Measurements of the Jet Internal Structure

Relevance to parton evolution in p+p and Au+Au collisions at STAR

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What do we want to measure?

- Parton shower (jet evolution) in vacuum is inherently a multi-scale processes
  - momentum and angular/virtuality scale
- In heavy ion collisions - we can relate the angular/virtuality scale to a resolution scale at which the jet probes the medium

**Larkowski, et al.**
JHEP 05 (2014) 146

**Dasgupta et al.**
JHEP 09 (2013) 029

**Utilize SoftDrop algorithm**
- momentum scale - $z_g$
- virtuality/angular scale - $R_g$

**multi-scale jet evolution in vacuum**

Lets begin with this measurement in p+p
Jet reconstruction at STAR

- anti-$k_t$ Ch+Ne jets
- Nominal JetR = 0.4, $|\eta|+\text{JetR} < 1$
SubJet momentum fractions ($z_g$)

$p+p$ collisions @ 200 GeV

- $z_g$ in vacuum described by leading order MC generators

- Recover the universal $1/z$ behavior starting from $p_T \sim 20$ GeV/c

Larkoski et al., Phys. Rev. D 91 (2015) 111501
Groomed jet radius ($R_g$)  

**p+p collisions @ 200 GeV**

- SoftDrop $R_g$ reflects momentum dependent narrowing of jet structure (higher $p_T$ - narrower $R_g$)

- Overall shape in $R_g$ described by leading order models (opportunity to further tune MC at RHIC kinematics)
Dependence on the jet $R$

- $Z_g$ flattens at low $p_T$ for small $R$ jets
- Deviation from universal $1/z$ behavior for small $R$ and low $p_T$ due to reduced phase space/angular scale
- Moderate effect due to hadronization in PYTHIA-8
Recursive SoftDrop

Dreyer et al.
JHEP 06 (2018) 093

- Follow the leading split

\[ z_g' = \frac{p_T^{C'}}{p_T^{C'} + p_T^{B'}} \]

\[ R_g' = \Delta R(C', B') \]

In vacuum: opportunity to experimentally reconstruct the parton shower history

\[ \Rightarrow \text{Test self similarity of the AP splitting in p+p collisions} \]
First measurement of the jet internal structure via recursive SoftDrop at STAR

- 1st and 2nd splits are similar in both $z_g$ and $R_g$
- 3rd split is significantly constrained in phase space/angular scale - Deviation from universal $1/z$ behavior
What do we want to measure?

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  - Momentum and Angular/Virtuality Scale
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**Multi-scale jet evolution in vacuum**

Interaction of the jet w/ the medium could depend on the resolution scale

- Majumder, A and Putschke, J
  - Phys. Rev. C 93 (2016) 054909
- Mehtar Tani, Y and Tywoniuk, K
  - Phys. Rev. D 98 (2018) 051501(R)

Partonic energy loss as a function of the resolution scale -> jet’s angular scale
Jet selection in Au+Au events

Select events based on High Tower (HT) trigger
highest tower $E_T > 5.4$ GeV/c

Hard Core jets
$p_T^{\text{const}} > 2$ GeV/c
$p_T^{\text{Lead-jet}} > 16$ GeV/c
$p_T^{\text{Recoil-jet}} > 8$ GeV/c

$\Delta R$ (Lead-jet, HT) < 0.4
$\Delta \phi$ (Recoil-jet, HT) > $2\pi/3$

Matched jets
$p_T^{\text{const}} > 0.2$ GeV/c
$\Delta R$ (jet, HC-jet) < 0.4

$p_T^{\text{const}} > 2$ GeV/c cut removes almost all background
$p_T^{\text{const}} > 0.2$ GeV/c geometric matching recovers all constituents

See Nick Elsey's Talk on Tuesday 11:25 am Parallel-2

Raghav Kunnawalkam Elayavalli, HP 2018
SoftDrop $R_g$ in the presence of Au+Au event

