Jets for non-jet people

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What do I want to learn?
The cartoon picture
Probing the Quark Gluon Plasma

Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe
Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
Probes of the Quark Gluon Plasma

Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe
Probes of the Quark Gluon Plasma
Probes of the Quark Gluon Plasma

nucleus

nucleus

ATLAS

Calorimeter Towers


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What am I measuring?
Definition of a jet
Factorization theorem

- Assumption: Parton distribution functions, perturbative cross section, fragmentation function factorize
- What people really mean by “perturbatively calculable”
  - $D$ and $f$ are explicitly non-perturbative!
  - $D$ is for parton $c \rightarrow$ hadron $h$
    Not what is experimentally measured
- Most theories for jet quenching modify fragmentation function $D$

\[
\frac{d^3 \sigma^h}{dy d^2 p_T} = \frac{1}{\pi} \int d x_a \int d x_b f^A_a(x_a) f^B_b(x_b) \frac{d \sigma_{ab \rightarrow cX}}{d \hat{t}} \frac{D^h_c(z)}{z}
\]

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Jet finders
What is a jet?
What is a jet?

A measurement of a jet is a measurement of a parton.
What is a jet?

A measurement of a jet is a measurement of a parton.
What is a jet?

$p+p$ dijet
What is a jet?

“I know it when I see it”

US Supreme Court Justice Potter Stewart, Jacobellis v. Ohio
Jet finding algorithms

- Any list of objects works as input
- Use the same algorithm on theory & experiment
- Output only as good as input
Jet finding

in pp collisions

- Jet finder: groups final state particles into jet candidates
  - Anti-$k_T$ algorithm

- Depends on hadronization

- Ideally
  - Infrared safe
  - Colinear safe

Snowmass Accord: Theoretical calculations and experimental measurements should use the same jet finding algorithm. Otherwise they will not be comparable.
Jets in principle

- Jet measures **partons**
- Hadronic degrees of freedom are integrated out
- Algorithms are infrared and colinear safe

![Diagram of jet formation and properties](http://www.koeln-theorie.physik.uni-mainz.de/Dateien/Zappenhof-3.pdf)
**k_T jet finding algorithm**

**Particles, clusters**

**k_T algorithm**

\[ k_T = p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \]

- For all \( i, j \), calculate:
  \[ d_{ij} = \min \left( p_{T,i}^2, p_{T,j}^2 \right) \]
  \[ \Delta R_{ij}^2 \]
  \[ d_{ij} = p_{T,i}^2 \]

- Combine smallest \( d_{ij} \)
  If \( d_{IB} \) smallest, \( d_{IB} \rightarrow \text{jet} \)

Repeat until no particles left

**Jet candidates**

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anti-$k_T$ jet finding algorithm

Particles, clusters

**$k_T$ algorithm**

- For all $i, j$
- Calculate:
  
  $d_{ij} = \min\left(\frac{\Delta R_{ij}^2}{R^2}, \frac{\Delta R_{ij}^2}{R^2}\right)$

  
  $d_{ij} = \min\left(p_{T,i}^{-2}, p_{T,j}^{-2}\right)$

- Combine smallest $d_{ij}$
  
  If $d_{ib}$ smallest, $d_{ib} \rightarrow$ jet

Repeat until no particles left

Jet candidates

**Equations**

\[ k_T = p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \]

\[ p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \]

\[ d_{ib} = p_{T,i}^{-2} \]

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Cambridge/Aachen jet finding algorithm

\[ k_T = p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \]

- For all \( i,j \) calculate:
  \[ d_{ij} = \frac{\Delta R_{ij}^2}{R^2} \]
  \[ d_{iB} = 1 \]

- Combine smallest \( d_{ij} \)
  If \( d_{iB} \) smallest, \( d_{iB} \rightarrow \) jet
  Repeat until no particles left

Parties, clusters

Jet candidates
A jet is what a jet finder finds.
Jet cross-section in pp
\[ \sqrt{s} = 2.76 \text{ TeV}, R = 0.2 \text{ Inclusive} \]

Green and magenta bands: NLO on Parton level

Blue band: NLO + hadronization

Hadronization calculations necessary to describe data
Jet ratios in pp
\[ \sqrt{s} = 2.76 \text{ TeV}, \ R = 0.2, 0.4 \text{ Inclusive} \]
Mini-summary

