Quarkonium Physics at SPD NICA

Amaresh Datta
(on behalf of the SPD Collaboration)

Dzhelepov Laboratory of Nuclear Problems
JINR, Dubna, Russia

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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 the 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 ($J/\Psi, \Psi(2S), \chi_{c1,c2}, \eta_c$)
  3. Prompt photons (γ)

Spin Physics Detector Overview

- **Vertex Detector** : MicroMegas in the 1st stage, replaced by silicon vertex detector (DSSD or MAPS) in the 2nd stage
- To reconstruct secondary vertices with precision ($\sigma \leq 50\ \mu$m)
- **Primary Tracker** : straw tubes of diameter 1 cm
- 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 $\sim$ 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 information from tracker) identification, hadron calorimetry
- Time-of-Flight (**TOF**) and Aerogel detectors for particle identification
- 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 undergoing optimizations
- Solenoid magnet outside ECAL (as opposed to initial design 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

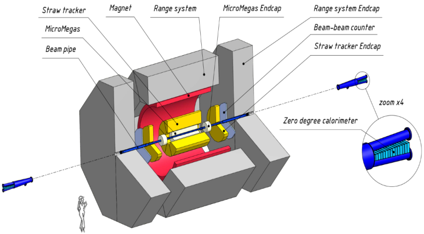


Figure 2: Schematic of SPD detector system : 1st Stage

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

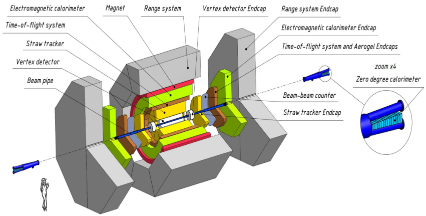


Figure 3: Schematic of SPD detector system : 2nd Stage

Physics Processes of Interest at SPD

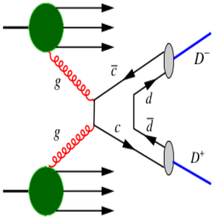


Figure 4: Feynman diagram of open charm

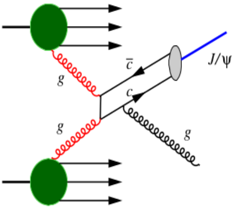


Figure 5: Feynman diagram of charmonium

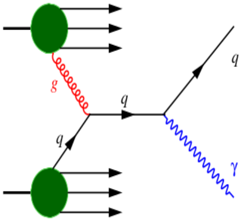


Figure 6: Feynman diagram of prompt photon

Charmonium production dominated by *gluon* − *gluon* process at SPD energies
Prompt photon channel is the cleanest for interpretation

Physics Processes of Interest

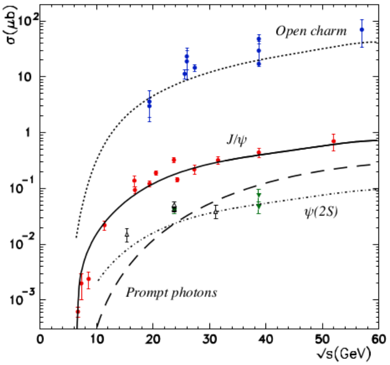


Figure 7: Process cross-sections as function of energy (Eur. Phys. J. C23, 527-538, 2002)

- Open charm production (D mesons) : highest cross-section and orders of magnitude combinatorial background, VD crucial for secondary vertex
- Charmonium production ($J/\Psi, \Psi(2S), \eta_c, \chi_c$) : 2 orders smaller cross-section but cleaner measurements via dimuon decays primarily, RS performance crucial
- Prompt photons : above 3 GeV/c photons are of interest, decays from π^0, η and fragmentation photons are background, *isolation cuts* are important

