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χ_c and χ_b meson production in high multiplicity events

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Recent studies of heavy J/ψ and D-mesons production by the ALICE and STAR collaborations revealed a pronounced dependence of the cross-section on multiplicity of co-produced charged particles. One of the possible explanations of this phenomenon is the enhanced contribution of multipomeron configurations. We suggest that the study of the multiplicity dependence of P-wave quarkonia (e.g. χ_c and χ_b mesons) could provide decisive evidence in favor of this explanation. Due to different quantum numbers, the P-wave quarkonia will not get contributions from the three-pomeron mechanism, and for this reason should have significantly milder dependence on multiplicity. We also present detailed production cross-sections in the kinematics of ongoing experiments at LHC and RHIC.

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1. Introduction

The production of heavy mesons is conventionally described in approaches based on either gluon-gluon or pomeron-pomeron fusion processes (see [1] for an overview). At the very high energies available at the LHC, the gluon densities are enhanced and potentially could lead to sizable multigluon corrections in all high-energy processes. However, for quarkonia usually such multigluon contributions are disregarded altogether. Theoretically, this is justified in the heavy quark mass limit, when the interactions of heavy quarks with gluonic fields become perturbative. While in general this approach gives a consistent description, its precision tests are challenging due to poorly known nonperturbative parameters which describe late-stage hadronization (e.g. fragmentation functions, wave functions or Long Distance Matrix Elements (LDMEs)). Moreover, the latter parameters are usually extracted together with the data which are being described, and the analyses have demonstrated their considerable scheme dependence [2–4], contradicting their expected universality. Furthermore, recent STAR and ALICE measurements [5–8] of D-meson and quarkonia cross-sections as a function of multiplicity of co-produced charged hadrons, are at tension with all models based on the gluon-gluon fusion picture [9], thus opening the possibility for other mechanisms. It is known from early studies in the Regge approach that the multiplicity enhancement is related to contributions of multipomeron fusion, and for this reason the discrepancy between the experimental data and the gluon-gluon fusion might signal a sizable contribution of such mechanisms. Approaches based on this picture have been successfully applied to J/ψ and D-meson production [10–15], suggesting that the three-pomeron fusion could contribute up to 40 per cent of heavy meson yields. This finding requires independent cross-checks for a better understanding of the role of the three-pomeron mechanism.

In this proceeding we analyze the production of the P-wave quarkonia (χ_c and χ_b mesons) and argue that its dependence on multiplicity of co-produced hadrons could help to understand the role of multipomeron mechanisms. Numerically the cross-sections of P-wave quarkonia are comparable by an order of magnitude to that of S-wave, and for this reason their experimental studies should be straightforward. Previous studies in the collinear and k_T factorization frameworks [16–21] found that a two-gluon fusion mechanism gives the dominant contribution and can describe the available experimental dependence of the cross-section on rapidity and transverse momenta. Due to the spin-orbital interaction, in experiments the P-wave quarkonia show up as triplets with different spin-parity J^P. A comparison of experimental data for the production of different χ_{cJ} and χ_{bJ} states potentially provides a very sensitive tool for testing the spin structure of the interaction. For this reason we expect that the use of P-wave quarkonia for studies of the multiplicity could be extremely useful. Since most studies of high-multiplicity events are realized in the small-x kinematics, for our theoretical studies we used a color dipole framework (also known as CGC/Saturation or CGC/Sat) [22–24]. Its extension to the description of high-multiplicity events is well-known from the literature [25–27].

The proceeding is structured as follows. In the next section 2 we briefly summarize the main theoretical results for the production cross-sections of P-wave quarkonia and compare the theoretical expectations with available experimental data. In Section 3 we discuss the dependence on multiplicity and make conclusions.