- Jets are not partons
- Good jet finders:
  - Infrared and collinear safe
  - $k_T$, anti-$k_T$, Cambridge/Aachen, SISCone
- Jet is defined by jet finder, its parameters
- PDFs, fragmentation functions non-perturbative
  $\rightarrow$ all jet measurements sensitive to somewhat non-perturbative effects
- Good agreement between theory and experiment
Jets in A+A collisions
What assumptions am I making?
p+p vs A+A

p+p di-jet event in STAR

Central Au+Au collision in STAR
Signal vs Background:
The standard paradigm

Background

Signal
Signal vs Background:
The standard paradigm

Background

Combinatorial jets

Signal
Signal vs Background: The standard paradigm

Background

Combinatorial jets = “fake” jets

Signal
Signal vs Background:
The standard paradigm

*Some gray areas

Background

Combinatorial jets

Signal

*Some gray areas
Jet finding in AA collisions

- Jet finder: groups final state particles into jet candidates
  - Anti-$k_T$ algorithm
- Combinatorial jet candidates
- Energy smearing from background
- Sensitive to methods to suppress combinatorial jets and correct energy
- Focus on narrow/high energy jets
**TennGen** background generator

**Event properties**
- Even event planes fixed at $\Psi=0$
- Odd planes at random $\phi$
- Multiplies from ALICE PRC88 (2013) 044910

**Track properties**
- Random $p_T$
- Random $\phi$

No jets! No resonances
Emulates hydro correlations

**Momentum spectra**

**Polynomial Fit**

**Azimuthal asymmetries**
PYTHIA Angantyr


- Based on PYTHIA 8
  Sjöstrand, Mrenna & Skands,
  JHEP05 (2006) 026

- Based on Fritiof & wounded nucleons

- N-N collisions w/fluctuating radii → fluctuating $\sigma$

Lots of jets! And resonances!
No hydrodynamics, no jet quenching
Area-based background subtraction


\[ k_T = p_T, \Delta R_{ij} = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2} \]

- For all \( i,j \) calculate:
  \[ d_{ij} = \min\left(p_{T,i}^2, p_{T,j}^2\right) \Delta R_{ij}^2 \]
  \[ d_{iB} = p_{T,i} \]
- Combine smallest \( d_{ij} \)
  If \( d_{iB} \) smallest, \( d_{iB} \rightarrow \text{jet} \)
Repeat until no particles left

Jet candidates

Median \( \rho = p_T / A \)

\[ p_T^{\text{jet}} = p_T^{\text{reco}} - \rho_{\text{median}} A^{\text{jet}} \]
Background density $\rho$

- FastJet $k_t$ ($p_t^{\text{min}} = 0.15 \text{ GeV/c}$)
- Fit: $(-3.3^{\pm 0.3} \text{ GeV/c} + (0.0623^{\pm 0.0002} \text{ GeV/c}) \times N_{\text{raw}}^{\text{input}}$)

Pb-Pb $\sqrt{s} = 2.76 \text{ TeV}$

- Fit: $-1.20 \text{ GeV/c} + 0.0611 \text{ GeV/c} \times N_{\text{raw}}^{\text{input}}$  
  - Background Generator

Random cones

\[ \phi \]

Real jets

\[ R=0.4 \]

Excluded

Excluded

\[ \eta \]
Random cones in ALICE

- Estimate $\rho$
  - $k_T$ jet finder $\rightarrow$ jet candidates
  - $\rho = \text{Median}(p_T/A)$
- Draw Random cone

$$\delta p_T = p_{T}^{\text{reco}} - \rho A$$
Random cones

\[ \delta p_T = p_{T,\text{cone}} - \rho A_{\text{cone}} \] (GeV/c)
Shape of width of the distribution

Single particle spectra

\[
f_\Gamma(p_T, p, b) = \frac{b}{\Gamma(p)} (bp_T)^{p-1} e^{-bx}
\]

\[
dN \propto f_\Gamma(p_T, 2, b) = b^2 p_T e^{-k p_T}
\]

\[
\mu_{p_T} = \frac{p}{b}, \sigma_{p_T} = \sqrt{\frac{p}{b}}
\]

