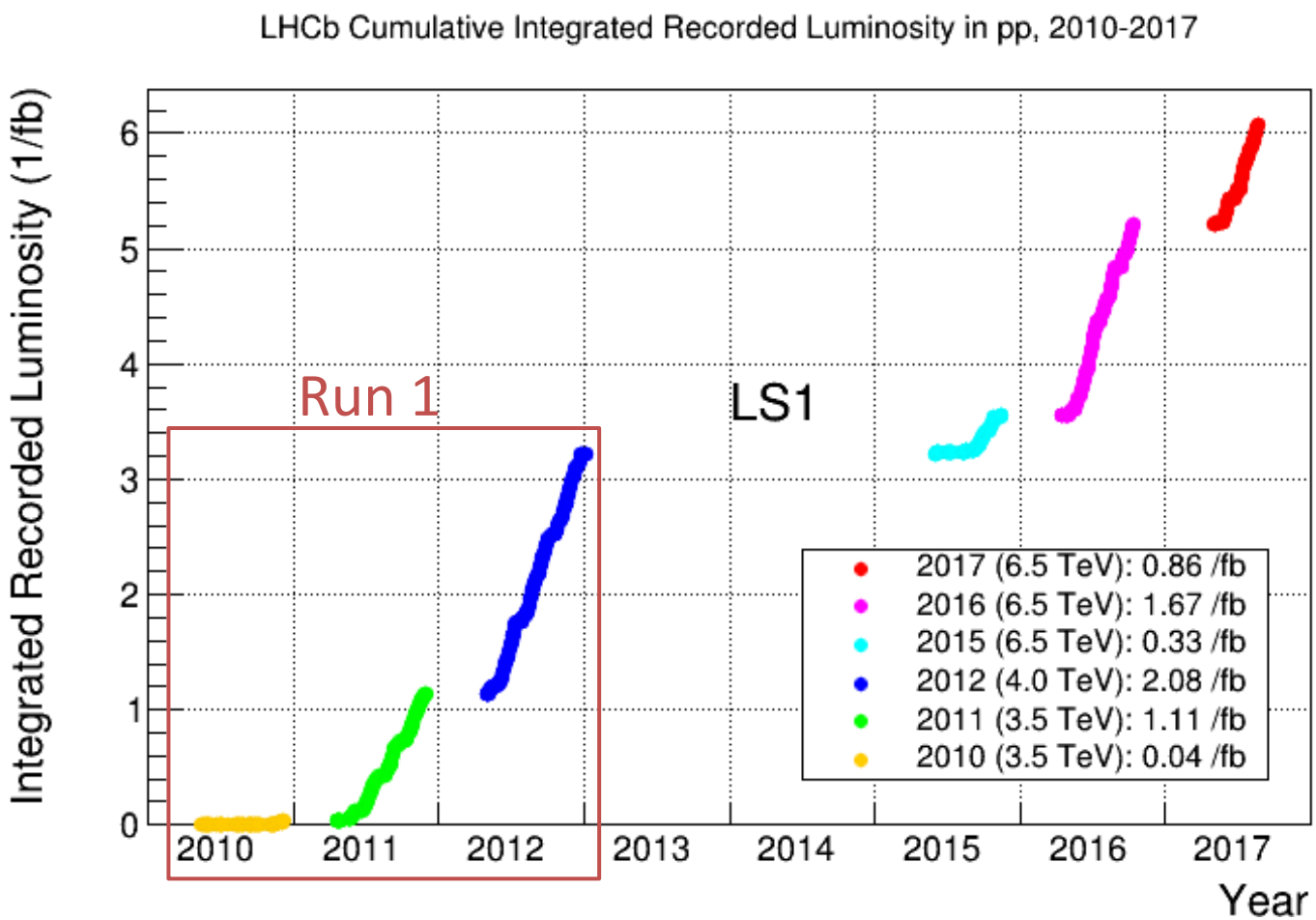
- **CPV in mixing** $|q/p| \neq 1$
  - Expected to be small for the B meson system
  - Will not discuss this further today (although LHCb has made important measurements in last couple of years)

[Phys. Rev. Lett. 114 (2015) 041601]

[Phys. Rev. Lett. 117 (2016) 061803]



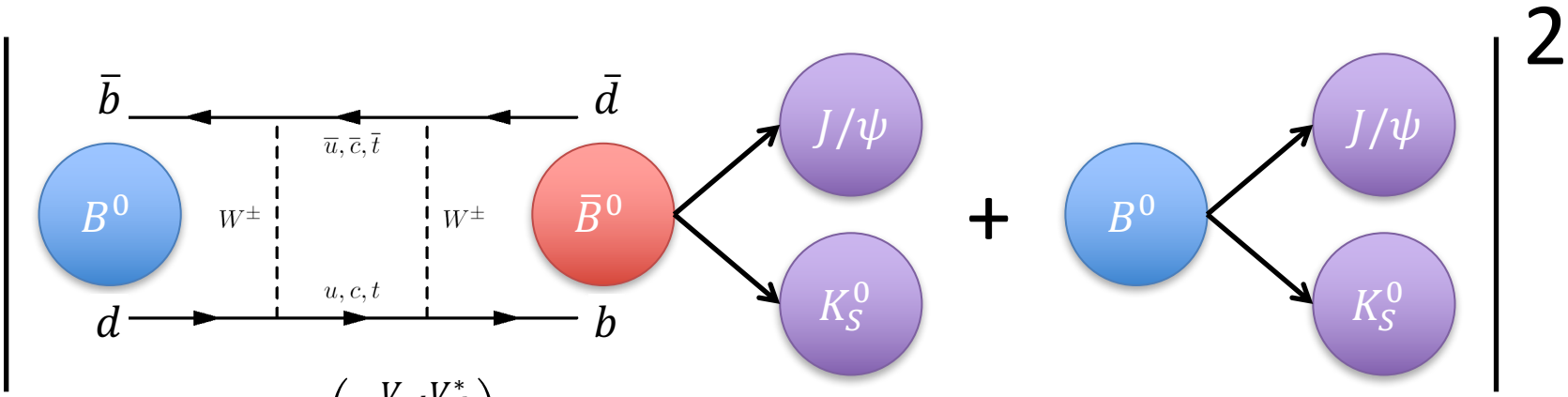
Data Sample



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

Measurements of the angle β

$B^0 \sim \bar{B}^0$ mixing phase



$$\beta = \arg\left(-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$

- Neutral B mesons exhibit mixing through box diagram
- Decays to *CP* eigenstates allow to probe the mixing phase β through the interference between decays with and without mixing
- Make comparison of direct and indirect determinations (as well as direct determinations in different decays) to probe possible new physics contributions

Time-dependent asymmetries

- The time-dependent CP asymmetry is given by:

assuming $\Delta\Gamma_d \approx 0$

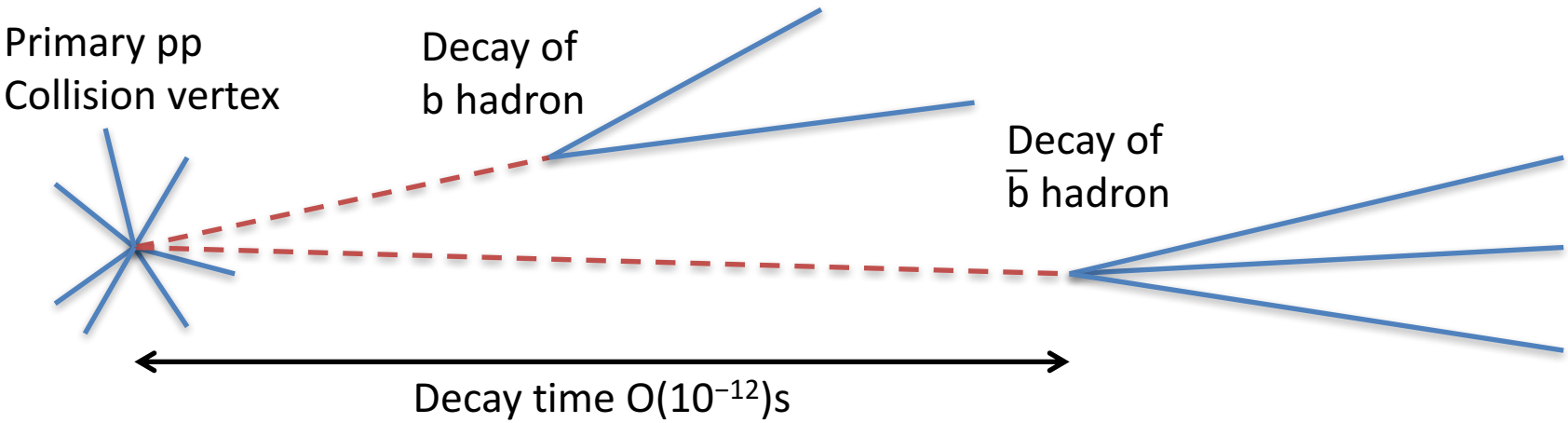
$$A_{CP}^{f}(t) = \frac{\Gamma[\bar{B}^0(t) \to f] - \Gamma[B^0(t) \to f]}{\Gamma[\bar{B}^0(t) \to f] + \Gamma[B^0(t) \to f]} = -C_f \cos(\Delta m_d\, t) + S_f \sin(\Delta m_d\, t)$$

$$C_f = \frac{1 - |\lambda_f|^2}{1 + |\lambda_f|^2} \qquad S_f = \frac{2\mathrm{Im}\lambda_f}{1 + |\lambda_f|^2} \qquad \lambda_f = \frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- $\frac{\bar{A}_f}{A_f}$ is the ratio of decay amplitudes
- $\frac{q}{p}$ is related to the neutral B mixing
- In absence of CPV in decay and CPV in mixing:

  $C_f \approx 0$ and $S_f \approx -\eta_f \sin 2\beta$
- Where η_f is the *CP* eigenvalue of the final state

