Prospects on fixed-target heavy ion physics opportunities at CERN

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The phase diagram of QCD at low baryonic density

**Explored at collider energy**
- RHIC (Au-Au) $\sqrt{s_{NN}}=0.2$ TeV
- LHC (Pb-Pb) $\sqrt{s_{NN}}=5.02$ TeV

**Main results**
- High energy density QGP formed ($\varepsilon >> \varepsilon_c \sim 1$ GeV/fm$^3$)
- Long-lived QGP phase (perfect fluid)
- Smooth cross-over between hadronic matter and QGP (no latent heat)

**But we still do not now if QCD has a true phase transition**
Many effective models suggest \textbf{1st order phase transition ending with a critical point (CP)}

High $\mu_b$ accessible at lower collision energy ($\sqrt{s_{NN}} < \sim 20$ GeV)

CP main motivation of RHIC BES:
- some intriguing results from phase 1, but statistically limited
A new experiment at the CERN SPS: NA60+

Investigation of the QCD phase transition at high-$\mu_B$ by precision measurements of hard and electromagnetic processes

Electromagnetic processes
- temperature of the system (QGP and/or Hadronic) \(\rightarrow\) nature of the phase transition
- approach to QCD chiral symmetry restoration

Hard QCD processes
- probe Quark-Gluon Plasma and its transport properties
A new experiment at the CERN SPS: NA60+

Investigation of the QCD phase transition at high-$\mu_B$ by precision measurements of hard and electromagnetic processes

First studies carried out by NA60 (2003-2004), only top SPS energy

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

Proposal: study Pb-Pb collisions at lower SPS energies, down to $\sqrt{s_{NN}}=4.9$ GeV for Pb-Pb, via an energy scan

Strong physics case: QCD phase transition if it exists, is likely the only one involving fundamental degrees of freedom of standard model accessible to laboratory experiments
Uniqueness of CERN SPS/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>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>SIS100 CBM, HADES</td>
<td>2.7–5.5</td>
<td>740–510</td>
<td>&gt;MHz</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>RHIC STAR</td>
<td>3–19.6</td>
<td>710–200</td>
<td>~1 kHz</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>NICA MPD</td>
<td>4–11</td>
<td>620–320</td>
<td>~7 kHz</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Nuclotron BM@N</td>
<td>2.3–3.5</td>
<td>800–660</td>
<td>20–50 kHz</td>
<td>(yes)</td>
<td>no</td>
</tr>
<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)

Energy range complementary to FAIR/GSI

Ideal mapping of a large region of the QCD phase diagram with rare processes

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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
Energy scan at SPS energy

Muon spectrometer length needs to be scaled, to keep the same center of mass coverage at the various collision energies.

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**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: factor 3 better resolution (5 µm)
- Material budget of 50 µm thickness: factor 10 smaller $X_0$

**NA60: profit of new development with TowerJazz process 65 nm**

Significantly improved performance:

- Pixel pitch < 20 µm
- Large area (wafer-scale) with stitching
- Radiation tolerance: $O(10^{15}) \, n_{eq}/cm^2$
- Data rate: 100 MHz/cm^2
- Event time resolution: 200 ns

Heavy ion physics opportunities at CERN, J-Parc Symposium 2019
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**

A novel large area, fast, radiation-tolerant monolithic active pixel sensor for tracking devices of unprecedented precision

- **Funded project with 1 MEuro** (starting September 2019)
- **Cagliari University, Bari University and Politecnico, INFN** (G. Usai et al.)

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

New sensor suitable for different applications:

- NA60+
- ALICE LS3 upgrade
- CLIC vertex detector
- Proton computer tomography scan for hadron therapy

**Migration of the design to Tower 65 nm → <20 µm pixel pitch**

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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/ion = **50 kHz/cm²** in innermost region
Still factor **10 lower** than inner LHCb chambers!

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Closing in on detector choices: muon selection

Default choice → Resistive Plate Chambers (RPC)

Set-up identical to ALICE:
- 2 stations, 2 planes each

Maximum size of Bakelite Electrodes → 300 × 180 cm²

Under discussion:
- **Muon triggering (50 kHz dimuon signal):**
  o ask for a coincidence of 3 out of 4 planes

- **Triggerless readout:**
  o All collisions are readout; RPCs used for muon identification
Dimuon spectra with NA60+

**Physics Goal:**
- **Thermal spectrum (QGP+hadronic), J/ψ**

**Statistics goal:**
- $2 \cdot 10^7$ reconstructed signal pairs in 0-5% central events - factor 100 over NA60
- Similar data sets at several different energies in $6 < \sqrt{s} < 17$ GeV

**Requires:**
- Subtraction of background
- Subtraction of $\eta$, $\omega$, $\phi$, DD and Drell-Yan
- Acceptance correction
Exploring the QCD phase transition

