

Polarization variables in inclusive J/ψ production at HERA in the k_t-factorization approach

S. P. Baranov[1)]

P.N. Lebedev Institute of Physics RAS, 119991 Moscow, Russia

Submitted 1 September 2008

In the framework of k_t-factorization approach, the process of inclusive photoproduction of J/ψ mesons at HERA conditions is considered. The spin density matrix elements are calculated, and the predictions are compared with recent experimental data.

PACS: 12.38.Bx, 13.85.Ni, 14.40.Gx

1. Introduction. Polarization of quarkonium states produced in hadron-hadron and lepton-hadron collisions at high energies is known to play important role in understanding the interaction dynamics. In particular, the polarization observables are thought to be useful in discriminating the color singlet and color octet production mechanisms, as well as collinear and k_t-factorization approaches.

In general, the spin density matrix of a vector particle (such as the J/ψ and Υ mesons) depends on three papameters that can be measured experimentally by observing the double differential angular distribution of the decay products. The latter reads for the leptonic decay $J/\psi \to l^+l^-$ [1]

$$\frac{d\sigma}{d\cos\theta\; d\phi} \propto 1 + \lambda \cos^2\theta + \mu \sin 2\theta \cos\phi + \frac{\nu}{2} \sin^2\theta \cos 2\phi \quad (1)$$

with θ and ϕ being the polar and azimuthal angles of the decay lepton measured in the J/ψ rest frame. Up to now, a sizeable literature devoted to this subject has been accumulated on both theoretical and experimental sides. However, most of the papers are only concentrated on the parameter λ, while the parameters μ and ν have acquired rather negligible attention, if any.

Writing this note is motivated by the new experimental data on the parameters λ and ν, recently reported by the ZEUS collaboration [2] at HERA. The goal of the present study is to give an immediate reply and derive theoretical predictions on the parameters λ, μ, and ν in the k_t-factorization approach. The calculation of μ and ν in the k_t-factorization approach has never been done before and is presented here for the first time.

1)e-mail: baranov@sci.lebedev.ru

2. Theoretical framework. In the present analysis we strictly follow the approach described in detail in the earlier publication [3]. For the reader's convenience, we only briefly recall here the corner-stones of the theoretical scheme.

The production of J/ψ mesons is considered in the framework of perturbative QCD and nonrelativistic bound state formalism [4]. Only the color singlet contribution is taken into account, as the experimental data on the differential cross sections show no need in the color-octet mechanism, at least as far as the ep interactions are concerned [5 – 7]. The calculation is based on the off-shell photon-gluon fusion subprocess; the corresponding Feynman diagram is displayed in Fig.1.

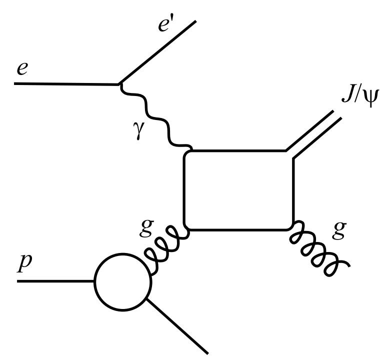

Fig.1. Feynman diagram representing the inclusive production of J/ψ meson via the color singlet photon-gluon fusion mechanism

The spin projection operator [4] $J(\epsilon_\psi) = \widehat{\epsilon_\psi}(\widehat{p_c} + m_c)/\sqrt{m_\psi}$ included in the partonic subprocess amplitudes guarantees the proper quantum numbers of the created $c\bar{c}$ pair, $J^{PC} = 1^{--}$. In accordance with the nonrelativistic approximation, the charmed quarks are assumed to each carry one half of the J/ψ momentum, $p_c = p_{\bar{c}} = p_\psi/2$, $m_c = m_\psi/2$, and the J/ψ formation probability is determined by a single parameter, the value of wave function at the origin of coordinate space $|\Psi(0)|^2$, which is known from the J/ψ leptonic decay width [8].

When calculating the spin average of the matrix element squared, we substitute the full lepton tensor for the photon polarization matrix:

$$\overline{\epsilon_1^\mu \epsilon_1^{*\nu}} = [4p_e^\mu p_e^\nu - 2(p_e k_\gamma) g^{\mu\nu}]/(k_\gamma)^2, \quad (2)$$

where p_e is the initial electron momentum and k_γ the photon momentum.

