Feasibility studies of Λ transverse polarization in inelastic proton–proton interactions at beam momentum 158 GeV/c at NA61/SHINE at the CERN SPS

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Λ hyperon particle

Discovered in 1950

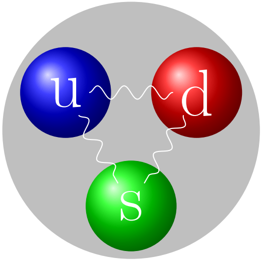
$\Lambda = uds$

$J^P = \frac{1}{2}^+$

Mass: $m = 1.116$ GeV/c

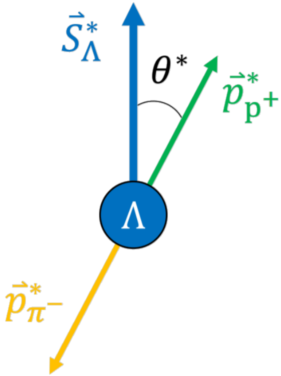
Lifetime: $\tau = 2.6 \cdot 10^{-10}$ s,
$c\tau = 7.89$ cm.

Main decay mode: $p\pi^-$ (BR = 63.9%)



In the weak decay $\Lambda \to p + \pi^-$, the proton tends to be emitted along Λ polarization vector. If θ^* is the angle between daughter proton momentum and Λ polarization vector in hyperon rest frame, then:

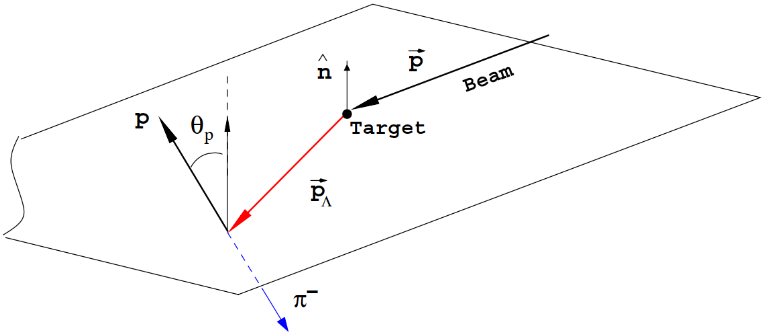
$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha P \cos\theta^*).$$



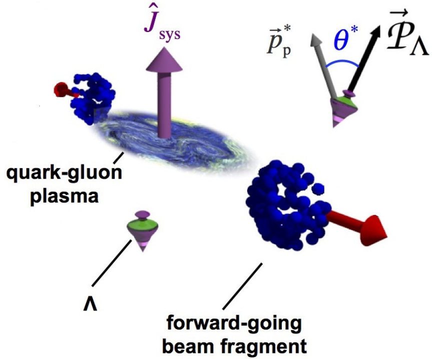
PDG 2024

Λ polarization

Transverse polarization
(since 1975)



Global polarization
(found in 2017 by STAR)



Pics: The STAR Collaboration, Yu. Naryshkin.

