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Dzhelepov Laboratory of Nuclear Problems

FINAL REPORT ON THE SUMMER STUDENT PROGRAM

"Transverse Single-Spin Asymmetry for inclusive η mesons at forward rapidity in SPD-NICA"

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Abstract

There is experimental evidence of non-zero and increasing transverse spin asymmetry values for inclusive pions and η mesons at forward rapidities. It seemingly contradicts pQCD theoretical predictions that the transverse spin effects should be suppressed at leading twist. Understanding the large transverse spin asymmetries could help to clarify spin-momentum correlations in initial and final state interactions. The Spin Physics Detector (SPD), aimed to study the spin structure of the proton and deuteron and other spin phenomena with polarized beams at a collision energy up to $\sqrt{s} = 27\ \mathrm{GeV}$, is a good opportunity to measure light mesons at forward rapidities, where the largest transverse spin effects have been observed. In this report, we present an estimation of the accuracy level that can be expected in the measurements of the transverse single spin asymmetry for the inclusive η mesons in SPD. This is investigated with Monte Carlo simulations in the frame of the SpdRoot code.

Introduction

The proton spin in terms of its constituent particles, after more than 40 years of research, is not fully understood yet. At the beginning, the simplest model of the proton spin structure assumed that valence quarks would carry all the proton spin, so one could expect that the total spin, being the proton a fermion (spin = ½) would be the direct sum of two parallel quark spins and one antiparallel. This was tested with deep inelastic electron-nucleon scattering (DIS) experiments and culminated in the 1987 experiment by the European Muon Collaboration (EMC), which found that only a small fraction of the spin (~30%) is carried by quarks, giving rise to what was called "proton spin crisis."

The polarized structure of the proton is a fundamental issue in Quantum Chromodynamics (QCD). This is the theory that describes the strong interaction between the quarks and gluons. After an exhaustive study of QCD, it has been possible to predict that the proton spin comes from the total quark spin, the gluon spin contributions and the orbital angular momentum of both quarks and gluons. The determination of the contribution of each of these elements, could give rise to a solution to the proton spin crisis. However, it remains largely unexplored the orbital momentum effects, as well as the contributions not yet constrained of the sea quark-antiquark pairs and gluons which carry a fraction of the proton's momentum, being a still unsolved problem in particle physics. That continues to be one of the key priorities of the scientific community today.

The Spin Physics Detector (SPD), is a universal facility for studying the nucleon spin structure and other spin-related phenomena with polarized beams of protons and deuterons. It is under construction and will be installed at one of the two points of interaction of the Nuclotron based Ion Collider facility (NICA). It will have the typical barrel geometry of collider detectors, where the particle tracking and identification capabilities is based on modern technologies. It offers a unique possibility to operate with polarized proton and deuteron beams at a collision energy up to $27\ \mathrm{GeV}$ and a luminosity up to $10^{32}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ [*1*].

Sizeable single transverse-spin asymmetries (A_{N}), as large as 40%, has been observed in a variety of experiments with polarized hadrons. These non-zero A_{N} cannot originate from hard-partonic scattering, therefore the sizeable A_{N} could be explained from spin-momentum correlations in initial and final state interactions. The measurements of the A_{N} provides a good opportunity to better understand the strong interaction and hadron structure, since it is connected to the transverse motion of partons inside the transversely polarized hadron. The A_{N} determination for the inclusive η meson are related to the Sivers, Collins and Boer-Mulders transverse momentum, being the quarks the main contributors [*1*]. In the future measurements in the SPD experiment, this could be an important source of information about quark TMD functions.

The objective of the analysis resumed in this report was to estimate the accuracy level with which it is possible determine the transverse single spin asymmetry for inclusive η mesons from p+p collisions, detected in the ECAL-endcaps of SPD.

