On measurements of Λ transverse polarization in p+p interactions within NA61/SHINE at the CERN SPS

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Outline

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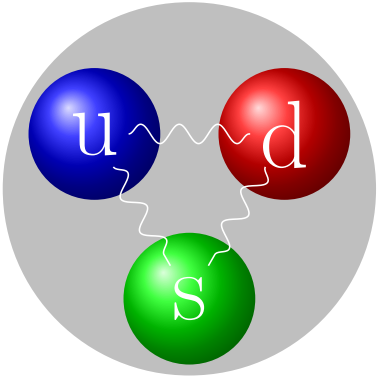
- Polarization bias due to Λ selection cuts and limited detector acceptance
- Polarization bias due to magnetic field
- Summary

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%)

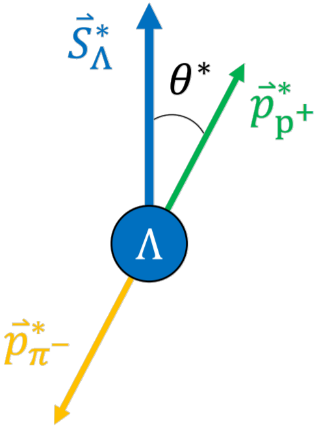


In the weak decay $\Lambda \to p + \pi^-$, daughter proton distribution function has the following form:

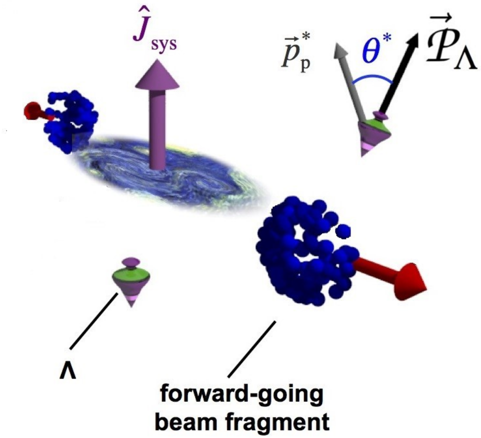
$$\frac{dN}{d\Omega} = \frac{1}{4\pi}(1 + \alpha \cos\theta^*),$$

where θ^* is the angle between daughter proton momentum and Λ spin vector in hyperon rest frame, and $\alpha = 0.732 \pm 0.014$.

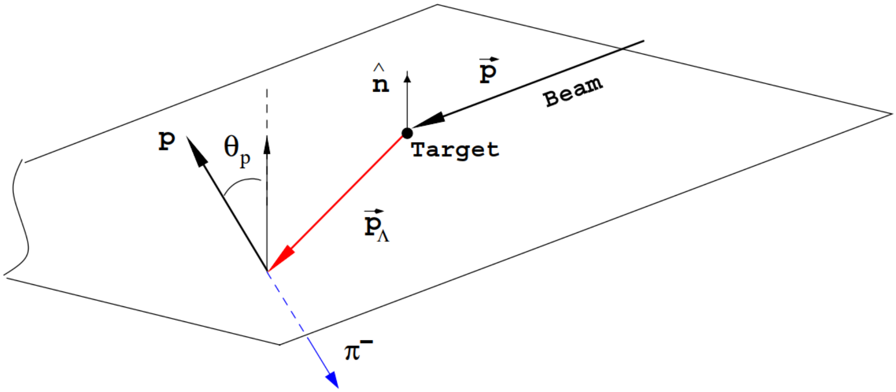
PDG 2020



Global and transverse Λ polarization



Global polarization (2017 STAR paper in Nature)

