Correlation measurements of mid-rapidity charged particles and jets with event activity at backward-rapidity (Au-going) in 200 GeV p+Au collisions at STAR

David Stewart for the STAR Collaboration
Why small systems?

Initially

Stepping stone towards probing the Quark Gluon Plasma (QGP) in “large” systems …

Currently

… with discovery of flow-like signals, small systems are being actively probed for other QGP-like signals

✦ Soft physics
  Collective flow, particle spectra at freeze-out etc…

✦ Hard physics
  Jet quenching/modification, high $p_T$ particle suppression…

image and points: Livio Bianchi @ QuarkMatter2018
Jet introduction

- Hard scatterings of partons occur early in collisions and subsequent products may interact with a medium.
- Final state particles are algorithmically clustered together into objects called jets which are associated (by the observer) with the initially scattered partons.
- Modification of jets is used to probe existence and properties of a QGP.
Minimum bias jet measurements in small systems

- Small systems have been studied for evidence of jet modification / suppression
- If we anticipate no final state effects, we expect the ratio of jet spectra per binary collision in p+A collisions to pp collisions to be unity ($R_{p+A}^{ch\ jet} \approx 1$)
- Caveat: even if a strong interacting medium were formed, it may be too small to modify jet spectra

**ALICE**

**PHENIX**

**ATLAS & CMS**
When binned by high-|\eta| Event Activity, findings:

$$R_{\text{jet High EA}}^{(p/d)+A} < 1 \quad \& \quad R_{\text{jet Low EA}}^{(p/d)+A} > 1$$

![Graph showing \(R_{pPb}\) vs. \(p_T\) for different centrality bins.]  

- 2013 \(p+Pb\) data, 27.8 nb\(^{-1}\)  
- 2013 \(pp\) data, 4.0 pb\(^{-1}\)  

\(y^*\) range: -0.3 < \(y^*\) < +0.3

**PHENIX**  
\(d+Au, \sqrt{s_{NN}} = 200\) GeV  
anti-\(k_t\), \(R=0.3\) jet

- 60-88%  
- 40-60%  
- 20-40%  
- 0-20%  
- E-loss 0-20% (Kang et al)
What happened?

Possibilities

- Number of binary collisions ($N_{\text{coll}}$) from Glauber model is OK:
  - Jet modification present
  - Physics of each binary collision not uniform
- Determination of $N_{\text{coll}}$ and/or mapping of EA to $N_{\text{coll}}$ is uniquely different in small systems

Current results/thoughts

- Theory conserving p/d energy suggests anti-correlation between multiplicity & hard scattering (therefore modify Glauber) (e.g. Kordell II & Majumder, PRC 97 (2018))
- Correlation between suppression and total $p$-going jet momentum ($\rho_{\text{tot}}$ vs $p_T$ at ATLAS)
- Semi-inclusive measurements, circumventing $N_{\text{coll}}$ entirely at ALICE, report null result at mid-rapidity (low $\rho_{\text{tot}}$) (PRC 91 (2015))
Motivation to measure semi-inclusive jet spectra

- Jet spectra per trigger ("S" in the equations below) in process \( p+Au \to t+\text{jet}+X \) can probe if all the following are not simultaneously true without actually calculating \( N_{\text{coll}} \):
  A. Trigger and jet production both scale with \( N_{\text{coll}} \)
  B. Event activity (EA) selection, while scaling monotonically in \( N_{\text{coll}} \), not autocorrelated with jet or trigger generation
  C. No EA related modification of jet spectra

- Specifically:

\[
S \equiv \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}}{dp_{T,\text{jet}}} = \frac{1}{\mathcal{L}\sigma_{p+Au \to t+X}} \frac{d(\mathcal{L}\sigma_{p+Au \to t+X})}{dp_{T,\text{jet}}}
\]

- By condition A:

\[
\sigma_{p+Au \to X} = N_{\text{coll}}\sigma_{pp \to X} \Rightarrow S = \frac{1}{N_{\text{coll}}\sigma_{pp \to t+X}} \frac{d(N_{\text{coll}}\sigma_{pp \to t+X})}{dp_{T,\text{jet}}}
\]