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2. Production mechanisms of P-wave quarkonia

The production of quarkonia at high energies proceeds in the target rest frame via the intermediate formation of the heavy $\bar{Q}Q$ pair, and its hadronization into a quarkonium state. In the LHC kinematics the light-cone gluon fractions $x_{1,2}$ are small, so it is convenient to use the color dipole framework (also known as CGC/Sat), which describes yhr interactions with the target in terms of dipole amplitudes. The cross-section of P-wave quarkonia production via the two-pomeron fusion process in the dipole approach, as was demonstrated in [28] , is given by

$$\frac{d\sigma_M\left(y,\,\sqrt{s}\right)}{dy\,d^2p_T} = \int d^2k_T x_1\, g\left(x_1,\,\boldsymbol{p}_T-\boldsymbol{k}_T\right)\int_0^1 dz_1\int_0^1 dz_2\int\frac{d^2r_1}{4\pi}\int\frac{d^2r_2}{4\pi}\times \tag{1}$$
$$\times\int d^2\boldsymbol{b}_{21}e^{i\boldsymbol{b}_{21}\cdot\boldsymbol{k}_T}\left\langle\Psi_{\bar{Q}Q}^{\dagger}\left(r_1,\,z_1\right)\,\Psi_M\left(r_1,\,z_1\right)\right\rangle\left\langle\Psi_{\bar{Q}Q}^{\dagger}\left(r_2,\,z_2\right)\,\Psi_M\left(r_2,\,z_2\right)\right\rangle^*\times$$
$$\times N_M\left(x_2;z_{1,}\,\boldsymbol{r}_1;\,z_2,\,\boldsymbol{r}_2;\,\boldsymbol{b}_{21}\right)+\left(x_1\leftrightarrow x_2\right),$$

$$N_M\left(x;\,z_{1,}\,\boldsymbol{r}_1;\,z_2,\,\boldsymbol{r}_2;\,\boldsymbol{b}_{21}\right) = N\left(x,\,\boldsymbol{b}_{21}+\bar{z}_2\boldsymbol{r}_2+\bar{z}_1\boldsymbol{r}_1\right)+N\left(x\,\boldsymbol{b}_{21}-z_1\boldsymbol{r}_1-z_2\boldsymbol{r}_2\right)- \tag{2}$$
$$-N\left(x,\,\boldsymbol{b}_{21}+\bar{z}_2\boldsymbol{r}_2-z_1\boldsymbol{r}_1\right)-N\left(x,\,\boldsymbol{b}_{21}-\bar{z}_1\boldsymbol{r}_1-z_2\boldsymbol{r}_2\right),$$
$$x_{1,2}\approx\frac{\sqrt{m_M^2+\langle p_{\perp M}^2\rangle}}{\sqrt{s}}e^{\pm y}, \tag{3}$$

where y and p_T are the rapidity and transverse momenta of the produced quarkonia in the center-of-mass frame of the colliding protons; $(z_i,\,\boldsymbol{r}_i)$ are the light-cone fractions of the quark and the transverse separation between quarks inside the dipole (with subindices $i = 1, 2$ standing for the amplitude and its complex conjugate respectively); $\boldsymbol{b}_{21}$ is the difference of impact parameters of the dipoles in the amplitude and its conjugate. We also use the notation $\Psi_M(r,\,z)$ for the light-cone wave function of quarkonium M ($M = \chi_c,\,\chi_b$), and $\Psi_{\bar{Q}Q}$ for the quark-antiquark component of the gluon light-cone wave function. The amplitude N_M depends on a linear combination of forward dipole scattering amplitudes $N\left(y,\,\boldsymbol{r}\right)\equiv\int d^2\boldsymbol{b}\,N\left(y,\,\boldsymbol{r},\,\boldsymbol{b}\right)$, as given in (2). The notation $xg\left(x,\,\boldsymbol{k}_T\right)$ in (1) is used for the unintegrated gluon PDF, and can be related to the dipole scattering amplitude $N\left(y,\,\boldsymbol{r}\right)$ introduced earlier as

$$x\,g\left(x,\,k^2\right) = \frac{\partial}{\partial\mu_F^2}\left[\frac{C_F\mu_F}{2\pi^2\bar{\alpha}_S}\int d^2r\,\frac{J_1\left(r\,\mu_F\right)}{r}\nabla_r^2\mathcal{N}\left(x,\,\boldsymbol{r}\right)\right]\Bigg|_{\mu_F^2=k^2}. \tag{4}$$

This result allows us to rewrite (1) entirely in terms of the dipole amplitudes $N(\ldots)$. For phenomenological estimates, in what follows we will use the impact parameter dependent CGC parametrization of the color dipole amplitude $N\left(x,\,\vec{r},\,\vec{b}\right)$, with the set of parameters from [29]. In Figure 1 we compare the expectations of the color dipole approach for the cross-sections of χ_{c1}, χ_{c2} mesons with experimental data from the LHC. As we can see, the model provides a very reasonable description of experimental data. A detailed comparison with earlier data from Tevatron, as well as predictions for the future LHC runs might be found in our recent paper [28].

