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

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(On behalf of the SPD collaboration)

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Plans for the Presentation

- Introduction
- Physics goals and detector system
- Focus on nucleon spin structure
- Measurements, expectations, challenges
- Status and schedule of SPD
- Summary

Spin Physics Detector (SPD) at NICA

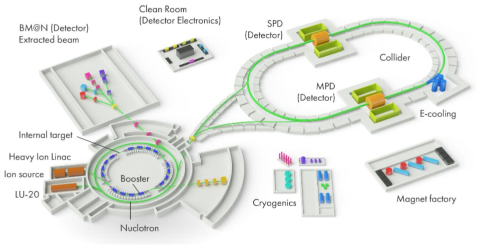


Figure 1: NICA - Nuclotron-based Ion Collider fAcility at the Joint Institute for Nuclear Research (JINR) at Dubna

Prime focus at SPD : parton distribution functions (PDFs) of gluons

- Polarized collisions
  1. $p^\uparrow p^\uparrow$ up to $\sqrt{s} = 27$ GeV
  2. $d^\uparrow d^\uparrow$ up to $\sqrt{s} = 13.5$ GeV
- Beam polarization $|P| \sim 70\%$

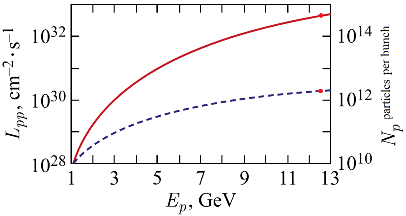


Figure 2: Luminosity and bunch intensity : SPD TDR

SPD Kinematics

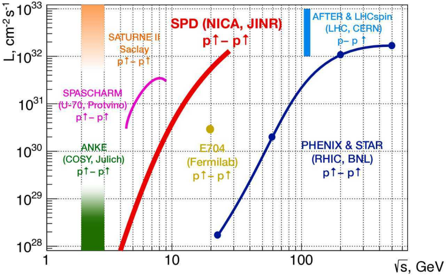


Figure 3: Luminosity vs. energy : SPD CDR

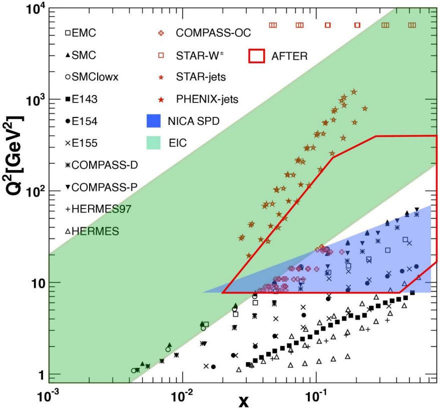


Figure 4: Kinematic coverage for major probes at the SPD : charmed mesons, high-p_T photons and charmonia : CDR

SPD Stage I : Physics

A sample of the physics topics that will be probed at Stage-I of SPD :

- Spin effects in pp, dd (quasi-)elastic scattering
- Charmonium production near threshold
- Strange hypernuclei production
- Spin effects in hyperon production
- Spin structure of multi-nucleon short-range correlations
- Fluction-fluction interactions and di-baryon production

SPD Stage I : Detector

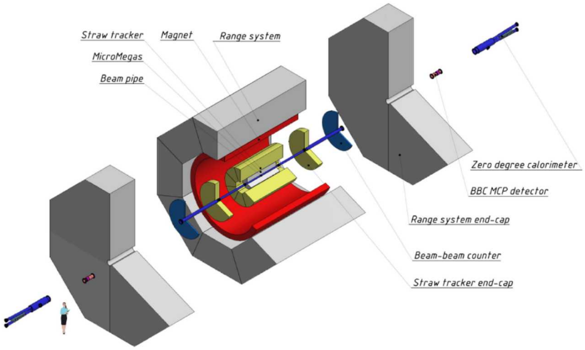


Figure 5: SPD detector in Stage I : SPD TDR

- Trackers:charged track and momentum, limited PID through energy deposition
- Range System:hadronic calorimeter, muon/hadron separation

