A skeptic’s guide to jets
Part 1: Jet spectra

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Questions an experimentalist should ask

- What do I want to learn?
- What am I measuring?
- What assumptions am I making?
- What are the dominant uncertainties?
- How do I compare to models?

The answers for jets are highly non-trivial!
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

nucleus

nucleus

ATLAS


Calorimeter Towers

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Probes of the Quark Gluon Plasma
“Simple” example: Single hadrons
Nuclear modification factor

- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-$p_T$ probes (jets) are suppressed, this is evidence of jet quenching

$$R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma_{pp}/dp_Td\eta}$$

Enhancement

Suppression

"soft"

"hard"
Nuclear modification factor

- Charged hadrons (colored probes) suppressed in Pb—Pb
- Charged hadrons not suppressed in p—Pb at midrapidity
- Electroweak probes not suppressed in Pb—Pb
Electromagnetic probes – consistent with no modification – medium is transparent to them

Strong probes – significant suppression – medium is opaque to them - even heavy quarks!
What am I measuring?
Definition of a jet
Theoretical calculations
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 $D$

$$
\frac{d^3\sigma^h}{dy \, d^2p_T} = \frac{1}{\pi} \int d \, x_a \int d \, x_b \, f^A(a)(x_a) f^B(b)(x_b) \frac{d\sigma_{ab \rightarrow cX}}{d\hat{t}} \frac{D^h_c(z)}{z}
$$
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

Beam pipe
What is a jet?

“I know it when I see it”

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

- Tracks
- Clusters
- Particles

Jet finding algorithm

Jet candidates

- 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 collinear safe

**Image from:** [http://www.ok-ads-theorie.physik.uni-mainz.de/Dateien/Zappenhof3.pdf](http://www.ok-ads-theorie.physik.uni-mainz.de/Dateien/Zappenhof3.pdf)
$k_T$ jet finding algorithm

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

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

  $d_{iB} = p_{T,i}^2$

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

Repeat until no particles left

Jet candidates
anti-$k_T$ 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:
  \[ d_{ij} = \min \left( p_{T,i}^{-2}, p_{T,j}^{-2} \right) \frac{\Delta R_{ij}^2}{R^2} \]
  \[ d_{iB} = p_{T,i}^{-2} \]
- Combine smallest $d_{ij}$
  If $d_{iB}$ smallest, $d_{iB} \rightarrow$ jet
Repeat until no particles left

**Jet candidates**
Cambridge/Aachen 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:
  - \( d_{iB} = 1 \)
  - \( d_{ij} = \left( \frac{\Delta R_{ij}^2}{R^2} \right) \)
- Combine smallest \( d_{ij} \).
  - If \( d_{iB} \) smallest, \( d_{iB} \rightarrow \text{jet} \)
  - Repeat until no particles left

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

arXiv:1301.3475
PLB: 10.1016/j.physletb.2013.04.026
Jet ratios in pp

$\sqrt{s} = 2.76$ TeV, $R = 0.2$, 0.4 Inclusive

\[ \sigma(R=0.2)/\sigma(R=0.4) \]

- anti-$k_T$, $|\eta|<0.5$
- ALICE pp $\sqrt{s} = 2.76$ TeV
- Systematic uncertainty
- LO (G. Soyez)
- NLO (G. Soyez)
- NLO + Hadronization (G. Soyez)

arXiv:1301.3475
PLB: 10.1016/j.physletb.2013.04.026
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
  → 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

Combinatorial jets

Background

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 $p_T$
- $v_n$
- No jets! No resonances
- Emulates hydro correlations

#### Momentum spectra
- Blast Wave Fit
- $K^+$ ALICE PLB720 (2013) 52-62

#### Polynomial Fit
- $v_n$
- ALICE JHEP 1609 (2016) 164

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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

\[ \phi, \eta, E, n, e, g (a, r, b, u, n, i, t, s) \]


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

- 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 \( \rho = p_T / A \)

\[ p_T^{\text{jet}} = p_T^{\text{reco}} - \rho_{\text{median}} A^{\text{jet}} \]