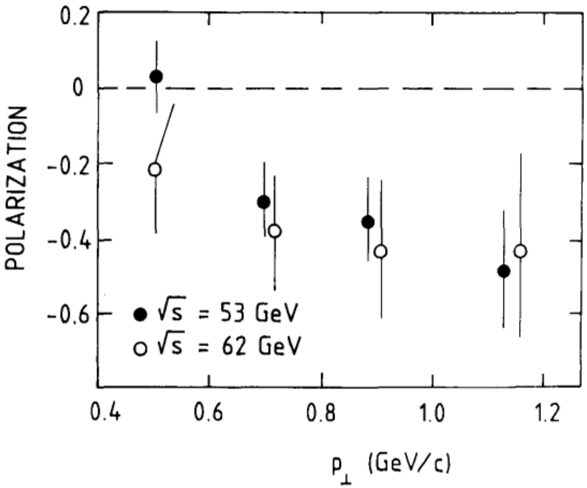


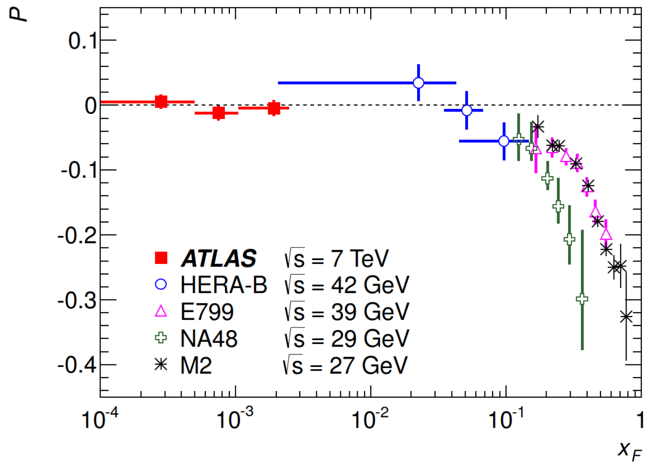
Transverse polarization (since 1975)

Nature 548, 62–65 (2017); Int. J. Mod. Phys. A 1990.05:1197-1266.

Pics: BNL, Yu. Naryshkin.

World p-p and p-A transverse polarization data





Λ polarization in the p-p interaction as a function of transverse momenta $p_\perp$ measured at the CERN Intersecting Storage Rings (1979).

The Λ transverse polarization measured by ATLAS (pp), HERA-B (pC, pW), NA48 and E799 (pBe), and M2 (pN) experiments.

Apostolos D. Panagiotou, Int. J. Mod. Phys. A 1990.05:1197-1266.

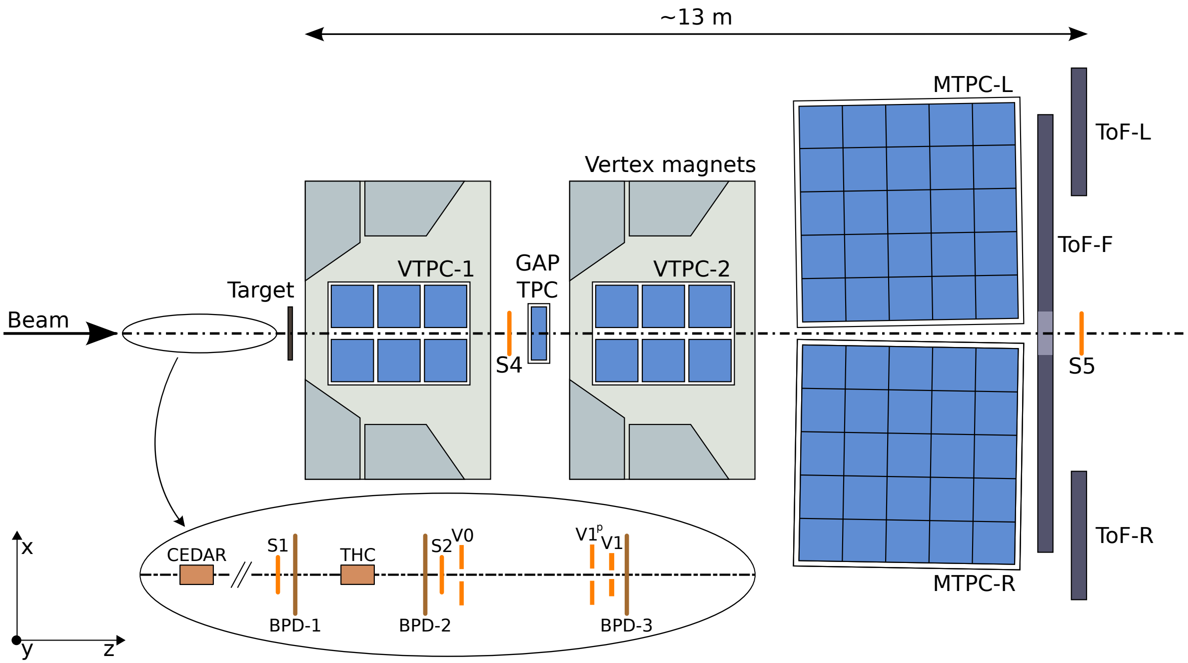
ATLAS Collaboration, Phys. Rev. D 91, 032004 (2015).

