Heavy flavor and high p_{T} results from STAR

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In these proceedings, we present an overview of recent measurements from heavy flavor and jet production in Au+Au and p+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV in STAR. We also discuss the recent development on jet substructure measurements in $p+p$ collisions.

1 Introduction

Hard probes, such as heavy flavor particles and jets, are tools for studying the hot, dense quantum chromodynamic (QCD) matter known as the Quark-Gluon Plasma (QGP), which is created in relativistic (or high-energy) heavy-ion collisions. They are produced from the hard scattering early in the collision and hence witness the QGP evolution and are ideal probes of its properties. Furthermore, hard probe production in vacuum can be described by perturbative QCD (pQCD). Upon understanding the production of heavy flavor particles and jets in vacuum (p+p) and assessing the cold nuclear matter (CNM) effects in p+Au collisions, their modification in heavy-ion (A+A) collisions can be attributed to interactions with the QGP.

2 Measurements

2.1 p+p collisions

Substructure observables characterize jet formation and evolution from the initial hard-scattered parton through the radiation shower and eventual hadronization that results in a jet. A hard scattered parton loses energy by showering particles which are then clustered as constituents into a jet. The SoftDrop grooming algorithm [1] is widely used because it takes advantage of the approximate angular ordering inherent in a QCD shower by performing jet re-clustering using an angular-ordered algorithm. This allows us to access information about a jet's formation history, including the momentum fraction and angle at each splitting, and drops softer splittings which are more difficult to describe with pQCD.

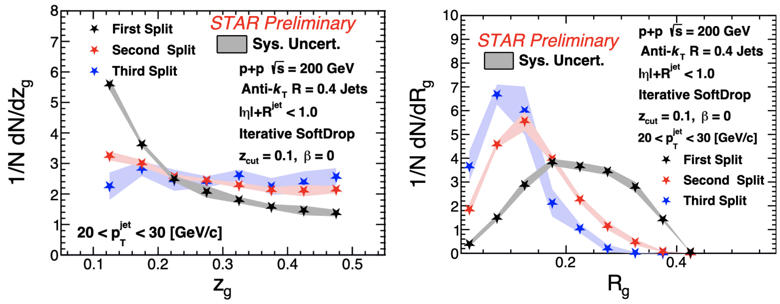

Figure 1 – The momentum fraction, z_g (left), and opening angle between prongs, R_g (right), for first (black), second (red), and third (blue) hard splittings.

Figure 1 shows the shared momentum fraction ($z_g = \min(p_{\mathrm{T},1}, p_{\mathrm{T},2})/(p_{\mathrm{T},1}+p_{\mathrm{T},2})$, on the left) and opening angle between prongs (R_g, on the right) at the first three splittings of jets, following the hard prong in each case, from $p+p$ collisions at $\sqrt{s_{\mathrm{NN}}} = 200$ GeV in STAR. There are clear changes in the z_g and R_g distributions going from the first split to the second and third splits. At the first split, z_g is steep, meaning that early emissions carry a smaller fraction of the jet's total momentum. The z_g shape is less steep at the second split and becomes flat at the third split, where the two prongs are more evenly balanced. The distribution of R_g favors larger angles at the first split, and shifts to smaller angles with subsequent emissions. Together, these observables show that jets have softer radiations at wide angles upon their creation and they tend toward harder and narrower emissions as time evolves.

2.2 p+A collisions

While $p+p$ collisions serve as the vacuum reference, p+A connects this reference to heavy-ion systems and acts as an experiment to test the null hypothesis that there are final state effects in A+A collisions not due to QGP. This assumes that there are no QGP effects present in p+A systems and observed deviations from $p+p$ result from CNM. All effects of increasing the size of the colliding ions that are not due to hot nuclear matter are considered CNM effects.

