J/ψ production and spin effects in collisions of unpolarized protons

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Outline

Introduction

SPD NICA is the project to study of spin physics in collisions of polarized protons

A_N and A_{LL} in the J/ψ production as tool

- A.Karpishkov, M.Nefedov and V.Saleev, Estimates for the single-spin asymmetries in the $pp^{\uparrow} \to J/\psi X$ process at PHENIX RHIC and SPD NICA, Phys. Rev. D104(2021) no.1, 016008
- Double longitudinal spin asymmetries A_{LL} in J/ψ production, see talk by **Igor Denisenko and Anton Karpishkov**.

Spin effects can be studied in collisions of unpolarized protons

- Production of the polarized J/ψ mesons
- Production of the different charmonium states $\eta_c, J/\psi, \chi_{cJ}$
- In the TMD factorization, $f_1^g(x, q_T, \mu)$ - unpolarized gluon distribution and $h_1^{\perp g}(x, q_T, \mu)$ - linearly polarized gluon distribution (Boer-Mulders function)

Factorization approaches: CPM and TMD PM

Collinear parton model (CPM)

- $q_{1,2T} \simeq 0$ and $p_T \geq \mu_F \sim m_{J/\psi}$

$$\begin{aligned}\sigma(pp \to J/\psi X) &= \int dx_1 \int dx_2 f_g(x_1,\mu_F) f_g(x_2,\mu_F) \hat{\sigma}(g+g \to J/\psi + X) + \\ &+ \mathcal{O}(\Lambda^2_{QCD}/\mu^2_F)\end{aligned}$$

- There are calculations in LO, NLO, NNLO, ... in the strong constant α_S

Factorization approaches: CPM and TMD PM

TMD PM by Collins, Soper, Stermann

- $q_{1,2T} \sim p_T$ and $\Lambda_{QCD} \sim p_T << \mu_F$

$$\sigma^{TMD}(pp \to \eta_c X) = \int dx_1 d^2 q_{1T} \int dx_2 d^2 q_{2T} F_g(x_1, q_{1T}, \mu_F, \mu_Y) \times$$

$$\times F_g(x_2, q_{2T}, \mu_F, \mu_Y) \hat{\sigma}(g + g \to \eta_c + X) + \mathcal{O}(< q_T^2 > / \mu_F^2) +$$

- $$\begin{aligned} \frac{d\sigma^{TMD}(p + p \to \eta_c X)}{dp_T dy} &= \sigma_0(s, M_{\eta_c}, \mu) \int \frac{d^2\mathbf{b}}{(2\pi)^2} e^{i\mathbf{b}\cdot\mathbf{q}_T} \times \\ &\times \tilde{F}_{g/P_1}(x_1, \mathbf{b}, \mu, \zeta_1) \tilde{F}_{g/P_2}(x_2, \mathbf{b}, \mu, \zeta_2) + \\ &+ Y(M, y, \mathbf{p}_T) + \text{ suppressed corrections} \end{aligned}$$

where $\tilde{F}_{g/P}(x, \mathbf{b}, \mu, \zeta)$ is universal TMD PDFs with evolution.

$$\tilde{F}_{g/P}(x, \mathbf{b}, \mu, \zeta) \leftrightarrows F_{g/P}(x, \mathbf{k}_T, \mu, \zeta)$$

Factorization approaches: CPM and TMD PM

Evolution in TMD PM

$$\frac{\partial \ln \tilde{F}(x,b,\mu,\zeta)}{\partial \sqrt{\zeta}} = \tilde{K}(b,\mu)$$

$$\frac{d\tilde{K}}{d\ln\mu} = -\gamma_K\left(\alpha_S(\mu)\right)$$

$$\frac{d\ln \tilde{F}(x,b,\mu,\zeta)}{d\ln\mu} = \gamma_F\left(\alpha_S\left(\mu\right), \frac{\zeta^2}{\mu^2}\right)$$

Gluon TMD PDF is unknown

- A. Vladimirov: fit of quark TMD PDFs in DY, $p_T \leq 0.2 \times Q$
- In the conventional TMD PM, the final state should be colorless: $q + \bar{q} \to \gamma^*(Z)$, $q + \bar{q}' \to W$ or $g + g \to H$.
- In case of charmonium production, $g + g \to \eta_c(\chi_{c0,c2})$, if CSM production mechanism is realized
- M. G. Echevarria, Proper TMD factorization for quarkonia production: $pp \to \eta_{c,b}$ as a study case // JHEP **10**, 144 (2019) – **PDF+Shape function**

