

## Jet Measurements at STAR

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Jets are an important tool to explore the properties of the hot and dense nuclear matter created in heavy-ion collisions. However, full jet reconstruction in such events is a challenging task due to the extremely large and fluctuating background, which generates a large population of combinatorial jets that overwhelm the true hard jet population.

In order to carry out accurate, data-driven jet measurements over a broad kinematic range in these conditions of small signal to background, we use modern approaches in order to measure inclusive charged jet distributions and semi-inclusive charged jet distributions recoiling from a high momentum trigger in central Au+Au collisions. In addition we present the measurement of the di-jet transverse momentum asymmetry,  $A_J$ . These jet measurements allow a direct comparison of jet quenching at RHIC and the LHC.

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## 1. Motivation

Hard scattering processes produce partons with high transverse momentum  $p_T$ . These recoiled partons fragment and then hadronize into a collimated stream of mesons and baryons. These final state hadrons are clustered into a jet, which should reflect the kinematics of the hard scattered parton. Due to the fact that jets originate from hard processes, perturbative QCD is applicable for calculation of their cross-section. The pQCD calculations describe measurements of jet production in elementary collisions (pp, e+e) with high accuracy [1].

In heavy-ion collisions, jets are produced in an early stage of the collision, allowing them to interact with the surrounding medium (quark gluon plasma, QGP). A parton traverses through the hot, dense, strongly interacting medium, losing energy via radiative and collisional processes, which will soften and broaden the final state jet [2]. By comparing properties of jets in heavy-ion collisions with theoretically well described jets in elementary collisions, one can indirectly study properties of the QGP. Jets are therefore a good probe of the QCD matter.

## 2. Experimental Setup and Data-sets

Analyses presented in this proceeding are based on data recorded by the Solenoidal Tracker At RHIC (STAR), which is a complex detector consisting of several sub-detectors and full azimuthal coverage. Its main sub-detector is a large Time Projection Chamber (TPC) capable of tracking and identification of charged particles down to a transverse momentum of 100 MeV/c. The TPC is surrounded by a Barrel Electromagnetic Calorimeter (BEMC) and other detectors such as Time Of Flight (TOF) and Muon Telescope Detector (MTD) and a massive solenoidal 0.5 T magnet. Full description of the STAR experiment and its main sub-detectors can be found in [3, 4, 5].

Inclusive and semi-inclusive jet analyses use minimum bias (MB) data from Au+Au collisions at an energy per nucleon pair of  $\sqrt{s_{NN}}=200$  GeV recorded by the STAR experiment at RHIC in 2011. Events with TPC multiplicities corresponding to 0-10% and 60-80% most central Au+Au collisions and having the  $z$  position of the primary vertex within 30 cm from the center of the TPC are further used in these data analyses.

The  $|A_J|$  analysis uses High-Tower (HT) triggered events (events with energy deposit in a BEMC tower above a certain threshold) recorded by the STAR experiment in Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV in 2007 with the TPC multiplicity corresponding to the 0-20% most central Au+Au collisions.

## 3. Jet Reconstruction

Inclusive and semi-inclusive jet analyses presented below use the TPC tracks to reconstruct charged jets. The TPC tracks were required to have transverse momenta  $p_T > 0.2$  GeV/c, pseudo-rapidity  $|\eta| < 1$  and at least 20 TPC space-points.

The di-jet asymmetry  $|A_J|$  measurement is based on full jets, utilizing also energy deposited in the BEMC towers. 100% hadronic correction was applied to the BEMC towers (the entire  $p_T$  of a track matched to a calorimeter tower is subtracted from that tower's energy).

The TPC tracks (and calorimetric towers) were collected into jets using the anti- $k_T$  algorithm provided by the FastJet package [6, 7]. The jet area  $A$  was then calculated using the population of soft “ghost particles” [8]. The background energy was subtracted jet-by-jet from the reconstructed jet transverse momentum by

$$p_{T,\text{jet}}^{\text{reco}} = p_{T,\text{jet}} - \rho \times A \quad (3.1)$$

where  $\rho$  is the background median energy density calculated for each event as

$$\rho = \text{med}\left\{\frac{p_{T,\text{jet}}^i}{A_i}\right\} \quad (3.2)$$

where the index  $i$  goes through all reconstructed jets in the event (with exclusion of the 2-3 hardest jets in the event). The background jets are reconstructed using the  $k_T$  algorithm.

