Measurement of splittings along a jet shower in $\sqrt{s} = 200$ GeV $pp$ collisions at STAR

Raghav Kunnawalkam Elayavalli (Yale/BNL)
For the STAR Collaboration
Physics of jet substructure

Jet evolution/parton shower in vacuum is described by two fundamental scales - angle/virtuality ($\theta$) and momentum fraction ($z$).

Utilize algorithmic structure of jet finding via re/de-clustering techniques.

Probe fundamental QCD properties via parton shower e.g. virtuality evolution.

Tuning Monte-Carlo generators and (improving on) hadronization models as a function of $\sqrt{s}$.
What do we want to measure?

We want to translate an intrinsic (and unmeasurable) parton shower to experimentally accessible observable(s).

Gluon jet $g \rightarrow g + g$

Reconstructed jet

Clustering

Parton shower $g \rightarrow g + g$

$13.1 \text{ GeV}$

$12.7 \text{ GeV}$

$0.4 \text{ GeV}$

$2 \text{ GeV}$

$10.7 \text{ GeV}$

$6.3 \text{ GeV}$

$4.3 \text{ GeV}$

$3.9 \text{ GeV}$

$1.3 \text{ GeV}$

$5 \text{ GeV}$

$0.41 \text{ GeV}$

$3.9 \text{ GeV}$

$0.41 \text{ GeV}$
• Require subjet momentum fraction to pass

\[
\frac{z_g}{p_{T,1}} = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut} (R_g/R_{jet})^\beta
\]

\[
z_{cut} = 0.1
\]

\[
\beta = 0
\]
• Require subjet momentum fraction to pass

\[
z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}} > z_{cut}(R_g/R_{jet})^\beta
\]

\[
z_{cut} = 0.1 \\
\beta = 0
\]

• With the two surviving branches (first hard split) - we define observables that characterize jet substructure \(z_g, R_g\)
Correlations between substructure observables at the first split

See Monika Robotková’s talk later today!

Evolution of the splitting observables as we travel along the jet shower

Main physics question of today’s talk!
We can implement the SoftDrop procedure throughout the C/A tree -

- Follow the hardest branch - Iterative SoftDrop
- Following all branches - Recursive SoftDrop

\[ n_{SD}, z^n_g, R^n_g \]
Jet reconstruction at STAR

- Anti-$k_T$ Ch+Ne jets
- Nominal $R_{jet} = 0.4$, $|\eta_{jet}| + R_{jet} < 1$

2012 $pp$, $\sqrt{s} = 200$ GeV
Measure the splittings along the jet clustering tree

- Enables a study of self-similarity and effect of restricting available phase space for radiation due to virtuality evolution

\[ \tau_f \approx \frac{1}{\omega \theta^2} \]
Measure the splittings along the jet clustering tree

- Enables a study of self-similarity and effect of restricting available phase space for radiation due to virtuality evolution

- **Given a jet** ($p_T^{\text{jet}}$) what are the $z_g$, $R_g$ at 1st, 2nd and 3rd splits? **Follow a jet**
  - Compare these distributions at varying jet kinematics
  - Indirect constraint on splitting kinematics

- **Given a split** ($p_T^{\text{initiator}}$), what are the $z_g$, $R_g$ for 1st, 2nd and 3rd splits? **Follow a split**
  - Compare these at varying initiator kinematics (direct handle on splits)
  - Indirect constraint on jet kinematics
**Need for unfolding**

Finite detector efficiency and resolution can alter the splits that are reconstructed in the detector. Observables ($p_T^{\text{jet}}$, $\text{initiator}$, $z_g$, $R_g$) at a given split are smeared. Splitting hierarchy also modified going from particle to detector level jets.

Details of unfolding and systematic uncertainties available in backup.
Fully corrected results

1st, 2nd, 3rd splits for various $p_T^{jet}$

- **Given a jet ($p_T^{jet}$)** What are the $z_g$, $R_g$ at 1st, 2nd and 3rd splits? Follow a jet...

- **Significant differences between first, second and third splits**

- **Splitting ‘z’ becomes flat and the $R_g$ quite narrow** for the third split where we observe collinear emissions
Fully corrected results

1st, 2nd, 3rd splits for various $p_T^{\text{initiator}}$

- Given a split ($p_T^{\text{initiator}}$), what are the $z_g, R_g$ for 1st, 2nd and 3rd splits? Follow a split...

- Splits are directly comparable with each other - only difference is where they occur in the shower

- Significant differences in second split $z_g$ (similar $R_g$) for initiator vs. jet momenta selection
Comparisons with leading order MC - $R_g$ for various initiator $p_T$

- Three MC (PYTHIA 6, PYTHIA 8, HERWIG 7) models describe the overall trend of narrowing of jet substructure for higher splits.

