

High multiplicity pp events and J/ψ production at energies available at the CERN Large Hadron Collider

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(Received 20 April 2012; published 6 September 2012)

We discuss the dependence of J/ψ production on the charged particle multiplicity in proton-proton collisions at CERN Large Hadron Collider (LHC) energies. We show that, in the framework of parton saturation or string interaction models, the hard J/ψ production exhibits a significant growth with the multiplicity, which is stronger than linear in the high density domain. This departure from linearity, that should affect any hard observable, applies for high multiplicity proton-proton collisions in the central rapidity region and is a consequence of the parton saturation or the strong interaction among color ropes that take place at LHC energies. Our assumption, the existence of coherence effects present in proton-proton collisions at high energy, can also be checked by studying the particular shape of the probability distribution associated to the J/ψ production. Predictions for the forthcoming p Pb collisions at LHC energies are presented.

DOI: 10.1103/PhysRevC.86.034903

PACS number(s): 12.38.Mh, 25.75.Nq, 21.65.Qr

I. INTRODUCTION

Relativistic Heavy Ion Collider (RHIC) [1–4] and CERN Large Hadron Collider (LHC) [5–7] data on heavy-ion collisions have shown several important features which indicate the formation of a high density partonic medium with characteristic properties as the low shear viscosity and high opacity. Since the energy density achieved in high multiplicity events produced in pp collisions at LHC is comparable to the reached density in CuCu central collisions or AuAu peripheral collisions at $\sqrt{s_{NN}} = 200$ GeV, it is pertinent to wonder about the possibility to obtain a similar high density medium which would be reflected in experimental observables, similar to heavy-ion collisions. An illustration of this would be the predicted ridge structure [8,9] observed by CMS collaboration [10] in pp collisions. Also, the eventuality that other observables, as long range rapidity correlations [11–13], energy loss [14], or the elliptic flow [15,16], are measurable in pp collisions, has been reckoned with in different frameworks.

We address here to the J/ψ production in high multiplicity pp collisions. We will show that the rise of J/ψ production in the highest multiplicity events observed by the ALICE collaboration [17] can be naturally explained as a consequence of string interaction or parton saturation. This feature is particularly important, since, due to the absence of nuclear effects in this case, it can be used as a baseline in order to disentangle different mechanisms that are expected in heavy-ion collisions, as the J/ψ suppression due to sequential dissociation [18] or the J/ψ enhancement due to the recombination of uncorrelated c and \bar{c} quarks [19].

II. OUR APPROACH

Our main assumption, shared by many of the mentioned approaches, is the fact that, in high-energy hadronic collisions, all projectiles, be it protons or nuclei, have finite spatial extension and thus collide generically at finite impact parameter by means of elementary parton-parton collisions. We may consider the color ropes or flux tubes—*strings*—as the

fundamental variables of our description. They are formed in each parton-parton collision and they constitute the elementary sources of particle production. In this string framework, the number of parton-parton collisions is reflected as the number of produced strings, N_s . These strings have non-negligible transverse size, of the order of 0.2–0.3 fm and different space-time rapidities, and they can interact—*overlap*—so reducing the effective number of sources, in particular in which concerns soft particle production.

Consider now the hard particle production. The number of initially produced J/ψ , $n_{J/\psi}$, can be taken as proportional to the number of collisions, in analogy to any hard process. In the string-like models, this number corresponds to the number of produced strings, N_s . On the other hand, the rapidity multiplicity distribution $dN/d\eta$ —mainly soft—is not proportional to the number of collisions, but mostly to the number of participants. This reduction can be considered as a consequence of shadowing [20], parton saturation [21] or string interactions—*percolation*— [22]. In other words, in the string models, the J/ψ multiplicity behaves proportional to the number of strings N_s . On the contrary, the charged particle multiplicities suffer a strong reduction due to the interaction among the strings and behave roughly as $\sqrt{N_s}$. This behavior has striking consequences, as we will see below.

