Quarkonium Physics at SPD NICA

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Introduction to SPD

Figure 1: NICA facility at Joint Institute of Nuclear Research (JINR) in Dubna, Russia

The proposed Spin Physics Detector (SPD) will be an excellent laboratory to probe nucleon structure, especially polarized Parton Distribution Functions (PDF) of gluons

- At NICA accelerator facility in JINR, SPD experiment will be able to measure cross-sections and spin asymmetries from polarized (with 70% polarization)
    1. $p + p$ at $\sqrt{s} = 27$ GeV
    2. $d + d$ at $\sqrt{s} = 13.5$ GeV
- SPD plans to focus on three measurement channels :
    1. Open charm mesons (D^+D^-, $D^0\bar{D}^0$)
    2. Charmonia (J/Ψ and heavier)
    3. Prompt photons (γ)

Spin Physics Detector Overview

- **Vertex Detector** : MicroMegas and silicon vertex detector (DSSD or MAPS)
- To recontruct secondary vertices with precision ($\sigma \leq 50~\mu$m)
- **Tracker** : metalized PET straws
- Tracking of charged particles with spatial resolution $\sigma \sim 150~\mu$m, $\frac{dE}{dx}$ of charged tracks
- Momentum measurement $\frac{\delta p_T}{p_T} \sim 2\%$ at $p \sim 1$ GeV/c
- **Solenoidal** magnetic field, up to 1T
- **Electromagnetic Calorimeter** to determine energy of photons and electron with precision $\frac{\delta E}{E} \sim \frac{5\%}{\sqrt{E(GeV)}}$
- **Range System** : for muon and neutron (combining info with tracker) identification, hadron calorimetry
- Beam Beam Counter (**BBC**) and Zero Degree Calorimeter (**ZDC**) at high rapidity range : local polarimetry and luminosity counters

SPD Detectors : Stage 1

- Since initial planning, SPD design have some changes
- Solenoid magnet outside ECAL (as opposed to initial dsign of six coils inside ECAL)
- Staged production of SPD system
- 1st stage : Range System, Magnet, Tracker, MicroMegas vertex detector
- 1st stage : (possibly) BBC, ZDC, ECAL in one end-cap

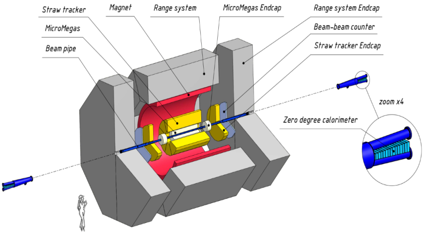


Figure 2: Schematic of SPD detector system : 1st Stage

SPD Detectors : Stage 2

- Staged production of detector system
- BBC, ZDC installed
- Include ECAL
- More precise MAPS vertex detector replacing MicroMegas
- TOF in barrel, TOF+Aerogel in end-cap

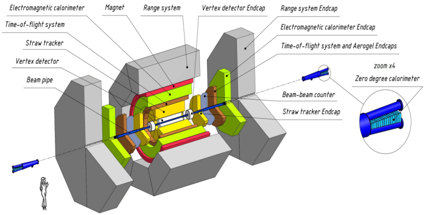


Figure 3: Schematic of SPD detector system : 2nd Stage

Polarized Beams at NICA

Spin Transparency mode (discreet energy values) :

- polarized $p + p$ with beam energy up to 3.75 GeV
- polarized $d + d$ with beam energy up to 1.3 GeV

After installation of two Siberian snakes in each ring and electron cooling in booster :

- Transversely polarized $p + p$ with beam energy up to 12.6 GeV
- Longitudinally polarized $p + p$ with beam energy up to 12.6 GeV
- Transversely polarized $d + d$ with beam energy up to 6.3 GeV/n
- Longitudinally polarized $d + d$ with beam energy up to 4.2 GeV/n

