Measuring thermal dimuons at high baryochemical potential with the NA60+ experiment at the CERN SPS

G. Usai – University of Cagliari (Italy)
for the NA60+ Collaboration

https://na60plus.ca.infn.it

Introduction

NA60+ is a new experiment conceived to perform high μ_B studies of hard and electromagnetic probes of the quark gluon plasma at CERN SPS energies through a beam energy scan ($\sqrt{s_{NN}}$~5-17 GeV). The covered μ_B range at the SPS, approximately from 220 to 550 MeV, is a completely unexplored domain for hard/e.m. related observables. The experiment is designed to precisely measure muon pairs (thermal and quarkonia) and hadrons (open HF and strangeness).

At low invariant masses M<1 GeV (LMR), thermal dimuon production is largely mediated by the light vector mesons ρ, ω and ϕ. The broad ρ(770) is by far the most important, due to its strong coupling to the $\pi^+\pi^-$ channel and its lifetime of only 1.3 fm, making it subject to regeneration in the much longer-lived fireball. At intermediate masses M>1 GeV (IMR), where hadronic spectral functions become increasingly uniform, Planck-like thermal radiation is expected from both hadronic and partonic sources.

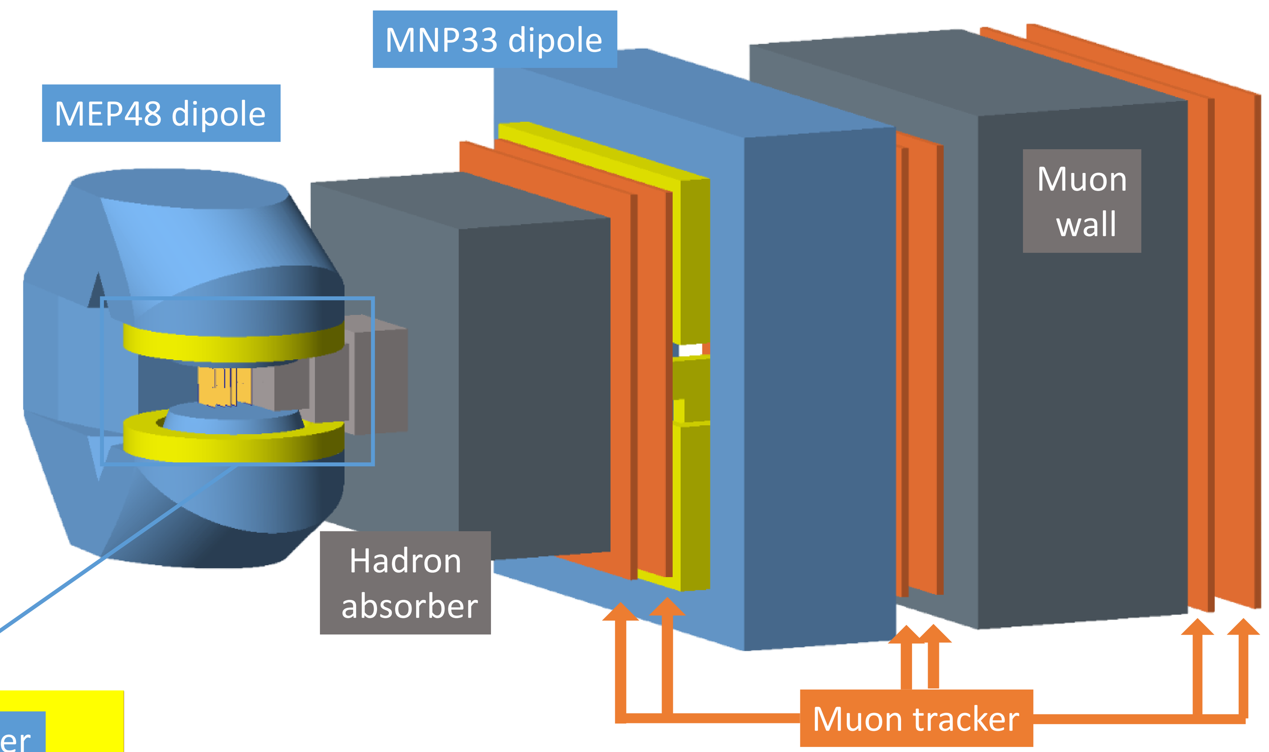
Thermal dimuons allow the medium temperature to be measured – a fundamental observable that can provide information on the QCD phase transition. Precision study of the in-medium spectral function provides furthermore invaluable insight on the expected restoration of QCD chiral symmetry.