The jet resolution parameter  $R$ , which determines the size of the reconstructed jet, was chosen to be 0.2, 0.3 and 0.4. All jets are required to lie within the fiducial rapidity acceptance  $|\eta| < 1 - R$ .

#### 4. Inclusive Charged Jet Measurements

The inclusive jet cross-section in p+p collisions represents an important observable that is calculable in pQCD. In heavy-ion collisions jet fragmentation will be affected by the presence of the hot and dense medium created in these collisions. Therefore it is of a high importance to compare the p+p measurements with those in the nucleus-nucleus collisions.

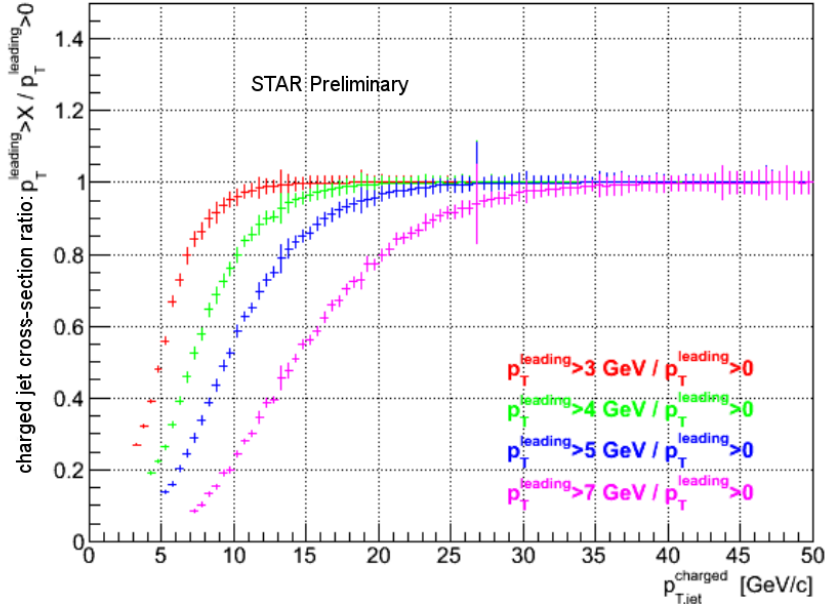
Jet reconstruction in the environment of the heavy-ion collisions has to correct for the large and highly fluctuating background. In order to reduce the combinatorial jet background in the Au+Au collisions a cut on the transverse momentum of the leading hadron in the jet (hadron with the highest transverse momentum) is applied. In our case we impose a cut of  $p_T^{\text{leading}} > 5 \text{ GeV}/c$ . Such a cut induces a fragmentation bias, which needs to be systematically studied (see Fig. 1). However, as there are no requirements on the rest of the jet constituents, the effect of the bias is negligible for high-momentum jets.

The most significant effect which needs to be taken into account in this analysis is the large background fluctuation. The jet response to such fluctuations is measured on ensemble basis by embedding simulated jets into real events. By comparing the momenta of the embedded jet and the geometrically matched reconstructed jet one can evaluate the response in terms of the  $\delta p_T$  distribution

$$\delta p_T = p_{T,\text{jet}}^{\text{reco}} - p_{T,\text{jet}}^{\text{emb}} = p_{T,\text{jet}} - \rho \times A - p_{T,\text{jet}}^{\text{emb}} \quad (4.1)$$

It has been shown [9] that the shape of the  $\delta p_T$  distribution is almost independent of the fragmentation model of the embedded jet. Also the dependency of the  $\delta p_T$  distribution on the momentum of the embedded probe is very weak as can be seen in Fig. 2.

The  $\delta p_T$  distribution is sampled in order to produce the corresponding response matrix  $\mathbf{R}_{\delta p_T} \left[ p_{T,\text{jet}}^{\text{reco}}, p_{T,\text{jet}}^{\text{emb}} \right] = \mathbf{R}_{\delta p_T} \left[ p_{T,\text{jet}}^{\text{emb}} + \delta p_T, p_{T,\text{jet}}^{\text{emb}} \right]$ . The detector response is approximated by the parametrization of the TPC tracking efficiency which was estimated by the embedding of simulated tracks into real events and running the TPC track reconstruction algorithm on such events.



