



Transverse polarization measurement of Λ hyperons in $p\text{Ne}$ collisions at $\sqrt{s_{\text{NN}}} = 68.4 \text{ GeV}$ with the LHCb detector

LHCb collaboration[†]

Abstract

A measurement of the transverse polarization of the Λ and $\bar{\Lambda}$ hyperons in $p\text{Ne}$ fixed-target collisions at $\sqrt{s_{\text{NN}}} = 68.4 \text{ GeV}$ is presented using data collected by the LHCb detector. The polarization is studied using the decay $\Lambda \rightarrow p\pi^-$ together with its charge conjugated process, the integrated values measured are

$$P_{\Lambda} = 0.029 \pm 0.019 (\text{stat}) \pm 0.012 (\text{syst}),$$

$$P_{\bar{\Lambda}} = 0.003 \pm 0.023 (\text{stat}) \pm 0.014 (\text{syst}).$$

Furthermore, the results are shown as a function of the Feynman x variable, transverse momentum, pseudorapidity and rapidity of the hyperons, and are compared with previous measurements.

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1 Introduction

The spontaneous transverse polarization of Λ hyperons, spin 1/2 baryons with a mass of 1115.683 ± 0.006 MeV/ c^2 [20], was first observed in 1976 in unpolarized fixed-target collisions of protons with an energy of 300 GeV and a beryllium target [1]. This result was in contradiction with the expectation that the large number of final states in high-energy particle production would suppress polarization effects and showed that spin effects contribute significantly even at high-energy. A polarizing fragmentation function, denoted by D_{1T}^\perp , has been proposed in Refs. [2–4] to account for the polarized production of Λ hyperons. The mechanism involving the D_{1T}^\perp function is the same as that used in the framework of the transverse-momentum-dependent unpolarized fragmentation functions (TMDs) to describe the fragmentation of an unpolarized quark into a transversely polarized hadron. The spin and azimuthal asymmetries observed at sufficiently large energy scales cannot be explained by asymmetries at the level of the hard partonic process, instead their origin must lie in soft processes. By maintaining an explicit dependence on the intrinsic partonic motion, TMDs account for spin and momentum correlations at the soft level, potentially explaining the observed asymmetries. Since these functions arise from soft mechanisms, they are difficult to calculate from first principles. Hence, just as with collinear parton distribution functions and fragmentation functions, one possible approach is to determine them from experimental data. Several attempts were made to describe Λ polarization, both on the theoretical and experimental sides, at different accelerators and center-of-mass energies. Particularly relevant are the measurements from the STAR experiment at RHIC [5] and Belle at KEKB [6]. None of these results led to a fully satisfactory answer, and the mechanism giving rise to Λ polarization is still unclear. In this paper, a measurement of transverse Λ and $\bar{\Lambda}$ polarization is presented, using the LHCb experiment in a fixed-target configuration. The polarization is determined using proton-neon (p Ne) data collected in 2017 from collisions at a nucleon-nucleon center-of-mass energy of $\sqrt{s_{\text{NN}}} = 68.4$ GeV, generated by a 2.5 TeV proton beam incident on neon nuclei at rest and corresponding to an integrated luminosity of 24.9 nb $^{-1}$. The hyperons are reconstructed through the decays $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$. The results are obtained as a function of the transverse momentum (p_T) of the hyperon, the pseudorapidity (η), the rapidity (y) and the Feynman variable $x_F = \frac{2 \cdot p_L}{\sqrt{s_{\text{NN}}}}$ (where p_L is the longitudinal momentum of the particle), as a non trivial dependence of the polarization on these variables has been reported in other publications [7].

2 The LHCb detector

The LHCb detector [8, 9] is a single-arm forward spectrometer, designed for the study of particles containing c or b quarks, covering the pseudorapidity range $2 < \eta < 5$. The detector includes: a silicon-strip vertex locator (VELO), three tracking stations of silicon-strip detectors and straw drift tubes, two ring-imaging Cherenkov detectors (RICH) 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) [10] 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 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 rapidity hemisphere, due to the boost induced by the high-energy proton beam, which points to the positive- z direction.