We need an observable that is more robust to the AuAu fluctuating underlying event but still sensitive to jet kinematics.
TwoSubJet z/θ

• Cluster all jet constituents into anti-kt jets of smaller radii (0.1)

• Choose the leading and subleading SubJets

• $z_{SJ} = \frac{\text{Blue } p_T}{(\text{Blue } p_T + \text{Red } p_T)}$

• $\theta_{SJ} = \Delta R (\text{Blue Axis, Red Axis})$

\( \theta_{SJ} \) in the presence of Au+Au event

- \( \text{anti-}k_t \ R_{\text{jet}}^{\text{jet}} = 0.4 \)
- \( \text{Ch+Ne Jets, } |\eta|+R_{\text{jet}}^{\text{jet}} < 1.0 \)
- \( 20.0 < p_T < 30.0 \text{ [GeV/c]} \)
- \( \text{Recoil jets } \Delta \phi_{\text{jet, HT}} > 2\pi/3 \)
- \( \text{Constituent-subtracted jets} \)
  Berta, P et al. JHEP 06 (2014) 092

- \( \theta_{SJ} \) (w/ \( R=0.1 \) SubJets)
  less sensitive to AuAu underlying event

Comparisons between Au+Au and p+p Embedded in Au+Au to isolate quenching effects
TwoSubJet (R=0.1) observables in Au+Au

- Fix trigger jet selection:
  Study recoil HardCore/Matched Jets ($p_T^{const} > 0.2$ GeV/c)

- Matched jet’s SubJet $p_T > 3$ GeV/c: reduce sensitivity to UE fluctuations

- TwoSubJet tagging purity > 98%

- Systematic uncertainty applied to the embedded p+p curves
  - relative tower energy scale (2%)
  - tracking efficiency (6%)
  - TwoSubJet tagging fake rate (2%)
TwoSubJet observables
anti-\(k_t\) R=0.1 SubJets

- For both \(z_{SJ}\) and \(\theta_{SJ}\), we observe **no significant difference in shape** due to jet quenching
- The \(z_{SJ}\) distribution is biased towards harder splits (in vacuum ~ earlier formation time)
For the first time - we differentially utilize an angular scale

Select jets with a particular angular scale ($\theta_{SJ}$)

Tagging Efficiency: Probability that $p+p \oplus Au+Au$ and the $p+p$ jet utilized in the embedding have a resolved $\theta_{SJ}$ in the same range.

Let's look at standard jet quenching observables - $A_J$ and Recoil Jet Yield
HardCore $A_J$

$p_T^{\text{const}} > 2$ GeV/c

Significant modifications in Au+Au for our $\theta_{SJ}$ selections in comparison to p+p $\oplus$ Au+Au
Matched jets of different \( \theta_{SJ} \) selections are balanced at RHIC

\[
A_J = \frac{p_T^{Trig} - p_T^{Recoil}}{p_T^{Trig} + p_T^{Recoil}}
\]
Recoil matched jet yield

\( p_T^{\text{const}} > 0.2 \ \text{GeV/c} \)

- Normalized per dijet yield
- Confirmation that Matched jets recover the energy lost by quenching within \( R = 0.4 \)
- Observe no significant differences between \( \theta_{\text{SJ}} \) selections

STAR Preliminary

2007 Au+Au, 2006 p+p 200 GeV
anti-\( k_t \) \( R_{\text{jet}} = 0.4 \), Ch+Ne Jets, \( h_{\text{jet}} + R_{\text{jet}} < 1.0 \) 0-20%
anti-\( k_t \) \( R_{\text{jet}} = 0.1 \) Subjet \( p_T > 2.97 \ \text{GeV/c} \)

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Conclusions

• **First fully unfolded** $z_g$ and $R_g$ in $p+p$ collisions at RHIC kinematics
• Radial scans highlight deviations from universal $1/z$ behavior due to phase space constraints
• Recursive SoftDrop offers experimental access to the parton shower

