Amplitude analysis and polarisation measurement of the Λ_c^+ baryon in $pK^-\pi^+$ final state for electromagnetic dipole moment experiment

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Electromagnetic dipole moments

- Magnetic (MDM) and electric (EDM) dipole moments are electromagnetic properties proportional to the particle spin

$$\hat{\boldsymbol{\mu}} = g \frac{\mu_B}{\hbar} \hat{\mathbf{S}} \qquad \qquad \hat{\boldsymbol{\delta}} = d \frac{\mu_B}{\hbar} \hat{\mathbf{S}}$$

- Elementary particles $g = 2+$ QFT loop corrections
- Composite particles $g \neq 2$ depending on their structure

→ Probe for baryon structure

Low-energy QCD physics

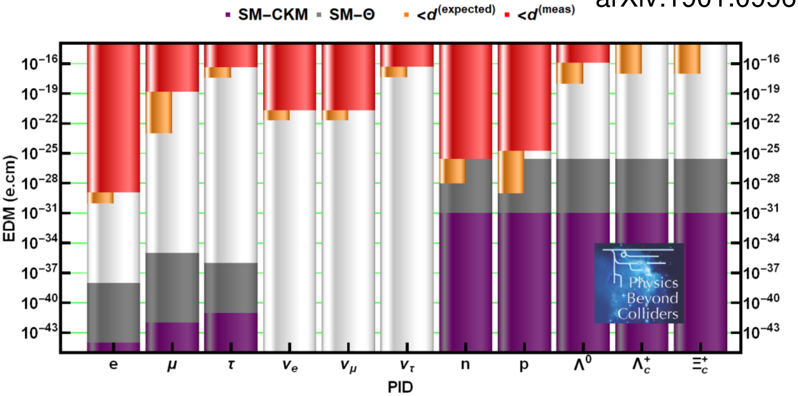
- EDM violates time-reversal and parity symmetries
- No flavour-diagonal *CP*-violation sources in the SM

→ Probe for new physics

No SM background

EDM measurements

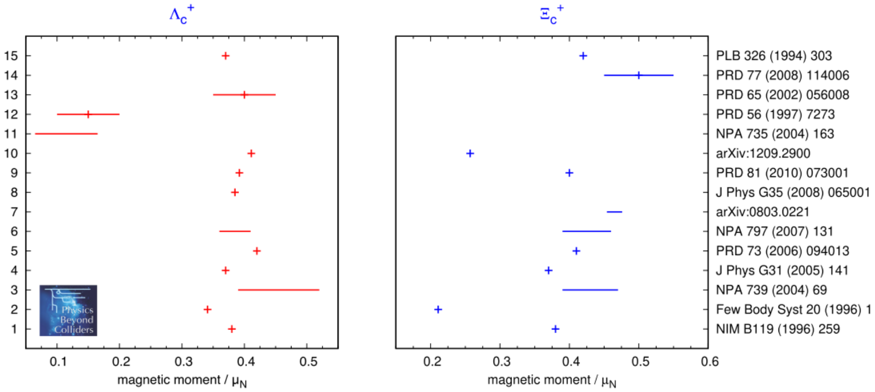
arXiv:1901.09966



- EDMs probed in different systems: leptons, nucleons, nuclei, atoms, and Λ baryon
- Heavy baryon and τ lepton EDMs never measured so far; only indirect limits from other measurements available

MDM as probe for baryon structure

arXiv:1901.04482



- No heavy baryon MDM measurement performed to date, precise measurement can discriminate among different theoretical models

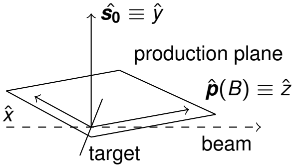
DMs from spin precession

- Three ingredients needed:

- Polariser
- (Strong) Electromagnetic field
- Polarimeter

DMs from spin precession

- **Polariser**:
- *p*-nucleus collisions produce baryons with polarisation orthogonal to the *p*-*B* production plane for parity symmetry in strong interactions



- Measured for with strange baryons, indications for significant polarisation also for with Λ_c^+
  - But at smaller energies than at LHC

$\rightarrow$ Λ_c^+ **polarisation measurement in p-Ne fixed target collisions at with** $\sqrt{s} = 68.6\,\mathrm{GeV}$ **at LHCb**

