Local polarimetry with π^0 in SPD at NICA

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Abstract. The Spin Physics Detector (SPD) will be installed in the second interaction point of the Nuclotron-based Ion Collider fAcility (NICA) at the Joint Institute for Nuclear Research in Dubna. The main goal is to study the spin structure of the proton and deuteron, and other spin-related phenomena with polarized proton and deuteron beams at a collision energy up to $\sqrt{s} = 27$ GeV and luminosity up to 10^{32} cm^{-2}s^{-1}. For local polarimetry and luminosity control in SPD, several detectors are proposed. This work presents an analysis of the possibilities of using the inclusive $p + p \to \pi^0 + X$ reaction, in the end-caps of the electromagnetic calorimeter (ECAL) for local polarimetry purposes. The accuracy of the azimuthal asymmetry of this reaction, as a measure of the beam polarization, is investigated with Monte Carlo simulations in the frame of the SpdRoot code.

1. Introduction

The main objective of SPD is to investigate polarized phenomena in order to disentangle crucial issues of the nucleon spin physics. In this context, the polarimetry plays an important role. It is necessary to have a good monitoring of polarization and luminosity, trying to make the number of ions that are polarized in the needed direction as large as possible. At the same time, spin-dependent physical observables have to be extracted from the spin asymmetry measurements, which in turn, should be correctly scaled according to the degree of the beam polarization.

Measurement and monitory systems in NICA are planned to provide precise, relative and absolute determination of the polarization degree of the beams. However the major polarimetry methods provide an information which needs to be cross-checked locally in each detector experiment. The local online monitoring of the beam polarization, with independence of the major polarimeters, should help to reduce the systematic errors coming from polarization variations.

In SPD, the transverse single-spin azimuthal asymmetry can be exploited to measure the degree to which the beam polarization is transverse (vertically or radially) or longitudinal. The main challenge of the local polarimetry in SPD is the lack of data from pp collisions in the energy range of a few MeV's up to $\sqrt{s} = 27$ GeV ($\sqrt{s}$ is the center-of-mass energy). Several detectors are suggested to participate in the local polarimetry. Such is the case of the Beam-Beam Counters

(BBC) which are intended to measure the azimuthal asymmetry of inclusive charge particles, and the Zero Degree Calorimeter (ZDC) that will measure very forward neutrons. In addition, the use of the inclusive $p + p \to \pi^0 + X$ reaction, where π^0s are detected in the end-caps of the ECAL is suggested in the conceptual design of SPD [1]. The later is investigated in this work.

The transverse-single asymmetry (A_{N}) is the ratio of the difference to the sum, of the spin dependent cross sections with opposite transverse polarizations. In this case, only one of two colliding protons is transversely polarized:

$$A_{\mathrm{N}}(p^{\uparrow} + p \to \pi^0 + X) = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \tag{1}$$

The A_{N} dependence of hadron cross-sections in $p^{\uparrow}p$ ($\overline{p}^{\uparrow}p$) reactions in the energy regime where perturbative QCD (pQCD) is applicable, is expected to be negligibly small in the lowest-order QCD approximation. According the leading-twist pQCD expectations the A_{N} should be suppressed at the partonic level as $\frac{\alpha_{\mathrm{s}} m_{\mathrm{q}}}{\sqrt{s}}$, where α_{s} is the coupling constant of QCD and m_{q} is the quark mass. Hence, spin asymmetries cannot be successfully described within a simple collinear and leading-twist parton model [2]. By the other hand, several experiments have shown non-negligible spin-dependent asymmetries of pions produced via transversely polarized proton beams. Such is the case of the sizeable asymmetry values observed in inclusive charge [3, 4] and neutral pions [5–8] produced in $p^{\uparrow}p$ ($\overline{p}^{\uparrow}p$) reactions, mainly at large x-Feynman, $x_{\mathrm{F}} = 2p_{\mathrm{L}}/\sqrt{s}$, where p_{L} is the momentum of the pion along the beam direction. This apparent contradiction with pQCD calculations has motivated new theoretical works along with additional experimental studies in order to interpret the non-zero asymmetries in hadron reactions where partonic QCD descriptions are more relevant, thus clarifying the transverse spin structure of the proton. Different, but mutually supportive approaches have been suggested in order to account for the experimental values of spin asymmetry, i.e. the Sivers effect [9], the Collins effect [10], the collinear twist-3 formalism [11], and sort of combination of them.

Results of the transverse single spin asymmetry of π^0, π^+ and π^-, obtained by the collaborations E704 and E581, are shown on the left panel of figure 1. Data exhibit large A_{N} values, that increase at $x_{\mathrm{F}} \geq 0.3$. Their signs follow the polarization of the valence quarks in the pions. The A_{N} of π^0 is almost twice smaller than for charge pions, however, the advantage for π^0 is that it can be selected in a relative easy way through the invariant mass of the two-photon decay, not requiring the track reconstruction. This becomes a convenient option for polarimetry purposes.

The right panel of figure 1 shows the result of A_{N} vs. x_{F} in transversely polarized proton-proton collisions at forward rapidities in a wide energy range. The asymmetries are nearly independent of the collision energy. The p_{T} cut applied in those measurements was 0.5, 1.0, 1.2 and 2 GeV/c for $\sqrt{s} = 19.4$, 62.4, 200 and 500 GeV, respectively.