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Background density $\rho$

FastJet $k_t$ ($p_t^{\text{min}} = 0.15 \text{ GeV/c}$)

Fit: $(-3.3\pm0.3) \text{ GeV/c} + (0.0623\pm0.0002) \text{ GeV/c} \times N_{\text{raw}}^{\text{input}}$

$\rho (\text{GeV/c})$ vs $N_{\text{raw}}^{\text{input}}$

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

ALICE

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

Random cones

R=0.4

Real jets

Excluded

Excluded

X
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

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

\[ \delta p_T, \ (0\text{-}10\%) \ \text{Pb-Pb} \]
- Data
  \[ \mu = -0.50 \pm 0.01 \ (\text{GeV}/c) \]
  \[ \sigma = 9.72 \pm 0.01 \ (\text{GeV}/c) \]
- Angantyr
  \[ \mu = -1.74 \pm 0.30 \ (\text{GeV}/c) \]
  \[ \sigma = 9.97 \pm 0.18 \ (\text{GeV}/c) \]
- Background Generator
  \[ \mu = -0.48 \pm 0.12 \ (\text{GeV}/c) \]
  \[ \sigma = 7.36 \pm 0.05 \ (\text{GeV}/c) \]

JHEP 03 (2012) 053

\[ f : a_p = 144.3, \ a_b = 1.4 \ c/\text{GeV} \]

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Shape of width of the distribution

Single particle spectra

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

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

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

\[ N = \frac{A_{\text{total}}}{\pi R^2}, \quad \mu_{\text{total}} = \frac{N p}{b} = N \mu_{p_T}, \quad \sigma_{\text{total}} = \sqrt{N p} / b = \sqrt{N} \sigma_{p_T} \]

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:

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

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

\[ \sigma(p_T) (\text{GeV}/c) \]

- random cones
- RC (w/o lead. jet)
- RC randomized γ from Poissonian limit
- Poissonian limit + \( v_2 \) (\( v_{\text{np}}^2 = 2 N_A^2 v_2^2 \))
- Poissonian limit + \( v_2, v_3 \) (\( v_{\text{np}}^2 = 2 N_A^2 (v_2^2 + v_3^2) \))

\[ \delta p_T \text{ width (GeV)/c} \]

- Background Generator, no \( v_n \)
- Background Generator, with \( v_n \)
- Equation 3
- Equation 4

Data / Prediction

- Small deviations

\( \text{Pb-Pb } \sqrt{s} = 2.76 \text{ TeV} \)
\( R = 0.4, p_T^{\text{min}} = 0.15 \text{ GeV}/c \)

**TennGen**
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

\[ \sigma(p_T) \text{ (GeV/c)} \]

- random cones
- RC (w/o lead. jet)
- RC randomized \( \gamma \phi \)
- Poissonian limit
- Poissonian limit + \( v_2 \) (\( \sigma(p_T) = 2N_A v_2^2 \))
- Poissonian limit + \( v_2 + v_3 \) (\( \sigma(p_T) = 2N_A (v_2^2 + v_3^2) \))

Pb-Pb \( \sqrt{s} = 2.76 \text{ TeV} \)

\[ N_{\text{raw}} \text{ vs } N_{\text{input}} \]

Data / Prediction

Angantyr

Doesn’t go away with random track orientation!
Shape of width of the distribution

Single particle spectra

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

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

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

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

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

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

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

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

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

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

Assumes shape

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

Assumes uncorrelated number fluctuations

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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
What you see depends on what you're looking for
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

Constituent biases don't matter that much up here

But they do matter down here!
Jet $R_{AA}$

LHC Run1 Data; PbPb (0-10%) $\sqrt{s_{NN}} = 2.76$ TeV

- CMS 1609.05383
- ALICE PLB 746(2015) 1-14
- ATLAS PRL 114(2015) no.7

$R_{AA}$ vs Jet $p_T$ [GeV/c]

arXiv:1705.01974

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Jet $R_{AA}$

LHC Run1 Data; PbPb (0-10%) $\sqrt{s_{NN}} = 2.76$ TeV

CMS 1609.05383
ALICE PLB 746(2015) 1-14

$R = 0.2$
$R = 0.3$
$R = 0.4$
$R = 0.4$

arXiv:1705.01974

Tension between ATLAS & ALICE/CMS
Background subtraction method:

