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Production of $\chi_{ci}\chi_{cj}$ pairs in proton-proton collisions in k_T-factorization and collinear approaches

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Here we present recent results of our calculations of χ_c pair production, mainly in the single parton scattering (SPS) mode. An important feature is that the single-gluon exchange mechanism can to some extent mimic the behaviour of double parton scattering (DPS) production. Off-shell matrix elements for $g^*g^* \to \chi_{cJ_1}\chi_{cJ_2}$ were derived and then used in the k_T-factorization approach for the $pp \to \chi_{cJ_1}\chi_{cJ_2}$ reaction. Different combination of the χ_c mesons are considered. A similar analysis is repeated for the collinear factorization approach, but now including the associated production with a gluon (jet). The leading order contributions ($2 \to 2$ processes) are rather small, compared to the k_T-factorization result. But the addition of $2 \to 3$ processes helps to recover the latter results.

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1. Introduction

In this contribution we review our recent studies of χ_c-pair production in k_T-factorization [1] and of the of χ_c-pairs associated with a gluon (jet) in collinear factorization [2].

One of the motivations of these works lies in the recent interest in double parton scattering processes (DPS). Indeed, the charmonium and open charm production is expected to be an important probe of DPS mechanisms. For example, the production of J/ψ-pairs has been suggested as a probe of double-parton scattering (DPS) processes [3]. The importance of the DPS production mode in the open charm production has been stressed in [4]. As far as charmonia are concerned, the cross sections for production of J/ψ-pairs were measured at the Tevatron [5] and the LHC [6, 7, 8, 9].

There are a number of puzzles in the description of these data, though. For example the single parton scattering (SPS) leading order of $\mathscr{O}(\alpha_S^4)$ (the so-called "box-mechanism", see e.g. [10, 11]) does not describe all the kinematical distributions well in the case of the ATLAS and CMS data. In particular, at large rapidity distance Δy between two J/ψ mesons the "box mechanism" falls short of experimental data.

If one ascribes all the discrepancy between data and the box-mechanism SPS mode to DPS processes, the normalization of DPS comes out a factor ~ 2.5 larger than in other hard processes.

It is still an open issue at the moment whether this points to a nonuniversality of DPS effects or whether there are additional single parton scattering mechanisms not taken into account up to now. This is part of the motivation why we looked into SPS processes which contribute at large rapidity distance between charmonia.

Beyond that, the χ_{cJ}-production is a convenient testbed for calculations of SPS and DPS mechanisms, as the leading order production mechanism (in the color singlet model) is just a $2 \to 1$ gluon fusion ($gg \to \chi$) process.

2. Production of χ_c-pairs

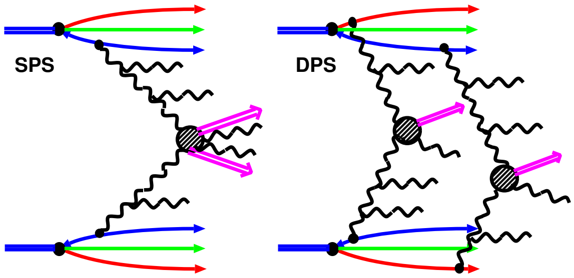

Figure 1: A sketch of the single parton scattering (SPS) and double parton scattering (DPS) production modes.

In the standard hard scattering approach, the cross section of production of a pair of quarkonia a, b is calculated from a convolution of parton densities with a parton-level cross section (see the left diagram in Fig. 1). However at high energies, favored by the rise of the gluon distribution at small x there is a sizable contribution from processes in which two or more hard processes proceed in the same proton-proton collision (see the right diagram in Fig. 1). We can think of it as an inelastic interaction involving the simultaneous participation of two parton chains.

One often assumes the factorized ansatz for the production cross section in the DPS mode:

$$\frac{d\sigma_{\rm DPS}(pp\to abX)}{dy_a dy_b d^2\vec{p}_{aT} d^2\vec{p}_{bT}} = \frac{1}{1+\delta_{ab}}\,\frac{1}{\sigma_{\rm eff}}\,\frac{d\sigma(pp\to aX)}{dy_a d^2\vec{p}_{aT}}\,\frac{d\sigma(pp\to bX)}{dy_b d^2\vec{p}_{bT}}\,. \tag{2.1}$$

