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PHYSICS OF ELEMENTARY PARTICLES AND ATOMIC NUCLEI. THEORY

Small-p_T Production of Polarised J/ψ Mesons within the Soft Gluon Resummation Approach

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Abstract—In this work we use the Soft Gluon Resummation approach as a noncollinear factorization model to describe polarisation of J/ψ within NRQCD as a hadronization model. We extract nonperturbative LDME for octet color states of charmonium by fitting them to unpolarised J/ψ production data of PHENIX and STAR collaborations at $\sqrt{s} = 200$ GeV. We make prediction for an angular coefficient λ as a polarisation indicator for J/ψ in the helicity frame and compare it with the PHENIX polarisation data.

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INTRODUCTION

One of the main tasks of the future experimental program of SPD NICA is studying of J/ψ production in proton–proton collisions at the energy up to $\sqrt{s} = 27$ GeV [1]. Mainly J/ψ mesons are produced in gluon–gluon fusion subprocesses that allows to get information on gluon parton distribution functions (PDF) of a proton. We try to describe prompt J/ψ production at small transverse momenta p_T of charmonium within the TMD (Transverse Momentum Dependent) factorization using the Soft Gluon Resummation (SGR) approach. The standard way to apply a factorization model with the NRQCD framework is to fit nonperturbative parameters of NRQCD to unpolarised J/ψ data and further to test them with J/ψ polarisation data. We've done that for PHENIX and STAR experimental data at the $\sqrt{s} = 200$ GeV, and then we've used these parameters to provide estimations for J/ψ polarisation for PHENIX.

SOFT GLUON RESUMMATION APPROACH

The general factorization approach for description of particle production at the $p_T \ll Q$ (where Q is a hard scale of the process, for heavy quarkonium being equal to a mass of the final state M) in hadron collisions is the TMD factorization [2]. Similarly to collinear parton model, the TMD prescribes the final state cross section to be represented as a convolution of a partonic subprocess cross-section and PDFs. The TMD PDFs are distributions of initial partons by their momentum, including transverse components, and their evolution obeys Collins–Soper equations [3].

There are various ways to express TMD PDF and to experimentally extract them further, one of them is the Soft Gluon Resummation approach [4, 5]. Within the TMD the initial partons' momenta are $q_i^\mu = x_i p_i^\mu + q_{iT}^\mu$ with longitudinal momentum fractions x_i, protons' momenta p_i and transverse components $q_{iT}^2 = -\mathbf{q}_{\mathbf{iT}}^2$. Corrections of order $(\mathbf{q}_{\mathbf{iT}}^2/M^2)$ are neglected so that the initial partons are on-shell, $q_i^2 = 0$.

The SGR factorization formula reproduces the general TMD expression for small transverse momentum production [3]:

$$d\sigma = \int dx_1 dx_2 d\mathbf{q}_{\mathbf{1T}} d\mathbf{q}_{\mathbf{2T}} \times F(x_1, \mathbf{q}_{\mathbf{1T}}, \mu, \zeta_1) F(x_2, \mathbf{q}_{\mathbf{2T}}, \mu, \zeta_2) d\hat{\sigma}, \tag{1}$$

with $F(x, \mathbf{q}_\mathbf{T}, \mu, \zeta)$ as TMD PDF and $d\hat{\sigma}$ as a hard-scale cross section of a partonic subprocess $2 \to 1$ which are leading order (LO) contributions with respect to α_s. The scale evolution of TMD PDF can be factorized in a Fourier-conjugated space of impact parameter $\mathbf{b}_\mathbf{T}$ with the Sudakov perturbative factor S_P [6] which considers one soft gluon emission in leading logarithmic (LL) and LO approximation. The transverse motion of partons is expressed with a nonperturbative factor S_{NP} which is only phenomenological for now, so we take it in the form $S_{NP}(Q, b_T) = (A \ln Q + B) b_T^2$ for initial quarks [7] and change color factor to apply it to gluons [8]. SGR

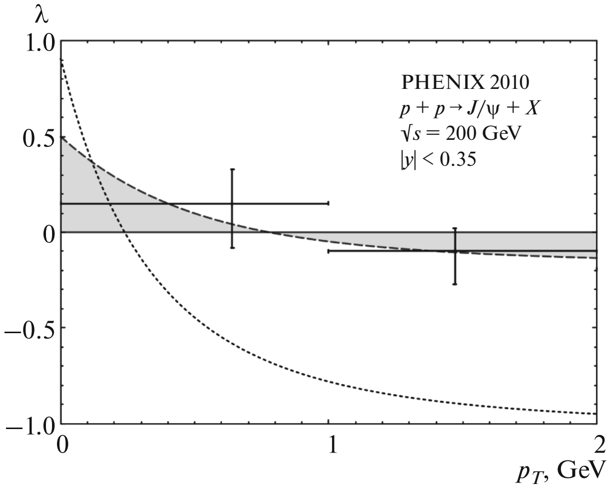

Fig. 1. Angular coefficient λ versus transverse momentum p_T of J/ψ for PHENIX. Solid line—polarisation from $J/\psi\left[{}^1S_0^{(8)}\right]$ only, dashed line—from $J/\psi\left[{}^3P_0^{(8)}\right]$ and $J/\psi\left[{}^3P_2^{(8)}\right]$, shaded area—from direct J/ψ production, dotted line—from feed-down of χ_{cJ} states. Experimental data was taken from [13].

