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Measurements and understanding of fundamental properties of hot and dense nuclear matter with HADES

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Abstract. Heavy ion collisions at few GeV per nucleon energy range according to microscopic transport model calculations, create matter with densities several times larger that the ground density and heated to temperatures of 90 MeV. At such conditions the fundamental properties of the particles might be modified. Promising observables are the rare (multi-) strange hadrons and dileptons. The High Acceptance DiElectron Spectrometer was designed to measure rare and penetrating probes. It is a fixed target experiment located at SIS18 accelerator at GSI, Darmstadt, Germany. Recent results on dileptons and strangeness production in Au+Au collisions at center of mass energy $\sqrt{s_{NN}} = 2.42$ GeV are presented. Moreover, future experiments and upgrades of the apparatus are discussed.

1. Introduction

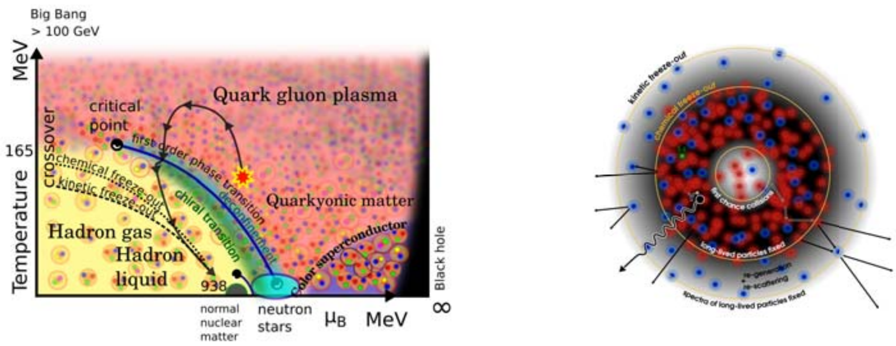

Figure 1. Cartoon of a phase diagram of QCD matter (left) and the time evolution of a heavy-ion collision. Red circles: inelastic collisions, blue: elastic (right).

Heavy-ion collisions at relativistic energies provide a laboratory in which hot and dense strongly interacting matter is created. According to a qualitative picture of the phase diagram of QCD matter as a function of temperature and baryochemical potential μ_B, shown in Figure 1, different phases might exist[1]. The transition boundary between confined matter into hadrons and the deconfined quark-gluon plasma remains a question, especially its location and width[2]. It is thought that hadronic degrees of freedom at high enough densities will disappear and another phase of chirally restored matter emerge. Also, theoretical and experimental efforts are done in

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addressing the possibility of existence of more exotic quark grouping structures as well as inhomogeneous or mixed phases[1][3]. At bombarding energies of few GeV the so called resonance matter is formed, composed of nucleons and their excited states with mesons, mostly pions. During the collision, different regions of the phase diagram can be accessed. In the beginning, the first nucleon-nucleon interactions take place, resulting in an increase of temperature and baryochemical potential by increasing the density of the system, then the formed matter cools down until inelastic and elastic collisions terminate[4] as shown in the left panel of Figure 1. This matter seems to have features of a thermalized system from measured abundances of hadrons in the final state[5][6]. The spectral function of the ρ meson, when produced within a hot and dense hadronic state is modified[7]. This feature is essential to describe the low-mass dilepton yields[8]. The production of virtual photons, strange and double-strange hadrons, proton number fluctuations, azimuthal flow are the main observables in HADES. Currently, HADES is the only experiment exploring the high baryochemical potential region.

2. The HADES

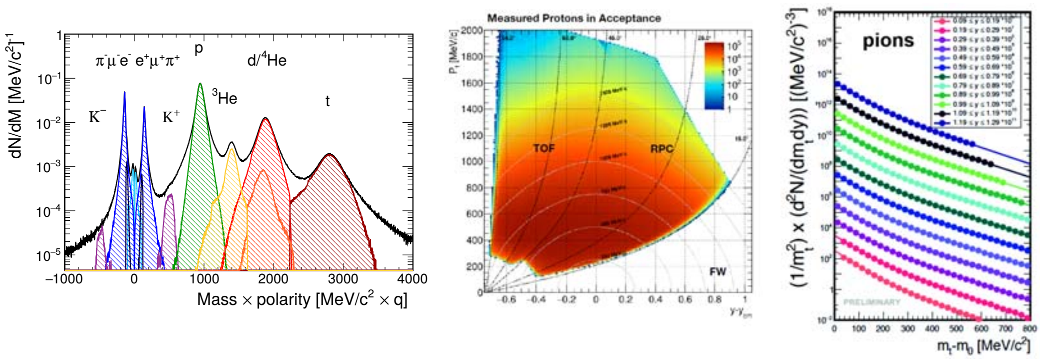

Figure 2. HADES performance: the mass times polarity spectrum (left), the measured protons in the P_T-Y plane (middle) and the differential distribution of negative pions (right).

