NA60+ status report

E. Scomparin – INFN Torino for the NA60+ Collaboration

- Progress since last plenary meeting
  - Submission of an Expression of Interest to SPSC
  - Approval/funding of R&D program by INFN
  - Starting work on detector sub-projects
  - Refining physics performance studies (realistic detector choice)
NA60+ at the CERN SPS

Study of hard and electromagnetic processes at CERN-SPS energies: an investigation of the high-$\mu_B$ region of the QCD phase diagram

No results exist below top SPS energy, $\sqrt{s_{NN}}=17.3$ GeV for Pb-Pb

Strong physics case for a new experiment, proposing to study Pb-Pb collisions at lower SPS energies, down to $\sqrt{s_{NN}}=4.9$ GeV for Pb-Pb, via an energy scan

Part of a strong effort of the heavy-ion community for the study of the high $\mu_B$ region

Unique $\rightarrow$ couples extensive $\mu_B$ coverage and precision measurements of dileptons and charm

E. Scomparin – PBC Working Group Meeting 5-6 November 2019
The four “pillars” of the NA60+ physics case

Measure:

- **Thermal dimuons from QGP/hadronic phase**: caloric curve for first order transition
- **$\rho-a_1$ modifications**: chiral symmetry restoration
- **Quarkonium suppression**: signal of deconfinement
- **Hadronic decays of charmed mesons/baryons**: QGP transport coefficients
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Extract temperature via fit
\[ \frac{dN}{dM} \propto M^{3/2} \exp\left(-\frac{M}{T_S}\right) \]
Look for a plateau when building $T_S$ vs $\sqrt{s}$

Full chiral $\rho-a_1$ mixing is expected to provide a 20-30% enhancement in the region $1<M<1.4$ GeV/c$^2$
The four “pillars” of the NA60+ physics case

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- **Thermal dimuons from QGP/hadronic phase**: caloric curve for first order transition
- **$\rho - \sigma_1$ modifications**: chiral symmetry restoration
- **Quarkonium suppression**: signal of deconfinement
- **Hadronic decays of charmed mesons/baryons**: QGP transport coefficients

Explore the centrality dependence of $J/\psi$ suppression vs $\sqrt{s}$ → Detect deconfinement threshold

Measure 2 and 3 prong decays of charmed mesons and baryons

$R_{AA}, v_2$ : transport coefficients

$\Lambda_c/D$ : study hadronization mechanisms
NA60+ Expression of Interest

- Observables
- Requirements
- Experimental layout
- Detectors
- Physics performances
- Competition with other measurements

Signed by 82 physicists from France, Germany, India, Italy, Japan, Switzerland, USA

http://cds.cern.ch/record/2673280

Expression of Interest for a new experiment at the CERN SPS: NA60+

NA60+ Collaboration

Abstract

The exploration of the phase diagram of Quantum ChromoDynamics (QCD) is carried out by studying ultrarelativistic heavy-ion collisions. The energy range covered by the CERN SPS ($\sqrt{s_{NN}} \approx \{5, 8, 11, 17\} \text{ GeV}$) is ideal for the investigation of the region of the phase diagram corresponding to finite baryochemical potential ($\mu_B$), and has been little explored up to now. In this Expression of Interest, we describe the physics motivations and the exploratory studies for a new experiment, NA60+, that would address several observables which are fundamental for the understanding of the phase transition between hadronic matter and a Quark–Gluon Plasma (QGP) at SPS energies. In particular, we propose to study, as a function of the collision energy, the production of thermal dimuons from the created system, from which one would obtain a caloric curve of the QCD phase diagram that is sensitive to the order of the phase transition. In addition, the measurement of $p\pi$ mixing contribution would provide crucial insights into the restoration of the chiral symmetry of QCD. In parallel, studies of heavy quark and quarkonium production would also be carried out, providing sensitivity for transport properties of the QGP and the investigation of the onset of the deconfinement transition.

The document describes an experimental set-up which couples a vertex telescope based on monolithic active pixel sensors (MAPS) to a muon spectrometer with tracking (GEM) and triggering (RPC) detectors within a large acceptance toroidal magnet. Results of physics performance studies for most observables accessible to NA60+ are discussed, showing that the results of the experiment would lead to a significant advance of our understanding of (non-perturbative) strong interaction physics. It is also shown that beam intensities of the order of $10^{17}$ lead ions/s are required in order to obtain meaningful results on the various physics topics. Such intensities can presently be reached only in the ECN3 underground hall of the SPS. In addition, the support and engagement of CERN for the development, construction and operation of the toroidal magnet is considered crucial for the success of the project.

