PROCEEDINGS OF SCIENCE

Studying Nucleon Spin Structure at the Spin Physics Detector (SPD)

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Primary focus of the Spin Physics Detector (SPD) at the Nuclotron based Ion Collider fAcility (NICA) is to study nucleon spin structure in the three dimensions. At the SPD, measurements of cross-sections and spin asymmetries sensitive to the unpolarized and various polarized (helicity, Sivers, Boer-Mulders) gluon distributions will be performed. Measurements from the collisions of polarized protons (deuterons) of energies up to 27 (13.5) GeV with luminosity up to 10^{32}cm^{-2} s^{-1} (10^{31}cm^{-2} s^{-1}) will provide data in the moderate and large Bjorken-x, making them complementary to the present (i.e. STAR, PHENIX) and future (i.e. EIC, AFTER) high energy spin experiments. This will allow for a much improved global analyses and understanding of spin structures of a basic building block of Nature. With polarized deuteron collisions, SPD will be a unique laboratory for probing tensor polarized gluon distributions.

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1. Introduction

Following the development of the collinear parton distributions to describe the nucleons inside hadrons, many experiments (electron-positron annihilation, deep inelastic scattering, fixed target and collider hadron collisions) in the past decades provided cross-sections and asymmetry measurements sensitive to various unpolarized and polarized PDFs of quarks. This has led to sets of collinear PDFs [NNPDF[1], DSSV[2]] of quarks and (to a lesser extent) gluons with ever improving precision. However, since the measurements of large single spin asymmetries of pions in the E704 experiment [E704], it has become necessary to look beyond the collinear descriptions and to include transverse momenta (Transverse Momentum Dependent PDFs or TMDs) or transverse positions (Generalized Parton Distributions or GPDs). TMD PDFS and/or Fragmentation Functions (FF) are required to explain the large single spin asymmetries observed.

In the first half of this decade a significant stride has been made to include semi inclusive DIS and hadron collision asymmetry measurements performing 'global analyses' to extract parametric forms of the TMD distributions [JAM[3], MAPS[4]]. Unfortunately, as in the case of the collinear PDFs, accessing gluons via rarer processes is more difficult and the data scant. Spin Physics Detector (SPD)[5] is a future all purpose detector system planned at the Nuclotron based Ion Collider fAcility (NICA) at the Joint Institute for Nuclear Research (JINR) at Dubna, Russia. Its primary focus will be to measure cross-sections and asymmetries sensitive to various gluon distributions.

2. Physics Goals and Detector

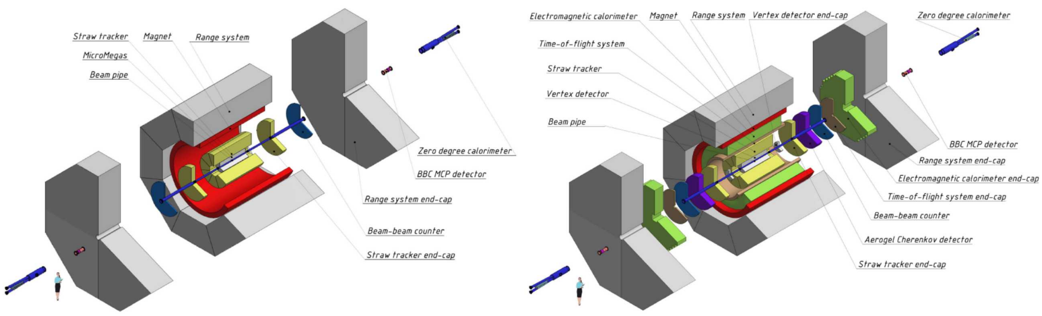

Figure 1: SPD detector system at stage I (left) and stage II (right)

2.1 Stage I

In its early stages of operation, NICA aims to deliver polarized proton and deuteron beams of energies up to $\sqrt{s_{NN}}$ = 10 GeV with luminosity of $10^{31} cm^{-2} s^{-1}$ for pp and $10^{30} cm^{-2} s^{-1}$ for dd collisions. SPD detector[6] in stage-I (Figure 1 (left)) is designed to take advantage of the low energies and luminosities with a barrel part and two end-caps. The barrel part for the first stage will consist of a solenoid magnet, providing field of up to 1.2 T allowing determination of particle momenta. Radially outward from the aluminium beam-pipe, the barrel section will consist of : 1) Micromegas based vertex detector (MVD) aiding momentum determination 2) Multi-layer tracker with metal-coated polyethylene terephthalate (PET) straws arranged along Z (beam-direction) and at stereo directions U and V (at 5^0 angle with Z straws) with a spatial resolution of 150 μm. Besides providing momenta of charged particle tracks, straw-tracker (ST) will also allow limited range particle identification using the energy loss ($-\frac{dE}{dx}$) in the straw layers. 3) Range System (RS) just outside the magnet consisting of mini drift tubes and layers of iron as absorbing material, functioning as a hadronic calorimeter and muon identifier. Each end-cap will consist of MVD, ST, beam-beam counter (BBC) to provide local polarimetry, RS and zero-degree polarimeter (ZDC) providing luminosity control and selection criteria for events with spectator neutrons.

