NA60+
Status and plans

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The high energy frontier: present status

- QCD phase diagram mostly investigated around $\mu_B=0$:
  - Cross-over transition at $T_c=155$ MeV
  - Produced matter: strongly interacting QGP $\rightarrow$ nearly ideal fluid
Largely unexplored:
- Existence of critical point and first order phase transition put forward

First order phase transition:
- Measurement would provide first direct evidence (in thermodynamic sense) of a phase transition to the QGP

Additional chiral phase transition:
- Exploration of changes in the hadron spectrum
The low energy frontier: the QCD phase diagram at high baryon potential $\mu_B$

- Largely unexplored:
  - Existence of critical point and first order phase transition put forward

- First order phase transition:
  - Measurement would provide first direct evidence (in thermodynamic sense) of a phase transition to the QGP

- Additional chiral phase transition:
  - Exploration of changes in the hadron spectrum

Low energy experiments at different facilities:
- RHIC, SPS, NICA, FAIR, (JPARC?)
Investigating the QCD phase diagram at high $\mu_B$: dilepton measurements

- First order phase transition:
  - Caloric curve $T$ vs energy density

- Chiral symmetry restoration:
  - $\rho/a_1$ chiral mixing ➔ first measurement of spectral properties of $a_1$ at chiral restoration

- $J/\psi$ and open charm at low energies
Investigating the QCD phase diagram at high $\mu_B$: dilepton measurements

- First order phase transition:
  - Caloric curve $T$ vs energy density (more comprehensive performance plot)

- Chiral symmetry restoration:
  - $\rho/a_1$ chiral mixing $\rightarrow$ first measurement of spectral properties of $a_1$ at chiral restoration

- $J/\psi$ and open charm at low energies (first studies on charm)
First order phase transitions and caloric curves

- Caloric curve and phase diagram of water

NA60+: principle of the measurement of T vs energy density

- **T**: fit of dilepton mass spectrum in 1.5<M<2.5 GeV after charm and Drell-Yan subtraction
  \[ \frac{dN}{dM} \approx M^{3/2} \exp\left(-\frac{M}{T}\right) \]

- **T_{slope}** tracks the initial temperature of the medium

- Measurement performed at several collision energies (beam energy scan)

Acceptance corrected spectra:
- \( \sqrt{s}=17.3 \text{ GeV (x100)} \) \( E_{\text{lab}}=160 \text{ GeV} \)
- \( \sqrt{s}=8.8 \text{ GeV (x10)} \) \( E_{\text{lab}}=40 \text{ GeV} \)
- \( \sqrt{s}=6.3 \text{ GeV (x1)} \) \( E_{\text{lab}}=20 \text{ GeV} \)

Dashed lines: theoretical estimate (PLB 753 (2016) 586)
Black lines 1-1.5 GeV: Fit with \( \frac{dN}{dM} \approx M^{3/2} \exp\left(-\frac{M}{T}\right) \)
NA60+: expected performance for caloric curve

Indication of flattening around $v \approx 5-10$ GeV $\Rightarrow$ unique energy interval covered by SPS
QCD chiral symmetry restoration

\[ \langle \bar{q}q(T) \rangle / \langle \bar{q}q \rangle_0 \]

Vacuum

Chiral Restoration

\[ \rho_V \]

\[ \rho_A \]

\[ \int \frac{ds}{\pi} (\rho_V - \rho_A) = -m_q \langle \bar{q}q \rangle \]

Dropping Masses?

Melting Resonances?

[Fodor et al.'10]
Ultimate test of chiral restoration:

- show that the vector ($\rho$) and axial-vector ($a_1$) spectral functions should become (almost) degenerate

$a_1$ never measured in nuclear collisions. How to measure it?
Ultimate test of chiral restoration:
- show that the vector ($\rho$) and axial-vector ($a_1$) spectral functions should become (almost) degenerate

$a_1$ never measured in nuclear collisions. How to measure it?

