

Diffractive χ Production at the Tevatron and the LHC

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We present predictions for the diffractive production of χ mesons in the central rapidity region usually covered by collider detectors. The predicted cross sections are based on the Bialas-Landshoff formalism for both exclusive and inclusive production and makes use of the DPEMC Monte-Carlo simulation adapted with kinematics appropriate for small-mass diffractive production. We compare generator-level results with a CDF measurement for exclusive χ production, and study background and other scenarios including the contribution of inclusive χ production. The results agree with the Tevatron data and are extrapolated, highlighting the exclusive χ_{c_0} production at LHC energies. A possible new measurement at the Tevatron using the $D\mathcal{O}$ forward detectors is investigated, taking advantage of the dominance of exclusive production for high enough diffractive mass fraction.

I. INTRODUCTION

Exclusive and inclusive central diffractive production of heavy states have been studied previously in the double Pomeron exchange formalism (DPE) [? ? ? ? ? ? ? ?], and experimental results have been presented [?], attracting theoretical attention. Indeed, massive dijets have been copiously produced in inclusive diffractive production at the Tevatron and there is presently an active search for exclusive diffractive production of heavy states. One motivation for this search is that the Higgs boson could be produced in such a mode, allowing for a good mass determination for this elusive particle if such exclusive events are identified [?]. However the estimated cross sections and signal-over-noise ratios are still a matter of debate.

One way to address this problem is looking for a similar production mechanism with lighter particles like the χ mesons [?]. This would give rise to high enough cross sections to check the dynamical mechanisms. Indeed, exclusive production of χ_c has been reported by the CDF collaboration [?] with an upper limit for the cross section of

$$\sigma_{exc}(p\bar{p} \rightarrow p + J/\psi + \gamma + \bar{p}) < 49 \pm 18(stat) \pm 39(sys) pb . \quad (1)$$

Our goal in the present paper is to analyse both exclusive and inclusive diffractive production of χ_{c_0} and χ_{b_0} in the context of the Tevatron, making useful predictions for the LHC. A possible new measurement using the $D\mathcal{O}$ forward detectors is also investigated. As a general framework, we use an extension to low mass states of the Bialas-Landshoff (BL) model [?] for both exclusive and inclusive production. More precisely, we consider the inclusive model as applied in Ref.[?] and the extension to purely exclusive processes [?], using the corresponding color-singlet ($J_z = 0$) subprocess cross sections of the original Bialas-Landshoff formalism for diffractive Higgs production [?], applied also to heavy quark pairs in [?]. In fact, in our approach, both inclusive and exclusive diagrams come from the

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same non-perturbative approach, originated in [?]. The model for exclusive production starts with the same soft Pomeron exchange diagrams (for ordinary dijet production the $gg \rightarrow gg$ diagrams are also included [?]) and corrects the result by non-perturbative rapidity-gap survival factors [? ?]. For inclusive production in the same framework, no such factor is applied, but the normalisation is fixed by fitting the CDF dijet data [?]. The energy dependence is related to the rise of ordinary hadronic cross-sections through features of the soft Pomeron [?]. We think that the non-perturbative Bialas-Landshoff approach is well suited for the production of relatively low-mass diffractive χ states¹.

The full kinematics is evaluated for low-mass exclusive production and implemented in the DPEMC Monte Carlo generator [?], originally designed for heavy mass states. We use the generator level distributions to estimate the measurements at detector level, and to study the systematic uncertainties due the lack of a full detector simulation.

The paper is divided in the following way: in section ??, we recall briefly the Bialas-Landshoff (BL) formalism for both exclusive and inclusive diffractive production and give the theoretical cross section formulae. They include the full diffractive kinematics for a low mass state, which is derived in section ?? and implemented in the DPEMC Monte Carlo. In section ??, we show the predictions for the exclusive and inclusive diffractive χ production cross sections at the Tevatron and LHC. In the subsequent section ?? we compare our predictions with the CDF measurement and investigate the possibility of a new measurement at the DØ detector in section ??. Section ?? is devoted to the predictions for exclusive χ_{c0} production at the LHC and in section ?? we present our conclusions and an outlook on this interesting mode of production.