- Up to $\sqrt{s} = 10$ GeV and reduced luminosity
- Solenoidal field $B \sim 1$ T
- BBC and ZDC for online polarimetry
- Micromegas central tracker
- Straw Tracker $\delta \sim 240\ \mu$m, $\delta(\frac{dE}{dx}) = 8.5\%$

SPD Stage II : Physics

- Primary focus : accessing gluon PDFs
  1. Unpolarized gluon PDF
  2. Gluon helicity PDF
  3. Gluon transverse momentum dependent (TMD) PDF (Sivers, Boer-Mulders)
  4. Transversity and tensor polarized gluon in deuteron (unique result at SPD)
- Test of QCD factorization
- Charmonia production mechanism

SPD Stage II : Detector

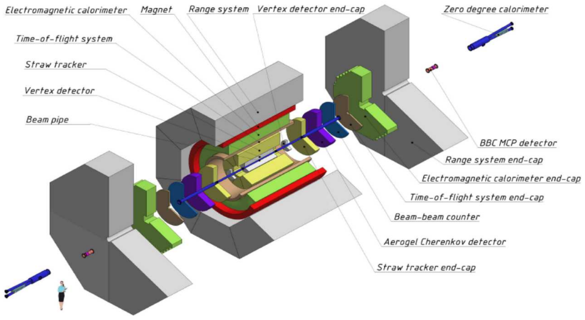
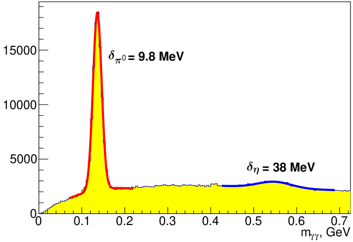


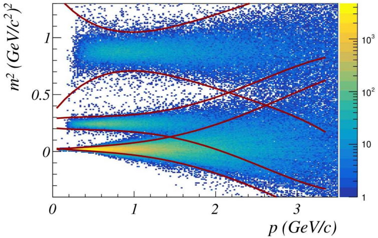
Figure 6: SPD detector in stage II : SPD TDR

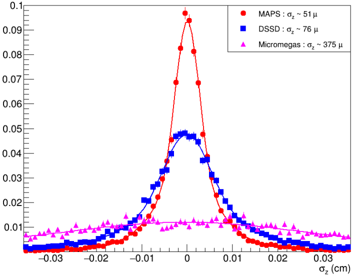
- Improved vertex detector for short lived particle decays
- TOF+FARICH for better PID
- ECAL for $\gamma, e^{\pm}$ identification

- Event rate at peak luminosity and energy $\sim$ 3 MHz
- Silicon vertex detector : MAPS/DSSD
- Electromagnetic calorimeter (ECAL) $\left(\frac{\delta_E}{E} = \frac{5\%}{\sqrt{E}} + 1\%\right)$
- Time of flight (TOF) for PID ($\delta_t \sim$ 50 ps), π/K separation upto 1.5 GeV/c
- Focusing RICH in end-caps, extend π/K separation upto 5.5 GeV/c

Detector Performances





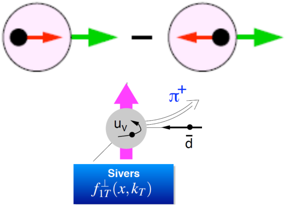


- Clockwise from lower left (SPD TDR) :
- Resolution of reconstructed D^0 vertex : $\delta_z \sim 50$ μm for MAPS
- Invariant mass of 2-photons : $\delta_m^{\pi^0} \sim 10$ MeV
- TOF performance:provides a 3σ separation of π/K up to 1.5 GeV/c
- Additionally:in the straw tracker, $\frac{\delta_{p_T}}{p_T} \sim 2\%$ for 1 GeV/c tracks (magnetic field ~ 1 T)