- Therefore by B and C:

\[
S \equiv \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jet}}}{dp_{T,\text{jet}}} = \frac{1}{\sigma_{pp \to t+X}} \frac{d\sigma_{pp \to t+X}}{dp_{T,\text{jet}}} = \frac{1}{\sigma_{p+Au \to t+X}} \frac{d\sigma_{p+Au \to t+X}}{dp_{T,\text{jet}}}
\]

- If \( \frac{S_{[\text{high EA}]}}{S_{[\text{low EA}]}} \neq \text{unity} \) then A & B & C cannot all be true
**Subsystems of interest**

- Time Projection Chamber (TPC): charged tracks with $p_T$
- Barrel Electromagnetic Calorimeter (BEMC): energy deposition, primarily neutral particles
- Beam Beam Counter (BBC): plastic scintillators ($2<|\eta|<5.0$)
  - BBC, in Au-going direction, corrected for z-vertex and luminosity, is EA estimator
Motivation to measure EA at high-$\eta$ in Au-going direction

- Traditionally, EA at STAR has been measured by activity in TPC (-1\textless \eta \textless 1)
- However, when measuring jets in small systems, activity of jets strongly autocorrelates to mid-rapidity EA
- Therefore, EA is determined by activity in BBC at Au-going rapidity from -5\textless \eta \textless -2

- At RHIC energies, kinematics are such that $\Delta \eta$ swing of recoil jets from high $p_T$ triggers in TPC rarely reaches BBC acceptance
STAR has a large $p+$Au 200 GeV dataset measured in 2015 with events triggered by both:

A. minimum bias triggers
B. high transverse energy ($E_T$) hits in BEMC, i.e.:
   
   $$p+Au \rightarrow \text{BEMC}_{\text{hit}} + \text{jet} + X$$

EA spectra presented are determined by signal in BBC in Au-going direction.

![Graph showing EA spectra](image_url)
Measured correlations: mid-rapidity tracks to EA at backward-\(\eta\)

- Unfolding \(p_T\) spectra in each bin using a response matrix of embedded tracks provides a measure of average \(N_{ch}\) and \(\Sigma p_T\) as correlated to EA

- Expected positive correlation between EA and probability of a mid-rapidity trigger weakens for increasing trigger energies

- \(\langle N_{ch}\rangle\) increases substantially moving from min bias to a 4-8 GeV trigger, but only modestly with a 8-12 GeV trigger

- Total number of tracks and sum \(p_T\) scale as expected
Strong positive correlation evolves to anti-correlation with harder triggers
Clustering uncorrected tracks into jets

- Same charged tracks (uncorrected) have been clustered into jets, and compared in highest 0-30% and lowest 70-90% EA
- Data binned in $\Delta \phi$ in $\pi/8$ slices
- N.B.: Jet embedding is ongoing; jets presented in this talk are raw, uncorrected, detector level

STAR Preliminary

$p+Au \sqrt{s_{NN}} = 200$ GeV
Recoil and transverse spectra

Detector level uncorrected
Open Markers: 70-90% EA
Full Markers: 0-30% EA

- $(7/8)\pi < |\Delta \phi| < \pi$
- $(4/8)\pi < |\Delta \phi| < (5/8)\pi$
- $(3/8)\pi < |\Delta \phi| < (4/8)\pi$
- $(2/8)\pi < |\Delta \phi| < (3/8)\pi$
- $(1/8)\pi < |\Delta \phi| < (2/8)\pi$

At "jet-like" $p_T$, background (transverse $\Delta \phi$) negligible compared to recoil spectra

STAR Preliminary
$p+Au \sqrt{s_{NN}} = 200$ GeV
Anti-$k_T$ raw charged jets
$R = 0.4$, $|\eta_{jets}| < 0.6$
non-background subtracted
8 GeV trigger in BEMC

Open Markers: Low EA: 70-90%
Full Markers: High EA: 0-30%
Same-side and recoil spectra

Detector level uncorrected
Open Markers: 70-90% EA
Full Markers: 0-30% EA

- $\Delta \phi < \frac{1}{8} \pi$
- $|\Delta \phi| < \frac{1}{8} \pi$

$S = \frac{1}{N_{\text{trig}}} \frac{dN_{\text{jets-raw}}^{ch}}{dp_{T,jets-raw}^{ch}}$

$S_{EA(0-30\%)} \bigg\| S_{EA(70-100\%)}$

- The 8 GeV trigger biases the dijet selection
- Bias expected to decrease at higher $p_{T,jet}$