In particular, in the string percolation approach, the multiplicity distribution is given by

$$\frac{dN}{d\eta} = F(\rho)N_s\mu_1, \quad (1)$$

where μ_1 corresponds to the multiplicity of a single string in the rapidity range of interest, N_s is the number of produced strings and $F(\rho)$ corresponds to the damping factor induced by the string interaction,

$$F(\rho) = \sqrt{\frac{1 - e^{-\rho}}{\rho}}. \quad (2)$$

Note that, within the damping factor, $1 - e^{-\rho}$ represents the fraction of the total area that is covered by strings. The

interaction among strings and the consequent damping factor is a function of the the string density, $\rho = \frac{N_s \sigma_0}{\sigma}$, where σ_0 is the transverse area of one string, $\sigma_0 = \pi r_0^2$, $r_0 \sim 0.25$ fm, and σ corresponds to the transverse area of the collision. So the existence of many strings—directly related to the number of available partons—effectively screens the charged particle multiplicities, which agrees qualitatively with the concept of saturation.

On the other hand, assuming the proportionality between the number of produced J/ψ and the number of collisions,

$$\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle} = \frac{N_s}{\langle N_s \rangle}, \quad (3)$$

it is possible to obtain the relation between the charged particle multiplicity and the number of produced J/ψ , that, accordingly to Eqs. (2) and (3), will obey

$$\frac{dN}{d\eta} = \left(\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle} \right)^{1/2} \left[\frac{1 - e^{-\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle} \langle \rho \rangle}}{1 - e^{-\langle \rho \rangle}} \right]^{1/2}, \quad \text{where} \quad (4)$$

$$\langle \rho \rangle = \langle N_s \rangle \frac{\sigma_0}{\sigma}.$$

At low multiplicities, where the number of strings $\langle N_s \rangle$ is small, the above equation gives rise to the linear dependence

$$\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle} = \frac{\frac{dN}{d\eta}}{\langle \frac{dN}{d\eta} \rangle}. \quad (5)$$

On the contrary, at high multiplicities, the bracket in the right hand side of Eq. (4) can be approximated by $\langle \rho \rangle^{-1/2}$. One obtains in this case

$$\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle} = \langle \rho \rangle \left(\frac{\frac{dN}{d\eta}}{\langle \frac{dN}{d\eta} \rangle} \right)^2. \quad (6)$$

Thus the linear dependence obtained previously for low multiplicities, Eq. (5), changes to an squared dependence when high multiplicity events are at play.

Note that in the above equations we have used the approximation $\langle f(\rho) \rangle = f(\langle \rho \rangle)$. As the average refers to minimum bias distributions, and since we have considered smooth profile functions for the proton, this approximation is valid.

In order to compare with the available pp experimental data, we take $\sigma = \sigma_{\text{inel}}^{pp} = 70$ mb [23] as the transverse area of the collision. The number of strings, $\langle N_s \rangle$, can be obtained from the SFM code [24], a Monte Carlo code based on the quark gluon string model, similar to the dual parton model [25] or EPOS [26]. Moreover, the value of N_s can also be checked using the expression derived in Ref. [27], $\langle N_s \rangle = b + (2 - b) \left(\frac{s}{s_0} \right)^\lambda$, where $\lambda = 0.2-0.3$, $b = 1.37$ and the low energy threshold $\sqrt{s_0} = 10$ GeV. We obtained, for the central rapidity region, $\langle N_s \rangle = 16$, while in the forward rapidity region the number of strings is smaller, $\langle N_s \rangle = 8$. The reason for this difference is the fact that, while the long strings—stretched between valence quarks and diquarks of the colliding protons—cover most of the rapidity range thus contributing to both central and forward rapidity production, the short strings—stretched between sea quarks and antiquarks—are mostly created in the central rapidity region only.

