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Measurement of a caloric curve and chiral symmetry restoration with the NA60+ experiment at the CERN SPS

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NA60+ is a new proposed experiment designed to study the phase diagram of the strongly interacting matter at high baryochemical potentials, ranging from 200 to 550 MeV. It is focused on precision studies of thermal dimuons, heavy quarks, strangeness and hypernuclei production in Pb-Pb collisions. These processes will be studied as a function of the collision energy with high-intensity Pb beams provided by the CERN SPS, performing an energy scan from $\sqrt{s_{\rm NN}}$ = 6 GeV (corresponding to $E_{\rm lab}$ ~20 A GeV) or even lower, if provided, up to top SPS energy ($\sqrt{s_{\rm NN}}$ = 17.3 GeV, $E_{\rm lab}$ =158 A GeV).
The experimental apparatus is composed of a vertex telescope located close to the target and a muon spectrometer located downstream of a hadron absorber. The vertex telescope will consist of several planes of ultra-thin, large area Monolithic Active Pixel sensors (MAPS) embedded in a dipole magnetic field. The muon spectrometer will utilize large area gaseous detectors for muon tracking and a toroidal magnet based on a new light-weight and general-purpose concept.
An ambitious physics program is foreseen, which includes the study of the order of the phase transition at large baryochemical potential through the measurement of a caloric curve and the search for chiral symmetry restoration effects through the $\rho - a_1$ chiral mixing.
This paper will focus on the physics motivations for these measurements based on thermal dimuons. A description of the experimental set-up will be given together with the results of the physics performance studies. Finally, the present status of the project and the outlook will be briefly discussed.

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1. Introduction

High-energy heavy-ion collisions at the SPS, RHIC, and the LHC have investigated QCD matter at high temperatures and small baryo-chemical potential, $\mu_B \sim 0$. Data are consistent with a cross-over phase transition from hadronic confined matter to a plasma of quarks and gluons (QGP) with a pseudo-critical temperature of $T_{\rm pc} \sim 155\,\text{MeV}$ [1] . Furthermore, chiral symmetry is essentially restored for temperatures $T \sim 180\,\text{MeV}$ [2, 3].

Rather little is known at high μ_B, but theoretical calculations suggest a potentially rich phase structure including the emergence of a first-order transition along with a second-order critical endpoint [4]. This transition regime might be investigated by measuring the temperature as a function of collision energy - a *caloric curve*. Thermal dimuons provide a precise thermometer that is independent of the blue shift effect imparted on momentum spectra. For dilepton masses above 1.5 GeV/c^2 one has $dN/dM \propto M^{3/2}\exp(-M/T_{slope})$, where T_{slope} is a space-time average of the time-dependent temperature T during the fireball evolution, strongly biased towards the early stage [5].

The broadening of the ρ-meson spectral function observed at SPS [6–8] and later at RHIC energies [9, 10] is consistent with chiral symmetry restoration [11]. However, an unambiguous way to observe chiral symmetry restoration would be to measure also the chiral partner a_1. Even if the latter cannot be reconstructed exclusively in heavy-ion collisions, the so called $\rho - a_1$ chiral mixing mechanism provides access to the properties of the a_1, leading to a measurable increase of the yield of thermal dileptons in the mass range 0.9-1.4 GeV/c^2 [11].

The experimental programme of NA60+ proposes to perform an energy scan with Pb-Pb collisions in the interval $\sqrt{s_{NN}}$ =6 -17 GeV (E_{lab} = 20-160 AGeV), with particular focus on $\sqrt{s_{NN}}$ < 10 GeV, which is believed to be essential to map out the phase transition regime at high μ_B, with the possible discovery of a plateau in the caloric curve built with dilepton slopes T_{slope}. Pb-Pb collisions at low energies, where the QGP radiation becomes suppressed and possibly negligible, are also ideal to study in detail the chiral mixing.

2. Detector concept and running conditions

The proposed new experimental set-up includes: (i) a vertex spectrometer, for a precise measurement of the momentum and production angle of the large amount of produced charged particles ($dN_{\rm ch}/d\eta > 400$ in central Pb–Pb collisions at top SPS energy); (ii) a muon spectrometer, which measures muon tracks which are filtered by a thick hadron absorber, positioned downstream of the vertex spectrometer. A conceptual drawing of the set-up is shown in Fig. 1.