Tannenbaum, PLB(498),1–2,Pg.29-34(2001)

\[
\mu_{total} = \frac{Np}{b} = N \mu_{p_T}, \sigma_{total} = \sqrt{Np} = \sqrt{N} \sigma_{p_T}
\]

\[
\Sigma p_T \text{ of } N \text{ particles} \rightarrow N\text{-fold convolution:}
\]

\[
f_N(p_T, p, b) = f_\Gamma(p_T, Np, b)
\]

\[
\frac{dpT_{total}}{dy} \propto f_N(p_T, Np, b)
\]

\[
N = \frac{N_{total}}{A_{total}} \pi R^2
\]

\[
\mu_{p_T} = \frac{Np}{b} = N \mu_{p_T}, \sigma_{p_T} = \sqrt{Np} = \sqrt{N} \sigma_{p_T}
\]

Add Poissonian fluctuations in N: \[
\sigma_{total} = \sqrt{N \sigma_{p_T}^2 + N \mu_{p_T}^2}
\]

Add non-Poissonian fluctuations in N due to flow

\[
\sigma_{total} = \sqrt{N \sigma_{p_T}^2 + (N + 2 \sum_n \nu_n^2) \mu_{p_T}^2}
\]
Width vs multiplicity

**ALICE**

*Pb-Pb* $\sqrt{s} = 2.76$ TeV

$R = 0.4$, $p_{T\text{min}} = 0.15$ GeV/c

**TennGen**

Small deviations
Mixed events

- Gets background up to a normalization factor
- Good agreement with the data... but 20% discrepancies still within uncertainties
- In measurement with background suppressed (h-jet correlations)
- Did not see such agreement at the LHC
Width vs multiplicity

ALICE

Pb-Pb at 2.76 TeV
R = 0.4, p_{Tmin} = 0.15 GeV/c

$\sigma(\delta p_T) (\text{GeV/c})$

Doesn’t go away with random track orientation!

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Shape of width of the distribution

Single particle spectra

\[ f_{\Gamma}(p_T, p, b) = \frac{b}{\Gamma(p)} (bp_T)^{p-1} e^{-bx} \]

\[ \frac{dN}{dy} \propto f_{\Gamma}(p_T, 2, b) = b^2 p_T e^{-kp_T} \]

\[ \mu_{p_T} = \frac{p}{b}, \sigma_{p_T} = \frac{\sqrt{p}}{b} \]

Tannenbaum, PLB(498),1–2,Pg.29-34(2001)

Assumes shape

Σp_T of N particles \(\rightarrow\) N-fold convolution:

\[ f_N(p_T, p, b) = f_{\Gamma}(p_T, Np, b) \]

\[ \frac{dp_T^{\text{total}}}{dy} \propto f_N(p_T, Np, b) \]

\[ N = \frac{N_{\text{total}}}{A_{\text{total}}} \pi R^2 \]

\[ \mu_{\text{total}} = \frac{Np}{b} = N \mu_{p_T}, \sigma_{\text{total}} = \frac{\sqrt{Np}}{b} = \sqrt{N} \sigma_{p_T} \]

Add Poissonian fluctuations in N: \(\sigma_{\text{total}} = \sqrt{N \sigma_{p_T}^2 + N \mu_{p_T}^2} \)

Add non-Poissonian fluctuations in N due to flow

\[ \sigma_{\text{total}} = \sqrt{N \sigma_{p_T}^2 + (N + 2 \sum_n n^2 \nu_n^2) \mu_{p_T}^2} \]

Assumes uncorrelated number fluctuations
Mini-summary

- Jet finders put all input clusters, tracks in a jet candidate
- Background is *dominated* by random particles
  - But 5% effects from flow
- Models have background too!
  - And it doesn’t agree with data!
  - Sensitive to multiplicity, shape of spectrum
Jets in A+A collisions: Dealing with background
Focus on smaller angles

- **Pros**
  - Background is smaller
  - Background fluctuations smaller

- **Cons:**
  - Modifications expected at higher R
  - Biases sample towards quarks

*Aside: “quark” and “gluon” jet only defined at leading order.*
Focus on high $p_T$

- **Pros:**
  - Reduces combinatorial background

- **Cons:**
  - Cuts signal where we expect modifications
  - Could bias towards partons which have not interacted
  - Biases sample towards quark jets