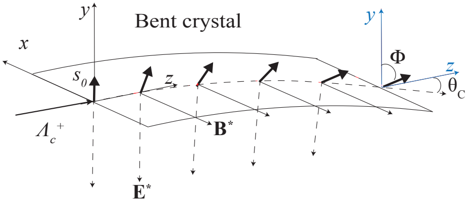
DMs from spin precession

- **(Strong) Electromagnetic field**:

- Interatomic electric field $\boldsymbol{E} \approx 10^{11} eV/m$ of a bent crystal
- Spin after channeling along the crystal with deflection angle θ_C

$$\mathbf{s} = s_0 \left(\frac{d}{g-2}(1-\cos\Phi), \cos\Phi, \sin\Phi \right)$$

$$\Phi \approx \frac{g-2}{2}\gamma\theta_C$$



- Main MDM precession in the bending plane, the EDM producing an orthogonal spin component otherwise not present

DMs from spin precession

- **Polarimeter**:
- Measurement of the heavy baryon polarisation after channeling reconstructing the decay angular distribution
- $\Lambda_c^+ \to pK^-\pi^+$ main decay channel, $\mathcal{B} \approx 6\%$, allowing polarisation measurement with best precision
  - Two-body decays have lower $\mathcal{B} \lessapprox 1\%$ and involve long-living strange particles
- Previous amplitude analysis on ≈ 1000 events performed by E791 experiment (Phys. Lett. B471 (2000) 449) not useful
- Millions of events recorded by LHCb from semileptonic production $\Lambda_b^0 \to \Lambda_c^+ \mu^- X$

$\to$ **Amplitude analysis of the with $\Lambda_c^+ \to pK^-\pi^+$ decay at LHCb**

Physics with amplitude analysis

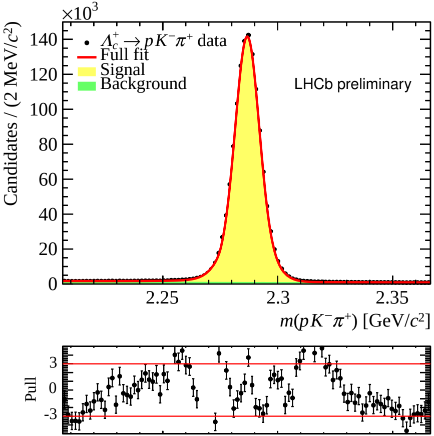
- Study of the decay structure
  - Resonance composition, characterisation and interference
- Polarisation measurements
  - Essential information for heavy baryons dipole moment measurement
- Parity-violation studies
  - P-violation determines correlation between polarisation and decay kinematics

$$\frac{dN}{d\Omega^*} \propto 1 + \alpha_f \, \mathbf{s} \cdot \hat{\mathbf{k}},$$

- *CP*-violation searches with enhanced sensitivity
  - Decay structure allow to search and localise *CP*-violation sources

$\Lambda_c^+ \to pK^-\pi^+$ decays from semileptonic production

- Considered $\Lambda_c^+ \to pK^-\pi^+$ decays from Λ_b^0 semileptonic decays
  - $\Lambda_c^+\mu^-$ vertices displaced from pp collision vertex
- Very pure selection exploiting LHCb particle identification
  - $\sim$ 1 million of $\Lambda_c^+ \to pK^-\pi^+$ candidates from 2016 dataset only
  - Negligible background contribution $\approx 1.7\%$

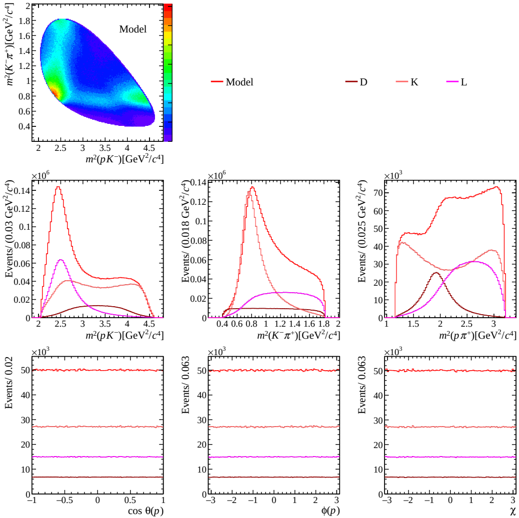


Helicity amplitudes

- Decay model written in the **helicity formalism** with a new method I developed addressing the issue of the matching of final particle spin states among different decay chains in full generality for generic multi-body decays
  - The definition of proton helicity states is different for different decay chains: they need to be matched to a reference set of spin states
- This method ensure a correct matching for generic multi-body decays, preprint arXiv:1911.10025
- Allows a good fit of the $\Lambda_c^+ \to pK^-\pi^+$ distributions, which was impossible with the matching method used in literature, proved wrong