The A_{N} of the η meson

The A_{N} dependence of hadron cross sections in $p^{\uparrow}p$ reactions in the energy regime where pQCD is applicable, was initially predicted to be almost zero. Namely, the transverse spin effects should be suppressed in the simplest parton topology. However, experiments carried out in FERMILAB in the nineties, observed not negligible values of A_{N} in measurements at forward rapidity, of inclusive π^0[*2*], $\pi^{\pm}$ [*3*] and η mesons [*4*] from $p^{\uparrow} + p$ @ $\sqrt{s} = 19.4\ \mathrm{GeV}$, well within the energy range of pQCD. These results are shown together in the left panel of figure 1. Later experiments from PHENIX and STAR collaborations showed that the A_{N} is nearly independent of the collision energy. They measured the A_{N} of inclusive neutral pions and η mesons in transversely polarized proton-proton collisions covering a wide energy range $\sqrt{s} = 19.4 - 500\ \mathrm{GeV}$.

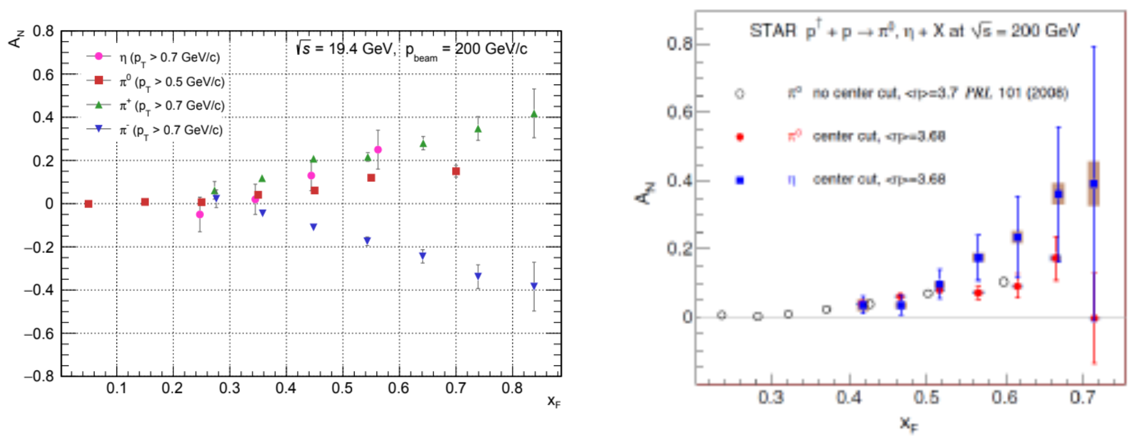

Figure 1. Transverse single spin asymmetry versus x_{F} for inclusive π^0 and η production, using polarized proton beams at $\sqrt{s} = 19.4\ \mathrm{GeV}$ (left) and $\sqrt{s} = 200\ \mathrm{GeV}$ (right).

The A_{N} of η mesons, just like that of pions, starts to be different from zero at $0.3 < x_{\mathrm{F}} < 0.4$ and exhibits values larger from those of π^0 in its upward trend. Different theoretical approaches have been suggested to account for the experimental values of spin asymmetry, i.e. the Sivers effect, the Collins effect, the collinear twist-3 formalism and a sort of combinations of them. The transverse single-spin asymmetry was measured by the STAR collaboration, for the π^0 and η mesons in parallel, at $\sqrt{s} = 200\ \mathrm{GeV}$, where the x_{F} was extended to 0.75 (Fig. 1b). It led to a result according to which the $\mathrm{A_N}(\eta)$ is 2.2 standard deviations larger than $A_{\mathrm{N}}(\pi^0)$ for $0.55 < x_{\mathrm{F}} < 0.75$[*5*]. Here, a pQCD based model was applied, suggesting that $\mathrm{A_N}(\eta)$ can be understood within the framework of pQCD. The model generated an $\mathrm{A_N}(\eta)$ that is much larger than that of the π^0, by assuming a considerable initial-state effect for strange quarks, although is yet unknown if a similar difference can arise from the fragmentation process via the Collins effect.

