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Open questions in quarkonium and electromagnetic probes

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Abstract

In my (“not a summary”) talk at the Hard Probes 2006 conference, I gave “a personal and surely biased view on only a few of the many open questions on quarkonium and electromagnetic probes”. Some of the points reported in that talk are exposed in this paper, having in mind the most important of all the open questions: do we have, today, from experimental data on electromagnetic probes and quarkonium production, convincing evidence that shows, beyond reasonable doubt, the existence of “new physics” in high-energy heavy-ion collisions?

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The first experimental measurements of photon and dilepton production in high-energy heavy-ion collisions took place 20 years ago, at the CERN SPS, with Oxygen ions accelerated to 200 GeV per nucleon. Many difficulties make these measurements particularly challenging. In particular, the production cross-sections of such particles as the J/ψ and ψ' are very low, the branching ratios of the decay channels $\rho, \omega, \phi \rightarrow l^+l^-$ are very small, the backgrounds from $\pi^0 \rightarrow \gamma\gamma$ and other hadronic decays are very high, etc. Under these conditions, it is quite remarkable that significant physics progress actually resulted from the first generation of SPS experiments (none of the AGS heavy-ion experiments measured dileptons or photons). It is important to keep in mind that these experiments were built in a very short time and, most of them if not all, used existing detectors with only minimal additions or modifications. For instance, the NA38 experiment was proposed to the SPS committee in 1985 (to search for thermal dimuons) and was taking data one year later, with newly built beam detectors, an active target system and an electromagnetic calorimeter, added to the muon spectrometer used by NA10 since 1980. Now that most people in our field work in experiments that cost in excess of 100 million Swiss francs, it might be worth recalling that the (much cheaper) 17 m long muon spectrometer built by NA10 worked in the NA10 experiment for 5 years and in the NA38, NA50 and NA60 “heavy-ion experiments” for 18 years! Surely a very good deal.

Already in this first generation of SPS heavy-ion experiments, using beams of Oxygen and Sulphur ions, several observations indicated the presence of “anomalies” in the measured data. Until 1995, many people argued that the drop of the ratio between the J/ψ and the “Drell-Yan continuum” production cross-sections, from p-U to O-U to S-U collisions and from peripheral to central O-U and S-U collisions, as measured by NA38, constituted a clear signature of QGP formation, following the prediction published in 1986, in what is nowadays arguably the most famous paper of our field [1] (cited almost 1000 times by now).

In parallel, an excess in the production of low mass dielectrons was found by the CERES collaboration and interpreted as a possible indication that chiral symmetry was (approximately) restored in the matter produced in S-Au collisions at SPS energies.

Also the continuum dimuons with masses below the J/ψ peak were under scrutiny, by NA38 and Helios-3. Both experiments found an excess in the production yield of such dimuons in Sulphur induced collisions, with respect to the yields expected from a superposition of Drell-Yan dimuons and muon pairs from simultaneous semi-muonic decays of (correlated) pairs of D mesons. These observations were taken seriously because the same analyses could reproduce the data collected in proton-nucleus collisions, with normalisations compatible with the expectations available at the time. Possible explanations of this “intermediate mass region dimuon excess” included thermal dimuons (maybe emitted from the QGP phase) and modifications of the pair correlations of the D mesons while traversing the medium produced in the nuclear collisions.

Between 1994 and 2000, a second important step took place at the SPS, with

several data taking periods with Pb ions, at 158 GeV and lower energies. The new experiments confirmed the observation of excess production of low and intermediate mass dileptons, now in Pb induced collisions. The situation changed, however, in the case of the production and suppression of charmonium states, in particular thanks to a much better understanding of the proton-nucleus reference data. In the case of the J/ψ , we now think that the “normal nuclear absorption” already present in p-A collisions, and nicely reproduced by a simple model based on the Glauber formalism with a single “absorption cross section” parameter, σ_{abs} , can also account for the “suppression pattern” measured in S-U collisions, with the same σ_{abs} value, indicating that the J/ψ is not sensitive to the medium formed in such collisions, contrary to what happens in Pb-Pb collisions, where an extra and significant suppression is seen, beyond the expected “normal nuclear absorption curve”, for the most central collisions (Fig. 1-left). In the case of the ψ' , on the other hand, there is a very significant extra suppression observed already in S-U collisions, with respect to the p-A reference, and no significant change is visible between the S-U and Pb-Pb suppression patterns (Fig. 1-right).

