Spin Physics Detector : An Overview

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Plans for the Presentation

- Introduction
- Physics goals and detector : In stages
- Physics in focus
- Measurements, expectations, challenges
- Status and schedule
- Summary

Spin Physics Detector (SPD) at NICA

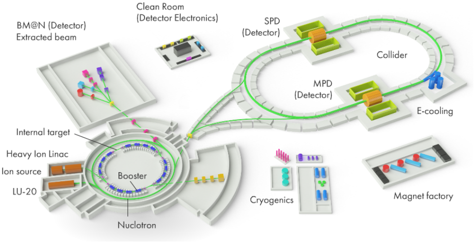


Figure 1: NICA - Nuclotron-based Ion Collider fAcility

Prime focus at SPD : to probe unpolarized and polarized gluon parton distribution functions (PDFs) inside nucleons

- Polarized collisions
  1. $p^{\uparrow}p^{\uparrow}$ at $\sqrt{s} = 27$ GeV
  2. $d^{\uparrow}d^{\uparrow}$ at $\sqrt{s} = 13.5$ GeV
  3. $p^{\uparrow}d^{\uparrow}$ at $\sqrt{s} = 19$ GeV
- with polarization $|P| \sim 70\%$

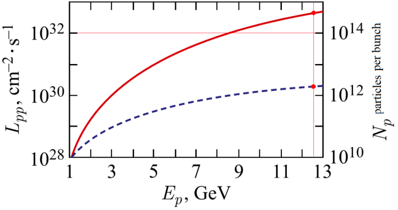
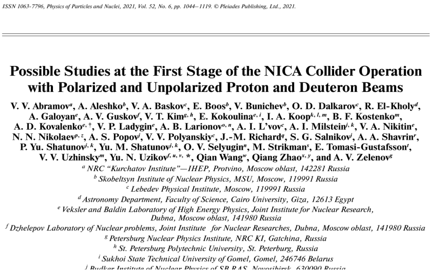


Figure 2: Luminosity and bunch intensity

SPD Stage I : Physics



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Possible Studies at the First Stage of the NICA Collider Operation with Polarized and Unpolarized Proton and Deuteron Beams

V. V. Abramov[a], A. Aleshko[b], V. A. Baskov[c], E. Boos[b], V. Bunichev[b], O. D. Dalkarov[c], R. El-Kholy[d], A. Galoyan[e], A. V. Guskov[f], V. T. Kim[g, h], E. Kokoulina[e, i], I. A. Koop[k, l, m], B. F. Kostenko[m], A. D. Kovalenko[e, †], V. P. Ladygin[e], A. B. Larionov[o, n], A. I. L'vov[c], A. I. Milstein[j, k], V. A. Nikitin[e], N. N. Nikolaev[p, z], A. S. Popov[j], V. V. Polyanskiy[c], J.-M. Richard[q], S. G. Salnikov[j], A. A. Shavrin[r], P. Yu. Shatunov[j, k], Yu. M. Shatunov[j, k], O. V. Selyugin[n], M. Strikman[s], E. Tomasi-Gustafsson[t], V. V. Uzhinsky[m], Yu. N. Uzikov[f, u, v, *], Qian Wang[w], Qiang Zhao[x, y], and A. V. Zelenov[g]

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[j] Budker Institute of Nuclear Physics of SB RAS, Novosibirsk, 630090 Russia

Figure 3: Physics of Particles and Nuclei 52, 1044 (2021), arXiv:2102.08477

- Spin effects in *pp*, *dd* elastic scattering
- Charmonium production near threshold
- Strange hypernuclei production
- Spin effects in hyperon production
- Multiquark correlations
- Dibaryon production
- Light and intermediate nuclei collisions

