CP violation with charmed baryons at LHCb

Alex Pearce

on behalf of the LHCb collaboration

Tuesday 26th June 2018

Workshop on singly and doubly charmed baryons, LPNHE, Paris

Introduction

- Violation of *CP* symmetry is a necessary condition for baryogensis
- CP violation searches in baryon decays probe this phenomenon directly
  - Different dynamics expected to contribute than in meson decays, e.g. W exchange
- Charm sector is complimentary to beauty, as new physics may couple differently
  - Heavy flavour studies go hand-in-hand with direct searches

Experimental status

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The focuses so far (dramatically oversimplified)

1. Amplitude analyses with $D^0 \to K^-\pi^+\pi^-\pi^+$ and $D^0 \to K^0_S h^- h^+$
2. Mixing in $D^0 \to K^+\pi^-$
3. Direct and indirect CPV in $D^0 \to h^- h^+$
   - Most precise measurements probing $\mathcal{O}(10^{-4})$
4. Direct CPV in D^+ and D_s^+ decays

Most precise D^0 results from LHCb, others from BESIII, Belle, BaBar, and CLEO

Experimental status with baryons

- Only a few *CP* violation searches performed using charmed baryons
  - All in Λ_c^+ decays!
- Precisions in range $\mathcal{O}(1\text{–}10\,\%)$, not enough to reach $\mathcal{O}(0.1\,\%)$ SM expectations
- Typically probe decay asymmetry parameters α and $\bar{\alpha}$

$\mathbf{\Lambda_c^+}$ $\quad I(J^P) = 0(1/2^+)$

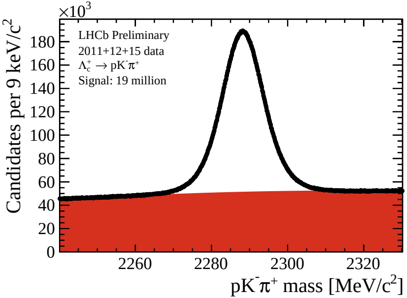
The parity of the Λ_c^+ is defined to be positive (as are the parities of the proton, neutron, and Λ). The quark content is udc. Results of an analysis of $pK^-\pi^+$ decays (JEZABEK 1992) are consistent with $J = 1/2$. Nobody doubts that the spin is indeed 1/2. We have omitted some results that have been superseded by later experiments. The omitted results may be found in earlier editions.

Λ_c^+ MASS	2286.46 ± 0.14 MeV
Λ_c^+ MEAN LIFE	$(2.00 \pm 0.06) \times 10^{-13}$ s (S = 1.6)
Λ_c^+ DECAY PARAMETERS	
α FOR $\Lambda_c^+ \to \Lambda\pi^+$	-0.91 ± 0.15
α FOR $\Lambda_c^+ \to \Sigma^+\pi^0$	-0.45 ± 0.32
α FOR $\Lambda_c^+ \to \Lambda\ell^+\nu_\ell$	-0.86 ± 0.04
Λ_c^+, $\overline{\Lambda}_c^-$ *CP*-VIOLATING DECAY ASYMMETRIES	
$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda_c^+ \to \Lambda\pi^+$, $\overline{\Lambda}_c^- \to \overline{\Lambda}\pi^-$	-0.07 ± 0.31
$(\alpha + \bar{\alpha})/(\alpha - \bar{\alpha})$ in $\Lambda_c^+ \to \Lambda e^+\nu_e$, $\overline{\Lambda}_c^- \to \overline{\Lambda} e^-\bar{\nu}_e$	0.00 ± 0.04

What about LHCb?

