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Dilepton measurements with NA60

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The NA60 experiment at the CERN SPS has measured muon pair production in In-In and p-A collisions. A significant excess with respect to expected sources has been observed, for In-In interactions, in the mass region below the J/ψ, likely connected with thermal dimuon production. A study of the transverse momentum distribution of the excess suggests that a significant fraction of the thermal emission is of partonic origin. Furthermore, a suppression of the J/ψ yield beyond pure nuclear absorption has been observed, with an onset of the effect at $N_{\text{part}} \sim 80$. The J/ψ production has also been studied for the first time in p-A collisions at 158 GeV, the same energy of the In-In data sample, providing an important reference for the charmonium suppression studies. In this paper, the available results are presented, and future perspectives are shortly discussed.

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1. Introduction and experimental set-up

The study of muon pair production in ultrarelativistic heavy-ion collisions is among the richest sources of information on the features of the produced strongly-interacting medium. From the physics point of view, the study of the muon pair continuum is potentially sensitive to thermal production and gives also access to the study of the open charm yield. On top of that, resonances decaying into two muons (ρ, ω, ϕ and J/ψ) have always been considered, in various ways, as potential probes of the deconfined phase. From the experimental point of view, the relatively unambiguous particle identification technique, based on hadron filtering through a thick absorber, allows running at high beam intensities (more than 10^7 incident ions/s at SPS energies). As a consequence, huge statistics can be collected for processes with large production cross sections, and also relatively rare channels can be investigated. The main drawback to such a kind of measurement is the loss of resolution in the muon measurement induced by the multiple scattering of the muons in the hadron absorber. Furthermore, a significant combinatorial background, due to uncorrelated decays of π and K, can be present. This contribution is particularly important at low ($m_{\mu\mu} < 1$ GeV) and intermediate masses (1< $m_{\mu\mu} < 2.5$ GeV).

The situation drastically improved in recent years, thanks to the NA60 experiment. In its set-up, a conventional muon spectrometer (MS), inherited by the previous NA50 [1] experiment, was coupled to a vertex telescope (VT), based on Si pixel detectors and positioned in a dipole field [2, 3]. Thanks to its excellent granularity (the pixel size was 50×425 μm^2), the VT allowed tracking in the high-multiplicity environment created in nucleus-nucleus collisions. By matching the tracks measured in the MS with the corresponding tracks in the VT, one can access the kinematical variables of the muons before their distortion due to multiple scattering and energy loss fluctuations in the hadron absorber. As a consequence, there is an improvement of the dimuon mass resolution, particularly important at low masses (from $\sim$70 to $\sim$20 MeV for the ω) and an accurate determination of the origin of the muons can be performed [4]. The matching technique also allows a reduction of the combinatorial background levels, since most muons from π and K decays do not point to the target. The described set-up is complemented by a beam tracker (BT) giving, with a $\sim$20 μm accuracy, the transverse coordinate of the incident beam particles, and by a Zero-Degree Calorimeter (ZDC) [5], which measures the energy of spectator nucleons providing a direct estimate of the number $N_{\rm part}$ of participant nucleons.

With this set-up, NA60 has studied In-In collisions at 158 GeV/nucleon and p-A collisions at 158 and 400 GeV. On one hand, the aim of nucleus-nucleus data taking was to clarify the observations obtained by previous experiments in the study of the muon pair continuum in the low and intermediate mass regions. Experiments like CERES [6], Helios-3 [7] and NA38/NA50 [8] had in fact measured an excess over the expected dimuon sources, but a satisfactory interpretation of these observations was missing, also because of intrinsic experimental limitations. Among them, we can mention the low statistics collected by CERES (which studied the e^+e^- channel) and the impossibility of separating, in the intermediate mass region, the contribution of open charm decays from prompt dimuon production. On the other hand, the discovery of the anomalous J/ψ suppression, carried out by NA50 [9], had such a large impact on the field, that a similar study performed with lighter colliding ions was considered as very interesting. In particular, the aim was to identify a "scaling" variable for the onset of the suppression as a function of centrality (number of partici-

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pants, energy density...), in order to obtain more information on the underlying physics mechanism. On top of nucleus-nucleus data, p-A collisions represent a necessary set of reference data. In particular, for the first time, NA60 has taken data at 158 GeV, the same energy of the nucleus-nucleus data sample. In this way, no theoretical rescaling of the experimental results is needed, leading to an overall reduction of the systematic errors involved in the comparison procedure.