Factorization approaches: CPM and TMD PM

Generalized parton model

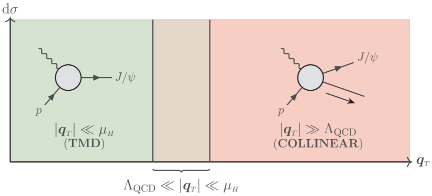
- $q_{1,2T} \sim p_T$ and $p_T \sim \mu_F$

$$\sigma(pp \to J/\psi X) = \int dx_1 d^2 q_{1T} \int dx_2 d^2 q_{2T} F_g(x_1, q_{1T}, \mu_F) \times$$

$$\times F_g(x_2, q_{2T}, \mu_F) \hat{\sigma}(g + g \to J/\psi + X)$$

$$F_g(x, q_T, \mu_F) = f_g(x, \mu_F) \times \exp(-q_T^2 / < q_T^2 >) / (\pi < q_T^2 >)$$

$$< q_T^2 > \sim 1 \text{ GeV}^2 >> \Lambda_{QCD}^2$$



Hadronization mechanisms: CSM, NRQCD and CEM

J/ψ production

- Baier, Ruckl, Berger, Jones [1983] – Color Singlet Model (CSM): $g+g \to c\bar{c}[^3S_1^{(1)}]+g$ and $g+g \to c\bar{c}[^1S_0^{(1)}]$, LDME $<\mathcal{H}[^{1,3}S_{0,1}^{(1)}]>\sim |\Psi_{\mathcal{H}}(0)|^2$.
- Bodwin, Braaten, and Lepage [1995] – NRQCD: $g+g \to c\bar{c}[^3S_1^{(1)}],[^1S_0^{(8)}],[^3P_J^{(8)}]$ as perturbative series in v^0, v^2, ...
- Fritzsch, Halzen [1977] – Color Evaporation Model (CEM):

$$\sigma(J/\psi) = F_{J/\psi}\int_{2m_c}^{2m_D}\frac{d\sigma(gg\to c\bar{c})}{dM_{c\bar{c}}}dM_{c\bar{c}}$$

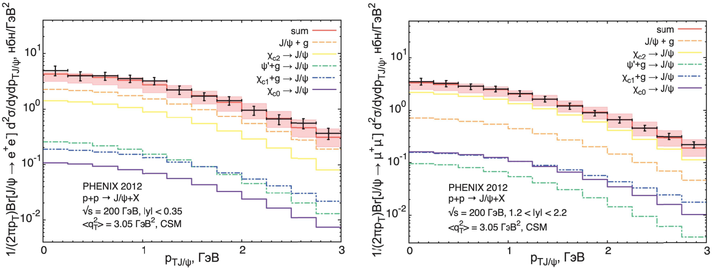
Ma and Vogt [2016] – Improved Color Evaporation Model (ICEM)

$$\sigma(J/\psi) = F_{J/\psi}\int_{M_{J/\psi}}^{2m_D}\frac{d\sigma(gg\to c\bar{c})}{dM_{c\bar{c}}}dM_{c\bar{c}}$$

