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ELEMENTARY PARTICLES AND FIELDS
Experiment

Prospects of Open-Charm Asymmetry Measurements at the SPD

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Abstract—The Spin Physics Detector (SPD) at the Nuclotron based Ion Collider fAcility (NICA) is designed to study nucleon spin structure in the three dimensions. At design energy, the leading mechanism of charm meson pair production in proton–proton collisions is the gluon fusion. At the SPD, charmed mesons can be detected via their hadronic decay channels. While these measurements are challenging due to orders of magnitude larger hadronic background, we demonstrate the capacity to obtain asymmetry measurements that can make an impact on the present understanding of gluon Transverse Momentum Dependent (TMD) distributions inside protons.

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1. INTRODUCTION AND MOTIVATION

At a peak design capacity, NICA will provide polarized proton collisions ($\sqrt{s} = 27$ GeV) with luminosity of $10^{32}\text{cm}^{-2}\ s^{-1}$. The SPD [1] will allow measurements of cross-sections and spin asymmetries sensitive to the unpolarized and various polarized gluon distributions inside the nucleons. At the SPD kinematic, the measurements will be sensitive to the gluon distributions in the high Bjorken-x ($x \geq 0.1$) region, making them complementary to future experiment like EIC and AFTER-LHC which will probe very low Bjorken-x regions.

Large transverse single spin asymmetries (TSSA) observed in the early 1990's contradicted the leading-twist pQCD expectations that TSSA would be suppressed by the quark mass. In the striking results from E704 [2], asymmetries as large as 40% were observed (Fig. 1*a*) at large Feynman-x for pions with a clear charge dependence.

Various mechanisms of spin–momentum correlation are used to describe the measured TSSA of hadrons. Transverse momentum (k_T) dependent parton distributions can generate TSSA, as suggested by Sivers [3]. Chiral-odd fragmentation functions (FF) as suggested by Collins [4] can generate TSSA from the scattered parton. Interference between quark and gluon fields in the initial or final states can also produce such asymmetries.

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Gluon Sivers Function (GSF) is of particular focus for the future measurements at the SPD. GSF can be described as below:

$$\hat{f}(x, \mathbf{k}_\perp; \mathbf{S}_T) = f_1(x, \mathbf{k}_\perp^2) - \frac{(\hat{\mathbf{P}} \times \mathbf{k}_\perp).\hat{\mathbf{S}}_\perp}{M} f_{1T}^\perp(x, \mathbf{k}_\perp^2), \quad (1)$$

where $f_1(x, \mathbf{k}_\perp^2)$ is the unpolarized TMD-PDF and, $\mathbf{S}_T$, $\mathbf{P}$ and M are respectively transverse spin, momentum and mass of the hadron. The function $f_{1T}^\perp(x, \mathbf{k}_\perp^2)$ describing the asymmetric distribution of partons inside the hadron with light-cone momentum x and transverse momentum $\mathbf{k}_T$ is the Sivers Function.

Measurements from DIS experiments like COMPASS and HERMES have allowed global analysis (combining with Drell–Yan, e^+e^- annihilation) to attempt extraction (Fig. 1*b*) of Quark Sivers Function (QSF) [5]. Dearth of experimental data sensitive to the gluon TMD distributions is the main obstacle for similar extraction of the GSF. Future SPD measurements sensitive to the GSF are therefore crucial in improving our present understanding.

2. DETECTOR AND PERFORMANCE

The SPD will be a symmetrical detector system with a barrel part and two end-caps [6]. At the peak design stage, three major probes will be in focus, namely: open-charm mesons, charmonia mesons and direct photons. In the kinematic regime for the SPD measurements, each of the categories is dominated by gluon interactions. Of these, this work

