

# Overview of STAR results on correlations, jets and heavy-flavor production

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**Abstract.** Measurements of jets and heavy-flavor production play an important role in understanding properties of hot and dense nuclear matter created in high energy heavy-ion collisions. As direct measurements of jets are difficult due to large underlying background, jet properties can be also studied via di-hadron and multihadron correlations. In this contribution to these proceedings, an overview of recent STAR results on correlations, jet-hadron correlations, and heavy-flavor production in Au+Au collisions at top RHIC energy ( $\sqrt{s_{NN}} = 200$  GeV) is given. In order to draw quantitative conclusions on properties of the hot and dense nuclear matter created in Au+Au collisions, reference measurements in elementary proton-proton collisions and d+Au collisions are essential to estimate contributions due to cold nuclear matter effects and are discussed as well.

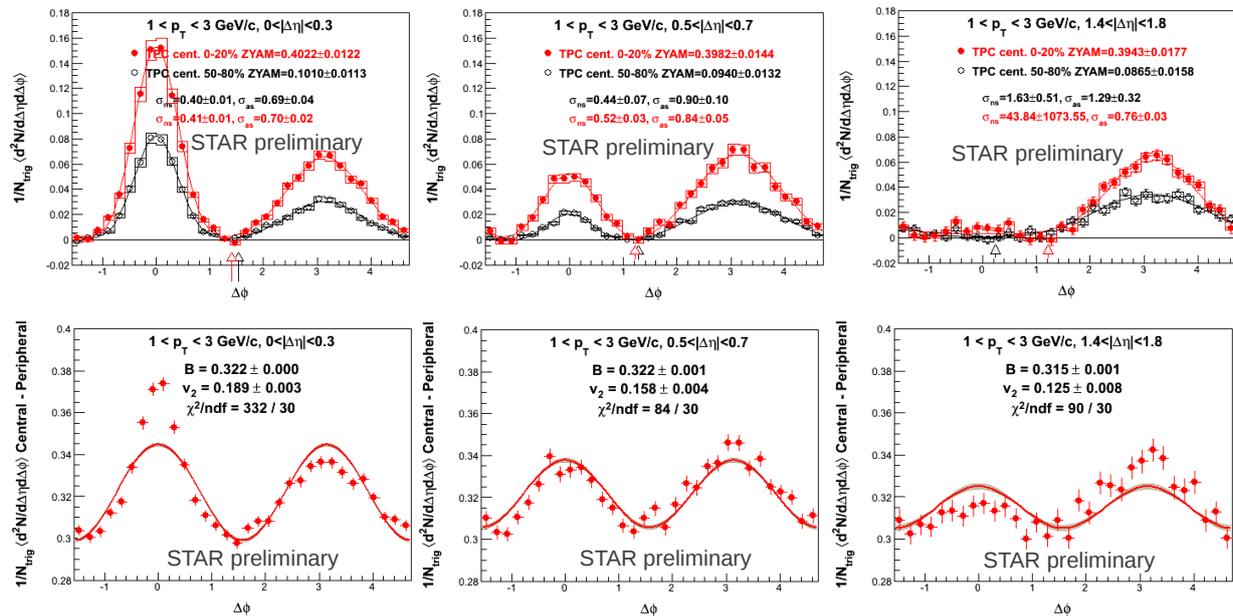
## 1. Introduction

Exploration of nuclear matter under extreme conditions of temperature and energy density is on the forefront of experimental and theoretical research pursued in nuclear physics. By combining multiple experimental signatures, experiments at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory have concluded that a new state of nuclear matter was created in central Au+Au collisions at the center of mass energy  $\sqrt{s_{NN}} = 200$  GeV per nucleon-nucleon pair [1–4] with properties of a strongly coupled liquid with a very low ratio of shear viscosity to entropy. The nuclear matter created at RHIC is opaque to the passage of energetic quarks and gluons which is reflected in a large suppression of particle production at large transverse momenta ( $p_T$ ) relative to elementary p+p collisions. This effect, commonly referred as to “jet quenching”, is observed for light as well as heavy quark flavors. In this proceedings, an overview is given of recent STAR results on measurements of correlations at intermediate and high  $p_T$ , jets and heavy flavor production, the so called hard probes, in p+p, d+Au and Au+Au collisions at top RHIC energy. Latest STAR measurements of identified two-particle correlations as well as direct photon elliptic flow measurements are reported in [5, 6] as presented at this workshop.

