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Charged pion production in few-GeV heavy-ion collisions measured with HADES

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The focal point of this contribution is the production of charged pions in Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.4 GeV registered by the HADES experiment in March 2019. Pions are produced abundantly in such collisions and provide a good probe for investigating the nature of nuclear matter in the extreme conditions attained by HADES. This work provides a short overview of the HADES experiment and its components. Among the products of relativistic Ag+Ag collisions charged pions were identified using the dependence of velocity and/or energy losses on momentum. Transverse mass and rapidity distributions of pions were obtained in four centrality classes spanning 40% of most central events. The reconstructed phase-space distribution is used as a starting point for total pion yield calculations and further studies. This research project was financially supported by the GET_INvolved ERASMUS+ Programme of GSI/FAIR, HADES and the University of Warsaw.

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1. Introduction

Experiments carried out with the fixed-target experiment **HADES** (**H**igh **A**cceptance **Di**-**E**lectron **S**pectrometer) [1] measure products of heavy-ion collisions in the beam energy regime of a few GeV per nucleon. Its large acceptance and unprecedented precision give insight into the extremely hot and dense nuclear matter produced in such reactions allowing the study of strongly interacting matter in states far from stability. The main area of study for HADES is relativistic nucleus-nucleus (AA) collisions, however the collaboration has also performed experiments with pA, π^-A and pp collisions. In these experiments the equation of state (EoS) of nuclear matter is probed by comparing the distributions and yields of emitted particles to theoretical predictions calculated using transport models. The abundance of available energy in the collision zone allows for production of many particles (hadrons, including those with strange quarks, and leptons) which are not found in ordinary matter. Charged pions are the lightest hadrons known within the Standard Model with a mass of 139.6 MeV/c^2 [2] and so they are produced abundantly in heavy ion collisions in the few-GeV energy regime.

Charged π mesons, being two particles of the same multiplet, are well suited probes of the Coulomb potential of the collision zone. This effect can be seen in the low-m_T part of their emission spectra (as already observed by HADES in Au+Au collisons [3]). Comparing them with theoretical models allows an estimation of the size of the collision zone. Moreover a systematics of the Coulomb potential as a function of the beam energy is being mapped. While a considerable part of pions is produced directly in the collision zone, many of them originate from decays of other particles. Decays of Δ resonances (excited nucleons) into channels such as $\Delta^+ \to n\pi^+$ or $\Delta^0 \to p\pi^-$ give insight into the dynamics of Δ baryons. This contribution focuses on the reconstruction of charged pion production in Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.4 GeV which were registered by the HADES experiment during its experimental run in March 2019.

2. The HADES experiment

HADES is a detector setup measuring tracks of particles produced in collisions of hadronic matter at relativistic energies in the fixed-target mode. HADES is connected to the SIS18 (**S**chwer**i**onen**s**ynchrotron 18) accelerator located in GSI (Darmstadt, Germany) which delivers beams of accelerated protons or heavy ions in the energy range of a few *A* GeV. The setup achieves high precision and acceptance in the measurement of both hadrons and leptons. This section provides an overview of the setup's key components for hadron track reconstruction.

HADES is mostly built in a hexagonal symmetry with respect to the beam axis, and the sketch of a section along it is depicted in Figure 1. Before entering the main body of the spectrometer, the beam of accelerated particles encounters the START detector which registers the passage of the charged particle shortly before the target - this serves as a timestamp for time-of-flight measurement. Together with an absence of signal from the VETO detector, both pieces of information are crucial for the beam trigger. The collision products emitted within the laboratory angles $\theta \in [18, 85]^\circ$ then go through four planes of **MDC** (**M**ulti-wire **D**rift **C**hambers) which are proportional chambers registering the energy of hits and their precise location. Planes I and II are located in front of the superconducting magnet whereas planes III and IV are placed behind it. Every pair of points in space defines a line passing through them and so the MDC allows an estimation of the particle's trajectory before and after having passed through the magnetic field. This deflection is strictly connected to the particle's momentum $\vec{p}$, which can be thus reconstructed from the MDC hits.

