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Charmonium and heavy quarks: status and future perspectives

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Abstract. The study of the production of heavy quarks and quarkonia in ultra-relativistic heavy-ion collisions is crucial for our understanding of high-temperature QCD. In particular, quarkonia states are sensitive to the presence of a deconfined state, and the study of heavy quark propagation in the medium created in the collision gives important information on the attained parton density. In this paper, I will shortly review the main questions that can be addressed by the study of these hard probes, summarize the SPS and RHIC results presented at this Conference and outline possible developments in the field.

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1 Introduction

The study of hard probes has been, from the very beginning of the quest for the quark–gluon plasma, one of the key tools at our disposal in the field of ultra-relativistic heavy-ion collisions. In particular, the early prediction of charmonium suppression as a signature of deconfinement [1], followed by the nearly immediate availability of experimental results, has triggered an enormous amount of studies. Now, after almost 20 years of work at the SPS, a reasonably clear picture is emerging, and recent RHIC results are starting to extend this picture to a higher energy domain.

On the contrary, the study of open charm production, the natural reference for the charmonium suppression measurements, is only now making its first steps, with the NA60, PHENIX and STAR experiments. The first results show intriguing features and a detailed understanding of the related physics topics seems to be within reach in the near future.

2 Charmonium suppression at SPS energies

The first results on J/ψ suppression appeared at the very beginning of the history of QGP physics [2,3]. It was immediately realized that the main issue concerning the interpretation of the data is related to the amount of suppression that has to be attributed to "normal" hadronic processes. Only when a proper understanding of the size of such processes is reached, any claim for "anomalous" suppression effects can be justified. This consideration has lead to a huge experimental effort, carried out by the NA38, NA50, NA51 and NA60 Collaborations, which measured charmonium production for a large variety of systems, from pp and p–A collisions, to S–U and, finally, In–In and Pb–Pb. At this Conference, a comprehensive summary of this saga has been presented [4], and other talks have given important hints to clarify the picture that has emerged [5,6].

Basically, from the study of proton induced collisions on various target nuclei, the absorption cross section for J/ψ on nuclear matter has been accurately estimated [7,8]. This is one of the hadronic effects that may mask the suppression induced by the deconfined state. The results from various data sets, taken at 400 and 450 GeV/c incident energy, and analyzed in the framework of the Glauber model, imply $\sigma_{\mathrm{abs}}^{J/\psi} = 4.18 \pm 0.35$ mb. It has been stressed [5] that old, higher values for this quantity were due to unaccounted relative biases between NA51 and NA38 data. Starting from this result, it has been shown [5] that also the J/ψ yield observed in S–U data, up to central collisions, can be understood assuming that normal nuclear absorption is the only source of suppression. This result poses new constraints to the long-debated influence of hadronic comovers on the J/ψ suppression in nuclear collisions [9–11].

Moving to Pb–Pb interactions, the well-known anomalous suppression [12], that sets in for semiperipheral Pb–Pb collisions, has been confirmed also in the most recent NA50 data set [4,13], taken in experimental conditions much improved with respect to the past (see Fig. 1). This result, one of the most intriguing of the whole SPS program, has often been interpreted as the proof of the formation of a deconfined state (see e.g. [14]). If recent lattice results on the temperature values needed to melt the J/ψ in a quark–gluon plasma ($T > 2T_{\mathrm{c}}$) [15,16] would be confirmed, then the observed effect might rather be due to the

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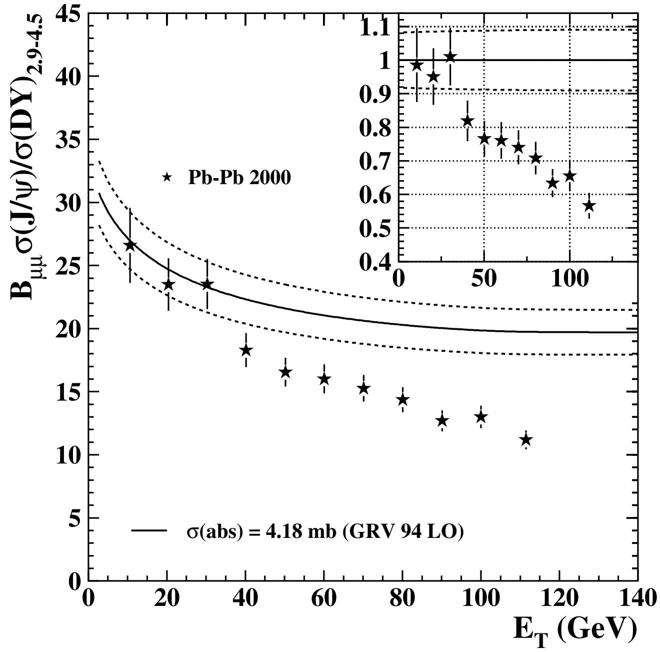