Physics Processes of Interest

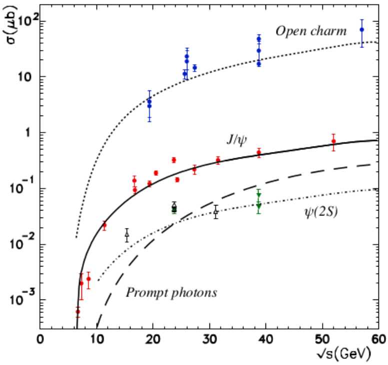


Figure 4: Process cross-sections as function of energy (Eur. Phys. J. C23, 527-538, 2002)

- Open charm productions (D mesons) : highest cross-section and orders of magnitude combinatorial background, VTX detector crucial
- Charmonium productions ($J/\Psi, \Psi(2S), \eta_c, \chi_c$) : 2 orders smaller cross-section but cleaner measurements via dimuon decays primarily, RS performance crucial
- Prompt photons : decays from π^0, η and fragmentation photons are background

Physics Processes of Interest at SPD

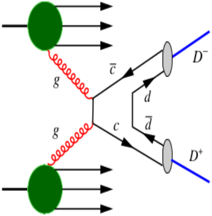


Figure 5: Schematic of open charm

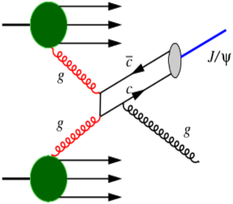


Figure 6: Schematic of charmonium

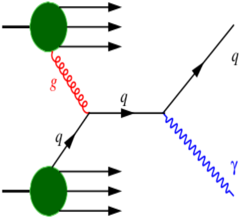


Figure 7: Schematic of prompt photon

Charmonium production dominated by *gluon* – *gluon* process at SPD energies

Charmonia Detection at SPD

- J/Ψ primarily via dimuon decay channel
- $\Psi(2S)$ and χ_c possibly via decay channels involing J/Ψ which in turn decay into two muons
- η_c possibly via $p\bar{p}$ decay channel
- Range System : layers of Fe and silicon strips (layers at stereo angles) for tracking

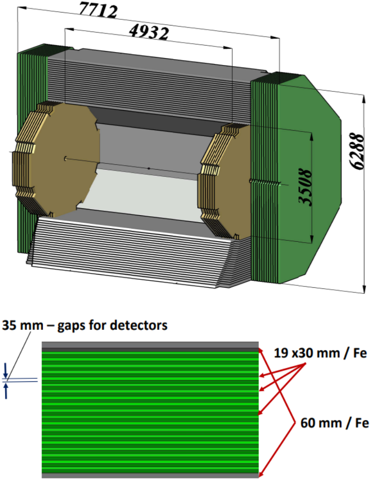


Figure 8: Schematic of Range System at SPD

TMD PDFs Accessed at SPD

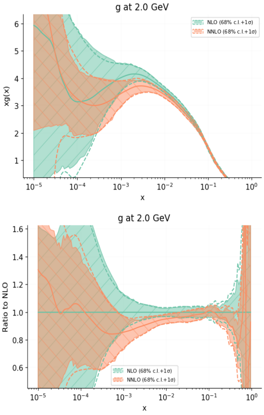
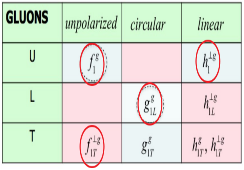


Figure 9: NNPDF coll. arXiv:1706.00428



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

- Gluon TMD PDFs accessed at SPD
- Left: unpol. gluon PDF (notice the uncertainties in large-x as well as small-x) : NNPDF 3.1
- Right: gluon helicity : DSSV(top), quark Sivers : JAM (bottom)

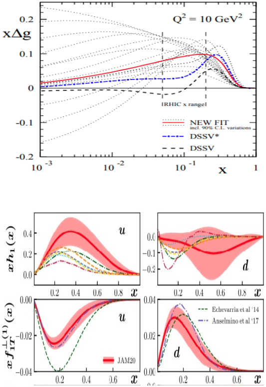


Figure 10: Phys. Rev. Lett. 113, 012001(2014) (top), Phys. Rev. D 102, 054002 (2020) (bottom)

SPD Design and Kinematic Coverage

SPD will contribute data in the large Bjorken x range

Design luminosity $10^{32} cm^{-2} s^{-1}$
Energy range up to 27 GeV for $p^{\uparrow} + p^{\uparrow}$