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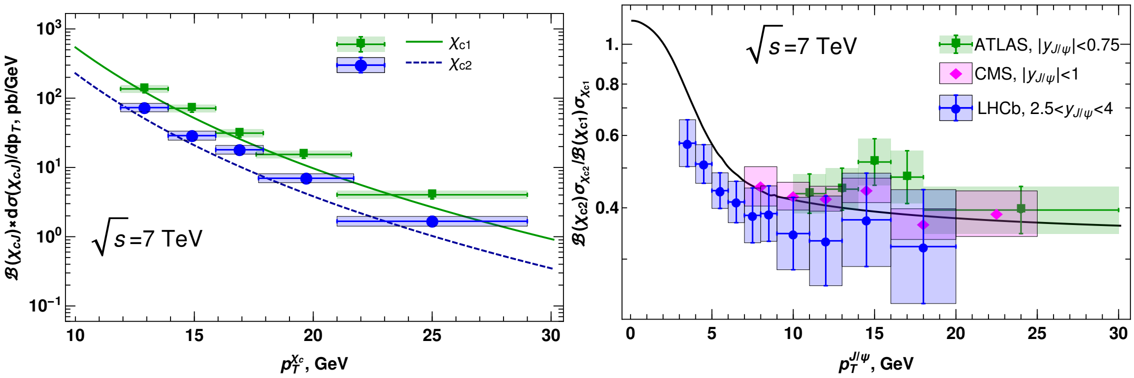

Figure 1: Left: Color dipole model expectation for the χ_{c1} and χ_{c2} cross-sections. Experimental data are from ATLAS [30]. Right: Theoretical expectations for the ratio of χ_{c1} and χ_{c2} yields at central rapidities. The experimental data are from the ATLAS [30], CMS [31] and LHCb [32] experiments. We included LHCb data, which were measured at off-forward rapidities, because the rapidity dependence of the χ_{c1} and χ_{c2} cross-sections is the same and thus will cancel in the ratio. For better visibility we use a logarithmic scale in the vertical axis.

3. Multiplicity dependence

The multiplicity enhancement in high-energy processes is related to the contributions of the multipomeron mechanisms. Since the probability of high-multiplicity events decreases rapidly as function of the number of produced charged particles $N_{\rm ch}$, usually the results are discussed in terms of the *relative* multiplicity dependence of different processes. In the case of quarkonia production, the results are usually presented for a self-normalized ratio

$$\frac{dN_M/dy}{\langle dN_M/dy\rangle}=\frac{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,n\right)/dy}{d\sigma_M\left(y,\,\eta,\,\sqrt{s},\,\langle n\rangle=1\right)/dy}\Bigg/\frac{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,n\right)/d\eta}{d\sigma_{\rm ch}\left(\eta,\,\sqrt{s},\,Q^2,\,\langle n\rangle=1\right)/d\eta} \tag{5}$$

where $n=N_{\rm ch}/\langle N_{\rm ch}\rangle$ is the relative enhancement of the charged particles in the bin, $w\left(N_M\right)/\langle w\left(N_M\right)\rangle$ and $w\left(N_{\rm ch}\right)/\langle w\left(N_{\rm ch}\right)\rangle$ are the self-normalized yields of quarkonium M and charged particles (minimal bias) events in a given multiplicity class; $d\sigma_M\left(y,\,\sqrt{s},\,n\right)$ is the production cross-section for M, with rapidity y and $\langle N_{\rm ch}\rangle=\Delta\eta\, dN_{\rm ch}/d\eta$ charged particles in the pseudorapidity window $(\eta-\Delta\eta/2,\;\eta+\Delta\eta/2)$. Physically the ratio (5) is proportional to the *conditional* probability to observe a heavy quarkonium M in a final state with $N_{\rm ch}$ charged particles. For the moderate values of $n\lesssim 10$ in pp collisions, due to the Local Parton-Hadron Duality (LPHD) hypothesis, the number of produced charged particles is directly proportional to the number of partons which stem from the individual pomerons.

