φ Meson Production in In-In Collisions and the φ Puzzle

M Floris for the NA60 Collaboration
Universit`a degli Studi di Cagliari and INFN Sezione di Cagliari, strada prov.le per Sestu km 0.700, 09042, Monserrato (Cagliari)
E-mail: michele.floris@ca.infn.it

Abstract. The NA60 experiment measured dimuon production in In-In collisions at 158 AGeV. This paper presents a high statistics measurement of \( \phi \to \mu\mu \) with the specific objective to provide insight on the \( \phi \) puzzle, i.e. the difference in the inverse \( T \) slopes and absolute yields measured by NA49 and NA50 in the kaon and lepton channel, respectively. Transverse momentum distributions were studied as a function of centrality. The slope parameter \( T \) shows a rapid increase with centrality, followed by a saturation. Variations of \( T \) with the fit range of the order of 15 MeV were observed, possibly as a consequence of radial flow. The \( \phi \) meson yield normalized to the number of participants increases with centrality and is consistently higher than the yield measured by the NA49 experiment at any centrality.

One of the most striking predictions of QCD is the occurrence of a phase transition from hadronic matter to a deconfined plasma of quarks and gluons, when sufficiently high energy densities are reached. Strangeness enhancement was proposed long ago as a signature of such phase transition [1]. Experimentally, a rather interesting observable is the \( \phi \) meson, due to its \( s\bar{s} \) valence quark content. Moreover, it has been argued that close to the phase boundary, the spectral function of the \( \phi \), and thus its mass, width and branching ratios, could be modified [2]. The yield and transverse momentum spectra of the \( \phi \) meson were studied extensively at the SPS in Pb-Pb collisions at 158 A GeV. The NA49 experiment measured the \( \phi \to KK \) channel [3] (with statistics limited to \( p_T \lesssim 1.6 \text{ GeV} \)), while the NA50 experiment measured the \( \phi \to \mu\mu \) channel [4] (with acceptance limited to \( p_T > 1.1 \text{ GeV} \)). Both experiments observed an enhancement of the \( \phi \) yield with the size of the collision system. However, the absolute yields measured in the common kinematic window (transverse momentum, rapidity and Collins-Soper angle) disagree by a factor of about two [5]. It was suggested that kaon absorption or rescattering prevents the reconstruction of most in-matter \( \phi \to KK \) decays, in particular at low transverse momentum, while the \( \phi \) mesons decaying in the lepton channel would not be affected [2, 6, 7]. The effect predicted by these models, however, is smaller than the observed difference. NA49 and NA50 disagree also on the inverse \( T \) slopes determined from the transverse momentum spectra. The NA49 inverse slopes

‡ The full list of authors can be found at the end of this volume.
are consistently larger and with a stronger centrality dependence than those measured by NA60. This could be partly due to radial flow which tends to make the $T$ slopes extracted from a low $p_T$ region higher. A further increase of the NA49 slopes might be due to the depletion of the $\phi \rightarrow KK$ at low transverse momentum. The discrepancy in absolute yields and slopes became known as the $\phi$ puzzle [2, 8]. Production of $\phi$ in central Pb-Pb collisions was recently studied also by the CERES collaboration [9] both in the kaon and in the dielectron channel. The measured inverse slope and yield are compatible with the NA49 results in both channels, although the $ee$ measurement is affected by large uncertainties.

This paper presents a high statistics measurement of $\phi \rightarrow \mu\mu$ in In-In collisions at 158 A GeV, with the specific objective to provide insight into the $\phi$ puzzle. The sample consists of 360000 signal pairs, with $\sim$70 000 events lying in the $\phi$ peak. The signal/background ratio integrated over centrality is $\sim 1/3$ below the $\phi$ peak. The data were divided in 5 centrality bins, selected on the basis of the number of participants, with $\langle N_{\text{part}} \rangle = 15, 39, 75, 132, 183$. The number of participants was estimated from the charged tracks multiplicity measured in the vertex detector, matching the knee at high multiplicities to a Glauber calculation and assuming a linear relation $N_{\text{part}} \propto N_{\text{ch}}$. For more details on the analysis procedure and on backgrounds subtraction see Ref. [10, 11].