The analyzing power is used to measure the transverse single-spin asymmetry, and can be defined as,

$$A_N\left(p^{\uparrow} + p \to \pi^0 + X\right) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \quad (1)$$

where $\sigma^{\uparrow}$ and $\sigma^{\downarrow}$ denote the inclusive production cross-sections with opposite transverse polarization of one of the colliding particles. There are not many measured data in the energy range of SPD. In this work, the azimuthal spin asymmetry for η mesons is determined through the Monte Carlo simulation of inclusive η mesons detected in the end-caps of the SPD electromagnetic calorimeter. The end-caps of ECAL cover a pseudo-rapidity of $1.3 < |\eta| < 3.8$. Since in the beams cannot be polarized in our Monte Carlo simulations, the asymmetries are expected to be zero. We estimate the accuracy of the asymmetry, by using the statistical errors of the A_{N} values obtained in this simulation and combining them with the values A_{N} measured by the STAR collaboration [4].

Monte Carlo simulations

The simulations are performed in the frame of SpdRoot version 4.1.5. This is the offline software for the SPD experiment, stemmed from FairRoot and aimed to perform simulations and analysis devoted to SPD. It contains experiment-specific libraries and script artifacts which permits to gather information about the interactions occurring in the detector environment during the experiment.

An amount of $\sim 10^8$ inelastic $p + p$ interactions were generated using Pythia 8 as particle generator, configured for minimum bias, with a Gaussian distributed vertex smeared with $\sigma_z = 30\ cm$ and $\sigma_{x,y} = 0.1\ cm$. Two collision energies were studied: $\sqrt{s} = 10$ GeV and $\sqrt{s} = 27$ GeV. Only photons with $E_\gamma > 0.4$ GeV were accepted in the endcaps of ECAL, and η mesons were reconstructed through the invariant mass of the two-photon combinations. A cut on the transverse momentum, $p_T > 0.5\ \mathrm{GeV}/c$, was imposed for photon pairs. The M_{inv} spectra were fitted with the sum of a normalized Gaussian function for the η peak and a 2^{nd} degree polynomial to account for the combinatorial background:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} exp\left[-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2\right] + p_1 + p_2 x + p_3 x^2 \quad (2)$$

The η yield, was extracted from the combinatorial invariant mass distribution with a peak mass windows defined in $\pm 3\sigma$.

Figure 2 shows the yield of η mesons in $(x_{\mathrm{F}}, p_{\mathrm{T}})$ bins, in the 2π azimuthal coverage of the right endcap of the ECAL. It was estimated for 10 minutes of data taking for $\sqrt{s} = 10$ GeV and $\sqrt{s} = 27$ GeV. Here it can be seen the region that is expected to be covered in SPD for each mentioned energy. At $\sqrt{s} = 27$ GeV the transverse momentum of η mesons extends to $p_{\mathrm{T}} = 2.5\ \mathrm{GeV}/c$ in the interval $0.1 < x_{\mathrm{F}} < 0.8$, with the mean p_{T} increasing with x_{F} up to $\langle p_T \rangle = 1.14\ \mathrm{GeV}/c$. At $\sqrt{s} = 10\ \mathrm{GeV}$ the x_{F} coverage is extended to $x_{\mathrm{F}} = 0.9$ with mean transverse momenta not exceeding $\langle p_T \rangle = 0.8$ (Fig. 3).

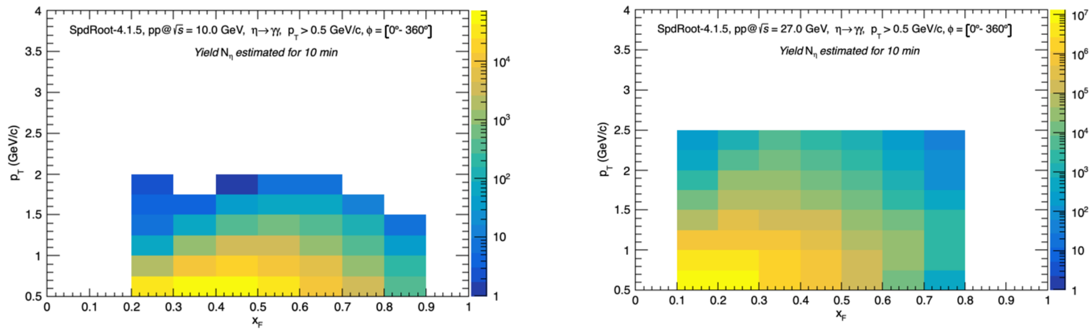

Figure 2. Kinematic topology of reconstructed η mesons in the right endcap of ECAL, for $\sqrt{s} = 10\ \mathrm{GeV}$ (left) and $\sqrt{s} = 27\ \mathrm{GeV}$ (right).