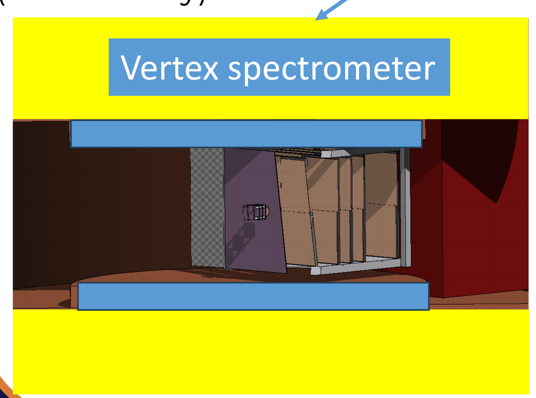
Measuring muon pairs with NA60+

The experimental set-up is formed by:

- a muon spectrometer (dipole magnetic field, MWPC/GEM tracking detectors)
- a vertex spectrometer (dipole magnetic field, large area MAPS sensors, stitching technology)

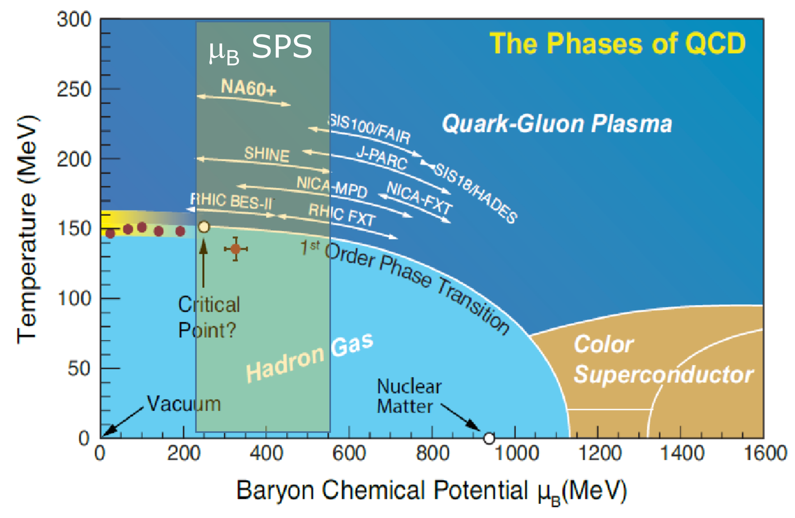
N.B. MNP33 dipole from NA62 to replace the originally foreseen toroid (under study)





- ❑ The apparatus will be adapted to the varying beam energy by scaling the absorber thickness and moving the tracking stations
- ❑ Very high beam intensity! → Pb-Pb interaction rate ~ 150 kHz
- ❑ Minimum bias trigger (open charm hadronic decays) or triggerless readout under study