- **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

What you see depends on where you look

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

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

\( p_T > 100 \text{GeV/c} \)

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

\( z = \frac{p_T}{E_{\text{jet}}} \)

High \( p_T \)

Low \( p_T \)

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 pT

• May also → survivor bias

• Background subtraction should be part of definition of algorithm
What are the dominant uncertainties?
Analysis steps

Tracks → 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
Unfolding

\[ \tilde{\nu} = R\tilde{\mu} + \tilde{\beta} \]

- \(\tilde{\nu}\) : the “true” histogram
- \(\nu\) : the actual data we measure
- \(\tilde{\beta}\) : background
- \(R\) : the response matrix

\[ \nu_i = \sum_{j=1}^{M} (R_{ij}\mu_j) + \beta_i \]
Simple Solution (Inversion)

- Rearrange $\tilde{v} = R\tilde{\mu} + \tilde{\beta}$ to get $\tilde{\mu} = R^{-1}(\tilde{v} - \tilde{\beta})$

- Problem: we don’t have $\tilde{v}$, we have $\tilde{n}$, the measured data, which is subject to statistical fluctuations.

- We assume $n_i$ is the maximum likelihood estimator for $\nu_i$, then solve for the estimator $\hat{\mu} = R^{-1}(\tilde{n} - \tilde{\beta})$.

- $R^{-1}$ is obtained from $R$ through simple matrix inversion
Iterative Bayesian Method

- Using prior knowledge, start with an initial guess for the distribution of true histograms $P^0 (\mu)$

- Use Bayes’ Theorem to invert the response matrix $P(\hat{\mu}_i | v_j^{sig}) = \frac{P(v_j^{sig} | \hat{\mu}_i) P^0(\hat{\mu}_i)}{\sum_{l=1}^{M} P(v_j^{sig} | \hat{\mu}_l) P^0(\hat{\mu}_l)}$

- $\hat{\mu}_i = \frac{1}{\epsilon_i} \sum_{j=1}^{N} v_j^{sig} P(\hat{\mu}_i | v_j^{sig})$ where $\epsilon_i$ is the detector efficiency

- Plug in the newly obtained $P(\hat{\mu}_i | v_j^{sig})$ and $\hat{\mu}_i$ as new priors, then repeat

- Terminate before the wildly oscillating true inverse is reached (usually $\sim 4$ iterations) to preserve some smoothness
RooUnfold-Bayes

- RooUnfoldTest.cxx
- method = Bayes
- Exponential training and testing
About unfolding...

- d'Agostini (author of Bayesian unfolding algorithm) says you should avoid it if you can

- Necessary when experimental resolution is poor
  - Ex: Single particle spectra $\frac{\sigma_p}{w_{bin}} \ll 1$ → unfolding unnecessary
  - Ex: Jet spectra $\frac{\sigma_p}{w_{bin}} \approx 1$ → unfolding necessary

- Algorithm assumes response matrix is correct
  - Matching reconstructed and simulated jets is non-trivial!