Given the lack of data in the collision energy range that will be covered by SPD, in this work, the expected accuracy level for future polarimetry measurements is estimated on the basis of the azimuthal spin asymmetry of inclusive π^0 produced in pp collisions at $\sqrt{s} = 27$ GeV and detected in the end-caps of the SPD electromagnetic calorimeter (ECAL).

Unpolarized Monte Carlo simulation was used to estimate the expected statistical accuracy of the beam polarization. On this basis, the asymmetry can not be estimated. However, we can evaluate the statistical uncertainties from the π^0 yields of our simulation and, consequently combine them with the A_{N} values measured by the E704 Collaboration at Fermilab [5]. This enables to estimate the accuracy of the beam polarization measurements for any expected amount of data.

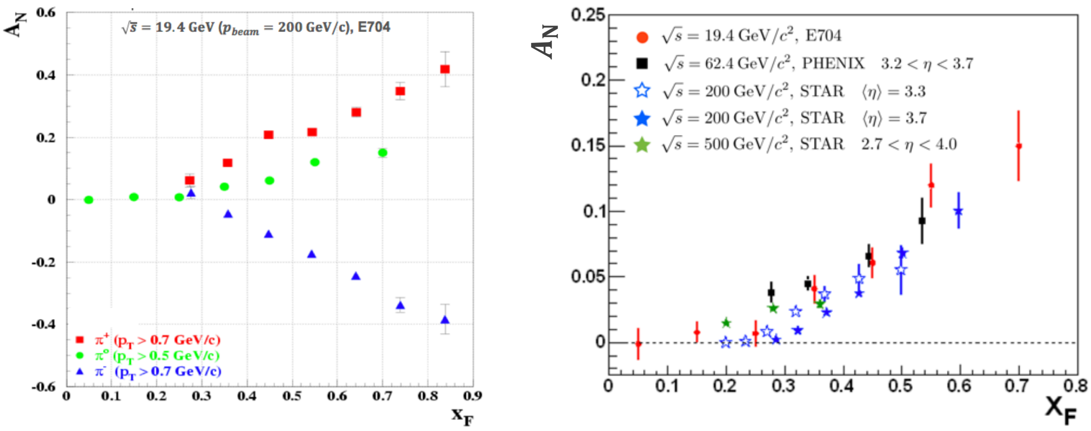

Figure 1. Transverse-single spin asymmetry $A_{\rm N}$ versus $x_{\rm F}$ for inclusive pion production, using 200 GeV ($\sqrt{s} = 19.4$ GeV) polarized proton beams, $p^{\uparrow\downarrow}p \to \pi^{\pm,0}$ [5] (left), and for $A_{\rm N}(\pi^0)$ at different collision energies [5, 7, 12, 13] (right).

2. Monte Carlo simulations

The Monte Carlo simulations of inelastic pp interactions, were performed using the offline software of the SPD experiment, SpdRoot version 4.1.6, which stems from the FairRoot software. The simulation step makes use of Geant4 tools [14] to transport the particles through the detector geometry. The multipurpose generator Pythia 8 [15], was used to produce $\sim 10^8$ pp collisions at $\sqrt{s} = 27$ GeV. This amount of generated events corresponds to the number of collisions produced in $\sim 47s$ ($\sigma^{pp}_{27{\rm GeV}} = 40$ mb, $L = 10^{32}$ cm^{-2}s^{-1}). The generation was configured for minimum bias (SoftQCD:inelastic), which in principle excludes elastic topologies.

The local polarimetry is an online procedure that requires fast reconstruction of the particle under consideration, which means that the information on the vertex position along the beam axis is unknown. For the present analysis the primary vertex was assumed at the origin $(0, 0, 0)$ in the event generation stage. In addition, it was smeared in accordance with the beam parameters adopted for NICA, consisting of a Gaussian with $\sigma_z = 30$ cm and $\sigma_{xy} = 0.1$ cm [16].

Photon candidates are reconstructed from energy deposits (clusters) in the ECAL, in an effort to address a more realistic scenario. Clusters belonging to the ECAL end-caps are selected with $E^{\gamma}_{min} = 400$ MeV in order to filter out some background. This is a rather conservative criterion is based on the measurement of the passage of vertical muons through the SPD-ECAL allowing to estimate the mean of the MIP (minimum ionizing particle) signal to be 240 MeV, with an energy resolution of 9.6% [1]. The two-photon decays are required to have $p_{\rm T} > 0.5$ GeV/c.

According to the current geometrical parameters of the ECAL, implemented in SpdRoot, the active part of the ECAL end-caps, covers the region of intermediate and near-forward pseudorapydity, $1.3 < |\eta| < 3.8$.

Two analysis methods are proposed in this work to extract the statistical uncertainty of the asymmetry. The first one is based in the cosine modulation fitting of the π^0 yield which is deduced from the signal of the invariant mass distribution. The second method uses the raw π^0 yield and makes the necessary corrections for the background. For both, π^0 candidates are reconstructed from the two-photon invariant mass spectra that are fitted with the combination of a normalized Gaussian signal and a 2^{nd} degree polynomial background. The first method is based on the π^0_s yields obtained by integrating the background–subtracted peak within 3σ from the mean value of the π^0 position. The second method, based on the raw π^0 yield includes all counts under the normal Gaussian plus polynomial distribution within a defined mass windows. The integral errors are calculated from the covariance matrix.