QCD phase diagram at high μ_B and thermal dimuons

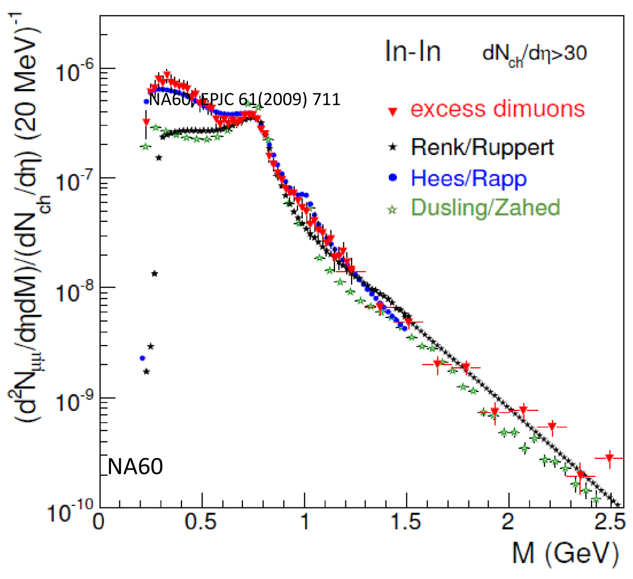


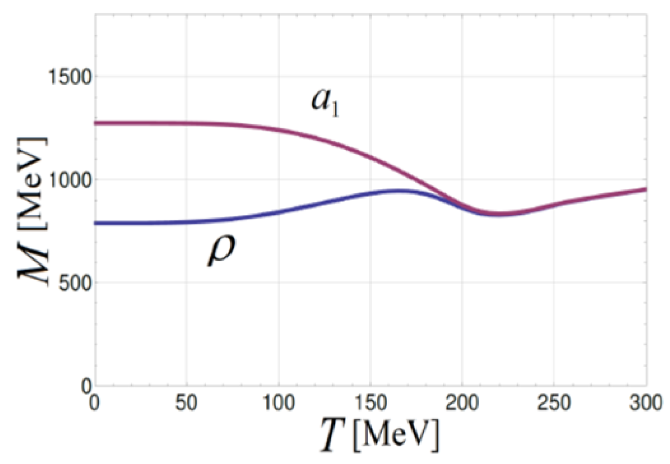
QCD phase diagram

Rather little is known about QCD matter 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. By lowering the collision energies, heavy ion experiments provide unique opportunities for systematic studies of a substantial part of the QCD phase diagram at high μ_B, thereby also promising to unravel connections between astrophysical systems and the early universe.

Medium temperature vs √s and the QCD phase transition

Thermal dimuons provide a precise thermometer by measuring the invariant mass slope in the mass region 1.5-2.5 GeV. This slope is an average temperature of the early stage of the system. The method was pioneered by the NA60 experiment. In the energy range covered by SPS, information in the region close to the deconfinement temperature can be extracted, with a possible signal of a first order phase transition.





Chiral symmetry restoration

Close to the phase boundary, chiral symmetry is restored and the ρ and a_1 chiral partners are predicted to become degenerate, essentially melting. While a strong ρ broadening was observed, the a_1 cannot be exclusively reconstructed in heavy ion collisions.

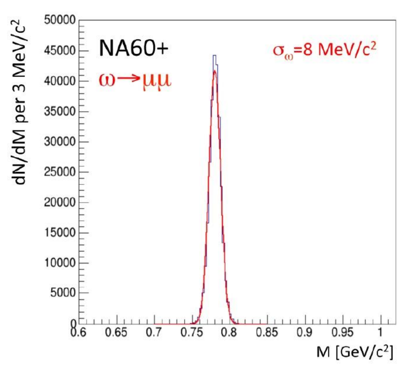
However, in the medium the chiral mixing of vector and axial vector correlators will lead to an enhancement in the 1-1.4 GeV dimuon mass region directly related to chiral restoration.

Elliptic flow

Thermal electromagnetic radiation, being penetrating, can be utilized to study the time dependence of the elliptic flow. In this way, key parameters of hydrodynamical simulations, typically extracted from hadronic spectra, like the shear and bulk viscosity coefficients or the initial conditions, can be extracted with better precision.

