A Journey in Jet Sub-Structure from RHIC to EIC

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1st Lund Jet Plane Institute @ CERN July 2023
Completing the RHIC mission

pQCD and npQCD at the EIC

Introduction, motivation and current status
Relativistic Heavy Ion Collider @ BNL
Next steps at RHIC!

“There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: (1) **Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales.** The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) **Map the phase diagram of QCD with experiments planned at RHIC.**” (completed data taking in 2021)
**sPHENIX**

Unique, purpose-built sPHENIX detector for precision on hard probes

**STAR**

Significant new forward and mid-rapidity capabilities of the upgraded STAR detector
RKE @ CERN, July 2023

Jets in $pp \sqrt{s} = 200$ GeV

Unique population of jets with varied substructure!
Scales extend from jet $p_T \rightarrow \Lambda_{QCD}$
Jet substructure @ RHIC

$12 < p_T^{jet} < 14.5$ GeV/c
$R = 0.3$ anti – $k_T$

$30 < p_T^{jet} < 40$ GeV/c
$R = 0.6$ anti – $k_T$

$\frac{dN}{dz} = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$

$z_g = \frac{p_{T,2}}{p_{T,1} + p_{T,2}}$

$\text{PHENIX preliminary}$

$\text{Groomed Subjet Momentum Fraction}$

$R = 0.6$
$30 < p_T^{jet} < 40$ GeV/c
$|\eta|<0.15$

$p+p, \sqrt{s}=200$ GeV

$\text{STAR data}$
$\text{Sys. Uncert}$
$\text{Kang et al.}$

$\text{Groomed Jet Mass}$ $|+R<1.0$
$\beta = 0$
$\text{SoftDrop } z_{cut} = 0.1$

$|+R<1.0$
$\beta = 0$

$\text{SoftDrop } z_{cut} = 0.1, \beta = 0$

$\text{PHYS.Lett.B 811 (2020) 135846}$

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Comparing STAR vs ALEPH

- $z_g$ is reasonable but very interesting differences in the $R_g$
Comparing STAR vs ALEPH

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These jets in pp collisions have a $\langle M \rangle \approx 3 - 5 \text{ GeV}/c^2$ plus there's hadronic component!

Yi Chen, et. al
JHEP 06 (2022) 008
Virtuality evolution within jets

- Narrower splittings result in a faster reduction of virtuality!

Monika Robotkova (CTU) @ HP 2023

Dasgupta et. al.
JHEP09 (2013) 029
• Shift in the scale of the splitting kinematics with opening angle!

$k_T = z_g p_{T,\text{jet}} \sin R_g$

Monika Robotkova (CTU) @ HP 2023
Dasgupta et. al. JHEP09 (2013) 029
Extending the dimensionality

\[ Q = \sum_{i \in J} \left( \frac{p_T^i}{p_T^T} \right)^\kappa \]

- Selecting on larger mass jets simultaneously sculpts your jet charge selection

\[ p + p \sqrt{s} = 200 \text{ GeV} \quad 20 < p_T < 30 \text{ GeV/c} \]

\[ \text{anti-}k_T \text{ full jets, } R=0.4, |\eta|<0.6 \]

Andreasson et al. (2020)

\[ \kappa = 0 \quad \text{Grant McNamara (Wayne) @ DNP 2022} \]
Multifold allowed us to measure this!

Youqi Song (Yale) @ DIS 2023

Andreassen et.al


The more you groom, the further along the shower you go!
Detour... PYTHIA 8 Detroit Tune

New Monte Carlo tune that accurately describes mid-rapidity data from RHIC to LHC

M Aguillar et. al, Phys. Rev. D 105 (2022) 1, 016011

\[ \sqrt{s} = 200 \text{ GeV} \quad \sqrt{s} = 13000 \text{ GeV} \]
Jets for QGP transport properties

This is inherently a two step process that is not mutually exclusive

Understand jet energy loss → Extract medium properties
Usefulness of differential measurements in heavy ions!

- Different methods of estimating angular dependence of quenching - subjets vs harder prongs!

Vary the jet selection bias - Substructure does not seem to be modified even though jets lose energy!
• Streaming readout allows high data-taking rate enabling slicing and dicing across phase-space

• Factor of 30 increase in data comparison to previous measurement on opening angle
New from sPHENIX!

sPHENIX Time Projection Chamber
First collision with TPC
2023-06-13, Run 10771
Au+Au sqrt(s_NN) = 200 GeV

sPHENIX Experiment at RHIC
Data recorded: 2023-05-22, 02:07:00 EST
Run / Event: 7156 / 12
Collisions: Au + Au @ √200 GeV

Di-Photon Mass [ADC]

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<th>Arbitrary Units</th>
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<tr>
<td>0.005</td>
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<tr>
<td>0.01</td>
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<td>0.015</td>
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<tr>
<td>0.02</td>
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sPHENIX Preliminary 6/13/2023
Au+Au $\sqrt{s_{NN}} = 200$ GeV 56k events
$\Sigma$ ADC_{emcal} < 275,000

- $\eta > 0$
- $\eta < 0$

cluster ADC > 500 $|\eta_{photon}| < 0.7$
Electron Ion Collider @ BNL
Recent Progress
Successful OPA Progress Review 1/2023
Significant Project staffing increases via IRA
Pursuing Long Lead (CD3a) followed by CD-2

The EIC will be the most advanced accelerator in the world and the only new collider built for decades. It will keep US capability in accelerators physics number one.
When?

