

1 Measurements of the jet internal sub-structure and 2 its relevance to parton shower evolution in p+p and 3 Au+Au collisions at STAR

Raghav Kunnawalkam Elayavalli for the STAR Collaboration*

Wayne State University, Detroit MI 48201

E-mail: raghavke@wayne.edu

Recent measurements of jet structure modifications at RHIC and LHC highlight the importance of differential measurements to study the nature of jet quenching. Since these jet structure observables are intimately dependent on parton evolution in both the angular and energy scales, measurements are needed to disentangle these two scales in order to probe the medium at different length scales to study its characteristic properties such as the coherence length. To that effect, the STAR collaboration presents fully unfolded results of a jet's sub-structure via the Soft-Drop shared momentum fraction (z_g) and the groomed jet radius (R_g) in p+p collisions at $\sqrt{s} = 200$ GeV as a function of jet momenta. Having established the p+p baseline, we present the first measurement of the jet's inherent angular structure in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV via an experimentally robust observable related to the SoftDrop R_g : the opening angle between the two leading sub-jets (θ_{SJ}). In Au+Au collisions at STAR, we utilize a specific di-jet selection as introduced in our previous momentum imbalance (A_J) measurement and the recoil jet spectra differentially as a function of jet transverse momentum belonging to particular angular lasses based on the θ_{SJ} observable. With such measurements, we probe the medium response to jets at a particular resolution scale and find no significant differences in quenching for jets of different angular scales as given by θ_{SJ} .

*International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions
30 September - 5 October 2018
Aix-Les-Bains, Savoie, France*

*Speaker.

4 1. Introduction

5 Relativistic ion collisions produce copious amounts of jets due to the hard scatterings between
 6 quarks and gluons of the colliding nuclei. Recent measurements at both RHIC and LHC along with
 7 theoretical advancements have shown the importance of studying and measuring the properties of
 8 these jets both in p+p and in heavy ion collisions (reviews of jet studies can be found here [1]).
 9 There are two natural scales that characterize a jet and its evolution: the momentum and the angular
 10 scales. First generation measurements have measured jet quenching in an inclusive manner via
 11 the momentum asymmetry in di-jet events and have further extensively studied the momentum
 12 dependence via nuclear modification factors and fragmentation functions. Jet-medium interaction
 13 could further be dependent on the resolution scale or the coherence length of the medium which
 14 sees the jet as a singular radiating object or a multi-prong object [2].

15 2. Jet sub-structure in p+p Collisions

16 In order to differentially study energy loss in the medium, the jet structure in vacuum has to
 17 be first understood i.e., the DGLAP splitting functions that govern parton evolution. In recent liter-
 18 ature, SoftDrop [3] has gained fame as an algorithm which can extract such scales experimentally
 19 with its procedure of walking backwards in the Cambridge/Aachen clustering tree until two sub-
 20 jets satisfy $z = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} (\Delta R/R)^\beta$ where z_g and R_g are the z and ΔR upon termination of
 21 the algorithm with $z_{cut} = 0.1$ and $\beta = 0$. It was shown that for such choices of z_{cut}, β the SoftDrop
 22 z_g distribution converges to the vacuum DGLAP splitting functions for $z > z_{cut}$ in a ‘‘Sudakov-safe’’
 23 manner [4].

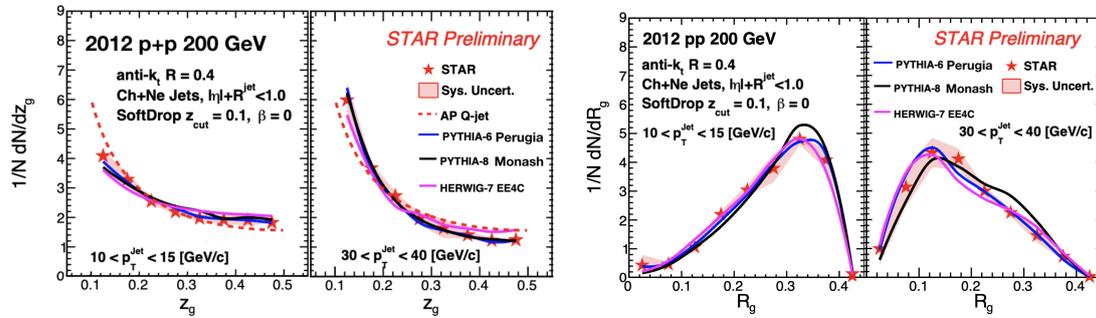


Figure 1: Fully unfolded measurement of the SoftDrop groomed sub-jet shared momentum fraction (z_g) and the groomed jet radius (R_g) in p+p collisions at $\sqrt{s} = 200$ GeV. The markers and lines are described in the text.