• **First differential measurement** of dijet $A_J/\text{Recoil Jet Coincidence}$ at different angular/resolution scales
  • **Significant modification** observed in HardCore $A_J$
  • Recover “lost energy” for Matched jets within the jet radius of $R=0.4$
• Next steps - higher statistics, kinematic reach, and centrality evolution —> then move towards semi-inclusive recoil jets
Bonus Slides!
Going from Partons to Jets

- Parton evolution characterized by the momentum and angular scales of its emissions
- In vacuum, this is governed by the DGLAP evolution equations

Hard Scattered partons in high energy collisions fragment and hadronize jets

Reconstruct Jets from tracks/towers based on clustering algorithms
Most popular - anti-$k_t$

Requires a minimum $p_T$ cut and an angular scale

Raghav Kunnawalkam Elayavalli, HP 2018
SoftDrop
(tools of the trade)

Larkoski et al., PRD 91, 111501 (2015)

Soft Drop Condition:
\[ z > z_{\text{cut}} \theta^\beta \]

- Reclustering w/ C/A ensures an angular ordered behavior in the tree
- Baseline behavior in p+p collisions shown to asymptote to AP splitting functions at high \( p_T \)

\[ z_g = \frac{\min(p_{T1}, p_{T2})}{p_{T1} + p_{T2}} \]

\[ R_g \]
\[ \Delta R(1, 2) \]
Detector Effects on SoftDrop in p+p simulations

- $z_g$ and $R_g$ resolutions are independent of the generator jet $p_T$.
- Bayesian 2D unfolding with jet $p_T$ vs $z_g$, and $p_T$ vs $R_g$.

$z_g = \frac{\min(pT_1, pT_2)}{pT_1 + pT_2}$

$R_g = \Delta R(1, 2)$
**p+p z_g and R_g**

**Systematic Uncertainties**

- Hadronic Correction (HC)
  - Using MIPs (no HC) and 0.5 HC
- Tower Scale - 3.8% in the tower gain
- Tracking - 4% variation (flat in track p_T)
- Unfolding (@ the response level) -
  - Prior shape variations
  - Varying the iteration parameter from 2 - 6 (nominal=4)

- anti-k_t R = 0.4
- SoftDrop z_{cut} = 0.1, \( \beta = 0 \)
- Ch+Ne Jets, |\eta| + |R| < 1

**Systematic Uncertainties**

[Diagram showing systematic uncertainties]
Need for differential measurements

- It is necessary to disentangle the correlations built within observables by selecting jets of a certain class.

- Does the medium resolve the two prongs of a jet as a single object or two individual objects?

- There are a variety of theoretical models and calculations that predict a larger absolute energy loss for jets of a large virtuality or wider resolution scales.
Jet SubStructure: $z_g$ in Au+Au

No significant modification on trigger and recoil side of hard-core dijets

Theoretical models capture this well

More statistics: Test downward slope

Ning-Bo Chang et al. QM18

Li & Vitev
arXiv: 1801.0008

Modelers: Be mindful of cuts and detector effects

Slide from Kolja Kauder, RHIC AGS Users Meeting 2018
TwoSubJet (R=0.1) $\theta_{SJ}$

Tagging Efficiency and Purity

- **Tagging Purity**: Given a $p+p \oplus Au+Au$ jet with two resolved SubJets, how often does the input $p+p$ jet utilized in the embedding also have two resolved SubJets.
  - For Matched jet $p_T > 10$ GeV, Purity $> 98$
  - Systematic uncertainty estimated by varying the SubJet $p_T$ threshold by 1 sigma variation in the background fluctuations

- **Tagging Efficiency**: Probability that a $p+p \oplus Au+Au$ and the $p+p$ jet utilized in the embedding has a resolved $\theta_{SJ}$ in the same range. These are the cases where both jets have two resolved SubJets.
  - $0.1 < \theta_{SJ} < 0.2$: Efficiency $> 99$
  - $0.2 < \theta_{SJ} < 0.3$: Efficiency $> 72$