Motivation

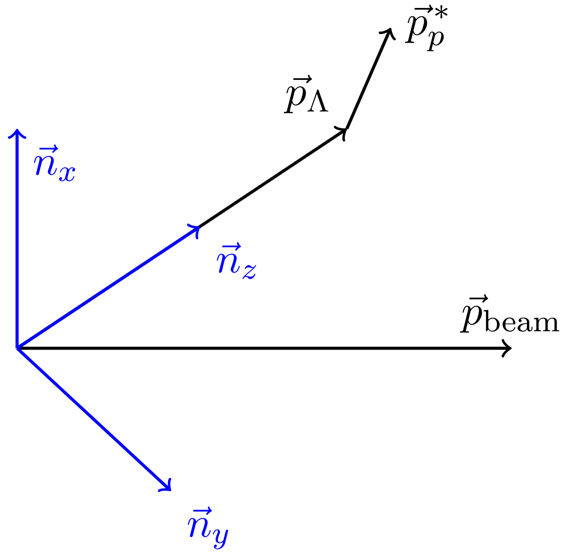
- None of the theoretical models describes well all experimental data on Λ polarization, its dependence on the transverse momentum of the hyperon and on the Feynman variable x_F
- These models are unsuccessful to predict polarizations for all hyperons and antihyperons

NA61/SHINE experimental setup for p+p (2009–2011)

15M p+p events were recorded



Transverse polarization definition and calculation



Production plane coordinate system:

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

$$\hat{n}_z = \frac{\vec{p}_\Lambda}{|\vec{p}_\Lambda|}$$

$$\hat{n}_y = \hat{n}_z \times \hat{n}_x$$

- Rotate from NA61 frame to Production plane coordinate system.
  $\vec{p}' = (\hat{n}_x \cdot \vec{p}_p, \hat{n}_y \cdot \vec{p}_p, \hat{n}_z \cdot \vec{p}_p)$
  $\vec{p}'_\Lambda = (0, 0, |\vec{p}_\Lambda|)$
- boost along $\hat{n}_z$ to Λ rest frame: $\beta = |\vec{p}_\Lambda|/E_\Lambda, \gamma = (1-\beta^2)^{-1/2}$.
  proton momentum: $\vec{p}_p^* = (p'_x, p'_y, \gamma(p'_z - \beta\sqrt{\vec{p}'^2 + m_p^2}))$

Transverse polarization definition and calculation

- Calculate cosine of angles between $\vec{p}_p^*$ and axes:

$$\cos\theta_i^* = \frac{p^*_{p\,i}}{\left|\vec{p}_p^*\right|},\ i = x, y, z$$

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

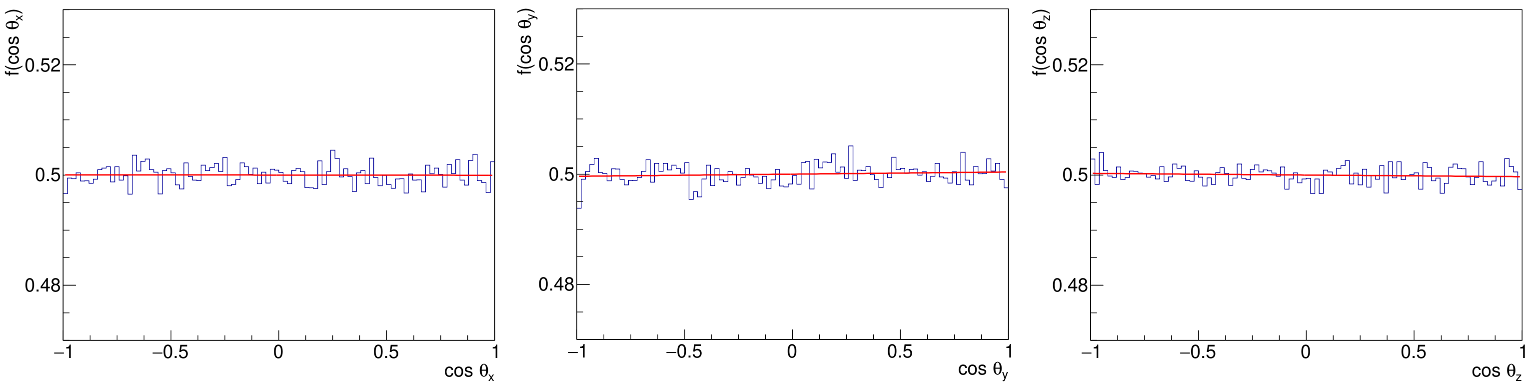
$$f(\cos\theta_i^*) = \frac{1 + \alpha P_i \cos\theta_i^*}{2},$$