The form of the gluon spin density matrix is different depending on whether the gluon is on shell (as is assumed in the conventional parton model) or off shell (in the k_t-factorization approach). For the general case, we adopt the k_t-factorization prescription [9 – 11]

$$\overline{\epsilon_g^\mu \epsilon_g^{*\nu}} = p_p^\mu p_p^\nu x_g^2/|k_{gT}|^2 = k_{gT}^\mu k_{gT}^\nu/|k_{gT}|^2, \quad (3)$$

where p_p is the initial proton momentum, x_g the gluon momentum fraction, and k_{gT} the component of the gluon momentum perpendicular to the beam axis. In the collinear limit, when $k_T \to 0$, this expression converges to the ordinary $\overline{\epsilon_g^\mu \epsilon_g^{*\nu}} = \frac{1}{2} g^{\mu\nu}$.

The outgoing gluon is assumed on-shell.

The only innovation made in the present study in comparison with [3] is in including the J/ψ decay step. Here, the spin density matrix of J/ψ meson is determined by the momenta l_1 and l_2 of the decay leptons and is taken in the form

$$\epsilon_\psi^\mu \epsilon_\psi^{*\nu} = 3(l_1^\mu l_2^\nu + l_2^\mu l_1^\nu - 2m_\psi^2 g^{\mu\nu})/m_\psi^2. \quad (4)$$

This expression is equivalent to the usual $\epsilon_\psi^\mu \epsilon_\psi^{*\nu} = -g^{\mu\nu} + p_\psi^\mu p_\psi^\nu/m_\psi^2$, but is better suited for our case because it gives access to the kinematic variables describing the orientation of the decay plane.

Let s be the total invariant energy squared, $s = (p_e + p_p)^2$; $k_{\gamma T}$, k_{gT}, ϕ_γ, and ϕ_g the transverse momenta and azimuthal angles of the initial (off shell) photon and gluon; and y_ψ, y_3, and ϕ_ψ the rapidities and the azimuthal angle of J/ψ meson and the accompanying gluon, respectively. Then, the fully differential cross section reads:

$$d\sigma(ep \to e'\psi X) = \frac{\alpha_s^2 \alpha^2 e_c^2 \, |\Psi(0)|^2}{16\pi s^2} \times \\ \times \frac{1}{4} \sum_{\text{spins}} \frac{1}{8} \sum_{\text{colors}} |\mathcal{M}(\gamma g \to \psi g)|^2 \times \\ \times \mathcal{F}(x_g, k_{gT}^2, \mu^2) \; dk_{\gamma T}^2 \, dk_{gT}^2 \, dp_{\psi T}^2 \times \\ \times dy_3 \, dy_\psi \, \frac{d\phi_\gamma}{2\pi} \, \frac{d\phi_g}{2\pi} \, \frac{d\phi_\psi}{2\pi}. \quad (5)$$

In order to estimate the degree of theoretical uncertainty connected with the choice of unintegrated gluon density $\mathcal{F}(x, k_T^2, \mu^2)$, we use two different parametrizations, which are known to show the largest difference with each other; namely, the ones proposed in Refs. [9] and [12].

In the first case [9], the unintegrated gluon density is derived from the ordinary (collinear) density $G(x, \mu^2)$ by differentiating it with respect to μ^2 and setting $\mu^2 = k_T^2$. In the approach of [12], the unintegrated density is calculated as the convolution of the ordinary gluon density with some universal weight factor. It represents a solution to the leading order BFKL equation [13] obtained in the double-logarithm approximation. In both cases we use the leading order Glück-Reya-Vogt (LO GRV) set [14] as the input collinear density. Hereafter, these two parametrizations will be referred to as 'dGRV' and 'JB', respectively. For comparison, the LO GRV set will also be used to show the predictions of collinear parton model.

