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The Physics program of the NA60+ experiment at the CERN SPS

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A new heavy-ion experiment on fixed target, NA60+, has been proposed at the CERN SPS for data taking in the next years. Its main goals will focus on precision studies of thermal dimuons, strangeness and heavy quark production in Pb-Pb collisions at center-of-mass energies ranging from 5 to 17 GeV. The experiment will profit from the high-intensity beams provided by the CERN SPS in a wide energy interval, that will provide a unique opportunity to investigate the region of the QCD phase diagram at high baryochemical potential, μ_B. The proposed experimental apparatus consists of a vertex telescope located close to the target and a muon spectrometer located downstream of a hadron absorber. The vertex telescope consists of several planes of monolithic active pixel sensors embedded in a dipole magnetic field. The muon spectrometer will utilize GEM detectors for muon tracking and a toroidal magnet based on a new light-weight and general-purpose concept. This apparatus, based on state-of-the-art technologies, will allow a very broad and ambitious physics program. The high-precision measurements of dimuon invariant mass distributions will open the possibility to investigate the order of the phase transition from the quark-gluon plasma to a hadron gas in the interval $\mu_B \sim 200-400$ MeV via the first measurement of the caloric curve. In addition, the first direct measurement of $\rho - a_1$ chiral mixing could be achieved by a precision measurement of the dimuon yield in the a_1 mass region. Furthermore, a simultaneous precision study of hidden and open charm will be carried out, by measuring charmonium states through dimuon decays and open-charm hadrons from their hadronic decays reconstructed from the tracks in the vertex telescope. Finally, precision measurements of strangeness production will also be performed, through the decays of strange hadrons detected in the vertex telescope.

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1. Introduction

The study of the QCD phase diagram is at present mainly restricted to the region of vanishing baryochemical potential, $\mu_B \sim 0$, where lattice QCD calculations predict a cross-over transition from the hadronic matter to the Quark-Gluon Plasma (QGP) around a critical temperature $T_c \approx$ 155 MeV. Measurements at the CERN-SPS, BNL-RHIC and CERN-LHC top energies provided information on the low μ_B part of the phase diagram, showing that a deconfined state of matter is reached, with properties consistent to the predictions from lattice QCD. Heavy-ion collisions at low center-of-mass (CM) energies provide a unique tool to investigate the QCD phase diagram at large μ_B. An energy scan at the CERN SPS, with CM energies ranging from 5 to 17 GeV per nucleon, will allow to access the phase diagram region $\mu_B \sim 200-400$ MeV (fig. 1), where key information can be obtained about the order of the phase transition at large μ_B, the presence of a critical point, the chiral symmetry restoration effects and the temperature at which the onset of the deconfinement takes place.

The NA60+ experiment was proposed [1] to study hard and electromagnetic probes in this μ_B region at the CERN SPS. Such measurements would address many yet uncovered points in the understanding of the QGP phase. The suppression of quarkonia states due to color screening is considered one of the most relevant signatures of deconfinement. The measurement of J/ψ suppression as a function of the CM energy would carry information on the onset of deconfinement. Measurements of p_T distributions and azimuthal anisotropy of open charm states would allow to determine the transport properties of the QGP at large values of μ_B. Electromagnetic probes, and in particular dileptons, would give insight on the temperature of the system via the measurement of the thermal dimuon mass spectrum, on chiral symmetry restoration effects and on the order of the phase transition [2, 3].

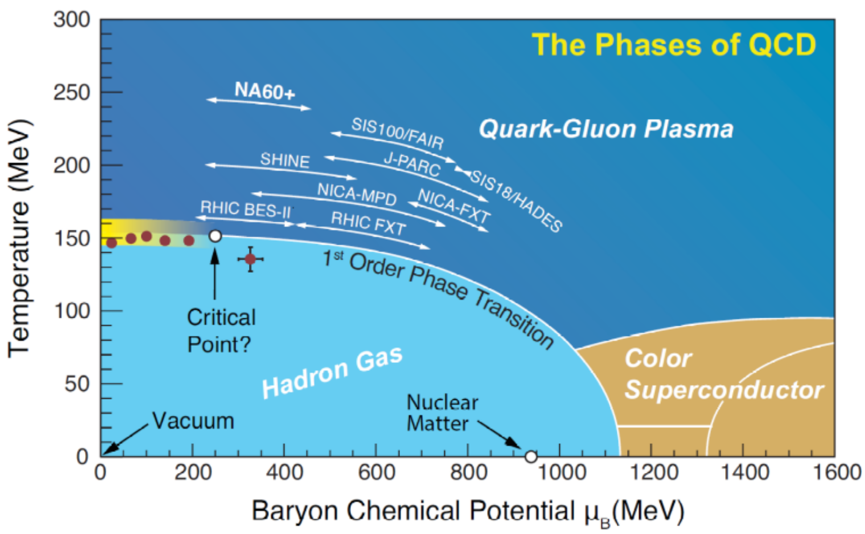

Figure 1: The QCD phase diagram (courtesy of Thomas Ullrich)

2. Detector concept

The design of the NA60+ detector is based on that of its predecessor NA60. The two main components of the apparatus are a muon spectrometer and a vertex telescope, separated by a hadron absorber.