The DPS cross section is written as a product of the inclusive single-particle spectra, and the cross section is normalized by the "effective cross section" $\sigma_{\rm eff}$. In the simplest model, the inverse of the effective cross section is related to the overlap of the parton densities of the participating hadrons in the transverse plane, $t_N(\vec{b})$:

$$\frac{1}{\sigma_{\rm eff}} = \int d^2\vec{b}\, T^2_{NN}(\vec{b})\,, \, T_{NN}(\vec{b}) = \int d^2\vec{s}\, t_N(\vec{s}) t_N(\vec{b}-\vec{s})\,. \tag{2.2}$$

The most important features of DPS are immediately obvious from Eq. 2.1. Each of the single particle spectra is a broad function of $y_{a,b}$, and thus the DPS distribution in rapidity distance $\Delta y = y_b - y_a$ will have a long range as well. As far as the size of the effective cross section is concerned, it is usually taken in the ballpark of $\sigma_{\rm eff} = 15\,$mb. This is consistent with a fair amount of hard processes, see e.g. a table in [7].

In the case of J/ψ-pair production the lowest-order "box-diagram" mechanism suggests a very clean separation of SPS versus DPS modes. Indeed, explicit calculations performed in k_T-factorization [11], show, that the J/ψ-pair distribution is sharply peaked around $\Delta y = 0$.

A main point of this presentation is the fact that the situation looks completely different for the case of production of a pair of χ_c mesons. Indeed, the χ_{cJ} states, which come in three different spins $J = 0,1,2$ have positive C-parity and thus couple to two gluons in a color singlet state. Consequently the mechanism of Fig. 2 with a t-channel exchange of a single gluon is possible. This t-channel exchange mechanism yields a $gg \to \chi\chi$ cross section which is independent of cm-energy in the high-energy limit. The matrix element for χ-pair production thus puts no penalty on large rapidity distance Δy between the χ_c-mesons.

The relevant amplitudes can be obtained from effective $g^*g^* \to \chi_{cJ}$ vertices for the fusion of two spacelike off-shell gluons. We adopt the color singlet model, where in the NRQCD limit the relevant vertices take the form

$$V^{ab}_{\mu\nu}(J,J_z;q_1,q_2) = -i4\pi\alpha_S\delta^{ab}\,\frac{2R'(0)}{\sqrt{\pi N_c M^3}}\sqrt{3}\cdot T_{\mu\nu}(J,J_z;q_1,q_2)\,. \tag{2.3}$$

Here $R'(0)$ is the derivative of the p-wave radial wave function at the origin. It is constrained e.g. by the $\chi_c 0,2 \to \gamma\gamma$ decay widthes. The explicit form of tensors $\cdot T_{\mu\nu}(J,J_z;q_1,q_2)$ has been obtained in Ref. [1] for all possible spin-states of the χ_c family. Notice that for the spin-1 meson χ_{c1} the vertex vanishes when both gluons go on-shell (as required by the Landau-Yang theorem), but it is generally non-zero off-shell.

These off-shell vertices are a necessary input for our k_T-factorization calculations including transverse momenta of incoming (off-shell) gluons.

We now come to the discussion of some selected results. In the left panel of Fig. 3 we show the distribution in rapidity distance Δy between mesons. Notice that here we only show as an

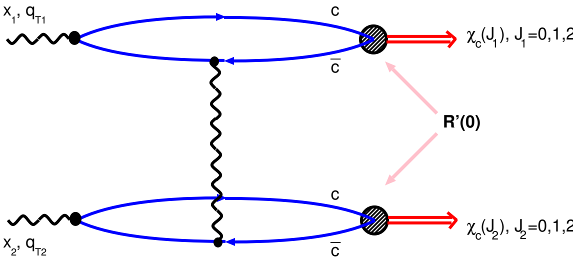

Figure 2: The gluon t-channel exchange mechanism for the rpoduction of $\chi_c\chi_c$ pairs.

