Jet quenching and energy loss: An experimentalist perspective.

Sevil Salur
Rutgers University
My Charge:

A pedagogical lecture on jet quenching and energy loss

- See Talks during 2018 Summer Workshops for latest beautiful results


https://www.bnl.gov/jets18/

https://indico.cern.ch/event/716363/
YOU MUST UNLEARN WHAT YOU HAVE LEARNED
My Charge:

A pedagogical lecture on jet quenching and energy loss...

Jets in the medium
My Charge:
A pedagogical lecture on jet quenching and energy loss...

Jets in the vacuum  Jets in the medium
Experimental search for “interesting” phenomena

• Look at elementary p+p and p+A collisions
  – Measure an observable (e.g. Hard probes such as jet production)
• Look at Heavy Ion collisions
  – Measure the same observable as we do in p+p and p+A
• Compare them, is there something new?

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A simple Physics Observable:

\[ R_{AA} \equiv \frac{\text{Yield in } A + A \text{ Events}}{N_{Bin} \left( \text{Yield in } p + p \text{ Events} \right)} \]

If no “effects”:
- R < 1 in regime of soft physics
- R = 1 at high-p_T where hard scattering dominates
Jets in the vacuum:

OBSERVATION OF JETS IN HIGH TRANSVERSE ENERGY EVENTS AT THE CERN PROTON ANTIPROTON COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

Jets are the experimental signatures of quarks and gluons. They are expected to reflect kinematics and topology of partons.
Jets in the vacuum

OBSERVATION OF JETS IN HIGH TRANSVERSE ENERGY EVENTS AT THE CERN PROTON ANTI-PROTON COLLIDER

UA1 Collaboration, CERN, Geneva, Switzerland

Jets are the experimental signatures of quarks and gluons. They are expected to reflect kinematics and topology of partons.

But Jets are Not Partons, Partons are Not Jets!
LHC data is dominated by jets

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> 50% of ATLAS & CMS papers use jets

Any analysis that require, quark, gluon, i.e., parton or their absence in an event.
Jet spectra with various R parameters from pp collisions are well understood. Consistent with calculations.
Summary of the cross section measurements of Standard Model processes.

Measuring known processes at LHC energies using Jets Triumph for SM and Theory Calculations.
Jets are complicated!

The whole event is color connected and at higher orders radiation can even be emitted.

A lot of complications!
- Underlying event
- Pileup
- Initial + final state radiation

An artistic view of a proton-proton scattering event at high energy (courtesy of F. Krauss)
Partons (quarks, gluons) are not trouble-free concepts...

- Partons split into further partons
- Jets are a way of thinking of the ‘original parton’
- A ‘jet’ is a fundamentally ambiguous concept (e.g. requires a resolution)

Jets are only meaningful once you’ve got a jet definition

courtesy of Gavin Salam
A resolution: SnowMass Accord

Toward a Standardization of Jet Definitions

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December 1990


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~10 years to realize the need!
ABSTRACT

In order to reduce uncertainties in the comparison of jet cross section measurements, we are proposing a standard jet definition to be adopted for QCD measurements involving light quarks and gluons. This definition involves the use of a cone in the $\eta - \phi$ metric with a radius of 0.7 units.

Several important properties that should be met by a jet definition are [3]:

1. Simple to implement in an experimental analysis;
2. Simple to implement in the theoretical calculation;
3. Defined at any order of perturbation theory;
4. Yields finite cross section at any order of perturbation theory;
5. Yields a cross section that is relatively insensitive to hadronization.

Must be stable for collinear splitting and soft gluon emission.

Experimental and theoretical definitions of jets must match!
A Variety Jet Reconstruction Algorithms

\[ R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \]

**Cone Algorithm: Top-down approach**

Sequential recombination: Bottom-up approach
Cluster pairs of objects close in relative \( p_T \)

**MC: proton-proton - single event**

- Cone jet
- Anti-\( k_T \) jet
- Fragmentation process
- Hard scatter

\( k_T \) jet
There is no an unambiguous definition of a jet
A jet is what a jet finder finds.

merge to hardest         merge to softest         merge to closest

There is no an unambiguous definition of a jet
A jet is what a jet finder finds – including pile-up & fake estimations

Most of the recent jet related developments involve corrections/removal of pile-up for precise jet reconstruction. 😊

An artistic view of a proton-proton scattering event at high energy (courtesy of F. Krauss)

Jets are even more complicated in heavy ion collisions!

