

**$J/\Psi$  production at high  $p_T$  in p+p and A+A collisions at STAR**

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The  $c\bar{c}$  bound state  $J/\Psi$  production at high  $p_T$  could be due to color-singlet or color-octet processes. But the details of the production mechanism and hadronization remain open questions. Depending on the production mechanism, high-pt  $J/\Psi$  production in nucleus-nucleus collisions can be used as a probe for heavy-quark energy loss, gluon energy loss or quarkonium hot-wind dissociation in QGP.

In this talk, we will present our analysis of mid-rapidity ( $|y| < 1$ )  $J/\Psi \rightarrow e^+e^-$  production at  $p_T \gtrsim 5$  GeV/ $c$  in p+p collisions at  $\sqrt{s} = 200$  GeV. The datasets are from RHIC year 2005 and 2006 runs, sampling a few (pb)<sup>-1</sup> of p+p collisions in a trigger on electron energy deposited in Electromagnetic Calorimeter. The differential cross sections provide a baseline for study of  $J/\Psi$  suppression at high  $p_T$  in heavy ion collisions at RHIC. The first measurements of high  $p_T$   $J/\Psi$ -hadron azimuthal angle correlation may shed light on the  $J/\Psi$  production mechanism and hadronization. Results from on-going analyses in Cu+Cu and Au+Au collisions at 200 GeV taken in year 2005 and 2007 from sampled equivalent luminosity of a few (pb)<sup>-1</sup> of underlying p+p collisions will also be presented.

**First measurement of the  $J/\psi$  elliptic flow parameter  $v_2$  in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV by the PHENIX experiment**

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Recent results indicate that the  $J/\psi$  suppression pattern differs with rapidity showing a larger suppression at forward rapidity.  $J/\psi$  suppression mechanisms based on energy density (such as color screening, interaction with co-movers, etc.) predict the opposite trend. On the other hand, it is expected that more  $c\bar{c}$  pairs should be available to form quarkonia at mid-rapidity via recombination. Even though available models fail to reproduce simultaneously all  $J/\psi$  data and lack of experimental inputs such as cold-nuclear matter effects, open charm cross-section or feed-down ratio, they provide a way to differentiate  $J/\psi$  production from initially produced  $c\bar{c}$  pairs and final state recombination of uncorrelated pairs, via the

rapidity and transverse momentum dependence of the elliptic flow ( $v_2$ ). Measuring the  $J/\psi$   $v_2$  would allow to quantify the collective behavior of the  $J/\psi$  meson and its precursors and better constrain the space-time evolution of heavy-particles in the matter.

During 2007 data taking at RHIC, a large sample of Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV was collected. The statistics has been highly increased compared to previous data set from 2004, thus allowing a more precise measurement of the  $J/\psi$  meson at both mid and forward rapidity. Furthermore, the PHENIX experiment benefited from the addition of a new detector, which improves the reaction plane resolution and allows us to measure the  $J/\psi$  elliptic flow parameter  $v_2$ . Comparing this measurement to the positive  $v_2$  measured for D-mesons (coming from non-photonic electrons) will help constrain the  $J/\psi$  production mechanisms and get a more precise picture on the proportion of  $J/\psi$  coming from direct production or charm quark coalescence.

Details on how the  $J/\psi$   $v_2$  is measured at both rapidities will be presented. The  $J/\psi$   $v_2$  as a function of transverse momentum will be compared to existing models.

## **$J/\psi$ suppression in p-A and In-In collisions at 158 GeV/nucleon**

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A high-statistics study of  $J/\psi$  production in p-A and In-In collisions at 158 GeV/nucleon has been carried out by the NA60 Collaboration at the CERN SPS.

In p-A collisions, the  $J/\psi$  production has been studied for the first time at the same energy of the previously taken nucleus-nucleus data (In-In by NA60 and Pb-Pb by NA50). We will present the first preliminary results on the cross section  $\sigma_{\text{abs}}$  for nuclear absorption, extracted by comparing the  $J/\psi$  yield on seven different targets (Be, Al, Cu, In, W, Pb and U). This quantity has a fundamental role in defining, for nucleus-nucleus collisions, the fraction of the observed  $J/\psi$  suppression due to cold nuclear matter effects.

We will also present results on the rapidity and transverse momentum distributions of the  $J/\psi$  produced in p-A collisions. By comparing the transverse momentum distributions in p-A and In-In, we will extract the nuclear modification factor  $R_{AA}(p_T)$ , that will be compared with results obtained at higher energy by PHENIX.

In nucleus-nucleus collisions, the azimuthal distributions of quarkonium, relative to the reaction plane, are expected to be sensitive to the various physics mechanisms at the basis of the anomalous suppression. We will show results on the azimuthal anisotropy of the  $J/\psi$  in In-In collisions, showing the dependence of the Fourier coefficient  $v_2$  on centrality and transverse momentum.

Finally, the already existing NA60 results on the anomalous  $J/\psi$  suppression are based on a normalization procedure that makes use of the Drell-Yan yield. This approach will be complemented by a study of the absolute cross sections, providing in this way an alternative, independent normalization of the nucleus-nucleus yield with respect to p-A.

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Quarkonia at finite temperature are an important tool for the study of quark-gluon plasma formation in heavy ion collisions. Although many efforts have been devoted to study the properties of  $Q\bar{Q}$  states in the deconfined medium, the intrinsic technical difficulties of lattice calculations, somehow limits the reliability and the scope of the results obtained so far. Potential model, on the other hand, provide a simple and intuitive framework for the study of quarkonium properties at finite temperature and they can provide a useful complement to the lattice calculations.

Since a formal derivation from first principles of the effective potential at finite temperature is not available yet, it is important to check the consistency of the potential model results with the whole body of lattice data. We present here a recent calculation of charmonium Euclidean correlators at  $T > T_c$ , employing effective potentials extracted from lattice data for the  $c\bar{c}$  free and internal energies and including the effect of zero modes in the lattice spectral functions (Fig.1). We find that a good description of the lattice correlators can be obtained in the  $P$ -wave channels, whereas in the  $S$ -wave ones small but systematic discrepancies between potential model and lattice data are found.

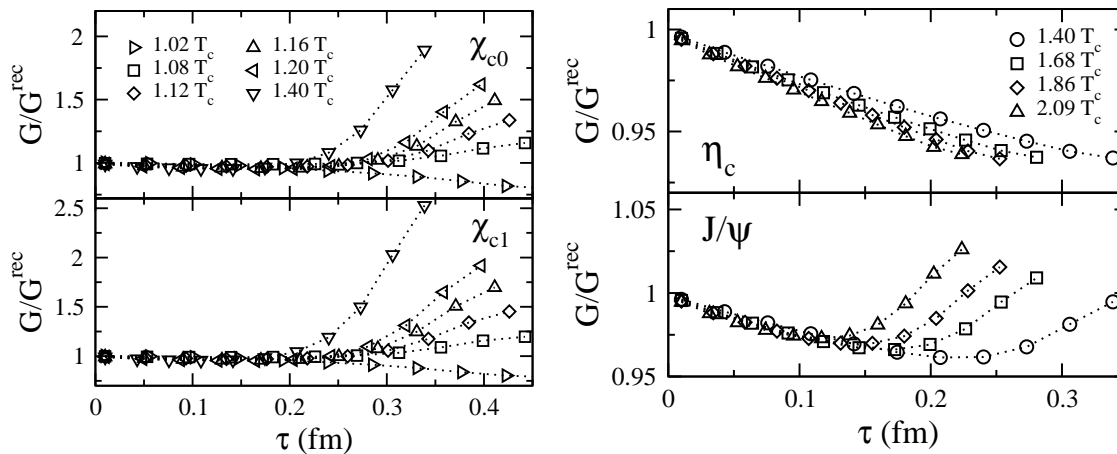


Figure 1: Ratio of the  $N_f = 2$  charmonium Euclidean correlators at various temperatures to the reconstructed one at  $T = 1.05T_c$ .

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## STATISTICAL HADRONIZATION OF CHARM: FROM FAIR TO LHC

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Charmonium production is considered, since the original proposal more than 20 years ago about its suppression in a Quark-Gluon Plasma (QGP) [1], as an important probe to determine the degree of deconfinement reached in the fireball produced in ultra-relativistic nucleus-nucleus collisions. In recent publications [2] we have demonstrated that experimental data on  $J/\psi$  and  $\psi'$  production in nucleus-nucleus collisions at the SPS and RHIC energies can be well described within the statistical hadronization model proposed in [3].