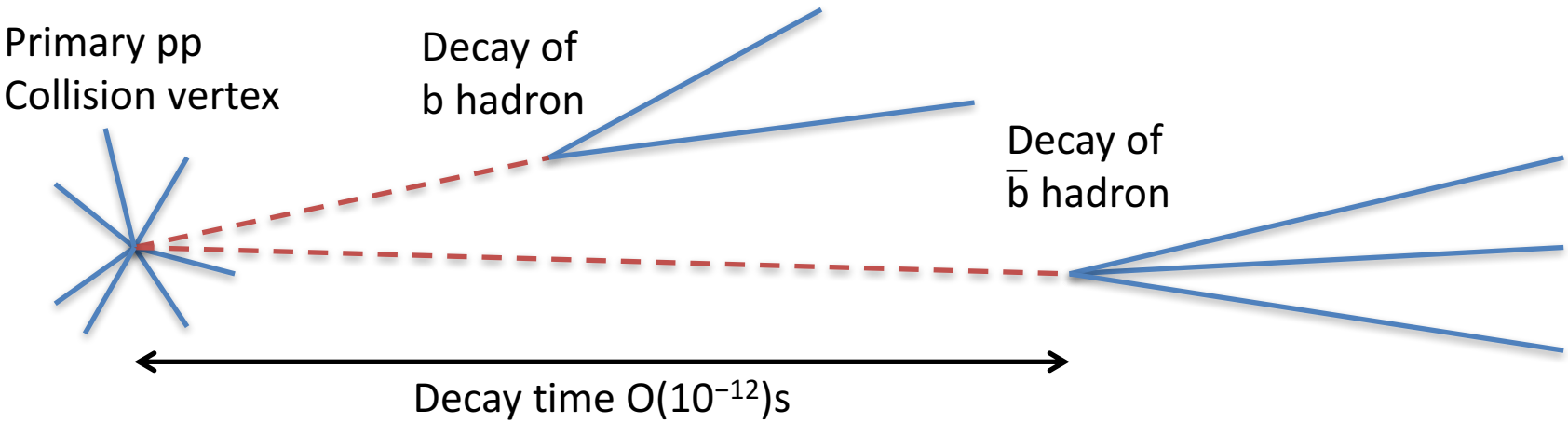
Time dependent analysis



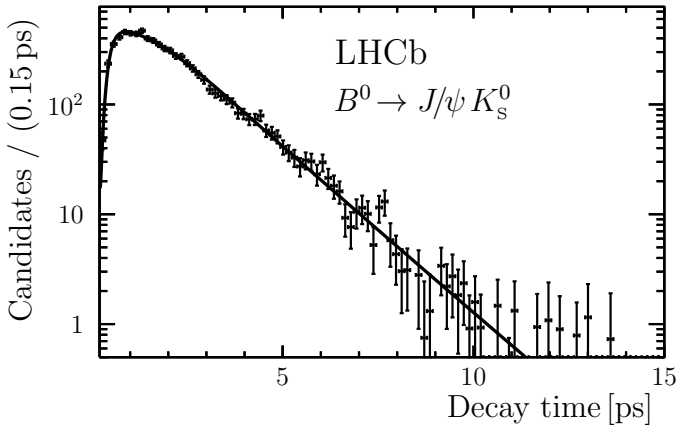
- Vertex measurements by LHCb VELO allow decay times of particles to be precisely determined
- Need also to tag the flavour of the signal at production
- Putting these two pieces of information together, can measure decay rates as a function of the decay time
- Hence allows mixing-induced CPV to be probed

arXiv:1709.03944 [hep-ex]

Time dependent analysis



- Need also to account for effects of:
  - Decay time acceptance (due to trigger and selection requirements)
  - Experimental resolution on the measurement of the decay time
  - Rate of mis-tagging the flavour



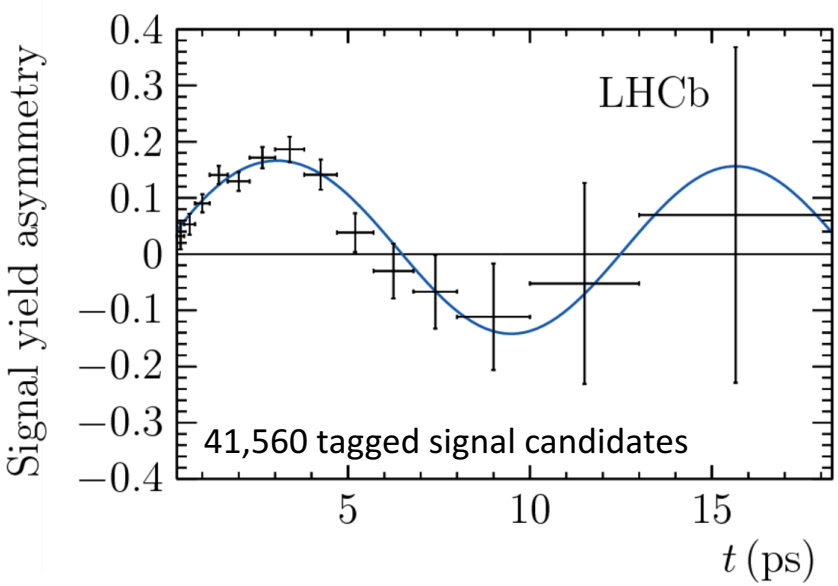
Phys. Rev. Lett. 115 (2015) 031601

Previous measurements

- LHCb measurement from 2015 used the decay:

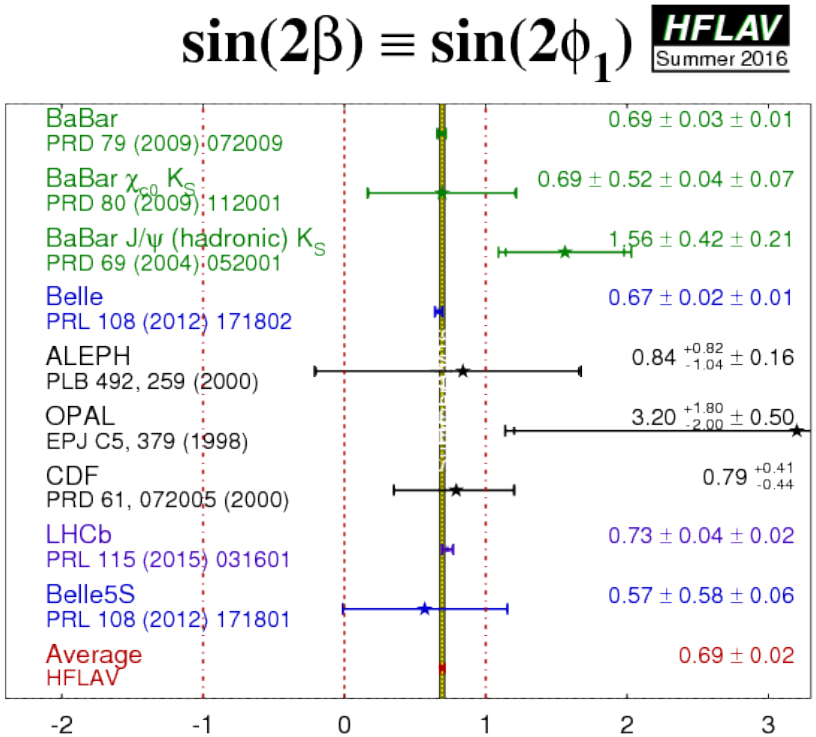
$$B^0 \to J/\psi(\to \mu^+\mu^-)K_S^0$$

- Its comparison with results from B factories (and other experiments) shown on right



$$S_{J/\psi K_S^0} = +0.731 \pm 0.035 \pm 0.020$$

$$C_{J/\psi K_S^0} = -0.038 \pm 0.032 \pm 0.005$$



cf. indirect determination (CKMfitter):

$$\sin 2\beta = 0.740^{+0.020}_{-0.025}$$

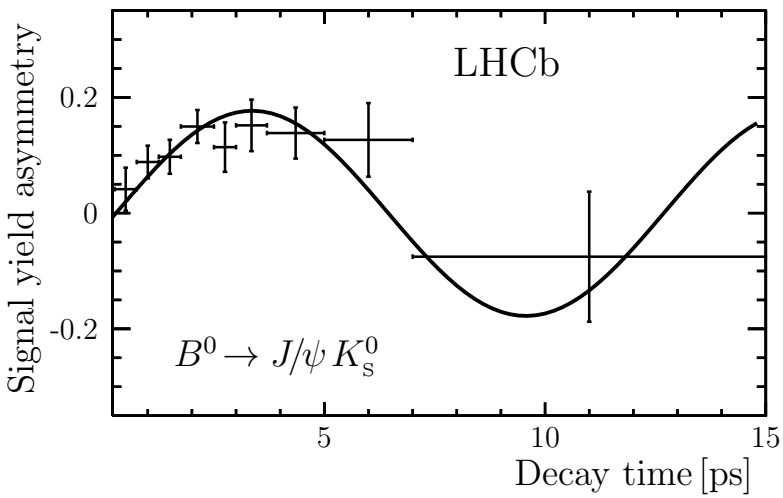
arXiv:1709.03944 [hep-ex]

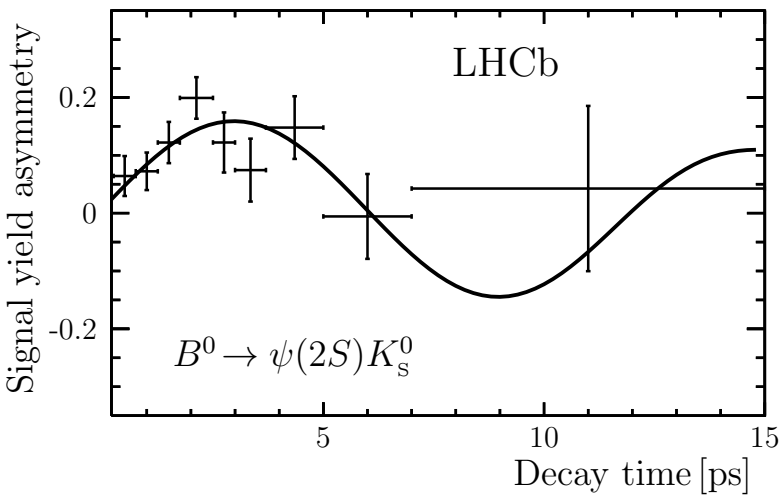
Time-dependent CP asymmetries

- Latest LHCb analysis adds two new decay modes:

$$B^0 \to J/\psi(\to e^+e^-)K_S^0$$
$$B^0 \to \psi(2S)(\to \mu^+\mu^-)K_S^0$$

- The fits to the B^0 candidate invariant mass spectra yield $10{,}630 \pm 140$ and 7970 ± 100 signal candidates, respectively
- Effective tagging efficiencies are $(5.93 \pm 0.29)\%$ and $(3.42 \pm 0.09)\%$





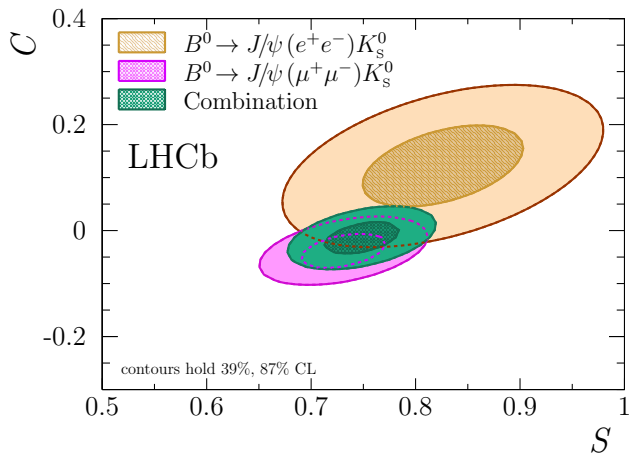
$$S_{J/\psi K_S^0} = +0.83 \pm 0.08 \pm 0.01$$
$$C_{J/\psi K_S^0} = +0.12 \pm 0.07 \pm 0.02$$

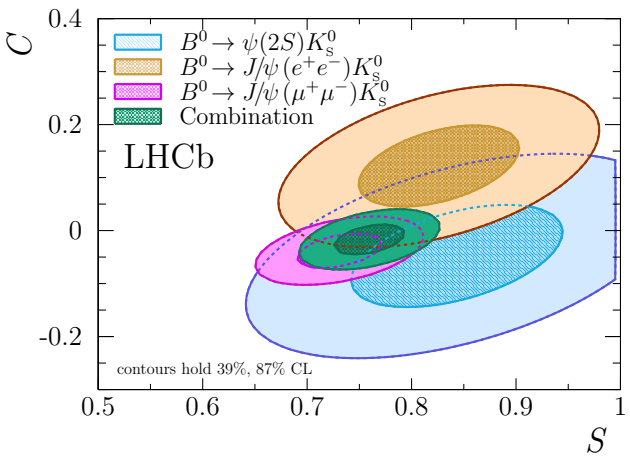
$$S_{\psi(2S)K_S^0} = +0.84 \pm 0.10 \pm 0.01$$
$$C_{\psi(2S)K_S^0} = -0.05 \pm 0.10 \pm 0.01$$

arXiv:1709.03944 [hep-ex]