Probing Gluon Spin Distributions at the SPD

	Unpolarized	Circular	Linear
Unpolarized	g(x) density		$h_1^{\perp g}(x,k_T)$ Boer-Mulders function
Longitudinal		$\Delta g(x)$ helicity	Kotzinian-Mulders function
Transverse	$\Delta_N^g(x,k_T)$ Sivers function	Worm-gear function	$\Delta_T g(x)$ transversity (deuteron only), pretzelosity

Figure 7: Various spin distributions of gluons that will be accessible via cross-section and asymmetry measurements at the SPD



- Unpolarized gluon distributions ($g(x)$)
- Gluon helicity PDF ($\Delta g(x)$)
- TMD gluon spin distributions i.e. Sivers ($\Delta_N^g(x, k_T)$), Boer-Mulders ($h_1^{\perp g}(x, k_T)$)
- Transversity ($\Delta_T g(x)$) : deuteron

Gluon Helicity $\Delta g(x)$

Important to understand proton spin as a whole (spin puzzle)

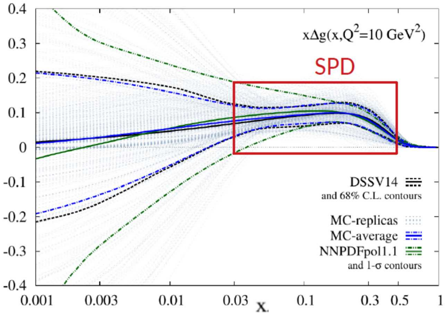


Figure 8: Gluon helicity distribution from DSSV group: Phys. Rev. D 100 114027(2019). Highlighted region shows where SPD will make a major impact

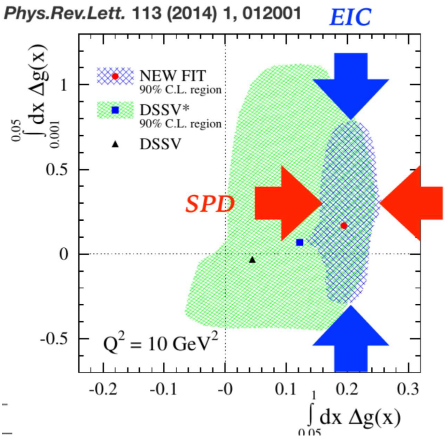


Figure 9: Truncated moments of $\Delta g(x)$ illustrate SPD impact on high-x and future EIC impact in low-x region

Gluon TMD : Sivers

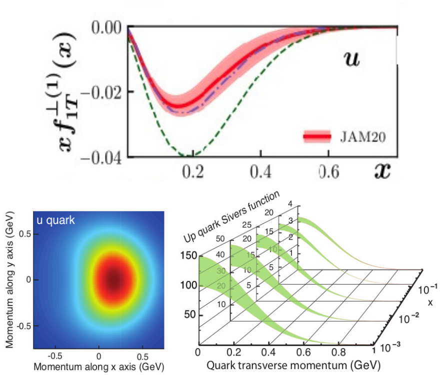


Figure 10: Extracted [above : Phys. rev. D 102, 054002, below : EIC white paper] quark Sivers as functions of x and k_T

- Sivers function can be described as a corrleation between parton k_T and hadron transverse spin
- Transverse single spin asymmetries (A_N) are sensitive to the gluon Sivers function
- Extracted in generalized parton model(GPM), color gauge invariant GPM(CGI-GPM) descriptions of partonic structure
- Unlike gluon helicity PDF, there has not been extraction of gluon Sivers from global analysis, SPD can provide much needed data points

SPD : Prominent Measurements

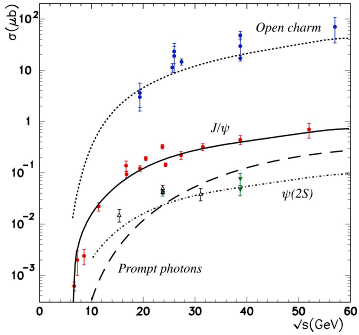


Figure 11: Partonic sub-process cross-sections from $p + p$ vs. collision energy : SPD CDR