Muons are detected by a magnetic spectrometer, composed of a toroidal magnet and four tracking stations. A new magnet, which should provide a field $B \cdot R \sim 0.2 - 0.5$ Tm is being designed and a small-scale prototype has been constructed and tested. The tracking stations will be equipped with about 330 GEM modules, each one measuring 50×110 cm^2, overlapping in both horizontal and vertical coordinates by 10 cm, covering a total surface of about 130 m^2. The GEM module design profits from the experience developed for the CMS muon system and the ALICE TPC upgrades. The expected spatial resolution is of $100 - 200$ μm. A trigger system, based on two RPC stations and placed after an additional graphite absorber, completes the muon spectrometer setup.

The width of the front absorber, as well as the position of the tracking stations will be changed depending on the beam energy, such that the detector keeps a good acceptance around mid-rapidity. The low-energy ($E_{\rm beam}/A = 20 - 40$ GeV) setup is reported in fig. 2. At high energy, $E_{beam}/A = 158$ GeV, the muon spectrometer will be moved forward by 3.3 m and the absorber thickness will be increased to 4.6 m.

The absorber provides the muon identification, and the distance from the interaction point to the absorber should be small to minimize the background muons from pion and kaon decays. However, at the same time the absorber introduces a deterioration in the muon momentum resolution, due to multiple scattering and fluctuations in the energy loss. This loss in resolution can be recovered by matching the muons reconstructed in the muon spectrometer with the charged tracks

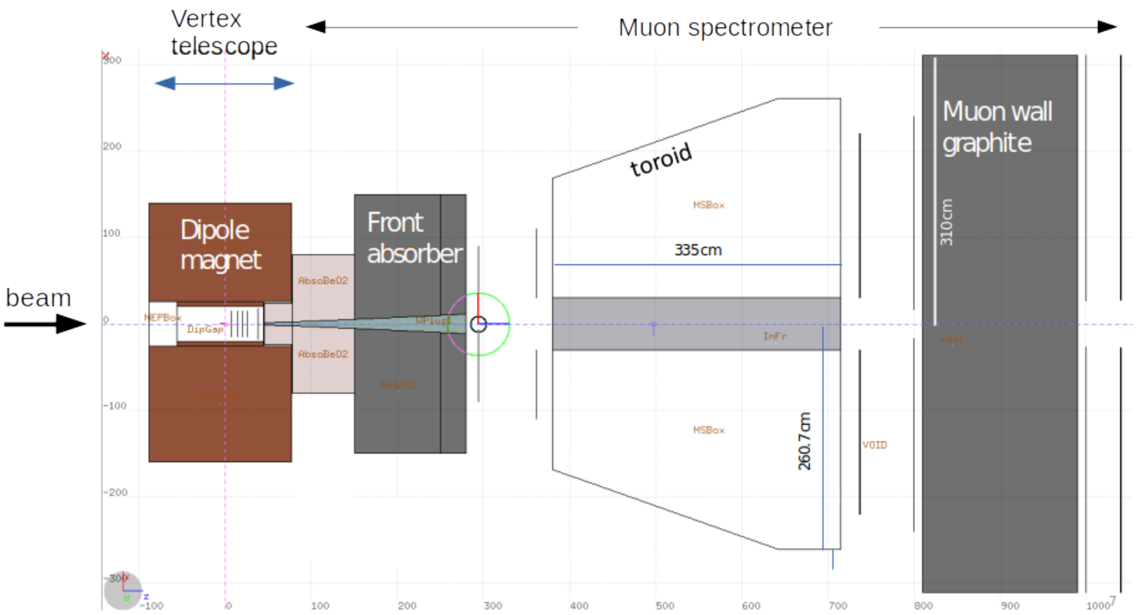

Figure 2: Layout of the proposed NA60+ apparatus in the low energy setup.

measured in the vertex telescope (VT), both in coordinates and momentum space. The VT can also be used for multiplicity measurements, and as a stand-alone detector for the study of hadronic decay channels of charm and strange hadrons.