**Figure 1:** Effect of the  $p_T^{\text{leading}}$  cut on PYTHIA charged jet spectra at  $\sqrt{s_{NN}}=200$  GeV and within STAR acceptance.

The tracking efficiency for hadrons is 68% at  $p_T=0.5$  GeV/c and 72% for  $p_T > 1$  GeV/c in central collisions.

Using jets generated by PYTHIA, a detector response matrix  $\mathbf{R}_{instr} [p_T^{\text{det}}, p_T^{\text{part}}]$  was calculated, where  $p_T^{\text{part}}$  is the transverse momentum of the generated (and reconstructed) PYTHIA jet and  $p_T^{\text{det}}$  is the momentum of the same (geometrically matched) jet after the tracking efficiency was applied to its constituents.

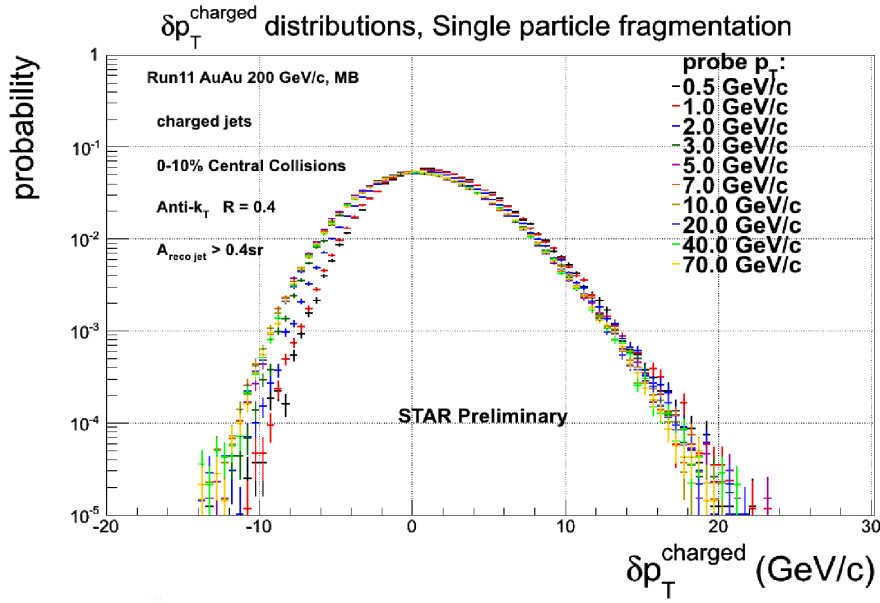
The full correction response matrix  $\mathbf{R}_{full}$  is obtained by multiplying the two response matrices

$$\mathbf{R}_{full} = \mathbf{R}_{\delta p_T} \times \mathbf{R}_{instr} \quad (4.2)$$

Using this response matrix and a power-law prior distribution, the jet transverse momentum spectrum is corrected for the background fluctuations and the TPC tracking efficiency via an iterative Bayesian unfolding [10]. No  $p_T$  cut-off is applied on the jet spectrum prior unfolding.

The systematic uncertainty arising from the unfolding was estimated by varying the power of the initial power-law prior distribution (from -3 to -6) and by varying the number of iterations. Another component of the systematic uncertainty comes from the uncertainty on the tracking efficiency. It was estimated by varying the tracking efficiency  $\pm 5\%$  (absolute).

After the unfolding procedure the jet spectrum is further corrected for the jet reconstruction efficiency by multiplying a given momentum bin with the inverse value of the corresponding efficiency. When calculating the jet reconstruction efficiency, one should not compare directly detector-level and particle-level distributions bin-by-bin. Due to the detector effects, a jet having  $p_{T,jet}^{\text{part}}$  will be typically detected with  $p_{T,jet}^{\text{det}} \neq p_{T,jet}^{\text{part}}$  and thus potentially migrate from  $i$ -th  $p_T$  bin to  $j$ -th. Comparing  $i$ -th bin of particle-level spectrum with  $i$ -th bin of detector level spectrum is



**Figure 2:**  $\delta p_T$  distribution for central Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV for several momenta of embedded probes.

