Challenges and problems in charmonium production at the SPD NICA

V. Saleev[1,2]

[1] Samara National Research University
[2] Joint Institute for Nuclear Research

30 November 2023
IHEP, Protvino

Talk at the XXXV International Workshop on High Energy Physics

Outline

1. SPD NICA
2. Charmonium production as tool
3. Prompt J/ψ production and hadronization models
4. A_{LL} in the J/ψ production
5. Polarized J/ψ production
6. η_c production for study gluon TMD PDF
7. A_N in the J/ψ production
8. Conclusions

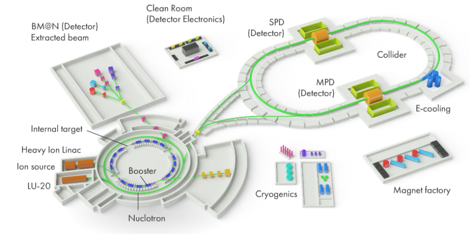
SPD NICA

Overview

- The Spin Physics Detector (SPD) collaboration proposes to install a universal detector in the second interaction points of the Nuclotron-based Ion Collider fAcility (NICA) that is under construction at the Joint Institute for Nuclear Research (Dubna) to study the spin structure of the proton and deuteron and the other spin-related phenomena with polarized proton and deuteron beams at a collision energy up to 27 GeV and luminosity up to 10^{32} cm^{-2} s^{-1}

SPD NICA

Overview



- The SPD is planned to operate as a universal facility for comprehensive study of the unpolarized and polarized gluon content of the nucleon at large Bjorken-x, using different complementary probes such as: charmonia, open charm and prompt photon production processes. The experiment aims to provide access to the gluon helicity, gluon Sivers and Boer-Mulders PDFs in the nucleon, as well as the gluon transversity distribution tensor PDFs in the deuteron, via the measurement of specific single and double spin asymmetries.

SPD NICA

Overview

- V. M. Abazov *et al.* [SPD proto], "Conceptual design of the Spin Physics Detector," [arXiv:2102.00442 [hep-ex]].
- A. Arbuzov, A. Bacchetta, M. Butenschoen, F. G. Celiberto, U. D'Alesio, M. Deka, I. Denisenko, M. G. Echevarria, A. Efremov and N. Y. Ivanov, *et al.* "On the physics potential to study the gluon content of proton and deuteron at NICA SPD," Prog. Part. Nucl. Phys. **119**, 103858 (2021)
- There are materials of 6 SPD Collaboration Workshops which were held till now. The last one was in Samara University in October, 2023 (https://indico.jinr.ru/event/3779/)
- SPD NICA operation start is planed in 2028

Charmonium production as tool

Collinear parton model ($p_T >> 1$ GeV)

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

$$\sigma^{++} = \sigma(p^{\rightarrow} + p^{\rightarrow}) \Rightarrow \Delta f_g(x, \mu)$$

TMD parton model ($p_T \leq 1$ GeV)

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

Charmonium production as tool

Hard probes at the SPD NICA

- **Charmonium production**
- $D-$meson production,
  A. Karpishkov and V. Saleev, "On Transverse Single-Spin Asymmetries in D-Meson Production at the SPD NICA Experiment," Phys. Part. Nucl. Lett. **20**, no.3, 360-363 (2023)]
- Large-p_T prompt photon production,
  1). V. A. Saleev and A. V. Shipilova, "Double Longitudinal-Spin Asymmetries in Direct Photon Production at NICA," Phys. Part. Nucl. Lett. **20**, no.3, 400-403 (2023)
  2). V. A. Saleev and A. V. Shipilova, "Gluon Sivers Function in Transverse Single-Spin Asymmetries of Direct Photons at NICA," Phys. Atom. Nucl. **85**, no.6, 737-747 (2022)

Prompt J/ψ production spectra and hadronization models

Color Singlet Model (CSM)

Historically, the first model of heavy-quarkonium production was the CSM: The production of bound state $\mathscr{C}$ is dominated by production of color-singlet $c\bar{c}$-pair with L and S quantum numbers given by NR potential model for this state. Probability of hadronization is proportional to $|R^{(k)}(0)|^2, (k = 0, 1, ...)$ from potential model.

