IL NUOVO CIMENTO **45 C** (2022) 134
DOI 10.1393/ncc/i2022-22134-4

COMMUNICATIONS: SIF Congress 2021

Study of Λ baryon polarization in $\Xi_c^0 \to \Lambda K^- \pi^+$ decays

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received 1 February 2022

Summary. — This work reports on a study of the polarization of Λ baryons in $\Xi_c^0 \to \Lambda K^- \pi^+$ decays. The Λ baryon polarization is measured by fitting the angular distribution of its decay products in the entire phase space and in different regions of it. The analysis is based on the Run 2 dataset collected by LHCb detector, corresponding to an integrated luminosity of 3.7 fb^{-1} at 13 TeV center-of-mass energy. The analysis is performed on a signal yield of about 60000 events.

1. – Introduction

The polarization mechanism of baryons in weak decays has not been systematically studied yet. The measurement of the baryon polarization is a very useful information to infer about the polarization of the constituent quarks. In addition, it can be exploited to measure electromagnetic dipole moments of the baryon itself [1]. The method is based on the phenomenon of spin precession in an external electromagnetic field. For long-lived Λ baryons with $c\tau \approx 8\,\text{cm}$, the magnetic field of the LHCb detector can be used for this purpose. The precession angle is obtained by comparing the spin polarization vector of the particles before and after the magnetic field region. This letter focuses on the polarization measurement of Λ baryons before the LHCb magnet. The decay considered is $\Xi_c^0 \to \Lambda K^- \pi^+$ (charge conjugation is implied throughout the document unless otherwise stated) due to the high signal yield expected among decays with similar topology. The branching ratio of this decay equals $1.45 \pm 0.33\%$.

2. – Selection of $\Xi_c^0 \to \Lambda K^- \pi^+$ decays

The data used in this analysis are collected with the LHCb detector from *pp* collisions during Run 2 (2015, 2016 and 2017) and correspond to an integrated luminosity of $3.7\,\text{fb}^{-1}$ at $13\,\text{TeV}$ center-of-mass (CM) energy. Since the CM energy of the *pp* collisions has not changed through the years, simulated events with 2017 beam conditions have been generated as representative for the full Run2 conditions. Events are selected by applying an online hardware trigger based on information from the calorimeter, followed by a software stage requiring tracks to have a transverse momentum $p_T > 500\,\text{MeV/c}$. Λ baryons are reconstructed combining two charged tracks compatible with a proton and a pion, which form a good-quality secondary vertex. The reconstructed Ξ_c^0 candidates are formed by combining a reconstructed Λ baryon and final state proton and kaon in a displaced vertex, with good quality tracks.

A binned Boosted Decision Tree classifier (BDT) is used to select signal and suppress background [2]. Candidates with an invariant mass in the range [2495, 2540] MeV/c^2 are selected as representative of the background. In this region, the combinatorial background is dominant. As signal proxy, Monte Carlo (MC) simulated events are used, in which the selected Ξ_c^0 candidates are required to be in the $\mathrm{m}(\Lambda K^- \pi^+)$ invariant mass range of [2445,2495] MeV/c^2. Finally, the optimized BDT is applied to data. To further suppress background, we apply particle identification (PID) selection criteria. The figure of merit chosen to optimize the BDT and PID cuts is the significance ($S/\sqrt{S+B}$). The fit to the invariant mass $\mathrm{m}(\Lambda K^- \pi^+)$ is performed after the full selection is applied to data. The signal is modelled by a Gaussian p.d.f., while the background is described by an exponential p.d.f. in order to extract the yields. From the fit to the $\mathrm{m}(\Lambda K^- \pi^+)$ distribution we obtain 64456 ± 579 signal candidates with a purity of 32%, which reaches 50% within 2σ from the central mass value. σ is obtained from the fit of the Gaussian p.d.f. and its value is $12\,\text{MeV/c}^2$.