Combination

- Combining these new measurements with the previous LHCb result produces a 20% reduction in the uncertainty
- Expected to improve precision in the World Average
- Consistent with B-factory measurements within 2σ
- Expected to further reduce the tension with the indirect determination





$$S_{J/\psi K^0_S} = +0.75 \pm 0.04$$
$$C_{J/\psi K^0_S} = -0.014 \pm 0.030$$

$$S_{(c\bar{c})K^0_S} = +0.760 \pm 0.034$$
$$C_{(c\bar{c})K^0_S} = -0.017 \pm 0.029$$

CPV in b-baryon decays

The search for CPV in b-baryons

CDF II

$\Lambda_b^0 \to ph^-$

Phys. Rev. Lett. 113 (2014) 242001

$A_{CP}(\Lambda_b^0 \to p\pi^-) = +0.06 \pm 0.07\ (stat) \pm 0.03\ (syst)$

$A_{CP}(\Lambda_b^0 \to pK^-) = -0.10 \pm 0.08\ (stat) \pm 0.04\ (syst)$

LHCb

$\Lambda_b^0(\Xi_b^0) \to K_s^0 ph^-$

JHEP 04 (2014) 087

$A_{CP}(\Lambda_b^0 \to K_s^0 p\pi^-) = 0.22 \pm 0.13\ (stat) \pm 0.03\ (syst)$

LHCb

$\Lambda_b^0(\Xi_b^0) \to \Lambda h^+ h^-$

JHEP 05 (2016) 081

$A_{CP}(\Lambda_b^0 \to \Lambda K^+\pi^-) = -0.53 \pm 0.23\ (stat) \pm 0.11\ (syst)$

$A_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = -0.28 \pm 0.10\ (stat) \pm 0.07\ (syst)$

LHCb

$\Lambda_b^0 \to \Lambda\eta, \Lambda\phi$

JHEP 09 (2015) 006

Phys. Lett. B 759 (2016) 282

Evidence for Λ_b^0 decay to $\Lambda\eta$ final state.

Observed $\Lambda_b^0 \to \Lambda\phi$ decay but CPV consistent with zero.

LHCb

$\Lambda_b^0 \to pK^-\mu^+\mu^-$

JHEP 06 (2017) 108

$\Delta A_{CP}(\Lambda_b^0 \to pK^-\mu^+\mu^-) = (-3.5 \pm 5.0 \pm 0.2)\times 10^{-2}$

$a_{CP}^{\hat{T}-odd} = (1.2 \pm 5.0 \pm 0.7)\times 10^{-2}$

Consistent with CP symmetry

LHCb

$\Xi_b^-(\Omega_b^-) \to ph^-h^-$

Phys. Rev. Lett. 118 (2017) 071801

1st observation of Ξ_b^- decay to charmless final state.

No CPV measurements performed yet.

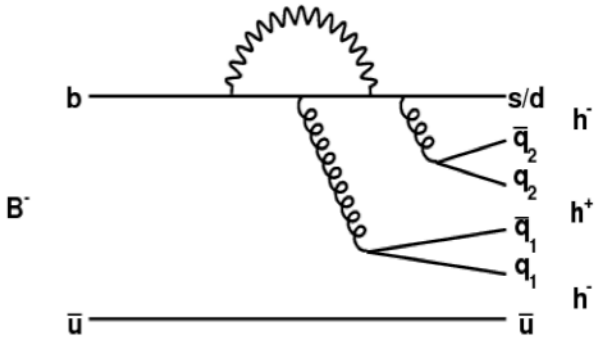
LHCb

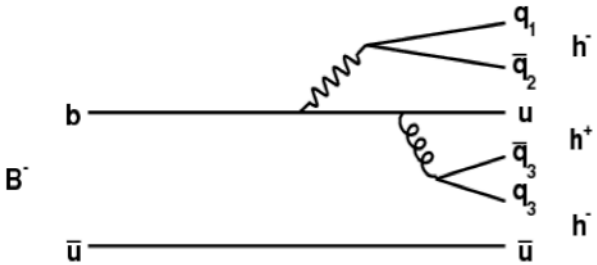
$\Lambda_b^0(\Xi_b^0) \to ph^-h^-h^+$

Nature Physics 13 (2017) 391–396

Will discuss this analysis in more detail on the following slides...

Why charmless decays?





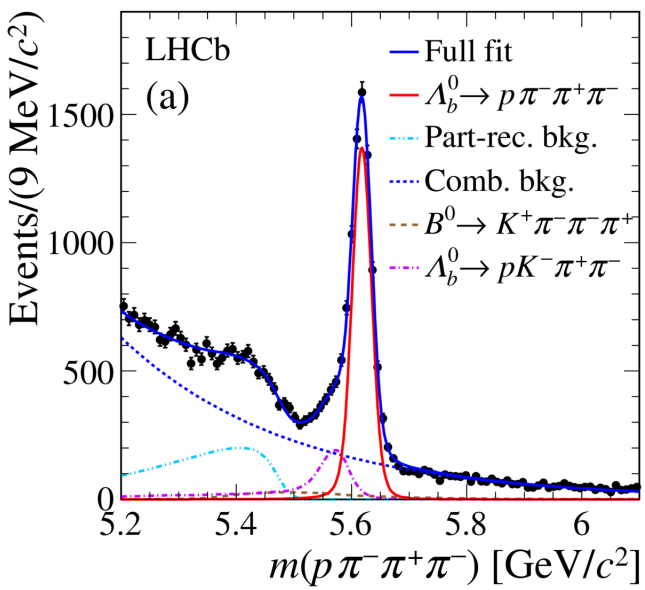
- Large CP asymmetries have been observed in many charmless B meson decays, e.g. $B^+ \to h^+h^+h^-$ [Phys. Rev. D 90 (2014) 112004]
- Contributions from both loop (penguin) and tree decay diagrams
- Have comparable magnitude and a relative weak phase (= γ in SM)
- Interference can therefore give rise to CP violation in decay
- Natural to expect (large) CPV in similar decays of b-baryons as well

Nature Physics 13 (2017) 391–396

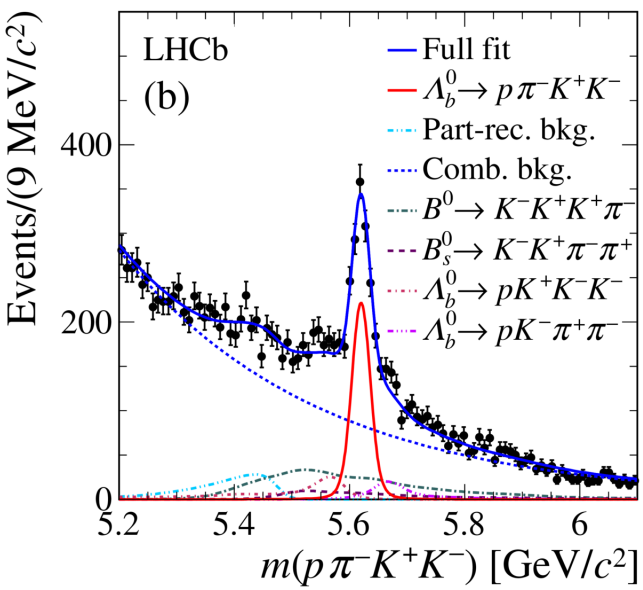
Search for CPV in $\Lambda_b^0 \to p\pi^- h^+ h^-$

- The $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ and $\Lambda_b^0 \to p\pi^- K^+ K^-$ decays, observed for the first time, are analysed to search for CP violation
- The $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+, p\pi^-\pi^+, pK^-K^+)\pi^-$ and $\Lambda_b^0 \to pK^-\pi^+\pi^-$ modes are used as control channels (for signal selection and systematic studies)

$N_{\Lambda_b^0 \to p\pi^-\pi^+\pi^-} = 6646 \pm 105$



$N_{\Lambda_b^0 \to p\pi^- K^+ K^-} = 1030 \pm 56$



Nature Physics 13 (2017) 391–396

Triple-product observables

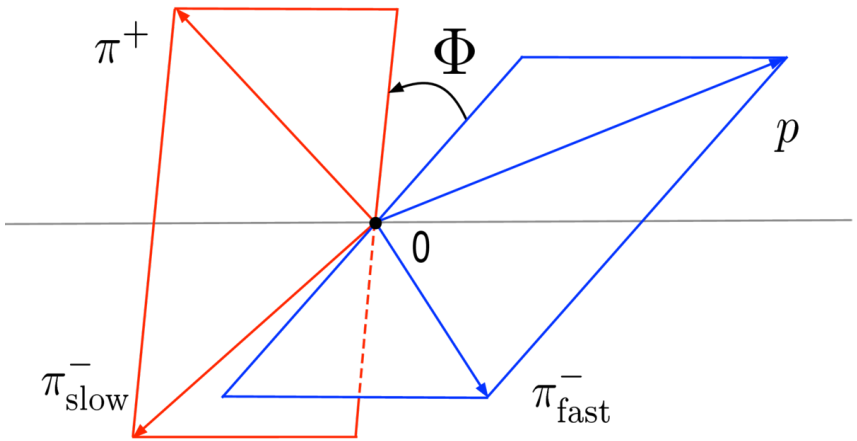
- Exploit the topology of the 4-body decay and construct observables that are scalar triple products of the final-state momenta
- From these $C_{\hat{T}}$ and $\bar{C}_{\hat{T}}$ observables, can define asymmetries that are odd under both the P and $\hat{T}$ operators

- For Λ_b^0 decays:

$$C_{\hat{T}} = \vec{p}_p \cdot \left(\vec{p}_{h_1^-} \times \vec{p}_{h_2^+}\right)$$

- For $\overline{\Lambda}_b^0$ decays:

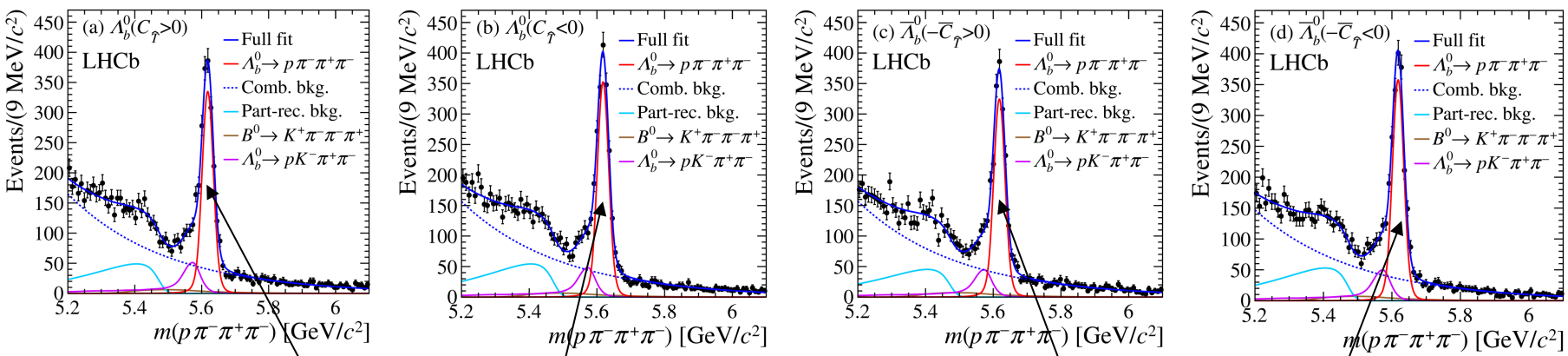
$$\bar{C}_{\hat{T}} = \vec{p}_{\bar{p}} \cdot \left(\vec{p}_{h_1^+} \times \vec{p}_{h_2^-}\right)$$