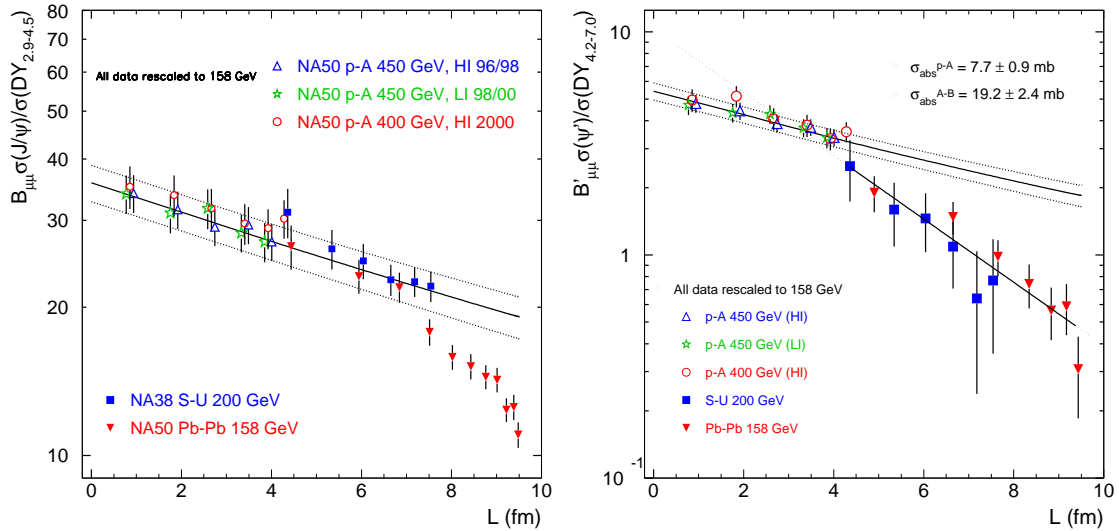


Figure 1: Left: The J/ψ suppression pattern as measured by NA38 and NA50, in p-A, S-U and Pb-Pb collisions, as a function of L , the distance of nuclear matter traversed by the charmonium, compared to the “normal nuclear absorption” band resulting from the Glauber fit to the p-A data [2]. The p-A and S-U data points, as well as the curves, have been rescaled to the conditions (energy and rapidity window) of the Pb-Pb data. Right: The suppression of the ψ' as measured by NA38 and NA50 in p-A, S-U and Pb-Pb collisions [3], compared to the normal nuclear absorption curve calculated using the Glauber formalism [4].

It can be easily argued that one of the most important “discoveries” of the first 10 years of heavy-ion experimentation at the CERN SPS, and not only in what concerns hard and electromagnetic probes, is that it is extremely important, indeed crucial, to

have very robust data collected in more elementary collision systems, such as proton-proton and proton-nucleus interactions, collected by the same experiments, at the same collision energies, and in the same phase space acceptance windows, as the heavy-ion measurements. Only after having a solid “expected baseline”, provided by a good understanding of the relevant physics processes and based, in particular, on detailed analyses of p-A data, we can realistically hope to identify patterns in the high-energy heavy-ion data that will clearly and convincingly signal the presence of “new physics” in the matter produced in those interactions.

It is important to recognise the effort made at RHIC in this respect, with pp and d-Au runs that have provided extremely valuable information to understand the observations made in Au-Au collisions. Unfortunately, for certain physics topics, such as J/ψ production, the presently available d-Au statistics is very limited; a high-statistics d-Au run should take place at RHIC at the earliest possible date.

At the SPS energies, the NA50 experiment has recently provided a very detailed analysis of J/ψ and ψ' production in p-A collisions [2], at 450 and 400 GeV, using 5 and 6 different nuclear targets, respectively, both in terms of absolute production cross sections (Fig. 2) and in terms of ratios between charmonia and Drell-Yan yields (Fig. 1).