Charmonia Detection at SPD

- J/Ψ via dimuon decay channel
- $\Psi(2S)$ and χ_c possibly via decay channels involving J/Ψ which in turn decays into two muons
- Muon identification and hadron separation are of paramount importance
- Range System : layers of *Fe* (3-6 cm) and interleaved (3.5 cm) Mini Drift Tubes (MDT) for tracking with perpendicular wires and strips
- Eight modules in the barrel and each end-cap in two halves
- RS weighs $\sim$ 810 tons, includes $\sim$ 8000 units of MDT

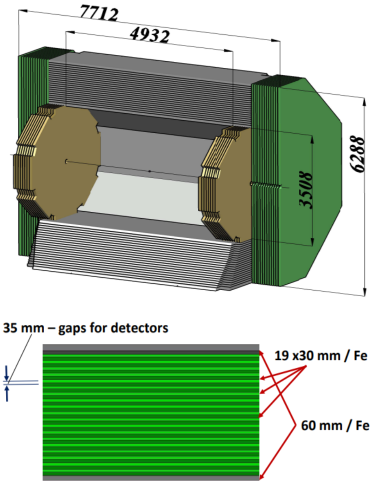


Figure 8: Schematic of Range System at SPD

Sample Usage of Range System

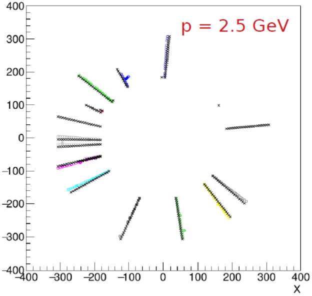


Figure 9: Sample simulated RS tracks of muons : longer tracks

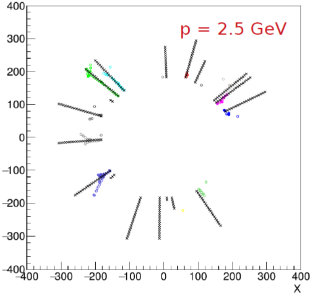


Figure 10: Sample simulated RS tracks of pions : shorter tracks and clusters

Black points are extrapolated track form the tracker and the colors represent actual hits in Range System

Pion suppression factor $\geq 97\%$ with muon selection efficiency $\geq 95\%$ can be achieved

Gluon TMDs Accessed at SPD

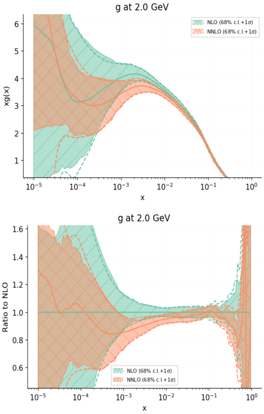


Figure 11: NNPDF coll. arXiv:1706.00428

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	$h_{1T}^g, h_{1T}^{\perp g}$

- Various gluon TMDs can be accessed at SPD (via cross-sections and asymmetries)
- 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)

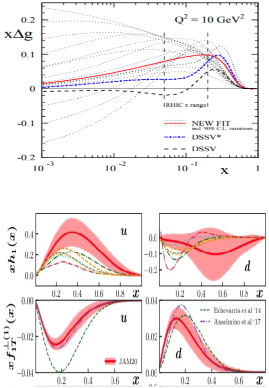


Figure 12: Phys. Rev. Lett. 113, 012001(2014) (top), Phys. Rev. D 102, 054002 (2020) (bottom)

