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: $5.9\pm1.5$(stat.)$\pm1.2$(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
Partonic radiation and onset of deconfinement

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

$\frac{dN}{dm_T} \approx \exp\left(-\frac{m_T}{T_{eff}}\right)$

Collective motion (radial flow)

$T_{eff} \approx T + M \langle v_R^2 \rangle$

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

- $T_{eff}$ 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

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<tr>
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<th>SPS</th>
<th>SIS100/300</th>
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<tr>
<td>Energy range:</td>
<td>11 – 158</td>
<td>&lt; 11 – 35 (45)</td>
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<tr>
<td>NA60 (2003)</td>
<td>2.5×10^6</td>
<td>5×10^5</td>
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<td>new injection scheme</td>
<td>10^8</td>
<td>10^7</td>
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<td></td>
<td>10^8</td>
<td>10^6</td>
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<tr>
<td>LHC AA</td>
<td>5×10^4</td>
<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) $\approx 5 \cdot 10^5$
  - NA60+: 4th generation experiment
  - Objective: $> 10^7$ 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 $20 < E_{\text{lab}} < 160$ GeV

Muon spectrometer
Toroid field ($R=160$ cm)

5 m

Compress the spectrometer reducing the absorber and enlarge transverse dimensions

Beam

Dimuons@160 GeV (NA60)
Rapidity coverage $2.9 < y < 4.5$

Dimuons@20 GeV
Rapidity coverage $1.9 < y < 4$

Longitudinally scalable setup for running at different energies
- Required rapidity coverage @20 GeV starting from $<y>=1.9$ ($\vartheta \sim 0.3$ 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)

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)

Hadron absorber (BeO, graphite – 240 cm)

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

Muon wall (graphite - 120 or 180 cm)
Performance studies: Pb-Pb 0-5% central collisions

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

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

Keep this distance as small as possible ~40 cm

- Beam Tracker
- Vertex Detector
- Dipole field

- Vertex
- Offset

- Muon wall (not to scale)
- Hadron absorber (not to scale)

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

Bkg 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: $L \approx 2.5 \cdot 10^6 \text{s}^{-1}$, $\lambda_i = 0.15$ (past NA60 conditions)
  - minimum bias trigger rate (essentially bkg rate) $\approx 15-20 \text{ kHz}$

- NA60+ improvements over NA60:
  - Higher trigger rate capability (limited to $< 4 \text{ kHz}$ in NA60)
  - Significantly larger acceptance, in particular for $M < 0.5 \text{ GeV}$: $> 10$
  - 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 $M \approx 2$ 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:
  - $0<y<1$; $\cos\theta_{CS}<0.5$; $\epsilon_{rec} \approx 10\%$
- $J/\psi$ 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
  - $B=1.47\ T$ @ $200\ \text{Amp},\ 200\ \text{V}$
  - $B\sim2.5\ T$ 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 1.2-1.6 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)
Summary

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

- Charmonium also part of the program from ≈ 60 AGeV to 160 AGeV

- Physics performance studies for LMR and IMR dileptons very encouraging
  - Progress in statistics of a factor ≈ 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