Diffractive Production of Quarkonium in Proton-Nucleus Collisions at Large Hadron Collider

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Introduction

In this work we investigate the phenomenological approaches of diffractive exclusive production of quarkonia in collisions proton-nucleus for the LHC³ energies. These bound states are called quarkonium in analogy with positronium states in electromagnetic interactions. Such production of charm-anticharm states, called exclusive, possesses an experimental signal more "clean" than inclusive production because it is characterized by low multiplicity of particles between final produced states and the incident protons of the collider beam [1]. This is an open topic in literature and theoretical predictions in energies window available data at LHC are crucial.

Theoretical Basis

In particular, we make use of theoretical models based in Regge's Theory and perturbative models of Quantum Cromodynamics (QCD). Furthermore, we consider the exchange Pomeron model, understood as virtual object that makes possible the exclusive (diffractive) production analysis; thus this is the focus of this work. The inclusive process production occurs in the following way: two hadrons (protons and/or nucleons) interact in collision, and this results in two quarks, a charm and an anti-charm. Then, we use a *color evaporation model* (CEM) in order to hadronize the two quarks to result in a quarkonium bound state. This model provides us a cross section for a process in which the partons (quarks and gluons) of two hadrons (protons and/or nucleons), namely h1 and h2, interact for producing a heavy state called quarkonium H

$$h_1 + h_2 \to H(nJ^{CP}) + X$$

given by the cross section of pair production of heavy quarks, summed over all color states and spin. All information on the non-perturbative transition of the pair $Q\bar{Q}$ for the heavy H quarkonium with quantum numbers J^{CP}, It is contained in the factor $F_{nJ^{CP}}$ that a priori depends of all quantum numbers [2,3]

$$\sigma(h_1 h_1 \to H[nJ^{CP}]X) = F_{nJ^{PC}} \bar{\sigma}(h_1 h_1 \to Q\bar{Q}X) \quad (1)$$

where $\bar{\sigma}(Q\bar{Q})$ is the total cross section of open production of heavy quarks calculated by integration over the invariant mass of massive pair $Q\bar{Q}$ on $2m_Q$ to $2m_O$, being $2m_O$ the associated mass of D meson. This can be written as

$$\sigma_{pp}(\sqrt{s}, m^2_Q) = \sum_{i,j=q,\bar{q},g} \int dx_1 dx_2 f_i^p(x_1, \mu^2_F) f_j^p(x_2, \mu^2_F) \times \hat{\sigma}_{ij}(\sqrt{s}, m^2_Q, \mu^2_F, \mu^2_R) \quad (2)$$

where x_1 and x_2 are the momentum fraction due to partonic collision, f_i^p is the parton distribution of protons (*Parton Distribution Function*); we assume also that the factorization and renormalization scale are identical, $\mu = \mu_F = \mu_R$. In this work we use $\mu = 2m_Q$, setting the quark mass equal to 1,4 GeV. Such parameters give us a reasonable description of open production of heavy flavors [4-6]. The factor $F_{nJ^{PC}}$ is determined experimentally [7] being equal to $F_{11} \approx 2{,}5 \times 10^{-2}$.

Now, we analyze the diffractive exclusive production, modeled by a *single exchange of pomeron*. For this, we will consider the approach given by Ingelman-Schlein (IS) [8], where the pomeron structure (quark and gluon content) is explored. In the case of single diffraction, a pomeron is emitted by one of the hadrons. This hadron is detected in principle, in the final state and the remaining hadrons spread in relation to the emitted pomeron. The diffractive cross section of one hadron-hadron collision is factorized as product of pomeron-hadron cross section and Pomeron flux factor [8]. The single diffraction event is represented by

$$h_1 + h_2 \to h_{1,2} + H(nJ^{CP}) + X$$

Its differential cross section is written as

$$\frac{d\sigma^{SD}(h_i + h_j \to h_i + H[nJ^{CP}] + X)}{dx_P{}^i d|t_i|} = F_{nJ^{CP}} \times f_{P/h_i}(x_P{}^i, |t_i|)\ \bar{\sigma}(P + h_j \to Q\bar{Q} + X) \quad (3)$$