The NA60+ Collaboration


May 2019
NA60+ within INFN

Project formally presented in Italy to INFN in June 2019

- **Goals:**
  - **Networking activity** to complete the apparatus studies and form the collaboration
  - **R&D** on different sub-detector systems

- Duration 2-3 years (2020-2022)
- Labs: Cagliari, Padova, Torino
- Contact persons: G. Usai, E. Scomparin

- **Approved by INFN “Commissione 3” (Nuclear Physics)**

- Funding in 2020 → 40.5 kE
  - 25 kE for R&D studies of the toroid magnet
  - 15.5 kE for meetings
NA60+: subprojects

**VERTEX TELESCOPE**
- Large area MAPS
- Stitching technology

**DIPOLE MAGNET**
Wide gap dipole (AMS, Goliath, ...)

**TOROID MAGNET**
R&D ongoing for cheap/light design

**TRACKING STATIONS**
Triple GEM amplification structure
- Operated with Ar-CO2
- 2D strip readout

**TRIGGER STATIONS**
Single gap RPC
- R/O on both sides
- Orthogonal strips

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Vertex spectrometer

Muon spectrometer
Vertex spectrometer: technology choice

Default choice ➔ **Monolithic Active Pixel Sensor (MAPS)**
Chosen for the upgrade of **ALICE Inner Tracker** (ALPIDE sensor)

**Advantages over hybrid pixel sensors**
- Sensor and frontend electronics in the same silicon wafer with NO Bump-bonding: factor 2 cost reduction
- pixel pitch of 30 µm or less: much better resolution
- Material budget of 50 µm thickness: factor 10 smaller $X_0$

**NA60: profit of new development with TowerJazz process 65 nm**
- Significantly improved performance:
  - radiation tolerance: $O(10^{15}) \text{ n}_{eq}/\text{cm}^2$
  - data rate: 100 MHz/cm²
  - Event time resolution: 200 ns
  - Very large area with stitching

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ALPIDE</th>
<th>Stitched MAPS (NA60+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Technology</td>
<td>Tower 180 nm</td>
<td>Tower 65 nm</td>
</tr>
<tr>
<td>Silicon thickness</td>
<td>50 µm</td>
<td>50 µm</td>
</tr>
<tr>
<td>Pixel size</td>
<td>$27 \times 29 \mu m^2$</td>
<td>$\varnothing(10 \times 10 \mu m^2)$</td>
</tr>
<tr>
<td>Chip dimension</td>
<td>$15 \times 30 mm^2$</td>
<td>scalable up to $150 \times 150 \text{ mm}^2$</td>
</tr>
<tr>
<td>Event-time resolution</td>
<td>$\sim 2 \mu s$ (ALICE operation)</td>
<td>$\sim 200$ ns</td>
</tr>
<tr>
<td>Max. particle fluence</td>
<td>$\sim 100$ MHz/cm²</td>
<td>$\sim 300$ MHz/cm²</td>
</tr>
<tr>
<td>Max. data rate</td>
<td>10 MHz/cm²</td>
<td>$\sim 100$ MHz/cm²</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>$&gt; 99%$</td>
<td>$&gt; 99%$</td>
</tr>
<tr>
<td>Fake hit rate</td>
<td>$\ll 10^{-6}$ /event/pixel</td>
<td>$\ll 10^{-6}$ /event/pixel</td>
</tr>
<tr>
<td>NIEL radiation tolerance</td>
<td>$1.7 \times 10^{13} \text{ n}_{eq}/\text{cm}^2$</td>
<td>$5 \times 10^{14}$ to $\sim 10^{15} \text{ n}_{eq}/\text{cm}^2$</td>
</tr>
</tbody>
</table>
These days, **stitching** is widely applied in the digital imaging industry (e.g. large flat panels for **medical and dental X-rays**).
**Stitched-MAPS: new R&D for a wafer-scale MAPS**

**PRIN 2018: STITCHED MAPS - a novel large area, fast, radiation-tolerant monolithic active pixel sensor for tracking devices of unprecedented precision**

- Funded project by Italy Research Ministry with **1 MEuro (started September 2019)**
- **Cagliari University, Bari University and Politecnico, INFN (G. Usai Principal Investigator)**

**Common R&D effort together with CERN and other labs**

- Kick-off meeting at CERN to agree specs of a new sensor suitable for different applications:
  - NA60+
  - ALICE LS3 upgrade
  - CLIC vertex detector
  - Proton computed tomography scan for hadron therapy

**Migration of the design to Tower 65 nm → 10 μm pixel pitch**
Silicon tracking stations for NA60+

Sensor periphery contains the control logic, the interfaces for the configuration of the chip and the serial data transmitters.