Nature Physics 13 (2017) 391–396

Asymmetry observables

- Divide data into 4 sub-samples depending on Λ_b^0 flavour and sign of the triple-product observable
- Determine signal yield in each sub-sample to construct the asymmetries



$$A_{\hat{T}}(C_{\hat{T}}) = \frac{N(C_{\hat{T}}>0) - N(C_{\hat{T}}<0)}{N(C_{\hat{T}}>0) + N(C_{\hat{T}}<0)}$$

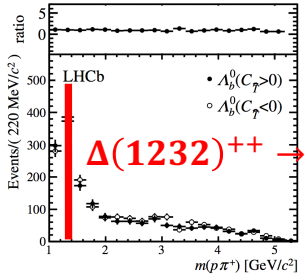
$$\overline{A}_{\hat{T}}(\overline{C}_{\hat{T}}) = \frac{\overline{N}(-\overline{C}_{\hat{T}}>0) - \overline{N}(-\overline{C}_{\hat{T}}<0)}{\overline{N}(-\overline{C}_{\hat{T}}>0) + \overline{N}(-\overline{C}_{\hat{T}}<0)}$$

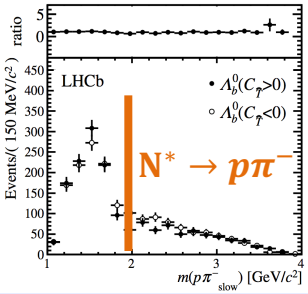
CP-violating asymmetry	$a_{CP}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} - \overline{A}_{\hat{T}}\right)$
P-violating asymmetry	$a_{P}^{\hat{T}\text{-odd}} = \frac{1}{2}\left(A_{\hat{T}} + \overline{A}_{\hat{T}}\right)$

Nature Physics 13 (2017) 391–396

Phase-space binning schemes

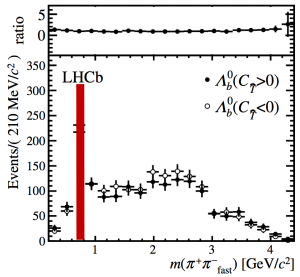
- Phase space integrated asymmetries found to be compatible P and CP conservation
- To enhance the sensitivity to localised effects, also measure the asymmetries in regions of phase space:

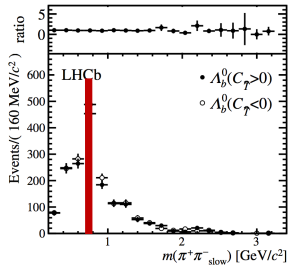




Phase space bin	$m(p\pi^+)$	$m(p\pi^-_{slow})$	$m(\pi^+\pi^-_{slow})$, $m(\pi^+\pi^-_{fast})$	$\lvert\Phi\rvert$
1	$(1.07, 1.23)$			$(0, \frac{\pi}{2})$
2	$(1.07, 1.23)$			$(\frac{\pi}{2}, \pi)$
3	$(1.23, 1.35)$			$(0, \frac{\pi}{2})$
4	$(1.23, 1.35)$			$(\frac{\pi}{2}, \pi)$
5	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{slow}) < 0.78$ or $m(\pi^+\pi^-_{fast}) < 0.78$	$(0, \frac{\pi}{2})$
6	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{slow}) < 0.78$ or $m(\pi^+\pi^-_{fast}) < 0.78$	$(\frac{\pi}{2}, \pi)$
7	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{slow}) > 0.78$ and $m(\pi^+\pi^-_{fast}) > 0.78$	$(0, \frac{\pi}{2})$
8	$(1.35, 5.34)$	$(1.07, 2.00)$	$m(\pi^+\pi^-_{slow}) > 0.78$ and $m(\pi^+\pi^-_{fast}) > 0.78$	$(\frac{\pi}{2}, \pi)$
9	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{slow}) < 0.78$ or $m(\pi^+\pi^-_{fast}) < 0.78$	$(0, \frac{\pi}{2})$
10	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{slow}) < 0.78$ or $m(\pi^+\pi^-_{fast}) < 0.78$	$(\frac{\pi}{2}, \pi)$
11	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{slow}) > 0.78$ and $m(\pi^+\pi^-_{fast}) > 0.78$	$(0, \frac{\pi}{2})$
12	$(1.35, 5.34)$	$(2.00, 4.00)$	$m(\pi^+\pi^-_{slow}) > 0.78$ and $m(\pi^+\pi^-_{fast}) > 0.78$	$(\frac{\pi}{2}, \pi)$

Reduce potential dilution of asymmetry





Scheme A: Isolate regions of phase-space with dominant resonant contributions

Scheme B: Exploit contributing resonance interference as function of $|\Phi|$

10 bins in $|\Phi|\left(\frac{i-1}{10}\pi, \frac{i}{10}\pi\right), (i=1,2,\ldots,10)$

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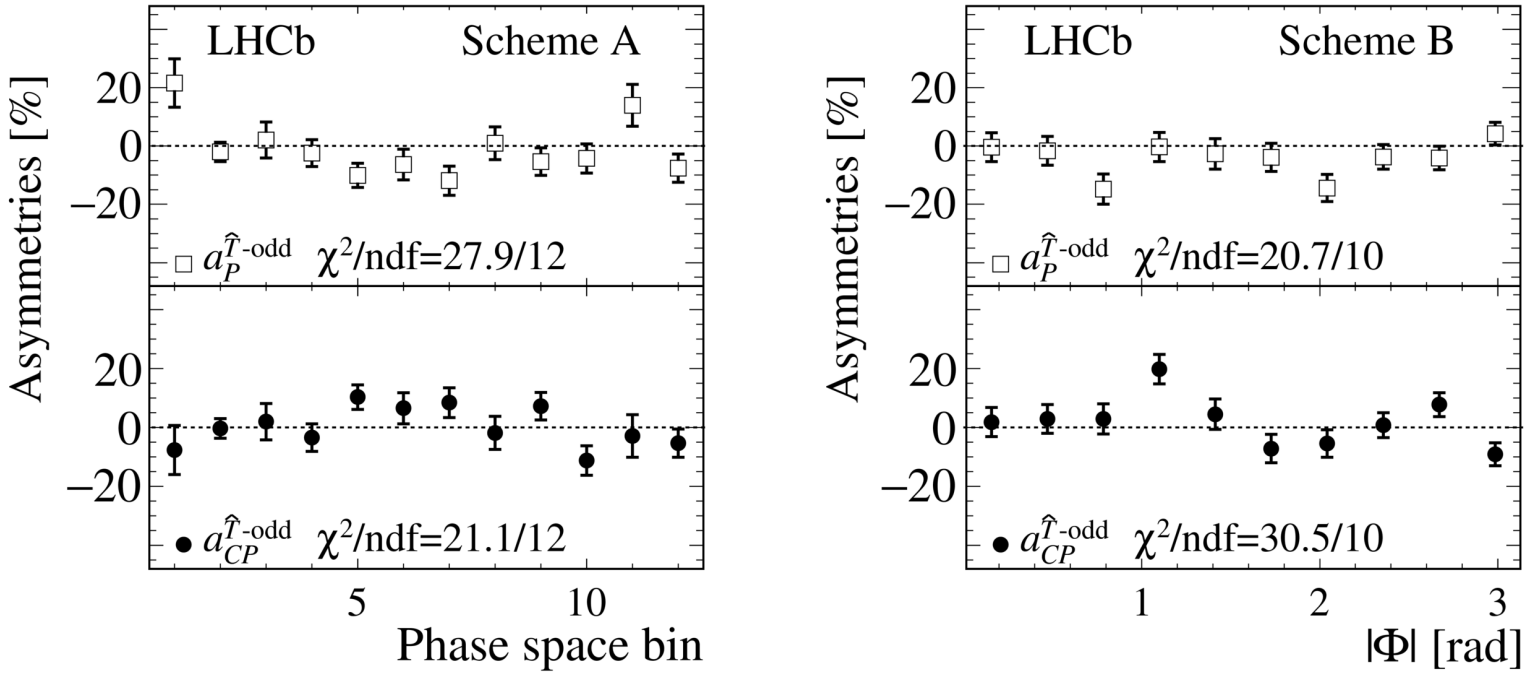
Evidence of CPV in $\Lambda_b^0 \to p\pi^+\pi^-\pi^+$



- Combined significance of the 2 binning schemes determined using a permutation test:
  - 3.3 σ deviation from *CP*-symmetry & 2.2 σ deviation from *P*-symmetry
- This constitutes first evidence for CPV in the baryon sector
- $\Lambda_b^0 \to p\pi^+K^-K^+$ (lower purity and yield) is found to be consistent with conservation of CP and P symmetries

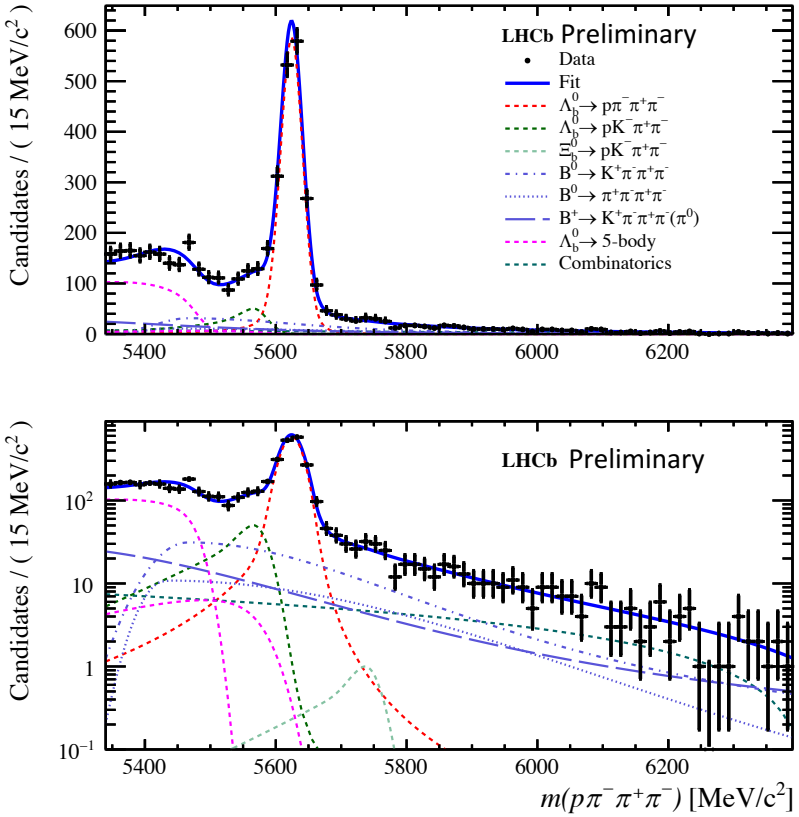
Branching fractions of $\Lambda_b^0/\Xi_b^0 \to ph^-h'^+h''^-$ decays

- New analysis aims to establish the signals and measure the branching fractions of whole family of these decays
  - with respect to normalisation channel: $\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$
- There are five final states, which are analysed simultaneously to improve control of systematics from mis-ID backgrounds etc.
- The 5D phase-space makes extremely difficult the ideal procedure of evaluating per-event efficiencies (as done in many 3-body decays, e.g. recent analysis of $B_{(s)}^0 \to K_S^0 h^+h'^-$ discussed yesterday)
- This analysis therefore aims to reduce to an absolute minimum the variation of the efficiency over the phase space
- Important consequence: must rely on hardware triggers made independent of the signal candidates – results in uniform, but reduced, efficiency

