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ϕ meson production in NA60

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Abstract. NA60 is a fixed-target experiment at the CERN SPS which measured dimuon production in nucleus–nucleus and proton–nucleus collisions. The experiment collected muon pair samples of unprecedented quality in heavy-ion experiments. This paper presents a high quality measurement of the p_{T} distribution of the ϕ meson, covering a broad p_{T} window. The data were collected in 2003 in In-In collisions at 158 GeV per nucleon. The results, presented as a function of centrality, were studied against several possible sources of systematic effects and proved to be fairly stable. We show that the inverse m_{T} slope measured in In-In collisions, in the $\phi \to \mu\mu$ decay channel, depends significantly on the range used to perform the fit. When the fit is performed at low transverse momentum, the effective inverse slope increases from peripheral to central collisions, as measured by other experiments. We finally show that our measurement for In-In is compatible with the overall systematics of T slope versus mass, measured in different collision systems by the NA49 experiment

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1 ϕ Production in heavy-ion collisions

The main goal of heavy-ion experiments is the detection of a phase transition from hadronic matter to a quark–gluon plasma. Strangeness enhancement was proposed long ago as one of its signatures [1]. The study of ϕ production in heavy-ion collisions is motivated by the fact that it carries information about strangeness production. It has been argued that close to the phase boundary the spectral function of the ϕ, and thus its mass, width and branching ratios, could be modified [2]. The study of its p_{T} distribution is also of great interest, for the reasons described below.

Under the assumption of thermal emission from a static source, one expects that particles are produced according to an exponential p_{T} distribution [3]. Transverse momentum distributions of particles in heavy-ion collisions are usually studied with the formula:

$$\frac{1}{p_{\mathrm{T}}}\frac{\mathrm{d}N}{\mathrm{d}p_{\mathrm{T}}} = C\mathrm{e}^{-\mathrm{m_T}/T}\,, \tag{1}$$

where T is the "temperature" of the emitting source.

In the case of an expanding source, that is in presence of *radial flow*, (1) is not valid anymore. Several attempts were made to generalise it, as the widely used model of [4]. Equation (1) was nevertheless used by several experiments to fit p_{T} distributions. The T parameter is usually referred

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to as "inverse slope" in this context. It should be noted that the T slope that one extracts from the fit, in general, will depend on the fit range, since real $p_{\rm T}$ distributions are not purely exponential. It can be shown that, at first order, the T slope at low $p_{\rm T}$ is given by:

$$T \simeq T_0 + \frac{1}{2}\, m\, \beta_{\rm T}^2\,, \qquad (2)$$

where T_0 is the temperature at freeze-out, m is the mass of the particle under study and $\beta_{\rm T}$ is the average transverse velocity of the expanding source (*radial flow* [5]). At high $p_{\rm T}$, the T slope extracted from the exponential fit is approximated by [5]:

$$T \simeq T_0 \sqrt{\frac{1+\beta_{\rm T}}{1-\beta_{\rm T}}}\,. \qquad (3)$$

What is measured is then an effective temperature, larger than the freeze-out temperature because of radial flow. The question of the flow of the ϕ meson is particularly interesting: because of its small rescattering cross-section with hadrons the ϕ meson is expected to obtain most of its flow from the parton phase produced in the early stages of heavy-ion collisions [6].

The yield and $p_{\rm T}$ spectrum of the ϕ meson were studied in Pb-Pb collisions at 158 A GeV incident beam energy by the NA49 experiment (in the $\phi \to KK$ channel [7], with statistics limited to $p_{\rm T} < 1.6$ GeV) and by the NA50 experiment (in the $\phi \to \mu\mu$ channel [8], with acceptance for $p_{\rm T} > 1.2$ GeV only). Both experiments estimated the inverse slope parameter T fitting $p_{\rm T}$ spectra with the exponential function (1). The T values found were in strong disagreement, both in what concerns the absolute value and the centrality dependence. The NA50 values were significantly lower than the NA49 ones and showed little dependence on centrality (they showed a flat behaviour within errors). The NA49 values, on the other hand, were shown to increase as a function of the number of participants. The measured yields were also in strong disagreement, the NA50 measurement exceeding the NA49 one by factors between two and four. These discrepancies are also known as the "ϕ puzzle" [2, 9].

