First results from NA60 on low mass muon pair production in In-In collisions at 158 GeV/nucleon

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Abstract. The NA60 experiment at the CERN SPS studies dimuon production in proton-nucleus and nucleus-nucleus collisions. The combined information from a novel vertex telescope made of radiation-tolerant silicon pixel detectors and from the muon spectrometer previously used in NA50 allows for a precise measurement of the muon vertex and a much improved dimuon mass resolution. We report on first results from the data taken for Indium-Indium collisions at 158 AGeV/nucleon in 2003, concentrating on a subsample of about 370 000 muon pairs in the mass range \( m < 1.2 \text{ GeV}/c^2 \). The light vector mesons \( \omega \) and \( \phi \) are completely resolved, with a mass resolution of about 23 MeV/c^2 at the \( \phi \). The transverse momentum spectra of the \( \phi \) are measured over the continuous range \( 0 < p_T < 2.5 \text{ GeV}/c \); the inverse slope
parameter of the spectra is found to increase with centrality, with an average value of $T = 252 \pm 3 \text{ MeV}$.

1. Introduction

The NA60 experiment was approved in the year 2000 to study a number of physics topics accessible through the measurement of muon pairs. All topics were studied by previous experiments, but were left with major open questions: (i) the excess emission of lepton pairs for masses below the $\rho$-resonance with the possible link to the chiral transition, (ii) the enhanced production of intermediate mass muon pairs with the ambiguity of either prompt thermal radiation or increased open charm production, and (iii) the precise mechanism underlying $J/\psi$ suppression, asking for a variation of the system size. This paper is restricted to the first topic, while the second and third are treated in another NA60 paper presented during this conference [1].

The NA45/CERES experiment has consistently observed an excess emission of electron pairs with invariant masses $0.2 < m < 0.6 \text{ GeV}/c^2$ above known sources from hadron decays, in S-Au and Pb-Au collisions, which is concentrated at low pair $p_T$ and scales steeper than linear with the associated charged particle multiplicity [2, 3]. The theoretical interpretation of this excess has been linked to the restoration of chiral symmetry in the hot and dense medium, leading to a “melting” of the $\rho$ with extra yield at lower masses and decreased yield at the nominal pole position [4]. However, statistical accuracy and mass resolution up to and including the 2000 data have not been sufficient to positively verify this scenario; the excess continuum seems structureless up to the $\rho/\omega$ region, and even $q\bar{q}$ annihilation cannot be ruled out at present. Better statistics, signal-to-background ratio and mass resolution are therefore required to clarify the existing ambiguities. The NA60 experiment has now potentially achieved this goal. However, only preliminary results can be presented at this stage, including raw spectra over the whole mass region. More detailed results are only given on the properties of the $\phi$.

2. Experimental set-up

The essential components of the NA60 experiment are shown in figure 1. The muon spectrometer previously used in NA10/NA38/NA50 consists of an air-core toroidal magnet, 8 multi-wire proportional chambers for muon tracking and momentum determination, and 4 scintillator hodoscopes for the muon pair trigger. A 5.5 m long hadron absorber before the spectrometer serves as the muon filter, with the usual drawbacks of such a set-up: energy loss and multiple scattering of the muons impair the mass resolution and prohibit an accurate vertex determination. The new silicon pixel telescope added by NA60 is used to track all charged particles in the vertex region before the hadron absorber and to determine their momenta independently of the muon spectrometer. It consists of a number of tracking planes with a total of 12 space points,
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Figure 1. Full NA60 set-up (upper) and detail of the target region (lower).

embedded in a 2.5 T dipole magnet. The planes are made from assemblies of detector chips bump-bonded to radiation-tolerant readout chips, developed for the ALICE and LHCb experiments at the LHC [5]. Each chip contains $256 \times 32$ pixels with a pixel size of $50 \times 425 \, \mu m^2$. Matching of the muon tracks before and after the hadron absorber both in coordinate and momentum space improves the mass resolution in the region of the light vector mesons $\omega, \phi$ by a factor of nearly 3, decreases the combinatorial background by (partial) kink-rejection of muons from $\pi$ and K decays, and finally allows the identification of displaced vertices of muons from D-decays for the measurement of open charm [1, 6].

Further components of the NA60 set-up are a beam tracker of 4 cryogenic silicon microstrip detectors upstream of the target to track the incoming beam particles, and a zero-degree quartz-fiber “spaghetti” calorimeter (“ZDC”) to tag the centrality (number of participants) of the collision. The high luminosity of NA50 is kept in NA60. Radiation tolerance and high readout speed of the silicon pixel telescope allow for beam intensities of $5 \cdot 10^7$ per 5 s burst for ions and $2 \cdot 10^9$ per 5 s burst for protons in connection with target thicknesses of more than 10% of an interaction length. The dimuon trigger is effective enough to record the resulting data rates without any centrality selection.