II. THE BIALAS-LANDSHOFF FORMALISM

One generally considers two types of DPE topologies for the production of a heavy state: exclusive DPE [? ? ? ? ?], where the central object is produced alone, separated from the outgoing hadrons by rapidity gaps:

$$hh \rightarrow h + \text{heavy object} + h , \quad (2)$$

and inclusive DPE [? ? ? ? ?], where the colliding Pomerons are resolved (very much like ordinary hadrons), accompanying the central object with Pomeron “remnants” (X,Y):

$$hh \rightarrow h + X + \text{heavy object} + Y + h . \quad (3)$$

in both cases h represents the colliding hadrons.

In general, exclusive production is considered most promising, since a better signal-to-background ratio is expected. Indeed, if the events are exclusive, *i.e.*, no other particles are produced in addition to the heavy object and the outgoing hadrons, the measurement of the scattered hadrons in near-beam detectors provides information on the mass of the heavy object [?], and the dynamics of the hard process. However, the approximations made for heavy mass states lead to inconsistent results in the case of lighter objects, so in our case we have to develop the full kinematics for all mass states.

In order to evaluate both inclusive and exclusive diffractive production, we use an extension [?] to the purely exclusive processes of the original Bialas-Landshoff formalism for diffractive Higgs production [?], also applied to heavy quark pairs [?]. In this extension, both inclusive and exclusive diagrams come from the same approach and are based on soft Pomeron exchange diagrams (for ordinary dijet production the $gg \rightarrow gg$ diagrams are also included [?]). In the exclusive case one has to correct the result by non-perturbative rapidity-gap survival factors [? ?], while in the inclusive case the normalisation is fixed [?] by reference with dijet production [?]. The values of the survival probabilities are the same as for the diffractive Higgs production in Ref. [?], namely 0.1 and 0.03 for respectively the Tevatron and the LHC. The energy dependence of the cross section is related to the rise of ordinary hadronic cross sections through features of the soft Pomeron [?].

With respect to previous works, the formulae of the Bialas-Landshoff cross sections have to include now the full kinematics for diffractive χ meson states and thus valid for small masses in general. This kinematics is explained in the next section. For the exclusive χ meson production in hadron-hadron collisions, one has

$$d\sigma_{\chi}^{exc}(s) = C_{\chi} \left(\frac{s}{M_{\chi}^2} \right)^{2\epsilon} \delta \left[\frac{M_{\chi}^2}{s} - \frac{M_{diff}^2}{s} \right] \prod_{i=1,2} \left\{ d^2v_i \frac{d\xi_i}{1-\xi_i} \xi_i^{2\alpha'v_i^2} \exp(-2\lambda_{\chi}v_i^2) \right\} , \quad (4)$$

¹ At this point, only χ_{c0} and χ_{b0} mesons can be evaluated. Indeed, due to non-zero p_{\perp} of the initial state (pp or $p\bar{p}$), there will be contributions of χ_{c2} and χ_{b2} in the exclusive amplitude. This will be discussed in a further paper.

where C_χ is the normalisation constant (cf. [?] for the Higgs boson), M_χ is the χ meson mass and λ_χ the slope at the Pomeron vertex. α' and ϵ are the standard soft Pomeron parameters [?]. The gluon-gluon χ_C coupling satisfying the $J_z = 0$ rule is taken as in Ref. [?]. The parameter C_χ contains a non perturbative part due to the gluon coupling G to the proton. We kept the original value in the model of Bialas Landshoff which means $G^2/4\pi \sim 1$. This is of course an order of magnitude, and it leads to an uncertainty on the exclusive production cross section.

Most importantly, M_{diff}^2 is the expression of the diffractive mass produced in the central region in terms of the kinematic variables. For low-mass states, as the χ 's, it sensibly differs from the expression for heavy diffractive states, as will be derived in the next section and in Appendix ???. This is one major modification one has to introduce w.r.t. the original formalism.