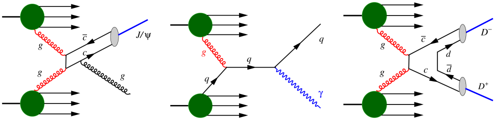


Figure 12: Sub-process diagrams

- Flagship probes at SPD accessing gluon content :
  1. gluon fusion to charmonia ($J/\Psi, \Psi(2S), \chi_{c_1/c_2}$), primarily via dimuon decay channel
  2. quark-gluon to prompt-photons, cleanest channel for interpretation
  3. gluon fusion to open-charm mesons, highest statistics but also very high background

Various SPD Probes

Probe	$\sigma_{27\,\text{GeV}}$, nb ($\times$BF)	$\sigma_{13.5\,\text{GeV}}$, nb ($\times$BF)	$N_{27\,\text{GeV}}$, 10^6	$N_{13.5\,\text{GeV}}$ 10^6
Prompt-γ ($p_T > 3$ GeV/c)	35	2	35	0.2
J/ψ	200	60		
$\to \mu^+\mu^-$	12	3.6	12	0.36
$\psi(2S)$	25	5		
$\to J/\psi\pi^+\pi^- \to \mu^+\mu^-\pi^+\pi^-$	0.5	0.1	0.5	0.01
$\to \mu^+\mu^-$	0.2	0.04	0.2	0.004
$\chi_{c1} + \chi_{c2}$	200			
$\to \gamma J/\psi \to \gamma\mu^+\mu^-$	2.4		2.4	
η_c	400			
$\to p\bar{p}$	0.6		0.6	
Open charm: $D\overline{D}$ pairs	14000	1300		
Single D-mesons				
$D^+ \to K^-2\pi^+$ ($D^- \to K^+2\pi^-$)	520	48	520	4.8
$D^0 \to K^-\pi^+$ ($\overline{D}^0 \to K^+\pi^-$)	360	33	360	3.3

Figure 13: Expected statistics for probes for one year of data at SPD

Charmonia Measurements

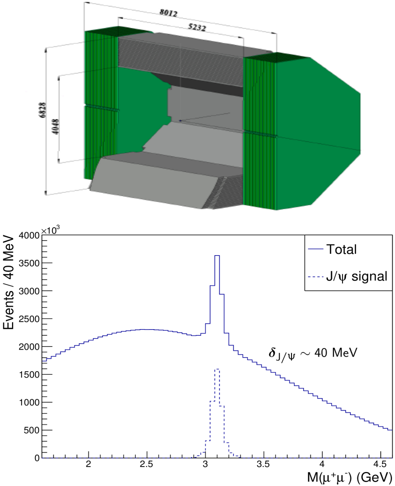


Figure 14: Above: Range System at SPD
Below: di-muon invariant mass spectra for J/Ψ : SPD TDR

- Productions are dominated by *gg* fusion at SPD kinematics
- Reconstructed from di-muon decay channels using Range System as muon identifier
- Hadronization poorly understood (various models : CSM, CEM, NRQCD)
- TMD factorization not always applicable
- J/Ψ most abundant $\sim$ 12 M events expected in one year of data in this channel

J/Ψ Double Helicity Asymmetry ($A_{LL}^{J/\Psi}$)

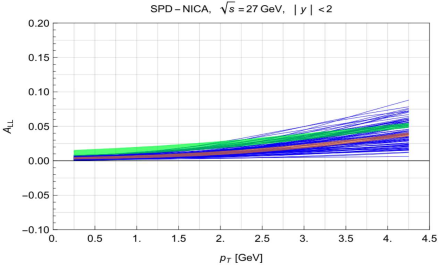


Figure 15: Estimated $A_{LL}^{J/\Psi}$ for different PDF replicas (brown and green bands are uncertainties for scale and LDME variations) : Physics 2023, 5(3), 672-687