In this contribution we demonstrate that regeneration of charmonia at the phase boundary provides a natural explanation of the maximum of  $R_{AA}^{J/\psi}$  observed at RHIC energy by the PHENIX collaboration [4]. We will confront the model with other available experimental data and provide predictions for the LHC energy, where qualitatively new features of  $J/\psi$  production are expected and await validation by data in the coming years. In addition we present the results of an exploratory study [5] of charmonium and open charm production close to the charm production threshold ( $\sqrt{s} \approx 6$  GeV), an energy domain which can be investigated in the CBM experiment at the future FAIR facility. Emphasis is placed on the identification of effects on charmed hadron production due to possible in-medium modifications of masses of hadrons with open charm.

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## Thermal Charm Production in QGP at LHC

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Charm production from the quark-gluon plasma created in the midrapidity of central heavy ion collisions at the Large Hadron Collider (LHC) is studied in the next-to-leading order in QCD. Using a schematic longitudinally boost-invariant and transversally expanding fire-cylinder model, we find that thermal charm production could be appreciably enhanced at LHC as a result of the high temperature that is expected to be reached in the produced quark-gluon plasma. Sensitivities of our results to the initial thermalization time and temperature of the quark-gluon plasma as well as the charm quark mass are also studied.

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We study heavy quarkonium properties in the Quark Gluon Plasma by computing an in-medium  $Q\bar{Q}$   $T$ -matrix within a reduced Bethe-Salpeter equation in both  $S$ - and  $P$ -wave channels [1,2]. The interaction kernel is extracted from recent finite-temperature lattice QCD calculations of the singlet free and internal energies of a  $Q\bar{Q}$  pair. The  $T$ -matrix approach is particularly suited for this problem as it provides a unified treatment of bound and scattering states, including nonperturbative threshold and rescattering effects, as well as the transition to the (perturbative) continuum. The  $T$ -matrix is applied to compute  $Q\bar{Q}$  spectral functions and Euclidean-time correlation functions.  $S$ -wave charmonia are found to gradually reduce their binding, but survive up to temperatures above  $2T_c$ , supporting lattice QCD spectral function analyses. Contrary to recent claims in the literature, the pertinent Euclidean correlators are found to be in good agreement with available lattice QCD correlators in axial-/vector and pseudo-/scalar channels [3]. The interplay of reduced binding energies, threshold effects and in-medium heavy-quark masses, as well as zero-mode excitations, turn out to be essential. We also investigate the impact of finite charmonium widths which are important for phenomenological applications in heavy-ion reactions.

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## $J/\psi$ production in $pp$ collisions at $\sqrt{s}=200$ GeV in the STAR Experiment

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In relativistic heavy ion collisions we expect the formation of a hot and dense matter where quarks and gluons would move freely, experiencing hadronic deconfinement. One of the experimental signatures of such a state of nuclear matter is the suppression of the  $J/\psi$  production by color screening, as firstly predicted by Matsui and Satz. Recent lattice QCD calculations predict that the temperature achieved by the medium is not high enough to dissolve the promptly formed  $J/\psi$ 's, but would be enough to melt excited  $c\bar{c}$  states, resulting in a suppression pattern due to feeddown. In order to verify such suppression, there must be a

baseline measurement to compare with the  $J/\psi$  production in  $A+A$  collisions. This baseline is the purpose of this reported measurement. The STAR experiment developed a specific trigger for  $J/\psi$  measurement in  $p+p$  collisions for the RHIC run of 2006, and the results of this measurement are presented in this work. We report results on total cross section and  $p_T$  spectrum.

## Upsilon production in p+p and Au+Au collisions in STAR

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The study of quarkonium production in relativistic heavy ion collisions provides insight into the properties of the produced medium. While the use of charmonium has a long history, it has become clear from lattice studies that a full spectroscopy including bottomonium can provide us a better thermometer for the produced matter. With the completion of the STAR Electromagnetic Calorimeter and with the increased luminosity provided by RHIC in runs 6 and 7, the study of  $\Upsilon$  production via the di-electron channel becomes possible. We present the results on  $\Upsilon$  measurements in p+p collisions from  $9 \text{ pb}^{-1}$  (Run 6) as well as preliminary results from Au+Au collisions (Run 7).

### TRANSVERSE MOMENTUM DEPENDENCE OF $J/\psi$ SHADOWING EFFECTS IN dAu COLLISIONS

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We present our results on  $J/\psi$  production in the framework of a new Monte Carlo code, based on the Glauber model, and where the cold nuclear matter effects -*shadowing*- have been introduced [1]. The inputs of our Monte Carlo are the  $J/\psi$  rapidity and transverse momentum extracted from  $\sqrt{s_{NN}} = 200 \text{ GeV}$  proton+proton data measured by the PHENIX experiments.

We investigate two different possibilities for the shadowing effects: the multiple scattering approach [2], that corresponds to recombination in the infinite momentum frame and which

results in absorption, and the evolution models [3], that study the  $Q^2$ -evolution of nuclear ratios of parton densities through the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution equations.

We present our results on the nuclear modification factor  $R_{dAu}$  as a function of rapidity  $y$ , number of collisions  $N_{coll}$  and transverse momentum  $p_T$ , compared to the existing PHENIX experimental data. We pay special attention to the behavior of  $R_{dAu}$  versus  $p_T$ , since its behaviour changes drastically depending on the type of shadowing considered, giving new experimental possibilities to discriminate between the different effects. Moreover, in our scenario it is also possible to estimate the amount of cold nuclear matter effects for nucleus+nucleus collisions both at RHIC and LHC energies.

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## Angular Dependence of the Gluon Radiation off Heavy Quarks

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We study the medium-induced radiative energy loss of heavy quarks outside a finite jet cone [1][2][3]. The gluon radiation spectrum deduced respectively by Magdalena Djordjevic and Miklos Gyulassy (N=1 opacity approximation) [4] and Urs Achim Wiedemann [1][5] in the multiple soft scattering approximation and single hard scattering approximation [6][7][8] are used. The results with dead cone approximation [7][9][10] are also calculated in our work. We find the effect of destructive interference plays an important role in gluon radiation for very small path length  $L$ , which leads to the negative value of medium-induced energy loss. Brownian  $\mathbf{k}_\perp$ -broadening effect is dominant in angular dependence of medium-induced gluon distribution. For the dead cone approximation, there is a maximum for the radiation energy loss outside a finite cone. While for gluon spectrum without the dead cone approximation, there is a minimum at small cone and a maximum at larger angle for small path length and for large path length the energy loss outside a cone decrease monotonously with the increase of angle due to the vanish of vacuum radiation at small angle [7][11].

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## ERROR BAND IN HEAVY QUARK THERMALIZATION: THE VIEWPOINT OF THEORY

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The so-called "thermalization" of heavy quarks in URHIC observed recently in non-photonic electrons yield at RHIC pleads toward the formation of a new state of matter, i.e. QGP. Among the theoretical approaches adopted in order to reproduce the unexpectedly large quenching of those quarks in the QGP, the pQCD line consists in considering  $2 \rightarrow 2$  collisional and  $2 \rightarrow 3$  radiative processes, either within some microscopic Markovian process "à la Boltzmann" [1] or via the transport coefficients implemented in an effective Fokker-Planck evolution equation [2,3]. In more recent approaches, relying on the concept of sQGP, one evaluates those transport coefficients by assuming the validity of the ADS/CFT correspondence.

At first view, this more "exotic" line leads to typical values of the nuclear modification function  $R_{AA}$  that are more compatible with experimental results than the pQCD approach. However, before any robust conclusion can be drawn, it is mandatory to implement one of the basic features of QCD – i.e. the running of the coupling constant  $\alpha_s$  – into the evaluation of the cross-sections and of the transport coefficients along the pQCD line. Following the recent work of one of us [4], we have performed this task for the case of  $2 \rightarrow 2$  processes (which dominate for heavy quarks produced at small  $p_t$ ) and implemented those into a realistic scenario of QGP evolution. In this contribution, we will present the phenomenological consequences of this theoretical improvement on the  $R_{AA}$  and  $v_2$  of the (D,B) mesons as well as on the non-photonic electrons.

We will also discuss the role of using either Boltzmann or Fokker-Planck equation as a model of the heavy quark evolution within QGP. Indeed, the number of collisions is marginally large enough to justify the Fokker-Planck approach on the theoretical ground, with the physical consequences that large fluctuations might be present for certain classes of events. Using the same background scenario for the QGP evolution and the same model for the  $2 \rightarrow 2$  collisions and the conversion "Q  $\rightarrow$  open flavor mesons  $\rightarrow$  electrons chain", we have been able to quantify the precise role of the evolution equation on the phenomenological observables, which should be included in the theoretical "error band".

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## Onset of $J/\psi$ Melting in Quark-Gluon-Fluid at RHIC

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Heavy quarkonia ( $J/\psi$ ,  $\psi'$ ,  $\chi_c$  and  $\Upsilon$ ) have long been considered as one of the most promising probes for the deconfinement of matter composed of quarks and gluons (Quark-Gluon-Plasma, QGP), since their production is expected to be suppressed due to color screening in the deconfinement matter [1].