where $\alpha = 0.732 \pm 0.014$.

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 for checking the systematic uncertanties.

Monte Carlo analysis

- 10^8 events of inelastic p+p simulated within EPOS & Geant3 at 158 GeV/c beam momentum
- In Geant3, $P_x \equiv 0$: no Λ polarization.
- 10^7 Λ's with $p\pi^-$ channel
- Crosscheck – distributions of $\cos\theta_i$:



$P_x = (-1.3 \pm 8.8) \cdot 10^{-4}$ $\quad P_y = (10.8 \pm 8.8) \cdot 10^{-4}$ $\quad P_z = (-8.1 \pm 8.8) \cdot 10^{-4}$

Phys. Rev. C **74** 044902 (2006); CERN Program Library Long Writeup W5013 (1993)

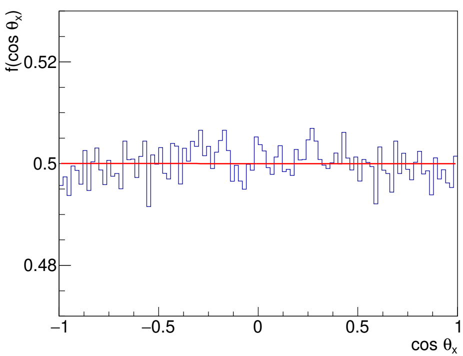
Bias due to Λ selection cuts and limited detector acceptance

Selection cuts$^{(*)}$ were applied:

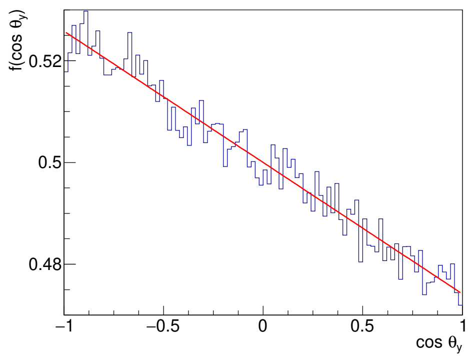
- Z difference between Λ vertex and primary vertex $\Delta z = z_{\Lambda} - z_{PV}$:

$$\begin{cases} \Delta z > 10 \text{ cm}, \ y < 0.25 \\ \Delta z > 15 \text{ cm}, \ 0.25 < y < 0.75 \\ \Delta z > 40 \text{ cm}, \ 0.75 < y < 1.25 \\ \Delta z > 60 \text{ cm}, \ y > 1.25 \end{cases}$$

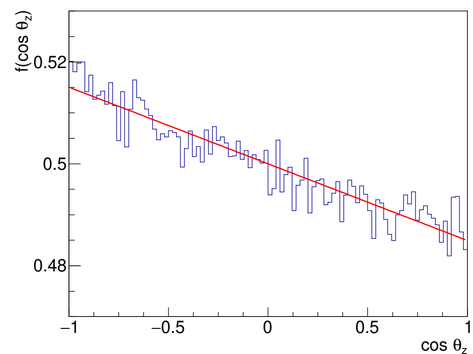
- Number of points in VTPC's >10 for both p and π^- tracks



