

Estimates for the single-spin asymmetries in $p^\uparrow p \rightarrow J/\psi X$ process at PHENIX RHIC and SPD NICA

A. V. Karpishkov^{1,2}, M. A. Nefedov¹, and V. A. Saleev^{1,2}

¹ Samara National Research University

² Joint Institute for Nuclear Research

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Generalized Parton Model (GPM) and it's application to calculation of SSA

Factorization schemes in different p_T -regions

The traditional Collinear Parton Model (CPM) is applicable in a region of high- p_T production

$$\mu \sim p_T \gg \Lambda_{QCD},$$

so we can neglect influence of small intrinsic \mathbf{q}_T of initial partons ($\langle q_T^2 \rangle \simeq 1 \text{ GeV}^2$).

But if we're interested in particle production in a region of $p_T \simeq \sqrt{\langle q_T^2 \rangle} \ll \mu$, we should take into account intrinsic q_T . It can be done within TMD approach, factorization for which has been proven in the limit $q_T \ll \mu$ [J. Collins, *Camb. Monogr., Part. Phys. Nucl. Phys. Cosmol.* **32**, 1-624 (2011)]. In our case, the hard scale μ is given by charmonium mass $m_C = 3.1 \div 3.7 \text{ GeV}$.

So we can use phenomenological TMD-ansatz, a so called Generalized Parton Model (GPM), initial partons in which are on-shell:

$$q_\mu = xP_\mu^+ + yP_\mu^- + q_{T\mu}, (q_\mu)^2 = 0, \quad (1)$$

and a factorized prescription for TMD parton distribution functions (PDFs) is used:

$$F_a(x, q_T, \mu_F) = f_a(x, \mu_F) G_a(q_T), \quad (2)$$

where $f_a(x, \mu_F)$ – corresponding CPM PDF, $G_a(q_T)$ – Gaussian distribution $G_a(q_T) = \exp(-q_T^2 / \langle q_T^2 \rangle_a) / (\pi \langle q_T^2 \rangle_a)$.

Factorization formula for the GPM

Within the GPM we can write the following expression for the differential cross-section of $2 \rightarrow 1$ hard subprocess $g(q_1) + g(q_2) \rightarrow C(k)$:

$$d\sigma(pp \rightarrow CX) = \int dx_1 \int d^2\mathbf{q}_{1T} \int dx_2 \int d^2\mathbf{q}_{2T} \times \\ \times F_g(x_1, q_{1T}, \mu_F) F_g(x_2, q_{2T}, \mu_F) d\hat{\sigma}(gg \rightarrow C), \quad (3)$$

where $C = J/\psi, \psi(2S)$ or $\chi_c(1P)$, and

$$d\hat{\sigma}(gg \rightarrow C) = (2\pi)^4 \delta^{(4)}(q_1 + q_2 - k) \frac{|\overline{M}(gg \rightarrow C)|^2}{2x_1 x_2 s} \frac{d^4 k}{(2\pi)^3} \delta_+(k^2 - m_C^2). \quad (4)$$

In a case of $2 \rightarrow 2$ subprocess $g(q_1) + g(q_2) \rightarrow C(k) + g(q_3)$, $C = J/\psi, \psi(2S)$ in formula (3) $d\hat{\sigma}(gg \rightarrow C)$ must be replaced by:

$$d\hat{\sigma}(gg \rightarrow Cg) = (2\pi)^4 \delta^{(4)}(q_1 + q_2 - k - q_3) \frac{|\overline{M}(gg \rightarrow Cg)|^2}{2x_1 x_2 s} \frac{d^3 k}{(2\pi)^3 2k_0} \frac{d^4 q_3}{(2\pi)^3} \delta_+(q_3^2). \quad (5)$$