For inclusive production, the cross sections are given by

$$d\sigma_\chi^{inc}(s) = C_\chi^{inc} \left(\frac{x_1^g x_2^g}{M_\chi^2} \right)^{2\epsilon} \delta \left(\xi_1 \xi_2 - \frac{M_\chi^2}{x_1^g x_2^g s} \right) \prod_{i=1,2} \left\{ G_p(x_i^g, \mu) d^2 v_i dx_i^g \frac{d\xi_i}{1-\xi_i} \xi_i^{2\alpha' v_i^2} \exp(-2\lambda_\chi v_i^2) \right\}, \quad (5)$$

where one makes use of the parton structure functions $G_p(x_i^g, \mu)$ in the Pomeron, for a given scale μ . Note that in Equation (??), the normalisation C_χ^{inc} is fixed by normalising the prediction on the measurement of the dijet diffractive cross section by the CDF collaboration [?].

In both equations, the variables v_i and ξ_i denote the transverse momenta and fractional momentum losses of the outgoing hadrons. In the second equation, x_i^g denote the fractional momentum carried by the gluons in the Pomeron. Note that in the inclusive case, the usual kinematics is used for $M_{diff}^2 \equiv \frac{M_\chi^2}{x_1^g x_2^g}$.

III. FULL KINEMATICS FOR EXCLUSIVE PRODUCTION

Let us first recall the method used to generate exclusive events in the DPMEC Monte Carlo generator [?]. The first step is to randomly generate t_1 , t_2 and ξ_1 , following an exponential distribution for $|t_i|$, where $|t_i|$ is the 4-momentum transferred and ξ_i is the momentum loss for the hadron i . Exclusive events have the property that the full energy available in the center-of-mass is used to produce the diffractive object, or in other words there is no Pomeron remnant. The diffractive mass can be expressed as:

$$M_{diff}^2 \approx s \xi_1 \xi_2. \quad (6)$$

The value of ξ_2 is thus imposed by this relationship. The produced events in the generator are then weighted as usual by the cross section.

The approximation (??) is no longer true for low mass states such as χ mesons, and we had to modify the method to generate events in this case. We derived the diffractive mass from full 4-momentum conservation (see Appendix A).

Using the full kinematics, Equation (??) is replaced by

$$M_{diff}^2 = s \times \left(1 + \frac{(1-\xi_1)(1-\xi_2)}{2\cos\theta_1\cos\theta_2} (1-\Omega) - \left(\frac{1-\xi_1}{\cos\theta_1} + \frac{1-\xi_2}{\cos\theta_2} \right) \right), \quad (7)$$

where $\Omega = -\cos\theta_1\cos\theta_2 + \sin\theta_1\sin\theta_2(\cos\varphi_1\cos\varphi_2 + \sin\varphi_1\sin\varphi_2)$, θ is the scattering angle and φ the polar angle. It is important to notice that this formula depends not only on ξ_1 and ξ_2 but also on the angles of the hadrons θ_1 , φ_1 and θ_2 , φ_2 . t and θ are related by the following formula:

$$\sin^2 \theta_{1,2} \sim \theta_{1,2}^2 = \frac{|t_{1,2}|}{(1-\xi_{1,2})(s/4)}. \quad (8)$$

We use the following method to generate low mass exclusive events within the framework of DPMEC [?]. We start by generating θ_1 , θ_2 (following an exponential distribution) and ξ_1 randomly, which gives t_1 by the equation (??). ξ_2 is then computed inverting equation (??), giving also t_2 . The events are then weighted according to the cross section. The new steps are thus to use the variables θ and ξ , avoiding the cumbersome solution of equation (??) in terms of ξ and t .