- CSM leads to a wrong shape of J/ψ p_T-spectrum at high energies both at LO and NLO of CPM
- It is theoretically inconsistent at NLO for production of P-wave states.

Prompt J/ψ production spectra and hadronization models

NRQCD

The NRQCD framework [G. T. Bodwin, E. Braaten, and G. P. Lepage, Phys. Rev. D 51, 1125 (1995)] describes heavy quarkonia in terms of Fock state decompositions. In case of orthoquarkonium state the wave function can be written as power series expansion in the velocity parameter $v^2 \sim 0.3$.

$$|J/\psi\rangle = \mathscr{O}(\upsilon^0)|c\bar{c}[^3S_1^{(1)}]\rangle + \mathscr{O}(\upsilon^1)|c\bar{c}[^3P_J^{(8)}]g\rangle + \mathscr{O}(\upsilon^2)|c\bar{c}[^3S_1^{(1,8)}]gg\rangle + \mathscr{O}(\upsilon^2)|c\bar{c}[^1S_0^{(8)}]g\rangle + \mathscr{O}(\upsilon^2)|c\bar{c}[^1D_J^{(1,8)}]gg\rangle + \dots$$

In the NRQCD effects of short and long distances are separated, and then the cross-section of heavy-quarkonium production via a partonic subprocess $a + b \to J/\psi + X$ can be presented in a factorized form:

$$d\hat{\sigma}(ab \to J/\psi X) = \sum_n d\hat{\sigma}(ab \to c\bar{c}[n]X)\langle\mathscr{O}^{J/\psi}[n]\rangle.$$

Prompt J/ψ production spectra and hadronization models

Color Evaporation Model (CEM) or Improved CEM

- In ICEM: all $c\bar{c}$ states with $M_C < M_{c\bar{c}} < 2M_D$ hadronize to charmonium C with the same probability F_C.
- ICEM can be viewed as NRQCD-factorization without velocity-scaling rules for probabilities F_C.
- By Ma and Vogt [2016] in ICEM

$$\frac{d\sigma}{d^3 p_C} = F_C \times \int_{M_C}^{2M_D} dM_{c\bar{c}} \frac{d\sigma}{d^3 p_{c\bar{c}}}$$

$$p_C = \frac{M_C}{M_{c\bar{c}}} p_{c\bar{c}}$$

A_{LL} in the J/ψ production

LO Collinear Parton Model

$$A_{LL} = \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}} = \frac{\Delta\sigma}{\sigma}$$

$$\Delta\sigma = \sum_n \langle \mathcal{O}^{J/\psi}[n] \rangle \sum_{i,j=g,q} \Delta f_i \otimes \Delta f_j \otimes \Delta\hat{\sigma}_{ij}[n]$$

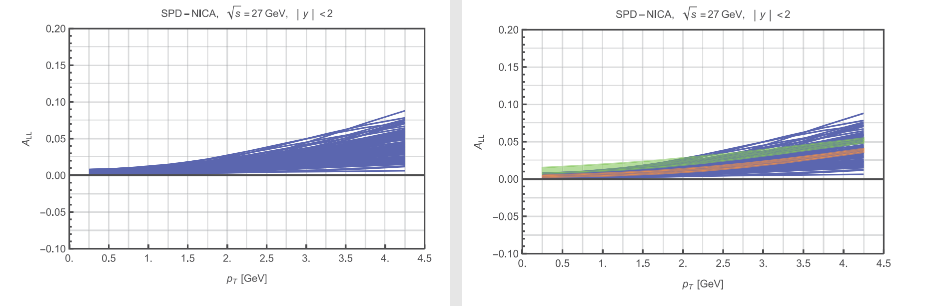
$$\sigma = \sum_n \langle \mathcal{O}^{J/\psi}[n] \rangle \sum_{i,j=g,q} f_i \otimes f_j \otimes \hat{\sigma}_{ij}[n]$$

Unpolarized partonic cross sections $\hat{\sigma}_{ij}[n]$ are well-known at LO ([P.L. Cho, A.K. Leibovich (1996)] and [R. Gastmans, W. Troost and T. T. Wu, Phys. Lett. B 184, 257-260 (1987)]).
LO calculations of $\Delta\hat{\sigma}_{ij}[n]$ can be found in [Klasen, Kniehl, Steinhauser, Phys.Rev.D 68 (2003) 034017].