Fig. 1. The (J/ψ)/DY cross section ratio as a function of transverse energy for the NA50 2000 Pb–Pb data sample, collected at 158 GeV/nucleon. The "normal" absorption curve has been calculated using the 400 and 450 GeV p–A data only. The errors include the effect of the energy rescaling procedure

melting of the less bound χ_c. The experiment in fact cannot distinguish primary J/ψ from the ones coming from radiative χ_c-decays.

A preliminary result from NA60 on J/ψ suppression has also been presented at this Conference [6]. Integrating over the collision centrality, it has been shown that an anomalous suppression is present also in the lighter In–In system. The suppression pattern as a function of centrality will hopefully be available soon. By comparing the suppression pattern in In–In and Pb–Pb as a function of different centrality variables (L, the density of participants or the energy density), it will be possible to look for a scaling variable for the anomalous J/ψ suppression. This result will help to clarify which is the physical variable driving the onset of the anomalous suppression.

Further results have been shown concerning the differential J/ψ distributions. In particular, NA50 has presented [4], from its last Pb–Pb data sample, the centrality dependence of J/ψ suppression for various transverse momentum bins. The result indicates that the bulk of the suppression occurs at relatively low p_{T} ($< 1.5\,\mathrm{GeV}/c$). This topic had been theoretically investigated in the past [17,18], trying to understand the sensitivity of this observable to the formation of a deconfined state. It would be very interesting to see if the results now available are consistent with such a scenario.

Preliminary results for a new observable, the polarization of the J/ψ produced in heavy-ion collisions, have been presented by NA60 [6]. It is known that in p–A collisions almost no polarization is observed [19]. A recent theoretical work [20] assumes that this absence of polarization is mainly due to non-perturbative effects, that may be screened away in case of QGP formation. This effect would lead to values of the polarization parameter, λ, of the order of 0.4. Although with rather large error bars, the NA60 result shows, for In–In collisions, a J/ψ polarization compatible with zero.

In parallel to the studies with heavy-ion beams, an important activity with proton beams has taken place in recent years. Basically, the E866 experiment at FNAL and HERA-B at DESY have performed a systematic study of J/ψ production and suppression in p–A collisions at 800 and 920 GeV/c incident momentum, respectively. A wide systematics on the α parameter, obtained through fits of the p–A data with the usual formula $\sigma_{pA} = \sigma_{pp} \cdot A^{\alpha}$, is available for many x_{F} and p_{T} bins [21,22]. While the observed increase of α as a function of p_{T} is understood in terms of initial state interaction of the incident gluon, the interpretation of the x_{F} dependence is not straightforward. In this optic it would be extremely interesting to have results for the negative x_{F} domain, where the formation time of the resonance is expected to be shorter than the time it needs to cross the nuclear medium. HERA-B has presented at this Conference a result (see Fig. 2), based on 15% of its last, high statistics data set, showing that their acceptance extends down to $x_{\mathrm{F}} \sim -0.3$, and that α is of the order of 0.95 in the region $x_{\mathrm{F}} < 0$, with an approximately flat behavior [23].