3. Numerical results The experimental data [2] have been collected from the following kinematic region: photon virtuality $Q^2 < 1\,\text{GeV}^2$; photon-proton total energy $50\,\text{GeV} < W < 180\,\text{GeV}$; J/ψ transverse momentum $1\,\text{GeV} < p_{\psi T} < 10\,\text{GeV}$; elasticity parameter $z = (p_\psi p_p)/(k_\gamma p_p)$, $0.4 < z < 0.9$. The angular analysis has been performed in the target frame, i.e., in the J/ψ rest frame with the reference axis z pointing in the direction of the initial proton momentum $-p_p$.

Our theoretical consideration was adjusted to the experimental binning and generally followed the experimental procedure. We have collected the simulated events in the specified bins of $p_{\psi T}$ and z, generated the decay lepton angular distributions according to the production and decay matrix elements, and then applied a three-parametric fit based on the formula (1)[2)].

The estimated values of λ, μ, and ν are shown in Fig.2. The results of our collinear calculations are fully consistent with the ones presented in Ref. [1]. The difference between the collinear and k_t-factorization approaches is clearly seen in the behavior of the parameter λ (which becomes negative at large p_t in the k_t-factorization), the parameter μ (wich stays positive) and the parameter ν (which, on the contrary, stays negative in the k_t-factorization). Consequently, not only the parameter λ but also the parameters μ and ν can be regarded as essential touchstones checking the J/ψ production mechanism and parton interaction dynamics.

[2)] The experimental statistics was insufficient to encourage the extraction of parameter μ from the double differential distribution (1), and so, the analysis was rather based on the single differential distributions $d\sigma/d\cos\theta \propto 1+\lambda\cos^2\theta$ and $d\sigma/d\phi \propto 3+\lambda+\nu\cos 2\phi$ yielding the parameters λ and ν.

