

Polarization Measurement of Λ_c^+ and $\bar{\Lambda}_c^-$ Baryons in $p - \text{Ne}$ Collisions at $\sqrt{s_{\text{NN}}} = 68.6 \text{ GeV}$

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The first measurement of the polarization of charm baryons by the LHCb experiment recorded in fixed-target mode is presented. The polarization of Λ_c baryons is studied in collisions of protons, at an energy of 2.51 TeV, incident on a gaseous target of neon, at a nucleon-nucleon center-of-mass energy of 68.6 GeV. The world's first measurement of separate-charge polarizations for Λ_c^+ and $\bar{\Lambda}_c^-$ baryons is performed, determining $P_{\Lambda_c^+} = (24 \pm 9 \pm 2)\%$, $P_{\bar{\Lambda}_c^-} = (-8 \pm 12 \pm 3)\%$, where the first uncertainty is statistical and the second systematic. The polarization is also measured in intervals of baryon transverse momentum and the Feynman- x variable.

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Charm-baryon polarization is a unique probe in high-energy physics, giving preferential access to heavy-quark spin-dependent physics in its production and subsequent hadronization. The heavy quark drives baryon properties, including polarization, since its mass is much larger than the typical energy scale of strong nuclear interactions [1–3]. This is in contrast with lighter baryons, whose polarization is not directly related to the spins of their constituents [4–6]. Strong interaction polarization arises mainly from spin-orbit correlations and final-state interactions of quarks, leading to different baryon and antibaryon polarization mechanisms due to the distinct role of valence and sea quarks. Polarization measurements provide tests for QCD dynamics in the nonperturbative regime, helping to distinguish among various models [7–27].

Experimentally, charm-baryon polarization arising from strong interactions remains a poorly explored topic. The averaged Λ_c^+ and $\bar{\Lambda}_c^-$ polarization has only been measured in π -nucleus fixed-target collisions by the NA32 [28] and E791 [29] experiments, for beam energies of 230 and 500 GeV, respectively. Both indicated a trend of increasing negative polarization with larger transverse momentum, p_T , though with large uncertainties. A similar p_T trend was also observed for strange Λ baryons in fixed-target experiments [30–36]. In addition, a trend of increasing polarization with $|x_F|$ has been observed for Λ baryons [32,34,35,37,38], where $x_F \equiv (2p_L/\sqrt{s_{\text{NN}}})$ is the Feynman- x variable, p_L is the baryon momentum component parallel to the beam axis in the center-of-mass frame, and $\sqrt{s_{\text{NN}}}$ the nucleon-nucleon

center-of-mass energy. However, no charm-baryon polarization measurement as a function of x_F has been performed to date. The E791 results have been used to develop a QCD-based hybrid model of inclusively produced charm baryons reproducing the p_T dependence [39]. No further theoretical studies of charm-baryon polarization have been done since then.

In this Letter, the first measurement of the polarization of charm baryons by the LHCb experiment in its fixed-target mode is presented. The polarization of Λ_c baryons is studied in collisions of protons, with an energy of 2.51 TeV, incident on a gaseous target of neon, taken in 2017. This corresponds to an energy $\sqrt{s_{\text{NN}}} = 68.6 \text{ GeV}$, an energy regime not previously tested for polarization studies. The dataset corresponds to an integrated luminosity of 21.7 nb^{-1} . This Letter contributes to the largely unexplored field of charm-baryon polarization measurements, providing new inputs to test low-energy QCD models for heavy-baryon spin physics and the kinematic dependencies observed in hyperon polarization. In addition, it improves different aspects of the previous polarization measurements, as described in the following.

The polarization is measured for the first time separately for the Λ_c^+ and $\bar{\Lambda}_c^-$ hadrons to probe their different production mechanisms. Their decays are reconstructed in the $\Lambda_c^+ \rightarrow pK^-\pi^+$ final state, with charge-conjugate states implied unless specified. The polarization is extracted using a detailed amplitude model [40]. The model is based on the helicity formalism, and, in contrast to what has been done previously, it ensures that the spin states of the final particles have the same exact definition for all the intermediate resonant contributions [41], permitting a correct description of interference effects. The amplitude model permits to combine the different sensitivities given by the many resonant contributions in the whole $\Lambda_c^+ \rightarrow pK^-\pi^+$ phase space to achieve the best precision on the polarization measurement. Indeed, the

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$\Lambda_c^+ \rightarrow pK^-\pi^+$ decay is the main Λ_c^+ decay channel and it has a large sensitivity to polarization, $\sqrt{3}S \approx 0.662$ [42], where $\sqrt{3}S$ is a quantity equivalent to two-body decay asymmetry parameters, linked to the amount of parity violation in the decay. The present Letter is based on a novel technique for a polarization measurement, where the amplitude model is determined from a different signal sample with larger statistics. The model description and parameters have been previously determined using a sample of 4×10^5 $\Lambda_c^+ \rightarrow pK^-\pi^+$ candidates recorded in semileptonic b -hadron decays from pp collisions by the LHCb experiment [42]. The E791 analysis [29] has previously explored a helicity-formalism-based technique, but the model did not consider the issue of the matching of final particle spin states, and was developed on a far smaller dataset. In addition, this Letter measures the polarization as a function of p_T and x_F in order to probe kinematic polarization dependencies, testing the trends suggested by previous charm and Λ measurements [30–38]. A significant Λ_c^+ polarization in fixed-target collisions at LHC beam energies would enable the measurement of charm-baryon electric- and magnetic-dipole moments via spin precession [43–51].

The LHCb detector is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$, described in detail in Refs. [52,53]. The detector used to collect the data analyzed in this Letter includes a silicon-strip vertex locator (VELO), three tracking stations of silicon-strip detectors and straw drift tubes, two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons, a calorimeter system consisting of scintillating-pad and preshower detectors, electromagnetic and hadronic calorimeters, and a muon detector composed of alternating layers of iron and multiwire proportional chambers. The System for Measuring the Overlap with Gas (SMOG) [54] enables the injection of gases with a pressure of $\mathcal{O}(10^{-7})$ mbar in the beam pipe section inside the VELO, allowing LHCb to effectively operate as a fixed-target experiment. The SMOG system thus provides a unique opportunity to study proton-nucleus and nucleus-nucleus collisions with various gaseous targets using the LHC beams. In this configuration, the LHCb acceptance extends to the negative center-of-mass rapidity hemisphere $-2.5 < y^* < 0$, due to the boost induced by the high-energy proton beam.

Fixed-target p Ne collision events were only recorded when a bunch in the beam pointing toward the LHCb detector crossed the interaction region without a corresponding bunch in the beam pointing in the opposite direction. In order to suppress background pp collision events, the z coordinate of the p Ne primary vertex (PV) is required to lie outside the region $z_{PV} \in [-100, 100]$ mm, where $z_{PV} = 0$ mm is at the center of the pp interaction region, and the standard deviation of the distribution is about 50 mm. Events lying inside the region are retained

only if no hits are detected in the VELO stations upstream of the interaction region.

Efficiencies are estimated using samples of simulated $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays from p Ne collisions. Unpolarized $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays are uniformly generated over the phase space using PYTHIA [55] with a specific LHCb configuration [56] and with colliding-proton beam momentum equal to the momentum per nucleon of the beam and target in the center-of-mass frame. The decays of unstable particles are described by EVTGen [57], in which final-state radiation is generated using Photos [58]. The four-momenta of signal decay particles are extracted and embedded into p Ne events generated with the EPOS event generator [59], which models the underlying inelastic collision. The interaction of the generated particles with the detector and its response are implemented using the Geant4 toolkit [60,61] as described in Ref. [62]. Simulated distributions are validated on data, correcting observed differences using the gradient-boosted decision tree weighting technique from the HEP-ML package [63].