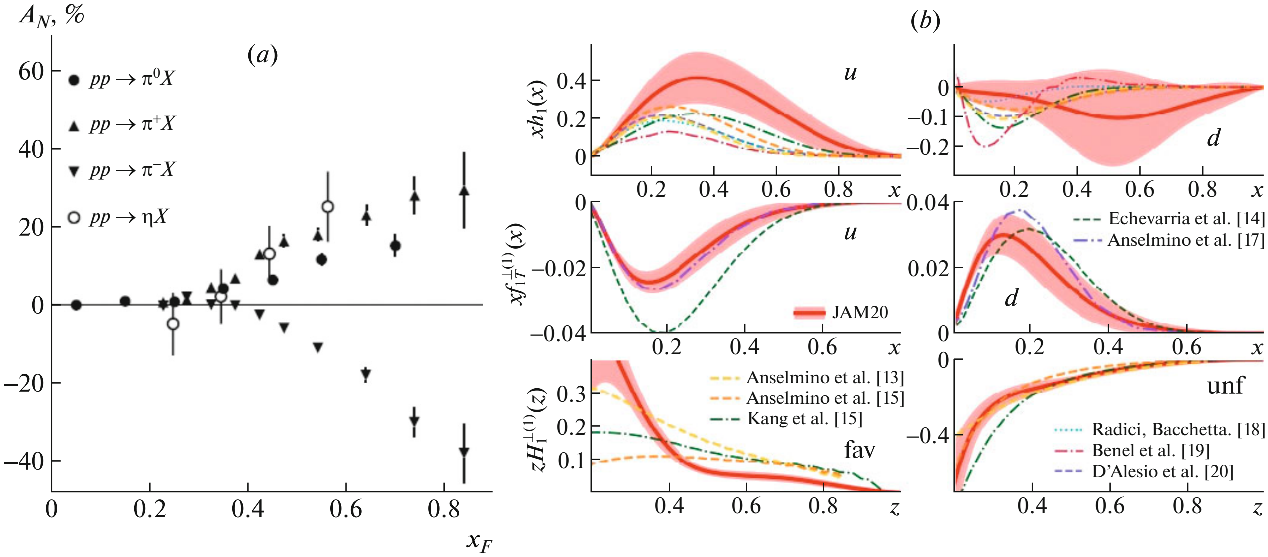

Fig. 1. Pion TSSA from E704 [2] (*a*) and extracted QSF from global analysis by JAM20 collaboration [5] (*b*).

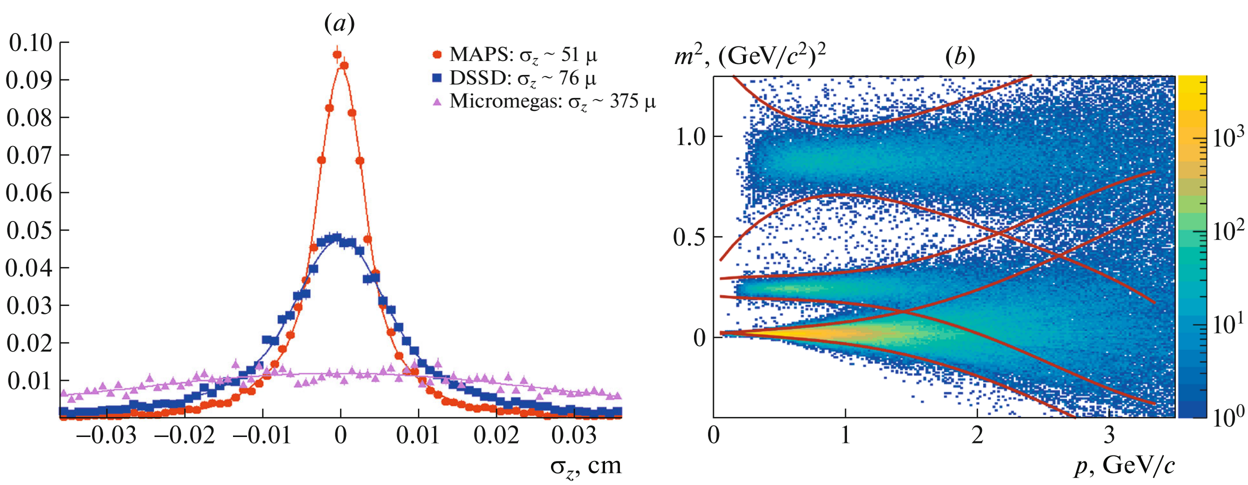

Fig. 2. Secondary vertex resolution along beam direction from the silicon vertex detector (*a*) and TOF performance in particle identification (*b*).

will describe the methodology and expectations for the open-charm meson measurements.

At the SPD, D mesons produced in the open-charm sub-process will be detected via their hadronic decay channels (i.e. $D^0 \to \pi^+ K^-$, $D^+ \to \pi^+\pi^+K^-$). Subsystems crucial for these measurements are MAPS based Silicon Vertex Detector (for reconstruction of secondary vertex of D meson decays), PET Straw Tracker (for charged track reconstruction and momentum determination) and Time-of-Flight Detector (for particle identification).

Performance studies based on the current design [6] show (Fig. 2*a*) the secondary vertex position resolution ($\sim 50\ \mu$m) that can be achieved and the performance of the TOF detector in π/K separation (up to $\sim$1.5 GeV/c momentum) (Fig. 2*b*).

3. MONTE CARLO SIMULATION STUDY

For the present work, Monte Carlo simulations were performed. Proton–proton collisions were simulated with Pythia 8 event generator and Geant4 description (under SpdRoot framework, a CERN Root based software) was used to simulate detector responses.

