Transverse momentum of J/ψ produced in Oxygen-Uranium collisions at 200 GeV per nucleon

NA38 Collaboration

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Abstract : *The study of the J/ψ transverse momentum distribution in oxygen-uranium reactions at 200 GeV/nucleon shows that $< P_T >$ and $< P_T^2 >$ increase with the transverse energy of the reaction. Muon pairs in the mass continuum do not exhibit the same behaviour. The comparison of the J/ψ production rates in central and peripheral collisions shows a significant diminution for low P_T central events.*

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The study of 200 GeV/nucleon oxygen-uranium interactions has shown that the production of J/ψ relative to muon pairs in the continuum mass region decreases with increasing transverse energy produced in the collision [1]. This result is in agreement with the prediction first made by Matsui and Satz [2] in the case of a quark-gluon plasma (QGP) formation in which the color screening effect inhibits the binding of quarks c and $\bar{c}$ leading to a J/ψ. As pointed out later [3], this suppression should particularly occur for low transverse momentum c-$\bar{c}$ pairs. In this letter, the transverse momentum dependence of the J/ψ and continuum dimuons production is investigated, as a function of the transverse energy.

The data were collected at the CERN-SPS with the NA38 detector exposed to an incident beam of 10^7 ions/second. Muon pairs were detected with a spectrometer in the rapidity range $2.8 \leq y_{lab} \leq 4.0$ in correlation with the transverse energy, E_T, produced in the collision and measured with an electromagnetic calorimeter. Dimuon mass and transverse momentum resolutions are both approximatively 300 MeV (FWHM). Experimental details and data selection criteria can be found elsewhere [1,4].

The opposite sign (OS) muon pairs, $\mu^+\mu^-$, are mainly produced by vector mesons decay, Drell-Yan mechanism, $D\bar{D}$ pairs, as well as by a large amount of background resulting from the decay of pions and kaons emitted in the collision. These meson decays lead also to like sign (LS) muon pairs, $\mu^+\mu^+$ and $\mu^-\mu^-$. The OS mass distribution shows a large J/ψ peak lying above a steeply decreasing continuum [1]. The LS mass spectrum decreases and vanishes in the J/ψ mass region ($2.7 \leq M_{\mu\mu} \leq 3.5$ GeV/c^2). The contribution of the background in the OS transverse momentum spectrum is estimated from the LS distributions by :

$$2\sqrt{\frac{dN}{dP_T}^{++}\frac{dN}{dP_T}^{--}} \tag{1}$$

The same formula applied to other kinematical variables such as mass, Feynman's variable X_F, polar and azimuthal angles θ and ϕ, gives the amount of background in the corresponding OS spectra. This procedure requires the two following assumptions :

a) the distributions of the π and K multiplicities obey a Poisson law. This point has been investigated by a Monte-Carlo simulation using FRITIOF to generate O-U events. Deviations from the Poisson law slightly underestimate the background at low E_T but have a negligible effect on the P_T distributions.

b) the probability to detect a muon is independent of the sign of the second one. This condition is almost fulfilled for $M_{\mu\mu} \geq 1.7$ GeV/c^2 when an "image cut" is applied. This image cut rejects dimuons which do not remain in the acceptance if the sign of any muon of the pair is changed. The final selection leads to a sample of 6185 OS and 79 LS events in the J/ψ mass region. In the continuum region, i.e $1.7 \leq M_{\mu\mu} < 2.7$ GeV/c^2 and $M_{\mu\mu} > 3.5$ GeV/c^2, the corresponding numbers are 7808 and 5095.

