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# Polarization measurement and prospects at LHCb

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**Abstract.** With its precise vertex reconstruction and particle identification capabilities, the LHCb detector is ideally suited to study the production and polarization of primary and secondary particles. In particular, as the origin of hyperon polarization from unpolarized proton-proton and proton-nucleus collisions is not yet fully understood, measurements in different collision systems and kinematic ranges must be provided. In this contribution, recent LHCb measurements of hyperon polarization in fixed-target modes are discussed, including their implications for hadronization modification in small collision systems and for transverse-momentum-dependent parton distributions and fragmentation functions.

## 1 Introduction

The spontaneous transverse polarization of $\Lambda$ hyperons in unpolarized hadronic collisions constitutes a fundamental challenge in quantum chromodynamics (QCD). Since its discovery in 300 GeV proton-beryllium collisions in 1976 [1], this phenomenon has defied conventional expectations of polarization suppression in high-energy multiparticle production. The observed GeV-scale spin-momentum correlations strongly suggest non-perturbative QCD mechanisms encoded in transverse-momentum-dependent (TMD) fragmentation functions, particularly the $D_{1T}^{\perp}$ function [2, 3]. Despite recent advances from RHIC-STAR [4] and Belle [5] experiments, the energy evolution and system-size dependence of polarization effects remain poorly understood, necessitating precision measurements across diverse collision systems.

The LHCb experiment's fixed-target configuration with the SMOG system [6] provides a novel platform to investigate $\Lambda/\bar{\Lambda}$ polarization in proton-neon ($p$Ne) collisions at $\sqrt{s_{\rm NN}} =$ 68.4 GeV. This energy regime bridges the gap between traditional fixed-target experiments (e.g., HERA-B [7], NA48 [8]) and collider measurements, while the target geometry uniquely extends measurable Feynman-$x$ $x_F = \frac{2p_{\rm L}}{\sqrt{s_{\rm NN}}}$ into the negative region, where $p_{\rm L}$ is longitudinal momentum. Utilizing 24.9 nb$^{-1}$ of data from LHC Run 2, we present the first polarization study in $p$Ne collisions through parity-violating decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$. The analysis spans pseudorapidity $2 < \eta < 5$, systematically examining polarization dependencies on $x_F$, transverse momentum ($p_{\rm T}$), pseudo-rapidity $\eta$, and rapidity ($y$).

## 2 The LHCb SMOG system and data set

The System for Measuring the Overlap with Gas (SMOG) is a fixed-target experiment built into the LHCb detector. The data used in the $\Lambda$ transverse polarization measurement is col-

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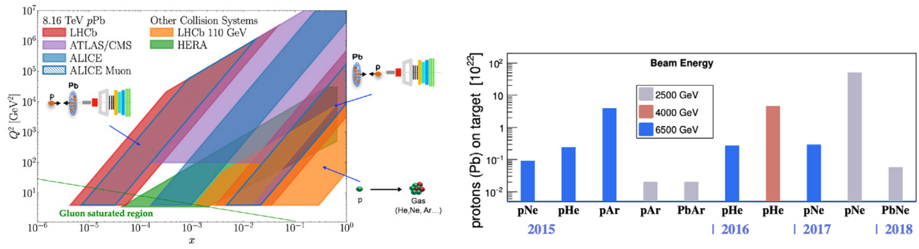


**Figure 1.** The (left) comparison between LHCb acceptance in Bjorken-$x$ and $Q^2$ plane with other experiments and (right) sample collected by SMOG between 2015 and 2018.

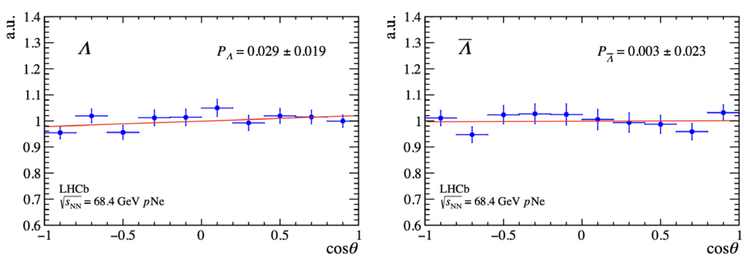


**Figure 2.** Fit to the $\cos\theta$ distributions for both $\Lambda$ and $\bar{\Lambda}$, to extract magnitude of polarization.

lected in proton-Neon collisions by SMOG in 2017, with a total luminosity 24.9 nb$^{-1}$. It uses the LHC's 2.5 TeV proton beam to collide with neon gas injected into the vertex locator (VELO) region, with gas density adjustable up to $10^{-6}$ g/cm$^3$ (set to $2.5 \times 10^{-7}$ g/cm$^3$ during Run 2). These collisions produce $p$Ne interactions at a nucleon-nucleon energy of $\sqrt{s_{\mathrm{NN}}} = 68.4$ GeV, bridging the gap between lower-energy fixed-target experiments ($\sim 40$ GeV) and high-energy collider studies ($> 100$ GeV). SMOG's elongated gas target ($\sim 1$ m along the beam) and LHCb's forward-focused detector ($2 < \eta < 5$) measure the high Feynman-$x$ and intermediate $Q^2$ region, as shown in Fig. 1, probing the target-fragmentation region where quark-gluon interactions dominate-a regime previously inaccessible in polarization studies.