IV. EXCLUSIVE AND INCLUSIVE χ_{C_0}, χ_{B_0} PRODUCTION CROSS SECTIONS

Table (??) presents our results for the cross section predictions at the Tevatron and the LHC. The energy dependence for the exclusive production cross section can be seen in the Fig. ?? for the χ_{b_0} (left) and χ_{c_0} (right) mesons. The gap survival probability (the probability of the gaps not to be populated) S_{gap}^2 is taken to be 0.1 at the Tevatron and 0.03 at the LHC (cf. A.B. Kaidalov et al in [?]).

| $\sigma(nb)$ | Tevatron $\sqrt{s} = 1.96$ TeV | LHC $\sqrt{s} = 14$ TeV |
|----------------------------|--------------------------------|-------------------------|
| $\sigma_{exc}(\chi_{c_0})$ | 1.17×10^3 | 0.804×10^3 |
| $\sigma_{exc}(\chi_{b_0})$ | 4.4 | 3.29 |
| $\sigma_{inc}(\chi_{c_0})$ | 1.8×10^4 | 4.8×10^4 |
| $\sigma_{inc}(\chi_{b_0})$ | 20 | 1.8×10^2 |

TABLE I: Cross sections (in nb) for exclusive and inclusive production at the Tevatron and the LHC.

Note that our estimates for exclusive χ_{c_0} production at the Tevatron are higher than other recent predictions [?]. The differences arise mainly because of the distinct Pomeron fluxes in the models, which means that the BL exclusive cross section has a smoother dependence with the center of mass energy (\sqrt{s}) (see Fig. ??). We should also note that our model does not contain Sudakov factors contrary to Ref. [? ?]. The effect of the Sudakov suppression is however supposed to be small at small masses, and plays a more important role at higher masses.

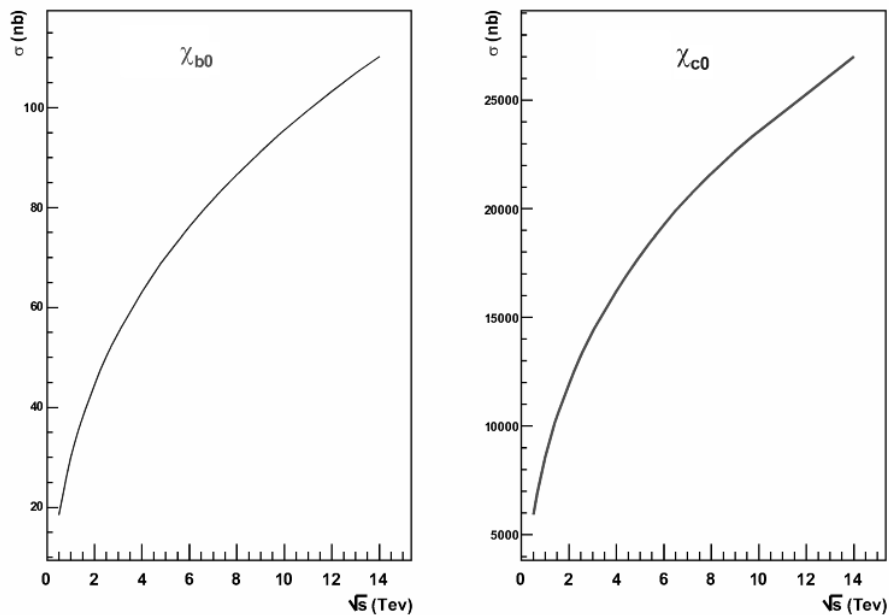


FIG. 1: Exclusive Production cross section of χ_{b_0} (left) and χ_{c_0} mesons (right).

Possible sources of background for exclusive production include:

- cosmic events which can fake an exclusiveness;
- exclusive and inclusive χ_2 production;
- quasi-exclusive χ production, which are defined by a high mass fraction F_M (e.g. $F_M \geq 0.75-0.95$),

where the mass fraction F_M is the ratio between M_χ and the total diffractive mass M_{diff} . We will study this last contamination to the exclusive signal in the following.

