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The NA60+ experiment at the CERN SPS: physics goals and prospects

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The region of the QCD phase diagram at high-μ_B can be accessed by fixed-target experiments working at future or existing facilities providing nuclear beams in the multi-GeV energy range. In particular, the CERN SPS is able to provide high-intensity beams over a wide energy interval ($\sqrt{s_{NN}} = 5 - 17$ GeV) that are ideal for the study of rare signals. An Expression of Interest has been presented for a new experiment at the CERN SPS, NA60+, aimed at measuring hard and electromagnetic probes in nuclear collisions with unprecedented precision with an energy scan. The physics goals of such an experiment are very broad and ambitious. On one hand, NA60+ proposes the investigation of the order of the phase transition to the QGP in the region
$200 < \mu_B < 400$ MeV with the first measurement of a caloric curve, and the first direct measurement of the $\rho - a_1$ chiral mixing by a precision measurement of the dimuon yield in the a_1 mass region. These physics topics can be addressed via the study of the thermal dimuon continuum from threshold up to 3 GeV. On the other hand, the study of the transport properties of the QGP close to the threshold energy for the occurrence of deconfinement can be accessed for the first time by a simultaneous precision study of hidden and open charm. The measurements of charmonium and open charm states are performed through dimuon and hadronic decays, respectively. In this contribution, the physics case of the experiment will be reviewed and selected results on the physics performance studies will be shown.

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1. Introduction and physics motivation

The study of electromagnetic probes represents a crucial tool to learn about the early state of ultrarelativistic heavy-ion interactions (URHI). In particular, virtual photons which can be detected as lepton pairs are emitted all along the collision history but their yield is dominated by the high-temperature phase. The T_{slope} parameter in the spectral shape of the dilepton invariant mass spectrum can be considered as a space-time average of the thermal temperature T over the fireball evolution. With this approach, the former NA60 experiment at the CERN SPS measured the medium temperature in In–In collisions at $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV. By studying the mass region $1.5 < m_{\mu\mu} < 2.5$ GeV/c^2 the value $T_{\mathrm{slope}} = 205 \pm 12$ MeV was obtained, showing that the transition to the Quark-Gluon Plasma (QGP) is produced at top SPS energy. At much lower energy (Au–Au collisions at $\sqrt{s_{\mathrm{NN}}} = 2.42$ GeV), the HADES Collaboration has measured, in the dielectron mass region $0.3 < m_{\mu\mu} < 0.7$ GeV/c^2 and after subtracting the contribution from conventional hadronic sources, a value $T_{\mathrm{slope}} = 71.8 \pm 2.1$ MeV, showing that although the deconfinement temperature was not reached, a hot system with density up to three times the normal nuclear density was produced. Accurate dilepton studies via an energy scan in the interval between these two measurements would provide information on the region of the "transition temperature" associated with the change in the degrees of freedom of the system. A measurement of T_{slope} vs $\sqrt{s_{\mathrm{NN}}}$ would give access to a "caloric curve" where the signal from a first-order phase transition to QGP, expected in this energy range, could also be detected.

Another well-known observation related to dilepton studies, the broadening of the $\rho-$meson spectral function, is qualitatively consistent with the occurrence of chiral symmetry restoration, but a more quantitative investigation would require the study of the chiral partner a_1. The latter has no direct coupling to the dilepton channel and one of the consequences is the presence of a dip, in the vacuum, in the corresponding mass range ($\sim$ 1.2 GeV/c^2) of the dilepton spectrum. Since chiral symmetry restoration implies a mixing of vector and axial-vector correlators, a relative enhancement of the dilepton rate in the region $1 < m_{\mu\mu} < 1.4$ GeV/c^2, filling this dip, might be expected. Low-energy measurements are expected to be more sensitive to this effect as the background from semi-leptonic decays of open-charm hadron pairs becomes negligible, and the thermal dilepton yield from the hot QGP phase is also smaller.