STAR Preliminary
$p+Au \sqrt{s_{NN}} = 200$ GeV
Anti-$k_T$ raw charged jets
$R = 0.4$, $|\eta|<0.6$
non-background subtracted
8 GeV trigger in BEMC

Initial Stages 2019
Suppression of all spectra

At $p_T$ above ~10 GeV/c clear suppression in high-EA events compared to low-EA events.
Clear spectra modification:

- STAR 200 GeV p+Au, charged, raw jets
- PHENIX 200 GeV d+Au fully corrected jets
- ATLAS 5020 GeV p+Pb fully corrected jets
Clear suppression of high EA semi-inclusive jet spectra observed in 200 GeV p+Au collisions at STAR

This suppression indicates that for p+Au 200 GeV, at least one of the following is not true:

A. Trigger and jet production both scale with $N_{\text{coll}}$
B. Event activity (EA) at backward-$\eta$ is not autocorrelated with jet or trigger production
C. There is no EA-related modification of jet spectra

These can be further probed with:

- Checking if scaling of trigger and soft production can be separated
  - Probe with underlying event in transverse direction
- Studying full jets and varying trigger $p_T$
  - Address effects of using a neutral particle as a trigger with charged jets
- Comparison to theory
  - Unfold jets
EXTRA SLIDES
There is an enhancement over background from the recoil angle in $\phi$ in the $(6/8)\pi-(7/8)\pi$ and $(5/8)\pi-(6/8)\pi$ bins.

This compares reasonably with recoil $\Delta \phi$ swings in jets in Au+Au 200 GeV collisions.
Jet $\eta$ swing of recoil jets in $\phi$ for Au+Au at STAR

Figure 10. Recoil jet distributions after mixed event subtraction.

(a) STAR Au+Au, $s_{NN}=200$ GeV, 60%-80% R=0.3, $9.0 < p_T^{trig} < 30.0$ GeV/c

(b) PYTHIA p+p, $s_{NN}=200$ GeV

(c) $9<\mathbf{p}_{T,jet}^{rec, ch}<$13 GeV/c

(d) $15<\mathbf{p}_{T,jet}^{rec, ch}<$33 GeV/c

(e) $\mathbf{p}_{T,jet}^{rec, ch}=$13

(f) $\mathbf{p}_{T,jet}^{rec, ch}=$33

Panel (c) shows the ratio of the SE and ME recoil jet distributions for $\eta$ in the range $9<\mathbf{p}_{T,jet}^{rec, ch}<$13 GeV/c, with values of $\sigma_1=0.20$ rad, $\sigma_2=0.00$ rad, and $\sigma_3=0.33$ rad. Panel (d) shows the ratio for $\mathbf{p}_{T,jet}^{rec, ch}=$15, with values of $\sigma_1=0.14$ rad, $\sigma_2=0.33$ rad, and $\sigma_3=0.33$ rad. Panel (e) shows the ratio for $\mathbf{p}_{T,jet}^{rec, ch}=$33, with values of $\sigma_1=0.17$ rad, $\sigma_2=0.00$ rad, and $\sigma_3=0.36$ rad.
Event and Track Cuts

✦ Event cuts:
   ✦ Vertex Ranking > 0
   ✦ $|Z_{\text{primary vertex}}| < 10$ cm
   ✦ $Z_{\text{DCx}} < 27,000$
   ✦ $|Z_{\text{vertex}} - Z_{\text{vertex position detector}}| < 6$ cm

✦ Track cuts
   ✦ $N_{\text{hits}}/N_{\text{hits-possible}} > 0.52$
   ✦ $\text{DCA}_{\text{track}} < 3$ cm
   ✦ $0.2$ GeV < $p_{\text{T,track}}$ < $30$ GeV
   ✦ $|\eta| < 1.0$

✦ Jets:
   ✦ R=0.4
   ✦ anti-$k_T$ clustering algorithm using FastJet 3.3.0
   ✦ composed of detector level, un-corrected tracks
   ✦ $|\eta| < 0.6$ (for jet center – individual tracks may extend to $|\eta| < 1.0$)
   ✦ Are not background subtracted
   ✦ The trigger which defines $\varphi = 0$ is defined as the highest $E_T$ BEMC hit in the event
   ✦ The azimuth of the jets are relative to the trigger in the event
Spectra in three EA bins for raw, uncorrected tracks

