Lepton-pair production in nuclear collisions - past, present, future

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Abstract

The key results on lepton-pair production in ultra-relativistic nuclear collisions are shortly reviewed, starting at the roots of $pp$ collisions in the seventies, and ending at the perspectives of the colliders RHIC and LHC. The presence is dominated by the recent precision results from NA60 at the CERN SPS, culminating in the first measurement of the in-medium $\rho$ spectral function and the transverse flow of the associated thermal radiation. The seeming cut-off of the flow above the $\rho$ may well be the first direct hint for thermal radiation of partonic origin in nuclear collisions. The major milestones in the theoretical developments are also covered.

Key words: Relativistic heavy-ion collisions, Quark-gluon plasma, Lepton Pairs

PACS: 25.75.-q, 12.38.Mh, 13.85.Qk

1. The past: from $pp$ to the first results in $AA$ collisions

The interest in continuum lepton-pair production in high-energy collisions dates back to the seventies, triggered by the detection of the Drell-Yan process $^1$ and the $J/\psi$. The latter, in particular, sharpened the attention to anything which might still have escaped detection, and a flood of new experimental findings on lepton pairs appeared, both for low masses (LMR, $M<1$ GeV) and for intermediate masses (IMR, $1<M<2.5$ GeV). The results were usually compared to expectations from an “hadron-decay cocktail”, containing all contributions known at that time. An excess of single leptons and lepton pairs above the known sources was indeed found, coined “anomalous” pairs, and created great excitement. A review of the situation in the LMR region as of 1984 is contained in $^2$. Unfortunately, the results did not survive critical reassessment in later years, and they were finally recognized by Helios-1 $^3$ and, with higher precision, by CERES $^4$ as due to a severe underestimate of the contribution from $\eta$ Dalitz decays. Only one result, obtained at the ISR at $\sqrt{s}=63$ GeV $^5$, survived as non-trivial up to today. In the IMR
region, some excess-pair production was also suspected for a long time, due to insufficient knowledge of the contribution from open charm decays on top of Drell-Yan. Any significant anomaly in this region was only ruled out much later, see e.g. [6].

Ironically, these dubious \( pp \) results led already in the late seventies to two seminal theoretical papers, which had an enormous influence on the nascent field of high-energy \( AA \) collisions. Bjorken and Weisberg [7] were the first to propose partons \( \text{produced} \) in the collision to be a potential further source of continuum lepton pairs, beyond the intrinsic partons in the collision partners responsible for Drell-Yan; they estimated the resulting excess above the latter to be a factor of 10-100 in the LMR region. Shuryak [8] proposed the production of deconfined partons in thermal equilibrium during the collision and phrased the terms “Quark Gluon Plasma” for the created medium and “Thermal Radiation” for the emitted lepton pairs in the IMR region [9].

The first systematic discussion, including both particle and nuclear physicist, on the experimental and theoretical aspect of QGP formation in ultra-relativistic nuclear collisions took place at the Quark Matter Conference 1982 in Bielefeld [10]. The basic instrumental elements of the first-generation experiments at the CERN SPS as well as the basic theoretical ideas on all observables were addressed. The principal conclusions for lepton pairs were as follows. (i) The physics of dileptons (virtual photons) may be both more rich and more rigorous than that of real photons, due to the existence of two independent variables instead of one (\( M, p_T \) vs. \( p_T \)), and due to the simpler lowest-order rates (\( \propto \alpha^2 \text{em} \) vs. \( \alpha \text{em} \cdot \alpha_s \)). (ii) Thermal dilepton production in the LMR region may be dominantly hadronic, mediated by the broad vector meson \( \rho \) (770) in the form \( \pi^+\pi^- \rightarrow \rho \rightarrow l^+l^- \); due to its short lifetime of only 1.3 fm, the observation of a “melting” (broadening) and/or mass shift may serve as a prime probe of \( \text{chiral symmetry restoration} \) [11]. (iii) Thermal dilepton production in the IMR region may be dominantly partonic, mediated in the form \( q\bar{q} \rightarrow l^+l^- \), and may serve as a prime probe of \( \text{deconfinement} \) (the idea of \( J/\psi \) suppression was not yet born). Classical theoretical papers on continuum lepton pairs with a broad view appeared soon after [12,13].

