Jet experiment overview

Laura Havener, Yale University
RHIG/AGS Users Meeting 2024, BNL
Wednesday, June 12th, 2024
Jets as a tool to study QCD

non-perturbative (np)QCD

perturbative (p)QCD

Collision

Fragmentation

hadrons $\pi^\pm$, $K^\pm$, ...

Credit: Eric M. Metodiev
Jets as a tool to study QCD

Connect measurable hadrons to unmeasurable partons

non-perturbative (np)QCD

perturbative (p)QCD

Multi-scale dynamic objects whose complex structure contains QCD information

Credit: Eric M. Metodiev
Measuring jets in a detector

Hadronized particles from the parton shower form tracks in a tracking detector or clusters of energy in a calorimeter.

Grouped together using jet clustering algorithms to form experimental jets with a $p_T$ and resolution parameter $R$. 

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Jet kinematics: QCD knob

\[ \frac{d\sigma^2}{dy dp_T} \]

Jet $p_T$ [GeV]

CMS JHEP 03 (2017) 156
Jet kinematics: QCD knob

**Caveat: approximate ranges!**

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Jet kinematics: QCD knob

\[ \frac{d\sigma^2}{dydp_T} \sim \alpha_s(Q) \]

**Caveat: approximate ranges!**

Jet \( p_T \sim Q^2 \)

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Jet substructure

High energy physics community designed jet substructure tools for particle physics searches and to study fundamental QCD.

Complex patterns contain information about original parton shower and confinement transition.
Jet substructure

High energy physics community designed jet substructure tools for particle physics searches and to study fundamental QCD

Complex patterns contain information about original parton shower and confinement transition

Measure subjets within jet: proxy for the hard parton splittings

Dreyer et al. JHEP 12 (2018)
Lund plane: visualize patterns inside of jets

Phase space of jet splittings

\[ \ln \left( \frac{1}{\Delta R} \right) \]

\[ \ln \left( k_T \right) \]

\[ \rho_{T1} = (1-z) \rho_T \]

\[ \rho_{T2} = z \rho_T \]

Partons

Hadrons

constant z

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**Lund plane: visualize patterns inside of jets**

**Phase space of jet splittings**

$k_T$: relative transverse momentum

\[ k_T = z p_T \sin(\Delta R) \]

\[ p_{T1} = (1-z)p_T \]

\[ p_{T2} = z p_T \]

\[ \ln\left(\frac{1}{\Delta R}\right) = \ln(k_T) \]

Momentum scale

**Partons**

**Hadrons**

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Lund plane: visualize patterns inside of jets

Phase space of jet splittings

$k_T$: relative transverse momentum
$\Delta R$: opening angle

Partons

Momentum scale

$\ln(1/\Delta R)$

Angular scale

$\ln(k_T)$

$\rho_{T1} = (1-z)\rho_T$

$\rho_{T2} = z\rho_T$

$\Delta R$

$k_T = z\rho_T \sin(\Delta R)$

constant $z$

Hadrons

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Lund plane: visualize patterns inside of jets

Phase space of jet splittings

$k_T$: relative transverse momentum
$\Delta R$: opening angle

Formation time: how long until the splitting occurred

Y. L. Dokshitzer, et.al.

$t_f \approx \frac{1}{k_T \Delta R^2}$

$\ln(1/\Delta R)$  Angular scale

$\ln(k_T)$  Momentum scale

$k_T = z p_T \sin(\Delta R)$

$p_{T1} = (1-z)p_T$

$p_{T2} = zp_T$

Partons

Hadrons

Early times

Late times

Momentum scale

Angular scale
Lund plane: phase space of QCD

$k_T \sim \Lambda_{QCD}$ accesses confinement transition

Running of the QCD coupling constant sculpts the shape of the plane

Isolate different QCD effects and inform simulations

$$\ln(k_T)$$

$$\ln(1/\Delta R)$$

$p_{T1} = (1-z)p_T$

$p_{T2} = zp_T$

$k_T = zp_T \sin(\Delta R)$

Partons

Hadrons

**pQCD**

**npQCD**

**UE**

**hard, wider splittings**

**soft, large angle radiation**

**hard, collinear radiation**

**constant z**

**hadronization**

**soft, collinear**
Measured Lund plane

Make projections to isolate regions of phase space and make detailed comparisons to generators.