## 2. Di-hadron correlations in d+Au collisions

Long-range correlations in pseudo-rapidity (the so called “ridge”) at near side of trigger hadron were discovered at RHIC almost a decade ago [7, 8] and were systematically studied in [9, 10]. The origin of this phenomenon in heavy-ion collisions is most probably connected with initial state fluctuations resulting in triangular flow ( $v_3$ ) [11]. Recent measurements at LHC energies of di-hadron correlations in small systems, such as p+p [12, 13] and p+Pb [14–16] collisions, revealed



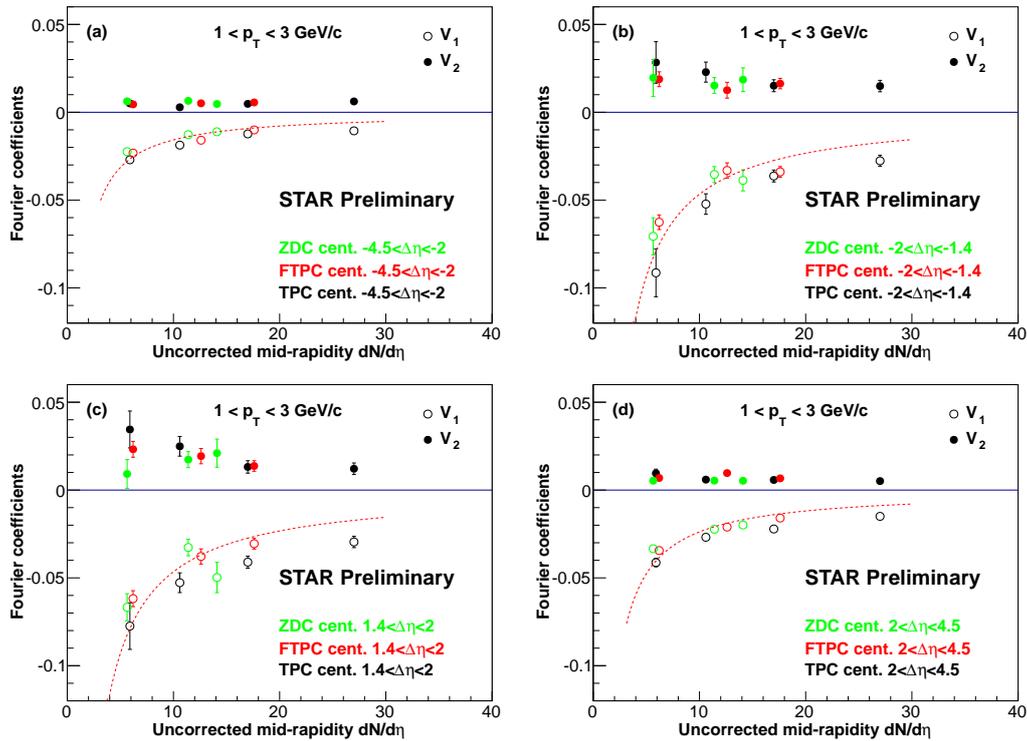


**Figure 1.** Top row: Di-hadron correlations in three  $|\Delta\eta|$  intervals:  $0 < |\Delta\eta| < 0.3$  (left),  $0.5 < |\Delta\eta| < 0.7$  (middle),  $1.4 < |\Delta\eta| < 1.8$  (right) in 50-80% (open black symbols) and 0-20% (close red symbols) d+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. The centrality was determined from charged particle multiplicity in TPC. Both trigger and associated charged particles have  $p_T = 1$ -3 GeV/c and  $|\eta| < 1$ . The boxes indicate systematic uncertainties due to ZYAM background subtraction. Bottom row: Correlation patterns left after subtracting central and peripheral correlations functions from the top row. The curves correspond to  $B(1 + 2v_2^2 \cos(2\Delta\phi))$  fit of the data.