In this paper we report on new measurements in the muon channel done by the NA60 collaboration in In-In collisions at 158 A GeV incident beam energy, which can help understanding the ϕ puzzle. We present $p_{\rm T}$ distributions of the ϕ, measured in the $\phi \to \mu\mu$ channel with very good $p_{\rm T}$ coverage and fitted with the exponential function (1). The new collision system, moreover, adds further information to the general systematics.

2 The NA60 experiment

NA60 is a fixed-target experiment devoted to the study of dimuon production in proton–nucleus (p-A) and nucleus–nucleus collisions at the CERN SPS. Its apparatus is composed of 4 main detectors: a muon spectrometer, a silicon vertex detector, a zero degree calorimeter (ZDC) and a silicon beam tracker. A detailed description of the apparatus can be found in [10–12]. Here we only briefly mention the detector concept.

The muon spectrometer is placed after a hadron absorber, which stops most of the hadrons before they can reach the trigger hodoscopes and the tracking chambers. The muon spectrometer also provides the very selective "dimuon trigger", which allows the experiment to collect data at high beam intensities, so as to integrate large dimuon statistics. To ensure that only muons can trigger the experiment, the hadron absorber is complemented by a 1.2-meter-long iron wall, placed before the last trigger station at the end of the muon spectrometer. The drawback of the hadron absorber is that it introduces fluctuations of energy loss and multiple scattering, which result in a degraded resolution of the dimuon mass and of the coordinates of the interaction vertex.

The vertex detector is placed inside a 2.5 T dipole magnet. It reconstructs charged tracks before the hadron absorber in the window $3.0 \lesssim y \lesssim 4.3$. The resolution on the determination of the vertex position is 10–20 μm in the transverse coordinates and $\sim 200\,\mu$m for the longitudinal coordinate. In order to identify the muons in the vertex region, the tracks reconstructed in the muon spectrometer are extrapolated back to the target region and matched to the tracks reconstructed in the vertex detector. This is done comparing both angles and curvatures. Once identified, the muons are refitted using the joint information of the muon spectrometer and of the vertex detector. We shall refer to these tracks as "matched muons". This technique allows to overcome the limitations due to the hadron absorber and thus results in much improved mass resolution and vertexing capability, with respect to previous

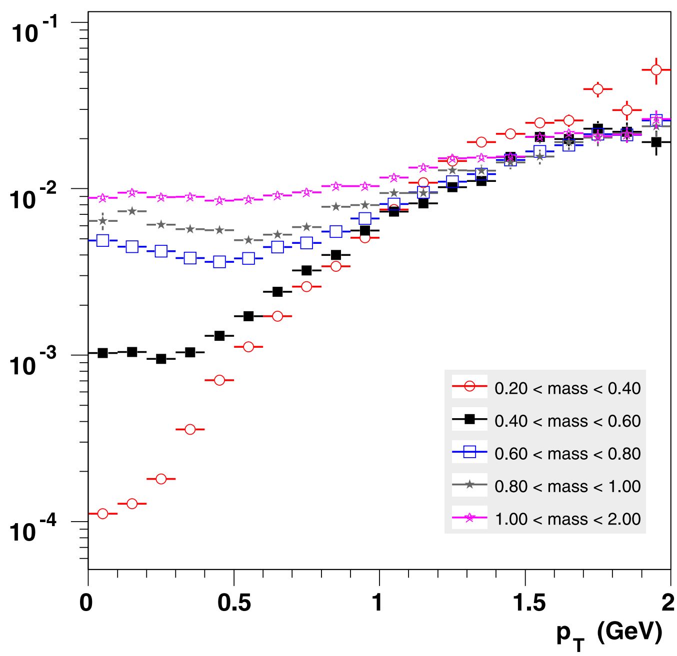

Fig. 1. Dimuon geometrical acceptance as a function of $p_{\rm T}$ in several mass windows

dimuon experiments. The mass resolution decreases from around 80 MeV to 23 MeV at the ϕ peak, independent of centrality, when using the information from the vertex detector. Furthermore, the dipole field in the target region significantly increases the acceptance of low p_{T} and low mass dimuons, with respect to previous dimuon experiments (Fig. 1).

The Zero Degree Calorimeter measures the forward energy of non-interacting beam fragments. It can thus be used to estimate the centrality of the collisions.

The beam tracker measures the transverse coordinates of incoming beam particles, before they hit the target. It puts useful constraints on the events, which can be used off-line to impose cuts or to make the data reconstruction faster. This detector is extremely radiation hard, as required since it is hit by all the beam particles delivered to the target region [13].