Four-momenta of initial partons are on mass-shell ($q_1^2 = q_2^2 = 0$) and have longitudinal (along the Z -axis) and transverse parts:

$$q_1^\mu = \left(x_1 \frac{\sqrt{s}}{2} + \frac{\mathbf{q}_{1T}^2}{2\sqrt{s}x_1}, \mathbf{q}_{1T}, x_1 \frac{\sqrt{s}}{2} - \frac{\mathbf{q}_{1T}^2}{2\sqrt{s}x_1} \right)^\mu, \quad (6)$$

$$q_2^\mu = \left(x_2 \frac{\sqrt{s}}{2} + \frac{\mathbf{q}_{2T}^2}{2\sqrt{s}x_2}, \mathbf{q}_{2T}, -x_2 \frac{\sqrt{s}}{2} + \frac{\mathbf{q}_{2T}^2}{2\sqrt{s}x_2} \right)^\mu. \quad (7)$$

Single Spin Asymmetry

In inclusive process $p^\uparrow p \rightarrow \mathcal{C}X$ ($\mathcal{C} = J/\psi, \chi_c, \psi(2S)$) SSA is defined as:

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} = \frac{d\Delta\sigma}{2d\sigma}. \quad (8)$$

The numerator and denominator of A_N have the form:

$$d\sigma \propto \int dx_1 \int d^2 q_{1T} \int dx_2 \int d^2 q_{2T} F_g(x_1, q_{1T}, \mu_F) F_g(x_2, q_{2T}, \mu_F) d\hat{\sigma}(gg \rightarrow \mathcal{C}X), \quad (9)$$

$$d\Delta\sigma \propto \int dx_1 \int d^2 q_{1T} \int dx_2 \int d^2 q_{2T} [\hat{F}_g^\uparrow(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_g^\downarrow(x_1, \mathbf{q}_{1T}, \mu_F)] \\ \times F_g(x_2, q_{2T}, \mu_F) d\hat{\sigma}(gg \rightarrow \mathcal{C}X), \quad (10)$$

where $\hat{F}_g^{\uparrow,\downarrow}(x, q_T, \mu_F)$ is the distribution of unpolarized gluon (or quark) in polarized proton.

Following the Trento conventions [A. Bacchetta, U. D'Alesio, M. Diehl and C. A. Miller, *Phys. Rev. D* **70**, 117504 (2004)], the gluon Sivers function (GSF) can be introduced as

$$\Delta \hat{F}_g^\uparrow(x_1, \mathbf{q}_{1T}, \mu_F) \equiv \hat{F}_g^{(\uparrow)}(x_1, \mathbf{q}_{1T}, \mu_F) - \hat{F}_g^{(\downarrow)}(x_1, \mathbf{q}_{1T}, \mu_F) = \\ = \Delta^N F_g^\uparrow(x_1, \mathbf{q}_{1T}^2, \mu_F) \cos(\phi_1) \equiv \left(-2 \frac{q_{1T}}{M_p} \right) F_{1T}^{\perp g}(x_1, \mathbf{q}_{1T}^2, \mu_F) \cos(\phi_1). \quad (11)$$

Moreover, GSF must satisfy the positivity bound $\forall x_1, q_{1T}$:

$$\left| \Delta^N F_g^\uparrow(x_1, \mathbf{q}_{1T}^2, \mu_F) \right| \leq 2F_g(x_1, q_{1T}, \mu_F). \quad (12)$$

Single Spin Asymmetry in CGI-GPM framework

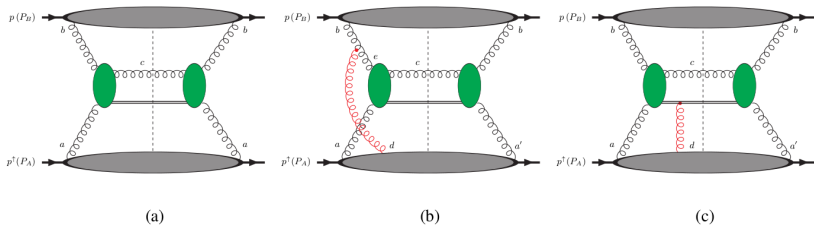


Figure 1 : LO diagrams for the process $p^\uparrow p \rightarrow J/\psi X$, assuming a color-singlet production mechanism, within the GPM (a) and the CGI-GPM (b), (c). It turns out that only initial state interactions depicted in (b) contribute to the SSA. Figure is from [D'Alesio *et al.*, Phys. Rev. D **96**, 036011 (2017)].