A measurement of the dilepton mass spectrum not only gives access to electromagnetic probes but allows studying several hadron species that decay to electron/muon pairs. When considering URHI a prominent role is played by charmonium vector states and in particular by the J/ψ, which is expected to melt, mainly via color screening, in presence of a deconfined phase. While a significant suppression effect was observed at top SPS energies by the NA50/NA60 experiments, at lower energies no results are available. Likely, the effect observed at $\sqrt{s_{\mathrm{NN}}} = 17.3$ GeV is dominated by the melting of the relatively weakly bound χ_{c} and $\psi(2\mathrm{S})$ states that have a non negligible decay feed-down to the J/ψ. Moving towards lower energy with a scan may allow detecting the suppression threshold for charmonia and correlate this information with T_{slope} from thermal dilepton measurements. In addition, chiral symmetry restoration may entail a strong variation of the (J/ψ)/D ratio close to this threshold, making simultaneous measurements of hidden and open charm extremely interesting. In itself, accessing open charm production for the first time in this energy domain would allow an estimate of transport properties of heavy quark via measurements of the nuclear modification factor R_{AA} and of the azimuthal anisotropy (elliptic flow, v_2). Further measurements of D_{s} and Λ_{c} are also extremely interesting to investigate the hadronization processes. For open charm measurements the possibility of accessing hadronic decays would be necessary in order to achieve a good precision in the results.

All the measurements described above could be performed with an experiment that includes a muon spectrometer complemented by a vertex spectrometer for the precise measurement of the various decay channels and to separate prompt and non-prompt lepton production. The former NA60 experiment was based on this concept, and in the following the project of a new experiment (NA60+) employing state-of-the-art detection techniques and aimed at a measurement of dileptons and heavy quarks via an energy scan at the CERN SPS will be presented, together with the results of various physics performance studies. An Expression of Interest [1] was presented in 2019 to the SPS and PS Experiment Committee (SPSC) and the bibliography quoted there should be consulted also for these proceedings.

2. The NA60+ experiment

In order to investigate the physics topics introduced in the previous Section an experimental apparatus was designed and various R&D projects were started. The experiment will be based on a muon spectrometer, which includes a toroidal magnet with a length of ~ 3 m, radius at entrance $0.3 < R < 1.7$ m, radius at exit $R = 3$ m and field $B \times R = 0.2 - 0.25$ T·m. The tracking of the muon candidates will be be performed by a system of 4 GEM stations, two of them upstream (size 3×3 m^2) and two downstream of the magnet (7×7 m^2), with one tracking layer per station. They will be structured in tracking modules employing a triple amplification structure with a short drift gap of ~ 3 mm and 2D strip readout. Downstream of the tracking system a graphite wall and a system of two stations each one featuring two RPC planes will be used as a muon identifier and to provide a trigger to the experiment. The RPCs will be single-gap detectors, with Bakelite electrodes, read out on both sides with orthogonal strips with a pitch varying from 1 to 4 cm. The muon spectrometer is separated from the target region by a thick absorber, mainly composed of graphite, that filters out hadrons produced in the interaction. Close to the target, a vertex spectrometer consisting of 5 silicon tracking planes based on the MAPS technology will be arranged to form a 40 cm long telescope immersed in a ~ 1 T·m dipole field. Large area sensors ($15 \cdot 15$ cm^2) will be built, using a stitching technique which is being developed in synergy with ALICE. By matching the candidate tracks in the muon spectrometer to the corresponding tracks in the vertex spectrometer, a precise measurement of the muon kinematics becomes possible, overcoming the degradation induced by multiple scattering and energy loss in the absorber. The set-up can be adapted to a varying beam energy by scaling the absorber thickness and moving the position of the tracking stations in such a way to keep always a ~ 1 rapidity unit acceptance close to mid-rapidity.