unexpected ridge-like structures as well. In high-multiplicity p+p collisions, an extended ridge-like structure was observed at near side of the trigger hadron at low and intermediate transverse momenta. In p+Pb collisions, when subtracting correlations in low-multiplicity events from high-multiplicity events, two ridge-like structures were observed - one on the near side and one on the away side of the trigger hadron. The yields at both near and away side of the trigger hadron were found to be within uncertainties equal in the studied kinematic range and the widths show no significant evolution with collision multiplicity compared to p+p collisions. The “ridge-like” pattern is much stronger in p+Pb collisions keeping the same charged particle multiplicity as in p+p collisions.

This novel ridge structure triggered intense theoretical discussions and its origin is not fully understood. Various mechanisms proposed to explain the origin of the ridge in high-multiplicity p+p and p+Pb collisions include color field connections in the longitudinal direction [17–19] jet-medium [20] and multi-parton induced interactions [21, 22], and collective effects in high multiplicity p+p and p+Pb collisions [23–26]. On the experimental side the observation of the ridge in cold nuclear matter at LHC lead to a renewed interest in d+Au collisions at RHIC in an effort to search for similar effects at lower collision energy. PHENIX has published their results in [27]. Here we discuss recent STAR measurements of di-hadron correlation in d+Au collisions.

The presented analysis is based on d+Au data set measured in 2003 at  $\sqrt{s_{NN}} = 200$  GeV. The trigger particles were reconstructed in the Time Projection Chamber (TPC) within pseudorapidity  $|\eta| < 1.0$ . These trigger particles were then correlated with associated particles



**Figure 2.** Centrality dependence of Fourier coefficients  $V_1$  and  $V_2$  of di-hadron correlation functions in d+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV for four  $\Delta\eta$  ranges (see legend). Results from all three centrality definitions are shown (see legend). Both trigger and associated charged particles have  $p_T = 1\text{--}3$  GeV/ $c$  and  $|\eta| < 1$ . The line represents a fit of  $V_1$  by a function proportional to  $1/(dN/d\eta)$ .

from the TPC (“TPC-TPC” correlations) or with those measured in Forward Time Projection Chambers (“TPC-FTPC” correlations) placed at  $-3.8 < \eta < -1.8$  and  $1.8 < \eta < 3.8$ , respectively. The correlation functions were normalized per trigger particle and corrected for reconstruction efficiency of associated particles. The two-particle acceptance in  $\Delta\eta - \Delta\phi$  was corrected by mixed event technique. The correlations were analyzed as a function of centrality and  $\Delta\eta$ . To define centrality of d+Au collisions, three methods were used: multiplicity of charged particles in the TPC within  $|\Delta\eta| < 0.5$ , multiplicity of charged particles within  $-3.8 < \eta < -1.8$  in the FTPC in the Au-beam direction, and neutral energy measured in the Zero Degree Calorimeter (ZDC) also placed in the Au-beam direction.

An example of the corrected di-hadron TPC-TPC correlations for transverse momentum  $p_T = 1\text{--}3$  GeV/ $c$  in two multiplicity classes (0-20% and 50-80%) and three  $|\Delta\eta|$  windows is presented in Figure 1. The upper row shows correlations in the two centrality bins after background subtraction based on the ZYAM method [28]. The systematic errors due to ZYAM subtraction are shown as boxes around the measured data points. In the bottom row of Figure 1 the correlations patterns are displayed after subtracting correlations in the mentioned centrality bins (i.e. central-peripheral). In the latter case, no background subtraction method is needed. Projections of the remaining “central-peripheral” correlation patterns to  $\Delta\eta$  separately for near and away-side region in  $\Delta\phi$ , show a Gaussian-like excess at near side and an approximately uniform away side. For further details as well as HIJING model comparisons we refer reader to results presented at [29].

