Amplitude analyses for heavy baryon electromagnetic dipole moment measurements

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Electromagnetic dipole moments

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

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

- 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

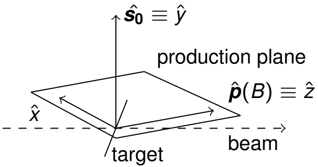
Heavy baryon MDMs/EDMs

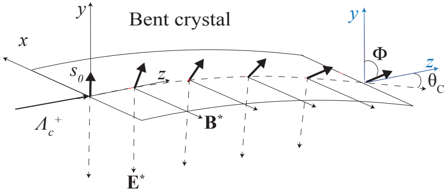
- MDMs/EDMs directly measured for nucleons and strange baryons
- Never measured for heavy (charm and beauty) baryons
- Experimentally challenging due to short lifetimes
- Only indirect limits existing

- Recently, an experiment for the first heavy baryon direct MDMs/EDMs measurement has been proposed
- See Refs. EPJC 77 (2017) 181, EPJC 77 (2017) 828
- SELDOM project funded by ERC
- Part of CERN Physics Beyond Colliders proposals for fixed-target experiments at the LHC, arXiv:1901.09966
- Installation within LHCb experiment under study

Experiment concept

- Source of polarised baryons
- Selected from *p*-nucleus collisions, with polarisation orthogonal to the *p*-baryon production plane for parity symmetry in strong interactions





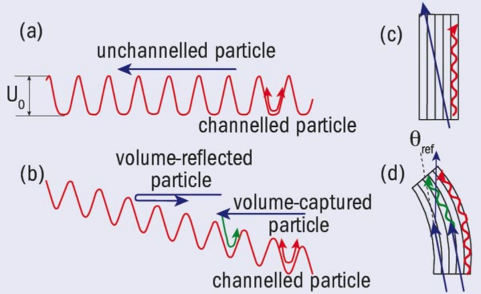
- Intense EM field enough to induce significant spin precession before the baryon decay

→ Exploit the interatomic electric field $\boldsymbol{E} \approx 10^{11}\, eV/m$ of a bent crystal

- Derived spin evolution equations in which EDM effects are treated as small corrections to the MDM induced precession

Particle channeling in bent crystals

- Positive particles can be trapped between crystal atomic planes, acting as potential barriers
- In bent crystals channeled particles are deflected by following planar channels
- The electric field deflecting the particle, providing the centripetal force, produce the desired spin precession

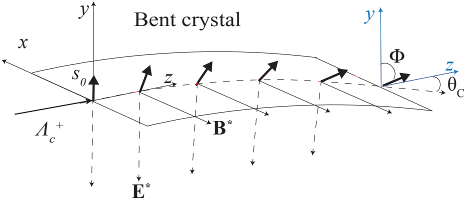


Charm baryons spin precession

- 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
- Spin precession proportional to $\gamma\theta_C$: need high momentum baryons and high crystal bending angle
- Measurement of the heavy baryon polarisation after channeling by studying the angular distribution of their decays, via amplitude analysis

Physics with amplitude analysis

- Understanding of the intermediate states contributing to the decay
  - Resonance composition, characterisation and interferences
  - Spectroscopy searches: new hadronic resonances and exotic states like tetra/penta-quarks
- Polarisation measurements
  - Additional information carried by baryons w.r.t. mesons
- Parity-violation studies
  - P-violation determines correlation between polarisation and decay kinematics
- *CP*-violation searches with enhanced sensitivity
  - Decay structure allow to search and localise *CP*-violation sources

Amplitude analyses of $\Lambda_c^+ \to pK^-\pi^+$ decay

- Λ_c^+ is the most abundant charm baryon
- Best precision on charm quark dipole moments
- Three-body $\Lambda_c^+ \to pK^-\pi^+$ decay is its main decay channel ($\mathcal{B} \approx 6\%$), allowing polarisation measurement with maximum statistics
- Two-body decays have lower branching fractions ($\lesssim 1\%$) and involve long-living strange particles
- Amplitude analysis on ≈ 1000 $\Lambda_c^+ \to pK^-\pi^+$ events performed by E791 experiment (Phys. Lett. B471 (2000) 449)
- Large samples of $\Lambda_c^+ \to pK^-\pi^+$ decays (order 1M events) recorded by the LHCb experiment
- Amplitude analyses for both weak and strong interaction Λ_c^+ production ongoing

