Experimental overview of some dilepton signatures

L. Kluberg

Ecole Polytechnique and IN2P3-CNRS, Palaiseau, France

Thanks to a deeper insight into specific details, the results obtained for various dilepton signatures now reveal new unexpected features which call for "new physics" to be accounted for.

1. Introduction

In the field of ultra-relativistic heavy ion interactions (URHI), prompt dileptons are an ideal experimental tool to look for QGP formation. They probe the early stages of the collision and are only slightly perturbed after production. Experiments are difficult because very specific detectors are needed, cross-sections are usually small and background is often huge. These features imply that devoted experiments with appropriate trigger capabilities are a must to enter the sector.
At CERN, dileptons have been studied by the NA34/Helios and NA38/NA50 experiments using dimuon spectrometers adapted from the old NA3 and NA10 experiments. The CERES experiment, somewhat later, used an especially designed dielectron detector.
After 13 years of experimental work with URHI beams at the CERN SPS and on the eve of the RHIC era, it has to be admitted that the dilepton sector has been a real source of surprising and exciting results, unsuccessfully accounted for by conventional explanations. This talk reminds some of these results which appear today as established experimental facts.

2. "Low" invariant mass dileptons ($\mathbf{M}_{ll} < 1$ GeV/c^2)

2.1. Low mass electron pairs

Low mass electron pairs have been extensively studied by the CERES [1] experiment. As shown in Figs. 1 and 2, the mass spectrum of dielectrons produced in p-Be and p-Au with 450 GeV/c incident momentum protons are fairly well accounted for, in the invariant mass range below 1.5 GeV/c^2, by the "known" expected sources, i.e. the ρ, ω and ϕ resonances together with light meson Dalitz decays. In 158 GeV/c per incident nucleon Pb-Au reactions, a significant enhancement of electron pairs is observed for masses lower than the ρ mass (Fig. 3). The enhancement amounts to $2.6 \pm 0.5 \pm 0.6$ for masses between 0.25 and 0.7 GeV/c^2, with respect to the expected contributions, calculated with experimentally measured particle ratios and kinematical distributions adjusted to Pb-Pb measurements. The observed enhancement exhibits two particularly interesting features. (a) It increases linearly with charged particle multiplicity for all masses up to 0.88 GeV/c^2 except in the pure continuum range [0.25–0.68 GeV/c^2] where the increase is

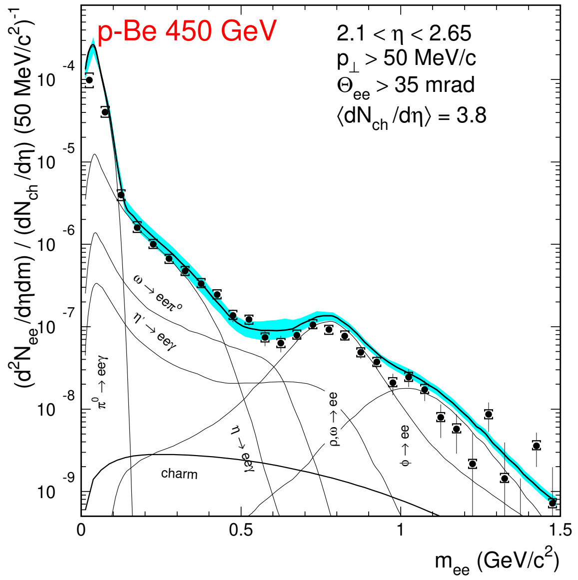

Figure 1. Dielectron invariant mass spectrum for p-Be collisions, superimposed to the expected sources.

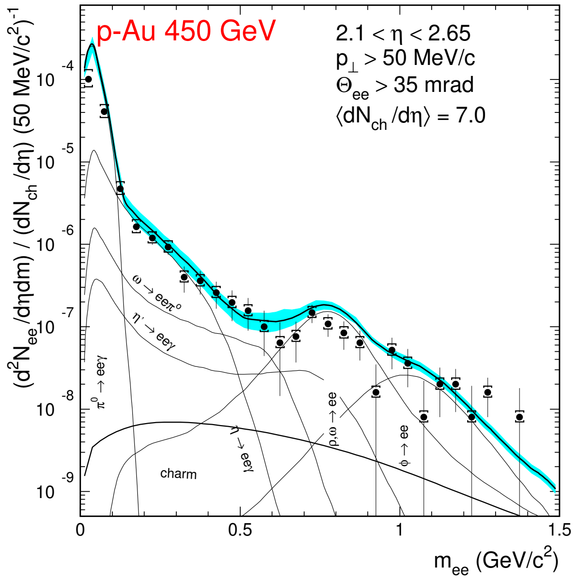

Figure 2. Same as Fig. 1 for p-Au interactions.

