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Correlations in J/ψ pair production as SPS versus DPS discriminators

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We focus on the problem of disentangling the single (SPS) and double (DPS) parton scattering modes in the production of J/ψ pairs at the LHC conditions. Our analysis is based on comparing the shapes of the differential cross sections and on studying their behavior under imposing kinematical cuts. On the SPS side, we consider the leading-order $\mathcal{O}(\alpha_s^4)$ contribution with radiative corrections (taken into account in the framework of the k_t-factorization approach) and the subleading $\mathcal{O}(\alpha_s^6)$ contribution from pseudo-diffractive gluon-gluon scattering represented by one gluon exchange and two gluon exchange mechanisms. We come to the conclusion that disentangling the SPS and DPS modes is rather difficult on the basis of azimuthal correlations, while the rapidity difference looks more promising, provided the acceptance of the experimental detectors has enough rapidity coverage.

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1. Introduction

In the last years, the production of J/ψ pairs has attracted a significant renewal attention in the context of searches for double parton scattering processes [1]. A number of discussions has been stimulated by the recent measurement [2] of the double J/ψ production cross section at the LHCb experiment at CERN. Theoretical estimates based on both collinear [3, 4, 5] and k_t-factorization [6] approaches show that the single (SPS) and double (DPS) parton scattering contributions are comparable in size and, taken together, can perfectly describe the measured cross section.

To disentangle the SPS and DPS mechanisms one needs to clearly understand the production kinematics. Naive expectations that the SPS mechanism should result in the back-to-back event configuration received no support from the later calculations. Including the initial state radiation effects ([5, 7]) washes out the original azimuthal correlations, thus making the SPS and DPS samples very similar to each other. One cannot exclude, however, that the situation may change under imposing certain cuts on the J/ψ transverse momenta. On the other hand, it has been suggested [5, 8] that the DPS production is characterized by a much larger rapidity difference between the two J/ψ mesons. The goal of the present study is to carefully examine the J/ψ pair production properties in the different kinematical domains paying attention to the different contributing processes.

2. Theoretical framework

2.1 SPS contributions

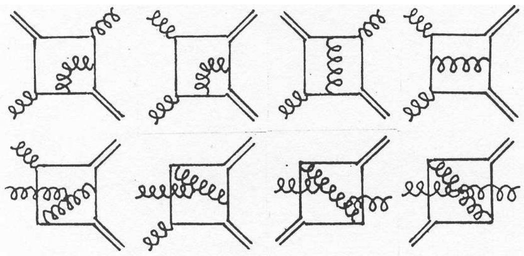

Figure 1: Examples of Feynman diagrams representing the leading-order gluon-gluon fusion subprocess $gg \to J/\psi J/\psi$.

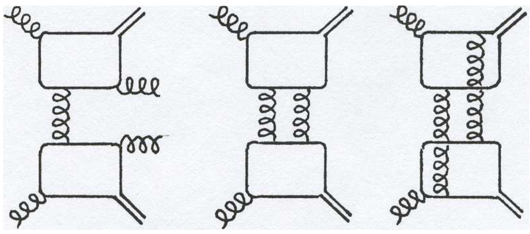

Figure 2: Examples of Feynman diagrams representing the production of J/ψ pairs in pseudo-diffractive gluon-gluon scattering.

At the leading order, $\mathscr{O}(\alpha_s^4)$, the SPS subprocess $g+g \to J/\psi + J/\psi$ is represented by a set of 31 "box" diagrams, with some examples displayed in Fig. 1. Our approach is based on perturbative QCD, nonrelativistic bound state formalism, and the k_t-factorization ansatz [9, 10, 11] in the parton model. The calculation of this subprocess is identical to that described in Ref. [7]. We have carefully checked that our present results are consistent with earlier calculations made in the collinear limit [13, 14]. Using the k_t-factorization approach we go beyond the Leading-Order approximations by including the initial state radiation corrections in the form of evolution of gluon densities. Numerical results shown in the next section have been obtained using the $A0$ gluon distribution from Ref. [15].