Baryon polarisation

- Baryon polarisation defined with respect to a reference coordinate frame, defining the three spin operators $\hat{S}_i$
- Quantum spin state expressed in terms of simultaneous $\hat{S}^2$, $\hat{S}_z$ eigenstates $|sm\rangle$
- Most general quantum state for a spin 1/2 baryon, allowing for statistical ensembles of particles, is described by the density matrix

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

with polarisation components P_i being the expectation values of the spin operators

Examples of baryon polarisation frames

- Any physically well defined choice for the polarisation frame is possible, up to the experimentalist interest
- For heavy baryon dipole moments measurement, the natural frame is the bent crystal reference one, where spin precession occurs
- Strong production: polarisation orthogonal to the production plane $\boldsymbol{P} \parallel \boldsymbol{p}(p) \times \boldsymbol{p}(B)$ in laboratory frame due to parity conservation
- Weak production: polarisation expected along $\boldsymbol{p}(B)$ in mother baryon frame due to parity violation
- Helicity frame choice(s): z quantisation axis parallel to baryon momentum, $S_z \parallel \boldsymbol{p}(B)$

Helicity formalism

- Amplitude model written following the helicity formalism
- Helicity is the spin projection along particle momentum $\hat{\lambda} = \hat{\boldsymbol{S}} \cdot \boldsymbol{p}/|\boldsymbol{p}|$
  - Invariant under rotations and boosts $\parallel$ $\boldsymbol{p}$
  - Application of the spin-orbit combination of angular momenta to relativistic processes thanks to helicity transformation properties
- Three-body decay amplitude decomposed in single two-body $A \rightarrow BC$ amplitudes defined in terms of final-state helicities
- Factored in three terms: Complex couplings × Rotation matrix × Mass dependence

$$\mathcal{A}^{A\rightarrow BC}_{m_A,\lambda_B,\lambda_C} = \mathcal{H}^{A\rightarrow BC}_{\lambda_B,\lambda_C} \times D^{J_A}_{m_A,\lambda_B-\lambda_C}(\phi_B,\theta_B,0)^* \times \mathcal{R}(m^2_{BC})$$

Helicity formalism

- Complex couplings encode the decay dynamics, to be determined from fit to experimental data
- NB: they are assumed to be mass-independent
- Wigner D-rotation matrix expresses the spin basis rotation from *A* polarisation frame to *B* helicity frame
- NB: the *B* helicity frame is defined up to rotations around its momentum. The definition of $\boldsymbol{S}_x$, $\boldsymbol{S}_y$ operators must be specified.
- Invariant mass dependence: parametrisation of the *A* particle width
- Needed for intermediate resonant states. Lineshape function dependent on the specific resonance
- NB: the helicity formalism is relativistic but not explicitly covariant

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

- 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

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

Proton spin rotation

- Definition of the proton helicity frame depends on the particular decay chain considered (i.e. the proton momentum in the resonance rest frame)
- Amplitudes can be summed only if the proton spin is referred to a single frame, of arbitrary choice
- Additional rotation to be applied to the helicity amplitudes: given reference proton spin states $|1/2, \lambda_p\rangle$ and a different basis $|1/2, \lambda'_p\rangle$, amplitudes are rotated as

$$\mathcal{A}^{[R_i]}_{m_{\Lambda_c^+}, \lambda_{R_i}, \lambda_p}(\Omega) = \sum_{\lambda'_p} D^{1/2}_{\lambda'_p, \lambda_p}(\alpha, \beta, \gamma)^* \mathcal{A}^{[R_i]}_{m_{\Lambda_c^+}, \lambda_{R_i}, \lambda'_p}(\Omega)$$