The first generation of SPS experiments sensitive to continuum lepton pairs, Helios-2 and NA38, found one anomaly [6], but did not follow up its significance at that time. Only in the next generation, with CERES, Helios-3 and NA50, clear signs of new physics appeared in a broader way, 13 years or more after the Bielefeld workshop. The experimental results from CERES for S-Au [14] in the LMR region are shown in Fig. 1 (left). A large excess of pairs above the known hadron decays is seen. This gave an enormous boost to theory, with hundreds of publications. A small fraction of those, relying on \( \rho \) production without in-medium effects, is contained in the figure. The pole region is enhanced because of regeneration via \( \pi^+\pi^- \rightarrow \rho \) during the fireball expansion, but the bulk of the excess residing below the pole is not at all described. Only switching-on in-medium effects, e.g. mass shifts, based on a direct connection to the restoration of chiral symmetry [15], or broadening, based on a hadronic many-body approach [16], leads to a satisfactory description, while not discriminating between the two. This ambivalent situation also persisted into the Pb-beam era, as illustrated in Fig. 1 (right) for the CERES 1995/96 data [17] (and still valid for the 2000 data [18]): the main two scenarios [19,20] fit the data equally well, and the true in-medium properties of the \( \rho \) could unfortunately not be clarified, due to insufficient data quality.

The excess of pairs observed by Helios-3 [21] for S-W with respect to p-W is shown in Fig. 2 (left). It is seen here to also occur in the IMR region, not only at low masses, and
led to a further important theoretical step: the recognition of the role of chiral (V-A) mixing with possibly sizable contributions from \( \pi\alpha_1 \) processes \[22\]. A strong excess of pairs was finally also reported by NA50 \[23\], Fig. 2 (right), attributed at that time to either enhanced charm production or thermal radiation. The former was never followed up theoretically, while the latter received a quantitative description in terms of hadron-parton duality, not explicitly specifying the sources \[24\] (see plot). Experimentally, the role of open charm and the nature of the thermal sources dominating the IMR region remained open.

2. The present: results from NA60 at the CERN SPS

NA60 is a third-generation experiment, built specifically to follow up the open issues addressed in the previous section. It combines the muon spectrometer previously used by NA50 with a novel radiation-hard silicon pixel vertex tracker, embedded in a 2.5 T...
dipole magnet in the target region [25]. Track matching between the two spectrometers, both in coordinate and momentum space, improves the dimuon mass resolution by a factor of 4 relative to NA50 and allows to distinguish prompt from decay dimuons, while the radiation hardness of the Si tracker together with a very high readout speed allow to maintain the high luminosity of common dimuon experiments. The enormous jump in technology is responsible for the corresponding jump in data quality now achieved by NA60.

Fig. 3. Dilepton invariant mass spectra [26,27]. Right: isolation of the excess (triangles, see text).

The results reported here were obtained from the analysis of data taken in 2003 for In-In at 158 AGeV. Fig. 3 (left) illustrates the data sample obtained in the LMR region [26,27,28]. After subtracting the combinatorial background, determined by event mixing, and the signal fake matches between the tracks of the two spectrometers, determined by overlay MC, the resulting net spectrum contains about 440 000 muon pairs. The vector mesons ω and φ are completely resolved; the mass resolution at the ω is 20 MeV. The improvements over CERES are a factor of >1000 in statistics and a factor of 2-5 in mass resolution. The centrality of the events is tagged by determining the associated charged-particle multiplicity density dN_{ch}/dη from the tracks of the Si telescope. The peripheral data (4-30) can essentially be described by the expected electromagnetic decays of the neutral mesons, i.e. the 2-body decays of the η, ρ, ω and φ resonances and the Dalitz decays of the η, η' and ω [26,27]. This is not true for the total data as plotted in Fig. 3 (right), due to the existence of a strong excess of pairs. To isolate this excess with a priori unknown characteristics without any fits, the cocktail of the decay sources is subtracted from the total data using local criteria, which are solely based on the mass distribution itself. The ρ is not subtracted. The excess resulting from this difference formation is illustrated in the same figure. In practice, the procedure is done separately for each centrality window and, in connection with the p_{T}-spectra, for each p_{T} bin (see [26,27,28] for details and error discussion).

The evolution of the spectral shape of the excess vs. centrality [26,27,28] is most remarkable: a peaked structure is always seen, residing on a broad continuum with a yield strongly increasing with centrality, but remaining essentially centered around the position of the nominal ρ pole. These qualitative features are consistent with an interpre-
tation of the excess as dominantly due to $\pi^+\pi^-$ annihilation. Fig. 4 shows the data for
$110<dN_{ch}/d\eta<170$ in comparison to the two main theoretical scenarios discussed before:
broadening of the $\rho$ (Rapp/Wambach [19]), and dropping mass of the $\rho$ (Brown/Rho [20]),
both evaluated for In-In at $dN_{ch}/d\eta=140$ for the same fireball evolution [29]. Since agree-