24 The p+p data for the groomed jet structure measurements were collected with the STAR detec-
 25 tor [5] during the 2012 run at $\sqrt{s_{NN}} = 200$ GeV. Jets are reconstructed from charged tracks in the
 26 Time Projection Chamber (TPC) and energy depositions in the Barrel ElectroMagnetic Calorime-
 27 ter (BEMC) using the anti- k_r algorithm as implemented in the FastJet package [6], hereafter refer-
 28 enced as Ch+Ne jets. For additional details regarding event/track/tower quality selections, please
 29 refer to [7, 8]. For the inclusive p+p analysis, events are selected by an online jet patch trigger
 30 which is a 1×1 patch in $\eta - \phi$ with the total sum E_T in the patch to be greater than 7.3 GeV.

Two-dimensional unfolding in p_T and z_g or R_g respectively, was done using Bayesian unfolding as implemented in the RooUnfold package [9, 10] with four iterations. The response matrix is created from a PYTHIA-6 (Perugia Tune, slightly adapted to STAR data) prior and a GEANT-3 simulation of the STAR detector. The systematic uncertainties for data are taken as a quadrature sum resulting from the following sources: tracking efficiency (4%), tower gain calibration (3.8%), hadronic correction to the tower energy scale (described in [7]) and unfolding related sources including varying the iteration parameter from 2 to 6 and the prior in the response matrix.

Figure 1 shows the fully unfolded z_g and R_g distributions for two jet p_T selections, 10-15 and 30-40 GeV/c, respectively. The STAR data are shown in the red filled star markers with the red shaded region corresponding to the overall systematic uncertainty. Leading order Monte Carlo (MC) generators such as PYTHIA-6 Perugia tune, PYTHIA-8 Monash, and Herwig-7 EE4C UE tune in the blue, black and magenta lines are also plotted for comparison to the data. For the z_g observable, we also provide the symmetrized DGLAP splitting functions (noted as AP Q-Jet in the figure) at leading order in the red dashed lines for quark jets (with the splitting being similar for quark and gluon initiated jets). All the models studied reproduce the general trends seen in the data, particularly the dependence on the jet momenta leading to a steeper z_g distribution and a narrower R_g .

3. Jet Angular Scale in Au+Au Collisions

The Au+Au data used in these proceedings were collected during the 2007 run with its corresponding reference p+p run in 2006 at $\sqrt{s_{NN}} = 200$ GeV. Since the jet patch trigger is saturated in an Au+Au event, we employ a high tower (HT) trigger, requiring at least one BEMC tower with $E_T > 5.4$ GeV. Event centrality in Au+Au is determined by the raw charged track multiplicity in the TPC within $|\eta| < 0.5$ and we show only events in the 0-20% centrality range. In Au+Au events, we have two separate jet collections given by the HardCore selection [7], where jets are clustered with objects (tracks/towers) with $p_T > 2$ GeV/c, and Matched jets which are clustered from the constituent-subtracted [12] event with our nominal $p_T > 0.2$ GeV/c for constituents, and are geometrically matched to the HardCore jets ($\Delta R < 0.4$). Further event selection criteria include a minimum p_T requirement for HardCore di-jets ($p_T^{\text{Lead}} > 16, p_T^{\text{SubLead}} > 8$ GeV/c) and an azimuthal angle ($|\Delta\phi(\text{Lead}, \text{SubLead})| > 2\pi/3$) selection to focus on back-to-back di-jets.

In our studies, we found the groomed jet radii (R_g) to be highly sensitive to the fluctuating underlying event found in Au+Au collisions and therefore we devised a new observable involving sub-jets of a smaller radius reconstructed within the original jet (see here [11] for a recent theoretical article demonstrating similar classes of observables). For our nominal anti- k_t jets of $R = 0.4$, we reconstruct an inclusive set of anti- k_t sub-jets with $R = 0.1$ from the original jet's constituents. An absolute minimum sub-jet p_T requirement of 2.97 GeV/c is enforced in central Au+Au collisions to reduce sensitivity to the background fluctuations. The two observables related to the momentum and angular scales are then defined as follows $z_{SJ} = \frac{\min(p_T^{SJ1}, p_T^{SJ2})}{p_T^{SJ1} + p_T^{SJ2}}$, $\theta_{SJ} = \Delta R(SJ1, SJ2)$ where $SJ1, SJ2$ are the leading and sub-leading sub-jets, respectively.

