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Semi-inclusive charged jet production dependence on event activity at high backward-rapidity in $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ p+Au collisions at STAR

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8 These proceedings present measurements of mid-rapidity semi-inclusive charged jet spectra and acoplanarity in relation to event activity (EA) at backward-rapidity (Au-going) in $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ p+Au collisions at STAR. Small system jet measurements have been motivated by apparent flow signals in these systems, suggestive of QGP formation. These specific small system jet measurements are particularly timely because they are the first semi-inclusive jet spectrum measurements in small systems at RHIC energy. As such, they complement results from PHENIX, ATLAS, and ALICE, which collectively are not yet well understood. The new STAR semi-inclusive jet spectra are dependent on EA; they are distinctly anti-correlated. Evidence is presented, using both the new measurements and simulation, that this anti-correlation results from constraints in the phase space of the initial collisions.

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The observation of flow-like signals in *pp* collisions about a decade ago [1] has precipitated a resurgence of interest in the heavy-ion community in studying small systems (*pp*, d+A, He^3+A, or p+A collisions) for results attributed to final-state, quark gluon plasma (QGP), effects in A+A collisions (such as collectivity). Due to their early formation times, jets have proven to be valuable probes of hot nuclear matter effects in A+A collisions, and a natural venue of investigation for possible analogous hot nuclear matter effects in small systems.

Several methods of normalization are used for jet modification measurements. Inclusive jet production per binary nucleon-nucleon collision ($N_{\rm coll}$) can be compared to *pp* results ($R_{\rm AA}$, $R_{p\rm A}$, $R_{d\rm A}$, $R_{\rm He^3A}$); they may be compared semi-inclusively as production per-trigger; or the shape of their per-jet distributions may be compared, such as dijet momentum balance distributions. Primary jet quenching observables include transverse momentum ($p_{\rm T}$) spectra, acoplanarity (jet azimuthal distribution relative to a trigger), momentum imbalances with a recoil partner, and possible substructure modifications.

When not binned by event activity (EA), all reported inclusive measurements of $R_{p\rm A}$ and $R_{d\rm A}$ ($R_{p/d\rm A}$) have been consistent with scaled *pp* results [2–5]. However, when binned by high-rapidity EA, both ATLAS and PHENIX reported enhancement (suppression) of $R_{p/d\rm A}$ for peripheral (central) events. Intriguingly, ATLAS showed that the p-going jet spectra modification appeared to scale with Bjorken-x. When measuring recoil jet spectra per trigger (a high-$p_{\rm T}$ hadron) at a lower Bjorken-x, ALICE found no modification [6], setting an out-of-jet cone energy transport limit. The jet modification in the ATLAS measurement, if resulting only from out-of-cone energy transport, violate the limit set at ALICE. The question still under study is if the modifications observed by ATLAS and PHENIX are indeed dependent on Bjorken-x and hence not seen at the kinematics probed by ALICE, or if they result from misclassifying centrality (and therefore $N_{\rm coll}$) due to phase space constraints and/or other mechanisms correlating the multiple scatterings of the proton [8]. In parallel efforts, measurements of dijet momentum balance, acoplanarity, and jet mass distributions (shape measurements normalization per dijet or per jet) in p+Pb at the LHC have found no modification relative to *pp* collisions [9–11].

The STAR measurements reported here are for mid-rapidity charged jets whose spectra is normalized by number of triggers of high energy hits at mid-rapidity in the Barrel Electromagnetic Calorimeter. Event activity (EA) is measured in the pseudorapidity (η) range of $[-5, -3.4]$. These jets access similar Bjorken-x ranges as the ATLAS and PHENIX results while avoiding $N_{\rm coll}$ scaling uncertainties. The jet spectra (for $p_{\rm T,jet}^{\rm ch} > 5\,{\rm GeV}/c$) per trigger are clearly suppressed in high EA events compared to low EA events, as shown in Fig. 1. This is also qualitatively present in PYTHIA 8 simulations, which has no mechanisms modeling jet modification from hot or cold nuclear matter effects.

