Dimuon Production In PbPb Collisions at 20-160 AGeV at the CERN SPS: Mapping the QCD Phase Diagram in the Transition Region

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NA60+: prime physics goal

- Systematic measurement of EM radiation over the full energy range from SIS-100/300 to top SPS: ≈20 AGeV to 160 AGeV

RHIC:
- good coverage, but much lower statistics than fixed target experiments

FAIR (CBM):
- SIS-100 (>2020) limited coverage
- SIS-300 better coverage but unclear timeline (>2025)

SPS:
- Wide coverage of phase diagram
- Existing facility
- Competitive high-intensity beams
- Other experimental program (NA61) already ongoing
Dileptons in the LMR (M<1 GeV): $\rho$ spectral function

- High energy: 160 AGeV In-In

- Low energy: only one low-statistics measurement in Pb-Au at 40 AGeV

- Broadening of $\rho$ spectral function driven by the total baryon density
  - should get maximal at low energy

- Measurement of $\rho$ spectral function with utmost precision
  - Possible surprises? Critical point?

Enhancement factor: $5.9\pm1.5({\text{stat.}})\pm1.2({\text{syst.}})$
Dileptons in the IMR: source temperature and chiral symmetry restoration

Physics processes in IMR
- Drell-Yan (power law \( \sim M^n \))
- Thermal radiation
  - QGP
  - Hadron gas

Thermal spectrum for \( M > 1.5 \) GeV (flat spectral function) \( \sim M^{3/2} \exp(-M/T) \):
- fit gives average T of emitting source

Chiral symmetry restoration: hadronic radiation for \( M < 1.5 \) GeV dominated by \( 4\pi \) processes via \( a_1 \pi \rightarrow \mu\mu \) (chiral mixing)

Lower energy: decrease of QGP, DY and open charm
- improved sensitivity to excess from hadronic radiation

CERN Courier 11/2009, 31-35

Hees – EM probes Trento workshop - 2013
**Partonic radiation and onset of deconfinement**

- Disentangling QGP vs hadronic radiation \(\Rightarrow\) \(m_T\) spectra in different mass bins

\[
\frac{1}{m_T} \frac{dN}{dm_T} \approx \exp\left(-\frac{m_T}{T_{\text{eff}}}\right)
\]

- Hadronic radiation: \(T_{\text{eff}}\) rise consistent with radial flow of a hadronic source: \(\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-\) in LMR; 4\(\pi\) in IMR (the latter negligible at 160 AGeV)

- QGP radiation: \(T_{\text{eff}}\) almost flat, consistent with an early source with low flow (dominant at 160 AGeV)

- \(T_{\text{eff}}\) vs \(M\) sensitive to QGP vs hadronic yield - for decreasing collision energy, increase of HG radiation/decrease of QGP \(\Rightarrow\) progressive reduction/disappearance of drop

- Systematic precision measurement from SPS energies down to SIS100 energies
Charmonium production in AA: top to low SPS energies

- Anomalous suppression relevant for PbPb collisions, but almost no suppression for the lighter InIn system at 158 AGeV

- Identify thresholds for charmonium suppression via SPS energy scan

- Topmost SPS energy: detailed study of $\chi_c$ by detecting the decay photon (originally part of NA60 program)
### Comparison of ion beams

<table>
<thead>
<tr>
<th></th>
<th>SPS</th>
<th>SIS100/300</th>
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<tbody>
<tr>
<td>Energy range: [AGeV]</td>
<td>11 – 158</td>
<td>&lt; 11 – 35 (45)</td>
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<tr>
<td>Beam intensity [Hz]</td>
<td></td>
<td></td>
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<tr>
<td>Target thickness [λ_i]</td>
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<tr>
<td>Interaction rate [Hz]</td>
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<tr>
<td>NA60 (2003)</td>
<td>2.5×10^6</td>
<td>5×10^5</td>
</tr>
<tr>
<td>New injection scheme</td>
<td>10^8</td>
<td>10^7</td>
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<tr>
<td></td>
<td>10^8</td>
<td>10^6</td>
</tr>
<tr>
<td>LHC AA</td>
<td></td>
<td>5×10^4</td>
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<td></td>
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<td>10^5 - 10^7</td>
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- Luminosity at the SPS comparable to that of SIS100/300
- No losses of beam quality at lower energies except for emittance growth
- RP: seems not a problem in EHN1
- Pb beams presently scheduled for the SPS in 2016-2017, 2019-2021
Running conditions foreseen

