Charm baryon amplitude analyses and polarisation measurements

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Motivation: Baryon amplitude analyses

- Spectroscopy
  - Baryon decays often feature complicated phase-space structures
  - Excellent place to search for new baryonic and exotic pentaquark states
- Parity-violation
  - Measurement of decay asymmetry parameters
- CP-violation
  - Still unobserved for baryons
  - Comparison of baryon-antibaryon amplitude models or basis to tailor model-independent searches
  - Resonance interference patterns can enhance sensitivity

Motivation: Polarisation

- Baryon amplitude analyses can be used to measure baryon polarisation vector $\boldsymbol{P}$
- Polarisation is excellent probe for baryon production physics, with no meson counterpart (see *e.g.* JHEP 1511 (2015) 067)
  - Strong production: anchor points for low-energy QCD
  - Weak production: additional observable for New Physics tests
- Once amplitude model is determined, can be applied to other polarisation measurements

Motivation: Baryon EMDMs

- Access to charm baryon polarisation allows the measurement of electromagnetic dipole moments (EMDMs) measurement via spin precession
  - Amplitude model provides the polarimeter needed to probe polarisation before and after spin precession in electromagnetic field
  - Polarisation measurements for different energies and production systems needed to understand underlying physics mechanism
- EDMs background-free probe for new-physics, MDMs interesting for low-energy QCD
- EMDMs measurement of short-lived particles using bent crystals is the target of the ERC CoG SELDOM project
- Proposed a dedicated fixed-target experiment at the LHC, ALADDIN
  - Letter-of-Intent recently submitted to the LHCC

Analyses in LHCb

- LHCb data feature charm baryon decays in a wide variety of production modes: from beauty hadron semileptonic (SL) decays, prompt *pp* collisions or heavy ion collisions, also in fixed target mode

- SL samples studied to determine amplitude models for polarisation measurements
  - Large polarisation from parity-violating weak decay gives full sensitivity on decay amplitude
  - Cleaner samples with more regular detector efficiency, suitable for amplitude fit with tens of free parameters

- Other samples can be used to study kinematic-dependent production-dependent charm baryon polarisation
  - From 100 GeV (fixed-target) up to 13 TeV (*pp* collisions) center-of-mass energy

Analyses at LHCb Milano

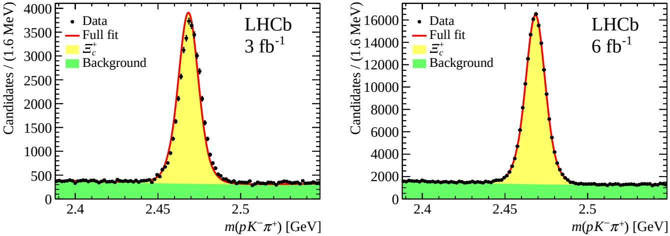
- $\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis from SL production (published, Phys. Rev. D 108 (2023) 012023)
- $\Xi_c^+ \to pK^-\pi^+$ amplitude analysis from SL (paper in preparation, LHCb-PAPER-2024-034)
- Prompt $\Xi_c^+ \to pK^-\pi^+$ polarisation measurement (completed, in LHCb review)
- Λ_c^+ polarisation measurement in p-Ne fixed-target collisions (ongoing)
- Will focus on the last three analyses

$\Xi_c^+ \to pK^-\pi^+$ SL analysis

$\Xi_c^+ \to pK^-\pi^+$ SL decay selection

- Selection consisting of
  - BDT selection against combinatorial background
  - Vetoes removing charm meson and clone bkgs
- Signal region for amplitude fit $|m(pK^-\pi^+) - m(\Xi_c^+)_{\rm PDG}| < 15\,\mathrm{MeV}$ (efficiency $\geq$ 99%)

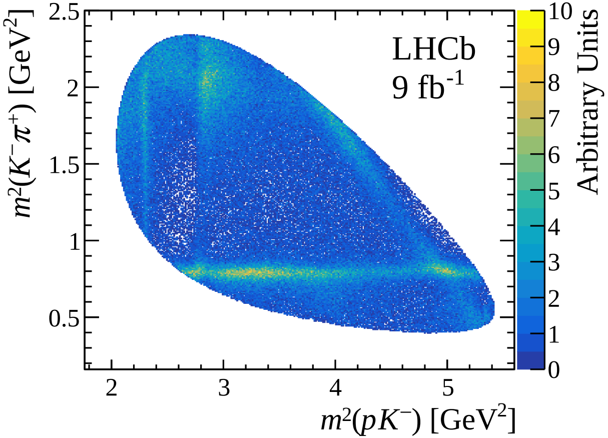
- Signal events: 151887 (35265) for Run 2 (Run 1)
- f_b is 14.4% (15.6%) for Run 2 (Run 1),
  - Fixed in amplitude fit



