Experiments on Lepton Pairs
The CERN SPS Era

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Trento, November 30, 2015
High-Energy Nucleus-Nucleus Collisions: Prime Goal of Dilepton Experiments

Precision study of the QCD phase diagram

Phase transitions
✓ Probe the quark-hadron transition
✓ Probe the chiral transition (origin of light hadron masses)
   Beam-energy scans down to low energies mandatory

Bulk properties
Probes high-temperature partonic matter: early Universe
Probes high-density baryonic matter: neutron stars
Theoretical guidance for the QCD phase diagram

Small $\mu_B$ (Lattice QCD)
crossover transition
$\varepsilon_c \sim 1$ GeV/fm$^3$, $T_c \sim 160$ MeV

Large $\mu_B$, moderate $T$ (field th.)
QCD critical point,
1st order transition

$\mu_B$ related to density of (baryons - anti-baryons)


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


Chiral symmetry breaking: masses of the 6 quark flavours

SPS
LHC
non-int. limit

$3p/T^4$
$3s/4T^3$
$\varepsilon/T^4$

deconfinement transition
Lattice QCD, $\mu_B=0$

chiral symmetry restoration

$<qq> \sim -1.6$ fm$^{-3}$
QCD phase diagram and accelerator energies

Very high energies, central production
(LHC; RHIC)

Moderate and low energies:
SPS
(BES-RHIC; FAIR; NICA)

$\mu_B$ related to density of (baryons - anti-baryons)
Observables and physics goals: dilepton production

time evolution of a nuclear collision

\[ \ell^+ + \ell^- \]

Freeze-Out

QGP

Hadron Gas

\[ T = 240 \rightarrow 170 \]

\[ 170 \rightarrow 110 \]

\[ \sim 110 \text{ (MeV)} \]

Lepton pairs emitted at all stages; no final state interactions

difficulties: \( 10^{-4} (\alpha_{em}^2) \) of hadrons; overlay of different sources

\[ NN \text{-collisions:} \]

Drell-Yan, DD pairs (physical background)

\[ QGP: \]

thermal \( q\bar{q} \) annihilation (deconfinement)

\[ \text{Hot+Dense Hadron Gas:} \]

\( \rho (\rho-a_1) \) modification (chiral restoration)

\[ \text{Freeze-out:} \]

free hadron decays (physical background)
Electromagnetic probes: dileptons vs. real photons

photons: 1 variable: $p_T$
lepton pairs: 2 variables: $M, p_T$

relevant for thermal radiation:
$p_T$ sensitive to temperature and expansion velocity
$M$ only sensitive to temperature (Lorentz invariant)

for flat spectral functions, i.e. for hadron-parton duality ($M>1.5$ GeV)

\[ dN/dM \sim M^{3/2} \times \exp(-M/T) \quad \Rightarrow \text{‘Planck-like’} \] (see next slide)

the only Lorentz-invariant thermometer of the field

\[ q \quad \gamma \quad q \quad \rightarrow \quad \text{QCD Compton} \]
\[ q \quad \bar{q} \quad \ell^+ \quad \ell^- \quad \rightarrow \quad \text{qq annihilation} \]

lowest order rate $\sim \alpha_{em} \alpha_s$

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

dileptons more rich and more rigorous than photons
Dilepton Rate in a strongly interacting medium

\[ \frac{dN_{ee}}{d^4x d^4q} = \frac{-\alpha_{em}^2}{\pi^3 M^2} f^B(q_0,T) \times \text{Im } \Pi_{em}(M,q;\mu_B,T) \]

\[ \text{Im } \Pi_{em} \sim \text{Im } D_{\rho} + \ldots \quad \text{Im } \Pi_{em} \sim N_c \sum (e_q)^2 \]

after integration of rate equation over momenta and emission 4-volume:

hadron basis

\[ \frac{dN_{\mu\mu}}{dM} \propto M^{3/2} \times \langle \exp(-M/T) \rangle \times \langle \text{spectral function}(M) \rangle \]

M<1.5 GeV

M>1.5 GeV

‘Planck-like’→ thermometer distinguishes partons and hadrons
Dileptons and the spectral functions of the chiral doublet $\rho/a_1$

P-S, V-A splitting in the physical vacuum due to spontaneous breaking of chiral symmetry

- Thermal dileptons with $M<1$ GeV mostly mediated by the vector meson $\rho (1^{--})$
- Strong coupling of $\gamma^*$ to $\rho$ (VMD)
- Life time $\tau_\rho = 1.3$ fm $<< \tau_{\text{collision}} > 10$ fm (unique in the PDG)
- Continuous "regeneration" by $\pi^+\pi^- \rightarrow \text{sample in-medium evolution}

Axial vector $a_1 (1^{++})$ accessible through chiral mixing ($\pi a_1 \rightarrow \mu^+\mu^-$, ‘4π’)

ALEPH data: Vacuum

Melting Resonances?