A slew of measurements are planned for the first stage of the experiment. For example : 1) Spin dependent amplitudes of pd scattering in dd collisions are the simplest process which includes both pp and pn amplitudes involved. Asymmetries of pd process in dd collisions will be measured to extract pp and pn spin dependent elastic scattering amplitudes which are essential in theoretical interpretation of nuclear spin observables. 2) Elastic pp scattering at large angles have been shown to have oscillating behavior as function of collision energy. SPD is expected to provide high precision data over a range of energies to test models giving rise to such phenomenon. 3) Large angle ($\theta \sim 90^0$) production of pions and protons will be measured to study expected contributions from multi-quark flucton-flucton interactions. 4) Angular correlation of $\lambda\bar{\lambda}$ pair will be measured to study possible quantum entanglement in the quark-pair and non-locality in the subsequent hadronization process. 5) Exclusive ϕ meson production at the SPD will be measured to study production mechanism (pion exchange vs. pomeron-odderon meson vertex).

2.2 Stage II

In the second stage of operations, NICA is expected to deliver polarized proton and deuteron beams at the designed peak luminosity and energy. The SPD detector[6] will also be upgraded (Figure 1 (right)). 1) MVD will be replaced by an improved multi-layer silicon vertex detector (SVD) from one of the two options : (a) monolithic active pixel sensor (MAPS) or (b) double-sided silicon strip detector (DSSD). The SVD besides improving momentum resolution will also provide secondary vertex spatial resolution of 40-60 μm. 2) Time-of-flight (TOF) detector with a timing resolution of 50 ps providing π/K separation for up to track momentum of 1.5 GeV/c. 3) Electromagnetic calorimeter (ECAL) with an energy resolution of $\frac{\delta E}{E} \sim \frac{5\%}{\sqrt{E}} \bigoplus 1\%$ 4) Two end-caps are designed to have an additional particle identification capability in the form of focusing aerogel RICH (FARICH) Cherenkov detector which will provide π/K separation up to 5.5 GeV/c momentum.

At the final stage of the experiment, the primary focus will be cross-sections and asymmetry measurements (double helicity asymmetries A_{LL} and single transverse spin asymmetries or TSSA A_N) that are sensitive to the gluon distributions inside nucleons. Measurements particularly sensitive to the gluon distributions in the high Bjorken-x range ($x \geq 0.2$) will improve gluon helicity distributions ($\Delta g(x)$) and provide much needed data to be used in future to extract gluon TMDs (i.e. Sivers, Boer-Mulders).

3. Measurements and Possible Impacts

At the SPD, three main probes will be measured namely, charmonia, prompt photons and open-charm mesons. Each of these, in the range of NICA collision energies, are dominantly produced

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via scattering of gluons, making them efficient tools to study the gluons structure in the nucleons. Following subsections briefly describe the salient features of each channel.

3.1 Charmonia

At the NICA energies, charmonia productions are expected to be dominated by the gluon-gluon fusion process. At the SPD, charmonia will be detected via di-muon decay channel using the Range System as the muon identifier. Most abundant of these would be the J/Ψ with expected 12 millions being produced in one year of recorded data with peak luminosity. In addition, $\Psi(2S)$ can be detected via $\mu^+\mu^-$ and $\mu^+\mu^-\pi^+\pi^-$ channels. Rarer charmonia like χ_{c1} and χ_{c2} can be measured via $\gamma\mu^+\mu^-$ channel. Misidentified pions are the largest source of background for these studies.

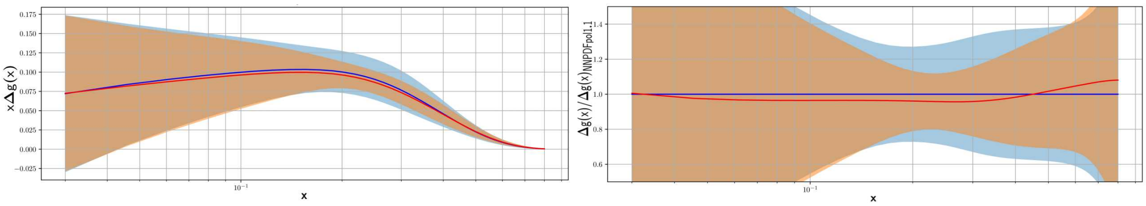

Figure 2: Gluon helicity function $\Delta g(x)$ (left) and ratio (right) of $\Delta g(x)$ with and without SPD $A_{LL}^{J/\Psi}$

Measurements of J/Ψ cross-sections and comparisons with theoretical estimations are crucial in improving poorly understood hadronization models of charmonia productions. SPD will also measure both the A_{LL} and the A_N of J/Ψ productions. Figure 2 illustrates the impact of the high-precision measurements of $A_{LL}^{J/\Psi}$ at the SPD (estimates using NNPDF NLO unpolarized[1] and NNPDFpol1.1 polarized[7] sets) on the present knowledge of the gluon helicity function. It is expected to reduce the uncertainties of gluon helicity PDF in the Bjorken-x range $0.2 \leq x \leq 0.5$.