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

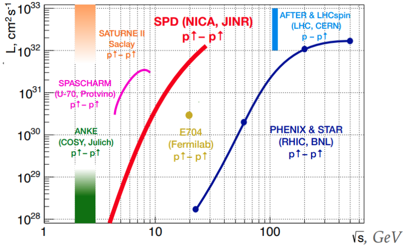


Figure 13: Luminosity (L) and center of mass energy (S) range : SPD CDR

SPD will contribute data in the large Bjorken x range

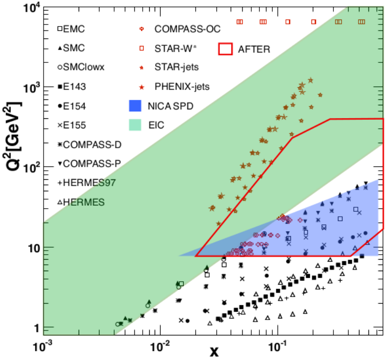


Figure 14: Energy transfer (Q^2) and momentum fraction (x) range : SPD CDR

J/Ψ Detection at SPD

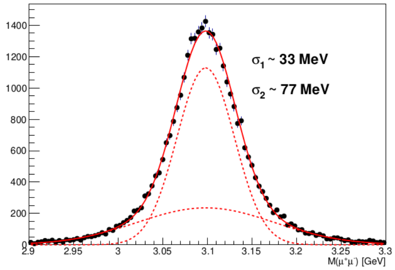


Figure 15: J/Ψ from dimuon invariant mass : resolution $\sigma_m \sim 30$ MeV : SPD CDR

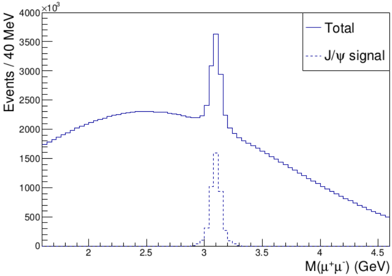


Figure 16: J/Ψ after one year of data at design luminosity at SPD

$J/\Psi \to \mu^+\mu^-, BR = 0.0596$

Observables : cross-sections, transverse single spin asymmetry (A_N), double helicity asymmetry (A_{LL}) as functions of p_T, x_F

Expected statistics : 4.6 M selected events per year at design luminosity

Quantities related to J/Ψ we can measure at SPD

- Various QCD factorization schemes based on the kinematic regime :
  - collinear parton model(**CPM**)
  - TMD, generalized parton model(**GPM**)
  - Parton Reggeization Approach (**PRA**)
- Hadronization process of scattered $c\bar{c}$ not well understood
  - color singlet model (**CS**)
  - non-relativistic QCD (**NRQCD**, probably the most rigorous)
  - color evaporation model (**CEM**) or the 'improved' version (**ICEM**) - close to NRQCD without velocity scaling)

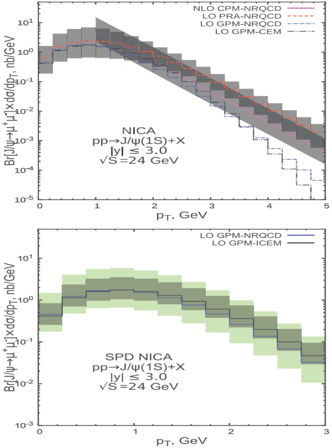


Figure 17: Predicted model dependent J/Ψ cross-sections at SPD (Phy. Rev. D 104, 016008 (2021))

Model Dependent Transverse Single Spin Asymmetry of J/Ψ

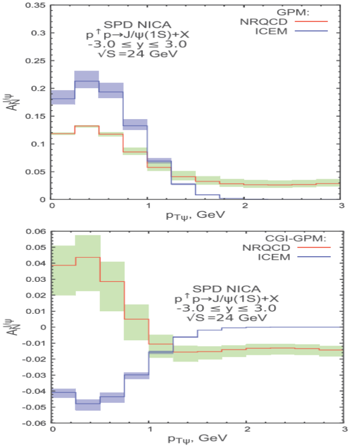


Figure 18: J/Ψ SSA as function of p_T (Phy. Rev. D 104, 016008 (2021))

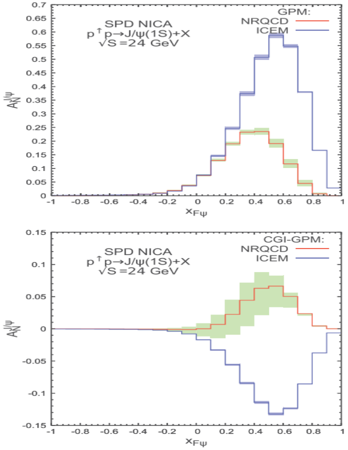


Figure 19: J/Ψ SSA as function of x_F (Phy. Rev. D 104, 016008 (2021))