Visual features emerge

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Grooming away soft radiation

\[ \ln \left( \frac{1}{\Delta R} \right) \]

constant \( z \)

hard, wider splittings

hard, collinear radiation

soft, collinear hadronization

soft, large angle radiation

npQCD

pQCD

UE
Grooming away soft radiation

\[
z_g = \frac{\min(p_{Ti}, p_{Tj})}{p_{Ti} + p_{Tj}}
\]

Soft Drop grooming selects the first hard splitting to remove the soft background contribution.

\[
z_g > z_{\text{cut}} \theta^\beta \quad \theta = \frac{\Delta R}{R}
\]

- **Hard, wider splittings**
- **Soft, large angle radiation**
- **Soft, collinear**
- **Constant z**
- **Hadronization**

\[
p_{Ti} + p_{Tj}
\]

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Grooming away soft radiation

Shared momentum fraction
\[ z_g = \frac{\min(p_{T_i}, p_{T_j})}{p_{T_i} + p_{T_j}} \]

Distance between subjets
\[ R_g = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]

Soft Drop grooming selects the first hard splitting to remove the soft background contribution

\[ z_g > z_{\text{cut}} \theta^{\beta} \quad \theta = \frac{\Delta R}{R} \]

\[ R_g = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]
Multi-dimensional jet substructure

Groomed Lund plane: $R_g$ vs. $z_g$

- $0 \leq R_g < 0.15$
- $0.15 \leq R_g < 0.30$
- $0.30 \leq R_g \leq 0.40$

**STAR Preliminary**
- $p+p \sqrt{s} = 200$ GeV
- anti-$k_T$ + C/A, $R = 0.4$
- SoftDrop $z_{cut} = 0.1$, $\beta = 0$
- $20 \leq p_{T,\text{jet}} \leq 25$ GeV/c

Evolves from **soft large-angle** to **collinear hard splittings**

**Collinear Drop:**
probes the soft component

Collinear Drop:

Less groomed soft component
for **wider splittings**

See Y. Song talk yesterday
New jet substructure tool: energy correlators

Measure the angular correlation between hadron pairs inside a jet.

\[ R_L = \sqrt{\Delta \eta_{ij} + \Delta \phi_{ij}} \]

Defined from first principles QFT, no grooming required!

Separate the pQCD and npQCD scales.

Komiske et al arxiv:2201.07800
Lee, Mecaj, Moult arxiv:2205.0314
Energy correlators as a separation of scales

\[ R_L = \sqrt{\Delta \eta_{ij} + \Delta \phi_{ij}} \]

\[ R_L p_T^{\text{jet}} \sim \Lambda_{\text{QCD}} \]

Small \( R_L \): free hadrons (npQCD)

Confinement transition between two regions

Large \( R_L \): partons (mostly pQCD)

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Strong coupling from 3 to 2 point correlators

\[ E3C/E2C \propto \alpha_s \ln(R_L) \]

Ratio cancels some npQCD effects

Small \( R_L \): flat with jet \( p_T \)

Large \( R_L \): scales with jet \( p_T \) (running coupling)

Extract \( \alpha_s(m_Z) \) from slope -> most precise extraction from jet substructure!

\[ \alpha_s = 0.1229 + 0.0014 \text{(stat.)} + 0.0030 \text{(theo.)} - 0.0023 \text{(exp.)} - 0.0012 \text{(stat.)} - 0.0033 \text{(theo.)} - 0.0036 \text{(exp.)} \]
Jet quenching in the quark-gluon plasma

Proton-proton collision

Heavy-ion collision
Jet quenching in the quark-gluon plasma

Jet quenching: partons strongly interact with the QGP medium

Energy loss and complex structure modified

Evolves through entire QGP evolution encoding information about its properties
Different jet-medium interactions

Inelastic collisions (radiative)

Elastic collisions (collisional)

Credit: C. Beattie
Different jet-medium interactions

Medium-induced splittings

Inelastic collisions (radiative)

Elastic collisions (collisional)

Moliere scattering
Different jet-medium interactions

Medium-induced splittings

Inelastic collisions (radiative)

Elastic collisions (collisional)

Moliere scattering

\[ \hat{q} = \frac{\langle k^2 \rangle}{L} \]  
Momentum broadening
Different jet-medium interactions

Medium-induced splittings

Inelastic collisions (radiative)

Medium response

\[ \hat{q} = \frac{\langle k^2 \rangle}{L} \]

Momentum broadening

Elastic collisions (collisional)

Moliere scattering
Different jet-medium interactions

Medium-induced splittings

Inelastic collisions (radiative)

Moliere scattering

Elastic collisions (collisional)

Medium response

(De)coherence

\[ \hat{q} = \frac{\langle k^2 \rangle}{L} \]

Momentum broadening

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Different jet-medium interactions

Medium-induced splittings

Jet responds to medium?

Inelastic collisions (radiative)

Jet resolves quasi-particles in medium?