In GPM (Fig. 1 (a)) we can write the numerator of the asymmetry as follows:

$$d\Delta\sigma \propto \left(-2 \frac{q_{1T}}{M_p} \right) F_{1T}^\perp g(x_1, \mathbf{q}_{1T}^2, \mu_F) \cos(\phi_1) \otimes F_g(x_2, q_{2T}, \mu_F) \otimes H_{gg \rightarrow cd}^U, \quad (13)$$

where $H_{gg \rightarrow cd}^U = \overline{|M(gg \rightarrow cd)|^2}$.

Single Spin Asymmetry in CGI-GPM framework

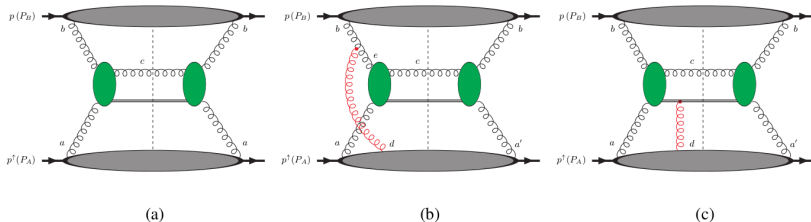


Figure 2 : LO diagrams for the process $p^\uparrow p \rightarrow J/\psi X$, assuming a color-singlet production mechanism, within the GPM (a) and the CGI-GPM (b), (c). It turns out that only initial state interactions depicted in (b) contribute to the SSA. Figure is from [D'Alesio *et.al.*, Phys. Rev. D **96**, 036011 (2017)].

Formally, the numerator of the asymmetry in the CGI-GPM approach ([L. Gamberg and Z. B. Kang, Phys. Lett. B **696**, 109 (2011)]) can be obtained from eq. (13) by with the substitution:

$$\begin{aligned}
 F_{1T}^{\perp g} H_{gg \rightarrow J/\psi g}^U &\rightarrow \frac{C_I^{(f)} + C_{F_c}^{(f)}}{C_U} F_{1T}^{\perp g(f)} H_{gg \rightarrow J/\psi g}^U + \frac{C_I^{(d)} + C_{F_c}^{(d)}}{C_U} F_{1T}^{\perp g(d)} H_{gg \rightarrow J/\psi g}^U \equiv \\
 &\equiv F_{1T}^{\perp g(f)} H_{gg \rightarrow J/\psi g}^{Inc(f)} + F_{1T}^{\perp g(d)} H_{gg \rightarrow J/\psi g}^{Inc(d)}. \quad (14)
 \end{aligned}$$

Color factors and Feynman rules in the CGI-GPM framework

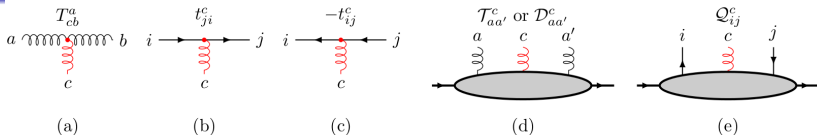


Figure 3 : CGI-GPM color rules for the eikonal three-gluon (a), quark-gluon (b) and antiquark-gluon (c) vertices. The color projectors for the gluon (d) and the quark color projectors (e) are shown as well. The eikonal gluon has color index c . Figure is from [D'Alesio *et al.*, *Phys. Rev. D* **96**, 036011 (2017)].

The color factors are:

$$\mathcal{T}_{aa'} = \mathcal{N}_{\mathcal{T}} T_{aa'}^c, \mathcal{D}_{aa'}^c = \mathcal{N}_{\mathcal{D}} D_{aa'}^c, \mathcal{Q}_{ij}^c = \mathcal{N}_{\mathcal{Q}} t_{ij}^c, \quad (15)$$

where $T_{cb}^a \equiv -if_{acb}$, $D_{bc}^a \equiv d_{abc}$, $\mathcal{N}_{\mathcal{T}} = \frac{1}{\text{Tr}[T^c T^c]} = 1/(N_c(N_c^2 - 1))$,

$\mathcal{N}_{\mathcal{D}} = \frac{1}{\text{Tr}[D^c D^c]} = 1/((N_c^2 - 4)(N_c^2 - 1))$, $\mathcal{N}_{\mathcal{Q}} = \frac{1}{\text{Tr}[t^c t^c]} = 2/(N_c^2 - 1)$.