Mechanical support structures and cooling only on the borders, outside from acceptance.

Opens up the possibility of producing:
- **thin** (0.05 – 0.1% $X_0$)
- **large area** (~ 15 × 15 cm$^2$) sensors $\rightarrow$ ideal for NA60+
- **high granularity** (<5 µm resolution)
Silicon tracking stations for NA60+

60x60 cm$^2$ station: based on a 15x15 cm$^2$ station surrounded by a ring of 12 sensors
E. Scomparin – PBC Working Group Meeting 5-6 November 2019

Dipole magnets: AMS superconducting dipole

- $\sim 0.8$ T
- Length 1 m
- Gap 1 m
- Informal discussions with AMS people
- Magnet stored at CERN but cryogenic system dismantled, AND difficult to recover
- Plenty of space to accommodate vertex telescope but physics performance studies not satisfactory

\[ \text{AMS - superconducting magnet (Initial setting)} \]
Large superconducting spectrometer dipole magnet located in the H8 beamline in the North Area facility of CERN
- 3 T
- Length O(1 m)
- Gap O(1.5 m)

Property of CMS collaboration
Large spectrometer dipole magnet located in the H4 beamline in the North Area facility of CERN
- 1.5 T
- Length O(1 m)
- Gap 1 m

Availability to be investigated, could be a **reasonable choice** for NA60+
Study of thermal radiation at 40 GeV with GOLIATH vs 3 T dipole (EOI) setup:

- comparable signal/background
- comparable precision for temperature and chiral excess
Tracking stations: GEM modules

Double 3-GEM modules with 2D strip readout

- module size: $50 \times 110 \text{ cm}^2$
- 300 modules $\rightarrow$ 1000 GEMs (with spares)
- NS2 system (like CMS) for faster module assembly (no gluing)
- Gas: Ar-CO$_2$ or Ar-CO$_2$-CF$_4$
  - Non flammable
  - No ageing effects observed
- 1 M electronic channels
- Readout options: VFAT-3, VMM-3 chips

Needs a collaboration of 3-4 production institutes and optimized workflow
GEM R&D

GEM prototype for the NA60+ muon tracker designed in TUM Munich
(T. Dahms, L. Fabbietti, P. Gasik et al.)

Construction of a $20 \times 20 \, \text{cm}^2$ prototype:
- Triple GEM amplification structure
- Operated with Ar-CO$_2$
- 2D strip readout with SRS (scalable readout system) based on the new VMM3 ASIC

Goals:
- Test cabling and support structures and its alignment with the chamber staggering
- Expose to test beam for tracking tests
Toroid magnet: a new general-purpose device

**Open toroid for NA60+**
- Field circling the beam axis
- $L = 3m$
- $0.3 < R < 1.65$ m at entrance
- $0.3 < R < 2.95$ m at exit
- $B \cdot R \sim 0.2-0.25$ Tm

**Minimal design:**
- Concept put forward by F. Bergsma, P.A. Giudici (CERN-EP-DT-EF)
- **Easy to build**
- **Much cheaper than ACM**

- **8 sectors (octants)**, tangentially displaced wrt cylinder axis
- Conductors made of **aluminium**
- Segments consist of a single winding, straight conductors joined by screws (Meccano-like)

E. Scomparin – PBC Working Group Meeting 5-6 November 2019
Started collaboration with **CERN-EP-DT-EF group**

Discussions with INFN referees/experts (R. Musenich)

Ongoing tests of **mechanical stability of connections** (welding vs screwing)

Single winding design requires very high currents
   → power supply expensive (several hundred kCHF)

Alternative solutions:
   → increase the **number of turns**
   → Increase the **number of spokes**: from 8 to 20
      (keeping the integrated transverse thickness fixed)

Muons crossing >1 spoke could suffer **too much scattering**
   → Investigating the problem via Fluka simulations
Further steps towards LOI: muon selection

Default choice → **Resistive Plate Chambers (RPC)**

Set-up identical to ALICE:
- 2 stations, 2 planes each
- Simulation studies of radiation load ongoing (FLUKA)

Under discussion:
- **Muon triggering (~50 kHz dimuon signal):**
  - ask for a coincidence of 3 out of 4 planes
- **Triggerless readout:**
  - All collisions are readout; RPCs used for muon identification

Maximum size of Bakelite Electrodes → 300 × 180 cm²
Recent news: Physics Briefing Book (European Strategy)