Dropping Masses?
In-medium changes of the $\rho$ properties (relative to vacuum)

Selected theoretical references (status 2005)

<table>
<thead>
<tr>
<th>Reference</th>
<th>mass of $\rho$</th>
<th>width of $\rho$</th>
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</thead>
<tbody>
<tr>
<td>Pisarski 1982</td>
<td>←</td>
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<tr>
<td>Leutwyler et al 1990 ($\pi,N$)</td>
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<tr>
<td>Brown/Rho 1991 ff</td>
<td>←</td>
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<tr>
<td>Hatsuda/Lee 1992</td>
<td>←</td>
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<tr>
<td>Dominguez et. al 1993</td>
<td>←</td>
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<tr>
<td>Pisarski 1995</td>
<td>←</td>
<td>←</td>
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<tr>
<td>Chanfray, Rapp, Wambach 1996 ff</td>
<td>←</td>
<td>←</td>
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<tr>
<td>Weise et al. 1996 ff</td>
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</table>

very confusing, experimental data crucial
Dilepton observables directly related to the QCD phase diagram

Signals of deconfinement transition

- $T$ of thermal $\ell^+\ell^-$ (high $M$)
- $T_{\text{eff}}$ of thermal $\ell^+\ell^-$
  - ✓ $T>T_c$ partonic, $T<T_c$ hadronic sources
  - ✓ drop of inverse slope of $m_T$ spectra
    (based on soft EoS above $T_c$)

Signals of chiral symmetry restoration

- $\rho$ spectral function
- Chiral mixing
  - ✓ in-medium properties (indirect probe)
  - $a_1$ ‘visible’ in $\ell^+\ell^-$ channel (direct probe)

Common to both transitions

- Beam energy scan
  (below $\sqrt{s}$ of 20 GeV/u)
- Onset of transitions
- Order of transitions
- Critical point
  (structure in scan; extended $\tau_{FB}$)
Experiments and Results
### Roots of Heavy Ion Physics at the CERN SPS

**Colloquium CERN 60th, H. Specht, 2014**

<table>
<thead>
<tr>
<th>Worksh./Conf.</th>
<th>Accelerators</th>
<th>Physics</th>
<th>Persons/Actions</th>
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<tbody>
<tr>
<td><strong>1974</strong></td>
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<tr>
<td>Columbia</td>
<td>BEVALAC LBL</td>
<td>EoS Compress. Nucl. Matt.; π Condensates</td>
<td>Contract LBL-GSI (Grunder-Bock, Stock)</td>
</tr>
<tr>
<td>(BeV/u Coll. of HI)</td>
<td>(1\textsuperscript{st} beam)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1975 -1978</strong></td>
<td>Start ISR Discuss. (Pugh/Santa Fe')</td>
<td>First ideas on QGP</td>
<td>CERN DG L. van Hove (1977)</td>
</tr>
<tr>
<td>LBL and GSI</td>
<td></td>
<td>Cabibbo/Parisi 1975</td>
<td></td>
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<tr>
<td>(alternating)</td>
<td></td>
<td>Dileptons in pp</td>
<td></td>
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<tr>
<td><strong>1979</strong></td>
<td></td>
<td>αα collisions ISR</td>
<td>M. Jacob, B. Willis et al.</td>
</tr>
<tr>
<td>Pre QM LBL</td>
<td>VENUS Prop. LBL</td>
<td></td>
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<tr>
<td>SIS100 Prop. GSI</td>
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<tr>
<td><strong>1980</strong></td>
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<tr>
<td>'I QM' GSI</td>
<td>SIS12/100 Prop. GSI</td>
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<tr>
<td><strong>1981</strong></td>
<td>Start SPS Discussion</td>
<td></td>
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<tr>
<td>BNL (ISABELLE)</td>
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<td></td>
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<tr>
<td><strong>1982</strong></td>
<td></td>
<td></td>
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<tr>
<td>II QM Bielefeld</td>
<td>ISR to be stopped</td>
<td></td>
<td>PS Prop. Stock et al. (\textsuperscript{16}O ECR ion source)</td>
</tr>
<tr>
<td>(M. Jacob/H. Satz)</td>
<td>(CERN Council)</td>
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<tr>
<td><strong>1983</strong></td>
<td></td>
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<tr>
<td>III QM BNL</td>
<td>ISR last run</td>
<td></td>
<td>SPS LoI Willis et al.</td>
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<tr>
<td><strong>1984</strong></td>
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<tr>
<td>IV QM Helsinki</td>
<td>SPS-CERN firm</td>
<td></td>
<td>Contract CERN/GSI/LBL</td>
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<td></td>
<td>AGS-BNL firm</td>
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<td></td>
<td>SIS18-GSI firm</td>
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<td>Approval of 1\textsuperscript{st} Gen. Experiments at SPS</td>
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</tbody>
</table>
The 1970’s: dilepton experiments in pp and theoretical ideas

