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Spectra and polarizations of prompt J/ψ at the NICA within collinear parton model and parton Reggeization approach

A. V., Karpishkov[1†], **M. A., Nefedov**[1,2‡] **and V. A., Saleev**[1,3*]

[1]Samara National Research University, Samara, 443086 Russia
[2]II. Institut für Theoretische Physik, Universität Hamburg, Hamburg, 22761 Germany
[3]Joint Institute for Nuclear Research, Dubna, 141980 Russia

E-mail: [†]`karpishkoff@gmail.com`,[‡]`nefedovma@gmail.com`,[*]`saleev@samsu.ru`

Abstract. We study prompt production of J/ψ at the energy range of the NICA collider within the parton Reggeization approach (PRA) applying the non-perturbative QCD (NRQCD) factorization model for $c\bar{c} \to J/\psi$ transition. We calculate transverse momentum distribution for direct J/ψ as well as for J/ψ from decays of higher-lying charmonium states. Production of polarized J/ψ is studied and parameter λ_θ as a function of transverse momentum is calculated. The comparison with predictions obtained in calculations based on the next-to-leading approximation of the collinear parton model is done.

1. Introduction

A study of J/ψ production in collisions of non-polarized, as well as longitudinally and transversally polarized protons is included to the investigation program on Spin Physics Detector (SPD) at the new facility NICA of the JINR. It is of special interest as a testing ground for non-relativistic QCD (NRQCD) factorization picture of heavy quarkonium production.

2. Theoretical framework

2.1. The Parton Reggeization Approach

Here we will shortly discuss key points of the PRA. The PRA is based on three main ingredients: a factorization formula for hard processes in the modified Multi-Regge Kinematics (mMRK) [1], unintegrated parton distribution functions (unPDFs) in the Kimber-Martin-Ryskin (KMR) model [2] and a Lagrangian in the Lipatov's Effective Field Theory (EFT) of Reggeized gluons [3] and Reggeized quarks [4], which allow us to obtain gauge-invariant amplitudes of hard processes with off-shell initial-state partons.

The k_T-factorization formula which is obtained in Ref. [1] from mMRK approximation for the squared amplitude of auxiliary hard subprocess $g(p_1) + g(p_2) \to g(k_1) + \mathcal{Y}(P_{\mathcal{A}}) + g(k_2)$ has the form:

$$d\sigma = \int\limits_0^1 \frac{dx_1}{x_1} \int \frac{d^2\mathbf{q}_{T1}}{\pi} \Phi_g(x_1, t_1, \mu^2) \int\limits_0^1 \frac{dx_2}{x_2} \int \frac{d^2\mathbf{q}_{T2}}{\pi} \Phi_g(x_2, t_2, \mu^2) \cdot d\hat{\sigma}_{\mathrm{PRA}}, \tag{1}$$

where $t_{1,2} = -\mathbf{q}_{T1,2}^2$ – squared transverse momenta of initial-state reggeized gluons, $d\hat{\sigma}_{\rm PRA}$ is a differential cross section, which contains a partonic probability density $\overline{|\mathcal{A}_{\rm PRA}|^2}$ calculated in the PRA. $\mathcal{A}_{\rm PRA}$ is an amplitude with initial-state gluons, which are, actually, off-shell ($q_{1,2}^2 = -t_{1,2} < 0$), but nevertheless the amplitude *is gauge-invariant* because initial-state gluons are treated as Reggeized ones ($\mathcal{R}$). It is calculated using the Gauge Invariant Effective Field Theory(EFT) for Multi-Regge processes in QCD [3], the Feynman rules of the EFT can be found in Ref. [5].

For the calculations of observables at relatively low pp center-of-mass energies, the normalization condition

$$\int\limits_0^{\mu^2} dt\ \Phi_i(x,t,\mu^2) = x f_i(x,\mu^2), \tag{2}$$

for the unPDF becomes a particularly important constraint, ensuring the consistency with calculations in Collinear Parton Model at highest values of p_T. In Ref. [6] (Eqns. 12-13) we have proposed a version of “integral formula” for KMR unPDFs, which ensures constraint (2) exactly. We will use the unPDFs obtained in this way from MSTW-2008 PDFs [7] in the numerical calculations performed in the present paper.