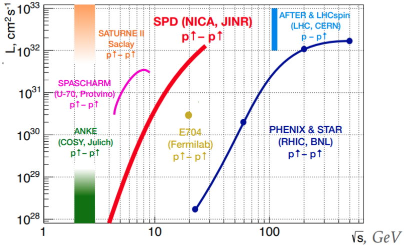


Figure 11: Luminosity (L) and center of mass energy (S) range : SPD CDR

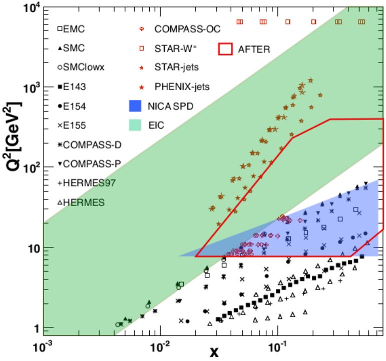


Figure 12: Energy transfer (Q^2) and momentum fraction (x) range : SPD CDR

J/Ψ Production at SPD

- Hadronization process of scattered $c\bar{c}$ from the interacting gg or $q\bar{q}$ not well understood
- Various models, applicable to different kinematic regimes available :
- color singlet model (**CSM**)
- non-relativistic QCD factorization (**NRQCD** - probably the most rigorous model), can use collinear (**CPM**) or generalized (**GPM**) parton models for factorization
- color evaporation model (**CEM**) or the 'improved' version (**ICEM**) - close to NRQCD without velocity scaling)

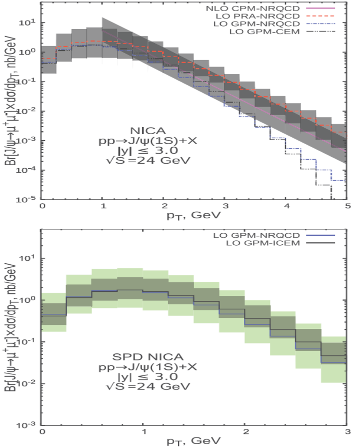


Figure 13: Predicted model dependent J/Ψ cross-sections at SPD (Phys. Rev. D 104, 016008 (2021))

J/Ψ Detection at SPD

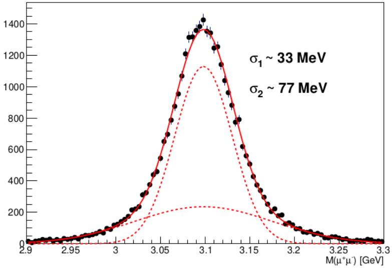


Figure 14: J/Ψ from dimuon invariant mass : resolution $\sigma_m \sim 30$ MeV : SPD CDR

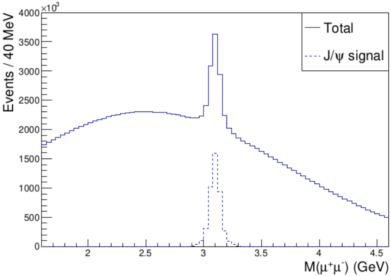


Figure 15: J/Ψ after one year of data at design luminosity at SPD

Pion suppression rate $\sim$ 97% with muon selection efficiency $\sim$ 95% or higher can be expected

Model Dependent J/Ψ Transverse Asymmetry

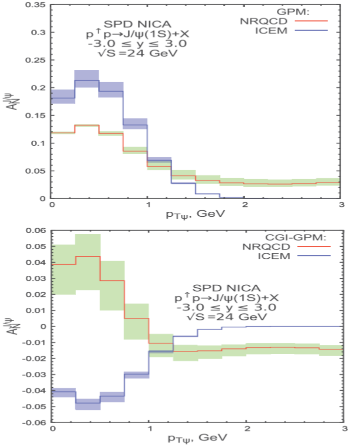


Figure 16: J/Ψ SSA as function of p_T (Phy. Rev. D 104, 016008 (2021))