4.4.3 Future opportunities for fixed-target experiments

The RHIC fixed-target programme, planned to start in 2020, will cover $\sqrt{s_{NN}} = 3.0 - 7.7$ GeV, corresponding to $\mu_B \simeq 400-700$ MeV. The approved FAIR accelerator will deliver high-intensity beams ($\sqrt{s_{NN}}$ up to 5 GeV) starting in 2025; the CBM detector aims at a collision rate of 10 MHz with continuous readout and online tracking and event selection. The NA61/SHINE experiment at SPS, currently being upgraded with vertex capability (using pixel sensors developed for ALICE), will extend in the coming years its suite of observables into the charm sector. An experiment at the SPS (NA60+) dedicated to thermal dimuon, open and hidden charm measurements is currently under design and aims at collision rates of 10 MHz [140]. The possibility of a heavy-ion programme with similar characteristics as that at FAIR is currently being considered for the J-PARC facility. The physics motivation [141] is common for all these fixed-target experimental programs and it is shared as well by the BES programme at RHIC and by the NICA programme [142, 143]. It is the investigation of hot and compressed baryon-rich matter, with special focus on the discovery of the critical point and (consequently) of a first order phase transition in the QCD phase diagram.

Confirms the interest of the heavy-ion community:
- in the investigation of the high-$\mu_B$ region of the QCD phase diagram
- in a specific project like NA60+ that covers a well defined set of physics observables relevant in this context
Cost and timeline (preliminary!)

Cost: first estimate contained in the EOI

<table>
<thead>
<tr>
<th>Item</th>
<th>R&amp;D (kCHF)</th>
<th>Construction (kCHF)</th>
<th>Total Cost (kCHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixel CMOS sensors</td>
<td>700</td>
<td>700</td>
<td>1400</td>
</tr>
<tr>
<td>Sensor test</td>
<td>100</td>
<td>150</td>
<td>250</td>
</tr>
<tr>
<td>Thinning/dicing</td>
<td>200</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1000</strong></td>
<td><strong>1150</strong></td>
<td><strong>2050</strong></td>
</tr>
</tbody>
</table>

Vertex tracker

Muon tracker

<table>
<thead>
<tr>
<th>Item</th>
<th>Baseline 4 stations (kCHF)</th>
<th>Expanded 6 stations (kCHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GEM foils</td>
<td>1000</td>
<td>1500</td>
</tr>
<tr>
<td>NS2 frames</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>Drift + Readout</td>
<td>250</td>
<td>375</td>
</tr>
<tr>
<td>FEE</td>
<td>2800</td>
<td>4200</td>
</tr>
<tr>
<td>HV system</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Mechanical support</td>
<td>500</td>
<td>750</td>
</tr>
<tr>
<td>Gas system</td>
<td>200</td>
<td>300</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>5250</strong></td>
<td><strong>7875</strong></td>
</tr>
</tbody>
</table>

Mechanics, cooling, readout electronics: ~1.5 MCHF

Magnets: to be evaluated
Trigger system: 3.5 – 4 MCHF

Sharing of responsibilities necessitates the completion of the formation process of the collaboration → goal for LOI

Timeline
- 2020-2022 → project finalization, submission and approval of the proposal
- 2023-2025 → construction
- 2026 and beyond → data taking in parallel with the LHC run 4
Conclusions

- First official document finalized: EoI (http://cds.cern.ch/record/2673280)
- Mentioned in the European Strategy Briefing Book

- Work started on the subprojects
  - Vertex spectrometer \(\rightarrow\) **strong R&D project**
  - Toroid magnet \(\rightarrow\) **collaboration with CERN**
  - Tracking detector \(\rightarrow\) **design started, need strong group(s) to join**
  - Dipole magnet \(\rightarrow\) **inquiry within CERN to reuse an existing device**
  - Trigger detector \(\rightarrow\) **to be started**

- **Physics case already strong**, refining physics performance studies

- Main goal for 2020
  - **Strengthen the Collaboration**
  - **Finalize letter of intent to the SPSC**
Backup
Considerations from the community

The heavy-ion community at large considers the physics that can be explored by NA60+ as **strategic for the field** in the next decade.

2. At lower center of mass energies where the highest baryon densities are reached, advances in accelerator and detector technologies provide opportunities for a new generation of precision measurements that address central questions about the QCD phase diagram.

The Town Meeting also observed that the CERN SPS would be well-positioned to contribute decisively and at a competitive time scale to central open physics issues at large baryon density with proposals like NA60+. In particular, the CERN SPS will remain also in the future the only machine capable of delivering heavy ion beams with energies exceeding 30 GeV/nucleon, and the potential of investigating charm production and rare penetrating probes at this machine is attractive.