A strong suppression of  $J/\psi$  production in central Au+Au collisions at the center of mass energy per nucleon ( $\sqrt{s_{NN}}$ ) of 200 GeV has been observed by the PHENIX experiment at the Relativistic Heavy Ion Collider (RHIC) [2].

We develop a hydro+ $J/\psi$  model in which hot quark-gluon fluid is described by full (3+1)-dimensional relativistic hydrodynamics and  $J/\psi$  is treated as an impurity traversing through the matter [3]. The experimental  $J/\psi$  suppression pattern in midrapidity in Au+Au collisions at RHIC is reproduced well by the sequential melting of  $\chi_c$ ,  $\psi'$  and  $J/\psi$  in dynamically expanding fluid as shown in Fig. 1. The melting temperature of directly produced  $J/\psi$  is well constrained by the participant-number dependence of the  $J/\psi$  suppression and is found to be  $\sim 2T_c$ .

Recently we calculated  $J/\psi$  azimuthal anisotropy ( $v_2$ ) as functions of the number of the participants and  $p_T$  in Au+Au collisions at RHIC. We extended the calculation of the survival probability and  $v_2$  of  $J/\psi$  from midrapidity to the forward rapidity ( $y \sim 2$ ) region. We also studied the survival probability and  $v_2$  of  $J/\psi$  for the case where  $J/\psi$  is completely thermalized in hot quark-gluon fluid and for the case where the melting temperature has  $p_T$  dependence of  $J/\psi$ , which is inferred from the hot-wind (AdS/CFT correspondence) calculation [4].

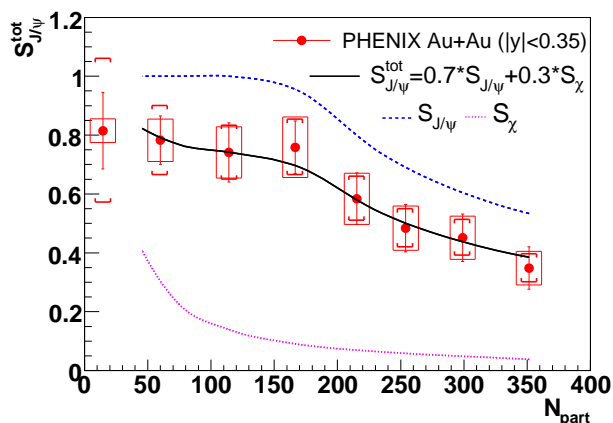


Figure 2: Survival Probability of  $J/\psi$  as a function of the number of participants. Red points and lines are the experimental and hydro- $J/\psi$  model results, respectively. Melting temperature of  $J/\psi$  is  $2.02T_c$ .

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# Measurements of heavy quark production via single leptons at PHENIX

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The measurement of the semi-leptonic decay of D and B mesons is a well established experimental method for investigating heavy quark production in p+p and heavy ion collisions. PHENIX possesses the capability to measure single leptons in both the electron channel at mid rapidity and the muon channel at forward rapidity. These measurements are made in wide ranging production environments at RHIC, from the single point-like QCD interactions of p+p collisions to the dense partonic fluid produced in central Au+Au collisions. Measurements in p+p collisions permit tests of state-of-the-art pQCD calculations at  $\sqrt{s}=200$  GeV and allow for estimates of both the total charm cross section and its rapidity evolution. Heavy quark measurements in p+p also provide a key baseline in the nuclear modification factor,  $R_{AA}$ , against which the heavy-ion single lepton measurements are quantified. The simultaneous observation of non-zero heavy quark azimuthal anisotropy  $v_2$  and suppressed  $R_{AA}$  reflect the existence of a dense partonic medium in the most central Au+Au collisions. Extending the heavy quark measurements to Cu+Cu and d+Au and examining the rapidity dependence will provide additional insight into heavy quark production at RHIC. This talk presents the most recent PHENIX single lepton measurements and discusses our evolving understanding of heavy flavor production at RHIC in terms of the current theoretical landscape.

## NEW RESULTS ON $\Upsilon$ PRODUCTION USING p+p and p+d INTERACTIONS

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New results from Fermilab E866/NuSea are reported. E866 has completed a high statistics measurement of  $\Upsilon$  production using an 800 GeV/c proton beam on liquid hydrogen and deuterium targets. The dominance of the gluon-gluon fusion process for  $\Upsilon$  production at this energy implies that the cross section ratio,  $\sigma(p+d \rightarrow \Upsilon)$ , is sensitive to the gluon content in the neutron relative to that in the proton. Over the kinematic region  $0 < x_F < 0.6$ , this ratio is found to be consistent with unity, in striking contrast to the behavior of the Drell-Yan cross section ratio  $\sigma(p+d)_{DY}/2\sigma(p+p)_{DY}$ . This is consistent with no charge symmetry breaking effect in the gluon distributions. Also the difference between the Drell-Yan and the  $\Upsilon$  cross section ratios will be shown, which clearly reflect the different underlying mechanisms in these two processes. The  $\Upsilon$  production cross sections are also compared with the  $(p+d)$  and  $(p+Cu)$  cross sections from earlier measurements. Other related heavy quark results

from E866 will be shown, as well as what closely related future results can be expected from its follow-on experiment, E906, which has now received funding for detector construction.

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**Measurement of non-photonic electrons in Cu+Cu collisions  
at  $\sqrt{s_{NN}} = 200$  GeV at STAR.**

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High-energy nucleus-nucleus collisions at RHIC allow the study of the behavior of nuclear matter at high temperatures, where a new phase of matter, the quark-gluon plasma is predicted to exist. All partons are thought to lose energy through gluon radiation as they pass through the hot and dense nuclear matter; however heavy quarks are expected to lose less energy than light quarks and gluons due to the suppression of small-angle gluon radiation. Non-photonic electrons (proxies for heavy quarks) are suppressed by a factor of  $\sim 5$  in central Au+Au collisions relative to  $p + p$  collisions at  $\sqrt{s_{NN}} = 200$  GeV. This suppression is larger than most current theoretical predictions and has led to a re-examination of heavy-quark energy loss in the medium.

A measurement of the non-photonic electron spectrum in Cu+Cu collisions at  $\sqrt{s_{NN}} = 200$  GeV is presented. The spectrum is compared to the non-photonic electron yields from  $p + p$  and Au+Au collisions at the same energy to extract the nuclear modification factor and the dependence of the non-photonic electron yield on system size.

**Charmonium absorption in the pre-hadronic medium:  
a transport model study**

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Up to date, a simultaneous description of the seemingly energy-independent suppression of  $J/\Psi$  together with its narrow rapidity distribution and a strong elliptic flow of charmed hadrons found at RHIC has presented a challenge to microscopic theories. The large discrepancies were striking in view of the success of the hadron-string transport theories in describing lower energy charmonium data and lead to the conjecture that the difference between the measured yields and transport predictions was due to a neglect of the possible transition from hadronic to partonic matter, e.g. strongly-interacting QGP (sQGP). In the present contribution, we report new results on the charmonium nuclear modification factor

$R_{AA}$ , phase-space ( $y, p_T$ ) distributions, the elliptic flow  $v_2$  of  $J/\Psi$  and  $D$  mesons, and the ratios  $\langle J/\Psi \rangle / \langle \pi \rangle$  and  $\Psi'/(J/\Psi)$  from FAIR to RHIC energies.

Based on the microscopic Hadron-String-Dynamics (HSD) transport theory, we incorporate the following scenarios for the additional - partonic-medium induced - absorption of charmonium: (1) threshold melting mechanism; (2) dissociation by the scattering on the hadron-like correlators; (3) strong absorption on pre-hadrons, scaled with the number of constituent quarks.

As pointed out some years before by various authors the recreation of charmonia by  $D + \bar{D}$  mesons is mandatory at high bombarding energies. This is also in the spirit of microscopic transport theories including detailed balance (as in HSD).

First, we test HSD results for charmonium production in  $pp$  and  $dAu$  reactions against the recent data, which is crucial in order to obtain an accurate baseline for the study of anomalous suppression. In a next step we establish that the interaction of  $J/\Psi$  with comoving mesons in the late stages of  $AA$  collisions (when the energy density falls below  $\simeq 1$  GeV/fm<sup>3</sup>) gives a sizable contribution to the deviation of  $R_{AA}$  from one and should be consistently included when comparing models for sQGP-induced absorption to the data. Finally, we find evidence for strong interaction of charmonia in the pre-hadronic medium, which leads to dramatically different  $R_{AA}(y)$  compared to earlier calculations. We show that the result for the elliptic flow  $v_2(J/\Psi)$  varies substantially depending on the microscopic reaction scenario in the early stage of the collision. As a consequence of this sensitivity of  $v_2$ , we suggest that measurements of charm collective flow will give quantitative information on transport properties of the created plasma as well as on the hadronization dynamics.