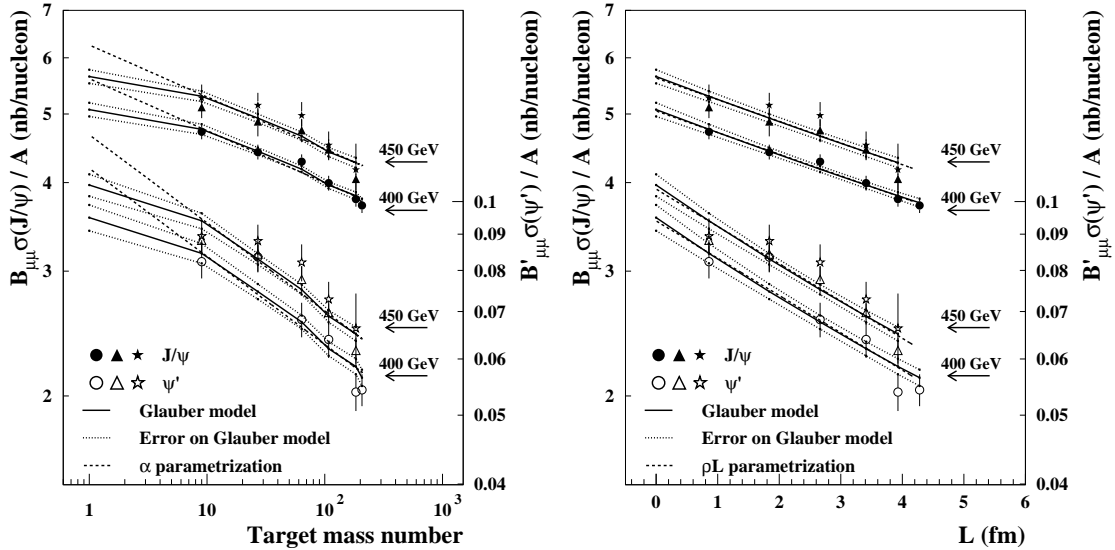


Figure 2: The J/ψ and ψ' production cross sections measured in p-A collisions by NA50, as a function of the mass number of the target nuclei (left), and of L (right). The lines represent fits to three commonly used parameterizations of the “normal nuclear absorption”.

The results, corresponding to 16 different data sets collected between 1996 and 2000, in different experimental conditions, give a rather consistent picture of the J/ψ and ψ' “normal nuclear absorptions”, with absorption cross sections $\sigma_{\text{abs}}^{J/\psi} = 4.5 \pm 0.5 \text{ mb}$ and $\sigma_{\text{abs}}^{\psi'} = 8.3 \pm 0.9 \text{ mb}$ from the production cross-sections, and $\sigma_{\text{abs}}^{J/\psi} =$

4.2 ± 0.5 mb and $\sigma_{\text{abs}}^{\psi'} = 7.7 \pm 0.9$ mb from the cross-section ratios.

However, it is important to keep in mind that a significant fraction of the observed J/ψ mesons result from decays of ψ' and χ_c mesons, that the ψ' has a higher σ_{abs} value (at least at mid-rapidity), and that this is likely to also be the case for the χ_c , a larger and more weakly bound charmonium state than the J/ψ . If we assume that 60% of the observed J/ψ mesons are directly produced, 30% result from χ_c decays and 10% from ψ' decays, and if, furthermore, we calculate σ_{abs} geometrically, as πr^2 , with $r_{J/\psi} = 0.25$ fm, $r_{\psi'} = 2 \times r_{J/\psi}$ and $r_{\chi_c} = 1.5 \times r_{J/\psi}$, we can redo the Glauber calculation, now without leaving σ_{abs} as a free parameter, and we obtain an equally good description of the J/ψ data (Fig. 3), with a reduced χ^2 of 1.0 (by chance?). Besides, the value of $\sigma_{\text{abs}}^{\psi'}$ from this very simple model is 7.85 mb, in perfect agreement with the NA50 measurements (by chance?).

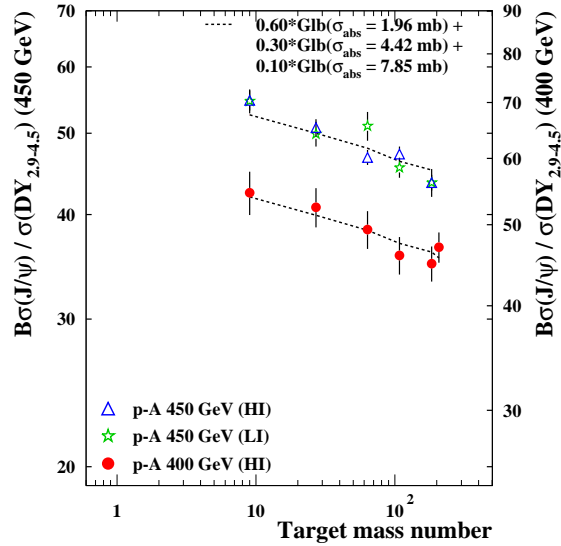


Figure 3: NA50 p-A values of the J/ψ over Drell-Yan cross-section ratio, as a function of A , compared to a Glauber calculation taking into account the feed-down contributions from higher $c\bar{c}$ states.

The values of σ_{abs} mentioned here are “effective” values, corresponding to a convolution of the final state absorption which affects the produced $c\bar{c}$ states while traversing the nuclear matter, with initial state effects, such as the nuclear effects on the gluon distribution functions. According to the well-known EKS98 model of nuclear effects on the parton distribution functions [5], charm production at SPS energies, and at mid-rapidity, is in the anti-shadowing region, leading to an initial state $c\bar{c}$ production enhanced in p-Pb collisions, say, with respect to the case when nuclear effects are neglected (Fig. 4).

