New Jet Methods for High-Multiplicity Environments

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Based on work (some preliminary) with
Matteo Cacciari, Juan Rojo, Sebastian Sapeta, Gregory Soyez
Radiation from high-momentum quarks & gluons traversing hot medium can tell us about the medium.
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Introduction

Jets in LHC $pp$ collisions

Use jets to reconstruct quarks from decay of some new heavy object
e.g. a Higgs boson

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proton

anti–proton

$\times 20$
Common challenge: large contamination

A pp event (LHC 5.5 TeV, Pythia)
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Contamination in jet

RHIC AuAu:
\[\mathcal{O}(40 \text{ GeV})\]

LHC PbPb:
\[\mathcal{O}(100 \text{ GeV})\]

LHC pp (hi-lumi)
\[\mathcal{O}(5 - 40 \text{ GeV})\]

A pp event (LHC 5.5 TeV, Pythia), embedded in a HI collision background (Hydjet 1.5)
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A pp event (LHC 5.5 TeV, Pythia), embedded in a HI collision background (Hydjet 1.5) and an actual STAR event
What are ingredients of jet finding in noisy environments?

1. Jets
2. Jet areas
3. Noise estimation
4. Noise subtraction
[5. Noise suppression]
A jet algorithms provides a mapping:

\[ \text{particles} \rightarrow \text{jets} \]

Simplest pp jet algorithm is “Cambridge/Aachen”

Dokshitzer et al '97
Wengler & Wobisch '98

Repeatedly recombine closest pair of objects, until all separated by

\[ \Delta R_{ij}^2 = \Delta y_{ij}^2 + \Delta \phi_{ij}^2 > R^2. \]

\( R \) parameter sets angular resolution
\( \phi \) assumed 0 for all towers
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Jet areas

Jets are made of a finite number of pointlike particles.

Area not unambiguous concept

Jet areas must be defined

Add many soft particles to event $10^{-100}$ GeV each

$A \propto \# \text{ inside jet}$

Cacciari, GPS & Soyez '08

measure of jet’s susceptibility to contamination from soft radiation
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Areas for 3 jet algorithms

A family of algorithms, all cluster pair with smallest $d_{ij}$:

$$d_{ij} = \min(p_{ti}^{2p}, p_{tj}^{2p}) \frac{\Delta R_{ij}^2}{R^2}$$

$$p = \begin{cases} 
1 & k_t \\
0 & C/A \\
-1 & \text{anti-}k_t 
\end{cases}$$
Estimating $\rho \equiv$ background noise level

Most jets in event are “background”

Their $p_t$ is correlated with their area.

\[ \rho \simeq \text{median} \left\{ \frac{p_{t,\text{jet}}}{A_{\text{jet}}} \right\} \]

Median limits bias from hard jets
Cacciari & GPS ’07
HIC Jets, G. Salam (p. 10)
Jet methods

Subtracting noise from jets

\[ p^{\text{subtracted}}_{t,\text{jet}} = p_{t,\text{jet}} - \rho \times A_{\text{jet}} \]

\[ A_{\text{jet}} = \text{jet area} \]

\[ \rho = p_t \text{ per unit area from underlying event} \]

(or “background”)

This procedure is intended to be common to pp, pp with pileup (multiple simultaneous minbias) and HIC

NB in AuAu at RHIC: \( p^{\text{subtracted}}_{t,\text{jet}} = 20 - 50 \text{ GeV}, \rho \simeq 80 \text{ GeV} \text{ and } A_{\text{jet}} \simeq 0.5 \)
Use at RHIC
This method is basis of STAR jet results

Method designed to minimise biases, but some still persist. STAR corrects remaining biases based (partly) on Monte Carlo modelling.

Question: can we calculate size of biases? Can we further reduce them? Identify complementary methods?
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Context: a steeply falling X-section

RHIC Inclusive jet spectrum

pp, $\sqrt{s} = 200$ GeV, no UE, Pythia 6.421, FastJet 2.4
C/A R=0.6, $|y| < 1$
Context: a steeply falling X-section

To help think about impact of falling cross section at RHIC, approximate it as:

\[ \frac{d\sigma}{dp_t} \sim \exp(-0.3p_t / \text{GeV}) \]

Interplay of PDFs & \(1/p_t^4\) matrix element
The problem is basically about **subtracting the correct** amount of “underlying event” from each jet, in order to reconstruct correct jet energy.

