Probing the gluon Sivers function in $p^{\uparrow}p \to J/\psi X$ at SPD NICA

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SPD Physics and MC meeting

CPM, **GPM**, TMD, PRA, k_T-factorization

- CPM: $q_\mu = xP^+_\mu$, $q^2 = 0$, $f(x, Q)$, DGLAP, QCD for amplitudes + NLO + NNLO
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- GPM: $q_\mu = xP^+_\mu + yP^-_\mu + q_{T\mu}$, $q^2 = 0$, $F(x, q_T, Q) = f(x, Q) * G(q_T)$, DGLAP for $f(x, Q)$, QCD for amplitudes
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- TMD: $q_\mu = xP^+_\mu + yP^-_\mu + q_{T\mu}$, $q^2 = 0$, $F(x, q_T, Q, \zeta)$, CS evolution equations for $F(x, q_T, Q, \zeta)$, QCD for amplitudes, $q_T << Q$
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- PRA: $q_\mu = xP^+_\mu + q_{T\mu}$, $q^2 = q_T^2 \neq 0$, $F(x, q_T, Q,) = C(x, q_T, Q) \otimes f(x, Q)$, DGLAP for $f(x, Q)$, Lipatov effective field theory for off-shell amplitudes, Reggeized partons
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- k_T-factorization: $q_\mu = xP^+_\mu + q_{T\mu}$, $q^2 = q_T^2 \neq 0$, $F(x, q_T)$, BFKL for $F(x, q_T)$ and $x << 1$, Lipatov's effective field theory for off-shell amplitudes (Reggeized partons).

GPM - Generalized Parton Model

Factorization in GPM at $q_{1,2T} << M$

$$E\frac{d\sigma}{d^3p}(pp \to J/\psi X) = d\sigma = d\sigma_{gg} + d\sigma_{q\bar{q}}$$

$$d\sigma_{gg} = \int dx_1 \int d^2q_{1T} \int dx_2 \int d^2q_{2T} F_g(x_1, q_{1T}, \mu) F_g(x_2, q_{2T}, \mu) \times$$
$$\times \frac{\overline{|M(gg \to J/\psi + \ldots)|^2}}{16\pi^2 x_1 x_2 S} \delta(\hat{s} + \hat{t} + \hat{u} - M^2)$$

$$d\sigma_{q\bar{q}} = \sum_q \int dx_1 \int d^2q_{1T} \int dx_2 \int d^2q_{2T} F_q(x_1, q_{1T}, \mu) F_{\bar{q}}(x_2, q_{2T}, \mu) \times$$
$$\times \frac{\overline{|M(q\bar{q} \to J/\psi + \ldots)|^2}}{16\pi^2 x_1 x_2 S} \delta(\hat{s} + \hat{t} + \hat{u} - M^2) + (q \leftrightarrow \bar{q})$$

$\sigma^{inc} = \sigma(pp \to J/\psi + X)$

$$\sigma^{inc} = \sigma^{prompt} + \sigma^{B \to J/\psi}$$
$$\sigma^{prompt} = \sigma^{direct} + \sigma^{\chi_c, \psi' \to J/\psi}$$

SSA - Single Spin Asymmetry

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

$$d\sigma^{\uparrow} = E\frac{d\sigma}{d^3p}(p^{\uparrow}p \to J/\psi X)$$

SSA - Single Spin Asymmetry

M. Anselmino et al., PRD 70, 074025 (2004)

$$\begin{aligned}
d\sigma^{\uparrow} - d\sigma^{\downarrow} &= \int dx_1 \int d^2 q_{1T} \int dx_2 \int d^2 q_{2T} \Delta^N F_g^{\uparrow}(x_1, q_{1T}, \mu) F_g(x_2, q_{2T} \times \\
&\times \frac{\overline{|M(gg \to J/\psi + ...)|^2}}{16\pi^2 x_1 x_2 S} \delta(\hat{s} + \hat{t} + \hat{u} - M^2) + \\
&+ \sum_q \int dx_1 \int d^2 q_{1T} \int dx_2 \int d^2 q_{2T} \Delta^N F_q^{\uparrow}(x_1, q_{1T}, \mu) F_{\bar{q}}(x_2, q_{2T} \times \\
&\times \frac{\overline{|M(q\bar{q} \to J/\psi + ...)|^2}}{16\pi^2 x_1 x_2 S} \delta(\hat{s} + \hat{t} + \hat{u} - M^2) + (q \leftrightarrow \bar{q})
\end{aligned}$$

$$\Delta^N F_g^{\uparrow}(x_1, q_{1T}, \mu) = F_g^{\uparrow}(x_1, q_{1T}, \mu) - F_g^{\downarrow}(x_1, q_{1T}, \mu)$$