3. Statistical uncertainty $\sigma_{A_{\mathrm{N}}}$ of the asymmetry

The A_{N} is defined as the ratio $\frac{\sigma^{\uparrow}-\sigma^{\downarrow}}{\sigma^{\uparrow}+\sigma^{\downarrow}}$ of the difference to the sum of cross sections with opposite transverse polarizations (up$^{\uparrow}$/down$^{\downarrow}$) of the colliding particles. This asymmetry has to do with the spin of only one beam that is polarized on an axis perpendicular to the momentum. Therefore, A_{N} depends on the azimuth of the observable, that is to say, the π^0 yield ($N_{\pi^0}(\phi)$) from pp collisions. The uncorrected transverse asymmetry, is first order an azimuthal cosine modulation. Hence, assuming that the beam polarization is known, the transverse asymmetry can be represented in terms of N, as follows,

$$\frac{1}{P}\frac{N^{\uparrow}(\phi) - RN^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + RN^{\downarrow}(\phi)} = 1 + A_{\mathrm{N}}\cos(\phi), \tag{2}$$

being $R = L^{\uparrow}/L^{\downarrow}$ the relative luminosity between the polarized crossings having spin up and spin down, respectively. Similarly, we have the azimuthally dependent cross section, relying on the spin dependence of π^0 yields in presence of polarized beams. In this case the A_{N} is the amplitud of azimuthal angular modulation of the cross section of the outgoing scattered particles with respect to the transverse spin direction of the polarized proton,

$$\frac{d\sigma}{d\phi} = \frac{d\sigma}{d\phi}_0 (1 + P \cdot A_{\mathrm{N}}\cos(\phi)), \tag{3}$$

$$N_{\pi^0}(\phi) = 1 + b \cdot \cos(\phi), \tag{4}$$

here $\frac{d\sigma}{d\phi}_0$ is the unpolarized differential cross section and P is the beam polarization. The equation 4 presents the pure cosine function (ϕ_0 =0) in a simplified approach. In principle, a free phase ($\phi_0 \neq 0$) should be added to check for deviations of the beam polarization from the vertical direction. In real situations, a constant term $\neq 0$ might be also added to account for the relative luminosity effects that could deviate from $R = 1$.

3.1. Method 1: Extraction of $\sigma_{A_{\mathrm{N}}}$ from the cosine modulation coefficient

Each ECAL end-cap covers 2π in azimuth, having the hole for the beam pipe in the center. In this analysis, each end-cap was divided in 8 azimuthal sectors (ϕ bins). For each ϕ bin counts N_{π^0} were determined in 6 x_{F} intervals, assuming Poisson distribution on N_{π^0} so that the statistical uncertainty of yields obeys $\sigma_{\mathrm{N}} = \sqrt{N}$. The invariant mass distributions of $\gamma\gamma$ pairs for six x_{F} intervals in one of the eight ϕ bins ($90^{\circ}-135^{\circ}$) is shown in figure 2. The fit of the normalized gaussian signal after the background subtraction is represented with a blue line, while the 2^{nd} degree polynomial fitted background is represented with green line. In the interval $x_{\mathrm{F}} = [0.5, 0.6]$ there is not apparent π^0 signal allowing us to make a proper fit, as can be seen in the sixth panel of the figure 2.

Yields N_{π^0}, for each x_{F} interval, are plotted as function of ϕ and fitted with a cosine function $f(x) = a_0 \cdot (1 + a_1 \cdot cos(a_2 + x))$ based on Eq. 4. Consequently, A_{N} can be extracted from the modulation amplitud $a_1 = P{\cdot}A_{\mathrm{N}}$, where the polarization was assumed as $P = 0.7$. The statistical uncertainty $\sigma_{A_{\mathrm{N}}}$ is the error of the fit parameter corresponding to the amplitud modulation a_1.

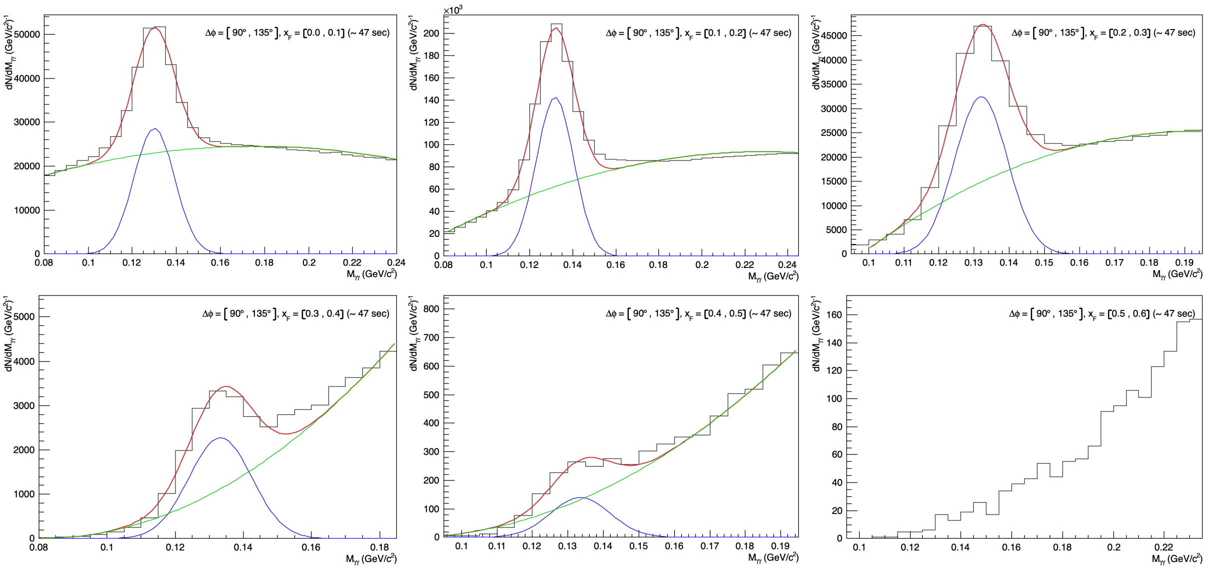

Figure 2. Invariant mass of photon pairs, for 6 $x_{\rm F}$ intervals in the azimuthal bin $\Delta\phi = [90^\circ, 135^\circ]$ in the ECAL end-cap, $z > 0$. The photon pair transverse momentum is $p_{\rm T} > 0.5$.