Vertex spectrometer The magnetic field for the momentum measurement in the vertex spectrometer will be provided by the MEP48 dipole magnet, stored at CERN, which can deliver a 1.5 T field over a 400 mm gap. The vertex telescope consists of 5 identical silicon pixel planes positioned at $7 < z < 38$ cm starting from the most downstream target. The absorber starts at ~ 45 cm from the interaction point, providing a good rejection of background muons from pion and kaon decays. Each plane, featuring a material budget of 0.1% X_0 and intrinsic spatial resolution of ~5 μm, is formed by 4 large area monolithic pixel sensors (MAPS) of 15x15 cm^2 each. The total active area is ~ 0.5 m^2. An R/D on a new generation of wafer-scale MAPS based on stitching is on-going in

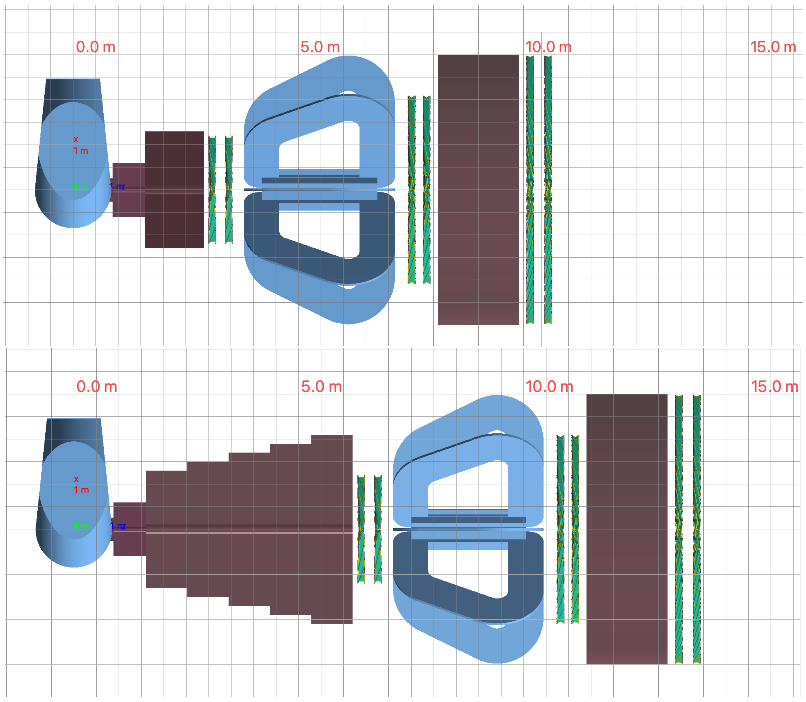

Figure 1: Top: set-up adapted to low-energy collisions, with a thinner hadron absorber and the muon spectrometer relatively closer to the target. Bottom:the set-up intended for high-energy collisions.

synergy with ALICE. A GEANT4 rendering of the silicon telescope inside the MEP48 dipole is shown in Fig. 2.

Muon spectrometer A thick hadron absorber (2.5 to 5 m, depending on collision energy), with an upstream section composed of BeO, followed by graphite, is positioned in front of the muon spectrometer. It has relatively high density and limited Z, so to limit multiple scattering of the muons.

The set-up of the spectrometer includes six tracking stations. The first two stations are located after the hadron absorber and upstream of a toroidal magnet, while the following ones are installed downstream of it, providing in this way four space points with $\sim$ 200 μm spatial resolution. Following a design typical of this kind of spectrometers (NA50/60, ALICE), a thick graphite wall allows further filtering of hadrons that may have survived the hadron absorber, and is followed by two final tracking stations. Detector R/D is on-going, with GEM and/or MWPC as candidate technical solutions.