A very simple calculation indicates that the “convoluted” σ_{abs} value, 4.2 mb, becomes around 6 mb if we explicitly take into account the anti-shadowing effect, using the EKS98 model. This value is more directly comparable to the values obtained

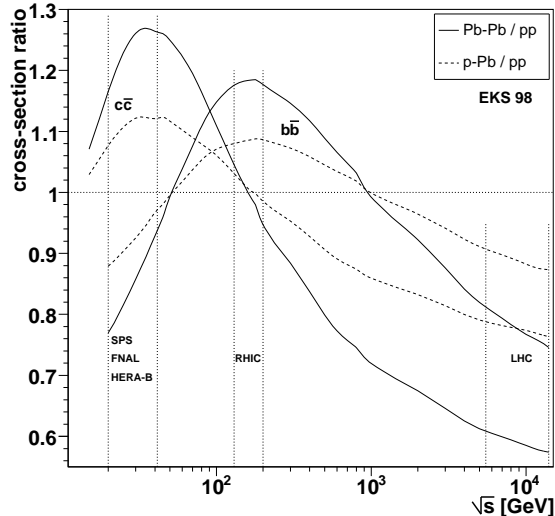


Figure 4: Changes induced on the $c\bar{c}$ (and $b\bar{b}$) cross-sections, in p-Pb and Pb-Pb collisions, by the nuclear modifications of the PDFs, at mid-rapidity [6].

from the d-Au data of PHENIX, between 0 and 3 mb, which were also obtained after taking into account the (EKS98) nuclear effects on the PDFs [7].

The observation that the σ_{abs} values at SPS and RHIC energies are considerably different raises the question of whether σ_{abs} varies within the energy range covered by the fixed-target experiments. A detailed analysis of all the available data, with the Glauber formalism, including nuclear effects on the PDFs and properly accounting for the feed-down sources, is beyond the scope of this paper. Let us simply state that the (initial and final state) nuclear absorption of the J/ψ , if parameterized with the A^α expression, leads to values of α that, at mid-rapidity, increase with collision energy (Fig. 5-left).

It is very interesting to notice that the values of α measured at three significantly different (fixed-target) energies, at mid-rapidity, show a perfect scaling as a function of p_T (Fig. 5-right). We may conjecture, then, that the observed increase of α with energy is actually due to a convolution between the increase of α with p_T and the increase of the average p_T of the J/ψ with the collision energy (Fig. 6).

From the previous lines, and also considering that the level of (anti-)shadowing changes with the collision energy (Fig. 4), it seems natural to deduce that the σ_{abs} value at 158 GeV, the energy of the Pb-Pb collisions, will be somewhat higher than the value determined at 400/450 GeV. A stronger “normal nuclear absorption” will lead to a decrease of the “extra suppression” presently seen in the Pb-Pb J/ψ data. We will know more once the NA60 collaboration extracts σ_{abs} from the p-A data collected at 158 GeV. At this moment, however, in the absence of that measurement, we cannot really argue that we have a robust reference baseline at the energy of the heavy-ion data. Hence, the “anomalous” aspect of the J/ψ suppression pattern seen in heavy-ion collisions has not yet been *convincingly* demonstrated, and requires, in

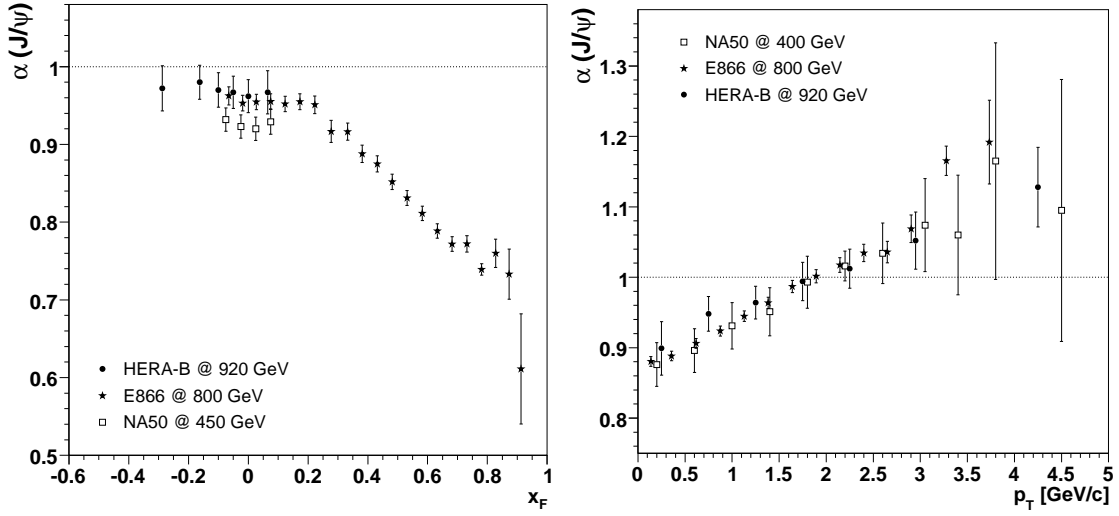


Figure 5: The nuclear-dependence α parameter as a function of x_F (left) and of p_T (right), for J/ψ mesons measured at three different collision energies, in p-A collisions [8].