To obtain the transverse momentum distributions the following procedure has been used as it takes into account the background and gives a correct estimate of the global errors. The method has been applied separately for muon pairs in the continuum mass region and in the J/ψ mass region. The observed OS spectrum is a sum of three terms

$$\left(\frac{dN_{OS}}{dP_T}\right)^{all}_{fields} = \frac{dN_{signal}}{dP_T} + \left(2\sqrt{\frac{dN}{dP_T}^{++}\frac{dN}{dP_T}^{--}}\right)_{field+} + \left(2\sqrt{\frac{dN}{dP_T}^{++}\frac{dN}{dP_T}^{--}}\right)_{field-} \tag{2}$$

The signal distribution $\frac{dN_{signal}}{dP_T}$ is related to the physical distribution $\frac{dN}{dP_{T_{phys}}}$ by

$$\frac{dN_{signal}}{dP_T} = \int S(P_{Tphys} \rightarrow P_T)\ A(P_{Tphys})\ \left(\frac{dN}{dP_{T_{phys}}}\right) dP_{T_{phys}} \tag{3}$$

where $S(P_{T_{phys}} \rightarrow P_T)$ and $A(P_{T_{phys}})$ are the smearing and acceptance functions.

The physical distribution $\frac{dN}{dP_{T_{phys}}}$ is parametrized phenomenologically according to $P_T e^{-\alpha(P_T)^{\beta}}$. This parametrization, which does not explicitely depend on the muon pair mass, is nevertheless able to reproduce our data, 95% of which lie in the narrow mass interval 1.7-2.7 GeV/c^2.

For muon pairs in the continuum mass region, the background distributions $\frac{dN}{dP_T}^{++}$

and $\frac{dN}{dP_T}^{--}$ for each sign of the magnetic field have been analytically parametrized to overcome statistical fluctuations in the data. In the J/ψ mass region where the number of LS events is small, the two last terms in equation 2 are neglected.

For the determination of the acceptance and smearing functions, an iterative procedure has been used. Dimuons are generated separately for J/ψ and continuum events, according to parametrized physical distributions in each kinematical variable. For a given initial set of the parameters, the individual muons are tracked through the apparatus and the accepted events are reconstructed exactly as the data. A new set of parameters is then determined by a simultaneous fit to the experimental OS and LS distributions, leading to new values of the acceptance and smearing functions. The final set of the parameters is given in table 1.

The P_T acceptance for J/ψ generated events, is displayed in fig.1. The small contribution ($\approx 6\%$) from the continuum in the J/ψ region is taken into account in the fit procedure. The results of the fits are shown in fig. 2 for J/ψ events and in fig. 3 for the continuum.

In order to study the behaviour of the P_T dependence as a function of the centrality of the collision, the same analysis is applied to six different intervals of the neutral transverse energy E_T^0 (fig.4). E_T^0 is deduced from the measured E_T, used in [1], by correcting for the contribution of the charged particles [4,5].

The parameters α and β are given in table 2 for each E_T^0 bin. In contrast to the J/ψ, the continuum events do not exhibit any significant E_T^0 dependence within the errors which are mostly due to the background. The average values of P_T and P_T^2 are shown in table 3 and figs 5a and 5b. As indicated in table 1, it has been assumed that the P_T and X_F distributions are uncorrelated. From a dedicated study in different E_T^0 intervals [6], it has been found that the effect of a correlation between both variables is negligible on the P_T acceptance and leads to a systematic error of 1% on the $< P_T >$ and $< P_T^2 >$ values. It should be noticed that the average values of P_T are higher for J/ψ than for events in the mass continuum and similar to those measured with proton beams on heavy targets [7-9]. On the other hand, J/ψ 's show a significant increase of $< P_T >$ and $< P_T^2 >$ with E_T^0. For $< P_T^2 >$, this feature can be seen from a linear fit which leads to a slope of $(9.7 \pm 0.9)\, 10^{-3}$ (GeV/c)^2/GeV. The corresponding value for events in the mass continuum is $(0.4 \pm 1.3)\, 10^{-3}$ (GeV/c)^2/GeV.