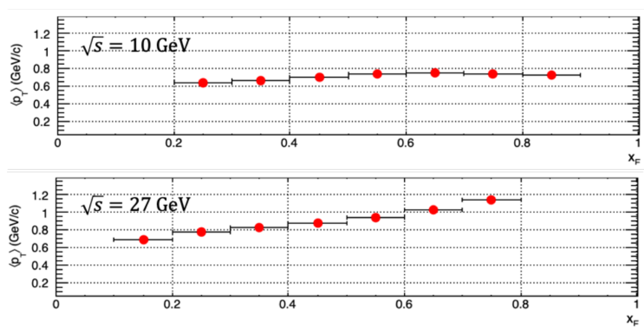

Figure 3. Kinematic topology of reconstructed η mesons in the right endcap of ECAL, for $\sqrt{s} = 10\ \mathrm{GeV}$ (upper) and $\sqrt{s} = 27\ \mathrm{GeV}$ (lower).

Extraction of A_{N}

The analyzing power is an asymmetry in the azimuthal distribution of the particles. In order to extract it, we should keep in mind that in presence of polarized beams the azimuthally dependent cross section can be written as following,

$$\frac{d\sigma}{d\phi} = \frac{d\sigma}{d\phi_0}[1 + P \cdot A_{\mathrm{N}} \cdot \cos(\phi)] \tag{3}$$

where, $\frac{d\sigma}{d\varphi_0}$ is the unpolarized differential cross section, P is the vertical beam polarization, and A_{N} is the analyzing power. In terms of yields it can be formulated as,

$$N_\eta(\phi) = N_{\eta_0}[1 + P \cdot A_{\mathrm{N}} \cdot \cos(\phi)] \tag{4}$$
$$N_\eta(\phi) = 1 + amp \cdot \cos(\phi) \tag{5}$$

The azimuthal coverage, 2π, of each ECAL endcap is divided into eight azimuthal bins. For each ϕ bin, the N_η was determined as function of x_F being $\Delta x_F = 0.1$. The statistical uncertainty of the η-mesons yield was calculated as $\sqrt{N_\eta}$. An example of fitted invariant mass spectra in one of the eight azimuthal sectors in which the ECAL endcap was divided, is shown in figures 4 and 5, for $\sqrt{s} = 10$ GeV and $\sqrt{s} = 27$ GeV, respectively. The η-mesons yield was determined from the integral of the Gaussian peak (red line in the plots) in a mass windows limited by $\pm 3\sigma$.