Principle of the measurement

$a_1$ not coupled to dileptons in vacuum

But in nuclear medium:

$\pi a_1 \rightarrow \mu\mu$ in $1.5 < M < 1.5$ GeV via chiral mixing

$\Rightarrow$ direct evidence of chiral symmetry restoration
NA60+: performance for $\rho-a_1$ chiral mixing

- Sensitivity to mass spectrum region $1 < M < 1.5$ GeV close to onset of deconfinement:
  - very small QGP, large $\pi a_1$ yield

![Plot of NA60+ Central PbPb for $\rho-a_1$ mixing](chart.png)

- Solid line: theory estimate
  - PLB 753 (2016) 586
Charmonium at low energies

- Full SPS energy (160 GeV): $J/\psi$ anomalous suppression relevant for PbPb collisions
- Energy scan: investigation of onset of $J/\psi$ suppression → relation to onset of deconfinement
- Other possible measurements: $\psi(2S), \chi_c$
NA60+: charmonium at low energies

- Full SPS energy (160 GeV): $J/\psi$ anomalous suppression relevant for PbPb collisions
- Energy scan: investigation of onset of $J/\psi$ suppression $\Rightarrow$ relation to onset of deconfinement
- Other possible measurements: $\psi(2S), \chi_c$

- $J/\psi$ production feasible from top SPS energy down to $\sim$40-50 GeV
  - Large acceptance: $\sim$20%
  - Total sample of $\sim2-3 \cdot 10^4$ $J/\psi$
NA60+: charmonium and open charm at low energies

- At onset of deconfinement:
  - Change of $D\bar{D}$ production rate?
  - Onset of $J/\psi$ suppression

- Unique simultaneous measurement of $J/\psi + D\bar{D}$ vs energy:
NA60+: first performance studies for open charm

- Measurement of open-charm: Hadronic decays ($D \rightarrow K\pi$ and $D \rightarrow K\pi\pi$)
- standalone track reconstruction in the silicon vertex tracker

- First studies at 160 GeV:
  - Very high rec eff ≈70-80%
- Next step: simulation of signal embedded in full event
Experimental conditions for dilepton measurements at the CERN SPS

Beams:
- Energy scan in the interval $\sqrt{s} \approx 5$-17 GeV ($E_{\text{lab}} \approx 11$-160 GeV) with Pb beams
- Beam intensity $\sim 10^7/s$ or more $\Rightarrow$ Interaction rate $\sim O($MHz$)$
- Dedicated run at each energy in a few weeks beam-time period
- $p$-Pb needed at least for some energy for reference measurements (Drell-Yan)

Statistics goals:
- $5 \cdot 10^7$ reconstructed pairs from thermal radiation per energy point (statistics increase by a factor $\approx 100$ over NA60 at each energy)
- $2-3 \cdot 10^4$ reconstructed $J/\psi$ mesons per energy point (and larger for open charm)
Why large interaction rates to study dileptons

Interaction Rates $I_R$ (Luminosity × $\sigma_{int}$)
- Fixed target (SPS, SIS100): $10^6$-$10^7$/s
- Colliders (LHC upgrade): $5\times10^4$/s

Dilepton production: rare processes

lowest order rate $\sim \alpha_{em}^2$

Signal/Background ratio $S/B$ (B - combinatorial background)
- range of B/S for different experiments: 20 or more $\Rightarrow$ $B/S >> 1$

Effective signal size: $S_{eff} \sim I_R \times S/B$ reduction by factors of 20-1000!
\[ B(z) = \frac{B_0}{R} \]

\[ \sqrt{s} = 6.3 \text{ GeV} \quad (E_{\text{lab}} = 20 \text{ GeV}) \] setup

**Apparatus layout**

- **Hadron absorber**
- **Graphite**
- **BeO**

**Trigger:** 2 stations of RPCs, ...

**Muon Tracking:** 4 stations of GEMs

**Vertex spectrometer:** 2-3 T dipole field stations of MAPS

**Toroid magnet**

- 300 cm
- 120 cm
- 240 cm

\[ \approx 4.5 \text{ m} \]
Apparatus layout

Based on established detector technologies

μs=6.3 GeV ($E_{\text{lab}}=20$ GeV) setup

$B(z) = \frac{B_0}{R}$

μon Tracking:
4 stations of GEMs

Vertex spectrometer:
2-3 T dipole field
stations of MAPS

Hadron absorber
Graphite
BeO

Toroid magnet

Trigger:
2 stations of RPCs, ...

≈4.5 m

300 cm
240 cm
120 cm

200 cm
Installation

The only available installation site is ECN3:
- Coexistence of NA62 (or KLever) with another experiment is excluded
- A second beamline for heavy ions can be implemented without NA62/KLever and NA60+/Dirac+ coexistence is possible
Cost, timeline, collaboration

- The estimated cost is in the range of 15-25 MEuros, depending in particular on the cost of the magnet for the muon tracking.
- Data taking: might start from 2025 onward.
- Medium-size collaboration of 50-100 researchers.
- Informal interest from groups from several institutions:
  - Cagliari (INFN), Padova (INFN), Torino (INFN), Munich (TUM), Stony Brook University, Rice University, Lyon (IPNL), Kolkata (Saha institute).
- Structured document (LOI or similar) to be prepared in next months.
backup
Dilepton experiments – present and future