2.2. Short- and long-distance matrix elements of charmonium production

Due to sufficiently large masses of charmonium states under study applying of NRQCD factorization model [8] is acceptable. In the NRQCD a cross section of quarkonia production is factorized to short- and long-distance matrix elements (LDMEs). The first ones can be obtained in the form of perturbative series in α_s and v – relative velocity of final heavy quarks. But LDMEs describes non-perturbative transitions of heavy quark pair into quarkonia, thus it must be extracted from data.

For the short-distance matrix elements at the quark level we consider following PRA subprocesses:

$$\mathcal{R} + \mathcal{R} \ \rightarrow\ c\bar{c}[^1S_0^{(8)}, ^3S_1^{(8)}, ^3P_J^{(1)}, ^3P_J^{(8)}], \tag{3}$$

$$\mathcal{R} + \mathcal{R} \ \rightarrow\ c\bar{c}[^3S_1^{(1)}] + g, \tag{4}$$

Amplitudes with $c\bar{c}$ Fock state $^{2S+1}L_J^{(1,8)}$ with the spin S, total angular momentum J, orbital angular momentum L in the singlet (1) or in the octet (8) color state we obtained applying projectors on spin-singlet or spin-triplet state and projectors on color-singlet or color-octet state to an amplitude of $c\bar{c}$-pair production [9, 10].

3. Results and discussion

Since in our predictions we use modified unPDFs, we have performed a new fit of LDMEs, see Tab. 1.

To extract LDMEs we used data of CDF [12,13], CMS [14] and ATLAS [15,16] collaborations. We should note, that CDF data [12,13], include region of small transverse momenta $p_T \leq 2m_c$. In this region, PRA prediction is well-defined, unlike predictions in NLO of CPM, and allows us to distinguish contributions of LDMEs $\langle \mathcal{O}^{J/\psi}[^1S_0^{(8)}]\rangle$ and $\langle \mathcal{O}^{J/\psi}[^3P_0^{(8)}]\rangle$ and also LDMEs $\langle \mathcal{O}^{\psi'}[^1S_0^{(8)}]\rangle$ and $\langle \mathcal{O}^{\psi'}[^3P_0^{(8)}]\rangle$.

We provide our predictions for the kinematical region of the NICA collider, namely $\sqrt{S}$ = 24 GeV, $0 < p_{T\psi} < 10$ GeV and $|y_\psi| < 3.0$. In our analysis we consider both direct and feed-down decay contributions of ψ', χ_{cJ} to the J/ψ production (as in NLO CPM calculation [11]).

Table 1. LDMEs for J/ψ, ψ' and χ_{cJ} using KMR unPDFs with exact normalization in comparison with NLO CPM fit [11].

LDME	Fit within the LO of PRA	Fit within the NLO CPM [11]
$\langle\mathcal{O}^{J/\psi}[^3S_1^{(1)}]\rangle \times \text{GeV}^{-3}$	1.30	1.32
$\langle\mathcal{O}^{J/\psi}[^3S_1^{(8)}]\rangle \times 10^3\ \text{GeV}^{-3}$	1.63±0.02	1.68±0.46
$\langle\mathcal{O}^{J/\psi}[^1S_0^{(8)}]\rangle \times 10^3\ \text{GeV}^{-3}$	0.±0.99	30.4±3.5
$\langle\mathcal{O}^{J/\psi}[^3P_0^{(8)}]\rangle \times 10^2\ \text{GeV}^{-5}$	1.54±0.03	−0.908±0.161
$\langle\mathcal{O}^{\psi'}[^3S_1^{(1)}]\rangle \times 10\ \text{GeV}^{-3}$	6.5	7.6
$\langle\mathcal{O}^{\psi'}[^3S_1^{(8)}]\rangle \times 10^3\ \text{GeV}^{-3}$	1.06±0.05	2.80±0.49
$\langle\mathcal{O}^{\psi'}[^1S_0^{(8)}]\rangle \times 10^3\ \text{GeV}^{-3}$	0.±0.83	−2.47±3.70
$\langle\mathcal{O}^{\psi'}[^3P_0^{(8)}]\rangle \times 10^2\ \text{GeV}^{-5}$	1.21±0.04	0.168±0.185
$\langle\mathcal{O}^{\chi_{c0}}[^3P_0^{(1)}]\rangle \times 10^2\ \text{GeV}^{-5}$	8.9	10.7
$\langle\mathcal{O}^{\chi_{c0}}[^3S_1^{(8)}]\rangle \times 10^4\ \text{GeV}^{-3}$	2.81±0.23	22.0±10.0
$\chi^2/d.o.f.$	1.32	