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

\[ \frac{dN}{dM} \propto M^{3/2} \exp(-M/T_s) \]

- \( T_s \rightarrow \) 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

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Physics performance: nature of the phase transition

**Measurement of medium T from thermal dimuons → Caloric curve:**
- Map the evolution of T vs collision energy with **MeV precision**
- 1\textsuperscript{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**
Chiral symmetry restoration in heavy ion collisions

Chiral symmetry: fundamental property of QCD and standard model

Lattice QCD: melting of the chiral condensate at the phase boundary

ρ meson in In-In collisions (NA60):
- strong broadening observed (no mass shift) → ‘hadron melting’
- indirect evidence of chiral symmetry restoration

No direct measurement of chiral restoration: requires access to chiral partner $a_1$
Direct measurement of chiral restoration: $\rho-a_1$ mixing

- 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
- Sensitivity might improve further at $\sqrt{s}=6.3$ GeV (theoretical input needed)
Quarkonium production at low energies

*J/ψ suppression observed from top SPS to LHC* energy → Related to *color screening* in deconfined matter

Look for the **onset of J/ψ suppression** due to melting of $X_c$ and $ψ(2S)$ and corresponding disappearance of their decay $J/ψ$ (direct $J/ψ$ likely not melting at SPS energy)

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

Measurement of **other quarkonium states** ($ψ(2S)$, $χ_c$) → studies ongoing

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Open charm at low energies

Charm diffusion coefficient larger in hadronic phase than in a QGP around $T_c$ (measurement also important for LHC!)

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: D mesons

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

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

High precision data:
- More than $3\times10^6$ $D^0$ at $\sqrt{s_{NN}}=17.3$ GeV
- Systematics at different energies

Unique simultaneous measurement of hidden and open-charm

Measurement of other states ($D_s$, $\Lambda_c$) highly relevant $\Rightarrow$ studies ongoing
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

The NA60+ Collaboration


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

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Outlook

**CERN SPS/NA60+:** unique opportunity for investigating fundamental aspects of QCD phase diagram

- Presently discussed within CERN Physics Beyond Colliders and European Particle Physics Strategy Upgrade (EPPSU)

**Timeline**

- 2019-22 → formation of collaboration; detector R&D (pixels, toroid magnet starting now)
- 2020/21 → after EPPSU output CERN decision about approval
- 2023-25 → construction

**Data taking**

- From 2026 → in parallel with LHC run 4

**Dedicated workshop at ECT* - Trento on the NA60+ physics:**

- Exploring high-$\mu_B$ matter with rare probes – 21-25 September 2020

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Silicon tracking stations

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 \((\sim 15 \times 15 \ cm^2)\)
sensors \(\rightarrow\) ideal for NA60+
- high granularity \(<5 \ \mu m\ \text{resolution}\)
Silicon tracking stations for NA60+

60x60 cm² station: based on a 15x15 cm² station surrounded by a ring of 12 sensors

<table>
<thead>
<tr>
<th>Station</th>
<th>z (cm)</th>
<th>pixel sensors/station</th>
<th>approximate area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S0</td>
<td>7.0</td>
<td>4</td>
<td>30x30</td>
</tr>
<tr>
<td>S1</td>
<td>15.0</td>
<td>4</td>
<td>30x30</td>
</tr>
<tr>
<td>S2</td>
<td>20.0</td>
<td>4</td>
<td>30x30</td>
</tr>
<tr>
<td>S3</td>
<td>27.0</td>
<td>4</td>
<td>30x30</td>
</tr>
<tr>
<td>S4</td>
<td>38.0</td>
<td>16</td>
<td>60x60</td>
</tr>
</tbody>
</table>
GEM modules

Double 3-GEM modules with 2D strip readout

- module size: $50 \times 110 \text{ cm}^2$
- 300 chambers $\rightarrow$ 1000 GEMs (with spares)
- NS2 system (like CMS) for faster chamber 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 several production institutes and optimized workflow

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Muon tracker stations: layout

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
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
**CERN-EP-DT-EF: a new general-purpose toroid**

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

**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)

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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


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

**Fit of mass spectrum for $M>1.5$ GeV → thermometer!**

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$\alpha_1$ 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:

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

$\varepsilon = T^2/6f_\pi^2$

The admixture of the $\alpha_1$ resonance, via the axial-vector correlator, thus entails an enhancement of the dilepton rate for $M \sim 1 - 1.4$ GeV

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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:
  o 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?
  o Can a sequential suppression be established (similarly to what done at LHC for the $\Upsilon$)?
  o 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 $\psi(2S)$)

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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+

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NA60+ project: present status

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.

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

**Project discussed within CERN Physics Beyond Colliders QCD Working Group Report arXiv:1901.04482**

**NA60+ presented at the EPPSU (European Strategy for Particle Physics) symposium (Granada 2019) for Hot & Dense QCD**

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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 asked 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**