In detecting D mesons via hadronic decay channels, the largest challenge is reducing the background arising from random combinations of hadrons. In order to suppress background, two separate sets of events were studied: (1) four million events of open-charm sub-processes to study the behavior of the signal (S) and (2) forty million minimum bias (excepting elastic sub-process) events for the background (B). High quality tracks were selected and Kalman filter based KFParticle package was used to reconstruct decay vertices for all possible combinations of pions

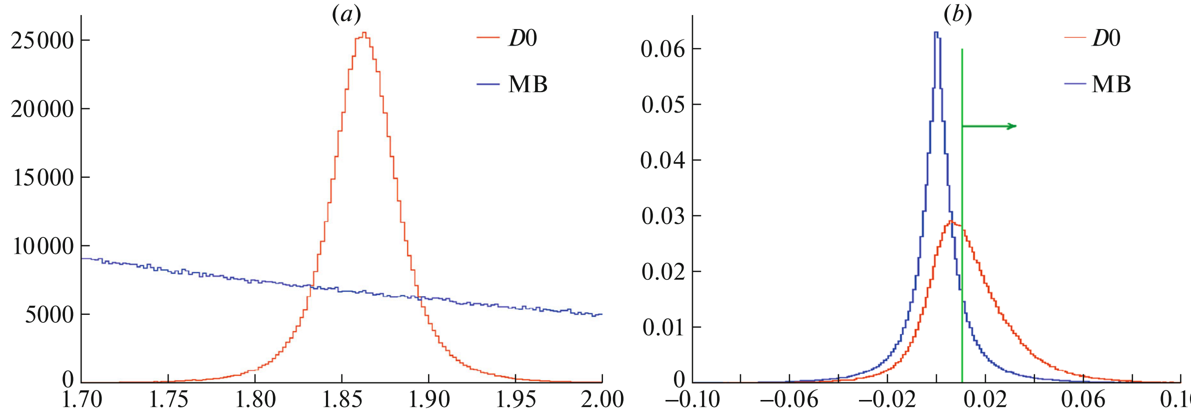

Fig. 3. Invariant mass distribution of π^+K^- (a) and decay length (b) for both D^0 meson signal and combinatorial background from minimum bias events.

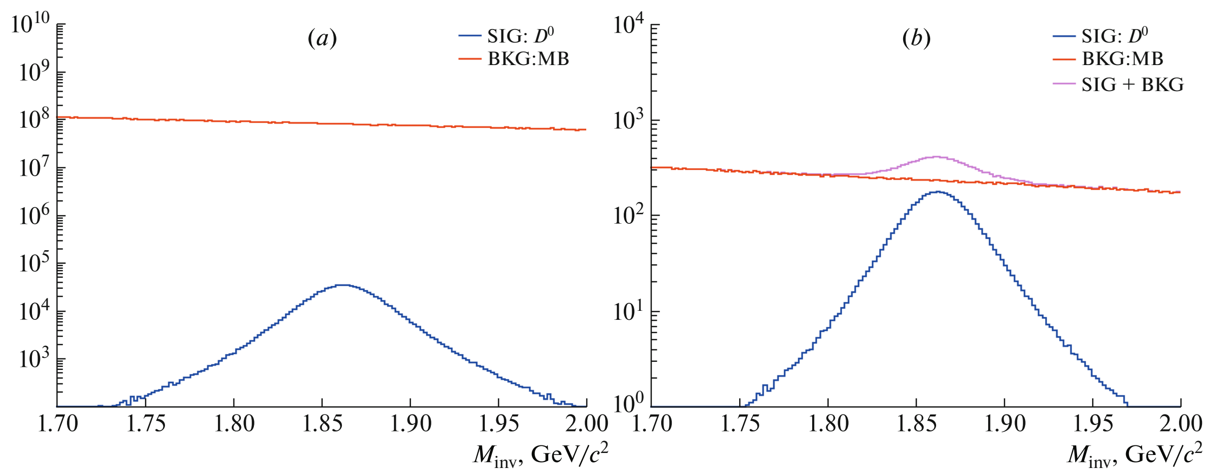

Fig. 4. Invariant mass distributions of π^+K^- scaled for one year of recorded data at the SPD [7] before (a) and after applying background suppressing selection criteria (b).

and kaons. In the limited mass range shown here (Fig. 3a), 633533 D^0 and 1.02634×10^6 combinatorial background were reconstructed.