$\Xi_c^+ \to pK^-\pi^+$ amplitude analysis

- Amplitude analysis done closely following $\Lambda_c^+ \to pK^-\pi^+$ one
  - Same definitions, code

- Amplitude model built from contributions visible in the Dalitz plot and PDG resonances
- Contributions improving the fit quality are retained
- Those with similar quality considered for systematic uncertainty evaluation



Ξ_c^+ polarisation frame

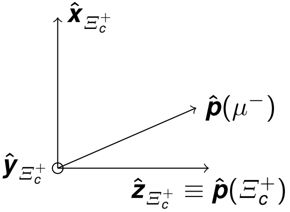
- polarisation measured in two Ξ_c^+ helicity rest frames, with orthogonal components defined from the muon direction

- Approximate *B* rest frame: default for amplitude fit
- Laboratory frame: specific polarisation fit

$$\hat{\boldsymbol{z}}_{\Xi_c^+} = \hat{\boldsymbol{p}}(\Xi_c^+)$$

$$\hat{\boldsymbol{x}}_{\Xi_c^+} = \frac{\boldsymbol{p}(\Xi_c^+) \times \boldsymbol{p}(\mu^-)}{\left|\boldsymbol{p}(\Xi_c^+) \times \boldsymbol{p}(\mu^-)\right|} \times \hat{\boldsymbol{p}}(\Xi_c^+)$$

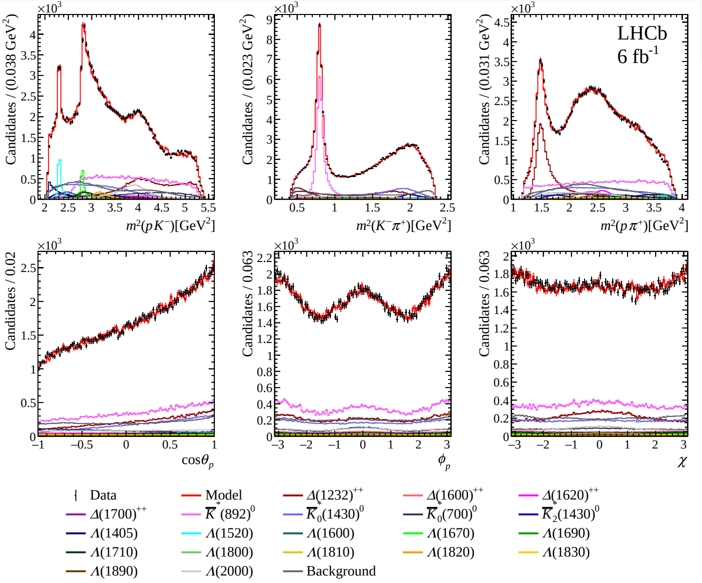
$$\hat{\boldsymbol{y}}_{\Xi_c^+} = \hat{\boldsymbol{z}}_{\Xi_c^+} \times \hat{\boldsymbol{x}}_{\Xi_c^+}$$



- Longitudinal (P_z) and transverse (P_x) polarisation are T-even, while normal (P_y) polarisation is T-odd
- P_y can be produced only by T-violation or (EM) final state interactions, see Sozzi, *Discrete symmetries and CPV*

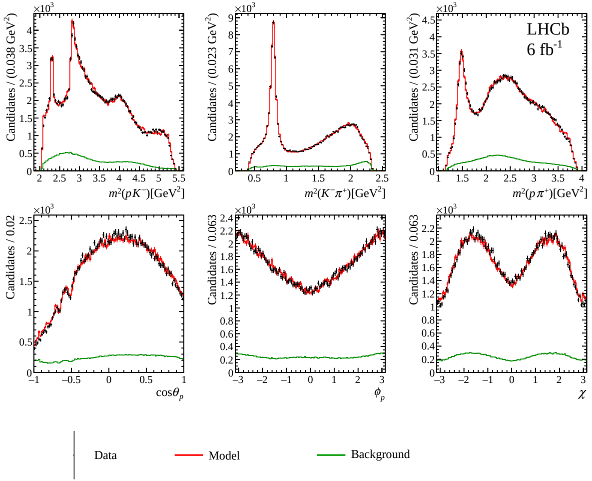
$\Xi_c^+ \to pK^-\pi^+$ model

- Determined a default model (Figure, Run 2)
- All parameters measured, including polarisation in approx B system
- Alternative models with similar quality considered for systematic uncertainties
- polarisation weakly dependent on specific amplitude model



$\Xi_c^+ \to pK^-\pi^+$ lab polarisation fit

- Default model used for a polarisation-only fit to determine ***P*** in lab system (Figure, Run 2)