Lepton pair data in the IMR
Christenson et al., PRL 1970

BNL data

Drell/Yan, PRL 1970
hard production from valence and sea quarks

Lepton pair data in the LMR
Anderson et al., PRL 1976
(Summary HJS, QM1984)

FNAL data

Bjorken/Weisberg, PRD 1976
dileptons from produced (‘wee’) partons
> Drell-Yan by factors of 10-100

Lepton pair data in the IMR
Branson et al., PRL 1977

E.Shuryak, PLB 1978
thermal dileptons from ‘Quark Gluon Plasma’

Problematic data, but milestones in theoretical interpretation

First theory paper on ‘Quark Matter’ (T-\(\mu_B\) plane): M.Cabibbo/G.Parisi PLB 1975
Dilepton experiments at the CERN SPS

first generation
1984 – 1987
HELIOS/NA34-2
NA38

second generation
1988 – 2000
CERES/NA45
HELIOS/NA34-3
NA38/NA50

third generation
2002 – 2004
NA60
First-generation Experiments (‘Recuperation Era’)  

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Description</th>
<th>Approval Date</th>
</tr>
</thead>
</table>
| NA34-2     | $4\pi$ calorim., Si, hadron spectrom., dimuons, $\gamma$’s  
(U-scint.cal. + Nal R807/808, **NA3** spectrom.,…) | 11/1984 |
| NA35       | streamer chamber, mid-rapidity calorim.,…  
(NA5 str.ch.+cal., magn. WA78, NA24 $\gamma$ PPD,) | 11/1984 |
| NA36       | TPC, calorim., $\rightarrow$ strange mesons, hyperons  
(EHS+new TPC,) | 11/1984 |
| NA38       | dimuon spectrom., $\rightarrow$ thermal radiation, charmonia  
(NA10+active target + EM cal.,…) | 09/1985 |
| WA80       | plastic ball, EM calorimeters, multiplicity detect.  
(plastic ball GSI/LBL, Pb-glass,) | 09/1985 |
| WA85/      | $\Omega'$ spectrometer, $\rightarrow$ strange mesons, hyperons  
($\Omega'$ spectrometer + RICH) | 04/1987 |
$1^{\text{st}}$ and $2^{\text{nd}}$ generation Experiments 1984-2000 (LMR)

NA34-1 (1984)
N.McCubbin

pBe collisions $e^+e^-, \mu^+\mu^-, e\mu, \gamma$

2 years after the first O beam 1986

NA34-2 (1984)
H.Specht

AA collisions $(\mu^+\mu^-), \gamma$ hadrons

NA45 (1989), $e^+e^-$
H.Specht

NA34-3 (1989), $\mu^+\mu^-$
G.London

NA44 (1989), hadrons
H.Bøggild

Hans J. Specht, Trento, ECT* 2015
Example of results from NA34-1: ‘anomalous’ dileptons

\[ \eta \rightarrow \mu^+\mu^- \gamma \]

\rightarrow underestimate of \eta-Dalitz in all previous experiments (but not in pp at the ISR)

no LMR excess in p-Be within errors

\rightarrow no ‘anomalous’ dileptons in low-energy p-Be (pp-like)


much reduced set-up compared to NA34-2

restricted to \( e^+e^-, \mu^+\mu^-, e\mu, \gamma \)