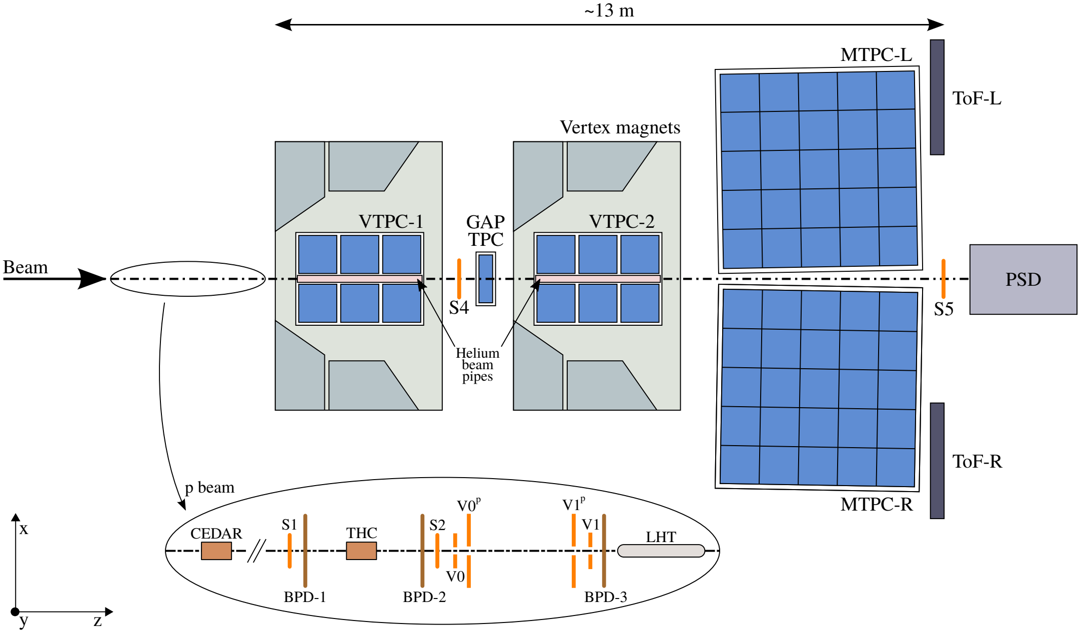
Motivation

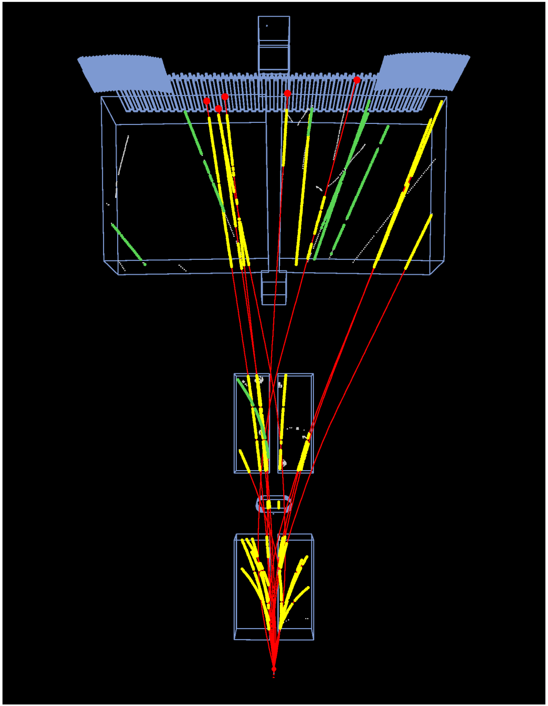
None of the theoretical models (Lund model[1,2], DeGrand-Miettinen model[3,4], etc.) explains all experimental data, including other hyperons/antihyperons.

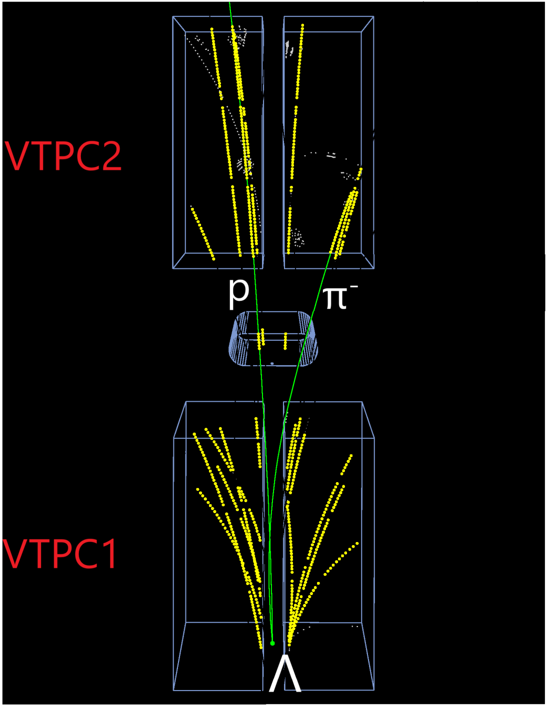
The comprehensive data collected by the NA61/SHINE experiment during a two-dimensional scan in beam momentum and system size (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb) give a potential for systematic studies of dependence of the Λ polarization on these parameters.