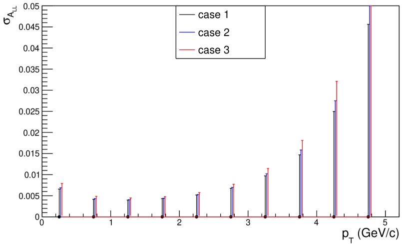


Figure 16: Projected statistical uncertainties for $A_{LL}^{J/\Psi}$ measurements from one year of recorded data at the SPD in p_T for three different selection criteria of muon polar angle θ_μ : SPD CDR

- $A_{LL}^{J/\Psi} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}_{LL}^{gg \to J/\Psi + x}$
- Sensitive to gluon helicity PDF
- SPD kinematic will probe $x_{Bjorken} \sim 0.03 - 0.5$

Impact of SPD $A_{LL}^{J/\Psi}$ Measurements

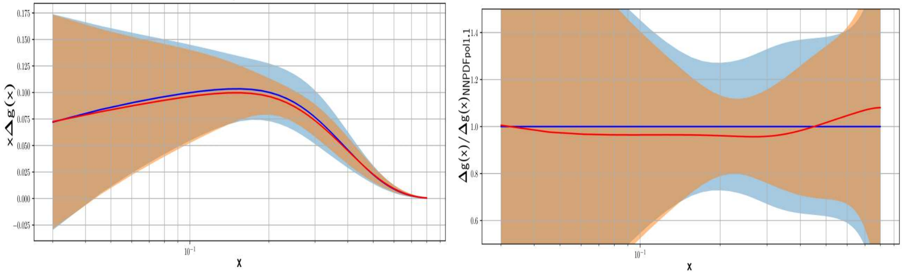


Figure 17: Estimated impact of $A_{LL}^{J/\Psi}$ measurements at the SPD on the gluon helicity distribution $\Delta g(x)$. Blue and red lines show the mean of the NNPDFpol1.1 replica sets before and after the re-weighting, respectively. Light blue and light orange bands show the corresponding standard deviation uncertainties (Physics 2023, 5(3), 672-687).

SPD impact in $0.1 \leq x \leq 0.6$ range

J/Ψ Single Transverse Spin Asymmetry ($A_N^{J/\Psi}$)

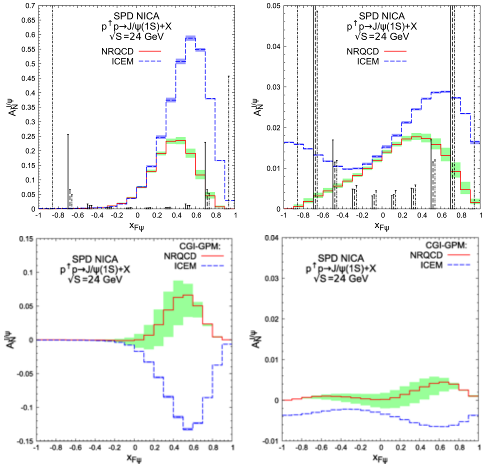


Figure 18: $A_N^{J/\Psi}$ predictions for SPD kinematics (and projected uncertainties for one year of recorded data) [Phys. Rev. D *104*, 016008]

- Top to bottom : GPM and CGI-GPM. Left to right : SIDIS1 and D'Alesio parameterization of Sivers Function
- Various combinations of PDFs and hadronization models illustrate strong model dependence
- For example, asymmetry predictions using SIDIS1 and d'Alesio params. are different by an order of magnitude
- SPD measurements and precision can be crucial in restricting such model dependence in future