3 Data sample and analysis strategy

The p Ne sample was taken during the pp data-taking period. Fixed-target events were collected only when a bunch in the beam pointing towards the LHCb detector crossed the interaction region without a corresponding bunch in the beam pointing to the opposite direction. To suppress the remaining pp background, the z -coordinate of the p Ne primary vertex (PV) is required to lie in the fiducial region $z_{\text{PV}} \in [-200, -100] \cup [100, 150]$ mm.¹ Furthermore, events with more than four hits in the VELO stations upstream of the interaction region are rejected. The online event selection is performed by a trigger [11], that requires at least one track reconstructed in the VELO. Since the Λ reconstruction requires two tracks, this trigger condition does not bias the measurement. In the offline selection, the Λ candidates are required to be reconstructed from proton and pion tracks with opposite charge, forming a vertex with a good-quality fit. Protons and pions are required to have a minimum transverse momentum of 100 MeV/ c and a minimum momentum of 2 GeV/ c . Particle identification (PID) requirements based on the information from the RICH detectors are applied to select protons. Finally, to suppress the contribution of nonprompt Λ hyperons, the impact parameter of the Λ candidate with respect to the PV is required to be less than 1.5 mm, which reduces this contribution to about 5%. Figure 1 shows the $p\pi^-$ and $\bar{p}\pi^+$ invariant-mass distributions obtained after all the selection criteria have been applied. The distributions are fitted with the convolution of a Cauchy and a Gaussian function to describe the signal shape and a first-order polynomial to model the background.

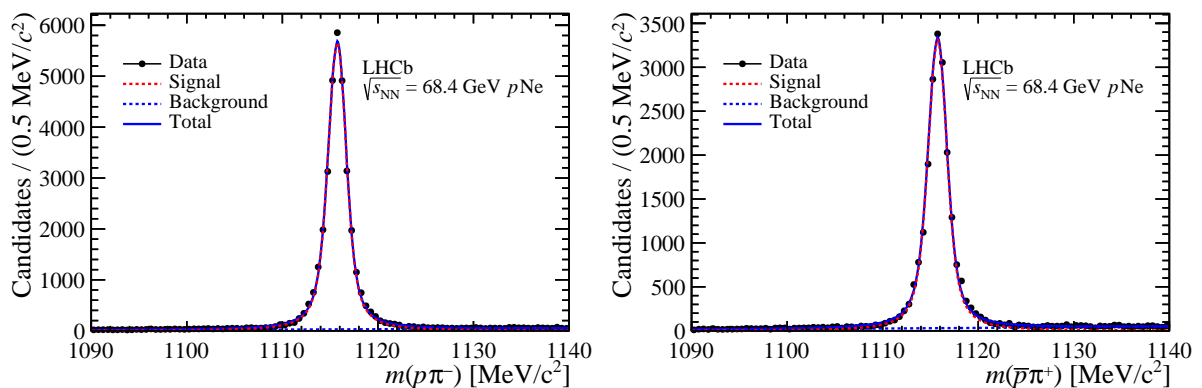


Figure 1: Invariant-mass distributions for (left) Λ and (right) $\bar{\Lambda}$ candidates after all selection requirements are applied. The fit result is overlaid on the data.

¹ $z_{\text{PV}} = 0$ is the z coordinate of the center of the pp interaction region.

