The NA60+ experiment at the CERN SPS: physics goals and prospects

E. Scomparin (INFN Torino) for the NA60+ collaboration

- Introduction: dileptons and hard probes at CERN SPS energy
- NA60+ physics goals
- Status of the experiment and physics performance studies
- Outlook
Dilepton studies at CERN SPS energy

- NA60 → low- and intermediate-mass dileptons at top SPS energy
  - First precision measurement of
    - in-medium $\rho$ modifications
    - Temperature via thermal dimuons in $1.5<m_{\mu\mu}<2.5$ GeV/c$^2$

Region below top SPS energy almost unexplored

- Only a CERES measurement (low-mass dileptons at $\sqrt{s_{NN}}=8.8$ GeV)
  - Dielectron excess (central Pb-Au)
  - Indication (1.8 $\sigma$) for excess due to in-medium modifications of $\rho$ spectral function

R. Arnaldi et al. (NA60), EPJC 61(2009) 711

D. Adamova et al. (CERES), PRL91 (2003)042301
Study of dilepton production at low energy

- HADES (SIS) and NA60 (SPS) have provided dilepton $T_{\text{slope}}$ measurements
- A study of the $T_{\text{slope}}$ evolution in $\sqrt{s_{\text{NN}}} \sim 3-20$ GeV may provide accurate information on the region of the "transition temperature" associated with the change in the degrees of freedom of the system

→ Strong motivation for a measurement of a caloric curve $T_{\text{slope}}$ vs $\sqrt{s_{\text{NN}}}$ with a few percent accuracy
Dilepton spectrum and chiral symmetry restoration

- Broadening of $\rho$-meson spectral function is qualitatively consistent with chiral symmetry restoration $\Rightarrow$ need to investigate the chiral partner $a_1$

- No direct coupling of axial states to the dilepton channel $\Rightarrow$ in vacuum the $(e^+ e^- \to \text{hadrons})$ cross section has a dip in the $a_1$ mass range

- Chiral symmetry restoration $\Rightarrow$ mixing of vector (V) and axial-vector (A) correlators $\Rightarrow$ enhancement of the dilepton rate for $m_{\mu\mu} \sim 1-1.4$ GeV/$c^2$

- Low-energy measurement expected to be more sensitive to chiral restoration effects $\Rightarrow$ (Exponential) thermal dimuon yield from QGP becomes smaller $\Rightarrow$ Contribution from open charm becomes relatively negligible
Open charm at SPS energy

- No results available below top SPS energy
- NA60 In-In dimuons $\sqrt{s_{NN}} = 17.3$ GeV
  $\rightarrow \sigma_{cc} = 9.5 \pm 1.3\pm 1.4 \, \mu$b

- D-meson $p_T$ distributions and azimuthal anisotropy
  $\rightarrow$ Time spent in QGP and hadronic phase varies as a function of energy $\rightarrow$ important constraints for the estimate of the charm diffusion coefficient $D_s$
  $\rightarrow$ Charm quark thermalization in a short-lived QGP
- $D_s^+, \Lambda_c$
  $\rightarrow$ Hadronization studies (quark recombination)
- Charm cross section
  $\rightarrow$ Potentially sensitive to chiral symmetry restoration, due to reduction of DD threshold
- Charm production in pA
  $\rightarrow$ Sensitive to nPDFs
  $\rightarrow Q^2 \sim 10-40$ GeV$^2$ and $0.1 < x_{Bj} < 0.3$ ($p_T < 3$ GeV/c)
  (from anti-shadowing to EMC region)

Charm production at SPS energy is an uncharted territory!

F. Scardina et al., PRC96 (2017) 044905

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Charmonium at SPS energy

- The only “hard probe” studied at the SPS

- $J/\psi$
- 30% suppression for central Pb-Pb events at top SPS energy, after accounting for CNM effects

  → Compatible with suppression of more weakly bound $\chi_c$ and $\psi(2S)$ states decaying to $J/\psi$

- $\psi(2S)$
- Exhibits strong suppression already in peripheral Pb-Pb collisions, up to a factor ~5 for central collisions

  → sensitivity to the hadronic phase

- Energy scan towards low SPS energy

  → Detect suppression threshold and correlate with $T$ via thermal dimuons

  → Strong variations of the ratio $J/\psi/D$ at deconfinement threshold?