LHCb-PAPER-2017-034
in preparation

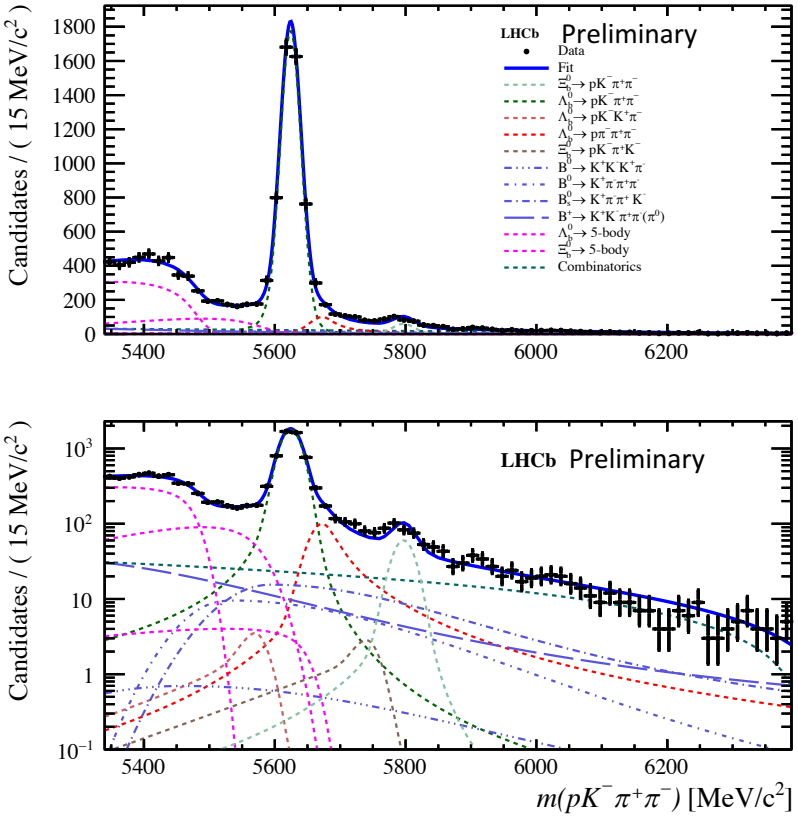
Fit results

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



1809 ± 48

$\Lambda_b^0/\Xi_b^0 \to pK^-\pi^+\pi^-$



5193 ± 76 183 ± 22

LHCb-PAPER-2017-034
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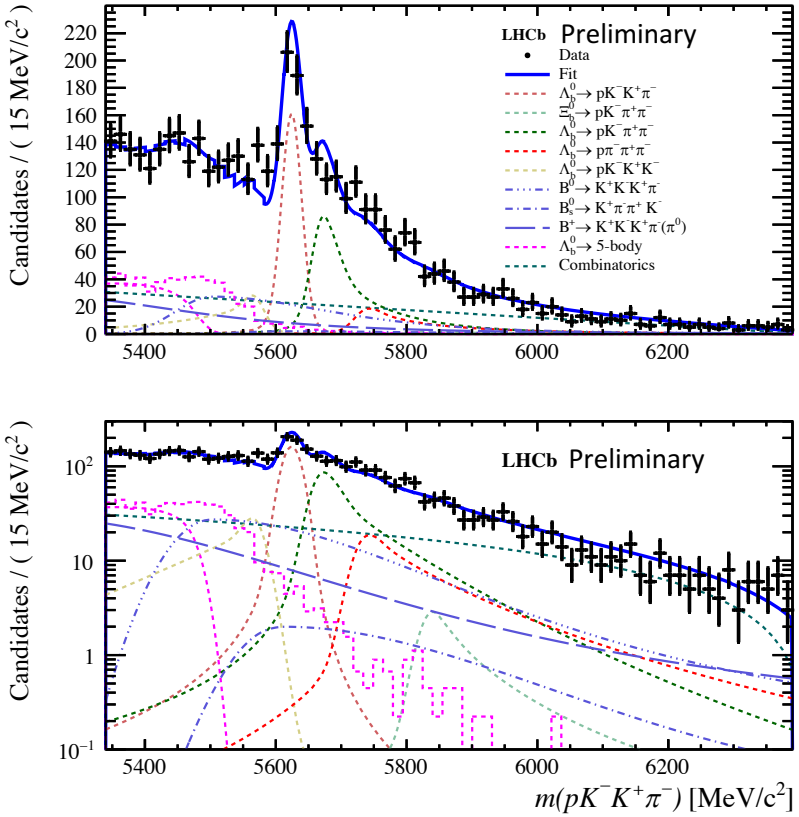
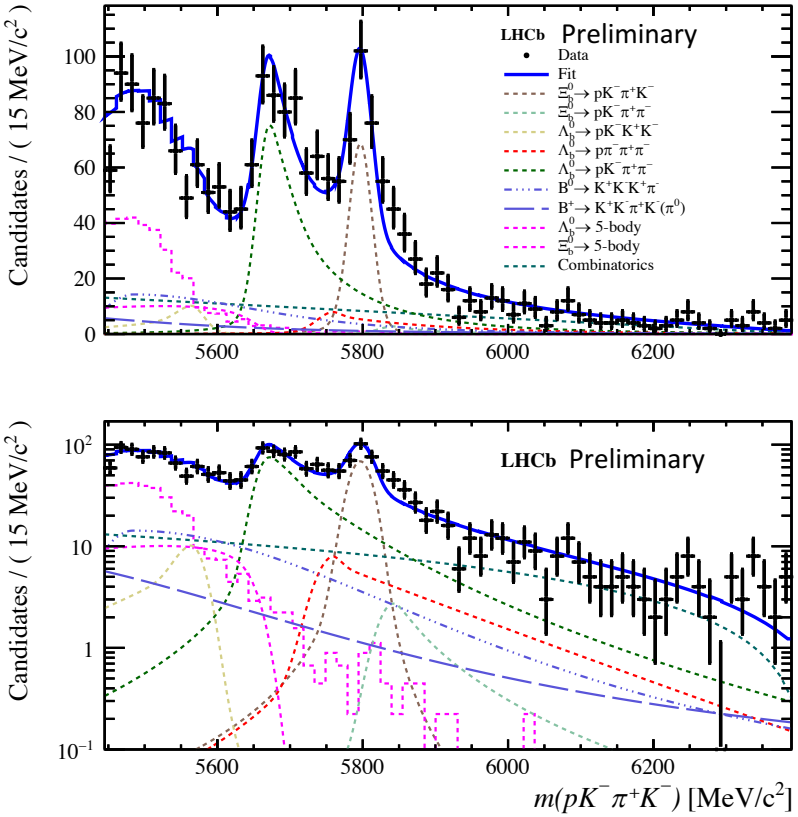
Fit results

$\Lambda_b^0 \to pK^-K^+\pi^-$



444 ± 30

$\Xi_b^0 \to pK^-\pi^+K^-$



199 ± 21

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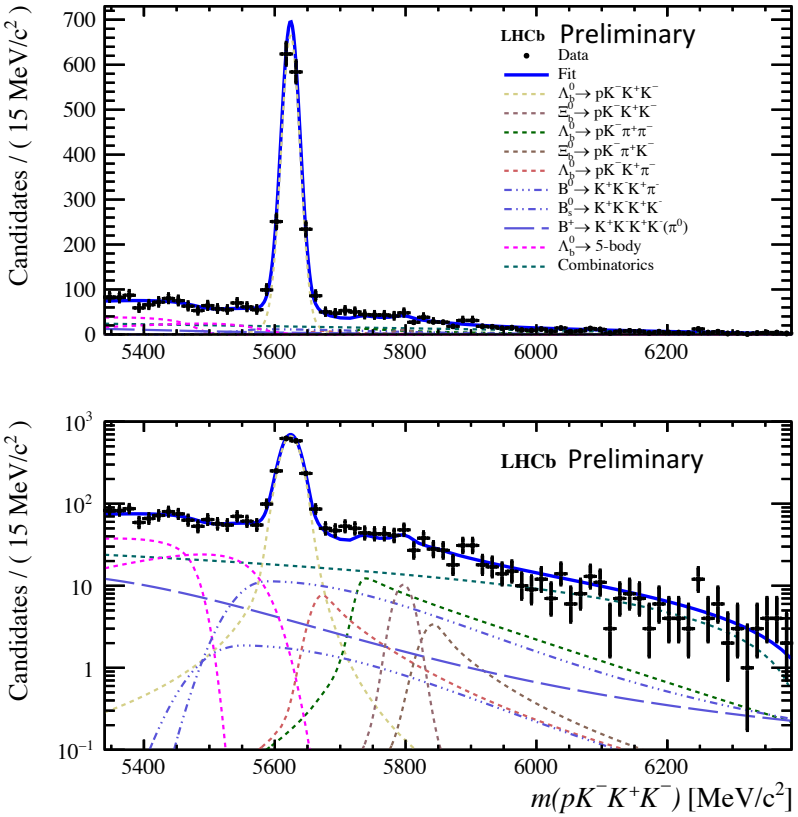
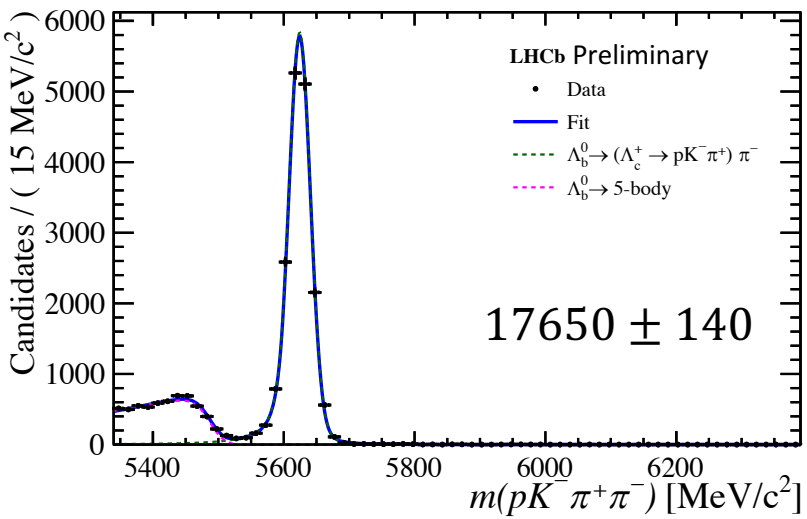
Fit results

$\Lambda_b^0/\Xi_b^0 \to pK^-K^+K^-$



1706 ± 46 $\quad$ 27 ± 14

$\Lambda_b^0 \to \Lambda_c^+(\to pK^-\pi^+)\pi^-$



- All decays searched for are observed except for $\Xi_b^0 \to pK^-K^+K^-$, for which the signal significance is 2.3σ

NEW!