- **Energy scan**
  - tentatively: 20-(30)-40-(60)-80-(120)-160 AGeV

- **Objectives for total sample of reconstructed pairs**
  - **NA60 (2003):** total sample (thermal + cocktail) ≈ 5 \cdot 10^5
  - **NA60+:** 4th generation experiment

  - **Goal:** > 10^7 rec pairs from thermal radiation at each energy

- **Ion beams**
  - Consistent use of Pb ions for all energies

- **Proton beams**
  - Needed for reference measurements (Drell-Yan and charmonium)
NA60+ detector concept

Two-spectrometer concept (successfully exploited by NA60)

- Hybrid silicon pixel detectors (High luminosity of dimuon experiments must be maintained)
- Tracking and trigger stations: GEMs and/or MWPCs
- Track matching in coordinate and momentum space
  - improved dimuon mass resolution
  - distinguish prompt from decay dimuons
Measuring dimuons at 20<$E_{lab}$<160 GeV

Muon spectrometer
Toroid field (R=160 cm)

Compress the spectrometer reducing the absorber and enlarge transverse dimensions

Longitudinally scalable setup for running at different energies
- Required rapidity coverage @20 GeV starting from $\langle y \rangle = 1.9$ ($\vartheta \sim 0.3$ rad)
- 5 silicon pixel planes at $7 < z < 38$ cm
- Pixel plane:
  - 400 $\mu$m silicon + 1 mm carbon substrate
  - silicon material budget $\approx 0.5\% X_0$
  - 10-15 $\mu$m spatial resolution
The muon spectrometer

Muon Tracker
✓ 4 tracking stations (z=295, 360, 550, 650 cm)

Hadron absorber (BeO, graphite – 240 cm)

Toroid magnet:
✓ 150 cm long; R≈230 cm
✓ B ≈0.5/R Tesla

Trigger stations
✓ 2 trigger stations placed after muon wall (ALICE-like) at z = 840, 890 cm
✓ No particular topological and p_T constraints introduced contrary to NA60 hodo system (muons required in different sextants)
Performance studies: Pb-Pb 0-5% central collisions

- **Signal**
  - Hadron cocktail generator derived from NA60 Genesis using statistical model (Becattini et al.);
    \[
    \frac{dN_{\text{ch}}}{d\eta} = 270
    \]
  - Thermal radiation generator based on theoretical calculation in PbPb at 40 GeV (R. Rapp)
  - Drell-Yan and open charm estimated with Pythia

- **Fast simulation tool and reconstruction tool**
  - Apparatus defined in terms of geometry and material for each layer
  - Multiple scattering generated in gaussian approximation (Geant code)
  - Energy loss simulated with Bethe-Bloch neglecting energy fluctuations
  - Reconstruction based on Kalman filter with embedding on full event in pixel detector
  - Fake match: one or more wrong hits associated to track
Combinatorial background

Keep this distance as small as possible ~40 cm

Fluka
- Full hadronic shower development in absorber
- Punch-through of primary and secondary hadrons (p, K, π)
- Muons from secondary hadrons

Background generation
- Parametric π and K event generator (built-in decayer for π and K)
- Apparatus geometry defined in consistent way with fast simulation tool
- Hits in detector planes recorded in external file for reconstruction
Triggering on dimuons and expected sample size

- Triggering scheme under investigation:
  - tracklet reconstruction in trigger stations after muon wall + fast track reconstruction in muon stations

- Beam intensity: $L \approx 2.5 \cdot 10^6/s$, $\lambda_i=0.15$ (past NA60 conditions)
  - minimum bias trigger rate (essentially bkg rate) $\approx 15$-$20$ kHz

- NA60+ improvements over NA60:
  - Higher trigger rate capability (limited to $< \approx 4$ kHz in NA60)
  - Significantly larger acceptance, in particular for $M<0.5$ GeV: $>10$
  - Pb-Pb vs In-In

- 15-20 days of beam time in Pb-Pb at 40 GeV
  - $\approx 10^7$ reconstructed pairs from thermal radiation in central collisions
Pb-Pb 0-5% central collisions: data sample

Pb-Pb 40 GeV NA60+
0-5% central collisions

\[ S \approx 2 \cdot 10^7 \]

\(<S/B> \approx 1/12\)

- Subtraction of:
  - Combinatorial background
  - Fake matches

- Precision of combinatorial background subtraction: 0.5%

- 2 \cdot 10^7 reconstructed signal pairs

Mass resolution: 10-15 MeV at the \( \omega \) position
Minimum bias collisions: progress in statistics over NA60 by a factor $\approx 100$
Pb-Pb 0-5% central collisions: LMR (M<1 GeV)