The $\Lambda_c^+ \rightarrow pK^-\pi^+$ decays are reconstructed from combinations of three charged tracks forming a vertex separated from the PV. Only events with a single reconstructed PV are retained for further analysis. Charged tracks are required to be identified as hadrons by loose particle-identification criteria, and must have $p_T > 200$ MeV, momentum $p > 3$ GeV, and be significantly displaced from the PV. Natural units with $\hbar = c = 1$ are used throughout. All reconstructed tracks and vertices are required to have good quality fits. Further selection criteria are imposed to reduce the combinatorial background arising from random combinations of tracks. These require each track to be within the LHCb detector pseudorapidity acceptance, $2 < \eta < 5$, and to pass particle-identification criteria obtained from neural network classifiers, which combine information from the different subdetectors [64]. Reconstructed Λ_c^+ candidates are required to have a decay vertex displaced in the direction of the momentum, a small impact parameter with respect to the PV and a maximum value of the angle between the momentum vector and the flight direction of 0.25 rad. No evidence of misidentified, wrongly reconstructed heavy-hadron decays or candidates originating from beauty-hadron decays is found.

A boosted decision tree (BDT) classifier [65] is used to further reduce the combinatorial background. The classifier is trained on the $\Lambda_c^+ \rightarrow pK^-\pi^+$ simulation sample as a proxy for the signal, and on data candidates in invariant-mass sidebands as a proxy for the background, with sidebands defined as $40 < |m(pK^-\pi^+) - m(\Lambda_c^+)| < 100$ MeV, and $m(\Lambda_c^+)$ the known Λ_c^+ mass [66]. The k -folding technique is applied [67] to limit the possible bias due to the limited signal proxy yield. The BDT exploits quantities related to the decay topology and particle identification, as well as p_T and momentum of the Λ_c^+ candidates. A selection requirement on the BDT classifier

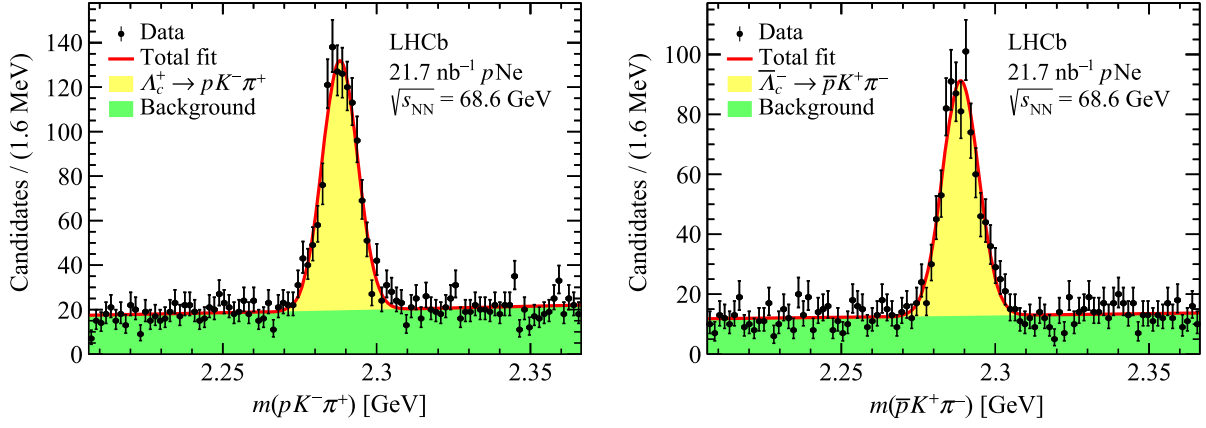


FIG. 1. Distributions of the $pK^-\pi^+$ invariant mass of selected (left) Λ_c^+ and (right) $\bar{\Lambda}_c^-$ candidates. The results from the fit described in the text are also shown.

output is chosen by optimizing the figure of merit $N^2/(N+B)^{3/2}$, where N and B are the fitted signal and background yields in the signal region, defined as that for which $m(pK^-\pi^+)$ is within ± 15 MeV of the known Λ_c^+ mass [66].

The distributions of the invariant mass, $m(pK^-\pi^+)$, of selected Λ_c^+ and $\bar{\Lambda}_c^-$ candidates are shown in Fig. 1. Extended unbinned maximum-likelihood fits are performed to determine the signal and background yields after the selection. The signal shape is modeled with a Gaussian probability density function, while an exponential model is used to describe the combinatorial background. Candidates within the signal region are retained for the polarization measurement. The Λ_c^+ and $\bar{\Lambda}_c^-$ signal yields are respectively determined to be 997 ± 39 and 710 ± 32 , with background fractions of $(27.0 \pm 1.1)\%$ and $(25.1 \pm 1.2)\%$, where the uncertainties are statistical only. The measured signal yields are consistent with a substantial particle-antiparticle production asymmetry, which is expected in proton-induced fixed-target collisions at these center-of-mass energies.

The baryon polarization is measured with respect to the production plane formed by the beam direction, taken as the z axis of the polarization system, and the baryon momentum, whose vector product defines the transverse polarization component, constituting the y axis. This is the only component measured in this Letter, as the others are forbidden by parity conservation in strong interactions. The five variables describing the $\Lambda_c^+ \rightarrow pK^-\pi^+$ decay phase space are chosen to be the squared invariant masses m_{pK}^2 and $m_{K^-\pi^+}^2$, and quantities that describe the decay orientation with respect to the polarization system $\cos\theta_p$, ϕ_p and χ . The angles θ_p and ϕ_p are the polar and azimuthal angles of the proton momentum, while χ is the angle between the plane formed by the proton momentum and the beam direction, and the plane formed by the kaon and pion momenta, where the momenta are expressed in the Λ_c^+ rest frame. The Λ_c^+ and $\bar{\Lambda}_c^-$ transverse polarizations are

measured by independent maximum-likelihood fits to phase-space distributions fixing the amplitude model to that previously determined by the LHCb Collaboration [42], with the other polarization components fixed to zero. Nonuniformity of the detector acceptance across the $\Lambda_c^+ \rightarrow pK^-\pi^+$ phase space is incorporated using simulation following the method outlined in Ref. [42], while the background contribution is accounted for using factorized Legendre-polynomial expansions, derived from the mass sidebands in data. The fit implementation is based on a version of the `TensorFlowAnalysis` package [68] adapted to three-body amplitudes in five-dimensional phase-space fits [46].

Statistical uncertainties are determined using a non-parametric bootstrapping technique from the standard deviation of 1000 pseudoexperiments generated from the data fit result. The systematic uncertainty associated to the $\Lambda_c^+ \rightarrow pK^-\pi^+$ amplitude model uncertainty is estimated using the alternative models described in Ref. [42], representing a variety of descriptions for the resonant and spin structure of the decay. The systematic uncertainty associated to the background description includes the contribution arising from the background fraction, varied according to its uncertainty, and from its parametrization, which is estimated by considering alternatives derived from bootstrapped data samples extracted from the mass sidebands. The uncertainty associated to the description of detector efficiency effects is estimated by varying the calibration samples via bootstrapping and changing the parameters of

TABLE I. Systematic uncertainty contributions to the Λ_c^+ and $\bar{\Lambda}_c^-$ polarization measurements.