The extension of the color dipole approach for the description of high-multiplicity events has been extensively studied in the literature [25–27], and for the kinematics of moderate values of n might be taken into account adjusting the value of the saturation scale Q_s as $Q_s^2\left(x,\,b;\,n\right)=n\,Q^2\left(x,\,b\right)$. For phenomenological estimates of the multiplicity dependence, we will consider the setup in which both quarkonia and hadrons are collected at central rapidities $|\eta|,\;|y|\le 1$, where the strongest multiplicity dependence was observed for J/ψ and D-mesons. In Figure 2 we show the multiplicity dependence of χ_{cJ} mesons for different values of spin (J) and energies. The expected

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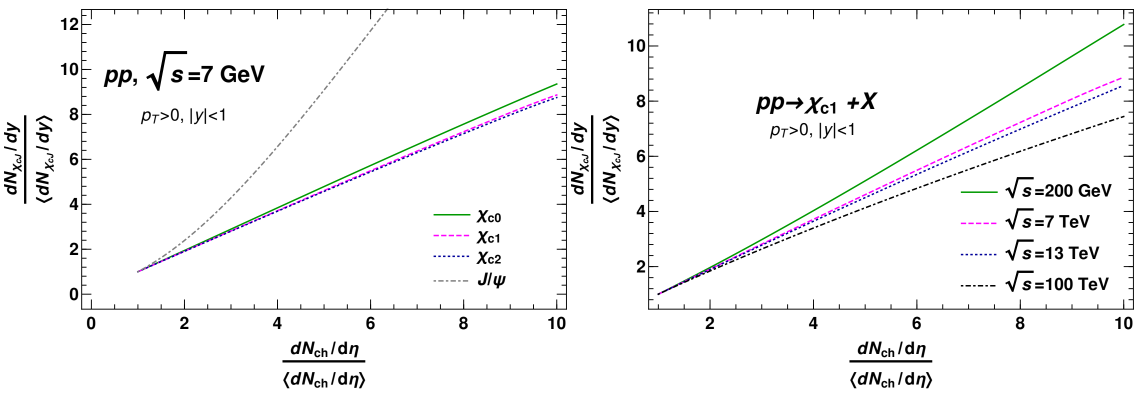

Figure 2: Left: The multiplicity dependence for different χ_{cJ} states. For the sake of reference we also added a dot-dashed grey curve from [10, 11] which describes experimentally the observed multiplicity dependence of J/ψ mesons. Right: Dependence of the multiplicity shapes on energy of pp collision . The plot is done for χ_{c1} meson production, but the results for χ_{c0}, χ_{c2} are almost identical. All plots in this Figure are done assuming that charged particles and quarkonia are collected at central rapidities ($|\eta, y| < 1$), similar to what is available for J/ψ production from [33].

dependence is much milder than that of the $1S$ quarkonia (dot-dashed curve with label "J/ψ"). This happens because for the P-wave quarkonia, due to its quantum numbers, the contribution of the three-pomeron mechanism is less important, and each (cut) pomeron contributes to the multiplicity dependence with a factor $\sim n^{\langle\gamma_{\rm eff}\rangle}$, where the parameter $\gamma_{\rm eff} \approx 0.65 - 0.75$. The cross-sections of χ_b mesons have similar dependence on multiplicity (detailed predictions might be found in [28]).

To summarize, we analyzed in detail the hadroproduction of $1P$-quarkonia in the color dipole approach. We found that the theoretical expectations for the p_T-dependent cross-section are in agreement with available experimental data for χ_{c1} and χ_{c2} mesons. We also made predictions for χ_b mesons, which might be checked in the ongoing and future experiments, both at RHIC and at LHC. We expect that the multiplicity dependence of the P-wave quarkonia cross-sections is significantly milder than that of $1S$ quarkonia (J/ψ, Υ...). This happens because for the P-wave quarkonia the dominant mechanism is the two-pomeron fusion, whereas the three-pomeron contributions are strongly suppressed. An experimental confirmation of this result could serve as a decisive evidence in favor of models which explain multiplicity enhancement seen in $1S$ quarkonia as a manifestation of multipomeron contributions.

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