SPD Stage I : Detector

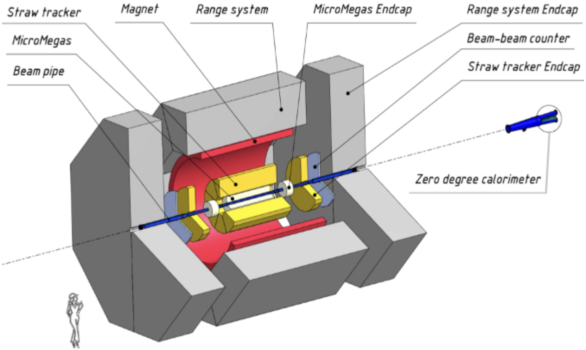
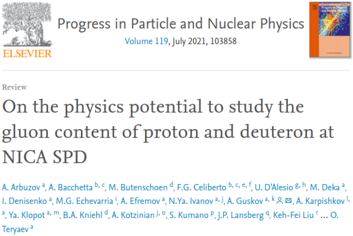


Figure 4: SPD detector in Stage I

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

- Possible light ion collisions alongside *pp*, *dd*
- 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 $\delta \sim 150\ \mu$m, $\delta(\frac{dE}{dx}) = 8.5\%$

SPD Stage II : Physics



Progress in Particle and Nuclear Physics
Volume 119, July 2021, 103858

Review

On the physics potential to study the gluon content of proton and deuteron at NICA SPD

A. Arbuzov [a], A. Bacchetta [b, c], M. Butenschoen [d], F.G. Celiberto [b, c, e, f], U. D'Alesio [g, h], M. Deka [a], I. Denisenko [a], M.G. Echevarria [i], A. Efremov [a], N.Ya. Ivanov [a, j], A. Guskov [a, k], A. Karpishkov [l, a], Ya. Klopot [a, m], B.A. Kniehl [d], A. Kotzinian [j, o], S. Kumano [p], J.P. Lansberg [q], Keh-Fei Liu [r] … O. Teryaev [a]

Figure 5: Progress in Particle and Nuclear Physics 119 (2021), arXiv:2011.15005

- 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

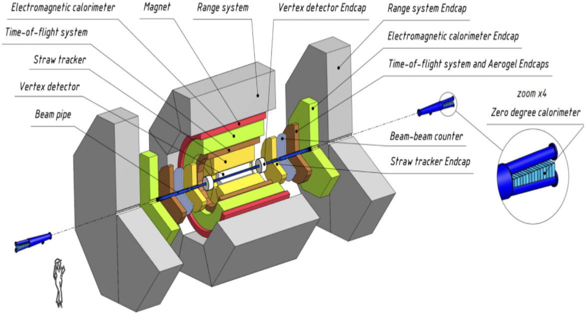
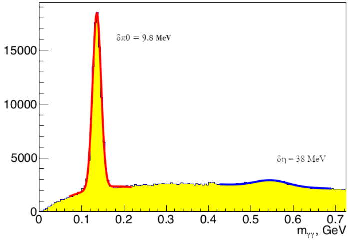


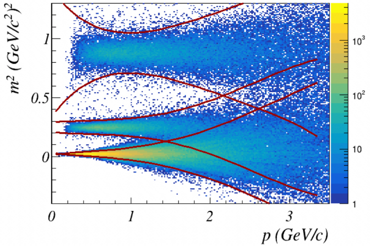
Figure 6: SPD detector in stage II

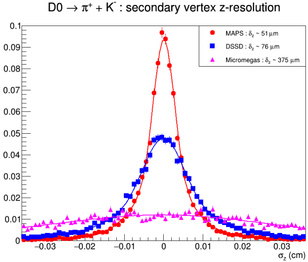
- Improved vertex detector for short lived particle decays
- TOF+AGel for better PID
- ECAL for $\gamma, e^{\pm}$ identification

- Event rate at peak luminosity and energy ~ 3 MHz
- Silicon vertex detector : MAPS/DSSD
- Time of flight (TOF) for PID ($\delta_t \sim 50$ ps), π/K separation upto 1.5 GeV/c
- Electromagnetic calorimeter (ECAL) $(\frac{\delta_E}{E} = \frac{5\%}{\sqrt{E}} + 1\%)$
- Aerogel counter in endcaps, extends π/K separation upto 2.5 GeV/c