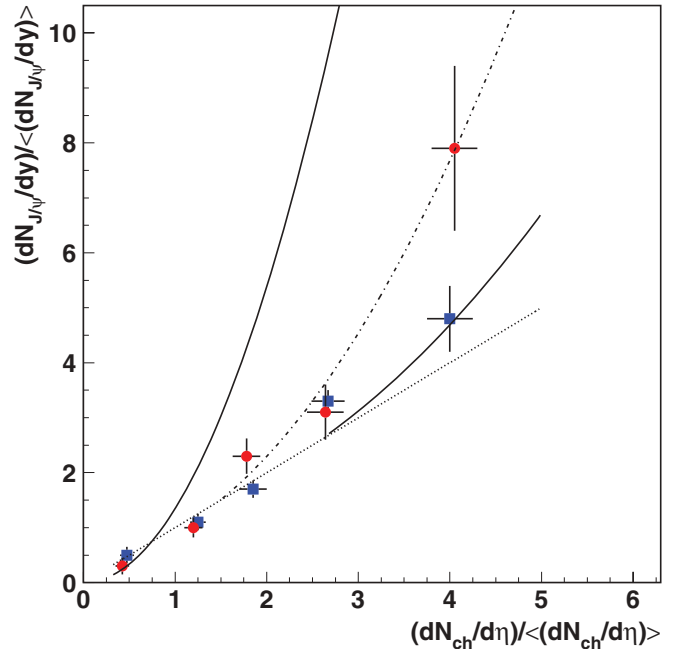


FIG. 1. (Color online) Our results for pp collisions in the central ($|y| < 0.9$, dashed line) and forward ($2.5 < y < 4$, dotted line) rapidity range, together with the experimental data for the central (circles) and forward (squares) rapidity regions from the ALICE Collaboration [17]. The linear behavior (solid line) and our prediction for $p\text{Pb}$ collisions (dashed-dotted line) at 7 TeV are also plotted.

III. RESULTS

In Fig. 1 we show our results for pp collisions for both the central and forward rapidity range, together with the experimental data from the ALICE Collaboration [17]. We observe a good agreement. The main uncertainty of our evaluation concerns the value of $\langle N_s \rangle$, which can induce an uncertainty in the $\langle \rho \rangle$ value of 20%, of the same order of the last experimental point error. Moreover, it would be most interesting to measure $\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle}$ at larger multiplicity, $\frac{dN}{d\eta} / \langle \frac{dN}{d\eta} \rangle \simeq 8-10$ to check the behavior of data. Note that for this high pp multiplicities, the values of the parton densities ρ are comparable to those obtained in CuCu central collisions or AuAu peripheral collisions at RHIC energies, where J/ψ melting is observed. If experimental data were significantly lower than our curve, this would be an indication of J/ψ suppression in absence of any nuclear effect.

Our study can be extended to pA collisions, by considering that the corresponding number of strings is proportional to the one in pp multiplied by the number of pA collisions ν , $\langle N_s^{pA} \rangle = \nu \langle N_s^{pp} \rangle$. In the rapidity range $-4 < \eta < -2$ and for $p\text{Pb}$ collisions at 7 TeV, $\nu \simeq 6$, according to Glauber models. Note nevertheless that in the case of pA collisions we can expect that other cold nuclear matter effects, namely shadowing and nuclear absorption can be at play. However, these effects saturate quite fast with centrality, so their influence in the ratio $\frac{dn}{d\eta} / \langle \frac{dn}{d\eta} \rangle$ should cancel out for $\frac{dn}{d\eta} > \langle \frac{dn}{d\eta} \rangle$. Our predictions for the LHC forthcoming $p\text{Pb}$ collisions are shown in Fig. 1.

Our assumption, the existence of coherence effects present in pp collisions at high energy, can also be checked by studying the probability distribution associated to the J/ψ production, $P_c(n)$. $P_c(n)$ refers to the charged particle multiplicity distribution associated with charm production—the probability of producing n particles, being, at least one of them, a J/ψ . This distribution is given by

$$P_c(n) = \frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle} P(n), \quad (7)$$

where $P(n)$ alludes to the usual charged particle minimum bias distribution. The above equation corresponds to the well-established universal relation between minimum bias distribution P and the multiplicity distribution associated to the production of a rare event c , P_c [28,29]. This formula is valid in any model of particle production based on the superposition of the contributions from elementary partonic interactions—as it is the case in most of the multiple scattering models—when the kind of events triggered is shadowed only by events of the same kind, and not for the whole of events. In addition to this requirement, these events must have a small cross section. In other words, one can say that the rare events are those produced only by one of the elementary interactions, the probability of it occurring twice in one collision being negligible. This is the case if one is triggering on a heavy particle like the J/ψ , and it would also be the case when studying Υ production or multiplicity distributions associated to W , Z^0 production in pp collisions. The validity of Eq. (7) has been checked for several cases in AA and pp collisions [28,29]. Moreover, a different trend for the multiplicity distributions for interactions with and without charm, in agreement with our expectations, was already obtained more than twenty years ago by NA27 Collaboration [30] in pp collisions. This difference was interpreted to be due to the more central nature of collisions leading to charm production. This is also the case in our approach, when taking the shape given by Eq. (7).