## **Nuclear effects in charmonium production in proton-nucleus collisions at fixed-target energies**

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The production yields of the  $J/\psi$ ,  $\psi'$  and  $\chi_c$  states are expected to be significantly suppressed by “colour screening” if a QCD medium with deconfined quarks and gluons is formed in high-energy heavy-ion collisions. However, already in proton-nucleus collisions the charmonia production cross sections scale less than linearly with the number of binary nucleon-nucleon collisions. This “normal nuclear absorption” needs to be very well understood so that a robust baseline reference can be established, with respect to which we can clearly and unambiguously identify the signals of “new physics” specific to the high density QCD medium.

The NA50 experiment at the CERN-SPS made a detailed study of  $J/\psi$  and  $\psi'$  production in proton-nucleus collisions, at 400 and 450 GeV, with six different nuclear targets. Comparing the measured production cross sections to calculations based on the Glauber formalism, the “absorption cross sections”,  $\sigma_{\text{abs}}$ , were determined to be  $4.5 \pm 0.5$  mb and  $8.3 \pm 0.9$  mb,

respectively for the  $J/\psi$  and  $\psi' c\bar{c}$  states, using the GRV LO 94 set of parton distribution functions and neglecting any initial state nuclear effects. These values are then used in the studies of the heavy-ion data collected at a significantly lower energy, 158 GeV, assuming no changes in the initial or final state cold nuclear effects between the two energies.

In this talk we present a detailed study of the cold nuclear matter effects affecting charmonia production in p-nucleus collisions. We consider four different sets of PDFs (GVR LO 94, GRV LO 98, CTEQ6L and MRST2001LO), without and with nuclear effects, modelled through three different parametrisations (EKS98, nDS and HKM). Furthermore, we take into account that a significant fraction of the observed  $J/\psi$  mesons result from decays of  $\psi'$  and  $\chi_c$  states, which have different  $\sigma_{\text{abs}}$  values. We compare our calculations with the charmonia cross section ratios measured between different nuclear targets, at mid-rapidity, by NA3 (at 200 GeV), NA50 (at 400/450 GeV), E866 (at 800 GeV) and HERA-B (at 920 GeV). We conclude that there is a significant energy dependence of  $\sigma_{\text{abs}}$  in this energy range and we estimate the  $\sigma_{\text{abs}}$  values extrapolated to the SPS heavy-ion energy ( $E_{\text{lab}} = 158$  GeV) and to the RHIC energy ( $\sqrt{s} = 200$  GeV).

**Observation of two statistically significant thresholds  
in the  $J/\psi$  suppression pattern  
measured in heavy-ion collisions at the CERN SPS**

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In the deconfined phase of strongly interacting matter, the QCD binding potential is screened so that, with increasing energy density, the heavy quarkonium states “dissolve” into open charm or beauty mesons. Different quarkonia have different binding energies and, hence, are expected to dissolve at successive *thresholds* in the energy density or temperature of the medium. In particular, the  $\psi'$  and  $\chi_c c\bar{c}$  states should be easier to “melt” than the more strongly bound  $J/\psi$  state. Since a sizeable fraction ( $\sim 35\%$ ) of the  $J/\psi$  mesons are produced (in pp collisions) through decays of the heavier  $c\bar{c}$  states, the  $J/\psi$  production yield is expected to suffer two significant “drops”, when the temperature of the produced system exceeds the values above which the  $\psi'$  and the  $\chi_c$  can no longer form.

In this talk I present a quantitative statistical analysis of the  $J/\psi$  survival probability versus collision centrality, measured in Indium-Indium and Lead-Lead collisions, at  $\sqrt{s} = 17$  GeV, by the NA60 and NA50 experiments at the CERN SPS. These two suppression patterns are in very good agreement with each other, when observed as a function of the number of participant nucleons,  $N_{\text{part}}$ , a quantity determined (through the Glauber model) from the same Zero Degree Calorimeter (ZDC) detector in both experiments. I show that, given the very good accuracy of the In-In data points, the measured *shape* rules out any reasonably *smooth* suppression curve, including all presently available theoretical models based on hadronic absorption. On the contrary, the In-In suppression pattern is perfectly compatible with a *step function* in  $N_{\text{part}}$ , with a step at  $N_{\text{part}} \sim 90$ , smeared in accord with the measured resolution of  $E_{\text{ZDC}}$ . Furthermore, the four Pb-Pb data points measured for  $N_{\text{part}} > 200$  require the existence of a second step, at  $N_{\text{part}} \sim 250$ .

In summary, the  $J/\psi$  survival probabilities measured at the SPS in In-In and Pb-Pb colli-

sions rule out “smooth suppression models” and are perfectly compatible with the step-wise pattern expected if the QGP state is produced at top SPS energies.

## $J/\psi$ suppression vs $N_{part}$ at forward and mid-rapidity at RHIC in colour screening mechanism

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The suppression of heavy-quarkonia ( $J/\psi$ ,  $\chi_c$ ,  $\psi'$ ,  $\Upsilon$ ) due to colour screening has been proposed as a probe for deconfinement [1]. We have extended our previous work [2] on  $J/\psi$  suppression in the colour screening scenario in order to study rapidity dependence by explicitly introducing the rapidity variable in a consistent manner. We have also parameterized the pressure instead of energy density in the transverse plane and used bag model EOS for QGP. Moreover, we assume that the QGP is expanding in the longitudinal direction obeying Bjorken boost invariant hydrodynamics. Our model predictions exploit the recent lattice results for the dissociation temperature and formation time of quarkonia. Finally, sequential melting of higher resonances e.g.,  $\chi_c$ ,  $\psi'$  is also considered. The present formulation has been applied to the recent PHENIX data of  $J/\psi$  suppression at mid and forward rapidity in Au+Au collisions at RHIC [3].

Our formulation is based on the published work of ref. [2,4]. Consider a nucleus-nucleus collision in which thermalized plasma is formed at time  $\tau_i$ . We assume here that  $c\bar{c}$  pair is created at coordinate  $(r_1, \phi_1, z_1)$  inside a cylinder of length  $L_1$ . Let  $r_s$  be the radius of the contour of constant pressure  $P_s$  or energy density  $\epsilon_s$  determined by bag model EOS and dissociation temperature of  $J/\psi$  at a general transverse plane. The quarkonium pair will escape the screening region and form  $J/\psi$  if  $|\vec{r} + \vec{v}_T t| \geq r_s$  with  $t$  being the formation time of  $J/\psi$  in fireball frame. Finally, we obtain the following expression for survival probability of  $J/\psi$  in the medium

$$S = 2(\alpha + 1) \int_0^{R_T} dr_1 r_1 [1 - (r_1/R_T)^2]^\alpha \int_{-L_1/2}^{L_1/2} \phi_{max}(r_1, z_1) dz_1 / \pi R_T^2 L_1$$

, where  $\phi_{max}(r_1, z_1)$  is the positive root of the inequality  $\cos(\phi) \geq Y$  with  $Y \equiv [(r_s^2 - r_1^2) - v_T^2 t^2] / 2r_1 |v_T| t$ .

We show in the present work that the centrality dependence of the  $J/\psi$  suppression data at mid-rapidity and forward rapidity recently available from PHENIX experiment at RHIC can be explained well invoking QGP formation scenario based on the bag model EOS. We also find that the present model gives more  $J/\psi$  suppression at forward rapidity as compared to mid-rapidity which shows quite good agreement with the recent PHENIX data. The physical reason for the good fit is that the proper time induced inhomogeneity with respect to various  $z$  planes (where the  $J/\psi$  mesons trajectory reaches) is properly incorporated.

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## Consequences of a $\Lambda_c/D$ enhancement effect the non-photonic electron nuclear modification factor in central heavy ion collisions at RHIC energy

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The RHIC experiments have measured the nuclear modification factor  $R_{AA}$  of non-photonic electrons in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. This  $R_{AA}$  exhibits a large suppression for  $p_t > 2$  GeV/ $c$  which is commonly attributed to heavy-quark energy loss. In order to reproduce satisfactorily the data, energy-loss models assume a heavy-quark energy loss similar to that of light quarks. However, it is expected that the heavy-quark radiative energy loss is smaller than the light quark one because of the so-called dead-cone effect. In this paper, we show that a charm baryon/meson enhancement, as it is observed for light and strange quarks, can explain part of the suppression. This phenomenon has been put forward in a previous work. At variance, we show here that a  $\Lambda_c/D$  ratio close to unity, as observed for light and strange quarks, could explain 20 – 25% of the suppression of non-photonic electrons in central Au+Au collisions. This effect remains significant at relatively high non-photonic electron transverse momenta of 8 – 9 GeV/ $c$ .

