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# Quarkonia measurements in the STAR Experiment.

**Jaroslav BIELCIK for the STAR Collaboration***
*Department of Physics, Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Brehova 7, Prague, 11519, Czech Republic*
*E-mail:* jaroslav.bielcik@fjfi.cvut.cz

The calculations of Quantum Chromodynamics on lattice showed that under conditions of high energy density or high temperature nuclear matter undergoes a phase transition from state of confined quarks and gluons to deconfined state, the Quark-Gluon Plasma (QGP). Such conditions were present in first moments after the Big Bang in the early universe and can be created in laboratory by colliding of heavy ions with sufficient energy. During the last decade, the STAR experiment at Relativistic Heavy Ion Collider has studied the properties of the QGP.
One of the most prominent signatures of QGP formation is the Debye screening of the quark-antiquark potential resulting in quarkonia suppression in central heavy-ion collisions. However, cold nuclear effects, heavy quark recombination and hot wind dissociation could influence the measured quarkonia yields. Measurements of different quarkonia states in different collision systems and centralities are necessary to extract the color-screening effects. Quarkonia measurements allow to extract the thermodynamic properties, since different quarkonia states have different binding energy and therefore disassociate at different temperature of QGP.
In this paper, we will report on the recent STAR measurements of $J/\psi$ and $\Upsilon$ production at mid-rapidity in $p+p$, $d$+Au and Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. We will also present the $J/\psi$ polarization measurement in $p+p$ collisions and the $J/\psi$ elliptic flow measurement in Au+Au collisions.

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## 1. Introduction

Since the year 2000 the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory has been systematicallystudying the properties of hot and dense nuclear matter, Quark-Gluon Plasma (QGP) by the means of heavy-ion collisions [1, 2].

The suppression of quarkonia production is considered to be an excellent probe of color deconfinement in the QGP, because of a color Debye screening of di-quark potential in hot and dense nuclear matter that significantly modify quarkonia production. It is predicted that due to different binding potential of various quarkonia states their production is suppressed above some temperature, that is different for each particular state [3]. However, the effects of color deconfinement have to be disentangled from other competing effects that could influence the quarkonia production. These include cold nuclear matter effects (nuclear absorption, shadowing) and recombination. Previous measurements at RHIC energies showed that the suppression of J/$\psi$ as a function of collision centrality is similar to that observed at the CERN SPS energy. This is puzzling since the temperature and energy density reached in these collisions is significantly lower than at RHIC. Another interesting quarkonium to study is $\Upsilon$. It is expected that $\Upsilon$(1S) state does not dissociate at RHIC energies [3], but $\Upsilon$(2S) and $\Upsilon$(3S) do. This could provide the information about the temperature reached in heavy-ion collisions.

## 2. J/$\psi$ measurements

STAR can measure quarkonium production in di-electron channel due to large acceptance and good electron identification with combination of information from Time Projection Chamber (TPC), Time of Flight detector (TOF) and Barrel Electromagnetic Calorimeter (BEMC). It is possible to take an advantage of high-tower trigger during the data taking in order to enhance the high-$p_T$ part of the spectrum. The high-tower trigger selects the events where the signal in at least one tower of BEMC is above the predefined threshold corresponding to the desired value of deposited energy.

The recent STAR J/$\psi$ measurements [4] in $p+p$ collisions with combination of previously published results [5] cover large $p_T$ range: 0< $p_T$ < 14 GeV/$c$ (see Figure 1 in Ref. [4]). The Color Evaporation Model (CEM) for prompt J/$\psi$ production [6] describes the data well for measured range. It includes direct production and contributions from excited states, however it does not contain the contributions from B feeddown. The J/$\psi$ at production at high-$p_T$ is also well described by Non-Relativistic QCD (NRQCD), next-to-leading order (NLO) Color Singlet and Color Octet (CS+CO) model [7], while it is underestimated by next-to-next-to-leading order (NNLO*) Color Singlet (CS) model for direct J/$\psi$ production [8]. Additional measurement that is sensitive to production mechanisms is the measurement of J/$\psi$ polarization. The preliminary STAR measurement of polarization parameter $\lambda_\theta$ in helicity frame at rapidity $|y| < 1$ and in $p_T$ range 2< $p_T < 5$ GeV/$c$ showed no significant J/$\psi$ polarization within current uncertainties [9].