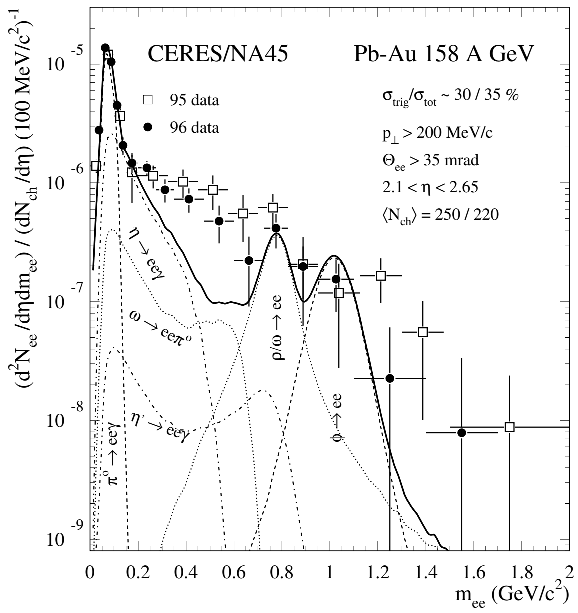

Figure 3. Dielectron invariant mass spectrum for Pb-Au collisions, superimposed to the expected sources.

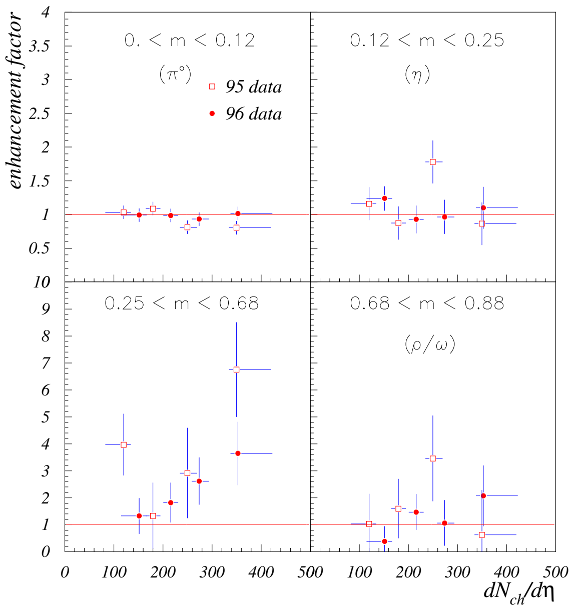

Figure 4. Centrality dependence of the enhancement factor for Pb-Au interactions.

faster than linear for multiplicity densities higher than 150 per unit rapidity (Fig. 4). (b) It is particularly visible for low transverse momentum pairs, i.e. $p_\perp^{ee} < 500$ MeV/c, and significantly weaker for higher values (Figs. 5 and 6). Tests against an experimental bias due to some remaining background contamination have been performed, both by using a "pure background" sample of events to check the background subtraction procedure

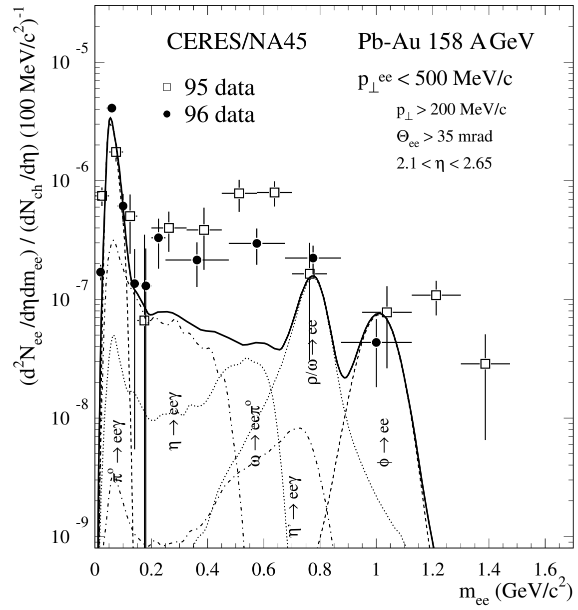

Figure 5. Same as Fig. 3 for electron pairs with transverse momentum lower than 500 MeV/c.

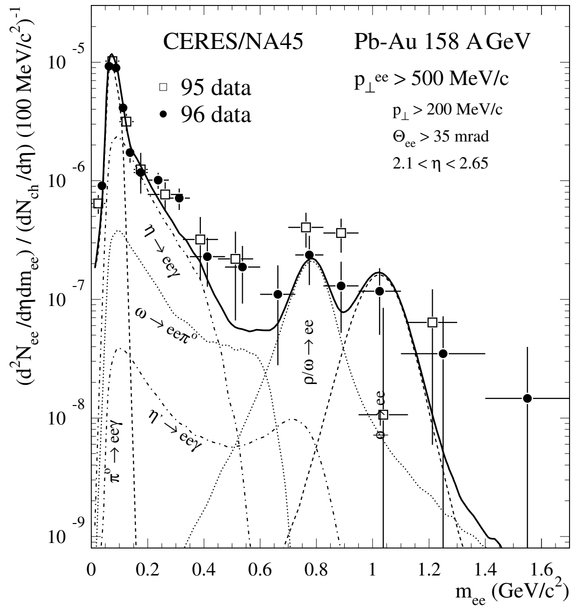

Figure 6. Same as Fig. 5 for electron pairs with transverse momentum higher than 500 MeV/c.

and by "artificially" increasing the background/signal ratio. The stability of the signal obtained *in fine* does not support the possibility of a trivial background effect, as could be suggested by the two mentioned features of the observed enhancement. However, in order to firmly establish an overproduction of low mass electron pairs, the experiment has to significantly improve its mass resolution, statistics and signal/background ratio and explore, with such an upgraded apparatus, the whole centrality range.