In the LHCb acceptance, at $\sqrt{s} = 13\,\text{TeV}$[1]

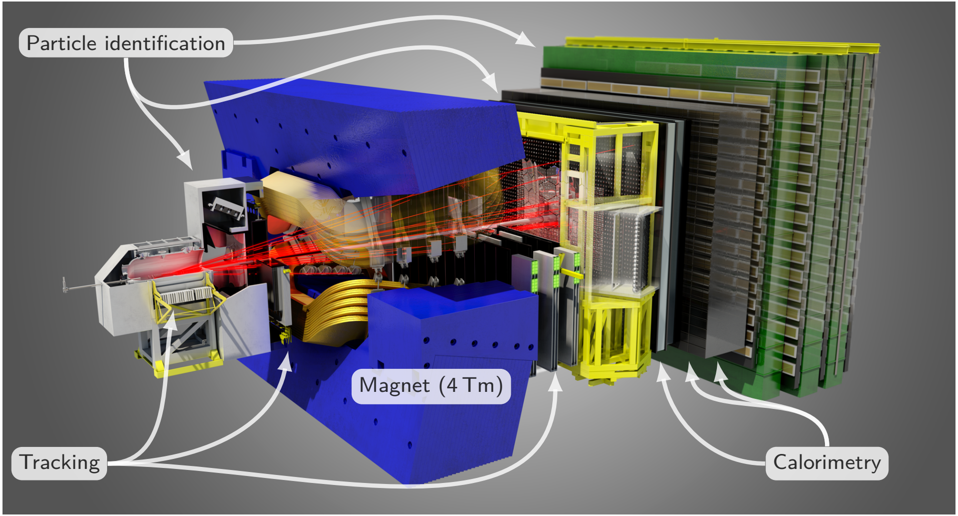
$$\sigma(pp \to c\bar{c}X) = (2369 \pm 192)\,\mu\text{b}$$



LHCb-CONF-2016-005

- The LHCb experiment is *uniquely* capable of collecting enormous samples of charm decays
  - Already have world's largest, unlikely to be surpassed any time soon (decades?)
- *Huge* potential for LHCb to provide new, precise input!

[1] JHEP **03** (2016) 159, JHEP **09** (2016) 013, JHEP **05** (2017) 074



VELO	Primary and secondary vertex, impact parameter
TT, IT, OT	Momentum of charged particles
RICHs	$K^{\pm}$, $\pi^{\pm}$, and $p/\overline{p}$ PID
MUON	Trigger on high p_{T} $\mu^{\pm}$, add PID
SPD/PS	Separate $\gamma/e^{\pm}$ and $h^{\pm}/e^{\pm}$
ECAL/HCAL	EM/hadronic energy
High-level trigger	Fully reconstruct exclusive decays

Experimental challenges

We have a great detector and all this data, what's the problem?

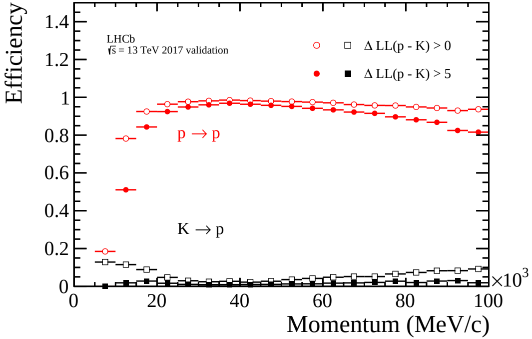
1. The proton
2. Multibody decays, therefore phase spaces are *at least* 5D
    - Phenomenologically very interesting, though!
3. Controlling systematic effects down to the available statistical precision

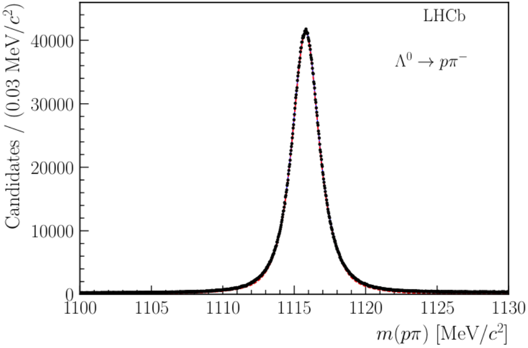
Protons

- All baryon decays cascade down to final states with an odd number of protons
- An experimenter must then understand:
    1. Proton particle identification performance
    2. Proton/antiproton interaction asymmetry with the detector material
- Absolute performance determination requires unbiased source
- Challenging because protons are typically used as a ‘tag’ of a baryonic signal decay
    - Proton often carries large momentum fraction and hence fires low-level triggers
    - Tight proton PID required to suppress large backgrounds from meson decays