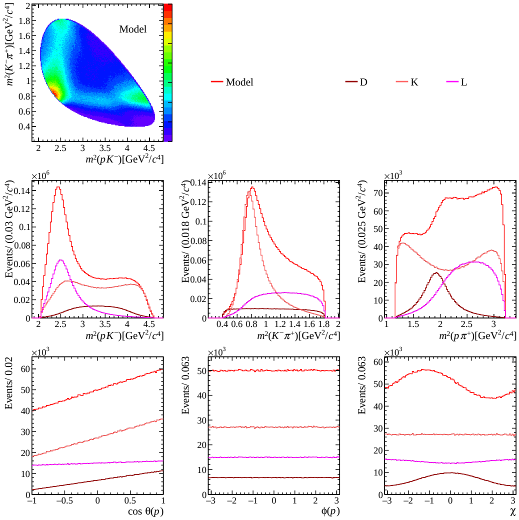
Tests

- Spin matching methods tested for $\Lambda_c^+ \to pK^-\pi^+$ amplitudes exploiting properties from rotational invariance
  - Decay rate isotropic for zero polarisation
  - Invariant mass distributions independent of polarisation
- Satisfied by our method, not by the older one
- Proven equivalence between our method and the Dalitz-plot decomposition one



Analytical study of the $\Lambda_c^+ \to pK^-\pi^+$ decay rate

- $\Lambda_c^+ \to pK^-\pi^+$ amplitude also studied analytically
- Understood polarisation signatures on decay rate
- Proven that interference effects gives sensitivity to all the amplitude model parameters
- Allowing simultaneous measurement of amplitude model and polarisation vector
- Published, AHEP (2020) 7463073



Maximum likelihood fit

- Model parameters (polarisation, couplings, resonance parameters) determined from data by minimising the negative log-likelihood

$$-\log \mathcal{L}(\omega) = -\sum_{i=1}^{N} \log\left[p(\Omega_i|\omega) + \frac{p_{bkg}(\Omega_i)I(\omega)}{\epsilon(\Omega_i)}\frac{n_{bkg}}{n_{sig}}\right] + N\log I(\omega) + \mathrm{constant},$$

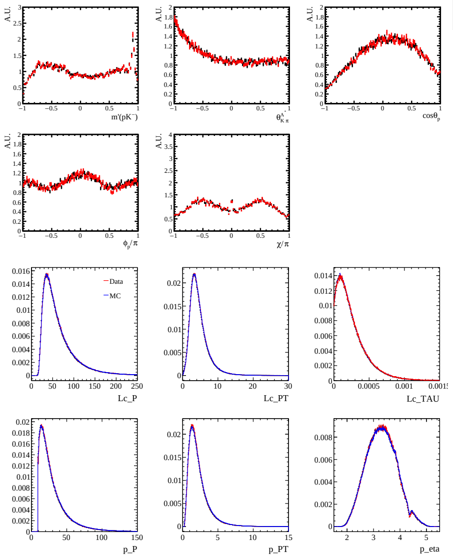
- Efficiency and background parametrisation added, their contribution suppressed by $n_{bkg}/n_{sig} \approx 1.7\%$
- Normalisation $I(\omega)$ computed directly using simulated events reconstructed by LHCb

Amplitude fit

- Fitting code developed basing on TensorFlowAnalysis package, based on machine-learning framework Tensorflow
- Minimisation performed with the MINUIT package
- Performed on 100k $\Lambda_c^+ \to pK^-\pi^+$ candidates, with 450k MC events for integration/efficiency folding
- Performed different times with randomised starting values for floating parameters, best result chosen according to best log-likelihood