2.2. Low mass muon pairs

Experiments NA38 and NA50 [2] have studied the low invariant mass muon pairs. Within the limited transverse mass acceptance of the spectrometer, these muon pairs originate mainly from the ρ, ω and ϕ resonances with a reduced contribution from the η and ω Dalitz decays. Figure 7 shows the p-U dimuon mass spectrum superimposed to the expected contributions, including $D\bar{D}$ production and decay as well as $q\bar{q}$ annihilation down to an invariant mass of 1.5 GeV/c^2. The data exceed the expected sources by $\simeq 30\%$ below 400 MeV/c^2 and by $40\pm3\%$ in the mass range 400–650 MeV/c^2. When the $q\bar{q}$ annhilation curve is extended to lower masses, using, as a rough estimate, a simple extension of the Drell-Yan calculation (performed with the Pythia event generator), the p-U mass distribution is rather well reproduced (Fig. 8). In the case of the ion data, the expected mass spectrum has been calculated using the same sources as in the p-U case, including the Drell-Yan extension to low masses. The hadronic sources have been scaled with the pion multiplicity and the hard processes with the product $A \times B$. The comparison between data and expected sources in the mass interval 400–650 MeV/c^2 does not show any significant enhancement neither for Sulphur-induced reactions (Table 1) nor in the case of Pb-Pb (Fig. 9). These results do not imply necessarily a contradiction with

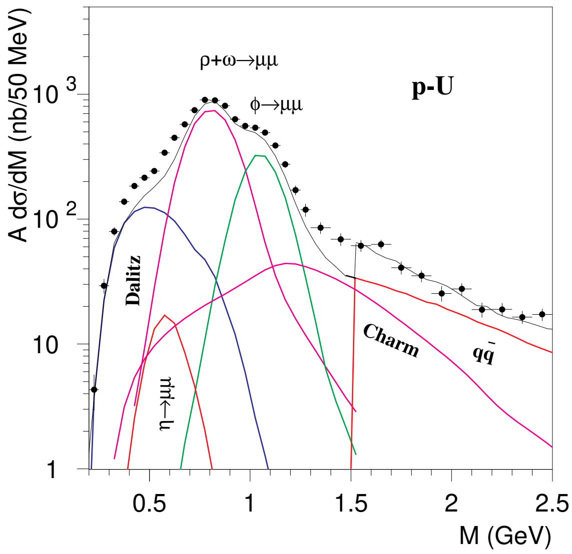

Figure 7. Dimuon mass distribution measured in p-U collisions, compared to the superposition of expected processes.

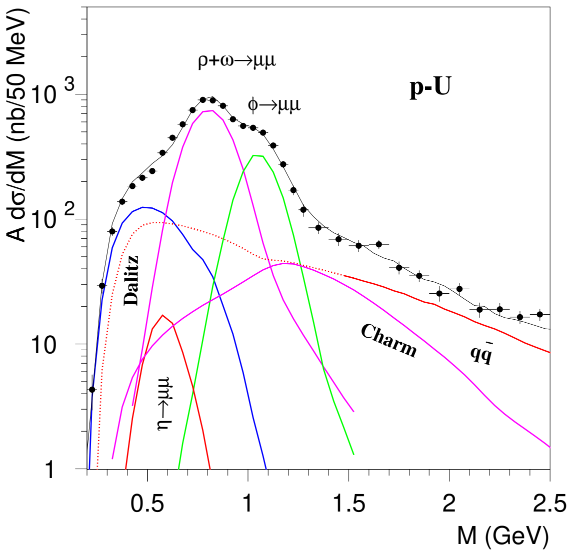

Figure 8. Same as Fig. 7 roughly extrapolating to lower masses the contribution due to $q\bar{q}$ annihilation.

the CERES data as only high transverse momentum muon pairs (> 1 GeV/c) are studied here. A new experiment with an extended transverse momentum coverage and improved mass resolution is clearly needed to clarify the situation.