Proton identification efficiency

- Can reconstruct clean $\Lambda^0 \to p\pi^-$ samples with no proton ID
- Use a smaller sample of $\Lambda_c^+ \to pK^-\pi^+$ decays for high momentum samples
  - Calibration samples must have kinematic overlap with signal decay of interest





LHCb-DP-2018-001

- Proton ID efficiency determination is generally not a problem at LHCb

Proton detection asymmetry

- Any measured absolute baryon asymmetry eventually depends on the proton detection asymmetry

$$A_{\text{Reco.}}(p) = \frac{\epsilon_{\text{Reco.}}(p) - \epsilon_{\text{Reco.}}(\overline{p})}{\epsilon_{\text{Reco.}}(p) + \epsilon_{\text{Reco.}}(\overline{p})}$$

- Collecting an unbiased sample means knowing a proton is present, but not explicitly reconstructing it!
- Very difficult to suppress backgrounds without *any* proton ‘handle’
- Candidate tag-and-probe processes, e.g. $J/\psi \to p\overline{p}$ or $B^0 \to \overline{\Lambda}_c^- \overline{p}\pi^+\pi^-$, are relatively rare
  - Want large samples to accurately parameterise asymmetries in kinematics

Working around the proton detection asymmetry

1. Form observables insensitive to experimental asymmetries, e.g. ΔA_{CP}
2. Take asymmetries from simulation, applying conservative systematic uncertainties
   - See, for example, Chinese Physics C Vol. **40** No. 1 (2016) 011001

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Option 1

- Requires at least two decay modes
- Very robust experimentally
- Typically harder to interpret theoretically

Option 2

- Systematic dominants the measurement
- Ultimate precision no better than 1 %
- Clean interpretation

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- An absolute measurement of the proton detection asymmetry is a priority for LHCb...
- ...but it's very tricky! Stay tuned

Measurements

So far, we have one charmed baryon CPV publication

- *CP* asymmetry difference in $\Lambda_c^+ \to ph^-h^+$ decays[2]

But also have other interesting singly-charmed baryon results

- Search for the rare decay $\Lambda_c^+ \to p\mu^+\mu^-$[3]
- $\Lambda_c^+ \to ph^-h^+$ branching fractions[4]
- New excited Ω_c^0 states[5]

I will leave discussion on doubly-charmed results and all prospects to Murdo and Jibo

[2] JHEP **03** (2018) 182
[3] Phys. Rev. D **97**, 091101 (2018)
[4] JHEP **03** (2018) 043
[5] Phys. Rev. Lett. **118** 182001 (2017)

CP violation in Λ_c^+ decays

- Search for CPV in $\Lambda_c^+ \to pK^-K^+$ and $p\pi^-\pi^+$ decays

$$A_{CP}(f) = \frac{\Gamma(f) - \Gamma(\bar{f})}{\Gamma(f) + \Gamma(\bar{f})}$$

- Rates are hard, yields are easier

$$A_{\mathrm{Raw}} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})}$$

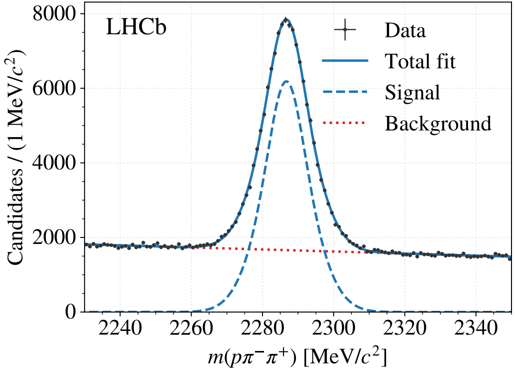
- Form a difference between modes to cancel background asymmetries