The cosine fittings for five $x_{\rm F}$ intervals, at $\sqrt{s} = 27$ GeV are shown in figure 3. It can be noted that the lower π^0 yields correspond to the higher $x_{\rm F}$ values.

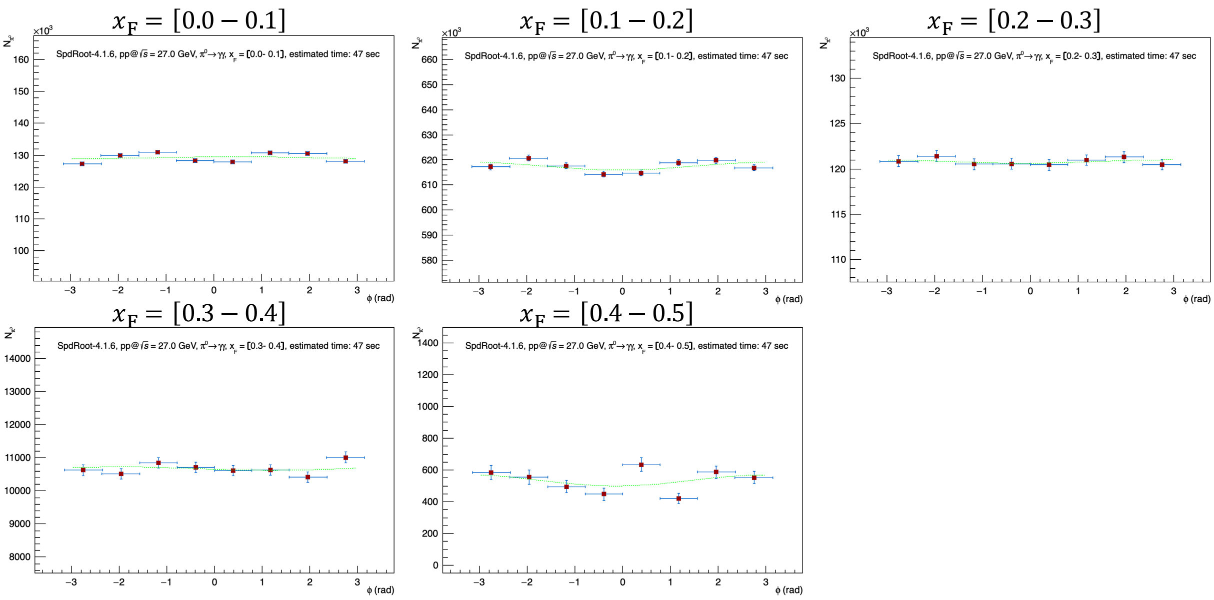

Figure 3. Cosine modulation fittings of $N_{\pi^0}(\phi)$ in $x_{\rm F}$ intervals at $\sqrt{s} = 27$ GeV.

The π^0 yields for each $x_{\rm F}$ are uniformly distributed in ϕ bins (Fig. 3). In such circumstances, the proposed analysis method relies on the cosine fit of a flat distribution. For evaluating the reliability of this analysis strategy a simple toy model was created, where two distributions are generated within the same limits $(-\pi, \pi)$, one is flat $(y = 1)$ and the other one outlines a more realistic scenario with a cosine distribution $(1 + [0] \cdot cos(x))$. Both distributions were fitted with the same cosine modulation function $(f(x) = [1] \cdot (1 + [0] \cdot cos(x + [2])))$. The uncertainty of the modulation coefficient was extracted from both fits and finally the two case estudies were compared.

In the left panel of figure 4 the uncertainties of the modulation coefficients, obtained from both cases, were plotted for nine modulation sizes in both cases of study. The uncertainties extracted from the fitting of the flat distribution (red circles) remain constant, while for the cosine modulation (black circles) the uncertainties gradually decline with the increasing of the modulation size. The fraction of both uncertainties is depicted in the right panel of this figure. It can be observed that the uncertainties extracted from the fit of the flat distribution slightly exceeds the cosine modulated one, thus reaching $\sim$10% for a modulation size equal to 0.5. This suggests that σ_{A_N} can be estimated with this method, in a reasonably precise way.