- Corrects for multiple experimental effects simultaneously
  - Difficult to disentangle different effects
  - Leads to non-trivial uncertainty correlations between data points due to algorithm
  - May not handle systematic correlations between effects correctly
Jets in ALICE: Response Matrix Construction

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

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

- \( \text{RM}_{\text{det}} \): Detector response matrix
- \( \text{RM}_{\text{bkg}} \): Background fluctuation matrix
- \( \text{RM}_{\text{tot}} = \text{RM}_{\text{bkg}} \times \text{RM}_{\text{det}} \)

- Anti-\( k_T \) \( R = 0.2 \)
- \( p_{T,\text{track}} > 0.15 \text{ GeV/c} \)
- \( E_{T,\text{cluster}} > 0.30 \text{ GeV} \)
- \( p_{T,\text{leading}} > 5 \text{ GeV/c} \)

\[ \text{Pb-Pb \( s_{NN} = 2.76 \text{ TeV} \) 0-10\% Centrality} \]

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Pythia \( s = 2.76 \text{ TeV} \)

ALICE PERFORMANCE 19/06/2013

ALICE PERFORMANCE 15/10/2012
Jets in ALICE: Response Matrix Construction

\begin{align*}
\text{RM}_{\text{det}} \times \text{RM}_{\text{bkg}} &= \text{RM} \\
\text{RM}_{\text{bkg}} \quad \text{and} \quad \text{RM}_{\text{det}} \quad \text{are approximately factorizable}
\end{align*}

\text{Anti}-k_T \ R=0.2 \\
\quad p_{T,\text{track}} > 0.15 \ \text{GeV/c} \\
\quad E_{\text{T,cluster}} > 0.30 \ \text{GeV} \\
\quad p_{T,\text{leading}} > 5 \ \text{GeV/c}

\begin{align*}
\text{(a) } \text{RM}_{\text{det}} & \quad \text{Detector response matrix} \\
\text{(b) } \text{RM}_{\text{bkg}} & \quad \text{Background fluctuation matrix} \\
\text{(c) } \text{RM}_{\text{tot}} &= \text{RM}_{\text{bkg}} \times \text{RM}_{\text{det}}
\end{align*}

\text{Pb-Pb} \ \sqrt{s_{NN}}=2.76 \ \text{TeV} \\
0-10\% \text{ Centrality}

\text{ALICE PERFORMANCE} \\
15/10/2012 \\
\text{ALICE PERFORMANCE} \\
19/08/2013

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**Jets in ALICE: Response Matrix Construction**

**RM_{det}** and **RM_{bkg}** 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

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

**Pb-Pb \(s_{NN} = 2.76\) TeV
0-10\% Centrality**

*ALICE PERFORMANCE* 15/10/2012

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Response matrix includes assumptions about

- Detector response
  - Including particle composition of jets!
- Fragmentation and hadronization
  - How does hadronization influence the width of your jet?
- Background and/or background fluctuations
- How you match reconstructed (“detector level”) and true (“particle level”) jets
Jet Momentum Resolution

Jet resolution
- Dominated by background fluctuations at low momentum
- Dominated by detector effects at high momentum
Mini-summary

- Jet energy resolution is fundamentally large
  - Measuring multiple correlated particles!
  - Be skeptical of jet measurements with <10% uncertainties
- Unfolding is complicated, often unstable, and hard
- Construction of response matrix includes several assumptions
Jets in A+A collisions: How to compare to models
Snowmass Accord: 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?
Monte Carlo Model

HepMC

HEPData → Rivet

Comparison to data

Christine Nattrass (UTK), uBNL 2020
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

Workshop to implement RHIC analyses in Rivet

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

Antonio Carlos Oliveira da Silva
Christine Nattrass

Registration
Registration for this event is currently open.

Support
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There are no materials yet.
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.
Analysis steps: Full Monte Carlo

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

- Jet spectrum smeared by energy resolution
- Unfolding – corrects for background fluctuations
- Corrected spectra

**Graphs**
- Lead-lead (Pb-Pb) at $\sqrt{s_{NN}} = 2.76$ TeV
  - Jet spectrum (left)
  - Unfolded spectra (center)
  - Corrected spectra (right)
Comparison to data

Unfold to correct for fluctuations

Christine Nattrass (UTK), uBNL 2020
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!
A skeptic’s guide to jets
Part 2: Where we are going

Christine Nattrass
University of Tennessee, Knoxville
There is no particionic energy loss.
There is only partionic energy redistribution.
What is jet (sub)structure?