Polarisation

- **First precision measurement of the Ξ_c^+ polarisation vector**, uncertainties order 0.01

- Large polarisation measured in both polarisation frames
  - approx B: more longitudinal than transverse, $P \approx 66\%$
  - lab: more transverse (P_x) than longitudinal (P_z), $P \approx 63\%$
- Normal polarisation (P_y), sensitive to $\hat{T}$-odd effects and final-state interactions, compatible with zero

Component	Value (%)
P_x (approx B)	$22.15 \pm 0.70 \pm 0.42 \pm 0.81$
P_y (approx B)	$-0.69 \pm 0.69 \pm 0.16 \pm 0.35$
P_z (approx B)	$-62.8 \pm 0.8 \pm 1.1 \pm 1.5$
P_x (lab)	$57.5 \pm 0.7 \pm 1.0 \pm 1.0$
P_y (lab)	$-0.64 \pm 0.68 \pm 0.13 \pm 0.23$
P_z (lab)	$-26.8 \pm 0.7 \pm 0.6 \pm 2.0$

Polarisation

- Ξ_c^+ polarisation shares same features observed for Λ_c^+ one, but for some slight differences
- Dominant component reduced, subdominant increased, reduced magnitude
  - Differences at few % level
- Differences have limited significance, but are consistently observed in both polarisation systems
- First investigation of strangeness-related polarisation in charm baryons

Amplitude model

- **Measured all fit parameters and fit fractions**
- Main contributions:

Resonance	Fit Fraction (%)		Stat. Unc.		Model Unc.		Syst. Unc.
$K^*(892)$	28.28	$\pm$	0.29	$\pm$	0.53	$\pm$	0.80
$\Delta^{++}(1232)$	17.73	$\pm$	0.35	$\pm$	0.48	$\pm$	0.45
$K_0^*(1430)$	14.2	$\pm$	0.7	$\pm$	3.2	$\pm$	1.9

- Higher contribution of Λ^* and K^* states in $\Xi_c^+ \to pK^-\pi^+$ than in $\Lambda_c^+ \to pK^-\pi^+$ decay
  - Qualitatively explainable by the presence of a valence s quark in the Ξ_c^+ baryon

Parity-violation & Sensitivity to polarisation

- Parity-violation observable from asymmetries in polarised processes
  - *e.g.* Mme Wu et al. 1957 experiment with polarised nuclei
- Measured decay asymmetry parameters characterizing two-body decays for each resonant contribution
  - Some are nonzero, indicating parity-violation in their decay
- Large sensitivity to the Ξ_c^+ polarisation of the $\Lambda_c^+ \to pK^-\pi^+$ decay observed
  - Measured by $\sqrt{3}S$ quantity ranging between zero and one

$$\sqrt{3}S = 0.680 \pm 0.005 \pm 0.013$$

- This, combined with excellent reconstruction efficiency of $\Xi_c^+ \to pK^-\pi^+$ decay, makes this channel suitable for polarisation measurements

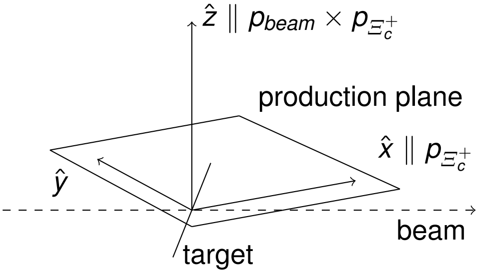
$\Xi_c^+ \to pK^-\pi^+$ prompt analysis

$\Xi_c^+ \to pK^-\pi^+$ prompt analysis

- Analysis work by S. Libralon
- Selection strategy similar to semileptonic production
- Prompt events separated from decays displaced from the *pp* collision vertex using impact parameter information

- polarisation system defined by production plane, with P_z in orthogonal direction
  - polarisation within the plane forbidden by parity conservation

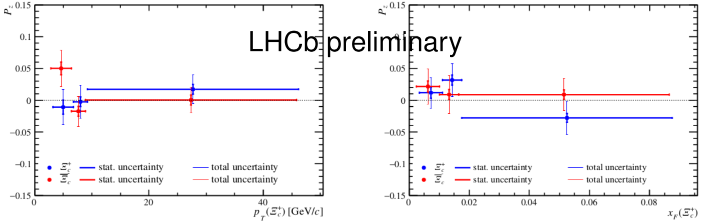
- polarisation measured in bins of p_{T} and $x_F = p_z / p_{beam}$, separately for Ξ_c^+ and $\overline{\Xi}_c^-$
- All three polarisation components determined in the fit
  - P_x, P_y should be compatible with zero