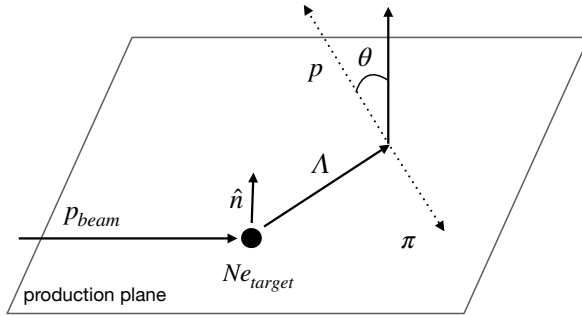


Figure 2: Sketch of the Λ production and decay. The polarization vector \hat{P}_Λ is aligned with the normal vector \hat{n} to the Λ production plane; θ is the angle between the momentum of the decay proton and \hat{n} in the Λ rest frame.

The decays $\Lambda \rightarrow p\pi^-$ and $\bar{\Lambda} \rightarrow \bar{p}\pi^+$ exhibit significant parity violation, resulting in large asymmetries in the angular distribution of their decay particles. In particular, the angular distribution of the proton in the Λ rest frame is given by

$$\frac{dN}{d\cos\theta} = \frac{dN_0}{d\cos\theta}(1 + \alpha P_\Lambda \cos\theta), \quad (1)$$

where θ is the angle between the proton momentum and the normal (\hat{n}) to the production plane spanned by the beam and the Λ momentum directions as sketched in Fig. 2, $\frac{dN_0}{d\cos\theta}$ is the decay distribution for unpolarized Λ hyperons, P_Λ is the magnitude of the Λ polarization, and α is the value of the parity-violating decay asymmetry for the channel under study of the Λ hyperon. The magnitude of the polarization is determined from a fit to the angular distribution of the proton in 10 bins of $\cos\theta$.

4 Simulation and efficiencies

Efficiencies are estimated using samples of fully simulated events. The simulated decays are reconstructed and analyzed using the same software tools as those used to process the data. In the simulation, Λ hyperons are generated using PYTHIA [12] with a specific LHCb configuration [13] and with colliding-proton beam momentum equal to the momentum per nucleon of the beam and target in the centre-of-mass frame. The decays of unstable particles are described by EVTGEN [14], in which final-state radiation is generated using PHOTOS [15]. The four-momentum of the Λ decay particles is then embedded into p Ne minimum bias events that are generated with the EPOS event generator [16]. The interaction of the generated particles with the detector and its response are implemented using the GEANT4 toolkit [17, 18] as described in Ref. [19].

After reconstruction, the simulated samples are weighted to improve agreement with data. Weights are calculated as the ratio between the normalized data and simulated distributions as a function of p_T , η and z_{PV} with

$$w(p_T, \eta, z_{PV}) = w(p_T, \eta) \cdot w(z_{PV}), \quad (2)$$

where $w(p_T, \eta)$ is evaluated in 6 intervals of transverse momentum between 300 and 2500 MeV/c and 7 intervals of pseudorapidity between 2 and 5. The weights $w(z_{PV})$ are

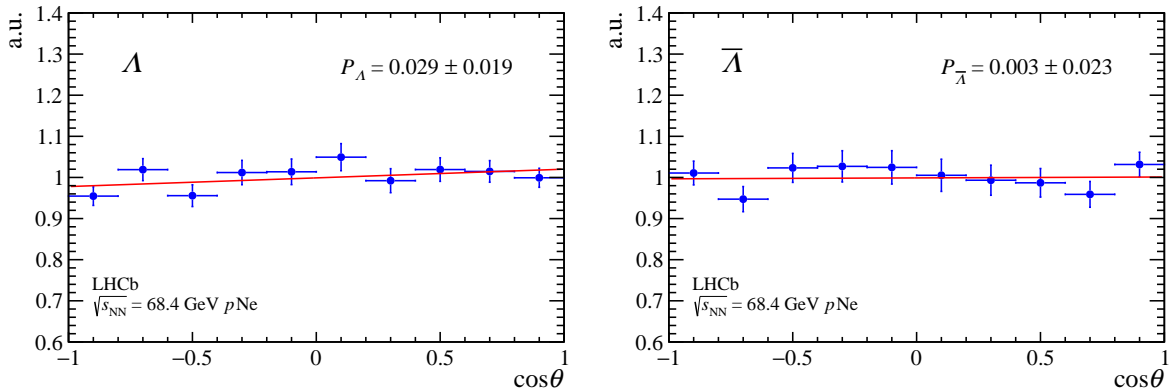


Figure 3: Efficiency-corrected $\cos\theta$ distributions, for (left) Λ and (right) $\bar{\Lambda}$ hyperons. The result of the fit is overlaid (red line).