Detector Perfomance

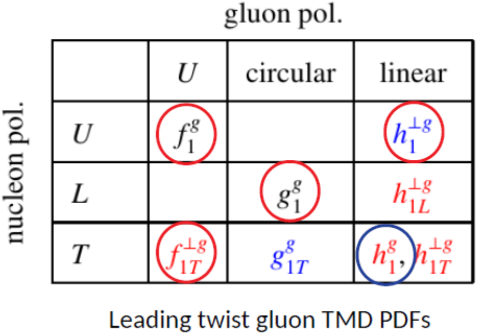






- Clockwise from lower left :
- Resolution of reconstructed D^0 vertex : $\delta_z \sim 50\ \mu$m for MAPS
- Invariant mass of 2-photons : $\delta_m \sim 10$ MeV
- TOF performance:provides a 3σ separation of π/K upto 1.5 GeV/c
- Additionally: $\frac{\delta_{p_T}}{p_T} \sim 2\%$ for 1 GeV/c tracks with magnetic field ~ 1 T

Probing Gluon Spin Distributions at SPD



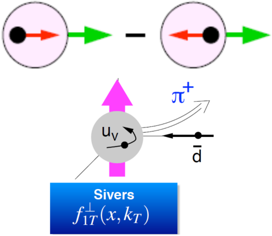
gluon pol.

nucleon pol.

	U	circular	linear
U	f_1^g		$h_1^{\perp g}$
L		g_1^g	$h_{1L}^{\perp g}$
T	$f_{1T}^{\perp g}$	g_{1T}^g	h_1^g, $h_{1T}^{\perp g}$

Leading twist gluon TMD PDFs

Figure 7: Various spin distributions of gluon that will be accessible via SPD measurements



- Unpolarized gluon distributions (f_1^g)
- Gluon helicity PDF (g_1^g)
- TMD spin distributions i.e. Sivers ($f_{1T}^{\perp g}$), Boer-Mulders ($h_1^{\perp g}$)
- Transversity (h_1^g) : deuteron

Gluon Helicity $\Delta g(x)$

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

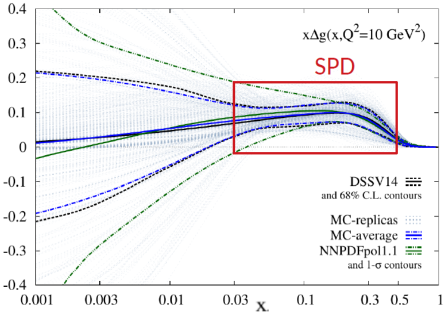


Figure 8: Gluon helicity distribution from DSSV group:PRD100 114027(2019). Highlighted region shows where SPD will make a major impact

Phys.Rev.Lett. 113 (2014) 1, 012001

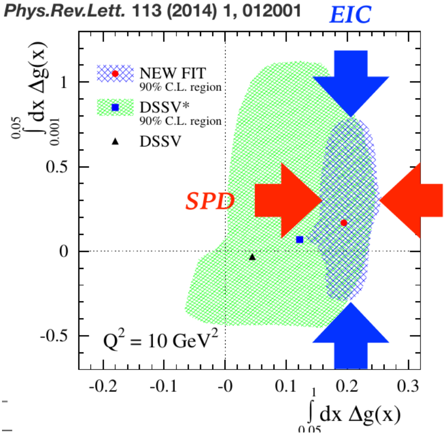


Figure 9: Truncated moments of $\Delta g(x)$ illustrates SPD impact on high-x and future EIC impact in low-x region

Gluon TMD : Sivers

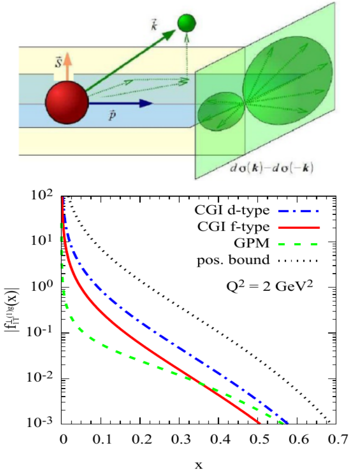


Figure 10: First k_T moment of gluon Sivers for GPM and CGI-GPM (PRD99, 036013 (2019)

- 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 : Measurements

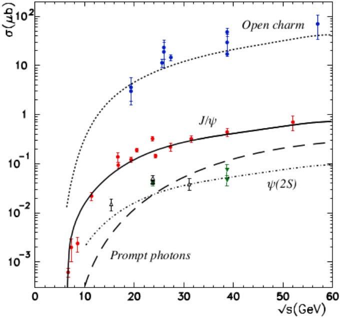


Figure 11: Partonic sub-process cross-sections from $p + p$ vs. collision energy : SPD CDR