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## Heavy-flavor particle correlations in STAR via electron azimuthal correlations with open charm mesons

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The study of heavy-flavor production in heavy-ion collisions provides key tests of parton energy-loss models and, thus, yields profound insight into the properties of the produced highly-dense QCD matter. Surprisingly, RHIC measurements in central gold-gold collisions have shown that the high- $p_T$  production of electrons from semi-leptonic charm and bottom decays is suppressed to the same level as observed for light-quark hadrons, which was not expected owing to the dead-cone effect. Energy-loss models describe the observed suppression reasonably well only if the bottom contribution to the non-photonics electrons is very small. Since the measurements are sensitive to the sum of charm and bottom decays, it is of great interest to disentangle the relative contributions experimentally.

In this contribution, we report first STAR measurement on heavy-flavor particle correlations in proton-proton collisions. Heavy-flavor (charm and bottom) events are clearly identified and separated through their characteristic decay topology using azimuthal correlation of non-photonics electrons and reconstructed open charmed mesons, which yield important information about the underlying production mechanism. The specific advantage of this correlation method, in contrast to the conventional heavy-quark measurements, is the possibility to efficiently trigger on heavy-quarks with high transverse momentum using their decay electrons. The results are compared to dedicated simulations from PYTHIA and MC@NLO event generators. This novel correlation technique has the potential for comprehensive energy-loss measurements of heavy quarks in heavy-ion collisions.

## Quarkonia Melting Above Deconfinement

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We present a detailed analysis of quarkonium spectral functions and correlators from potential models. This analysis is the first one that describes lattice QCD data on correlators for all the charmonium and bottomonium channels. The analysis relies on a class of potentials constrained by the screening seen in lattice data on static quark-antiquark free energy [1]. While the correlation functions in the vector and pseudoscalar channel do not change much, we find no  $J/\psi$  and  $\eta_c$  states in the spectral functions. Only the 1S bottomonium ground state can survive deep in the deconfined phase. The analysis is first done in pure gluodynamics [1], for what extensive lattice data is available, and is extended to full QCD using preliminary lattice data in 2+1 flavor QCD with pion masses of 220 MeV from the RBC-Bielefeld Collaboration [2]. While for extreme choices of the potential that are still compatible with the lattice data, the spectral functions from the potential model show some bound state peaks, we find that color screening reduces the binding energies. This in turn makes it possible that the states dissociate by thermal activation [2]. Using estimates of the thermal activation rate and the calculated binding energies we give upper limits on the quarkonium dissociation temperatures in an equilibrated quark gluon plasma [2].

The more realistic situation, in which the quarkonium moves compared to the medium, is

also discussed.

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## Measurements of charm and bottom production in p+p collisions at $\sqrt{s} = 200\text{GeV}$ at RHIC-PHENIX

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Heavy quarks (charm/bottom) provide good probes of the hot and dense medium created in relativistic heavy ion collisions, since heavy quarks are produced at the beginning of collisions. Production of heavy quark has been studied by the PHENIX experiment at RHIC via measurement of single (non-photonic) electrons from semi-leptonic decays. A large suppression pattern and azimuthal anisotropy of single electron has been observed in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV, which are comparable to the light mesons. These results suggest large energy loss and flow of the heavy quarks in the hot and dense matter.

To understand of these surprising results and the interaction of heavy quarks in the hot and dense medium, experimental determination of production ratio of charm over bottom is one of the most important topics, since the behavior of bottom may differ from charm in the medium.

We measured the charm over bottom ratio via electron-hadron correlation in p+p collisions at  $\sqrt{s} = 200$  GeV. The measurement utilize the difference of semi-leptonic decay pattern between D and B hadrons. In addition, we observe clear signals of  $D^0$  meson via direct reconstruction in hadronic decay modes in p+p collisions at  $\sqrt{s} = 200$  GeV. The available results of direct measurement will be compared with the results of measurement via electron-hadron correlation as a cross check.

In this presentation we will show the latest results at PHENIX on production ratio of charm over bottom in p+p collisions at  $\sqrt{s} = 200$  GeV.

## CRITICAL BEHAVIOR OF $J/\psi$ ACROSS THE PHASE TRANSITION FROM QCD SUM RULES

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Nowadays charmonium has been regarded as one of the most important probes in relativistic heavy ion collisions because of its sensitivity to nature of the QCD matter. Since Matsui and Satz argued suppression of  $J/\psi$  would be caused by the Debye screening in the quark-gluon plasma [1], it has been extensively studied both theoretically and experimentally. Contrary to earlier expectations, however, recent lattice calculations of the charmonium spectral function based on the maximum entropy method suggest  $c\bar{c}$  forms bound states even in the deconfined matter [2]. The fact that  $J/\psi$  survives up to  $1.5 - 2T_c$  means quarks and gluons strongly interact and therefore non-perturbative effects persist at temperatures not much higher than  $T_c$ . Therefore, the suppression of  $J/\psi$  can not be an order parameter of QGP formation. In this talk, we discuss the sudden changes of mass and width of  $J/\psi$  across the phase transition using QCD sum rules. In QCD sum rules for charmonium, we can consistently take non-perturbative effects into account through gluon condensates. We extract the scalar and twist-2 part of the dimension-4 gluon operator from quenched lattice QCD results. Then, following the traditional method [3], we investigate how the mass and width change as temperature increases near but above  $T_c$ . Although the validity of the method seems to break down  $T > 1.05T_c$ , we found that there must be notable and sudden change of mass and/or width just above  $T_c$ . The mass is found to be decrease maximally 200 MeV if width remains unchanged while the width can be broaden to more than 100 MeV if the mass does not change. These spectral changes originate from the sudden change in the energy density across the phase transition and therefore will be a more direct probe of the strongly interacting plasma which will be created in the future experiments at LHC [4].

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## WEAK HADRONIC DECAYS OF BOTTOM MESONS EMITTING PSEUDOSCALAR AND A SCALAR MESONS

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Weak leptonic decays of B mesons are expected to provide a rich phenomenology yielding a wealth of information for testing the standard model and for probing the strong interaction dynamics. However, these decays are difficult to understand, since any weak process involving quarks is necessarily accompanied with nonperturbative quantum chromo dynamics (QCD) effects and cannot be calculated reliably from QCD Lagrangian. These are studied

in phenomenological approaches involving, the factorization hypothesis. The factorization scheme is assumed to calculate decay amplitude in terms of a few invariant formfactors, which provide essential information on the structure of the mesons and the interplay of the strong and weak interactions. This scheme has achieved considerable success in explaining most of the exclusive two-body nonleptonic weak decays of B mesons to pseudoscalar and vector mesons. However, B mesons, being heavy, can also emit heavier p-wave mesons.

Due to the fact that the identification of scalar mesons is difficult experimentally and the underlying structure of scalar mesons is not well established theoretically. Studies of the mass spectrum of scalar mesons and their strong as well as electromagnetic decays suggest that the mass of light scalar mesons below or near 1 GeV form an SU(3) flavor nonet and are predominately the  $q^2\bar{q}^2$  states as originally advocated by Jaffe, while the scalar mesons above 1 GeV can be described as a  $q\bar{q}$  nonet with a possible mixing with  $0^+$ ,  $q\bar{q}$  and glueball states. One hopes that through the study of  $B \rightarrow PS$  decays, old puzzle related to the internal structure and their related parameters, e.g. the masses and widths, of light scalar mesons could be understood in a better way.

In this paper, we study B decays emitting pseudoscalar and a scalar mesons in Cabibbo-favored and Cabibbo-suppressed modes. These modes give additional and complementary information about exclusive non-leptonic weak decays of B mesons. We obtain the decay amplitudes using the factorization hypothesis and predict the branching ratios of these decays in the naive spectator quark model. It is expected that some of these decay channels have large branching ratios and can be within the reach of future experiments.