Quarkonium physics not studied below top SPS energy!
NA60+

Study of hard and electromagnetic processes at the CERN-SPS: an investigation of the high-$\mu_B$ region of the QCD phase diagram via an energy scan ($\sqrt{s_{NN}}=6$ to 17 GeV)

Main features

- 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 (and J-PARC)

<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>
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<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>
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<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>
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<tr>
<td>RHIC STAR</td>
<td>3–19.6</td>
<td>710–200</td>
<td>~1 kHz</td>
<td>yes</td>
<td>yes</td>
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<tr>
<td>NICA MPD</td>
<td>4–11</td>
<td>620–320</td>
<td>~7 kHz</td>
<td>yes</td>
<td>yes</td>
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<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>
NA60+ set-up

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

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

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

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

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

Muon spectrometer length will be varied, to cover mid-rapidity at different collision energies

(for details on the set-up see G. Usai, poster presentation #208)
NA60+: muon detection performance

Detector performance studies → based on a simulation framework with a semi-analytical tracking algorithm (Kalman filter) FLUKA for hadronic background studies

- Full phase-space acceptance at dimuon low and intermediate masses → >1%
- Good coverage down to midrapidity AND zero $p_T$, realized at all energies by displacing the muon spectrometer

The mass resolution for resonances varies from <10 MeV ($\omega$) to ~30 MeV ($J/\psi$)
(factor >2 improvement with respect to NA60)
Dilepton spectrum

- Thermal dimuon distributions from Rapp et al., PLB753 (2016) 586
- Hadron cocktail from NA60 and statistical model (Becattini et al., PRC73 (2006) 044905)
- Drell-Yan and open charm from PYTHIA
- Combinatorial background: input spectra from NA49 measurements

- 2×10^7 reconstructed central Pb-Pb
  (1 month data taking at interaction rate ~1 MHz)
- S/B~1/18 at M=0.6 GeV/c^2
- Combinatorial background subtracted with 0.5% uncertainty

Factor ~100 improvement with respect to NA60 (min. bias)!
NA60+: physics goals and prospects

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- Thermal radiation yield
- Dominated by $\rho$ contribution at low mass
- Accessible up to $M=2.5-3$ GeV/$c^2$
- Drell-Yan contribution → to be also estimated via $p$-$A$ measurements

- Acceptance-corrected signal spectra fitted with $dN/dM=M^{3/2}\exp(-M/T_s)$ in the interval $1.5<M<2.5$ GeV/$c^2$
Accurate mapping of the region where the pseudocritical temperature is reached! Sensitive to potential effects expected in case of 1\textsuperscript{st} order phase transition!

\( T_{\text{slope}} \) measurement

\( T_{\text{pc}} = 156.5 \pm 1.5 \text{ MeV} \)

\( T_{\text{slope}} \) values from thermal yields in 1.5<M<2.5 GeV/c\(^2\)

Theory

\( \sqrt{s} > 6 \text{ GeV}, \text{ R. Rapp, PLB 753 (2016) 586} \)

\( \sqrt{s} < 6 \text{ GeV}, \text{ T. Galatyuk, EPJA 52 (2016) 131} \)

A few MeV accuracy can be reached (1.4 to 5 MeV for \( \sqrt{s}_{NN} \) to 6.3 to 17.3 MeV) on \( T_{\text{slope}} \)
- Simulations carried out by considering
  - No chiral mixing (dip in $1<M<1.4$ GeV/c$^2$)
  - Full $\rho$-$a_1$ chiral mixing

(modeled from Rapp, vanHees, PLB753 (2016) 586)

- A 20-30% enhancement is expected in case of full mixing

With the foreseen accuracy of the measurement the effect can be clearly detected!
Hard probes: open charm

- Hadronic decays of charmed particles can be reconstructed in the vertex spectrometer (no PID)

- $D^0 \rightarrow K^+\pi^-$ (POWHEG-BOX+PYTHIA6)
- Background from NA49 light hadron production data

- 0-5% Pb-Pb, $\sqrt{s_{NN}}=17.3$ GeV
- 1200 $p,K,\pi$ per event
- $8 \times 10^3$ candidates in $m_D \pm 60$ MeV
- $S/B \sim 10^{-7}$, enhanced with kinematic and geometric selections (equivalent to 30 days data taking at 150 kHz)

