Overview of the NA60+ experiment at the CERN SPS

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Abstract. NA60+ is a new experiment designed to study the phase diagram of the strongly interacting matter at CERN SPS energies, where the values of the baryochemical potential μ_B approximately range between 200 and 550 MeV. It is focused on precision studies of thermal dimuons, heavy quarks, and strangeness production in Pb–Pb collisions at center of mass energies ranging from 6 to 17 GeV per nucleon pair. In this paper the apparatus concept and the physics reach will be discussed.

1 Introduction

The QCD phase diagram at high μ_B values has been little explored so far. At low μ_B a transition between hadronic matter and Quark Gluon Plasma (QGP) at temperatures around 155 MeV has been observed [1]. At high μ_B, theoretical predictions suggest a complex structure with a possible first order transition ending with a critical point [2, 3]. Precise measurements of dileptons and charms at large μ_B are currently lacking.
NA60+ will study the region $200 < \mu_B < 550$ MeV via an energy scan at the SPS with Pb beams in the range $6 < \sqrt{s_{NN}} < 17$ GeV [4]. An ambitious physics program is foreseen, which includes the search for chiral-symmetry restoration effects through the $\rho - a_1$ mixing, the study of the order of the phase transition through the measurement of a caloric curve using thermal dileptons, the search for the onset of the deconfinement through the measurement of J/ψ suppression. Furthermore, the measurement of the transport properties of the medium via open charm states and the study of hadrochemistry via the detection of strange hadrons and hypernuclei are also part of the physics program.

2 Experimental apparatus

The NA60+ experimental apparatus is shown in Figure 1. A high intensity beam of $\sim 10^6$ ions/s will collide on a target system of five 1.5 mm thick Pb disks. The vertex telescope will start at ~7 cm from the target system along the beam line. It will consist of five layers of large area stitched Monolithic Active Pixel Sensors based on the TPSCo 65 nm imaging technology [5]. Stitching is a technique used to produce wafer-scale sensors larger than the lithographic reticle. The vertex telescope will be based on square sensors with a size of 15 cm, obtained by repeating through stitching 2.5 x 1.5 cm^2 sensor units. Each plane will be composed of 4 such sensors arranged as in Figure 2, leaving a hole in the center to allow the passage of the non interacting beam. The pixel pitch is ~ 20 μm, leading to a spatial

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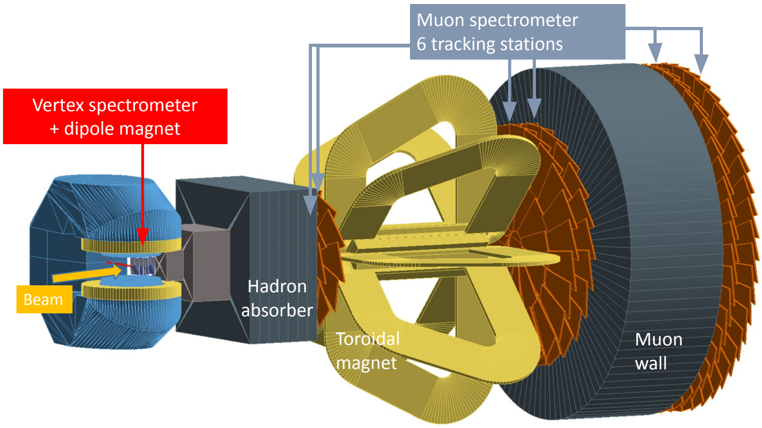

Figure 1. View of the NA60+ experimental apparatus. The beam is coming from the left side.

resolution better than 5 μm. The sensors have a very low material budget ($< 0.1\%$ X_0) and are glued on a support frame outside the acceptance made of graphite. The vertex telescope will be embedded in a 1.47 T dipole field provided by the MEP48 magnet, which is already available at CERN.

An absorber comprising a BeO and a graphite section will be placed after the vertex telescope to reduce the background in the muon spectrometer. The total interaction lengths will vary from 14.4 at 20 GeV/c to 26.1 at 150 GeV/c.