therefore not a good strategy and one has to take into account the above mentioned bin migration. Jet reconstruction efficiency was thus defined with respect to the particle-level jets as

$$\epsilon(p_{T,jet}^{part}) = \frac{\frac{dN_{jet}}{dp_{T,jet}^{det}} \otimes \widetilde{\mathbf{R}}_{instr}^{-1} \left[ p_{T,jet}^{part} \rightarrow p_{T,jet}^{det} \right]}{\frac{dN_{jet}}{dp_{T,jet}^{part}}} \quad (4.3)$$

where  $\frac{dN_{jet}}{dp_{T,jet}^{det}}$  and  $\frac{dN_{jet}}{dp_{T,jet}^{part}}$  are the detector-level and particle-level jet spectra. The expression in the numerator of Equation (4.3) is to be understood as unfolded and regularized detector-level spectrum. Unfolding of the detector-level spectrum was done using only the instrumental response matrix  $\mathbf{R}_{instr}$ .

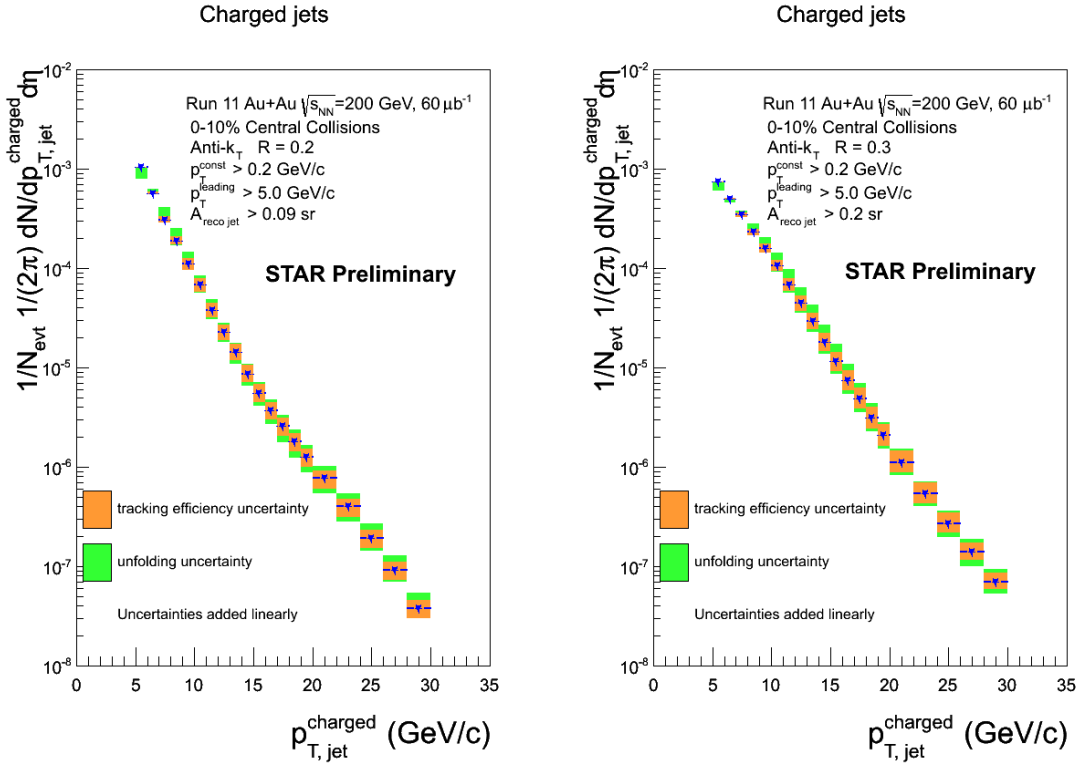
Fig. 3 shows the inclusive charged jet spectra for jet resolution parameters  $R = 0.2$  and  $0.3$ , corrected for the background fluctuations, TPC tracking efficiency and jet reconstruction efficiency. Systematic uncertainties from unfolding and tracking efficiencies are added linearly.

The low momentum part of the spectra is biased by the cut on the momentum of the leading hadron  $p_T^{leading} > 5$  GeV/c. PYTHIA simulations shown on Fig. 1 reveal that the effect of this bias is significant up to momenta  $p_{T,jet} \simeq 4 \cdot p_T^{leading} = 20$  GeV/c.

In order to calculate the charged jet nuclear modification factor  $R_{AA}$  a valid pp baseline is needed.