Another important issue for charmonium studies, thoroughly discussed at the Conference, is the contribution of excited charmonium states, especially the χ_c and the ψ',

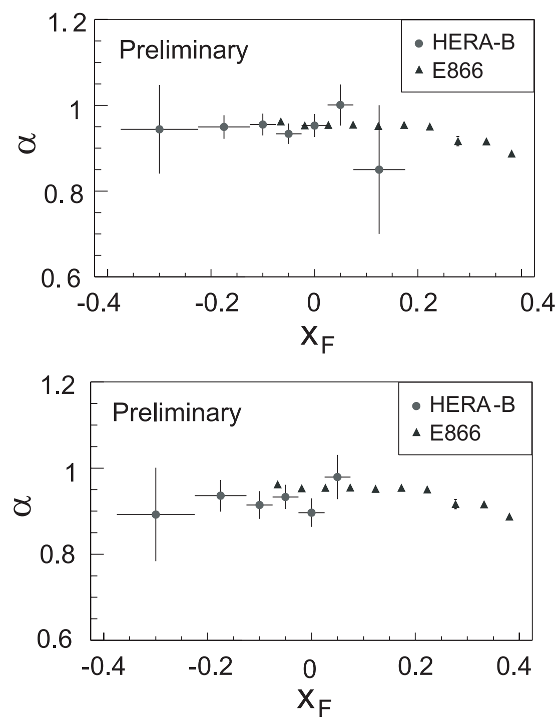

Fig. 2. The x_{F} dependence of the α parameter for the J/ψ. The two plots correspond to two different sets of data from the HERA-B experiment, and are compared with previous results from E866

to the J/ψ yield observed by the experiments. Even if for pp collisions the contributions of these resonances are approximately known, $\chi_c/(J/\psi) \sim 0.4$, $\psi'/(J/\psi) \sim 0.14$, a difference in the absorption cross section in nuclear matter for the excited states with respect to the J/ψ would sensibly alter these ratios in p–A and A–A collisions. As a consequence, it is important, to correctly set the baseline for the J/ψ suppression in nuclear collisions, to measure ψ' and χ_c production in p–A. While for ψ' rather good quality data exist (by E866 [21] and NA50/NA51 [7,8]), for the χ_c the first accurate results are appearing only now. In particular, HERA-B has reported the preliminary value 0.21 ± 0.05 for the ratio $\chi_c/(J/\psi)$, using part (15%) of the statistics from its last run (2002/2003) [23]. Once the full statistics will be available, it should be possible to extract α_{χ_c}, thanks to the availability of data on various nuclear targets. Also NA60 should report on this subject once its 2004 event sample will be analyzed.

In summary, charmonium suppression at fixed target energies is surely, in the hard probes domain, the most advanced topic, both in terms of theoretical and experimental efforts. However, it must be recognized that, in spite of the fact that we are dealing with a hard process, quantitative calculations of the production and hadronic suppression remain a difficult task. Fortunately, very good quality data exist, spanning the collision systems from p–p to Pb–Pb (NA50, E866, HERA-B). Even if the physics interpretation of the J/ψ suppression is still evolving, the anomaly observed in Pb–Pb has been confirmed by the most recent NA50 data, and observed by NA60 in the lighter In–In system. Globally, with the work done at the SPS, an important reference has been set for higher energy experiments at RHIC and LHC. Among the topics that still deserve attention, and possibly a measurement, I mention the investigation of the energy dependence of the charmonium suppression in p–A. The comparison between E866 results (800 GeV) and NA50 results (450 GeV) indicates, in the common kinematical domain, a sizeable difference in the absorption cross section for both the J/ψ and the ψ' states (for example, at mid-rapidity E866 quotes $\alpha_{\psi'} = 0.931 \pm 0.011$ while NA50 quotes $\alpha_{\psi'} = 0.858 \pm 0.017$). A measurement at SPS energy on a large kinematical domain is probably within the reach of NA60 and would be important for our understanding of the charmonia formation and interaction processes.

3 Charmonia at RHIC

Contrary to what happens at the SPS, charmonium physics at RHIC energy is making its first steps. The PHENIX experiment [24], with its muon and electron detection capability over a large kinematical window, provides an ideal tool to investigate J/ψ suppression effects. However, with respect to the SPS, new problems arise. First, the luminosity that can be reached at the ion collider is rather low, with respect to the fixed target environment. Secondly, the relatively large production cross section for $c\bar{c}$ pairs, about a factor 50 higher than at the SPS, leads to multiple production of heavy quarks. Therefore, on top of the possible suppression due to color screening, $c\bar{c}$ coalescence effects may be present and need to be correctly disentangled [25,26]. Finally, the feed-down effect from B-decays, negligible at the SPS, must be carefully estimated.

