Charm baryon amplitude analyses and polarization 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: Polarization

- Baryon amplitude analyses can be used to measure baryon polarization vector ***P***
  - Full phase space analysis needed (Dalitz + decay orientation d.o.f.)
- Polarization 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 polarization measurements
- For heavy baryons, multibody decays provide best statistics
  - $pK^-\pi^+$ is the main decay channel of Λ_c^+ (BF = 6.28%), with excellent reconstruction efficiency
- Essential for heavy baryon electromagnetic dipole moments measurement via spin precession in bent crystals (see PRD **103** (2021) 072003 and Refs therein)
  - SELDOM ERC project

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^+ polarization 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 polarization magnitude
- Non-zero polarization needed to determine entirely the amplitude model

- Conditions met by $\Lambda_c^+ \to pK^-\pi^+$ decays from weak production, having significant Λ_c^+ polarization
- Promptly-produced $\Lambda_c^+ \to pK^-\pi^+$ decays have insufficient polarization to fully determine amplitude model

Analyses in LHCb

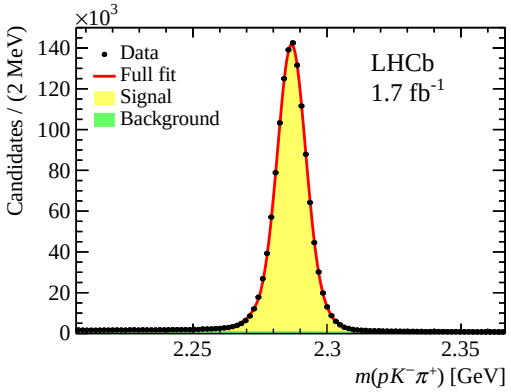
- LHCb provides very large samples of charm baryon decays, from beauty hadron semileptonic (SL) decays or from prompt *pp* collisions
- SL samples studied to determine amplitude models for polarization measurements
  - Large polarization from parity-violating weak decay gives full sensitivity on decay amplitude
  - Cleaner samples with more regular detector efficiency, suitable for amplitude fit with tens of free parameters
- Larger prompt samples useful to study kinematic-dependent production polarization
  - Application of the polarization measurement method with amplitude analysis
  - Study of strong production mechanism at 13 TeV center-of-mass energy

Analyses in LHCb

- $\Lambda_c^+ \to pK^-\pi^+$ amplitude analysis from SL production completed (DM @ INFN Milano), arXiv:2208.03262
  - Amplitude model available for Λ_c^+ spin precession and polarization measurements, *e.g.* in p-gas collisions
- Prompt $\Lambda_c^+ \to pK^-\pi^+$ analysis ongoing (L. Henry, E. Niel @ CERN, IJCLAB Paris)
  - Preliminary results obtained, with cross-check of amplitude model
- $\Xi_c^+ \to pK^-\pi^+$ SL & prompt analyses ongoing (DM, S. Libralon @ INFN Milano)
  - Polarimeter and study of production polarization also for the Ξ_c^+ charm and strange baryon
  - Preliminary results obtained
- This talk will cover activity @ INFN Milano

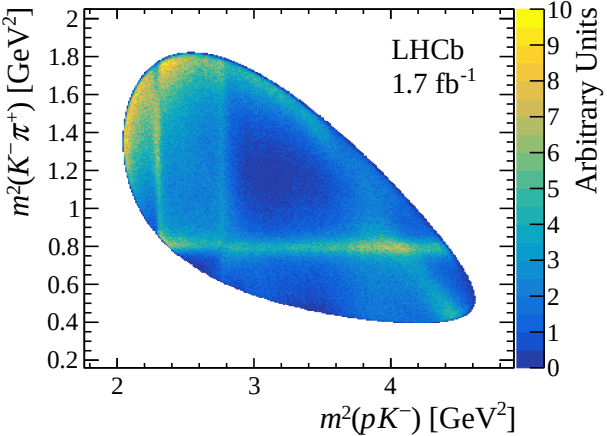
$\Lambda_c^+ \to pK^-\pi^+$ SL candidates selection