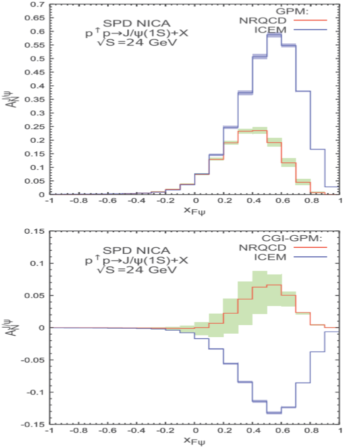


Figure 17: J/Ψ SSA as function of x_F (Phy. Rev. D 104, 016008 (2021))

J/Ψ Asymmetries

- Cross-section measurements at SPD energies can be very useful to contraining model dependence of the production of J/Ψ
- In turn, it can influence the model dependence of transverse single spin asymmetry predictions
- Moreover the SSA will help probe the gluon TMDs i.e. gluon Sivers function
- Helicity asymmetry prediction shows unceratinties with different LO replicas of long distance matrix elements (**LDME**)

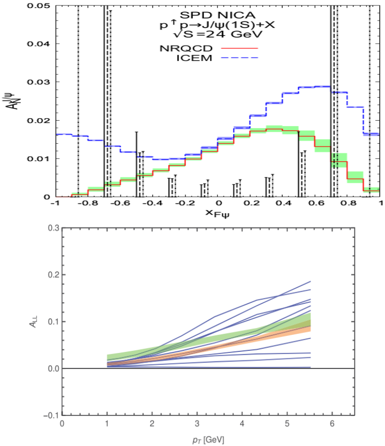


Figure 18: Stat. unceratinties of $A_N^{J/\Psi}$ (top), $A_{LL}^{J/\Psi}$ vs. p_T : courtesy V. Saleev et al. (bottom)

Probing Gluon Helicity with A_{LL}

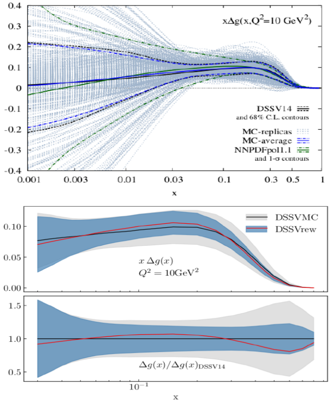


Figure 19: Gluon helicity distrbution $\Delta g(x)$ (above) and impact of prompt γ A_{LL} at SPD (below) : courtesy W. Vogelsang, D. de Florian

- Global analysis of world data is performed to extract helicity function
- Recent collaboration with DSSV group estimated impact of prompt A_{LL}^{γ} measurements at SPD with data taken at $\sqrt{s} = 27$ GeV with integrated lumniosity of 1 fb^{-1}
- SPD will make significant contributions at large Bjorken-x range ($x \geq 0.5$)
- With some clarity on model dependence from cross-section comparisons, we can perform estimate of impact of $A_{LL}^{J/\Psi}$

Other Charmonium Probes : $\Psi(2S)$, χ_c

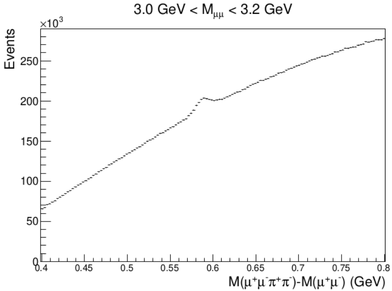


Figure 20: $\Psi(2S) \longrightarrow \pi^+\pi^- J/\Psi$: signal and combinatorial background for one year of data at design luminosity : SPD CDR

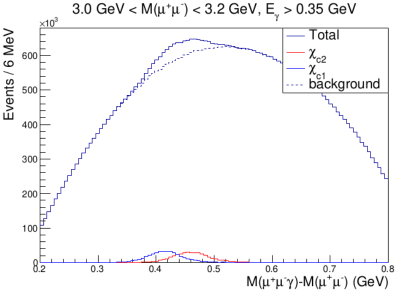


Figure 21: $\chi_c \longrightarrow \gamma J/\Psi$ signal and combinatorial background for one year of data at design luminosity : SPD CDR