From the experimental pp minimum bias distribution $P(n)$ measured by ALICE [17] for the rapidity range $|\eta| < 1.0$, and using the relation established in Eqs. (5) and (6) for the computation of $\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle}$ as a function of the multiplicity, one can calculate the probability distribution for the J/ψ , $P_c(n)$, accordingly to Eq. (7). Our results for pp in the central rapidity region are shown in Fig. 2, compared to the minimum bias distribution $P(n)$ in this region. A particular shape, characterized by a reduction of the probability for low multiplicities and an increase at high multiplicities when compared to the minimum bias distribution is obtained. Moreover, we have checked that, when using PYTHIA 6.4 in the Perugia 2011 tune [31,32] for the computation of $\frac{n_{J/\psi}}{\langle n_{J/\psi} \rangle}$ as a function of the multiplicity, accordingly to the result presented in Refs. [17,33] in the central rapidity region, and applying Eq. (7), the opposite behavior results.¹

¹According to Ref. [17], the PYTHIA result exhibits a decrease of the J/ψ multiplicity with respect to the event multiplicity, contrary to data.

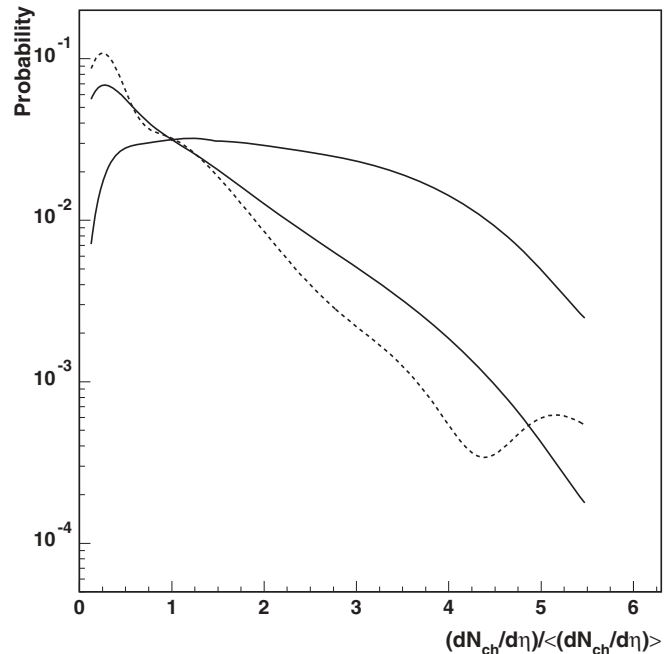


FIG. 2. Minimum bias experimental distribution $P(n)$ (solid line) compared to our obtained $P_c(n)$ distribution for the J/ψ (dashed line) and to the $P_c(n)$ distribution obtained when using PYTHIA for the J/ψ production (dotted line).

IV. CONCLUSION

In conclusion, we have reproduced here the rise of J/ψ production in the highest multiplicity events observed by the ALICE Collaboration in pp collisions. This increase, more pronounced in the central rapidity region, may be a consequence of the formation of a high density medium in pp collisions at LHC energies. In this case, the linear dependence of J/ψ production on the charged particle multiplicity obtained for low multiplicities—where the parton densities are smaller—changes to an squared dependence when high multiplicity events are at play, due to the high string densities.

This behavior can be checked by studying the probability distribution associated to the J/ψ production, compared to the minimum bias probability distribution. A particular shape, characterized by a reduction of the probability for low multiplicities and an increase at high multiplicities when compared to the minimum bias distribution would be obtained.

A similar behavior is obtained when studying J/ψ production in pPb collisions at similar energies, in absence of other cold nuclear matter effects.

ACKNOWLEDGMENTS

We are grateful to N. Armesto, G. Martinez, and C. A. Salgado for useful discussions. This work is supported by Ministerio de Economía y Competitividad of Spain (FPA2011-22776 and AIC-D-2011-0740) and FEDER.

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