Parton Distribution Functions (PDFs) in GPM

PDF in unpolarized proton

$$F_g(x, q_T, \mu) = f_g(x, \mu) G(q_T), \qquad G(q_T) = \frac{e^{-\vec{q}_T^{\,2}/<\vec{q}_T^{\,2}>}}{\pi < \vec{q}_T^{\,2} >}, \qquad x_{1,2} = \frac{q^0_{1,2} \pm q^3_{1,2}}{\sqrt{S}}$$

On-shell condition for initial partons: $q^2_{1,2} = 0$

$$q_1 = \left(x_1 \frac{\sqrt{S}}{2} + \frac{\vec{q}^{\,2}_{1T}}{2\sqrt{S} x_1}, \vec{q}_{1T}, x_1 \frac{\sqrt{S}}{2} - \frac{\vec{q}^{\,2}_{1T}}{2\sqrt{S} x_1} \right), \quad q_{1z} > 0$$

$$q_2 = \left(x_2 \frac{\sqrt{S}}{2} + \frac{\vec{q}^{\,2}_{2T}}{2\sqrt{S} x_2}, \vec{q}_{1T}, -x_2 \frac{\sqrt{S}}{2} + \frac{\vec{q}^{\,2}_{1T}}{2\sqrt{S} x_1} \right) \quad q_{2z} < 0$$

The Sivers function (M. Anselmino et al., PRD 70, 074025 (2004))

$$\Delta^N F_g(x, q_T, \mu) = \Delta^N f_g(x, \mu) G(q_T) \times \frac{2 q_T M}{q_T^2 + M^2} \times \cos(\phi_{q_T}), \qquad M^2 =< q_T^2 >$$

$$|\Delta^N F_g(x, q_T, \mu)| \leq 2 F_g(x, q_T, \mu)$$

PDFs in GPM

Estimation of maximum value of gluon SSA

$$\Delta^N F_g(x, q_T, \mu) \neq 0, \qquad \Delta^N F_q(x, q_T, \mu) = 0$$

Estimation of maximum value of quark SSA

$$\Delta^N F_q(x, q_T, \mu) \neq 0, \qquad \Delta^N F_g(x, q_T, \mu) = 0$$

Intrinsic transverse momentum

CPM: $< q_T^2 >= 0$

GPM [Anselmino et al. JHEP 1704 (2017) 046]: $< q_T^2 >= 0.25\text{GeV}^2$

GPM [M. Anselmino et al., PRD 70, 074025 (2004)]: $< q_T^2 >= 0.64\text{GeV}^2$

GPM [U. D'Alesio et al., PRD (2017), PRD (2019)], $< q_T^2 >= 1.00\text{GeV}^2$

J/ψ at PHENIX in GPM, Color Singlet Model, $g+g \to J/\psi + g$
U. D'Alesio et al., Phys.Rev.D 96 (2017) 3, 036011

$\sigma^{prompt} = 1.72 \times \sigma^{direct}$, in fact the ratio is not constant !

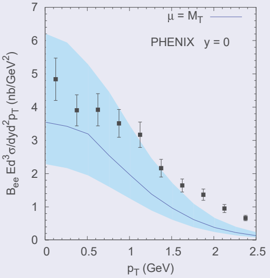


FIG. 1: Unpolarized cross section for the process $pp \to J/\psi X \to e^+e^- X$, at $\sqrt{s} = 200$ GeV in the central rapidity region $y = 0$, as a function of the transverse momentum p_T of the J/ψ. The theoretical curve is obtained by adopting the generalized parton model and the color-singlet production mechanism for the quarkonium. Data are taken from Ref. [50]. The uncertainty band results from varying the factorization scale in the range $M_T/2 \le \mu \le 2M_T$.