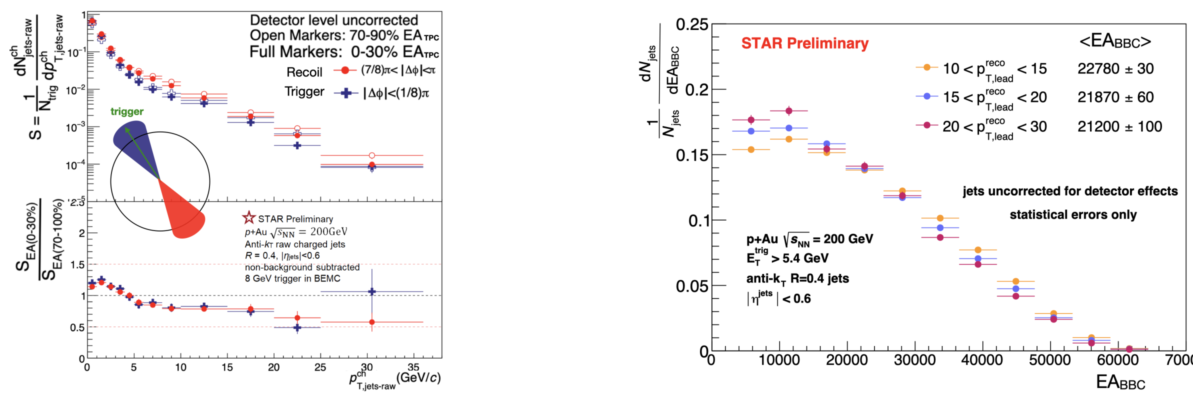

Figure 2 – The yield of charged jets per high-E_{T} trigger on the trigger- (blue) and recoil-sides (red) for events selected at high- (full markers) and low-EA (open markers) events (left). The distributions of EA measured at far-backward rapidity for three selections of leading jet p_{T} (right).

Both RHIC[2] and the LHC[3] have measured jet yield modification as a function of centrality in $p(d)$+A collisions; some of these unexpected observations are consistent with signatures resulting from modification in the hot nuclear matter. The plot on the left in Fig. 2 shows the yield of charged jets per high-transverse-energy (high-E_{T}) trigger on the trigger- and recoil-sides in $\sqrt{s_{\mathrm{NN}}} = 200$ GeV p+Au collisions at STAR. Yields are shown for events selected at high- and low-event activity ($\mathrm{EA_{TPC}}$), where $\mathrm{EA_{TPC}}$ is defined by charged track multiplicity in the mid-rapidity region azimuthally orthogonal to the trigger. There is a clear suppression of trigger- and recoil-jet yield in high-EA events relative to low-EA events. Additionally, the trigger-side jet suppression as a function of $\mathrm{EA_{TPC}}$ is consistent with that on the recoil-side; this observation is qualitatively inconsistent with a general expectation of jet quenching due to hot nuclear matter, where one would expect a trigger or surface bias to lead to greater suppression on the recoil-side.

The plot on the right in Fig. 2 shows the EA_{BBC} distributions as measured by soft particle production at large backward (Au-going) rapidities for three selections of the transverse momentum (p_T) of a triggered leading jet at mid-rapidity in these collisions. There is a clear anti-correlation between the hardness of the leading jet and the EA_{BBC}, despite being measured several units of rapidity apart, indicating an early-time dependence between the jet and soft particle production. This suggests that events with harder (softer) scatterings may be naively mis-classified as less (more) central when selected by soft particle production, thus explaining the observed jet yield modification.

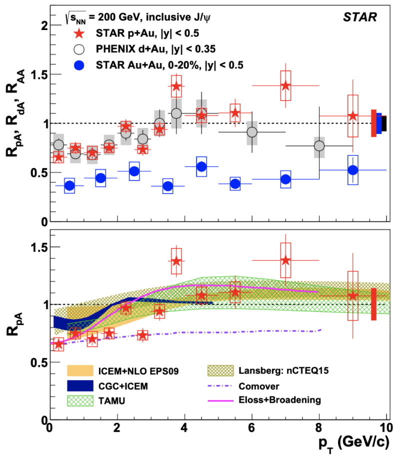

Figure 3 – Nuclear modification factors, $R_{p(d)\mathrm{A}}$, for inclusive J/ψ via dimuon in different collision systems at RHIC.

Inclusive yield of J/ψ, a charm-anticharm quark bound state, was recently measured in p+Au collisions at STAR via the dimuon channel; Fig. 3 shows the nuclear modification factor, $R_{\mathrm{A}(p,d)\mathrm{A}}$, for J/ψ in different collision systems as a function of p_T [4]. The nuclear modification factor should naively equal unity if there is no modification, and a value larger (smaller) than unity signals enhancement (suppression). $R_{p\mathrm{Au}}$ for J/ψ agrees with $R_{d\mathrm{Au}}$ as measured in PHENIX [5] and is consistent with models which only include CNM effects, showing clear CNM effects at low-p_T. At higher p_T, $R_{p(d)A}$ is consistent with unity; meaning little CNM is observed above 3 GeV/c in small systems within uncertainty, and the J/ψ suppression in central Au+Au events is mostly due to hot medium effects.

2.3 A+A collisions

The nuclear modification factor of J/ψ has been measured for several collision species at STAR; the plot on the left in Fig. 4 shows these values as a function of the mean number of participating nucleons (N_{part}). There is clear suppression in all species, and its dependence on mean N_{part} suggests that the J/ψ suppression depends on system size rather than collision geometry.