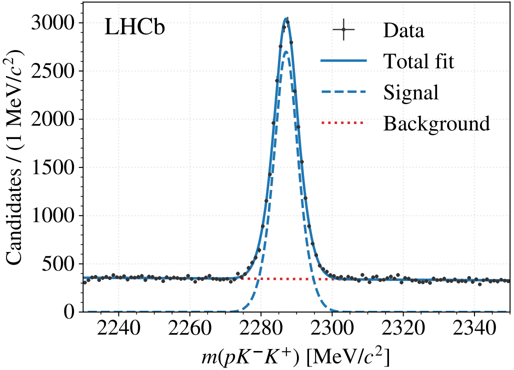
$$\begin{aligned} \Delta A_{CP} &= A_{\mathrm{Raw}}(pK^-K^+) - A_{\mathrm{Raw}}(p\pi^-\pi^+) \\ &\approx A_{CP}(pK^-K^+) - A_{CP}(p\pi^-\pi^+) \end{aligned}$$

- Baryon analogue to the $\Delta A_{CP}(D^0 \to h^-h^+)$ measurement
  - Generated a huge amount of interest in theory community!

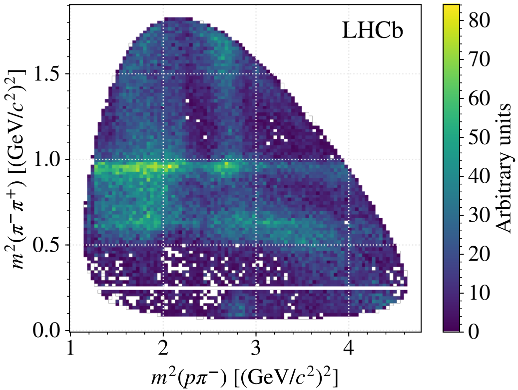
Reconstruction

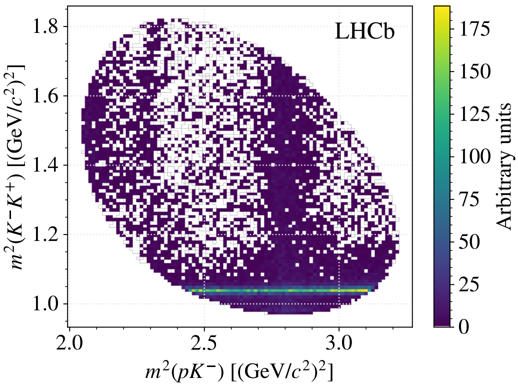
- Use $3\,\mathrm{fb}^{-1}$ of data, taken in 2011 and 2012
- To reduce large prompt backgrounds, reconstruct $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$





Phase space





- This measurement integrates across the 5D phase space
- Washes out potential +ve and −ve CPV variations
- Simpler (first!) measurement to make, but arguably harder to interpret

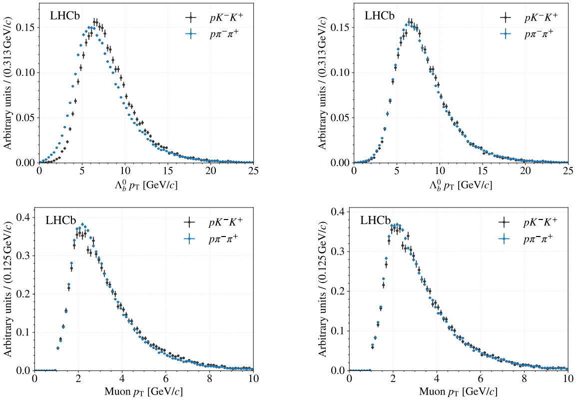
Kinematic equalisation

- Several asymmetries contribute to the yield asymmetry

$$A_{\mathrm{Raw}} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})}$$
$$\approx A_{CP}(f) + A_{\mathrm{Prod.}}(\Lambda_b^0) + A_{\mathrm{Reco.}}(\mu) + A_{\mathrm{Reco.}}(p)$$

- Production and reconstruction asymmetries depend only on object kinematics
- With equal kinematics between pK^-K^+ and $p\pi^-\pi^+$, ΔA_{CP} will contain contributions only from A_{CP}
- Employ a BDT-based weighting procedure to align Λ_b^0, muon, and proton kinematics in $p\pi^-\pi^+$ sample to pK^-K^+