To further investigate the E_T^0 dependence of the P_T distributions for the J/ψ, the transverse momentum distributions are compared in fig.6 for the two extreme E_T^0 bins. In order to make a direct comparison, these functions are normalized to the number of continuum events at the J/ψ mass in the corresponding E_T^0 interval, which is obtained from the mass distribution. A clear lack of low P_T events is observed in central collisions. The ratio $R(P_T)$ of these two distributions is displayed in fig.7. In the P_T range from 0. to 2.7 GeV/c, it increases from 0.4 to $\sim$1. The corresponding ratio of the raw data which, to the first order, is independent of the apparatus effects shows a similar trend as can be seen from fig.7.

The chosen parametrization of the P_T distributions fits well all the data. However, a more common one, using the transverse mass, i.e $P_T e^{-\frac{2}{<M_T>}\sqrt{M^2+P_T^2}}$, has also been studied [6]. It also shows a good agreement with the data. The values of the parameter $< M_T >$ for the J/ψ are listed on table 4. The mean values $< P_T >$ and $< P_T^2 >$ remain unchanged within half a standard deviation. However, as a consequence of this parametrization, the ratio $R(P_T)$ rises exponentially, a feature which is not seen on the data above 2 GeV/c.

In conclusion, the transverse momentum distribution of the J/ψ produced in oxygen-uranium collisions has been studied as a function of the transverse energy of the reaction. It has been shown that their mean values $< P_T >$ and $< P_T^2 >$ increase monotonically with E_T^0, which is not observed for muon pairs in the continuum. The suppression of the J/ψ production relatively to the continuum occurs for low transverse momentum values.

It is known from proton-nucleus experiments [7,8] that initial state interactions lead to multiple scattering of gluons before fusion and shift the P_T distributions towards higher P_T values when a J/ψ is produced in a nucleus instead of a proton. This effect has been extrapolated to nucleus-nucleus reactions by several authors [10-12]. With the addition of a P_T independent absorption term they account for a significant part of the measured P_T dependence. On the other hand, the observed increase of $< P_T >$ and $< P_T^2 >$ with E_T^0 together with the behaviour of the ratio $R(P_T)$ is in agreement with the original prediction [3], in the hypothesis of QGP formation, and with subsequent theoretical calculations [13-15] which take into account the dynamical evolution of the QGP phase.

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generation range	J/ψ	*Continuum*
$M\ (1.3 \rightarrow 6.0\ GeV/c^2)$	$M = 3.097$	$\frac{1}{M^{5.9}}$
$P_T\ (0. \rightarrow 5.\ GeV/c)$	$P_T \exp\left(-0.84 P_T^{1.67}\right)$	$P_T \exp\left(-1.60 P_T^{1.43}\right)$
$X_F\ (-.17 \rightarrow .65)$	$(1 - \lvert X_F \rvert)^{3.9}$	$(1 - \lvert X_F \rvert)^{4.5}$
$cos\theta\ (-.8 \rightarrow .8)$	$uniform$	$1 + \cos^2\theta$
ϕ	$uniform$	$uniform$

Table 1 : Distributions of the kinematical variables resulting from the fit procedure.

E_T^0 (GeV)	J/ψ mass region α	β	χ^2/dof	continuum region α	β	χ^2/dof
all E_T^0	0.84 ± 0.05	1.67 ± 0.05	0.7	1.60 ± 0.10	1.43 ± 0.07	0.7
$E_T^0 < 20$	0.96 ± 0.14	1.64 ± 0.15	0.5	1.23 ± 0.23	1.79 ± 0.24	1.0
$20 < E_T^0 < 31$	0.84 ± 0.09	1.67 ± 0.10	1.2	1.85 ± 0.28	1.28 ± 0.15	0.7
$31 < E_T^0 < 39$	0.78 ± 0.11	1.73 ± 0.15	0.4	1.22 ± 0.25	1.66 ± 0.23	0.9
$39 < E_T^0 < 45$	0.74 ± 0.14	1.73 ± 0.18	1.4	1.93 ± 0.40	1.28 ± 0.23	0.7
$45 < E_T^0 < 52$	0.75 ± 0.15	1.68 ± 0.20	0.7	1.66 ± 0.43	1.50 ± 0.32	0.8
$E_T^0 > 52$	0.64 ± 0.16	1.82 ± 0.25	0.9	1.91 ± 0.70	1.20 ± 0.32	0.6