evaluated in 6 intervals between -200 and 150 mm, ignoring the region between -100 and 100 mm outside the fiducial region considered in the analysis. Through the weighting procedure, the simulation is corrected on average by 6% as a function of transverse momentum and pseudorapidity, and by 4% as a function of z_{PV} , for both Λ and $\bar{\Lambda}$ hyperons. Accounting for efficiency factors, Eq. 1 is modified to

$$\frac{dN}{d\cos\theta} = \frac{dN_0}{d\cos\theta} (1 + \alpha P_\Lambda \cos\theta) \times \epsilon(\cos\theta) \times \epsilon_{PID}, \quad (3)$$

where ϵ_{PID} is the particle identification efficiency for the protons, estimated from dedicated calibration data samples and computed as a function of the proton kinematics. The $\epsilon(\cos\theta)$ term is the product of acceptance, reconstruction and selection efficiencies. It is determined using simulation as $\epsilon(\cos\theta) = f_{\text{rec}}(\cos\theta)/f_{\text{gen}}(\cos\theta)$, where f indicates the $\cos\theta$ distribution for generated candidates (f_{gen}), without any detector effect, or for fully reconstructed candidates (f_{rec}), with detector effects included. As the polarization effects are not included in the simulation, the generated $\cos\theta$ distribution is uniform. Since only the shape of the distribution is relevant, the efficiency is proportional to the reconstructed $\cos\theta$ distributions, and the generated one is ignored. To correct the angular distributions in data, in each $\cos\theta$ bin, the normalized number of candidates in the data is divided by the normalized number of candidates in the simulated reconstructed sample.

5 Results and systematic uncertainties

The proton angular distributions, after efficiency correction, are shown in Fig. 3. The function $f(\cos\theta) = A(1 + \alpha P_\Lambda \cos\theta)$ is fitted to the data distributions, where $\alpha = 0.746 \pm 0.007$ for Λ and $\alpha = -0.757 \pm 0.004$ for $\bar{\Lambda}$ are fixed to their world average value [20]. The magnitude of the polarization is given by the free parameter of the fit shown in Fig. 3.

Several sources of systematic uncertainties are considered. The fit to the invariant-mass distribution is repeated using a double-sided Crystal Ball function [21] instead of the convolution of a Cauchy and a Gaussian function for the signal shape, and a second-order polynomial instead of a first-order one for the background, and the values of the polarization are determined again. The systematic uncertainty is determined as the

Table 1: Contributions of systematic uncertainties on the polarization measurement for Λ and $\bar{\Lambda}$ hyperons.

Source	Λ	$\bar{\Lambda}$
Signal estimation	0.007	0.001
Background estimation	0.001	0.010
Kinematic weights	0.001	0.001
Multiplicity dependence	0.001	0.004
Binning of $\cos\theta$ distributions	0.007	0.006
PID efficiencies	0.002	0.005
Nonprompt contamination	0.005	0.002