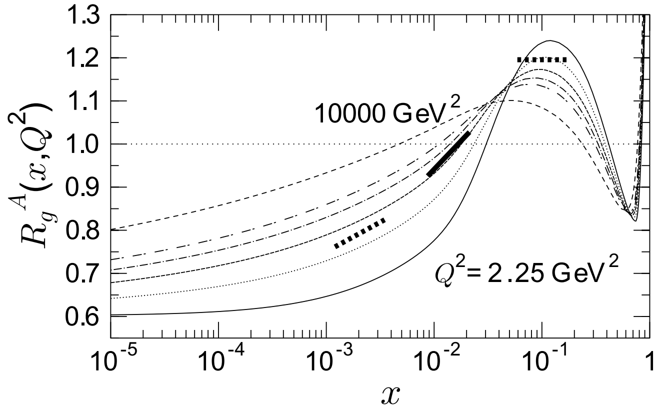

Fig. 3. Nuclear modification of the gluon structure functions. The dashed segments qualitatively represent the acceptance of the PHENIX muon arms, while the continuous segment shows the x-coverage for the central electron detector. For details on the various curves see [30]

For the moment a considerable effort has been put in setting an accurate baseline for the charmonium production in Au–Au collisions, by studying p–p and d–Au collisions at $\sqrt{s} = 200$ GeV [27,28]. These measurements are of course extremely important to understand shadowing and absorption effects that have to be taken into account in order to establish what would be the "normal" behavior for J/ψ production in nuclear collisions. In addition, the pp data are useful to constrain production models. Thanks to the wide angular coverage ($|\eta| < 0.35$ for electrons, $1.2 < |\eta| < 2.4$ for muons), more extended than in usual collider experiments, it has been possible to estimate the total cross section for J/ψ production. The values from Run-2 and a preliminary result from the higher-statistics Run-3 have been presented at the Conference [29]. Both color octet (COM) and color evaporation (CEM) models have been shown to agree with the measured values, even if some parameters, namely the factorization scale for the PDFs and the values of the charm quark mass, are tuned on the data.

Moving to d–Au collisions, the two muon arms allow PHENIX to cover both the regions where shadowing (North Muon Arm, $\langle x_2 \rangle \sim 0.003$) and anti-shadowing (South Muon Arm, $\langle x_2 \rangle \sim 0.09$) are expected (see Fig. 3). On the contrary, for the electron measurement, the two effects should balance. This is nicely seen in their $\mathrm{d}\sigma/\mathrm{d}y$ result for the J/ψ, that exhibit a clear asymmetry between positive and negative rapidity (see Fig. 4). The overall shadowing effect turns out anyway to be small, since comparing d–Au and p–p data and performing a fit with the usual A^{α} parameterization one gets values compatible with 1, except for the point at larger x_2 ($\alpha = 0.92$). The relatively low statistics makes it difficult to disentangle the various nuclear effects. It has been shown anyway, by

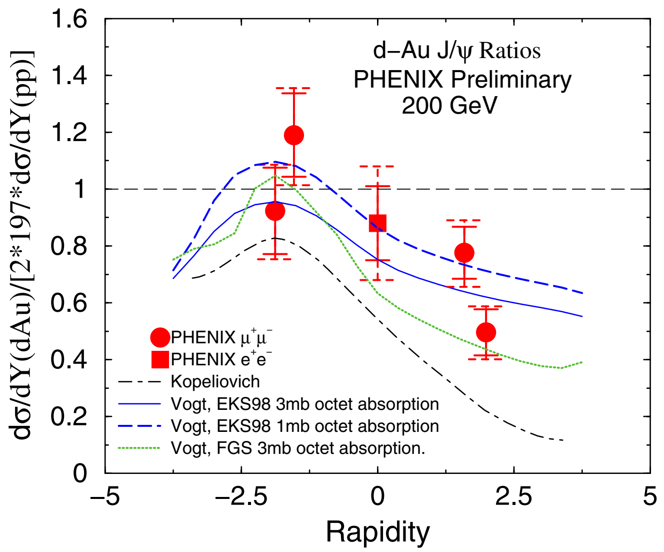

Fig. 4. Ratio between d–Au and pp J/ψ differential cross sections, divided by $2 \cdot 197$, versus rapidity. Predictions of various models are also shown [31,32]