An (HL-HE-)LHC/FCC based AA/pA/fixed-target program is unique and provides essential science at the frontline towards a profound understanding of particle physics.

A coherent and complementary “hot & dense QCD program” at the SPS brings valuable and unique contributions in the exploration of the QCD phase diagram.

Conclusions at the CERN Town Meeting 2018: Relativistic Heavy Ion Collisions
https://indico.cern.ch/event/746182/

Conclusions at the EPPSU (European Strategy for Particle Physics) symposium (Granada 2019) for Hot & Dense QCD
Muon tracking: choice of detector technology

Gas Electron Multipliers (GEM)
- Position resolution < 100 µm
- Timing resolution < 10 ns
- High rate capabilities of O(1 MHz/cm²)
- Radiation hardness
  - Can be stacked easily:
    - Higher gains (up to $10^5$)
    - Improved stability against electrical discharges
- Solution chosen for **ALICE TPC Upgrade** and **CMS Muon Endcap Upgrade**

**NA60+**: 4 stations, behind the absorber, total area 116 m²

Max. fluence per ion $8 \times 10^{-3} \times$ beam intensity of $6.6 \times 10^6$ ions/s = **50 kHz/cm² in innermost region**

Still factor **10 lower** than inner LHCb chambers!
Toroidal magnet for the muon spectrometer

NA60 used the ACM, an open toroid with field circling the beam-axis with an excellent field quality

Not suited for NA60+, which requires a larger angular coverage

Construction of a new ACM-like magnet
- Windings arranged in a very complicated way:
  - difficult to build
  - Very expensive: > 5 MCHF
Toroidal field

Physics performance studies to be re-evaluated with realistic field in order to finalize the design

• Approximately toroidal field with some inhomogeneity
• Possibility to add segments (same total current) to increase field homogeneity
• Not a problem with a precise mapping of the field
• Important to monitor possible changes as a function of time. Probes can be installed within the frame planes which have no acceptance
First studies of mechanical design

Main element:
- Central conductor $R=30$ cm, dimensions limited by aperture constraints
- Average power dissipation $\sim 500$ kW

Octant section:
- Bulk Aluminum bar solution, with deep-drilled holes (15 mm) for cooling water

Gaps between octants:
- Air or insulator

Position and diameter of the holes for the water to be optimized wrt thermal load

Integration and fixation of the radial spire element feasible
Integration of inlet and outlet water manifold feasible
Each water channel with same pressure drop
Toroidal magnet R&D


- Strong interest of CERN division to contribute to R&D:
  o field studies, electrical aspects, power supply
- **Contribution of INFN to mechanics design**  
- Kick-off meeting at CERN last May and regular meetings established

**Short term goal: Construction of a small-scale prototype (1 m length)**

- Test integration and fixation of the radial spire element with gold-plated contacts
- Test distribution of currents and uniformity of the field
- Test of cooling: Integration of inlet and outlet water manifold

*We asked 25 kEuro contribution to INFN for the mechanics – presently under discussion*
Further steps towards LOI: beam studies

Ion beams: investigation of impact of the beam spread in x-y

Rebuild of the end of P41 and H10 → two optics versions as for NA50 and NA60:
- Sharp focus: magnification \( \sim 0.4 \times 0.6 \)
- ‘Parallel’ (more parallel than sharp, but still a nice focus): magnification \( \sim 0.8 \times 0.8 \)

Top SPS energy:
This magnification applies to typical sigmas of 300 - 400 µm at T4 → the sigma at the NA60+ target could be:
- Sharp focus \( \sim 150/200 \) µm in X, 250 µm in Y
- ‘Parallel’ optics: \( \sim 350 \times 350 \) µm

Lower beam energies:
the beam spot scales with \( 1/\sqrt{p} \) in each plane
Further steps towards LOI: dipole magnet and VT setup

Present studies: 5 tracking stations inside a 3T dipole:
- Requires a new superconducting magnet

An important step forward would be the availability of an existing dipole

Completion of studies on:
- Field dipole:
  o Consider option of smaller fields values of 1.5-2T similar to a Goliath-like magnet (performance with an AMS-like magnet already tested and not satisfactory)
- Radius of central hole for non interacting beam passage
  o Possible limitation to coverage at high rapidities
- Spatial resolutions between 1-5 µm

Technical aspects to be detailed:
- **Mechanics integration** of tracking stations
- **Cooling**
Further steps towards LOI: layout of MS setup