A Whatever I am measuring!
B Any new jet observable
C Any observable which measures the structure of jets.
D A cool buzzword
E I don’t know but it sounds cool and gets me talks/grants
Types of observables

I. Minimally sensitive to structure

Observables
- (Jet) $R_{AA}$
- $A_j$
- $I_{AA}$
- (Jet) $v_2$

Jet properties:
- $E$

II. Sensitive to $<$structure$>$ of $<$jets$>$

Observables
- Fragmentation functions
- Jet shapes
- Correlations
- ...

Jet properties:
- $E$
- Const. $p_T$
- $\phi$, $\eta$

Average background subtraction OK

Higher precision

Higher/different sensitivity?

III. Sensitive to distribution of structures

Observables
- Girth
- Dispersion
- $p_T D$
- Jet mass
- ...

Jet properties:
- $E$
- Const. $p_T$
- $\phi$, $\eta$

IV. Sensitive to parton shower structure

Observables
- Grooming
- $N_{subjettiness}$
- ...

Jet properties:
- $E$
- Const. $p_T$
- $\phi$, $\eta$
- Multi-const. correlations

Jets required

Need new background subtraction technique

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Type I: Energy loss
Hadron-jet correlations

\[ \Delta I_{AA} = \Delta \frac{P_{\text{recoil}}}{P_{\text{PYTHIA}}} \]

Jet v2 suppression

\[ \gamma \text{-jet correlations} \]

\[ \gamma \text{-hadron correlations} \]

\[ [\text{Phys. Rev. C 90, 014909 (2014)}] \]

\[ [\text{Phys. Rev. Lett. 111, 152301 (2013)}] \]

\[ [\text{Phys. Lett. B 753 (2016) 511-525}] \]


\[ [\text{Phys. Rev. C 96, 024905 (2017)}] \]

\[ [\text{JHEP 09 (2015) 170}] \]

\[ [\text{Phys. Rev. C 90, 014909 (2014)}] \]

\[ [\text{Phys. Rev. D 82, 072001 (2010)}] \]

\[ [\text{Phys. Rev. C 90, 014909, 2010}] \]

\[ [\text{Physics Letters B 760 (2016)}] \]
Type II: Fragmentation
**Fragmentation functions with jets**

**Leading jet**

\[ p_T^{\text{leading}} - p_T^{\text{subleading}} \]

\[ A_j = \frac{p_T^{\text{leading}} - p_T^{\text{subleading}}}{p_T^{\text{leading}} + p_T^{\text{subleading}}} \]

**Di-jet asymmetry**

**Central Au+Au**

anti-\(k_T\) R=0.4

**Jets get wider and constituents get softer**

\[ z = \frac{p_T}{E_T} \]

**Di-hadron correlations**

[Lots of papers]

**Jet shapes**

Type III: Distribution of properties
Jet mass

\[ M = \sqrt{p^2 - p_T^2 - p_z^2} , \quad p = \sum_{i=1}^{n} p_{T_i} \cosh \eta_i , \quad p_z = \sum_{i=1}^{n} p_{T_i} \sinh \eta_i . \]

- Quenching models (JEWEL, Q-PYTHIA) show a larger mass than pp-like PYTHIA jets
- Pb-Pb measurement can discriminate among these predictions

arXiv:1702.00804

Christine Nattrass (UTK), uBNL 2020
\[ g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T} r_i \]

\[ p_T D = \sqrt{\frac{\sum_{i \in \text{jet}} (p_T^i)^2}{\sum_{i \in \text{jet}} p_T^i}} \]

\[ \text{LeSub} = p_T^{\text{leading}} - p_T^{\text{subleading}} \]

Jacques Nattress (UTK), uBNL 2020

Jets are slightly more collimated than in pp

Agrees with PYTHIA
Type IV: Declustering

Note: These slides are from Laura Havener

*A selection. Don’t be offended if I skip your favorite.
New tool: jet splittings

Interested in the original parton shower splittings of the jet
Which form subjets inside the jet!
Jet splittings: in vacuum

Vacuum jets splittings form at different times

\[ t_f^{\text{vac}} = \frac{1}{\theta^2 \omega} \]

Wider jets form earlier and narrower jets form later
Jet splittings: in medium

Vacuum splittings in/out of the medium

\[ t_f^{\text{vac}} = \frac{1}{\theta^2 \omega} \]

Medium-induced splittings from gluon radiation

\[ t_g^{\text{med}} = \sqrt{\frac{\omega}{\hat{q}}} \]
Jet splittings: in medium

Coherence: subjets *unresolved* and jet loses energy as a whole.