\eta-Dalitz determined by \( \eta \rightarrow \mu^+\mu^- \gamma \)
Dedicated di-electron spectrometer: CERES/NA45

focused on Low Mass Region (LMR)

Running periods:
- 1992-1993 $^{32}$S and proton beams
- 1995-1996 $^{208}$Pb beams

Cherenkov rings

Original set-up ($p$ and $^{32}$S):
- puristic hadron-blind tracking with 2 RICH detectors

Later addition ($^{208}$Pb):
- 2 SiDC detectors + pad (multi-wire) chamber

Low field (air coils), limited tracking $\rightarrow$ limited resolution
slow detectors, no trigger $\rightarrow$ very limited statistics

Cherenkov rings in RICH1
CERES setup 1994
CERES/NA45 results for S-Au

Data: QM'95; Phys.Rev.Lett.75 (1995)1272

\[ \pi^+\pi^- \to \rho \]

without in-medium effects

\[ \pi^+\pi^- \to \rho^* \to e^+e^- \], but in-medium effects required

strong excess of dileptons above meson decays

enormous boost to theory: 534 citations, most cited SPS paper (orig.data)

surviving interpretation: \( \pi^+\pi^- \to \rho^* \to e^+e^- \), but in-medium effects required

lasting ambiguity (10 a): mass shift and broadening indistinguishable

Hans J. Specht, Trento, ECT* 2015
Resolution and statistical accuracy improved, but mass shift and broadening still indistinguishable

CERES/NA45: Summary of the Pb-beam results


Combined 1995/96 data

C. Voigt and B. Lenkeit

PhD theses C. Voigt and B. Lenkeit
Upgraded CERES setup including a TPC (1999)

First run at 40AGeV → only dilepton data at low beam energies so far

Set-up 1999 (spokesperson J. Stachel)

- Addition of TPC with radial drift
  - slightly improved mass resolution
  - $dE/dx \rightarrow$ hadron identification
    improved electron ID

Runs in 1999/2000 at 40/158 AGeV

Enhancement relative to hadron decays:
$5.9\pm1.5\text{(stat.)}\pm1.2\text{(syst.)}$

Higher baryon density at lower energy (40 AGeV) → increased enhancement
Improved mass resolution (4% vs. 6.5%) → ω and φ well separated

“… between the ω and φ, the data clearly favor the broadening scenario…”
1st and 2nd generation Experiments 1985-2000 (IMR)

NA34-3 (1989)
G. London

- Full mass range
- Only S-beam

NA38 (1985)
L. Kluberg

- Dual goal:
- Charmonia
- Hard dimuon continua

NA50 (1992)
L. Kluberg
HELIOS/NA34-3 diumuon results for S-W


Excess dileptons in LMR and IMR relative to p-W, but LMR not really explored (resolution, forward y,...)

‘First’ clear sign of new physics in IMR

Excess in IMR relative to known sources vectors mesons, open charm and Drell-Yan quantified

Quantitative theoretical description of IMR excess by Lee and Gale, PRL 81 (1998) 1572. Leading source found to be $\pi a_1(4\pi) \rightarrow \mu^+\mu^-$ via chiral (V-A) mixing

QGP formation not considered

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Early NA38 and NA50 results compared


Clear enhancement above the known sources (Drell-Yan and open charm), rising from 1.3 in S-U to 2 in Pb-Pb
Final NA50 dimuon results for Pb-Pb

L. Capelli et al., QM2001, Nucl. Phys. A 698 (2002); final publ. draft on NA50 web page

Thermal radiation ($T_i=190$ MeV)

Rapp and Shuryak, PLB 473 (2000) 13

Enhanced open charm production

Ambiguity between thermal radiation and enhanced open charm ($D\bar{D}$)
New State of Matter created at CERN

At a special seminar on 10 February, spokespersons from the experiments on CERN’s Heavy ion programme presented compelling evidence for the existence of a new state of matter in which quarks, instead of being bound up into more complex particles such as protons and neutrons, are liberated to roam freely.

Theory predicts that this state must have existed at about 10 microseconds after the Big Bang, before the formation of matter as we know it today, but until now it had not been confirmed experimentally. Our understanding of how the universe was created, which was previously unverified theory for any point in time before the formation of ordinary atomic nuclei, about three minutes after the Big Bang, has with these results now been experimentally tested back to a point only a few microseconds after the Big Bang.