Table 1
Ratio “data over expected sources” in the mass interval 400–650 MeV/c^2, for proton and Sulphur-induced reactions. Only statistical errors are given.

p-U	1.00 ± 0.02
S-Cu	0.94 ± 0.06
S-U	1.18 ± 0.03

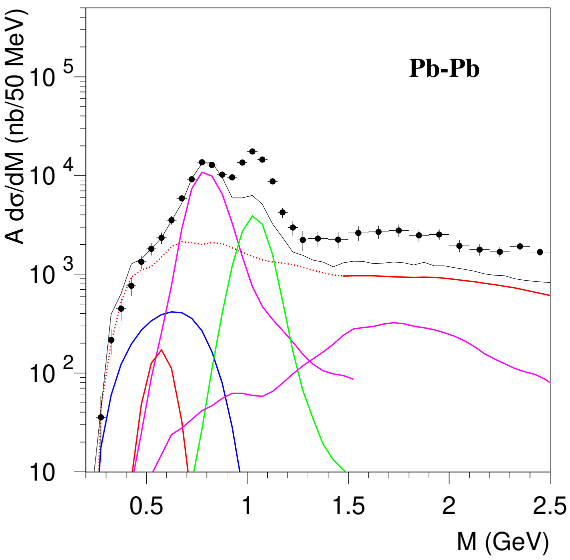

Figure 9. Same as Fig. 8 for Pb-Pb collisions.

3. Intermediate mass dileptons

The production of muon pairs in the “intermediate” invariant mass range, between the ϕ and the J/ψ resonances, is being studied in proton and ion-induced reactions by experiments NA38 and NA50 [3]. It has also been investigated by the Helios-3 experiment [4]. The mass continuum in this range is assumed to originate only from conventional sources, i.e., π and K decays (the combinatorial background), Drell-Yan annihilation and charmed meson production followed by simultaneous D and $\bar{D}$ semi-leptonic decays. The experimental data consist of various samples of p-A, S-U and Pb-Pb interactions collected respectively at 450, 200 and 158 GeV/c momentum (per incident nucleon) in similar kinematical regions. The physical signals lead to opposite-sign muon pairs. The combinatorial background has been carefully studied by simulation and is estimated from the like-sign muon pairs which are exclusively due to uncorrelated meson decays. Taking into account this combinatorial background, the mass spectra are fitted with the Drell-Yan and $D\bar{D}$ contributions, leaving their amplitudes free and using the shapes obtained by simulation techniques, to account for the experimental acceptance and resolution. The procedure leads to a quite fair description of the p-A data. Moreover, the cross-section for open-charm hadro-production at 450 GeV/c which is required to fit these data is compatible with the direct measurements done by several experiments both at CERN and at Fermilab. The same procedure is applied to the Pb-Pb data, where the study is done as a function of the centrality of the reaction. The Drell-Yan cross-section is taken from the fit to the data. When the open charm cross-section is just extrapolated from its p-A value, as expected for a hard process, a clear excess is observed in the data (Fig. 10), which increases as a function of the number of participants. The “excess” has the same mass distribution as the $D\bar{D}$ contribution and vanishes if the $D\bar{D}$ amplitude is left free instead of extrapolating it from the p-A data (Fig. 10). Under the assumption that the observed “excess” originates simply from $D\bar{D}$ overproduction, in the invariant mass range [1.5–2.5 GeV/c^2] the open charm enhancement increases with respect to p-A, up to a factor of about 3 for the most central Pb-Pb reactions (Fig. 11). The mass distribution of the “excess” observed in the data differs from the mass distribution of the combinatorial background, both for peripheral and for central collisions, which seems to discard a trivial background effect. Its open charm origin is further supported by the transverse momentum distributions of the collected muon pairs which are also fairly accounted for under the same assumption. Other possible explanations like an effect due to $D\bar{D}$ rescattering or the production of thermal dimuons need further and detailed investigations.

4. J/ψ suppression

The story of the discovery of “J/ψ suppression” is now 13 years old. Progress has been slow and the main milestones can be divided into three partially overlapping periods.

4.1. The “light” ion era: 1986-1995

It is worthwhile recalling that experiment NA38 was proposed and approved in 1985 to search for “thermal dimuons”, one of the signatures which, according to several authors, was supposed to reveal QGP formation. In 1986, H. Satz and T. Matsui predicted that colour screening in a QGP would prevent J/ψ formation in the deconfined interior of the

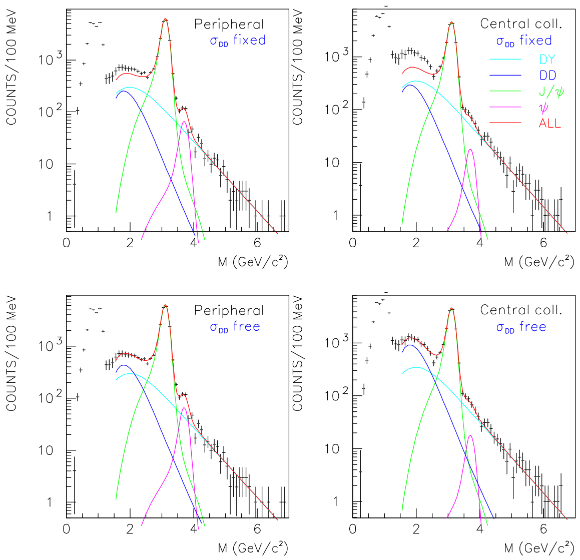

Figure 10. Dimuon mass distributions for Pb-Pb peripheral (left) and central (right) interactions after background subtraction. The $D\bar{D}$ cross-section is extrapolated from the p-A data (top) or left free to be determined by the fit itself (bottom).