"Quark" and "gluon" jets only defined at leading order!
Area-based subtraction

• ALICE/STAR
• Require leading track $p_T > 5$ GeV/c
  • Suppresses combinatorial “jets”
  • Biases fragmentation
• No threshold on constituents
• Limited to small R

Combinatorial “jets”
Survivor bias

- **WWII Example**: holes planes returning indicate where it’s *safer* to get hit
- We’re looking at the jets which *remain*
Bias & background

- **Experimental background subtraction methods:** complex, make assumptions, apply biases
- **Survivor bias:** Modified jets probably look more like the medium
- **Quark/Gluon bias:**
  - Quark jets are narrower, have fewer tracks, fragment harder [Z Phys C 68, 179-201 (1995), Z Phys C 70, 179-196 (1996), ]
  - Gluon jets reconstructed with $k_T$ algorithm have more particles than jets reconstructed with anti-$k_T$ algorithm [Phys. Rev. D 45, 1448 (1992)]
  - Gluon jets fragment into more baryons [EPJC 8, 241-254, 1998]
- **Fragmentation bias:** Experimental measurements explicitly select jets with hard fragments
Iterative procedure

- Used by ATLAS & CMS
- ATLAS
  - **Calorimeter jets**: Reconstruct jets with $R=0.2$. $v_2$ modulated $<\text{Bkgd}>$ estimated by energy in calorimeters excluding jets with at least one tower with $E_{\text{tower}} > <E_{\text{tower}}>$
  - **Track jets**: Use tracks with $p_T > 4$ GeV/c
  - Calorimeter jets from above with $E > 25$ GeV and track jets with $p_T > 10$ GeV/c used to estimate background again.
  - Calorimeter tracks matching one track with $p_T > 7$ GeV/c or containing a high energy cluster $E > 7$ GeV are used for analysis down to $E_{\text{jet}} = 20$ GeV
Jet $R_{AA}$

Tension between ATLAS & ALICE/CMS
ATLAS

Background subtraction method:

- **Iterative procedure**
  - **Calorimeter jets**: Reconstruct jets with $R=0.2$. $v_2$ modulated $\langle \text{Bkgd} \rangle$ estimated by energy in calorimeters excluding jets with at least one tower with $E_{\text{tower}} > \langle E_{\text{tower}} \rangle$
  - **Track jets**: Use tracks with $p_T > 4 \ \text{GeV/c}$
  - Calorimeter jets from above with $E > 25 \ \text{GeV}$ and track jets with $p_T > 10 \ \text{GeV/c}$ used to estimate background again.

- Calorimeter tracks matching one track with $p_T > 7 \ \text{GeV/c}$ or containing a high energy cluster $E > 7 \ \text{GeV}$ are used for analysis down to $E_{\text{jet}} = 20 \ \text{GeV}$

What you see depends on where you look

\[ \xi = \ln(1/z) \]

\[ z = \frac{p_T}{E_{jet}} \]

CMS Preliminary \( L_{int} = 150 \mu b^{-1} \)

- 2010, 0-30\%, Leading jet
- 2011, 0-10\%, Inclusive jet
- 2011, 10-30\%, Inclusive jet

JHEP10(2012)087
Mini-summary

- Most studies do one or more of the following:
  - Explicitly apply a (non-perturbative) bias
  - Implicitly apply a (non-perturbative) bias
  - Focus on small $R$
  - Focus on high $p_T$
- May also $\rightarrow$ survivor bias
- Background subtraction should be part of definition of algorithm
Jets in A+A collisions: How to compare to models
Analysis steps

Tracks → Jet finding algorithm → Jet candidates → Background subtraction

- Tracks
- Clusters
- Jet finding algorithm
- Jet candidates
- Background subtraction

Jet spectrum smeared by energy resolution, background fluctuations

Unfolding – corrects for single track reco $\varepsilon$, $E$ resolution, background fluctuations

Corrected spectra
Jets in ALICE: Response Matrix Construction

\[ \text{RM}_{\text{det}} \times \text{RM}_{\text{bkg}} = \text{RM} \]

RM_{\text{bkg}} and RM_{\text{det}} are approximately factorizable

Anti-\(k_T\) \(R=0.2\)

- \(p_{T,\text{track}} > 0.15\) GeV/c
- \(E_{T,\text{cluster}} > 0.30\) GeV
- \(p_{T,\text{leading}} > 5\) GeV/c

