CHARGED MULTPLICITIES AND $J/\psi$ SUPPRESSION AT SPS AND RHIC ENERGIES

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Charged multiplicities in nucleus-nucleus collisions are calculated in the Dual Parton Model taking into account shadowing corrections. Its dependence on the number of collisions and participants is analyzed and found in agreement with experiment at SPS and RHIC energies. Using these results, we compute the $J/\psi$ suppression at SPS as a function of the transverse energy and of the energy of the zero degree calorimeter. Predictions for RHIC are presented.

CHARGED MULTPLICITIES IN THE DUAL PARTON MODEL

In the Dual Parton Model (DPM) the charged multiplicity per unit rapidity in a symmetric collision is given by

$$
\frac{dN_{AA}^{ch}}{dy}(y,b) = n_A(b) \left[ N_{\mu}^{q\bar{q}^T}(y) + N_{\bar{\mu}}^{\bar{q}q^T}(y) + (2k - 2)N_{\bar{\mu}}^{q\bar{q}}(y) \right] + \left( n(b) - n_A(b) \right) \left( 2k N_{\bar{\mu}}^{q\bar{q}}(y) \right).
$$

Here $P$ and $T$ stand for the projectile and target nuclei, $n(b)$ is the average number of binary collisions and $n_A(b)$ the average number of participants of nucleus $A$. These quantities can be computed in a Glauber model. $k$ is the average number of inelastic collisions in $pp$ and $\mu(b) = kn(b)/n_A(b)$ is the total average number of collisions suffered by each nucleon. The first term in (1) is the plateau height in a $pp$ collision, resulting from the superposition of $2k$ strings, multiplied by $n_A$. Since in DPM there are two strings per inelastic collision, the second term, consisting of strings stretched between sea quarks and antiquarks, makes up a total number of strings equal to $2kn$.

The charged multiplicity produced by a single string is obtained by a convolution of momentum distribution function and fragmentation functions (eqs. (3.1) to (3.4) of [2]).

Shadowing corrections in Gribov theory are universal [3], i.e. they apply both to soft and hard processes. The reduction of the multiplicity resulting from shadowing corrections has been computed in [3]. These corrections are negligible at SPS energies but at RHIC energies they reduce the multiplicity by 40 to 50%.
We present the results obtained at two different energies: \( \sqrt{s} = 17.3 \) and 130 GeV. The corresponding non-diffractive cross-sections are \( \sigma_{ND} = 26 \) and 33 mb, respectively. We take \( k = 1.4 \) and 2.0 corresponding to \( dN_{pp}^{ND}/dy = 1.56 \) and 2.72. The result in absence of shadowing at \( \sqrt{s} = 17.3 \) is shown in Fig 1 (a). We obtain a mild increase of the multiplicity per participant consistent with the results of the WA98 Collaboration. This increase gets stronger with increasing energies. As we pointed out before, shadowing corrections are negligible at SPS energies but their effect is large at RHIC. Unfortunately, shadowing corrections have a rather large uncertainty at RHIC energies. Two alternative calculations of shadowing lead to the results at \( \sqrt{s} = 130 \) GeV shown by the solid lines in Fig 1 (b). Clearly, with the larger values of the shadowing corrections we obtain a quantitative agreement with the PHENIX data.

Note that our calculations refer to \( dN/dy \) while the first RHIC measurements refer to \( dN/d\eta \). The latter is, of course, smaller at mid rapidities. This difference is negligibly small as SPS where the laboratory pseudo-rapidity variable is used. However, at \( \sqrt{s} = 130 \) GeV where \( \eta_{cm} \) is used instead, their ratio can be as large as 1.3.

The predictions at \( \sqrt{s} = 200 \) GeV were also given in [1]. The predicted increase between 130 and 200 GeV is 13\% in quantitative agreement with the measurement by the Brahms Collaboration.

**J/ψ SUPPRESSION VS E_T AND E_2DC AT SPS**

In the comovers approach the \( J/ψ \) survival probability is the product of two factors \( S_{abs}(b,s) \cdot S_{co}(b,s) \). The first factor represents the suppression due to nuclear absorption of the \( c\bar{c} \) pair. Its expression, given by the probabilistic Glauber model, is well known. It contains a parameter, the absorptive cross-section \( \sigma_{abs} \). The second factor \( S_{co}(b,s) \) represents the suppression resulting from the interaction with comovers. They are given by
\[ S^{abs}(b,s) = \frac{[1 - \exp(-AT_A(s) \sigma_{abs})][1 - \exp(-B \ T_B(b-s) \sigma_{abs})]}{\sigma_{abs} \ AB \ T_A(s) \ T_B(b-s)} \]  
\[ S^{co}(b,s) = \exp \left[ -\sigma_{co} \frac{3}{2} N_{\text{YD}}(b,s) \elln \left( \frac{\frac{1}{3} N_{\text{YD}}(b,s)}{N_{\text{f}}} \right) \right] \]