3. Global results for low mass muon pairs

During the 5-week long Indium run in 2003, around $4 \cdot 10^{12}$ ions with an energy of 158 GeV/nucleon were delivered at the target, and a sample of 230 Million dimuon events (background dominated) were written to tape. The presently available dimuon mass spectra, without any centrality selection, are displayed in figure 2. The combinatorial
background of opposite-sign muon pairs is determined by mixing single muons from events with like-sign pairs; subtraction of this background from the measured opposite-sign pairs results in the net spectrum labeled “signal pairs”. The mean signal-to-background ratio is about 1/4. The net spectrum contains 370 000 pairs, corresponding to about 35% of the available total statistics; the final sample will therefore contain about 1 Million pairs with an effective statistics of \(10^6/(4+1)=200\,000\). Compared to the CERES Pb-Pb data 1995/96 [2] or 2000 [3], this is an improvement by a factor of roughly 1000. The enlarged low mass net spectrum on the right of figure 2 shows the light vector mesons \(\omega\) and \(\phi\) to be completely resolved. The mass resolution for the \(\phi\) is about 23 MeV/c\(^2\), independent of centrality. One can even recognize the rare \(\eta \rightarrow \mu\mu\) decay, which should lead to the first unambiguous cross section measurement of the \(\eta\) in nuclear collisions.

It should be stressed that the extension of the mass spectrum all the way down to the \(2m_\mu\) threshold is accompanied by a complete coverage in pair transverse momentum down to zero, albeit with decreasing acceptance by up to 2 orders of magnitude for the lowest masses. This presents a further drastic improvement compared to the NA50 set-up.

Although the statistics is high enough for finer binning, the data have so far only been subdivided into 4 coarse bins in associated charged particle multiplicity, as measured by the pixel telescope. The net invariant mass spectra for these 4 bins are shown in figure 3, arbitrarily normalized in the region of the \(\omega\) peak. One recognizes some relative variation at very low masses and about a factor of 2 increase in the \(\phi\). Stronger variations occur below the \(\omega\), between the \(\omega\) and the \(\phi\), and above the \(\phi\). Those
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Figure 3. Invariant mass spectra for 4 bins in associated charged particle multiplicity.

significantly above the $\phi$ are mostly due to the fact that hard processes scale with the number of binary nucleon-nucleon collisions rather than with $N_{\text{part}}$ (like the $\omega$). The quantitative judgment of the rest has to await a remaining correction to the mass spectra of figures 2 and 3 which has not yet been done: the subtraction of muon pairs arising from incorrect (“fake”) matches of muon tracks between the two spectrometers. This correction will also be obtained from mixing events, but the corresponding software has not yet been finalized. From overlay MC simulations it seems, however, that the level of fake matches is too small to account for the varying yield of dimuons in the neighborhood of the $\omega$ and $\phi$.

4. Detailed results for the $\phi$ meson

With the $\omega$ and $\phi$ so well resolved and isolated from the rest of the low mass pairs, a more detailed analysis has already been performed on the $\phi/\omega$ yield ratio and the transverse momentum distribution of the $\phi$ as a function of centrality. The analysis is based on the sample shown in figure 2, containing about 37 000 net events for the $\phi$ (14 000 effective statistics), after subtraction of the remaining underlying continuum. The $\phi/\omega$ yield ratio has been determined from the raw data by propagating the muon pairs arising from the known resonance ($\eta, \rho, \omega, \phi$) and Dalitz ($\eta, \eta', \omega$) decays through the NA60 set-up with GEANT, using the hadron-decay generator GENESIS [7] as an input. An additional continuum source with exponential fall-off beyond the $\phi$ and the level of fake matches as obtained from overlay MC simulations have been taken into
Account in an approximate way. The final result on $\phi/\omega$ is obtained by adjusting the input ratio $\phi/\omega$ of GENESIS such that the output fits the measured data. It should be stressed that the results are rather insensitive to the details of the procedure, with one exception: the $\rho/\omega$ ratio in the fit procedure is somewhat ill-defined, while the sum $\rho+\omega$ is stable. For this reason, the fit has been constrained to a fixed ratio $\rho/\omega = 1$. The whole procedure is done independently for each of the 4 multiplicity bins. The average multiplicity density in each of the bins is converted, via the correlation of multiplicity vs. ZDC energy, to average values for the number of participants $N_{\text{part}}$, using Glauber fits to the ZDC data. The results for $\phi/\omega$ are plotted in figure 4. Note that the errors are purely statistical; the systematic errors are under investigation. Results previously obtained by NA50 for the system Pb-Pb are shown for comparison. They have been derived from the published values of $\phi/(\rho+\omega)_{\mu\mu}$, again assuming $\rho/\omega = 1$ to be consistent, and correcting for the branching ratios of $\rho, \omega, \phi \rightarrow \mu\mu$. They are also corrected to correspond to the same cut $p_T > 1.1 \text{ GeV}/c$ for the $\rho, \omega, \phi$ rather than the common cut $m_T > 1.5 \text{ GeV}/c^2$, using the NA50 slope parameter value $T = 228 \text{ MeV}$ for the extrapolation. It is remarkable that the two data sets agree within errors, both in absolute value and in the slope vs. $N_{\text{part}}$. This implies $N_{\text{part}}$ to be a reasonable scaling variable for particle ratios in different collision systems, at least as long as $A$ is not too small.