$P_x = (-0.08 \pm 1.5) \cdot 10^{-3}$



$P_y = (-7.1 \pm 0.2) \cdot 10^{-2}$



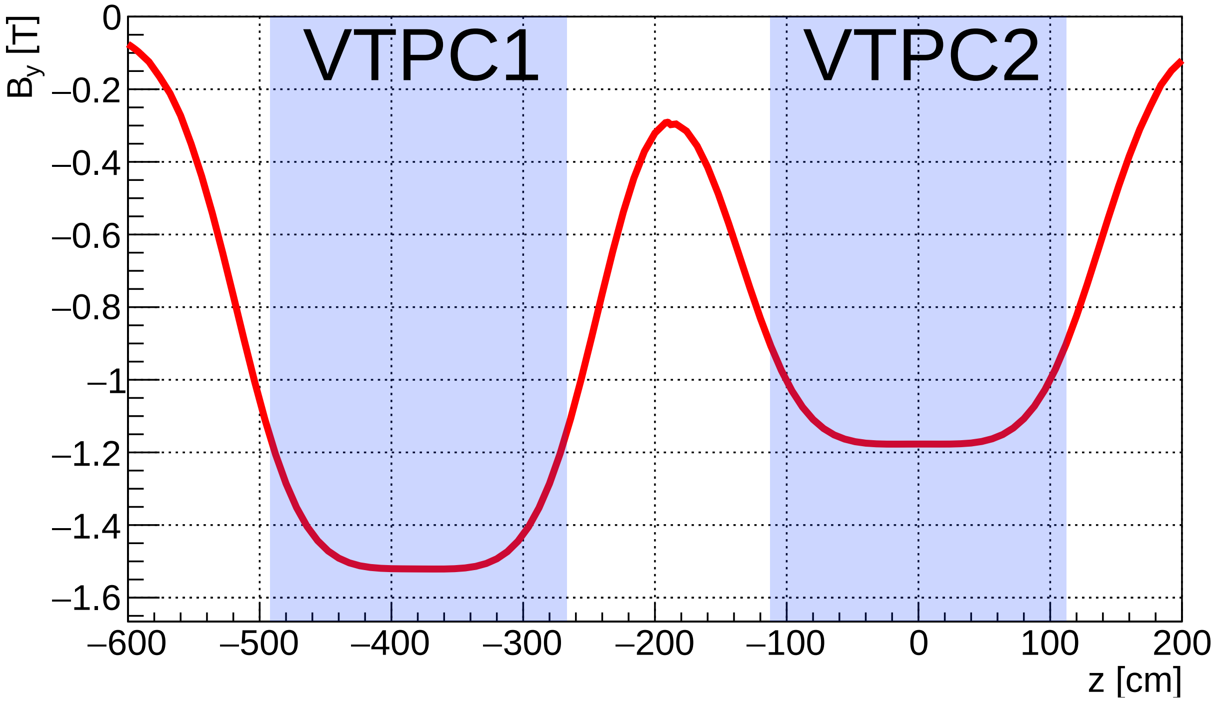
$P_z = (-4.1 \pm 0.2) \cdot 10^{-2}$

$^{(*)}$Eur. Phys. J. C (2016) 76: 198

Bias due to magnetic field

Strong magnetic field and its gradient!

How does it influence on polarization of Λ?



Λ precession: theory

Covariant equation of spin motion:

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

S^α - spin 4-vector, u^α - velocity 4-vector, μ - particle's magnetic moment.
Last term can be neglected (no force on Λ, see backup slide).
The equation of motion of the spin vector $\vec{S}$ in Λ rest frame is

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

where μ_N - nuclear magneton, $\mu_\Lambda = -0.613$[PDG] - Lambda magnetic moment in μ_N units, $\vec{B'}$ - magnetic field in rest frame in terms of lab magnetic field $\vec{B}$ (neglect electric field in Lab frame):

$$\vec{B'} = \gamma \vec{B} - (\gamma - 1)(\vec{B} \cdot \hat{p})\hat{p}, \qquad \hat{p} = \vec{p_\Lambda}/|\vec{p_\Lambda}|.$$