## ***J/ψ* production in Cu+Cu and Au+Au collisions at RHIC-PHENIX**

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Heavy quarkonia ( $J/\psi$ ,  $\psi'$ ,  $\chi_c$ ,  $\Upsilon$  etc.) are considered to be among the most important probes for the deconfined quark gluon plasma (QGP) created by relativistic heavy ion collisions. The yields of heavy quarkonia are expected to be suppressed in the QGP due to Debye screening of the color charge. The  $J/\psi$  is especially promising because of its large production cross section and di-lepton decay channels, which make it easily detected. The PHENIX experiment at RHIC is able to detect  $J/\psi$  at mid rapidity ( $|y| < 0.35$ ) via  $e^+e^-$  decays and at forward rapidity ( $1.2 < |y| < 2.2$ ) via  $\mu^+\mu^-$  decays. Models of  $J/\psi$  production in heavy ion collisions at RHIC energy contain a number of important competing effects, including reduction of  $J/\psi$  yields by cold nuclear matter effects, destruction of  $J/\psi$  due to interactions with thermal gluons in the QGP, reduced feed down from excited charmonium states that melt just above the QGP transition temperature, and enhancement of the yields due to coalescence of uncorrelated charm pairs. The recent PHENIX Au+Au data which were collected in 2004 at  $\sqrt{s_{NN}} = 200$  GeV showed that the  $J/\psi$  suppression at forward rapidity is larger than that at mid rapidity and the suppression at mid rapidity is similar

to that observed by NA50 at SPS in  $\sqrt{s_{NN}} = 17.3$  GeV Pb+Pb collisions. However, these results are not well understood theoretically. Systematic study of  $J/\psi$  production in heavy ion collisions across the entire range of  $N_{part}$  is needed to disentangle the competing effects. In 2005, PHENIX recorded Cu+Cu collisions at  $\sqrt{s_{NN}} = 200$  GeV to obtain precise data in the range  $N_{part} \leq 126$ , where Au+Au data is limited by statistics and systematic uncertainty. The final results of  $J/\psi$  in Cu+Cu collisions will be discussed and compared with PHENIX  $p+p$ ,  $d+Au$  and Au+Au measurements and various theoretical models to understand in-medium effects on  $J/\psi$  production.

## $\Lambda_c$ enhancement from strongly coupled quark-gluon plasma

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We propose the enhancement of  $\Lambda_c$  as a novel QGP signal in relativistic heavy ion collisions. The  $\Lambda_c$  is a unique baryon that is composed of a  $c$  quark and the isospin-spin zero combination of  $u$  and  $d$  quarks, which is expected to form the most attractive diquark. The magnetic interaction between the heavy quark and the diquark vanishes, and the  $c$  quark acts as a color source for the unperturbed diquark. Hence  $\Lambda_c$  is expected to host the most clear  $ud$  diquark structure, and can be regarded as an ideal two-body system of the  $c$  quark and  $ud$  diquark [1]. At the same time, the  $ud$  diquark may also exist in QGP [2]. This is expected from the strong coupling nature of sQGP, and has some relevance to the color superconductivity at high density, or to the Bose-Einstein Condensate (BEC) in the strong coupling regime. If we have the diquarks in QGP, the  $\Lambda_c$  baryon could be produced by the direct two-body collision between the  $c$  quark and the  $ud$  diquark, in addition to the expected three-body collision among the independent  $c$ ,  $u$  and  $d$  quarks. While the density of diquarks are smaller than that of the individual quarks, the larger probability for two-body collision over the three-body leads to the  $\Lambda_c$  enhancement over the expected production rate estimated from the three body collision only. Using the coalescence model, we find the ratio of  $\Lambda_c/D$  to be enhanced substantially compared with the calculation without the diquark correlation and over the experimental ratio found from elementary processes [3]. With the expected detector upgrades at RHIC and plans at LHC, the realistic measurements of  $\Lambda_c$  and  $D$  meson became feasible, and thus the observation of  $\Lambda_c$  enhancement would be one of promising future QGP signals, and provide an experimental means to probe the diquark correlation in QGP. Furthermore it would open a new way to make use of QGP as an experimental device to

investigate the possible diquark structure in heavy baryons:  $\Lambda_c$  and  $\Lambda_b$ .

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## Turning off the Charms

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The observed suppression of high- $p_T$  hadrons – a key signature of a quark-gluon plasma in heavy ion collisions – is often attributed to radiative energy loss of the parent partons. However, recent analyses of non-photonic electrons, which probe the energy loss of heavy quarks, compels an additional collisional quenching of considerable size [1].

Given the necessity of a detailed theoretical understanding of this mechanism, we emphasize that existing treatments have two crucial shortcomings:

- running of the strong coupling not taken into account – as analyzed in [2]
- inappropriate approximations for cross sections/phase space – as analyzed in [3]

We will present a genuine QCD calculation of the collisional energy loss of heavy quarks and discuss implications for the present picture of jet quenching.

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## $J/\psi$ azimuthal anisotropy relative to the reaction plane in Pb-Pb collisions at 158 A GeV/c.

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We present the results of a measurement of  $J/\psi$  azimuthal distribution relative to the reaction plane in Pb-Pb collisions at 158 GeV/nucleon.

Although charm thermalization and consequently  $J/\psi$  flow is not likely to be established at SPS energies, other physical mechanisms related to charmonium dissociation in the medium formed in the heavy ion collision are expected to introduce an anisotropy in the azimuthal

distribution of the observed  $J/\psi$  mesons. The measurement of  $J/\psi$  elliptic anisotropy, quantified by the Fourier coefficient  $v_2$ , is particularly important to constrain theoretical models which are able to explain the  $J/\psi$  suppression observed at SPS energies.

The analysis has been performed on a data sample of about 100000  $J/\psi$  events, collected in year 2000 by the NA50 Collaboration, under optimized experimental conditions. The reaction plane has been estimated from the azimuthal distribution of the neutral transverse energy in an electromagnetic calorimeter.

We present the measured numbers of  $J/\psi$  in different bins of azimuthal angle relative to the reaction plane, as well as the resulting values of the Fourier coefficients  $v_1$  and  $v_2$  as a function of the collision centrality and of the  $J/\psi$  transverse momentum.

## Charmed exotics in Heavy Ion Collisions

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Possible existence of exotic mesons consisting of two quarks and two anti-quarks was first suggested by Jaffe in the framework of the MIT bag model [1]. Recently, the discussions have been extended to include those containing heavy quarks, as several heavy mesons, that were observed in  $B$  meson decays, do not seem to fit well within the conventional quark model. Tetraquark mesons with two heavy anti-quarks  $\bar{Q}\bar{Q}$  and two light quarks  $qq$  ( $\bar{Q}\bar{Q}qq$ ), henceforth called  $T_{QQ}$ , and pentaquark containing heavy quark, such as  $\Theta_{cs}$  ( $uuds\bar{c}$ ), are particularly interesting as they are explicitly exotic from flavor considerations. Moreover, simple theoretical consideration based on the color-spin interaction shows that for such configurations the binding energy increases as the mass of the heavy quark increases.

However, producing the  $T_{QQ}$  from an elementary process is highly suppressed as it involves creating two  $\bar{Q}Q$  pairs from the vacuum. In contrast, in relativistic heavy ion collisions at LHC,  $\bar{c}c$  pairs are expected to be abundantly produced. Since the hadronization from the quark-gluon plasma produced in these collisions tends to follow a statistical description, production of exotic hadrons in heavy ion collisions at LHC is thus much more favorable than in elementary reactions.

In this talk, we first give a qualitative argument why multiquark hadrons consisting of heavy quarks are likely to exist. Then, using both the quark coalescence model and the statistical hadronization model, we then give estimates of how many tetraquarks  $T_{QQ}$  and charmed pentaquark baryons  $\Theta_{cs}$ , if they exist, will be produced in central heavy ion collisions at both RHIC and LHC [2]. Furthermore, we further discuss the decay modes of these charmed exotic hadrons in order to facilitate their detections in experiments. We thus argue that the

observation of explicitly exotic hadrons, including diquark correlation in QGP [3], is crucial for understanding the physics at LHC and RHIC.

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## A Measurement of the Open Charm Cross-Section in $\sqrt{s_{NN}} = 200$ GeV Cu+Cu Collisions at the STAR Experiment at RHIC

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In relativistic heavy-ion collisions, charm quarks are probably produced in gluon fusion reactions during the early, pre-thermalization stages of the system [1]. If charm is indeed produced in initial hard processes, one will observe that charm production scales with the number of binary (nucleon-nucleon) collisions. The charm production cross-section can be calculated in perturbative QCD by summing up Feynman diagrams at the "Next-to-Leading Order (NLO)" level [2].

The binary scaling of charm production as well as the predicted cross-section can be experimentally tested by the STAR experiment. Charm quarks are usually studied by looking at semi-leptonic decays to non-photonic electrons (or muons):  $D^0 \rightarrow e^- + X$  and  $D^0 \rightarrow \mu^+ + X$ . However, those measurements are indirect and can lead to a significant loss of information. The STAR experiment is the only one at RHIC currently capable of directly reconstructing  $D^0$  mesons via their hadronic decay products (thanks to the STAR Time Projection Chamber and the Time of Flight detector) in minimum bias heavy-ion collisions.

We report on a measurement of the open charm cross-section in  $\sqrt{s_{NN}} = 200$  GeV Cu+Cu collisions at the STAR experiment at RHIC. The cross-section was measured through a direct reconstruction of the  $D^0 \rightarrow K + \pi$  decay at mid-rapidity and then extrapolated to calculate a total cross-section. The charm cross-section as measured in  $\sqrt{s_{NN}} = 200$  GeV Cu+Cu collision is compared to previous experimental results from both the STAR and PHENIX experiments at RHIC and to theoretical predictions.