The collision triggers, in data and simulation, are provided by jets (or parts thereof) at mid-rapidity (mid-η). These jets are accompanied by dijet partners which are, at leading order, exactly opposite in azimuth and contribute to the spectra-per-trigger at $|\eta| < 0.6$. A correlation between jet spectra and EA may arise generally from three scenarios. First, there could be an actual correlation between the cross sections for hard scattering and the particles that contribute to EA. Second, an apparent correlation between cross sections could result in, due to methodology, auto-correlations among EA, jets, and/or triggers. A primary example of this for the STAR spectra would be a trivial autocorrelation from when the recoil dijet partner is not at mid-rapidity but instead fragments within

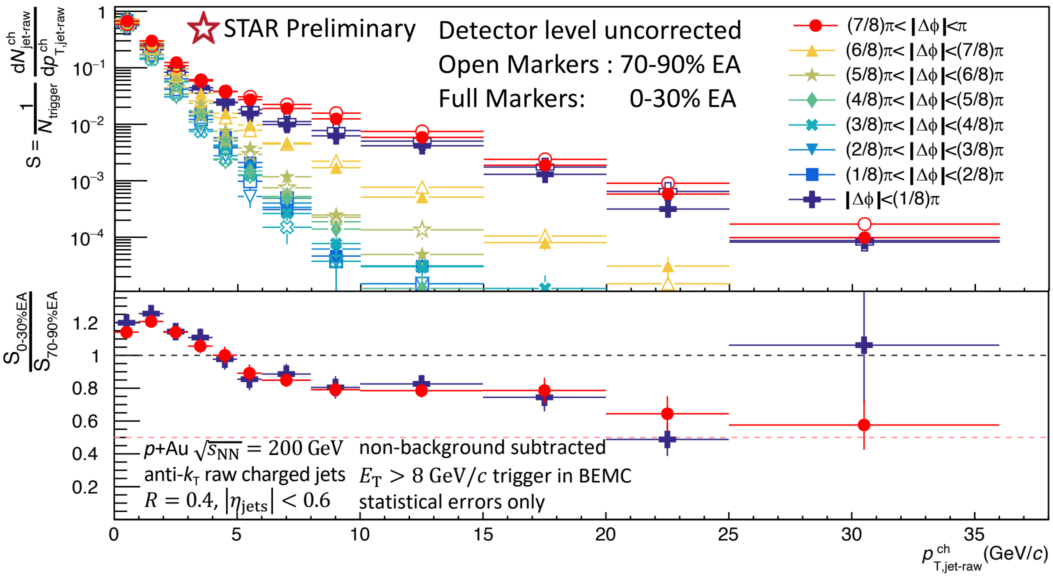

Figure 1: Top: raw, uncorrected, jet spectra per trigger in bins of high (0-30%) and low (70-90%) EA, sub-divided into bins of $|\phi_{\text{jet}} - \phi_{\text{trigger}}|$. Bottom: ratios of high-to-low EA jet spectra. EA is measured in the Au-going direction at $\eta \in [-5, -3.4]$.

the EA acceptance. These events would thereby preferentially lower the jet spectra per trigger while raising the measured EA. This has already been demonstrated not to be the case for this STAR measurement, as reported in [12]. Third, a correlation would result from actual jet modification occurring preferentially in high EA events relative to low EA events; for example, jet quenching in a QGP.

There are several empirical indications that the jet spectra suppression in high EA p+Au collisions measured by STAR results from phase space constraints and not from actual modification of generated jets. First, the comparable level of suppression for near-side and away-side jets in Fig. 1 is indicative of a common phase space constraint on the hard scattering itself and EA. When modified by a QGP, at least in A+A collisions, path-length differences modify spectra differently for near- and away-side jets.

Figure 2 presents jet acoplanrity, the correlation between $|\Delta\phi| = |\phi_{\text{jet}} - \phi_{\text{trigger}}|$. It shows the overall suppression of high-EA jet production. However, the recoil shape does not broaden as would be expected from jet quenching. Such a broadening has been reported by ALICE in $\sqrt{s} = 13$ TeV high multiplicity *pp* collisions. However, it was reported at this conference that a principle cause may be a selection bias towards tri-jet events [13]; whereas tri-jet events have negligible impact on the STAR results.