How much?

Cost Estimate Status (DOE)

CD-1 Approved Cost Range 1.7-2.8B

DOE total project cost estimate and overall project schedule provide the basis for the DOE funding profile.

$150M IKC assumptions: $50M accelerator $100M detector (1/3)

10% on LOE activities 35% on balance

Slides by Haiyan Gao (BNL ALD for NPP)
James Yeck (BNL ALD for EIC)
GHP 2023 @ Minneapolis
Jets at the EIC

Similar jet kinematics with varied flavor composition and interaction scales

$\sqrt{s} = 104$ GeV

PYTHIA 8.301 e+p DIS

$Q^2 > 10$ GeV$^2$

$e^- p_T > 5$ GeV/c

$\frac{1}{2\pi} \frac{d^2\sigma}{dp_T^2}$ [1/GeV/c]
Extracting physics via the angular structure of particle distribution within jets

See talk by Jack Holguin (Ecole) @ HP 2023

Devereaux et. al arXiv:2303.08143

Two-Point Energy Correlator
Approximated LO $z=1/2$

Holguin et. al. in preparation

$\Delta \Sigma^1 = \frac{1}{\Sigma^1} \frac{d\Sigma^1}{d\theta}$

$A^{1/6} \theta \sqrt{p_T}$

Deadcone

100 GeV Charm jet  Massless
Lund planes and projections at the EIC

Baseline at RHIC!


Energy correlators
Phys. Rev. Lett. 126, 112003

Provide ways to explore smoothly transition to non-perturbative regime
Potentially new ways to address EIC science ??
Why look at the formation time and charged particles

- Recent studies also show its usefulness from the theoretical POV on isolating regions where calculations are valid.

- Fuzzy area, but overall one can separate out ‘mostly’ perturbative and ‘mostly’ non-perturbative regions based on formation time.

\[ r_c(X) = \frac{d\sigma_{h_1 h_2}/dX - d\sigma_{h_1 h_2}/dX}{d\sigma_{h_1 h_2}/dX + d\sigma_{h_1 h_2}/dX} . \]

Y-T Chien, A Deshpande, M Mondal, G Sterman
arXiv: 2109.15318
• The era of precision jet substructure is upon us!

• Tools available that allow us to separate escape dependent physics for example - pQCD vs npQCD

• Track the space-time evolution of fundamental particles

• Interactions with a ‘medium’ are potentially imprinted on the
Backup
Conceptual picture of jets

Jet Clustering
What is jet substructure?

A useful way to tag jet populations

Physics motivate combinations of particles/tracks/towers 4-momenta

Exploiting the clustering information in addition to measured 4-momenta
Evidence for transition

- Transition indicated as a function of the opening angle - which we know is related to the time scale!

See talk by Andrew Tamis (Yale) @ HP 2023

See talk by Rey Cruz (LBNL) @ HP 2023

See talk by Rey Cruz (Yale) @ HP 2023

RKE (Vanderbilt) @ WSU 2023
First steps in space-time differential energy loss

\[ \tau^\text{vac} \equiv \frac{\omega}{k_T^2} = \frac{1}{\theta^2 \omega} \]

\[ \tau^\text{med} \equiv \frac{\omega}{k_T^2} = \sqrt{\frac{\omega}{\hat{q}}} \]

\[ \hat{q} \equiv \frac{d\langle k_T^2 \rangle}{dL} \]

Transport parameter
average energy lost to the medium per distance traversed
EECs in Heavy Ions

- Larger the \( \hat{q} \) -> peak shifted to the right

\[ \frac{1}{\Sigma^{(1)}_{\text{vac}}} \frac{d\Sigma^{(1)}}{d\theta} \]

\[ \ln \theta \]

\[ d\Sigma^{(1)}_{\text{med}} \]

\[ E=100 \text{ GeV}, L=10 \text{ fm} \]
- \( \hat{q} = 1.0 \text{ GeV}^2\text{fm}^{-1} \)
- \( \hat{q} = 2.0 \text{ GeV}^2\text{fm}^{-1} \)
- \( \hat{q} = 3.0 \text{ GeV}^2\text{fm}^{-1} \)
- Total
- Vacuum

\[ \frac{\theta_{\text{on}}/\theta_{\text{peak}}}{E} \]

\[ E (\text{GeV}) \]

\[ \theta_{\text{on}}/\theta_{\text{peak}} \sim E^{0.39} L^{-0.69} \hat{q}^{-0.36} : E < \hat{q}L^2 \]

\[ \theta_{\text{on}}/\theta_{\text{peak}} \sim E^{0.07} L^{-0.06} \hat{q}^{-0.03} : E > \hat{q}L^2 \]