In (3), \( N_{\text{YD}}(b,s) \) is the density of charged comovers (positives and negatives) in the rapidity region of the dimuon trigger and \( N_{\text{f}} = 1.15 \text{ fm}^{-2} \). \( \sigma_{co} \) is the corresponding density in \( pp \). The factor \( 3/2 \) in (3) takes care of the neutrals. In the numerical calculations we use \( \sigma_{abs} = 4.5 \text{ mb} \) and \( \sigma_{co} = 1 \text{ mb} \). We compute the density of comovers in the framework of the DPM as we have explained before.

This approach allows to compute the impact parameter of the \( J/\psi \) event sample. Experimental results of this quantity are plotted as a function of observable quantities such as \( E_T \) or \( E_{ZDC} \). Using the proportionality between \( E_T \) and multiplicity, we have

\[ E_T(b) = \frac{1}{2} q N_{\text{YD}}(b) \]  

The multiplicity of comovers \( N_{\text{YD}}(b) \) is determined using Eq. (4) in the rapidity region of the NA50 calorimeter (1.1 < \( y_{lab} < 2.3 \)). The factor 1/2 is introduced because \( N_{\text{YD}}(b) \) is the charged multiplicity whereas \( E_T \) refers to neutrals. Thus the coefficient \( q \) is close to the average energy per participant and its value can be determined from the position of the "knee" of the \( E_T \) distribution of the \( MB \) events measured by the NA50 Collaboration. We obtain \( q = 0.62 \text{ GeV} \).

The energy of the zero degree calorimeter is defined as

\[ E_{ZDC}(b) = [A - n_A(b)]E_{in} + \alpha n_A(b)E_{in} \]  

Here \( A - n_A(b) \) is the number of spectator nucleons of \( A \) and \( E_{in} = 158 \text{ GeV} \) is the beam energy. The last term represents the small fraction of wounded nucleons and/or fast secondaries that hit the ZD Calorimeter. The value of \( \alpha \) can be precisely determined from the position of the \( MB \) event sample measured by NA50. We obtain \( \alpha = 0.076 \). Eqs. (3) and (4) also lead to a correlation between (average values of) \( E_T \) and \( E_{ZDC} \). This correlation is close to a straight line and gives a good description of the experimental one.

To explain the experimental data beyond the knee of the \( E_T \) distribution we introduce two effects:

1. **Comovers fluctuations** [10]: We introduce the fluctuation in the density of comovers by replacing \( N_{\text{YD}}(b) \) in Eq. (3) by \( N_{\text{YD}}^2(b,s)F(b) \) where \( F(b) = E_T/E_T(b) \). Here \( E_T \) is the measured value of the transverse energy and \( E_T(b) \) is its average value given by Eq. (4) - which does not contain the fluctuations.

2. **\( E_T \) loss** [12]: In the \( J/\psi \) event sample, \( E_T \sim 3 \text{ GeV} \) is taken by the \( J/\psi \) trigger and, thus, the transverse energy deposited in the calorimeter by the other hadron species will be slightly smaller than the corresponding one in the \( MB \) event sample.

The results of our model for the ratio \( J/\psi \) over \( DY \), versus \( E_T \), in \( PbPb \) collisions at \( \sqrt{s} = 158 \text{ GeV} \), are shown in Fig. 2a and compared with NA50 data - both for the true \( J/\psi \) over \( DY \) ratio, and for the one obtained with the \( MB \) analysis. The results of the model for the true ratio are given by the dotted line (without fluctuations) and the dashed line (with fluctuations). In both cases the \( E_T \) loss mechanism is not taken into account. However, our results for the true ratio \( J/\psi \) over \( DY \) do not change, since the effect due to the \( E_T \) loss cancels in this ratio. We see that our results are in good agreement...
with the NA50 which do not extend beyond the knee. The other data in Fig. 2a are obtained with the MB analysis, and have to be compared with the dashed-dotted and solid curves (obtained taking into account the \( E_T \) loss). In this case the agreement with the NA50 data is substantially improved.

In Fig. 2b the results for the ratio \( J/\psi \) over \( DY \) versus \( E_{ZDC} \) are shown. These curves are obtained from the corresponding ones versus \( E_T \) applying the \( E_T - E_{ZDC} \) correlation \[13\]. Comparing the data with the model predictions, we see that a better description of the central data (small \( E_{ZDC} \)) is obtained when the \( E_T \) fluctuations are taken into account. This was to be expected since the fluctuations in \( E_T \) and \( E_{ZDC} \) are related to each other via the \( E_T - E_{ZDC} \) correlation. It is important to note that the effect of the \( E_T \) loss is not present in this case. Indeed \( E_{ZDC} \) measures the energy of spectators and it is not affected by the dimuon trigger. No disagreement between the data and the model predictions is observed in this case for very central events.