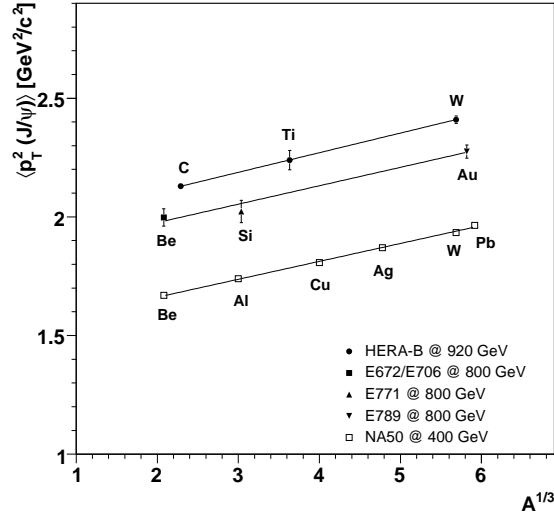


Figure 6: $\langle p_T^2 \rangle$ increases with the size of the target nuclei and with the energy of the collision [8].

particular, a more detailed understanding of charmonia production in elementary pp and p-A collisions.

The striking “change of slope” of the ψ' suppression pattern (Fig. 1-right) looks even more “anomalous” but, again, it occurs between the p-A and the S-U/Pb-Pb data points, collected with different collision systems and at significantly different energies. A convincing demonstration of “new physics” would require that the anomaly happens within a consistent set of data points (ideally, a single collision system, from

peripheral to central collisions). Unfortunately, poor statistics prevents NA60 from significantly contributing to the understanding of the ψ' suppression pattern. At this moment, and the situation is not likely to change in the coming years, we cannot say what is the nature of the “anomaly” seen in the ψ' suppression pattern between the p-A and the S-U/Pb-Pb colliding systems; maybe the extra suppression is due to the matter produced in the heavy-ion collisions; maybe that matter is in the QGP phase and “melts” the $c\bar{c}$ bound states; maybe this indicates that the critical energy density is reached already in the most peripheral S-U or Pb-Pb collisions at the SPS energies; maybe...

There is much more experimental information concerning the suppression of the J/ψ production yield, with the NA50 Pb-Pb pattern recently being complemented by PHENIX data taken at 10 times higher centre of mass energies [7] and by NA60 data taken with a smaller colliding system, In-In [9]. However, the present statistical uncertainties of the PHENIX measurements severely limit the insights gained from comparing the results obtained at both energies. Figure 7 is an attempt to integrate in a single plot, as a function of N_{part} the available mid-rapidity suppression patterns. The PHENIX results are R_{AA} , i.e. $N_{\text{Au-Au}}^{J/\psi}(c_i) / [N_{pp}^{J/\psi} \times N_{\text{coll}}(c_i)]$ (and similar for d-Au), where c_i represents the centrality bin. The NA38 and NA50 data points are the same as shown in Fig. 1-left, but normalised to the pp value, $R_{AA}^{J/\psi}(c_i) / R_{pp}^{J/\psi}$, where $R^{J/\psi}$ stands for $B \times \sigma^{J/\psi} / \sigma^{DY}$. The NA60 points were obtained by an approximate procedure, convoluting the In-In ratio “measured/expected” [9] with the Pb-Pb “normal nuclear absorption curve”, $N^{J/\psi}(c_i) / G^{J/\psi}(c_i) \times G^{J/\psi/DY}(c_i) / G_{pp}^{J/\psi/DY}$. In this representation, the different data sets are directly comparable, since Drell-Yan production scales with N_{coll} .

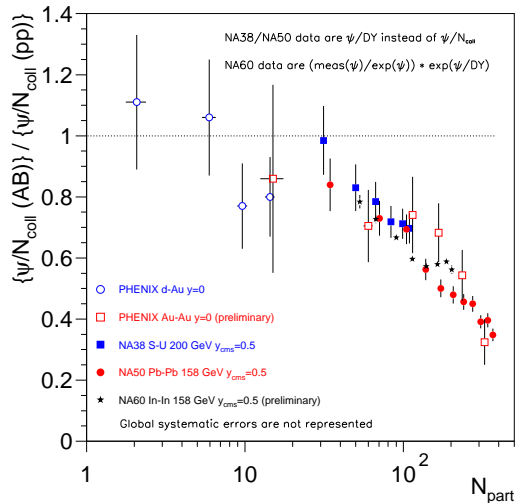


Figure 7: Comparison between the J/ψ suppression patterns observed at SPS and RHIC energies, as a function of N_{part} .