3 Analysis procedure

The indium-indium data were collected with a 158 A GeV ion beam in a 5-week-long run in 2003: 230 million dimuon triggers were recorded. In this paper we present results based on an effective statistics of 12 000 ϕ mesons, 50% of the collected statistics. The data were divided in five centrality bins as summarised in Table 1. The bins were selected using the number of charged tracks reconstructed in the vertex telescope. The raw number of charged tracks was converted to number of primaries taking into account secondaries production, acceptance and reconstruction efficiency. The number of primaries was converted to number of participants assuming $N_{\mathrm{part}} \simeq \mathrm{d}N_{ch}/\mathrm{d}y|_{3.7}$, which is correct within 10% [12].

To extract the information on ϕ production, spectra of matched muons were used. These are affected by two sources of background: the combinatorial background and the fake matches. The former is the contribution of uncorrelated muon pairs coming from the decay of pions and kaons. The latter comes from the fact that the matching procedure can associate a muon to a wrong track in the vertex telescope. When this happens, the kinematics of the matched muon are highly degraded. The combinatorial background is subtracted with an event mixing technique: two muons from different events are randomly paired to build an invariant mass spectrum, which is uncorrelated by construction. This technique automatically takes into account all experimental details, provided the muons are normalized with the correct occupancy probability, as extracted from the data [12, 14]. The NA60 apparatus not only triggers on opposite sign pairs ($\mu^+\mu^-$) but also on like sign pairs ($\mu^-\mu^-$ and $\mu^+\mu^+$), which contain uncorrelated muons only. The real and mixed spectra for the like-sign pairs should then be identical. This fact can be used to assess the quality of the estimated background. The accuracy was found to be $\sim 1\%$ over several orders of magnitude [12, 14]. Fake matches, on the other hand, can be estimated in two different ways. The first approach is an overlay Monte Carlo technique, where a Monte Carlo dimuon is reconstructed on top of a real event, allowing to check the probability of getting a fake match. The second method is an event mixing method, which extracts the probability distributions of fake matches from data alone. The basic idea is to match the tracks in the muon spectrometer from one event to the vertex tracks of a different event [12, 14]. All the matches obtained in this way are fake by construction. This technique is more complicated but more rigorous. The two methods agree within 5%. The spectrum before and after subtraction of combinatorial background and fake matches is shown in Fig. 2. The sample consists of 360 000 signal pairs, 50 000 events in the ϕ peak; this is reduced to an effective statistics of about 12 000, due to a signal/background ratio of less than 1/2 and some cut losses described in the next section.

To make sure that the apparatus and its peculiar acceptance are well understood, a detailed study of the peripheral data was performed, as discussed in [15]. It should however be noted that the acceptance at the ϕ mass is relatively flat as a function of p_{T} (Fig. 1).

Table 1. Centrality bins

i	$\mathrm{d}N_{ch}/\mathrm{d}\eta$ range	$\langle N_{\mathrm{part}}\rangle$
1	$4-25$	15
2	$25-50$	39
3	$50-95$	75
4	$95-160$	132
5	$160-250$	183 ± 1

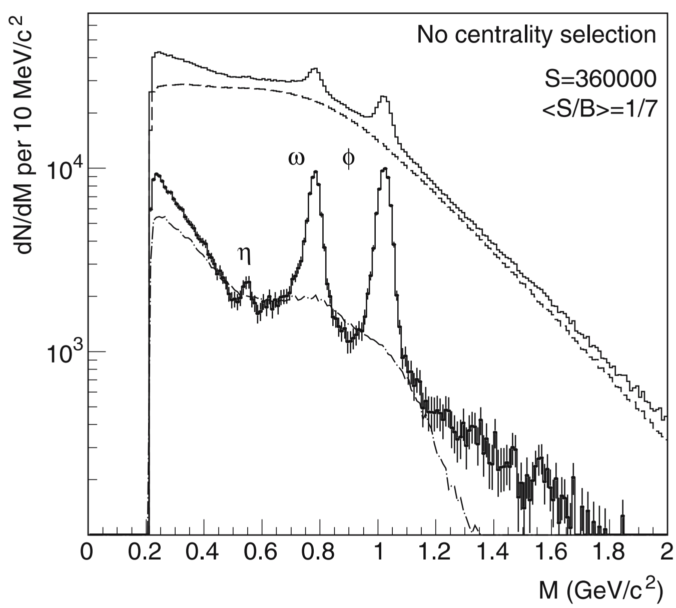

Fig. 2. Raw mass distribution (*continuous line*), fake tracks (*dot-dashed line*), combinatorial background (*dashed line*) and mass distribution after fake tracks and combinatorial background subtraction (*continuous curve with error bars*)