Minimum Bias Events (Left Column)

BEMC Triggered Events (Right Column)

\[
\frac{1}{N_{\text{ev}}} \frac{dN_{\text{ev}}}{dE_{\text{BBC}}} =
\begin{cases}
70\% < EA < 100\% \\
30\% < EA < 70\% \\
0\% < EA < 30\%
\end{cases}
\]

\[
\frac{1}{N_{\text{ev}}} \frac{dN_{\text{ev}}}{dN_{\text{ch}}} =
\begin{cases}
70\% < EA < 100\% \\
30\% < EA < 70\% \\
0\% < EA < 30\%
\end{cases}
\]

\[
\frac{1}{N_{\text{ev}}} \frac{dN_{\text{ev}}}{d(\Sigma p_{T}^\text{ch})} =
\begin{cases}
70\% < EA < 100\% \\
30\% < EA < 70\% \\
0\% < EA < 30\%
\end{cases}
\]

\[
\frac{1}{N_{\text{ev}}} \frac{dN_{\text{ev}}}{d(\text{max}(p_{T}^\text{ch}))} =
\begin{cases}
70\% < EA < 100\% \\
30\% < EA < 70\% \\
0\% < EA < 30\%
\end{cases}
\]
A single embedding response matrix was generated for all charged tracks, necessitating the relative production spectra of each particle species.

Measurements of $\pi^+$, $\pi^-$, $p$, and anti-proton data up to about 10 GeV at exist at STAR for d+Au and pp collisions at 200 GeV.

- $K^0_s$ spectrum has been measured up to about 5 GeV/c in 200 GeV pp collisions at STAR (PLB616, 8 (2005)).
- $K^+$ spectrum has been measured up to about 2.3 GeV/c in 200 GeV d+Au collisions at PHENIX (PRC 75, 64901 (2007)).
From both the pp and d+Au data, the $\pi^+$ and $\pi^-$ spectra were $m_T$ scaled (with a scaling factor of 2.0 from (PRC 75, 064901 (2007))) to generate the $K^+$ and $K^-$ spectra.

Each spectra was fit with a Levy function; these functional forms provided the priors used to weight and sum the six particle species’ response matrices to a single charge particle response matrix.

Differences in the final result from using the Kaon spectra from the d+Au collisions vs using the spectra from the pp collisions were accounted in the systematic errors for the results.
Embeded track efficiency x acceptance independent of $E_{A_{BBC}}$ decile of backward (Au-going) activity

Percentage of matched tracks does’t change with $E_{A_{BBC}}$ decile

STAR Preliminary
MC charged tracks embedded in
min. bias $p+Au \sqrt{s_{NN}} = 200$ GeV collisions
$|\eta_{\text{MC-tracks}}|<1.0$
Jet Median Background Estimator, skip 2 hardest, $l_{\eta_{\text{ghost}}} |<4, \text{area}_{\text{ghost}} =0.1$

- $\frac{dN_{\text{ev}}}{dp}$
- $\sum N_{\text{ev}}$

$\rho$ (GeV)

$\rho+\text{Au}\sqrt{s_{NN}} = 200$ GeV
Anti-$k_T$ raw charged jets
$R = 0.4$, $|\eta_{\text{jets}}|<0.6$
8 GeV trigger in BEMC

STAR Preliminary

$\star$
Theory result for modifying Glauber to converse $p_{tot}$ of d/p in binary collisions

- Traditional Glauber treats all $N_{coll}$ collisions as equal
- Modify Glauber for depletion of energy ($p_{total}$) of the proton/deuteron
- Primary result: more high energy jets (from $N_{coll}$) are correlated with lower overall multiplicity (by energy conservation)
- Takeaway: jet suppression and enhancement is predicted to result from mis-binning EA

$$R_{jet \text{ High EA}}^{(p/d)A} < 1 \quad \& \quad R_{jet \text{ Low EA}}^{(p/d)A} > 1$$

![Graph showing % Change of $N_{events}$ vs Leading $\pi^0$ pT (GeV) for d+Au, $\sqrt{s}=200$ AGeV]

- Low EA events getting extra counts
- High EA events getting less counts