It is also not simple to compare the SPS heavy-ion patterns. The S-U energy is different, it is a very asymmetric collision system, the Uranium nucleus is not spherical, and, besides, the centrality can only be determined from the E_T measurement, while the In-In centrality distribution is determined from the E_{ZDC} variable. The comparison between the In-In and Pb-Pb suppression patterns should suffer from less systematic uncertainties (same energy, symmetric collisions, spherical nuclei), especially if we take the Pb-Pb values from the NA50 E_{ZDC} analysis rather than from the E_T analysis; but we must keep in mind that NA50 reports the suppression pattern in terms of the J/ψ / DY cross-section ratio while NA60 (with much less high-mass Drell-Yan statistics and a perfect vertexing efficiency even in the most peripheral collisions) reports the measured J/ψ yield itself, directly normalised by the calculated “expected” nuclear absorption. These two procedures surely have very different sources of systematic uncertainties.

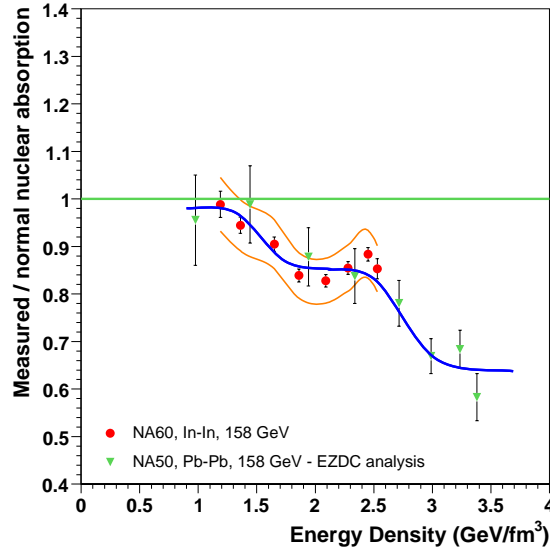


Figure 8: Comparison between the J/ψ suppression patterns observed in In-In and Pb-Pb collisions at the SPS, as a function of the energy density.

Figure 8 [10] compares the In-In and Pb-Pb suppression patterns, as a function of the energy density, estimated using a calculation based on the VENUS event generator. The observed pattern is consistent with a double step function (smeared by the resolution of the E_{ZDC} measurement), as would be expected in case the ψ' and χ_c states would be completely melted in the medium, above two different thresholds in energy density, leaving only the (more strongly bound) directly produced J/ψ mesons, around 60 % of the yield expected in the absence of anomalies [11]. However, there is a big difference between “the measurements are compatible with...” and “the measurements show, beyond reasonable doubt, that...”.

Concerning the intermediate mass region dimuons, there has been extremely significant progress provided by the NA60 experiment. The analysis reported at this

conference [12] convincingly shows (thanks to the very good vertexing accuracy of the data) that the excess dimuons seen in In-In collisions, with respect to the superposition of Drell-Yan dimuons and simultaneous semi-muonic decays of D meson pairs, is of a prompt nature (Fig. 9).

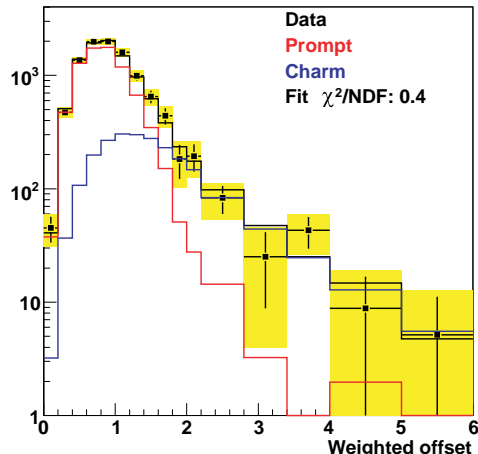


Figure 9: Demonstration that the intermediate mass dimuon excess is of prompt origin [12].

It is worth underlining that this eliminates the long-standing alternative that the signal excess would, in fact, be due to a small fraction of un-subtracted background from pion and kaon decays. It now remains to be understood what is the physics process responsible for this source of prompt dimuons. Maybe we are seeing thermal dimuons shining from a thermal medium (but, hadronic or deconfined?). However, once again, in order to clearly disclose any putative new phenomena, specific of nuclear collisions, we need to understand in detail the physics processes already contributing in the more “elementary” collisions.

The two physics processes that are expected to give sizeable yields of dimuons between the ϕ and the J/ψ peaks are the dimuons from $q\bar{q}$ annihilation (Drell-Yan) and the simultaneous semi-muonic decays of correlated charmed hadron pairs. Unfortunately, the Drell-Yan yields are not theoretically calculable in a reliable way for such low values of the dimuon mass, where higher order effects may be more important than at higher masses. Furthermore, even if the perturbative QCD calculations would be consistent with the proton-proton prompt dimuon continuum down to masses below 1.5 GeV, this could very well no longer be the case for proton-nucleus and nucleus-nucleus collisions, where contributions from interactions involving extra partons from the colliding hadrons may lead to a significant increase of the low-mass dimuon yield with respect to a linear scaling of the yield in elementary nucleon-nucleon interactions [13] (Fig. 10). Without having this possible source of *prompt* dimuons under control, through a detailed analysis of proton-nucleus data, there is little hope that we can find *clear* evidence for thermal dimuon production in heavy-ion data.