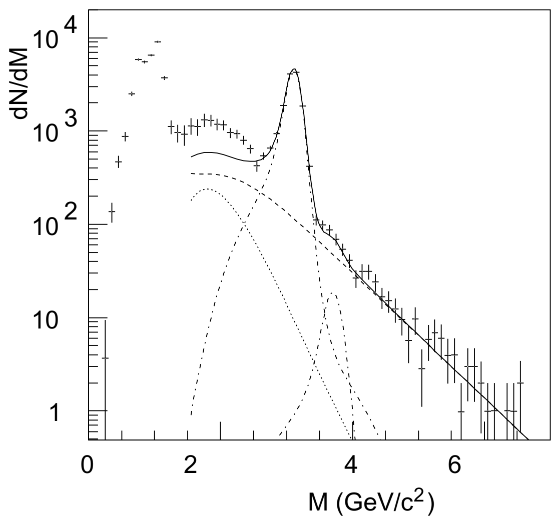

Fig. 5. Comparison between the data and the sum of the expected sources (solid line) for central Pb–Pb collisions, as measured by NA50. The Drell–Yan (dashed line), J/ψ, ψ' (dashed-dotted line) and open charm (dotted line) contributions are also shown. The excess in the IMR is clearly visible

comparing E866 and PHENIX data, that there is no x_2 scaling, thus indicating that the nuclear effects observed in $p(d)$–A collisions cannot be ascribed to shadowing effects only. Finally, also at RHIC the J/ψ p_{T} distributions clearly show a broadening in d–Au with respect to pp.

For Au–Au interactions the presently available results (2002 data) are, of course, not conclusive, due to their poor statistics [33]. The only conclusion claimed up to now is that models which predict a large J/ψ enhancement due to coalescence effects seem to be disfavored by the data. The 2004 Au–Au data, now being analyzed, will provide a statistics of the order of $3{\cdot}10^3$ J/ψ [29]. With such a sample it will be possible to analyze the centrality dependence of the J/ψ yield. It should be noted that the Drell–Yan reference, used at the SPS for the study of the J/ψ suppression, will not be available at RHIC, due to the lack of statistics. It could anyway be replaced by the (unsuppressed) open charm signal, provided that the systematics on its evaluation are well under control.

In summary, the first available results from PHENIX confirm that the experiment is very well suited for the study of charmonia production at $\sqrt{s} = 200\,\mathrm{GeV}$. Clearly, the effective impact of the data on our understanding of the various physics topics is nowadays limited by the machine luminosity. For example, any ψ' studies, or the detection of the bottomonium states, are out of the present reach. The foreseen upgrade towards RHIC-2, yielding a 40 times larger luminosity, is therefore mandatory for the completion of the quarkonia physics program [34].

4 Open charm production at the SPS

The study of open charm production has a twofold interest in heavy-ion physics. First, open charm is the natural (hard) reference for the charmonia suppression study. The other hard process used as a reference, Drell–Yan, does not share with charmonium the same initial state partons and therefore might be differently affected by initial state effects, such as shadowing. Secondly, heavy quarks, being produced in the first stages of the collision, may experience various effects (quenching, flow) that may be linked to the properties of the created medium. Unfortunately, non-negligible experimental difficulties have much delayed the study of open charm with respect to charmonia.

Until very recently, the available data from heavy-ion experiments at SPS have come from indirect measurements via dilepton pairs. As a first step, by performing a mass and p_{T} shape analysis of the distributions obtained in p–A collisions, the HELIOS-3 and NA38/NA50 experiments have singled out, in the region between the ϕ and the J/ψ (the so-called intermediate-mass region, or IMR), the contribution to the spectrum due to simultaneous semileptonic decays of D-meson pairs [35,36]. By means of extrapolations that make use of event generators (essentially PYTHIA) for the evaluation of the differential spectra, the total cross section for open charm production can be estimated. The results show that, within systematic errors of the order of 10–20%, there is good agreeement between such indirect measurements and direct measurements of open charm performed at previous SPS and FNAL experiments.