$A_N(J/\psi)$ at PHENIX in GPM, Color Singlet Model, $g + g \to J/\psi + g$
U. D'Alesio et al., Phys.Rev.D 96 (2017) 3, 036011

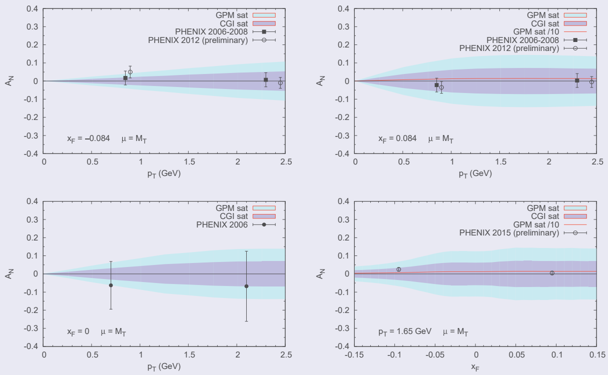
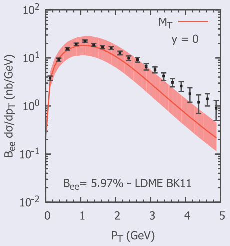


FIG. 3: Comparison of the available data from PHENIX [67, 68] with the bands of possible values of A_N, between the lower and the upper bounds ($\mathcal{N}_g(x) = \pm 1$), for the process $p^{\uparrow}p \to J/\psi\, X$ at $\sqrt{s} = 200$ GeV, calculated in both the GPM and CGI-GPM approaches. Upper panels: as a function of p_T at $x_F = -0.084$ (left) and $x_F = +0.084$ (right). Lower panels: as a function of p_T at $x_F = 0$ (left) and as a function of x_F at $p_T = 1.65$ GeV (right). The red solid lines represent an estimate obtained with $\mathcal{N}_g(x) = +0.1$ within the GPM approach (see text for details).

J/ψ at PHENIX in GPM, NRQCD
U. D'Alesio et al., Eur.Phys.J.C 79 (2019) 12, 1029

$g + g \to c\bar{c}[^3S_1^{(1)}] + g$
$g + g \to c\bar{c}[^3S_1^{(8)}, ^1S_0^{(8)}, ^3P_{0,1,2}^{(8)}] + g$ This is NLO and divergent contribution !

LO is $2 \to 1$ subprocesses, which is omitted $g + g \to c\bar{c}[^1S_0^{(8)}, ^3P_{0,2}^{(8)}]$



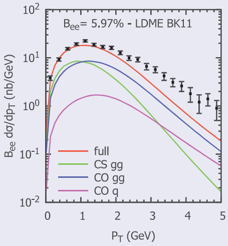


FIG. 1: Left panel: Unpolarized cross section for the process $pp \to J/\psi X$, as a function of P_T at $\sqrt{s} = 200$ GeV and $y = 0$, within the GPM approach compared with PHENIX data [38], obtained with the BK11 LDME set [48]. The band represents

J/ψ at PHENIX in GPM, NRQCD
U. D'Alesio et al., Eur.Phys.J.C 79 (2019) 12, 1029

$A_N^{J/\psi}(x_F)$ with different sets of color-octet NMEs: [BK2011], [SYY2013]

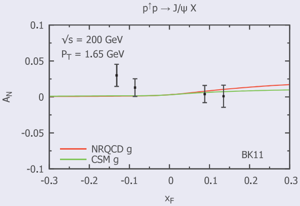


FIG. 4: Estimates of A_N for the process $p^{\uparrow}p \to J/\psi\, X$ as a function of x_F at $\sqrt{s} = 200$ GeV and $P_T = 1.65$ GeV, both in the CSM (green dashed line) and the NRQCD approach (red solid line), adopting the BK11 (left panel) and the SYY13 LDME set (right panel), compared against PHENIX data [8]. The curves are calculated adopting the parameters in Eq. (21) for the GSF.

Prompt J/ψ at in GPM + NRQCD

Color-singlet model

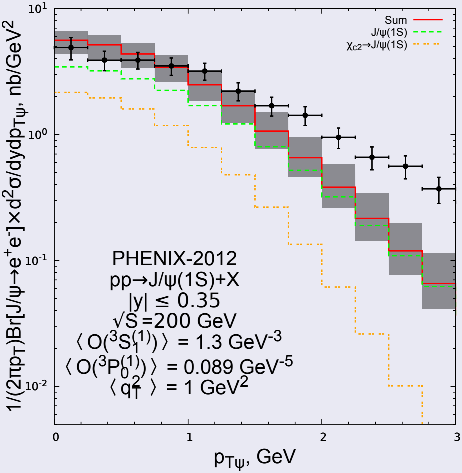
- Direct production ($2 \to 2$): $g + g \to c\bar{c}[1^3S_1^{(1)}] + g \Rightarrow J/\psi + g$
- Feed-down production ($2 \to 2$): $g + g \to c\bar{c}[2^3S_1^{(1)}] + g \Rightarrow \psi' + g$
- Feed-down production ($2 \to 1$): $g + g \to c\bar{c}[^3P_{0,2}^{(1)}] \Rightarrow \chi_{c0,2}$
- B.A.Kniehl, D.V.Vasin, V.A.Saleev, Phys.Rev.D 73 (2006) 074022.