A_{LL} in the J/ψ production

LO Collinear Parton Model

LO LDMEs from [Braaten, Kniehl, Lee, Phys.Rev.D62 (2000) 094005] together with NNPDF30-nlo-as-0119-nf-6 PDF set and NNPDFpol11-100 polarized PDF set.



Polarized prompt J/ψ production at the $p_T < 3$ GeV

LO TMD Parton Model and NRQCD
TMD PM by Collins-Soper-Sterman ⇒ Generalized Parton Model (GPM)

$$f_g(x,\mu) \quad \Rightarrow F_g^{TMD}(x,\mathbf{k}_T,\mu,\zeta),\ |\mathbf{k}_T| << \mu$$

$$\Rightarrow F_g^{GPM}(x,\mathbf{k}_T,\mu) = f_g(x,\mu)\Phi(|\mathbf{k}_T|),\ |\mathbf{k}_T| \le \mu$$

$$\Phi(|\mathbf{k}_T|) = 1/\pi a^2 \exp\left(-|\mathbf{k}_T|^2/a^2\right),\ a^2 = \langle \mathbf{k}_T^2 \rangle$$

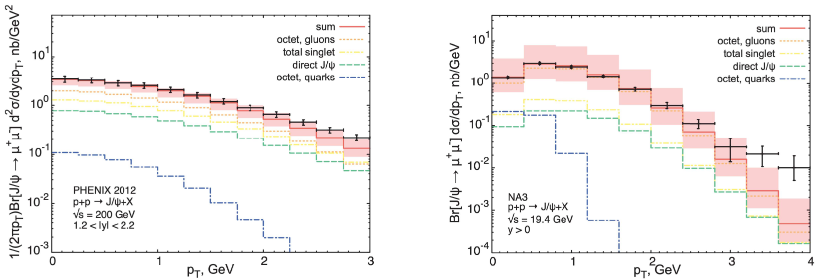
$$q_1 = x_1 P_1 + \tilde{x}_1 P_2 + q_{1T} \quad \tilde{x}_1 = \frac{\mathbf{q}_{1T}^2}{x_1 s},\ s = 2(P_1 P_2)$$

We estimate the experimental data will be for prompt J/ψ

$$\sigma^{J/\psi,\ \text{prompt}} = \sigma^{J/\psi}({}^3S_1^{(1)}) + \sigma^{\psi'}({}^3S_1^{(1)})\ \text{Br}(\psi' \to J/\psi + X) + \sigma^{\chi_{c0}}({}^3P_0^{(1)})\ \text{Br}(\chi_{c0} \to J/\psi + \gamma) +$$
$$+ \sigma^{\chi_{c1}}({}^3P_1^{(1)})\ \text{Br}(\chi_{c1} \to J/\psi + \gamma) + \sigma^{\chi_{c2}}({}^3P_2^{(1)})\ \text{Br}(\chi_{c2} \to J/\psi + \gamma).$$

Polarized prompt J/ψ production at the $p_T < 3$ GeV

Fitting of prompt J/ψ production at PHENIX and NA3



$\langle q_T^2 \rangle_g = 2.80$ GeV^2, $\langle q_T^2 \rangle_q = 1.30$ GeV^2 $\qquad$ $\langle q_T^2 \rangle_g = 0.85$ GeV^2, $\langle q_T^2 \rangle_q = 0.15$ GeV^2

$$M_7^{J/\psi} = (5.17 \pm 0.33) \cdot 10^{-2} \text{ GeV}^3, \quad \langle \mathcal{O}^{J/\psi}[^3S_1^{(8)}] \rangle = (0.00 \pm 0.26) \cdot 10^{-2} \text{ GeV}^3$$