- Smeared kinematics
- Create combinatorial “jets”
- Jet-medium interactions
Why do we want to do this difficult study in Nuclear Collisions?

Lifetime of QGP is short ($O(fm/c)$) - not feasible to probe it with an external probe!
Why do we want to do this difficult study in Nuclear Collisions?

So start with an internal probe!
Why do we want to do this difficult study in Nuclear Collisions?
Why do we want to do this difficult study in Nuclear Collisions?

Speeding Nuclei

Hot, Dense region... QGP?
Why do we want to do this difficult study in Nuclear Collisions?

Speeding Nuclei

Hot, Dense region... QGP?

Quarks and gluons lose energy in dense medium generated in collision

Jets have to pass through Hot, Dense Zone!
Why do we want to do this difficult study in Nuclear Collisions?

Diagnosing QCD medium: (simplified idea) pass a QCD-sensitive internal probe through it, then look for any modifications due to the medium.

Goal with jets: Extract QGP transport coefficients
- q: transverse momentum diffusion (radiative energy loss)
- e: longitudinal drag (collisional energy loss)
Why do we want to do this difficult study in Nuclear Collisions?

Our Goal is to study the fundamental physics processes of jet quenching in order to learn the properties of QGP.

Jets have to pass through Hot, Dense Zone!

energy in dense medium generated in collision
Heavy Ion Jets: First steps w/o jet reco
Electromagnetic probes – consistent with no modification – medium is transparent to them

Strong probes – significant suppression – medium is opaque to them - even heavy quarks!

Controls in ppb, dAu not suppressed.
Recent measurements extend to ~1 TeV!
• Leading hadron measurements do not capture the entire process

\[ R_{AA} \]

is not too discriminative between models

"Everybody can describe \( R_{AA} \)"

Courtesy of Carlota Andres
Leading hadron measurements do not capture the entire process.

Hadron $R_{AA}$ is not too discriminative between models.

“Everybody can describe $R_{AA}$.”

Courtesy of Carlota Andres
Heavy Ion Jets: First Steps w/o jet reco

$p+p \rightarrow \text{dijet}$

Jet Measurements are difficult!
Simplify the problem by looking only at the leading hadron.

Select high momentum particles
→ biased towards jets

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Heavy Ion Jets: First Steps w/o jet reco

Near side $\Delta \phi \approx 0$: p+p, Au+Au similar


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Heavy Ion Jets: First Steps w/o jet reco

$\Delta \phi \approx 0$: peripheral and central Au+Au similar to p+p
$\Delta \phi \approx \pi$: strong suppression of back-to-back correlations in central Au+Au


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Correlations: What to subtract?

Shown is the energy density in the transverse plane. For more information on the simulation refer to arXiv:1009.3244.

Jets $\rightarrow$ background for flow
Flow $\rightarrow$ background for jets
Correlations: What to subtract?

1. Ignore modulation of underlying event
2. Get external information about modulation
3. Extract modulation in the analysis

Courtesy of Eliane Epple
Near-Side Fit (NSF) method

No reaction plane dependence

(NOT used by this analysis)

- Robust, uses information from each event plane orientation
- Doesn't require independent measurements of $\nu_n$, extracted from fits
- Reconstructs signal with fewer assumptions and less bias while giving smaller errors than ZYAM

Courtesy of Joel Mazer
Near-Side Fit (NSF) method

No reaction plane dependence

(NOT used by this analysis)

Background removal of correlations is not as simple as first believed.
LHC Jet Machine:
Heavy Ion program started 8 years ago!
Run 1 (2010-2014)
Run 2 (2015-2018)
Run 3 And Beyond…
RHIC continues to take billions of collisions. With STAR and sPhenix, RHIC will continue to serve as the necessary QCD leverage arm!
We are building upon 25 years of cold QCD jet experience!

Many new techniques/variable are developed and we “hot QCD physicists 😊”, could utilize these new methods.
A jet is also never alone in HI collisions

ATLAS & CMS: iterative event-by-event rejection
ALICE & STAR: event by event averaged rejection

Experimental and theoretical definitions of jets must match!
Underlying event is the hardest to match.
Why do we do bkg subtraction?