So, correspondingly, for the f - and d -type GSF, the relative color factor is therefore calculated from Fig. 1(b) as follows:

$$C_I^{(f)} = -\frac{1}{2}C_U, C_I^{(d)} = 0. \quad (16)$$

And in CSM of the heavy quark-antiquark pair to the FSI, depicted in Fig. 1(c):

$$C_{F_c}^{(f)} = C_{F_c}^{(d)} = 0. \quad (17)$$

SSA in charmonium production at RHIC and NICA

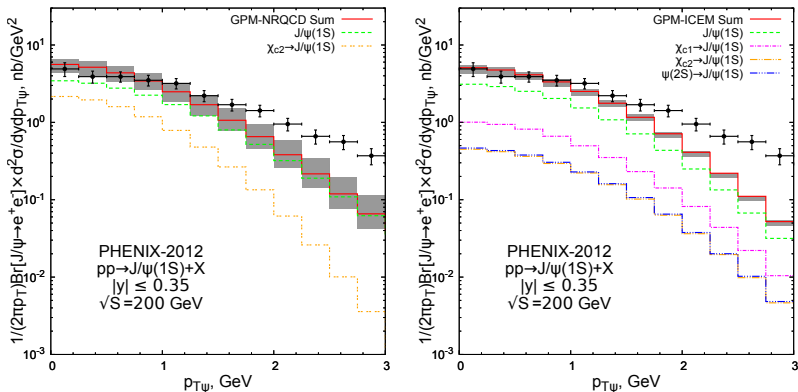
PHENIX-2012 data, $|y| \leq 0.35$, $\sqrt{S} = 200$ GeV.

Figure 4 : Differential cross-section of prompt J/ψ production as function of transverse momentum at $\sqrt{s} = 200$ GeV, $|y| \leq 0.35$. The theoretical results are obtained in GPM with $\langle q_T^2 \rangle = 1$ GeV². Left panel: NRQCD-factorization prediction with only color-singlet channels included. Right panel: ICEM-prediction. In the left panel, non-zero contributions from decays $\chi_{c0,1} \rightarrow J/\psi$ and $\psi(2S) \rightarrow J/\psi$ are not shown. Experimental data are from the Ref. [A. Adare *et al.* [PHENIX], Phys. Rev. D **85**, 092004 (2012)].

PHENIX-2012 data, $|y| \leq 0.35$, $\sqrt{S} = 200$ GeV.

Table 1 : The relative contributions of direct and feed-down production within NRQCD and ICEM. Experimental data of the PHENIX collaboration for $\sqrt{s} = 200$ GeV are from [A. Adare *et al.* [PHENIX], *Phys. Rev. D* **85**, 092004 (2012)].

\sqrt{s}	Model/Source of data	$\sigma^{\text{direct}} : \sigma^{\chi_{c1} \rightarrow J/\psi} : \sigma^{\psi(2S) \rightarrow J/\psi}$
24 GeV	NRQCD	0.58 : 0.39 : 0.03
	ICEM	0.68 : 0.25 : 0.07
200 GeV	NRQCD	0.61 : 0.34 : 0.05
	ICEM	0.61 : 0.30 : 0.09
200 GeV	PHENIX collab.	0.58 : 0.32 : 0.10

Table 2 : The values of hadronization probabilities of ICEM, which had been obtained via the fit of total cross-section of J/ψ -production at PHENIX. The fit of LHC data are taken from [V. Cheung and R. Vogt, *Phys. Rev. D* **98**, 114029 (2018)].