Moliere scattering

Medium response

Momentum broadening

Jet responds to medium?

Medium resolves color charges in jet?

Medium responds to jet?
Different probes, different mediums

Flavor and mass dependence

\[ \sim (9/4)^2 x \]

More complex structure -> more opportunities for interactions

Quark jets narrower than gluon jets

\[ E_{\text{loss}} > E_{\text{loss}} > E_{\text{loss}}^{\text{HQ}} > \]

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Different probes, different mediums

Flavor and mass dependence

- $E_{\text{loss}}^{\text{Gluon}} > E_{\text{loss}}^{\text{Light quark}} > E_{\text{loss}}^{\text{Charm}} > E_{\text{loss}}^{\text{Beauty}} > E_{\text{loss}}^{\text{Heavy quark}}$

More complex structure -> more opportunities for interactions

Quark jets narrower than gluon jets

Path length dependence

- $\sim L^2$
- $\sim L$

See M. Conner’s talk

System size ($p$, $O$, $Cu$, $Zr$, $Ru$, $Xe$, $Au$, $Pb$)

See V. Bailey’s talk

QGP at LHC hotter, denser, and longer lived than RHIC!
Large background due to the underlying event (UE) that contributes background energy inside the jet cone

Fake jets due to upward fluctuations

Challenging to remove, obscures physics and restricts where jets can be measured

Different techniques for each observable and experiment!
Jets lose energy in the medium

Before and after energy loss at fixed value of jet $p_T$

$$R_{AA} = \frac{\text{Pb-Pb}}{\text{scaled} \otimes \text{pp}}$$

< 1 is suppression
= 1 no suppression
> 1 enhancement

$$R_{AA} = \frac{\frac{1}{N_{\text{evt}}} \frac{d^2 N_{\text{jet}}^{\text{PbPb}}}{dpTdy}}{\langle T_{\text{AA}} \rangle_{\text{cent}} \times \frac{d^2 \sigma^{\text{pp}}_{\text{jet}}}{dpTdy}}$$

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Jets lose energy in the medium

\[ R_{AA} = \frac{Pb-Pb \overset{\text{scaled}}{\otimes} pp}{\text{pp}} \]

< 1 is suppression

Jet production is suppressed in the QGP over two orders of magnitude in jet momentum!
Energy loss dependence on parton flavor

Flavor and mass dependence

\[ E_{\text{loss}}^{\text{Gluon}} > E_{\text{loss}}^{\text{Light quark}} > E_{\text{loss}}^{\text{HQ}} \]

Gluon  Light quark  Heavy quark

Charm  Beauty
Energy loss dependence on parton flavor

Flavor and mass dependence

Energy loss depends on color charge

Caveat: “spectra steepness” plays a role!

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Energy loss dependence on parton flavor

Flavor and mass dependence

\[ E_{\text{loss}}^{\text{Gluon}} > E_{\text{loss}}^{\text{Light quark}} > E_{\text{loss}}^{\text{Heavy quark}} \]

Caveat: “spectra steepness” plays a role!

D0-tagged jets (charm)

Energy loss depends on color charge (and mass of parton?)

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Jet and medium evolving in space and time

Complex, dynamic structure accesses a more detailed picture
Lund plane: space-time structure of QGP

1: Decoherence
2: Coherence
3: Outside of medium
4: Medium-induced splittings
Focus on modification of jet core

Soft particles from background and medium response can obscure physics message

Solution: Apply grooming to suppress background and remove softer components to focus on hard splittings

Caveat: may remove physics
Focus on modification of jet core

\[ k_{Tg} \]

Quasi-particle structure?

\[ k_{Tg} \sim z_g p_T R_g \]

Resolution length?

\[ R_g = \sqrt{\Delta \eta^2 + \Delta \phi^2} \]

Isolate different jet-medium effects

\[ \ln\left(\frac{1}{\Delta R}\right) \]

\[ \ln(k_T) \]

Early times

Late times

medium

arXiv:1808.03689
Splitting angular scale probes color coherence

Narrowing feature observed that is consistent across jet $p_T$

ATLAS arXiv:2211.11470
Splitting angular scale probes color coherence

Narrowing is consistent with color decoherence models but is also described by quarks vs. gluons.

Resolution length of QGP?

ATLAS arXiv:2211.11470
Narrowing picture is persistent

Many substructure measurements show narrowing in QGP

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Narrowing?