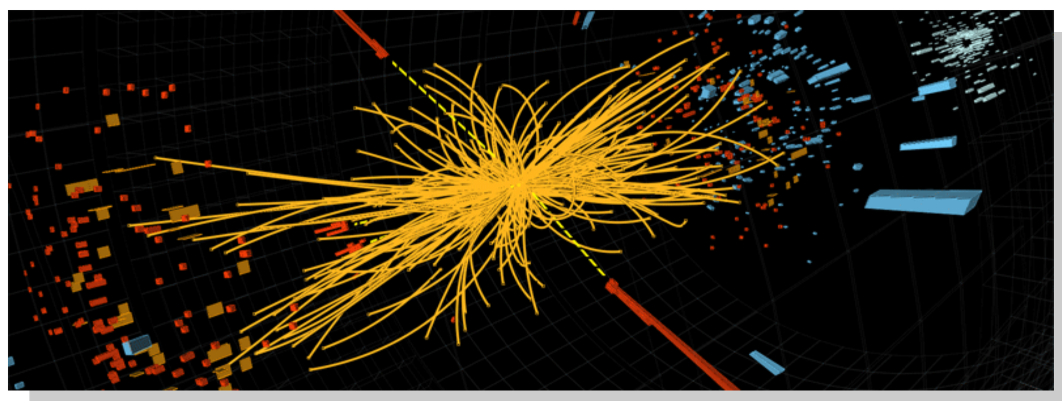
where the pomeron kinetic variable x_P is defined as $x_P{}^{(i)} = s_P{}^{(j)}$ and $\sqrt{s_P{}^{(j)}}$ is the centre of mass energy of jth pomeron-hadron system and $\sqrt{s_{ij}} = \sqrt{s}$ is the centre of mass energy of ith hadron-hadron. The transferred momentum in the hadron of i vertex is denoted by t_i .

Explicitly, the pomeron-hadron cross section is written as

$$\frac{d\sigma(P + h \to Q\bar{Q} + X)}{dx_1 dx_2} = \sum_{i,j=q\bar{q},g} \frac{f_{i/P}(x_1/x_P{}^{(1)}; \mu_F{}^2)}{x_P{}^{(1)}} \times f_{i/h_2}(x_2, \mu_F{}^2) \hat{\sigma}(\hat{s}, m_Q{}^2, \mu_F{}^2, \mu_R{}^2) + (1 \Leftrightarrow 2) \quad (4)$$

The flux factor gives the emission rate of pomeron by the hadron, here we use the experimental analysis of the diffractive structure function [9], where the dependency on x_P is parameterized using flux factor motivated by the theory of Regge

Research Process



Experimental Data (LHC)

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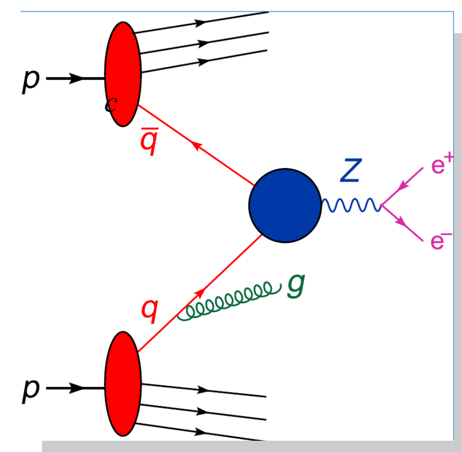

Application of theoretical models

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Numerical Analysis

```
include 'mrst2001lo.f'

program jpsi
implicit double precision
common /parametros/ mq2,
integer ee
external dsigmadxfdm

  open(unit=10, file='jps
```