$F_{\mathcal{C}}$	Our fit	The fit of LHC data
$F_{J/\psi}$	0.02	0.02
$F_{\chi_{c1}}$	0.06	0.18
$F_{\chi_{c2}}$	0.06	0.2
$F_{\psi'}$	0.08	0.12

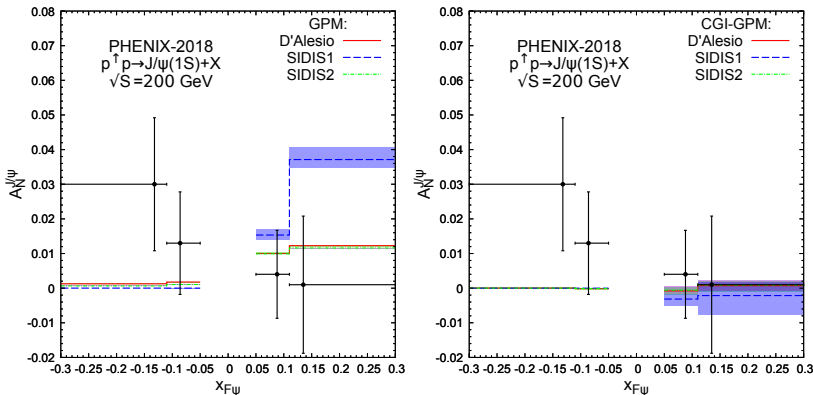
PHENIX-2018 data, $1.2 \leq |y| \leq 2.2$, $\sqrt{S} = 200$ GeV.

Figure 5 : SSA $A_N^{J/\psi}$ as function of x_F at $\sqrt{s} = 200$ GeV. The theoretical results are obtained in NRQCD with D'Alesio *et al.*, SIDIS1 and SIDIS2 parameterizations of GSFs. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. Experimental data are from Ref. [C. Aidala *et al.* [PHENIX], Phys. Rev. D **98**, 012006 (2018)].

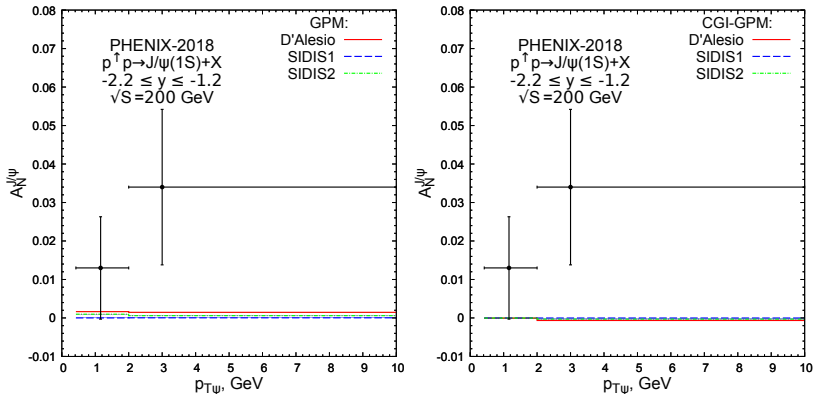
PHENIX-2018 data, $-2.2 \leq y \leq -1.2$, $\sqrt{s} = 200$ GeV.

Figure 6 : NRQCD predictions for SSA $A_N^{J/\psi}$ as function of J/ψ -transverse momentum at $\sqrt{s} = 200$ GeV. The theoretical results are obtained with D'Alesio *et al.*, SIDIS1 and SIDIS2 parameterizations of GSFs. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. Experimental data are from Ref. [C. Aidala *et al.* [PHENIX], Phys. Rev. D **98**, 012006 (2018)].