Various properties of the reconstructed invariant particle were compared for the signal and background. As a demonstration, decay length distribution (Fig. 3b) shows clear distinction between signal and background. Collinearity angle, distance between the daughter tracks, χ^2 and distance of invariant particle to the primary vertex were also studied. A set of selection criteria were chosen based on the corresponding figures of merit $\left(\frac{S}{\sqrt{S+B}}\right)$. Figure 4 illustrates the efficiency of the selection criteria, showing the orders of magnitude larger background (Fig. 4a) in one year of projected data and the impact of the selection criteria (Fig. 4b).

After the application of the set of selection criteria, from the initially reconstructed D^0 signal 11456 were retained whereas from among the combinatorial background only 8 survived. In the kinematic range of interest for large TSSA ($x_F \geq 0.2$), the signal and background counts were 3279 and 3 respectively. Artificially generated ratio of signal to background events were corrected with the expected process cross-sections (9.4 μb for the open-charm and 32.8 mb for the minimum bias, excepting elastic (Fig. 5a)) to arrive at $S/B = 1/8$ achieved in the high Feynman-x region ($x_F \geq 0.2$).

4. THEORETICAL EXPECTATIONS AND COMPARISONS

Recent works [8] have calculated Generalized Parton Model (GPM) (and its Colour Gauge Invariant variant CGI-GPM) based estimates of TSSA of inclusive D-mesons using different models of the GSF, namely, D'Alesio [9] and SIDIS1 [10] parameterizations. Peak value of TSSA using the SIDIS1 set of parameters was found to be almost an order of magnitude larger than that calculated using D'Alesio set of parameters. Such strong model dependence underscores the uncertainties from lack of experimental data.

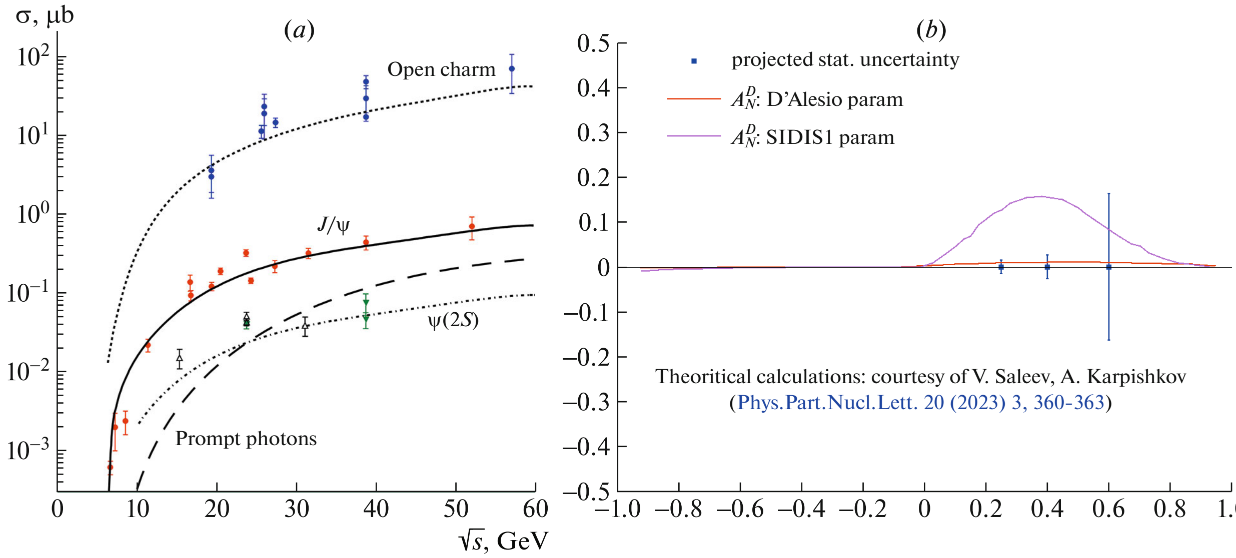

Fig. 5. Cross-sections of sub-processes [11] as function of collision energy (*a*) and projected statistical uncertainties [7] of D^0 for one year of data at the SPD compared with estimated TSSA with two different parameters of the GSF (*b*).

In Fig. 5*b*, projected statistical uncertainties for neutral D meson TSSA measurements in one year of recorded data at the SPD at peak design energy and luminosity are compared with inclusive D meson TSSA from theoretical calculations using the aforementioned two sets of parameters for the Gluon Sivers Function. The comparison clearly demonstrates the impact of results of future transverse single spin asymmetry of D mesons from open-charm processes at the SPD. These measurements will be able to reduce the model dependence significantly and improve on our current knowledge of the Gluon Sivers Function.

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CONFLICT OF INTEREST

As author of this work, I declare that I have no conflicts of interest.

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