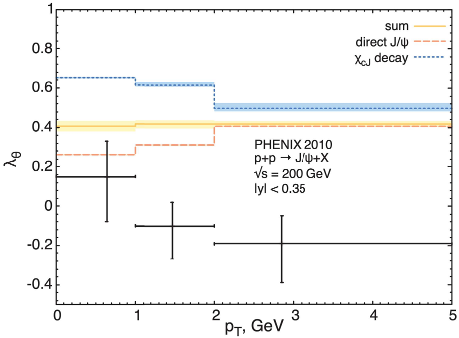
$$\langle \mathcal{O}^{\chi_{c0}}[^3S_1^{(8)}] \rangle = (4.12 \pm 3.55) \cdot 10^{-3} \text{ GeV}^3, \quad \chi^2/\text{d.o.f.} = 0.516$$

Polarized prompt J/ψ production at the $p_T < 3$ GeV

Polarized J/ψ production at PHENIX using GPM+NRQCD

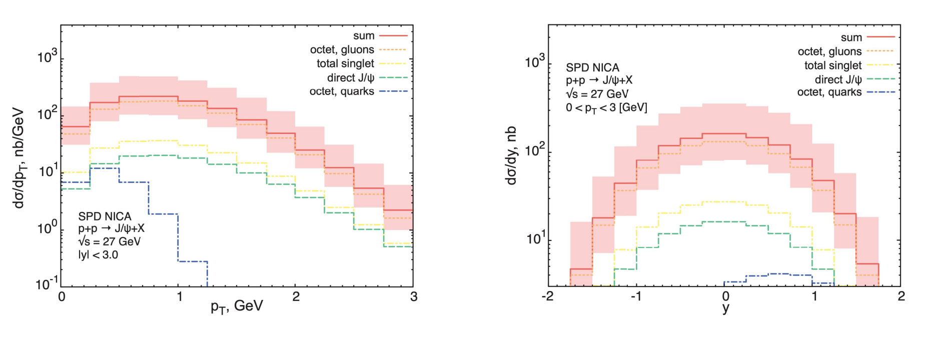
$$\frac{d\sigma}{d\Omega} \sim 1 + \lambda_\theta \cos^2\theta + \lambda_\varphi \sin^2\theta\, \cos 2\varphi + \lambda_{\theta\varphi} \cos\varphi,$$

$$\lambda_\theta = \frac{\sigma_\mathrm{T} - 2\,\sigma_\mathrm{L}}{\sigma_\mathrm{T} + 2\,\sigma_\mathrm{L}} = \frac{\sigma - 3\,\sigma_\mathrm{L}}{\sigma + \sigma_\mathrm{L}}$$



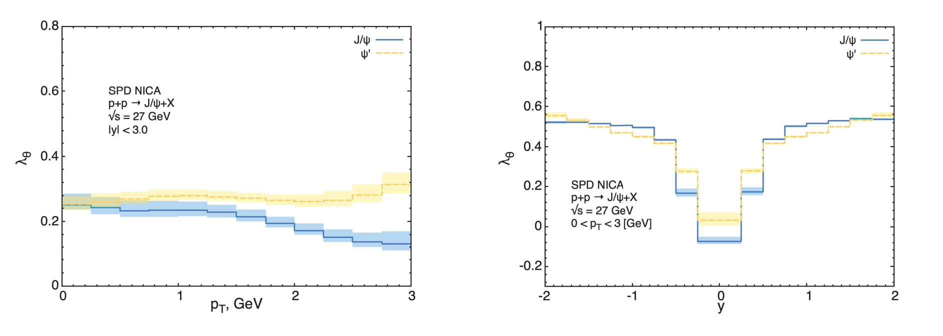
Polarized prompt J/ψ production at the $p_T < 3$ GeV