- Availability of emission phase space depends on both jet momenta and split # - similar peaks of $R_g$ for third splits on the left to second splits on the right.
Comparisons with leading order
MC - $z_g$ for various jet $p_T$

- Flattening of the splitting $z_g$ as we increase split number captured by the MC
- Small differences between PYTHIA and HERWIG seen in the first split appear to be reduced at the second/third splits
Conclusions

• Jet substructure program at STAR aims at **mapping jet evolution** at RHIC energies

• Data show a **gradual variation in the available phase space** along the jet shower
  • leading to modifications (e.g. virtuality evolution) in the observed splitting kinematics

• Observe **significantly harder/symmetric splittings** at the **third split** which are the **most collinear** in a shower

• First measurement that can potentially **distinguish experimental quantities in a ‘time scale’** via formation time of splits - Extremely useful in a heavy ion environment

• In our upcoming final results we will delve further into comparisons
  1. Various handles in the MC -
     A. hadronization (Sherpa - Lund vs Ahadic),
     B. parton shower (Herwig - angular vs dipole, Pythia - dire vs vinca vs $p_T$ ordered)
     C. tune variation in both PY6 and PY8 (STAR is currently working on a new PY8 tune via Professor and existing analysis in RIVET)
  2. In discussion with our theory colleagues on feasibility of calculations

• Subjets at RHIC allow to **disentangle perturbative and non-perturbative dynamics of jet evolution**
  • These **third splits** for our low $p_T$ jets end up quite close to $\Lambda_{QCD}$
Backup
Jets at RHIC

- Significantly steeper spectra compared to LHC
- Access to $10 \sim 60$ GeV/c Jets at $\sqrt{s} = 200$ GeV

Extending to lower jet momenta leads to varying $q/g$ fractions in pp collisions - interesting comparisons with similar kinematics at LHC (EIC)
Groomed Jet Mass

RHIC-tuned **PYTHIA-6** describes data
**HERWIG-7** under-predicts and **PYTHIA-8** over-predicts

Mass (angularity) $\sim z\theta^2$ Can we isolate these two scales in jets?
Evolution of jet mass as a function of jet momenta and radius

Increase in jet mass with increasing $p_T$ and $R$ is reduced with grooming - reduces overall impact of non-perturbative contributions to jets
**SoftDrop** $z_g = \frac{\min(p_{T,1}, p_{T,2})}{p_{T,1} + p_{T,2}}$

- Recover the universal $1/z$ behavior starting from $p_T \sim 25$ GeV/c
- **PYTHIA-6** and **PYTHIA-8** describe data
- **HERWIG-7** predicts harder splitting

\[ z_g = \min(p_{T,1}, p_{T,2}) \]

\[ \frac{1}{dN_{\text{jet}} / dz_g} \]

SoftDrop $R_g$  

$R_g = \Delta R(1,2)$

★ $R_g$ reflects momentum-dependent narrowing of jet structure

★ PYTHIA-6 describes data

★ PYTHIA-8 predicts larger groomed jet angular scale

Jet $p_T$

MC/Data

p+p $\sqrt{s} = 200$ GeV  
anti-$k_T$ $R = 0.4$ Jets  
$15 < p_{T,\text{jet}} < 20$ GeV/c  
$|\eta_{\text{jet}}| + R < 1.0$

20 < $p_{T,\text{jet}}$ < 25 GeV/c  
SoftDrop $z_{\text{cut}} = 0.1$, $\beta = 0$

STAR data  
Sys. Uncert.

25 < $p_{T,\text{jet}}$ < 30 GeV/c

30 < $p_{T,\text{jet}}$ < 40 GeV/c

40 < $p_{T,\text{jet}}$ < 60 GeV/c

PYTHIA 8 Monash  
HERWIG 7 EE4C


Raghav Kunnawalkam Elayavalli @ DIS 2021
• NLL calculations (w/o non-perturbative corrections) matches data at large jet R and $p_T$

• Significantly worse for jets of narrow R and low $p_T$ - tighter constraints on jet splittings
Recent measurements of Lund Plane and their projections at the LHC


• Each split along the harder branch makes an entry here in the 2D Lund plane
• Comparison with particle level MC w/ varied shower/hadronization models showcase differences
Recent measurements of Lund Plane and their projections at the LHC

- Lower $p_T$ jets at ALICE (20 - 120 GeV) also show interesting differences for large $k_T$ splits
- Lund plane integrates over splits - can we measure the evolution of these observables along the jet shower?
Shape correction

Unmatched splits/jets via matching criterion → Unmatched shape

Split Matching done via geometric matching

Trigger Inefficiency no matching geant event for pythia event → Particle level shape correction (inclusive)

Particle Level Split #

Detector Level Split #
Systematic Uncertainties

- Tracking efficiency : 4%
- Tower energy scale : 3.8%
- Hadronic correction (Matched track-tower energy subtraction) : 50% - 100%
- Bayesian unfolding iteration parameter : 2 - 6
- Prior shape variation : Priors reweighed at 1st, 2nd and 3rd split as seen in PYTHIA 6 vs PYTHIA 8 and HERWIG 7
- Split Matching criteria : $\Delta R < 0.075, 0.1, 0.125$
- Variation in truth level shape correction for trigger and jet finding efficiencies via differences observed in PYTHIA 6 vs PYTHIA 8 and HERWIG 7