Dimuon production in Pb-Pb collisions at 20-160 AGeV at the CERN SPS: Mapping the QCD phase diagram in the transition region with a new experiment

E Incani\textsuperscript{1,2}, G Usai\textsuperscript{1,2}
\textsuperscript{1} Dipartimento di Fisica, Universit\`a degli Studi di Cagliari, 09042 Monserrato, Italy
\textsuperscript{2} INFN - Sezione di Cagliari, Italy
E-mail: elisa.incani@ca.infn.it, gianluca.usai@ca.infn.it

Abstract.
In this paper new ideas to experimentally investigate the issues of chiral symmetry restoration and the first order phase transition in the region of moderate-large baryon density of the phase diagram of strongly interacting matter are presented. The experimental strategy to address these points is to use a new fixed-target experiment at the CERN SPS (Super Proton Synchrotron) dedicated to the measurement of the production of muon pairs with unprecedented precision. Dileptons offer the possibility to measure temperature to obtain a caloric curve and to probe chiral symmetry restoration by studying for the first time the mass modifications in a simultaneous measurement of the vector meson $\rho$ and its axial vector partner $a_1$.

1. Introduction
The theory of strong interactions, Quantum ChromoDynamics (QCD), predicts a phase transition at high temperature and/or baryon density between hadronic matter (where quarks and gluons are confined inside hadrons), and a deconfined state of matter, the so-called Quark-Gluon Plasma (QGP). The possible phases of strongly interacting matter can be displayed in a phase diagram as a function of its temperature and the baryon density (Fig. 1) [1].

At present, the QCD phase diagram was studied mainly in the region of low baryon density. In this regime the phase transition between hadronic matter and the QGP is a cross-over around a critical temperature of 155 MeV [1]. On the other hand, for moderate temperatures and high baryon densities, a first order transition is expected with the coexistence of a mixed-phase.

In vacuum chiral symmetry of the QCD is spontaneously broken. Most of the baryonic mass in the Universe arises from this breaking rather than from the Higgs coupling [2]. Corresponding to the phase transition to the deconfined phase, it is expected that chiral symmetry is restored.

The doublet of the vector meson and its axial vector partner, split in vacuum due to chiral symmetry breaking, should become degenerate at chiral restoration. Fig. 2 displays qualitatively two possibilities for the $\rho$ and $a_1$, known as dropping mass and melting resonance scenarios.

The basic aspects of the phase diagram structure not yet confirmed experimentally are:

- how chiral restoration affects the hadron spectrum;
the existence of the critical point and the first order transition.

In order to shed light on these fundamental phenomena, it is proposed a new experimental apparatus (here denoted NA60+) to measure the production of muon pairs with unprecedented precision in nucleus-nucleus collisions at the CERN SPS (Pb-Pb collisions over the energy range from $\sqrt{s_{NN}} \sim 6$ GeV up to 17 GeV in the centre-of-mass system, $\sim (20 \div 160)$ GeV/nucleon in the laboratory system) [1].

The presence of dileptons provides a probe of the expanding system, in fact they are produced at all stages of the evolution and also retain the primary informations of the system, because of the absence of any final state interaction.

In the low mass region ($M < 1$ GeV) the dilepton mass spectrum is dominated by the $\rho$ meson. Its spectral function has been precisely measured in Indium-Indium collisions at 160 GeV/nucleon by the NA60 experiment at the CERN SPS [3]. The intermediate mass region (1.1 GeV < $M$ < 3 GeV) is populated by the radiation emitted in the QGP via quark-antiquark annihilation and by the radiation emitted at a later stage from the hadronic medium. In particular, between 1.1 GeV < $M$ < 1.5 GeV the dominant hadronic process in the confined medium is $a_{1} \pi^{0} \rightarrow \mu^{+}\mu^{-}$. Contrary to $\rho$ meson, in high energy nuclear collisions no measurements exist for the axial-vector $a_{1}$. NA60+ proposes to perform a precision measurement of the $a_{1}$ at a collision energy close to the onset of deconfinement, where the QGP yield is very small or negligible.