- Tight selection of $\Lambda_c^+ \to pK^-\pi^+$ candidates based on PID and topological information
- Huge sample available
- 1.27 M from 2016
- Very small combinatorial background, negligible physical contributions
- Fit performed on subsample of 400k candidates (systematic $>$ statistical uncertainties)



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

- Code developed basing on TensorFlowAnalysis package, adapted for full phase space 5D amplitude fits
- 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



Λ_c^+ polarization frame

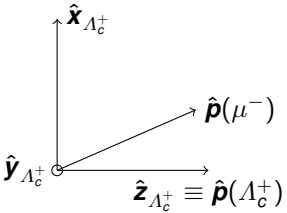
- Polarization measured in two Λ_c^+ helicity rest frames, with orthogonal components defined from the muon direction

- Laboratory frame: no reconstruction uncertainties
- Approximate B rest frame: closer to semileptonic decay physics

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

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

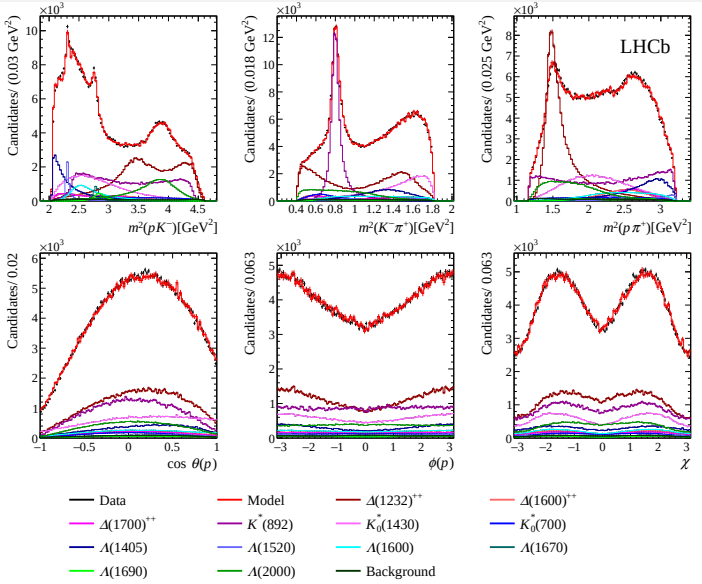
$$\hat{\boldsymbol{y}}_{\Lambda_c^+} = \hat{\boldsymbol{z}}_{\Lambda_c^+} \times \hat{\boldsymbol{x}}_{\Lambda_c^+}$$



- 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*

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

- Determined a default model (Figure)
- All parameters measured
- Alternative models with similar quality considered for systematic uncertainties
- Polarization weakly dependent on specific amplitude model



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

- Main contributions:

Resonance	Fit Fraction (%)		Stat. Unc.		Model Unc.		Syst. Unc.
$\Delta^{++}(1232)$	28.60	$\pm$	0.29	$\pm$	0.76	$\pm$	0.16
$K^*(892)$	22.14	$\pm$	0.23	$\pm$	0.64	$\pm$	0.04
$K_0^*(1430)$	14.7	$\pm$	0.6	$\pm$	2.7	$\pm$	0.1

- Large contribution in $m(pK^-) \approx 2\,\mathrm{GeV}$ region seen, where no clear resonances are reported by PDG
  - Described as $J^P = 1/2^-$ state, with mass $1970 \pm 4 \pm 13\ \mathrm{MeV}$ and width $148 \pm 7 \pm 18\ \mathrm{MeV}$
  - Compatible with PDG $\Lambda(2000)$

Λ_c^+ polarization

- Precision measurement of the Λ_c^+ polarization vector
  - Uncertainties order 0.01
- Large polarization measured in both polarization systems
  - Λ_c^+ HF from laboratory: more transverse (P_x) than longitudinal (P_z), $P \approx 66\%$
  - Λ_c^+ HF from approx B rest frame: more longitudinal than transverse, $P \approx 69\%$
- Normal polarization (P_y), sensitive to time-reversal violation effects and final-state interactions, compatible with zero in both systems