2. The continuum at low and intermediate masses

In the mass region below 2 GeV, after background subtraction, the In-In data sample contains about $3.6{\cdot}10^5$ muon pairs. It has been shown [10] that the peripheral data ($4< dN_{ch}/d\eta <30$) can be described by the expected electromagnetic decays of neutral mesons. This is not the case for more central events, where a strong excess is present. For such events, the excess has been isolated by subtracting the contribution of the hadronic cocktail, using a novel procedure based only on local criteria. The resulting spectrum (see Fig. 1(left)) shows a peaked structure, centered around the position of the ρ pole, residing on a broad continuum. As a function of centrality, the size of the excess strongly increases, while the peaked structure broadens, but remains centered at the ρ mass.

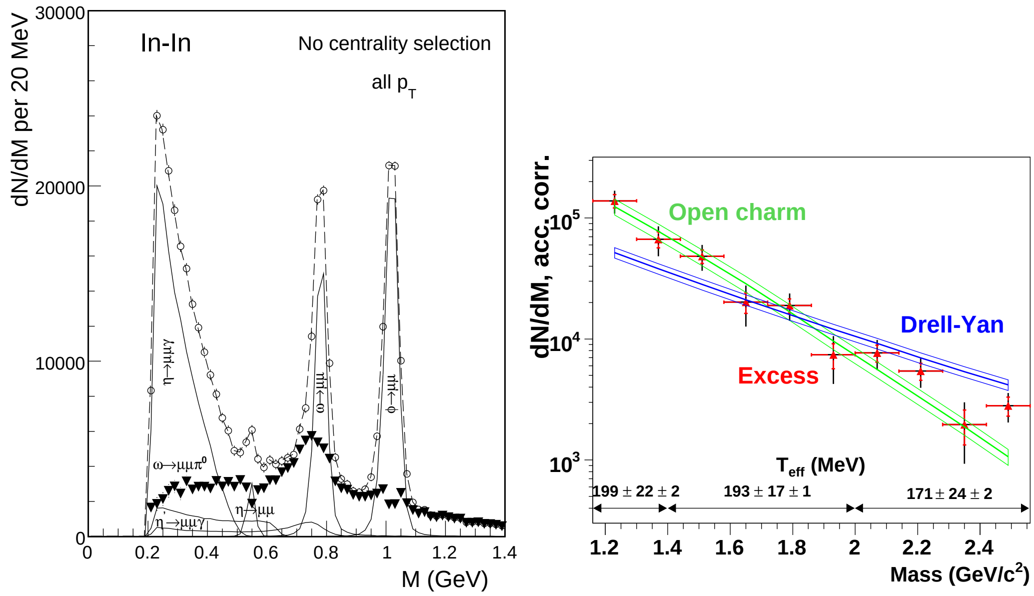

Figure 1: (left) The excess above the electromagnetic decays of neutral mesons in the low mass region. Total data (open circles), individual cocktail sources (solid), excess (thick triangles), sum of cocktail sources and difference data (dashed). (right) Excess mass distribution in the intermediate mass region and comparison to Drell-Yan and open charm. The inverse slope parameters T_{eff}, extracted from the p_T distributions, are also shown.

In the intermediate mass region, where the expected sources are the semileptonic decays of open charm pairs and the Drell-Yan process, the analysis is based on the study of the distributions of the offset of the dimuons from the interaction vertex. This analysis [11] shows that the observed open charm yield in In-In is consistent with an extrapolation of the results obtained in p-A collisions by NA50. On the other hand, we find an excess, coming from a prompt source, with a size 2.4 times larger than the expected Drell-Yan yield. Figure 1(right) shows the dimuon excess mass distribution observed in the intermediate mass region. The slope of the excess is found to be steeper than the expected Drell-Yan.

For $m_{\mu\mu} < 1$ GeV the dimuon excess is clearly dominated by the process $\pi^+\pi^- \to \rho \to \mu^+\mu^-$ with a strongly modified intermediate ρ. Various many-body hadronic models are able to describe the data with a strongly broadened intermediate ρ without any mass shift. On the other hand, there is not a unique interpretation for masses above 1 GeV. There are models able to describe this region in terms of partonic processes (the long sought radiation from the plasma) [12], others where the predominant processes are hadronic (4-pion annihilation or higher processes) [13]. This ambivalence reflects what is usually called parton-hadron duality.