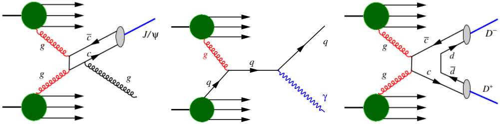
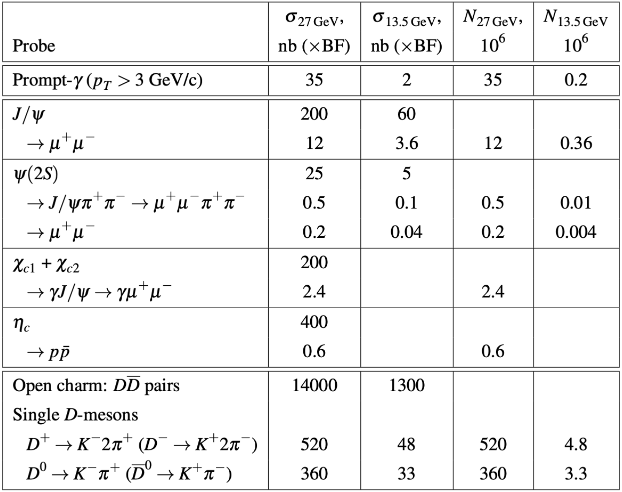


Figure 12: Sub-process diagrams

- 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	$\sigma_{27\,\mathrm{GeV}}$, nb (×BF)	$\sigma_{13.5\,\mathrm{GeV}}$, nb (×BF)	$N_{27\,\mathrm{GeV}}$, 10^6	$N_{13.5\,\mathrm{GeV}}$ 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

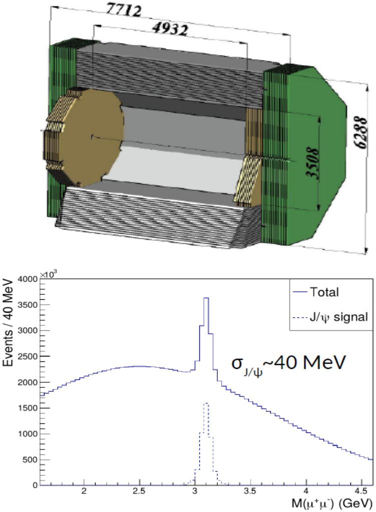
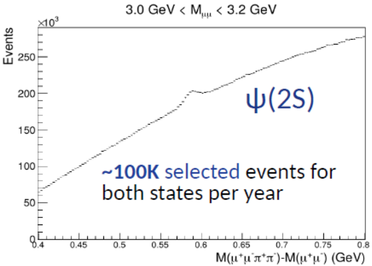


Figure 14: Above: Range System at SPD
Below: di-muon invariant mass spectra for J/Ψ

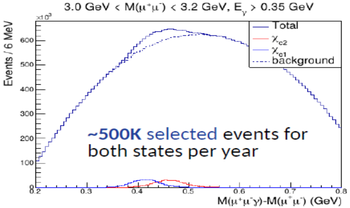
- Dominated by *gg* fusion at SPD kinematics
- Reconstructed from di-muon decay channel using Range System as muon identifier
- Hadronization poorly understood (various models : CSM, CEM, NRQCD)
- TMD factorization not always applicable
- J/Ψ most abundant $\sim$ 12 M events expected in one year of data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

Other Charmonia Probes



~100K selected events for both states per year

χ_{c1} and χ_{c2}



~500K selected events for both states per year

Figure 15: Di-muon invariant mass spectra for other charmonia probes

- $\Psi(2S)$ 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 production : both J/Ψ into dileptonic decay channel $\sim$ 100 events/year
- Limited η_c measurements could be possible

J/Ψ Double Helicity Asymmetry (A_{LL})