Kinematic equalisation

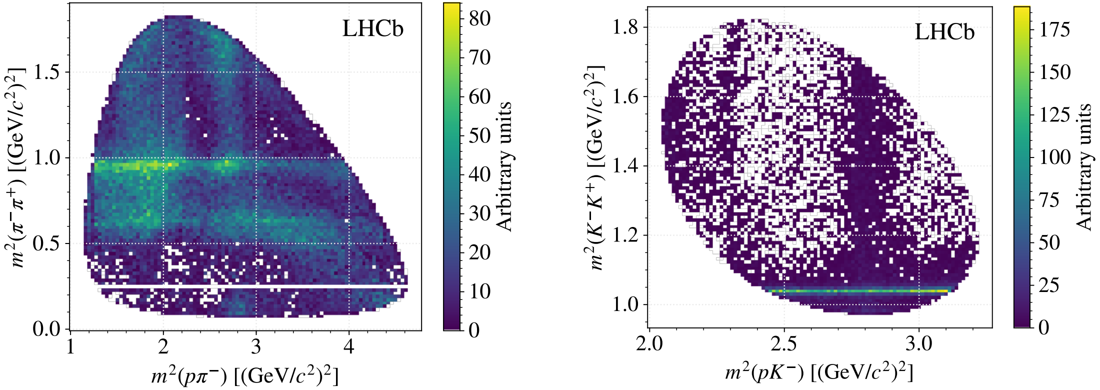


- The $p\pi^-\pi^+$ asymmetry is alternated by this procedure

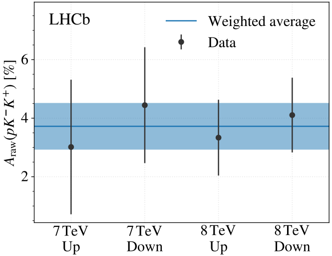
$$\Delta A_{CP}^{\mathrm{wgt}} \approx A_{CP}(pK^-K^+) - A_{CP}^{\mathrm{wgt}}(p\pi^-\pi^+)$$

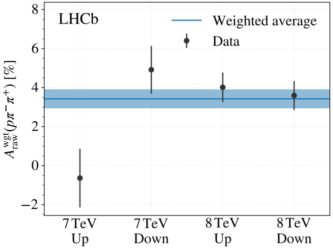
Efficiency corrections

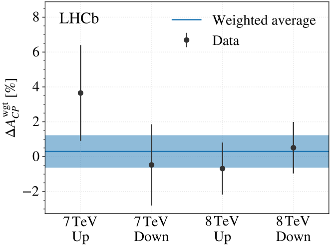
- Efficiencies varies across the complex 5D $\Lambda_c^+ \to p h^- h^+$ phase space
- CPV can also vary across this, so must correct for experimental effects



- Incorporate kinematic weights and efficiency corrections into yield extraction
- Measure asymmetries separately for each data-taking condition







Discussion

$$A_{\text{Raw}}(pK^-K^+) = (3.72 \pm 0.78)\,\%$$
$$A^{\text{wgt}}_{\text{Raw}}(p\pi^-\pi^+) = (3.42 \pm 0.47)\,\%$$
$$\Delta A^{\text{wgt}}_{CP} = (0.30 \pm 0.91 \pm 0.61)\,\%$$

- Significant non-zero raw asymmetries!
  - Not investigated further due to unknown proton detection asymmetry component
- Precise measurement, especially for a first
  - Largest systematic uncertainty, by far, from finite MC sample size
  - No showstoppers for Run 2 updates
- Next steps are mode- and phase-space-dependent measurements
- This shows what sorts of things we can do very well today

Summary

- LHCb has begun a program of CPV measurements with charmed baryons
- Per-mille precision is within reach for Λ_c^+, lots of first measurements possible for other states
- Looking forward to input from the community on interesting decay modes to study, and which baryons might yield particularly useful input
- CPV searches with baryons is particularly challenging, but focused effort is ongoing