Decoherence: medium *resolves* the subjets resulting in a stronger e-loss.

Medium-induced splittings

Vacuum splittings inside medium, resolved

Vacuum splittings inside medium, unresolved

Vacuum splittings outside medium
Exploring the Lund Plane: in vacuum

- Lund Diagram*: phase space of jet splitting
  JHEP 12 (2018)
- \( \log(k_T) > 0 \) separates perturbative from non-perturbative regime
- Formation time: how long until the splitting occurred
  \[ t_f = \frac{1}{(1-z)k_T \Delta R} \]

Y. L. Dokshitzer, et.al.

\[ p_{T1} = (1-z)p_T \]
\[ p_{T2} = zp_T \]

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

Y. L. Dokshitzer, et.al.

arXiv:1808.03689
Soft drop grooming

- Reconstruct anti-$k_T$ $R=0.4$ charged jets with jet-by-jet constituent background subtraction*

*IHEP 06 (2014) 092
Soft drop grooming

- Reconstruct anti-$k_T$ $R=0.4$ charged jets with *jet-by-jet constituent background subtraction*

Remove from each constituent inside the jet instead of from the whole jet

Jet-by-jet:

$$p_{T}^{\text{jet,corr}} = p_{T}^{\text{jet}} - \rho A$$

Track-by-track (i) in jet:

$$p_{T}^{i,\text{corr}} = p_{T}^{i} - \rho A$$

*JHEP 06 (2014) 092*
Groomed variables

- Soft drop grooming variables probe jet splitting
  
  \[ z_g = \frac{\min(p_{Ti}, p_{Tk})}{p_{Ti} + p_{Tk}} \]

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

  How symmetric is the jet splitting?

  How far apart are the subjets?

  \[ n_{S0} \text{: number of splittings passing Soft Drop} \]

  Number of subjets within a jet?
$z_g$: jet splitting

$z_g = \frac{\min(p_{T_i}, p_{T_1})}{p_{T_i} - p_{T_1}}$

asymmetric splitting: low $z_g$

symmetric splitting: high $z_g$

Suppression of symmetric splittings
$z_g$: opening angle

Wide: more significant suppression of symmetric splittings

Wide $R_g > 0.2$

Collimated $R_g < 0.1$

Narrow splittings enhanced

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Background
Unfolding: jet splitting

Uncorrelated background leads to subjets being picked up as incorrect or “fake” splittings

dominate at low $z_g$

and at large $R_g$

gone in $n_{SD}$?

Non-diagonal response prohibits unfolding
Mini-summary

- “Jet substructure” is used inconsistently
- Search for new observables
  - Haven’t really used most of the “old” ones!
- So far it’s a mixed bag
  - Many are insensitive
  - Some may have some promise
  - Background tricky
JETSCAPE
JET collaboration

\[ \chi^2_{\text{minimization}} \]

QGP brick + jet

Data

\[ \hat{q} = 1.2 \pm 0.3 \ \text{GeV}^2 \]
\[ \hat{q} = 1.9 \pm 0.7 \ \text{GeV}^2 \]

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Bayesian Statistical Analysis
Models and Data Analysis Initiative

http://madai.us

Model emulation
1) Run full model ~1000 times
2) MCMC parameter search uses emulator (interpolator) in lieu of full model