<table>
<thead>
<tr>
<th>The high energy frontier</th>
<th>The low energy frontier</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>- RHIC PHENIX, STAR</td>
<td>- RHIC LE STAR</td>
<td>M &lt;1 GeV $\rightarrow$ chiral restoration</td>
</tr>
<tr>
<td>- LHC ALICE</td>
<td>- SPS NA60+</td>
<td>M &gt;1 GeV $\rightarrow$ chiral restoration, hadrons vs. partons (precise meas. of T)</td>
</tr>
<tr>
<td>- SIS100 HADES, CBM</td>
<td>- NICA MPD</td>
<td>Dream: energy dependence from $\sqrt{s} = 4 – 5500$ AGeV</td>
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<tr>
<td></td>
<td></td>
<td>with data quality equivalent or better than NA60</td>
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<td></td>
<td></td>
<td>Principal obstacle to reach this:</td>
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<tr>
<td></td>
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<td>colliders not competitive to fixed-target experiments in terms of interaction rate</td>
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</tbody>
</table>
The STAR BES at RHIC for comparison

- **BES II goal**: statistics ranging from $400 \times 10^6$ mbias events ($\sqrt{s} = 19.6$ GeV) to $100 \times 10^6$ mbias events ($\sqrt{s} = 7.7$ GeV)

- **STAR fixed target**: energy range to be extended further down to $\sqrt{s} = 3$ GeV
  
  Statistics goal: $10^8$ mbias events/energy (same sensitivity as BES-II)

<table>
<thead>
<tr>
<th>Collision Energy (GeV)</th>
<th>BES-II Proposed Events Goal (M)</th>
<th>BES-I Events (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>100</td>
<td>4</td>
</tr>
<tr>
<td>9.1</td>
<td>160</td>
<td>N/A</td>
</tr>
<tr>
<td>11.5</td>
<td>230</td>
<td>12</td>
</tr>
<tr>
<td>14.5</td>
<td>300</td>
<td>20</td>
</tr>
<tr>
<td>19.6</td>
<td>400</td>
<td>36</td>
</tr>
</tbody>
</table>

In 2003 NA60 at $\sqrt{s}=17.3$ GeV collected $>200 \times 10^6$ triggered muon pairs. This means that BESII will not be able to reach even the precision of the former NA60 in dilepton measurements.
Dilepton production in high-energy nuclear collisions

time evolution of a nuclear collision

A+A \quad NN-coll. \quad QGP \quad Hadron Gas \quad Freeze-Out

“Hubble” expansion: \( T = 240 \rightarrow \approx 160 \) \quad 160 \rightarrow 110

\sim 110 \text{ (MeV)}

Lepton pairs emitted at all stages; no final state interactions

NN-collisions: (Drell-Yan), J/\psi, D\bar{D} pairs

QGP: thermal \( q\bar{q} \) annihilation

Hot+Dense Hadron Gas: \( \rho, \sigma_1\pi \rightarrow \ell^+\ell^- \)

Freeze-out: free hadron decays

Thermal dileptons
Thermal dilepton rate and the measurement of $T$

$$\frac{dN_{ee}}{d^4xd^4q} = \frac{-\alpha^2_{em}}{\pi^3 M^2} f^B(q_0, T) \times \text{Im} \Pi_{em}(M, q; \mu_B, T)$$

**Flat spectral function for $M>1.5$ GeV** $\Rightarrow$ mass spectrum after integration over momenta and emission 4-volume:

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

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

Robust theoretical result

**Fit of mass spectrum for $M>1.5$ GeV** $\Rightarrow$ thermometer!
NA60 measurement of $T$ at $\sqrt{s}=17.3$ GeV ($E_{\text{lab}}=160$ GeV): evidence of deconfinement

All physics background sources subtr. and integrated over $p_T$

Correction for acceptance and normalization to $dN_{\text{ch}}/d\eta$

effective statistics highest of all experiments, past and present (by a factor of nearly 1000)

$M<1$ GeV

$\rho$ dominates, ‘melts’ close to $T_c$

$M>1$ GeV

$\sim$ exponential fall-off $\rightarrow$ ‘Planck-like’

fit to $dN/dM \propto M^{3/2} \times \exp(-M/T)$

range $1.1-2.0$ GeV: $T=205\pm12$ MeV

$1.1-2.4$ GeV: $T=230\pm10$ MeV

$T>T_c=160-170$ MeV: partons dominate
Chiral symmetry breaking and the hadron spectrum