**FIG. 2.** a) Ratio \( J/\psi \) over \( DY \) versus \( E_T \) in PbPb collisions at 158 GeV \[12\]. The data are from ref. \[14\]. The data labeled with \( DY \) are for the true \( J/\psi \) over \( DY \) and they should be compared with the dotted and dashed lines obtained, respectively, without and with \( E_T \) fluctuations. The data labeled Min. Bias should be compared with the dashed-dotted and solid lines, obtained with the \( E_T \) loss. b) Ratio \( J/\psi \) over \( DY \) versus \( E_{ZDC} \) in PbPb collisions at 158 GeV per nucleon \[13\]. The dashed (dotted) curve is obtained from the dashed (dotted) one versus \( E_T \) applying the \( E_T - E_{ZDC} \) correlation and keeping the normalization unchanged. The data are from \[14\] \[15\]. The NA50 nuclear absorption curve is also shown.

### J/\psi SUPPRESSION AT RHIC

In order to compute the \( J/\psi \) suppression at RHIC in the comovers approach we need to know not only the effects of nuclear absorption and comovers interaction, but also the effect of shadowing – which becomes important at RHIC energies. Therefore, our predictions are only valid so far as the shadowing corrections cancel in the \( J/\psi \) over \( DY \) ratio – which is not necessarily the case \[16\].

For the comovers survival probability, Eq. \( (3) \), we keep the value \( \sigma_{co} = 1 \) mb as discussed above. The hadronic multiplicity at RHIC energies have been successfully evaluated in DPM \[1\]. Therefore, the prediction at RHIC for this survival probability is rather safe. The situation is quite different in what concerns the survival probability due to nuclear absorption. It is widely recognized \[16\] \[20\] that, at high
energy, when the coherence length becomes larger than the nuclear size, the probabilistic expression (2) is no longer valid. It has been shown in [20] that, at asymptotic energies, Eq. (3) is replaced by

$$S_{abs}(b, s) = \exp \left( -\frac{1}{2} \tilde{\sigma} A T_A(s) \right) \exp \left( -\frac{1}{2} \tilde{\sigma} B T_B(b - s) \right)$$

where $\tilde{\sigma}$ is the total $c\bar{c}$-N cross-section. If $\tilde{\sigma} \approx \sigma_{abs}$, the asymptotic result is not very different from the one obtained with the low energy formula – since Eqs. (2) and (3) differ only in the second correction term. This situation is expected if the $c\bar{c}$ pair is produced in a colorless state interacting as a dipole. However, the possibility has been advocated [18], that the $c\bar{c}$ pair is produced in a color state accompanied by light quarks – in order to make the system colorless. In this case the system interacts with a comparatively large cross-section $\tilde{\sigma} \sim 15 \div 20$ mb [17,18,21]. With such a cross-section it is possible to explain the large suppression of the $J/\psi$ observed at $x_F \sim 1$, without initial state energy loss of the projectile partons in the nucleus.

FIG. 3. Ratio $J/\psi$ over $DY$ versus charged multiplicity in Pb-Pb collisions at $\sqrt{s} = 200$ AGeV in the range $-0.5 < y^* < 0.5$. The dotted line is obtained with the low energy nuclear absorption Eq. (2) and $\sigma_{abs} = 4.5$ mb. The full line is obtained with the asymptotic expression Eq. (3) and $\tilde{\sigma} = 15$ mb.

The results for the ratio $J/\psi$ over $DY$ at mid-rapidities are presented in Fig. 3. The dashed line is obtained with Eq. (2) and $\sigma_{abs} = 4.5$ mb. The solid line is obtained with Eq. (3) and $\tilde{\sigma} = 15$ mb. As we see, the difference between the two predictions is very large.

The proposed way of measuring the $J/\psi$ suppression at RHIC is via the ratio $J/\psi$ over $\Upsilon$. For the latter, the situation is even more complicated. Due to its larger mass, the correlation length is smaller and Eq. (3) is not valid even at mid-rapidities. In this case a finite energy formula [17,18,20] has to be used – which interpolates between the low energy, Eq. (2), and the asymptotic (Eq. (3)) limits. Actually, even for $J/\psi$, Eq. (3) is not exact at mid-rapidities. We have estimated that using the finite energy formula with $\tilde{\sigma} = 15$ mb the ratio $J/\psi$ over $DY$ for central events is 40% higher than the solid line in Fig. 3. Therefore an accurate measurement in $pA$ interactions will be necessary in order to clarify the theoretical situation.

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