	Total	Model	Background	Efficiency
$P_{\Lambda_c^+}$	0.022	0.016	0.009	0.014
$P_{\bar{\Lambda}_c^-}$	0.031	0.016	0.018	0.020

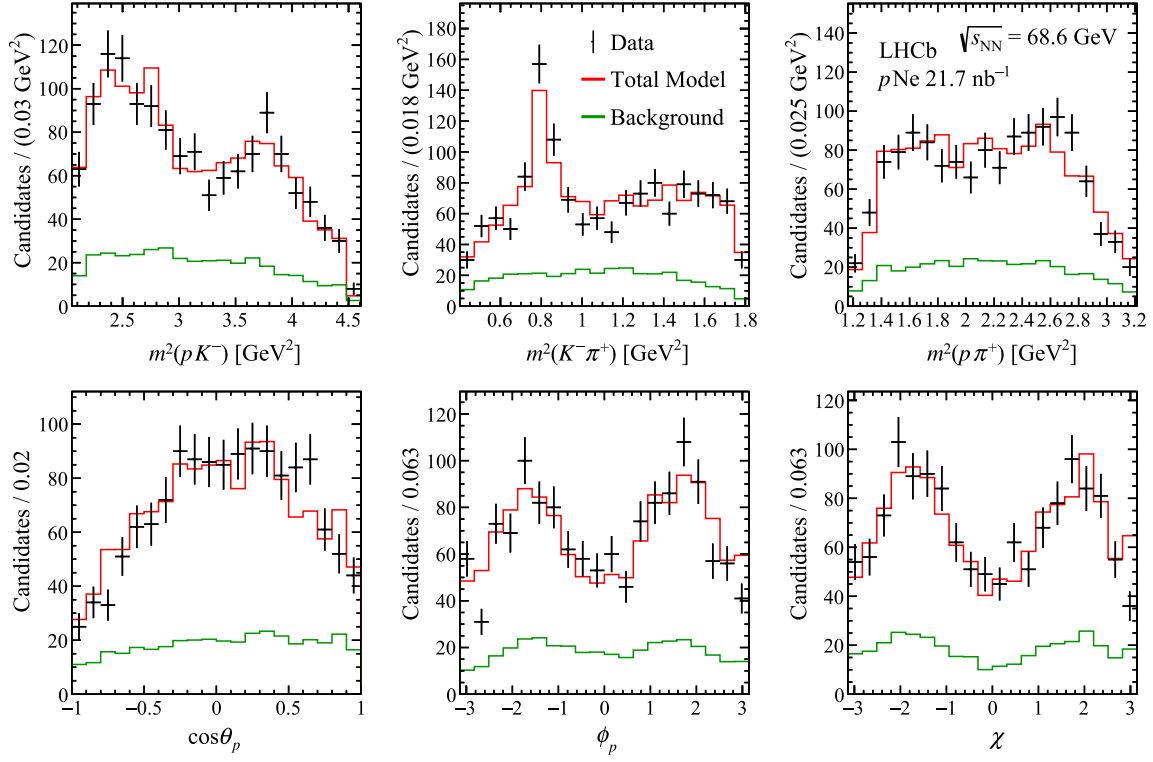
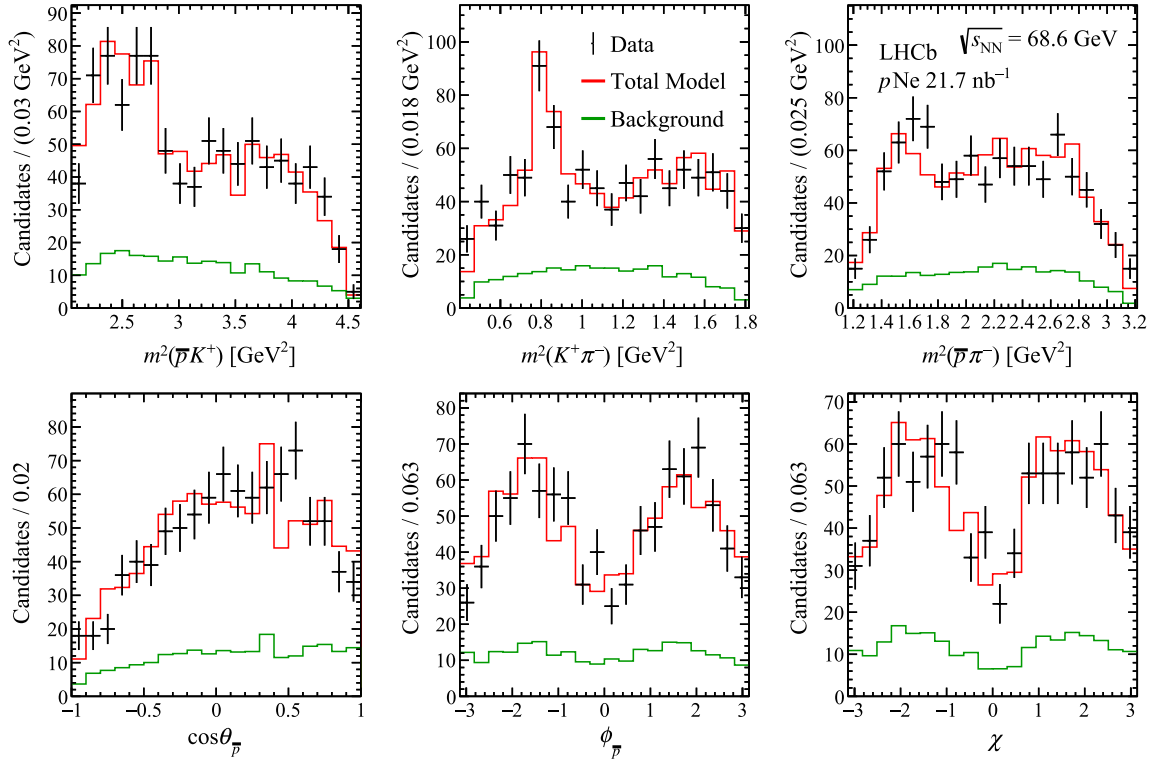

 FIG. 2. Comparisons of the phase-space projections between the data and the fitted model for the Λ_c^+ dataset.

 FIG. 3. Comparisons of the phase-space projections between the data and the fitted model for the $\bar{\Lambda}_c^-$ dataset.

TABLE II. Results of the differential polarization measurements.

	$P_{\Lambda_c^+} \pm (\text{stat}) \pm (\text{syst}) [\%]$	$P_{\bar{\Lambda}_c^-} \pm (\text{stat}) \pm (\text{syst}) [\%]$
$p_T < 2.8 \text{ GeV}$	$17 \pm 17 \pm 4$	$-2 \pm 20 \pm 4$
$2.8 \leq p_T < 4 \text{ GeV}$	$18 \pm 14 \pm 4$	$-6 \pm 17 \pm 5$
$p_T \geq 4 \text{ GeV}$	$45 \pm 17 \pm 4$	$-27 \pm 22 \pm 14$
$x_F < -0.15$	$41 \pm 17 \pm 5$	$-15 \pm 21 \pm 6$
$-0.15 \leq x_F < -0.06$	$9 \pm 14 \pm 3$	$-13 \pm 18 \pm 3$
$x_F \geq -0.06$	$42 \pm 18 \pm 6$	$2 \pm 20 \pm 8$

the decision tree employed. A negligible fit bias is observed. Systematic uncertainties for each contribution are reported in Table I. The stability of the measurement is tested by performing a fit in which all components of the polarization vector are allowed to vary independently for both the Λ_c^+ and $\bar{\Lambda}_c^-$ datasets. The polarization components within the production plane are found to be compatible with zero as required by parity symmetry, while no significant shift is seen for the transverse polarization component.