η_c Production at SPD

- A probe for which TMD-factorization is proven
- Any measurement of η_c production will be very useful
- Model dependent predictions, including parton Reggeization approach (**PRA** - from our Samara colleagues) at SPD kinematic are available
- Cross-section is $\sim 10\ \%$ compared to $J/\Psi \text{x} B(J/\Psi \longrightarrow \mu^+\mu^-)$

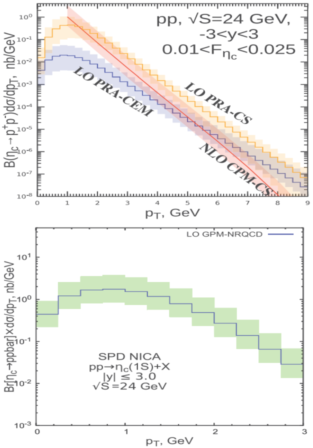


Figure 22: Model dependent Predictions of η_c production : Prog. in Nucl. and Part. Phys. 119, 103858 (2021)

η_c Measurement at SPD

- Golden channel for interpretation
- Typical decay channel for interest at SPD : $\eta_c \longrightarrow p\bar{p}$
- Orders of magnitude high combinatorial background
- Background suppression is key, machine learning techniques might help in online event selection
- MC simulation shows $J/\Psi \longrightarrow p\bar{p}$ normalized to expected one year of data (as PYTHIA does not hadronize to η_c)

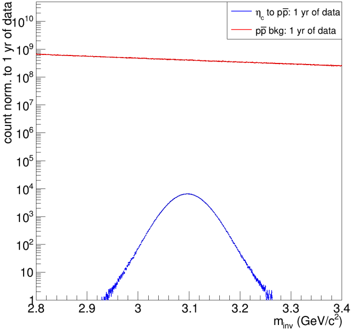


Figure 23: η_c signal ($\eta_c \longrightarrow p\bar{p}$) and combinatorial background for $p\bar{p}$ invariant mass spectra at SPD

Status of SPD Collaboration

- SPD collaboration officially formed in June, 2021
- Collaboration has 32 participant institutes from 14 countries
- SPD involves ~ 300 members
- SPD conceptual design report (CDR) has been published (https://arxiv.org/abs/2102.00442)
- Detector advisory committee (DAC) formed
- Work ongoing for the technical design report (TDR) to be published within the first half of 2022

Summary

- SPD detector system will be built in stages
- Until NICA upgrade with Siberian Snakes, SPD will record data from the lower end of the design energy range
- We are looking forward to J/Ψ measurements (cross-sections and various asymmetries) at various collision energies at SPD providing an increasing number of data points to constrain the model dependence of the hadronization
- SPD can provide important data to probe gluon sivers function via SSA and constrain gluon helicity at large-x regions with A_{LL}
- SPD can make measurements of heavier charmonia $(\Psi(2S), \chi_{c1,2})$ via decays involving J/Ψ
- Although difficult, we are hopeful of the possibilities of η_c measurements

Thank You

Backup

Range System and J/Ψ Detection

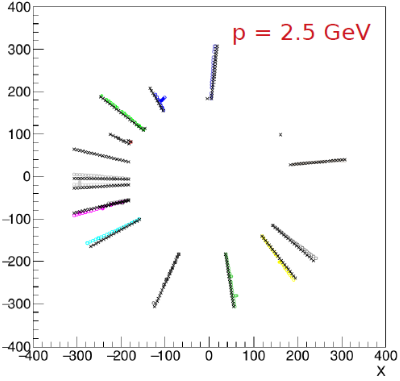


Figure 24: Sample simulated RS tracks of muons : longer tracks

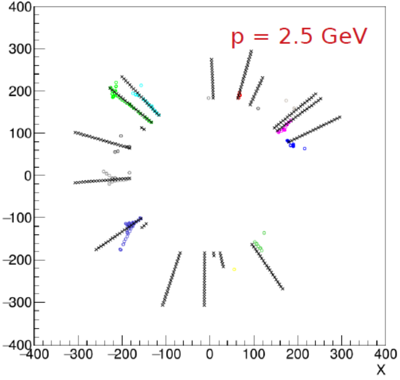


Figure 25: Sample simulated RS tracks of pions : shorter tracks and cluster