The VT consists of a dipole magnet and a tracking system based on pixel planes. The magnet considered for NA60+ is the CERN MEP48 dipole, that provides a field $B = 1.47$ T and an angular coverage of 21^0. The tracking system will consist of a set of (5 or 10) planes made of four large area Monolithic Active Pixel Sensors (MAPS) obtained by means of the stitching technology. The pixel dimensions are of about $15 \times 15\ \mu\text{m}^2$. The sensor thickness is of the order of 20 μm. Moreover, the mechanical supports and cooling are moved to the border. Therefore, the material budget in the sensitive area is very small, lower than $0.1\%X_0$, reducing the effect of multiple scattering in the VT. The expected spatial resolution is 5μm or better, with a gain of a factor of 2 with respect to the hybrid technology.

A high intensity beam is required for the measurement of hard and electromagnetic probes. The experiment is foreseen to use the H8 beam line at the CERN SPS, which can provide an intensity of 10^7 Pb ions per 20 s spill. The interaction rate is thus expected to be one order of magnitude higher with respect to other experiments in the same μ_B range. With a typical run time of one month per energy, a very significant statistics can be reached for each of the proposed measurements.

3. Physics performances

The physics performances of NA60+ were studied performing fast simulations of the signals with semi-analytical tracking based on the Kalman filter, while the simulation of the background was performed with FLUKA. The obtained opposite sign dimuon mass spectrum is shown in fig. 3.

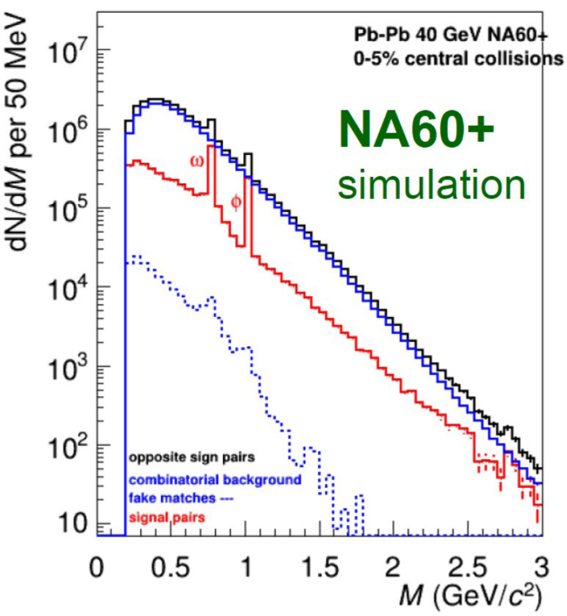

Figure 3: Simulated dimuon mass spectrum in central Pb-Pb collisions at $E = 40$ GeV per nucleon.

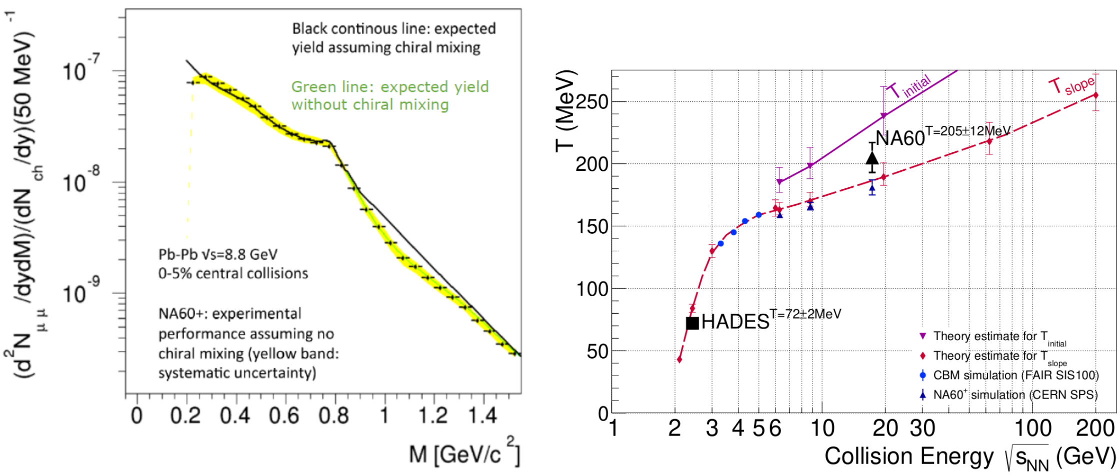

Figure 4: Left: dimuon mas spectrum expected assuming chiral mixing (black line) and without chiral mixing (green line). Right: medium temperature evolution vs $\sqrt{s_{NN}}$ in central Pb-Pb collisions using [2]. Measurements from NA60 [4] and HADES [5].