4 Transverse momentum distribution

To study the p_{T} spectrum of the ϕ we selected events in a small mass window centred at the ϕ pole (0.98 GeV $< M_{\mu\mu} <$ 1.06 GeV), from the mass distribution after combinatorial background subtraction. The p_{T} spectrum of the continuum below the ϕ was estimated and subtracted selecting events in two side mass windows (0.88 GeV $< M_{\mu\mu} <$ 0.92 GeV and 1.12 GeV $< M_{\mu\mu} <$ 1.16 GeV).

In the case of the analysis of the p_{T} spectrum fake tracks can be handled in 3 different ways. Besides the subtraction with the event mixing or the overlay Monte Carlo technique already discussed above, it is also possible not to subtract fake tracks explicitly. Since fakes are smooth as a function of mass (Fig. 2), at first order they are already subtracted by the subtraction of the side windows.

After subtraction of the combinatorial background, physical continuum and fake tracks, the p_{T} spectrum was corrected for acceptance and reconstruction efficiency. This was estimated with an overlay Monte Carlo simulation, as a 2-dimensional matrix in p_{T} and rapidity (Fig. 3). A full overlay Monte Carlo simulation is required for a proper estimate of reconstruction efficiency, which depends on the hit occupancy in the detector.

The resulting p_{T} distributions were studied as a function of centrality and fitted with the exponential function (1) in the range 0.0 GeV $< p_{\mathrm{T}} <$ 2.6 GeV to extract the T slope parameter, as shown in Fig. 4. The figure also shows the systematic error as a band, estimated as follows. The analysis was repeated with several different cuts and parameters selections: 90 different combinations were tested. The width and position of the side windows were varied, the different possibilities for the subtraction of fakes were implemented, the χ^2 cut on the matching was varied and two different rapidity windows were studied. The checks are summarised in the following list:

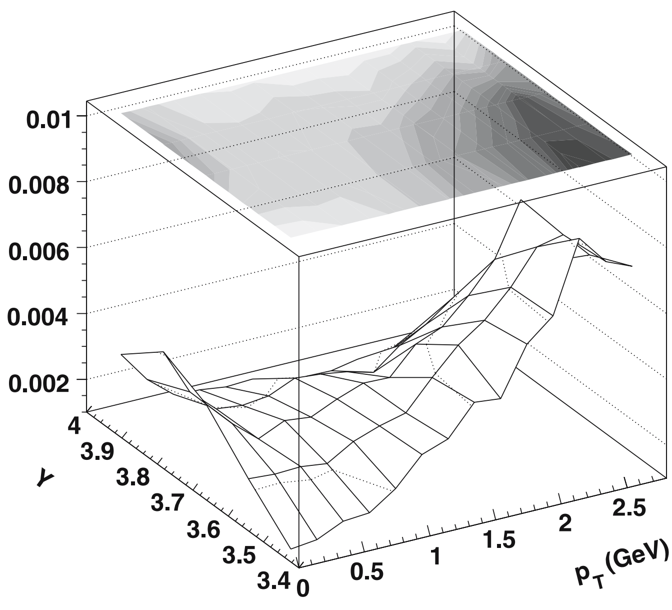

Fig. 3. Acceptance times reconstruction efficiency in central In-In collisions for the ϕ meson mass