Expected Precision of $A_N^{J/\Psi}$ at SPD

- Unpolarized cross-section measurements at SPD energies can be very useful for constraining model dependence of the production of J/Ψ
- In turn, it can influence the model dependence of transverse single spin asymmetry predictions
- SSA can be used in future to extract gluon TMDs i.e. gluon Sivers function from global analysis
- Plots on right demonstrate the extent of model dependence : different PDF parametrizations (D'Alesio and SIDIS1) predict order of magnitude different asymmetries

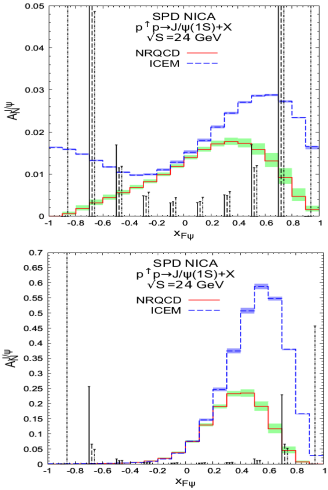
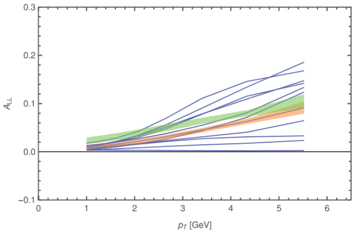


Figure 20: Expected precision compared to D'Alesio (top) and SIDIS1 (bottom) parametrizations of PDFs



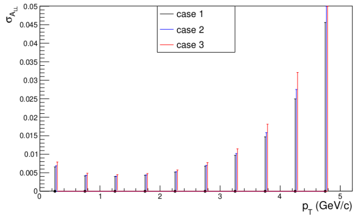


Figure 21: $A_{LL}^{J/\Psi}$ vs. p_T (top : courtesy M. Nefedov), precision for 1 year of data (bottom)

- Helicity asymmetry predictions with *NNPDF30_nl0_as_0119_nf_6* unpolarized and *NNPDFpol11_100* polarized PDFs at SPD at $\sqrt{s} = 24$ GeV (top left)
- A_{LL} for ten different replicas of $\Delta g(x)$ are shown, colored bands show scale and LDME uncertainties
- Expected precision with one year of data at design luminosity shown (bottom left)
- $A_{LL}^{J/\Psi}$ will probe large Bjorken-x region $x \geq 0.3$ and help constrain uncertainties in the region

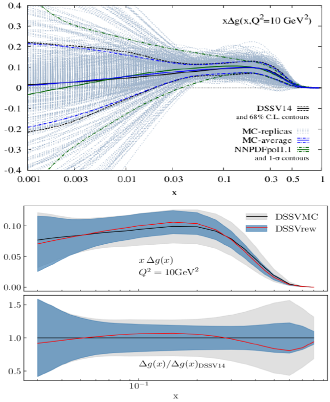


Figure 22: Gluon helicity distrbution $\Delta g(x)$ (above) and impact of prompt γ A_{LL} at SPD (below) : courtesy W. Vogelsang, D. de Florian

- $A_{LL}^{J/\Psi} \approx \frac{\Delta g(x_1)}{g(x_1)} \otimes \frac{\Delta g(x_2)}{g(x_2)} \otimes \hat{a}^{gg \to c\bar{c}}$
- Recent collaboration with DSSV group estimated impact of prompt photon A_{LL}^{γ} measurements at SPD for one year of data at design luminosity
- 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 similar estimates for $A_{LL}^{J/\Psi}$