[1]B. Andersson, G. Gustafson, G. Ingelman, Phys. Lett. B 85 (1979) 417–420
[2]B. Andersson, G. Gustafson, G. Ingelman, T. Sjöstrand, Phys. Rep. 97 (1983) 31–145
[3]T. A. DeGrand, H. I. Miettinen, Phys. Rev. D 24 (1981) 2419–2427
[4]T. A. DeGrand, H. I. Miettinen, Phys. Rev. D 23 (1981) 1227–1230

NA61/SHINE Experimental setup in 2009-2011






VTPC2
p
π⁻
VTPC1
Λ

Transverse polarization definition and calculation

Transverse polarization definition:

i. Rotate from Lab frame to production plane coordinate system:

$$\hat{n}_x = \frac{\vec{p}_{\text{beam}} \times \vec{p}_\Lambda}{|\vec{p}_{\text{beam}} \times \vec{p}_\Lambda|},\ \hat{n}_z = \frac{\vec{p}_\Lambda}{|\vec{p}_\Lambda|},\ \hat{n}_y = \hat{n}_z \times \hat{n}_x$$

ii. Boost along $\hat{n}_z$ to Λ rest frame.

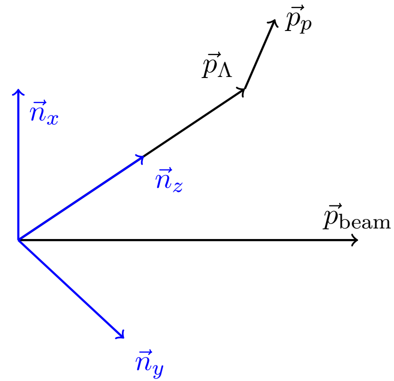
iii. Calculate cosine of angles between proton momentum $\vec{p}_p$ and axes:

$\cos\theta_i = p_{p\,i}/|\vec{p}_p|$, $i = x, y, z$

iv. Fit distribution of the $\cos\theta_i$ to the theoretical prediction and extract P_i – projection of polarization.

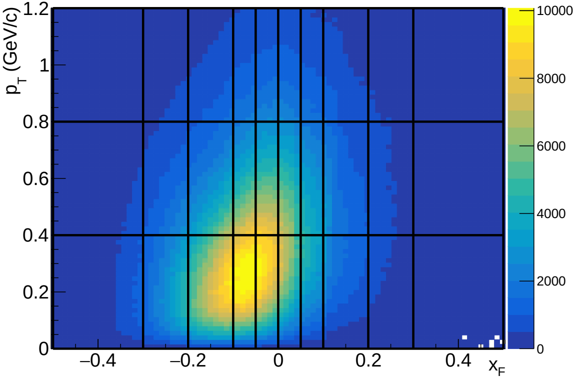
$$f(\cos\theta_i) = \frac{1 + \alpha P_i \cos\theta_i}{2},$$

where $\alpha = 0.732 \pm 0.014$ [PDG].

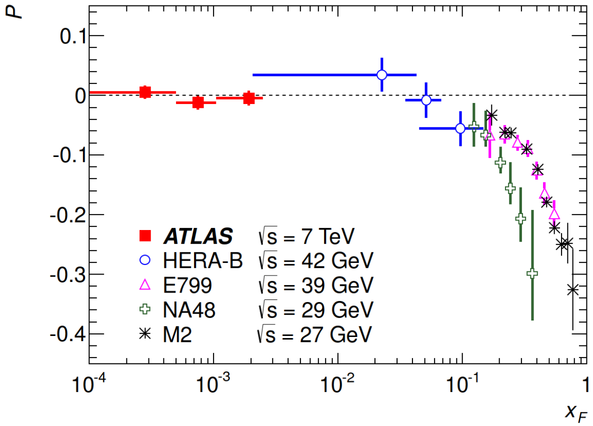


According to parity conservation in the strong interaction, $P_y \equiv P_z \equiv 0$ if the incident proton beam is unpolarized. Thus, the measurements of P_y and P_z are usually used to check the systematic uncertainties.

x_F-p_T distribution



Λ candidates in EPOS MC after data selection cuts



The Λ transverse polarization measured by ATLAS and others. For $p_{\text{beam}} = 158$ GeV/c, $\sqrt{s} = 17$GeV.

Expected signal: $P \approx 0.1$ at $x_F \approx 0.25$; zero for $p_T \approx 0$ and saturates at $p_T \approx 1$ GeV/c.