Component	Value (%)
P_x (lab)	$60.32 \pm 0.68 \pm 0.98 \pm 0.21$
P_y (lab)	$-0.41 \pm 0.61 \pm 0.16 \pm 0.07$
P_z (lab)	$-24.7 \pm 0.6 \pm 0.3 \pm 1.1$
P_x (approx B)	$21.65 \pm 0.68 \pm 0.36 \pm 0.15$
P_y (approx B)	$1.08 \pm 0.61 \pm 0.09 \pm 0.08$
P_z (approx B)	$-66.5 \pm 0.6 \pm 1.1 \pm 0.1$

Parity-violation & Sensitivity to polarization

- Parity-violation observable from asymmetries in polarized processes
  - *e.g.* Mme Wu et al. 1957 experiment with polarized 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 Λ_c^+ polarization of the $\Lambda_c^+ \to pK^-\pi^+$ decay observed
  - Measured by $\sqrt{3}S$ quantity ranging between zero and one (details in arXiv:2208.03262)

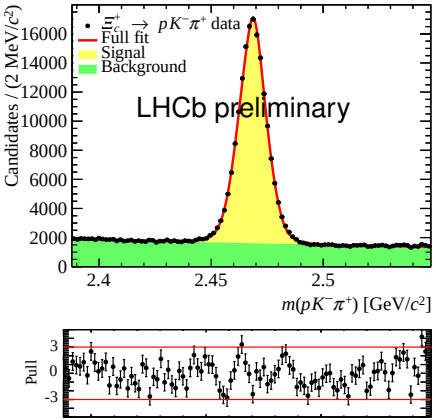
$$\sqrt{3}S = 0.662 \pm 0.005 \pm 0.010 \pm 0.007$$

- Considering the large BF, $\Lambda_c^+ \to pK^-\pi^+$ is the best channel to access Λ_c^+ polarization
  - $\Lambda_c^+ \to pK^-\pi^+$ amplitude model provides best polarization analyser

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

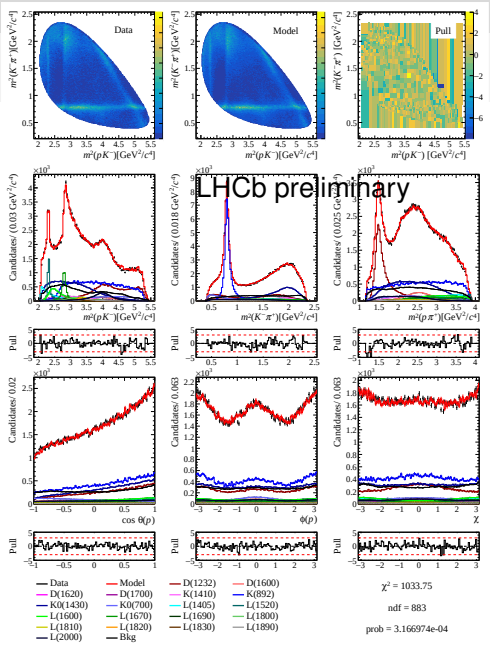
- $\Xi_c^+ \to pK^-\pi^+$ decay is suppressed both in production and decay w.r.t. $\Lambda_c^+ \to pK^-\pi^+$
  - Same strategy with more refined data analysis

- Multivariate (Boosted Decision Tree) selection based on PID, topological, momentum, track information
- $\approx$ 150k signal candidates from Run 2 samples
- One order of magnitude larger background contamination than Λ_c^+ case
- Physical contributions from three-body charm meson decays and ghost background studied and removed



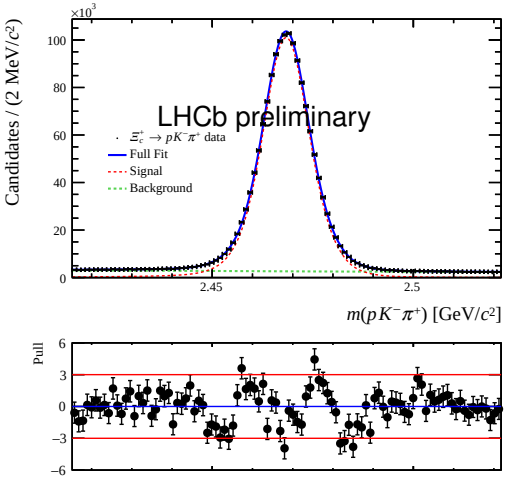
$\Xi_c^+ \to pK^-\pi^+$ SL amplitude analysis