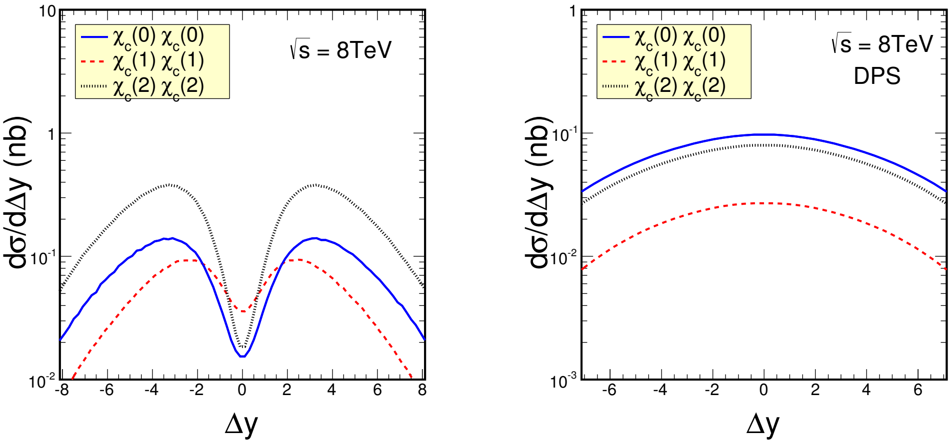

Figure 3: Distribution of χ_c-pairs in rapidity difference between mesons. Top panel: SPS mode, lower panel: DPS mode.

example the production of pairs of identical mesons, the full array of all possible combinations can be found in Ref. [1]. In the right panel of Fig. 3 we show distributions in Δy for the DPS mode, using $\sigma_{\rm eff} = 15\,$mb. We see, that these distributions are very broad and there overall magnitude is in the same ballpark as the SPS contribution. Of course there is no minimum at $\Delta y = 0$ for the DPS distributions. Thus we observe rather similar distributions in Δy for single and double parton scattering production of different χ_c-quarkonia states. This shows that both contributions must be included in analysis of future data for $\chi_{cJ_i}\chi_{cJ_j}$ production.

The large rapidity distance between mesons corresponds to a large phase pace for emission of additional gluons. We therefore studied in Ref.[2] the associated production of χ_c pairs with a gluon in the standard collinear factorization. There are two main contributions, shown in the diagrams of Fig. 4, firstly, the emission of a "leading gluon", where the gluon jet carries a large fraction of the momentum carried by one of the incoming gluons. The amplitude, say of diagram A in Fig.4 takes the form

$$\begin{aligned}\mathcal{M}_A &= i g_S f_{ab'c} \varepsilon^{\mu}(\lambda_a,q_a)\Gamma_{\mu\nu\rho}(q_a,p_g) n^{-\rho}\varepsilon^{\nu *}(\lambda_g,p_g)\frac{1}{t_1} n^{+\mu'}\mathcal{M}^{b'b}_{\mu'\nu'}(p_g-q_a,q_b;p_1,p_2)\varepsilon^{\nu'}(\lambda_b,q_b)\\ &= i g_S f_{ab'c}\, 2q_a^+ \delta_{\lambda_a\lambda_g}\frac{1}{t_1} n^{+\mu'}\varepsilon^{\nu'}(\lambda_b,q_b)\mathcal{M}^{b'b}_{\mu'\nu'}(p_g-q_a,q_b;p_1,p_2)\,, \qquad (2.4)\end{aligned}$$

where $\Gamma_{\mu\nu\rho}$ is the standard three-gluon vertex, and the $2\to 2$ amplitude $\mathcal{M}^{b'b}_{\mu'\nu'}$ is constructed from

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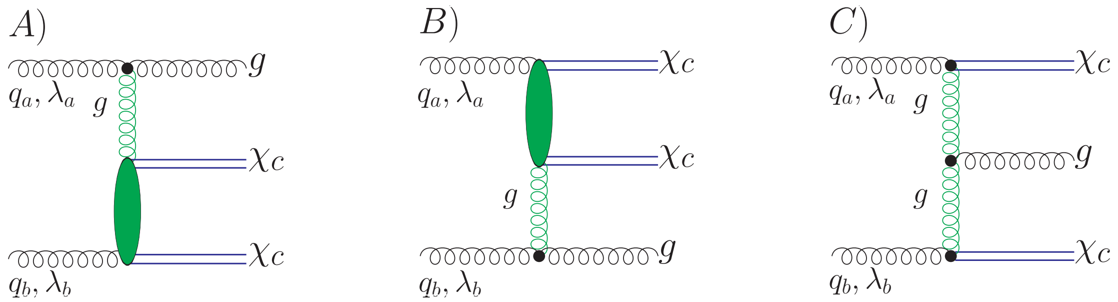

Figure 4: Feynman diagrams for the production of a χ_c-pair associated with a gluon.

the above quoted $g^*g^*\chi_{cJ}$vertices.