Next, Fourier analysis of the di-hadron correlations was performed for both TPC-TPC as well as TPC-FTPC correlations. The centrality dependence of the extracted Fourier coefficients  $V_n = \langle \cos(n\Delta\phi) \rangle$ , where  $n=1,2$  is shown in Figure 2. The  $V_1$  and  $V_2$  coefficients were calculated for all three centrality determination methods. The  $V_1$  coefficient is found to be inversely proportional to charged particle multiplicity  $dN/d\eta$  at mid-rapidity. The  $V_2$  coefficient is small and approximately independent of  $dN/d\eta$ . The physics mechanism which would explain non-zero values of the Fourier coefficients for “central-peripheral” correlations is currently under investigation [29].

### 3. 2+1 azimuthal correlations

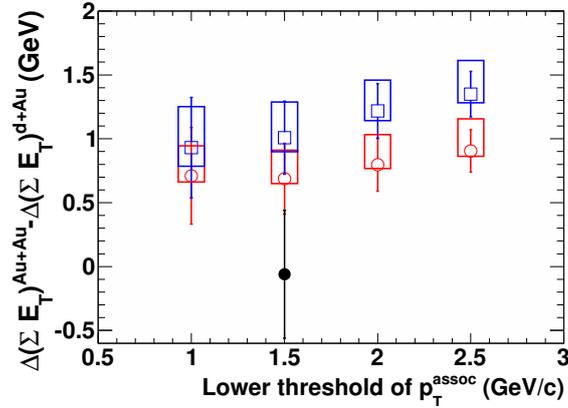
In [30], STAR introduced a novel method for investigating jet-medium interactions via a multi-hadron correlation technique (called “2+1”), where a pair of back-to-back hadron triggers with large transverse momentum is used as a proxy for a di-jet. In this first analysis, the results were reported for nearly-symmetric trigger pairs with the highest momentum threshold of the trigger hadron of 5 GeV/ $c$ . The distributions of associated hadrons were investigated in terms of shapes, approximated by a Gaussian peak, as well as per-trigger yields on each trigger side. The properties of the di-jet like correlations for the symmetric trigger case in central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV were found to be similar in both shape and magnitude to those in d+Au collisions. This observation was suggestive of a strong surface (tangential) bias of selected di-jets.

Here we report an extension of this analysis to higher primary trigger thresholds and asymmetric back-to-back triggers as a tool for changing the amount of surface bias [31]. As primary (T1) triggers, clusters measured in the STAR Barrel ElectroMagnetic Calorimeter (BEMC) with the transverse energy of at least 8 GeV were selected. A highest- $p_T$  charged particle, measured in the STAR TPC, in the back-to-back azimuthal region relative to T1 ( $|\phi^{T1} - \phi^{T2} - \pi| < 0.2$ ) with  $4 < p_T^{T2} < 10$  GeV/ $c$  was then selected as secondary trigger (T2). Following the notation introduced in [30], the  $\eta - \phi$  region close to T1 is defined as near-side region and  $\eta - \phi$  region close to T2 as the away-side region, respectively. The new analysis takes advantage of the triggering capabilities of the BEMC in Run7. This allowed for significant improvement of the kinematic reach and asymmetry. The correlations relative to T1 and T2 triggers were constructed using charged hadrons with transverse momentum  $p_T^{assoc} = 1-10$  GeV/ $c$ . To control the degree of the surface bias the relative energy balance between T1 and T2 was varied. For the most asymmetric trigger pair selection the T1 trigger had more than twice the energy of its T2 trigger partner.

The energy imbalance between the near- and away-side correlations is quantified by

$$\Delta(\Sigma E_T) = (E_T^{T1} + \Sigma p_T^{assoc,near}) - (p_T^{T2} + \Sigma p_T^{assoc,away}) \quad (1)$$

In Figure 3, the relative energy imbalance between central Au+Au and d+Au data (i.e.  $\Delta(\Sigma E_T)^{Au+Au} - \Delta(\Sigma E_T)^{d+Au}$ ), is shown for both the symmetric and asymmetric trigger cases. The errors shown include both statistical and systematic uncertainties. The observed relative energy imbalance for the asymmetric trigger pairs and studied  $p_T$  range of associated charged particles is consistent with non-zero values. The relative imbalance reaches the value of  $\sim 1.5$  GeV/ $c$  for the highest  $p_T$  associated bin and decreases with lowering  $p_T$  of the associated particles. This suggests that the energy missing from the away-side peak at higher  $p_T^{assoc}$  is converted into softer hadrons. This observation is in line with expectation that larger asymmetries are related to longer paths traversed in medium and consequently higher energy loss. The measured values of relative energy imbalance were found to be significantly smaller than expected in the path-dependent energy loss model [32], which predicts 3 GeV for the asymmetric trigger case. We note that the imbalance observable is, however, not sensitive to