Moult, et. al 2201.07800  \quad Andres, RKE, et. al 2209.11236
Let's quantify the splitting shapes

- We would nominally expect the following ordering: 1SD -> RSD -> LCP
- 1SD is a steeply falling distribution reminiscent of DGLAP leading order
- LCP is significantly peaked at larger values
- RSD is somewhere in the middle
How to think about the time observable

Large mass - early time - larger opening angle - large virtuality
Allows a selection of jets based on space-time structure
Measuring the parton shower

Studies of CNM and initial state vs resolution scale and $\tau_f$

- With splitting/dijet energies roughly 5-30 GeV, we can study resolutions $O(1-5)$ fm!
- Enabling differential measurements of similar kinematics but varying shower topology!
Di-hadron correlation based on the trigger particle (top left)

Marked suppression of 'Away side' or back-to-back yield
Evolution of jet quenching measurements at STAR


• Jet-hadron correlations show a marked suppression of associated tracks with $p_T > 2$ GeV

• Consequently, an enhancement of soft particles $0.2 < p_T < 2.0$ GeV is observed within the jet cone

Evolution of jet quenching measurements at STAR

- Central to peripheral ratios for reconstructed inclusive charged jets indicate \( \approx 60\% \) suppression
Selecting a di-jet sample at STAR

- Resulting di-jets free of combinatorial jets and background

HardCore Selection

\[ p_T > 2 \text{ GeV/c} \]

- Significant bias in jet fragmentation but lets utilize the bias to our advantage!
\[ A_J = \frac{p_{T,\text{jet}}^{\text{Trigger}} - p_{T,\text{jet}}^{\text{Recoil}}}{p_{T,\text{jet}}^{\text{Trigger}} + p_{T,\text{jet}}^{\text{Recoil}}} \]

- HardCore Dijets in Au+Au are imbalanced compared to p+p ⊕ Au+Au
- High p_T particles \((p_T > 2 \text{ GeV})\) lose energy in the medium
- Where is the quenched energy?
\[ A_J = \frac{p_{T,\text{jet}}^{\text{Trigger}} - p_{T,\text{jet}}^{\text{Recoil}}}{p_{T,\text{jet}}^{\text{Trigger}} + p_{T,\text{jet}}^{\text{Recoil}}} \]

- Matched jets recover the lost energy \((0.2 < p_T < 2\text{ GeV})\) within the jet cone \((R = 0.4)!\)
**Rg in a heavy ion environment**

- SoftDrop $R_g$ sensitive to background fluctuations

We need an observable that is more **robust** to the Au+Au fluctuating underlying event but still **sensitive** to jet kinematics
Introducing - subjets


- Cluster all jet constituents into anti-$k_t$ jets of smaller radius (0.1)
- Choose the leading and subleading SubJets
- $z_{SJ} = \frac{\text{Blue } p_T}{\text{Blue } p_T + \text{Red } p_T}$
- $\theta_{SJ} = \Delta R (\text{Blue Axis, Red Axis})$
Vacuum Splittings

Medium Induced Splittings
Parameters within PYTHIA that we tune

- Start from PYTHIA 8.303 w/ Monash tune with updated PDF to NNPDF 3.1 w/ LO $\alpha_s(M_Z) = 0.13$
- Reference Energy set to 200 GeV
- String parameters are left to the default Monash values
- Note: whatever Monash can’t do w.r.t strangeness or baryons etc… Detroit also cannot do.

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mode MultipartonInteractions:bProfile (default = 3; minimum = 0; maximum = 4)
Choice of impact parameter profile for the incoming hadron beams.
- option 0: no impact parameter dependence at all.
- option 1: a simple Gaussian matter distribution; no free parameters.
- option 2: a double Gaussian matter distribution, with the two free parameters coreRadius and coreFraction.
- option 3: an overlap function (i.e. the convolution of the matter distributions of the two incoming hadrons) of the form $\exp(-b^\text{expPow})$, where expPow is a free parameter.

parm ColourReconnection:range (default = 1.8; minimum = 0; maximum = 10.)
The range parameter defined above. The higher this number is the more reconnections can occur. For values above unity the reconnection rate tends to saturate, since then most systems are already connected with each other. This is why 10 is set as an effective upper limit, beyond which it is not meaningful to let the parameter go.
Differences between the parameter values for Monash and Detroit tunes

- Significantly smaller values for \( p_{T,0}^{\text{Ref}} \) and ecm exponent

Global \( \chi^2/n.d.f. = 1.2 \)
Both Monash and Detroit tunes can’t describe forward pion spectra from BRAHMS or STAR

New tune does worse than Monash

Simultaneous tune with mid-rapidity and larger tune-able phase space (ISR) unable to recover MC/data agreement