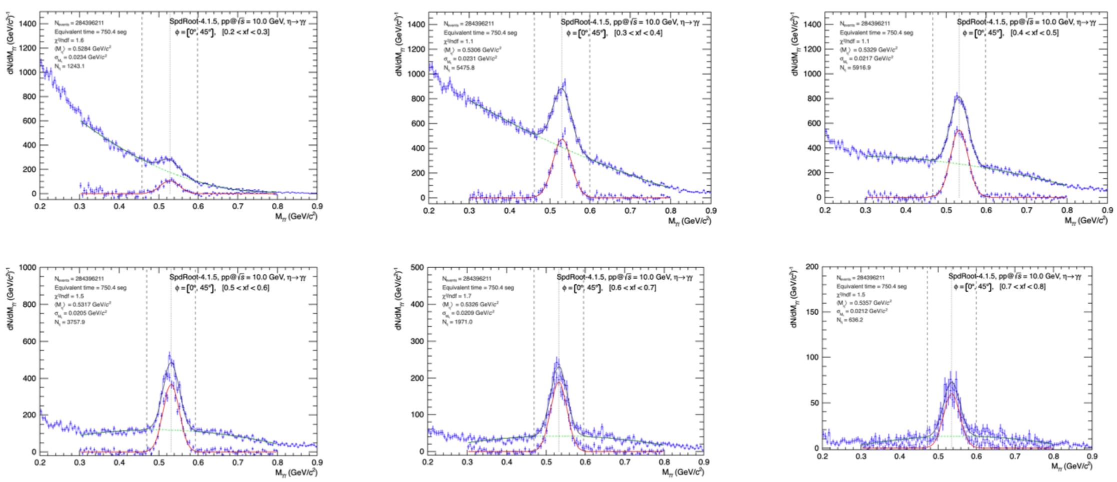

Figure 4. Invariant mass spectra ($\sqrt{s} = 10$ GeV) for one of the eight azimuthal sectors of the ECAL endcaps, $\phi = [0 - 45]$ deg. The vertical dot lines represent the mass window, from where the yield of η mesons was extracted.

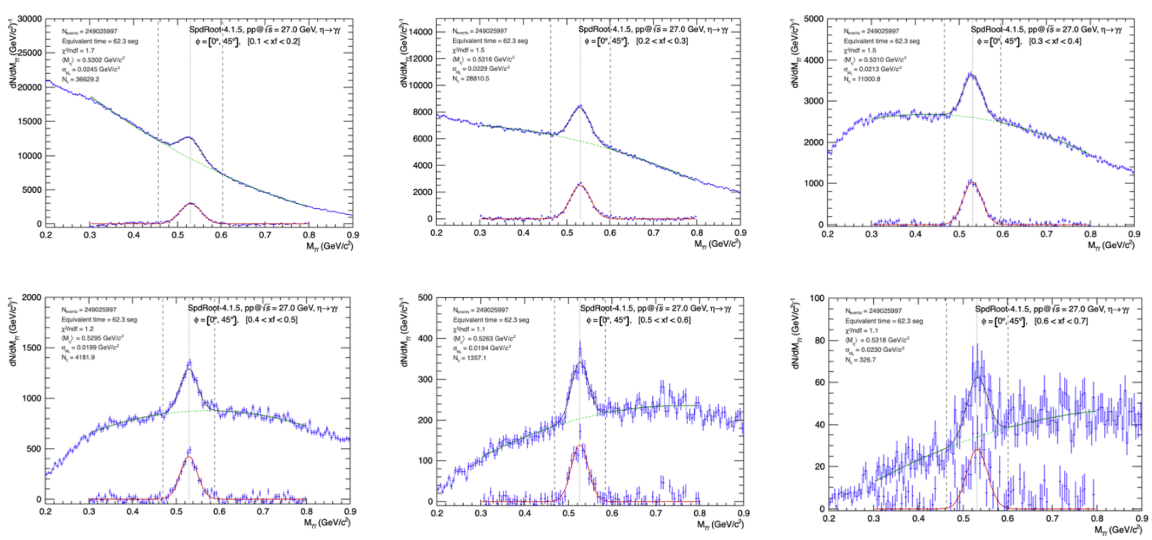

Figure 5. Invariant mass spectra ($\sqrt{s} = 27$ GeV) for one of the eight azimuthal sectors of the ECAL endcaps, $\phi = [0 - 45]$ deg. The vertical dot lines represent the mass window, from where the yield of η mesons was extracted.

The $N_\eta vs.\phi$ was plotted for each x_{F} interval, and fitted with the cosine function (Eq. 5). The A_{N} can be extracted from amplitude term (amp) of the cosine function, assuming that the beam polarization is $P = 0.7$. The statistical error of the A_{N} was taken from the uncertainty of the fit parameter corresponding to the amplitude term. The cosine fittings for six x_{F} intervals, at $\sqrt{s} = 10\ \mathrm{GeV}$ and $\sqrt{s} = 27\ \mathrm{GeV}$, respectively (Figs. 6,7).