In addition to the above, we also consider the pseudo-diffractive gluon-gluon scattering subprocesses of Fig. 2. Despite the latter are of formally higher order in α_s, they contribute to the events with large rapidity difference between J/ψ mesons and in that region can take over the leading-order 'box' subprocess. Our processes differ from the true diffraction in the sense that there occurs color exchange, and so, the rapidity interval between the two J/ψ 's may be filled up with lighter hadrons (thus showing no gap in the overall hadron density). Among the variety of higher-order contributions, the pseudo-diffractive subprocesses are of our special interest as they potentially can mimic the DPS mechanism having very similar kinematics. The evaluation of the one-gluon exchange diagrams $g(k_1)+g(k_2) \to J/\psi(p_1)+J/\psi(p_2)+g(k_3)+g(k_4)$ has also been performed in the k_t-factorization approach.

The two gluon exchange mechanism $g{+}g{\to}J/\psi{+}J/\psi$ has been previously considered in Ref. [16], where it was reduced to the production of J/ψ pairs in photon-photon collisions [17] by recalculating the appropriate color factor. We basically follow the same way in our present analysis, but use an updated gluon density [18]. The corresponding amplitude can be cast into the impact-factor representation [17]:

$$A(g_{\lambda_1}g_{\lambda_2} \to V_{\lambda_3}V_{\lambda_4};s,t) = is\int d^2\kappa\, \frac{\mathscr{J}(g_{\lambda_1}{\to}V_{\lambda_3};\kappa,q)\, \mathscr{J}(g_{\lambda_2}{\to}V_{\lambda_4};-\kappa,-q)}{[(\kappa+q/2)^2+\mu_G^2][(\kappa-q/2)^2+\mu_G^2]}, \tag{2.1}$$

and the cross section reads

$$\frac{d\sigma(gg{\to}VV;s)}{dt} = \frac{\mathscr{N}_c}{64\pi s^2}\sum_{\lambda_i}\left|A(g_{\lambda_1}g_{\lambda_2}{\to}V_{\lambda_3}V_{\lambda_4};s,t)\right|^2. \tag{2.2}$$

The subscripts λ_i denote the gluons' and vector meson helicities, and q is the transverse momentum transfer, $t \approx -q^2$. The color structure of the reaction is described by the factor $\mathscr{N}_c = (N_c^2{-}4)^2/[16N_c^2(N_c^2{-}1)]$, where $N_c = 3$. The amplitude remains always finite as the impact factors $\mathscr{J}$ vanish when $\kappa \to \pm q/2$. At small t, within the diffraction cone, the cross section is dominated by the s-channel helicity conserving amplitude. Then, the explicit form of the impact factor is

$$\mathscr{J}(g_\lambda{\to}V_\tau;\kappa,q) = \delta_{\lambda,\tau}\sqrt{4\pi\alpha_s^3}\int \frac{\psi(z,k)I(z,k,q)}{z(1-z)(2\pi)^3}\,dzd^2k, \tag{2.3}$$

where $\psi(z,k)$ is the light-cone wave function of the vector meson and z is the light-cone momentum fraction carried by the heavy quark. Neglecting the intrinsic motion of the quarks we set $\psi(z,k) = C\,\delta(z-\frac{1}{2})\,\delta^{(2)}(k)$, where the normalizing constant C is adjusted to the J/ψ leptonic width and is related to the radial wave function at the origin as $C^2 = 12\pi^5/(N_c^2 m_\psi^3)|\mathscr{R}(0)|^2$. Within the above approximation, we have

$$I(z,k,q) = \frac{m_\psi}{2}\left[\frac{1}{\kappa^2+m_\psi^2/4} - \frac{4}{q^2+m_\psi^2}\right]. \tag{2.4}$$

The cross section of the two-gluon exchange contribution is calculated in the collinear approximation with MSTW2008(NLO) gluon distribution function [18] and the factorization scale $\mu_f^2 = m_t^2$, where m_t is the J/ψ transverse mass.