$$
\begin{aligned}
\overline{|\mathcal{A}(g+g\to\mathcal{H}[^3P_0^{(1)}]|^2} &= \frac{8}{3}\pi^2\alpha_s^2\frac{\langle\mathcal{O}^{\mathcal{H}}[^3P_0^{(1)}]\rangle}{M^3},\\
\overline{|\mathcal{A}(g+g\to\mathcal{H}[^3P_1^{(1)}]|^2} &= 0,\\
\overline{|\mathcal{A}(g+g\to\mathcal{H}[^3P_2^{(1)}]|^2} &= \frac{32}{45}\pi^2\alpha_s^2\frac{\langle\mathcal{O}^{\mathcal{H}}[^3P_2^{(1)}]\rangle}{M^3},\\
\overline{|\mathcal{A}(g+g\to\mathcal{H}[^3S_1^{(8)}]|^2} &= 0,\\
\overline{|\mathcal{A}(g+g\to\mathcal{H}[^1S_0^{(8)}]|^2} &= \frac{5}{12}\pi^2\alpha_s^2\frac{\langle\mathcal{O}^{\mathcal{H}}[^1S_0^{(8)}]\rangle}{M},\\
\overline{|\mathcal{A}(g+g\to\mathcal{H}[^3P_0^{(8)}]|^2} &= 5\pi^2\alpha_s^2\frac{\langle\mathcal{O}^{\mathcal{H}}[^3P_0^{(8)}]\rangle}{M^3},\\
\overline{|\mathcal{A}(g+g\to\mathcal{H}[^3P_1^{(8)}]|^2} &= 0,\\
\overline{|\mathcal{A}(g+g\to\mathcal{H}[^3P_2^{(8)}]|^2} &= \frac{4}{3}\pi^2\alpha_s^2\frac{\langle\mathcal{O}^{\mathcal{H}}[^3P_2^{(8)}]\rangle}{M^3}.
\end{aligned}
\tag{37}
$$

$$
\begin{aligned}
&\overline{|\mathcal{A}(g+g\to\mathcal{H}[^3S_1^{(1)}]+g|^2}\\
&= \pi^3\alpha_s^3\frac{\langle\mathcal{O}^{\mathcal{H}}[^3S_1^{(1)}]\rangle}{M^3}\frac{320M^4}{81(M^2-\hat{t})^2(M^2-\hat{u})^2(\hat{t}+\hat{u})^2}\\
&\quad\times(M^4\hat{t}^2-2M^2\hat{t}^3+\hat{t}^4+M^4\hat{t}\,\hat{u}-3M^2\hat{t}^2\hat{u}+2\hat{t}^3\hat{u}\\
&\quad+M^4\hat{u}^2-3M^2\hat{t}\hat{u}^2+3\hat{t}^2\hat{u}^2-2M^2\hat{u}^3+2\hat{t}\hat{u}^3+\hat{u}^4),
\end{aligned}
\tag{38}
$$

