Constraining parton energy loss via angular and momentum based differential jet measurements at STAR

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Jets at RHIC

- Significantly steeper jet spectra compared to LHC
- Access to 15 - 60 GeV/c jets - Kinematic range offers sensitivity to study both QCD and HI physics (complementarity with LHC)

Jet evolution/parton shower in vacuum is described by two fundamental scales
- virtuality/opening angle
- momentum
Jet reconstruction at STAR

- anti-$k_T$ Charged + Neutral jets
- Nominal $R_{Jet} = 0.4, |\eta_{Jet}| + R_{Jet} < 1$

TPC + BEMC
Jet substructure measurements

- Correlate physical quantities in jet evolution to experimental observables
- SoftDrop Grooming reduces sensitivity to non-perturbative effects

- Splitting Functions
  - momentum scale - $z_g$
  - angular scale - $R_g$
- Invariant and Groomed Jet Mass ($z\theta^2$)

Study QCD in pp collisions at RHIC
Establish a vacuum baseline for HI measurements

$L_{g,\beta} = \min (p_{T1}, p_{T2})/(p_{T1} + p_{T2})$
$R_{g} = \Delta R(1, 2)$
$z_{g} > z_{\text{cut}} (0.1), \beta = 0$

Larkowski et al.

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pp jet substructure in STAR

- Jet substructure observables generally described by leading order tuned MC
- PYTHIA-8 and HERWIG-7 LHC tunes show deviations leading to an exciting opportunity to tune at RHIC kinematics!
Hard scattered parton emanating with early formation time probes evolution of QGP

Modifications of jet properties interpreted as medium interaction

Several MC implementations of jet energy loss

Jet quenching in a nutshell

Suppression of high-$p_T$ particles

Enhancement of low-$p_T$ particles

Jet broadening

Need for differential measurements that are able to distinguish between models!
Differential measurements of jet quenching at STAR

- We have two handles -
  - Jet Geometry Engineering (JGE) : Vary hardcore constituent threshold and jet finding radius for dijets
  - Given a dijet definition, measure jet modification as a function of opening angle
Identifying dijets

- Dijet selection with both leading and subleading momentum threshold
  \( p_T^{\text{Const}} = 2 \text{ GeV}/c \)
  \( p_T^{\text{Lead}} > 16 \text{ GeV}/c \)
  \( p_T^{\text{SubLead}} > 8 \text{ GeV}/c \)

- HardCore selection removes combinatorial jets

- Matching recovers the jet fragments/particles down to 0.2 GeV/c

- Dijet finding introduces a bias - Let's utilize the bias in a systematic fashion
Quantifying selection bias with Jet Geometry Engineering (JGE)

Systematically measure dijet $A_J$ in Au+Au across various jet definitions and compare with $p+p \oplus Au+Au$.
HardCore dijets

All selections of HardCore dijets are imbalanced - Modified due to partonic energy loss.
HardCore dijets

All selections of HardCore dijets are imbalanced - Modified due to partonic energy loss
Matched dijets vary from imbalanced (quenched energy not recovered) at small radii to balanced at large radii!
“Dialing in/out” the energy loss by varying HardCore constituent threshold and jet radius

Under the assumption of sensitivity to path length dependence of recoil jets - with a steeply falling spectra we evidently see JGE

Theoretical input and comparisons at RHIC energies are essential!
Differential measurements of jet quenching at STAR

• We have two handles -

  • Jet Geometry Engineering (JGE) : Vary hardcore constituent threshold and jet finding radius for dijets

  • Given a dijet definition, measure jet modification as a function of opening angle
Key idea
Use jet-substructure as a selection tool

Identify jet observable(s) sensitive to the parton shower kinematics

Partonic energy loss via a differential study in momentum scale and angular scale
Utilizing subjets of smaller R

Need techniques and observables that are robust to underlying event background especially at RHIC

- Recluster jet constituents with a smaller radius - identify regions of jet-like features within the mother jet
- Choose the leading and subleading Subjets
- \( Z_{SJ} = \text{subleading } p_T / (\text{subleading } p_T + \text{leading } p_T) \);
  \( \theta_{SJ} = \Delta R (\text{subleading, leading}) \)

\[ \sum_{p_T} p_T < 0.4 \text{ GeV}/c, \ 20 < p_T < 30 \text{ GeV}/c \]

Constituent-Subtracted Jets

\[ \theta_{SJ} (w/ R=0.1 \text{ subjets}) \text{ less sensitive } \]

Au+Au underlying event

Comparisons between Au+Au and p+p embedded in Au+Au to isolate quenching effects
TwoSubJet observables

- The $z_{SJ}$ distribution is biased towards harder splits
- For both $z_{SJ}$ and $\theta_{SJ}$, no significant difference in shape due to jet quenching