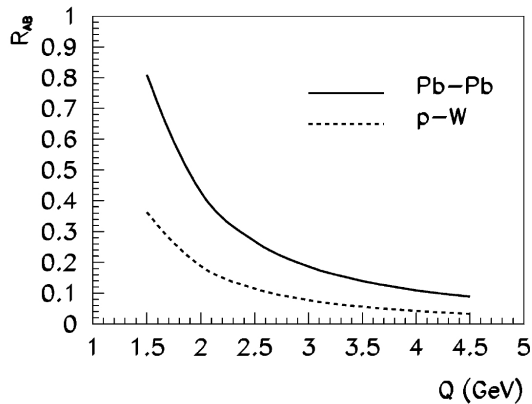


Figure 10: Ratio between the double-scattering and the single-scattering contributions to the Drell-Yan yield, versus dilepton mass, for p-W and Pb-Pb collisions, in the kinematical conditions of the NA60 experiment [13].

Also the understanding of the open charm baseline is under question, given that the charm production cross section deduced from the measurements made by many experiments (Fig. 11-left) is two times smaller than the value required to describe the dimuon data collected by NA50 in p-A collisions (Fig. 11-right). This indicates that there seems to be something “anomalous” already in the intermediate mass dimuons produced in the p-A collisions studied by NA50.

Reliable baseline measurements, made in elementary collisions, are also indispensable to correctly interpret photon and low mass dilepton production. In both cases, a large background from hadron decays needs to be removed so that we access a rare signal, which then needs to be understood as a convolution of several physics sources, maybe including thermal radiation from the QGP and/or from a hot hadron gas [17].

In the case of low mass dilepton production, the exceptional increase in statistics between the CERES Pb-Au data and the NA60 In-In data implies that the significance of the measurements is now determined by systematic uncertainties, related to experimental aspects like efficiencies and acceptances (increasingly difficult to keep under control as we move down in mass and p_T) and to the definition of the hadronic decay “cocktail”, given our limited knowledge of kinematical distributions, ρ/ω interference effects, the ω dimuon branching ratio, the ω form factor, the ρ mass line shape, and other “inputs” needed to define the “expected sources” reference.

We must also keep in mind that there are “normal nuclear effects” at play in low mass dilepton production, such as the increase of the ϕ/ω cross-section ratio in p-A collisions [18]. How much of the ϕ enhancement seen in heavy-ion collisions remains “anomalous” after accounting for a correct extrapolation of the p-A observations? And how can we conciliate our basic understanding of low mass dilepton production in “elementary” collisions with E325’s claim [19] that there are already “nuclear matter modifications” of the properties of the ρ , ω and ϕ mesons produced in p-Cu collisions at 12 GeV?

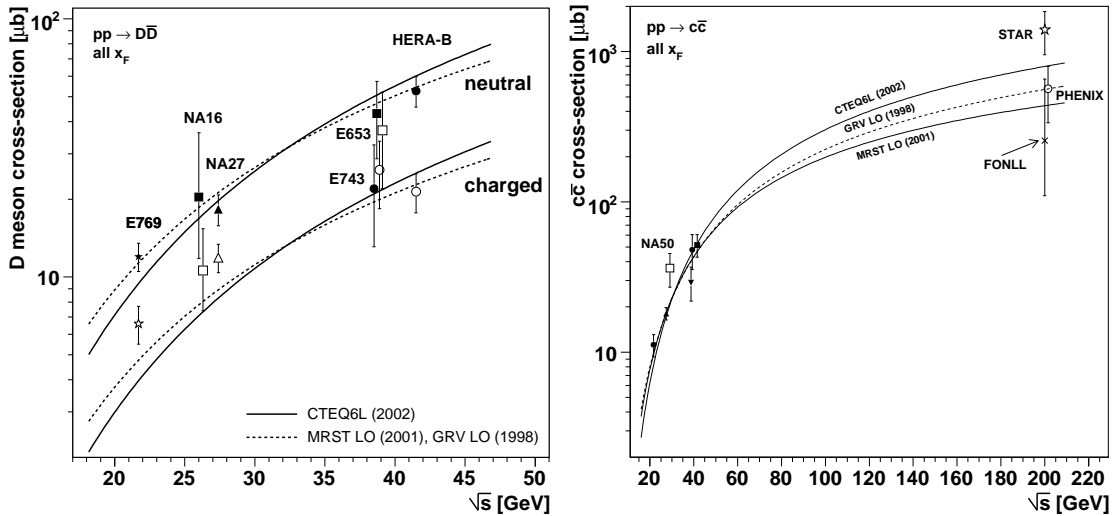


Figure 11: Compilation of production cross sections of charged and neutral D mesons (left) and total $c\bar{c}$ (right) as a function of \sqrt{s} , compared with curves calculated with Pythia [14] using three different sets of parton densities [6]. The value that best describes the NA50 p-A dimuon data [15] is a factor of two higher than expected from the interpolation of the direct measurements made by other experiments. Interestingly, the value recently measured by PHENIX [16], at much higher energies, is in good agreement with the extrapolation of the fixed-target data.