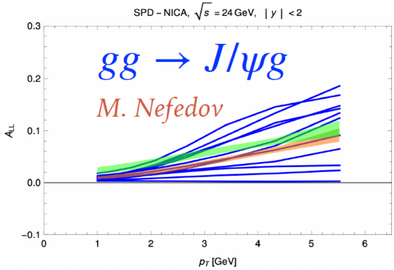


Figure 16: Estimated $A_{LL}^{J/\Psi}$ for different PDF replicas

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

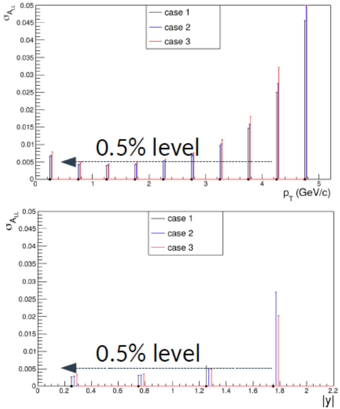


Figure 17: Projected statistical uncertainties for $A_{LL}^{J/\Psi}$ measurements in one year of data at SPD in p_T (above) and rapidity y (below)

J/Ψ Single Transverse Spin Asymmetry (A_N)

Projected stat. uncertainties and predictions from P RD104, 016008 (2021)

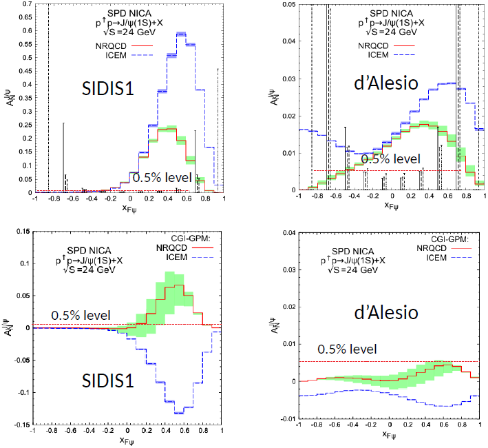
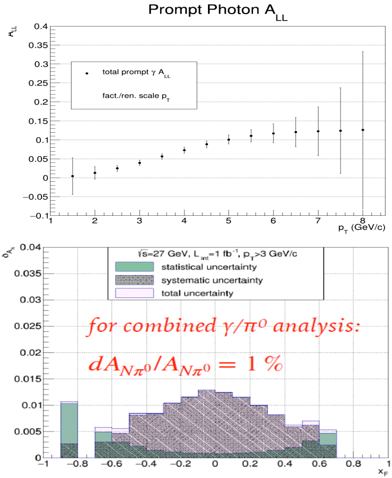


Figure 18: $A_N^{J/\Psi}$ predictions for SPD kinematics and projected uncertainties for one year of recorded data

- Various combinations of PDF and hadronization models illustrate the heavy model dependence and therefore our present limited understanding
- For example, asymmetry predictions using SIDIS1 and d'Alesio parametrizations are different by almost an order of magnitude
- SPD measurements and precision can be crucial in restricting such model dependence in future

Prompt Photon A_{LL}



for combined γ/π^0 analysis:

$$dA_{N\pi^0}/A_{N\pi^0} = 1\ \%$$

Figure 19: Above: predictions of A_{LL}^{γ} as function of p_T (W. Vogelsang), Below: estimation of uncertainty due to background

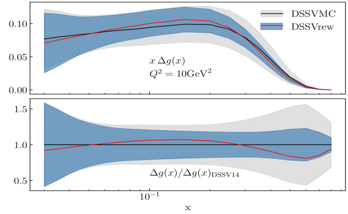


Figure 20: Impact of SPD A_{LL}^{γ} : Vogelsang, Sassot, Borsa

- A clean channel for interpretation
- Challenge : background photons from π^0 decays
- Estimates show SPD can reduce uncertainty at high $x_{Bjorken}$ by ≈ 2

Prompt Photon A_N

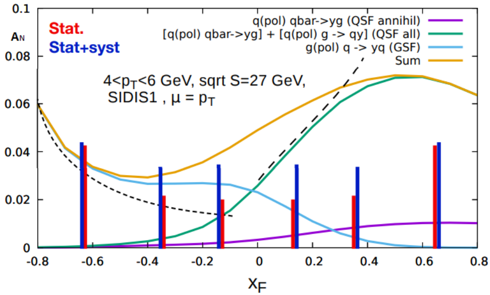


Figure 21: Predicted A_N^{γ} vs. x_F from V. Saleev, A. Shipilova with projected uncertainties for one year of data at SPD