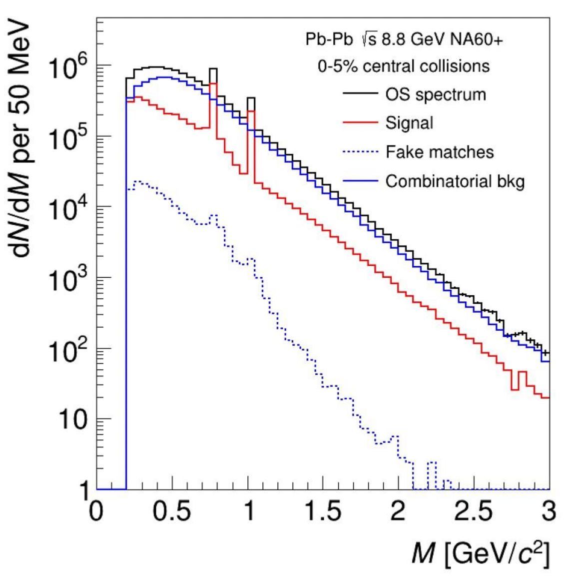
Thermal dimuons: performance studies

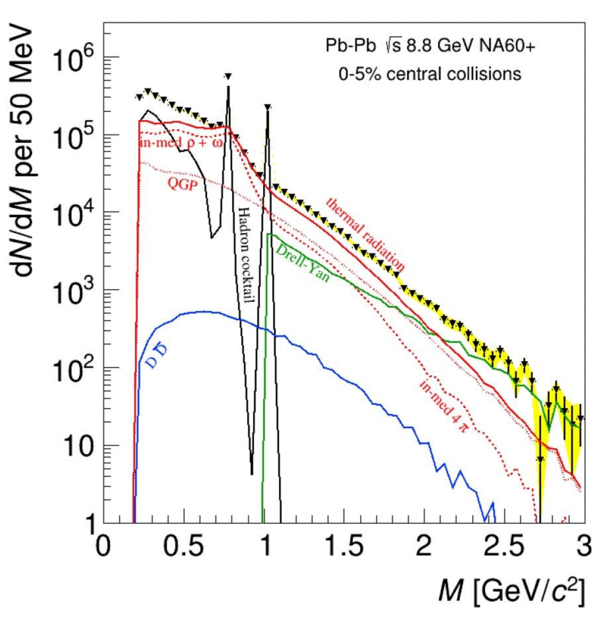
Signal extraction



Muon tracks are reconstructed by matching the tracks in the vertex and muon spectrometers:

→ very good mass resolution, ~8 MeV for the ω in the LMR



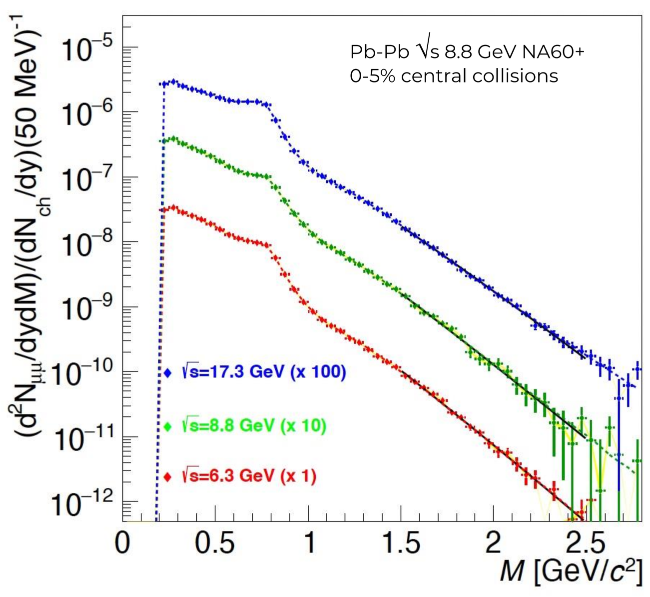


Top-left: reconstructed dimuon raw mass spectrum at √s=8.8 GeV for 0-5% most central collisions, corresponding to one month data taking. The combinatorial background arising from π and K decays has been evaluated with Fluka and is shown in black. The signal after subtraction of this background is shown in red in left plot and is exploded in the various components in the right plot.