$\Xi_c^+ \to pK^-\pi^+$ prompt polarisation

- Polarisation measured using amplitude model from SL analysis
- No evidence of polarisation orthogonal to the production plane

- Forbidden polarisation components also compatible with zero
  - Previous evidence of in-plane polarisation disappeared after completion of systematic uncertainties studies



Λ_c^+ polarisation in p-Ne collisions

Λ_c^+ polarisation in p-Ne collisions

- To date LHCb is the only experiment able to record fixed-target collisions at the LHC thanks to its gas target SMOG(2)
- p-Ne $\Lambda_c^+ \to pK^-\pi^+$ data allows to measure Λ_c^+ polarisation at unprecedented center-of-mass energy $\sqrt{s_{NN}} = 68.6\,\mathrm{GeV}$
- Long-standing effort: analysis started during DM PhD thesis, continued by A. Merli
  - priority to charm amplitude analysis, to provide required polarimeter
  - multiple challenges posed by difficult experimental conditions

Analysis challenges

- Dataset is small for charm baryon studies: selected $\Lambda_c^+ \to pK^-\pi^+$ events at 1000 order
  - Large uncertainties, difficult data-driven calibrations
- Fixed-target events are overimposed with *pp* collisions, to be separated
- Simulation of proton-nuclear interaction is more complicated and less known w.r.t. *pp* collisions
- Measurement of polarisation vector gives unphysical components, forbidden by parity-conservation in strong interactions
  - Likely due to some, still unclear, experimental effect

Re-analysis of $\Lambda_c^+ \to pK^-\pi^+$ SMOG data

- Recently started re-analysis of $\Lambda_c^+ \to pK^-\pi^+$ SMOG data
  - Simpler analysis trying to isolate origin of unphysical polarisation
  - Tight selection removing all *pp* events
  - Variations of selection, simulation calibration, polarisation definition considered
- Unphysical polarisation still present with small significance given uncertainties
  - Does not impact orthogonal polarisation component
- Other solutions under consideration:
  - simpler polarisation fit integrating over unphysical components
  - use of latest Run 3 SMOG2 p-gas data

Conclusions

- AdR work mainly focused on the development of charm baryon amplitude analyses and polarisation measurements
- Results obtained (last two years):

- $\Xi_c^+ \to pK^-\pi^+$ SL amplitude analysis completed, Phys. Rev. D paper draft in preparation, LHCb-PAPER-2024-034
  - Amplitude model ready for Ξ_c^+ polarisation measurements, in addition to the $\Lambda_c^+ \to pK^-\pi^+$ one
  - First Ξ_c^+ polarisation measurement
  - First comparison of polarisation values for charm baryons with/out strangeness

Conclusions

- $\Xi_c^+ \to pK^-\pi^+$ prompt polarisation measurement completed, at LHCb review stage
  - Measurement of Ξ_c^+ polarisation in p_{T}, x_F bins obtained
  - No polarisation evidence at 13 TeV CM energy
- Λ_c^+ polarisation in p-Ne collisions, ongoing
  - Started re-analysis of $\Lambda_c^+ \to pK^-\pi^+$ SMOG data addressing observed problems
  - Possible solutions identified
  - Further investigation and analysis completion will be the next main priority

Backup slides

Formalism for baryon amplitude analysis

- Full phase space amplitude analyses needed better understanding of baryon decay amplitudes

- Issues with rotational invariance observed in helicity formalism based $\Lambda_c^+ \to pK^-\pi^+$ amplitude model
  - Traced back to incorrect spin state definition among different decay chains
  - Basic quantum-mechanical properties of spin states under rotations neglected before
- Formalism adapted for decays featuring different interfering decay chains, AHEP (2020) 6674595
  - Developed general method to ensure same definition of final particle spin state (spin matching) among different chains
  - Supersedes and amends method used in previous analyses, notably LHCb pentaquark discovery paper *PRL 115 (2015) 072001*

Formalism for baryon amplitude analysis

- Demonstrated possibility to simultaneously determine $\Lambda_c^+ \to pK^-\pi^+$ amplitude model and Λ_c^+ polarisation AHEP (2020) 7463073
  - Analytical study of the constraints posed by the amplitude fit to the decay rate
  - Amplitude fit to pseudodata generated with toy $\Lambda_c^+ \to pK^-\pi^+$ description
- Results:
  - Interference effects among different decay chain contributions are crucial: give sensitivity to single helicity couplings and to polarisation magnitude
  - Non-zero polarisation needed to determine entirely the amplitude model
- Conditions met by $\Lambda_c^+ \to pK^-\pi^+$ decays from weak production, having significant Λ_c^+ polarisation
  - Promptly-produced $\Lambda_c^+ \to pK^-\pi^+$ decays have insufficient polarisation to fully determine amplitude model