The same experiments, when using the same technique in the analysis of nucleus–nucleus data, have found a significant excess with respect to expectations based on binary scaling of open charm production from p–A to A–A [35,36] (see Fig. 5). These puzzling observations have led to various speculations on the origin of the observed excess. A trivial origin as unsubtracted combinatorial background from π- and K-decays seems to be excluded (see [36] for a discussion). Moving to the possible physics origin, it has been shown that the differential distributions of the excess are in very good agreement with the ones expected for open charm dimuons. However, an enhancement of open charm production is not easy to explain theoretically. Other groups have speculated that a significant modification of the differential distributions of dileptons from open charm, due to in-medium effects, might lead to local enhancements of the yield in certain phase space regions [37]. Finally, it has been shown that the Pb–Pb excess in the intermediate-mass region can be attributed to the production of thermal dimuons, part of them coming from a deconfined phase with a temperature of about 200 MeV [38].

Clearly, to move a step forward in our understanding of open charm, a significant improvement is needed. This challenging task is at the core of the NA60 experiment [39]. This experiment couples the NA50 muon spectrometer, positioned downstream of a 5.5 m long hadron absorber, with a vertex detector based on silicon pixel planes. By matching the muons detected in the muon spectrometer with the corresponding tracks in the vertex detector, positioned upstream from the hadron absorber, it is possible to detect the typical offset of the muon coming from the semileptonic D-meson decay. While a complete reconstruction of the decay products of the charmed mesons is not possible, by selecting events with muons having offsets of the order of a few hundred μm one can obtain a sample dominated by open charm decays.

The first, preliminary results from NA60, based on the In–In data sample collected in 2003, have been presented at this Conference [40]. The matching of the muons to the tracks in the vertex spectrometer is performed in coordinate and momentum space. Basically, it has been shown that the resolution on the measurement of the muon's offset is better than 50 μm, confirming the expectation of the Monte-Carlo simulation. By applying a preliminary selection on the measured offset, a "prompt" and an "offsetted" event sample have been obtained. It has been shown (see Fig. 6) that in the "offsetted" sample the signal from short-lived resonances is, as expected, suppressed, while in the region between the ϕ and the J/ψ, where the open charm signal contributes, an enhancement is clearly seen. Further work is still needed in order to reach a quantitative estimate of the open charm cross section, especially for what concerns the subtraction of the events where a "fake" matching is present. Anyway these issues are under study and will likely be solved soon. In this way it will be possible to find an answer to the IMR puzzle raised by Helios-3 and NA38/NA50 and obtain a result on the open charm production that will have to be compared with the forthcoming RHIC data. Concerning the future, a further NA60 run with Pb-projectiles would be of first importance to complete the SPS systematics.

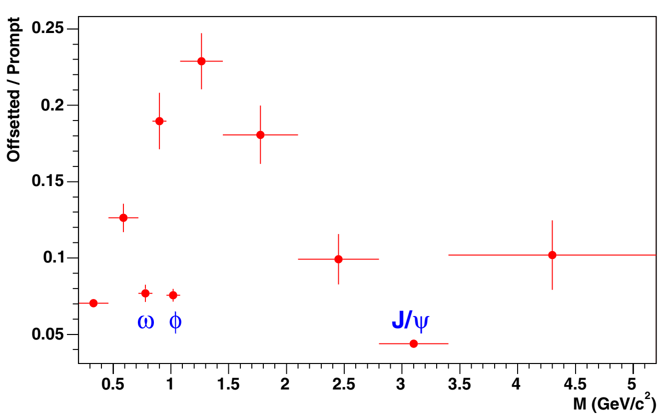

Fig. 6. Ratio between the "offsetted" and the "prompt" event sample, measured by NA60 in In–In collisions. The suppression of the short-lived resonances can be clearly seen

5 Open charm production at RHIC

At RHIC, the two large experiments, PHENIX and STAR, have used various techniques for the detection of open charm. Contrary to the charmonium measurement, here the machine luminosity is not a problem, since the cross section for open charm production is much larger. The first results that have appeared are based on the measurement of single electrons from semi-leptonic decays [41]. The main physics issues are the determination of the high p_{T} behavior of open charm production, as well as the measurement of the total cross section. The adopted technique clearly suffers from the large background due to various photon conversion processes. Even if the background subtraction techniques appear to be well under control, the "non-photonic" signal that includes the open charm decay contribution is significant only for $p_{\mathrm{T}} > 1.5\,\mathrm{GeV}/c$. Therefore, large systematic errors still affect the total cross section estimate.