Let’s measure the $A_J$ for wide vs. narrow recoil jets!
Dijet $A_J$

$A_J$ shape **different** for wide vs narrow jets

**Significant imbalance** for all $\theta_{SJ}$

**Matched $A_J$ similar** for wide vs. narrow jets

Balance indicating **recovery for all $\theta_{SJ}$**

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Conclusions

- RHIC tuned MC describe p+p jet substructure measurements very well
- Opportunity to understand/tune the jet shower/non-perturbative/ $\sqrt{s}$ dependence of MC models
- Jet Geometry Engineering - varying dijet constituent threshold and jet radius leads to dialing in/out energy loss!
- Narrow and wide recoil jets reveal similar behavior of modified/quenched HardCore and balanced Matched
- Quenched energy recovered within R=0.35

**Consistent picture of energy loss at RHIC**

given ‘Jet Geometry Engineering’ results in shorter path lengths and surface biases $\rightarrow$ splits most likely outside medium $\Rightarrow$ modification due to **radiation from a single color charge**

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STAR Preliminary
Moving forward

- Differential studies in both momentum and angular scales

- Utilize Jet Geometry Engineering biases to have a direct handle on energy loss in dijets

- Increase kinematic range of the dijet selection and centrality dependence

- Systematic mapping of the splitting phase space within jets - via formation time arguments
Backup slides
Radial Dependence on jet substructure in pp

SoftDrop Splitting $z_g$

SoftDrop $z_g$ is significantly dependent on the jet $p_T$ - higher $p_T$ leads to smaller $z_g$.

Larger radius jets include more softer radiation results in a more steeper $z_g$.

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Radial Dependence on jet substructure in pp
Groomed Jet Radius $R_g$

Clear evidence of jet $p_T$ dependent narrowing of jet substructure! high $p_T$ - small $R_g$
Radial Dependence on jet substructure in pp
Jet Mass and Groomed Jet Mass

• Jet mass increases with increased phase space (jet $p_T$) and inclusion of more wide-angle soft radiation (jet $R$), consistent with pQCD expectation
• SoftDrop groomed mass is observed to be closer to ungroomed parton level mass
What do we want to measure?

Microscopic properties of the QGP Medium - structure at varying scales

Interaction of the jet with the medium could depend on the resolution scale

Jets at RHIC kinematics are ideal to study these effects

Partonic energy loss via a differential study in momentum scale and angular scale
Semi-Inclusive recoils

- No selection on recoil jet momenta
- Statistical correction of the combinatorial jet yields via mixed events

**$I_{CP}$ for jets of varying radii**

The recoil coincidence yield for $R=0.2$ (left) jets are suppressed compared to $R=0.5$ (right).

\[ p_T \text{ shifts for } R=0.2 : -4.4 \pm 0.2 \pm 1.2 \text{ and } R=0.5 : -2.8 \pm 0.2 \pm 1.5 \]
Sensitivity of Matched dijet imbalance

- **Au+Au HT**
- **p+p HT ⊕ Au+Au MB**
- **Au+Au HT ⊕ Au+Au MB**

- Embedding a HardCore Au+Au dijet in a different Au+Au minimum bias event to check sensitivity to distinguish energy loss

- The blue markers are significantly different than both black and red markers implying we are sensitive to physics of energy loss
zg in Au+Au 200 GeV

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

- Theoretical models capture this well

- More statistics: Test downward slope

Note - These are detector level observables. Au+Au compared with p+p ⊕ Au+Au

Splitting unmodified for these matched jets
TwoSubJet ($R=0.1$) observables in Au+Au

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

- Matched jet’s Subjet $p_T > 3 \text{ GeV/c}$: reduce sensitivity to UE fluctuations

- TwoSubJet tagging fake rate ~ 2%

- Systematic uncertainty applied to the embedded p+p curves
  - relative tower energy scale (2%) 
  - tracking efficiency (6%)
  - Subjet threshold cut varied by +/- 1 sigma of background fluctuations
**SoftDrop R\(_g\) in the presence of Au+Au event**

- **anti-\(k_t\) R\(_{jet}\) = 0.4**
- **Ch+Ne Jets, |\(\eta|\) + R\(_{jet}\) < 1.0**
- **20.0 < \(p_T\) < 30.0 [GeV/c]**
- **Recoil jets \(\Delta\phi_{jet, HT} > 2\pi/3\)**
- **Constituent-subtracted jets**

Berta, P et al. JHEP 06 (2014) 092

**SoftDrop R\(_g\) sensitive to background fluctuations**

We need an observable that is more **robust** to the AuAu fluctuating underlying event but still **sensitive** to jet kinematics.
TwoSubJet (R=0.1) $\theta_{SJ}$

**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

- 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.
  - $0.1 < \theta_{SJ} < 0.2$: purity > 99%
  - $0.2 < \theta_{SJ} < 0.3$: purity > 72%
Recoil matched jet yield

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

- Confirmation that matched jets recover the energy lost by quenching within \( R = 0.4 \)

- Observe no significant differences among \( \theta_{\text{SJ}} \) selections
Two subjet distributions in PYTHIA-8

PYTHIA-8 anti-k$_t$ R=0.4 Jets

$10 < \text{Jet } p_T < 20 \text{ GeV/c}$