A warm magnet with an angular aperture of 0.29 rad is foreseen, composed of eight radial sectors, each one consisting of a number of windings, in order to reach the desired current. The strength of the magnetic field is $\sim$ 0.37 T at a radial distance of 1 m, with a $1/r$ dependence of the field. The total length of the magnet is 335 cm. The non-negligible technical challenges of such a project have led to the realization of a prototype in scale 1:5, to be considered as a testing bench for the possible solutions for the full-scale object.

The experiment can be located on the H8 beam line, in the PPE138 experimental zone of the CERN EHN1 hall. Integration and radiation protection studies have shown the possibility of

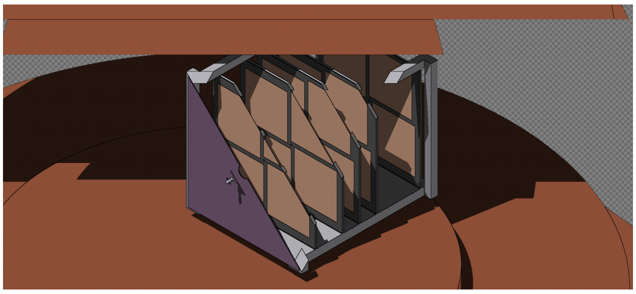

Figure 2: Exploded prospective view of the silicon pixel planes inside the MEP48 dipole. Each plane is formed by 4 large area MAPS and is housed inside an aluminum crate. The target system sits in front of the crate.

sustaining Pb beam intensities of the order of 10^7 per 10 s spill, provided that an adequate shielding is built around the experimental set-up. The experiment plans to perform measurements of Pb–Pb collisions at a single collision energy for each data taking period, typically one month per year. The program will need a minimum of 6-7 years of data taking, to provide a fine enough energy scan for the characterization of the QGP at various baryo-chemical potential and the search of signals related to the first order phase transition. Measurements with a Pb beam need to be complemented by corresponding data taking periods with a proton beam incident on various nuclear targets, collecting an equivalent luminosity and providing reference data for the correct quantitative interpretation of nuclear collision results.

3. Physics performance studies

Detailed performance studies were carried out for the 5% most central PbPb collisions at $\sqrt{s_{NN}}$ = 6.3, 8.8, 17.3 GeV. The differential spectra of thermal $\mu\mu$ pairs, $d^3N/(dMdp_tdy)$, are based on the in-medium ρ, ω and 4-pion spectral functions, QGP radiation and the expanding thermal fireball model of [5]. We present results for data samples collected in one month data taking at $\sqrt{s_{NN}}$=8.8 and 17.3 GeV, and in two months of data taking at $\sqrt{s_{NN}}$=6.3 GeV.

The left panel of Fig. 3 shows the signal reconstructed mass spectra (black) for Pb-Pb collisions at $\sqrt{s_{NN}}$ = 8.8 GeV after subtraction of the combinatorial background due to pion and kaon decays as well as fake matches. The 0.5% systematic uncertainty from the subtraction of combinatorial background is shown as a yellow band. For M < 1 GeV/c^2, the thermal radiation yield is dominated by the in-medium ρ. The ω and ϕ peaks are well resolved with a resolution better than 10 MeV/c^2 at the ω mass. The thermal spectra are measurable up to 2.5-3 GeV/c^2 at all energies. They are obtained after (i) subtraction of the hadronic cocktail for M < 1 GeV/c^2 of η, ω and ϕ decays into $\mu\mu$ as well as the η and ω Dalitz decays and (ii) subtraction of Drell–Yan as well as open-charm muon pairs for M > 1 GeV/c^2. After acceptance correction, the spectra are fit with $dN/dM \propto M^{3/2}\exp(-M/T_{\rm slope})$ in the interval M =1.5-2.5 GeV/c^2. The resulting spectra at $\sqrt{s_{NN}}$ = 6.3, 8.8, 17.3 GeV are shown in the right panel of Fig. 3. The theoretical spectra used as an input are shown as dashed lines, while the exponential fits are shown as black lines.