deviations of these results with respect to those of the default fit. Uncertainties related to the weighting procedure applied to the simulation are taken into consideration by carrying out 100 trials, randomly varying each weight within its uncertainty, calculating new values for the polarization, and taking as systematic uncertainty the largest difference in the polarization values compared to the default one. The choice of the variables used to weight the simulation is also considered; the uncertainty is calculated as the difference between the results obtained by using the track multiplicity and those obtained using the Λ pseudorapidity in the calculation of the weights. The choice of binning for the angular distributions affects the fit results. This is taken into account by repeating the polarization measurements using 5 bins instead of 10 in the angular distribution. Another contribution is associated with the estimation of PID efficiencies. An alternative approach is used, where the particle identification efficiencies are directly estimated from the simulation rather than using dedicated calibration samples. Another systematic uncertainty contribution arises from nonprompt Λ hyperon contamination in the data sample, which is estimated from simulation to account for 5% of the total yield. To estimate an upper limit on the nonprompt contamination, the impact parameter requirement (which retains approximately 50% of the nonprompt signal) is removed, the measurement is repeated and the difference with the baseline value is taken as systematic uncertainty. The systematic uncertainty due to the external parameter α is found to be negligible. The total systematic uncertainty is computed as the sum in quadrature of each contribution shown in Table 1. The systematic contributions are found to be small and the measurement is dominated by statistical uncertainties. The statistical effect on each systematic contribution is not negligible as reflected in the differences between Λ and $\bar{\Lambda}$ hyperons. The final polarization measurements are

$$P_{\Lambda} = 0.029 \pm 0.019 \text{ (stat)} \pm 0.012 \text{ (syst)} ,$$

$$P_{\bar{\Lambda}} = 0.003 \pm 0.023 \text{ (stat)} \pm 0.014 \text{ (syst)} .$$

The polarization measurements have also been performed in bins of p_{T} , η , y and x_{F} . The results are shown in Fig. 4 and listed in Table 2. Other experiments with different energies and collision systems have measured the Λ polarization. In its fixed-target configuration, the LHCb experiment covers an energy and kinematic range that is largely unexplored. Figure 5 compares and shows the agreement between the results of this paper with measurements from other experiments, including ATLAS [22], an experiment at the M2 beam-line at Fermilab [23], the E799 experiment [24], NA48 [25], and HERA-B [26]. The measurements reported here, and those from HERA-B, cover negative values of