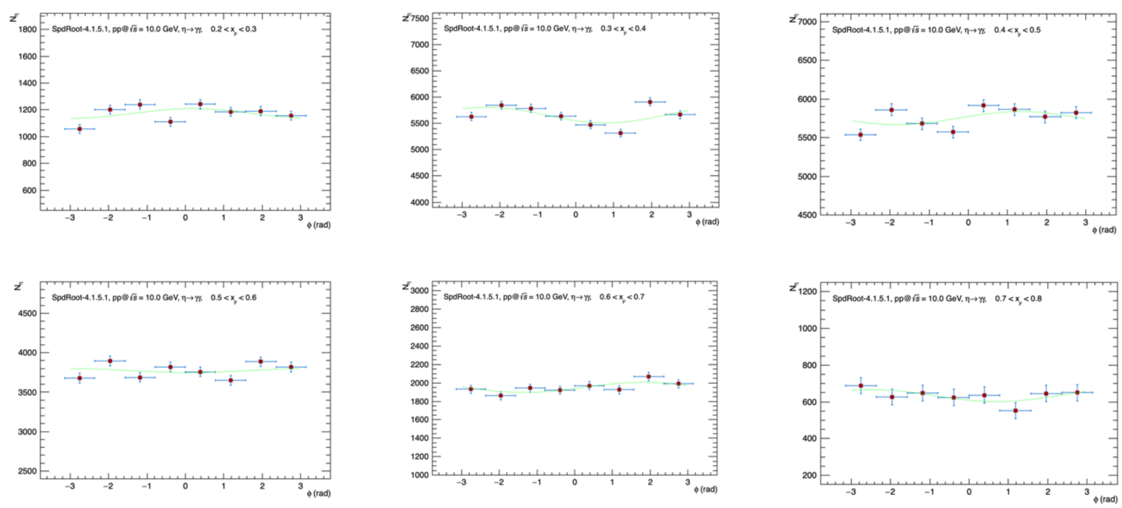

Figure 6. Cosine modulation fittings of $N_\eta(\phi)$ in six x_{F} intervals at $\sqrt{s} = 10\ \mathrm{GeV}$.

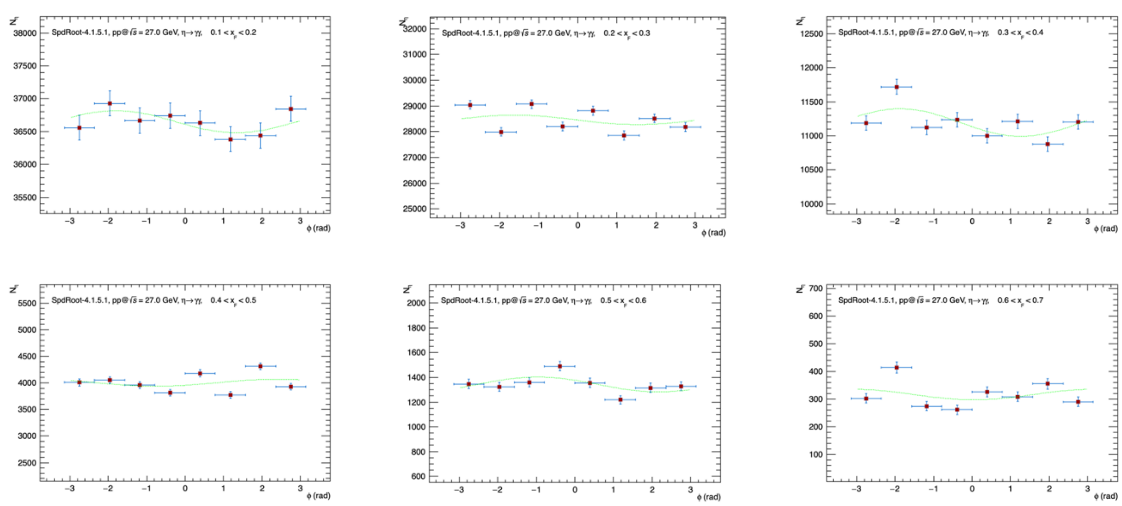

Figure 7. Cosine modulation fittings of $N_\eta(\phi)$ in six x_{F} intervals at $\sqrt{s} = 27\ \mathrm{GeV}$.

The extracted single spin asymmetries as function of x_{F}, are shown in figure 8. One can observe that A_{N} values deviate from zero and carry larger errors al higher x_{F}, which reveals the scarce statistics in this kinematic region. The asymmetry values are consistent with zero, because the simulation was based on non-polarized beams. However, the error bars, arisen from the fit parameter corresponding to the amplitude of the cosine function, make possible to compare this estimation with the results reported by the E704 Collaboration at $\sqrt{s} = 19.4$ GeV [4].