Feynman variable x_F defined as $x_F = (p_z)^{\text{CMS}} / (p_{\text{beam}})^{\text{CMS}}$. Fig. 2: 10.1103/PhysRevD.91.032004

Magnetic field impact on Λ polarization

- Λ hyperon has a magnetic moment $\mu_\Lambda = -0.613\mu_N$
- Its interaction (*precession*) with the magnetic field inside TPCs ($B \approx 1.5$T) may **bias** the measurements
- We showed that magnetic field impact on Λ polarization due to precession is smaller than detector acceptance-based polarization bias

Using Bargmann–Michel–Telegdi (BMT) equation

$$\frac{dS^\alpha}{d\tau} = \frac{ge}{2m}\left[F^{\alpha\beta}S_\beta + u^\alpha\left(S_\lambda F^{\lambda\mu}u_\mu\right)\right] - u^\alpha\left(S_\lambda\frac{du^\lambda}{d\tau}\right)$$

Or, simplified and in the Λ rest frame:

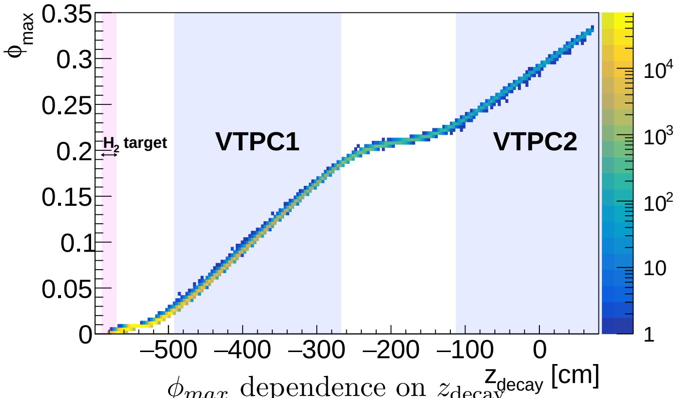
$$\frac{d\vec{S}}{d\tau} = \mu_\Lambda\mu_N\left[\vec{S}\times\vec{B}'\right]$$

Λ precession in magnetic field

The equation of motion of the spin vector $\vec{S}$ in Λ rest frame is

$$\frac{d\vec{S}}{d\tau} = \frac{\mu_\Lambda \mu_N}{\hbar}\left[\vec{S} \times \vec{B}\right]$$

Considering $dz = \frac{p_z}{mc} c d\tau$, **integrate eq.** using NA61/SHINE magnetic field $\vec{B}$ [7]. Initial condition: generate random spin vectors $\vec{S}$ uniformly distributed on unit sphere. Among these vectors, choose one with maximum angle change, $\phi_{\max} = \max(\angle(\vec{S}_{\text{init}}, \vec{S}_{\text{final}}))$.

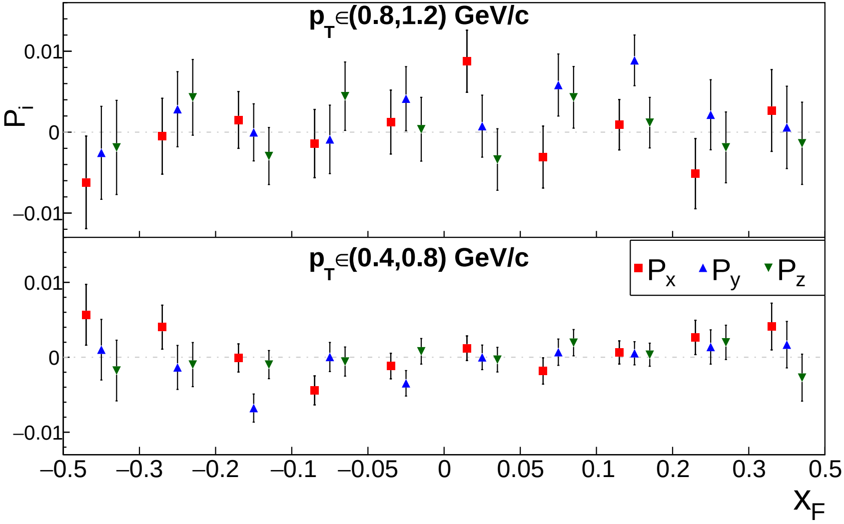


ϕ_{max} dependence on z_{decay}

To estimate magnetic field impact on Λ polarization bias, for every Λ,

- Assign polarization vector $\vec{S}$ uniformly distributed value,
- Propagate it in magnetic field until decay,
- Project $\vec{S}$ on $\hat{n}_x$, $\hat{n}_y$, $\hat{n}_z$ and fit their distributions.

Magnetic field impact: Λ polarization bias



Polarization vector P_i distribution for different (x_F, p_T) binning.

arXiv:2408.11050

Analysis procedure

- Build m_{inv} distributions based on selected $p\pi^-$ pairs, fit them, and extract number of Λ in particular bin.
- Determination of $\cos\theta_{x,y}$ distributions.
- Evaluation of corrections to the distributions based on experimental data and simulations.
- Calculation of the corrected $\cos\theta_{x,y}$ distributions.
- Calculation of statistical and systematic uncertainties.