Moving to the available results, PHENIX has presented the p_{T} spectrum of non-photonic electrons from p–p collisions at $\sqrt{s} = 200\,\mathrm{GeV}$ [42]. By comparing this result with PYTHIA, one can see that the event generator underestimates the measured data points for $p_{\mathrm{T}} > 2.5\,\mathrm{GeV}/c$. This discrepancy might be attributed to the presence of an electron signal due to B-decays, even if no definitive conclusion in this sense can be drawn for the moment. By integrating the measured single electron p_{T} distribution, PHENIX obtains an estimate of the total open charm cross section, in reasonably good agreement with the result of a NLO calculation [43].

With the same technique, the open charm yield has been measured in d–Au collisions at $\sqrt{s} = 200\,\mathrm{GeV}$. Scaling the d–Au single electron spectrum by the inverse of the number of N–N collisions N_{coll} and comparing the spectrum with a phenomenological fit of the pp data, one can study the influence of the nucleus on open charm production. As already observed at lower energy (by E866, for example), no significant nuclear effects are found. This observation is also in qualitative agreement with the absence of nuclear modifications, found in the $J/\psi \to e^+e^-$ data. Furthermore, the observation of the N_{coll} scaling of open charm production has been verified for various centrality bins defined for the d–Au system [42].

Finally, the single electron spectra from Au–Au collisions have been analyzed [44]. Even with the non-negligible systematic errors connected with this approach, it is already possible to address with these data two important physics questions. First, one can check if the quenching at high p_T, spectacularly observed in the light quark sector, holds also for heavy quarks. Second, it is possible to look for deviations from the N_{coll} scaling in the total yield, that might indicate an anomalous suppression or enhancement of open charm production in nucleus–nucleus collisions.

Concerning the p_T spectra as a function of centrality (see Fig. 7), no strong quenching is visible in any of the centrality bins. Anyway the rather poor statistics beyond $p_T \sim 2.5\,\mathrm{GeV}/c$ must be noted; the observation of really high transverse momenta will be possible only when the 2004 data analysis will be completed. Concerning the N_{coll} scaling for the single electron spectra, no strong deviations have been observed up to the most central Au–Au collisions. By fitting the data with the usual A^{α} parameterization the value $\alpha = 0.938 \pm 0.075(\mathrm{stat}) \pm 0.018(\mathrm{syst})$ has been obtained [42]. This value shows that no open charm enhancement is present at RHIC energy and might indicate that the IMR excess observed at the SPS is likely to be due to a different physics process.

Clearly, in order to significantly decrease the systematic errors of the single electron analysis technique, a measurement of the offset of the electron with respect to the interaction point (as done in NA60) would be necessary. The detector upgrade needed for this measurement is now in progress [34]. For the time being, an important result in this sense has been accomplished by STAR, that has performed a direct open charm hadronic decay reconstruction in d–Au collisions [45]. This measurement can provide an independent validation of the results obtained with the single electrons. At this Conference, results on D^0, $D^{\pm}$ and D^* have been presented [46]. The total cross sections measured by STAR, extrapolated from single electrons, and from the reconstruction of hadronic D-meson decays, are in good agreement. The observed discrepancy, at the 2σ level or less, between the PHENIX and STAR total cross sections, should not be considered as a serious problem at this preliminary stage.