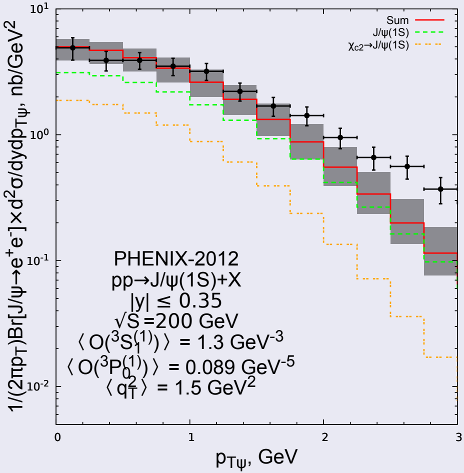
Prompt J/ψ spectra, PHENIX

$< q_T^2 >= 1\ \mathrm{GeV}^2$, $p_{T\psi} = \frac{M_\psi}{M_X} p_{T,X}$



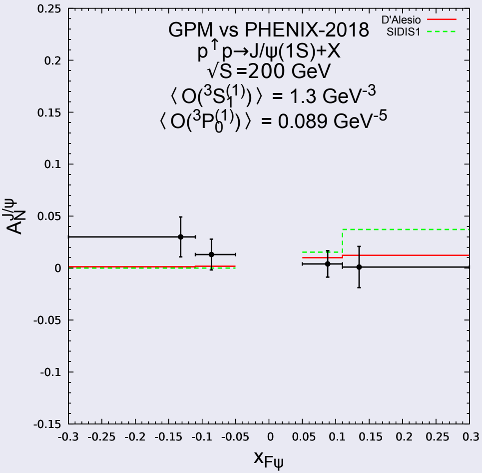
Prompt J/ψ spectra, PHENIX

$< q_T^2 >= 1.5$ GeV^2, $p_{T\psi} = \frac{M_\psi}{M_X} p_{T,X}$



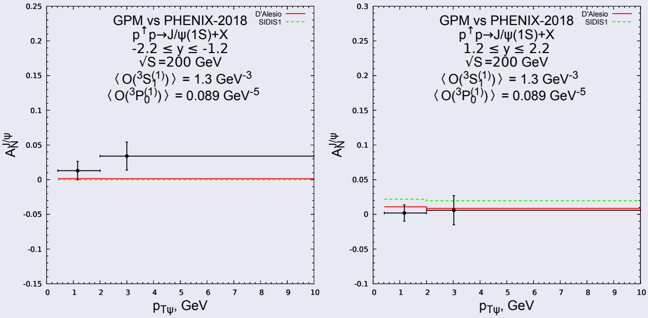
$A_N^{J/\psi}(x_F)$, PHENIX

$< q_T^2 >= 1$ GeV^2, $p_{T\psi} = \frac{M_\psi}{M_X} p_{T,X}$



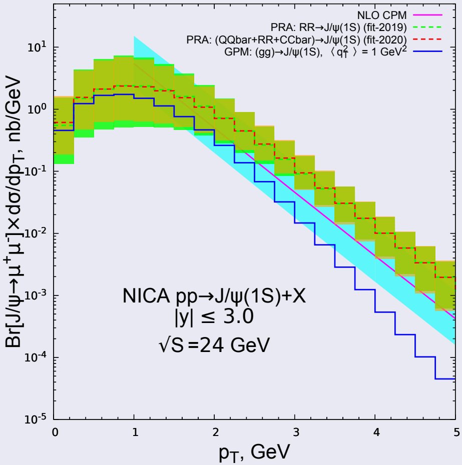
$A_N^{J/\psi}(p_T)$, PHENIX

$< q_T^2 >= 1\ \mathrm{GeV}^2$, $p_{T\psi} = \frac{M_\psi}{M_X} p_{T,X}$



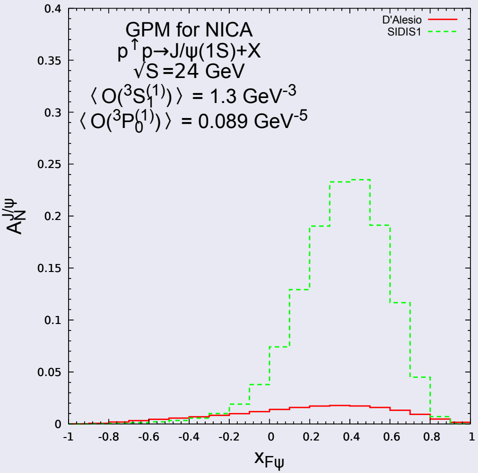
Prompt J/ψ spectra, SPD NICA

$< q_T^2 >= 1.0$ GeV^2, $p_{T\psi} = \frac{M_\psi}{M_X} p_{T,X}$



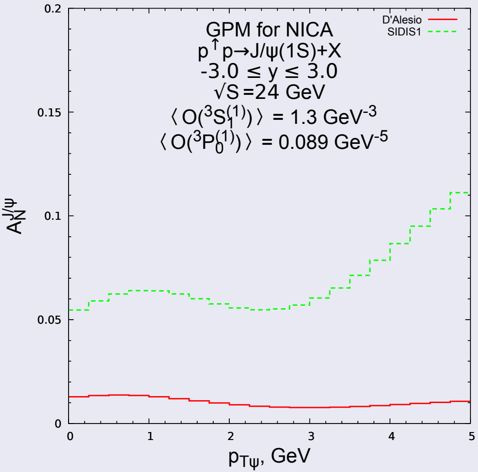
$A_N^{J/\psi}(x_F)$, SPD NICA

$< q_T^2 >= 1$ GeV^2, $p_{T\psi} = \frac{M_\psi}{M_X} p_{T,X}$



$A_N^{J/\psi}(p_T)$, SPD NICA

$<q_T^2>= 1\ \mathrm{GeV}^2$, $p_{T\psi} = \frac{M_\psi}{M_X} p_{T,X}$



Next step: compare prediction for $A_N^{J/\psi}$ in NRQCD and ICEM

Thank you for your attention!