Professor Luciano Maiani, CERN Director General, said “The combined data coming from the seven experiments on CERN’s Heavy ion programme have given a clear picture of a new state of matter. This result verifies an important prediction of the present theory of fundamental forces between quarks. It is also an important step forward in the understanding of the early evolution of the universe. We now have evidence of a new state of matter where quarks and gluons are not confined. There is still an entirely new territory to be explored concerning the physical properties of quark-gluon matter. The challenge now passes to the Relativistic Heavy Ion Collider at the Brookhaven National Laboratory and later to CERN’s Large Hadron Collider.”

The aim of CERN’s Heavy Ion programme was to collide lead ions so as to create, immensely high energy densities which would break down the forces which confined quarks inside more complex particles. A very high energy beam of lead ions (33 TeV) was accelerated in CERN’s Super Proton Synchrotron (SPS) and crashed into targets inside the seven different experimental detectors. The collisions created temperatures over 100 000 times as hot as the centre of the sun, and energy densities twenty times that of ordinary nuclear matter, densities which have never before been reached in laboratory experiments. The collected data from the experiments gives compelling evidence that a new state of matter has been created. This state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma, the primordial soup in which quarks and gluons existed before they clumped together as the universe cooled down.

The lead beam programme started in 1994, after the CERN accelerators had been upgraded by a collaboration between CERN and institutes in the Czech Republic, France, India, Italy, Germany, Sweden and Switzerland. A new lead ion source was linked to pre-existing, interconnected accelerators, at CERN, the Proton Synchrotron (PS) and the SPS. The seven large experiments involved measured different aspects of lead-lead and lead-gold collisions. They were named NA44, NA45, NA49, NA50, NA52, WA97/NA57 and WA98. Some of these experiments use multipurpose detectors to measure

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Preparatory Workshop Chamonix 1998

Press Conference CERN, 10 Feb. 2000

CERN DG L. Maiani

 Talks by all experiments

Paper PR01 U. Heinz and M. Jacob

‘White Paper’- U. Heinz and M. Jacob

CERN Courier, April 2000
"It walks like a duck, it quacks like a duck, . . .":

which more than 99.9% are hadrons. Evidence for or against formation of an initial state of deconfined quarks and gluons at the SPS thus must be extracted from a careful and quantitative analysis of the observed final state.

A common assessment of the collected data leads us to conclude that we now have compelling evidence that a new state of matter has indeed been created, at energy densities which had never been reached over appreciable volumes in laboratory experiments before and which exceed by more than a factor 20 that of normal nuclear matter. The new state of matter found in heavy ion collisions at the SPS features many of the characteristics of the theoretically predicted quark-gluon plasma.

. . .

has disappeared. It is expected that the present “proof by circumstantial evidence” for the existence of a quark-gluon plasma in high energy heavy ion collisions will be further substantiated by more direct measurements (e.g. electromagnetic signals which are emitted directly from the quarks in the QGP) which will become possible at the much higher collision energies and fireball temperatures provided by RHIC at Brookhaven and later the LHC at CERN.
3rd generation Experiment: Dimuons in NA60
(basic idea P. Sonderegger, exp. approved 2000, spokespersons C. Lourenço, later G. Usai)

Track matching in coordinate and momentum space
- Improved dimuon mass resolution
- Distinguish prompt from decay dimuons
- Additional bend by the dipole field
- Dimuon coverage extended to low $p_T$
- Radiation-hard silicon pixel detectors (LHC development)
- High luminosity of dimuon experiments maintained
In-In 158 GeV/u: NA60 2003 data and major analysis steps


EPJ C 59 (2009) 607

subtraction of combinatorial background and fake matches 
$\sim 10^6$ net, $10^8$ triggers, $10^{12}$ int.

subtraction of measured decay cocktail with accuracy of 2-3% 
$\rightarrow$ isolation of the LMR excess

IMR: subtraction of Drell-Yan and measured open charm
(by displaced decay vertices)

Final step: acceptance correction
reduce 4-dimensional acceptance correction in $M-p_T-y$-$\cos\Theta_{CS}$ to (mostly) 2-dim corrections in pairs of variables, separate for the excess and all other sources