**Figure 3.** The relative di-jet energy imbalance estimate  $\Delta(\Sigma E_T)^{Au+Au} - \Delta(\Sigma E_T)^{d+Au}$ . The open circles show results for primary triggers in (8-10) GeV, the open squares in (10,15) GeV. The solid data point is the result for symmetric trigger case from [30]. The figure is from [31].

cases when a part of energy deposited to the medium is converted to particle production within the angular selection of the near- and away-side peaks.

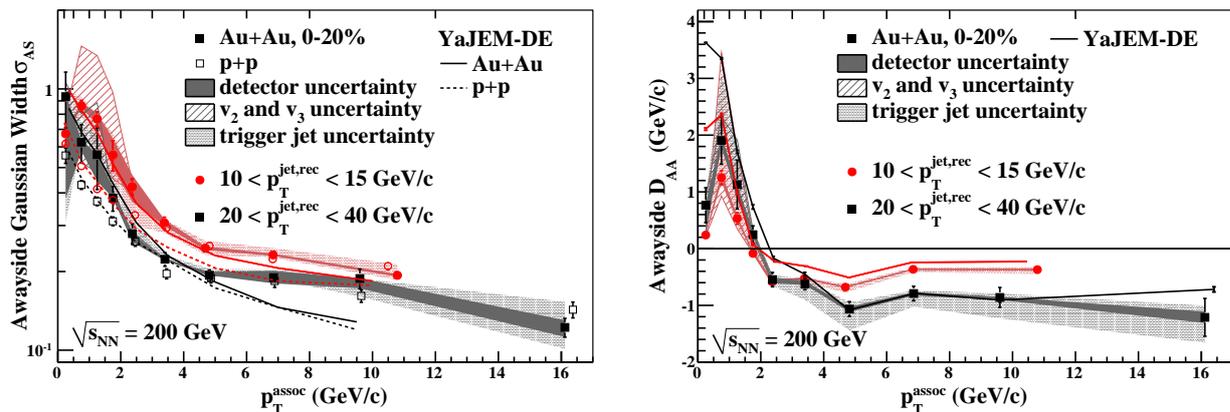
#### 4. Jet-hadron correlations

Jet-hadron correlations enable a more direct access to the parton energy in comparison with di-hadron correlations, which use a high  $p_T$  trigger hadron as a proxy of jet axis. At the same time, jet-hadron correlations increase the kinematic reach of the correlation measurements. The STAR experiment presented recently a novel study of jet-hadron correlations in p+p and central Au+Au collisions. To enhance contribution of jets, events were selected based on an online high-tower (HT) trigger in the BEMC with an energy deposition in at least one BEMC tower above 5.4 GeV. In addition, a common offline software HT threshold of 6 GeV was required as well. Jets were reconstructed using the anti- $k_T$  recombination algorithm [33] with a resolution parameter  $R = 0.4$  from charged tracks detected in the TPC and the transverse energy measured in the BEMC. To suppress background fluctuations, only tracks with  $p_T > 2$  GeV/c and BEMC towers with  $E_T > 2$  GeV were used to reconstruct jets. Furthermore, the reconstructed jet had to include as one of its constituents a BEMC tower that fired the HT trigger. To avoid double counting, a 100% hadronic correction scheme was applied to account for charged hadron energy deposition in the BEMC.

The jet-hadron correlations reported below [34] were defined as distributions in  $\Delta\phi = \phi_{jet} - \phi_{assoc}$ , where  $\phi_{jet}$  is the azimuthal angle of the axis of a reconstructed (trigger) jet and the associated particles are all charged hadrons in a given event. The distributions were corrected for single particle tracking efficiency and for detector pair acceptance by event mixing in  $\Delta\phi$ . To quantify the associated particle yields ( $Y$ ) and widths ( $\sigma$ ) of the near and away-side peaks, the correlation functions were fit with two Gaussians together with a background term modulated by elliptic ( $v_2^{assoc} v_2^{jet}$ ) and triangular ( $v_3^{assoc} v_3^{jet}$ ) Fourier components.