J/ψ production at NICA using GPM+NRQCD



Polarized prompt J/ψ production at the $p_T < 3$ GeV

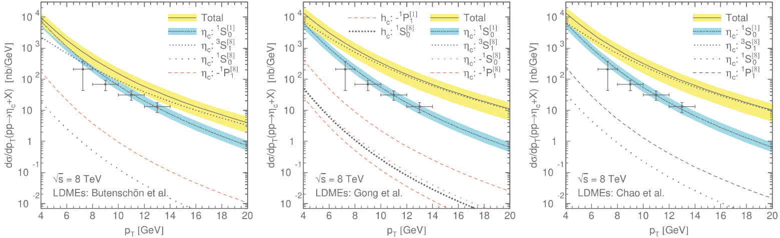
Polarized J/ψ production at NICA using GPM+NRQCD



η_c production for study gluon TMD PDF

Is it CSM dominant mechanism of η_c production ?

[Butenschön, Kniehl, He, 2014] Experimental data from [LHCb, 2014]:
$pp \to \eta_c(\to p\bar{p}) + X$ with $\sqrt{S} = 7$ and 8 TeV.



η_c production for study gluon TMD PDF

What the LHCb data for η_c production say us:

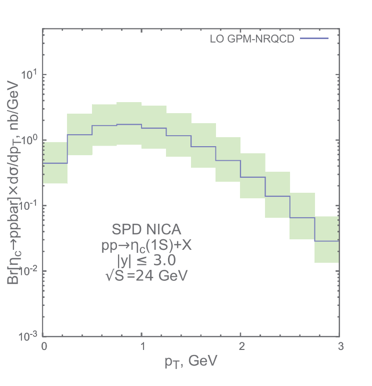
- CSM with $[^1S_0^{(1)}]$ describes LHCb data and CO contributions lead to significant overestimation
- Heavy-Quark-Spin-Symmetry (HQSS) of NRQCD fail
- Feeddown from h_c is negligible

Production of η_c may be a best tool for gluon TMD study

- Color singlet LDME $\langle \mathcal{O}[^1S_0^{(1)}] \rangle$ can be calculated in a non-relativistic potential model or extracted from the decay width $\Gamma(\eta_c \to \gamma\gamma)$
- Final state is colorless and we can neglect FS interactions with soft (Glauber) gluons, which destroy hard-soft factorization at $p_T << \mu$.
- The η_c production in two-gluon fusion may be considered like "Drell-Yan" process.

η_c production for study gluon TMD PDF

Prediction for η_c using GPM+CSM, $\langle k_T^2 \rangle = 1$ GeV^2



Prediction for η_c cross section at SPD NICA

$$\sigma \cdot B(\eta_c \to p\bar{p}) \simeq 0.7 \text{ nb}$$

$$\sigma \cdot B(\eta_c \to \gamma\gamma) \simeq 0.1 \text{ nb}$$

PYTHIA: $Signal/Background \simeq 10^{-3}$

A_N in the $p+p^{\uparrow} \to J/\psi X$ production

Transverse Single-Spin Asymmetry (TSSA) = A_N

$$A_N = \frac{d\sigma^{\uparrow} - d\sigma^{\downarrow}}{d\sigma^{\uparrow} + d\sigma^{\downarrow}} = \frac{d\Delta\sigma}{2d\sigma}$$

$$d\sigma \propto \int dx_1 \int d^2 q_{1T} \int dx_2 \int d^2 q_{2T} F_g(x_1, q_{1T}, \mu_F) F_g(x_2, q_{2T}, \mu_F) d\hat{\sigma}(gg \to J/\psi g),$$

$$d\Delta\sigma \propto \int dx_1 \int d^2 q_{1T} \int dx_2 \int d^2 q_{2T} [\hat{F}_g^{\uparrow}(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_g^{\downarrow}(x_1, \mathbf{q}_{1T}, \mu_F)] \times F_g(x_2, q_{2T}, \mu_F) d\hat{\sigma}(gg \to J/\psi g),$$

$$\Delta\hat{F}_g^{\uparrow}(x_1, \mathbf{q}_{1T}, \mu_F) \equiv \hat{F}_g^{(\uparrow)}(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_g^{(\downarrow)}(x_1, \mathbf{q}_{1T}, \mu_F)$$