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Branching fractions

- The preliminary results for absolute branching fractions are calculated using the world average values:

$$\mathcal{B}(\Lambda_b^0 \to \Lambda_c^+ \pi^-) = (0.430 \pm 0.036)\%$$

$$\mathcal{B}(\Lambda_c^+ \to p K^- \pi^+) = (6.46 \pm 0.24)\%$$

- In the case of the Ξ_b^0 decays, the results are a product of the BF and the currently unknown ratio of hadronisation fractions: $f_{\Xi_b^0}/f_{\Lambda_b^0}$
- The uncertainties are statistical, systematic and due to the two sub-BFs of the normalisation channel

$$\mathcal{B}(\Lambda_b^0 \to p\pi^-\pi^+\pi^-) = (1.90 \pm 0.06 \pm 0.10 \pm 0.16 \pm 0.07)\times 10^{-5}$$

$$\mathcal{B}(\Lambda_b^0 \to pK^-\pi^+\pi^-) = (4.55 \pm 0.08 \pm 0.20 \pm 0.39 \pm 0.17)\times 10^{-5}$$

$$\mathcal{B}(\Lambda_b^0 \to pK^-K^+\pi^-) = (0.37 \pm 0.03 \pm 0.04 \pm 0.03 \pm 0.01)\times 10^{-5}$$

$$\mathcal{B}(\Lambda_b^0 \to pK^-K^+K^-) = (1.14 \pm 0.03 \pm 0.07 \pm 0.10 \pm 0.05)\times 10^{-5}$$

$$\mathcal{B}(\Xi_b^0 \to pK^-\pi^+\pi^-)\times \frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} = (1.72 \pm 0.21 \pm 0.25 \pm 0.15 \pm 0.07)\times 10^{-6}$$

$$\mathcal{B}(\Xi_b^0 \to pK^-\pi^+K^-)\times \frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} = (1.56 \pm 0.16 \pm 0.19 \pm 0.13 \pm 0.06)\times 10^{-6}$$

$$\mathcal{B}(\Xi_b^0 \to pK^-K^+K^-)\times \frac{f_{\Xi_b^0}}{f_{\Lambda_b^0}} \in [0.11 - 0.25]\times 10^{-6}$$

Concluding remarks

- Wide spectrum of CP-violation measurements ongoing at LHCb

- Run 1 measurements of CKM angle β made in 3 "golden modes"
- Reduced uncertainty by 20% with the addition of two new modes

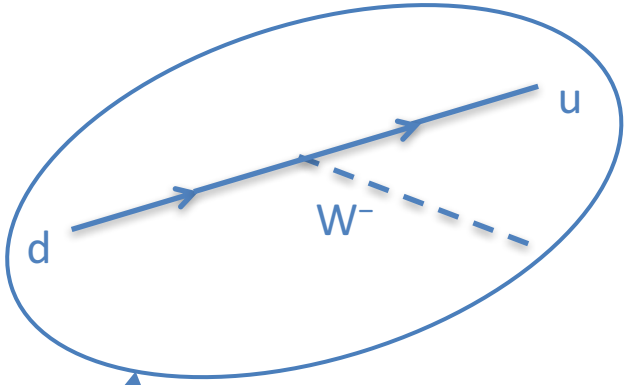
- Observation of *CP*-violation in b-baryons still elusive but first evidence now obtained from $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ decays
- Many other decay modes with newly established signals being studied

- Run 2 data sample being taken already exceeds size of Run 1 – look out for updates soon
- Many measurements also of CKM phases γ and β_s ongoing that I was not able to cover today

- Looking further forward, the LHCb upgrade will bring unprecedented precision in these areas
- Excellent prospects for making precision tests of the Standard Model explanation of CP violation

Backup Slides

CKM mechanism and CP violation



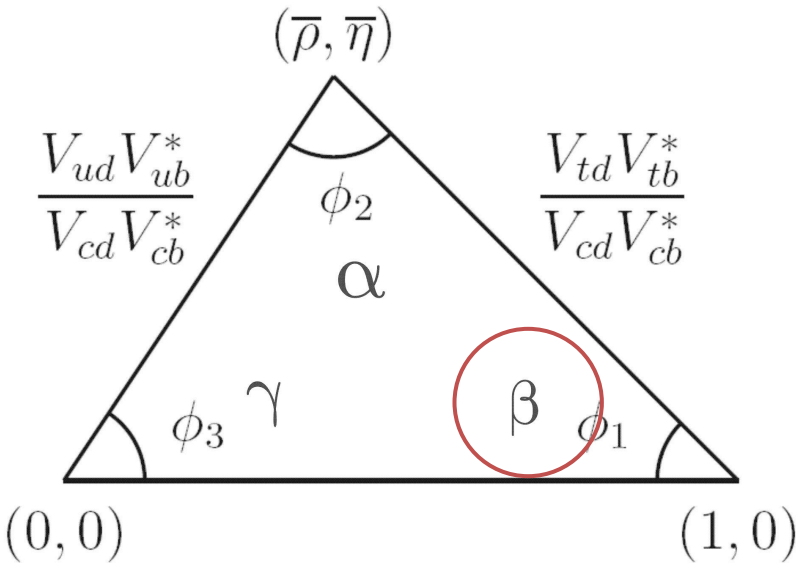
- Standard Model description of quark coupling to weak interaction

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

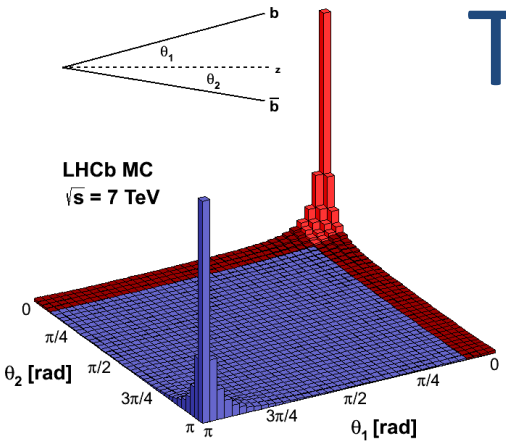
- CPV arises due to complex phase in the mixing matrix

- Convenient representation for *b*-hadron physics is the Unitarity Triangle

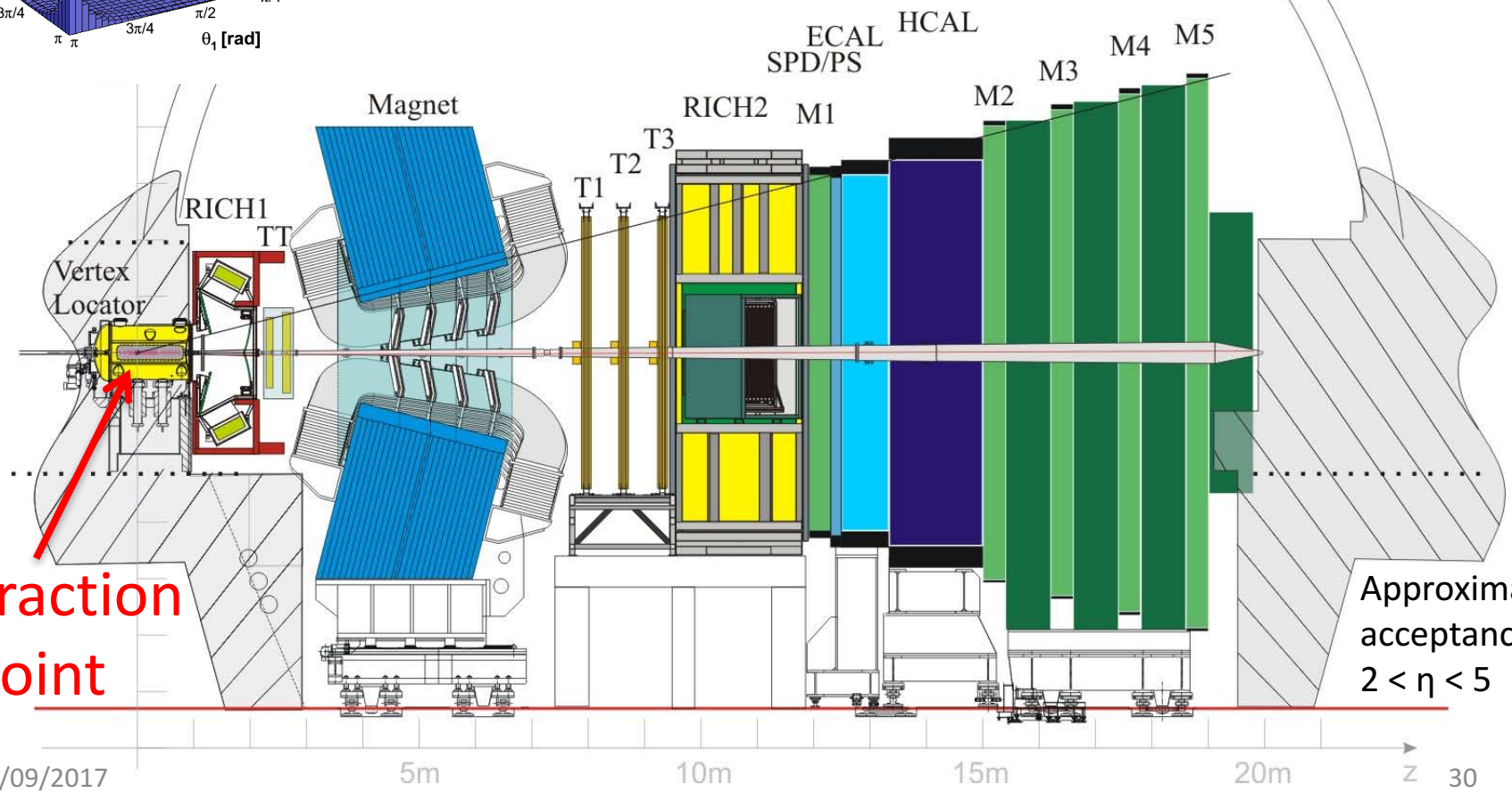
- Angles and side lengths can be measured through various B-decay processes



The LHCb detector



LHCb σ(pp → H_b X) @ 7 TeV = (72.0 ± 0.3 ± 6.8) μb
LHCb σ(pp → H_b X) @ 13 TeV = (154.3 ± 1.5 ± 14.3) μb
[Phys. Rev. Lett. 118 (2017) 052002]