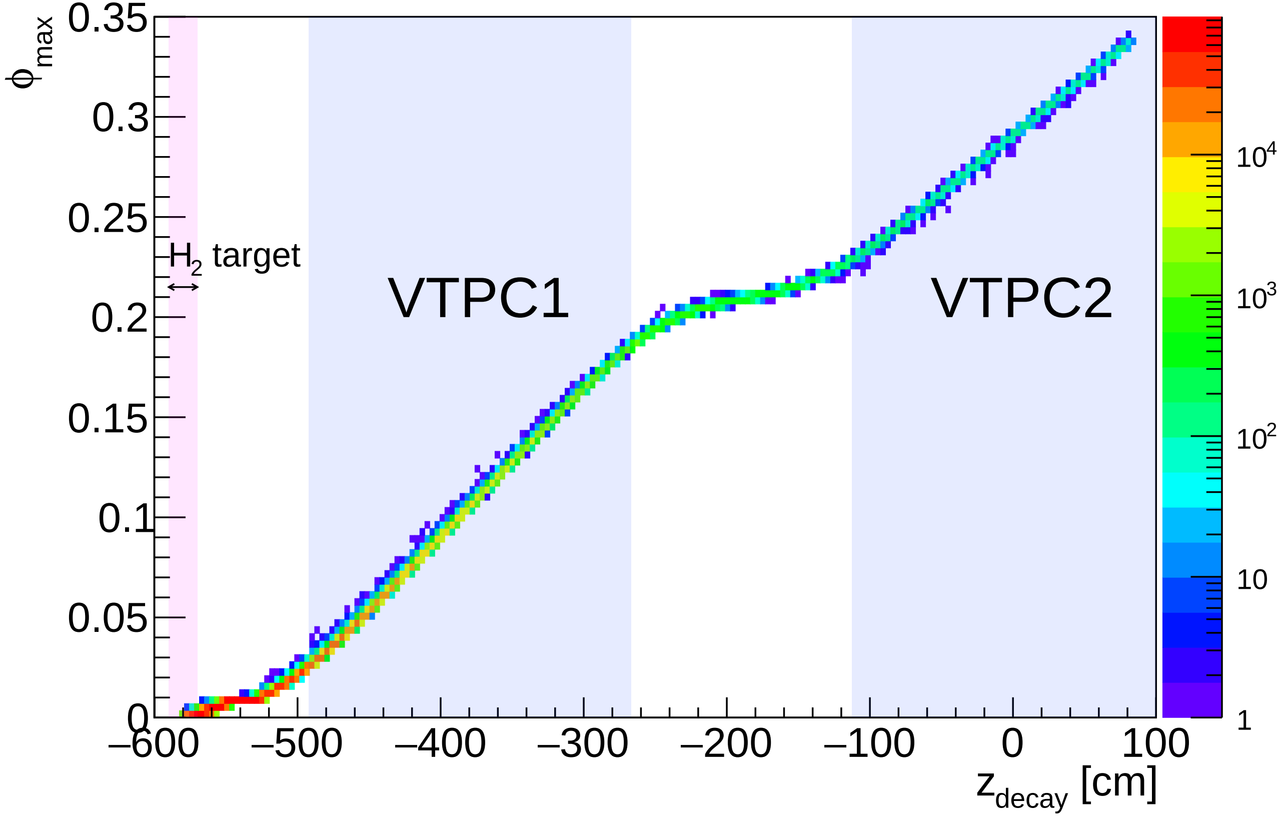
Λ precession: spin equation application

Considering $dz = \frac{p_z}{mc} c d\tau$, **The equation of motion of the spin vector $\vec{S}$ in Λ rest frame takes the form:**

$$\frac{d\vec{S}}{dz} = \frac{\mu_\Lambda \mu_N}{c\hbar(p_z/mc)} \left[\vec{S} \times \vec{B}'(x,y,z)\right]$$

Integrate with step $\Delta z = 1$ cm using NA61/SHINE magnetic field.
Initial condition: generate random 1000 spin vectors $\vec{S}$ uniformly distributed on unit sphere + 100 spin vectors $\vec{S}$ uniformly distributed on XZ plane.
Among these 1100 vectors, choose one with maximum angle change, $\phi_{\max} = \max(\angle(\vec{S}_{init}, \vec{S}_{final}))$.