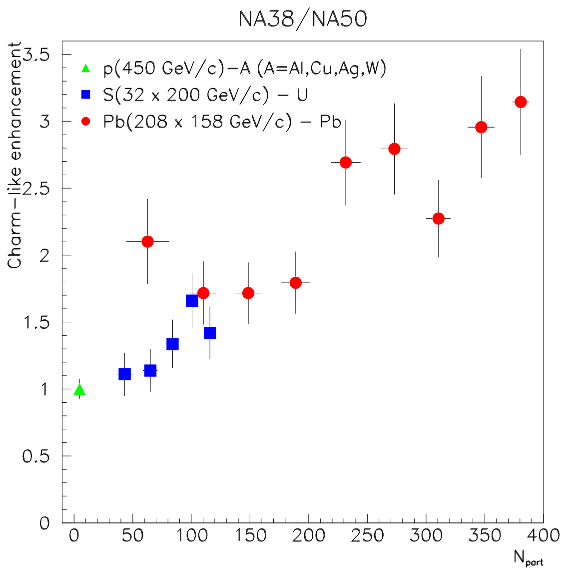

Figure 11. The open charm enhancement as a function of the number of participants. The observed "excess" is assumed here to originate from $D\bar{D}$ overproduction exclusively.

interaction region [5]. The first results obtained in Oxygen-Uranium interactions with 200 GeV/c incident momentum ions [6] did show that, with respect to the muon pair continuum of invariant mass around 3 GeV/c^2, the J/ψ observed yield was decreasing with increasing transverse energy. Despite the natural interest of this result, the conclusions of this first publication were clearly on the conservative side. A main step forward was made in 1991 when comparing the absolute cross-sections for the muon pair continuum and for J/ψ production (Fig. 12) as measured in p-Cu, p-U, O-Cu, O-U and S-U interactions at 200 GeV/c incident momentum [7]. This comparison confirmed previous J/ψ results obtained in proton-induced reactions by other experiments. It also allowed to state that, within errors, (a) the J/ψ cross-section integrated over all impact parameters did not show any stronger absorption in ion-ion interactions and (b) the continuum cross-section increased linearly with $A \times B$, as expected from a hard process.

4.2. The reference for "normality": 1992-1995

"Normal" J/ψ absorption was later clearly established with the comparison of the whole set of measurements made, with the same apparatus, on p-induced reactions at 450 and 200 GeV/c incident momentum and the full samples of light ion induced reactions [8]. It was thus shown that, as a function of the product $A \times B$ of the mass numbers of the projectile and target, the J/ψ cross-section per nucleon-nucleon collision has the same behaviour for p-induced reactions (from pp up to p-W) at 450 GeV/c and for proton and light ion induced reactions at 200 GeV/c incident momentum (from p-Cu to S-U). In particular, the measured cross section for S-U lies precisely where expected from the extrapolation of the other measurements (Figs. 13 and 14).

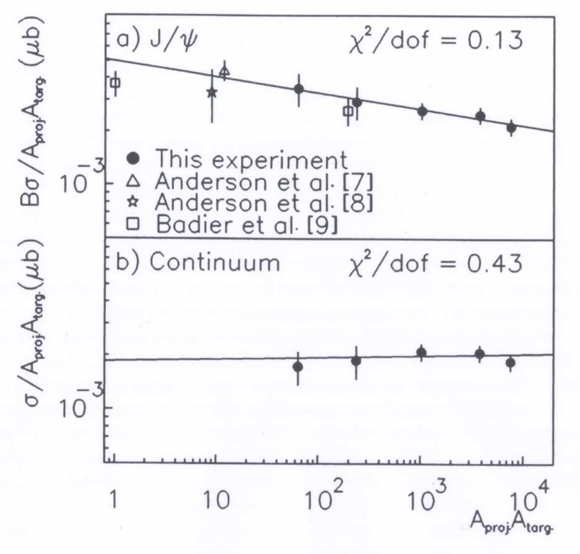

Figure 12. Cross-sections per nucleon for J/ψ and for muon pairs in the mass continuum.

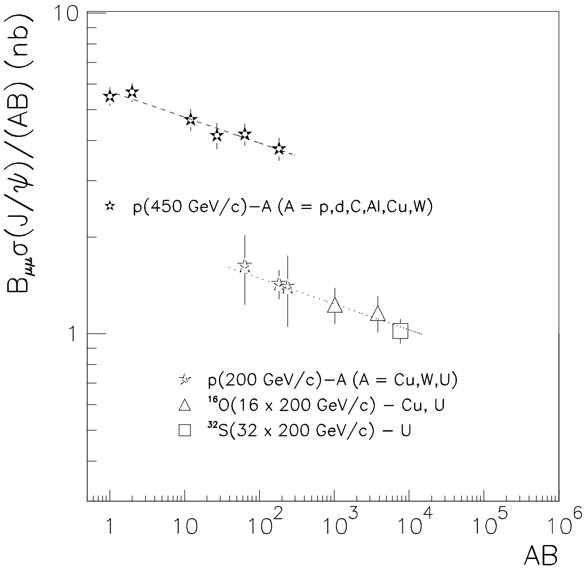

Figure 13. The J/ψ cross-sections per nucleon (multiplied by its decay branching ratio into two muons) for proton and light ion-induced reactions as measured at 450 and 200 GeV/c. The lines are the best fits of the power law $(A \times B)^{\alpha-1}$.