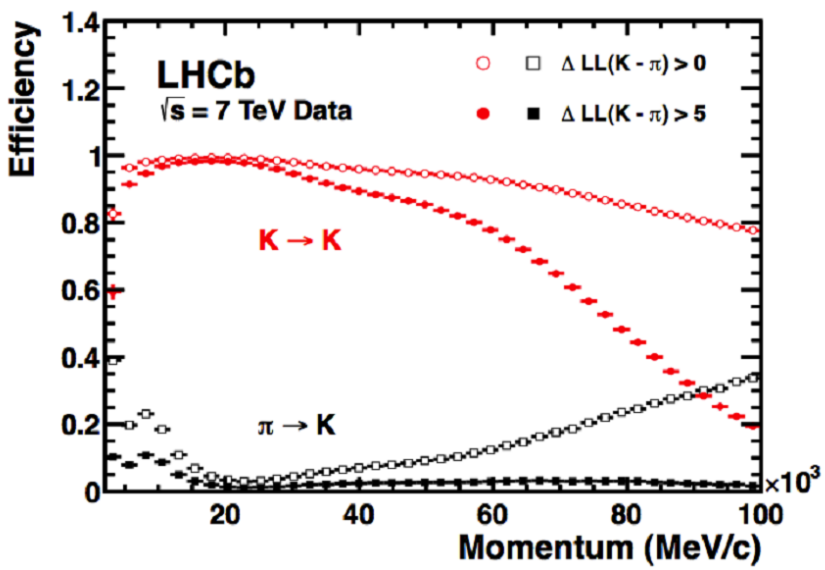
Interaction Point

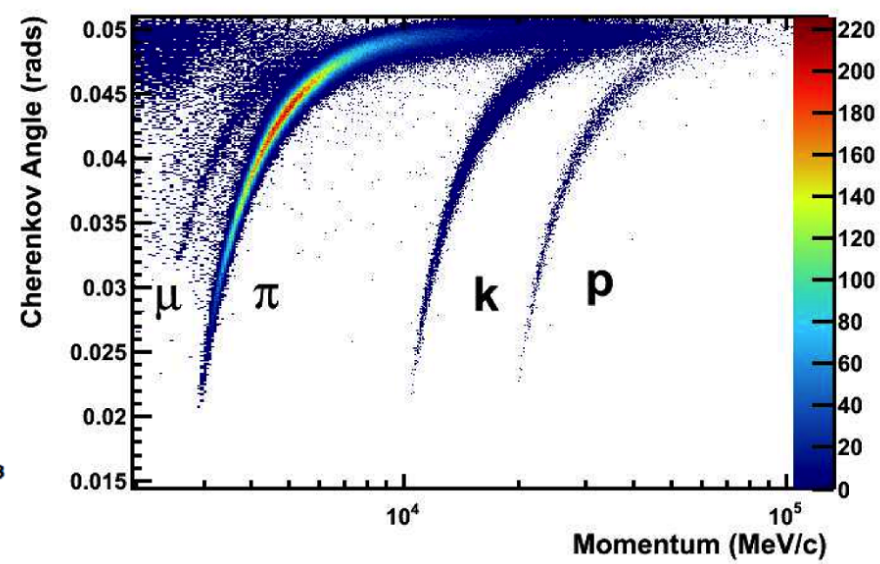
Approximate acceptance: 2 < η < 5

Kaon/pion separation

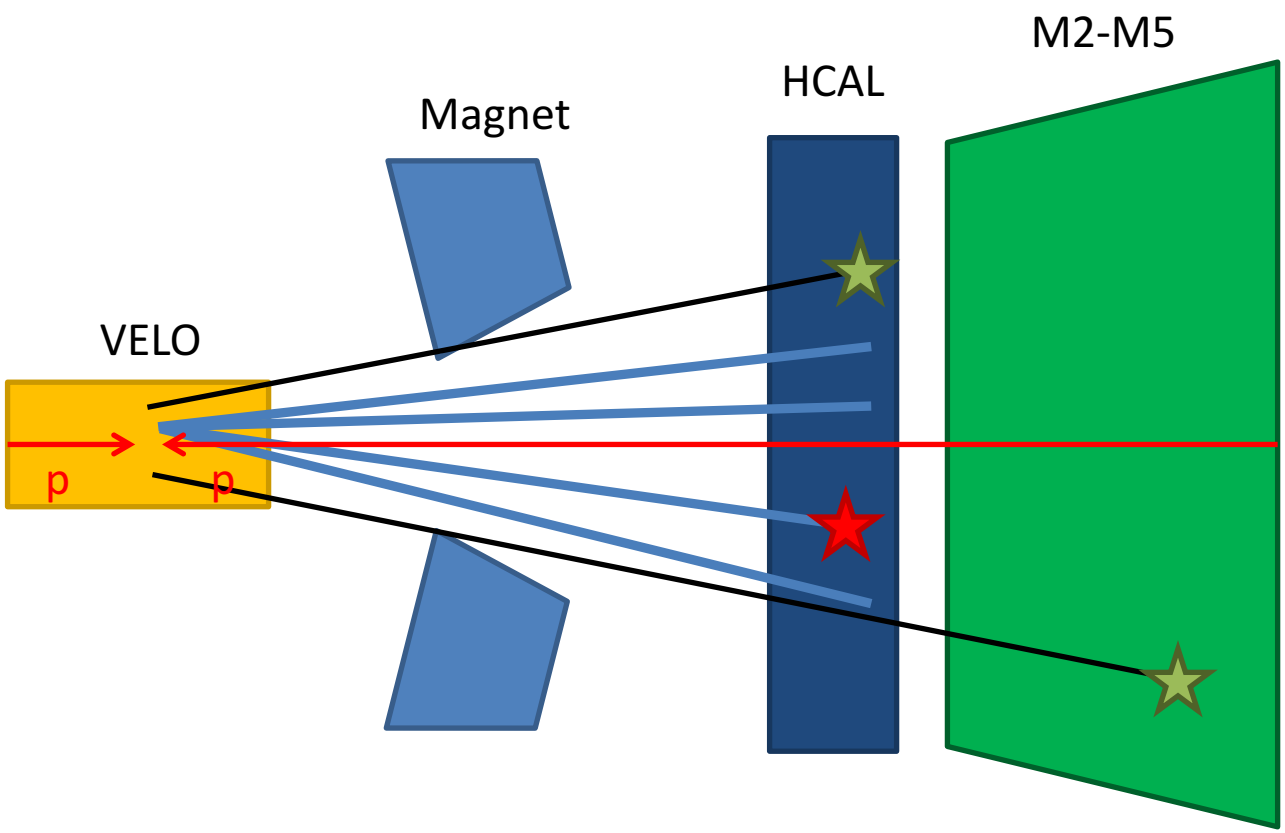
- Most particle identification information comes from the Ring Imaging Cherenkov detectors.
- Three different radiators provide separation over a wide momentum range.

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





Trigger categories



Trigger On Signal

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

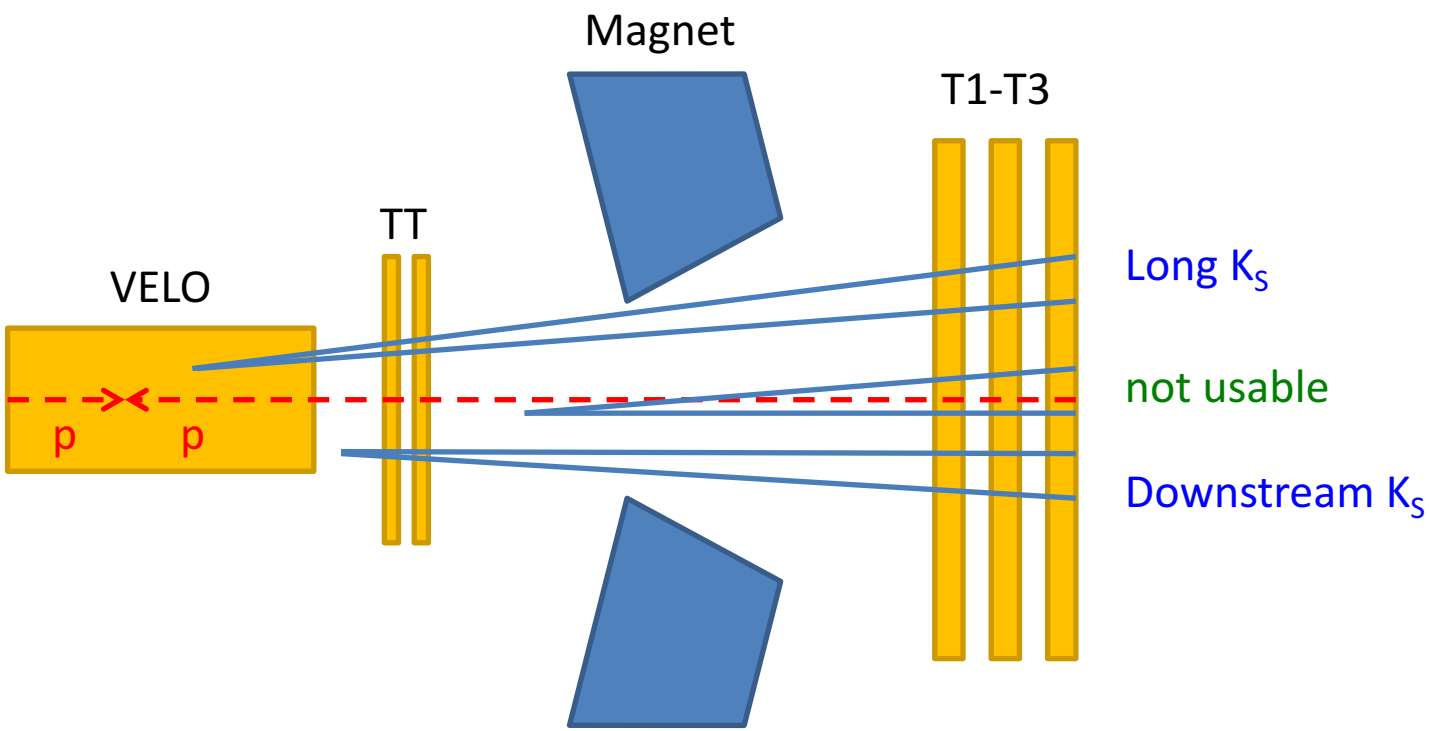
Trigger Independent of Signal

- 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

K_S^0 reconstruction

- K_S^0 decays to $\pi^+\pi^-$ divided into two categories:
  - Long: pion tracks have hits in the vertex detector (VELO)
  - Downstream: pion tracks have no VELO hits



Time-dependent decay rates

- For an initially pure flavour eigenstate, time evolution proceeds according to:

$$\frac{d\Gamma\left[B^0_{d,s}(t)\to f\right]}{dt} \propto e^{-\Gamma t}\left[\left(\left|A_f\right|^2+\left|\bar{A}_f\right|^2\right)\cosh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)+\left(\left|A_f\right|^2-\left|\bar{A}_f\right|^2\right)\cos\left(\Delta m_{d,s}\,t\right)\right.$$
$$\left.+2\mathrm{Re}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sinh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)-2\mathrm{Im}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sin\left(\Delta m_{d,s}\,t\right)\right]$$

$$\frac{d\Gamma\left[\bar{B}^0_{d,s}(t)\to f\right]}{dt} \propto e^{-\Gamma t}\left[\left(\left|A_f\right|^2+\left|\bar{A}_f\right|^2\right)\cosh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)-\left(\left|A_f\right|^2-\left|\bar{A}_f\right|^2\right)\cos\left(\Delta m_{d,s}\,t\right)\right.$$
$$\left.+2\mathrm{Re}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sinh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)+2\mathrm{Im}\left(\tfrac{q}{p}A_f^*\bar{A}_f\right)\sin\left(\Delta m_{d,s}\,t\right)\right]$$

- The time-dependent CP asymmetry is therefore:

$$A_{CP}(t)=\frac{\Gamma\left[\bar{B}^0_{d,s}(t)\to f\right]-\Gamma\left[B^0_{d,s}(t)\to f\right]}{\Gamma\left[\bar{B}^0_{d,s}(t)\to f\right]+\Gamma\left[B^0_{d,s}(t)\to f\right]}=\frac{-C_f\cos\left(\Delta m_{d,s}\,t\right)+S_f\sin\left(\Delta m_{d,s}\,t\right)}{\cosh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)+A_f^{\Delta\Gamma_{d,s}}\sinh\left(\tfrac{\Delta\Gamma_{d,s}}{2}t\right)}$$

$$C_f=\frac{1-\left|\lambda_f\right|^2}{1+\left|\lambda_f\right|^2}$$

$$S_f=\frac{2\mathrm{Im}\lambda_f}{1+\left|\lambda_f\right|^2}$$

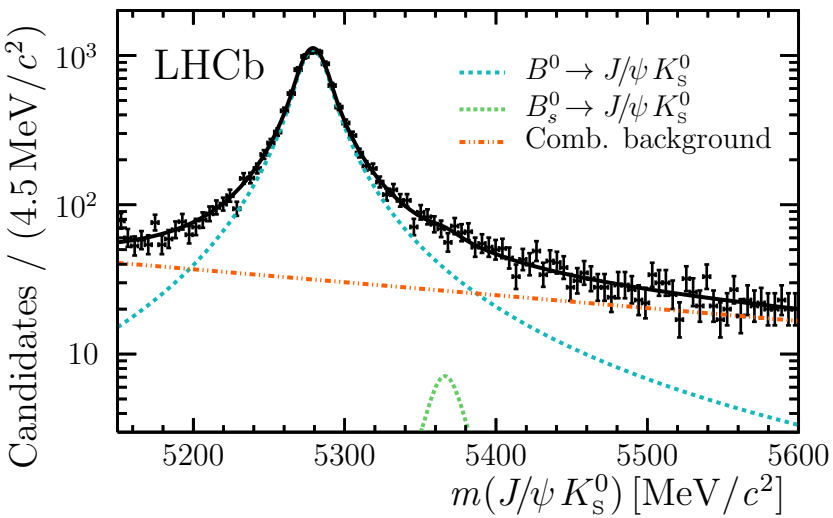
$$A_f^{\Delta\Gamma_{d,s}}=\frac{2\mathrm{Re}\lambda_f}{1+\left|\lambda_f\right|^2}$$