Proton spin rotation

- The definition of the reference proton spin frame must be consistent for all the three coordinates
- i.e. the three spin operators $\hat{S}_i$ for the proton must be the same
- Indeed, suppose one has two proton spin frames with coinciding z axis and different x, y axes
- they differ by a rotation around z, $e^{-i\psi\hat{S}_z}$
- its action changes the proton state phase

$$e^{-i\psi\hat{S}_z}|s,\lambda\rangle = e^{-i\psi\lambda}|s,\lambda\rangle \tag{1}$$

- The phase difference produce unphysical interference patterns

Polarised decay rate

- Polarised decay rate obtained summing helicity amplitudes over the initial Λ_c^+ generic density matrix $\rho_{\Lambda_c^+}$ and that of the unmeasured proton spin $\rho_p = \mathbb{I}/2$
- In matrix notation, with $T_{m_{\Lambda_c^+},\lambda_p} = \mathcal{A}_{m_{\Lambda_c^+},\lambda_p}(\Omega)$ is

$$p(A \to f) = \mathrm{tr}\left[\rho_A T \rho_f T^\dagger\right]$$

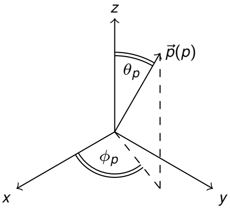
yielding

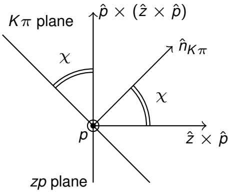
$$\begin{aligned} p(\Omega, \vec{P}) \propto \sum_{\lambda_p=\pm 1/2} \Big[& (1+P_z)|\mathcal{A}_{1/2,\lambda_p}(\Omega)|^2 + (1-P_z)|\mathcal{A}_{-1/2,\lambda_p}(\Omega)|^2 \\ & + (P_x - iP_y)\mathcal{A}^*_{1/2,\lambda_p}(\Omega)\mathcal{A}_{-1/2,\lambda_p}(\Omega) \\ & + (P_x + iP_y)\mathcal{A}_{1/2,\lambda_p}(\Omega)\mathcal{A}^*_{-1/2,\lambda_p}(\Omega)\Big]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

Baryon 3-body decay kinematics description

- Three-body decays described by 5 degrees of freedom: 12 four momenta components - 3 mass requirements - 4 energy-momentum conservation relations
- Decay confined to a decay plane: 2 two-body invariant mass Dalitz variables + 3 decay plane orientation angles → 5 phase-space variables
- For polarised baryons spherical symmetry is broken: decay plane orientation angles must be included in the amplitude analysis

- Euler rotation angles defined with respect to the baryon polarisation frame

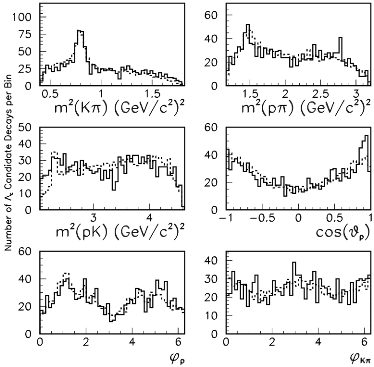


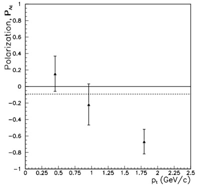


E791 amplitude analysis

Phys. Lett. B471 (2000) 449

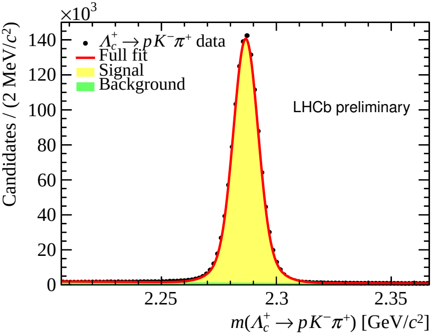
- E791 500 GeV π-Pt fixed-target experiment at FNAL
- 946 ± 38 $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays
- Trend of increasing negative polarisation with increasing p_T
- Problems (beyond statistics):
  - Amplitude model not correct (no proton spin rotation)
  - No separation between $\Lambda_c^+/\overline{\Lambda}_c^-$ events, may have different polarisation