In order to try clarifying this situation, NA60 has now focused its attention on the transverse momentum spectra, which encode information on the source temperature and on the collective motion (radial flow) that takes place during the fireball expansion. When the spectra are fitted with the simple Boltzmann-like function $dN/dp_{\rm T} = p_{\rm T}\exp(-m_{\rm T}/T_{\rm eff})$, the effective temperature $T_{\rm eff}$ extracted from the spectra is not any longer the source temperature. It is blue shifted (boosted) by the collective motion and acquires a linear dependence on mass. Since dimuons are emitted continuously during the whole fireball lifetime, they probe regions where the source temperature was high and the flow was small (early phases of the fireball with a low effective temperature close to the real source temperature), or regions where the temperature was low and the flow was high (later phases of the fireball lifetime with a larger effective temperature because the increasing flow boost predominates over the fireball cooling). In this way, dimuon transverse momentum spectra can be used as a diagnostic tool to access the emission region and may differentiate between a hadronic or a partonic nature of the source.

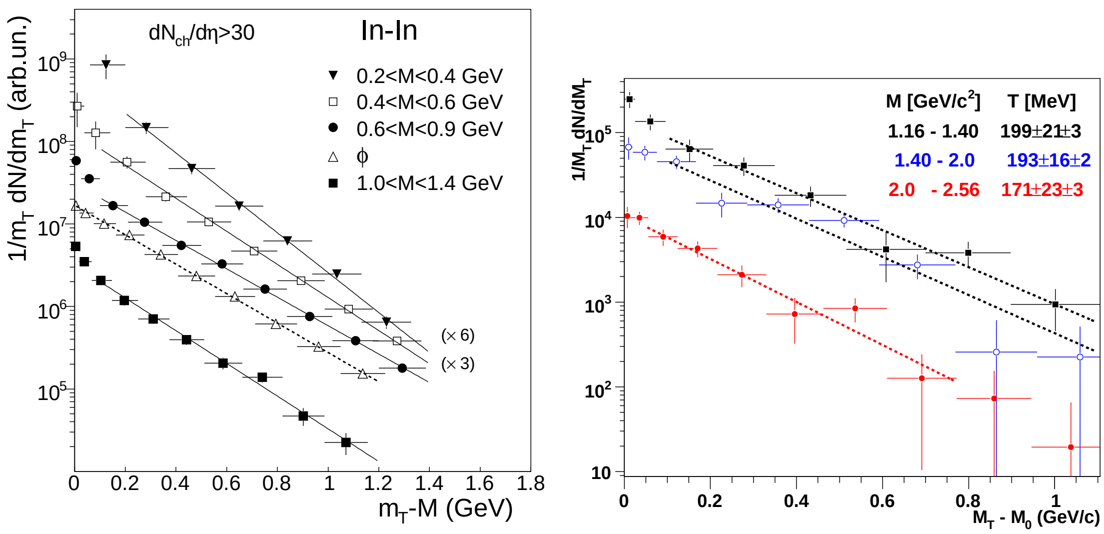

Figure 2: (left) Transverse mass spectra of the excess in the low mass region, in four different mass windows. The φ is also shown for comparison. (right) Transverse mass spectra of the excess in the intermediate mass region, for three mass windows.

The acceptance-corrected transverse momentum spectra of the excess were measured for several mass intervals from threshold up to 2.6 GeV. The results are shown in Fig. 2. They were fitted with the Boltzmann-like exponential function given above. The effective temperature T_{eff} as a function of the dimuon invariant mass is shown in Fig. 3. For comparison, also the temperature of the stable hadrons η, ω and ϕ, as measured by the same experiment, are shown (open circles). Several striking features are seen. First, the effective temperature of the excess shows an almost linear rise with mass up to $m_{\mu\mu} = 1$ GeV, as for the hadrons. As mentioned above, this is a rather clear evidence of radial flow.

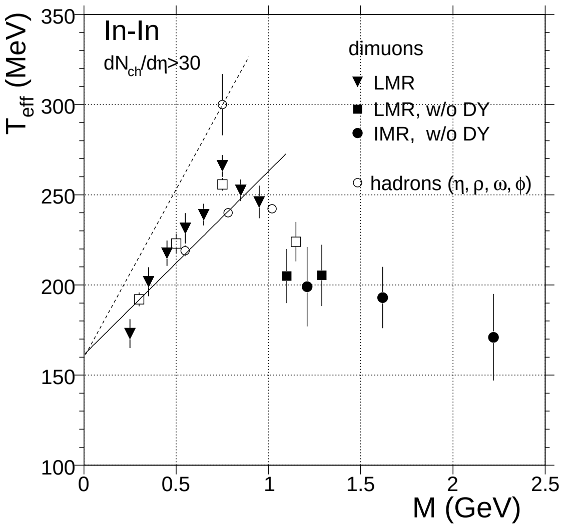

Figure 3: Inverse slope parameter T_{eff} vs. dimuon mass M for $\mathrm{d}N_{\text{ch}}/\mathrm{d}\eta > 30$.