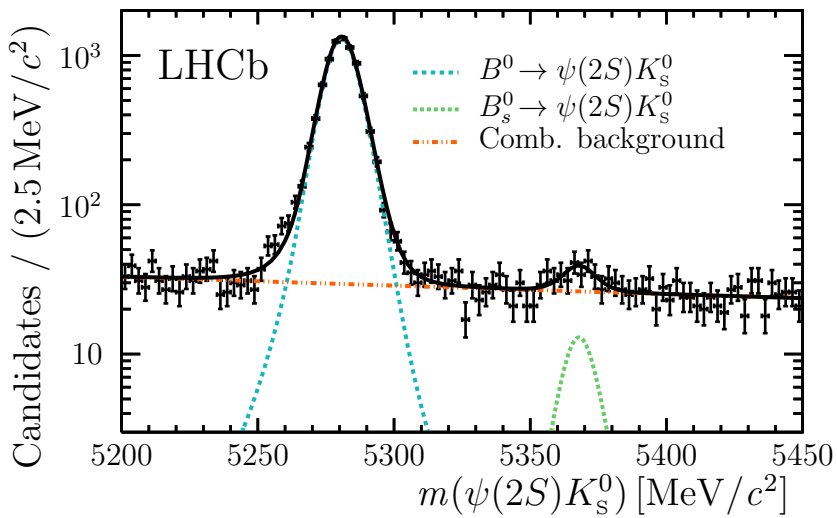
$$\lambda_f=\frac{q}{p}\frac{\bar{A}_f}{A_f}$$

- $\left|C_f\right|^2+\left|S_f\right|^2+\left|A_f^{\Delta\Gamma}\right|^2=1$
- $\frac{q}{p}$ is related to the neutral B mixing
- $\frac{\bar{A}_f}{A_f}$ is the ratio of decay amplitudes

arXiv:1709.03944 [hep-ex]

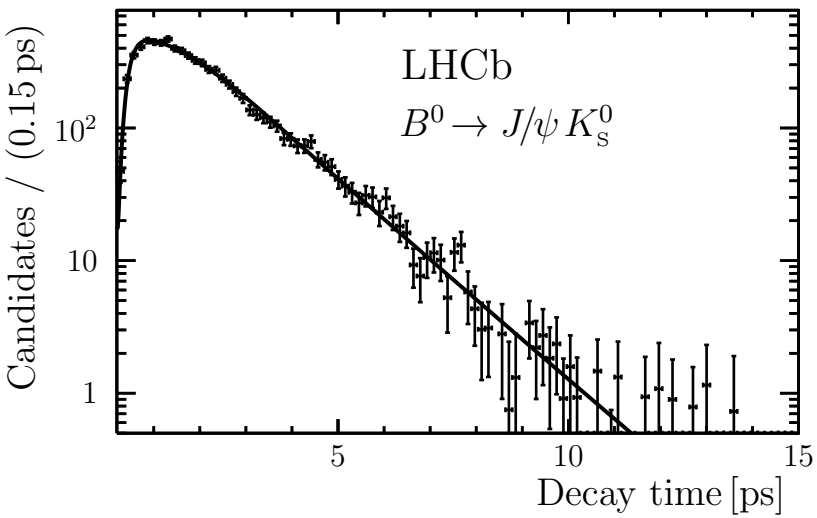
$B^0 \to (c\bar{c})K_S^0$ invariant mass distributions

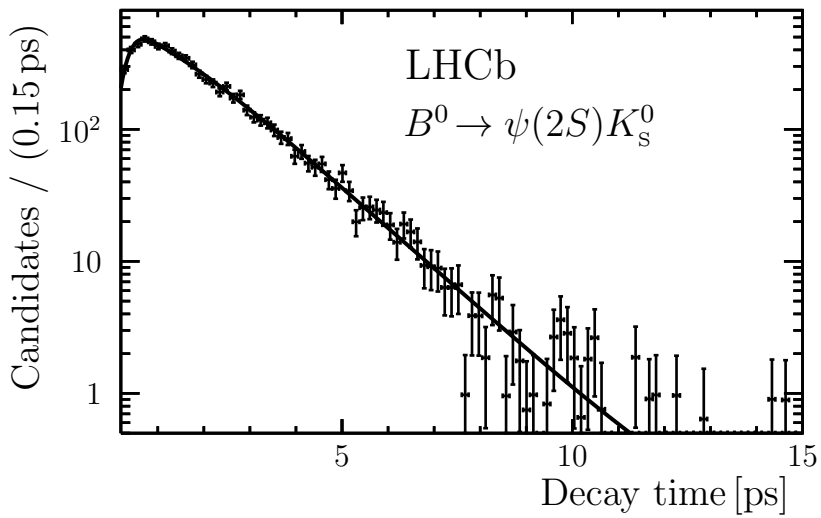




arXiv:1709.03944 [hep-ex]

$B^0 \to (c\bar{c})K_S^0$ decay time distributions





arXiv:1709.03944 [hep-ex]

$B^0 \to (c\bar{c})K_S^0$ tagging performance and external inputs

Tagger	$B^0 \to J/\psi\, K_S^0$	$B^0 \to \psi(2S) K_S^0$
OS	3.60(13)	2.46(5)
SS	2.40(28)	1.07(8)
OS + SS	5.93(29)	3.42(9)

Parameter	Value and uncertainty	Source
$A_P^{7\,\mathrm{TeV}}(J/\psi)$	$-0.0100 \pm 0.0084 \pm 0.0005$	[23]
$A_P^{8\,\mathrm{TeV}}(J/\psi)$	$-0.0077 \pm 0.0054 \pm 0.0004$	[23]
$A_P^{7\,\mathrm{TeV}}(\psi(2S))$	$-0.0143 \pm 0.0077 \pm 0.0005$	[23]
$A_P^{8\,\mathrm{TeV}}(\psi(2S))$	$-0.0138 \pm 0.0051 \pm 0.0003$	[23]
$\Delta m\,[\mathrm{ps}^{-1}]$	$0.5065 \pm 0.0016 \pm 0.0011$	[6]
$\tau\,[\mathrm{ps}]$	1.520 ± 0.004	[6]

arXiv:1709.03944 [hep-ex]

$B^0 \to (c\bar{c})K_S^0$ systematic uncertainties

Source	$B^0 \to J/\psi K_S^0$		$B^0 \to \psi(2S)K_S^0$	
	σ_S	σ_C	σ_S	σ_C
$\Delta\Gamma$	0.003	0.007	0.007	0.003
Δm	0.004	0.004	0.004	0.004
Production asymmetry	0.004	0.009	0.007	0.005
Tagging calibration	0.002	0.005	0.005	0.002
Decay-time bias	0.006	0.006	0.006	0.004
σ_t scaling	0.003	0.005	0.002	0.002
Decay-time efficiency	0.006	0.004	0.006	0.004
Total	0.011	0.016	0.014	0.010

Outlook for b-baryons

- Following establishment of signals in the other $ph^-h^+h^-$ final states, CPV is now being studied
- Analysis of $\Lambda_b^0 \to p\pi^-\pi^+\pi^-$ (and other modes) to be updated to include Run 2 data
- Exciting new prospects from recent first observation of $\Xi_b^- \to pK^-K^-$ [PRL 118 (2017) 071801]
- Very rich structure in these decays – possibility for amplitude analyses
  - See e.g. recent analysis of $\Lambda_b^0 \to D^0p\pi^-$ [arXiv:1701.07873]
- Open question is whether CPV effects (once they are observed) can be related back to fundamental CKM parameters

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Yields and efficiencies

Decay mode	Signal yield
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	1809 ± 48
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	5193 ± 76
$\Lambda_b^0 \to pK^-K^+\pi^-$	444 ± 30
$\Lambda_b^0 \to pK^-K^+K^-$	1706 ± 46
$\Xi_b^0 \to pK^-\pi^+\pi^-$	183 ± 22
$\Xi_b^0 \to pK^-\pi^+K^-$	199 ± 21
$\Xi_b^0 \to pK^-K^+K^-$	27 ± 14

2011

Decays	Ratios of efficiencies			
	Acceptance	Selection	PID	Vetoes
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	1.050 ± 0.004	0.425 ± 0.009	1.046 ± 0.010	0.712 ± 0.017
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	1.004 ± 0.004	0.432 ± 0.009	0.958 ± 0.009	0.744 ± 0.016
$\Lambda_b^0 \to pK^-K^+\pi^-$	0.970 ± 0.004	0.468 ± 0.010	0.874 ± 0.008	0.765 ± 0.050
$\Lambda_b^0 \to pK^-K^+K^-$	0.916 ± 0.003	0.452 ± 0.010	0.801 ± 0.007	0.787 ± 0.026
$\Xi_b^0 \to pK^-\pi^+\pi^-$	1.009 ± 0.004	0.424 ± 0.009	0.917 ± 0.008	0.659 ± 0.109
$\Xi_b^0 \to pK^-\pi^+K^-$	0.969 ± 0.004	0.450 ± 0.010	0.847 ± 0.008	0.752 ± 0.081
$\Xi_b^0 \to pK^-K^+K^-$	0.922 ± 0.003	0.429 ± 0.009	0.771 ± 0.007	0.819 ± 0.123

2012

Decays	Ratios of efficiencies			
	Acceptance	Selection	PID	Vetoes
$\Lambda_b^0 \to p\pi^-\pi^+\pi^-$	1.070 ± 0.003	0.433 ± 0.011	1.018 ± 0.013	0.693 ± 0.028
$\Lambda_b^0 \to pK^-\pi^+\pi^-$	1.020 ± 0.003	0.438 ± 0.011	0.922 ± 0.012	0.758 ± 0.032
$\Lambda_b^0 \to pK^-K^+\pi^-$	0.978 ± 0.003	0.462 ± 0.012	0.846 ± 0.011	0.742 ± 0.099
$\Lambda_b^0 \to pK^-K^+K^-$	0.928 ± 0.003	0.445 ± 0.012	0.783 ± 0.010	0.751 ± 0.036
$\Xi_b^0 \to pK^-\pi^+\pi^-$	1.019 ± 0.003	0.431 ± 0.011	0.902 ± 0.011	0.652 ± 0.082
$\Xi_b^0 \to pK^-\pi^+K^-$	0.979 ± 0.003	0.434 ± 0.011	0.829 ± 0.010	0.689 ± 0.074
$\Xi_b^0 \to pK^-K^+K^-$	0.929 ± 0.003	0.425 ± 0.011	0.764 ± 0.009	0.819 ± 0.123

Eur. Phys. J. C73 (2013) 2373

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	$\gamma\ (B \to D^{(*)}K^{(*)})$	~ 10–12° [244, 258]	4°	0.9°	negligible
	$\gamma\ (B_s^0 \to D_s K)$	–	11°	2.0°	negligible
	$\beta\ (B^0 \to J/\psi\ K_S^0)$	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}	–