- Same amplitude fit strategy of $\Lambda_c^+ \to pK^-\pi^+$ analysis
- Obtained preliminary amplitude fit on Run 2 data, polarization in approx *B* system
- Employed amplitude model with large number of resonances and fit parameters, to be refined
- Good description of phase space distributions: efficiency and background under control
- Amplitude fit to be done also for lab system polarization



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

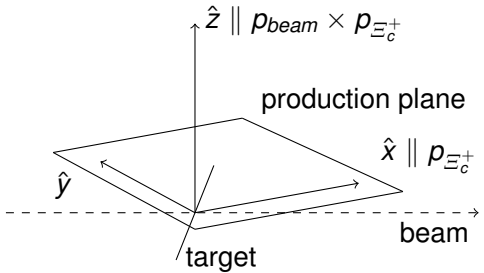
- Multivariate selection based on PID, topological, momentum, track information
- Contributions from three-body charm meson decays removed
- Prompt events separated from decays displaced from the *pp* collision vertex using impact parameter information
- $\approx$ 1.5M $\Xi_c^+ \to pK^-\pi^+$ candidates from 2016-18 samples
- Combinatorial background and non-prompt contaminations limited to 5% level



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

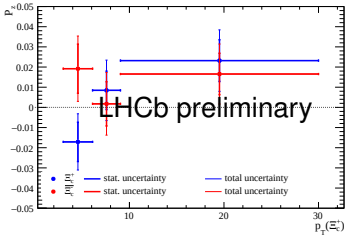
- Polarization system defined by production plane, with P_z in orthogonal direction
- Polarization within the plane forbidden by parity conservation

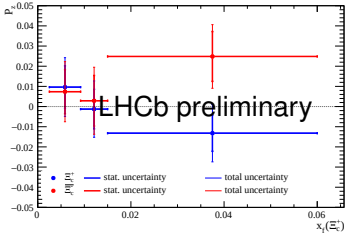
- Polarization measured in bins of p_{T} and $x_F = p_z/p_{beam}$, separately for Ξ_c^+ and $\overline{\Xi}_c^-$
- Bin-specific background and efficiency considered
- All three polarization components determined in the fit
- P_x, P_y should be compatible with zero, important cross-check of the measurement



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

- Polarization measured using preliminary amplitude model from SL analysis
- Preliminary results after systematic uncertainty evaluation obtained
- No evidence of polarization orthogonal to the production plane
- Small tensions of polarization components in prod plane w.r.t. zero, $\sim 2\sigma$, possibly due to systematic effects
- Under investigation, but measured P_z component seems largely unaffected by deviations in P_x, P_y





Conclusions

- $\Lambda_c^+ \to pK^-\pi^+$ SL amplitude analysis completed, arXiv:2208.03262, submitted to PRD
- Amplitude model ready for Λ_c^+ polarization measurements, *e.g.* in p-Gas SMOG collisions (Andrea's talk) and EMDMs measurements from spin precession
- Provides best polarimeter for the most abundant Λ_c^+ baryon
- First Λ_c^+ polarization measurement from beauty SL decays

Conclusions

- $\Xi_c^+ \to pK^-\pi^+$ SL amplitude analysis ongoing
  - Preliminary amplitude model obtained, with good control of efficiency and background
  - Will provide efficient polarimeter also for the Ξ_c^+ baryon
  - Comparison of polarization values for charm baryons with/out strangeness
- $\Xi_c^+ \to pK^-\pi^+$ prompt polarization measurement ongoing
  - Preliminary results for Ξ_c^+ polarization in p_{T}, x_F bins obtained
  - No evidence of Ξ_c^+ polarization at 13 TeV center-of-mass
  - Not directly relevant for EMDMs measurement, but nice application of the method