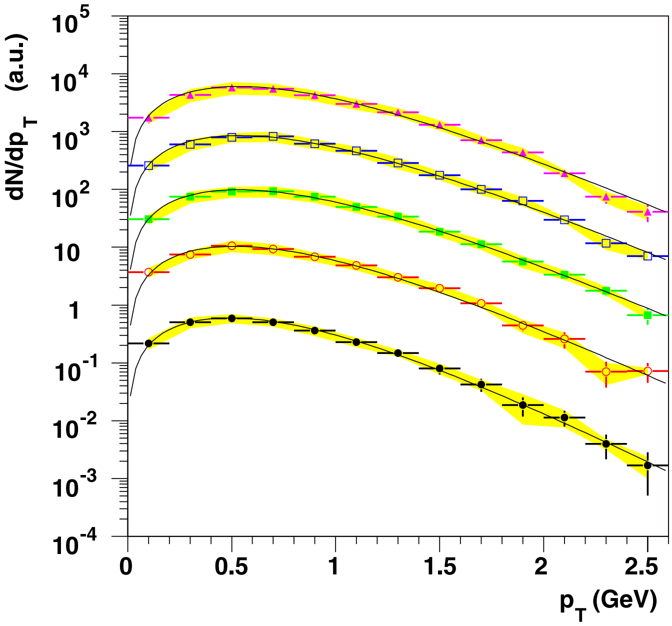

Fig. 4. ϕ transverse momentum distributions in indium-indium collisions as a function of centrality. From *top* to *bottom*: central to peripheral spectra. The *band* shows the systematic error

- χ^2 of matched muon < 1.5, < 2.2, < 3.0;
- No explicit fake subtraction, fake subtraction with overlay Monte Carlo, fake subtraction with mixing method;
- Side windows width $W_w = 60$ MeV, 80 MeV, 100 MeV, with side windows offset = 60 MeV;
- Side windows offset $W_d = 50$ MeV, 60 Mev, 70 MeV, with side windows width = 80 MeV;

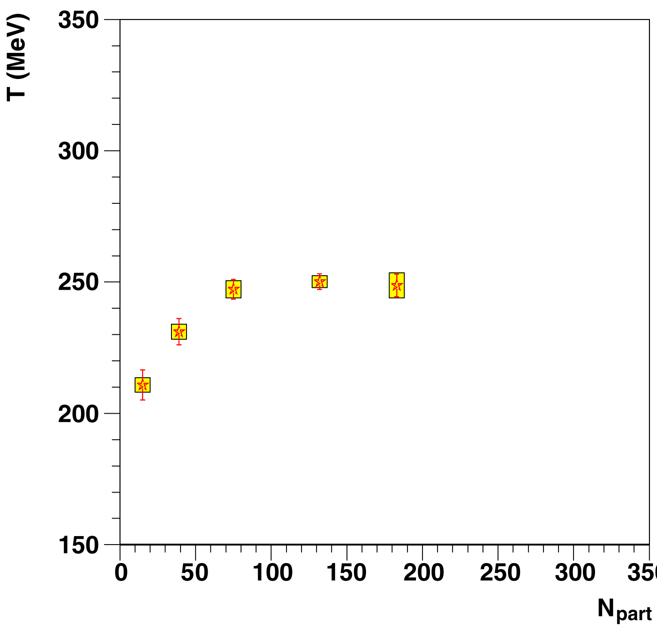

Fig. 5. T slope parameter as a function of the number of participants. Fit performed in the range 0.0 GeV $< p_{\mathrm{T}} <$ 2.6 GeV. The *boxes* show the systematic error

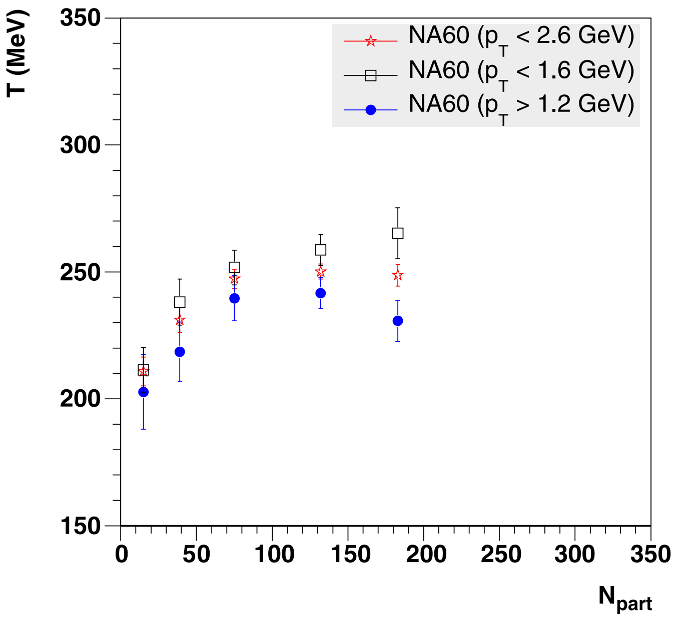

Fig. 6. T slope parameter as a function of the number of participants, estimated in three different p_T windows. Statistical errors only

– 2 different rapidity ranges: $3.4 < y < 4.0$ and $3.5 < y < 3.9$.