A_N in the $p+p^{\uparrow} \to J/\psi X$ production

Gluon Sivers function by "Trento" convention [*A. Bacchetta, U. D'Alesio, M. Diehl and C. A. Miller, Single-spin asymmetries: The Trento conventions, Phys. Rev. D* ***70****, 117504 (2004)*]

$$F_g^{\uparrow}(x,\mathbf{q}_T) = F_g(x,q_T) + \frac{1}{2}\Delta^N F_g^{\uparrow}(x,q_T)\mathbf{S}\cdot(\hat{\mathbf{P}}\times\hat{\mathbf{q}}_T),$$

$$\Delta\hat{F}_g^{\uparrow}(x_1,\mathbf{q}_{1T},\mu_F) \equiv \hat{F}_g^{(\uparrow)}(x_1,\mathbf{q}_{1T},\mu_F) - \hat{F}_g^{(\downarrow)}(x_1,\mathbf{q}_{1T},\mu_F) = \Delta^N F_g^{\uparrow}(x_1,\mathbf{q}_{1T}^2,\mu_F)\cos(\phi_1),$$

$$\Delta^N F_g^{\uparrow}(x,q_T^2,\mu_F) = 2\frac{\sqrt{2e}}{\pi}N_g(x)f_g(x,\mu_F)\sqrt{\frac{1-\rho_g}{\rho_g}}\frac{q_T}{\langle q_T^2\rangle_g^{3/2}}e^{-q_T^2/\rho_g\langle q_T^2\rangle_g}.$$

A_N in the $p+p^\uparrow \to J/\psi X$ production

$N_g(x)$ and 0_g

$$N_g(x) = N_g x^\alpha (1-x)^\beta \frac{(\alpha+\beta)^{\alpha+\beta}}{\alpha^\alpha \beta^\beta},$$

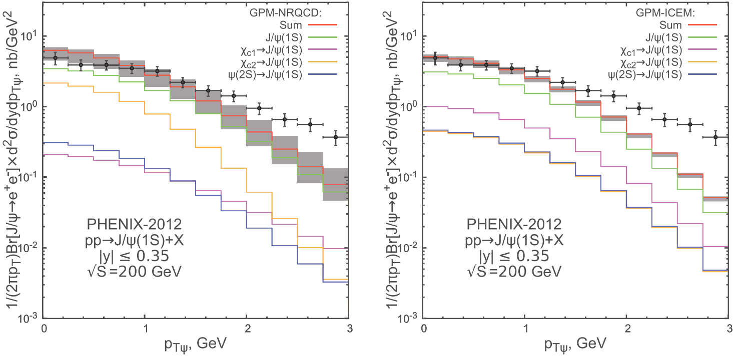
$$\rho_g = \frac{M'^2}{M'^2 + \langle q_T^2 \rangle}, 0 < \rho_g < 1$$

GSF parameters

GSF set	N_g	α_g	β_g	ρ_g	$\langle q_T^2 \rangle$, GeV^2
SDIS1	0.65	2.8	2.8	0.687	0.25
D'Alesio *et al.*	0.25	0.6	0.6	0.1	1.0

A_N in the $p+p^{\uparrow} \to J/\psi X$ production

Prompt J/ψ production fit at $\sqrt{s} = 200$ GeV and $p_T \leq 1$ GeV, $\langle q_T^2 \rangle \simeq 1$ GeV^2



A_N in the $p + p^{\uparrow} \to J/\psi X$ production

CGI-GPM approach [L. Gamberg and Z. B. Kang, Phys. Lett. B 696, 109 (2011)]

In standard TMD factorization (CSS model), this soft gluons $(q_T \sim \Lambda_{QCD} << \mu)$ are taken into account within the gauge-invariant definition of Sivers-like TMD PDF, which contains Wilson lines.
Sivers TMD PDF is process-dependent and we must decide how to extend factorization for Sivers effect to the processes with colored final-states $g + g \to J/\psi + g$.
In the CGI-GPM formalism is to extract above-mentioned process dependence from the TMD PDF to the hard-scattering coefficient. The effects of ISI and FSI are included in CGI-GPM via one-gluon exchange approximation. For the case of gluon Sivers effect, this approximation leads to appearance of independent GSFs of f-type and d-type. The coupling of additional "eikonal" gluon from the GSF to the hard process leads only to modification of the color structure of the latter one.