For $M > 1.5$ GeV the mass spectrum can be described using a simple formula: $dN/dM \propto M^{3/2} \exp(-M/T)$, where $T$ represents the average temperature of the emitting sources [4]. The temperature measurement was first pioneered by NA60 at the full SPS energy of 160 GeV/nucleon, the fit of the spectrum giving $T = (205 \pm 12)$ MeV [5, 6]. This is above critical temperature, thus showing that the QGP is already produced at this collision energy.

NA60+ proposes to measure for the first time the caloric curve with accurate temperature measurements as a function of energy density with a beam energy scan ($\sqrt{s_{NN}} = (6.2 \div 17.3)$ GeV), to search for a possible flattening of temperature where the phase transition occurs in the phase diagram. The energy density will be derived from the charged particle multiplicity density through Bjorken scaling or more advanced models [7].

In addition, the study of $J/\psi$ suppression and open-charm production are also expected to be
sensitive to the onset of deconfinement and might be studied with the proposed apparatus [1].

Various facilities can in principle investigate the high baryon densities region of the QCD phase diagram: CERN SPS, RHIC, NICA and FAIR (Fig. 1):

- The CERN SPS with its new injection scheme can deliver intense ion beams leading to interaction rates exceeding 1 MHz with a good energy coverage from 4.5 GeV to 17.3 GeV in centre-of-mass system. At present the NA61 experiment is running at the CERN SPS and it measures the production of hadronic and has a physics program complementary to the one proposed for NA60+.
- RHIC (energy coverage from $\sqrt{s_{NN}} \sim (7.5 \div 200)$ GeV), and NICA (reaching $\sqrt{s_{NN}} =11$ GeV) provide good energy coverage but the interaction rates are 2-3 orders of magnitude smaller than the SPS, so that high-precision measurements are not possible.
- FAIR SIS/100 is designed to provide high interaction rates (>1 MHz) but the energy coverage is extremely limited (with a maximum energy of $\sqrt{s_{NN}} =4.5$ GeV). FAIR SIS/300 might provide a larger coverage (up to $\sqrt{s_{NN}} =8$ GeV) but it is not approved at present and its operation would in any case only start well beyond 2030.

Consequently, no presently approved experiment is able to cover such a large energy interval and to collect at the same time the large statistics required for truly quantitative measurements. NA60+ would then represent a unique opportunity to investigate the QCD phase diagram in the next decade.

2. Experiment

The experimental program requires to collect data at different energies lower than full SPS energy of 160 GeV/nucleon (example 20-30-40-80-120-160 GeV/nucleon).

The objectives for the thermal radiation studies are:

- the isolation of dilepton spectrum from hadronic phase up to $M \sim 2$ GeV;
- measurements of temperature with an accuracy at the MeV level (more than $5 \cdot 10^7$ reconstructed pairs from thermal radiation per energy point);
- proton-nucleon collisions at some energy point.

This basic physics program might be accomplished in about 5 years of data-taking.

The apparatus couples a traditional muon spectrometer to a silicon vertex tracker placed before the hadron absorber, as pioneered by NA60 [3, 5, 8, 9]. NA60+ will increase the statistics by a factor $\sim 100$ over NA60 while retaining a very good signal-to-background ratio even in central Pb-Pb collisions (Fig. 3) [1].

The muon spectrometer is composed of 4 tracking stations and a toroid magnet placed in the middle of the tracking stations. It provides a field integral of 0.75 T·m at R=1 m (simulations for the lowest energies were also performed assuming a reduced field integral of 0.3 T·m at $R =1$ m).

Placed before the muon spectrometer, the hadron absorber allows muons to be selected. The idea is to have a similar signal-to-background ratio at all energy, implying an absorber system with a scalable thickness. At present an absorber was investigated for measurements at 20-40 GeV/nucleon. It consists of BeO-graphite sections, tuned in the best way to increase the hadron absorption, limiting the multiple scattering. A graphite wall is placed at the end before the trigger stations.