Secondly there is a contribution from the production of "central" gluons, which are emitted in rapidity space between the two mesons with a large difference in rapidity from either one. The diagram C pf Fig. 4 leads to the amplitude

$$\mathscr{M}_C = ig_S f_{a'b'c} V_1^{aa'}(q_a,p_1)\frac{1}{t_1}C^{\rho}(q_a-p_1,q_b-p_2)\varepsilon^*_{\rho}(\lambda_g,p_g)\frac{1}{t_2}V_2^{bb'}(q_b,p_2)\,, \tag{2.5}$$

where

$$\begin{aligned} V_1^{aa'}(q_a,p_1) &= \varepsilon^{\mu}(\lambda_a,q_a)V^{aa'}_{\mu\mu'}(J_1,J_{1z};q_a,p_1-q_a)n^{-\mu'} \\ V_2^{bb'}(q_b,p_2) &= \varepsilon^{\nu}(\lambda_b,q_b)V^{bb'}_{\nu'\nu}(J_2,J_{2z};q_b,p_2-q_b)n^{+\nu'}\,, \end{aligned} \tag{2.6}$$

and C^{ρ} is the g^*g^*g-Lipatov vertex (see e.g. [12]).

Some distributions, again in rapidity distance Δy between mesons are shown in Fig. 5. The production of leading gluons adds to the Born-result to recover the k_T-factorization result, while the production of central gluons gives rise to an about 20% enhancement of the cross section. Here one may think of $\alpha_S \cdot \Delta y$ as a large parameter which could be resummed in the future using a BFKL formalism.

3. Conclusions

Pair production of quarkonia is a topic that still poses puzzles to theorists. A quantitative understanding of DPS contributions requires not only a reliable formalism for its calculation but also a good understanding of SPS processes that can show similar behavior as DPS in many kinematic variables.

For the theoretically simplest case, the production of χ_c-pairs, we showed that the cross sections for different combinations of χ_c quarkonia the SPS and DPS cross sections are of the similar size, and both involve very broad distributions in rapidity distance Δy.

We have also shown, that an enhancement of the pair production cross section for χ_c-pairs can be expected from the higher order corrections, due to the large phase-space of gluon emission.

However, it turns out, that feed-down from χ-pairs into the J/ψ-pair channel does not resolve the discrepancy between different determinations of $\sigma_{\rm eff}$ [13].

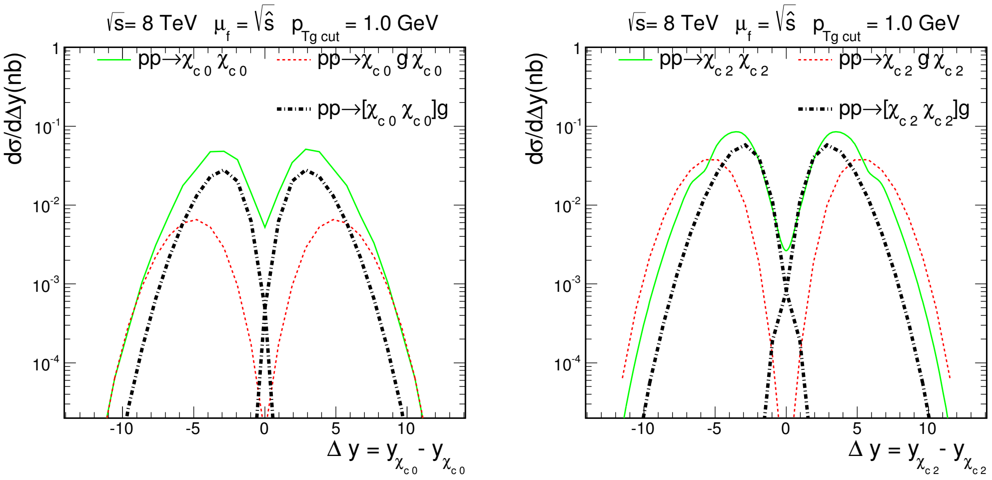

Figure 5: Distribution in rapidity between χ_0 mesons (top panel) and χ_{c2} mesons for the following different processes: Born-level production of χ_c-pairs, production of χ_c pairs with a leading gluon, and production of χ_c-pairs with a central gluon.

It might be necessary to look deeper into the fundamentals of DPS theory (see e.g. [14]) to understand the peculiar behaviour of charmonium pair production.

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