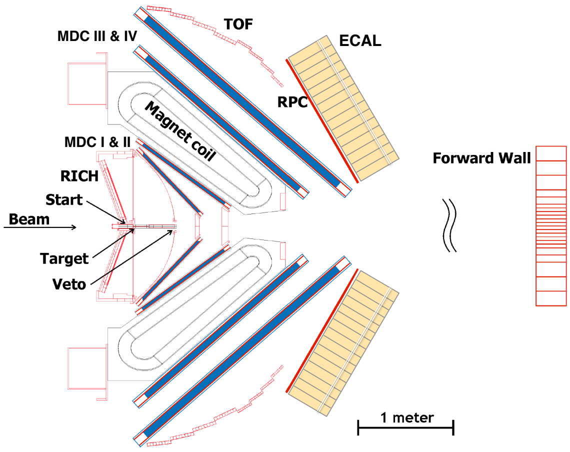

Figure 1: Schematic view of the HADES detector

Most particles produced in HADES will pass through one of the META detectors: **ToF** (**T**ime **o**f **F**light) or **RPC** (**R**esisitive **P**late **C**hamber). The information from these detectors is combined with the START signal to calculate the time-of-flight for a given track which, together with the track-based path length, is used to calculate the average velocity. The information about velocity and momentum is used to calculate the particle's mass. This gives us a full set of kinematic properties for a given track registered in HADES. The detectors of the META system are also used for determination of centrality for events. The spectrometer includes several other detectors not mentioned here - an exhaustive description of the various components of HADES and their applications, as well as of the momentum and mass reconstruction procedures, can be found in [1].

3. Analysis

3.1 Data selection

In March 2019 the HADES Collaboration carried out an Ag + Ag experiment. For thirty days the beam kinetic energy T_{beam} was 1.58 GeV per nucleon and for the three last days the experiment ran at a lower T_{beam} of 1.23A GeV. The lower energy part, corresponding to the center-of-mass energy of a nucleon-nucleon system $\sqrt{s_{NN}}$ of 2.4 GeV, is the focus of this work. Data collected by HADES during the higher energy Ag+Ag experiment is presented by M. Nabroth in this proceedings book [4]. After a data selection around 10^9 events were accepted. They were then divided into 10%-wide centrality classes, corresponding to 10% most central collisions, 10 - 20% most central collisions, etc. More about the centrality determination method used in HADES can be found in [5].

3.2 Charged pion identification

Charged particles can be identified by their dependence of velocity $|\vec{\beta}|$ on $|\vec{p}|$. The distribution of charged particle tracks in these variables is shown in Figure 2. The dashed bands delineate the range of tracks accepted as π^- and π^+, whose deviation from the analytical curve remains within 2 standard deviations. This approach, however, might be not sufficient for identifying positively charged pions since at higher momenta their distributions are contaminated with the strongest signal on the plane - protons. For a further purification of the π^+ signal we use an additional identification condition: the relation between energy losses in the MDC planes and the particle's momentum described by the Bethe-Bloch formula.

3.3 Phase-space distribution

The emission of particles can be described in the kinematic phase-space of transverse mass $m_T \equiv \sqrt{m^2 + p_x^2 + p_y^2}$ and rapidity $y \equiv \text{atanh}(\beta_z)$, where the Z-axis is defined as the beam axis. The goal of this analysis is to measure the $\frac{d^2N}{dm_T dy}$ phase-space distribution.

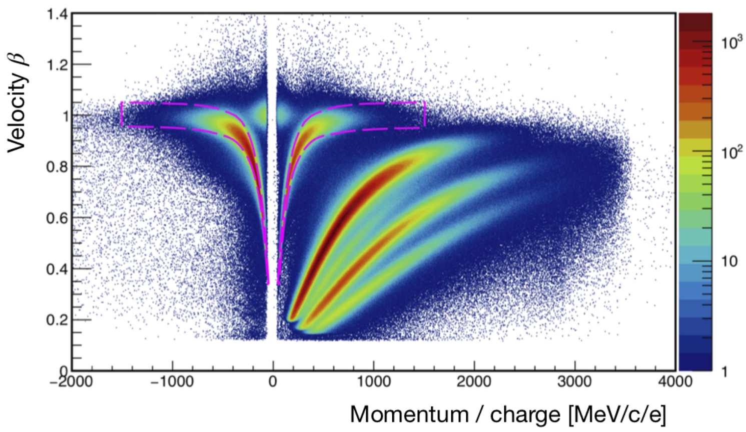

Figure 2: Identification plot of charged particles registered in the ToF detector based on the $|\vec{\beta}|$ vs. $|\vec{p}|$ relation. Regions enclosed by dashed curves are accepted as π^+ (right region) and π^- (left region).

The $\frac{d^2N}{dm_T dy}$ distribution needs to be also corrected for the efficiency and acceptance of the spectrometer in order to represent the physical result. These quantities are estimated using the UrQMD [6] transport model simulation of the collision and the virtual representation of the HADES setup within the GEANT framework [7]. The response of the detectors to the passage of reaction products is then processed by the same data analysis software, as the experimental data. The differential ratio of particles reconstructed this way to the simulated reaction products placed initially in the target is taken as the efficiency matrix.