ϕ_{max} dependence on z_{decay}



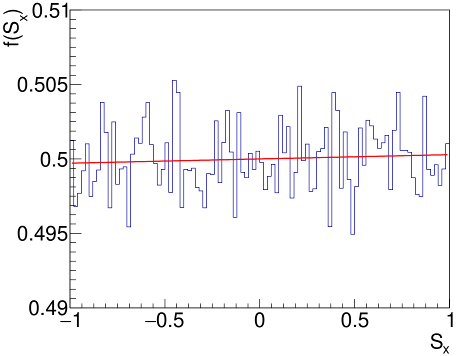
Magnetic field impact on Λ polarization estimation

How does magnetic field impact on Λ polarization?

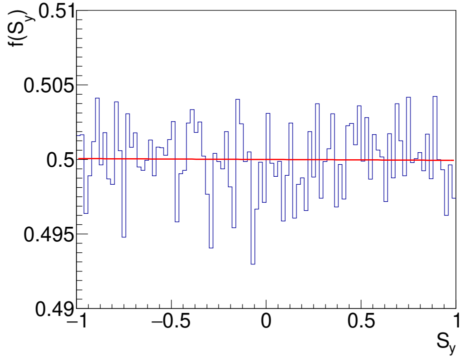
To estimate such effect, for every Λ,

- 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.

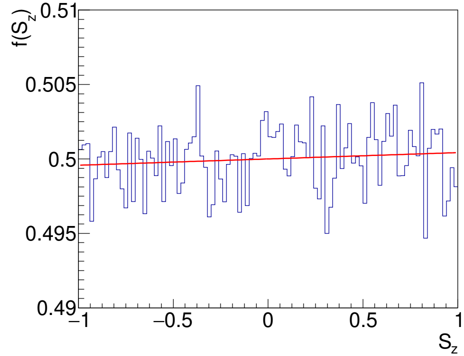
Distribution of $\vec{S}_{\text{init}}$ (before precession):



$P_x = (0.8 \pm 1) \times 10^{-3}$

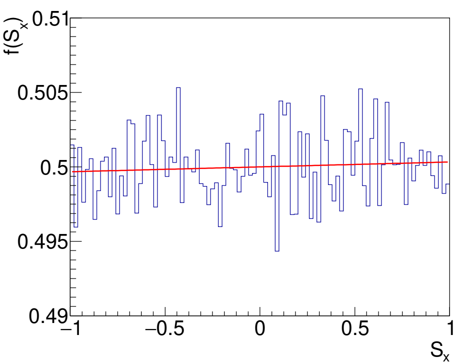


$P_y = (-0.2 \pm 1) \times 10^{-3}$

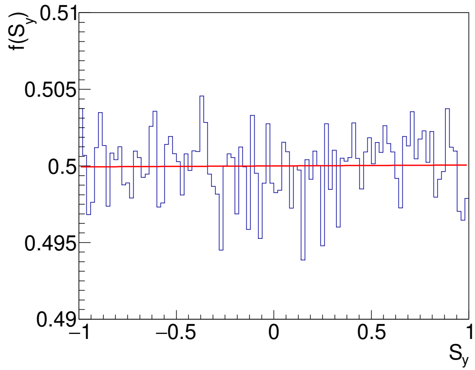


$P_z = (1.2 \pm 1) \times 10^{-3}$

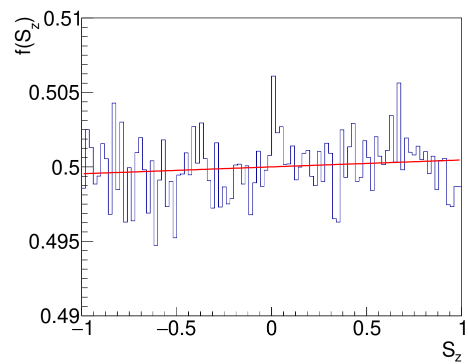
Distribution of $\vec{S}_{\text{final}}$ (after precession):



$P_x = (0.9 \pm 1) \times 10^{-3}$



$P_y = (0.2 \pm 1) \times 10^{-3}$



$P_z = (1.3 \pm 1) \times 10^{-3}$

Despite ϕ_{max} is significant, polarization bias is $\sim 10^{-4}$ due to averaging over all Λs.