Reconstructed MC and data selection cuts

Event (collision) selection cuts

- Main vertex exists
- Vertex fit is perfect
- Main vertex fitted within the 20 cm H_2 target ± 10 cm - VtxZ $\in (-600; -560)$ cm.
- Event is inelastic (S4 scintillator cut)

Tracks selection cuts

- One track is negatively charged, second - positive
- Min 10 clusters in at least one of VTPC1 and VTPC2 for both tracks
- Energy loss cut: dE/dx within 3σ around Bethe-Bloch
- MC analogy: reconstructed proton and pion matches to sim tracks

Λ candidate selection cuts

- To reduce background, z difference between Λ vertex and primary vertex $\Delta z = z_\Lambda - z_{PV} > 10$ cm
- V^0 momentum 'points' at the target: impact parameter at z fulfil $(0.5 \cdot b_x)^2 + (b_y)^2 < 1\ \text{cm}^2$
- $|\cos\theta_z| < 0.9$

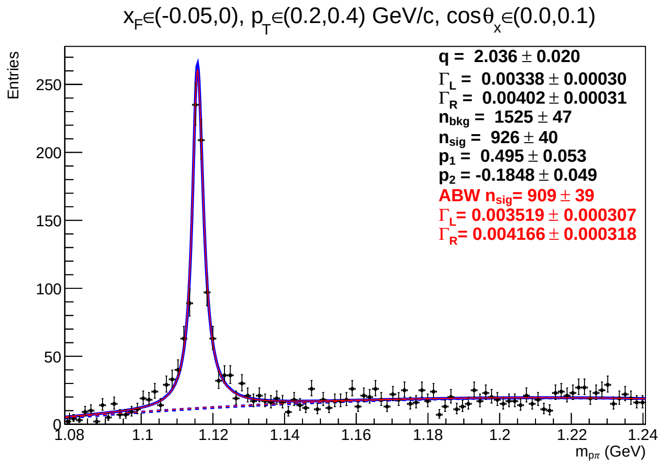
For details, see Eur. Phys. J. C (2016) 76: 198.

m_{inv} distributions fitting procedure

Signal as asymmetric q-Gaussian (Breit-Wigner if $q = 2$):

$$S(m) = N\left[1 + (q-1)\frac{(m - m_\Lambda)^2}{0.25\Gamma^2}\right]^{-\frac{1}{q-1}}$$

Background part is fitted with 2nd order polynomial.

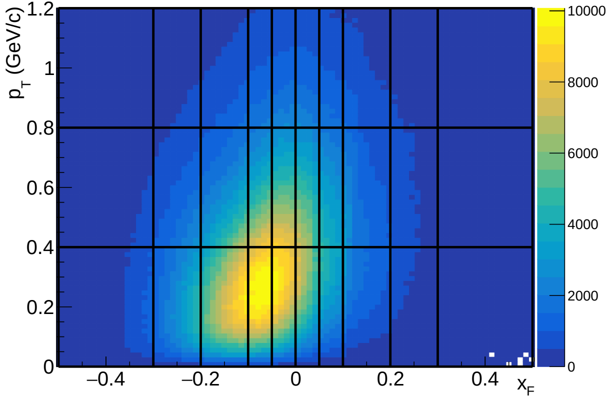


Red line - asym. Breit-Wigner, blue - asym. q-Gaussian, dashed lines - background fit

MC correction on MC data (closure test)

