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Dimuon and J/Ψ Production in Ultrarelativistic Ion Collisions

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Abstract

The NA38 results obtained both in oxygen-uranium and sulphur-uranium reactions at 200 GeV/nucleon indicate a strong transverse energy dependence of the J/Ψ to Continuum ratio. This effect had been predicted to occur in case of Quark-Gluon Plasma formation, but explanations by hadronic effects are not ruled out. NA34 presented their first, low mass dimuon spectrum.

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1. Introduction

Dimuon spectrometry as a means of exploring rare processes such as vector meson production, Drell – Yan mechanism or emission of virtual thermal photons, is very attractive since the trigger looks for tracks surviving complete absorption of the produced hadrons in a hadron dump, and is therefore highly efficient and very selective at the same time.

The two largest CERN dimuon spectrometers were integrated into the ion beam program. NA3 was exposed to a second target in NA34, and NA10 was complemented with an active target and an electromagnetic calorimeter to become NA38. The original main motivation were the thermal dimuons, but shortly before the first ion runs the interest shifted onto the J/Ψ , when Matsui and Satz [1] predicted its suppression in case of quark-gluon plasma (QGP) formation.

2. Dimuon Data from NA34 (HELIOS)

In spite of a non-ideal hadron dump made of uranium calorimeters which totalled 350 radiation lengths, a sample of some 700 low mass dimuons from ^{32}S -Pt interactions was obtained by the NA34 collaboration, for large lab rapidities ($y > 4.2$), where the decay background is tolerable [2]. It is probably too early to extract physics from this data, but the prospect for more dilepton physics with ion beams is very encouraging.

3. The NA38 Dimuon Experiment

This experiment measures mass and P_T spectra of dimuons produced at 200 GeV/nucleon and at the highest available luminosity; normal running conditions have been around $5 \cdot 10^6$ interactions per burst of 2 effective seconds. The spectrometer accepts dimuons in the c.m. (lab) rapidity range $-0.2 < y^* < 0.9$ ($2.9 < y < 4.0$). Spectrometer and hadron absorber geometry and the trigger accept muons of $P_{T,\mu} \geq 0.5$, $P_{L,\mu} \geq 4$ GeV/c. The mass resolution at the J/Ψ is 0.144 GeV/c². The resolution in P_T is ± 0.11 GeV/c.

The electromagnetic calorimeter was made of Pb and scintillating fibres (2/3 and 1/3 in volume) and covered an average lab pseudorapidity range $1.9 < \eta < 4.1$. It was exposed to intense radiation, and its central core had to be replaced roughly every 10 days of running with ion beams (corresponding to 1-2 Mrad). It was calibrated by electrons in situ (to ± 20 % for oxygen beam) and monitored continuously. It was 12 cm long and preceded by 10 cm of BeO (density 2.8). Some 2/3 of the recorded transverse energy E_T was due to photons, the remainder to charged particles having interacted before the end of the calorimeter. The recorded E_T is thus a measure of some 50 % of the total E_T in the same rapidity range (assuming two times more charged than neutral transverse energy) with a statistical error of the order of 10 % and an error in the comparison between oxygen and sulphur spectra of 20 %.

Table I shows the number of reconstructed $\mu\mu$ events for the four projectile-target combinations used: p – U, O – Cu, O – U, S – U. Of these, a beam hodoscope selected those which had one and only one good incoming particle within ± 20 nsec. An active target (10-17 subtargets totalling 20 % interaction probability, surrounded by 24 tiny cylindrical scintillators) was used to select single interactions in the target. These two cuts prevented effectively any pile-up in the measurement of the transverse energy. Finally, events were required to have 2 and only 2 muons in the spectrometer, whose trajectories had to be aligned with the target. The Table indicates the numbers of J/Ψ which satisfy these criteria.

The vast majority of the ion beam events at masses below 3 GeV/c² were pairs of pion or K decay muons, with 70 % more $^{++}$ than $^{--}$ like-sign pairs. The $^{+-}$ decay pairs were estimated from the like-sign pairs to amount to $2 \sqrt{N^{++} \cdot N^{--}}$, and were subtracted bin by bin.

Most of the presented data are not corrected for acceptance (which is 7 % at the J/Ψ). This means that the mass spectra are deformed, but in a way which does not depend on the reaction nor on E_T as long as the y and P_T dependences do not vary much.