Other Charmonia Probes

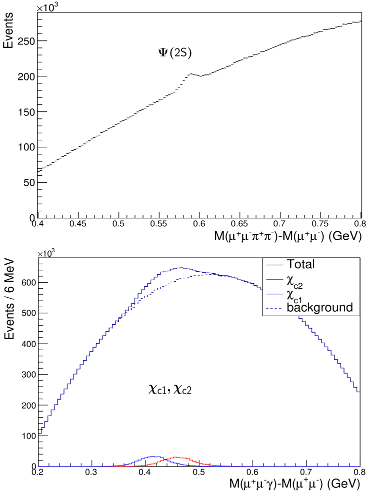


Figure 19: Di-muon invariant mass spectra for various charmonia probes : SPD CDR

- $\Psi(2S)$ via di-muon decay channels $(\mu^+\mu^-\pi^+\pi^-, \mu^+\mu^-)$: $\sim$ 700 K events/year
- χ_{c1}, χ_{c2} via di-muon decay channel $(\gamma\mu^+\mu^-)$: $\sim$ 2.4 M events/year
- Double J/Ψ productions : both J/Ψ into di-leptonic decay channels $\sim$ 100 events/year
- Limited η_c measurements could also be possible (of special ineterest as TMD factorization is proven for this probe)

Prompt Photon Double Helicity Asymmetry (A_{LL}^{γ})

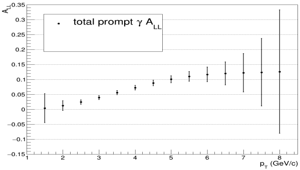


Figure 20: Predictions of A_{LL}^{γ} as function of transverse momentum p_T (Physics 2023, 5(3), 672-687)

Estimates (right plot) show that measurements at the SPD can reduce uncertainties of gluon heicity at large x by $\sim 1/2$

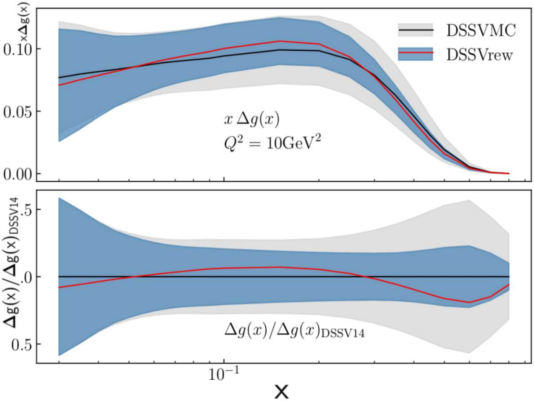


Figure 21: Impact of SPD A_{LL}^{γ} (Physics 2023, 5(3), 672-687) : Vogelsang, Sassot, Borsa

Prompt Photon Transverse Single Spin Asymmetry (A_N^γ)

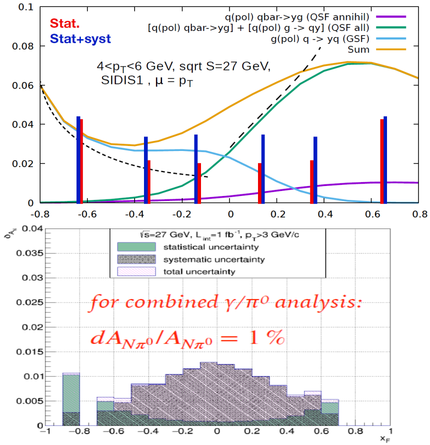


Figure 22: Above: Predicted A_N^γ vs. x_F from V. Saleev, A. Shipilova with projected uncertainties for one year of data at SPD Below: Estimation of uncertainty due to background : SPD CDR

- Prompt photon is an excellent channel to probe gluons as it does not include hadronization
- Challenge to remove stray photons from neutral light meson decays
- Uncertainties arising from photons from π^0 decays are estimated as systematic on lower left plot

Open Charm Measurements

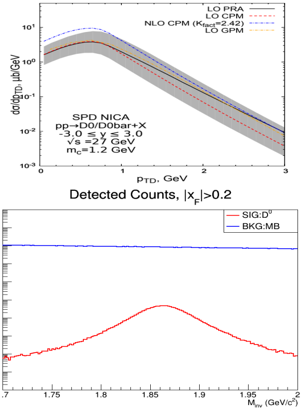


Figure 23: Above: inclusive D^0, $\bar{D}^0$ cross-section prediction (A. Karpishkov), Below: Projected π-K invariant mass spectra for one year of data at the SPD