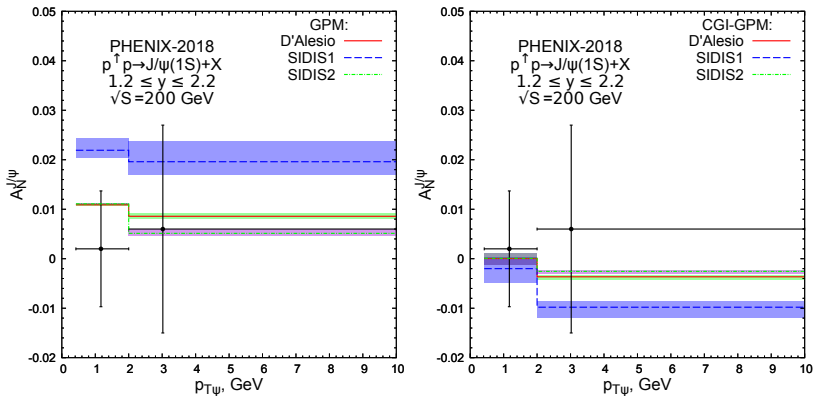
PHENIX-2018 data, $1.2 \leq y \leq 2.2$, $\sqrt{s} = 200$ GeV.

Figure 7 : NRQCD predictions for SSA $A_N^{J/\psi}$ as function of J/ψ -transverse momentum at $\sqrt{s} = 200$ GeV. The theoretical results are obtained with SIDIS1 and D'Alesio et al. parameterizations of GSFs. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. Experimental data are from Ref. [C. Aidala *et al.* [PHENIX], Phys. Rev. D **98**, 012006 (2018)].

Predictions for NICA (in different models), $|y| \leq 3$, $\sqrt{S} = 24$ GeV.

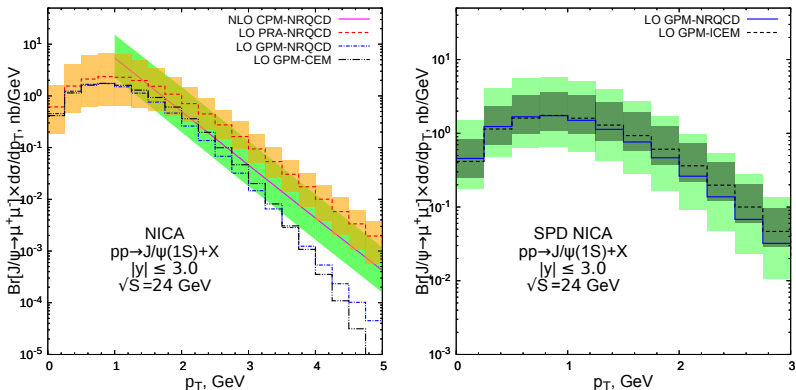


Figure 8 : Prompt J/ψ transverse momentum distribution at $\sqrt{s} = 24$ GeV, $|y| \leq 3$. Left panel: GPM results with $\langle q_T^2 \rangle = 1$ GeV² are shown by dash-dotted (NRQCD) and dash-double-dotted (ICEM) histograms. Solid and dashed histograms with uncertainty bands are PRA [A.V. Karpishkov, M.A. Nefedov and V.A. Saleev, *J. Phys. Conf. Ser.* **1435**, 012015 (2020)] and NLO CPM [M. Butenschön and B.A. Kniehl, private communication] predictions respectively. Right panel: GPM predictions in NRQCD (solid histogram with light green uncertainty band) and ICEM (dashed histogram with dark-green uncertainty band) approaches with their uncertainty bands shown.

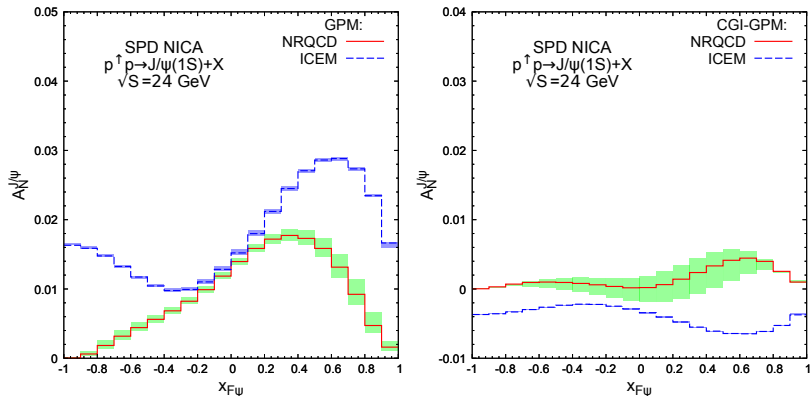
Predictions for SSA at NICA (D'Alesio), $|y| \leq 3$, $\sqrt{s} = 24$ GeV.