A_N in the $p + p^\uparrow \to J/\psi X$ production

CGI-GPM approach for CSM $(g + g \to J/\psi + g)$ and ICEM $(g + g \to c + \bar{c})$

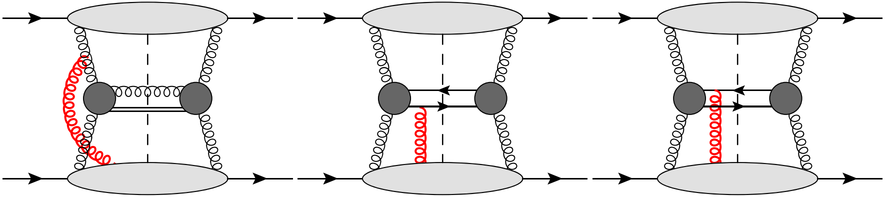
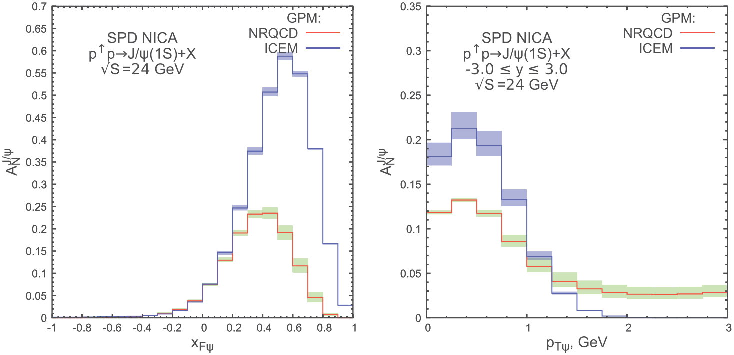


FIG. 2. Example diagrams for contributions to the numerator of TSSA in CGI-GPM. Left panel: ISI for production of ${}^3S_1^{(1)}$ state. Middle and right panels: FSI for $gg \to c\bar{c}$ process with both final-state quarks tagged.

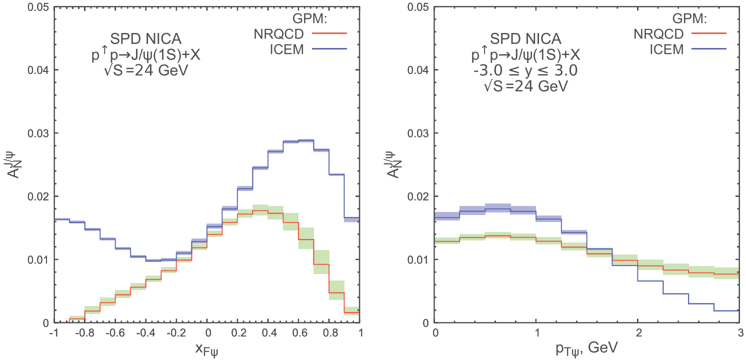
A_N in the $p+p^{\uparrow} \to J/\psi X$ production

$A_N^{J/\psi}$, prompt J/ψ, SIDIS1 parameterizations, GPM



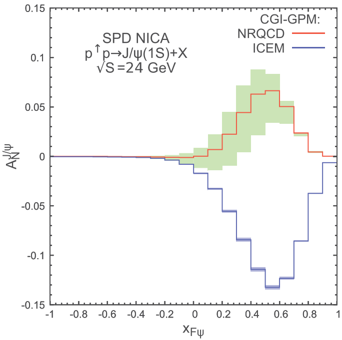
A_N in the $p + p^{\uparrow} \to J/\psi X$ production