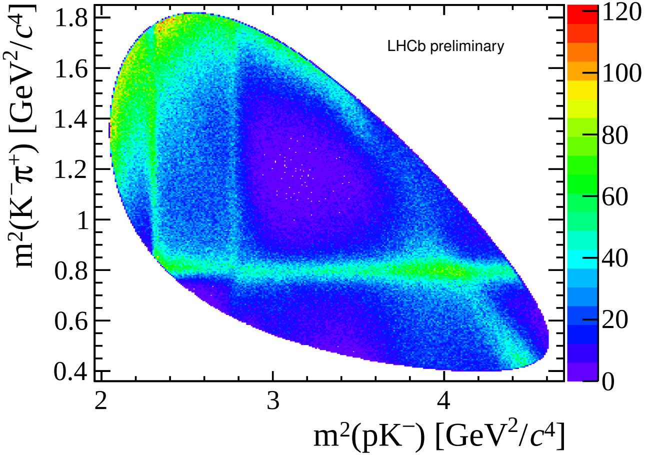
Latest improvements

- Finalisation and optimisation of the fitting code
- Introduction of background contribution via Legendre polynomial expansion
- Improvement of detector efficiency description, by correcting the simulation sample according to the Λ_c^+ kinematics observed in data
- Determination of the amplitude model
- Planned studies for systematic uncertainties evaluation



Model building

- Amplitude model built starting from contributions visible in the Dalitz plot and adding states according to PDG
- Fit quality measured by χ^2 test
- Contributions improving the fit are retained
- Those leading to similar quality will be considered for systematic uncertainty evaluation



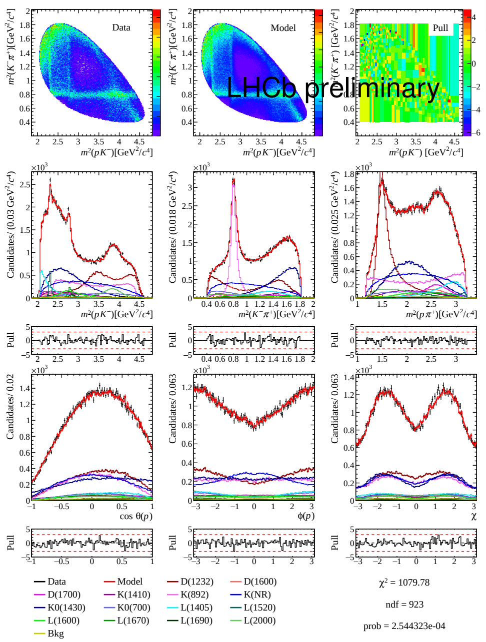
Current model

- Resonances parametrised by relativistic Breit-Wigner
  - Specific treatment for $\Lambda(1405)$, non-res K^* and $K_0^*(1430)$
- Most resonance parameters fixed to PDG mean values
- Ranges indicate limits for fitted values, reflecting PDG knowledge uncertainty or resolution effects

Resonance	J^P	BW mass (MeV)	BW width (MeV)
$\Lambda(1405)$	$1/2^-$	1405.1	50.5
$\Lambda(1520)$	$3/2^-$	1515 – 1523	10 – 20
$\Lambda(1600)$	$1/2^+$	1560 – 1700	50 – 250
$\Lambda(1670)$	$1/2^-$	1670	25
$\Lambda(1690)$	$3/2^-$	1690	60
$\Lambda(2000)$	$1/2^-$	1900 – 2100	20 – 400
$\Delta^{++}(1232)$	$3/2^+$	1232	120
$\Delta^{++}(1600)$	$3/2^+$	1500 – 1640	200 – 300
$\Delta^{++}(1700)$	$3/2^-$	1690 – 1730	220 – 380
Non-resonant	0^+		
$K_0^*(700)$	0^+	824	478
$K^*(892)$	1^-	890 – 900	47.3
$K^*(1410)$	1^-	1421	236
$K_0^*(1430)$	0^+	1425	270

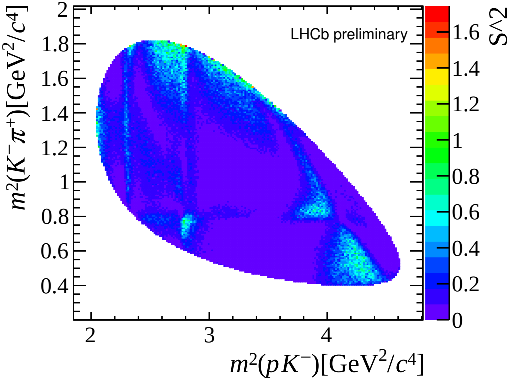
Current model

- Good fit, no evident discrepancies left
- Large contribution of "unexpected" $\Lambda(2000)$ $1/2^-$ state
- Significant interference effects
- Large, $> 60\%$, polarisation in $\Lambda_c^+ - \mu^-$ plane
- Normal ($\hat{T}$-odd) polarisation compatible with zero within 1%