Stations with triple GEM modules:
- module size: $50 \times 110 \text{ cm}^2$
- Modules staggering: $\sim 10 \text{ cm}$ overlap in each direction
- Up to $\sim 20 \text{ cm}$ shift in $z$ between the layers

More complicated designs also possible, but presumably not really needed

**Converge to a detailed mechanical design**
Installation site: discussions ongoing

- NA60+ needs a high intensity ion beam ($\sim 10^7$/s), now only available in ECN3

- Requires re-installation of the H10 beam line (beam optics existing and available)

- According to Conventional Beam working group, no viable solution to have NA62 (or any other future experiment like KLEVER) in the same counting room

We ask CERN (through the Physics Beyond Colliders initiative) to define a plan for the use and the development of the facilities of the laboratory, in such a way to allow both KLEVER and NA60+ to take data after LS3
Summary and outlook

R&D on different projects put on track and now starting:
- **Pixel sensor**: 1 MEuro funded in Italy for the development of a new large area MAPS
  - ongoing formation of a R&D collaboration with CERN and other labs
- **GEMS**: 30 kEuro funded at TUM (Germany) for module prototyping
- **Toroid magnet**: collaboration with CERN EP-DT-EF, request of funds to INFN submitted for prototype construction

Other important items:
- **Dipole magnet**: inquiry possible availability of an existing magnet
- **RPCs**: detail detector concept (trigger or triggerless readout to be defined)

**LOI:**
- Finalisation tentatively by *Fall/end of 2019*

**ECT* workshop dedicated to NA60+ physics** (organizers E. Scomparin, G. Usai, T. Dahms et al.): *Exploring high-$\mu_B$ matter with rare probes – september 2020*
**Experimental dimuon spectrum**

**Dimuon spectrum**: superposition of
- Drell-Yan and DD pairs (NN-coll.)
- Cocktail of hadronic resonance decays (M<1 GeV) (freeze-out)
- **Thermal radiation (QGP+hadronic)**
Phase transitions and caloric curves

- Caloric curve and phase diagram of water

 Thermal dilepton rate and medium temperature

\[
\frac{dN_{ee}}{d^4x d^4q} = -\frac{\alpha_{em}^2}{\pi^3 M^2} f^B(q_0, T) \times \text{Im} \Pi_{em}(M, q; \mu_B, T)
\]

**Flat spectral function for** \(M > 1.5\) \(\text{GeV}\) \(\rightarrow\) mass spectrum after integration over momenta and emission 4-volume:

\[
dN_{\mu\mu}/dM \propto M^{3/2} \times \langle \exp(-M/T) \rangle
\]

**T from dilepton spectrum:** average temperature which tracks initial temperature (dominant contribution from early stages)

**Fit of mass spectrum for** \(M > 1.5\) \(\text{GeV}\) \(\rightarrow\) thermometer!
Exploring phase transitions

The big question:
- How to establish whether there is a 1st order phase transition at high baryon density?

Caloric curve:
- Map the evolution of $T$ vs collision energy
- 1st order transition: plateau in a caloric curve
  - $T$ measurement from dimuon spectrum of thermal radiation for $M>1.5$ GeV: fit with $dN/dM \propto M^{3/2} \exp(-M/T_s)$
  - $T_s \rightarrow$ space-time average of thermal $T$ over fireball evolution
  - Beam energy scan to vary collision energy

Thermal spectrum (QGP+hadronic) after subtraction of $\eta$, $\omega$, $\phi$, DD and Drell-Yan
Towards chiral restoration: $\rho$ melting

- NA60 In-In 160 AGeV - data before acceptance correction

- Comparison to theoretical models:
  o Brown/Rho - dropping mass scenario
  o Rapp/Wambach – only broadening

Strong broadening of $\rho$ observed (no mass shift) → ‘hadrons melt’ (indirect) evidence of chiral symmetry restoration

On chiral restoration and $\rho$ melting: P.M.Hohler and R. Rapp, PLB 731 (2014) 103
$a_1$ and dileptons: vacuum vs medium

Axial states don’t couple to virtual photons

In vacuum (left) dip the region $M=1-1.5$ GeV: significant depletion

In the medium: chiral mixing
To lowest order in $T$, pion induced mixing of vector and axial-vector correlators:

$$\Pi_V(T) = (1 - \epsilon)\Pi_V(T=0) + \epsilon\Pi_A(T=0)$$

$$\epsilon = T^2/6f^2\pi$$

The admixture of the $a_1$ resonance, via the axial-vector correlator, thus entails an enhancement of the dilepton rate for $M \sim 1 - 1.4$ GeV
Physics performance: open charm