The muon spectrometer will comprise six stations with a modular design based on trapezoidal units. The first two stations will be composed of 12 overlapping petals, each rotated by 11°. The third and fourth stations will have a second ring of 24 petals, while the last two stations will have a third ring of 48 petals. FLUKA simulations showed that the maximum rate in the first station of the muon spectrometer will be $\sim$ 2 kHz for a Pb beam rate of 10^{-6} s^{-1}. These rates can be matched by MWPC and GEM. Prototypes with this technologies has already been built, proving a spatial resolution of 120 μm.

Between the second and third station, a warm toroidal magnet with a novel lightweight design with low material budget in the acceptance area will be used to measure the muon momentum. It is based on eight sectors with 12 turns per coil generating a magnetic field of $B_\phi \sim$ 0.3 Tm at r = 1 m at half of the magnet length. A 1:5 scale prototype has been built in collaboration by CERN and INFN. Measurements of the prototype magnetic field were found in agreement with the simulations within 3%.

A second absorber (muon wall) will be placed before the last two stations to stop the residual background. The muon spectrometer will be placed on rails, so as to adjust its length to better cover the mid-rapidity region at different energies.

The experiment will be installed at the PPE138 area of the CERN EHN1 hall on the H8 beam line. A new shielding capable of keeping dose levels below 3 μSv/h outside the experimental area has been designed [6]. Preliminary studies on beam optics have been performed, showing that it is possible to obtain a Pb beam with $\sigma \sim 250\,\mu$m for the moment up to an intensity of $\sim 2.7 \cdot 10^5$ ions/s at 150 GeV/c. Further tests at lower beam energies are planned for fall 2024.

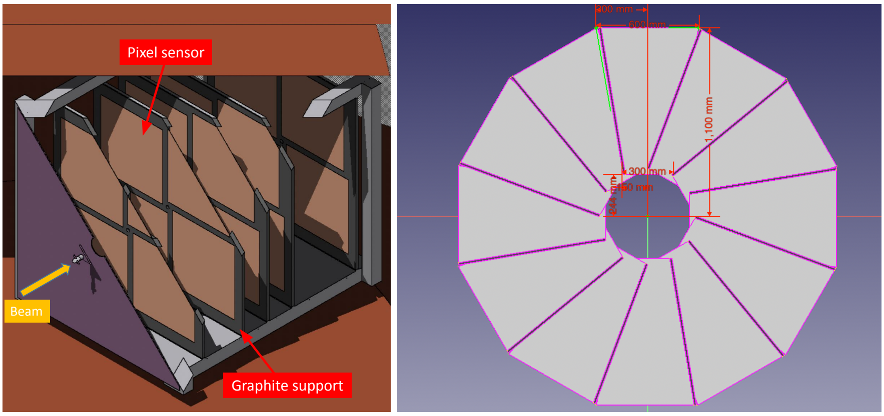

Figure 2. View of vertex telescope inside MEP48 (left), and of the sketch of one of the first two stations of muon spectrometer (right).

3 Physics performance

NA60+ will measure the thermal dimuons spectrum up to 2.5-3 GeV/c^2, collecting around $4 \cdot 10^6$ reconstructed dimuons in central Pb–Pb collisions at $\sqrt{s_{NN}}$ = 6.3 and 8.8 GeV, ~20 times larger statistics with respect to the previous NA60 experiment. Fitting the dimuon mass spectra for $M_{\mu\mu} > 1.5$ GeV/c^2 with $dN/dM_{\mu\mu} \propto M_{\mu\mu}^{-3/2} exp(-M_{\mu\mu}/T_{\mathrm{slope}})$, it will be possible to measure the slope parameter, related to the medium temperature, with an uncertainty of ~2%. This will provide an accurate mapping of the temperature vs $\sqrt{s_{NN}}$, i.e. a caloric curve (see Fig. 3).