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2.2 DPS contributions

Under the hypothesis of having two independent hard partonic subprocesses A and B in a single pp collision, and under further assumption that the longitudinal and transverse components of generalized parton distributions factorize from each other, the inclusive DPS cross section reads

$$\sigma^{\rm AB}_{\rm DPS} = \frac{m}{2}\frac{\sigma^A_{\rm SPS}\sigma^B_{\rm SPS}}{\sigma_{\rm eff}}, \qquad \sigma_{\rm eff} = \left[\int d^2b\,\left(T(\mathbf{b})\right)^2\right]^{-1}, \tag{2.5}$$

where $T(\mathbf{b}) = \int f(\mathbf{b_1})\,f(\mathbf{b_1}{-}\mathbf{b})\,d^2b_1$ is the overlap function that characterizes the transverse area occupied by the interacting partons, and $f(\mathbf{b})$ is supposed to be a universal function of the impact parameter $\mathbf{b}$ for all kinds of partons with its normalization fixed as $\int f(\mathbf{b_1})\,f(\mathbf{b_1}{-}\mathbf{b})\,d^2b_1\,d^2b = \int T(\mathbf{b})\,d^2b = 1$. The inclusive SPS cross sections $\sigma^A_{\rm SPS}$ and $\sigma^B_{\rm SPS}$ for the individual partonic subrocesses A and B can be calculated in a usual way using the single parton distribution functions. The symmetry factor m equals to 1 for identical subprocesses and 2 for the differing ones. We restrict ourselves to this simple form (2.5) regarding it as the first estimate for the DPS contribution. The CDF [20] and D0 [21] measurements give $\sigma_{\rm eff} \simeq 15$ mb, that constitutes roughly 20% of the total (elastic + inelastic) $p\bar{p}$ cross section at the Tevatron energy.

For the inclusive SPS cross section $\sigma^{J/\psi}_{\rm SPS}$ we take into account both the direct channel $g{+}g \to J/\psi{+}g$ and the production of P-waves $g{+}g{\to}\chi_{cJ}$ followed by radiative transitions $\chi_{cJ}{\to}J/\psi{+}\gamma$. The calculation of the relevant Feynman diagrams is done in the k_t-factorization approach. The computational technique and the parameter setting are explained in every detail in Ref. [12].

3. Results and discussion

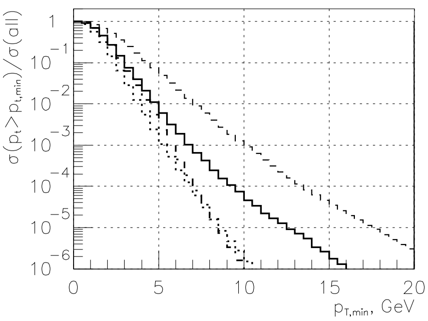

Figure 3: Fraction of the production cross section left after imposing cuts on the J/ψ transverse momentum. Dashed curve, SPS mode under requiring that one J/ψ meson has $p_T{>}p_{T,min}$; dash-dotted curve, the square of the dashed curve; solid curve, SPS mode with both J/ψ's having $p_T{>}p_{T,min}$; dotted curve, DPS mode with both J/ψ's having $p_T{>}p_{T,min}$.

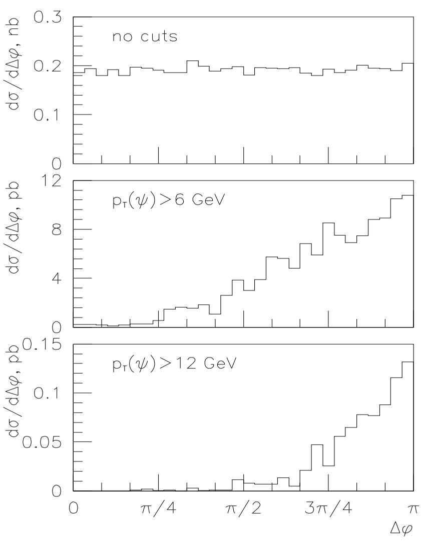

Figure 4: Azimuthal angle difference after imposing cuts on the J/ψ transverse momenta.

We start with discussing the role of kinematic restrictions on the J/ψ transverse momentum. Shown in Fig. 3 are the fractions of SPS events surviving after imposing cuts on $p_T(\psi)$. Dashed line corresponds to requiring $p_T(\psi) > p_{T,min}$ for only one (arbitrarily chosen) J/ψ meson with no restrictions on the other. Were the two J/ψ's produced independently, the probability of having $p_T(\psi) > p_{T,min}$ for the both J/ψ's simultaneously could be obtained by just squaring the single-cut probability (dash-dotted curve in Fig. 3). On the contrary, in the naive the back-to-back kinematics, a cut applied to any of the two J/ψ's would automatically mean the same restriction on the other, thus making no effect on the overall probability (dashed curve). The DPS production mode with cuts applied to both J/ψ mesons is represented by the dotted curve in Fig. 3. As one can see, this curve is rather close to that modeling the idealized independent SPS production.