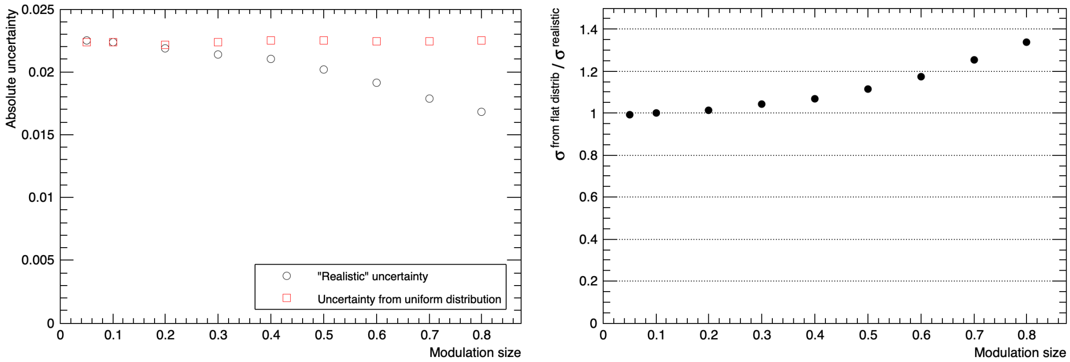

Figure 4. Simple toy model to study the reliability of extracting the statistical uncertainty of the modulation coefficient from the cosine fit of a uniform distribution. Left: uncertainty of the modulation coefficient in both cases (details on the text) vs. modulation size. Right: fraction of both uncertainties vs. modulation size.

The statistical uncertainty σ_{A_N} extracted from the cosine modulation fittings shown in figure 3, are shown in figure 5 as function of x_F. These values of σ_{A_N} make possible to compare this estimation with the results that came out from the scarce experimental data of asymmetry for $\sqrt{s} = 19.4$ GeV, reported by the collaboration E704 in Fermilab [5].

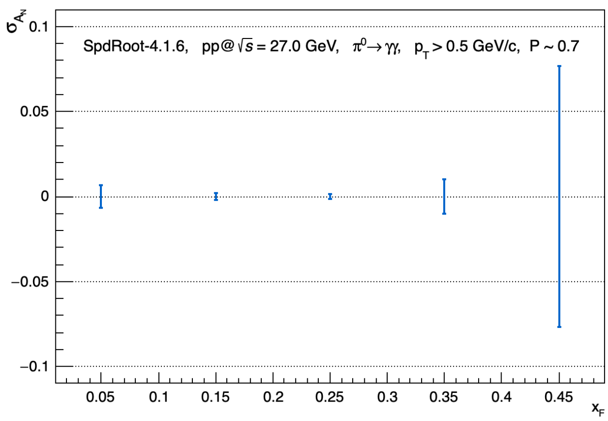

Figure 5. Statistical uncertainty of A_N for inclusive π^0 in simulated pp collisions at $\sqrt{s} = 27$ GeV, using the modulation coefficient of the cosine fitting. No correction for the background was done.

3.1.1. Estimation of the relative error of the polarization. The relative errors of the asymmetry δA_{N} have been calculated by using the statistical uncertainties $\sigma_{A_{\mathrm{N}}}$ obtained in this simulation and the experimental values of A_{N}^{exp} reported by the experiment E704 [5] which are assumed as the true values in the expression $\delta A_{\mathrm{N}} = \sigma_{A_{\mathrm{N}}}/A_{\mathrm{N}}^{exp}$. This allows to have an estimate of the accuracy that can be expected in the local polarimetry using the inclusive π^0 detected in the end-caps of the ECAL in SPD. The δA_{N} values from this simulation were estimated for 5 minutes of data taking and compared with the relative errors of the same experimental data published by E704 [5]. This is shown in figure 6.

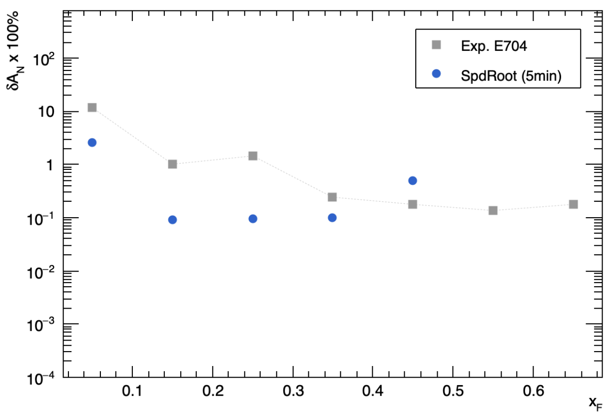

Figure 6. Relative error of A_{N} of the MC simulations with SpdRoot compared with data from E704. Dashed line is used only to guide the eyes.

Values of $A_{\mathrm{N}} > 0$ are expected for $x_{\mathrm{F}} > 0.3$ (see Fig. 1). This fact, makes the last two values of δA_{N} of particularly relevance in our analysis, the smaller of which is at $0.3 < x_{\mathrm{F}} < 0.4$ as shown in figure 6. So that, roughly speaking it might be expected a better accuracy of the asymmetry for inclusive π^0 detected in the end-caps of the ECAL in SPD, at $0.3 < x_{\mathrm{F}} < 0.4$.

If we take a look at the E704 experimental results (Fig. 7), it can be noted that at $x_{\mathrm{F}} > 0.3$ the asymmetry values are expected to be different from zero and linear rising. This can be used to predict the accuracy of the polarization measurements, since the error in the asymmetry should be dominated by the uncertainty of the polarization measurement, in particular for high statistics. At the same time, one of the largest uncertainties in a polarimeter comes from the asymmetry calibration, so that, we need to take into account the proportionality $\frac{\Delta A_{\mathrm{N}}}{A_{\mathrm{N}}} \sim \frac{\Delta P}{P}$.