Phase-space distribution comparisons between the data and the fitted model are shown in Figs. 2 and 3 for the Λ_c^+ and $\bar{\Lambda}_c^-$ datasets, respectively. The polarizations for the Λ_c^+ and $\bar{\Lambda}_c^-$ datasets are determined to be

$$P_{\Lambda_c^+} = [24.4 \pm 9.5(\text{stat}) \pm 2.2(\text{syst})]\%,$$

$$P_{\bar{\Lambda}_c^-} = [-8 \pm 12(\text{stat}) \pm 3(\text{syst})]\%.$$

An indication of a sizable Λ_c^+ polarization is present, having a statistical significance of 2.4σ , evaluated using pseudoexperiments. Compared with previous charm and Λ measurements, an opposite polarization is seen due to the negative x_F coverage of the LHCb SMOG data, and given $P(-x_F) = -P(x_F)$. The $\bar{\Lambda}_c^-$ polarization is compatible with zero within the uncertainty.

The differential polarization measurement is performed by splitting both datasets into three intervals of p_T and x_F , chosen in order to have a comparable number of candidates in each interval. Numerical polarization results are reported in Table II, and shown in the End Matter, which also provides background-subtracted p_T and x_F distributions. The larger Λ_c^+ polarization value in the highest p_T bin suggests a possible trend of increasing polarization with p_T , as seen in previous charm [28,29] and Λ measurements [30–38], although the statistical significance is inconclusive. No clear kinematic dependencies are visible for $\bar{\Lambda}_c^-$ polarization.

In summary, the first measurement of the polarization of charm baryons by the LHCb experiment in its fixed-target mode is reported. It provides the first separate Λ_c^+ and $\bar{\Lambda}_c^-$ polarization measurements, with the first investigation of charm-baryon x_F polarization dependence, using a novel helicity-formalism-based amplitude model technique. The Λ_c^+

and $\bar{\Lambda}_c^-$ polarizations are $P_{\Lambda_c^+} = [24 \pm 9(\text{stat}) \pm 2(\text{syst})]\%$ and $P_{\bar{\Lambda}_c^-} = [-8 \pm 12(\text{stat}) \pm 3(\text{syst})]\%$. The differential measurement hints at possible trends of increasing Λ_c^+ polarization with p_T as in previous measurements. These results are a first step toward the understanding of charm-baryon polarization mechanisms, contributing to the almost empty field of heavy-baryon polarization measurements, and paving the way for precise investigations with larger datasets.

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Data availability—The data that support the findings of this article are openly available [69].

- [1] T. Mannel and G. A. Schuler, Semileptonic decays of bottom baryons at LEP, *Phys. Lett. B* **279**, 194 (1992).
- [2] A. F. Falk and M. E. Peskin, Production, decay, and polarization of excited heavy hadrons, *Phys. Rev. D* **49**, 3320 (1994).
- [3] M. Galanti, A. Giammanco, Y. Grossman, Y. Kats, E. Stamou, and J. Zupan, Heavy baryons as polarimeters at colliders, *J. High Energy Phys.* **11** (2015) 067.
- [4] J. Ashman *et al.* (European Muon Collaboration), A measurement of the spin asymmetry and determination of the structure function g_1 in deep inelastic muon-proton scattering, *Phys. Lett. B* **206**, 364 (1988).
- [5] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Global analysis of helicity parton densities and their uncertainties, *Phys. Rev. Lett.* **101**, 072001 (2008).
- [6] C. Adolph *et al.* (COMPASS Collaboration), The spin structure function g_1^p of the proton and a test of the Bjorken sum rule, *Phys. Lett. B* **753**, 18 (2016).
- [7] B. Andersson, G. Gustafson, and G. Ingelman, A semi-classical model for the polarization of inclusively produced Λ^0 -particles at high energies, *Phys. Lett.* **85B**, 417 (1979).
- [8] J. Szwed, Hyperon polarization at high energies, *Phys. Lett.* **105B**, 403 (1981).
- [9] T. A. DeGrand and H. I. Miettinen, Models for polarization asymmetry in inclusive hadron production, *Phys. Rev. D* **24**, 2419 (1981); **31**, 661(E) (1985).
- [10] W. G. D. Dharmaratna and G. R. Goldstein, Gluon fusion as a source for massive-quark polarization, *Phys. Rev. D* **41**, 1731 (1990).
- [11] R. Barni, G. Preparata, and P. G. Ratcliffe, A simple explanation of hyperon polarization at high p_T , *Phys. Lett. B* **296**, 251 (1992).
- [12] J. Soffer and N. A. Törnqvist, Origin of the polarization for inclusive Λ production in pp collisions, *Phys. Rev. Lett.* **68**, 907 (1992).
- [13] Y. Hama and T. Kodama, Hyperon polarization in a hydrodynamical model, *Phys. Rev. D* **48**, 3116 (1993).
- [14] W. G. D. Dharmaratna and G. R. Goldstein, Single quark polarization in quantum chromodynamics subprocesses, *Phys. Rev. D* **53**, 1073 (1996).
- [15] S. M. Troshin and N. E. Tyurin, Hyperon polarization in the constituent quark model, *Phys. Rev. D* **55**, 1265 (1997).
- [16] L. Zuo-tang and C. Boros, Hyperon polarization and single spin left-right asymmetry in inclusive production processes at high energies, *Phys. Rev. Lett.* **79**, 3608 (1997).
- [17] J. Félix, On theoretical studies of Λ^0 polarization, *Mod. Phys. Lett. A* **14**, 827 (1999).
- [18] M. Anselmino, D. Boer, U. D'Alesio, and F. Murgia, Λ polarization from unpolarized quark fragmentation, *Phys. Rev. D* **63**, 054029 (2001).
- [19] Y. Kanazawa and Y. Koike, Polarization in hadronic Λ hyperon production and chiral-odd twist-3 distribution, *Phys. Rev. D* **64**, 034019 (2001).
- [20] M. Anselmino, D. Boer, U. D'Alesio, and F. Murgia, Transverse Λ polarization in semi-inclusive DIS, *Phys. Rev. D* **65**, 114014 (2002).
- [21] D. Boer, C. J. Bomhof, D. S. Hwang, and P. J. Mulders, Spin asymmetries in jet-hyperon production at LHC, *Phys. Lett. B* **659**, 127 (2008).
- [22] J. Zhou, F. Yuan, and Z.-T. Liang, Hyperon polarization in unpolarized scattering processes, *Phys. Rev. D* **78**, 114008 (2008).
- [23] K. Kanazawa, A. Metz, D. Pitonyak, and M. Schlegel, Single-spin asymmetries in the leptonproduction of transversely polarized Λ hyperons, *Phys. Lett. B* **744**, 385 (2015).
- [24] Y. Koike, K. Yabe, and S. Yoshida, Hyperon polarization from the twist-3 distribution in unpolarized proton-proton collision, *Phys. Rev. D* **92**, 094011 (2015).
- [25] Y. Koike, A. Metz, D. Pitonyak, K. Yabe, and S. Yoshida, Twist-3 fragmentation contribution to polarized hyperon production in unpolarized hadronic collisions, *Phys. Rev. D* **95**, 114013 (2017).
- [26] L. Gamberg, Z.-B. Kang, D. Pitonyak, M. Schlegel, and S. Yoshida, Polarized hyperon production in single-inclusive electron-positron annihilation at next-to-leading order, *J. High Energy Phys.* **01** (2019) 111.
- [27] U. D'Alesio, F. Murgia, and M. Zacccheddu, First extraction of the Λ polarizing fragmentation function from Belle e^+e^- data, *Phys. Rev. D* **102**, 054001 (2020).
- [28] M. Jeżabek, K. Rybicki, and R. Rylko, Experimental study of spin effects in hadroproduction and decay of Λ_c^+ , *Phys. Lett. B* **286**, 175 (1992).
- [29] E. M. Aitala *et al.* (E791 Collaboration), Multidimensional resonance analysis of $\Lambda_c^+ \rightarrow pK^-\pi^+$, *Phys. Lett. B* **471**, 449 (2000).
- [30] G. Bunce *et al.*, Λ^0 hyperon polarization in inclusive production by 300-GeV protons on beryllium, *Phys. Rev. Lett.* **36**, 1113 (1976).
- [31] K. Heller *et al.*, Polarization of Λ 's and $\bar{\Lambda}$'s produced by 400-GeV protons, *Phys. Rev. Lett.* **41**, 607 (1978); **45**, 1043(E) (1980).
- [32] B. Lundberg *et al.*, Polarization in inclusive Λ and $\bar{\Lambda}$ production at large p_T , *Phys. Rev. D* **40**, 3557 (1989).
- [33] B. S. Yuldashev *et al.*, Neutral-strange-particle production in $p^{20}\text{Ne}$ and $p\text{N}$ interactions at 300 GeV, *Phys. Rev. D* **43**, 2792 (1991).
- [34] E. J. Ramberg *et al.*, Polarization of Λ and $\bar{\Lambda}$ produced by 800-GeV protons, *Phys. Lett. B* **338**, 403 (1994).
- [35] V. Fanti *et al.*, A measurement of the transverse polarization of Λ -hyperons produced in inelastic $p\text{N}$ -reactions at 450 GeV proton energy, *Eur. Phys. J. C* **6**, 265 (1999).
- [36] G. Agakishiev *et al.* (HADES Collaboration), Lambda hyperon production and polarization in collisions of $p(3.5\text{ GeV}) + \text{Nb}$, *Eur. Phys. J. A* **50**, 81 (2014).
- [37] I. Abt *et al.* (HERA-B Collaboration), Polarization of Λ and $\bar{\Lambda}$ in 920 GeV fixed-target proton-nucleus collisions, *Phys. Lett. B* **638**, 415 (2006).
- [38] R. Aaij *et al.* (LHCb Collaboration), Transverse polarisation measurement of Λ hyperons in $p\text{Ne}$ collisions at $\sqrt{s_{NN}} = 68.4\text{ GeV}$ with the LHCb detector, *J. High Energy Phys.* **09** (2024) 082.
- [39] G. R. Goldstein, Polarization of inclusively produced Λ_c^+ in a QCD based hybrid model, [arXiv:hep-ph/9907573](https://arxiv.org/abs/hep-ph/9907573).
- [40] D. Marangotto, Extracting maximum information from polarised baryon decays via amplitude analysis: The $\Lambda_c^+ \rightarrow pK^-\pi^+$ case, *Adv. High Energy Phys.* **2020**, 7463073 (2020).