The extraction of the thermal spectra requires the subtraction of the Drell-Yan in the IMR → measured in pA at the same energies as Pb-Pb.

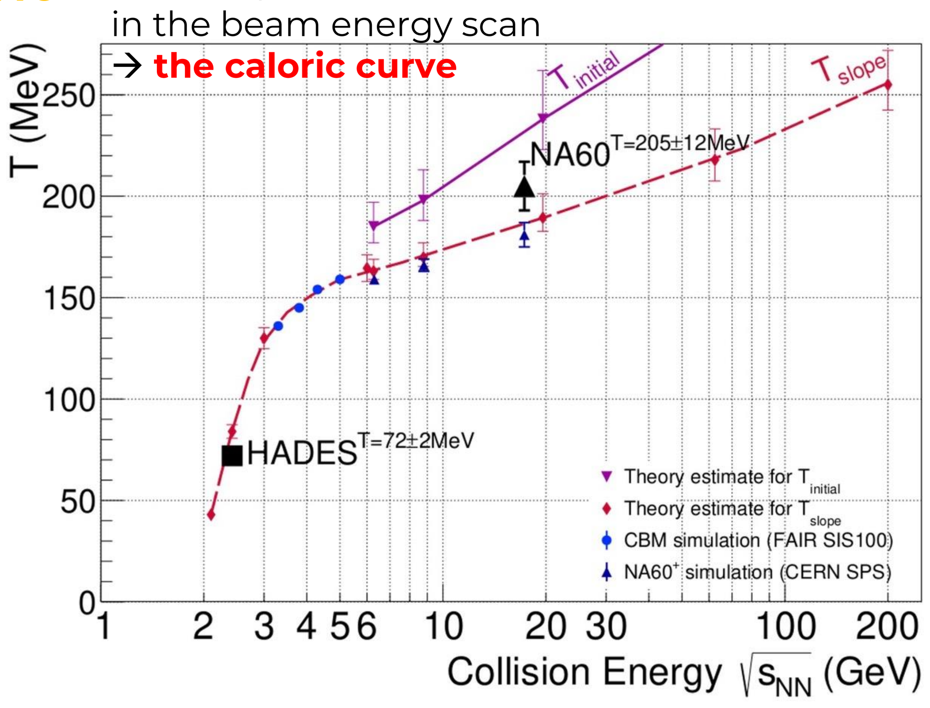
Thermal spectra and the caloric curve

Acceptance corrected thermal spectra are fit in the 1.5-2.5 GeV mass region.



The temperature evolution vs √s is determined in the beam energy scan

→ **the caloric curve**

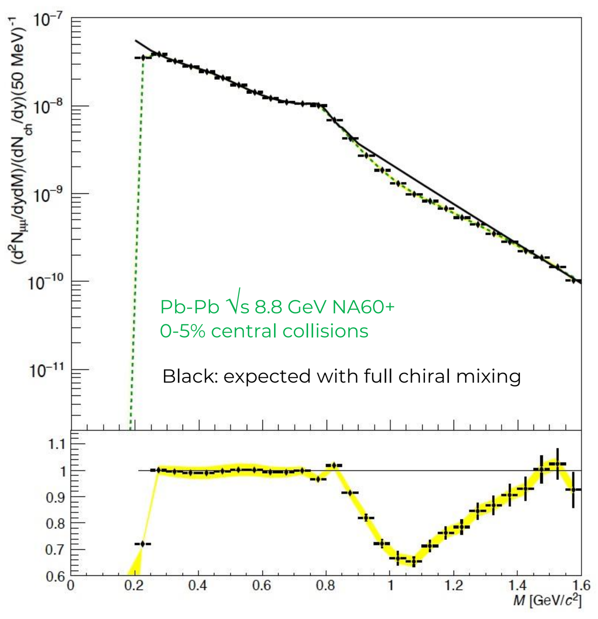


Energy (GeV)	Thermal pairs	T_{slope}
6.3	$3.52\cdot10^6$	$166\pm4.7\pm1$
8.8	$3.56\cdot10^6$	$169\pm4.4\pm1$
17.3	$9.70\cdot10^6$	$182\pm1.8\pm1$