Figure 3 presents a more direct empirical indication that the STAR jet suppression is due to phase space constraints. Raising the transverse energy requirement on triggers from $E_T \in (8, 12)$ GeV to $E_T > 12$ GeV corresponds to a ~20% drop in the the number of events in the highest EA bin in proportion to those in the lowest EA bin. This suppression of $E_T > 12$ GeV (for this EA selection) is comparable in magnitude to the suppression of jet spectra in Fig. 1. We also note new jet mass measurements in high and low EA *p*+Au collisions, which are normalized per jet rather than per trigger, also revealed no modification relative to *pp* collisions [14].

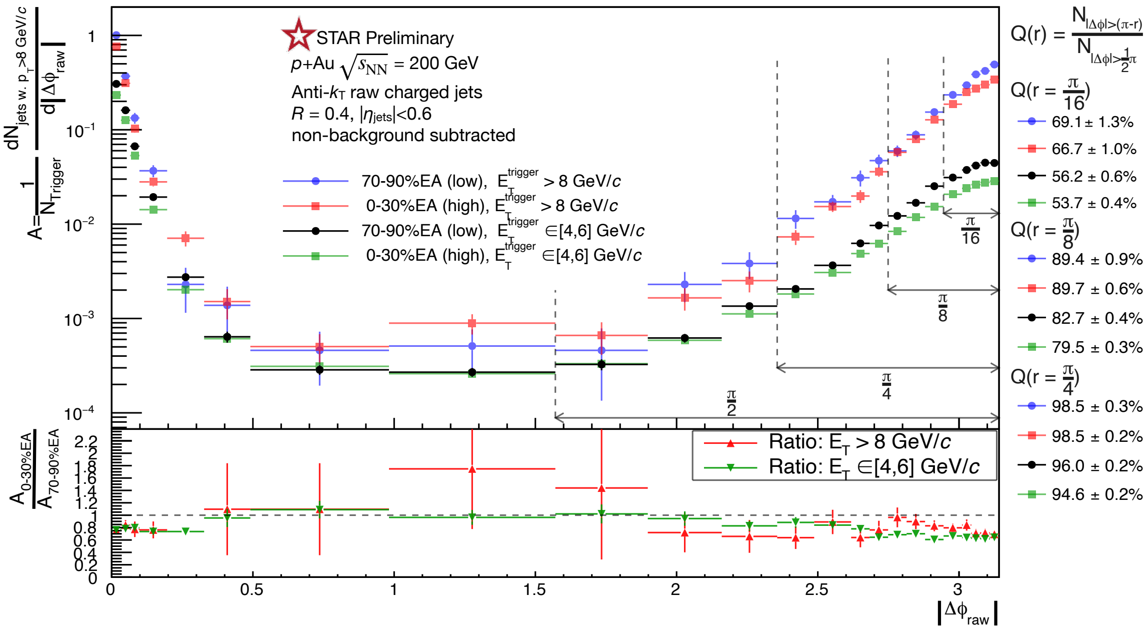

Figure 2: Acoplanarity: $|\phi_{\rm jet} - \phi_{\rm trig}|$ for all raw, anti-$k_{\rm T}$, $R = 0.4$, $p_{\rm T} > 8\,{\rm GeV}/c$, jets, within $|\eta_{\rm jet}| < 0.6$. Jets are uncorrected; however, the correction in ϕ for jets is expected to be minimal.

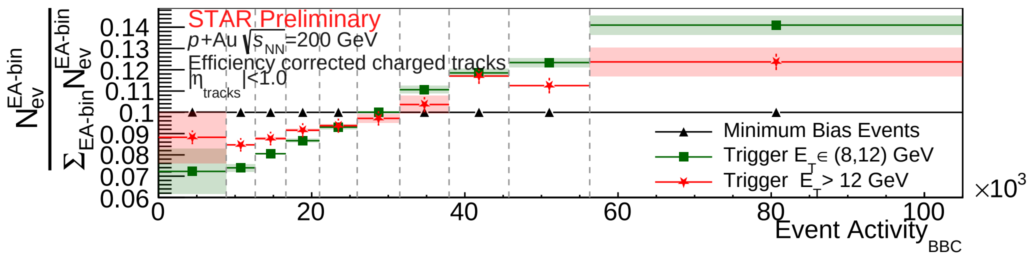

Figure 3: Fraction in each EA bin for MB events and events containing high-$E_{\rm T}$ tirggers. Decile boundaries are defined to contain 10% of the minimum bias events in each bin.