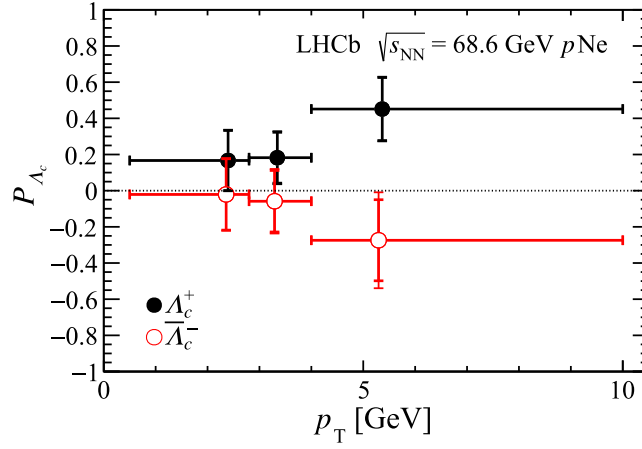
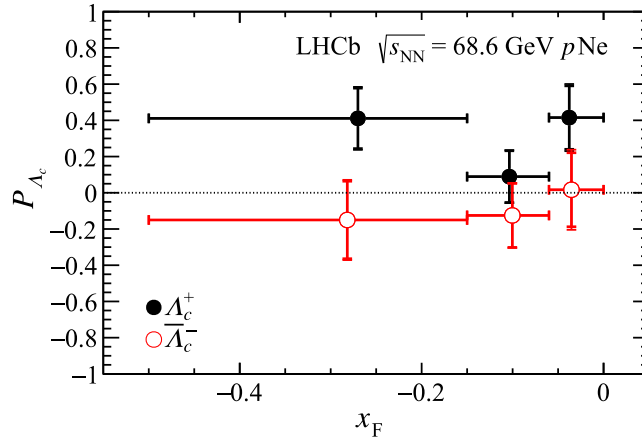
- [41] D. Marangotto, Helicity amplitudes for generic multibody particle decays featuring multiple decay chains, *Adv. High Energy Phys.* **2020**, 6674595 (2020).
- [42] R. Aaij *et al.* (LHCb Collaboration), Amplitude analysis of the $\Lambda_c^+ \rightarrow pK^-\pi^+$ decay and Λ_c^+ baryon polarization measurement in semileptonic beauty hadron decays, *Phys. Rev. D* **108**, 012023 (2023).
- [43] F. J. Botella, L. M. Garcia Martin, D. Marangotto, F. Martinez Vidal, A. Merli, N. Neri, A. Oyangueren, and J. Ruiz Vidal, On the search for the electric dipole moment of strange and charm baryons at LHC, *Eur. Phys. J. C* **77**, 181 (2017).
- [44] E. Bagli *et al.*, Electromagnetic dipole moments of charged baryons with bent crystals at the LHC, *Eur. Phys. J. C* **77**, 828 (2017).
- [45] A. S. Fomin *et al.*, Feasibility of measuring the magnetic dipole moments of the charm baryons at the LHC using bent crystals, *J. High Energy Phys.* **08** (2017) 120.
- [46] D. Marangotto, Amplitude analysis and polarisation measurement of the Λ_c^+ baryon in $pK^-\pi^+$ final state for electromagnetic dipole moment experiment, Ph.D. thesis, Università degli Studi di Milano, 2020, <https://cds.cern.ch/record/2713231>.
- [47] A. S. Fomin *et al.*, The prospect of charm quark magnetic moment determination, *Eur. Phys. J. C* **80**, 358 (2020).
- [48] D. Mirarchi, A. S. Fomin, S. Redaelli, and W. Scandale, Layouts for fixed-target experiments and dipole moment measurements of short-lived baryons using bent crystals at the LHC, *Eur. Phys. J. C* **80**, 929 (2020).
- [49] S. Aiola *et al.*, Progress towards the first measurement of charm baryon dipole moments, *Phys. Rev. D* **103**, 072003 (2020).
- [50] N. Neri *et al.*, Advancements in experimental techniques for measuring dipole moments of short-lived particles at the LHC, *Nucl. Instrum. Methods Phys. Res., Sect. A* **1069**, 169875 (2024).
- [51] K. Akiba *et al.*, ALADDIN: An LHC Apparatus for Direct Dipole moments INvestigation, CERN, Geneva, 2024, [10.17181/CERN.2G4V.0YAO](https://cds.cern.ch/record/271181).
- [52] A. A. Alves Jr. *et al.* (LHCb Collaboration), The LHCb detector at the LHC, *J. Instrum.* **3**, S08005 (2008).
- [53] LHCb Collaboration, LHCb detector performance, *Int. J. Mod. Phys. A* **30**, 1530022 (2015).
- [54] M. Ferro-Luzzi, Proposal for an absolute luminosity determination in colliding beam experiments using vertex detection of beam-gas interactions, *Nucl. Instrum. Methods Phys. Res., Sect. A* **553**, 388 (2005).
- [55] T. Sjöstrand, S. Mrenna, and P. Skands, A brief introduction to PYTHIA 8.1, *Comput. Phys. Commun.* **178**, 852 (2008).
- [56] I. Belyaev *et al.*, Handling of the generation of primary events in Gauss, the LHCb simulation framework, *J. Phys. Conf. Ser.* **331**, 032047 (2011).
- [57] D. J. Lange, The EvtGen particle decay simulation package, *Nucl. Instrum. Methods Phys. Res., Sect. A* **462**, 152 (2001).
- [58] N. Davidson, T. Przedzinski, and Z. Was, PHOTOS interface in c++: Technical and physics documentation, *Comput. Phys. Commun.* **199**, 86 (2016).
- [59] T. Pierog, Iu. Karpenko, J. M. Katzy, E. Yatsenko, and K. Werner, EPOS LHC: Test of collective hadronization with data measured at the CERN Large Hadron Collider, *Phys. Rev. C* **92**, 034906 (2015).
- [60] S. Agostinelli *et al.* (Geant4 Collaboration), Geant4: A simulation toolkit, *Nucl. Instrum. Methods Phys. Res., Sect. A* **506**, 250 (2003).
- [61] J. Allison *et al.* (Geant4 Collaboration), Geant4 developments and applications, *IEEE Trans. Nucl. Sci.* **53**, 270 (2006).
- [62] M. Clemencic, G. Corti, S. Easo, C. R. Jones, S. Miglioranza, M. Pappagallo, and P. Robbe, The LHCb simulation application, Gauss: Design, evolution and experience, *J. Phys. Conf. Ser.* **331**, 032023 (2011).
- [63] A. Rogozhnikov, Reweighting with boosted decision trees, *J. Phys. Conf. Ser.* **762**, 012036 (2016).
- [64] R. Aaij *et al.*, Selection and processing of calibration samples to measure the particle identification performance of the LHCb experiment in Run 2, *Eur. Phys. J. Tech. Instrum.* **6**, 1 (2019).
- [65] L. Breiman, J. H. Friedman, R. A. Olshen, and C. J. Stone, *Classification and Regression Trees* (Wadsworth international group, Belmont, California, 1984).
- [66] S. Navas *et al.* (Particle Data Group), Review of particle physics, *Phys. Rev. D* **110**, 030001 (2024).
- [67] A. Blum, A. Kalai, and J. Langford, Beating the hold-out: Bounds for K-fold and progressive cross-validation, in *Proceedings of the Twelfth Annual Conference on Computational Learning Theory*, COLT '99, (ACM, New York, NY, 1999), p. 203.
- [68] TensorFlowAnalysis: A collection of useful functions and example scripts for performing amplitude fits using TensorFlow, <https://gitlab.cern.ch/poluekt/TensorFlowAnalysis>.
- [69] LHCb Collaboration (2026), <https://cds.cern.ch/record/2954975>.
- [70] G. Aad *et al.* (ATLAS Collaboration), Measurement of the transverse polarization of Λ and $\bar{\Lambda}$ hyperons produced in proton-proton collisions at $\sqrt{s} = 7$ TeV using the ATLAS detector, *Phys. Rev. D* **91**, 032004 (2015).
- [71] R. Aaij *et al.* (LHCb Collaboration), Measurement of transverse Λ and $\bar{\Lambda}$ hyperon polarization in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, *Phys. Rev. D* **112**, 112022 (2025).