$$p_{T\,J/\psi} = \frac{M_{J/\psi}}{M_{c\bar{c}}}p_{T\,c\bar{c}}$$

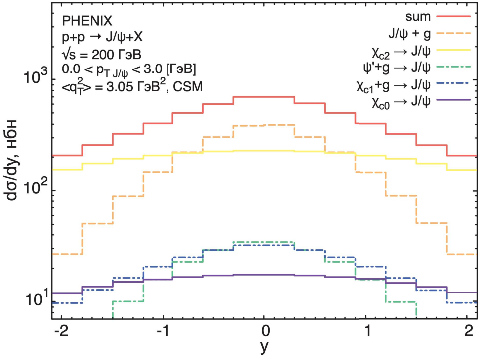
Prompt J/ψ production in the NRQCD

GPM + NRQCD, test of PHENIX and NA3 data



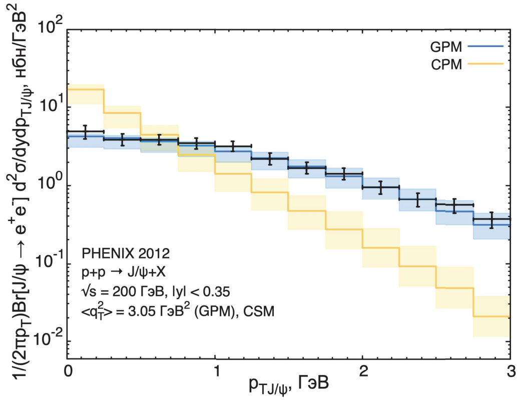
Prompt J/ψ production in the NRQCD

GPM + NRQCD, test of PHENIX and NA3 data



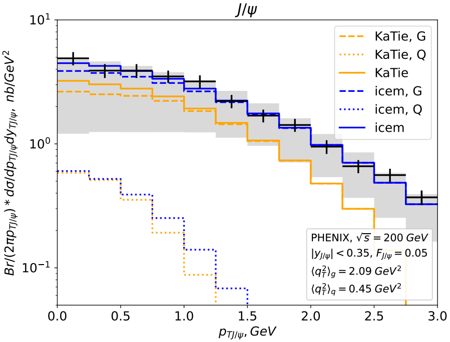
Prompt J/ψ production in the NRQCD

GPM versus CPM in the NRQCD



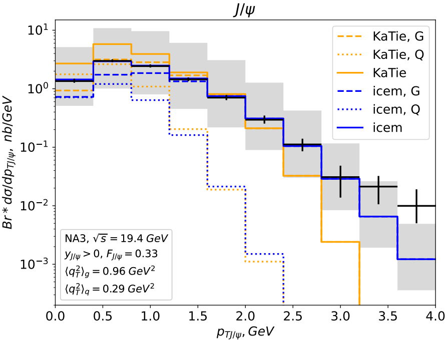
Prompt J/ψ production in the NRQCD

GPM + ICEM, test of the PHENIX and NA3 data



Prompt J/ψ production in the NRQCD

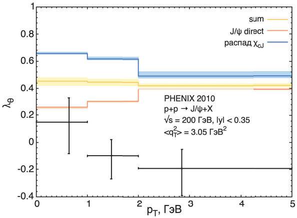
GPM + ICEM, test of the PHENIX and NA3 data

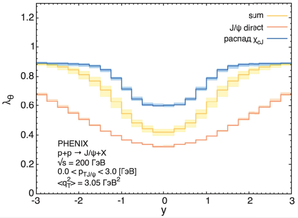


Polarized J/ψ production

Polarized J/ψ production using the NRQCD

$$\lambda_\theta = \frac{\sigma_T - 2\,\sigma_L}{\sigma_T + 2\,\sigma_L} = \frac{\sigma - 3\,\sigma_L}{\sigma + \sigma_L}.$$

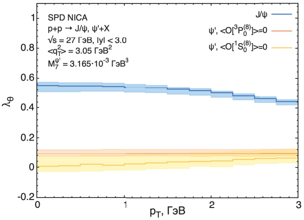


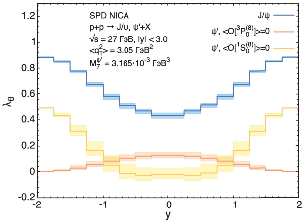


Polarized J/ψ production using the ICEM is in work till now ...

Polarized J/ψ production

Polarized J/ψ production iusing the NRQCD





$J/\psi+\gamma$ as a clean test of TMD gluon PDFs

$J/\psi+\gamma$ in the NRQCD only CS contribution in LO

$J/\psi+\gamma$ pair with the small total momentum originated from TMD PDFs

The gluon-TMD correlator

$$\Phi^g(x,q_T)=\frac{1}{2x}\left[-g_T^{\mu\nu}f_1^g(x,q_T)+\left(\frac{q_T^\mu q_T^\nu}{M^2}+g_T^{\mu\nu}\frac{q_T^2}{2M^2}\right)h_1^{\perp g}(x,q_T)\right]$$

$$g_T^{\mu\nu}=g^{\mu\nu}-\frac{P_1^\mu P_2^\nu+P_1^\nu P_2^\mu}{(P_1P_2)}$$

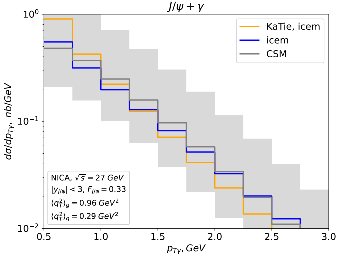
$$\begin{aligned} E\frac{d\sigma(pp\to J/\psi X)}{d^3p} &= \sigma_0(y,s)\Big[f_1^g(x_1,q_{1T})\otimes f_1^g(x_2,q_{2T})+ \\ &+ w(y,p_T,s)\otimes h_1^{\perp g}(x_1,q_{1T})\otimes h_1^{\perp g}(x_2,q_{2T})\Big] \end{aligned} \tag{1}$$