Always measuring less quenched jets that have survived the QGP -> selection bias

Comparing modified Pb-Pb vs. unmodified pp jet populations -> less quenched narrower jets remain

Du, Pablos, Tywoniuk, JHEP 21 (2020), 206
Brewer, et al PRL 122, 222301
Photon+jet substructure to reduce bias

- Photon-jets dominated by quark jets
- Photon tag provides approximate initial momentum of jet (no energy loss)

\[ x_{J\gamma} = \frac{p_{T,\text{jet}}}{p_{T\gamma}} \]

Laura Havener, Yale University
Photon+jet substructure to reduce bias

Select balanced configurations

\[ x_{J\gamma} > 0.8 \]

Include unbalanced configurations

\[ x_{J\gamma} > 0.4 \]

Less quenched jets: narrowing still observed

More quenched + unquenched jets: no modification
Search for quasi-particle structure of QGP

Search for Moilere scattering off quasi-particles in the medium \( k_{Tg} \sim z_g p_T R_g \)

Hardest \( k_T \) kicks: looked at groomed \( k_{Tg} \) for a hard kick at high \( k_T \)

Narrowing observed, no clear evidence but sensitive to differences in models

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Searching for the medium response

Enhancement of particle “Positive wake”

Depletion of particle “Recoil” “QGP hole” “Negative wake”

$Z^0$ and wake hadron correlation in Hybrid model

Credit: Yen-Jie Lee

Laura Havener, Yale University
Positive wake impact in hadron+jet correlations

Energy is transferred to large angles for every track $p_T$

And at larger $R$ and low $p_T$

Consistent with medium response
Isolate the diffusion wake

Consistent with no significant diffusion wake
Extracting QGP medium properties from jets

Bayesian analyses of LHC and RHIC data using jet $p_T$ and substructure to extract the QGP jet transport coefficient $q_{hat}$ using JETSCAPE framework.

Using experimental data to learn about the medium!

caveat: exploratory study with only 0-10%, simplified error treatment.
Summary and Outlook

Jets in vacuum isolate QCD effects and constrain MC generators

Correlations between observables gives the full picture of jet evolution

Jets provide a multi-scale probe of QGP medium

See significant jet suppression over multiple scales, including flavor dependence

Narrowing of jets in the QGP, consistent with color decoherence picture

Progress made towards understanding selection biases with photon+jets

No direct evidence for quasi-particle structure yet

Evidence of impact of medium response but no significant diffusion wake

Future: wealth of Run 3 data at LHC and sPHENIX results coming at RHIC

Differential, precise measurements from high statistics data -> apply differential tools
from pp to HIs like EECs and multi-dimensional Lund plane

Rare probes: photons and HF
Backup
Primary jet Lund plane density

- Primary Lund jet plane is filled with splittings from the hardest prong
  
  Andersson et al ZPC43 (1989)

- At leading order the emissions populate the plane uniformly

- Running of the coupling constant sculpts the plane!

Coupling constant

\[
d^2P = 2 \frac{\alpha_s(k_\perp)}{\pi} C_R \int \frac{d \ln(z \theta)}{d \ln(\frac{1}{\theta})}
\]

Color factor

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Jet Lund plane density

- Lund Diagram: phase space of jet splitting

\[
d^2P = 2 \frac{\alpha_s(k_{\perp}) C_R}{\pi} d \ln(z\theta) d \ln \left( \frac{1}{\theta} \right)
\]

- Color factor
- Coupling constant
- \( k_T \): relative transverse momentum
- Primary Lund jet plane filled with splittings from the hardest prong

Andersson et al ZPC43 (1989)
Dreyer et al JHEP 12 (2018)

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Lund plane measurement

- Recluster anti-$k_T$ $R = 0.4$ jets with C/A algorithm and follow primary splittings from the leading prong

\[ \sqrt{s} = 13 \text{ TeV} \]

<table>
<thead>
<tr>
<th></th>
<th>ALICE</th>
<th>ATLAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet $p_T$ (GeV/c)</td>
<td>20-120*</td>
<td>&gt; 675</td>
</tr>
<tr>
<td>Max $k_T$ (GeV/c)</td>
<td>5</td>
<td>&gt; 135</td>
</tr>
<tr>
<td>$\Delta R$</td>
<td>0.1 - R</td>
<td>0.005 - R</td>
</tr>
</tbody>
</table>

*charged-particle jets

- Fully corrected with 3D unfolding in axes of Lund plane and jet $p_T$

Image from Gregory Soyez
$R_g$ vs. $Z_g$

Evolves from soft large-angle to collinear hard splittings

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Multi-dimensional jet substructure

With Multifold obtain **6D correlation** between substructure observables measured!