Thus, the hadron absorber provides the muon identification, but at the cost of degrading the kinematics of the muons, because of energy loss fluctuations and multiple scattering. This problem is overcome by measuring particle tracks also before the hadron absorber with a silicon tracker (vertex spectrometer), which is the key element for a precision measurement of muons. Muon tracks are then matched to the tracks measured in the silicon vertex spectrometer in
coordinate and momentum space. In addition, the silicon tracker provides also the measurement of charged-particle multiplicity density, which can be used to estimate the energy density.

The vertex spectrometer consists of 5-10 stations of hybrid pixels or monolithic active pixel sensors immersed in a 1.2 T·m dipole field. The results presented in the following are based on the use of hybrid pixels, with a material budget per plane of $\sim 1\% X_0$ [10] and space resolution is 10-15 $\mu$m (40-50 $\mu$m pixel pitch). A disadvantage of this technology is the thickness of the sensors and readout chip. A very interesting alternative might be the monolithic active pixel sensors developed for LHC upgrades [11]: while these sensors have not yet the required readout speed, further developments might lead to competitive sensors in the near future.

The muon trigger is based on two trigger stations placed after the muon wall.

3. Performance study Pb-Pb collisions at 40 GeV/nucleon

First physics performance has been studied for Pb-Pb 0-5% central collisions at 40 GeV/nucleon ($\sqrt{s_{NN}} = 8.8$ GeV, $dN_{ch}/dy = 265$).

The dimuon mass spectrum is simulated as a superposition of various sources:

- the thermal $\mu^+\mu^-$ differential spectra $dN/dM_pTdpTdy$ based on the in-medium $\rho$, $\omega$, $4\pi$ spectral functions and the expanding thermal fireball model of [13], with subsequent improvements according to [14];
- the QGP spectrum calculated using a lattice-QCD constrained rate based on the equation of state of [15] with $T_c = 163$ MeV (critical temperature) and $T_{ch} = 148$ MeV (chemical freeze-out temperature);
- a hadron cocktail generator for the 2-body decays of $\eta$, $\omega$, $\phi$ and the Dalitz decays; $\eta \rightarrow \gamma\mu^+\mu^-$ and $\omega \rightarrow \pi^0\mu^+\mu^-$ based on the NA60 ones and on the statistical model of [12];
- Drell-Yan and open charm simulated with the Pythia event generator [16].

In Fig. 4 a data sample composed by $2 \cdot 10^7$ reconstructed pairs in central collisions, corresponding to a total sample of $\sim 5 \cdot 10^7$ integrated in centrality, is shown.

The total reconstructed mass spectrum is shown in black, the combinatorial background coming from muons produced by decays of primary or secondary hadrons is shown by the blue continuous line (simulated using the Fluka package [18, 19]) and the background coming from
wrong hadronic hits in silicon pixel planes, associated to a muon track, is shown by the blue dashed line (fake matches). This last contamination was taken into account at reconstruction level including the hadronic hits in the silicon stations according to the pion, kaon and proton multiplicities as measured at 40 GeV/nucleon by the NA49 experiment [17]. The net signal after the background subtraction is shown in red in Fig. 4, the average signal-to-background ratio is 1/12.

All the components of the signal spectrum after subtraction of the combinatorial background are shown in Fig. 5 (the uncertainty from the background subtraction is shown as a yellow band). In the low mass region in-medium $\rho + \omega$ dominates, while the QGP contribution is almost an order of magnitude smaller. The peaks of $\omega$ and $\phi$ mesons are well resolved (with a resolution of (10-15) MeV at the pole mass). This allows the in-medium thermal radiation to be precisely isolated by subtracting the hadron cocktail contributions with the data-driven
The technique mastered by NA60 [20]. The thermal spectrum is measurable up to (2.5-3) GeV and the QGP yield is still significant, according to the theoretical model considered. Drell-Yan curve exceeds the QGP only above (2.3-2.5) GeV, while the open charm yield is negligible.