If we take the 3 experimentad points of A_{N} for $0.3 < x_{\mathrm{F}} < 0.6$ from figure 7, and we assume that the beam polarization does not depend on x_{F}, we propose to estimate the relative error of the polarization as follows,

$$\delta \mathrm{P} = \frac{\Delta P}{P} = \frac{1}{\sqrt{\sum_{i=1}^{4} \frac{1}{\delta^2_{A_{\mathrm{N_i}}}}}} \tag{5}$$

where $\delta_{A_{\mathrm{N_i}}} = \frac{\Delta A_{\mathrm{N_i}}}{A_{\mathrm{N_i}}}$. The evaluation of Eq. 5 with those three data points gives rise to an accuracy of the beam polarization of 9.9%, which is very close to ∼10% uncertainty reported in the E704 publication at 1991 [5] . However, as it has been mentioned previously, in this simulation, for $x_{\mathrm{F}} > 0.3$ we can only count on two points where the π^0 yield can be extracted from a properly fitted signal. If we evaluate Eq. 5 with the two A_{N}^{exp} values given at $0.3 < x_{\mathrm{F}} < 0.5$ in figure 7,

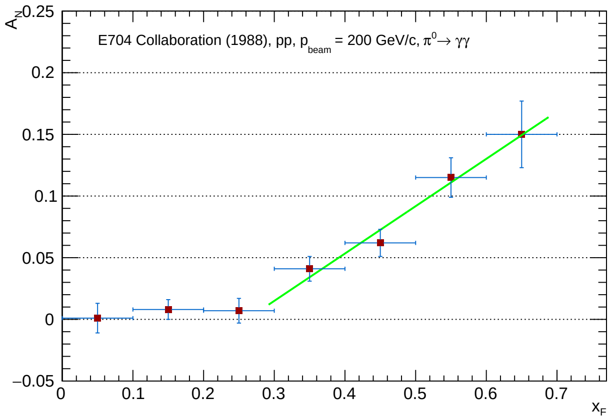

Figure 7. Experimental results of A_{N} as function of x_{F} for inclusive π^0 production by 200 GeV polarized proton beams, from the experiment E704 [5].

then δP is 14.3 %, which we find still reasonable. Thus, following the same reasoning, the equation 5 was evaluated with the two relative errors $\delta_{A_{\mathrm{N_i}}}$ calculated in this work in the interval $0.3 < x_{\mathrm{F}} < 0.5$ and scaled to different expected times of data taking, assuming that the beam intensity and the beam polarization remain stable over those periods of times. The resulting estimated relative errors of polarization using the method based on the cosine modulation fitting of $A_{\mathrm{N}}^{sig}(\phi)$ are shown in the table 1.

Estimated time	δP (%)
2 min	15.1
5 min	9.6
10 min	6.8
20 min	4.8
30 min	3.9
1 h	2.8

Table 1. Relative error of P, estimated for different times of data taking, based on the cosine modulation fitting method of the signal yield $N_{\pi^0}^{sig}$.

3.2. Calculation of $\sigma_{A_{\mathrm{N}}}$ after background correction

In experiments where typical asymmetry measurements take place, the measured quantity is the raw asymmetry A_{N}^{raw}. Its statistical uncertainty must be corrected for dilution due to the background under the π^0 peak in the invariant mass spectrum, so that the A_{N}^{sig} can be determined. The background asymmetry for this correction is usually based on the asymmetry measured in a combined mass region placed $\pm 3\sigma$ away from the signal peak position, which is then statistically subtracted from the A_{N}^{raw} taking into account the fraction ($r = N^{bkg}/N^{raw}$).

This, results in the signal asymmetry A_{N}^{sig} as follows,.

$$A_{\mathrm{N}}^{sig}(\phi) = \frac{A_{\mathrm{N}}^{raw} - r \cdot A_{\mathrm{N}}^{bkg}(\phi)}{1 - r} \tag{6}$$

N^{bkg} represents, in each ϕ bins, the counts under the invariant mass regions selected to make the background correction, while N^{raw} is the total of counts under the peak around the nominal π^0 mass.

The equation 2 outlines the way in which the asymmetry is obtained for both, A_{N}^{raw} and A_{N}^{bkg}. If we assume $N^{\uparrow} \sim N^{\downarrow} = N$, $R \sim 1$ and assume Poisson distribution of counts, that is $\sigma_N = \sqrt{N}$, the statistical uncertainty of raw and background asymmetry in each ϕ bin can be written in a simplified way, as follows,

$$\sigma_{A_{\mathrm{N}}}(\phi) = \frac{1}{P\langle|cos(\phi)|\rangle} \frac{1}{\sqrt{2N}} \tag{7}$$

The term $\langle|cos(\phi)|\rangle = \frac{\int_{\phi_1}^{\phi_2} cos(\phi)d\phi}{\phi_2 - \phi_1}$ in equation 7 is the average of the cosine of azimuth in the ϕ bin, while $\frac{1}{\langle|cos(\phi)|\rangle}$ fulfils the roll of azimuthal acceptance correction factor.

Finally the statistical uncertainty on the π^0 asymmetry after subtraction of background asymmetry is given by equation 8.

$$\sigma_{A_{\mathrm{N}}^{sig}}(\phi) = \frac{\sqrt{\sigma^2_{A_{\mathrm{N}}^{raw}}(\phi) - r^2 \cdot \sigma^2_{A_{\mathrm{N}}^{bkg}}(\phi)}}{1 - r} \tag{8}$$

Under this approach the yield of π^0 candidates in our simulation was determined for each x_F bin in the same way as explained in section 3.1, but instead of extracting the $N_{\pi^0}^{sig}$ by subtracting the background, $N_{\pi^0}^{raw}$ was obtained by counting all photon pair candidates under the peak. The invariant mass distributions, in our case, does not allow to select two mass background regions at both sides of the peak in order to perform background corrections. Therefore, we selected the background region defined by the 2^{nd} degree polynomial fit, under the same mass limits within which the raw counts were taken. So that $N^{raw} = N^{sig} + N^{bkg}$, and $r = N^{bkg}/N^{raw}$. Figure 8 illustrates how the regions for obtaining N^{raw} and N^{bkg} were separately defined for five x_{F} intervals in the azimuthal bin $[90° - 135°]$.