Collinear Drop: probes the soft component

Chien and Stewart JHEP 2020, 64 (2020).

$$\Delta M/M = \frac{M - M_g}{M}$$

Connect the npQCD and pQCD parts of the shower
Energy loss dependence on parton flavor

Flavor and mass dependence

- $E_{\text{loss}}$ > $E_{\text{loss}}$ > $E_{\text{loss}}^{HQ}$
  - Gluon
  - Light quark
  - Heavy quark

Dead-cone effect

- Large parton mass
- Small parton mass

Caveat: “spectra steepness” plays a role!

Energy loss depends on color charge (and mass of parton?)

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Jet structure is softened and broadened

Jet fragmentation: longitudinal profile of charged particles in a jet

Jet shape: radial profile of charged particles in a jet

**CMS Supplementary** JHEP 05(2018) 006

PbPb 404 µb⁻¹ (5.02 TeV) pp 27.4 pb⁻¹ (5.02 TeV)

0-10%

p_T >0.7 GeV

p_T >2 GeV

p_T >4 GeV

Energy transferred to soft particles inside the jet

Hardening of core: high z enhancement from quark vs. gluons?

Soft particles are at large angles from jet axis

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Energy correlators: new HI observable?

Clear distinction between perturbative and npQCD regions

Less sensitive to soft physics, may be more resilient to background?

No soft drop required: access all aspects of the jet evolution in medium including in-medium splittings?

See Carlota Andres BOOST talk for first look

Direct access to resolution length?
Regions of the Lund plane

Agreement with MC ~10% in most cases

A: low $k_T$ mostly NP

B: high $k_T$ mostly pert.

Herwig suppressed relative to data for hard collinear splitting
Regions of the Lund plane

Good agreement with MC in most cases

Differences seen for Herwig PS implementation

Differences seen for Sherpa hadronization implementation

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Generalize angularities

Exponents vary aspects of QCD

\[ \lambda_\beta = \sum_{i \in \text{jet}} z_i^\kappa \left( \frac{\Delta R_i}{R} \right)^\alpha \]

NNL’ pQCD calculations describe data fairly well in perturbative regions

\[ (p_T^D)^2 \]

\[ LHA \text{ Width Thrust} \]

\[ \text{Multiplicity} \]

\[ \lambda_\alpha \frac{d\sigma}{d\alpha} \]

\[ \lambda_\alpha \text{ scales from np to pert.} \]

\[ \lambda_{np} \leq \Lambda / (p_T^{ch\text{jet}} R) \]

\[ ALICE \text{ arXiv:2107.11303} \]

Data

- NLL’ @ PYTHIA8
- NLL’ @ Herwig7

Syst. uncertainty

\[ \alpha = 2 \times 0.65 \]

\[ \alpha = 3 \times 0.27 \]

Laura Havener, Yale University
Generalized angularities

Vary $R$, jet $p_T$, $\lambda$, $\beta$, $\kappa$ all changes the pert. to np scale!

\[ \lambda^\kappa = \sum_{i \in \text{jet}} z_i^\kappa \left( \frac{\Delta R_i}{R} \right)^\beta \]

$(p_T^D)^2 \sim \text{mass}$

LHA Width Thrust

Multiplicty

Exponents vary aspects of QCD

Shape and structure of jet varies significantly
Jets at RHIC vs. LHC

- Keep in mind: not a direct comparison, kinematics and QGP medium different!

QGP at LHC hotter, denser, and longer lived than RHIC!

<table>
<thead>
<tr>
<th></th>
<th>RHIC</th>
<th>LHC</th>
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<tbody>
<tr>
<td>Center-of-Mass</td>
<td>3-510 GeV</td>
<td>2.76-5.02 TeV</td>
</tr>
<tr>
<td>((\sqrt{s}))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collision systems</td>
<td>Many species</td>
<td>Pb, Xe, p</td>
</tr>
<tr>
<td>Effective</td>
<td>~220 MeV</td>
<td>~300 MeV</td>
</tr>
<tr>
<td>Detectors</td>
<td>STAR, PHENIX, sPHENIX</td>
<td>ALICE, ATLAS, CMS, LHCb</td>
</tr>
</tbody>
</table>

Jet spectra at RHIC is steeper and contains a higher quark fraction at the same \(p_T\).
Inclusive jet suppression

Overlap between ~50-70 GeV/c Signal/background higher in this region at LHC than RHIC

data = fake+real

broader shape

Steeper spectra at RHIC: same amount of e-loss -> lower $R_{AA}$

Overlap between ~50-70 GeV/c Signal/background higher in this region at LHC than RHIC

data = fake+real

broader shape

Steeper spectra at RHIC: same amount of e-loss -> lower $R_{AA}$