PDFs are expressed in terms of collinear PDF at the initial scale:

$$\hat{F}(x, b_T) = f(x, \mu_b') + \mathcal{O}(\alpha_s) + \mathcal{O}(b_T \Lambda\, QCD). \quad (2)$$

Besides, the scale prescription $\mu_{b'} = Qb_0/(Qb_T + b_0)$ followed by cutting off large b_T with $b_T \to b_T^*(b_T) = b_T\Big/\sqrt{1 + (b_T/b_{T,\max})^2}$ should be made for relevance of SGR PDF evolution [3]. The final expression for cross section can be written as follows

$$\frac{d^2\sigma}{dp_T dy} = \frac{\pi p_T \overline{|\mathcal{M}(2 \to 1)|^2}}{M^2 s} \times \int_0^\infty db_T\, b_T\, J_0(p_T b_T)\, e^{-S_P} e^{-S_{NP}}\, \hat{F}_1 \hat{F}_2, \quad (3)$$

with a rapidity y of charmonium, a center-of-mass energy $\sqrt{s}$, a Bessel function of the first kind and zeroth order J_0, the Fourier-transformed parton distributions $\hat{F}_i \equiv \hat{F}_i(x_i, b_T^*)$ and an amplitude $\mathcal{M}$ of a hard partonic subprocces.

HADRONISATION MODEL

We use the Nonrelativistic QCD (NRQCD) to describe hadronization of a produced heavy $c\bar{c}$-quark pair into an observable charmonium state $\mathcal{C}$ [9]. The NRQCD allows us to expand J/ψ wave function into Fock state series with respect to the relative velocity of the constituent quarks υ (for charmonium $\upsilon^2 \approx 0.3$). Within the NRQCD approach the cross section of the final state production is factorized into cross section of the quark pair production in some Fock state and a corresponding long-distance matrix element (LDME) which refers to hadronization of the produced quark pair:

$$d\hat{\sigma}(a + b \to \mathcal{C} + X) = \sum_n d\hat{\sigma}(a + b \to c\bar{c}[n] + X)\langle \mathcal{O}^{\mathcal{C}}[n]\rangle \big/ (N_{col} N_{pol}), \quad (4)$$

with N_{col} and N_{pol} for averaging over polarisation and color states. The quark pair cross section is calculated within the perturbative QCD by projecting quark pair amplitude onto states with corresponding momentum, spin and color quantum numbers. The LDME for singlet color states can be calculated with solving the Schroedinger equation with heavy quarkonium potential. By contrast with them, the octet states LDMEs have to be extracted directly from experimental data.

The following charmonium states produced in $2 \to 1$ subprocesses are relevant for the TMD factorization: ${}^1S_0^{(8)}$, ${}^3P_{0,2}^{(8)}$, ${}^3S_1^{(8)}$ for J/ψ and ${}^3P_{0,2}^{(1)}$, ${}^3S_1^{(8)}$ for χ_{cJ}.

CALCULATION RESULTS

Firstly, we've extracted the octet LDME for charmonium states named above by fitting them to unpolarised J/ψ production data of PHENIX [10, 11] (2012, 2007) and STAR [12] (2018) collaborations at $\sqrt{s} = 200$ GeV in the domain of $0 < p_T < 1$ GeV where the TMD factorization is applicable. The data for both central and mid-rapidity regions was considered.

Because some of contributions have identical p_T-dependence, their LDMEs can't be independently extracted from the data by fitting. That's why linear combination of them is formed as it was done here for J/ψ states: $M_7^{J/\psi} = \langle \mathcal{O}^{J/\psi}[{}^1S_0^{(8)}]\rangle + 7/m_c^2 \langle \mathcal{O}^{J/\psi}[{}^3P_0^{(8)}]\rangle$ with a charmed quark mass m_c.

Our fitting results are $M_7^{J/\psi} = (1.06 \pm 0.04) \times 10^{-1}$ GeV^3, $\langle \mathcal{O}^{J/\psi}[{}^3S_1^{(8)}]\rangle = (0.00 \pm 1.07) \times 10^{-3}$ GeV^3, $\langle \mathcal{O}^{\chi_{c0}}[{}^3S_1^{(8)}]\rangle = (0.00 \pm 1.20) \times 10^{-3}$ GeV^3, χ^2/d.o.f. = 0.41. LDME for sinlget color state that was used in calculations is $\langle \mathcal{O}^{\chi_{c0}}[{}^3P_0^{(1)}]\rangle = (8.9 \pm 1.3) \times 10^{-2}$ GeV^5. Besides, the heavy quark spin symmetry relations were used for LDMEs of the states with different total momenta J.

Zero values of some fitted LDME warn that the current fit can't be considered as full and rigorous. An obvious and important problem is a quite narrow p_T interval for fitting where we lack experimental data for distinguishing different contributions. The ${}^1S_0^{(8)}$ and

${}^3P_0^{(8)}$ contributions should dominate due to the NRQCD scaling rules, so it is enough of them only to describe the data. Despite on this problem, we still make estimation for J/ψ polarisation as the neglected contributions can be just small deviations to the dominant ${}^1S_0^{(8)}$ and ${}^3P_J^{(8)}$ polarisation yields. We calculate polarisation in the helicity frame as an angular coefficient $\lambda = (d\sigma_T - 2d\sigma_L)/(d\sigma_T + 2d\sigma_L)$ where subscripts refer to cross sections of transversely and longitudinally polarised charmonia. Results of the polarisation calculation for PHENIX are shown on the Fig. 1. We only have the linear combination of LDME for J/ψ so the polarisation of directly produced J/ψ lies somewhere in shaded area which agrees with the experimental data.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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