3. – Λ baryon polarization measurement

The polarization measurement is based on the angular distribution of the decay products. In particular, the decay considered is $\Lambda \to p\pi^-$ and its charge conjugate. Since Λ and p have spin 1/2 and π has spin 0, the angular distribution of the decay, obtained through the helicity formalism [3] is the following

$$\frac{\mathrm{d}N}{\mathrm{d}\Omega} \propto 1 + \alpha \vec{P} \cdot \hat{k}, \tag{1}$$

with the decay asymmetry parameter $\alpha = 0.732 \pm 0.014$, obtained from an independent experiment [4]. Here $\vec{P}$ is the polarization vector that we want to measure. The momentum direction of the proton in the Λ rest frame is expressed by the unit vector $\hat{k} = (\sin\theta_p \cos\phi_p, \sin\theta_p \sin\phi_p, \cos\theta_p)$, while the solid angle Ω equals $(\cos\theta_p, \phi_p)$, with θ_p and ϕ_p the polar and azimuthal angle respectively.

The model fitted to data, used to extract the Λ polarization $\vec{P}$ is defined as,

$$\frac{p(\cos\theta_p, \phi_p, \vec{P})\epsilon(\cos\theta_p, \phi_p)}{I(\vec{P})} \frac{S}{N_{tot}} + p_{bkg}(\cos\theta_p, \phi_p) \frac{B}{N_{tot}}, \tag{2}$$

where $\epsilon(\cos\theta_p, \phi_p)$ is the efficiency computed on MC sample and parametrized with Legendre polynomials. The Λ decay angular distribution $p(\cos\theta_p, \phi_p, \vec{P})$ is defined in eq. (1). The number of signal (S), background (B) and total (N_{tot}) events are those obtained from the invariant mass fit described in the previous section. $\mathrm{I}(\vec{P})$ is the normalization factor, and $p_{bkg}(\cos\theta_p, \phi_p)$ is the p.d.f. which describes the helicity angles distribution of the background. It is estimated with the upper sideband of the $\mathrm{m}(\Lambda K^- \pi^+)$ distribution in the range [2496, 2540] MeV/c^2. Finally, an extended maximum likelihood fit is performed to data. We obtain the Λ polarization measurement in its rest frame, where $\hat{z} = \hat{p}_{\Lambda}^{\Xi_c^0}$, $\hat{y} = \hat{p}_{beam}^{LAB} \times \hat{p}_{\Xi_c^0}^{LAB} \times \hat{p}_{\Lambda}^{\Xi_c^0}$ and $\hat{x} = \hat{y} \times \hat{z}$, where the superscript specifies the rest frame. The Λ polarization in the full phase space is measured to be

$$P_x = (0.14 \pm 0.01 \pm 0.01), \quad P_y = (0.023 \pm 0.013 \pm 0.005), \quad P_z = (0.042 \pm 0.014 \pm 0.004),$$

with $|\vec{P}| = 0.15 \pm 0.02 \pm 0.01$. The reported uncertainties are statistical and systematic, respectively. The dominant systematic uncertainty is due to the efficiency parametrization. It is estimated with pseudoexperiments generated with the nominal model and fitted changing the order of the Legendre polynomials which describe the efficiency. This result is obtained considering both Λ and $\bar{\Lambda}$ candidates, after checking that their polarization is compatible. The Dalitz plot of the decay is reported in fig. 1. Since the Λ baryons are produced in a weak decay, we naively expected a large parity violation, and hence a larger polarization than that observed. Possibly, two effects can cause a dilution of the Λ polarization when measured in the full phase space. The first cause is related to the production of Λ baryons via resonant states $(\Xi^*(1690)^-, \Xi^*(1820)^-, \Sigma^*(1385)^+)$ decays. These strong decays can introduce a polarization suppression, since the polarization of the mother hyperon is not completely transferred to the Λ baryon daughter [5]. The second reason is due to the presence of three different decay chains, *i.e.*, $\Xi^{*-}(\Lambda K^-)\pi^+, \Sigma^{*+}(\Lambda\pi^+)K^-$, and $K^{*0}(K^-\pi^+)\Lambda$, with different polarizations. The net effect is a dilution of the Λ polarization for all the events in the phase space originated from different decay chains.