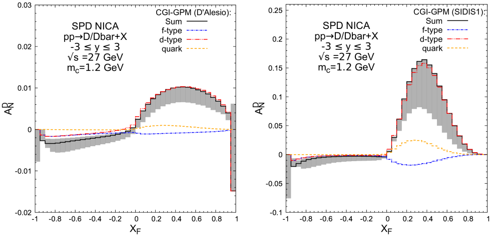


Figure 24: Predicted A_N at SPD kinematics (Prog. Part. Nucl. Phys. 2021, 119, 103858)

- Productions dominated (up to 70%) by gluon fusion
- Sensitive to gluon spin distributions
- Expected high A_N at $x_F \geq 0.2$
- Challenging measurement due to very high background ($B/S \sim 10^5$)

Neutral D Transverse Single Spin Asymmetry at the SPD

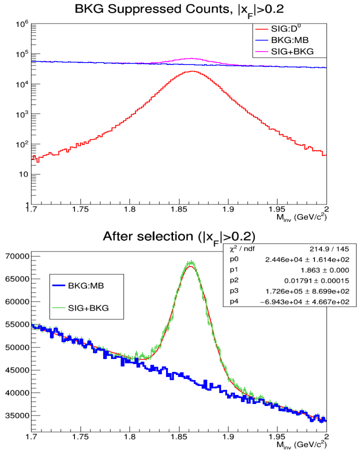


Figure 25: Above: Projected π-K invariant mass spectra after selection criteria are applied Below: $D^0 \to \pi^+ K^-$ fit to signal and background

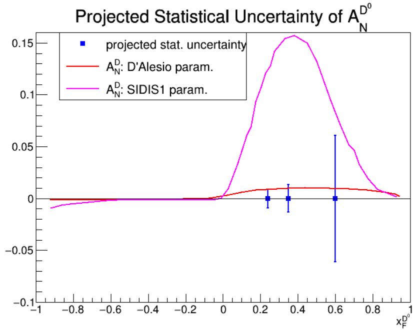


Figure 26: Predicted inclusive A_N^D at SPD kinematics with projected statistical uncertainties δ_N^{stat} for D^0 (Physics 2023, 5(3), 672-687)

Expected statistical precision should be able to (dis)favour GSF models decisively

The SPD : An International Collaboration

Figure 27: Members at the most recent SPD Collaboration Meeting. More than 400 members from 10 countries and growing.

The SPD : Present Status

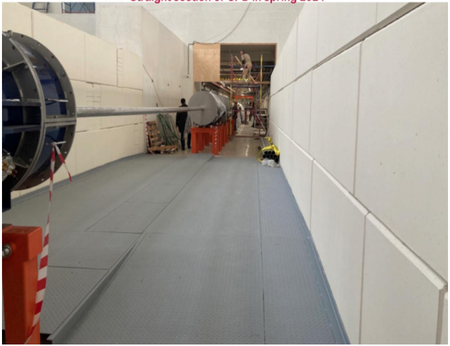
- Conceptual Design Report (CDR) was published in 2021
- CDR was approved by the JINR Program Advisory Committee (PAC) in Jan, 2022
- Technical Design Report (TDR) was published in 2023
- Independent Detector Advisory Committee (DAC) report submitted to the JINR PAC
- Project on track for development (`https://spd.jinr.ru/`)

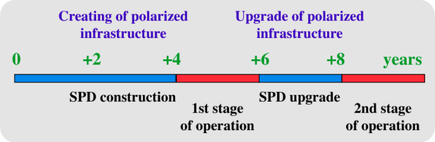
NICA : A Bird's Eye View

Figure 28: NICA complex with ongoing constructions

SPD Tentative Schedule

Straight section of SPD in spring 2024





- Detector development and testing are on track for the first phase of the SPD
- Due to quite different luminosity and multiplicity requirements, SPD and MPD typically will operate consecutively at NICA rather than concurrently