End Matter

The differential polarization measurement results are shown in Figs. 4 and 5. Systematic uncertainties separated by contribution are reported in Table III. Background-subtracted p_T and x_F kinematic distributions are reported in Fig. 6, separately for the Λ_c^+ and $\bar{\Lambda}_c^-$ candidates. The average p_T and x_F values, for the full

datasets and for each differential polarization fit bin, are reported in Tables IV and V, respectively.

The differential polarization measurement results as a function of p_T are qualitatively compared to those obtained by the E791 experiment [29] in Fig. 7. Even though both measurements show a possible trend of


 FIG. 4. Differential polarization measurements in p_T intervals, with (thick line) statistical and (thin line) total uncertainties reported.

 FIG. 5. Differential polarization measurements in x_F intervals, with (thick line) statistical and (thin line) total uncertainties reported.

increasing polarization with p_T , a quantitative comparison between them is not possible due to the different energy, collision system, and polarization measurement technique. The differential polarization measurement results as a

function of x_F are qualitatively compared to Λ polarization measurements [32,34,35,37,38,70,71] in Fig. 8. These results comprise Λ polarization measurements performed for varying energies and collision systems.

TABLE III. Systematic uncertainty contributions to the differential polarization measurements.

		Total	Model	Background	Efficiency
$P_{\Lambda_c^+}$	$p_T < 2.8$ GeV	0.038	0.030	0.001	0.024
	$2.8 \leq p_T < 4$ GeV	0.042	0.009	0.002	0.041
	$p_T \geq 4$ GeV	0.041	0.030	0.003	0.028
	$x_F < -0.15$	0.049	0.020	0.002	0.045
	$-0.15 \leq x_F < -0.06$	0.032	0.022	0.002	0.024
	$x_F \geq -0.06$	0.061	0.043	0.008	0.042
$P_{\Lambda_c^-}$	$p_T < 2.8$ GeV	0.036	0.025	0.003	0.025
	$2.8 \leq p_T < 4$ GeV	0.054	0.025	0.002	0.048
	$p_T \geq 4$ GeV	0.14	0.03	< 0.01	0.14
	$x_F < -0.15$	0.057	0.036	0.002	0.045
	$-0.15 \leq x_F < -0.06$	0.032	0.019	0.003	0.025
	$x_F \geq -0.06$	0.085	0.017	0.001	0.083