Pb-Pb \(s_{NN}=2.76\) TeV
0-10\% Centrality
Jets in ALICE: Response Matrix Construction

RM_{\text{det}} \times \text{X} \quad \text{RM}_{\text{bkg}} \quad \text{RM}

RM_{\text{det}} \text{ and } RM_{\text{bkg}} \text{ are approximately factorizable}

(a) RM_{\text{det}} \text{ Detector response matrix}
(b) RM_{\text{bkg}} \text{ Background fluctuation matrix}
(c) RM_{\text{tot}} = RM_{\text{bkg}} \times RM_{\text{det}}

Anti-\kT, R=0.2
\pT_{\text{track}} > 0.15 \text{ GeV}/c
\pT_{\text{cluster}} > 0.30 \text{ GeV}
\pT_{\text{leading}} > 5 \text{ GeV}/c

Pb-Pb \backslash s_{_{\text{NN}}} = 2.76 \text{ TeV}
0-10\% Centrality
Jets in ALICE: Response Matrix Construction

\[ \text{RM}_{\text{det}} \times \text{RM}_{\text{bkg}} = \text{RM} \]

\( \text{RM}_{\text{bkg}} \) and \( \text{RM}_{\text{det}} \) are approximately factorizable.

\( \text{Pb-Pb} \ s_{NN} = 2.76 \text{ TeV} \)

0-10% Centrality
Snowmass Accord: Forget the idea of a parton. Apply the same algorithm to data and your model. Then the measurement and the calculation are the same.
**Rivet:** Apply the same algorithm to data and your model. Then the measurement and the calculation are the same.
What is Rivet?
Why use Rivet?

- Facilitates comparisons between Monte Carlos and data
- It’s not that hard
- It preserves analysis details
Rivetizing Heavy Ion Collisions at RHIC 2020

November 30, 2020 to December 4, 2020
Online
US/Eastern timezone

Overview
Remote connection
Announcement
Registration
Participant List
Organizing Committee
Code of Conduct
HEPData@RHIC

Workshop to implement RHIC analyses in Rivet

Starts Nov 30, 2020, 9:00 AM
Ends Dec 4, 2020, 12:00 PM
US/Eastern

Online

Antonio Carlos Oliveira da Silva
Christine Nattrass

There are no materials yet.

Registration
Registration for this event is currently open.

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Jets in ALICE: Response Matrix Construction

RM_{det} \times RM_{bkg} \neq RM_{tot}

RM_{bkg} and RM_{det} are approximately factorizable

Anti-\kT R=0.2
\pT_{track} > 0.15 \text{ GeV/c}
\E_{\text{track}} > 0.30 \text{ GeV}
\p_{\text{leading}} > 5 \text{ GeV/c}

(a) RM_{det} Detector response matrix
(b) RM_{bkg} Background fluctuation matrix
(c) RM_{tot} = RM_{bkg} \times RM_{det}

\text{Pb-Pb} \ s_{NN}=2.76 \text{ TeV}
0-10\% Centrality
Analysis steps: Full Monte Carlo

1. **Particles**
2. **Jet finding algorithm**
3. **Jet candidates**
4. **Background subtraction**

- **Unfolding** – corrects for background fluctuations

Jet spectrum smeared by energy resolution

Corrected spectra
Comparison to data

Unfold to correct for fluctuations

Pb-Pb at $\sqrt{s_{NN}} = 2.76$ TeV

Signal-only Model
ex: JEWEL

Full Monte Carlo Model
ex: JETSCAPE, Argus, Jamin

HepMC
Rivet
HEPData

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Mini-summary

- Experimental techniques can bias measurement in subtle ways
  - Background subtraction
  - Kinematic cuts
  - Choice of jet finder, R
  - Centrality determination
  - Technique for finding reaction plane
- Unclear how these influence the measurement
- Safest to do the same analysis on data and model
  - But unfolding is necessary in a full Monte Carlo model!
Summary

- Jets are defined by a jet finder and its parameters
- All jet measurements are somewhat sensitive to non-perturbative effects
- Background for jets in heavy ion collisions dominated by random combinations of particles
  - Other effects ~5%
  - Not described well by theory
- Measurements may have a biased selection of jets
- Conservative approach: Treat models like data → Rivet!