In order to reach a high precision for dileptons and heavy quark measurements, a high interaction rate, 10^5–10^6 Hz, that can be reached only in a fixed-target configuration, will be needed. The experiment aims at performing an energy scan in the range $\sqrt{s_{\mathrm{NN}}} = 6 - 17.3$ GeV, accessible at the CERN SPS with beam energies between 20 and 160 GeV. Such an energy coverage is complementary to that of the future CBM experiment at FAIR ($2.7 < \sqrt{s_{\mathrm{NN}}} < 5.5$ GeV).

3. Physics performance studies

Detector performance studies were carried out by means of a simulation framework which includes a semi-analytical tracking algorithm based on the Kalman filter. The inclusion of the hadronic background component was modeled with FLUKA. The mass resolution for the resonances varies from < 10 MeV for the ω-meson to ~ 30 MeV for the J/ψ.

For dilepton studies, a simulation of the invariant mass spectrum has been performed, including thermal dimuon distributions from the model of Rapp et al. [2], a hadronic cocktail based on the statistical model [3], Drell-Yan and open charm contributions from PYTHIA6 and π/K input spectra for the combinatorial background taken from NA49 results. In Fig. 1 (left) the result corresponding to $2{\cdot}10^7$ reconstructed central Pb–Pb collisions at $\sqrt{s_{\rm NN}} = 8.8$ GeV is shown. This sample can be collected in one month of data taking at 1 MHz interaction rate. The signal over background ratio is $\sim 1/18$ at $m_{\mu\mu} = 0.6$ GeV/c^2 and a 0.5% uncertainty on background subtraction was assumed. In Fig 1 (right) the spectra after subtraction of the combinatorial background and of hadron sources, open charm and Drell-Yan are shown, for three collision energies. The values of $T_{\rm slope}$ extracted from a fit in the mass region $1.5-2.5$ GeV/c^2 have an uncertainty between 1.5 and 5 MeV ($\leq$2.5%). With such an accuracy, a detailed mapping of the region where the pseudocritical temperature is reached will become available. This results will also be sensitive to potential effects expected in case of a first order phase transition.

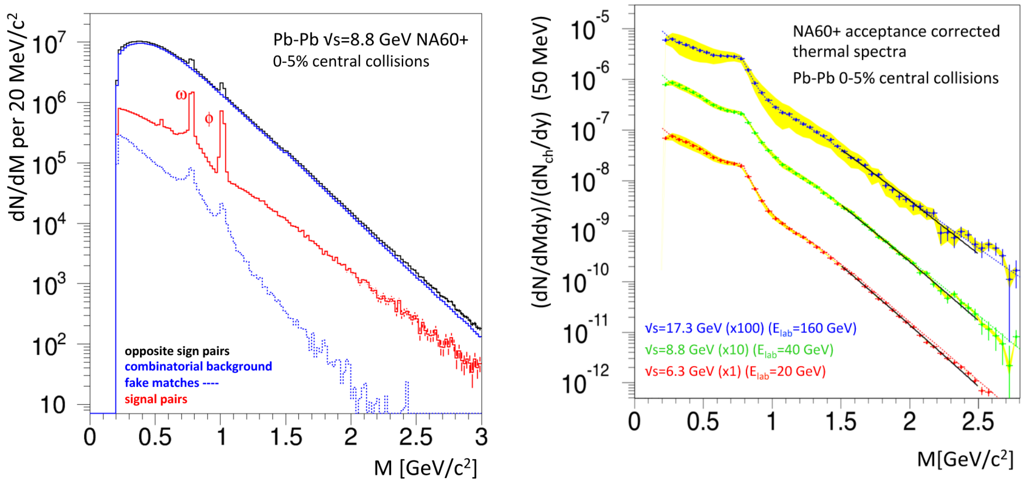

Figure 1: (Left) Expected sample in the 5% most central Pb–Pb collision at $\sqrt{s_{\rm NN}} = 8.8$ GeV. (Right) Acceptance corrected thermal spectra at different energies. Systematic uncertainties are shown as yellow bands.