Chiral symmetry breaking: masses of the 6 quark flavours


QCD mass (u,d) dominant in the visible part of the Universe

Vector-Axial vector splitting (also pseudoscalar-scalar) in the physical vacuum due to spontaneous breaking of chiral symmetry
Chiral symmetry restoration and the hadron spectrum

**at T_c: Chiral Restoration**

*Borsanyi et al., arXiv:1011.4030.v1 (2010)*

![Graph showing Chiral symmetry restoration](image1)

- **Lattice QCD, μ_B=0**

Vector and axial vector spectral functions expected to change (left: two possible qualitative scenarios)

**Chiral mixing** in the vector/axial vector spectral functions (at correlator level)

![Graph showing Chiral mixing](image2)

What visible effects on the dilepton spectrum?

In vacuum (left) the region M=1-1.5 GeV is **significantly depleted**.

**Chiral mixing:** M=1-1.5 GeV is filled by \( \pi a_1 \to \mu \mu \) (trace of bumpy structure from \( a_1 \)?)

➤ **direct evidence of chiral symmetry restoration**
The NA60+ proposal at the CERN SPS

- **NA60+ layout** close to NA60:
  - precision muon measurement with tracking before and after hadron absorber
  - possibility of adapting the set-up to cover the same kinematic region for various beam energies

- NA60 experiment was housed in the **ECN3 underground zone**
  - dismantled in 2010 to make space for NA62 installation

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**Diagram:**
- Beam tracker
- Dipole magnet
- Si-pixel tracker
- Targets
- Hadron absorber
- Muon trigger and tracking
- Magnetic field

Dimensions:
- $<1\text{m}$
- $\approx 10\text{m}$
Scalable spectrometer for a beam energy scan $\sqrt{s}=6-17$ GeV ($E_{\text{lab}}=20-160$ GeV)

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
NA60+ performance for thermal radiation in central Pb+Pb: data sample size and quality ($\sqrt{s}=8.8$ GeV; $E_{\text{lab}}=40$ GeV)

- $2 \cdot 10^7$ reconstructed signal pairs - factor 100 over NA60
- Combinatorial background: $\mu$ from $\pi,K$ or hadron puch-through - $B/S$ similar as in NA60
- Fake matches: signal $\mu$ matched to wrong track in pixel telescope - much better than NA60
- Mass resolution 10-15 MeV - factor $\approx 2$ better than NA60
NA60+ performance for central Pb+Pb in beam energy scan: data samples at \(\sqrt{s}=6.3-8.8-17.3\) GeV \((E_{lab}=20,40,160\) GeV\)

2 \(\cdot\) 10^7 reconstructed signal pairs at each energy

From full SPS energy towards low energy:
- Significant reduction of Drell-Yan
- Open charm becomes negligible
- Decrease of QGP
Signal mass spectrum: example for central Pb+Pb at √s=8.8 GeV

- Signal spectrum measurable up to 2.5-3 GeV:
  - Subtractions of comb. Bkg (0.5% precision)
  - Subtraction of fake matches

- Dilepton sources M<1 GeV:
  - Thermal radiation ρ+ω
  - Thermal radiation QGP
  - Freeze-out hadron cocktail (η, ω, φ) (M<1 GeV)

- Dilepton sources M>1 GeV:
  - Thermal radiation 4π
  - Thermal radiation QGP
  - Drell-Yan
  - Open charm
Compact setup: performance for central Pb+Pb at $\sqrt{s}=8.8$ GeV

$\omega$ $\phi$

$S \approx 2 \cdot 10^7$
$\langle S/B \rangle \approx 1/12$
$dN_{ch}/d\eta = 270$

Pb-Pb $\sqrt{s}=8.8$ GeV NA60+
0-5% central collisions

$dN/dM$ per 20 MeV

$dN/dM$ per 50 MeV

opposite sign pairs
combinatorial background
fake matches ----
signal pairs

hadron cocktail
thermal radiation
Drell-Yan
In-med Ar
QGP

Pb-Pb $\sqrt{s}=8.8$ GeV NA60+
0-5% central collisions

Compact setup: performance for central Pb+Pb at $\sqrt{s}=8.8$ GeV
Comparison of performance of different setups at $\sqrt{s}=8.8$ GeV

Very similar performance – T measurement practically identical

Large setup (max $R\approx 9$ m)

Compact setup (max $R\approx 7$ m)
The silicon telescope: a new generation tracker for ultra-precise measurements

- Main idea: based on monolithic active pixel sensors (MAPS)