The m_T vs. y distribution of charged pions within the acceptance of HADES and corrected for efficiency is shown in Figure 3 for two selected centrality classes: 0-10% and 30-40% most central events. The p_{max} cutoff (at 1500 MeV/c for π+ and 2000 MeV/c for π^-) is imposed during the identification procedure. Some entries were also rejected in the high-m_T region if they didn't meet track quality criteria. From this distribution a set of $\frac{dN}{dm_T}\Big|_{y=const}$ distributions is drawn. The rapidity distribution ($\frac{dN}{dy}$) is obtained by integrating the measured transverse mass distribution and adding the extrapolated yields. The rapidity distribution is then extrapolated to $\pm\infty$ and integrated to obtain the total $\pi^\pm$ multiplicity per event. This extrapolation can be done using various transport model simulations or a simple Gaussian distribution.

4. Summary

In his work, preliminary results of pion production in Ag+Ag collisions registered by HADES in March 2019 were presented. The relativistic energy of $\sqrt{s_{NN}}$ =2.4 GeV allowed for abundant production of $\pi^\pm$ mesons which were identified using their dependence between velocity and

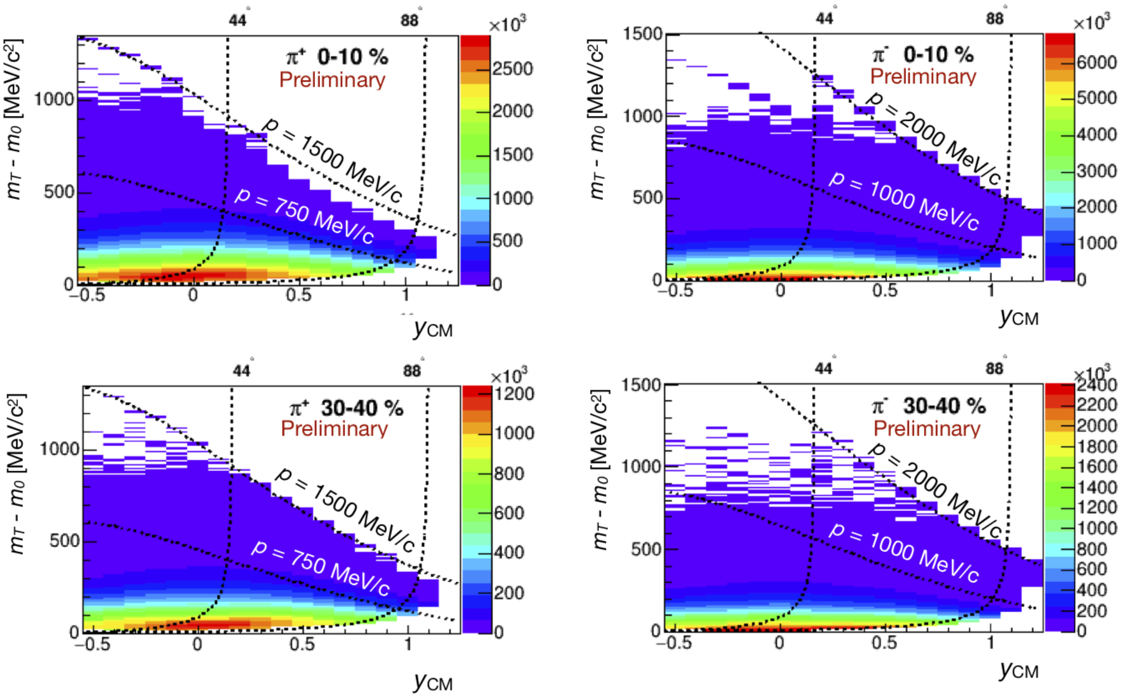

Figure 3: The distribution of charged pion (π^+ on the left, π^- on the right) yields in the plane spanned by rapidity (y_{CM}) and reduced transverse mass ($m_T - m_0$), bottom - 0-10%, top - 30-40% most central events. The plots show selected curves of $|\vec{p_{Lab}}|$ = const and θ_{Lab} = const in the phase space.

momentum. The π^+ dataset was further purified using an additional condition on energy losses in the MDC stations versus momentum. The distribution of pion production in the m_T vs. y phase-space was reconstructed and then corrected for efficiency of the HADES setup. Further analysis, such as the reconstruction of the total pion multiplicity and the Coulomb potential of the collision zone, as well as the azimuthal angle distributions (flow analysis), is ongoing.

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