In summary, while it is certainly true that there has been very considerable progress in the recent years regarding the diversity and quality of the measurements related to quarkonium and electromagnetic probes production in high-energy heavy-ion collisions, it remains a field with many open questions. Some of them might be given satisfactory answers once the data samples recently collected at the SPS and at RHIC are fully analysed. Others will presumably remain unanswered and would easily justify significant upgrades of existing experiments or even the construction of new ones, provided the allocated integrated beam time (and human resources) would properly match the investment required to build the new hardware. In any case, the present situation, after 20 years of efforts by many hundreds of physicists, remains unsatisfactory: we do not yet have convincing evidence, from experimental data on quarkonium or electromagnetic probes, that shows *beyond reasonable doubt* the existence of “new physics” in high-energy heavy-ion collisions.

This paper benefited from valuable discussions with several people, including, in particular, David d’Enterria, Gonalo Borges, Helena Santos, Helmut Satz, Hermine Wöhri, Louis Kluberg, Mike Leitch, Pietro Faccioli, Ramona Vogt, Raphaël Granier de Cassagnac and Roberta Araldi.

References

- [1] T. Matsui and H. Satz, Phys. Lett. B178 (1986) 416.
- [2] G. Borges, PhD Thesis, IST, Lisbon, Portugal, 2005.
G. Borges *et al.* (NA50 Coll.), Eur. Phys. J. C43 (2005) 161.
B. Alessandro *et al.* (NA50 Coll.), CERN-PH-EP/2006-018, EPJC, in print.
B. Alessandro *et al.* (NA50 Coll.), Eur. Phys. J. C39 (2005) 335.
- [3] H. Santos, PhD Thesis, IST, Lisbon, Portugal, 2004.
B. Alessandro *et al.* (NA50 Coll.), CERN-PH-EP/2006-019, EPJC, in print.
- [4] D. Kharzeev, C. Lourenço, M. Nardi and H. Satz, Z. Phys. C74 (1997) 307.
- [5] K.J. Eskola, V.J. Kolhinen and C. Salgado, Eur. Phys. J. C9 (1999) 61.
- [6] C. Lourenço and H.K. Wöhri, Phys. Rep. 433 (2006) 127.
- [7] S.S. Adler *et al.* (PHENIX Coll.), Phys. Rev. Lett. 96 (2006) 012304.
A. Bickley *et al.* (PHENIX Coll.), these proceedings.
- [8] M.J. Leitch *et al.* (E866 Coll.), Phys. Rev. Lett. 84 (2000) 3256.
P. Faccioli *et al.* (HERA-B Coll.), these proceedings.
B. Alessandro *et al.* (NA50 Coll.), Eur. Phys. J. C33 (2004) 31.
L. Ramello *et al.* (NA50 Coll.), Nucl. Phys. A774 (2006) 59, and N. Topilskaya *et al.* (NA50 Coll.), poster at the Quark Matter 2005 Conference.
- [9] R. Arnaldi *et al.* (NA60 Coll.), these proceedings.
- [10] C. Lourenço *et al.* (NA60 Coll.), “Int. Work. on Heavy Flavor Physics in Heavy Ion Collisions at the LHC”, ECT*, Trento, Italy, 2006.
- [11] F. Karsch, D. Kharzeev and H. Satz, Phys. Lett. B637 (2006) 75.
- [12] A. David *et al.* (NA60 Coll.), these proceedings.
- [13] J. Qiu and X. Zhang, Phys. Lett. B525 (2002) 265.
- [14] T. Sjöstrand *et al.*, Comp. Phys. Comm. 135 (2001) 238.
- [15] M.C. Abreu *et al.* (NA38 and NA50 Colls.), Eur. Phys. J. C14 (2000) 443.
- [16] A. Adare *et al.* (PHENIX Coll.), hep-ex/0609010.
- [17] G. David *et al.* (PHENIX Coll.), these proceedings.
- [18] H.K. Wöhri *et al.* (NA60 Coll.), Eur. Phys. J. C43 (2005) 407.
- [19] K. Ozawa *et al.* (KEK-E325 Coll.), Phys. Rev. Lett. 86 (2001) 5019.
F. Sakuma *et al.* (KEK-E325 Coll.), nucl-ex/0606029.