The main result is the caloric curve of Fig. 4 (left), which displays the temperature evolution as a function of collision energy. The dashed line is the $T_{\rm slope}$ from the theoretical model used

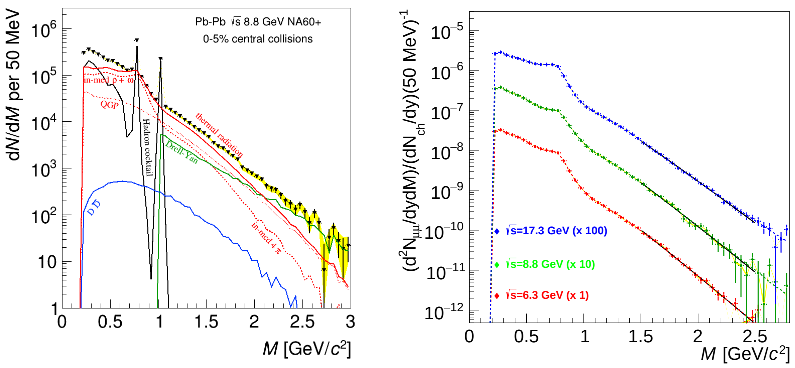

Figure 3: (Left) Expected signal sample in the 5% most central Pb-Pb collision at $\sqrt{s_{NN}}$ = 8.8 GeV after subtraction of combinatorial and fake match background. (Right) Acceptance corrected thermal spectra at $\sqrt{s_{NN}}$ = 6.3, 8.8, 17.3 GeV obtained after subtraction of open charm, Drell–Yan and hadronic cocktail. Model comparisons and exponential fits as discussed in the text are shown.

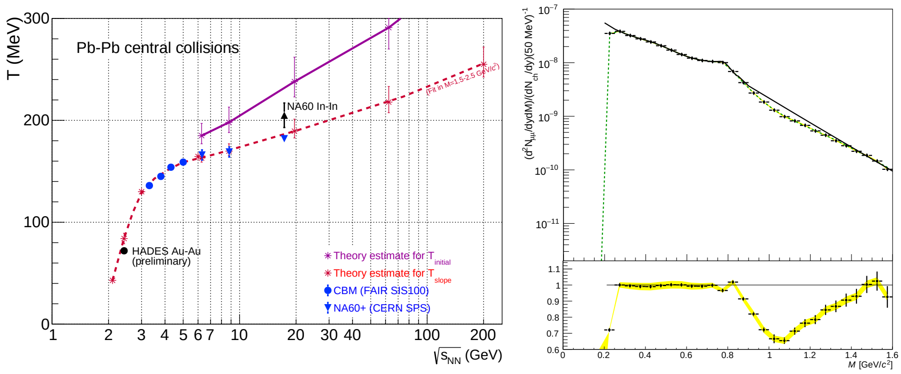

Figure 4: Left: caloric curve - medium temperature evolution vs $\sqrt{s_{NN}}$ in central Pb-Pb collisions. T_{initial} (magenta) and T_{slope} (red) are theoretical estimates for the initial medium temperature and T_{slope} [5, 12]. Blue triangles are the expected performance from NA60+ (CBM performance is also shown [13]). Right: thermal dimuon mass spectrum at $\sqrt{s_{NN}}$ = 8.8 GeV in case of no chiral mixing compared to the theoretical expectation (green line). The black line above 1 GeV/c^2 is the expectation from full chiral mixing [5].

as an input. At low energies, the temperatures can be measured with a combined statistical and systematic uncertainty of just a few MeV, thus showing that the experiment has a strong sensitivity to a possible flattening of the caloric curve in a region complementary to the one explored by CBM.

The acceptance corrected mass spectrum at $\sqrt{s_{NN}}$ = 8.8 GeV, based on the assumption of no chiral mixing, is compared to the expectation of full chiral mixing in Fig. 4 (right). As shown, the statistical and systematic uncertainty provide a very good sensitivity to a yield increase of ~20–30% due to chiral mixing.

4. Status of the project and outlook

At the end of 2022 a letter of intent [14] was submitted to the CERN SPSC, which recognized the fundamental interest of the proposed measurements. During 2024 the R/D on silicon sensors and muon tracking chambers will be completed and a technical proposal will be submitted by the end of 2024. The construction should take place during the LHC long-shutdown 3 (2026-28) and data taking is expected to start in 2029.

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