The explicit calculation (solid curve) lies between the two idealistic extreme cases related to the fully independent (dash-dotted curve) and fully back-to-back correlated (dashed curve) production of J/ψ pairs. In the region $p_{T,min} < 4$ GeV the solid and dash-dotted curves almost coincide, thus showing that the two J/ψ's are nearly idependent. With stronger cuts on $p_T(\psi)$, the curves diverge showing that the production of J/ψ's becomes correlated.

Another illustration of this property is given by the azimuthal angle difference $d\sigma(\psi\psi)/d\Delta\varphi$ exhibited in Fig. 4. The distribution looks flat for the unrestricted phase space, but tends to concentrate around $\Delta\varphi \simeq \pi$ when the cuts on $p_T(\psi)$ become tighter. In principle, one could get rid of the SPS contribution by imposing cuts like $p_T(\psi) > 6$ GeV, $\Delta\varphi < \pi/4$, but the DPS cross section would then fall from tens of nanobarns to few picobarns making the measurements hardly feasible in practice.

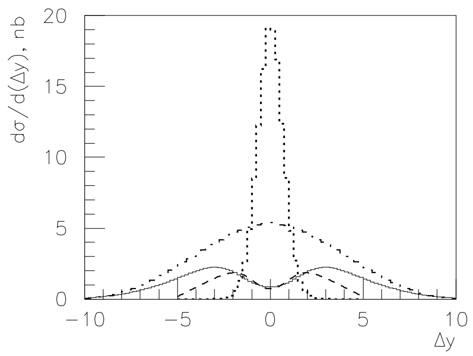

Figure 5: Distribution over the rapidity difference between J/ψ mesons. Dotted curve, SPS 'box' contribution; dashed curve, one-gluon exchange contribution multiplied by 1000; solid curve, two-gluon exchange contribution multiplied by 25; dash-dotted curve, DPS production.

Now we turn to rapidity correlations explained in Fig. 5. In the case of independent production (the DPS mode), the distribution over Δy is rather flat (dash-dotted curve in Fig. 5), while in the case of SPS 'box' contribution (dotted curve in Fig. 5) it is concentrated around $\Delta y \simeq 0$ and does not extend beyond the interval $|\Delta y| < 2$. In Fig. 5 we also show pseudo-diffractive contributions from the one- and two-gluon exchange processes of Fig. 2. As it was expected, these processes lead to relatively large Δy and even show maxima at $\Delta y \simeq \pm 2$. corresponding to J/ψ mesons moving in the directions of the initial gluons. At the same time, the absolute size of the pseudo-diffractive cross sections is found to be remarkably small. The reasons taking credit for this smallness are: the presence of two extra powers of α_s; the large typical rapidity difference making the invariant mass of the final state relatively large; and, what is most important, the color factors. Namely, the square of the color amplitude of the first diagram in the first row of Fig. 1 gives $[\frac{2}{3}\delta^{ab}]^2 = 32/9$. Similarly, for the diagrams in the second row we have $9/2$ and 9. For comparison, the color amplitude of the first diagram in Fig. 2 yields after squaring $[\frac{1}{4}d^{ace}\frac{1}{4}d^{bde}]^2 = \frac{1}{256}\frac{200}{9} \simeq 0.1$. Note that all the considered contributions are of the same order in N_c.

4. Conclusions

We have considered the production of J/ψ pairs at the LHC energies via SPS and DPS processes taking into account several possible contributing subprocesses. We find it rather difficult to disentangle the SPS and DPS modes on the basis of azimuthal or transverse momentum correlations: the difference becomes only visible at sufficiently high p_T, where the production rates are, indeed, very small. Selecting large rapidity difference events looks more promising. The leading order SPS contribution is localized inside the interval $|\Delta y| \leq 2$ (and continues to fall down steeply with increasing $|\Delta y|$), while the higher order contributions extending beyond these limits are heavily suppressed by the color algebra and do not constitute significant background for the DPS production.

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