V. COMPARISON WITH THE CDF LIMITS ON χ_{c0} PRODUCTION AT THE TEVATRON

As shown in table ??, exclusive χ_{c0} production at the Tevatron has a noticeable cross section, with the potential to be detected in the traditional decay $\chi_{c0} \rightarrow J/\psi(\rightarrow \mu^+ + \mu^-) + \gamma$. The CDF Collaboration has presented preliminary results [?] for exclusive $J/\psi + \gamma$ production using the rapidity gap selection of diffractive events in Run II ($\sqrt{s}=1.96$ TeV). The cuts used by CDF are the following: $p_T(\mu^\pm) \geq 1.5$ (GeV), $|\eta(\gamma)| \leq 3.5$ and $|\eta(\mu^\pm)| \leq 0.6$. The CDF collaboration provided an upper limit on χ_{c0} production cross section at the Tevatron, uncorrected for residual backgrounds such as cosmics ²:

$$\sigma_{exc}(p\bar{p} \rightarrow p + J/\psi + \gamma + \bar{p}) < 49 \pm 18(stat) \pm 39(sys) pb. \quad (9)$$

If we apply the CDF cuts at generator level, we predict the following cross section

$$\sigma_{exc}(p\bar{p} \rightarrow p + \chi_{c0}(\rightarrow J/\psi\gamma) + \bar{p}) = 61pb. \quad (10)$$

In order to make a more realistic comparison, we need also to consider the non-exclusive background which can enter directly in the experimental cross section determination. In particular, the contamination due to quasi-exclusive events need to be considered properly. In this class of events the QCD radiation, or in other words the energy loss in the Pomeron remnant and in soft QCD radiation, is small. CDF remove most of the inclusive background using a cut on the mass fraction, $F_M > 0.85$. For exclusive events, F_M is expected to be close to one, since the full available energy is used to produce the χ meson, and smaller than one for inclusive events. However, this cut is of course applied at the detector level by the CDF collaboration, whereas we can only apply it at the generator level. Due to the fact that we are missing the smearing between detector and generator levels, we choose to investigate the effect on the cross section due to various mass-fraction cuts, as displayed in Table ??.

We also compared the transverse momentum (p_T) distributions of the χ_{c0} for inclusive, exclusive and quasi-exclusive production, the latest defined as $F_M \geq 0.75$ (Fig. ??). As expected, the exclusive p_T distribution reaches higher values, so this variable could be used to enhance the exclusive production signal.

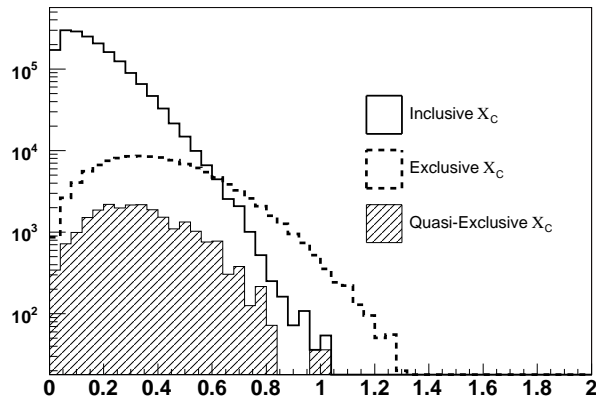


FIG. 2: Transverse momentum of χ_{c0} for exclusive production (solid line), inclusive production (dashed line) and for quasi-inclusive events (filled) at $\sqrt{s} = 1.96$ TeV (the normalization used a luminosity of $100 nb^{-1}$).

The quasi-exclusive contamination to the exclusive signal also suffers from the unknown gluon density in the Pomeron at high β in particular. This uncertainty, estimated to be about 50% [?], can be taken into account by multiplying the gluon density in the Pomeron, measured at HERA, by a factor $(1 - \beta)^\nu$ where ν varies between -1.0 and 1.0 [?]. If ν is negative, we enhance the gluon density at high β by definition. The QCD fits to the HERA data lead to the following value of the ν parameter: $\nu = 0.0 \pm 0.6$.

² This cross section has been corrected for the J/Ψ branching ratio into muons.

In summary, the sources of contamination to the exclusive signal can derive from the smearing in the mass fraction, which is a pure experimental effect, or the uncertainties in the gluon density in the Pomeron, which is a theoretical limitation.

