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ScienceDirect
Nuclear Physics A 00 (2010) 1–4
www.elsevier.com/locate/nuclphysa

Latest results on charmonium and open charm at the CERN SPS

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Abstract

The NA60 Collaboration has studied muon pair production in p-A and In-In collisions at SPS energy. In the charm sector, the main focus is on the measurement of the J/ψ, but also open charm production can be addressed through the measurement of continuum muon pairs from semi-leptonic decays of charmed hadrons. In this contribution the latest results obtained on J/ψ suppression in cold and hot nuclear matter will be presented. In addition, first preliminary results on the A-dependence of open charm production in p-A collisions at 400 GeV will be discussed.

Keywords:

1. Introduction

The suppression of charmonium states in nuclear collisions is considered as one of the most powerful signatures of the production of a deconfined state [1]. However, it was soon realized that cold nuclear matter effects (CNM), and in particular the interaction of the projectile and target nucleons with the $c\bar{c}$ pair, may sizeably contribute to the observed suppression [2]. Such effects are usually studied in p-A collisions, then extrapolated to A-A and compared with the observed yield in nuclear collisions, as a function of centrality. At SPS energy, the discovery of an anomalous J/ψ suppression, i.e. exceeding CNM effects [3], triggered a lot of theoretical and experimental work on the subject. In particular, the NA60 experiment has studied J/ψ production in In-In collisions [4], a lighter system which can be useful, in comparison with Pb-Pb, to investigate the centrality dependence of the anomalous suppression. Furthermore, NA60 has studied for the first time J/ψ production in p-A collisions at 158 GeV [5], at the same energy and in the same kinematical domain of Pb-Pb and In-In. Data have also been taken for p-A collisions at 400 GeV, an energy already accessed by the NA50 experiment.

It is well known that the so-called CNM effects are the result of a superposition of various initial- (shadowing, incident parton energy loss) and final-state effects ($c\bar{c}$ pair dissociation, final state energy loss). Open charm shares with charmonium most of the initial-state effects and the study of its production in p-A collisions may help in disentangling their contribution to charmonium production. Studies on CNM effects on open charm production are not as accurate as for the J/ψ, and various experiments even give apparently inconsistent results [6, 7]. Therefore, NA60 has performed an exploratory study of open charm in the dimuon channel, since events with semileptonic decays of charmed meson pairs give a detectable signal in the invariant mass continuum between the ϕ and the J/ψ (the so-called Intermediate Mass Region, IMR).

2. J/ψ production in p-A and A-A collisions

The study of p-A collisions in the NA60 experiment was mainly motivated by the need of a solid reference for the interpretation of nuclear collision results. Seven nuclear targets (Be, Al Cu, In, W, Pb, and U) were simultaneously exposed to the beam. The sophisticated NA60 experimental set-up [8], based on a high-resolution vertex spectrometer coupled to the muon spectrometer inherited from NA50, made it possible to unambiguously identify the target in which the J/ψ was produced as well as measure muon pairs from its decay with a $\sim$ 70 MeV invariant mass resolution.

Cold nuclear matter effects have been evaluated comparing the cross section ratio $\sigma^{J/\psi}_{pA}/\sigma^{J/\psi}_{p\mathrm{Be}}$, for each nucleus with mass number A, relative to the lightest target (Be). The beam luminosity factors cancel out in the ratio, apart from a small beam attenuation factor. However, since the sub-targets see the vertex spectrometer from slightly different angles, the track reconstruction efficiencies do not completely cancel out. Therefore an accurate evaluation of the time evolution of such quantities was performed target by target, with high granularity and on a run-per-run basis. The results [5], shown in Fig. 1(Left), are integrated over p_T and are given in the rapidity region covered by all the sub-targets, $0.28 < y_{\mathrm{CMS}} < 0.78$ for the 158 GeV sample and $-0.17 < y_{\mathrm{CMS}} < 0.33$ for the 400 GeV sample. Systematic errors include uncertainties in the target thickness, the rapidity distribution used in the acceptance calculation, and the reconstruction efficiency. Only the fraction of systematic errors not common to all the points is shown since it affects the evaluation of nuclear effects.