In the present study we concentrate on the p_T-distribution $d\sigma/dp_T$ and the polarization parameter λ_θ, which is defined as follows:

$$\lambda_\theta(p_T) = \frac{\sigma_T - 2\sigma_L}{\sigma_T + 2\sigma_L} = \frac{\sigma - 3\sigma_L}{\sigma + \sigma_L}, \tag{5}$$

where σ_T and σ_L are cross-sections of production of quarkonium with transverse or longitudinal polarization in the s-channel helicity frame, respectively.

The renormalization and factorization scales are set to be $\mu_R = \mu_F = \xi_{R,F}\sqrt{M_{\psi T}^2 + p_{\psi T}^2}$, where $\xi = 1$ for the central values of our predictions. We vary $1/2 < \xi_{R,F} < 2$ independently for each scale and take maximal total deviations from central value of the cross section to estimate theoretical uncertainties (green bands on our plots).

As we can see on the left panel of Fig. 1, predictions for p_T-distribution of charmonium production within LO PRA are in good agreement with predictions of NLO CPM for $p_T > 2$ GeV, while at small p_T NLO CPM predictions are inapplicable due to large double-logarithmic corrections $\sim \left(\log^2 p_T/(2m_c)\right)$ which are resummed in unPDFs of PRA in Leading Logarithmic Approximation.

From right panel of Fig. 1 one can see, that predictions of polarization parameter $\lambda_\theta(p_T)$ in NLO CPM and in LO PRA are quite different, mostly due to different values of LDMEs coming form the fit (see Tab. 1).

Of course, at the energies of the NICA collider it is necessary to include not only gluon initial evolution contribution, but also quark ones. That task will be a part of our future work.

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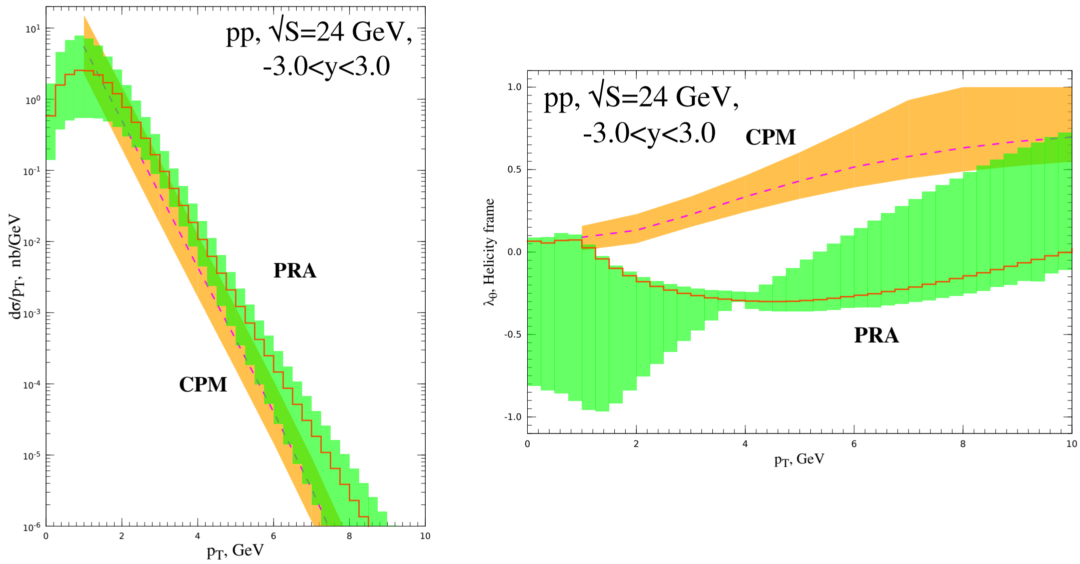

Figure 1. p_T-spectrum (left panel) and λ_θ polarization parameter (right panel) of J/ψ production in pp-collisions within NLO CPM [11] (magenta dashed line) and LO PRA (red solid line).

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