Figure 9 : Comparison of predictions for SSA $A_N^{J/\psi}$ as function of x_F at $\sqrt{s} = 24$ GeV in NRQCD (solid histogram) and ICEM (dashed histogram) approaches. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. The D'Alesio *et al.* parametrisation of GSFs is used.

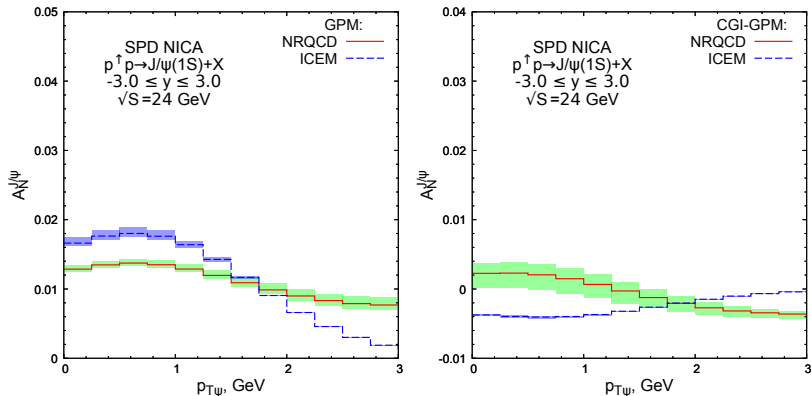
Predictions for SSA at NICA (D'Alesio), $|y| \leq 3$, $\sqrt{s} = 24$ GeV.

Figure 10 : Comparison of predictions for SSA $A_N^{J/\psi}$ as function of p_T at $\sqrt{s} = 24$ GeV in **NRQCD** (solid histogram) and **ICEM** (dashed histogram) approaches. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. The D'Alesio *et al.* parametrisation of GSFs is used.

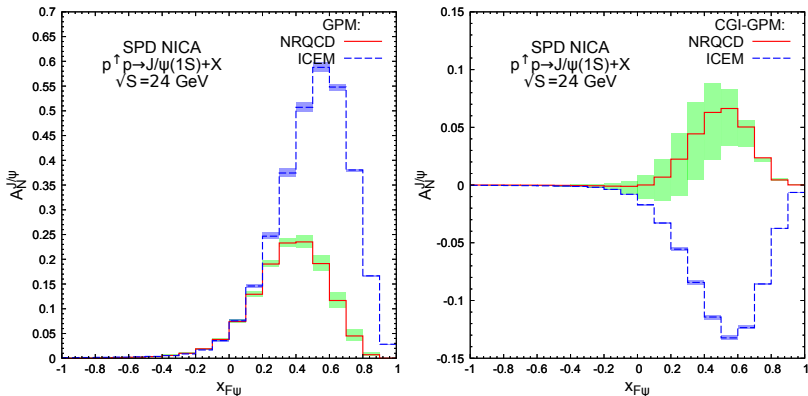
Predictions for SSA at NICA (SIDIS1), $|y| \leq 3$, $\sqrt{S} = 24$ GeV.

Figure 11 : Comparison of predictions for SSA $A_N^{J/\psi}$ as function of x_F at $\sqrt{s} = 24$ GeV in NRQCD (solid histogram) and ICEM (dashed histogram) approaches. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. The SIDIS1 parametrisation of GSFs is used.