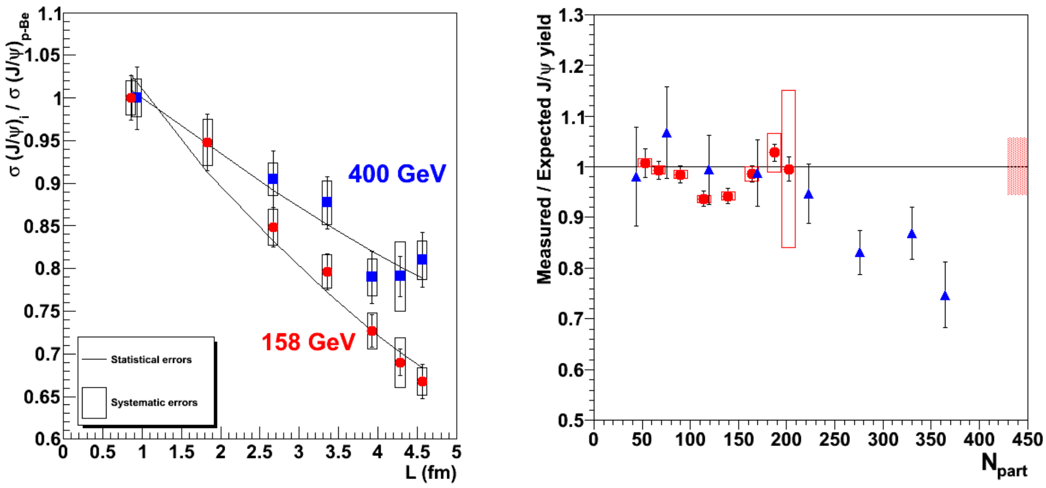

Figure 1: Left: the J/ψ cross section ratios for p-A collisions at 158 GeV (circles) and 400 GeV (squares) as a function of L, the mean thickness of nuclear matter traversed by the J/ψ ; Right: Anomalous J/ψ suppression in In-In (circles) and Pb-Pb collisions (triangles), as a function of N_{part}. The boxes around the In-In points represent correlated systematic errors. The filled box on the right-hand side corresponds to the uncertainty in the absolute normalization of the In-In points. A 12% global error, due to the uncertainty on $\sigma^{J/\psi}_{\mathrm{abs}}$ at 158 GeV, is not shown.

Nuclear effects have usually been parameterized by fitting the A dependence of the J/ψ production cross section using the expression $\sigma^{J/\psi}_{pA} = \sigma^{J/\psi}_{pp} A^{\alpha}$. Alternatively, the effective absorption cross section, $\sigma^{J/\psi}_{\mathrm{abs}}$ can be extracted from the data using the Glauber model. Both α and $\sigma^{J/\psi}_{\mathrm{abs}}$ are effective quantities since they represent the strength of the cold nuclear matter effects that reduce the J/ψ yield. However, they cannot distinguish between the different effects, e.g. shadowing and nuclear absorption, contributing to this reduction. The results in Fig. 1(Left) were used to extract $\sigma^{J/\psi}_{\mathrm{abs}} = 7.6 \pm 0.7\,(\mathrm{stat.}) \pm 0.6\,(\mathrm{syst.})$ mb (corresponding to $\alpha = 0.882 \pm 0.009 \pm 0.008$) at 158 GeV and $\sigma^{J/\psi}_{\mathrm{abs}} = 4.3 \pm 0.8\,(\mathrm{stat.}) \pm 0.6(\mathrm{syst.})$ mb ($\alpha = 0.927 \pm 0.013 \pm 0.009$)) at 400 GeV. Thus $\sigma^{J/\psi}_{\mathrm{abs}}$ is larger at 158 GeV than at 400 GeV. The 400 GeV result is, on the other hand, in excellent agreement with the previous NA50 result obtained at the same energy [9].

The p-A results at 158 GeV have been collected at the same energy and in the same rapidity range of the SPS A-A data. It is therefore natural to use these results to calculate the expected magnitude of cold nuclear matter effects on J/ψ production in nuclear collisions. In order to do so, the expected shape $dN^{\mathrm{expect}}_{\mathrm{J}/\psi}/dE_{\mathrm{ZDC}}$ of the J/ψ distribution as a function of the forward energy E_{ZDC} (the centrality estimator used for these studies) has been determined using the Glauber model. The J/ψ yield is assumed to scale with the number of NN collisions. The effective J/ψ absorption cross section in nuclear matter is assumed to be the same as the value measured in p-A at 158 GeV. The measured J/ψ yield,