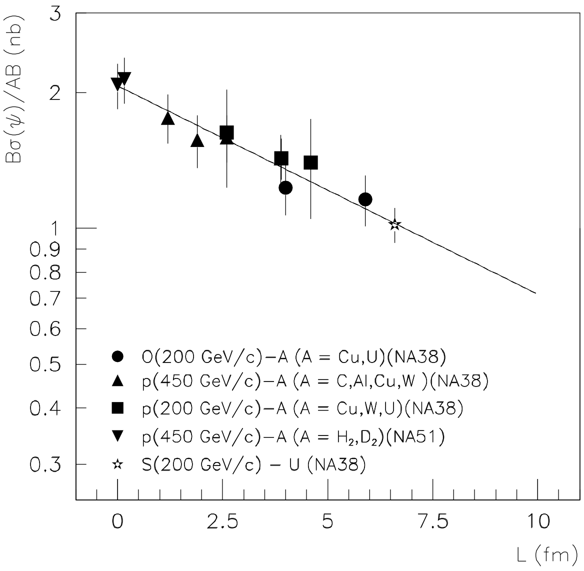

Figure 14. Same as Fig. 13 with the 450 GeV/c data rescaled to the energy and rapidity range of the 200 GeV/c measurements, as a function L. The line is the simple fit which accounts for "normal" nuclear absorption.

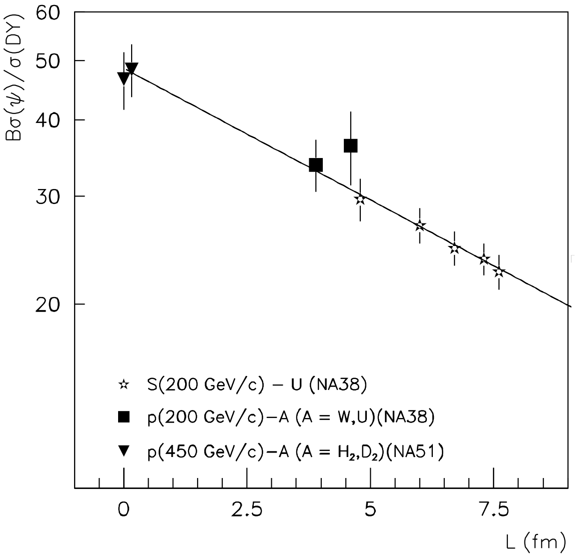

Figure 15. The ratio of the J/ψ to Drell-Yan cross-sections for p and S-induced reactions (the NA51 measurements are rescaled to 200 GeV/c).

This "normal" absorption is interpreted as due to final interactions between the charmonium state and the surrounding matter. It depends directly on the number of nucleons that the created state can interact with. This number is proportional to the length L of nuclear matter (weighted by the local nuclear density) that the $c\bar{c}$ traverses while escaping from the interaction region. The "normal" absorption cross-section can be calculated from the measurements shown in Fig. 14 and amounts to 7.2 ± 1.2 mb. A more precise reference can be obtained from the ratio of the J/ψ to the Drell-Yan cross-section, which is proportional to the J/ψ cross-section "per nucleon" and, moreover, free from most systematic errors. The full calculation leads to an absorption cross-section of 6.4 ± 0.8 mb, from the measurements shown in Fig. 15.

4.3. "Anomalous J/ψ suppression" in Pb-Pb interactions:1995-1999

Pb ion beams of 158 GeV/c incident momentum, available at CERN starting from 1994, open up a new era in the study of J/ψ suppression [9]. It is first shown that, from p-p up to and including Pb-Pb interactions, the Drell-Yan muon pair cross-section does behave precisely as expected from calculations (Fig. 16). The Drell-Yan cross-section is indeed proportional to the number of elementary nucleon-nucleon collisions. On the other hand, for Pb-Pb interactions, the J/ψ "cross-section per nucleon-nucleon collision" is a factor 0.74 ± 0.06 lower than expected from the simple extrapolation of the "normal" J/ψ absorption (Fig. 17).

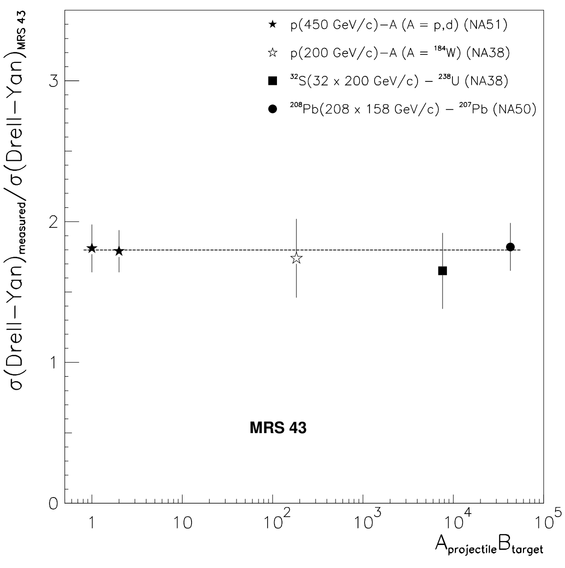

Figure 16. The ratio of the measured to the computed Drell-Yan cross-section as a function of the product A×B of the projectile and target atomic mass numbers. The dashed line shows the average value of the five measurements.