We shortly refer to each of these systematic checks as a "test" in the following.

The dN/dp_T distributions for each of the tests were fitted independently, leading to a distribution of values for T. The best estimate of points in the dN/dp_T distribution and of T for each centrality bin was computed as the arithmetic mean of the corresponding result in the different systematic tests. To this "best estimate" a statistical error equal to the mean of statistical errors in the different tests is assigned. The systematic error is estimated as the RMS of these distributions. The resulting effective T as a function of the number of participants is depicted in Fig. 5, for the fit range $0.0\,\text{GeV} < p_T < 2.6\,\text{GeV}$. The T slope is seen to increase with centrality in the most peripheral bins and then saturates.

The fit was repeated in two sub-ranges ($0.0\,\text{GeV} < p_T < 1.6\,\text{GeV}$ and $1.2\,\text{GeV} < p_T < 2.6\,\text{GeV}$), corresponding to the experimental windows of the NA49 and NA50 experiments, respectively. The results are shown in Fig. 6, where they are compared to the results in the full fit range $0.0\,\text{GeV} < p_T < 2.6\,\text{GeV}$. They are shown again in Fig. 7 and Fig. 8, where our points are also compared to the results of the other experiments.

As can be seen, the NA60 result is in agreement with the NA49 one, as the T slope increases with centrality. The numerical value is also in agreement: our central data point, fitted in the NA49 p_T range, is compatible with the NA49 systematics of T versus mass [16], the In-In point lying in between the Pb-Pb and the Si-Si points, as shown in Fig. 9. The T slope is seen to increase approximately linearly with the mass of the particle, as suggested by (2), and increases for larger collision systems. The lines in the picture are meant to guide the eye.

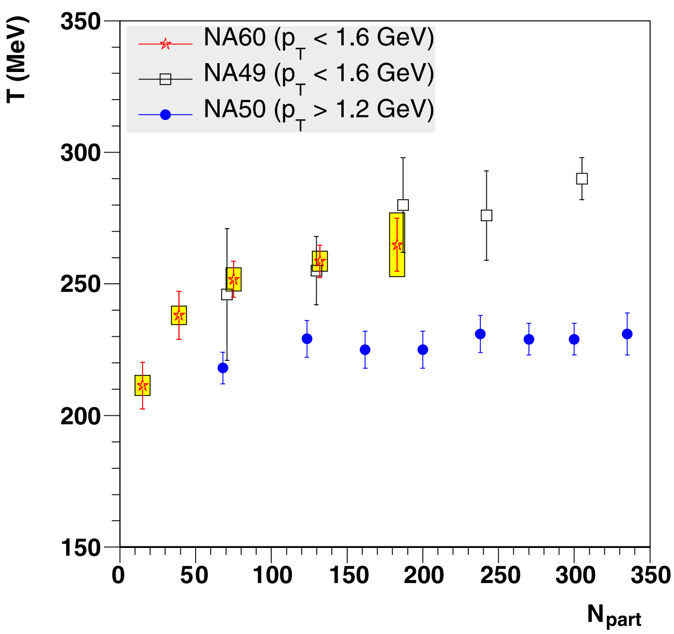

Fig. 7. T slope parameter as a function of the number of participants (*open red stars*). Fit performed in the range $0.0\,\text{GeV} < p_T < 1.6\,\text{GeV}$. Compared to the T slope measured in Pb-Pb collisions by the NA49 experiment (*open black squares*) and NA50 experiment (*full blue circles*). The *boxes* show the systematic error