- Thermal radiation yield dominated by in-medium $\rho+\omega$
- Precise isolation of excess à la NA60
Pb-Pb 0-5% central collisions: full mass spectrum

- Thermal radiation yield up to 2.5-3 GeV
- QGP yield still significant at 40 GeV
- Drell-Yan gets stronger than QGP above 2.5 GeV
- Open charm yield negligible
Inclusive excess mass spectrum: NA60+ (40 AGeV PbPb) vs NA60 (160 AGeV InIn)

- All known sources subtracted; mass spectra integrated over $p_T$
- Mass spectra fully corrected for acceptance
Inclusive excess mass spectrum: hadronic radiation

- Mass Spectrum fully corrected for acceptance

- Performance for study of hadronic radiation in IMR. Scenario with
  - Negligible QGP radiation
  - Hadronic radiation for Pb-Pb central collisions at 20/40 GeV
  - Same background level as Pb-Pb 40 GeV

- Stand-alone study of excess up to \( M \approx 2 \text{ GeV} \)
- Best sensitivity to \( \rho-a_1 \) chiral mixing
**Pb-Pb 0-5% central collisions: performance of \( T_{\text{eff}} \) measurement from \( m_T \) spectra**

- **Thermal radiation in Pb-Pb at 40 GeV** (Rapp)
  - **hadronic radiation**: \( T_{\text{eff}} \) increases monotonically from LMR to IMR up to highest masses
  - **QGP radiation**: \( T_{\text{eff}} \) variation almost negligible

- **Experimental measurement**
  - \( T_{\text{eff}} \) can be extracted in several mass intervals up to \( \approx 2.5 \) GeV
  - Strong sensitivity to distinguish even a small contribution of QGP down to the onset
NA60+: charmonium measurements in Pb-Pb at low energy

- Kinematic cuts and reconstruction efficiency:
  - $0<y<1; \cos \theta_{CS}<0.5; \varepsilon_{rec} \approx 10\%$

- $J/\psi$ suppression: assume a factor 3 as at 160 AGeV (pessimistic ansatz)

- Energy scan down to $E_{lab} \approx 60$ AGeV
- Measurement with comparable statistics as at topmost SPS energy ($N_{J/\psi} \approx 10^4$) possible within the proposed frame
Magnets and muon system

- Dipoles: investigating re-use of PT7 or MEP48

- MEP48
  - Gap width 410 mm, diameter 1000 mm
  - $B = 1.47 \, \text{T} \, @ \, 200 \, \text{Amp}, \, 200 \, \text{V}$
  - $B \approx 2.5 \, \text{T}$ reducing the gap size to 200 mm

- Toroid magnet
  - Ongoing discussion with CERN experts
  - Proposal for an "hexagonal cone" shape with the required angular acceptance
  - The estimated cost should not exceed $\approx 1.5-2 \, \text{MEuro}$

- Muon tracking stations and absorbers
  - Option of complete construction with GEMs considered ($\approx 140 \, \text{m}^2$)
  - Absorbers
  - Estimated cost $\approx 7-10 \, \text{MEuro}$
Options for the pixel telescope

- Baseline option investigated: detector based on hybrid pixels
  - pitch 30-50 μm
  - silicon material budget ≈ 0.5% $X_0$

- Exploration of existing technologies or new developments for LHC upgrades (past example in NA60: ATLAS pixels)

- Estimated cost: 2-3 MEuro (was 0.5 MCHF in NA60)

2 Planes with different geometry using ATLAS pixel modules built and operated in NA60 2004 proton run
Summary

- Systematic measurement of EM radiation over the full energy range from SIS-100/300 to top SPS: $\approx 20 \text{ AGeV}$ to $160 \text{ AGeV}$

- Charmonium also part of the program from $\approx 60 \text{ AGeV}$ to $160 \text{ AGeV}$

- Physics performance studies for LMR and IMR dileptons very encouraging
  - Progress in statistics of a factor $\approx 100$ over NA60 within reach
  - New horizon for quantitative understanding of dilepton production (chiral symmetry restoration, onset of deconfinement)

- NA60+: two-spectrometer detector concept as NA60
  - Relatively low cost experiment: 10-15 Meuro
  - Collaboration would require 50-100 people

- Preparation of a document to serve as a basis for a letter of intent under way