Table II gives the quasi-exclusive cross section at the Tevatron after applying the CDF cuts, and different cuts on the mass fraction and values of the ν parameter. We thus find that the signal seen by the CDF collaboration could be explained by a combination of a higher gluon density at high β and some smearing effects due to the reconstruction of the mass fraction. Table III gives the exclusive production cross section after each of the CDF cuts.

| Mass Fraction Cut | $\nu = 0$ | $\nu = -1$ | $\nu = -0.5$ | $\nu = 0.5$ | $\nu = 1$ |
|-------------------|-----------|------------|--------------|-------------|-----------|
| ≥ 0.75 | 14.33 | 194.94 | 52.28 | 3.88 | 0.84 |
| ≥ 0.8 | 5.4 | 118.87 | 27.15 | 0.84 | 0.17 |
| ≥ 0.85 | 2.02 | 61.89 | 11.13 | 0.17 | 0 |
| ≥ 0.9 | 0.34 | 28.43 | 2.87 | 0 | 0 |
| ≥ 0.95 | 0.08 | 19.48 | 0.84 | 0 | 0 |

TABLE II: Quasi-exclusive cross section (in pb) at the Tevatron, after CDF cuts, using different F_M and gluon distributions.

| CDF cut | 1 | 2 | 3 | 4 | 5 |
|------------------------------|--------------------|--------------------|--------------------|-------|-------|
| Exclusive cross section (pb) | 5.56×10^3 | 7.97×10^2 | 5.25×10^2 | 61.47 | 61.21 |

TABLE III: Exclusive cross section $\sigma_{exc}(p\bar{p} \rightarrow p + \chi_{c0}(\rightarrow J/\psi\gamma) + \bar{p})$ (in pb) at the Tevatron energies for each CDF cut: 1 - one muon with $p_T \geq 1.5$; 2 - one muon with $p_T \geq 1.5$ and $|\eta| \leq 0.6$; 3 - two muons with $p_T \geq 1.5$; 4 - two muons with $p_T \geq 1.5$ and $|\eta| \leq 0.6$. 5 - same constraint of the forth column plus one gamma with $\eta \leq 3.5$.

VI. POSSIBILITY OF A NEW MEASUREMENT AT DØ

We now examine the possibility of measuring the exclusive χ_{c0} production at the Tevatron using the roman pot detectors in the DØ collaboration.

After interfacing the DPEMC generator with a program designed to propagate (anti)protons through the Tevatron lattice, from the DØ interacting point to the roman pot detectors [?], we can predict the number of events observed for different tagging configurations. The Forward Proton Detector (FPD) installed by the DØ collaboration [?] consists of eight quadrupole spectrometers, four being located on the outgoing proton side, and the other four on the antiproton side.

Each spectrometer allows the trajectory reconstruction of the outgoing protons and antiprotons near the beam pipe determining their energies and scattering angles. The quadrupole detectors are sensitive to outgoing particles with $|t| > 0.6 \text{ GeV}^2$ and $\xi < 3.10^{-2}$, with good acceptance for high mass objects produced diffractively in the DØ main detector.

We use the following selection cuts: ($(p_T(\mu^+) \geq 2.0 \text{ (GeV)} \text{ or } p_T(\mu^-) \geq 2.0 \text{ (GeV)})$ and $|\eta(\mu^\pm)| \leq 2.0$ and $|\eta(\gamma)| \leq 3.0$) (see Table ??).

| Regular Tevatron Stores - L = 100pb ⁻¹ | | | | |
|---|-------------------|-------------------|-------------------|-------------------|
| Scenario | A | B | C | D |
| 0 | 1.2×10^8 | 2.6×10^6 | 4.8×10^6 | 2.9×10^5 |
| DØ selection | 1.8×10^2 | 2.7×10^1 | 3.0×10^1 | 1.5 |

TABLE IV: Number of exclusive χ_{c0} events at the Tevatron (MC error $\sim 10\%$) for a regular Tevatron store. The scenario 0 represents all decay channels included without selection cuts. The columns represents the number of events: A - all (without p or \bar{p} tagging); B - tagged in the p side quadrupole; C - tagged in the \bar{p} side quadrupole and D - double tagged events in the quadrupoles.