The most significant results are summarized in Fig. 6, showing in red the thermal dilepton spectrum obtained after subtraction of the hadronic cocktail, Drell-Yan and open charm contributions (the latter being negligible at this energy).

The precision of the temperature measurement was assessed by fitting the distribution in the range (1.5 ÷ 2.5) GeV, with \( dN/dM \propto M^{3/2} \exp(M/T) \). In this way we find \( T = (163 \pm 4(\text{stat.}) \pm 1(\text{syst.})) \) MeV, in perfect agreement with the input value from the theoretical generator of 160 MeV. This shows that a high precision measurement is feasible.

Fig. 6 shows in green the thermal spectrum from hadronic phase \((\rho - a_1)\). The performance for the measurement of the thermal spectrum at the onset of deconfinement has been estimated considering a scenario without QGP and a measured thermal dilepton yield at the level of the in-medium \( \rho + \omega + 4\pi \). Moreover, a combinatorial background yield at the level of Pb-Pb central collisions at 20/40 GeV/nucleon was assumed. This shows that a study of the hadronic excess up to M~ 2 GeV is possible, with a very good sensitivity to \( \rho - a_1 \) chiral mixing.

4. Summary

NA60+ at the CERN SPS provides a unique opportunity for dilepton measurements with unprecedented precision over the widest possible energy range.

This new experiment will increase the statistics by a factor ~ 100 larger than NA60 and ~ \( 10^5 \) larger than the present experiments RHIC and LHC, promising a new horizon for a quantitative understanding of chiral symmetry restoration, onset of deconfinement and order transition.

References

[1] Dainese A et al. 2016 *Frascati Phys. Ser.* **62**
[2] Muller B 2005 *Nucl. Phys.* A **750** 84
[3] NA60 Collaboration, Arnaldi R et al. 2006 *Phys. Rev. Lett.* **96** 162302
[4] NA60 Collaboration, Specht H J et al. 2010, *AIP Conference Proceedings* **1322** 1-10
[5] NA60 Collaboration, Arnaldi R et al. 2009 *Eur. Phys. J.* C **59** 607623
[6] NA60 Collaboration, Specht H J 2010 *AIP Conf. Proc.* **1322** 110
[7] Csorgo T, Nagy M I, and Csanad M 2008 *J. Phys.* G **35** 104128
[8] Arnaldi R et al., NA60 Coll.2007 *Phys. Rev. Lett.* **99** 132302
[9] Arnaldi R et al., NA60 Coll.2008 *Phys. Rev. Lett.* **100** 022302
[10] Usai G. 2014, *Nucl. Phys.* A **931** 729734.
[11] ALICE Collaboration, Abelev B et al. 2014 *J.Phys.* G **41** 087002
[12] Becattini F, Manninen J, and Gazdzicki M 2006 *Phys. Rev. C* **73** 044905
[13] Rapp R and Wambach J 1999 *Eur. Phys. J.* A **6** 415420
[14] Van Hees H and Rapp R 2008 *Nucl. Phys.* A **806** 339387
[15] He M, Fries R J, and Rapp R, *Phys. Rev.* C **85** 044911
[16] Sjostrand T, Mrenna S, and Skands P Z 2006 *JHEP* **05** 026
[17] NA49 Collaboration, Afanasiev S V et al. 2002 *Phys. Rev.* C **66** 054902
[18] Bohlen T T, Cerutti F, Chin M P W, Fassò A, Ferrari A, Ortega P G, Mairani A, Sala P R, Smirnov G, and Vlachoudis V 2014 *Nuclear Data Sheets* **120** 211-214
[19] Ferrari A, Sala P R, Fassò A, and Ranft J 2005 *CERN-2005-10 INFN/TC,05/11, SLAC-R-773*
[20] NA60 Collaboration, Arnaldi R et al. 2006 *Phys. Rev. Lett.* **96** 162302