Take the model for the jet spectrum, \( \exp(-a p_t) \) \( \quad a = 0.3 \text{ GeV}^{-1} \)

Suppose you make a “mistake”:

- **Systematic offset in** \( p_t \) **by** \( \delta p_{t,\text{jet}} \)
  \[ \text{mistake in spectrum by factor } \exp(a \delta p_{t,\text{jet}}) \]
  \[ \text{If } \delta p_{t,\text{jet}} = 3 \text{ GeV, factor } = 2.5 \]

- **Gaussian error of std.dev.** \( \sigma_{\text{jet}} \) **in subtraction**
  \[ \text{mistake in spectrum by factor } \exp(a^2 \sigma_{\text{jet}}^2 / 2) \]
  \[ \text{If } \sigma_{\text{jet}} = 5 \text{ GeV, factor } = 3.1 \]

---

**You want to know** \( R_{AA} \) **to within a few tens of percent.**
Residual systematic offsets must be understood to within 1 GeV.
Fluctuations must be as small as possible, and accurately known.
Example #1: a bias

(background does not just linearly add noise to jet)
BACK REACTION

“How (much) a jet changes when immersed in a background”

Without background
BACK REACTION

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Slide from M. Cacciari
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With background

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Backreaction loss

Backreaction gain

Slide from M. Cacciari
Backreaction can be calculated (sort of...)

Soft & collinear approximation:

\[ \delta p_t^{BR} = B_{alg} \cdot \rho R^2 \frac{2C_i}{\pi} \alpha_s \ln \frac{p_t}{\rho R^2} \]

Cacciari, GPS & Soyez ’08
+ large corrections

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Cacciari, Rojo, GPS & Soyez, prelim.

anti-$k_t$ bias = 0, as expected
Backreaction can be calculated (sort of...)

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Different jet algorithms have different systematics
Use of more than one provides important cross-checks

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\( \text{anti-} k_t \) bias = 0, as expected
Example #2: another bias

is $\rho$ measured correctly?
Bias in median estimate for $\rho$?

What could go wrong?

- Rapidity and azimuth dependence of $\rho$ distribution means $\rho$ near jet $\neq \rho$ measured over large region. So try various regions:

  - Global
  - StripRange($\Delta$): $y_{\text{jet}} - \Delta, y_{\text{jet}} + \Delta$
  - CircularRange($\Delta$)
  - DonutRange($\delta, \Delta$)

- Median estimate $\neq$ mean contamination. Can be studied in toy models:

  $$\rho_{\text{median}} \approx \rho_{\text{true}} \left(1 - \frac{1}{3\nu R^2}\right)$$

  $\nu =$ number of particles / unit area

  With $\nu = 100, R = 0.4, \mathcal{O}(2\%) \to \mathcal{O}(1 \text{ GeV})$ on jet $p_t$

  Cacciari, GPS & Sapeta ’09, for measuring $\rho \sim 2 \text{ GeV}$ in pp collisions!
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Example #3: fluctuations
Fluctuations of amount of background / underlying-event in a square of unit area can be characterised in terms of $\sigma_{UE}$, which is $\mathcal{O}(10 \text{ GeV})$ at RHIC.

Dispersion in jet subtraction, $\sigma_{jet}$ is given by

$$\sigma_{jet} = \sigma_{UE} \times \sqrt{A_{jet}}$$

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Put in numbers and find $\sigma_{jet} \sim 7 \text{ GeV}$.

This is dangerous.

Steeply falling spectrum rescaled by $\times 10$?

Obvious solution: reduce $R$

But then lose gluon radiation.

Can be very severe with quenching.

cf. STAR tried $R = 0.2$ instead of 0.4
Reducing fluctuations, while limiting bias:

filtering
Idea to improve resolution for an LHC Higgs search in $H \rightarrow b\bar{b}$ decay mode!