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## Study of azimuthal angular correlations between non-photonic electrons and charged hadrons from $p + p$ collisions at $\sqrt{s_{NN}} = 200$ GeV in STAR

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Heavy quarks, charm and bottom, are believed to be produced mostly via initial gluon fusions in nuclear collisions at RHIC. Heavy quark propagation through the hot and dense medium created in heavy ion collisions can be a probe to properties of the medium. Recently a large suppression of non-photonic electrons up to a  $p_T$  of 10 GeV/ $c$  from central Au+Au collisions has been reported by STAR and PHENIX. Since both charm and bottom quarks may contribute to non-photonic electrons through semi-leptonic decays and their relative contributions are expected to be  $p_T$  dependent, it is important to experimentally determine the charm and bottom quark contributions separately.

We proposed to use azimuthal angular correlations between electrons and hadrons to study the charm and bottom contributions. Due to a large mass difference, the correlations from charm and bottom quark decays are different. We will present the latest results on the azimuthal angular correlations and estimate the relative  $D$  and  $B$  production. We combined the run 2005 and 2006  $p + p$  data from STAR to increase the statistics. Implications on bottom quark energy loss in the hot and dense medium will also be discussed.

## INCLUSIVE $J/\psi$ and $\chi_c$ MESON PRODUCTION IN PP COLLISIONS AT RHIC

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Recently, the PHENIX collaboration at the BNL Relativistic Heavy Ion Collider (RHIC) has measured inclusive  $J/\psi$  production in elementary proton-proton collisions [1]. While for the RHIC community the elementary  $pp$  cross section is only the baseline for the nuclear case, we wish to demonstrate that the elementary data by itself constitute a very valuable information about QCD dynamics in the region of intermediate values of gluon longitudinal momentum fraction  $x \simeq 10^{-2}$ – $10^{-1}$ .

For the last decade, the inclusive production of  $J/\psi$  mesons was a serious theoretical puzzle challenging our understanding of QCD, parton model, and the bound state formation dynamics.

The presentation will be based partially on our recent analysis [2]. Inclusive cross sections for  $J/\psi$  production in proton-proton collisions are calculated in the  $k_t$ -factorization approach for the RHIC energy. Several mechanisms are considered, including direct color-singlet mechanism, radiative decays of  $\chi_c$  mesons, decays of  $\psi'$ , open-charm associated production of  $J/\psi$

as well as weak decays of B mesons. Different unintegrated gluon distributions from the literature are used. We find that radiative  $\chi_c$  decays and direct color-singlet contributions constitute the dominant mechanism of  $J/\psi$  production. These process cannot be consistently treated within collinear-factorization approach. The results are compared with recent RHIC data [1]. The new precise data at small transverse momenta impose stringent constraints on UGDFs. Some UGDFs are inconsistent with the new data. The Kwieciński UGDFs give the best description of the data. In order to verify the mechanism suggested here we propose  $J/\psi$  – jet correlation measurement and an independent measurement of  $\chi_c$  meson production in  $\pi^+\pi^-$  and/or  $K^+K^-$  decay channels. Finally, we address the issue of  $J/\psi$  spin alignment. We discuss also detailed predictions of differential single particle distributions for  $P$ -wave mesons  $\chi_c(J^\pi)$ . The hadroproduction of those mesons was never carefully studied experimentally. The experimental results from RHIC are expected soon. Confrontation with experimental data would open a possibility to test different models of unintegrated gluon distributions and shed more light on the developments of gluonic cascades.

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## Self-consistent coupled-channel approach to $D$ and $\bar{D}$ in hot dense matter

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A self-consistent coupled-channel approach is used to study the properties of  $D$  and  $\bar{D}$  mesons in hot dense matter [1]. The starting point is a broken SU(4)  $s$ -wave Tomozawa-Weinberg interaction supplemented by an attractive isoscalar-scalar term [2]. The Pauli blocking effects, baryon mean-field bindings, and  $\pi$  and open-charm meson self-energies are incorporated in dense matter at finite temperature. The  $\Lambda_c$  and  $\Sigma_c$  resonances, which are generated dynamically in the  $DN$  sector [2,3], remain close to their free space position while acquiring a remarkable width because of the thermal smearing of Pauli blocking [4]. Therefore, the  $D$  meson spectral density shows a single pronounced peak close to the free mass that broadens with increasing density specially towards lower energies. In the  $\bar{D}N$  case, the low-density theorem is not a good approximation for the repulsive  $\bar{D}$  self-energy close to saturation density. We speculate about the existence of  $D$ -mesic nuclei as well as discuss the consequences for the  $J/\Psi$  suppression at FAIR (GSI).

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# CHARMONIUM DYNAMICS IN $dA$ and $AA$ AT RHIC and LHC

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Charmonium production in hadron-nucleus collisions is an important tool for understanding high-energy nuclear effects: in  $pA$  ( $dA$ ) collisions effects of multiple scattering and coherence are at play, while the more involved  $AA$  collisions provide additional information about final state interaction with the created medium. Measurements at RHIC have revealed several "puzzles" that refute simple model extrapolations from lower energies.

Contrary to most predictions, the absorptive cross section in  $dA$  at RHIC is strongly reduced. However, this is in line with recent considerations in the Glauber-Gribov theory [1], and we show that the experimental data is consistent with no absorption but, nevertheless, with shadowing [2]. This has also profound implications for the final state in  $AA$  collisions, which we will treat in terms of the comovers' interaction model [3]. The model is extended to include secondary charmonium production due to recombination. The improvement allows us to properly describe the centrality dependence of nuclear suppression at mid- and forward rapidities. Predictions are made for LHC for both  $pA$ , where a novel scaling in Bjorken  $x$  is expected to appear [4], and for  $AA$ , where recombination effects dominate for a certain range of centrality.

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## NONPERTURBATIVE HEAVY-QUARK DIFFUSION IN THE SQGP

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We evaluate heavy-quark transport properties in the Quark-Gluon Plasma (QGP) using a Brueckner-type many-body approach to calculate the in-medium  $T$ -matrix for heavy-light quark scattering [1]. The underlying heavy-light quark potentials are estimated from the heavy-quark free energy as recently computed in finite-temperature lattice QCD. All color channels in quark-antiquark and quark-quark interactions are included assuming Casimir scaling. Mesonic and (color-antitriplet) diquark channels support resonance structures up to temperatures of  $\sim 1.2$ - $1.5 T_c$ . These nonperturbative correlations provide a large interaction strength in the QGP at moderate temperatures. Pertinent charm-quark widths reach up to  $\sim 250$  MeV. The heavy-light quark  $T$ -matrix is used within a Fokker-Planck framework to compute heavy-quark diffusion coefficients, which are further implemented into Langevin simulations of Au-Au collisions at RHIC [2]. Hadronization is realized in a combined coalescence-fragmentation approach; pertinent single-electron decay spectra show fair agreement with RHIC data [3,4] for both  $R_{AA}$  and  $v_2$ . Uncertainties due to the extraction of the potential from lattice QCD are discussed. Our approach suggests an intimate relation between a strongly interacting QGP and (the onset of) quark coalescence close to  $T_c$ .

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## PREDICTING THE TOTAL CHARM CROSS SECTION

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We assess the theoretical uncertainties on the total charm cross section. We discuss the importance of the quark mass, the scale choice and the parton densities on the estimate of the uncertainty. We study the differences in the uncertainties arising from obtaining the total cross section by integrating kinematic distributions and by integrating the partonic

total cross sections. We conclude that due to the small charm quark mass, which amplifies the effect of varying the other parameters in the calculation, the uncertainty on the total charm cross section is difficult to quantify [1].

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## Cold Nuclear Matter Effects on $J/\psi$ as Constrained by Deuteron-Gold Measurements at $\sqrt{s_{NN}} = 200$ GeV in the PHENIX Experiment

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A new analysis of  $J/\psi$  production yields in deuteron-gold collisions at  $\sqrt{s_{NN}} = 200$  GeV has been performed using data taken by the PHENIX experiment in 2003. The high statistics proton-proton  $J/\psi$  data taken in 2005 is used to improve the baseline measurement and thus construct updated cold nuclear matter modification factors ( $R_{dAu}$ ). A suppression of  $J/\psi$  in cold nuclear matter is observed as one goes forward in rapidity (in the deuteron-going direction), corresponding to a region more sensitive to initial state low- $x$  gluons in the gold nucleus. The measured nuclear modification factors will be compared to theoretical calculations of nuclear shadowing to which a  $J/\psi$  (or precursor) break-up cross-section is added. Break-up cross-sections are obtained by fitting these calculations to the data using EKS and NDSG shadowing. Projections of these cold nuclear matter effects to copper-copper and gold-gold collisions will also be presented and compared to the latest PHENIX data.