- Measurement for $\Lambda_c \rightarrow pK\pi$ more challenging $\rightarrow$ 3-particle decay, $S/B \sim 10^{-10}$
- Alternatively, $\Lambda_c \rightarrow pK^0_S K^0_S \rightarrow \pi\pi$ (lower BR, lower background)
- Measurement of $D^+_S \rightarrow KK\pi$ in progress

Good prospects for a first low-energy measurement of charm in nuclear collisions!
Hard probes: charmonium

- p-A measurement → calibrate CNM effects (assume same effect as measured by NA60 at $\sqrt{s_{NN}} = 17.3$ GeV)

- Extrapolate CNM effect to Pb-Pb and compare with a scenario where anomalous suppression sets in at $N_{\text{part}} \sim 50$ and reaches 20% (was $\sim 30\%$ at $\sqrt{s_{NN}} = 17.3$ GeV)

- Assume 30 days of Pb beam and $\sim 10^7$ Pb/s

Good sensitivity to J/$\psi$ suppression onset

ψ(2S) pA → assume stronger suppression for ψ(2S) relative to J/$\psi$ (as measured by NA50 at $\sqrt{s_{NN}} = 29$ GeV)

Pb-Pb → assume factor $\sim 2$ stronger suppression for ψ(2S)

Look for the onset of ψ(2S) suppression
NA60+: project development

- Project started in 2011-2013 (Italian Research Ministry funding)
- Selected and followed (2017-2020) as one of the CERN future projects in the frame of the “Physics beyond Colliders” initiative → see QCD WG report, arXiv:1901.04482

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.

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

Conclusions of the EPPSU (European Strategy for Particle Physics) symposium (Granada 2019) for Hot & Dense QCD

2019: Expression of Interest to the SPSC → http://cds.cern.ch/record/2673280
Next step → Submission of a Letter of Intent for NA60+ to the SPSC
Ongoing detector studies

Stitched MAPS → novel large area, fast, radiation-tolerant monolithic active pixel sensors for tracking devices of unprecedented precision

Triple GEM amplification structure
- Operated with Ar-CO$_2$
- 2D strip readout

The contribution of new institutes will be essential for the success of the project!
Conclusions

- Precision studies of electromagnetic and hard probes in the region $6<\sqrt{s_{NN}}< 17$ GeV are currently lacking.

- The CERN NA60 experiment had obtained measurements with unsurpassed precision in the study of dilepton production at top SPS energy ($\sqrt{s_{NN}}=17.3$ GeV).

- NA60+: a new dimuon experiment with a similar concept but based on state-of-the-art technology choices may collect a factor $\sim100$ larger statistics for several collision energies at the SPS.

- Physics performance studies show that measurements of
  - Caloric curve from thermal dileptons
  - Continuum modifications due to chiral mixing
  - Open and hidden charm production
are within reach and would lead to significant advances in the field.

A Collaboration is being built and needs to be strengthened in order to bring the project to reality → you are welcome to contact us for discussions!
The NA60+ Collaboration

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

NA60+: physics goals and prospects

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Dilepton excitation function and fireball lifetime

- Fireball lifetime directly related to acceptance corrected low-mass dilepton yield in $0.3 > M > 0.75$ GeV
  → promising tool to detect “anomalous” variations as a function of collision energy

- Such variations could be triggered by the presence of a soft mixed phase during a first order transition
  → fireball lifetime anomalously increased due to the burning of latent heat
  → appearance a plateau in the thermal dilepton yield vs collision energy

Needs a precision measurement at energies below top SPS!
Thermal dimuons as a fireball chronometer

- Measurement of the thermal yield in $0.3 < M < 0.7 \text{ GeV/c}^2$
- Excellent accuracy $\rightarrow$ may allow a precise estimate of the fireball lifetime

“Anomalous” variations in the yields as a function of $\sqrt{s_{NN}}$, due to the burning of latent heat, could represent a promising to detect the presence of a first order phase transition.
NA60+: physics goals and prospects

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T. Galatyuk, QM2018
NA60+: integration studies

- Integration of the experiment in a CERN experimental hall is under study by CERN accelerator experts.

- ECN3 (high intensity hall) → fully exploit SPS luminosity, competition with non-HI experiments for the use of the beamline.

- EHN1 (surface hall) → max. beam intensity limited by radiation safety issues, no competition → 2 possible zones singled out (PPE134 most promising)

(see G. Usai, poster presentation #208)