A further study on the detection of a signal unambiguously related to chiral symmetry restoration was also performed by comparing simulations carried out by considering either no $\rho - a_1$ chiral mixing, which leads to a dip in the region $1 < m_{\mu\mu} < 1.4$ GeV/c^2, or full mixing, which leads to a filling of such a dip, according to the model of Ref. [2]. The difference among the two situations leads to a variation of ~ 30% in the mass region under consideration, which can indeed be detected with the accuracy of the measurements shown in Fig. 1.

For open charm measurements, the $D^0 \to K^+\pi^-$ channel was studied, producing events with the POWHEG-BOX + PYTHIA6 generator superimposed to a hadronic background tuned to NA49 data, amounting, for central Pb–Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV, to ~1200 particles (p,K,π) per event, and reconstructing the decay prongs in the vertex spectrometer. No PID is available, and in this way $8 \cdot 10^3$ candidates are expected in a 60 MeV region around the nominal mass. The very low signal over background ratio (10^{-7}) is then enhanced with kinematic and geometric selections, leading to the invariant mass spectrum shown in Fig. 2 (left), corresponding to a 30 days data taking at 150 kHz interaction rate. Studies on 3-prong decays of D_s and Λ_c are currently in progress.

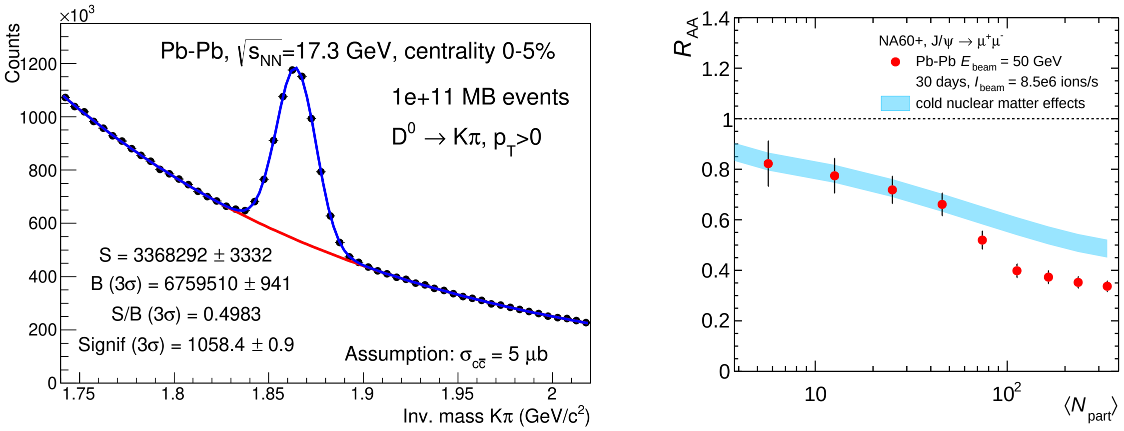

Figure 2: (Left) Projection for invariant-mass distribution of D^0 candidates in $5 \cdot 10^9$ central Pb–Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV. (Right) The J/ψ nuclear modification factor in Pb–Pb collisions at $\sqrt{s_{NN}} = 9.8$ GeV as a function of N_{part}, compared with expectations from CNM effects, shown as a blue band.

For quarkonium, a performance study was carried out assuming the onset of an anomalous J/ψ suppression for a number of participant nucleons $N_{part} > 50$, with a size reaching a maximum of 20% for the most central events. Since cold nuclear matter (CNM) effects are known to play an important role for this observable, a realistic p–A measurement involving 7 nuclear targets was also considered, and the corresponding accuracy for the estimate of CNM effects was taken into account. The result, corresponding to 30 days of Pb–Pb data taking with a beam intensity of 10^7 Pb/s at $\sqrt{s_{NN}} = 9.8$ GeV (50 GeV incident energy) is shown in Fig. 2 (right) as the expected N_{part}-dependence of R_{AA}. The extra suppression, in addition to CNM effects, can be clearly detected. Corresponding studies on the $\psi(2S)$ meson show that a measurement of the relative suppression of the two states can be carried out from top SPS energy down to $\sqrt{s_{NN}} \sim 12$ GeV.

References

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