Figure 4 shows correlations, from a PYTHIA 8 Agantyr model simulation, between EA and hardness of leading recoil jets at mid-rapidity for $\sqrt{s_{\rm NN}} = 200\,{\rm GeV}$ p+Au collisions. Binned by jet $p_{\rm T}$, the top panel shows the percentage of events in the high (low) EA bins, which decreases (increases) with increasing jet $p_{\rm T}$. The bottom panel shows the corresponding anti-correlation of EA to jet $p_{\rm T}$. Further invrestigations show that this behavior is not the result of a trivial autocorrelation caused by dijet fragments in the EA acceptance. Additionally, the simulations do not have jet quenching mechanisms; as such, the correlation modeled is between cross sections of jet production and EA production.

Investigations into the cause of the modeled correlations are ongoing. However, we note here that the Agantyr model does correlate energy and momentum conservation among all partonic scatterings in p+Au collisions [15]. This correlates a high-$p_{\rm T}$ jet production from one hard scattering with decreased EA elsewhere from other scatterings. However, we have not isolated the strength of this effect and PYTHIA 8 pp simulations with multi-parton interactions turned off (which does not have this effect) also demonstrate an anti-correlation between EA and mid-rapidity jet $p_{\rm T}$. In

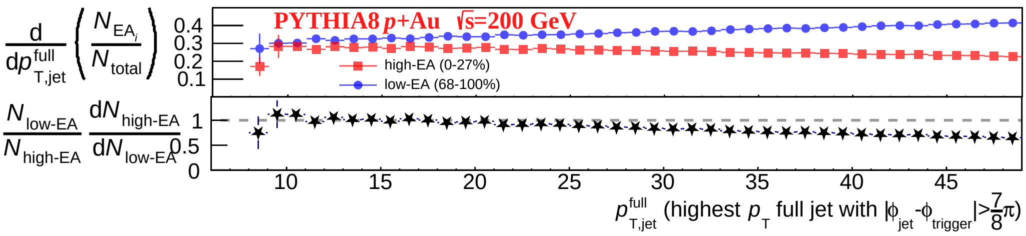

Figure 4: PYTHIA 8 Agantyr simulation of events triggered by a neutral particle with $E_\mathrm{T} > 8\,\mathrm{GeV}$ in $|\eta| < 1$. Events are binned by EA (the sum of particles within $\eta \in [-5, -3.5]$) and the leading recoil full jet p_T at mid-rapidity. Bottom panel: Ratio of the shapes of the high-EA to low-EA event distributions.

addition to the Agantyr model, other theories, using color fluctuations in the proton which may result in a "shrinking proton" at high Bjorken-x [16], have been proposed to explain this anti-correlation in the context of the ATLAS and PHENIX $R_{p/d\mathrm{A}}$ results. One model calculation found that energy conservation alone is sufficient to account for the $R_{p/d\mathrm{A}}$ modification [8], although it could not be determined if color transparency-like effects are also indicated.

In conclusion, semi-inclusive jet spectra at STAR from p+Au collisions at $\sqrt{s_\mathrm{NN}} = 200$ GeV are distinctly suppressed in high EA events relative to low EA events. These results confirm modification in a similar Bjorken-x range as the $R_{p/d\mathrm{A}}$ modification measured by PHENIX and ATLAS [2, 3]. However, acoplanarity measurements, PYTHIA-8 studies, and the spectra themselves, indicate that the new STAR results originate primarily from phase space constraints on the hard scattering cross section relative to generating high EA, rather than from jet quenching effects. These results motivate further studies to determine if this mechanism of phase space constraints are sufficient to explain all the reported jet measurements in p/d+A collisions at RHIC and the LHC.

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