Second, the effective temperature exhibits a sudden drop of almost 50 MeV at $m_{\mu\mu} = 1$ GeV. In addition, for masses beyond 1 GeV, T_{eff} remains at an approximately constant value. This feature reflects seemingly a condition of rather small or no flow. This observation could suggest, for $m_{\mu\mu} > 1$ GeV, that dimuons are emitted from a source which was dominant in an early stage of the fireball evolution, as the *partonic* process $q\bar{q} \to \mu^+\mu^-$ [14].

3. The J/ψ suppression in p-A and In-In collisions

The study of the J/ψ suppression in In-In [15] has been carried out using two different and complementary approaches. In the first, identical to the one adopted by NA38/NA50, the J/ψ yield has been normalized to the measured Drell-Yan events in the mass region $2.9 < m_{\mu\mu} < 4.5$ GeV/c^2. This quantity has the advantage of being free from the systematic errors connected with efficiency and luminosity calculations, but suffers from the low Drell-Yan statistics. The ratios $\sigma_{\text{J}/\psi}/\sigma_{\text{DY}}$ are then compared with the expected values in case of pure nuclear absorption. Such values have been obtained with the Glauber model, starting from the value $\sigma^{\text{abs}}_{\text{J}/\psi}$=4.18 $\pm$ 0.35 mb, measured by NA50 [16] in p-A collisions at 450 GeV. The result is plotted in Fig. 4(left). Clearly, to increase the statistical significance, the use of Drell-Yan should be avoided. This choice is the foundation of the second analysis approach, where the measured $\mathrm{d}N_{\text{J}/\psi}/\mathrm{d}E_{\text{ZDC}}$ has been directly compared to a calculated reference spectrum corresponding to a pure nuclear absorption scenario. The shape of such a reference has again been calculated in the frame of the Glauber model, with $\sigma^{\rm abs}_{J/\psi}$=4.18 mb. We do not have yet for our In-In data an absolute determination of the cross section $d\sigma_{J/\psi}/dE_{\rm ZDC}$. Therefore, we simply require the relative normalization between the measured and expected distributions to be equal, when integrated over centrality, to the same quantity obtained from the study of $\sigma_{J/\psi}/\sigma_{\rm DY}$, i.e. 0.87±0.05. The result of this analysis is also plotted in Fig. 4(left). Of course, the agreement between the results of the two analyses is significant only in terms of shape, since the normalization of the second analysis has been forced to be the same of the first one. Since with this approach the statistical errors are negligible (∼2%, with the chosen centrality binning) a careful estimate of the systematic errors is mandatory [17]. It turns out that there is a ∼ 10% error, independent of centrality, essentially due to uncertainties in the Glauber model parameters and in our knowledge of the inputs that enter in the nuclear absorption calculation. On top of that, (small) uncertainties on the link between $E_{\rm ZDC}$ and the number of participant nucleons $N_{\rm part}$, due to the contribution of non-spectator energy to the measured signal, induce a non-negligible systematic error for very central events. Of course, most effects discussed here also affect the determination of $\sigma_{J/\psi}/\sigma_{\rm DY}$, although their effect in absolute terms is in this case much less important. The result plotted in Fig. 4(left) clearly indicates an anomalous suppression of the J/ψ yield for $N_{\rm part} > 80$, with a saturation of the effect for central In-In collisions. In Fig. 4(right) we compare the suppression pattern obtained by NA60 with the NA50 results for Pb-Pb collisions [16]. Within errors, the two behaviours look compatible, showing that $N_{\rm part}$ could be a good scaling variable for the onset of the anomalous suppression.