## 3 Transverse polarization of $\Lambda/\bar{\Lambda}$

The LHCb experiment measured the transverse polarization of $\Lambda$ and $\bar{\Lambda}$ hyperons produced in $p$Ne collisions at $\sqrt{s_{\mathrm{NN}}} = 68.4$ GeV using their decay channels $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ [9]. The polarization magnitude $P$ was extracted by fitting angular distributions of decay products with the function $\frac{dN}{d\cos\theta} = \frac{dN_0}{d\cos\theta}(1 + \alpha P_\Lambda \cos\theta)$, where $\theta$ is the angle between the proton momentum and the normal to the production plane spanned by the beam and the $\Lambda$ momentum direction, $N$ is the count of $\Lambda$ yield and $\alpha$ is the value of the parity-violating decay asymmetry for the $\Lambda$ hyperon and is fixed to its world-average value ($0.746 \pm 0.007$ for $\Lambda$ and $-0.757 \pm 0.004$ for $\bar{\Lambda}$). The function $f(\cos\theta) = A(1 + \alpha P_\Lambda \cos\theta)$ is fitted to the data distribution, as shown in Fig. 2. The values for the magnitude are,

$$
\begin{aligned}
P_\Lambda &= 0.029 \pm 0.019(stats) \pm 0.012(syst) \\
P_\Lambda &= 0.003 \pm 0.023(stats) \pm 0.014(syst)
\end{aligned}
\tag{1}
$$

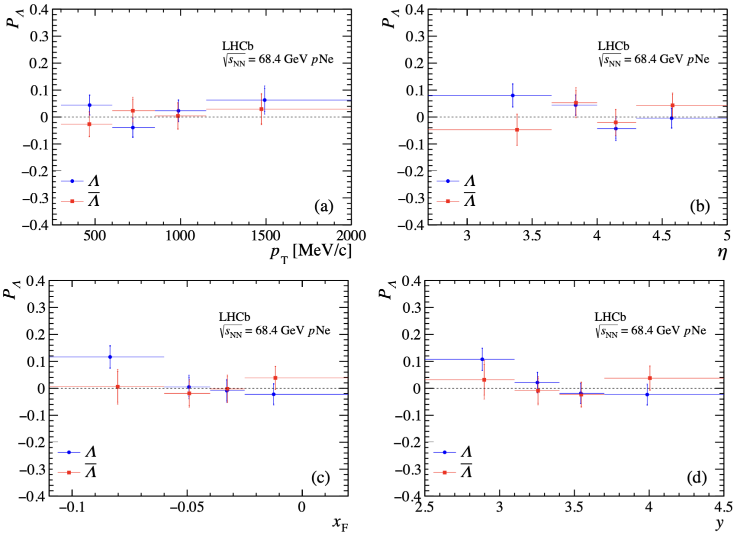


**Figure 3.** Transverse polarization as function of (a)$p_{\rm T}$, (b)$\eta$, (c)$x_F$ and (d) $y$, the blue dots represent $\Lambda$ and the red dots represent $\bar{\Lambda}$.

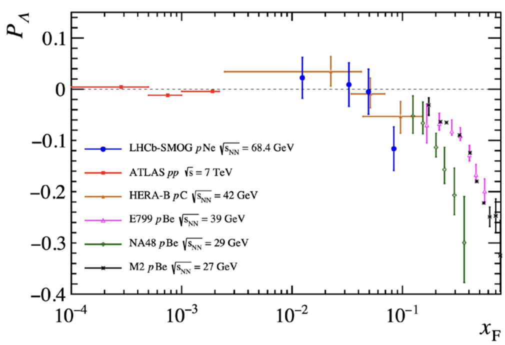


**Figure 4.** Comparison of polarization as a function of $x_F$ for $\Lambda$ hyperons obtained in experiments with different energies and with different colliding systems [7, 8, 10–12].

The measurements were extended to kinematic bins of transverse momentum ($p_{\rm T}$), pseudorapidity ($\eta$), rapidity ($y$), and Feynman $x_F$, as shown in Fig. 3. No significant transverse polarization for $\bar{\Lambda}$ observed in either kinematic bins of the listed variables, nor in the overall kinematic region. A non-zero transverse polarization is found for $\Lambda$ in the highest $|x_F|$ bin. The $x_F$ dependence of transverse polarization is compared with other experiments [7, 8, 10–12], where the values are first transformed using the following symmetry of the transverse polarization $P_\Lambda(-x_{\rm F}) = -P_\Lambda(x_{\rm F})$. Good agreement is achieved, as shown in Fig. 4.

## 4 Prospects

The SMOG2 upgrade [13] at LHCb significantly enhances fixed-target physics capabilities by introducing a high-density gas target system with precise control over gas species ($H_2$,

$D_2$, $O_2$) and optimized collision geometry. This upgrade achieves a two-orders-of-magnitude increase in instantaneous luminosity, enabling LHCb to collect unprecedented data volumes. Simultaneous operation of collider ($pp$) and fixed-target ($p$Ar/$p$Ne) modes allows unique cross-programmatic analyses, such as direct comparisons between collision systems. The expanded kinematic reach in rapidity, transverse momentum and Feynman $x_F$ complements existing measurements and addresses gaps in hyperon polarization and charm physics. This upgrade aligns with the 2020 European Strategy for Particle Physics, offering a cost-effective way to extend the LHC's scientific reach to probe fundamental QCD processes and astrophysical phenomena like cosmic ray antiprotons.

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