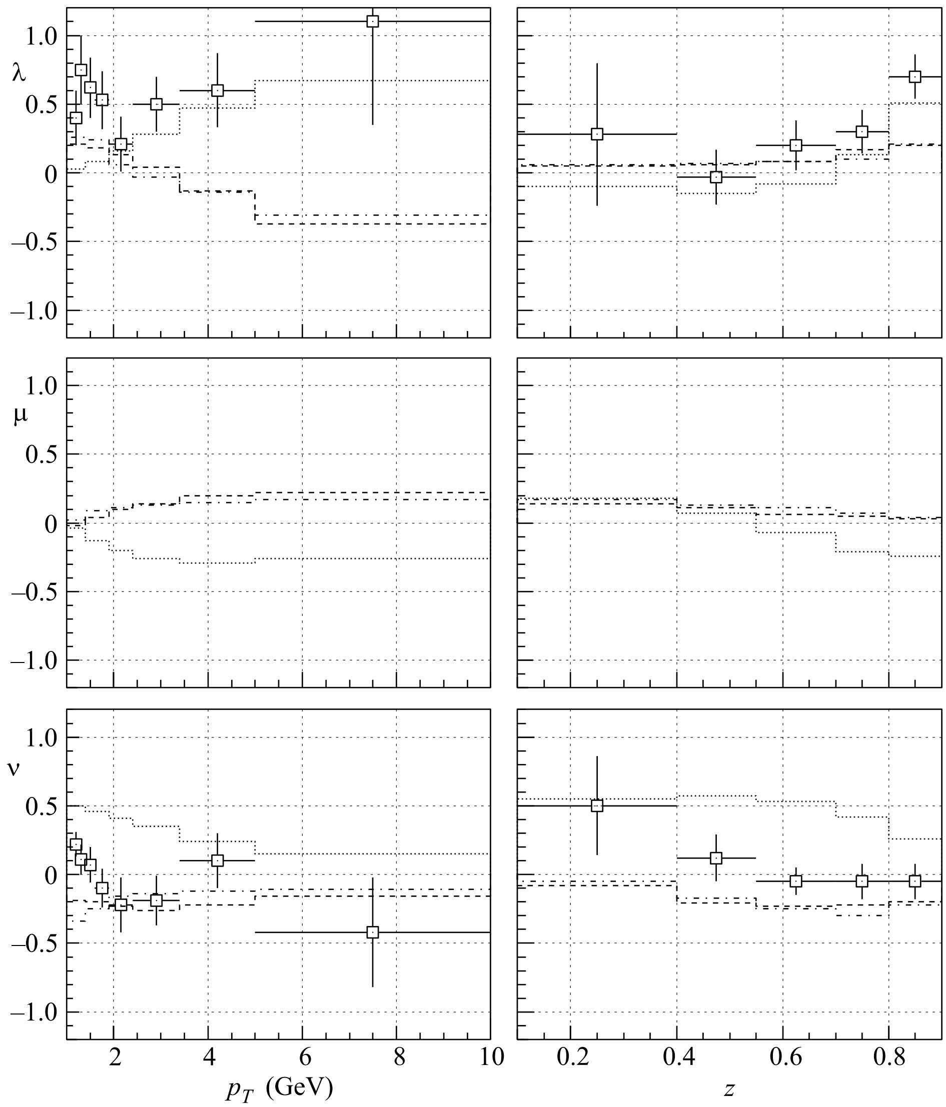

Fig.2. Polarization parameters λ (upper row), μ (middle row), and ν (lower row) as functions of the J/ψ transverse momentum $p_{\psi T}$ (left column) and inelasticity z (right column). Dotted histograms, predictions of the LO color singlet collinear parton model with GRV [14] gluon density; dashsed and dash-dotted histograms, predictions of the k_t-factorization approach with dGRV [9] and JB [12] gluon densities, respectively; □ – experimental data [2]

However, the agreement with the newly collected experimental data remains though acceptable, but still poor, and the comparison between the data and theoretical calculations is yet inconclusive, giving preference to neither collinear nor k_t-factorization approach.

This work was supported by the Russian Foundation for Basic Research under grant 08-02-00896 and by DESY Directorate in the framework of Moscow-DESY project on Monte-Carlo implementation for HERA-LHC.

1. M. Beneke, M. Kramer, and M. Vänttinen, Phys. Rev. D **57**, 4258 (1998).
2. ZEUS Collaboration, A. Bertolin, in: *5th International Workshop on Heavy Quarkonia*, Hamburg, October 2007; R. Brugnera, in: *XVI International Workshop on Deep Inelastic Scattering*, London, April 2008.
3. S. P. Baranov, Phys. Lett. B **428**, 377 (1998).
4. C.-H. Chang, Nucl. Phys. B **172**, 425 (1980); R. Baier and R. Rückl, Phys. Lett. B 102, 364 (1981); E. L. Berger and D. Jones, Phys. Rev. D **23**, 1521(1981); H. Krasemann, Z. Phys. C **1**, 189 (1979); G. Guberina, J. Kühn, R. Peccei, and R. Rückl, Nucl. Phys. B **174**, 317 (1980).
5. M. Krämer, Nucl. Phys. B **459**, 3 (1996).
6. S. P. Baranov and N. P. Zotov, J. Phys. G **29**, 1395 (2003); A. V. Lipatov and N. P. Zotov, Eur. Phys. J. C **27**, 87 (2003).

7. ZEUS Collaboration, S. Chekanov, M. Derrick, S. Magill et al., Eur. Phys. J. C **44**, 13 (2005).
8. Particle Data Group, W.-M. Yao, C. Amsler, D. Asner et al., J. Phys. G **33**, 1 (2006).
9. L. Gribov, E. Levin, and M. Ryskin, Phys. Rep. **100**, 1 (1983); E. Levin and M. Ryskin, Phys. Rep. **189**, 268 (1990).
10. S. Catani, M. Ciafaloni, and F. Hautmann, Phys. Lett. B **242**, 97 (1990); Nucl. Phys. B **366**, 135 (1991).
11. J. C. Collins and R. K. Ellis, Nucl. Phys. B **360**, 3 (1991).
12. J. Blümlein, J. Phys. G **19**, 1623 (1993); DESY 95-121 (1995).
13. E. A. Kuraev, L. N. Lipatov, and V. S. Fadin, Sov. Phys. JETP **45**, 199 (1977); Ya. Balitsky and L. N. Lipatov, Sov. J. Nucl. Phys. **28**, 822 (1978).
14. M. Glück, E. Reya, and A. Vogt, Eur. Phys. J. C **5**, 461 (1998).