The medium modification of near and away-side peaks was then quantified by studying their Gaussian widths as well as by  $D_{AA}$  defined as:

$$D_{AA}(p_T^{assoc}) \equiv Y_{AuAu}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{AuAu} - Y_{pp}(p_T^{assoc}) \cdot \langle p_T^{assoc} \rangle_{pp}. \quad (2)$$



**Figure 4.** (Left): The Gaussian widths of the away-side jet peak ( $\sigma_{AS}$ ) in Au+Au (solid symbols) and p+p (open symbols) for two ranges of  $p_T^{jet,rec}$ : 10-15 GeV/c (red circles) and 20-40 GeV/c (black squares). (Right) The away-side momentum difference  $D_{AA}$  for two ranges of  $p_T^{jet,rec}$ : 10-15 GeV/c (red circles) and 20-40 GeV/c (black squares). The data are compared to YaJEM-DE model calculations (solid and dashed lines) from [35].

and  $\Sigma D_{AA}$  which is a measure of the energy balance over the entire  $p_T^{assoc}$  range:

$$\Sigma D_{AA} \equiv \sum_{p_T^{assoc} bins} D_{AA}(p_T^{assoc}) \quad (3)$$

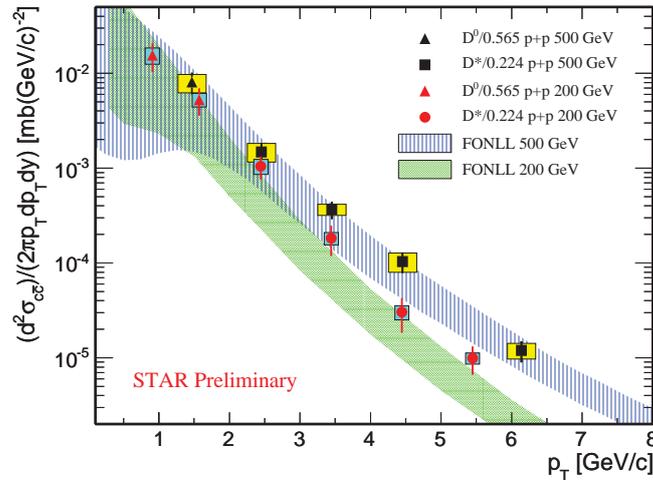
Any deviations from zero would indicate in-medium modification of fragmentation patterns.

As the trigger jet is expected to have a surface bias, the recoiling parton will travel a significant distance through the medium. This should be reflected in an enhanced partonic energy loss and quenching on the away side. The away-side Gaussian widths ( $\sigma_{AS}$ ) and  $D_{AA}$  are shown in Figure 4 for two ranges in reconstructed jet transverse momentum,  $p_T^{jet,rec}$ . The away-side widths at high  $p_T^{assoc}$  are on average the same in both p+p and Au+Au collisions pointing to the fact that high  $p_T$  fragments are not deflected in the medium. The widths at low  $p_T^{assoc}$  are suggestive of in-medium broadening, but the systematic errors due to flow subtraction are large and measurements of jet flow are necessary before any quantitative conclusions can be drawn. The away-side  $D_{AA}$  exhibits suppression of high  $p_T^{assoc}$  hadrons and enhancement of low- $p_T^{assoc}$  fragments in Au+Au. This indicates softening of fragmentation in Au+Au relative to p+p collisions. A detailed study of  $\Sigma D_{AA}$  values [34] also indicated that the high  $p_T^{assoc}$  suppression is largely balanced by the low- $p_T^{assoc}$  enhancement.

The data in Figure 4 are compared to theoretical calculations from YaJEM-DE [36] Monte Carlo model of in-medium shower evolution. The model incorporates both radiative and collisional energy loss and is successful in describing a range of high  $p_T$  observables at RHIC. The redistribution of energy from high to low- $p_T$  charged particles which remain correlated with the jet is quantitatively consistent with the YaJEM-DE model expectations.