For a meaningful comparison between Au+Au and a p+p reference, the effects of background fluctuations and detector inefficiencies must be taken into account. To achieve this, HT-triggered p+p data from 2006 is embedded into minimum bias Au+Au data ($p+p \oplus \text{Au+Au}$) from 2007,

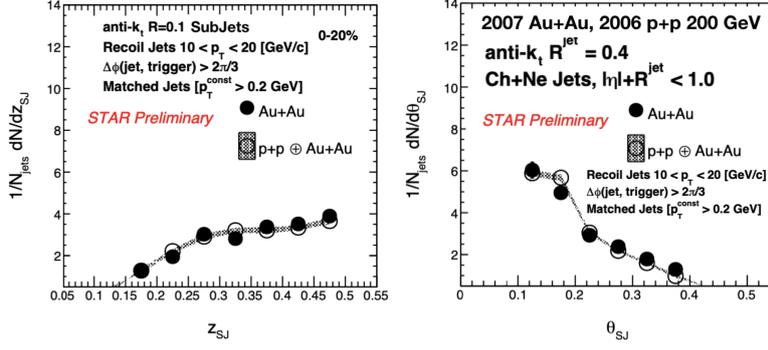


Figure 2: TwoSubJet observables (z_{SJ} - left and θ_{SJ} - right) comparing Au+Au (solid circles) and p+p embedded in Au+Au (open circles including the systematic uncertainties in the shaded region) for recoil Matched jets (anti- k_t $R = 0.4$ jets with $R = 0.1$ sub-jets) in the p_T range 10-20 GeV/c.

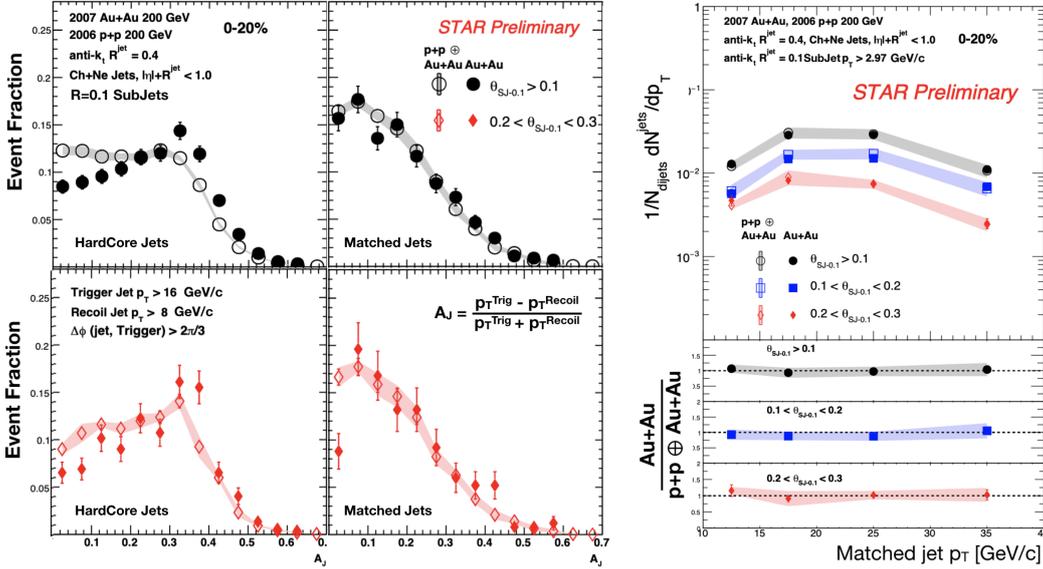


Figure 3: Hardcore and Matched (left figure) di-jet asymmetry ($|A_J|$) and the Matched recoil jet yield (right figure) along with the ratios shown in the bottom right panels. Markers are described in the text.