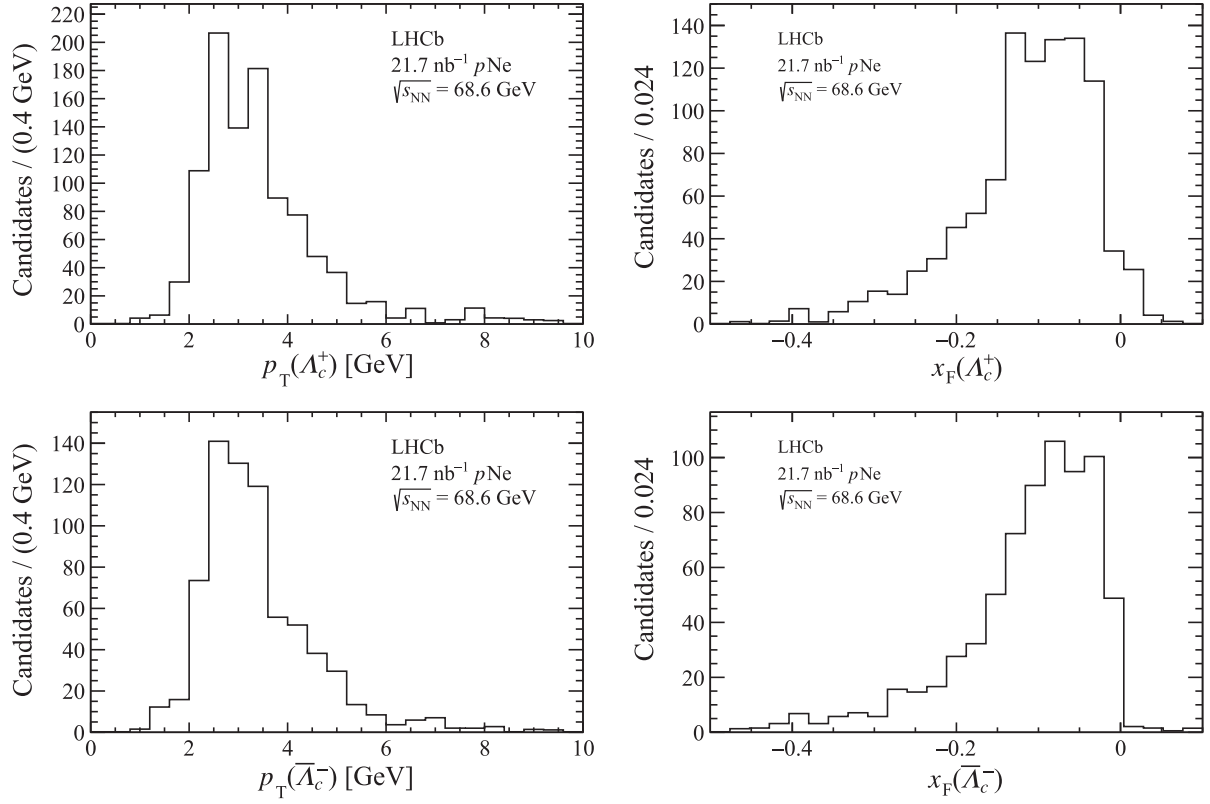

 FIG. 6. Background-subtracted (left) p_T and (right) x_F distributions of Λ_c^+ (top) and $\bar{\Lambda}_c^-$ (bottom) baryon candidates.

 TABLE IV. Average p_T values for the full dataset and the differential fit bins.

Bin	$\langle p_T \rangle(\Lambda_c^+)$ [GeV]	$\langle p_T \rangle(\bar{\Lambda}_c^-)$ [GeV]
Full range	3.50	3.46
$p_T < 2.8$ GeV	2.40	2.36
$2.8 \leq p_T < 4$ GeV	3.34	3.29
$p_T \geq 4$ GeV	5.37	5.30

 TABLE V. Average x_F values for the full dataset and the differential fit bins.

Bin	$\langle x_F \rangle(\Lambda_c^+)$	$\langle x_F \rangle(\bar{\Lambda}_c^-)$
Full range	-0.128	-0.126
$x_F < -0.15$	-0.270	-0.282
$-0.15 \leq x_F < -0.06$	-0.104	-0.100
$-0.06 \leq x_F < 0$	-0.038	-0.035

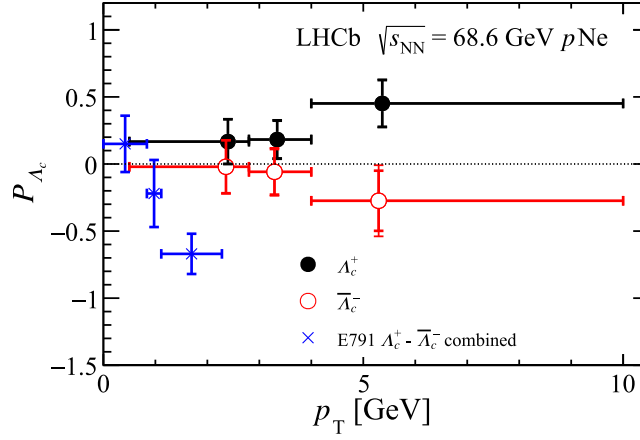


FIG. 7. Differential polarization measurements in p_T intervals, with (thick line) statistical and (thin line) total uncertainties reported, compared to (blue crosses) E791 experiment results.

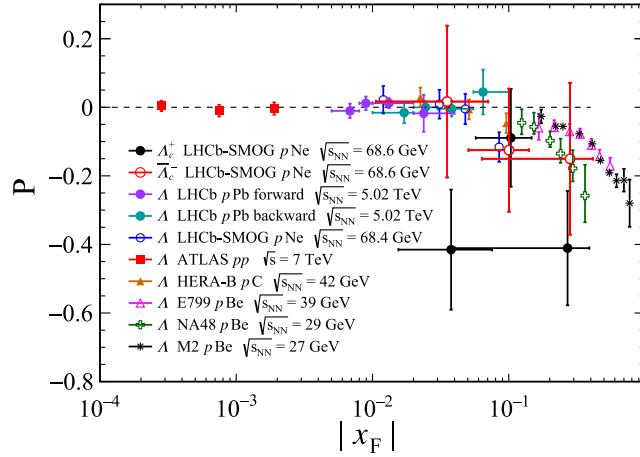


FIG. 8. Differential polarization measurements in x_F intervals compared to different Λ polarization measurements [32,34,35,37,38,70,71]. The Λ_c^+ polarization results are plotted with an opposite sign for a better comparison due to the negative x_F coverage of the LHCb SMOG data, and given $P(-x_F) = -P(x_F)$.

- R. Aaij³⁸, A. S. W. Abdelmotteleb⁵⁸, C. Abellan Beteta⁵², F. Abudinén⁶⁰, T. Ackernley⁶², A. A. Adefisoye⁷⁰, B. Adeva⁴⁸, M. Adinolfi⁵⁶, P. Adlarson⁸⁶, C. Agapopoulou¹⁴, C. A. Aidala⁸⁸, Z. Ajaltouni¹¹, S. Akar¹¹, K. Akiba³⁸, P. Albicocco²⁸, J. Albrecht^{19,b}, R. Aleksiejunas⁸², F. Alessio⁵⁰, P. Alvarez Cartelle^{57,48}, R. Amalric¹⁶, S. Amato³, J. L. Amey⁵⁶, Y. Amhis¹⁴, L. An⁶, L. Anderlini²⁷, M. Andersson⁵², P. Andreola⁵², M. Andreotti²⁶, S. Andres Estrada⁴⁵, A. Anelli^{31,c}, D. Ao⁷, C. Arata¹², F. Archilli³⁷, Z. Areg⁷⁰, M. Argenton²⁶, S. Argüedas Cuendis^{9,50}, L. Arnove^{31,c}, A. Artamonov⁴⁴, M. Artuso⁷⁰, E. Aslanides¹³, R. Ataíde Da Silva⁵¹, M. Atzeni⁶⁶, B. Audurier¹², J. A. Authier¹⁵, D. Bacher⁶⁵, I. Bachiller Perea⁵¹, S. Bachmann²², M. Bachmayer⁵¹, J. J. Back⁵⁸, Z. B. Bai⁸, P. Baladron Rodriguez⁴⁸, V. Balagura¹⁵, A. Balboni²⁶, W. Baldini²⁶, Z. Baldwin⁸⁰, L. Balzani¹⁹, H. Bao⁷, J. Baptista de Souza Leite², C. Barbero Pretel^{48,12}, M. Barbetti²⁷, I. R. Barbosa⁷¹, R. J. Barlow^{64,a}, M. Barnyakov²⁵, S. Barsuk¹⁴, W. Barter⁶⁰, J. Bartz⁷⁰, S. Bashir⁴⁰, B. Batsukh⁵, P. B. Battista¹⁴, A. Bavarchee⁸¹, A. Bay⁵¹, A. Beck⁶⁶, M. Becker¹⁹, F. Bedeschi³⁵, I. B. Bediaga²