Full $\rho - a_1$ chiral mixing would produce a 20-30% enhancement in dilepton yield in the region $0.8 < M_{\mu\mu} < 1.5$ GeV/c^2 [7]. NA60+ will be able to measure the yield in this mass region with enough precision to detect such an enhancement, which is a direct signal of chiral symmetry restoration.

Furthermore, the first measurement of the dimuon elliptic flow below RHIC energies will be performed.

NA60+ will measure a J/ψ measurement down to $\sqrt{s_{NN}}$ = 9.8 GeV and the ψ(2S) down to $\sqrt{s_{NN}} \sim 15$ GeV. Results on J/ψ production vs $\sqrt{s_{NN}}$ might allow to detect the onset of the suppression. Cold nuclear matter effects will be calibrated with dedicated p-A runs.

Open charm can be measured using the vertex telescope alone. In fact, stringent topological selections on the displaced decay vertex ($c\tau \sim 60 - 300\mu$m) can be applied thanks to the very high precision tracking of the vertex telescope. Figure 3 shows the expected invariant mass distribution measurement of the D^0 at $\sqrt{s_{NN}}$ = 10.6 GeV in central Pb–Pb collision. The high significance of the signal will open the possibility of performing differential studies of yield and v_2 as a function of p_T, y, and centrality. The D^+, D_s^+, Λ_c^+, and possibly $\Xi_c^{0,+}$ can be measured as well.

A similar approach can be used to study also the strange particles K_S^0, Λ^0, ϕ, Ξ^-, Ω^- and hypernuclei, with the possibility to perform precise multi-differential measurements. Hypernuclei at low $\sqrt{s_{NN}}$ are produced more abundantly than at RHIC or LHC energies. Thanks to the high statistics that can be collected, high precision measurements of the hypernuclei (${}^3_\Lambda$H, ${}^4_\Lambda$He, ${}^5_\Lambda$He) properties will become possible, including possibly the discovery of Ξ and Σ hypernuclei.

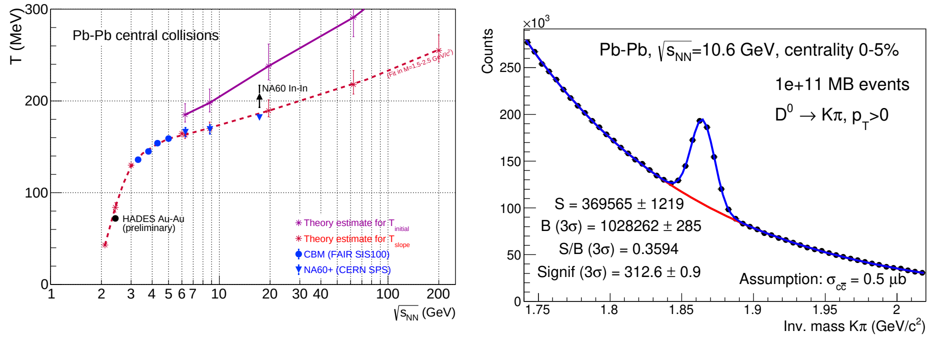

Figure 3. The expected performance for the measurement of a caloric curve by NA60+ and CBM (blue marker), together with the current measurements (black marker), and theoretical predictions for T_{slope} and the initial temperature [7] (left). The expected invariant mass distribution for the $D^0 \to K\pi$ at $\sqrt{s_{NN}}$ = 10.6 GeV (right).

4 Prospects and conclusion

The state-of-the-art technology proposed for the detectors, together with the high intensity beam, will allow for unprecedented high-precision measurement of electromagnetic probes, charmed hadrons, strange particles, and hypernuclei at the SPS energies.
NA60+ is part of the CERN Physics Beyond Collider initiative, a larger effort to complement the physics programs of the existing and future colliders. A letter of intent was submitted to the SPSC in December 2022, and a positive feedback was received. The collaboration is working to submit a technical proposal by early 2025. The plan is to start building the experiment in 2026 and start taking data in 2029. At least 7 years of data taking are foreseen, with one energy point with p-A and Pb–Pb per year. Each year, the data taking will last ~ 1 month in Pb–Pb, and a few weeks for p-A.

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