~1-3% uncertainty on the evaluation of T_{slope}

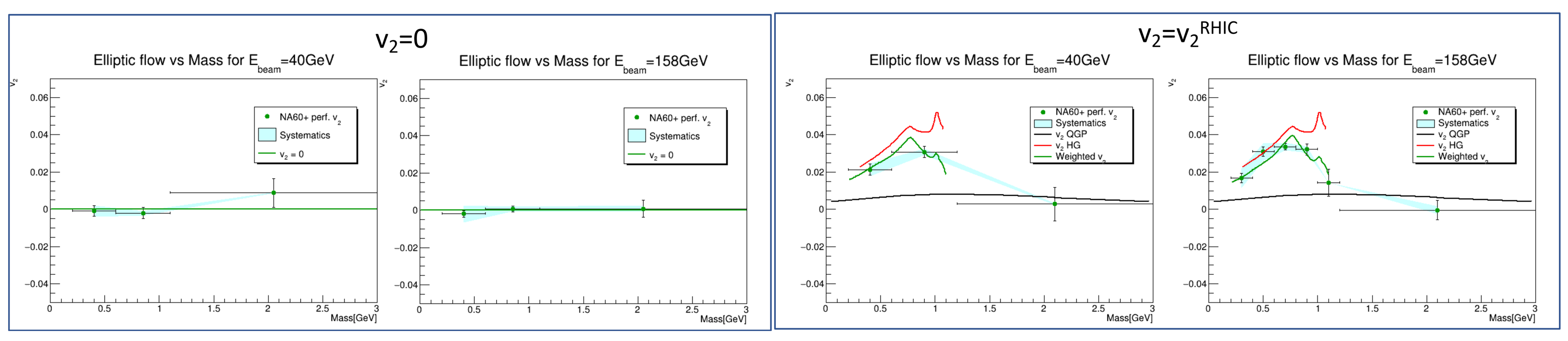
Accurate mapping of the region where T_{pc} is reached:
→Strong sensitivity to possible flattening due to 1st order transition

Chiral symmetry restoration



The sensitivity to a yield increase is studied comparing the reconstructed thermal spectrum without chiral restoration to the expectation with full chiral mixing. Small statistical and systematic uncertainties provide a very good sensitivity to an increase of the yield due to chiral mixing of 20-30%.

Elliptic flow of thermal dimuons



The v_2 of thermal radiation was never measured. Theory predictions for RHIC indicate an almost linear increase of v_2 versus mass for the hadronic phase, while a small v_2 in the IMR dominated by QGP.

Since there are no theory predictions at SPS energies, two different scenarios were considered to estimate the NA60+ performance: zero flow and a flow corresponding the RHIC level.

The plots show rather good performances, from top SPS energy down to at √s= 8.8 GeV, to determine a non-zero v_2 in several mass bins.

Final considerations, next steps

- ❑ Higher interaction rates with respect to other facilities/experiments working in the same energy range (RHIC, NICA, …)
- ❑ Complementarity with corresponding measurements to be carried out at CBM/FAIR
- ❑ Start data taking after CERN Long Shutdown 3, ~7 years of data taking performing an energy scan

Useful documents

- ❑ Project developed in the frame of the CERN Physics Beyond Collider Initiative, https://pbc.web.cern.ch
- ❑ Expression of Interest submitted to SPSC in May 2019, http://cds.cern.ch/record/2673280
- ❑ Letter of Intent submitted to SPSC in December 2022, https://arxiv.org/abs/2212.14452
- ❑ Submission of experiment proposal foreseen in spring 2025

HP2024 NAGASAKI