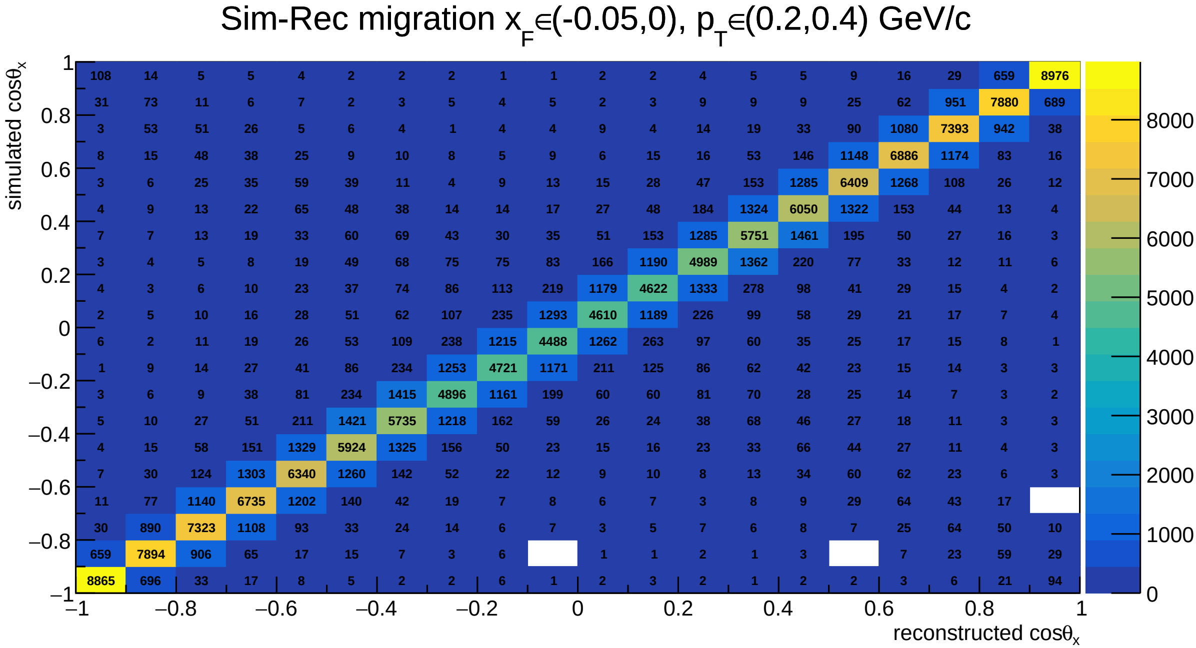
Divide into bins $(x_F, p_T, \cos\theta_j)$,
$\cos\theta_j$: 20 bins in $[-1, 1]$.
Unfolding methods:
2. Response matrix inversion.
3. Bayesian Unfolding: (init guess is uniform, then update using Bayes' theorem).

Used MC models are EPOS and FTFP (we expect $P_x \equiv P_y \equiv 0$).

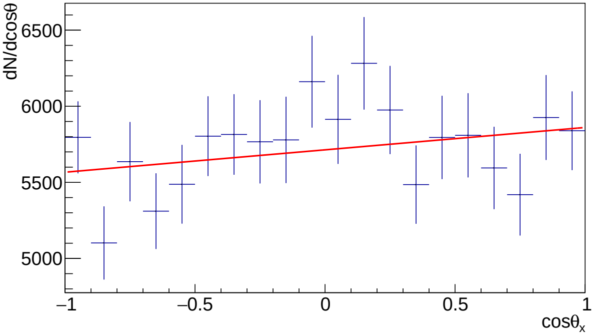


Λ candidates in EPOS MC after data selection cuts

Response Matrix: FTFP

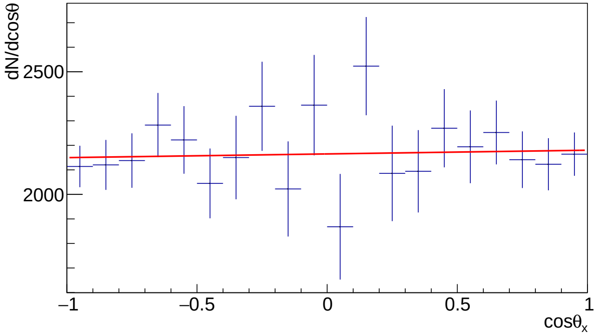


EPOS data unfolded by inversion using FTFP model



$$P_x(\%) = 3.5 \pm 2.4$$

$$x_F \in (-0.5, -0.3), p_T \in (0.8, 1.2)\ \text{GeV}/c$$



$$P_x(\%) = 1.0 \pm 2.6$$

$$x_F \in (-0.05, 0), p_T \in (0.8, 1.2)\ \text{GeV}/c$$

Summary

- NA61/SHINE has a large potential to study Λ transverse polarization in p–p and p–A collisions.
- Magnetic field impact on Λ polarization due to precession is zero within stat. uncertainty.
- EPOS-FTFP correction: introduced bias up to several % that may be treated as systematic uncertainty.
- Data (31 mln of inelastic p–p events) is currently under analysis.

Thank you!

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