The measurement of cold nuclear effects on J/$\psi$ production in $d$+Au collisions at 200 GeV was reported in Ref. [4]. The J/$\psi$ nuclear modification factor in $d$+Au collisions was compared to model predictions for the cold nuclear matter effects including the modified EPS09 nuclear parton distribution functions [10]. The nuclear absorption cross section of $\sigma_{abs} = 2.8^{+3.5}_{-2.6}$(stat.)$^{+4.0}_{-2.8}$(syst.)$^{+1.8}_{-1.1}$ (EPS09) mb was obtained.

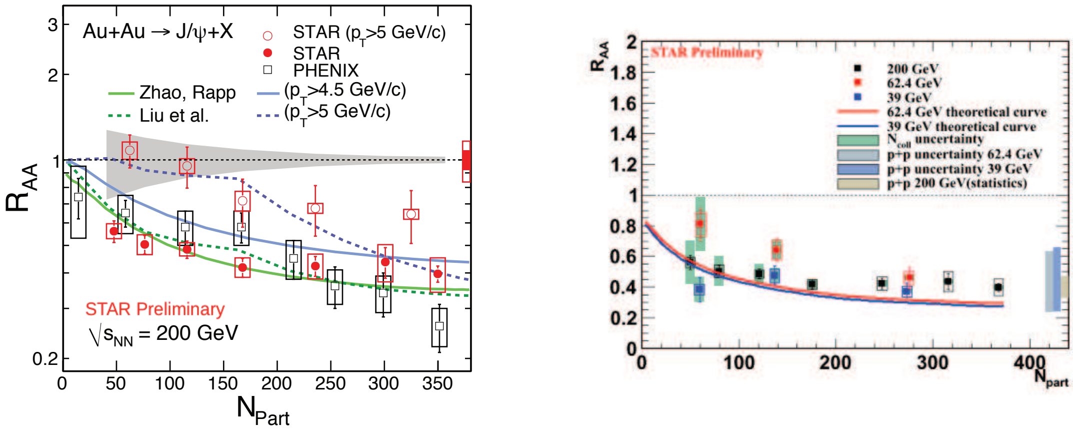


**Figure 1:** The nuclear modification factor as a function of number of participating nucleons in Au+Au collisions measured by the STAR experiment. Left: J/$\psi$ $R_{AA}$ for $p_T$-integrated data from STAR (red full circles) and PHENIX (black open squares) compared to high-$p_T$ measurements ($p_T$ >5 GeV/$c$) [5] (red open circles). Theoretical models Lu [11] and Zhao [12] are also shown. Right: Measurement at 39 and 62.4 GeV energy compared to model of Zhao [12].

In Figure 1 (left) the nuclear modification factor of J/$\psi$ production in Au+Au 200 GeV as a function of number of participating nucleons measured by the STAR experiment is presented. The suppression of J/$\psi$ production is observed with $R_{AA} \sim 0.4$ for most central collisions. No significant dependence on centrality is observed above $N_{part}$ = 150. The suppression of J/$\psi$ with large transverse momentum $p_T > 5$ GeV/$c$ is significantly smaller as compared to J/$\psi$ $p_T$ integrated values.

In addition in Figure 1 (right) the nuclear modification factor of J/$\psi$ production for Au+Au 62.4 and 39 GeV is shown. Please note that the calculation from CEM model [13] is used as a reference. There is a similar suppression observed in energy range from 39 to 200 GeV within the large uncertainties.

The measurement of azimuthal anisotropy can bring additional information about the J/$\psi$ production mechanism (direct pQCD production or recombination). The measurement of azimuthal anisotropy (elliptic flow $v_2$) of J/$\psi$ production [14] as a function of transverse momentum for minimum bias 0-80% most central Au+Au collisions at 200 GeV is presented in Figure 2 (left). In contrary to $v_2$ of hadrons consisting of light quarks, the elliptic flow of J/$\psi$ is found to be consistent with zero at $p_T > 2$ GeV/$c$. This disfavors the production scenario that J/$\psi$ is produced dominantly by coalescence from (anti-)charm quarks which are thermalized and flow with the medium [15] (model [30] in Figure 2 (left)).