In order to study the $p_T$ distributions, events in a small mass window centered at the $\phi$ pole were selected (0.98 GeV $< M_{\mu\mu} <$ 1.06 GeV). The spectrum of the continuum below the $\phi$ 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). After subtraction of the combinatorial background, physical continuum and fake tracks, the kinematic distributions were corrected for acceptance times reconstruction efficiency, estimated with an overlay Monte Carlo simulation (a Monte Carlo dimuon is reconstructed on top of a real event). In principle this correction should be evaluated as a 3-dimensional
matrix, as a function of $p_T$, $y$ and $\cos \theta_{CS}$. This approach also requires fiducial cuts to remove the phase space corners, with a corresponding loss in statistics. In order to preserve the available statistics, a 1-dimensional correction as a function of the variable under study was used, after a careful tuning of the input kinematic distribution via an iterative procedure. In order to extract the inverse slope parameter under study was used, after a careful tuning of the input kinematic distribution via an iterative procedure. In order to extract the inverse slope parameter $T$, the $p_T$ distributions were fitted with the exponential function $1/p_T dN/dp_T = \exp(-m_T/T)$. The NA60 acceptance goes down to $p_T = 0$ GeV and the $p_T$ spectra have statistics up to $\gtrsim 2.6$ GeV. The fit was repeated in the full range $0.0$ GeV $< p_T < 2.6$ GeV and in the two sub-ranges ($0.0$ GeV $< p_T < 1.6$ GeV and $1.1$ GeV $< p_T < 2.6$ GeV), corresponding to the experimental windows of the NA49 and NA50 experiments, respectively. The $\chi^2$/ndf of the fits ranges between 0.6 and 1.5. The $T$ measured in the full range shows a rapid initial increase with centrality, followed by a saturation. It should be noticed that in presence of radial flow the $T$ slopes extracted from exponential fits depend on the fit range. The results in the sub-ranges are shown in figure 1 compared to the results of the other experiments. As seen in the figure, when the fit is performed at high $p_T$, there is a decrease of the average value of $T$ and a flatter trend with centrality. The maximum difference, in the most central bin, is of the order of $\sim 15$ MeV. The discrepancy between NA50 and NA49 seems not consistent with the $T$ slope variation observed in the NA60 data, suggesting that some other mechanism like kaon absorption/rescattering may be at play. A direct comparison of the absolute values of $T$ between NA60 and the Pb-Pb experiments is not straightforward due to possible system-size effects.

Two different approaches with largely independent systematics were used to determine the average number of $\phi$ mesons produced per interaction, $\langle \phi \rangle$. In the first, the $\phi$ cross section integrated in centrality $\sigma_\phi$ has been evaluated using the observed number of $\phi$ mesons and the number of incident ions measured with 2 independent beam counters. $\langle \phi \rangle$ was then calculated dividing $\sigma_\phi$ by the total inelastic In-In cross section, estimated with the general formula $\sigma_{inel,AB} = \pi r_0^2 \left[ A^{1/3} + B^{1/3} - \beta \left( A^{-1/3} + B^{-1/3} \right) \right]$, where $A$ and $B$ are the mass numbers of the two nuclei, $r_0 = 1.25$ fm and $\beta = 0.83 \ [13]$. In the second approach the $J/\psi$ was used as a reference. $\langle \phi \rangle$ can be calculated from the measured ratio $\langle \phi \rangle / \langle J/\psi \rangle = (N_\phi/A_{\phi}\times \varepsilon_{rec,\phi})/(N_{J/\psi}/A_{J/\psi}\times \varepsilon_{rec,J/\psi})$. Once corrected for anomalous and nuclear absorption, $\langle J/\psi \rangle$ scales with the number of binary collisions and can be written as $\langle J/\psi \rangle = (\sigma_{NN}^{J/\psi}/\sigma_{NN}) \cdot N_{coll}$. By multiplying this value by the above ratio, one obtains $\langle \phi \rangle$. The 2 methods agree within $\sim 10\%$. The $\phi$ enhancement is determined by normalizing the yield to the number of participants. Figure 2 shows the ratio $\langle \phi \rangle / N_{part}$ and the comparison to the NA49 measurements in several collision systems [14] [15] [16]. The $\phi$ enhancement in In-In with respect to p-p reaches a factor of 5 in the most central collisions. As seen, the observed $\phi$ enhancement observed by NA49 is consistently smaller at any centrality. NA49 showed that the $\phi \rightarrow KK$ breaks $N_{part}$ scaling, and that $\langle \phi \rangle / N_{part}$ for central collisions and for several collision system already saturates for Si-Si collisions. The value of $\langle \phi \rangle / N_{part}$ for central In-In collisions in the muon channel exceed the corresponding values for Pb-Pb collisions in the kaon channel, suggesting that the NA60 $\mu\mu$ data do not follow the trend measured by NA49.
Figure 2. $\phi$ yield normalized to the number of participants in full phase space and corrected for the branching ratio. Compared to the NA49 measurement in several collision systems. The error bar of the Pb-Pb data includes statistical and systematic error. Square brackets: total error (statistical and systematic). C, Si and peripheral In points displaced by $\pm 2$ participants to improve readability.

In the kaon channel. A further reduction of the systematic uncertainties is currently in progress. An unambiguous comparison to the NA50 result in full phase space is not possible, due to lack of consensus on the value of the slope parameter in Pb-Pb collisions (see above). An extrapolation with the extreme hypotheses $T = 220$ MeV and $T = 300$ MeV leads to much larger values with respect to In-In, even in the upper-bound scenario $T = 300$ MeV. The measurements of the CERES experiment do not rule out differences of the order of those observed by NA60, due to the large uncertainties on the $ee$ measurements.

In conclusion, the long-standing $\phi$ puzzle is yet to be clarified. The on-going analysis of the $\phi \rightarrow KK$ channel in the NA60 data may be decisive to clarify the picture.

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