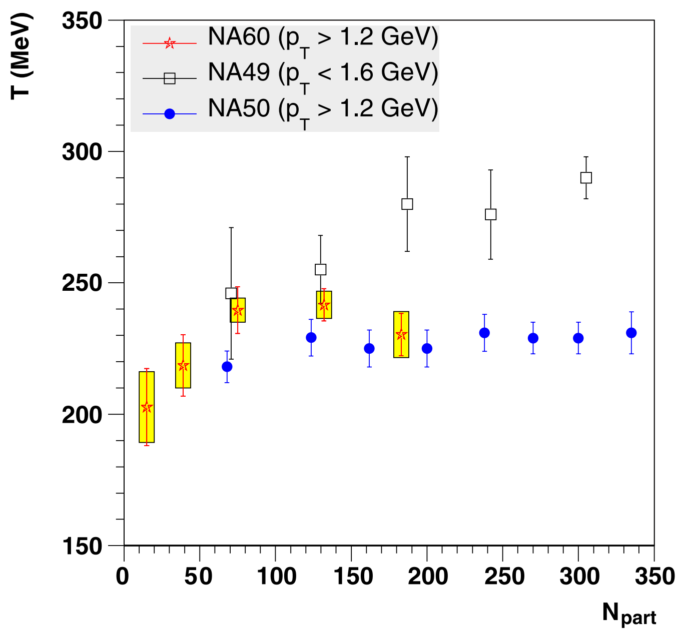

Fig. 8. T slope parameter as a function of the number of participants (*open red stars*). Fit performed in the range $1.2\,\text{GeV} < p_T < 2.6\,\text{GeV}$. Compared to the T slope measured in Pb-Pb collisions by the NA49 experiment (*open black squares*) and NA50 experiment (*full blue circles*). The *boxes* show the systematic error

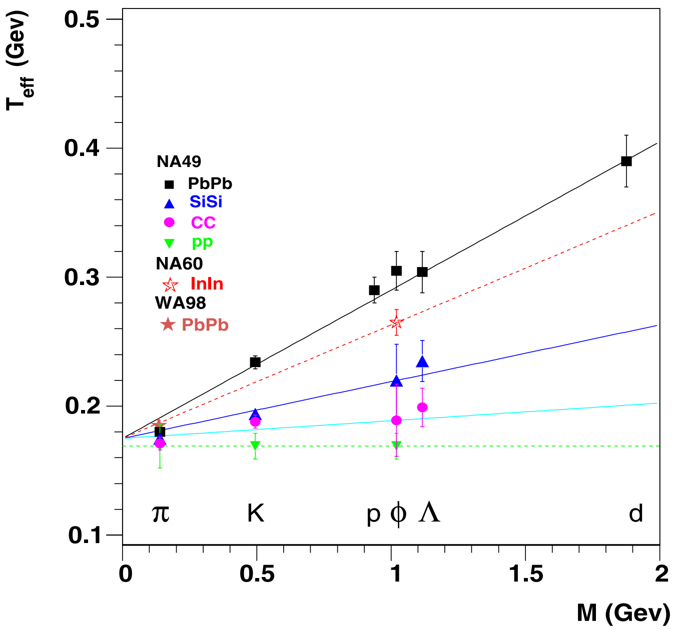

Fig. 9. T slope parameter as a function of particle mass for central events in several collision systems. The NA60 data point was obtained from a fit in the range 0.0 GeV $< p_T <$ 1.6 GeV

When the fit is repeated in the NA50 range, our points get flatter as a function of centrality and the average value of T becomes lower (Figs. 8 and 6).

In case of presence of radial flow, the effective T extracted from an exponential fit depends on the fit range (see Sect. 1, (2) and (3)). A comparison in terms of T slopes of results of experiments having different p_T coverage is not entirely sensible. Quantitatively, the discrepancy between NA50 and NA49 seems to be larger then suggested by our data (Fig. 6), though a conclusion is not possible, due to the different collision system probed by NA60. We can nevertheless conclude that the disagreement between the T slope measured by NA50 and NA49 was not due to the different decay channels probed, since there is complete consistency between NA60 and NA49 when the fit is repeated in the same p_T range.

Due to the strong hints for the presence of radial flow, a proper "flow analysis" of the NA60 data is the next natural step of this work. We are currently working on such an analysis and it will be discussed in a forthcoming paper. The discrepancy between NA50 and NA49, however, is not limited to the shape of the p_T distributions, but also involves the absolute yields. We have not yet measured absolute cross-sections, as this requires a careful understanding of the trigger efficiency. Future measurements of absolute yields and the measurement of the $\phi \to KK$ channel in NA60 (if feasible [17]) could also help to clarify this issue.

5 Summary

In this paper NA60 results on ϕ production in In-In collisions at 158 A GeV incident beam energy were presented. The p_T spectra of the ϕ was fitted with an exponential function for several centrality bins. The results were found to depend on the particular fit range considered, presumably as a consequence of radial flow. When fitted in a range consistent with the NA49 p_T coverage, our results were found to be compatible with NA49. The next natural steps foreseen for this analysis are a proper radial flow study and the measurement of absolute yields. These will contribute to definitively clarify the "puzzle" discussed in this paper.

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