## 5. Semi-Inclusive Recoil Charged Jet Measurements

A way to avoid the bias on the jet fragmentation caused by imposing a momentum cut on the jet constituents is to bias the event selection instead. This can be done by selecting a high momentum



**Figure 3:** The unfolded  $p_T$  spectrum of charged jets in central Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV for  $R = 0.2$  (left) and  $R = 0.3$  (right).

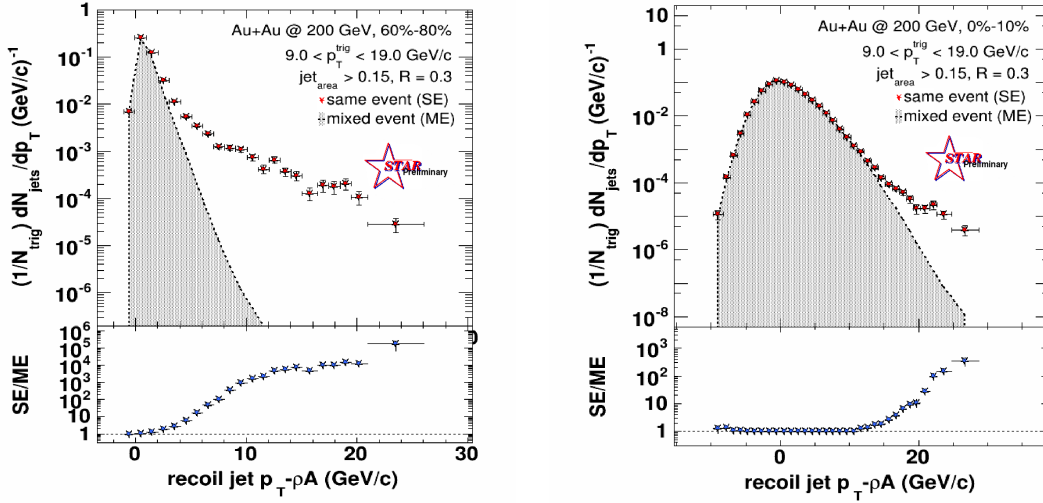
hadron trigger. Jets reconstructed on the away side in azimuth will be completely unbiased with respect to their fragmentation (there is no need to impose a cut on the constituents' momenta). Furthermore such a jet population will be biased towards larger path-length in the medium making it a viable probe of the medium. An observable which is easily calculable by means of pQCD is the recoil jet yield per trigger. Jets are reconstructed with anti- $k_T$  algorithm with resolution parameter  $R = 0.3$ . The azimuthal acceptance of the recoil jets is chosen to be within 45 degrees from the recoil direction opposite to the trigger hadron,

$$|\phi_{Jet} - (\phi_{Trig} + \pi)| \leq \pi/4. \quad (5.1)$$

The hadron trigger momentum range is chosen to be 9-19 GeV/c.

A unique mixed event method was developed which should describe the background as closely as possible. The mixed event is created by replacing all tracks in a real event by randomly selected tracks from randomly chosen events (one track from one event) from the same centrality bin, event plane direction bin and primary vertex  $z$  position bin. All high momentum tracks ( $p_T > 3$  GeV/c) which could possibly come from a hard jet are discarded. This creates a perfectly uncorrelated sample of tracks which preserve some important features of the real events, e.g. the detector acceptance inefficiencies.

The jet reconstruction algorithm is then run on the mixed event (ME) sample with the same settings as on the real events (“same event”, SE). The obtained ME jet spectrum is normalized by



**Figure 4:** Uncorrected recoil charged jet spectrum in comparison with mixed event spectrum in peripheral (left) and central (right) Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV.

matching the integral of the left hand side (LHS) of the spectrum with the LHS of the SE spectrum. The size of this normalization region was systematically varied and the resulting variance was included in the systematic uncertainties.

Fig. 4 shows both the same event and mixed event recoil charged jet spectra in peripheral and central Au+Au collisions normalized per trigger yield. As one would expect, the background is much less severe in the peripheral collisions than in the most central ones. The bottom panels show the ratio SE/ME. In central collisions, the low momentum spectrum is dominated by the background. Since the ratio SE/ME is consistent with unity up to 10 GeV/c in the central collisions (right bottom panel), this means the background is perfectly described by the mixed event. The recoil jet signal is then extracted by subtracting the mixed event spectrum from the same event.