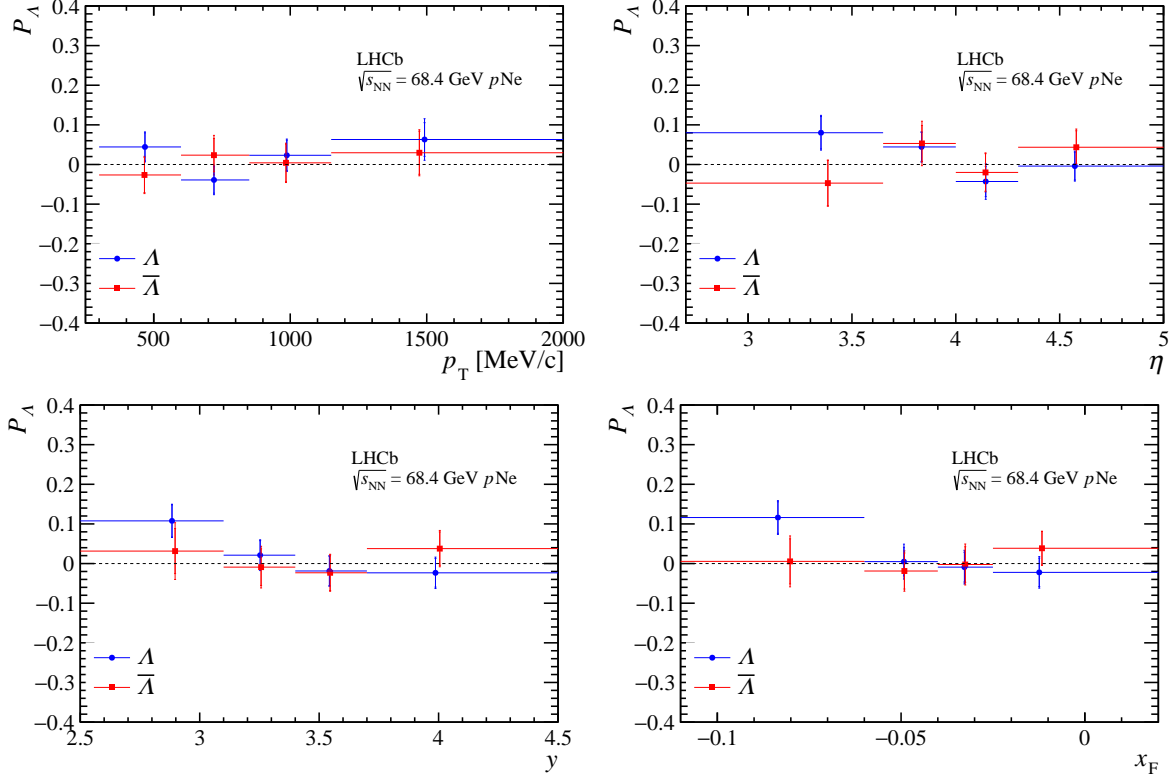


Figure 4: Polarization as a function of (a) p_T , (b) η , (c) x_F and (d) y . Blue (red) symbols are for Λ ($\bar{\Lambda}$). In each plot the data is integrated over the $0.3 < p_T < 3$ GeV/ c and/or $2 < \eta < 5$ kinematic range.

x_F , so the results are first transformed using the following symmetry of the transverse polarization $P_\Lambda(-x_F) = -P_\Lambda(x_F)$, and then compared with the other measurements.

6 Conclusions

A measurement of transverse polarization of Λ and $\bar{\Lambda}$ hyperons in p Ne collisions at $\sqrt{s_{NN}} = 68.4$ GeV by the LHCb experiment is presented. This analysis exploits the innovative and unique fixed-target apparatus at LHC. The measurement in a new collision system and region of phase space can provide additional insights on the mechanism of Λ polarization, which can still not be calculated in quantum chromodynamics. The polarization is measured through the decay $\Lambda \rightarrow p\pi^-$ and its charge conjugate, and is studied both as integrated values and in different bins of four kinematic variables: p_T , η , x_F , and y .

The integrated results are

$$P_\Lambda = 0.029 \pm 0.019 \text{ (stat)} \pm 0.012 \text{ (syst)},$$

$$P_{\bar{\Lambda}} = 0.003 \pm 0.023 \text{ (stat)} \pm 0.014 \text{ (syst)}.$$

The polarization values obtained in this analysis are compatible with previous measurements, in particular with the HERA-B results which cover a similar x_F interval. The agreement is noteworthy considering the different experiments and colliding systems.