Since counts N^{raw}, N^{bkg} *vs.* x_{F}, are distributed uniformly in 8 ϕ bins, raw and background statistical uncertainties $\sigma_{A_{\mathrm{N}}^{raw}}$ and $\sigma_{A_{\mathrm{N}}^{bkg}}$ were estimated for each ϕ bin. The statistical uncertainty of the π^0 signal asymmetry was calculated according the equation 8 for each ϕ bin. The eight resulting $\sigma_{A_{\mathrm{N}}^{sig}}(\phi)$ were statistically combined to estimate the statistical uncertainty of the π^0 signal asymmetry as function of x_{F}:

$$\sigma_{A_{\mathrm{N}}^{sig}}(x_{\mathrm{F}}) = \frac{1}{\sqrt{\sum_{i=1}^{8} \frac{1}{\sigma^2_{A_{\mathrm{N}}^{sig}}(\phi_{\mathrm{i}})}}} \tag{9}$$

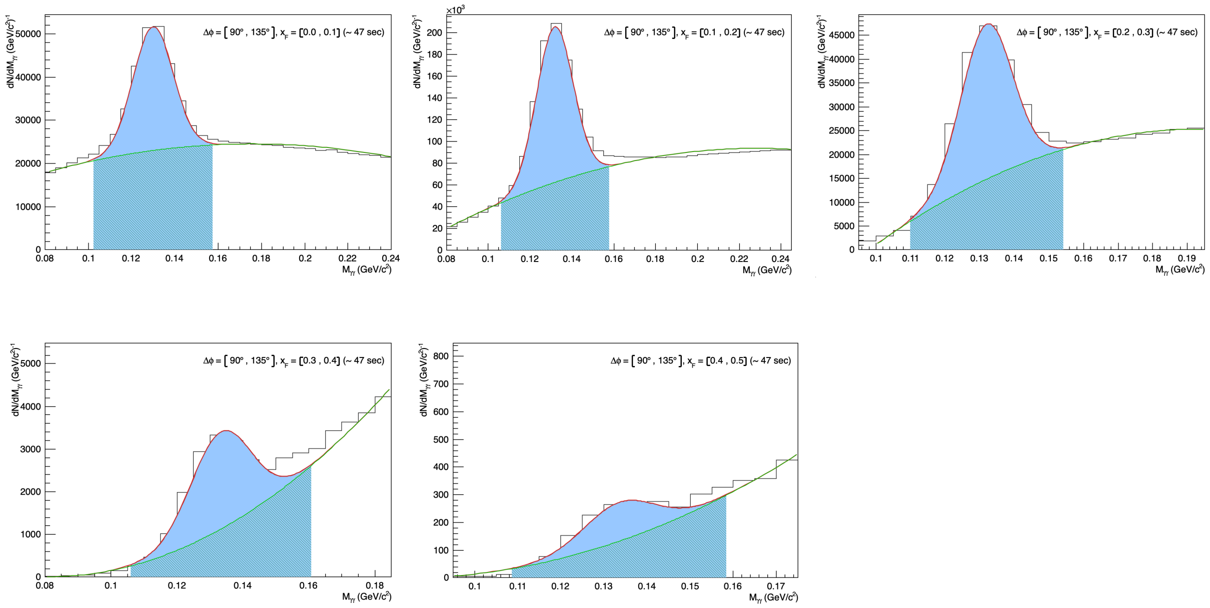

Figure 8. Invariant mass of photon pairs, for 6 x_{F} intervals in the azimuthal bin $\Delta\phi = [90°, 135°]$ in the ECAL end-cap, $z > 0$. Illustration of mass regions were N^{raw} and N^{bkg} were obtained.

4. Results

The x_{F} dependence of $\sigma_{A_{\mathrm{N}}^{sig}}$ obtained by using the two methods described in sections 3.1 and 3.2 are shown in figure 9.

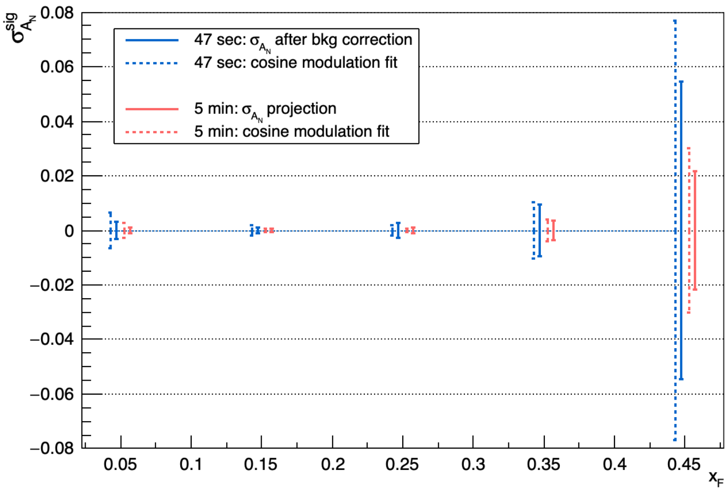

Figure 9. Statistical uncertainty of A_{N}^{sig} for inclusive π^0 in simulated pp collisions at $\sqrt{s} = 27$ GeV, after background correction of the raw asymmetry.