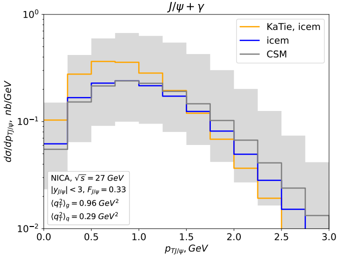
$J/\psi + \gamma$ as a clean test of TMD gluon PDFs

$$
\begin{aligned}
\frac{d\sigma(J/\psi\gamma)}{dQdY\,d^2p_T d\Omega} &= F_1 f_1^g(x_1,q_{T1}) \otimes f_1^g(x_2,q_{T2}) + \\
&+ F_3\cos(2\phi) w_3 \otimes f_1^g(x_1,q_{T1}) \otimes h_1^{\perp g}(x_2,q_{T2}) + \\
&+ F_3\cos(2\phi) w_3 \otimes f_1^g(x_2,q_{T2}) \otimes h_1^{\perp g}(x_1,q_{T1}) + \\
&+ F_4\cos(4\phi) w_4 \otimes h_1^{\perp g}(x_2,q_{T2}) \otimes h_1^{\perp g}(x_1,q_{T1})
\end{aligned} \tag{2}
$$

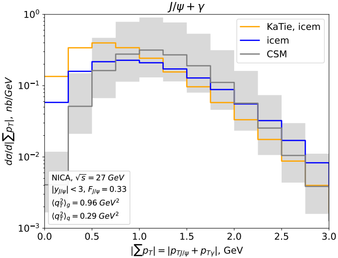
$d\Omega = d\cos\theta d\phi$ - Collins-Soper angles.

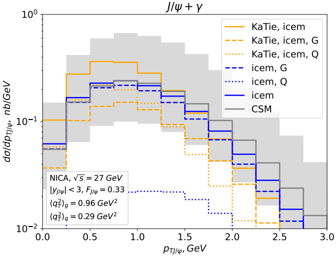
$J/\psi + \gamma$ as a clean test of TMD gluon PDFs



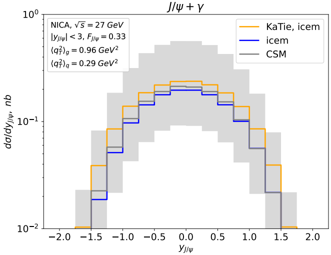


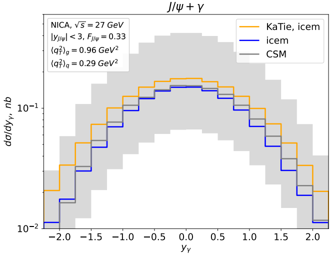
$J/\psi + \gamma$ as a clean test of TMD gluon PDFs



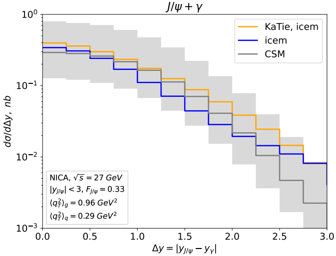


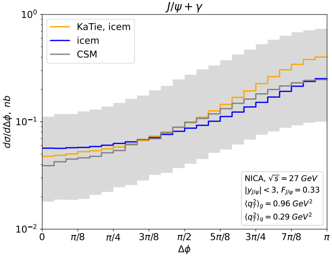
$J/\psi + \gamma$ as a clean test of TMD gluon PDFs



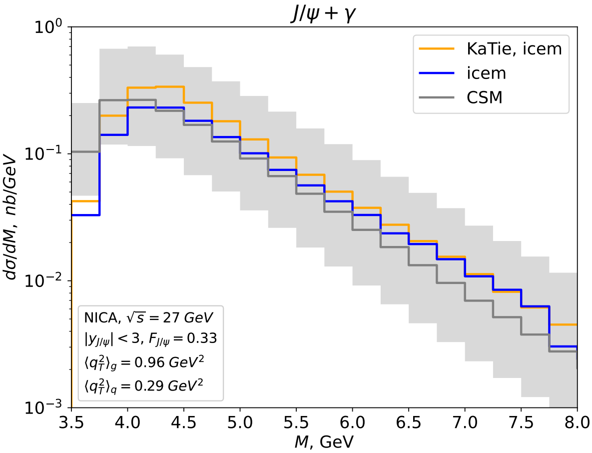


$J/\psi + \gamma$ as a clean test of TMD gluon PDFs





$J/\psi + \gamma$ as a clean test of TMD gluon PDFs



$J/\psi + \gamma$ as a clean test of TMD gluon PDFs

- There are not experimental data for $J/\psi + \gamma$ production and the measurement the cross section at the NICA may be very interesting
- The analysis of the ratio "signal/bachground" will be presented in the talk by **Lev Alimov** today.
- It is interesting to estimate the contribution of the gluon Boer-Mulders TMD PDF in polarized J/ψ production

Thank you for your attention!