Summary

- NA61/SHINE has a large potential to study Λ transverse polarization in p–p and p–A collisions.
- Geometrical acceptance significantly biases the result and it should be taken into account via MC corrections.
- Magnetic field impact on Λ polarization due to precession is smaller than detector acceptance-based polarization bias.
- To limit possible precession-based bias, $\Delta z < 1$ m ($\phi_{\mathrm{max}} < 0.05$) cut can be used.

Next step: proceed to analyse real p-p data at 158 GeV/c beam momentum.

Thank you!

Backup Slides

Gradient force

Covariant equation of spin motion:

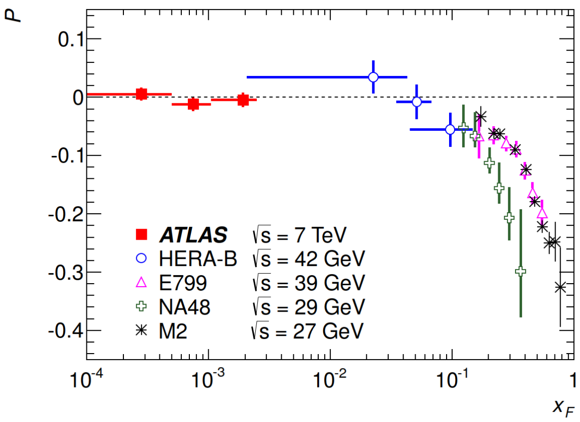
$$\frac{dS^\alpha}{d\tau} = \mu \left[F^{\alpha\beta} S_\beta + u^\alpha \left(S_\lambda F^{\lambda\mu} u_\mu \right) \right] - u^\alpha \left(S_\lambda \frac{du^\lambda}{d\tau} \right)$$

Estimate impact of force $\vec{F} = \vec{\nabla}(\vec{m} \cdot \vec{B}) = \sum_k m_k \vec{\nabla} B_k$.
In lab frame, magnetic field change by $\Delta B_y = 1.5$ **T**
over distance along z axis $L = 1.5$ **m**.
Due to dime dilation, $L = \gamma c \tau$, $\gamma \approx 19$, $p_\Lambda \approx 21$ **GeV/c**,
where τ is Λ mean lifetime.
Nuclear magneton $\mu_N = 3 \cdot 10^{-8}$ **eV/T**,
Λ magnetic moment $|\vec{m}| \approx 0.6 \mu_N$.
In rest frame, the momentum change: $\Delta \vec{p} = \vec{F} \cdot \tau = m_y \vec{\nabla} B_y \tau$.
Even if $\vec{m}$ aligned with y axis,

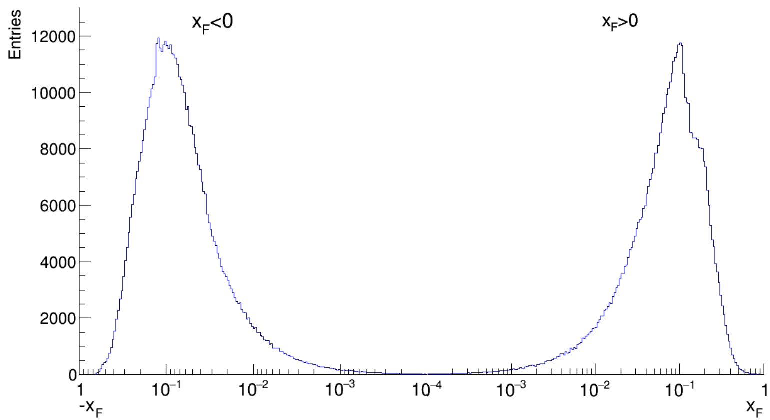
$$\Delta p_z = 0.6 \mu_N \frac{\gamma \Delta B_y}{L/\gamma} \tau \approx 5 \cdot 10^{-7} \ \mathbf{eV/c}$$

Speed: $v/c \approx 5 \cdot 10^{-16}$.
Max spin vector change: $\left| \Delta \vec{S} \right| \sim (v/c)^2 \sim 10^{-31}$.

x_F distribution



The Λ transverse polarization measured by ATLAS compared to measurements from lower center-of-mass energy experiments.



x_F distribution