Hans J. Specht, Trento, ECT* 2015
Thermal dimuon mass spectrum: proof of deconfinement

all physics background sources subtr.
integrated over $p_T$
fully corrected for acceptance
absolutely normalized to $dN_{ch}/\eta$
effective statistics highest of all experiments, past and present
(by a factor of nearly 1000)

$M<1$ GeV
$\rho$ dominates, ‘melts’ close to $T_c$ (sl.35)

$M>1$ 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

Perfect agreement in absolute terms
Rapp: ‘spectrum directly reflects thermal emission rate’

chronometer
fireball life-time 6.5±1 fm

no baryons
broadening of the ρ dominated by baryon interactions
Update of the v.Hees/Rapp description of the NA60 data


First-Order EoS + HTL Rate

**R.Rapp, FAIR Workshop, Worms (2014)**

Lattice EoS + Lat-QGP Rate

Various changes, including an increase of $T_i$ from 190 to 235 MeV, strongly affect the partition QGP/HG

→ IMR now properly described
→ LMR spectral shape robust
Theoretical description of LMR by Endres et al.


Basis: Coarse-graining approach plus UrQMD transport model

ρ spectral function a la Rapp/Wambach
perfect agreement in absolute terms

partonic emission dominant for $M > 1.5$ GeV

decofinement at SPS energies now well described by four independent groups
Towards chiral restoration: mass shift vs. broadening


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**NA60 acceptance compensates for the phase space factors of thermal radiation: flat spectral function in $\rightarrow$ flat spectrum out (by pure chance)**

- Only broadening of $\rho$ observed, no mass shift $\rightarrow$ ‘hadrons melt’

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**On chiral restoration and $\rho$ melting: P.M.Hohler and R. Rapp, PLB 731 (2014) 103**

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Hans J. Specht, Trento, ECT* 2015
The other variable of dileptons: $p_T$ spectra – ’Barometer’

transverse mass: $m_T = (p_T^2 + M^2)^{1/2}$


all $m_T$ spectra exponential for $m_T$-$M > 0.1$ GeV; $< 0.1$ GeV

fit with $1/m_T \, dN/m_T \sim \exp(-m_T/T_{\text{eff}})$; $T_{\text{eff}}$ – ‘effective temperature’
The rise and fall of radial flow of thermal dimuons

Initial linear rise of $T_{\text{eff}}$ with $M$

two components in $m_T$ spectra: thermal and radial collective
(‘Hubble’) expansion

$T_{\text{eff}} \sim T_f + M \langle v_T \rangle^2 \quad v_T \sim 0.5c$

Rise up to 1 GeV consistent with radial flow of a hadronic source
(here $\pi^+\pi^- \rightarrow \rho \rightarrow \mu^+\mu^-$)

Drop at 1 GeV signals sudden transition to a low-flow, i.e. an early source $\rightarrow$ partonic origin
(here $q\bar{q} \rightarrow \mu^+\mu^-$)

Dominance of partons for $M>1$ GeV also from $p_T$ spectra
Combined conclusions from mass and $p_T/m_T$ spectra

**Lattice QCD:**
- Rapid rise of energy density $\varepsilon$, slow rise of pressure $p$ (far from ideal gas)

**EoS above $T_c$ very soft initially ($c_S$ minimal)

**M >1 GeV: parton-dominated**
- $T_{eff}$ independent of mass within errors

**mass spectrum:**
- $T = 205\pm12$ MeV
- $<T_{eff}> = 190\pm12$ MeV

- Same values within errors

Negligible flow $\rightarrow$ soft EoS above $T_c$
Centrality dependences: the ‘$\rho$ clock’

Comprehensive results on the centrality dependence of all acceptance-corrected mass and $p_T/m_T$ spectra and their correlations

Specific example: shape of the $\rho$ spectral function (data before acc. corr.)


rapid initial increase of relative yield; reflects the number of $\rho$ regenerated in $\pi^+\pi^-\rightarrow\rho^*\rightarrow\mu^+\mu^-$

→ ‘$\rho$ clock’

monotonic increase of the width, approaching that of a flat distribution

→ ‘melting’ of the $\rho$
Angular distributions

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta \ d\phi} = \left( 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right)
\]

\(\lambda, \mu, \nu\): structure functions related to helicity structure functions and the spin density matrix elements of the virtual photon

Choice of reference frame: Collins-Soper (CS)

In rest frame of virtual photon:

\(\theta\): angle between the positive muon \(p_{\mu^+}\) and the z-axis.

z axis: bisector between \(p_{\text{proj}}\) and \(-p_{\text{target}}\)

Expectation: completely random orientation of annihilating particles (pions or quarks) in 3 dimensions would lead to \(\lambda, \mu, \nu = 0\)
Results on structure coefficients $\lambda$, $\mu$, $\nu$

*Phys. Rev. Lett. 102 (2009) 222301*

$\lambda = -0.13 \pm 0.12$

$\mu = 0.05 \pm 0.03$ (~0 as expected)

set $\mu = 0$ and fit projections

fit function for polar angle

$$\frac{dN}{d |\cos \theta|} \propto \left(1 + \lambda \cos^2 \theta \right)$$

fit function for azimuth angle

$$\frac{dN}{d |\phi|} \propto \left(1 + \frac{1}{3} \lambda + \frac{\nu}{3} \cos 2\phi \right)$$

Zero polarization within errors

example:

excess $0.6 < M < 0.9$ GeV

Hans J. Specht, Trento, ECT* 2015
Outlook: the present world scene and beyond

The high energy frontier
- RHIC  PHENIX, STAR
- LHC  ALICE

The low energy frontier
- RHIC BES  STAR
- SPS  NA60+
- (SIS300  CBM)
- SIS100  CBM, HADES
- NICA  MPD

‘Interaction’ Rate [Hz]

- $10^7$  NA60+
- $10^6$  CBM
- $10^5$  ALICE Run3
- $10^4$  NICA MPD
- $10^3$  STAR

As important: ratio Signal/(Combinatorial Background) $S/B \sim 1/(20-1000)$

effective signal size: $S_{eff} \sim IR \times S/B$  reduction by 20-1000 !
Present Physics Conclusions from Dileptons

Planck-like exponential mass spectra, exponential $m_T$ spectra, zero polarization and general agreement with thermal models consistent with interpretation of excess dimuons as thermal radiation.

Emission sources of thermal dileptons mostly hadronic ($\pi^+\pi^-$ annihilation) for $M<1$ GeV, and mostly partonic ($q\bar{q}$ annihilation) for $M>1$ GeV; associated temperatures quantified; hints at soft EoS close to $T_c$: proof for deconfinement already at SPS energies.

In-medium $\rho$ spectral function identified; no significant mass shift of the intermediate $\rho$, only broadening; (indirect) proof for chiral symmetry restoration.

Future: much more emphasis to be placed on running at energies optimal for the study of the QCD phase transitions and high baryon densities. Most suitable machine SPS, complemented by SIS100.
The NA60 experiment

LMR results in pp at ISR energies

the only LMR excess ever established in pp; multiplicity dependence almost quadratic

Challenge for the future

unification of dilepton excess with ‘soft photons’:


Hans J. Specht, Trento, ECT* 2015
CERES/NA45: low-mass dielectrons in pA


p-Be and p-Au data well described in terms of known hadronic sources
SPS Proposals NA34-1, NA34-2 and NA34-3 (HELIOS)

**NA34-1**

**NA34-2**

**NA34-3**

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**Abstract**

We propose to examine in detail the characteristics of ultra-relativistic nucleus-nucleus interactions using the beams of 200 GeV/v of the SPS. The experiment combines a calorimeter coverage with measurements of inclusive particle spectra, two-particle correlations, low- and high-energy jet hadron and photons. A multi-namer active target allows maximum interaction rates with a minimum of secondary interactions.

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*Permanent address: Saclay, France*
PROPOSAL

STUDY OF ELECTRON PAIR PRODUCTION IN
HADRON AND NUCLEAR COLLISIONS AT THE CERN SPS

U. Faschingbauer, M.G. Trauth, J.P. Wurm
Max-Planck-Institut für Kernphysik, Heidelberg, Germany

A. Drees, P. Fischer, P. Glässel, M. Gackes, D. Irmscher, L.H. Olsen, A. Pfeiffer,
H. Ries, A. Schön, H. Sickmüller, H.J. Specht (Spokesman), T.S. Ulrich
Physikalisches Institut, Universität Heidelberg, Germany

E. F. Barash, A. Breskin, R. Chechik, Z. Frenkel,
D. Sauvage, V. Steiner, I. Tseruya
Weizmann Institute of Science, Rehovot, Israel