- Measurement of $p_T$ distributions and azimuthal anisotropies of D mesons
- Extract fundamental transport coefficients of QGP (HQ diffusion coefficient)
- Measurement of $D_s$ and $\Lambda_c$ → hadronization mechanisms and quark recombination

Low energy Pb-Pb

- Charm diffusion coefficient larger in hadronic phase than in a QGP around $T_c$
  (measurement also important for precision estimates of diffusion coefficients at LHC!)
- Observe a strong enhancement of $\Lambda_c/D$, thanks to large baryonic number in the fireball
- Ideal normalization for $J/\psi$ measurements
- Possible effects on the DD threshold approaching chiral symmetry restoration
- $p$-$A$: constraints to parameterizations of nPDFs ($x \sim 0.1-0.3$, $Q^2 \sim 10-40$ GeV$^2$)

Physics performance: open charm

- Large uncertainties on gluon nPDF, over all the $x_{Bj}$ range (especially in recent parameterization)

- NA60+ offers a unique opportunity to investigate the large $x_{Bj}$ region

- Low energy $\rightarrow$ from antishadowing to EMC and Fermi motion region

- Perform measurement with various nuclear targets $\rightarrow$ also access A-dependence of nPDF

- High statistics measurement mandatory $\rightarrow$ only accessible to NA60+

K. Eskola et al, arXiv:1612.05741
Low-SPS energy charmonium production

- Extract information of the fundamental in-medium QCD force in the region of finite $\mu_B$ and at energy densities smaller than in the collider energy range

- Possible observables:
  - Top SPS energy: $J/\psi$ suppression compatible with feed-down effects from $\chi_c$ and $\psi(2S)$ → do direct $J/\psi$ continue to survive at high baryon density?
  - Can a sequential suppression be established (similarly to what done at LHC for the $\Upsilon$)?
  - Study interaction of charmonia in confined matter via p-A collisions → separate hot and cold matter effects → investigate inelastic reaction rates in hadronic matter (small for $J/\psi$, possibly significant for $\chi_c$ and $\psi(2S)$)
The phase diagram of QCD

Phase diagram of QCD: temperature vs net baryonic density ($\mu_B$)

**Low $\mu_B$**

**Explored at collider energy**

- RHIC (Au-Au) $\sqrt{s_{NN}} = 0.2$ TeV
- LHC (Pb-Pb) $\sqrt{s_{NN}} = 5.02$ TeV $\rightarrow$ **ALICE**

**Main results**

- High energy density QGP formed ($\varepsilon \gg \varepsilon_c \sim 1$ GeV/fm$^3$)
- Long-lived QGP phase (perfect fluid)
- Smooth cross-over between hadronic matter and QGP (no latent heat)
The phase diagram of QCD

Phase diagram of QCD: temperature vs net baryonic density $\mu_B$

**High $\mu_B$**
Accessible at lower collision energy ($\sqrt{s_{NN}} \sim 20$ GeV)

**Little explored until now**

**Big questions**
- 1st order phase transition ending with critical point?
- Equation of state of dense matter?
- Chiral symmetry restoration at phase boundary?
A new experiment at the CERN SPS: NA60+

Physics goal

**Study of hard and electromagnetic processes at CERN-SPS energies:** an investigation of the high-$\mu_B$ region of the QCD phase diagram

**Electromagnetic processes:** information on the temperature of the system (QGP and/or hadronic), the nature of the phase transition and the approach to QCD chiral symmetry restoration

**Hard QCD processes:** probe the Quark-Gluon Plasma and study its transport properties

First studies carried out by NA60 (2003-2004), only In-In and top SPS energy
Physics performance: nature of the phase transition

Measurement of medium $T$ from thermal dimuons $\rightarrow$ Caloric curve:
- Map the evolution of $T$ vs collision energy with **MeV precision**
- $1^{\text{st}}$ order transition: plateau in a caloric curve

Only two measurements at present:
- NA60: $T_s = 205 \pm 12$ MeV
- HADES: $T_s = 72 \pm 2$ MeV (prelim.)

**No other experiment** able to measure $T$ in the wide SPS energy range

Complementary to future measurement at FAIR energies
Physics performance: $\rho-a_1$ mixing

NA60 found strong modification of the $\rho$ in nuclear collisions: chiral symmetry restoration?

Unknown: what happens to the chiral partner $a_1$?