![Fig. 4. Comparison of the NA60 excess data to theoretical model results [26] (see text).](image)

ment between modeling and data would imply agreement both in shape and yield, the
model results are normalized to the data in the mass interval $M<0.9$ GeV, just to be
independent of the uncertainties of the fireball evolution. The unmodified $\rho$, also shown
in Fig. 4 (Vacuum $\rho$), is clearly ruled out. The dropping-mass scenario is also ruled out,
showing the much improved discrimination power of NA60. The broadening scenario, on
the other hand, fits perfectly well for $M<0.9$ GeV. It is important to note that the data
as shown have not been corrected for the mass- and $p_T$-dependent acceptance of the
NA60 setup, requiring the model results to be propagated through the acceptance filter
for fair comparison to the data. By pure coincidence, as long as no $p_T$ cut is applied, that
filtering nearly compensates for all the phase space factors associated with the thermal
dilepton radiation, and just leaves a mass spectrum equivalent to the spectral function
of the $\rho$, averaged over momenta and the complete space-time evolution of the fireball,
within an accuracy of about 10% [27]. The flat part of the measured spectrum may thus
reflect the early history close to the QCD phase boundary, while the narrow peak on top
may be due to the late part close to thermal freeze-out.

By now, several new sets of model descriptions have appeared [30,31,32]. All of them
are based on broadening of the $\rho$, and all of them describe the data reasonably well,
even in absolute terms. The fireball evolution, quite different in these sets, takes explicit
account both of temperature and of baryon density, and the latter seems clearly required
to describe the low-mass tail of the spectral function [30], in accord with conclusions
reached previously by CERES from an increase of the excess at the lower beam energy of
40 AGeV [33]. The mass region $M>0.9$ GeV is now also addressed and again reasonably
well described, in terms of either hadronic processes [30] ($4\pi$...), or partonic processes [31]
($q\bar{q}$), reflecting the traditional ambivalence of hadron-parton duality in the mass domain
in this region.
How could one distinguish? As already emphasized above, lepton pairs are characterized by two variables, \( M \) and \( p_T \). The latter contains not only contributions from the spectral function, but encodes in fact the key properties of the expanding fireball, temperature and transverse (radial) flow. In contrast to hadrons, however, which always receive the full asymptotic flow at the moment of decoupling, lepton pairs are continuously emitted during the evolution, sensing small flow and high temperatures at early times, and increasingly larger flow and smaller temperatures at later times. Potentially therefore, the resulting space-time folding over the temperature-flow history offers access, through the measurement of \( p_T \) spectra, to the emission region of the dileptons and may thus differentiate between a hadronic and a partonic nature of the emitting source [13,34].

\[
0.2 < M < 0.4 \text{ GeV} \\
0.4 < M < 0.6 \text{ GeV} \\
0.6 < M < 0.9 \text{ GeV} \\
0.9 < M < 1.4 \text{ GeV} \\
\phi \\
\omega
\]

Fig. 5. Acceptance-corrected transverse mass spectra of the excess (in four mass windows), the \( \phi \) and the \( \omega \). Left: all centralities [28,35,36]. Right: very peripheral events [36].

\( p_T \)-spectra of the excess radiation in the LMR region, fully corrected for acceptance, have recently become available [28,35,36]. The acceptance correction is done in a fine grid in the \( M-p_T \) plane to be independent of the properties of the source; details can be found in [28,36]. Fig. 5 (left) displays the centrality-integrated data in the form of invariant \( m_T \)-spectra, where \( m_T = (p_T^2 + M^2)^{1/2} \), for four mass windows. At very low \( m_T \), a steepening is observed in all cases, contrary to the expectation for radial flow at masses above the pion mass; the \( \phi \), plotted for comparison, does not show that (while pions themselves do). For very peripheral data, shown in Fig. 5 (right), the phenomenon disappears, and the \( \rho \)-like window and the \( \omega \) become identical. At higher \( m_T \), the spectra monotonically flatten with mass, reminiscent of radial flow, but then steepen again above the \( \rho \); this striking feature will be addressed below.

The central NA60 results for the IMR region [35,37,38] are illustrated in Fig. 6. By measuring the offset between the muon tracks and the main interaction vertex, the contributions to the prompt and to the offset part (from \( D \) decays) can be disentangled. As shown in the left panel, the offset distribution is perfectly consistent with no charm enhancement, expressed by a fraction of 0.9 of the canonical level, while the enhancement seen before by NA50 [23] and now reconfirmed by NA60 has to be solely attributed to the prompt part, expressed by a factor of 2.4 of the Drell-Yan level: a further milestone in experimental results. The right panel contains the decomposition of the total data into
Drell-Yan, open charm and a prompt excess obtained as the difference with respect to the total. The excess part is seen to exhibit the same fall-off vs. mass as charm, steeper than DY. It increases with centrality, and its transverse momentum spectra are also much steeper than DY \[35,37\]. The fit temperatures of the \( m_T \)-spectra associated with 3 mass windows are indicated on the bottom of the figure. There are all indications that this is the thermal radiation addressed already by NA50 as one the options (see Fig. 2, right).