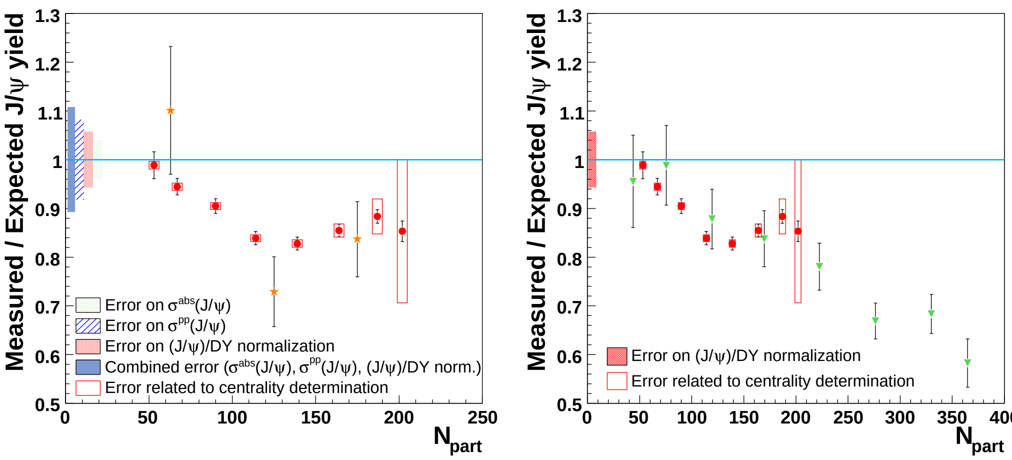

Figure 4: (left) Centrality dependence of the J/ψ suppression measured in In-In collisions. The stars correspond to the ratio between measured and expected $\sigma_{J/\psi}/\sigma_{\rm DY}$, while the circles refer to the ratio between the measured J/ψ yield and nuclear absorption calculations. Systematic errors are also shown. (right) Comparison between the In-In (NA60, circles) and Pb-Pb (NA50, triangles) suppression patterns.

Several theoretical predictions for the In-In suppression pattern were formulated before the NA60 experimental results became available. They include a model where the anomalous suppression is due to interaction with hadronic comovers [18], another where the effect of dissociation and regeneration in a fully thermalized QGP and in the later hadronic stage is considered [19], and finally a model where parton percolation occurs, with an onset at $N_{\rm part} \sim$140 [20]. It is interesting to note that although these models were explicitely tuned on the already available Pb-Pb results, none of them, as can be seen in Fig. 5(left) is able to quantitatively reproduce the In-In points (even if the overall size of the effect is reasonably reproduced). Other theoretical calculations appeared once the J/ψ suppression results were available. More in detail, a study of the effect of a thermalized hadronic gas on the J/ψ has been carried out [21] in the frame of the Constituent Quark-Meson model. The comparison of this calculation with data shows that for both Pb-Pb and In-In hadronic effects alone cannot account for the observed anomalous suppression. Finally, a study of J/ψ suppression at SPS and RHIC energies, based on the HSD transport approach, has been recently performed [22]. Also in this case, a quantitative comparison between our final set of results and this calculation is still not satisfactory.

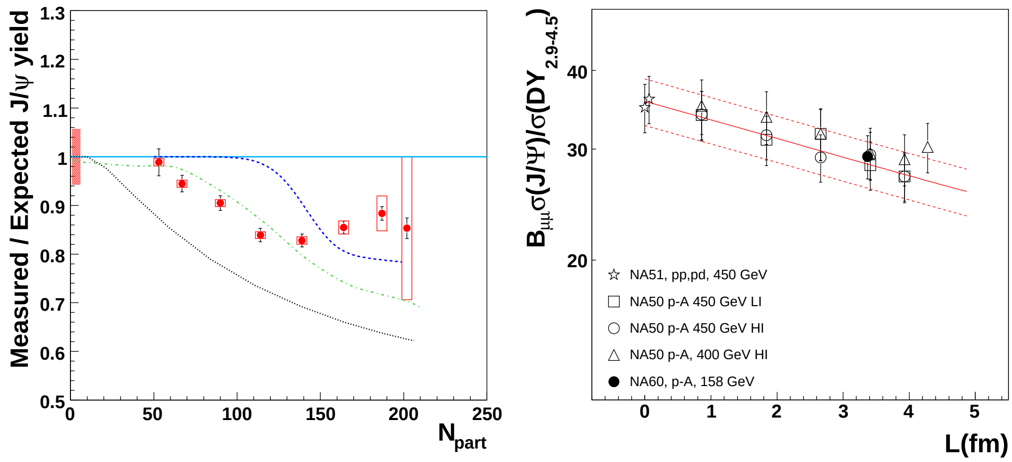

Figure 5: (left) Comparison between the In-In suppression pattern and the theoretical predictions of Ref. [18](dotted line), [19](dashed-dotted line), [20](dashed line). (right) Compilation of the $\sigma_{{\rm J}/\psi}/\sigma_{\rm DY}$ values measured in p-A collisions at the SPS, rescaled, when necessary, to 158 GeV incident energy. The lines indicate the results of a Glauber fit to the p-A data and the size of the error. The full circle indicates the preliminary NA60 result for p-A collisions at 158 GeV.