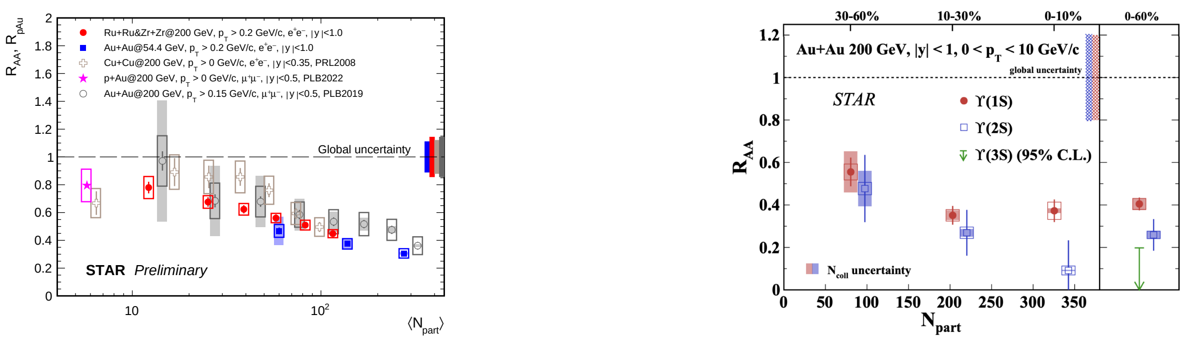

Figure 4 – The nuclear modification factor, $R_{p(\mathrm{A})\mathrm{A}}$, for J/ψ as a function of N_{part} in different collision systems at STAR (left), and for different Υ excited states (right).

The Υ meson, a bottom-antibottom quark bound state, is also modified in the presence of the QGP. Modification of different excited states of the Υ can probe the QGP temperature; a hotter medium will "melt" these excited states, resulting the suppression in their yields. The plot on the right in Fig. 4 shows R_{AA} for the Υ(1S) and Υ(2S) states as a function of N_{part}, as well as their R_{AA} values and the upper bound for the Υ(3S) state in the 0-60% centrality range [6]. All states show significant suppression, which is larger in more central events. Furthermore, we see sequential suppression of excited states, consistent with the expectation of greater suppression in states with lower binding energies.

The STAR collaboration performed an analysis to investigate modification of jet substructure in the hot and dense medium; the dijet asymmetry, A_J (the fraction of the dijet momentum carried by the lower-p_T subjet), was measured as a function of the opening angle between the two hardest subjets, θ_{SJ}. Figure 5 shows these measurements for hardcore dijets (having constituents with $p_T \geq 2$ GeV/c) on the left and for jets matched to the hardcore dijets on the right [7]. The hardcore dijets are imbalanced and show disagreement with $p+p$ embedded into minimum-bias Au+Au ($p+p \oplus$ Au+Au) at all θ_{SJ}, thus they are modified in the medium. Conversely, the matched dijets are balanced and agree with $p+p \oplus$ Au+Au; the energy missing in the hardcore jets is recovered in the low-p_T constituents. Additionally, there is no angular dependence, indicating that the recoil jet loses energy as single color charge radiating in medium.

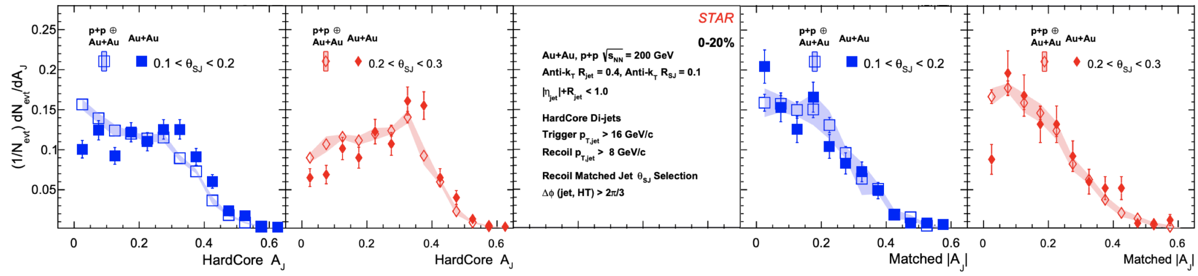

Figure 5 – The dijet asymmetry (A_J) as a function of the opening angle (θ_{SJ}) between the two hardest subjets for hardcore (left) and matched (right) jets in central Au+Au and $p+p \oplus$ Au+Au collisions.

3 Conclusion

Understanding hard probes in vacuum and small collision systems is necessary to quantify their modification in heavy-ion collisions. Substructure measurements were presented from $p+p$ collisions at STAR to characterize jets in the absence of QCD medium. In p+Au collisions, jet and event activity measurements suggest that apparent modification in small systems may be due to correlations between hard and soft production processes leading to a mis-classification of event centrality, and the inclusive J/ψ yield shows clear CNM effects only at low-p_T. Several measurements were shown of modification of hard probes in heavy-ion events: nuclear modification of J/ψ as a function of mean N_{part} shows that suppression depends on energy density; suppression of Υ yield is larger for more central collisions and for higher excited states; and the hardcore and matched dijet asymmetry measurements as a function of subjet opening angle indicate that recoil jets radiate as a single charge, losing energy in the form of low-p_T constituents.

Acknowledgments

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