The recoil jet spectrum shown in Fig. 5 is not corrected for the background fluctuations and detector effects yet. However, as a first approximation, it can be compared with PYTHIA 8 p+p spectrum smeared with  $\delta p_T$  distribution, hence simulating the effect of the presence of heavy-ion collision background, and with tracking efficiency applied to the PYTHIA jets constituents.

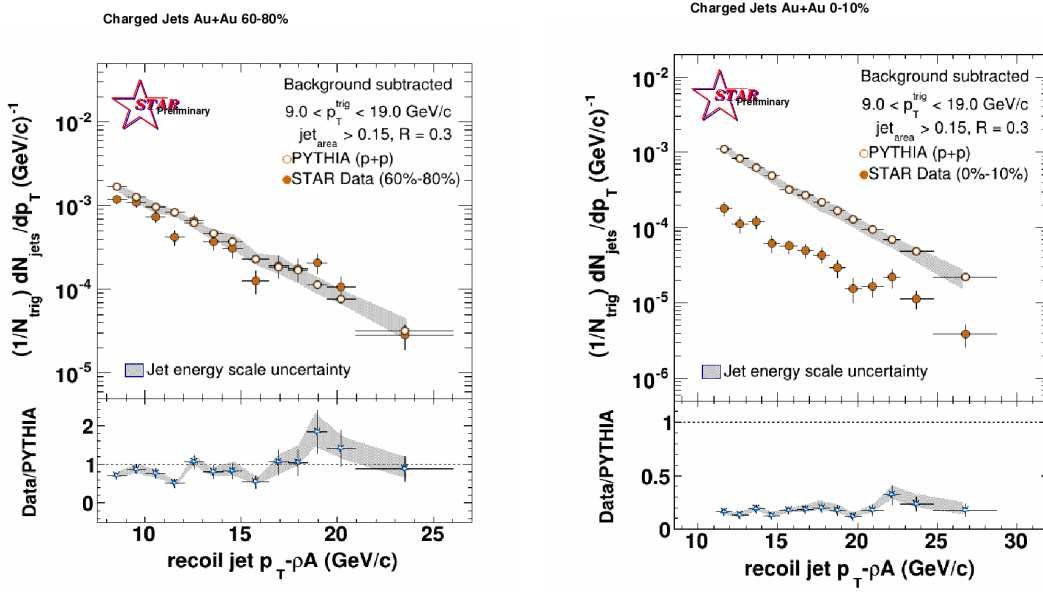
Such “detector level” recoil jet spectra normalized per trigger yield are shown on Fig. 5 both for the peripheral and central Au+Au collisions. In peripheral collisions there is no sign of a suppression of the Au+Au spectra with respect to PYTHIA, as can be seen from the ratio plot in the bottom. However in central Au+Au collisions a strong suppression is evident.

## 6. $|A_J|$ Measurements

The di-jet imbalance  $A_J$  is defined as

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}} \quad (6.1)$$





**Figure 5:** Charged recoil jet spectrum after background subtracted in peripheral (left) and central (right) Au+Au collisions at  $\sqrt{s_{NN}}=200$  GeV compared with PYTHIA charged recoil jet spectrum smeared with background fluctuations and simulated detector effects.

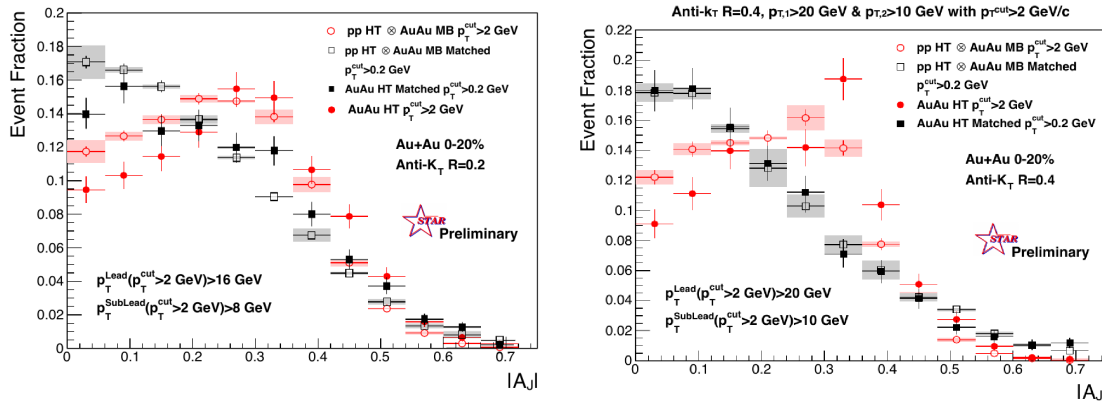
with  $p_{T,1}$  and  $p_{T,2}$  being the transverse momentum of the leading (most energetic) and sub-leading (second most energetic) jet. In the absence of a medium in the elementary collisions, produced pairs of jets have the same  $p_T$  and are back-to-back with an azimuthal angle difference  $\Delta\phi = \pi$  (at leading order pQCD). In heavy-ion collisions on the other hand it is expected that the presence of the hot, dense and strongly interacting medium would lead to the observation of highly unbalanced di-jets.