The central information extracted from the \( m_T \) spectra, expressed as the inverse slope parameter \( T_{\text{eff}} \) vs. dimuon mass, is shown in Fig. 7 \[35,38\]. This unifies the data from the LMR and IMR regions, including a common fit range \( (0.4<p_T<1.8 \text{ GeV}) \) and subtraction of charm throughout. The hadron data for \( \eta, \omega \) and \( \phi \) obtained as a by-product of the cocktail subtraction are also plotted. The parameter \( T_{\text{eff}} \) is seen to rise nearly linearly with mass up to the pole position of the \( \rho \), followed by a sudden decline to a rather constant level of 190 MeV above. The excess data along the rise are quite close to the hadron data. However, the peak of the \( \rho \), residing on the broad underlying continuum,
can be interpreted as the freeze-out (vacuum) $\rho$ without in-medium effects \cite{30,31,32} and analyzed separately by a side-window subtraction method, resulting in a value for $T_{\text{eff}}$ of about 300 MeV (also contained in Fig. 7). The observed linear rise of $T_{\text{eff}}$ with mass of the excess can therefore be considered as qualitatively consistent with the expectations for radial flow of an in-medium hadronic source (here $\pi^+\pi^- \rightarrow \rho$) decaying into lepton pairs. The absolute values of $T_{\text{eff}}$ are well below the hadron line defined by the vacuum $\rho$, as expected, and the other hadrons freeze-out earlier, due to their smaller coupling to the pions. It is interesting to note that the large difference of $>50$ MeV in $T_{\text{eff}}$ between the vacuum $\rho$ and the $\omega$ (same mass) quantitatively disappears for the lowest peripheral “pp-like” selection $dN_{\text{ch}}/d\eta<10$, as visible in the right panel of Fig. 5.

The sudden decline of $T_{\text{eff}}$ at masses $>1$ GeV is the other most remarkable feature in Fig. 7. If the rise is due to flow, the sudden transition to a seeming low-flow scenario is hard to reconcile with emission sources which continue to be of dominantly hadronic origin in this region. A more natural explanation would then be a transition to a qualitatively different source, implying dominantly early, i.e. partonic processes like $q\bar{q} \rightarrow \mu^+\mu^-$ for which flow has not yet built up \cite{31}. While still controversial \cite{30}, this may well be the first direct hint for thermal radiation of partonic origin, breaking hadron-parton duality for the yield description in the mass domain.

3. Future: the options

There are altogether four options in sight which will have the chance to advance the field further: at RHIC, LHC, SPS and FAIR. At RHIC, PHENIX is the only experiment capable to measure lepton pairs both in the LMR and the IMR region. First results on electron pairs, showing an excess, have already appeared \cite{39,40}, but proper tools for the rejection of low-mass Dalitz and conversion pairs have not yet been available, and the present data quality is therefore severely limited by S/B ratios of $<1/1000$. A second-generation upgrade at PHENIX will soon become available to cope with rejection, relying on a “hadron-blind-detector” (a RICH) within a field-free region including the interaction vertex \cite{39}; the required magnet geometry, based on a double coil arrangement, was proposed in the course of the CERES R&D \cite{41}. At the LHC, the LMR region is probably unaccessible, due to prohibitive charged particle multiplicity densities, but the (even extended) IMR region is covered both by ALICE and CMS and may lead to exciting new results. On top, both colliders offer an excellent chance for a revisit of pp collisions also in the LMR region, made attractive through record-like Bjorken energy densities. At the SPS, a continuation of NA60 is conceivable, both for Pb-beams and for lower beam energies. The existence proof for success exists; the rest is a (possibly unsurmountable) mixture of elements which are beyond pure science. At FAIR, finally, a multi-purpose detector (CBS) is in an early stage of development, meant to also cover lepton pairs. In all probability, the time horizon is here beyond a decade.

4. Conclusions

Since QM 1982 in Bielefeld, 25 years have passed (a whole generation), and only now initial central issues seem to be clearing up. The first accurate measurement of the $\rho$ spectral function in the hot and dense environment of the QCD phase transition exists,
but a solid theoretical link to chiral restoration is still missing. The first hint for thermal radiation of mostly partonic origin exists, but it surely requires theoretical consolidation. The field takes a long breath indeed...

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