The analysis of the transverse momentum spectra of the $\phi$ has been done in a straightforward way. The raw data are obtained by selecting a narrow window around the $\phi$ peak in the net spectrum of figure 2, and then subtracting the content of 2 side-
windows symmetrically placed around the peak. It was verified that the results are completely insensitive to the choice of width and position of the side-windows, up to the extreme of applying the whole procedure to the gross spectrum before subtraction of the combinatorial background. The raw data were then corrected for acceptance, using a 2-dimensional acceptance matrix in $p_T$ and $y$ obtained from a detailed simulation of the NA60 set-up, and finally converted to invariant relative cross sections $1/p_T dN/dp_T$.

The acceptance correction is quite uncritical, since the acceptance varies by less than a factor of 2 over the whole $p_T$ range. Finally, the invariant cross sections were fitted with the simple form $\exp(-m_T/T)$ to extract the slope parameters $T$ in a way consistent with other publications. The spectra and associated $T$ values show no variation with $y$ within errors. The $y$-integrated data for $3.3 < y < 4.1$ are plotted in figure 5 separately for the 4 bins in associated charged particle multiplicity density. The data extend up to $p_T = 2.5$ GeV/$c$; for the full-statistics sample, a limit of 3.5 GeV/$c$ may be reachable. The slope parameters derived from the fits are well defined within the chosen parametrization. The average slope parameter over the whole range in multiplicity and $p_T$ is $T = 252 \pm 3$ MeV; if the fit is restricted to $p_T < 1.5$ GeV/$c$ (NA49 range) or $m_T > 1.5$ GeV/$c^2$ (NA50 range), the resulting values are $256 \pm 3$ and $245 \pm 5$, respectively, i.e. nearly identical within errors.

The tendency of the slope parameter $T$ to rise with $\langle dN_{ch}/d\eta \rangle$ or $N_{part}$ is clearly borne out in figure 6. For comparison, this plot also contains the slope parameters reported by NA49 for Pb-Pb on $\phi \to KK$ [9], and those from NA50 for Pb-Pb on

Figure 5. Transverse momentum spectra of the $\phi$ meson for 4 bins in associated charged multiplicity density. The errors are purely statistical; the systematic errors are under investigation.
Figure 6. Slope parameters $T$ of the transverse momentum spectra of the $\phi$ meson for different experiments at 158 GeV/nucleon. The errors shown for NA60 are purely statistical; the systematic errors are under investigation, but are presently believed to be $\leq 10$ MeV.

$\phi \rightarrow \mu\mu$. Remarkably, NA60 and NA49 agree in the region of overlap in $N_{\text{part}}$ within the rather large errors of NA49. Whether that bears on the famous “$\phi$-puzzle”, originally discussed in view of the discrepancy between NA49 and NA50 for Pb-Pb \cite{10}, remains to be seen. A difference now also exists between NA60 and NA50 for which we have no obvious explanation, and the usefulness of $N_{\text{part}}$ as the proper scaling variable between different systems for quantities other than particle ratios is in any case not proven. A consistent solution of the $\phi$-puzzle by NA60 would require parallel data on $\phi \rightarrow \text{KK}$ for the In-In system. Such an analysis, based solely on track information from the pixel telescope, is indeed in progress. Work on a precision determination of the mass and width of the $\phi$, which addresses further aspects of in-medium effects on the $\phi$, is also in progress.

5. Conclusions

The NA60 experiment is setting new standards in the data quality of muon pair measurements. A high statistics run with protons on many different nuclear targets is presently being performed to provide precision reference data for all three major aspects of the NA60 program. Specifically, the low mass region will benefit from unprecedented sensitivity to sources other than the known meson decays.
References

[1] Onishi H et al (NA60 Collaboration) 2005 J. Phys. G: Nucl. Part. Phys. (these proceedings)
[2] Agakichiev G et al (CERES Collaboration) 1995 Phys. Rev. Lett. 75 1272
   Agakichiev G et al (CERES Collaboration) 1998 Phys. Lett. B 422 405
   Lenkeit B et al (CERES Collaboration) 1999 Nucl. Phys. A 661 23c
[3] Marín A et al (CERES Collaboration) 2005 J. Phys. G: Nucl. Part. Phys (these proceedings)
[4] Rapp R and Wambach J 2000 Adv. Nucl. Phys. 25 1
   Brown G E and Rho M 2002 Phys. Repts. 363 85
[5] Keil M et al 2004 Preprint CERN-PH-EP-2004-021: to appear in Nucl. Instr. Meth.
[6] Shahoyan R et al (NA60 Collaboration) 2004 Hard Probes Conference (Ericeira Portugal)
[7] Damjanovic S De Falco A and Wöhri H 2003 NA60 Internal Note
[8] Jouan D et al (NA50 Collaboration) 2004 J. Phys. G 30 S277
[9] Friese V et al (NA49 Collaboration) 2002 Nucl. Phys. A 698 487c
[10] Shuryak E V 1999 Nucl. Phys. A 661 119c

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