Keep hardest $\mathcal{O}(\alpha_s)$ gluon emission in jet, while throwing out soft “junk”

Butterworth, Davison, Rubin & GPS ‘08

1. Consider a jet
2. View it on smaller angular resolution scale $R_{filt}$
3. Take (e.g.) 2 hardest “subjets” leading quark + 1 gluon
4. The result is a “filtered” jet

Related ideas by Ellis, Vermillion & Walsh ’09 and Krohn, Thaler & Wang ’09
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Idea to improve resolution for an LHC Higgs search in $H \rightarrow b\bar{b}$ decay mode!

Keep hardest $\mathcal{O}(\alpha_s)$ gluon emission in jet, while throwing out soft “junk”

Butterworth, Davison, Rubin & GPS ’08

1. Consider a jet
2. View it on smaller angular resolution scale $R_{filt}$
3. Take (e.g.) 2 hardest “subjets” leading quark + 1 gluon
4. The result is a “filtered” jet

Related ideas by Ellis, Vermillion & Walsh ’09 and Krohn, Thaler & Wang ’09
Reconstructed mass for jets from decay of high-$p_t$ Higgs-boson
[without pileup]

Among the techniques adopted in search for $H \rightarrow b\bar{b}$ at LHC
Impact of filtering on dispersion in HIC

Filtering reduces jet area by $\sim \frac{1}{2}$

Fluctuations $\propto \sqrt{A}$ should go down by $\sim \sqrt{\frac{1}{2}}$

And they do
Impact of filtering on dispersion in HIC

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And they do

Filtering’s reduction of dispersion from 7 GeV to 5 GeV means experimental “unfolding” might be factor 3 instead of factor 10

Numbers are rough – intended to give an idea of impact

Alternative ideas: see Cole & Lai ’08
Does filtering introduce new biases in jets in quenched case?

Vacuum QCD: we know how much gluon radiation we lose

QCD in medium: extra medium-induced radiation lost?
Filtering

PT SHIFT

**UNQUENCHED**

- RHIC, unquenched
- $|y|<1, R=0.4$
- Cam/Aachen
- anti-$k_t$
- Cam+filt.

**QUENCHED**

- RHIC, quenched
- $|y|<1, R=0.4$
- Cam/Aachen
- anti-$k_t$
- Cam+filt.

DISPERSION

- RHIC, unquenched
- $|y|<1, R=0.4$

- RHIC, quenched
- $|y|<1, R=0.4$
Summary LHC (Pythia/Hydjet)

UNQUENCHED

PT SHIFT

DISPERSION

QUENCHED
It’s still early days for jet-finding in HIC (& high-luminosity LHC)

*It’s a tough job to accurately remove 40 GeV of noise from a 40 GeV hard jet in the context of a steeply falling cross-section.*

Theory calculations can guide the choices one makes

- Give us an idea of size of corrections semi-independently of Monte Carlo
  
  Some of them are rather large

- Tell us which approaches are complementary in their systematics
  
  Adding to robustness of experimental measurements, e.g. $k_t$ v. anti-$k_t$
  
  NB: it’s still hard to estimate how quenching affects systematics

- Guide design of new tools that have smaller systematics
  
  Like filtering, yet to be tried out at RHIC

Important potential for cross-fertilization between ideas in HIC and LHC pp programs.
EXTRAS
Dispersion for non central AuAu

RHIC, unquenched, |y|<1, R=0.4, Donut(R,3R)

- solid: anti-$k_t$
- dashed: C/A(filt)

$p_t$ dispersion [GeV]

$p_t, \text{hard}$ [GeV]
$P_t$ shift for non central AuAu

RHIC, unquenched

- $|y|<1$, $R=0.4$
- anti-$k_t$, Donut(R,3R)

C/A(filt), Donut(R,3R)

anti-$k_t$, Strip(3R)
Anti-$k_t$ jet spectrum, pp $\sqrt{s} = 200$ GeV

Diagram showing the jet spectrum with plots for LO QCD and NLO QCD. The spectrum is for anti-$k_t$, R=0.4, $|y|<1$, with CTEQ6.6. The graph displays the differential cross section $d\sigma/dp_t$ in units of nb/GeV against $p_t$ in GeV. The error bars are shown at various values of $p_t$. The scale is logarithmic for the cross section and linear for $p_t$. The plot includes a legend and error bands.