In order to study the effect of the fragmentation bias, two jet samples were compared. A highly biased jet sample was obtained by requiring the jet constituents' momentum to satisfy  $p_{T,const} > 2$  GeV/c. The jet imbalance  $A_J^{biased}$  was then calculated for leading jets with momentum  $p_{T,jet}^{Lead} > 20$  GeV/c (16 GeV/c for  $R=0.2$ ) and sub-leading jets with  $p_{T,jet}^{SubLead} > 10$  GeV/c (8 GeV/c for  $R=0.2$ ). A second jet sample was created by imposing only minimal cut on jet constituents  $p_{T,const} > 0.2$  GeV/c. Leading and sub-leading jets were geometrically matched with jets from the first sample. Using this unbiased jet sample the jet imbalance  $A_J^{unbiased}$  was calculated.

As a baseline HT pp events from 2006 embedded into Au+Au MB events from 2007 were also used. These events were created to test whether the jet imbalance is merely due to the fluctuating background under the jets, and not any QGP effect.

Fig. 6 shows calculated values of di-jet imbalance  $A_J^{biased}$  (circles) and  $A_J^{unbiased}$  (squares) in triggered central Au+Au collisions (full symbols) and pp events embedded into minimum bias Au+Au events (open symbols). Jets with  $R = 0.2$  (left) possess significant difference between Au+Au and pp collisions, both for the biased and unbiased jet sample. However a good agreement between Au+Au and pp events in case of  $R = 0.4$  for unbiased jets (containing soft particles) is observed. Such an energy restoration within the cone of  $R = 0.4$  has not been observed at the LHC





**Figure 6:**  $|A_J|$  of full jets with resolution parameter  $R = 0.2$  (left) and  $R = 0.4$  (right) in Au+Au collisions (full symbols) and pp collisions with embedded Au+Au background (open symbols) at  $\sqrt{s_{NN}}=200$  GeV.

[11, 12].

## 7. Conclusions and Outlook

We have presented recent measurements of inclusive charged jet spectra in central Au+Au collisions corrected for the background fluctuations and detector effects. The low momentum part of the presented spectra exhibits a bias due to the cut on the leading hadron momentum. However a valid pp baseline is necessary in order to calculate the charged jet nuclear modification factor  $R_{AA}$ .

In central Au+Au collisions, the semi-inclusive recoil charged-jet spectrum normalized per trigger shows a strong suppression relative to the "detector level" PYTHIA pp spectrum. There is no evidence of suppression in peripheral Au+Au collisions.

The measurement of the di-jet momentum imbalance  $|A_J|$  reveals energy recovery in the most central Au+Au collisions for larger jets with  $R = 0.4$  when low momentum particles are included in the jet. The observation that for  $R = 0.4$  the energy lost is recovered within the cone of the jet is different than what has been seen at the LHC.

However the  $A_J$  measurement and the recoil-jet measurement are significantly different analyses due to a strong selection bias of the  $A_J$  measurement (and also some bias due to the hadron trigger in the recoil-jet analysis) and hence their observations should not be directly compared.

All the presented analyses will be further improved by utilizing the high statistics 2014 data with more than one billion Au+Au events at  $\sqrt{s_{NN}}=200$  GeV. As a next step, inclusive and semi-inclusive jet analyses will also use the information from the BEMC thus extending their kinematic reach.

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