## 5. Open charm production

Particles containing a charm ( $c$ ) or a beauty ( $b$ ) quark, the so called heavy flavors, provide due to their large mass better sensitivity to medium properties than light quarks. However, the rate of heavy flavor production is much smaller therefore requiring large data samples. In recent years, the increased luminosity of RHIC and data taking rates allowed to significantly improve statistics and thus investigate in a systematic way the charm production. The charm production



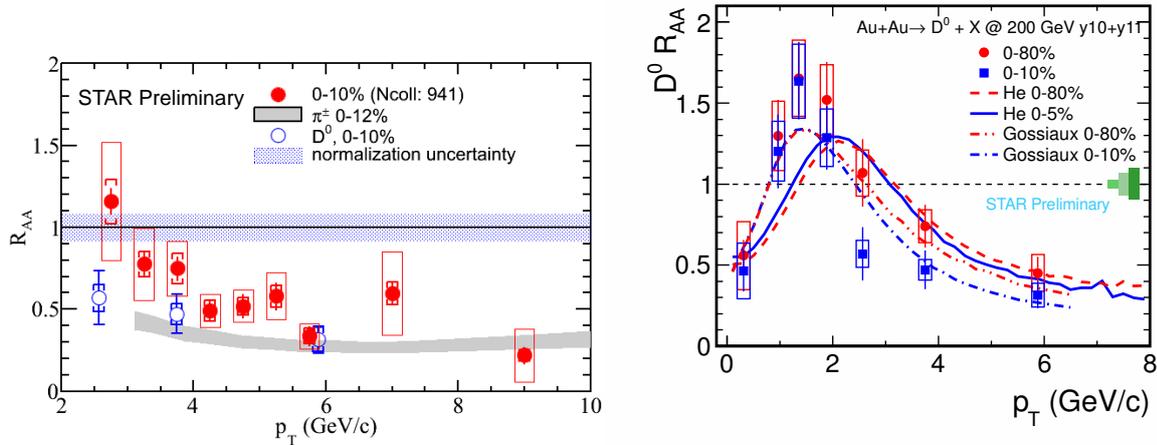
**Figure 5.** Transverse momentum dependence of  $c\bar{c}$  production cross section calculated from  $D^0$  and  $D^*$  yields in p+p collisions at  $\sqrt{s} = 200$  GeV [37] and 500 GeV [38]. The data are compared to FONLL calculations [39].

can be indirectly measured via electrons from heavy-flavor decays, also commonly referred to as “non-photonic electrons” (NPE) produced from semileptonic heavy-flavor decays. A direct access to charm production requires reconstruction of e.g.  $D$  mesons containing the  $c$  quark.

For measurements in heavy-ion collisions it is essential to understand first heavy flavor production in elementary collision systems such as p+p. Here we feature the most recent STAR measurement of  $c\bar{c}$  production cross section from hadronic decays of  $D^0$  and  $D^*$  mesons in p+p collisions at  $\sqrt{s} = 200$  GeV [37] and 500 GeV [38]. The corresponding charm spectra are shown in Figure 5 and are compared to the Fixed-Order-Next-to-Leading-Logarithm (FONLL) calculations from [39]. The FONLL calculations are found to agree well with data given current experimental and theoretical uncertainties. These measurements constitute an important baseline for similar measurements in heavy-ion collisions.

It was originally expected that in the medium, due to a suppression of gluon radiation at small angles known as the “dead cone” effect [40], heavy quarks will exhibit less suppression than light quarks. However, already the first measurements in central Au+Au collisions at RHIC revealed that production of NPE shows surprisingly similar level of suppression as that of light quarks [41–43]. Several mechanisms have therefore been suggested to explain the large NPE suppression in addition to radiative energy loss. Models, which also incorporate collisional energy loss and energy loss due to in-medium dissociation of heavy flavor  $D$  and  $B$  mesons, were proven to be more successful in the description of NPE  $R_{AA}$ , see e.g. [44–46].