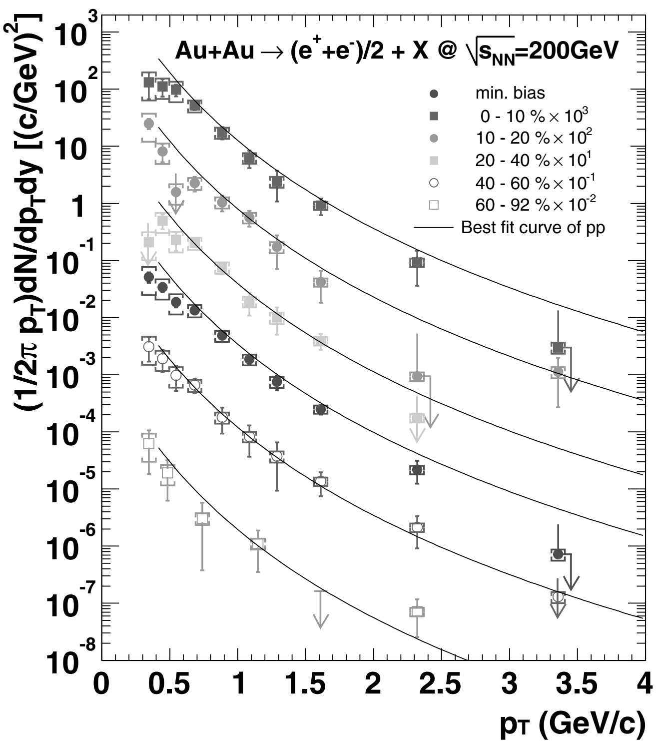

Fig. 7. Transverse momentum spectra of single electrons from heavy-flavor decays, as measured by PHENIX. The sets of points correspond to various centrality bins. The continuous lines show the extrapolation of p–p data, scaled by the nuclear overlap function T_{AA}

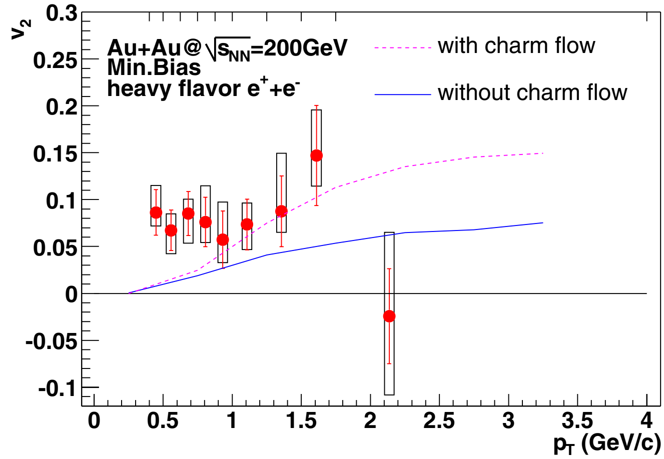

Fig. 8. Preliminary results from Au–Au collisions on the elliptic flow of electrons from heavy-flavor decays

Between the various open charm topics presently under investigation, one of the most promising is the study of the flow of c-quarks. Basically, it has been observed that the single electron p_T spectra cannot discriminate between the "classical" scenario where open charm is treated as a hard process, and a scenario where there is an early thermalization of the c-quarks that then participate in the collective flow [47]. To solve the issue, a direct measurement of the c-quark flow is necessary [48]. Preliminary results by PHENIX and STAR seem to indicate that a sizeable flow signal is present for electrons from heavy quark decays [49, 50] (see Fig. 8). If this effect will be confirmed after a full understanding of the various systematics, we would have a first important indication for strong collective effects on heavy quark production.

In summary, the study of open charm production at RHIC, performed through the indirect measurement of single electron spectra, has already given quite interesting results. In particular, the observation of N_{coll} scaling up to the most central Au–Au collisions excludes any significant suppression or enhancement of open charm production at $\sqrt{s} = 200\,\mathrm{GeV}$. Furthermore, the observation of the flow of c-quarks, if confirmed, would significantly change the current understanding of the propagation of heavy quarks in the medium created in the collisions. For the near future, apart from the improvements due to the larger statistics collected in 2004, a significant step forward will be performed once the detector upgrades will be finally available [34].

6 Conclusions

After almost 20 years, the study of quarkonia and heavy quark produced in heavy-ion collisions continues to be a hot and lively physics topic. At the SPS, the anomalous J/ψ suppression is considered one of the golden signatures of deconfinement, even if the related theoretical interpretation is still under discussion. The study of open charm is making its first steps, and promising results from NA60, PHENIX and STAR are now starting to appear. We should achieve, in a few years from now, a satisfactory understanding of the various physics issues, needed in order to fully profit of the new investigation window that will be opened by the LHC, well beyond the critical temperature for the phase transition. In parallel, of course, it would be extremely interesting to continue addressing specific questions relative to the SPS and RHIC energy domains, where one can investigate effects connected with the crossing of the border between hadronic and deconfined matter.

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