(Other groups are expected to join later)

Abstract

We propose to measure $e^+e^-$ pairs produced in hadron and nuclear collisions at
SPS energies. The goal is to systematically study the pair continuum in the mass
region from 100 MeV/$c^2$ to beyond 3 GeV/$c^2$ and the vector mesons $\rho/\omega$ and $\phi$. The
experimental set-up is centered around a novel magnetic spectrometer, based solely on
ring-image Cherenkov techniques. The apparatus also allows a high-statistics study of
real photons and high-$p_T$ pions.
SPS Proposals NA38 and NA50

**NA38**

**EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH**

CERN LIBRARIES, GENEVA

CM-P00044680

PROPOSAL

**STUDY OF HIGH-ENERGY NUCLEUS-NUCLEUS INTERACTIONS**

WITH THE ENLARGED NA60 DINGUO SPECTROMETER

Bergen¹-Bordeaux²-CERN³-Clermont-Ferrand⁴-
Ecole Polytechnique-Lisbon⁵-Lyon⁶-Meudon⁷-Orsay⁸-
Strasbourg⁹-Valencia¹¹ Collaboration


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2 Centre d’Etudes Nucléaires, Univ. de Bordeaux I, Gradignan, France.
3 CERN, Geneva, Switzerland.
4 Lab. de Physique Corpusculaire, Université de Clermont-Ferrand, France.
5 LPNHE, Ecole Polytechnique, Palaiseau, France.
6 INT, Instituto Nacional de Investigaciones Científicas, Lisbon, Portugal.
7 Inst. de Physique Nucléaire, Université de Lyon, Villeurbanne, France.
8 Inst. de Physique Nucléaire, Université de Neuchâtel, Neuchâtel, Switzerland.
9 Centre de Recherches Nucléaires and Université Louis Pasteur, Strasbourg, France.
10 Facultad de Ciencias (IFC), Burjassot, Valencia, Spain.
11 At present Fellow at CERN, Geneva, Switzerland.

**NA50**

**PROPOSAL**

**STUDY OF MUON PAIRS AND VECTOR MESONS PRODUCED IN HIGH ENERGY Pb-Pb INTERACTIONS**

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**Speaker : L. Kluberg**

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Note: Discussions are under way with the Institute of Atomic Physics, Bucharest, Romania, in view of a collaboration on this Proposal.
Electromagnetic Transition Form Factors of the $\eta$ and $\omega$ Dalitz decays
Electromagnetic Transition Form Factors

The high quality of the peripheral $\text{In-In}$ data offers the possibility to measure, with a much higher accuracy than before, the transition form factors of $\eta \rightarrow \mu^+ \mu^- \gamma$ and $\omega \rightarrow \mu^+ \mu^- \pi^0$.

Probability of formation of a lepton pair with mass $m_{\mu^+ \mu^-}$ in a Dalitz decay strongly modified by the dynamic electromagnetic structure arising at the vertex of the transition $A \rightarrow B$. Formal description by $|F_{AB}(m_{\mu \mu}^2)|^2$.

$$\frac{dN(A \rightarrow B\mu^+ \mu^-)}{dm_{\mu \mu}^2} = [\text{QED}(m_{\mu \mu}^2)] \times |F_{AB}(m_{\mu \mu}^2)|^2$$

By comparing the measured spectrum of lepton pairs in decay $A \rightarrow B \mu^+ \mu^-$ with a QED calculation for point-like particles it is possible to determine experimentally the transition form factors $|F_{AB}|^2$. 
Isolating the Dalitz region in the peripheral data


Subtraction of:
- $\eta$, $\omega$, $\phi$ resonance decays
- $\eta'$ Dalitz decay ($\eta'/\eta=0.12$)
- Uncorr. $\mu^+\mu^-$ from DDbar

(Both nearly negligible; \(\chi^2/\text{ndf} \approx 1\), globally and locally)

Correct for acceptance

Fit remaining sources $\eta$, $\omega$ and $\rho$;

Anomaly of $\omega$ form factor directly visible in the spectrum
Final results on form factors


Perfect agreement of NA60 and Lepton G, confirming \(\omega\) anomaly

Large improvement in accuracy; for \(\omega\), deviation from VMD \(\sim 10\sigma\)
NA60 results in the new edition of the PDG

First result from a heavy-ion experiment in the PDG ever