Table 1. Data used, J/Ψ to Continuum Ratios, Spectral Shape Parameter.

Reaction	p – U	O – Cu	O – U	S – U
Reconstr. dimuons Good J/Ψ ($2.7 < M < 3.5$)	700 000 4 904	845 000 5 100	2 250 000 7 225	5 300 000 12 760
Results of fits, $M > 1.7 \text{ GeV}/c^2$, M_c fitted :				
R (all E_T)	17.7 ± 1.3	15.9 ± 1.2	13.3 ± 0.7	10.8 ± 0.6
M_c (GeV/c^2)	$1.32 \pm .14$	$1.15 \pm .07$	$1.14 \pm .10$	$1.12 \pm .14$
R(high E_T)/R(low E_T)	–	$0.82 \pm .19$	$0.52 \pm .09$	$0.50 \pm .06$
Results of fits, $M > 2.1 \text{ GeV}/c^2$, fixed $M_c = 1.14 \text{ GeV}/c^2$:				
R (all E_T)	$19.9 \pm .90$	$14.6 \pm .60$	$13.0 \pm .40$	$12.6 \pm .30$
R(high E_T)/R(low E_T)	–	$0.69 \pm .09$	$0.52 \pm .07$	$0.49 \pm .04$

4. NA38: R, the J/Ψ / Continuum Ratio

Figure 1 shows the mass spectra obtained in S–U collisions at small and large E_T . We are interested here in the part of the spectrum above $M = 1.7 \text{ GeV}/c^2$, which includes the J/Ψ meson.

The numbers of produced J/Ψ 's must be normalized to some process of clearly understood physical meaning, in order to be able to interpret comparisons between different reactions and between E_T intervals within a given reaction. The NA38 collaboration uses the Matsui–Satz prescription [1], and assumes that the Continuum, i.e. the events above $M = 1.7 \text{ GeV}/c^2$ and outside the J/Ψ and the Ψ' have a production cross section similar to the Drell–Yan mechanism, i.e. proportional to $\Lambda_{\text{proj}} \cdot \Lambda_{\text{tgt}}$, and for given E_T intervals, to $\Lambda_{p,\text{proj}} \cdot \Lambda_{p,\text{tgt}}$. Here, Λ_{proj} and Λ_{tgt} are the projectile and target atomic numbers, and $\Lambda_{p,\text{proj}}$ and $\Lambda_{p,\text{tgt}}$ are the numbers of “participating” nucleons, i.e. those nucleons in each ion which penetrate the other ion during the collision. The relationship between E_T and $\Lambda_{p,\text{proj}}$ (and $\Lambda_{p,\text{tgt}}$) is needed to compute the energy density. It is calculated using HIJING generated interactions between hard sphere nuclei, and E_T values renormalized to the experimental distributions. For each ion reaction, we use 6 E_T intervals which contain roughly equal numbers of dimuon events, and correspond hence to unequal shares of the minimum-bias hadronic cross section, of which the first E_T bin covers roughly 50 %, and the last roughly 4 %. Note that for p–U interactions, there is almost no correlation between the number of participant nucleons (or the impact parameter) and the neutral E_T .

The mass distributions above $M = 1.7 \text{ GeV}/c^2$ are fitted to a sum of gaussians centered on the J/Ψ and on the Ψ' , and of a Continuum term $\text{const}/M^3 \cdot \exp(-M/M_c)$. The ratio $R = J/\Psi / \text{Continuum}$ is defined as sketched in Fig. 1, as the number of fitted J/Ψ divided by the number of fitted continuum events in the mass interval $2.7 < M < 3.5 \text{ GeV}/c^2$.

Fig. 1. a) Dimuon mass spectra observed in S-U collisions for low and high E_T , and illustration of the fitting procedure (see text). b) The background/signal ratio for S-U collisions.

5. NA38: Results and Discussion

As shown in Table I, and exemplified in Fig. 1, the ratio R decreases markedly both with increasing size of the interacting nuclei, and with increasing E_T (from $R = 13.1 \pm 1.0$ for $3 < E_T < 51$ GeV to $R = 6.5 \pm 0.5$ for $E_T > 125$ GeV in the two S-U spectra shown in Fig. 1). The decrease amounts to a factor of 2 between the two extreme of 6 E_T bins for both O-U and S-U reactions. This result cannot be due to an inadequate background subtraction procedure, since it does not change when the background to signal ratio in the continuum is halved by moving the lower limit of the fitted mass range from 1.7 to 2.1 GeV/c^2 (Fig. 1b and Table I).