3.2 Prompt Photon

Prompt photons in the leading order may be produced via Compton scattering of gluons or $q\bar{q}$ annihilations. However, at NICA energies, gluon scattering is the dominant process. Fragmentation contribution form scattered quark is expected to be only $15-30\%$[8], making the probe an excellent choice to study gluon (spin) structure in nucleon. At the SPD, the measurements will be performed using the Electromagnetic Calorimeter. Photons from decays of light neutral mesons (π^0, η) are expected to be the largest source of background for the prompt photon measurements.

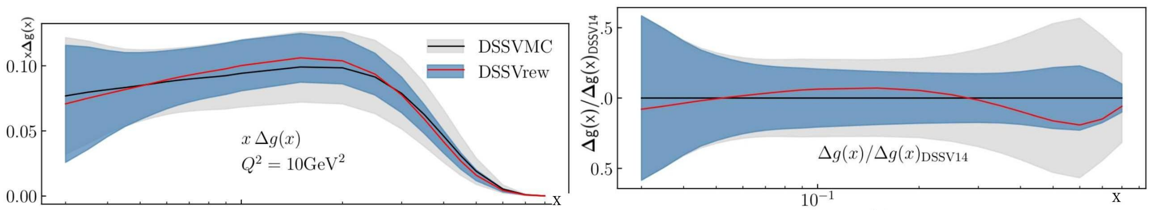

Figure 3: Gluon helicity function $\Delta g(x)$ (left) and ratio (right) of $\Delta g(x)$ with and without SPD A_{LL}^{γ}

A study using the NNPDF3.0[1] unpolarized and DSSV14[2] polarized PDF estimates the impact of the double helicity asymmetry of prompt γ at the SPD. Figure 3 shows that uncertainties of the gluon helicity $\Delta g(x)$ can be reduced by almost a factor of 2 in the range of $0.2 \le x \le 0.8$ by including SPD A^{γ}_{LL} measurements.

3.3 Open Charm

The dominant process of open-charm meson production at the NICA energies is the gg fusion (compared to the $q\bar{q}$ annihilation), making them useful tools to probe gluons structure. At the peak NICA energy of 27 GeV, open-charm meson production cross-sections are expected to be almost two orders higher than the J/Ψ charmonium production, making it statistically the most abundant channel. At the SPD, charmed mesons will be detected via their hadronic decay channels (i.e. $D^0 \to \pi^+ K^-, D^+ \to \pi^+\pi^+K^-$ and their antiparticle counterparts). However, pions and kaons from other hard processes create orders of magnitude more numerous combinatorial background necessitating very careful analysis to suppress background (Figure 4 (left)).

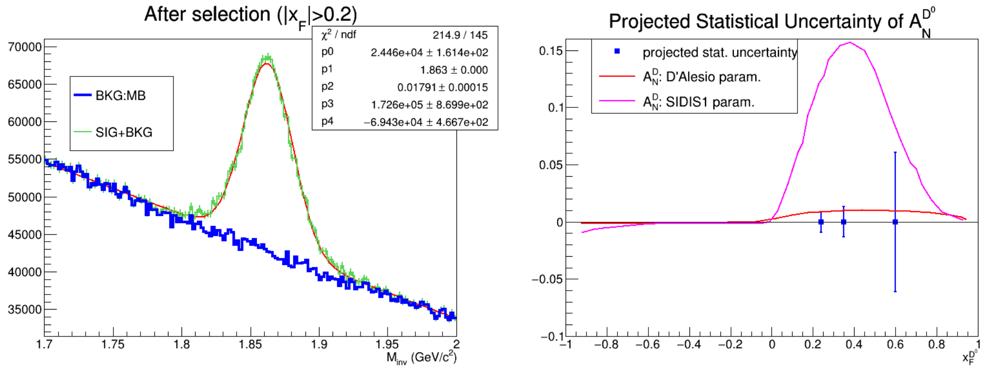

Figure 4: Invariant mass fit to extract D^0 mesons (left) and comparison of projected SPD uncertainties to the predictions of inclusive D meson A_N (right)

Estimates of the inclusive D meson TSSA using the color gauge-invariant generalized parton model (CGI-GPM) with two different sets of parameters for the gluon Sivers function (GSF) namely, D'Alesio et al.[9] and SIDIS1[10] have been compared to the projected statistical uncertainties of neutral D-meson TSSA measurements at the SPD. Figure 4 (right) shows that SPD measurements will be extremely helpful in reducing model dependence of the GSF.

4. Summary

The Spin Physics Detector (SPD) has a wide ranging measurements planned for the two stages of its operation, especially focussing on measurements sensitive to the gluon distributions in nucleons in stage II. SPD will make high precision cross-sections and asymmetry measurements that will be complementary to the present (i.e. COMAPSS, HERMES, STAR, PHENIX) and future (i.e. EIC, AFTER, LHCSpin) spin experiments providing crucial data for a better understanding of the three dimensional structure of the constituents of nucleons.

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