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



Model building

- Resonance contributions expected from PDG
  - $\Lambda^* \to pK^-$: many states from 1.4 to 1.9 GeV, including the $\Lambda^*(1405)$ under-threshold
  - $K^* \to K^-\pi^+$: $K^*(892)$, and $K^*(1410)$, $K^*(1430)$ peaking outside the allowed phase
  - $\Delta^{*++} \to p\pi^+$: $\Delta^*(1232)$ plus some states in 1.6-1.7 GeV region
- Resonance lineshapes parametrised by default with relativistic Breit-Wigner lineshapes multiplied by angular barrier terms and corrected by Blatt-Weisskopf form factors
  - $\Lambda^*(1405)$ parametrised with a sub-threshold relativistic Breit-Wigner (featuring a different mass-dependent width to parametrise pK channel opening, arXiv:1711.09854)
  - Spin-zero K^* contribution included using LASS parametrisation, Nucl. Phys. B296 (1988) 493

Maximum likelihood fit

- Model parameters (ω, including polarisation, couplings, resonance parameters) are determined by maximum-likelihood fit, minimising

$$-\log \mathcal{L}(\omega) = -\sum_{i=1}^{N} \log p_{tot}(\Omega_i|\omega),$$

in which $p_{tot}(\Omega_i|\omega)$ represents the total fitting PDF,

$$p_{tot}(\Omega_i|\omega) = \frac{p(\Omega_i|\omega)\epsilon(\Omega_i)}{I(\omega)}\frac{n_{sig}}{N} + p_{bkg}(\Omega_i)\frac{n_{bkg}}{N},$$

Maximum likelihood fit

- If background contributions are negligible, the fitting PDF becomes

$$p_{tot}(\Omega|\omega) = \frac{p(\Omega|\omega)\epsilon(\Omega)}{Norm(\omega)}$$

- Efficiency-corrected normalisation computable using flat phase-space events simulated through full detector reconstruction

$$Norm(\omega) = \int p(\Omega|\omega)\epsilon(\Omega)d\Omega = \int p(\Omega|\omega)d\Omega' = \sum_{i=1}^{N_{MC}} p(\Omega_i|\omega)$$

- Efficiency term becomes an irrelevant constant term of the log-likelihood

$$-\log\mathcal{L}(\omega) = -\sum_{i=1}^{N}\left[\log p(\Omega_i|\omega)/Norm(\omega) + \log\epsilon(\Omega_i)\right]$$

Amplitude fit tools

- Fitting tools for baryon amplitude analyses developed in LHCb under the TensorFlowAnalysis (TFA) package
- TFA exploits the machine-learning framework TensorFlow flexibility for the definition of the amplitude model
- Tensorflow is based on the computer algebra paradigm: the user describes the computation, leaving the package to run it.
- It handles tensor data, optimises automatically the computational graph, and compiles for different architectures
- TFA is interfaced with the MINUIT minimisation package, which allows the computation of statistical uncertainties

Conclusions

- Heavy baryon EDM/MDM measurements now possible exploiting LHC high energy and bent crystal intense electric fields via spin precession
- Amplitude analyses allow best precision on polarisation measurements for heavy baryons decaying to multibody final states, like the Λ_c^+
- Amplitude model including generic baryon polarisation states can be written in the helicity formalism
- Large samples of $\Lambda_c^+ \to pK^-\pi^+$ decays recorded by LHCb
- Computational tools for maximum-likelihood fits developed
- Amplitude analysis of $\Lambda_c^+ \to pK^-\pi^+$ decays with large statistics at LHCb under way