- Prompt photon is an excellent channel to probe gluon as it does not require fragmentation function/parameterizations
- Challenge to remove stray photons from neutral light meson decays
- Uncertainties arising from photons from π^0 decays are estimated as systematics on lower left plot

Open Charm Measurements

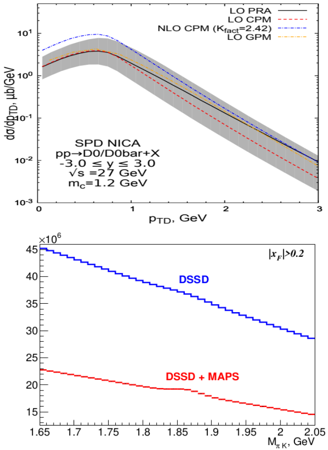


Figure 22: Above: inclusive $D^0, \bar{D}^0$ cross-section prediction (A. Karpishkov), Below: $D^0 \to \pi^+ K^-$ invariant mass in MC

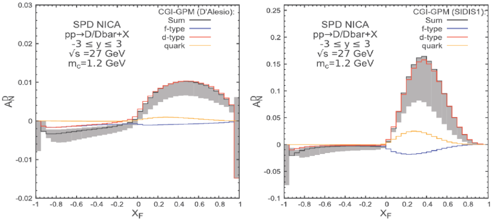


Figure 23: Predicted A_N at SPD kinematics

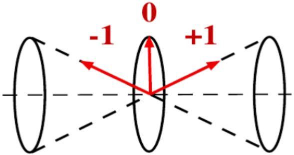
- Sensitive to gluon spin distributions
- Expected high A_N at $x_F \geq 0.2$
- Challenging measurement due to very high background ($B/S \sim 10^5$)
- Ongoing MC study to reduce background

Deuteron at SPD

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

Nonbaryonic content of deuteron:

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



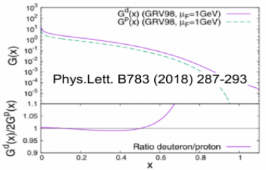
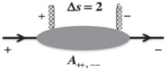
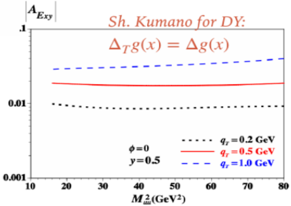


Fig. 6. Gluon PDF in the deuteron and in the nucleon.

Unpolarized gluons at high x:

Gluon transversity

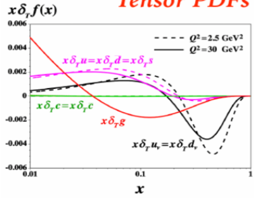




Sh. Kumano for DY:

$\Delta_T g(x) = \Delta g(x)$

Tensor PDFs



SPD : International Collaboration

32 institutes from 14 states,
~300 members

Figure 24: International Members of SPD Collaboration

SPD : Present Status

- Conceptual Design Report (CDR) was published (arXiv:2102.00442) last year (updated early this year)
- CDR has been approved by the JINR Program Advisory Committee (PAC) in Jan, 2022
- Technical Design Report (TDR) is being prepared and will be presented in the first half of 2023

NICA : A Bird’s Eye View

Figure 25: NICA complex with ongoing constructions

SPD : Constructions

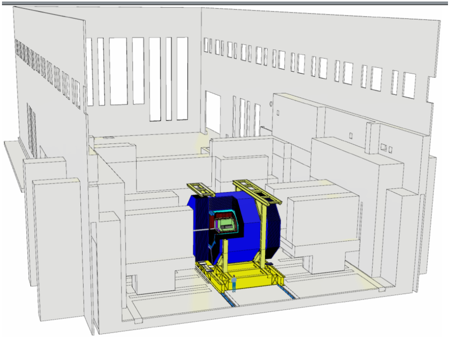
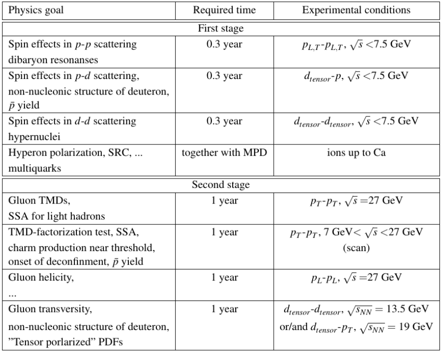