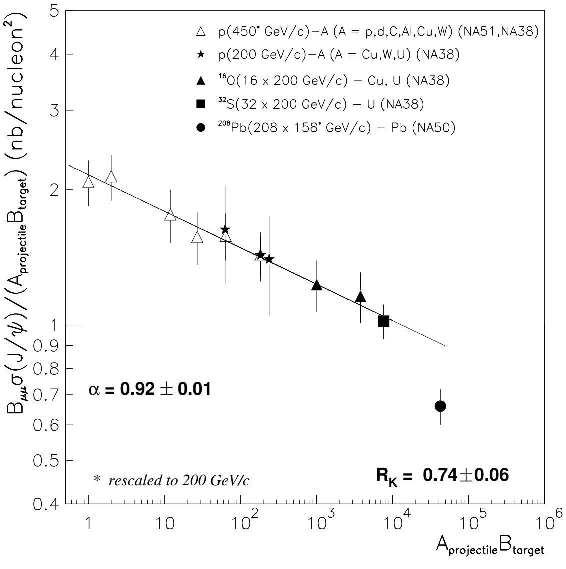

Figure 17. The J/ψ "cross-section per nucleon-nucleon collision" as a function of the product A×B of the projectile and target mass numbers. When necessary, the results are rescaled to 200 GeV/c incident momentum.

As a function of centrality, the ratio of J/ψ to Drell-Yan cross-sections, hence proportional to the J/ψ cross-section per nucleon-nucleon collision, exhibits the "normal" absorption behaviour for the most peripheral Pb-Pb interactions. It also shows an increasing departure from "normality" with increasing centrality of the collision (Fig. 18).

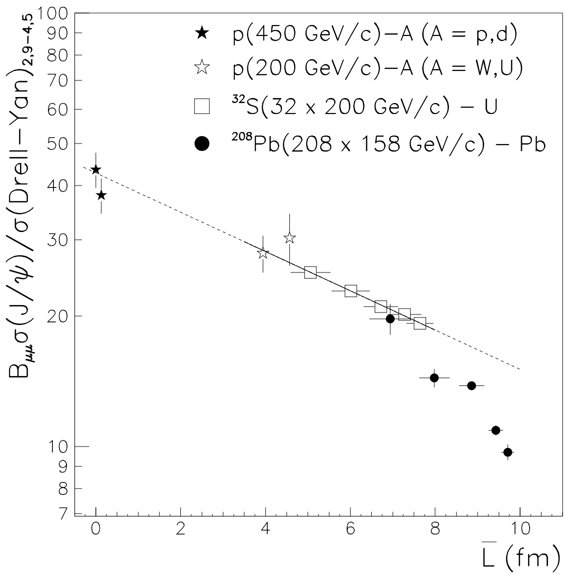

Figure 18. The ratio of the J/ψ to Drell-Yan cross-sections as a function of $\bar{L}$. All the results are plotted for 200 GeV/c incident momentum for comparison purposes, using the GRV LO p.d.f. in the rescaling procedure.

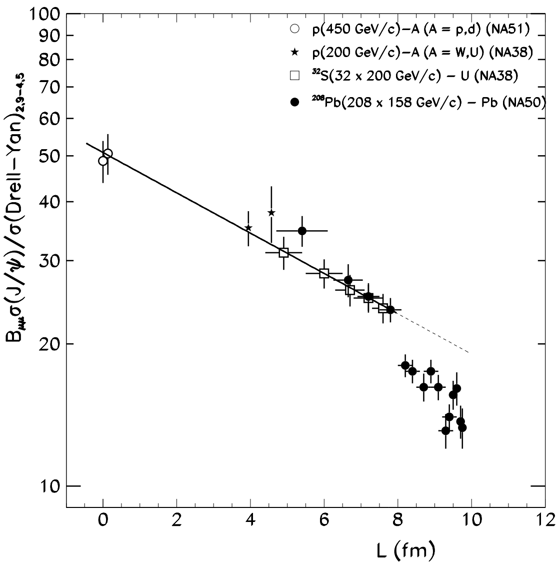

Figure 19. Same as Fig. 18 based on the largest sample of Pb data. The p-A and S-U results are rescaled to 158 GeV/c incident momentum, for comparison purposes, using the MRS 43 p.d.f. in the calculations.