For reasons already outlined, we do not use the E_T dependence of R for p-U (which is measured to be very weak).

Fig. 2. E_T independence is observed for two Continuum parameters : a) M_c for O-U and S-U, and b) $\langle P_T^2 \rangle$ for O-U, while $\langle P_T^2 \rangle$ of the J/ψ markedly increases with E_T . (Top scale for S-U, bottom scale for O-U).

Is the change in R due to a decrease of J/ψ production, or could it be due to an increase of the Continuum (which then would not be dominantly of Drell-Yan type) ? Two indirect pieces of evidence, both shown in Fig. 2, favour the J/ψ suppression hypothesis. The spectral shape parameter, M_c , does not depend on E_T , nor on the beam ion (Fig. 2a). The P_T distribution of the J/ψ widens with increasing E_T (Fig. 2b and 3), the one of the Continuum does not (Fig. 2b). Work is in progress on the relative normalization of the p-U, O-U and S-U data, a more direct way of checking whether the Continuum cross section does depend linearly on A_{proj} .

Fig. 3. Ratio $R(P_T)$ of P_T distributions of J/ψ at high and low E_T , for a) O-U and b) S-U reactions. The data are normalized to the Continuum events (integrated over P_T , for lack of statistics) in the same E_T intervals.

Fig. 3 shows explicitly that the J/ψ suppression is associated with low P_T ; near $P_T = 2-3$ GeV/c, the J/ψ to Continuum ratio is compatible with being E_T independent. (For lack of space, we skip the recently enriched debate on the P_T issue).

Are there plausible explanations for the observed A_{proj} and E_T dependence of R besides the QGP model of [1] ? The A_{tgt} dependence of J/ψ production in p-nucleus reactions has been measured extensively (see e.g. [3]). It has been attributed to final state nucleon-J/ψ interactions and extrapolated to the E_T dependence in ion-nucleus reactions by [4] who could however not account for an E_T dependence of R exceeding 15 %.

Fig. 4. J/Ψ / Continuum ratios versus Bjorken's energy density ϵ which also represents the density of produced pions. See text for p–U and (extrapolated) p–p bands. (Data from fits for $M > 2.1 \text{ GeV}/c^2$).

Final state interactions of the J/Ψ with the produced hadrons appear to have more scope. In Fig. 4, all J/Ψ to Continuum ratios R are plotted with respect to one single variable, $\epsilon = 2 \cdot E_T / (2.2 \cdot \pi \cdot 1.15^2 \cdot \Lambda_{p,proj}^{2,3})$. The numerical factors come from: $E_T^{TOT} = 2 \cdot E_T$, $\Delta\eta = 2.2$, $r_0 = 1.15 \text{ fm}$. ϵ is Bjorken's energy density [5], which governs the formation of QGP, and is also proportional to the density of produced hadrons. Qualitatively, a QGP model should lead to a kink at a value of ϵ where the transition starts, while hadronic final state interaction models [6] entail a rather smooth behaviour, and should make use of a reasonably low value of the hadron- J/Ψ inelastic cross section.

The shape of the curve in Fig. 4 is difficult to judge since there are no low ϵ ion beam points, and the p–U data are somewhat ill defined both in R (encompassing the two values obtained with free and with constrained M_C parameter) and in ϵ (there are arguments against using the measured proton radius, which would anyway yield an energy density larger with proton than with ion beams). The only reaction which should yield a ratio R at an undoubtedly low ϵ would be p–p, which has not been measured and was instead extrapolated from the p–U data using the $\text{Atgt}^{\Delta\infty}$ dependence of R for p-nucleus reactions measured by [3] to be $\Delta\infty = -.06 \pm .03$. (The vertical extension of the indicated p–p region includes the two R values for p–U of Table 1; its horizontal extension corresponds to proton radii of 1.15 and 0.75 fm, and to the measured hadron multiplicity [7]).

There is room for some further theoretical and/or experimental refinements. Already, the debate is open regarding the interpretation of the observed suppression of the production of the J/Ψ by a factor of four, between p–p and high E_T O–U and S–U, as compared to a hard process. Being a rather pure $c\bar{c}$ system, the J/Ψ is expected to interact rather weakly except with charmed quarks and/or a Quark-Gluon Plasma.

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