The result of the Monte Carlo simulation of 100 million events is shown in light blue, which is equivalent to a data collection period of 47 seconds, while the statistical uncertainty of the asymmetry expected to be measured in 5 minutes of data taking time is shown in red color (Fig. 9). For each estimated time the results obtained by both methods are compared. The dash lines represent the uncertainty $\sigma^{sig}_{A_\mathrm{N}}(x_\mathrm{F})$ calculated from the cosine modulation fitting of $N^{sig}_{\pi^0}$ counts uniformly distributed in ϕ bins. With this method no correction due to the background was made because the π^0 signal was directly extracted from the Gaussian fit after subtraction of the polynomially fitted background (Sec 3.1). The solid lines represent the calculated uncertainty $\sigma^{sig}_{A_\mathrm{N}}(x_\mathrm{F})$ based on the method of subtracting the background asymmetry and its corresponding statistical uncertainty from the analogous raw quantities, taking into account the background correction factor (Sec 3.2). As shown in figure 9, for each x_F interval the background correction method leads to a slightly smaller $\sigma^{sig}_{A_\mathrm{N}}$ than the modulation fitting method of the signal asymmetry. The difference between both methods is more notable at $x_\mathrm{F} > 0.4$. With both methods $\sigma^{sig}_{A_\mathrm{N}}(x_\mathrm{F})$ is smaller for longer estimated time of data taking.

Within the framework of the two approaches proposed in this work the statistical uncertainties $\sigma^{sig}_{A_\mathrm{N}}(x_\mathrm{F})$ were divided by the absolute value of the experimental results of the collaboration E704 [5] in order to obtain the x_F dependence of the relative errors as described in section 3.1.1. Subsequently, they were combined for estimating the relative errors of the polarization δP according to the equation 5, and scaled for different estimated periods of data collection. The final results of δP by both methods are shown in table 2.

	δP (%)	
Estimated time	Method 1	Method 2
2 min	15.1	13.9
5 min	9.6	8.8
10 min	6.8	6.3
20 min	4.8	4.4
30 min	3.9	3.6
1 h	2.8	2.5

Table 2. Comparison of estimated relative error of P, for different expected times of data taking, using two methods. Method 1: cosine modulation fitting of $N^{sig}_{\pi^0}(\phi)$ without correction for the background. Method 2: background correction of $\sigma^{raw}_{A_\mathrm{N}}$.

4.1. Effect of the spin angle smearing on the asymmetry

In NICA, the online polarization control is proposed to be performed when the collider operates in spin transparency mode, and the direction of the polarization can be defined by means of the solenoid magnetic field measurement. The possible effect of the spin direction variations under the magnetic field of the SPD solenoid, on the asymmetry, was also investigated. With this purpose, a toy Monte Carlo based analysis was carried out. If we assume a proton travelling a distance $Z = 60$ cm under the magnetic field $B = 1$T, we may calculate the angle ϕ_{max} of the spin precessing around a vector perpendicular to the beam direction, as follows,

$$\phi_\mathrm{max} = \frac{g_\mathrm{p} \cdot \mu_\mathrm{N} \cdot B}{\beta\gamma\hbar c} Z, \qquad Z = 60cm, \quad \phi_0 = \phi_0(Z) \tag{10}$$

In Eq. 10, we have well known constants, as the g-factor of protons $g_\mathrm{p} = 5.586$, the nucleon magneton μ_N and the β , γ Lorentz factors.

A cosine function $(1 + [0] \cdot \cos(x + [1]))$, was created to randomly generate ϕ. The parameter [0], accounting for the amplitud of the modulating cosine function, is assigned discrete input values which are fixed in the interval [0.01 - 0.1]. Those fix modulation values corresponds to asymmetry values in the range [0.014 - 0.143], on the assumption that $P = 0.7$. The parameter [1] in turn, was set according to $Z/60 \cdot \phi_{\max}$, being $\phi_{\max} = 0.0372$ rad (2.13°) while Z was described by a Gaussian distribution, with $\sigma = 30$, in the limits $Z = \pm 60$ cm.

Once the random ϕ has been extracted, histograms of $d\mathrm{N}/d\phi$ *vs* A_{inp} were created and fitted with a new cosine function, from where a new amplitud parameter, A_{rec}, has been extracted and compared with A_{inp}. As a result, the asymmetry was reconstructed with a statistical accuracy of ± 0.006 in all the x_{F} range. When referring to the particular x_{F} range where sizeable values of asymmetry are expected, the asymmetry modification was evaluated as $|A_{\mathrm{rec}} - A_{\mathrm{inp}}|/A_{\mathrm{inp}}$, resulting in 10 % at $x_F = 0.35$ and 4 % at $x_F = 0.7$.

5. Conclusions

The energy and position of π^0 decayed photons in the end-caps of the SPD ECAL are quantities which are accessible online, with necessity of particle identification or vertex reconstruction. On these bases, the accuracy of the beam polarization has been estimated for *pp* collisions at 27 GeV, through Monte Carlo simulations in the frame of the SpdRoot-4.1.6 software. The π^0 decays registered in the ECAL end-caps of SPD provide an accuracy of the beam polarization of ∼9.6 % for 27 GeV after 5 minutes of data taking.

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