Present state of the art: the ALICE ALPIDE sensor for the ITS upgrade

- 7 layers
- 12.5 Gigapixels
- binary readout
- ~ 10 m² active surface
The Alpide pixel sensor

CMOS Pixel Sensor - TowerJazz 0.18μm CMOS Imaging Process

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (25μm) on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance (~fF)
- Reverse bias voltage (-6V < V_{BB} < 0V) to substrate (contact from the top) to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors (full CMOS circuitry within active area)
# The Alpide pixel sensor: performance

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Inner Barrel</th>
<th>Outer Barrel</th>
<th>ALPIDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silicon thickness</td>
<td>50μm</td>
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<tr>
<td>Spatial resolution</td>
<td>5μm</td>
<td>10μm</td>
<td>~ 5μm</td>
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<tr>
<td>Chip dimension</td>
<td>15mm x 30mm</td>
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<td>✓</td>
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<tr>
<td>Power density</td>
<td>&lt; 300mW/cm²</td>
<td>&lt; 100mW/cm²</td>
<td>&lt; 40mW/cm²</td>
</tr>
<tr>
<td>Event-time resolution</td>
<td>&lt; 30μs</td>
<td></td>
<td>~ 2μs</td>
</tr>
<tr>
<td>Detection efficiency</td>
<td>&gt; 99%</td>
<td></td>
<td>✓</td>
</tr>
<tr>
<td>Fake-hit rate *</td>
<td></td>
<td>&lt; 10⁻⁶/event/pixel</td>
<td>&lt;&lt;&lt; 10⁻⁶/event/pixel</td>
</tr>
<tr>
<td>NIEL radiation tolerance **</td>
<td>1.7x10¹³ 1MeV nₑₑq/cm²</td>
<td>10¹² 1MeV nₑₑq/cm²</td>
<td>✓</td>
</tr>
<tr>
<td>TID radiation tolerance **</td>
<td>2.7Mrad</td>
<td>100krad</td>
<td>tested at 350krad</td>
</tr>
</tbody>
</table>

* revised numbers w.r.t. TDR  
** including a safety factor of 10, revised numbers w.r.t. TDR
Monolithic pixels and fixed target operation

- **Advantages:**
  - significantly reduced cost
  - exceedingly small material budget (0.1-0.3% $X_0$)
  - highly granular - excellent spatial resolution (5 $\mu$m)
  - improved background rejection for thermal radiation
  - precision measurement of charm

- **Improvements for operation with fixed-target experiment:**
  - increase of factor $\approx 5$ in readout speed
    - might be possible from trade-off with power consumption
  - Increase of radiation hardness
    - feature of the TowerJazz CMOS process would allow the NIEL to be increased up to $10^{15}$ $n_{eq}/cm^2$!
Development of new very large area MAPS sensors

*Stitching* : possibility to fabricate wafer-size chips ➔ allows very large sensors to be produced

Example of pixel plane with just 4 ≈15x15 cm² sensors with total material budget of 0.1% $X_0$!

Submission of a request for funds in Italy for the development of a new generation of very large area MAPS
The silicon telescope with very large area MAPS

- Possibility to construct tracking planes from such a sensor excluding all services and mechanical support structures from the acceptance
- Material budget for tracking stations of about 0.1% $X_0$!
From full SPS energy towards low energy:

- Significant reduction of Drell-Yan
- Open charm becomes negligible
- Decrease of QGP
QCD chiral symmetry breaking in vacuum

Vacuum

- $V[\tau \to 2n\pi \nu_\tau]$
- $A[\tau \to (2n+1)\pi \nu_\tau]$
- $\rho(770) + \text{cont.}$
- $a_1(1260) + \text{cont.}$

$\rho_V$

$\rho_A$

$M \text{ [GeV/c}^2\text{]}$

$N(1535)$

$\sigma$

(400–1200)

$\rho$

(770)

$\pi$

(140)

$J^P=0^\pm$

$1^\pm$

$1/2^\pm$
Chiral symmetry restoration: vector spectral function

- High precision measurement by NA60 in In-In collisions at 160 AGeV
- Enormous broadening of $\rho$: $> 400$ MeV

On chiral restoration and $\rho$ melting:

*P.M.Hohler and R. Rapp, PLB 731 (2014)*

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High precision measurement by NA60 in In-In collisions at 160 AGeV

Enormous broadening of $\rho$: > 400 MeV

Resonance melting $\Rightarrow$ hadronic rate approaches QGP rate

Suggestive for deconfinement and chiral restoration

Robust modeling in heavy-ion collisions

On chiral restoration and $\rho$ melting:

P.M.Hohler and R. Rapp, PLB 731 (2014) 103