- No direct coupling of $a_1$ to dilepton channel, but chiral mixing $\rho-a_1$ via $4\pi$ states $\rightarrow$ leads to yield enhancement in $1<M<1.5$ GeV

- Measurement challenging, but sensitivity to enhancement! ($\sim 30\%$ effect)

Signal optimized at low energy (QGP negligible)

- Very difficult if/not impossible to measure at RHIC/LHC energies

Physics performance: quarkonium production

Low SPS energy → Look for the onset of the suppression

J/ψ suppression observed from top SPS (NA50/60) to LHC energy
→ Related to color screening in deconfined matter

No existing data below $\sqrt{s_{NN}}=17.3$ GeV

High precision measurements possible down to $\sqrt{s_{NN}}=10$ GeV and no other experiment able to do the measurement (pA measurements also mandatory)

Measurement of other quarkonium states ($\psi(2S)$, $\chi_c$) highly relevant → studies ongoing
Physics performance: open charm

Extract fundamental transport coefficients of QGP (HQ diffusion coefficient) and study hadronization mechanisms and quark recombination

$D^0 \to K\pi$ as benchmark (3 prong decay studies in progress)

N.B.: $S/B$ before selection is $\sim 10^{-7}$!

High precision data:
- More than $3 \times 10^6$ $D^0$ at $\sqrt{s_{NN}} = 17.3$ GeV
- Systematics at different energies

Unique simultaneous measurement of hidden and open-charm

Measurement of other states ($D_s^0$, $\Lambda_c$) also highly relevant → studies ongoing
High energy setup ($\sqrt{s}=17$ GeV, $E_{\text{lab}}=160$ GeV)

Low energy setup ($\sqrt{s}=6-8$ GeV, $E_{\text{lab}}=20-40$ GeV)

**Scaling** in terms of:
- absorber thickness
- longitudinal positions of detectors
Uniqueness of NA60+

NA60+ is part of a considerable effort of the community for the study of the high $\mu_B$ region of the phase diagram → Several facilities and experiments planned in the next decade

<table>
<thead>
<tr>
<th>Facility/Experiment</th>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$\mu_B$ (MeV)</th>
<th>Interaction rate</th>
<th>Dileptons</th>
<th>Charm</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPS NA60+</td>
<td>~6–17.3</td>
<td>440–220</td>
<td>&gt;MHz</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>SPS NA61/SHINE</td>
<td>~5–17.3</td>
<td>540–220</td>
<td>5 kHz</td>
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<td>yes</td>
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<tr>
<td>SIS100 CBM, HADES</td>
<td>2.7–5.5</td>
<td>740–510</td>
<td>&gt;MHz</td>
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<td>yes</td>
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<tr>
<td>RHIC STAR</td>
<td>3–19.6</td>
<td>710–200</td>
<td>~1 kHz</td>
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<td>yes</td>
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<tr>
<td>NICA MPD</td>
<td>4–11</td>
<td>620–320</td>
<td>~7 kHz</td>
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<td>yes</td>
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<tr>
<td>Nuclotron BM@N</td>
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<td>800–660</td>
<td>20–50 kHz (yes)</td>
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<tr>
<td>J-PARC-HI DHS, D2S</td>
<td>2–6.2</td>
<td>840–480</td>
<td>&gt;MHz</td>
<td>yes</td>
<td>(yes)</td>
</tr>
</tbody>
</table>

CERN SPS/NA60+ is central and unique:

- Coverage of a very wide $\mu_B$ region
- Precision physics: possibility of reaching very high interaction rates (>MHz)
- Complete physics reach for dileptons and charm

Energy range complementary to FAIR/GSI

Ideal mapping of a large region of the QCD phase diagram with rare processes
NA60+ project development

2011-13 funded PRIN for first NA60+ simulation studies (G. Usai et al.)


2018 Contribution to European Strategy arXiv:1812.07948

2019 Expression of Interest to the SPSC: http://cds.cern.ch/record/2673280

Fall 2019 ➔ Submit a Letter of Intent for NA60+ to the SPSC
Physics performance studies only need minor adjustments
Detector studies: from conceptual design + detector options to a more realistic design, with preliminary sharing between groups
NA60+: physics observables

Emphasis on (di)muon production

Experimental apparatus: based on a muon spectrometer, coupled to a vertex detector, which provides accurate information on the primary and secondary vertices

Optimized to measure:
- Thermal dimuons from QGP/hadronic phase: caloric curve for first order transition
- $\rho-a_1$ modifications: chiral symmetry restoration
- Quarkonium suppression: signal of deconfinement

With the same experiment one can also address:
- Hadronic decays of charmed mesons/baryons: QGP transport coefficients

Study of these physics topics: high intensity Pb beams ($> 10^7$ ions/s) p-A also mandatory, to calibrate cold matter effects