The High Acceptance DiElectron Spectrometer is a fixed target, low mass, multipurpose detector optimized to measure rare and penetrating probes in elementary and heavy ion collisions. It is installed at SIS18 synchrotron at GSI, Darmstadt. The main particle identification method is the correlation between the velocity and the momentum of reconstructed traces. The time-of-flight measurement is performed by the combination of times from a diamond START, located in front of the target, and two STOP detectors located after the tracking stations based on fast plastic scintillator (150 ps) and resistive plate chamber technology (81 ps). Momentum is reconstructed from the bending of the particle trajectory in a strong magnetic field measured by four stations of low-mass Mini Drift Chambers with accuracy of 150 μm which corresponds with a mass resolution for dileptons at the ω pole mass of 16 MeV/c^2. Specific energy loss measured by the tracking and the scintillator detectors provides additional separation capability. Electron identification is enhanced by two detectors: a hadron blind Ring-Imaging Cherenkov and Pre-Shower detectors. For more details see [9].

3. Results from Au+Au at 2.42 GeV

The 2012 experiment was dedicated to measure Au+Au collisions at 2.42 GeV. A gold beam, with 2×10^6 ions/s was focused on a 15-fold gold target. The multiplicity trigger selected the 47% most central collisions[10]. In total 7.3×10^9 events where recorded. The reconstructed mass spectrum from velocity and momentum is shown in the left panel of Figure 2. A clear hierarchy in production is already observed at raw level. The large acceptance coverage and

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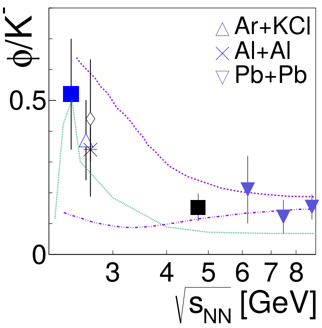

Figure 3. ϕ over K^- ratio as a function of center of mass energy for different systems. Square symbols stand for Au+Au reactions[11].

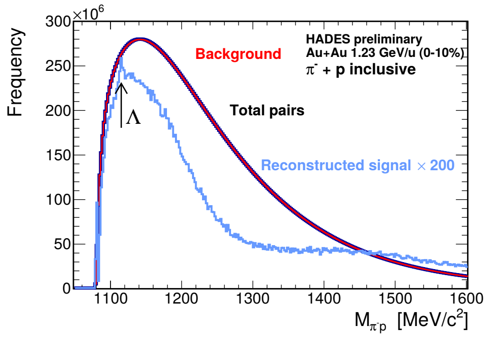

Figure 4. $\pi^- p$ invariant mass in 10 % most central Au+Au collisions at 2.42 GeV (blue) shown together with the total pairs (black) and combinatorial background obtained with the iterative technique (red).

good efficiency allows differential analysis as shown for protons and pions in the middle and right panels of Figure 2.

Electron identification was improved by introducing multidimensional multivariate analysis combining different observables into an artificial neural network for identification of single electrons. Further selections were applied in order to suppress the combinatorial background produced by conversion photons, mainly from π^0 and η mesons and from partially reconstructed electrons. Then in each event all the possible pairs of electrons are created, being many of them background. The like-sign method is used to calculate the combinatorial background contribution. The good signal-to-background ratio and the high statistics will allow to investigate the differential production distribution of virtual photons and contrast measurement with models[12]. Moreover, the previously measured at same energy reference spectra by HADES of p+p and p+n reactions and the freeze-out contributions that can be obtained from hadron analyses allow to access medium radiation[13][14].

The excellent identification capabilities allowed to reconstruct a complete set of strange hadrons. The large ϕ yield accounts for 25 % of all K^-. The ϕ to K^- ratio grows with decreasing collision energy[11] as shown in the Figure 3. This fact implies that the K^- transverse spectra is modified by the kinematics of the K^- from ϕ decay. The observation of a different slope for the strange and anti-strange kaons, interpreted as an effect of a sequential freeze-out, was revised. Once corrections of the K^- spectrum are included, both slopes of the transverse momentum distributions of K^+ and K^- are compatible within uncertainties and the former interpretation becomes doubtful[11].

In order to characterize the produced matter the Collaboration currently focuses on the following observables: strangeness production[15], net-proton number fluctuations[16], flow of hadrons[10] and virtual photons[13][14], production of pions[17] and eta mesons[18] and production of baryonic resonances. An example of an uncorrected reconstructed signal of $\pi^- p$ pairs is shown in Figure 4. In order to achieve an accurate combinatorial background, a special iterative technique has been developed[19]. The goal is to provide a complete set of observables to allow detailed comparisons to models.