We note that the number of events in double tagged configuration is quite small after applying the selection cuts, so this configuration might not be useful. However, a single tag event with a rapidity gap on the other side yields a good number of events, with the additional benefit of having the kinematics determined for one of the scattered particles.

VII. EXCLUSIVE χ_{c_0} PRODUCTION AT THE LHC

From the results on section IV, we expect a high production cross section of χ_c mesons at the LHC. We can estimate the number of events accessible to the TOTEM/CMS detectors, benefitting from the good acceptance of the TOTEM detectors for low mass objects. The TOTEM acceptance for the high β^* optics and low ξ values is typically 90 %, for the range $0 < |t| < 1 \text{ GeV}^2$. Then for 10 pb^{-1} of data, 5.3×10^6 double tagged events are predicted, with no requirement in the central detector activity. In this way, one might look for the χ_{c_0} in the reconstructed diffractive mass.

If central activity is required, the lowest possible muon p_T cut at low luminosity is on the order of $p_T \geq 1.5$ (GeV) for $|\eta| \leq 2.4$ [?]. Otherwise, the muon p_T threshold would be 4 (GeV), which is too high for exclusive χ_{c_0} production. The predictions for exclusive and quasi-exclusive production at the LHC are shown in tables ?? and ??. We note that the number of events can be dominated by exclusive production, independent of uncertainties in the gluon distribution, if a high enough cut on the mass fraction can be made, for instance at 0.95, which requires a good coverage of the CMS detector at high rapidities.

| Mass Fraction Cut | $\nu = 0$ | $\nu = -1$ | $\nu = -0.5$ | $\nu = 0.5$ | $\nu = 1$ |
|-------------------|-----------|------------|--------------|-------------|-----------|
| ≥ 0.9 | 1.35 | 138.11 | 17.88 | 0.34 | 0.17 |
| ≥ 0.95 | 0 | 13.83 | 1.18 | 0 | 0 |

TABLE V: Quasi-exclusive cross section (in pb) at the LHC, after central activity cuts, using different mass fractions and gluon distributions, defined in section V.

| Central cut | 1 | 2 | 3 | 4 |
|------------------------|--------------------|--------------------|--------------------|--------------------|
| Total | 3.74×10^3 | 1.43×10^3 | 3.64×10^2 | 1.27×10^2 |
| After Totem Acceptance | 3.03×10^3 | 1.16×10^3 | 2.95×10^2 | 1.03×10^2 |

TABLE VI: Exclusive cross section (in pb) $\sigma_{exc}(p\bar{p} \rightarrow p + \chi_{c_0} (\rightarrow J/\psi\gamma) + \bar{p})$ at the LHC energies for each central cut: 1 - one muon with $p_T \geq 1.5$; 2 - one muon with $p_T \geq 1.5$ and $|\eta| \leq 2.4$; 3 - two muons with $p_T \geq 1.5$; 4 - two muons with $p_T \geq 1.5$ and $|\eta| \leq 2.4$.

VIII. CONCLUSION

We calculate the diffractive production cross section for χ mesons at the Tevatron and LHC using an extended version of the Bialas-Landshoff model, including the full kinematics needed for low mass states. Both exclusive and inclusive production have been evaluated and discussed with various physically motivated cuts at generator level. The results can be listed as follows.