A crucial step forward is made with the fourfold sample of events collected in the fall of 1996 which allows a much more detailed study of the suppression as a function of centrality (Fig. 19). The suppression pattern clearly confirms that peripheral Pb-Pb interactions exhibit the "normal" behaviour already measured for lighter projectiles. It shows, moreover, that the J/ψ cross-section drops by about 20% within a narrow impact parameter range [7.3–8.3 fm]. Unfortunately, for the most central reactions, this data sample is suspected of a systematic bias due to reinteractions within the thicker (12 mm long, 30 % of λ_I) target used to increase the number of collected events.

In order to clarify the trend of the suppression pattern for the smallest impact parameters, a special data collection is made in 1998 with the thinnest target (3 mm long) compatible with the necessary statistical accuracy. Preliminary results, obtained with this most recent sample of events, do confirm the suspected systematic bias. The Pb-Pb data are studied directly as a function of the neutral transverse energy produced in the reaction, as measured by the electromagnetic calorimeter in the pseudorapidity window [1.1–2.3]. The J/ψ cross-section per nucleon-nucleon collision is computed from the J/ψ and "minimum bias" samples of events (open symbols in Fig. 20). This allows to improve on the statistical accuracy available from the directly observable Drell-Yan events (used for the measurements plotted with closed symbols in Fig. 20). Combined with the previous results, limited to their unbiased range, the most recent data indicate that the departure from the normal nuclear absorption increases dramatically for the most central Pb-Pb interactions, as can be seen from Fig. 20.

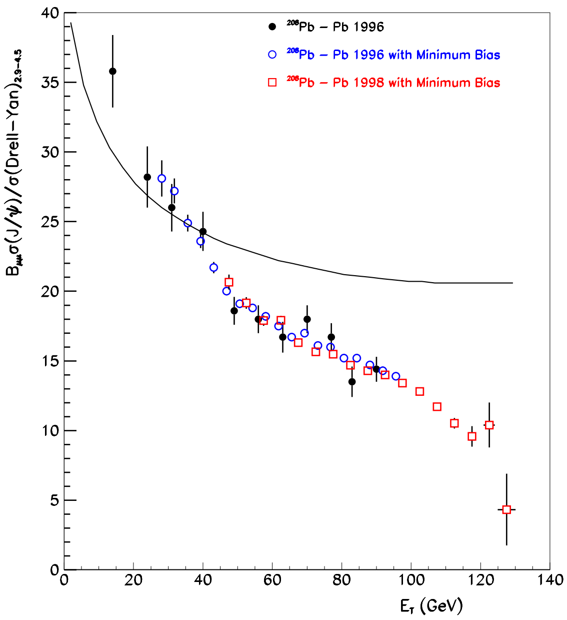

Figure 20. The ratio of the J/ψ to Drell-Yan cross-sections for Pb-Pb reactions. The curve shows the "normal" suppression due to nuclear absorption as deduced from the measurements done with lighter projectiles or targets.

On the contrary, the observed pattern can be described on the basis of charmonia "melting" induced by the temperature and density conditions created in 158 GeV Pb-Pb interactions. The χ_c resonance is first suppressed, under less extreme conditions linked to its binding energy and radius (the non-suppressed χ_c resonance, normally produced in the interaction, decays into a J/ψ that cannot be distinguished experimentally in the detector from a directly produced one). In a second step, i.e. when more extreme conditions are reached, the directly produced J/ψ resonance is suppressed in the deconfined medium.

In an effort to explain the experimentally observed J/ψ suppression, several conventional hadronic models have been built, not including a phase transition to deconfined matter. None of them is able to account simultaneously for the detailed suppression pattern observed in Pb-Pb and for the "normal" suppression observed with lighter projectiles [10]. Moreover, the new behaviour observed for the most central Pb-Pb collisions, presented for the first time in this Conference, is in basic contradiction with the systematic saturation obtained from any of these conventional models.

4.4. Conclusion

The ion program developed at CERN since 1986 has led to a set of impressive results. Among the different QGP signatures that have been explored, dilepton signals have led to established experimental facts which, at least for some of them, cannot be accounted for without calling for some "new physics", as the formation of a Quark-Gluon Plasma.

Acknowledgement: The author is grateful to C. Lourenço for having carefully read the manuscript.

REFERENCES

1. B. Lenkeit *et al.*, Contribution to this Conference and references therein.
2. M.C. Abreu *et al.*, submitted to Euro. Phys. J. C, CERN-EP/99-112.
3. C. Lourenço *et al.*, Nucl. Phys. A566 (1994) 77c; E. Scomparin *et al.*, Nucl. Phys. A610 (1996) 331c; P. Bordalo *et al.*, Contribution to this Conference.
4. A.S. Angelis *et al.*, CERN-EP/98-92.
5. T. Matsui and H. Satz, Phys. Lett. B178 (1986) 416.
6. M. Abreu *et al.*, Phys. Lett. B220 (1989) 471.
7. M. Abreu *et al.*, Phys. Lett. B270 (1991) 105.
8. M. Abreu *et al.*, accepted by Phys. Lett. B, CERN-EP/99-113.
9. C. Cicaló *et al.*, Contribution to this Conference and references therein.
10. C. Gale and J. Kapusta, Contribution to this Conference and references therein.