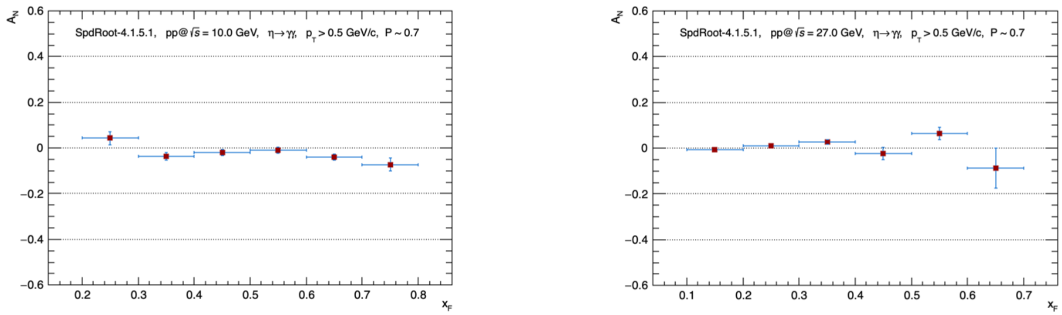

Figure 8. Single spin asymmetry A_{N} vs. x_{F} of inclusive η mesons at $\sqrt{s} = 10$ GeV (left) and $\sqrt{s} = 27$ GeV (right).

Estimation of the relative error of A_{N}

The relative error ($\Delta A_{\mathrm{N}}/A_{\mathrm{N}}$) in three intervals of x_{F} are shown in figure 9 as function of estimated times of data-taking ranging from 2min to 60min. This calculation was based on the statistical uncertainties (ΔA_{N}) obtained in this work and the data of A_{N} reported by the experiment [4], which corresponds to the three x_{F} points where $A_{\mathrm{N}} \neq 0$. The expected event rates in SPD, for $\sqrt{s} = 10$ GeV and 27 GeV are about 0.38 MHz and 4MHz, respectively.

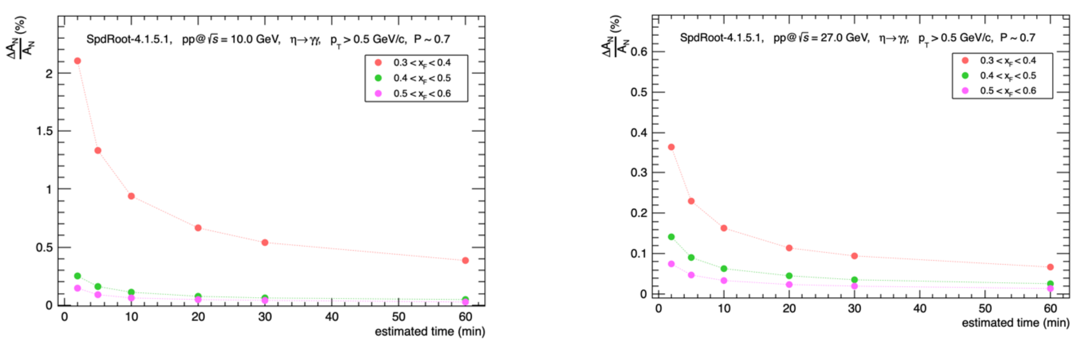

Figure 9. Relative errors of A_{N} vs. estimated time of data taking, in three x_{F} intervals, at $\sqrt{s} = 10$ GeV (left) and $\sqrt{s} = 27$ GeV (right).