The mass resolution for $M = M_\omega$ is ~ 7 MeV/c^2, about one third of the NA60 resolution at the same mass. Besides the signal, composed of muon pairs, two sources of background are visible: the combinatorial background and the fake matches contribution. The former is due to uncorrelated pairs of muons mainly originated from pion and kaon decays. The latter is due to incorrect matches between muons reconstructed in the muon spectrometer and tracks reconstructed in the vertex telescope. Both contributions can be evaluated using event mixing techniques and subtracted to the opposite sign mass spectrum. The signal mass spectrum resulting after background subtraction is dominated by the hadronic cocktail for $M < 1.5$ GeV/c^2. In this region, a precision measurement of the ρ spectral function can be performed, complementing the NA60 measurement in In-In at top SPS energy with results at lower energy.

In the region $1 < M < 1.5$ GeV/c^2, a dimuon enhancement due to the chiral mixing between the ρ and its chiral partner a_1 via 4π states can be observed [3]. Simulations were carried out assuming two scenarios: in one case, no chiral mixing was imposed, while in the other full mixing was assumed. Results, plotted in the left panel of fig. 4, show that a 20-30% enhancement is expected in case of full mixing. With the foreseen accuracy of the measurement, the effect can be clearly observed by NA60+. For $M > 2$ GeV/c^2, after subtracting the Drell-Yan and open charm contributions, the mass spectrum is dominated by thermal dimuons, that can be fitted to a thermal distribution of the form $dN/dM \propto M^{-3/2}\exp(-M/T_S)$. The parameter T_S represents a space-time average of the thermal temperature over the fireball evolution and can be determined with a precision of the order of 10 MeV. Measurements of T_S vs $\sqrt{s_{NN}}$ at low energy (< 10 GeV) may allow to discover a plateau in the caloric curve (fig. 3, right) that would be present in case of a phase transition of the first order [2].

Charmonium suppression was extensively studied at the SPS, where the NA50 collaboration observed a suppression of $\sim 30\%$ of the J/ψ meson yield in central Pb-Pb collisions at the top SPS energy ($\sqrt{s_{NN}} = 17.3$ GeV) that could not be ascribed to cold nuclear matter effects alone [6]. The suppression is qualitatively consistent with the melting of the less bound χ_c and $\psi(2S)$ states in a deconfined medium, which would lead to a suppression of the J/ψ produced from the decays of these particles. At present, no measurement is available at lower energy. NA60+ aims to extend the measurements down to $E_{\text{lab}}/A = 40$ GeV in order to search for the onset of the deconfinement. By correlating the measurement with the corresponding determination of the temperature obtained from thermal dimuons, one could obtain the temperature at which the χ_c and $\psi(2S)$ melt. With one month data taking at an intensity of 5×10^5 Pb ions per second, a number of J/ψ in the range $1.5 - 20 \times 10^4$, depending on the beam energy, may be reconstructed. Also cold nuclear matter effects have to be determined precisely, therefore, data taking with p-A collisions are mandatory at each CM energy. A 15-days long data taking with a beam intensity of $3 \cdot 10^8$ protons/s on 7 nuclear targets is planned to measure the J/ψ production cross section as a function of the mass number.

Open charm measurements can be performed reconstructing the decays of charmed hadrons into two or three charged hadrons, using the vertex telescope as a stand-alone detector. The huge combinatorial background can be reduced by applying geometrical selections on the displaced decay vertex topology, profiting from the fact that the $c\tau$ for these decays is about $60 - 310\mu$m, and therefore the decay vertices are displaced by a few hundred μm from the interaction point. A high resolution on the vertex reconstruction is needed. The MAPS technology can provide a signal to background ratio ~ 10 times higher than the corresponding value obtainable with hybrid pixel sensors. As of today, no open charm measurement has been performed below the top SPS energy. In one month data taking, more than $3 \cdot 10^6$ D^0 can be reconstructed in central collisions at $\sqrt{s_{NN}} = 17.3$ GeV, allowing for a precise determination of the yield and elliptic flow as a function of p_T, rapidity and centrality. At $\sqrt{s_{NN}} = 10.6$ GeV due to the lower production cross section, the number of reconstructed D^0 is expected to be lower by about an order of magnitude. Still, the measurement will be feasible with a statistical precision at the level of the percent.

Finally, strangeness measurements in the hadronic decay channels will allow to explore the low multiplicity region for the understanding of strangeness enhancement with multiplicity. The high statistics expected to be collected will guarantee a high p_T-reach, the study in narrow centrality bins and an extention to multistrange hadrons of the elliptic flow measurements.

The broad physics program of the NA60+ experiment provides a strong motivation for its realization. The goal is to start data taking in 2027, with LHC run 4.

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