## 3. Upsilon measurements

The measurement of $\Upsilon$ is a very clean probe of properties of QGP at RHIC. Several effects that make it difficult to interpret the charmonium data are smaller, such as co-mover absorption and recombination. STAR has reported $\Upsilon$ measurements in di-electron channel in $p+p$ [16], $d$+Au [17] and Au+Au [18] collisions. Recently STAR reported $\Upsilon$ results from large statistics data sample

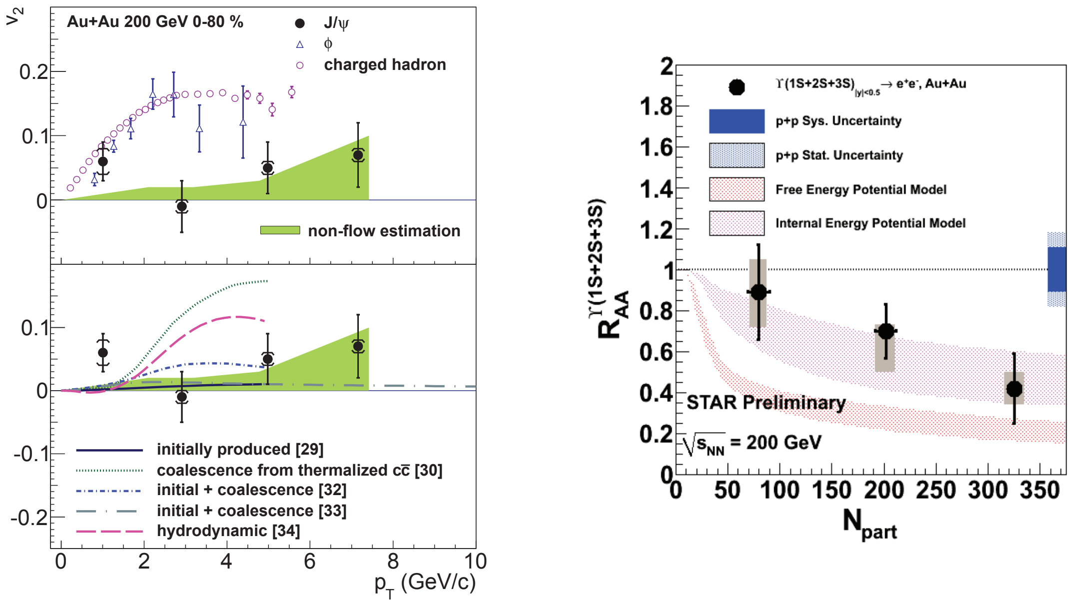


**Figure 2:** Left: The measurement of azimuthal anisotropy parameter $v_2$ of J/$\psi$, hadrons, and $\phi$. Lines indicate several theoretical models. Taken from Ref. [14]. Right: The measurement of ϒ(1S,2S,3S) nuclear modification factor as a function of number of participating nucleons. Theoretical model Ref. [19] is also shown for two different shapes of diquark potentials.

collected year 2010 for Au+Au 200 GeV collisions [9], see Figure 2 (right). The increase of suppression as a function of the number of participants was observed. The ϒ(1S,2S,3S) suppression is consistent with the scenario that 2S, 3S and excited states completely melt [19]. Future measurements with recently installed Muon Telescope Detector in STAR will significantly improve the measurements of separate ϒ states in di-muon channel at midrapidity. In the combination with new Heavy Flavor Tracker it will be possible to address the B→J/$\psi$ channel.

## 4. Summary

In summary, the measurements of quarkonia production provide important information about the properties of hot and dense nuclear matter. The suppression of J/$\psi$ production in central Au+Au collisions at 200 GeV is observed and it is decreasing at larger $p_T$. This suppression is similar also at 39 and 62.4 GeV collision energy. The elliptic flow of J/$\psi$ is found to be consistent with zero within statistical errors at $p_T > 2$ GeV/$c$. The ϒ suppression was observed in central Au+Au collisions and it is consistent with only 1S state survival. New upgrades of STAR detectors with Heavy Flavor Tracker and Muon Telescope Detector will allow to perform more precise quarkonium measurement in di-muon channel in near future at RHIC.

## 5. Acknowledgments

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