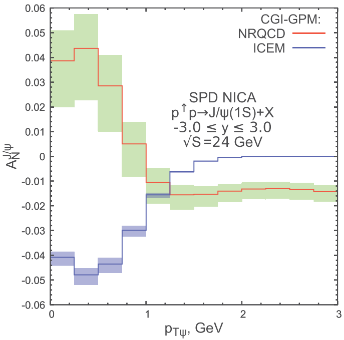
$A_N^{J/\psi}$, prompt J/ψ, D'Alesio parameterizations, GPM



A_N in the $p+p^{\uparrow}\to J/\psi X$ production

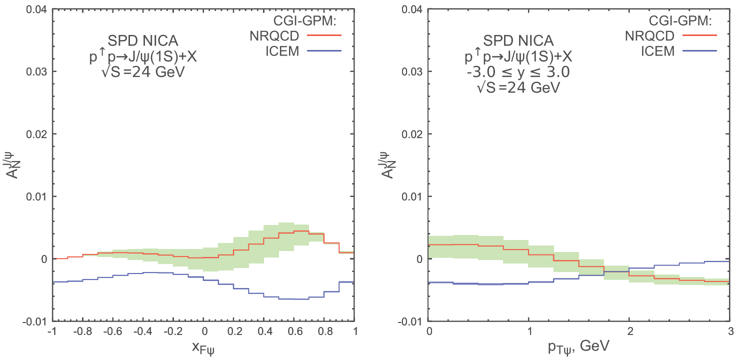
$A_N^{J/\psi}$, prompt J/ψ, SIDIS1 parameterizations, CGI-GPM





A_N in the $p + p^\uparrow \to J/\psi X$ production

$A_N^{J/\psi}$, prompt J/ψ, D'Alesio parameterizations, CGI-GPM



Conclusions

- Predicted in the LO CPM+NRQCD $A_{LL}^{J/\psi}$ is about 1-5 % at the SPD NICA. It may be visible experimentally.
- Polarized J/ψ production at low p_T is very sensitive for hadronization model. Additional theoretical study in TMP parton model is needed.
- The η_c production may be very perspective for study of gluon TMD PDFs, but S/B ratio estimates as very small
- Theoretical prediction for $A_N^{J/\psi}$ strongly depends on the model of TMD-factorization, GPM or CGI-GPM
- Theoretical prediction for $A_N^{J/\psi}$ strongly depends on the hadronization model, CSM, or NRQCD, or ICEM

Charmonium production as tool

TMD parton model ($p_T \leq 1$ GeV)

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

Publications

1. A. Karpishkov, M. Nefedov and V. Saleev, Estimates for the single-spin asymmetries in the $p^{\uparrow}p \to J/\psi X$ process at PHENIX RHIC and SPD NICA, Phys. Rev. D **104** (2021) no.1, 016008
2. Anufriev A.V., Saleev V.A. *Production of η_c with two-photon decay in the GPM at the energies of NICA*, Vestnik of Samara University. Natural Science Series, 2022, vol. 28, no. 12, pp. 128136.
3. Alimov L.E., Saleev V.A. *Associative production of J/ψ-mesons and direct photons at the energy of the NICA collider*, Vestnik of Samara University. Natural Science Series, 2023, vol. 29, no. 2, pp. 4861.
4. V. A. Saleev and A. V. Shipilova, Double Longitudinal-Spin Asymmetries in Direct Photon Production at NICA, Phys. Part. Nucl. Lett. **20** (2023) no.3, 400-403
5. A. Guskov, A. Datta, A. Karpishkov, I. Denisenko and V. Saleev, Probing Gluons at the Spin Physics Detector,[arXiv:2304.04604 [hep-ex]].
6. A. Karpishkov and V. Saleev, On Transverse Single-Spin Asymmetries in D-Meson Production at the SPD NICA Experiment, Phys. Part. Nucl. Lett. **20** (2023) no.3, 360-363
7. V. A. Saleev and A. V. Shipilova, Gluon Sivers Function in Transverse Single-Spin Asymmetries of Direct Photons at NICA, Phys. Atom. Nucl. **85** (2022) no.6, 737-747

Thank you for your attention!