Sensitivity to polarisation study

- Computed average event Fisher information for the reduced model from Dalitz fits
  - S $\approx$ 0.38
  - Effective $\alpha \approx$ 0.65
  - Almost independent on the particular amplitude model assumed
- Similar to that assumed for $\Lambda_c^+ \to \Delta^{++} K^-$ decays in the Λ_c^+ dipole moments sensitivity study
- Can increase the useful $\Lambda_c^+ \to pK^-\pi^+$ decay statistics to measure the Λ_c^+ dipole moments by a factor six



Progress on Λ_c^+ polarisation in p-Ne analysis

- New p-Ne data sample from reprocessing of LHCb Ion and Fixed-target datasets
  - Better efficiency on $\Lambda_c^+ \to pK^-\pi^+$ decays, increasing the available statistics to perform the polarisation measurement
- New simulation sample reproducing $\Lambda_c^+ \to pK^-\pi^+$ decays in fixed-target conditions
  - One order of magnitude larger than the previous
  - Allows refined signal selection and better description of the detector response

Prospects

- Systematic uncertainty evaluation only missing piece to completion
- Analysis started review process within LHCb Charm working group
- Aiming presentation at winter conferences
- $\Lambda_c^+ \to pK^-\pi^+$ amplitude model constitutes input for the Λ_c^+ polarisation measurement in p-Ne fixed target collisions, which will be the next main focus

Backup Slides

Amplitude model for $\Lambda_c^+ \to pK^-\pi^+$ decay

- Amplitudes built for each intermediate resonance R
  $\Lambda_c^+ \to R\{p, K^-, \pi^+\}$, $R \to \{K^-\pi^+, p\pi^+, pK^-\}$
  multiplying two-body helicity amplitudes, e.g.

$$\mathcal{A}^{[R]}_{m_{\Lambda_c^+},\lambda_R,\lambda_p}(\Omega) = \mathcal{A}^{\Lambda_c^+ \to R\pi^+}_{\lambda_R,0}\,\mathcal{A}^{R \to pK^-}_{\lambda_p,0}$$

- Total helicity amplitudes for definite initial and final particles helicities obtained summing over all intermediate resonance helicity states

$$\mathcal{A}_{m_{\Lambda_c^+},\lambda_p}(\Omega) = \sum_{i=1}^{N_R} \sum_{\lambda_{R_i}=-J_{R_i}}^{J_{R_i}} \mathcal{A}^{[R_i]}_{m_{\Lambda_c^+},\lambda_{R_i},\lambda_p}(\Omega)$$

Polarised decay rate

- Generic Λ_c^+ particle polarisation in a given coordinate frame described by the density matrix

$$\rho^{\Lambda_c^+} = \frac{1}{2}(\mathcal{I} + \boldsymbol{P}\cdot\boldsymbol{\sigma}) = \frac{1}{2}\begin{pmatrix} 1+P_z & P_x - iP_y \\ P_x + iP_y & 1-P_z \end{pmatrix}$$

- Decay probability distribution obtained summing modulo squared helicity amplitudes over initial Λ_c^+ polarisation and unmeasured final particles helicities

$$\begin{aligned} p(\Omega, \boldsymbol{P}) \propto \sum_{m_p=\pm 1/2} \Big[&(1+P_z)|\mathcal{A}_{1/2,m_p}(\Omega)|^2 + (1-P_z)|\mathcal{A}_{-1/2,m_p}(\Omega)|^2 \\ &+ (P_x - iP_y)\mathcal{A}^*_{1/2,m_p}(\Omega)\mathcal{A}_{-1/2,m_p}(\Omega) \\ &+ (P_x + iP_y)\mathcal{A}_{1/2,m_p}(\Omega)\mathcal{A}^*_{-1/2,m_p}(\Omega)\Big] \end{aligned}$$

Baryon 3-body decay kinematics description

- Three-body decays described by 5 degrees of freedom: 2 two-body "Dalitz" invariant masses + 3 decay plane orientation angles
- For polarised baryons spherical symmetry is broken: decay plane orientation angles must be included in the amplitude analysis

- Euler rotation angles ϕ_p, θ_p, χ from polarisation frame to decay plane