Of course, in order to claim that an anomalous suppression of the J/ψ has been observed, the production in p-A collisions must be accurately known. Up to now, at SPS energy, such knowledge came from measurements performed at 450 and 400 GeV, covering the rapidity range $-0.5 < y_{cm} <$ 0.5 [23]. Performing an analysis in the frame of the Glauber model, two parameters are needed in order to fit the data, the cross section for elementary collisions $(\sigma_{{\rm J}/\psi}/\sigma_{\rm DY})^{pp}_{E_0}$ at the energy E_0 under consideration and the nuclear absorption cross section for the produced J/ψ, $\sigma^{\rm abs}_{{\rm J}/\psi}$. In order to obtain the expected yield for the rather different energy and kinematical domain of the heavy-ion data (158 GeV/nucleon and 0< y_{cm} <1), a rescaling of these parameters becomes necessary. Up to now, it was assumed that $\sigma^{\rm abs}_{{\rm J}/\psi}$ does not change as a function of the incident proton energy, and the cross section for elementary collision was rescaled using a procedure detailed in [16, 24]. In order to avoid the systematic errors connected with this procedure, NA60 has measured J/ψ production in p-A collisions at 158 GeV, in the same kinematical domain of the nucleus-nucleus data. A target box containing nine subtargets, made of seven different materials (Be, Al, Cu, In, W, Pb and U) has been used, with the vertex spectrometer helping to recognize the target where the muon pair has been produced. An analysis of the A-dependence of the J/ψ production cross section would require of course a complete understanding of the local efficiency of the vertex tracker, since its angular coverage for the various targets is slightly different. Since this work is still in progress, for the moment a preliminary analysis has been performed, using only the muon spectrometer information. More in detail, one simply requires the extrapolation of the muon tracks to the target region to lie inside the target box. This cut has not enough resolution to identify the target where the interaction has taken place, but nevertheless efficiently rejects the background due to parasitic interactions outside the target region (e.g. in the hadron absorber). In this way, one can determine an average $\sigma_{J/\psi}/\sigma_{DY}$ ratio, that can be now plotted together with the previous results, as a function of L, the mean thickness of nuclear matter crossed by the produced J/ψ. Taking into account the nuclear composition of the target system, we have, for this set of data, $\langle L \rangle = 3.4$ fm. In Fig. 5(right) we show such a plot, where the closed circle indicates our preliminary result. It can be seen that there is a very good agreement with the set of p-A data taken at higher energy, and rescaled to 158 GeV. This result shows that the rescaling of the elementary production cross section is indeed correct, and reinforces the claim that the suppression observed for In-In and Pb-Pb collisions is not compatible with a pure nuclear absorption scenario.

4. Conclusions and future perspectives

The results obtained by NA60 clearly represent a significant advance in our understanding of the processes involving lepton pair production in heavy-ion collisions. In particular, evidence for radial flow of dileptons has been reached, and the sudden decrease of this effect at masses larger than 1 GeV might indicate a transition from a hadronic to a partonic source. Furthermore, the J/ψ anomalous suppression has been studied with unprecedented accuracy, and an onset of this effect at $N_{\rm part} \sim 80$ has been found. $N_{\rm part}$ may also represent a good scaling variable for the suppression, seen the rather good agreement between the In-In and Pb-Pb suppression patterns, when plotted as a function of this variable.

All these results prove that a dimuon experiment with good vertexing capabilities can provide detailed answers to many significant physics questions. On the other hand, a single run with an In beam at 158 GeV/nucleon represents only a tiny fraction of the physics potential accessible to such an experiment. In particular, we believe that a study of thermal dimuon production, of open charm and of J/ψ suppression in the energy range accessible to the SPS ($\sim$40–160 GeV/nucleon) would be very interesting, since it would allow us to explore the evolution of such observables in a region of increasing baryon density. Furthermore, the results of such an experiment would provide a natural bridge between the existing results at top SPS energy and the forthcoming ones from the CBM experiment [25] at the lower-energy FAIR facility.

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