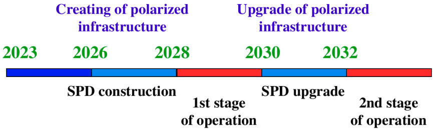
Figure 26: Schematic of SPD detectors in the experimental hall

Figure 27: SPD experimental hall under construction

SPD Tentative Schedule



Physics goal	Required time	Experimental conditions
First stage		
Spin effects in p-p scattering dibaryon resonanses	0.3 year	$p_{L,T}$-$p_{L,T}$, $\sqrt{s}$ <7.5 GeV
Spin effects in p-d scattering, non-nucleonic structure of deuteron, $\bar{p}$ yield	0.3 year	d_{tensor}-p, $\sqrt{s}$ <7.5 GeV
Spin effects in d-d scattering hypernuclei	0.3 year	d_{tensor}-d_{tensor}, $\sqrt{s}$ <7.5 GeV
Hyperon polarization, SRC, ... multiquarks	together with MPD	ions up to Ca
Second stage		
Gluon TMDs, SSA for light hadrons	1 year	p_T-p_T, $\sqrt{s}$ =27 GeV
TMD-factorization test, SSA, charm production near threshold, onset of deconfinment, $\bar{p}$ yield	1 year	p_T-p_T, 7 GeV< $\sqrt{s}$ <27 GeV (scan)
Gluon helicity, ...	1 year	p_L-p_L, $\sqrt{s}$ =27 GeV
Gluon transversity, non-nucleonic structure of deuteron, "Tensor porlarized" PDFs	1 year	d_{tensor}-d_{tensor}, $\sqrt{s_{NN}} = 13.5$ GeV or/and d_{tensor}-p_T, $\sqrt{s_{NN}} = 19$ GeV



- Expected data acquisition for stage I in 2028 and stage II in 2032
- Due to different luminosity and multiplicity requirements, SPD and MPD typically will operate consecutively at NICA

Summary and Outlook

- Spin Physics Detector (SPD) at the NICA facility in JINR will be a unique facility that will focus on studying the unpolarized and polarized gluon distributions inside protons and deuterons from $p + p$ and $d + d$ collisions upto $\sqrt{s} = 27$ GeV
- In the first stage, SPD physics program : spin effects in p-p, p-d, d-d elastic scattering, hyperon and hypernuclei production,threshold production of charmonia and more
- In the second stage the experiment will probe charmonia $(J/\Psi, \Psi(2S), \chi_c)$, prompt-photon and open-charm (D-meson) productions and asymmetries
- SPD measurements will be sensitive to
  1. unpolarized gluon PDF
  2. gluon helicity
  3. gluon TMD (Sivers, Boer-Mulders)
  4. gluon transversity in deuteron
- SPD contribution 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

SPD Kinematics

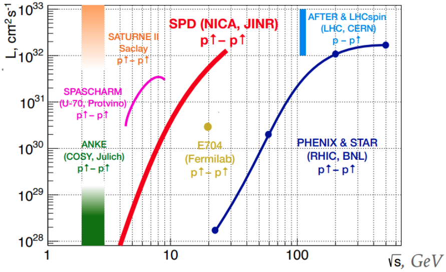


Figure 28: Luminosity and energy chart

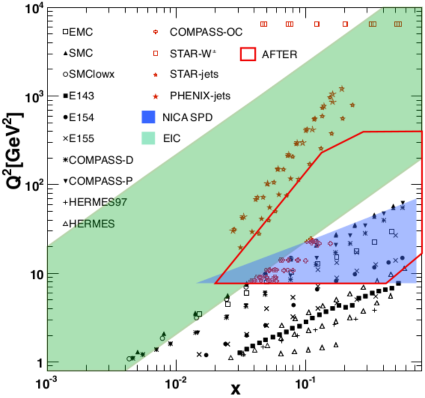


Figure 29: Kinematics chart