- The results for exclusive production at the Tevatron agree with a recent CDF upper limit for the exclusive production of χ_{c_0} , with the default parameters of the model (assuming that the non perturbative gluon coupling to the proton $G^2/4\pi \sim 1$);
- In the same conditions, the non-exclusive background (in particular “quasi-exclusive” events which we evaluate from the inclusive spectrum) can reach similar levels as the exclusive signal, due to experimental and theoretical uncertainties, making difficult to establish the observation of exclusive events within the current parameters;
- The possibility of observing exclusive χ_{c_0} production at the Tevatron, using the DØ forward detector is thoroughly investigated, showing the possibility of a measurement if a tight cut on the ratio between the χ_{c_0} mass and the total diffractive mass can be performed successfully.
- Exclusive production at the LHC, using the CMS/TOTEM detectors, is also investigated and appears promising, but again a high enough cut on the mass fraction is to be made before the observation of exclusive production can be established with a good confidence level. It could be suitable for a mass fraction, for instance at 0.95, which requires a good coverage of the CMS detector at high rapidities.

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Appendix A: Exclusive Production kinematics

Due the low mass of the χ mesons, we must evaluate the full kinematics of an exclusive production. The start point is the 4-momentum conservation in the center-of-momentum frame. Using the approximation $m_p = m_{\bar{p}} = 0$, where p and \bar{p} represent the colliding particles, we can make $E_{p,\bar{p}} = |\vec{k}_{p,\bar{p}}|$, and show that:

$$s = (k_p + k_{\bar{p}})^2 - (\vec{k}_p + \vec{k}_{\bar{p}})^2 + M_{diff}^2 + 2E_M(k_p + k_{\bar{p}}) - 2\vec{k}_M \cdot (\vec{k}_p + \vec{k}_{\bar{p}}) \quad (\text{A1})$$

where $\vec{k}_{p,\bar{p}}$ is the particle 3-momentum, s is the center-of-mass energy, M_{diff} is the diffractive mass, and E_M and \vec{k}_M are the respective energy and momentum of the produced state.

Due to energy and 3-momentum conservation $E_M = \sqrt{s} - k_p - k_{\bar{p}}$ and $\vec{k}_M = -(\vec{k}_p + \vec{k}_{\bar{p}})$. Moreover, we define

$$\vec{k}_p \cdot \vec{k}_{\bar{p}} \equiv \Omega k_p k_{\bar{p}} \quad (\text{A2})$$

where $\Omega = -\cos\theta_p \cos\theta_{\bar{p}} + \sin\theta_p \sin\theta_{\bar{p}}(\cos\varphi_p \cos\varphi_{\bar{p}} + \sin\varphi_p \sin\varphi_{\bar{p}})$, θ is the scattering angle and φ the polar angle. Using equation (??) and the conservation constraints in equation (??), it can be shown that

$$s = 2k_p k_{\bar{p}}(1 - \Omega) + M_{diff}^2 + 2\sqrt{s}(k_p + k_{\bar{p}}) - 4k_p k_{\bar{p}}(1 - \Omega) \quad (\text{A3})$$

Thus

$$M_{diff}^2 = s + 2k_p k_{\bar{p}}(1 - \Omega) - 2\sqrt{s}(k_p + k_{\bar{p}}) \quad (\text{A4})$$

using the definition of ξ

$$\xi_{p,\bar{p}} = 1 - \frac{k_z^{final}}{k_z^{initial}} \Rightarrow k_{p,\bar{p}} = \frac{\sqrt{s}/2}{\cos\theta_{p,\bar{p}}}(1 - \xi_{p,\bar{p}}) \quad (\text{A5})$$

Using equation (??) in (??):

$$\frac{M_{diff}^2}{s} = 1 + \frac{(1 - \xi_p)(1 - \xi_{\bar{p}})}{2\cos\theta_p \cos\theta_{\bar{p}}}(1 - \Omega) - \left(\frac{1 - \xi_p}{\cos\theta_p} + \frac{1 - \xi_{\bar{p}}}{\cos\theta_{\bar{p}}} \right) \quad (\text{A6})$$

In the case of $|t_{p,\bar{p}}| \rightarrow 0$, which means $\theta_{p,\bar{p}} \rightarrow 0$, the relation $M_{diff}^2 = s\xi_p \xi_{\bar{p}}$ is obtained.

Note that for convenience in the main text, the proton kinematics are labeled by the index 1 and the antiproton by 2.

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