To test our hypothesis, we select different regions of the phase space where one resonant contribution is dominant. Considering Λ baryons produced mostly in $\Xi_c^0 \to \Lambda K^*$ (table I), we observe that the parity violation in the dominant weak decays allows higher polarization along the Λ momentum direction (P_z). To test the dilution introduced by different decays interference, we select the previous region with non negligible contribution of the other resonances. The polarization measured is

$$P_x = 0.19 \pm 0.04 \pm 0.01 \quad P_y = (-2.7 \pm 3.2 \pm 4.5) \cdot 10^{-2} \quad P_z = 0.14 \pm 0.03 \pm 0.01.$$

Compared to the previous result, we allowed more resonances to contribute and a lower P_z is measured. This supports the hypothesis that considering different decay

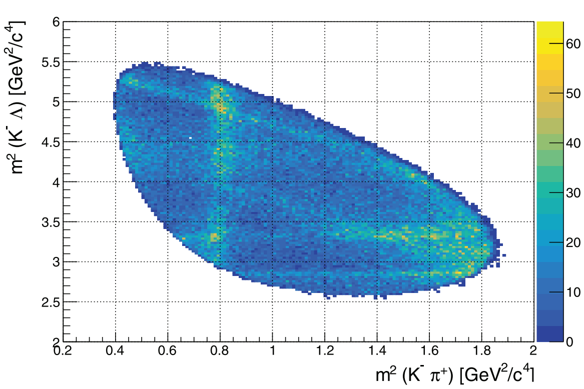

Fig. 1. – Dalitz plot. The resonances identified in the $m^2(K^-\pi^+)$, $m^2(K^-\Lambda^+)$ and $m^2(\Lambda\pi^+)$ spectra are $K^*(892)^0$, $\Xi^*(1690)^-$ and $\Xi^*(1820)^-$, and $\Sigma^*(1385)^+$, respectively.

TABLE I. – Λ *polarization measurement in regions of the phase space with different dominant decay chains.*

Dominant decay	P_x	P_y	P_z
$\Xi_c^0 \to \Lambda K^*(892)^0$	$0.28 \pm 0.08 \pm 0.01$	$0.04 \pm 0.07 \pm 0.05$	$0.34 \pm 0.08 \pm 0.01$
$\Xi_c^0 \to \Xi^*(1690)^- \pi^+$	$0.06 \pm 0.06 \pm 0.01$	$-0.03 \pm 0.05 \pm 0.05$	$-0.20 \pm 0.05 \pm 0.01$
$\Xi_c^0 \to \Xi^*(1820)^- \pi^+$	$0.17 \pm 0.03 \pm 0.01$	$-0.01 \pm 0.03 \pm 0.05$	$0.001 \pm 0.03 \pm 0.$
$\Xi_c^0 \to \Sigma^*(1385)^+ K^-$	$0.23 \pm 0.05 \pm 0.01$	$0.07 \pm 0.04 \pm 0.05$	$0.10 \pm 0.05 \pm 0.01$

chains together leads to a dilution in the polarization. Finally, we select Λ baryons mostly produced by strong decays of $\Xi^*(1690)^-$, $\Xi^*(1820)^-$ or $\Sigma^*(1385)^+$. In these regions, we observe a lower polarization with respect to that of Λ baryons directly produced by Ξ_c^0 decays without an intermediate strong resonance (table I).

4. – Conclusion

Measurements of the Λ baryon polarization have been performed, in the whole phase space of the 3-body $\Xi_c^0 \to \Lambda K^- \pi^+$ decay and also selecting regions dominated by resonances, as for example the $K^*(892)^0$, the $\Xi^*(1690)^-$, $\Xi^*(1820)^-$ and $\Sigma^*(1385)^+$ regions. To perform this measurement, a selection of the $\Xi_c^0 \to \Lambda K^- \pi^+$ events has been optimized. After a multivariate and a particle identification optimization, we are left with a sample with about 50% purity. This study helps in understanding the Λ polarization production in 3-body decays, with many resonant states. Λ baryons from $\Xi_c^0 \to \Lambda K^- \pi^+$ decays are produced in different decay chains and also via strong decays of intermediate resonances, which seems to explain the relatively small polarization of the Λ baryons compared to two-body weak decays. If high polarization is required, such as in the case of electromagnetic dipole moments measurements, it is needed to consider quasi-two-body decays.

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The author would like to thank F. Martinez Vidal, A. Merli, N. Neri and J. Ruiz Vidal.

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