Summary and Outlook

- Spin Physics Detector (SPD) at the NICA facility will be a unique facility focusing on the unpolarized and polarized gluon distributions inside protons and deuterons from $p+p$ and $d+d$ collisions up to $\sqrt{s} = 27$ and 13.5 GeV respectively
- In the first stage, SPD will probe several interesting unpolarized and spin-dependent effects from $p+p$ and $d+d$ at low ($\sqrt{s_{NN}} = 5-10$ GeV) energies
- In the final stage, SPD measurements (of charmonia ($J/\Psi, \Psi(2S), \chi_c$), prompt-photon and open-charm (D mesons)) will be sensitive to
  1. unpolarized gluon PDF
  2. gluon helicity
  3. gluon TMD (Sivers, Boer-Mulders)
  4. gluon transversity in deuteron
- SPD contributions to the polarized gluon distributions will be complementary to similar existing and future collider (RHIC, EIC) and fixed target (AFTER, LHC-Spin) experiments

Thank You

Backup

Bayesian Re-weighting

- Each data point is used with its error (assumed Gaussian) to create MC replicas in the multi-Gaussian data space (virtual ensemble of data sets)
- PDF sets (u,d,s, anti-quarks, g etc.) are extracted from EACH data replica
- The average gives the central value and the standard deviation is the natural uncertainty of the PDF

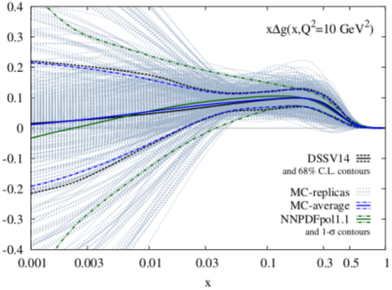


Figure 29: Phys. Rev. D 100, 114027 (2019)

Re-weighting Technique to Quantify Impact of New A_{LL}

- Once extracted, the set of replica PDFs can be used to measure the impact of a new asymmetry measurement WITHOUT doing full global analysis again
- *"The Bayesian reweighting is fully equivalent to a refit including the additional set of data ..."*
- Example shows the impact of STAR mid rapidity dijet result on the central value and the uncertainty band of the gluon helicity

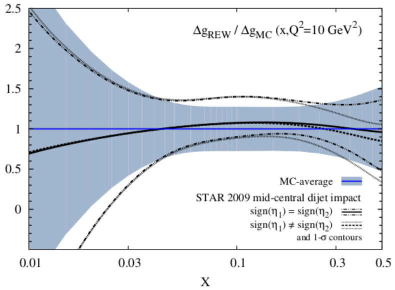


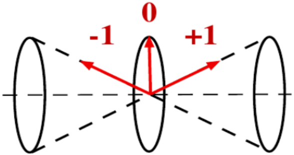
Figure 30: Phys. Rev. D 100, 114027 (2019)

Deuteron at SPD

$\sigma(x_F, p_T)$, vector and tensor angular asymmetries

Nonbaryonic content of deuteron:

$$|6q\rangle = c_1|NN\rangle + c_2|\Delta\Delta\rangle + c_3|CC\rangle$$



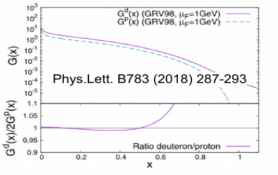
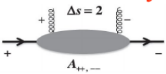
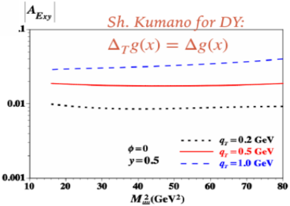


Fig. 6. Gluon PDF in the deuteron and in the nucleon.

Unpolarized gluons at high x:

Gluon transversity





Tensor PDFs