CP violation with charmed baryons at LHCb

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on behalf of the LHCb collaboration

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Workshop on singly and doubly charmed baryons, LPNHE, Paris
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
1. No CPV observed in *any* charm system
2. Very little experimental input in charmed baryons 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 $D^0 \to K_S^0 h^-h^+$
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 $\Lambda_c^+$ decays!
- Precisions in range $\mathcal{O}(1\mbox{--}10\%)$, not enough to reach $\mathcal{O}(0.1\%)$ SM expectations
- Typically probe decay asymmetry parameters $\alpha$ and $\bar{\alpha}$

\[ \Lambda_c^+ \quad I(J^P) = 0(1/2^+) \]

The parity of the $\Lambda_c^+$ is defined to be positive (as are the parities of the proton, neutron, and $\Lambda$). The quark content is $uudc$. 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 We have omitted some results that have been superseded by later experiments.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.

<table>
<thead>
<tr>
<th>$\Lambda_c^+$ MASS</th>
<th>$2286.46 \pm 0.14$ MeV</th>
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<tbody>
<tr>
<td>$\Lambda_c^+$ MEAN LIFE</td>
<td>$(2.00 \pm 0.06) \times 10^{-13}$ s ($S = 1.6$)</td>
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What about LHCb?

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

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

- 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!

\[\begin{align*}
\text{Candidates per 9 keV/c} \\
\text{pK}^-\pi^+ \text{ mass [MeV/c}^2]\end{align*}\]

LHCb-CONF-2016-005

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\(^{1}\)JHEP 03 (2016) 159, JHEP 09 (2016) 013, JHEP 05 (2017) 074
The LHCb experiment


Particle identification

Tracking

Magnet (4 Tm)

Calorimetry

VELO Primary and secondary vertex, impact parameter

TT, IT, OT Momentum of charged particles

RICHs $K^\pm$, $\pi^\pm$, and $p/\bar{p}$ 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 \textit{at least} 5D
   - Phenomenologically very interesting, though!
3. Controlling systematic effects down to the available statistical precision
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

- 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

\[ A_{\text{Reco.}}(p) = \frac{\epsilon_{\text{Reco.}}(p) - \epsilon_{\text{Reco.}}(\bar{p})}{\epsilon_{\text{Reco.}}(p) + \epsilon_{\text{Reco.}}(\bar{p})} \]

- 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. \( J/\psi \rightarrow p\bar{p} \) or \( B^0 \rightarrow \bar{\Lambda}_c^- p\pi^+\pi^- \), are relatively rare
  - Want large samples to accurately parameterise asymmetries in kinematics
1. Form observables insensitive to experimental asymmetries, e.g. $\Delta A_{CP}$
2. Take asymmetries from simulation, applying conservative systematic uncertainties
   - See, for example, Chinese Physics C Vol. 40 No. 1 (2016) 011001
Working around the proton detection asymmetry

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- Requires at least two decay modes
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**Option 2**
- Systematic dominants the measurement
- Ultimate precision no better than 1%
- Clean interpretation

- 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 $\Lambda_c^+ \rightarrow p h^- h^+$ decays\(^2\)

But also have other interesting singly-charmed baryon results

- Search for the rare decay $\Lambda_c^+ \rightarrow p \mu^+ \mu^-$\(^3\)
- $\Lambda_c^+ \rightarrow p h^- h^+$ branching fractions\(^4\)
- New excited $\Omega_c^0$ 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
CP violation in $\Lambda_c^+$ decays

- Search for CPV in $\Lambda_c^+ c \rightarrow pK^- K^+$ 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

\[ A_{Raw} = \frac{N(f) - N(\bar{f})}{N(f) + N(\bar{f})} \]

- Form a difference between modes to cancel background asymmetries

\[ \Delta A_{CP} = A_{Raw}(pK^- K^+) - A_{Raw}(p\pi^- \pi^+ \approx A_{CP}(pK^- K^+) - A_{CP}(p\pi^- \pi^+) \]

- Baryon analogue to the $\Delta A_{CP}(D_0 \rightarrow h^- h^+)$ measurement

- Generated a huge amount of interest in the theory community!
Search for CPV in $\Lambda_c^+ \rightarrow pK^-K^+$ and $p\pi^-\pi^+$ decays

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Baryon analogue to the $\Delta A_{CP}(D^0 \rightarrow h^-h^+)$ measurement

- Generated a huge amount of interest in theory community!
- Use 3 fb$^{-1}$ of data, taken in 2011 and 2012
- To reduce large prompt backgrounds, reconstruct $\Lambda_b^0 \rightarrow \Lambda_c^+ \mu^- \chi$
• 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
Several asymmetries contribute to the yield asymmetry

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

- Production and reconstruction asymmetries depend only on object kinematics
- With equal kinematics between \( pK^-K^+ \) and \( p\pi^-\pi^+ \), \( \Delta A_{\text{CP}} \) will contain contributions only from \( A_{\text{CP}} \)
- Employ a BDT-based weighting procedure to align \( \Lambda_b^0 \), muon, and proton kinematics in \( p\pi^-\pi^+ \) sample to \( pK^-K^+ \)
The $p\pi^-\pi^+$ asymmetry is alternated by this procedure

$$\Delta A_{CP}^{\text{wgt}} \approx A_{CP}(pK^-K^+) - A_{CP}^{\text{wgt}}(p\pi^-\pi^+)$$
Efficiencies varies across the complex 5D $\Lambda^+_c \to p\pi^- h^+$ 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

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

- 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
• LHCb has begun a program of CPV measurements with charmed baryons
• Per-mille precision is within reach for $\Lambda_c^+$, 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