72 in the same centrality range (0-20%). During embedding, we account for the relative tracking
 73 efficiency ($90\% \pm 7\%$) and relative tower energy scale ($100\% \pm 2\%$), with a one sigma variation
 74 taken as systematic uncertainties. Figure 2 shows the detector level TwoSubJet z_{SJ} (left) and θ_{SJ}
 75 (right) distributions for constituent-subtracted Matched recoil jets with $R = 0.1$ sub-jets (henceforth
 76 denoted as $SJ - 0.1$ in the figures) recoiling off the trigger (selected with a $|\Delta\phi(\text{jet}, \text{HT})| > 2\pi/3$),
 77 in the p_T range 10-20 GeV/c. Results are observed to be similar in both Au+Au and p+p \oplus Au+Au.
 78 We also observe a remarkable difference in the shape of z_{SJ} when compared to that of the SoftDrop
 79 z_g , which is caused by selecting the core of the jet. The θ_{SJ} for jets within the considered p_T range
 80 peaks at small values and includes a natural lower cutoff at the sub-jet radius and we now select
 81 jets based on this distribution.

82 Di-jet asymmetry for both Hardcore and Matched jets (left panels) are shown in Figure 3. The

83 right panels of Figure 3 show the yield of Matched recoil jets normalized per di-jet for the different
 84 θ_{SJ} selections and the ratios of Au+Au/p+p in the bottom panels. The black, blue and red markers
 85 represent recoil jets with selections on θ_{SJ} [0.1, 0.4], [0.1, 0.2] and [0.2, 0.3], respectively, for inclu-
 86 sive, narrow and wide jets. We observe a clear di-jet imbalance indicating jet quenching effects in
 87 the $|A_J|$ distributions (comparing Au+Au to p+p \oplus Au+Au) for all HardCore jets including the wide
 88 angle jets. The Matched jets on the other hand are balanced at RHIC energies, as evident by ratios
 89 in the bottom right panels consistent with unity. This is consistent with our earlier measurement [7].
 90 We also note that wide angle jets are still balanced indicating no apparent distinction between wide
 91 and narrow jets by the medium in our selection. Further detailed differential analyses are required
 92 with the high statistics 2014 data set to extract the medium resolution scale or the coherence length
 93 and the effect on standard jet quenching observables at RHIC energies.

94 4. Conclusions

95 STAR has presented the first fully unfolded SoftDrop z_g and R_g measurements of inclusive
 96 jets with varying transverse momentum in p+p collisions at $\sqrt{s}=200$ GeV. The measurements are
 97 overall reproduced by current leading order Monte Carlo event generators for both z_g and R_g for
 98 jets in our kinematic acceptance and reflect the momentum dependent narrowing of jet structure.
 99 Due to the sensitivity of the SoftDrop observables to the Au+Au underlying event, we introduce
 100 and measure the TwoSubJet observables, z_{SJ} and θ_{SJ} for R=0.1 anti- k_t sub-jets as representing
 101 the momentum and angular scales of a jet in a heavy ion environment. We measure the di-jet
 102 momentum asymmetry and the recoil jet yield with the special di-jet selection at STAR and find that
 103 HardCore di-jets are imbalanced and Matched di-jets are balanced for jets of varying angular scales.
 104 We find no significant difference in the quenching phenomenon for both wide and narrow jets
 105 leading to the conclusion that these special jets do not undergo significantly different jet-medium
 106 interactions due to their varying angular scales.

107 References

- 108 [1] M. Connors, R. Reed, S. Salur, C. Nattrass, Rev. Mod. Phys. 90, (2018) 025005
 109 [2] Y. Mehtar Tani, K. Tywoniuk, Phys. Rev. D 98 (2018) 051501(R)
 110 [3] A. J. Larkoski, S. Marzani, G. Soyez, J. Thaler, Soft Drop, JHEP 05 (2014) 146
 111 [4] A. J. Larkoski, S. Marzani, J. Thaler, Phys. Rev. D 91 (11) (2015) 111501
 112 [5] K. H. Ackermann et. al., Nucl. Instrum. Methods Phys. Res., Sect. A 499, (2003) 624
 113 [6] M. Cacciari, G. P. Salam, and G. Soyez, J. High Energy Phys. 04 (2008) 005.
 114 [7] L. Adamczyk, et al., Phys. Rev. Lett. 119 (6) (2017) 062301
 115 [8] Nick Elsey for the STAR Collaboration, these proceedings
 116 [9] T. Adye et. al. hepunx.rl.ac.uk/~adye/software/unfold/RooUnfold.html
 117 [10] G. D'Agostini, arXiv:1010.0632
 118 [11] L. Apolinário, J. G. Milhano, M. Ploskon, X. Zhang, Eur. Phys. J. C78 (2018) no.6, 529
 119 [12] P. Berta, M. Spousta, D. W. Miller, R. Leitner, J. High Energy Phys. 1406 (2014) 092