## Gluon Propagator and Heavy Quark Potential in Anisotropic Plasma

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We calculate the effect of quark-gluon plasma momentum-space anisotropies on the heavy-quark potential and determine how these momentum-space anisotropies modify the long distance behavior of the potential. Due to the breaking of symmetry in the  $p_T$ - $p_L$  plane the potential depends on the direction of the quark-antiquark separation so that pairs separated along the beamline direction experience a different potential than those separated perpendicular to the beamline. To make quantitative calculations of the effect we use semi-classical

transport theory [1] and introduce the parton momentum-space anisotropy by a rescaling of one direction in momentum space parameterized by an anisotropy parameter,  $\xi$  [2]. To perform the analysis we then derive a symmetric 4-tensor basis which allows us to construct the anisotropic gluon propagator in general covariant gauge. Using this tensor basis we then evaluate the effect of finite anisotropy on the heavy quark potential analytically in the small- $\xi$  limit and numerically for general  $\xi$ . We find that for any non-zero  $\xi$  the typical binding energy energies for heavy quark-antiquark systems increase which would naively imply that in an anisotropic plasma that heavy mesons should experience less suppression.

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# Charmonium in strongly coupled Quark-Gluon Plasma

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The growing consensus that quark-gluon plasma at RHIC/SPS is strongly-coupled (sQGP) suggests a radically different framework for examining charmonium production in heavy-ion collisions.

We present both semi-analytical treatment of Fokker-Planck (FP) evolution in pedagogical examples and numerical Langevin simulations of evolving  $c\bar{c}$ -pairs on top of a hydrodynamically expanding fireball. Unlike others, we emphasize the important role not only of the drag force but also of *mutual*  $c\bar{c}$  interaction in plasma. We show that it strongly affects the diffusion and increase the probability for  $J/\psi$  survival. Both approaches demonstrate rapid equilibration in momenta and when the pair's interaction is included, much less "dissolution" of the  $J/\psi$ -states than previously predicted. The results are compared to RHIC data.

We also use our Langevin calculation to predict dilepton invariant mass spectra for dileptons originated from charm semileptonic decays. Those are strongly affected by drag force in matter, which turn back-to-back correlation at early time into positive correlation at later time, induced by hydro. We conclude that at  $M > 3\text{ GeV}$  most observed (by PHENIX at RHIC) dileptons cannot come from charm.

## Effect of Partonic Wind on Charm Quark Correlations in High-energy Nuclear Collisions

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In high-energy collisions, massive heavy quarks are produced back-to-back initially and they are sensitive to early dynamical conditions. The strong collective partonic wind from the fast expanding quark-gluon plasma created in high-energy nuclear collisions modifies the correlation pattern significantly. As a result, the angular correlation function for  $D\bar{D}$  pairs is suppressed at the angle  $\Delta\phi = \pi$ . While the hot and dense medium in collisions at RHIC ( $\sqrt{s_{NN}} = 200$  GeV) can only smear the initial back-to-back  $D\bar{D}$  correlation, a clear and strong near side  $D\bar{D}$  correlation is expected at LHC ( $\sqrt{s_{NN}} = 5500$  GeV).

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## Limits on the Viscosity to Entropy Density Ratio from PHENIX Data on Single Electron Production

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The strong elliptic flow discovered at RHIC, together with its detailed dependence on particle mass and on transverse momentum, are well-described by ideal hydrodynamics calculations which ignore viscous effects. However, as noted by Danielewicz and Gyulassy [1], straightforward arguments based on the uncertainty principle suggest that the viscosity for any thermal system must be non-zero. This observation was extended by Kovtun, Son and Starinets (KSS) [2], who demonstrated that conformal field theories with gravity duals have a ratio of viscosity  $\eta$  to entropy density  $s$  of  $1/4\pi$  (in natural units). KSS conjectured that this value is a bound for any relativistic thermal field theory, that is,  $\eta/s \geq 1/4\pi$ .

Estimates for the value of this ratio in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV based on flow [3,4], fluctuations [5] and entropy production [6] all suggest that  $\eta/s$  for the QGP created in these collisions can not exceed the KSS bound by more than a factor of  $\sim 4$ . By requiring a simultaneous description of the energy loss ( $R_{AA}(p_T)$ ) and flow ( $v_2(p_T)$ ) of single electrons from semi-leptonic decays of heavy flavor, the PHENIX experiment obtained an estimate  $\eta/s \approx (1.3 - 2)(1/4\pi)$  [7]. Prospects for an improved understanding of the extraction of  $\eta/s$  from PHENIX data on heavy flavor production will be presented, along with a discussion of current theoretical work on constraining the transport properties of the medium from the experimental data.

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**Charm Content in Jets from  $p + p$  Collisions at  $\sqrt{s} = 200$  GeV  
 in the STAR Experiment**

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In hadron collisions at high energies, the gluon splitting process becomes potentially important in heavy quark pair production. The multiplicity of heavy quarks in jets can be calculated in perturbative QCD, and the leading nonperturbative correction is believed to be very small. Gluon fusion into heavy flavor pair results in a hard contribution to the fragmentation into charm hadrons, while gluon splitting process results in a soft contribution.

In this talk, we report the first measurements of  $D^{*\pm}$  production in jets from p+p collisions at  $\sqrt{s} = 200$  GeV with the STAR experiment at RHIC. The measurements will be compared with pQCD calculations and world data points at various kinematic ranges. The measurements give insight into the charm production mechanism, which is of importance to both the heavy ion and spin physics programs at RHIC.

**Effect of heavy-quark energy loss on the single muon  $p_t$  spectrum  
 in Pb–Pb collisions at  $\sqrt{s_{NN}} = 5.5$  TeV**

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Muons from semi-leptonic decays of heavy quarks and leptonic decays of intermediate vector bosons (W, Z) are the main contributors to the single-inclusive muon transverse momentum ( $p_t$ ) distribution from  $\sim 5$  GeV/c up to  $\sim 60$  GeV/c at LHC energies. As inferred from non-photonic electron suppression at RHIC energies [1,2], heavy quarks traversing a QCD medium might lose energy. On the contrary, W and Z boson decay muons do not interact strongly and can be considered as medium-blind references [3]. We compute the effect of heavy quark radiative energy loss on the single muon spectrum in Pb–Pb collisions at  $\sqrt{s_{NN}} = 5.5$  TeV in the framework of the Parton Quenching Model (PQM) [4], extended to any rapidity [5]. In the PQM model, the energy loss is calculated within the BDMPS formalism [6] via mass-dependent quenching weights [7]. Our results show that due to heavy quark energy loss, the single muon spectra in the intermediate- $p_t$  range of 5 – 25 GeV/c would be suppressed by a factor 2 – 4 in the most central (0 – 10%) collisions. The muon spectrum above 30 GeV/c is dominated by W boson decays and therefore we expect little or no modification. Our estimations indicate that the muon  $p_t$  distribution presents a shift of about 5 – 7 GeV/c of the crossing-point between muons from heavy quark and W boson decays in the most central (0 – 10%) collisions. In addition, the nuclear modification factor,  $R_{AA}$ , and the central to peripheral ratio,  $R_{CP}$ , of the muon high  $p_t$  distribution are computed. Results are presented in the pseudo-rapidity range covered by the LHC experiments,  $|\eta| < 4$ .

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## Heavy Quark Spectroscopy

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Nonrelativistic Schrödinger wave equation has been solved to calculate the mass spectrum of heavy quarkonium made up of top quark and antiquark of different flavours namely  $\bar{s}, \bar{c}$ ,  $\bar{b}$  and  $\bar{t}$ . Calculations have been performed with four different types of quark-antiquark potentials namely: Cornell, power law, Song- Lin and Turin. These potentials vary in their behaviour in different region. The variation in the  $t\bar{t}$  spectra with top quark mass changing from 15 GeV to recently reported value of 178 GeV has also been studied

We study the temperature dependence of parton energy loss in the medium by introducing the temperature into QCD running coupling  $\alpha_s$  and Debye mass  $\mu_D$ [5][6][7], and calculate the parton energy loss by using the reaction operator approach [1][2] and the single hard scattering approximation scenario[3] of energy loss. Comparing with the results predicted from Ref. [1][2][3], which reproduce the data of Au-Au collision at  $\sqrt{s_{NN}}=130$  GeV in RHIC, we get the medium temperature is 320 MeV at this condition. And the temperature we get is also consistent with the result got by hydrodynamic model in Ref. [4]. Results of heavy parton, charm and bottom, energy loss are also predicted of LHC energies by setting the value of temperature to be 500 MeV and 800 MeV, respectively. The partons will suffer more energy loss when at higher temperature. And the energy loss of heavier quark bottom is increasing more sharply than the energy loss of charm quark as the temperature rising up.

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