$dN_{J/\psi}/dE_{ZDC}$, is normalized to $dN^{\rm expect}_{J/\psi}/dE_{ZDC}$ using the procedure detailed in Ref. [4]. This procedure previously did not take shadowing effects into account when extrapolating from p-A to A-A interactions. In p-A collisions, only the target partons are affected by shadowing while in A-A collisions effects on both the projectile and target must be taken into account. If shadowing is neglected in the p-A to A-A extrapolation, a small bias is introduced, resulting in an artificial $\sim$ 5% suppression of the J/ψ yield with the EKS98 parameterization [10]. Therefore, if shadowing is properly accounted for in the p-A to A-A extrapolation, the amount of the anomalous J/ψ suppression is reduced. Figure 1(Right) presents the results for the anomalous J/ψ suppression in In-In and Pb-Pb collisions [5] as a function of $N_{\rm part}$, the number of participant nucleons. Up to $N_{\rm part} \sim 200$ the J/ψ yield is, within errors, compatible with the extrapolation of cold nuclear matter effects. When $N_{\rm part} > 200$, there is an anomalous suppression of up to $\sim 20-30\%$ in the most central Pb-Pb collisions. The anomalous suppression is smaller than in previous estimates [3], since in the past a smaller $\sigma^{J/\psi}_{\rm abs}$, extracted fron data taken at higher energy (400 GeV), was used to evaluate cold nuclear matter effects.

3. Open charm production in p-A collisions at 400 GeV

The IMR of the dimuon invariant mass spectrum in p-A collisions can be described as a superposition of two physics signals: muon pairs from the Drell-Yan process (DY) and semi-leptonic decays of charmed hadron pairs ($D\overline{D}$). In addition, a combinatorial background from uncorrelated π and K decays can also give a sizeable contribution. The NA50 experiment had evaluated with this technique $D\overline{D}$ production in p-A collisions at 450 GeV [11], using four nuclear targets. Since the signal to background ratio was very low (S/B$\sim$0.05) the large systematic uncertainties due to background subtraction prevented a target-by-target determination of the $D\overline{D}$ contribution. The chosen approach was a simultaneous fit of the p-A mass spectra, imposing the ratio $D\overline{D}/DY$ to be constant vs A. In this way it was possible to determine an open charm cross section and compare it to other measurements from fixed-target experiments, but not to investigate its A-dependence.

In NA60, thanks to the very good accuracy on the muon production point ($\sim$30 μm in the transverse coordinate [8]) it is possible to efficiently reject combinatorial background. Indeed, in the IMR, the S/B ratio is 60 times more favourable than in NA50 and such a cleaner environment has allowed for the first time a target-by-target determination of the $D\overline{D}$ yield. In Fig. 2(Left) we show the invariant mass spectrum in the region $m_{\mu\mu} > 1.5$ GeV/c^2 for p-U collisions at 400 GeV, together with the result of a fit which includes the J/ψ, ψ', DY and $D\overline{D}$ contributions. The expected mass shapes for the various processes have been evaluated through a Monte-Carlo simulation based on PYTHIA [12] with the GRV94LO [13] parton distribution functions. These simulations also provide the values of the acceptances within the selected kinematical domain $-0.17 < y_{\rm CMS} < 0.33$.

One clearly sees that the combinatorial background, obtained with a mixed-event approach [8], plays a minor role. The DY contribution has been tied to the statistically much larger J/ψ signal using the ratios (J/ψ)/DY obtained by NA50 at the same energy/kinematic domain [9]. Such a fit satisfactorily describes the spectrum of Fig. 2(Left), with χ^2/ndf=0.68, as well as the spectra corresponding to the other nuclear targets.

The A-dependence of open charm production has been investigated by studying the acceptance-corrected ratio (J/ψ)/$D\overline{D}$ as a function of A. In this way the systematic errors connected with the luminosity evaluation cancel out. The preliminary result is shown in Fig. 2(Right). By fitting the points with the A^α parameterization one can extract $\alpha_{J/\psi/D\overline{D}}$ = 0.97 ± 0.03(stat.) ± 0.01(syst.). The systematic error has been evaluated by varying around the chosen default values the fit starting point, the maximum χ^2 for the muon tracks and the normalization of the combinatorial background. The uncertainties on the (J/ψ)/DY ratios from NA50 have also been taken into account in the systematic error determination.