Here we demonstrate the large suppression of charm production on the newest STAR data [38, 47]. The left panel of Figure 6 shows the nuclear modification factor of NPE and  $D^0$  mesons in 0-10% most central Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. As it can be seen, the suppression of NPE and charm mesons is consistent with each other and with that of pions. In the right panel of Figure 6 a closer investigation of  $R_{AA}$  of  $D^0$  mesons in central as well as minimum bias Au+Au collisions in the transverse momentum range  $0 < p_T < 6$  GeV/c is shown. The  $R_{AA}$  has a peaked structure with a maximum between  $p_T = 1-3$  GeV/c. At higher momenta ( $p_T > 3$  GeV/c), there is a strong suppression of  $D^0$  yields which increases with centrality. This indicates a large energy loss of charm quarks traversing through the medium. The data are also compared with two transport model calculations [48, 49] based on the relativistic Langevin



**Figure 6.** (Left) Transverse momentum dependence of nuclear modification factor of non-photonic electrons (full circles) and  $D^0$  mesons (open circles) in 0-10% most central Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV. For comparison the nuclear modification factor of pions is shown as well (grey band). (Right) Nuclear modification factor of  $D^0$  meson vs  $p_T$  for 0-10% and 0-80% centralities in Au+Au collisions at  $\sqrt{s_{NN}} = 200$  GeV. The data are compared to two transport model calculations (see legend). Error bars on the data points are statistical while boxes represent systematic uncertainties. The figures are from [38].

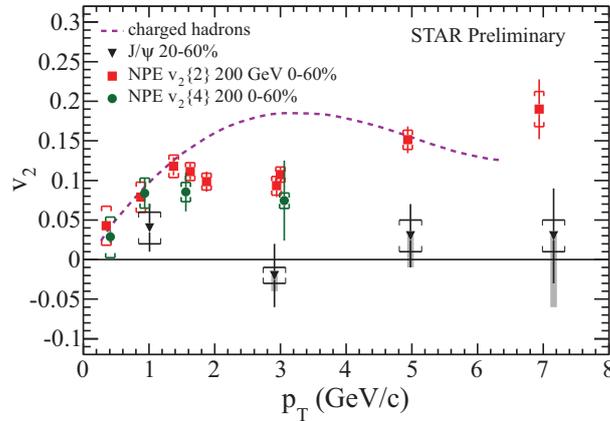
simulation. The calculations describe well the shape of the nuclear modification factor and interpret the maximum as being caused by the transverse flow picked up from the expanding medium. In addition, a large anisotropic elliptic flow ( $v_2$ ) of NPE has been observed in Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV as demonstrated in Figure 7. The  $v_2$  was measured by 2-particle correlation method and 4-particle cumulant method, where the latter one shows consistently smaller  $v_2$  values as expected due to smaller contribution of non-flow effects. These  $v_2$  values are systematically higher than those measured at lower collision energies  $\sqrt{s_{NN}} = 39$  and 62.4 GeV, respectively [47]. The large  $v_2$  values provide additional indication of strong interaction of charm quarks with the medium and pose a challenge for model calculations to describe simultaneously both  $R_{AA}$  and  $v_2$ . However, future measurements of  $v_2$  of charmed mesons are needed to obtain direct information about charm elliptic flow.

## 6. Outlook

In this contribution to these proceedings, only a selection of recent STAR results on correlations, jets, and heavy flavor production could be featured. Recent progress in studies of fully reconstructed jets in combination with high statistics Run-11 Au+Au data sample is expected to bring new insights into energy loss in medium created at top RHIC energy. From 2014 onward, the STAR experiment will run with greatly enhanced detection capabilities of heavy-flavor particles allowing direct reconstruction of secondary vertices of charm and beauty hadron decays. This together with the higher RHIC luminosity will enable STAR to enter a new era of precision and comprehensive measurements for rare probes of the nuclear matter.

## Acknowledgements

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**Figure 7.** Measurement of heavy flavor electron (NPE) elliptic flow  $v_2$  as a function of  $p_T$  in 0-60% Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV. For comparison, the charged hadron (dashed line) and  $J/\psi$  (closed triangle down) elliptic flow is also shown. The figure is taken from [47].

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