4. Detector upgrade and the physics program for FAIR Phase-0

A new experimental campaign with HADES is planned in 2018-2019. Several detectors upgrades are ongoing to extend capabilities of the spectrometer. Photon reconstruction allows to measure

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Figure 5. ECAL frame (left), the PaDiWa-AMPs read-out board (middle) and lead glass module resolution as a function of the incident photon energy (right).

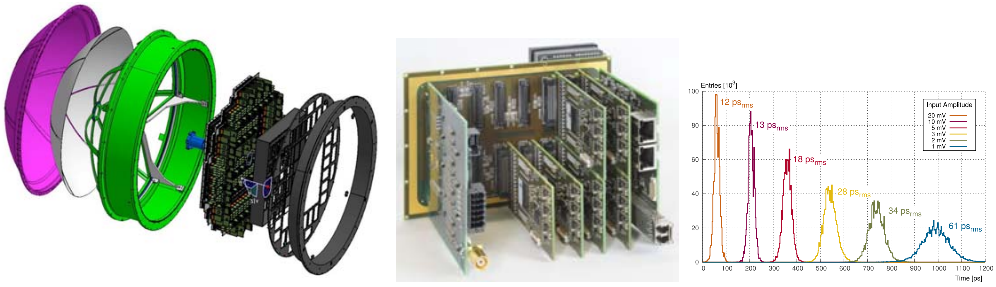

Figure 6. Constituents of the upgraded RICH detector (left), one module for 6 MAPMTs (middle) and the time resolution of the FEE as a function of the pulse amplitude (right).

new reaction channels like neutral mesons, strange baryons $\Sigma(1385)$ and $\Lambda(1405)$ or direct photon production in both elementary and heavy ion reactions. For that reason, the HADES is replacing the Pre-Shower detector by an electromagnetic calorimeter (ECAL) which is going to cover forward angles from 16^o to 45^o and almost full azimuth[20]. The Cherenkov light is produced in 987 lead glass modules, recovered from the OPAL experiment, and collected by 1.5" EMI 9903KB and 3" R6091 Hamamatsu photomultipliers. The readout is based on the PaDiWa-AMPs boards with TDC and charge-to-width measurement connected to the TRB3[21]. The expected energy resolution is better than 6% for a 1 GeV photon. The recently installed frame, the read-out board and the module performance are shown in the Figure 5.

Quantum efficiency of detection of UV-photons has been significantly improved by recent developments in Bialkali photo-cathodes present in the Hamamatsu H12700 series flat panel multianode photomultipliers (MAPMT). These detectors where chosen to replace the CsI photon converters and the Multi-Wire Proportional Chambers of the RICH detector as shown in Figure 6. The same model will be used by the CBM RICH detector and both Collaborations are developing the required read-out electronics together. The large effective area together with a large packing due to a square geometry and a low cross-talk probability will provide an excellent single electron identification efficiency. In total, 432 MAPMTs with 27.6k readout channels will cover a sensitive area of about 1.3 m^2. The readout is segmented into modules of 10x15 cm^2, each of them houses 2x3 MAPMTs with 384 individual 5.8x5.8 cm^2 channels. The MAPMT read-out including all the stages between the analogue pre-amplification to the digital output data stream are implemented in the DiRich board based on off-the-shelf components. The core of the system is

Figure 7. PANDA tracker plane[22].

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an FPGA which works as a TDC, discriminator, threshold generator and DAQ network stack[23].

The forward acceptance at low polar angles between 0.5^o and 6.5^o is going to be significantly increased by the installation of a Forward Detector System. It comprises two low material budged tracking stations of 2% X_0, developed for the PANDA experiment[22], placed 3.1 and 4.6 m downstream of the target based on self-supporting straw tubes with 10 mm diameter filled with 90/10 Ar/CO_2 mixture arranged in four planes per station with different orientations. Simulations show that it will have 0.5 mrad angular resolution for a 2 GeV/c protons. The particle identification bases on the specific energy loss and the time of flight provided by a fast Resistive Plate Chamber detector located behind the two tracking modules as it operates in a magnetic-free region.

The main program for the upcoming experiments is to continue the study of baryon-rich matter in medium-heavy systems like Ag+Ag at $1.65A$ GeV, where abundant strangeness and vector meson are produced. Also the existence of the secondary pion beam [24] opens the door to measure the electromagnetic structure of baryons and the role of the ρ meson in their decays into di-leptons[25]. Differential cross-sections of hadronic final states can be analyzed in the Partial Wave Approach in order to access the baryon-meson coupling and to improve substantially the world data base for PWA[26].

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