Threshold Production of J/Ψ

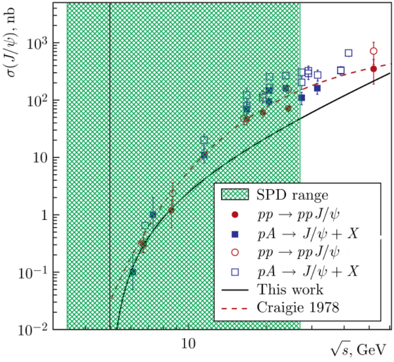


Figure 23: J/Ψ production cross-sections as a function of energy. Green shaded region showing SPD energy range : Phys. of Part. and Nucl. 52, 1044-1119 (2021)

- Threshold production of chamonium i.e. $(p+p \longrightarrow p+p+J/\Psi)$ starts above $\sqrt{s} \sim 4.97$ GeV
- Especially helpful in understanding charm creation in the nonperturbative QCD regime
- Large isotopic dependence is expected : $\frac{\sigma(np\to npJ/\Psi)}{\sigma(pp\to ppJ/\Psi)} \sim 5$
- Measurements from $d+d$ can be particularly useful in testing isotopic dependence and accessing hidden color part of d wave function

J/Ψ Polarization

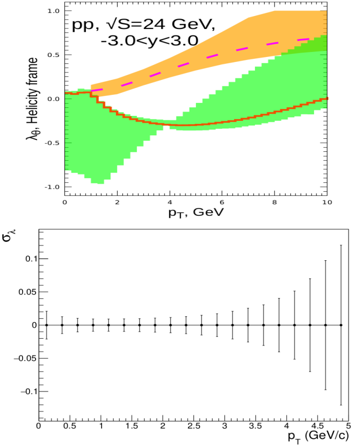


Figure 24: Predicted λ_θ vs. p_T (top : J.Phys.Conf.Ser. 1435 (2020)), expected precision with 1 year of data (bottom : SPD CDR)

- $\frac{d\sigma}{dcos\theta_\mu} \propto 1 + \lambda_\theta cos^2\theta_\mu$, where θ_μ is the angle between muon and J/Ψ momenta in helicity frame
- $\lambda_\theta = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L}$ gives the relation between trans. and long. polarized cross-sections
- Prediction (top left) shows two models : (1) NLO CPM + NRQCD : dashed line with orange band (2) LO PRA + NRQCD : solid line with green band
- Bands show factorization and renormalization scale uncertainty
- Model dependent predictions can be tested at SPD (precision with one year of data at design luminosity)

Associated J/Ψ Production at SPD

- Interesting probe : associated J/Ψ production i.e. J/Ψ-pair to probe gluon TMDs (EPJ C80, 87 (2020))
- First measured at NA3 experiment in 1982
- At high energies, production dominated by $gluon - gluon$ fusion
- Can be a probe for multi-parton interactions
- Expected cross-section 27 ± 10 pb at $\sqrt{s} = 27$ GeV (Phys. Lett. B 158, 85 (1985))
- Expected statistics : 50-100 selected events for both dimuon and dielectron decay modes

Other Charmonium Probes : $\Psi(2S)$ at SPD

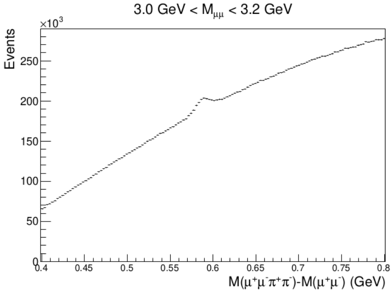


Figure 25: $\Psi(2S) \longrightarrow \pi^+\pi^- J/\Psi$: signal and combinatorial background for one year of data at design luminosity : SPD CDR

- $\Psi(2S) \to \pi^+\pi^- J/\Psi,\ BR = 0.347$
- $m_{\Psi(2S)} = 3.686$ GeV
- Measurements posible at SPD : plot on the left shows peak in the invariant mass difference $M(\pi^+\pi^-\mu^+\mu^-) - M(\mu^+\mu^-)$
- Observable : cross-sections at function of p_T, x_F
- Expected statistics : 100K selected events per year at design luminosity