Monte Carlo models

Data

Prior

Posterior

Constraint of QGP properties

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JETSCAPE Event generator

Jet Energy-loss Tomography with a Statistically and Computationally Advanced Program Envelope

http://jetscape.wayne.edu/

Realistic medium

Realistic jets

Realistic Monte Carlo Model

Experimental techniques

Realistic theoretical calculations

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Event Generator + Bayesian Statistical analysis

Data

Realistic theoretical calculations

Bayesian Statistical Analysis

Constraint of QGP properties

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Conclusions
Conclusions

- Jets are complicated and hard to measure to high precision
- Much of the physics we want does not require them
- Extra insight from studying them anyways
- Be skeptical, especially of background subtraction
- Make sure the measurement is comparable to model
The End
Exploring the Lund Plane: in medium

- Jet splittings in heavy-ion (HI) collisions
  - Splittings happen at different times
    - Earlier/wider splittings experience more medium
  - Vacuum splittings vs. non-perturbative in-medium splittings
  - Coherence vs. decoherence

\[ p_{T1} = (1-z)p_T \]
\[ p_{T2} = zp_T \]
Exploring the Lund Plane: in medium

- Jet splittings in heavy-ion (HI) collisions

  1: Vacuum splitting outside of medium

  2: Vacuum splitting in-medium, resolved (decoherence)

  3: Vacuum splittings in-medium, unresolved (coherence)

  4: Medium-induced splittings
Jets in ALICE: Response matrix $\text{RM}_\text{det}$

$\text{RM}_\text{det}$ quantifies detector response to jets

- “Particle” level jets – defined by jet finder on MC particles
- Pythia with Pb-Pb tracking efficiency
- “Detector” level jets – defined by jet finder after event reconstruction through GEANT
- Particle level jets are geometrically matched to detector level jets
- Matrix has a dependence on spectral shape and fragmentation

Jet-finding efficiency is probability of a matched particle level jet

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**Pythia $\sqrt{s}$ = 2.76 TeV**

- Leading track $p_T > 5$ GeV/c
- $R = 0.2$

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**ALICE PERFORMANCE**

25/06/2013

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**ALICE PERFORMANCE**

19/06/2013

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**Pythia $\sqrt{s} = 2.76$ TeV**

**ALICE PERFORMANCE**

19/06/2013

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**Leading track $p_T > 5$ GeV/c**

R = 0.2

- Particle Level
- Detector Level

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Modified fragmentation

- Enhancement at low z
- No modification/enhancement at high z?

\[ z = \frac{p_T}{E_Y} \]
**n_{SD}: iterative declustering**

New ALICE measurement at 5.02 TeV

Modification: enhancement at small $n_{SD}$ and suppression at intermediate $n_{SD}$

Consistent with wider/earlier being suppressed in the medium, leading to more jets with lower $n_{SD}$

*arXiv:1907.11248v1*
Di-jet asymmetry

Anti-$k_T$ R=0.4, $p_T^{\text{Leading}}>20 \text{ GeV}$ & $p_T^{\text{SubLeading}}>10 \text{ GeV}$ with $p_T^{\text{cut}}>2 \text{ GeV}/c$

Au+Au di-jets more imbalanced than p+p for $p_T^{\text{cut}}>2 \text{ GeV}/c$

Kolja Kauder, RHIC/AGS
User's Meeting 2016
arXiv:1609.03878

Sys. Uncertainties:
- Tracking: 6%
- Tower energy scale: 2%

$A_j = \frac{p_T^{\text{Leading}} - p_T^{\text{Subleading}}}{p_T^{\text{Leading}} + p_T^{\text{Subleading}}}$

Au+Au di-jets more imbalanced than p+p for $p_T^{\text{cut}}>2 \text{ GeV}/c$

Central Au+Au
anti-$k_T$, R=0.4

Preliminary

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A_j for matched di-jets (R=0.4)
Width vs multiplicity

Discrepancy not from an excess of jets!
Jet-hadron correlations

- Jets are broader, constituents are sottter
- Also seen in:
  - Di-hadron correlations [Lots of papers]
  - Dijet asymmetry with soft constituents [PRL119 (2017) 62301]