Results Vs Experimental data

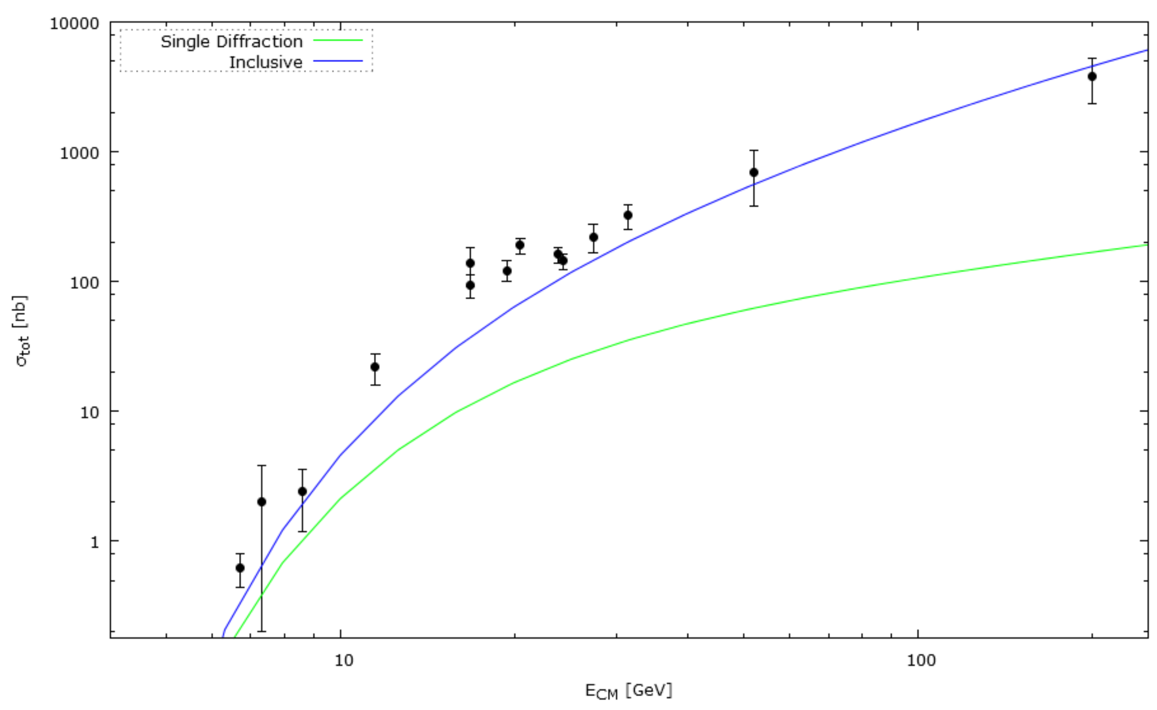

Figure 1. Total cross section versus centre of mass energy for inclusive hadronic production (blue curve). The green curve represents the total cross section for diffractive production.

$$f_{P/p}(x_P, t) = A_P \cdot \frac{e^{B_P t}}{x_P{}^{2\alpha_P(t)-1}} \quad (5)$$

where the pomeron's trajectory is assumed linear, $\alpha_P(t) = \alpha_P(0) + \alpha'_P t$, and the parameters $\alpha_P(0)$ and α'_P are obtained from the adjustment for the H1 FPS Data [9]. In addiction, in (4) the partonic distribution function $f_{i/h_2}(x_2, \mu_F{}^2)$, that in the numeric calculations was used the DPDF's (Diffractive Partonic Distribution Function) from the collaboration H1 FPS [9], [10] e [11] for PDF's.

We must also include corrections of multiple-pomerons exchange. In this calculation, we will consider the modification of the cross section by scattering effects of multiple pomerons due to the hadrons involved, a proton and a lead nucleus (Pb).

This is taken into account through the gap survival probability factor, $\langle |S|^2 \rangle = 4.39$, which can be described in terms of screening corrections or absorption [12,13,14] given by

$$A_{eff} = A \int d^2B\, T_A(B) \exp(-A\sigma^{in} T_A(B))$$

This suppression factor of a hard process accompanied by a rapidity gap does not only depend of probability of survival initial state, but it is also sensitive to the spatial distribution of partons within the input hadrons and so the dynamics of the entire diffractive part of the scattering matrix. The survival factor of *large rapidity gap* (LRG) on one hadronic final state is the probability of a given LGR not be filled in by subproducts, that originates from the soft rescattering of spectator partons and/or of gluons emitted by partons belonging to hard interaction.

Results and Final Considerations

Our analyzes were calculated numerically using algorithms in FORTRAN both for inclusive case and for the *diffractive* process, providing us the differential cross section $d\sigma/dy$ and σ_{TOT} in function of centre of mass energy of process.

The analyzes concluded that, with enough reliability, the theoretical prediction produced by numerical analysis agrees with the accelerators data including the LHC data for the inclusive process. Figure 1 displays a summary of the analysis. The experimental data on the inclusive production in the high energy regime are presented in their proper errors (up 200GeV regarding the RHIC accelerator). The blue line represents the theoretical prediction of the color evaporation model in function of the center of mass energy. The behavior and the order of magnitude are consistent with the data. In short, these promising results led us to develop predictions now for exclusive diffractive production processes of charmonium in p-Pb collisions. The green line represents the total cross section of the single diffraction quarkonium J/ψ production, which by the gap survival factor, allows estimate estimate the production rate for this process.

We obtained the following predictions for the LHC energy regime: 852 nb e 992 nb, for energies of 5,02 TeV and 8,8 TeV respectively. Here we use the gap survival factor given by reference [12] and again, the partonic distributions of collaborations [9,10,11]. That is, to obtain the predictions p-A, we multiply the result of the p-p process by the respective gap survival factor (assuming very weak dependence of the inelastic cross section with energy).

References

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³ LHC: The Large Hadron Collider is a hadron collider in operation at CERN (European Organization for Nuclear Research) located on the frontier between France and Switzerland. It has about 27km in circumference and is close to 100 meters deep in the ground, and until then the largest experiment carried out by humans. Furthermore, this magnificent instrument was made possible through the collaboration of 100 countries, involving more than 1.000 scientists. This only reinforces the power that mutual collaboration has to do science.