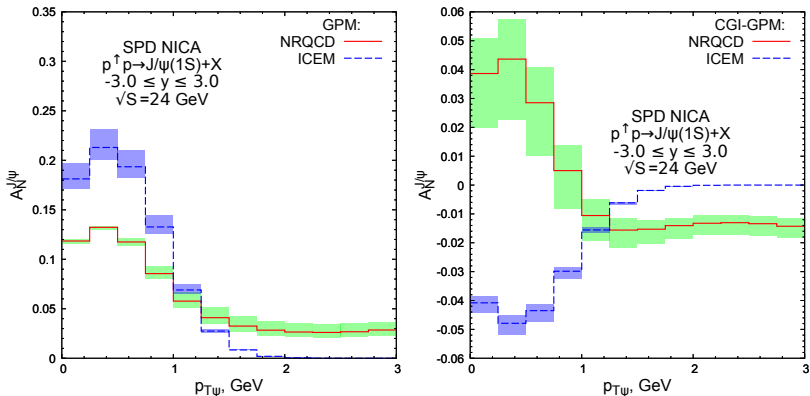
Predictions for SSA at NICA (SIDIS1), $|y| \leq 3$, $\sqrt{S} = 24$ GeV.

Figure 12 : Comparison of predictions for SSA $A_N^{J/\psi}$ as function of p_T at $\sqrt{s} = 24$ GeV in NRQCD (solid histogram) and ICEM (dashed histogram) approaches. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. The SIDIS1 parametrisation of GSFs is used.

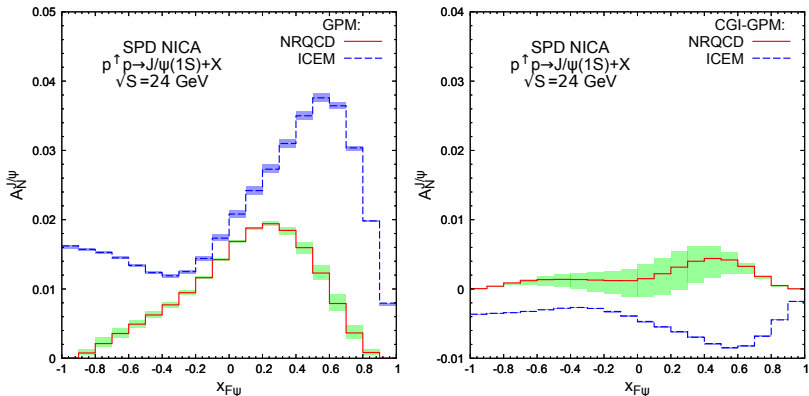
Predictions for SSA at NICA (SIDIS2), $|y| \leq 3$, $\sqrt{S} = 24$ GeV.

Figure 13 : Comparison of predictions for SSA $A_N^{J/\psi}$ as function of x_F at $\sqrt{s} = 24$ GeV in NRQCD (solid histogram) and ICEM (dashed histogram) approaches. Left panel: GPM-prediction. Right panel: CGI-GPM-prediction. The SIDIS2 parametrisation of GSFs is used.

Summary

- We have found that taking into account only color-singlet production mechanism, the good description of prompt J/ψ transverse momentum spectra at small $k_{T,J/\psi} < m_{J/\psi}$ can be achieved in GPM. Our NRQCD calculation leads to total cross-section ratios of direct and feed-down contributions in good agreement with experimental data.
- The CGI-GPM formalism, which includes effects of ISIs and FSIs under a one-gluon exchange approximation, can reproduce the twist-3 collinear factorization formalism (see [L. Gamberg and Z. B. Kang, *Phys. Lett. B* **696**, 109 (2011)] and [D'Alesio *et.al.*, *Phys. Rev. D* **96**, 036011 (2017)] for details).
- The Color Gauge Invariant formulation of the GPM is able to reproduce the expected opposite relative sign of the Sivers asymmetries, due to the effects of FSIs and ISIs.
- In CGI-GPM within both the frameworks of CSM and ICEM the process $p^\uparrow p \rightarrow \mathcal{H}X$ of *direct production* of $J/\psi(\psi')$ is sensitive to f -type GSF. While the χ_c production within the CSM is sensitive to d -type GSF and to f -type within the ICEM.
- In the CSM it is better to measure separately direct and feed-down contributions to the J/ψ asymmetry (at least for D'Alesio and SIDIS2 parametrizations). While in the ICEM it is better to look at the *sum* of both contributions.

Thank you for your attention!