Other Charmonium Probes : χ_{c1}, χ_{c2} at SPD

- $\chi_{c1} \to \gamma J/\Psi, \; BR = 0.343$, $\chi_{c2} \to \gamma J/\Psi, \; BR = 0.19$
- $m_{\chi_{c1}} = 3.511$ GeV, $m_{\chi_{c2}} = 3.556$ GeV, mass difference $\sim$ 45 MeV
- Mass resolution at SPD enough to measure the χ_{c1}, χ_{c2}
- Observable : cross-sections as functions of p_T, x_F
- Relative contribution of χ_{c1}, χ_{c2}
- Expected sttaistics : 500K selected events per year data at design luminosity (30% feed-down)

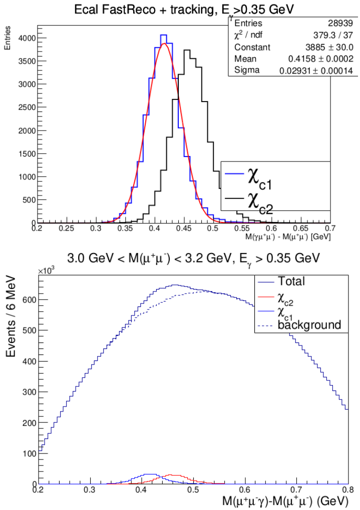


Figure 26: Invariant mass (top), signal and combinatorial background (bottom) : SPD CDR

η_c Production at SPD

- The only 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** - applicable at both low and high p_T ranges) at SPD kinematic are available
- $\eta_c \to p\bar{p}, \; BR = 1.45 \times 10^{-3}$, $\eta_c \to \lambda\bar{\lambda}, \; BR = 1.07 \times 10^{-3}$

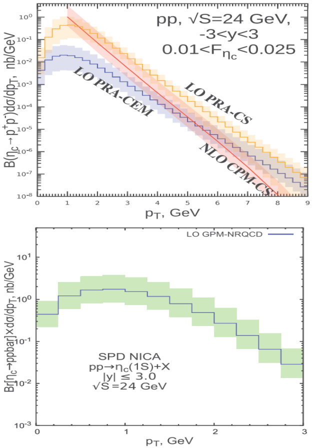


Figure 27: Model dependent Predictions of η_c production : Prog. in Nucl. and Part. Phys. 119, 103858 (2021)

η_c Measurement at SPD

- Orders of magnitude higher 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) : signal to background at peak $\sim 10^{-3}$
- Expected statistics : 600K events before selection for $p\bar{p}$
- Also of interest $\eta_c \longrightarrow \Lambda\bar{\Lambda}$ (signal to background in the peak $\sim 7.6 \times 10^{-4}$)

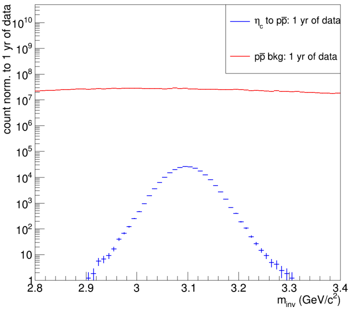


Figure 28: η_c signal ($\eta_c \longrightarrow p\bar{p}$) and combinatorial background for $p\bar{p}$ invariant mass spectra at SPD

Status of SPD Collaboration

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

Summary

- SPD detector system will be built in stages
- With NICA upgrade including Siberian Snake magnets (to counter depolarization effects), SPD will record data at design energy
- We are looking forward to J/Ψ measurements (cross-sections, various asymmetries, polarization) 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 Bjorken-x regions with A_{LL}
- SPD can make measurements of heavier charmonia $(\Psi(2S), \chi_{c1}, \chi_{c2})$ via decays involving J/Ψ
- Although difficult, we are hopeful of the possibilities of η_c measurements

Thank You

Backup

Polarized Beams at NICA

Spin Transparency mode:

- 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