Table 2 : *Parameters of the P_T distributions in the different E_T^0 intervals and χ^2/dof values obtained from the maximum likelihood fit procedure.*

E_T^0 (GeV)	J/ψ mass region		continuum region	
	$< P_T >$	$< P_T^2 >$	$< P_T >$	$< P_T^2 >$
all E_T^0	1.12 ± 0.01	1.63 ± 0.03	0.85 ± 0.02	0.97 ± 0.04
$E_T^0 < 20$	1.05 ± 0.02	1.43 ± 0.05	0.85 ± 0.03	0.95 ± 0.07
$20 < E_T^0 < 31$	1.12 ± 0.02	1.63 ± 0.06	0.83 ± 0.04	0.96 ± 0.10
$31 < E_T^0 < 39$	1.13 ± 0.02	1.64 ± 0.07	0.90 ± 0.05	1.07 ± 0.11
$39 < E_T^0 < 45$	1.17 ± 0.03	1.76 ± 0.09	0.81 ± 0.06	0.90 ± 0.14
$45 < E_T^0 < 52$	1.18 ± 0.03	1.80 ± 0.09	0.80 ± 0.07	0.86 ± 0.15
$E_T^0 > 52$	1.20 ± 0.04	1.85 ± 0.12	0.85 ± 0.08	1.03 ± 0.16

Table 3 : *Mean values of* P_T *(GeV/c) and* P_T^2 $(GeV/c)^2$ *calculated from the* J/ψ *and the continuum distributions.*

	J/ψ mass region	
E_T^0 (GeV)	$< M_T >$ (GeV/c^2)	χ^2/dof
all E_T^0	0.463 ± 0.005	0.9
$E_T^0 < 20$	0.409 ± 0.008	0.6
$20 < E_T^0 < 31$	0.462 ± 0.011	1.2
$31 < E_T^0 < 39$	0.468 ± 0.013	0.4
$39 < E_T^0 < 45$	0.501 ± 0.016	1.5
$45 < E_T^0 < 52$	0.512 ± 0.017	0.7
$E_T^0 > 52$	0.528 ± 0.022	0.9

Table 4 : *Values of the* $< M_T >$ *parameter of the* P_T *distributions functions of the transverse mass.*

Figure captions

Fig. 1 : J/ψ acceptance as a function of the transverse momentum P_T.

Fig. 2 : P_T data distribution and fit for opposite sign dimuons in the J/ψ mass region.

Fig. 3 : P_T data distributions and fits for the events in the continuum mass region: opposite sign dimuons (upper distribution) and like sign dimuons ($\mu^+\mu^+, \mu^-\mu^-$ for both magnet polarities).

Fig. 4 : E_T^0 distribution for opposite sign dimuons with $\mathrm{M}_{\mu\mu} \geq 1.7$ GeV/c^2, corrected for target efficiency. The arrows indicate the 6 chosen E_T^0 intervals.

Fig. 5a : $< P_T >$ as a function of E_T^0, for the J/ψ and the continuum mass region events.

Fig. 5b : $< P_T^2 >$ as a function of E_T^0, for the J/ψ and the continuum mass region events.

Fig. 6 : P_T distributions for the J/ψ in the two extreme E_T^0 bins, normalized to the number of continuum events, N_c, at the J/ψ mass. The curves correspond to the envelope of all the functions with parameters within the covariance ellipsis.

Fig. 7 : The $\mathrm{R}(\mathrm{P}_T)$ distribution, represented by its envelope, together with the ratio of the raw data.