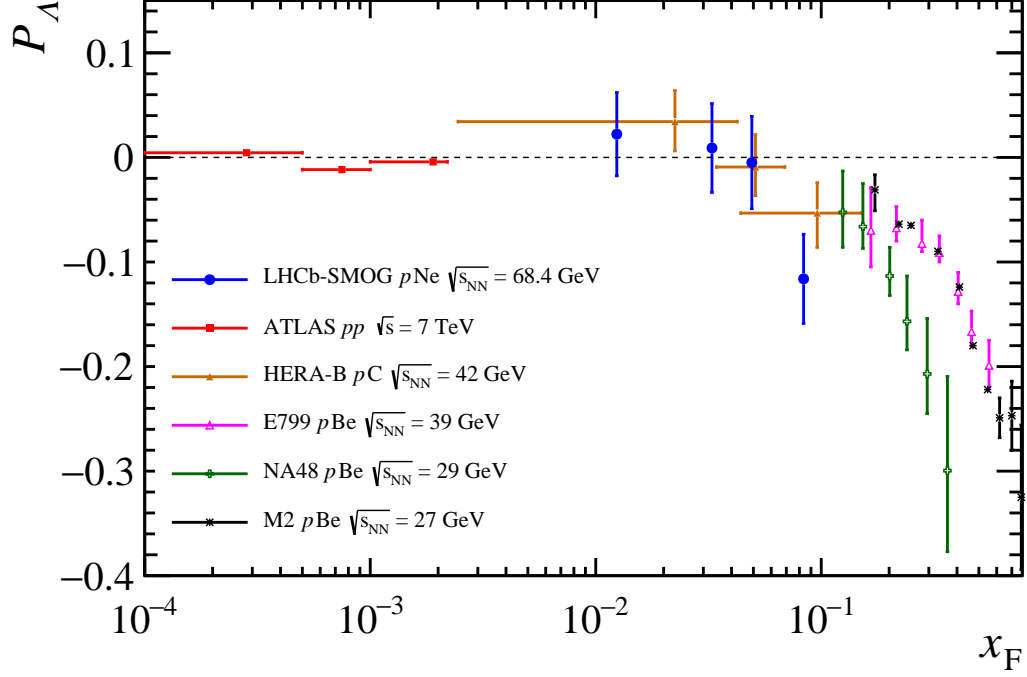


Figure 5: Comparison of polarization as a function of x_F for Λ hyperons obtained in experiments with different energies and with different colliding systems.

The LHCb fixed-target program has become particularly active since the installation of the SMOG2 system, which increases data luminosity by more than two orders of magnitude compared to the SMOG system used in this analysis. With the new data, we expect to explore different target species and improve our reach into the lower negative regions of x_F which have been poorly explored so far.

Table 2: Polarization in bins of p_T , η , x_F , and y for Λ and $\bar{\Lambda}$. The first uncertainties are statistical and the second are systematic.

	P_Λ	$P_{\bar{\Lambda}}$
p_T [MeV/c]		
[300, 600]	$0.044 \pm 0.035 \pm 0.013$	$-0.026 \pm 0.044 \pm 0.015$
[600, 850]	$-0.039 \pm 0.033 \pm 0.016$	$0.023 \pm 0.042 \pm 0.027$
[850, 1150]	$0.023 \pm 0.038 \pm 0.015$	$0.004 \pm 0.047 \pm 0.015$
[1150, 3000]	$0.063 \pm 0.042 \pm 0.031$	$0.029 \pm 0.054 \pm 0.021$
η		
[2.00, 3.65]	$0.080 \pm 0.040 \pm 0.016$	$-0.047 \pm 0.057 \pm 0.011$
[3.65, 4.00]	$0.044 \pm 0.036 \pm 0.012$	$0.053 \pm 0.045 \pm 0.033$
[4.00, 4.30]	$-0.043 \pm 0.038 \pm 0.024$	$-0.020 \pm 0.047 \pm 0.014$
[4.30, 5.00]	$-0.004 \pm 0.035 \pm 0.014$	$0.043 \pm 0.042 \pm 0.020$
x_F		
[-0.250, -0.060]	$0.116 \pm 0.040 \pm 0.015$	$0.006 \pm 0.057 \pm 0.030$
[-0.060, -0.040]	$0.005 \pm 0.036 \pm 0.025$	$-0.018 \pm 0.045 \pm 0.023$
[-0.040, -0.025]	$-0.009 \pm 0.037 \pm 0.020$	$0.002 \pm 0.045 \pm 0.026$
[-0.025, 0.100]	$-0.022 \pm 0.036 \pm 0.017$	$0.038 \pm 0.042 \pm 0.008$
y		
[2.0, 3.1]	$0.107 \pm 0.040 \pm 0.011$	$0.031 \pm 0.057 \pm 0.044$
[3.1, 3.4]	$0.021 \pm 0.036 \pm 0.013$	$-0.009 \pm 0.046 \pm 0.025$
[3.4, 3.7]	$-0.019 \pm 0.037 \pm 0.010$	$-0.023 \pm 0.045 \pm 0.013$
[3.7, 5.0]	$-0.023 \pm 0.036 \pm 0.016$	$0.038 \pm 0.042 \pm 0.018$

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






























































































LHCb collaboration

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