Finally, using the $\alpha_{J/\psi}$ values obtained by NA50 [9], and combining statistical and systematic uncertainties, it is possible to evaluate $\alpha_{D\overline{D}}$ = 0.96 ± 0.03. At 400 GeV, in the kinematical domain corresponding to this measurement, the gluonic parton distribution function (PDF) is expected to be anti-shadowed [14]. This initial-state effect would lead to $\alpha_{D\overline{D}}$ >1, with preliminary estimates in the range 1.05-1.1 [15], depending on the adopted parameterization of nuclear effects on PDF.

The analysis method described in this Section can in principle be applied also to the 158 GeV data sample. However, going towards such a small energy, the $D\overline{D}$ cross section decreases faster than the DY one. In this way the $D\overline{D}$ contribution to the IMR becomes much smaller than the DY. Furthermore, no results on the (J/ψ)/DY ratios,

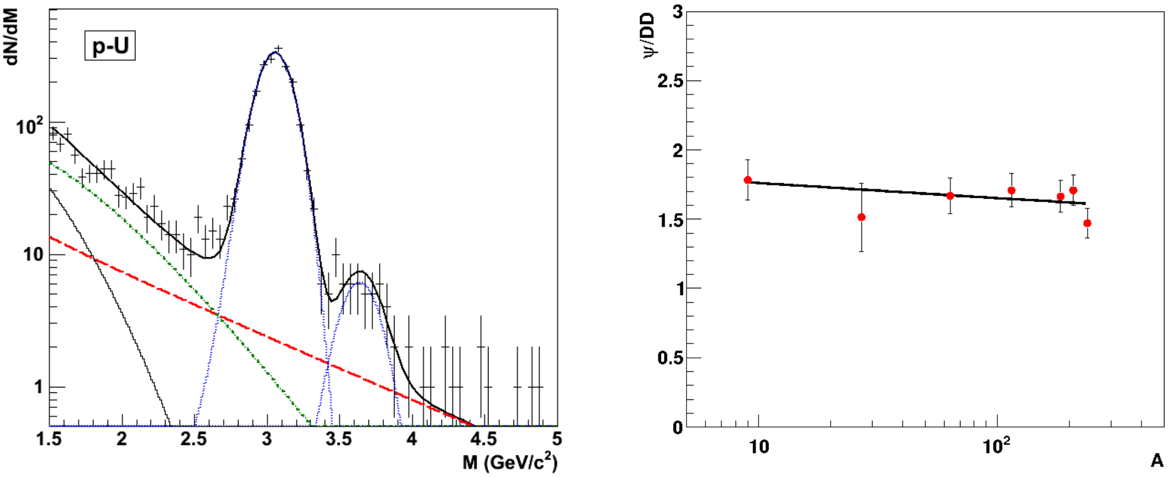

Figure 2: Left: Fit to the dimuon invariant mass spectrum for p-U collisions at 400 GeV.The dashed line represents the DY, the dot-dashed line the $D\overline{D}$, the thin continuous line the combinatorial background. The resonance contributions are shown as dotted lines; Right: the ratio (J/ψ)/$D\overline{D}$ as a function of A, together with the result of the A^{α} fit. The plotted errors are purely statistical.

which are used to constrain the DY contribution, are available at this energy. Work is in progress to estimate the larger systematic errors in these more unfavourable conditions.

4. Conclusions

The NA60 experiment has performed a measurement of cold and hot nuclear matter effects on J/ψ production at SPS energy. In the charmonium sector J/ψ production has been measured in p-A at 158 GeV, the same energy of nuclear collisions studied by NA50 and NA60, and at 400 GeV. CNM effects become stronger when the incident proton energy decreases. CNM effects measured at 158 GeV have been extrapolated to the conditions expected for nuclear collisions, and the expected J/ψ yield has been compared to In-In and Pb-Pb results. A clear sign of an anomalous J/ψ suppression has been found for Pb-Pb, for N_{part} >200.

A preliminary measurement of open charm production in p-A collisions at 400 GeV has also been carried out, and an evaluation of CNM effects has been performed. The preliminary NA60 result ($\alpha_{D\overline{D}}$ = 0.96 ± 0.03) seems to indicate that together with anti-shadowing, which would give $\alpha_{D\overline{D}}$ >1, other suppression mechanisms should be present.

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