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 G. Bencivenni²⁸, E. Ben-Haim¹⁶, A. Berezhnoy⁴⁴, R. Bernet⁵², A. Bertolin³³, F. Betti⁶⁰, J. Bex⁵⁷,
 O. Bezshyyko⁸⁷, S. Bhattacharya⁸¹, M. S. Bieker¹⁸, N. V. Biesuz²⁶, A. Biolchini³⁸, M. Birch⁶³,
 F. C. R. Bishop¹⁰, A. Bitadze⁶⁴, A. Bizzeti^{27,d}, T. Blake^{58,e}, F. Blanc⁵¹, J. E. Blank¹⁹, S. Blusk⁷⁰,
 V. Bocharnikov⁴⁴, J. A. Boelhaave¹⁹, O. Boente Garcia⁵⁰, T. Boettcher⁸⁹, A. Bohare⁶⁰, A. Boldyrev⁴⁴,
 C. Bolognani⁸⁴, R. Bolzonella^{26,f}, R. B. Bonacci¹, N. Bondar^{44,50}, A. Bordelius⁵⁰, F. Borgato^{33,50}, S. Borghi⁶⁴,
 M. Borsato^{31,c}, J. T. Borsuk⁸⁵, E. Bottalico⁶², S. A. Bouchiba⁵¹, M. Bovill⁶⁵, T. J. V. Bowcock⁶², A. Boyer⁵⁰,
 C. Bozzi²⁶, J. D. Brandenburg⁹⁰, A. Brea Rodriguez⁵¹, N. Breer¹⁹, J. Brodzicka⁴¹, J. Brown⁶², D. Brundu³²,
 E. Buchanan⁶⁰, M. Burgos Marcos⁸⁴, C. Burr⁵⁰, C. Buti²⁷, J. S. Butter⁵⁷, J. Buytaert⁵⁰, W. Byczynski⁵⁰,
 S. Cadeddu³², H. Cai⁷⁶, Y. Cai⁵, A. Caillet¹⁶, R. Calabrese^{26,f}, L. Calefice⁴⁶, M. Calvi^{31,c}, M. Calvo Gomez⁴⁷,
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 Y. Cao⁶, S. Capelli³¹, M. Caporale²⁵, L. Capriotti²⁶, R. Caravaca-Mora⁹, A. Carbone^{25,h}, L. Carcedo Salgado⁴⁸,
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 M. Cattaneo⁵⁰, G. Cavallero²⁶, V. Cavallini^{26,f}, S. Celani⁵⁰, I. Celestino^{35,j}, S. Cesare^{50,k}, A. J. Chadwick⁶²,
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 S. Chernyshenko⁵⁴, X. Chiopoulous⁸⁴, V. Chobanova⁴⁵, M. Chrzaszcz⁴¹, A. Chubykin⁴⁴, V. Chulikov^{28,36,50},
 P. Ciambione²⁸, X. Cid Vidal⁴⁸, G. Ciezarek⁵⁰, P. Cifra⁵⁰, P. E. L. Clarke⁶⁰, M. Clemencic⁵⁰, H. V. Cliff⁵⁷,
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 P. Collins⁵⁰, T. Colombo⁵⁰, M. Colonna¹⁹, A. Comerma-Montells⁴⁶, L. Congedo²⁴, J. Connaughton⁵⁸,
 A. Contu³², N. Cooke⁶¹, G. Cordova^{35,j}, C. Coronel⁶⁷, I. Corredoira¹², A. Correia¹⁶, G. Corti⁵⁰,
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 R. Currie⁶⁰, C. L. Da Silva⁶⁹, S. Dadabaev⁴⁴, X. Dai⁴, E. Dall'Occo⁵⁰, J. Dalseno⁴⁵, C. D'Ambrosio⁶³,
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 U. De Freitas Carneiro Da Graca^{2,o}, E. De Lucia²⁸, J. M. De Miranda², L. De Paula³, M. De Serio^{24,p},
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 B. Delaney⁶⁶, J. Deng⁸, V. Denysenko⁵², O. Deschamps¹¹, F. Dettori^{32,n}, B. Dey⁸¹, P. Di Nezza²⁸,
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 A. Doheny⁵⁸, C. Dong^{4,l}, F. Dordei³², A. C. dos Reis², A. D. Dowling⁷⁰, L. Dreyfus¹³, W. Duan⁷⁴, P. Duda⁸⁵,
 L. Dufour⁵¹, V. Duk³⁴, P. Durante⁵⁰, M. M. Duras⁸⁵, J. M. Durham⁶⁹, O. D. Durmus⁸¹, A. Dziurda⁴¹,
 A. Dzyuba⁴⁴, S. Easo⁵⁹, E. Eckstein¹⁸, U. Egede¹, A. Egorychev⁴⁴, V. Egorychev⁴⁴, S. Eisenhardt⁶⁰,
 E. Ejopu⁶², L. Eklund⁸⁶, M. Elashri⁶⁷, D. Elizondo Blanco⁹, J. Ellbracht¹⁹, S. Ely⁶³, A. Ene⁴³, J. Eschle⁷⁰,
 T. Evans³⁸, F. Fabiano¹⁴, S. Faghih⁶⁷, L. N. Falcao^{31,c}, B. Fang⁷, R. Fantechi³⁵, L. Fantini^{34,q}, M. Faria⁵¹,
 K. Farmer⁶⁰, F. Fassin^{83,38}, D. Fazzini^{31,c}, L. Felkowski⁸⁵, C. Feng⁶, M. Feng^{5,7}, A. Fernandez Casani⁴⁹,
 M. Fernandez Gomez⁴⁸, A. D. Fernez⁶⁸, F. Ferrari^{25,h}, F. Ferreira Rodrigues³, M. Ferrillo⁵², M. Ferro-Luzzi⁵⁰,
 S. Filippov⁴⁴, R. A. Fini²⁴, M. Fiorini^{26,f}, M. Firlej⁴⁰, K. L. Fischer⁶⁵, D. S. Fitzgerald⁸⁸, C. Fitzpatrick⁶⁴,
 T. Fiutowski⁴⁰, F. Fleuret¹⁵, A. Fomin⁵³, M. Fontana^{25,50}, L. A. Foreman⁶⁴, R. Forty⁵⁰, D. Foulds-Holt⁶⁰,
 V. Franco Lima³, M. Franco Sevilla⁶⁸, M. Frank⁵⁰, E. Franzoso^{26,f}, G. Frau⁶⁴, C. Frei⁵⁰, D. A. Friday^{64,50},
 J. Fu⁷, Q. Fühling^{19,57,b}, T. Fulghesu¹³, G. Galati^{24,p}, M. D. Galati³⁸, A. Gallas Torreira⁴⁸, D. Galli^{25,h},
 S. Gambetta⁶⁰, M. Gandelman³, P. Gandini³⁰, B. Ganie⁶⁴, H. Gao⁷, R. Gao⁶⁵, T. Q. Gao⁵⁷, Y. Gao⁸, Y. Gao⁶,
 Y. Gao⁸, L. M. Garcia Martin⁵¹, P. Garcia Moreno⁴⁶, J. García Pardiñas⁶⁶, P. Gardner⁶⁸, L. Garrido⁴⁶, C. Gaspar⁵⁰,
 A. Gavrikov³³, L. L. Gerken¹⁹, E. Gersabeck²⁰, M. Gersabeck²⁰, T. Gershon⁵⁸, S. Ghizzo^{29,i},
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 R. Henderson¹⁴, R. D. L. Henderson¹, A. M. Hennequin⁵⁰, K. Hennessy⁶², J. Herd⁶³, P. Herrero Gascon²²,
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 E. Jimenez Moya⁹, N. Jindal⁹⁰, M. John⁶⁵, A. John Rubesh Rajan²³, D. Johnson⁵⁵, C. R. Jones⁵⁷, S. Joshi⁴²,
 B. Jost⁵⁰, J. Juan Castella⁵⁷, N. Jurik⁵⁰, I. Juszczak⁴¹, K. Kalecinska⁴⁰, D. Kaminaris⁵¹, S. Kandybei⁵³,
 M. Kane⁶⁰, Y. Kang^{4,1}, C. Kar¹¹, M. Karacson⁵⁰, A. Kauniskangas⁵¹, J. W. Kautz⁶⁷, M. K. Kazanecki⁴¹,
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