Figure 9 suggests that a better precision of the A_{N} measurement for inclusive η mesons, is expected at $0.5 < x_F < 0.6$, and after 10 minutes of data taking, under the assumption that the beam polarization is stable. If we look at the A_{N} data of the E704 experiment [4], we note that at $x_{\mathrm{F}} > 0.3$ the asymmetry is linear increasing (Fig. 10). We estimated the relative error by taking the three points with non-zero asymmetries according with the experimental data and evaluating them in the following expression,

$$\frac{\Delta A_N}{A_N} = 1 \Big/ \sqrt{\sum_i \frac{1}{\delta_i^2}} \quad \text{, where } \delta_i = \Delta A_{\mathrm{N_i}}/A_{\mathrm{N_i}} \qquad (6)$$

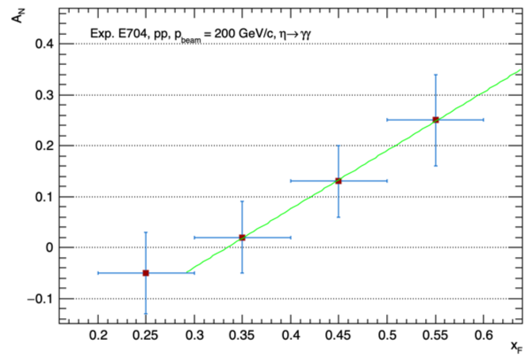

Figure 10. Experimental results from the E704 collaboration, of A_{N} vs. x_{F} for the inclusive η-mesons produced with a polarized proton beam ($p_{\mathrm{beam}} = 200\ \mathrm{GeV}$) and a fix target [4].

The obtained $\Delta A_{\mathrm{N}}/A_{\mathrm{N}}$, was scaled to different times of data taking (see Table 1).

Estimated time	$\Delta A_{\mathrm{N}}/A_{\mathrm{N}}$ (η mesons)	
	$\sqrt{s} = 10\ \mathrm{GeV}$	$\sqrt{s} = 27\ \mathrm{GeV}$
2 min	12.60 %	6.54 %
5 min	7.97 %	4.14 %
10 min	5.63 %	2.93 %
20 min	3.98 %	2.07 %
30 min	3.25 %	1.69 %
1 h	2.30 %	1.19 %

Table 1. Estimated relative errors of A_{N} for the the inclusive η-mesons production in transverse polarized proton collisions in SPD.

Conclusions.

The statistical accuracy of the A_{N}, for inclusive η mesons, at $\sqrt{s} = 10\ \mathrm{GeV}$ and $27\ \mathrm{GeV}$, in SPD ECAL endcaps, was estimated for different times of data taking assuming stable polarization. The estimated relative errors are based in the statistical uncertainties of the A_{N} obtained in the present analysis, combined with the A_{N} data measured by FNAL E704 collaboration, corresponding to a collision energy equivalent to $19.4\ \mathrm{GeV}$. For this analysis, it was also taken into account that the transverse single spin asymmetry is nearly independent of the collision energy, which has been extensively demonstrated in measurements of neutral pions, but not so much for η mesons. We plan to extend this simulation analysis to other mesons, and, in all cases it is necessary to further work in a detailed analysis of the detector performance for those particle detections.

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References.

[1] Abazov V M et al. (The SPD Collaborations). (2021). Conceptual design of the Spin Physics Detector. DOI: 10.48550/arXiv.2102.00442.

[2] Adams D L et al. (The FNAL-E581/E704 Collaborations). (1992). Large-x_F Spin Asymmetry in π^0 Production by 200 GeV Polarized Protons. *Z. Phys. C*, 56, 181 – 184.

[3] Adams D L et al. (The FNAL-E704 Collaboration). (1991). Analyzing power in inclusive π^+ and π^- Production at High x_F with 200 GeV Polarized Proton Beam. *Phys. Lett. B* 264, 462 - 466.

[4] Adams D L et al. (The FNAL-E704 Collaboration). (1998). Measurement of single spin asymmetry in η-meson production in $p_\uparrow p$ and $\vec{p}_\uparrow p$ interactions in the beam fragmentation region at 200 GeV/c. *Nucl. Phys. B* 510, 3 - 11.

[5] Adamczyk L et al. (The STAR Collaboration). (2012). Transverse Single-Spin Asymmetry and Cross-Section for π^0 and η Mesons at Large Feynman-x in $p^\uparrow + p$ Collisions at $\sqrt{s} = 200\ \mathrm{GeV}$. *Phys. Rev. D* 86, 051101.