- “Experimental and theoretical definitions of jets must match!”
- Poor understanding of the non-perturbative physics
- Essential for HI physics to access low pt kinematics
- Soft sector Phenomenological modeling lacks accuracy.

Allows comparisons using event generators, parton/string models, NLO and holographic calculations...

Our theory colleagues are on board!
Experimental Challenges:
“Removal of Fake Jets”

All corrections including fake jets treatment ($p_T$ constituent $>5-8$ GeV/c) done with Pythia fragmentation!

CMS, PRC 90 (2014) 024908
All corrections including fake jets treatment ($p_T$ constituent $>$ 5-8 GeV/c) done with Pythia fragmentation!

**Experimental Challenges:**

“Removal of Fake Jets”

- Are we throwing away the physics that we are interested in?
- Introducing biases?
- How to make the most of it?
What are the necessary components of a background subtraction algorithm?

- Can be used to achieve our physics goal
- Can be used in experimental measurements
- Can be used in theoretical calculations

Minimal assumption on the factorization of “soft” physics and “hard” physics.

Classification should be theoretically sound and reproducible in calculations.
What are the necessary components of a background subtraction algorithm?

- Can be used to achieve our physics goal
- Can be used in experimental measurements
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Minimal assumption on the factorization of “soft” physics and “hard” physics.

Classification should be theoretically sound and reproducible in calculations.

Don’t do background subtraction if it is not necessary – provide raw measurements along with corrected results & corrections.
Some Lessons

Event display physics:
In central collisions many of the di-jets are observed to be not balanced!
Angular correlations of jets is unmodified by the medium Energy imbalance increases with centrality!

**Use Asymmetry ratio:**

\[ A_j = \frac{E_T^{j1} - E_T^{j2}}{E_T^{j1} + E_T^{j2}} \]
Angular correlations of jets is unmodified by the medium
Energy imbalance increases with centrality!

Studying Back-to-back jets

\[ A_j = \frac{E_T^j - E_T^{j2}}{E_T^j + E_T^{j2}} \]

No significant dependence on leading jet \( p_T \)
Studying back-to-back results: Unfolded results

2D unfolding to account for migration in the $p_T$ of each jet separately.

Significant dependence on leading jet $p_T$
Studying back-to-back results: Unfolded results

2D unfolding to account for migration in the $p_T$ of each jet separately.

Significant dependence on leading jet $p_T$

Interpretation depends on assumptions for corrections!
“More Sensitive” Jet Substructure Observables?

To what extent can the identities of underlying partons be deduced from properties of the jets they produce?

Jet Shapes and Fragmentation Functions are expected to be sensitive to the possible medium response to hard probes and induced radiation.
Jet Shapes:

Broadened jet shape due to the possible medium response to hard probes and induced radiation!
Fragmentation Functions

Enhancement of particles with a small fraction and a large fraction pT
Measurement of jet fragmentation into charged particles in pp and PbPb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \)

The CMS collaboration

**Abstract**: Jet fragmentation in pp and PbPb collisions at a centre-of-mass energy of 2.76 TeV per nucleon pair was studied using data collected with the CMS detector at the LHC. Fragmentation functions are constructed using charged-particle tracks with transverse momenta \( p_T > 4 \text{ GeV}/c \) for dijet events with a leading jet of \( p_T > 100 \text{ GeV}/c \). The fragmentation functions in PbPb events are compared to those in pp data as a function of collision centrality, as well as dijet-\( p_T \) imbalance. Special emphasis is placed on the most central PbPb events including dijets with unbalanced momentum, indicative of energy loss of the hard scattered parent partons. The fragmentation patterns for both the leading and subleading jets in PbPb collisions agree with those seen in pp data at 2.76 TeV. The results provide evidence that, despite the large parton energy loss observed in PbPb collisions, the partition of the remaining momentum within the jet cone into high-\( p_T \) particles is not strongly modified in comparison to that observed for jets in vacuum.
Measurement of jet fragmentation into charged particles in pp and PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV

The CMS collaboration

**Abstract**: Jet fragmentation functions for charged hadrons produced at forward rapidities in PbPb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV per nucleon pair were measured using the CMS detector at the Large Hadron Collider (LHC). Fragmentation functions for charged hadrons with pseudorapidities $|\eta| < 1$ and pseudorapidity $2.8 < \eta < 4.9$, and transverse momenta $p_T > 4$ GeV/$c$ from leading and subleading jet fragmentation functions in PbPb collisions at higher centrality, as well as data from pp collisions at lower centrality PbPb events including centralities of 0-30% and 30-100%, are shown. The results of the hard scattered parent particles and subleading jets in PbPb collisions agree with those seen in pp data at 2.76 TeV. The results provide evidence that, despite the large parton energy loss observed in PbPb collisions, the partition of the remaining momentum within the jet cone into high-$p_T$ particles is not strongly modified in comparison to that observed for jets in vacuum.
Jet Fragmentation Functions

Interpretation depends on where you look!
A template type analysis: Quark-gluon discrimination

Compared to gluon jets, quark jets in vacuum have:
1. Fewer constituents
2. Narrower shape
3. Harder fragmentation function and less symmetric energy sharing among constituents

1. Multiplicity: Total, Charged, Neutral → Particle-Flow in CMS
2. Width Variables

\[
\sigma = \sqrt{\sigma_1^2 + \sigma_2^2}
\]

3. Energy Sharing Variables: Pull, R, \( p_T D \), Girth

\[
|t| = \left| \frac{\sum_i p_{T,i}^2 \mid r_i \mid \mathbf{\bar{r}}_i}{\sum_i p_{T,i}^2} \right| \quad \mathbf{\bar{r}}_i = (\Delta \eta_i, \Delta \phi_i)
\]

\[
R = \frac{\max (p_{T,i})}{\sum_i p_{T,i}} \quad p_T D = \sqrt{\sum_i p_{T,i}^2} \quad p_T D = 1 \text{ single jet constituent}
\]

\[
g = \sum_i \frac{p_{T,i}^2}{p_{T,jet}^2} |r_i| \quad p_T D = 0 \rightarrow \text{number of jet constituents}
\]
A template type analysis: Quark-gluon discrimination in pp

Likelihood based discriminator obtained by combining 3 variables:
- Total multiplicity
- Minor axis
- $p_T D$

Good background rejection and signal efficiency
Stability vs pile-up is under investigation
Is not directly applicable yet to AA but combine it with other taggers.

http://cds.cern.ch/record/1599732/files/JME@13@002@pas.pdf
https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsJME13002

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Jet Shape Variables in PbPb: Dispersion & Girth

\[ p_T D = \frac{\sqrt{\sum_i p_{T,i}^2}}{\sum_i p_{T,i}} \]

\[ g = \sum_i \frac{p_{T,i}^i}{p_{T,jet}^i} |r_i| \]

\( p_T D \) distribution shifted to larger values
A selection bias towards quark jets & harder fragmenting jets?

Jet girth (the \( p_T \) weighted jet) width is narrower!
Possible bias towards quark jets?
Heavy Flavour Parton Dependence

3+ Body Secondary Vertex Tagging:
light vs c

Corrected Secondary Vertex Mass:
c vs b

suppression of b quarks in PbPb, while no suppression in pPb collisions


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Caveat: b/c jet might not be original!

At high pt region, mass effect can be neglected

Huang, Kang, Vitev

Explore multi tags such as c/b jet with D/B and γ. Many new results released!
Z/Y+jets at 5 TeV PbPb

Z bosons and photons aren’t affected by medium. Energy of the jet before energy loss is known.

CMS PAS HIN-15-013

Z/γ+jets at 5 TeV PbPb

Z/γ+jets at 5 TeV PbPb

Jets loose ~15% energy due to medium interaction
Higher statistics Future LHC data is needed!
Utilize tools developed for pp 😊 - Jet Grooming:

the systematic removal of a subset of the jet constituents

→ remove soft and wide-angle radiation from the jet

High-pT regime: $p_T > 2m/R$

Decay is collimated i.e., $qq$ are in the same jet.

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Utilize tools developed for pp 😊 - Jet Grooming:

the systematic removal of a subset of the jet constituents
remove soft and wide-angle radiation from the jet

Many methods

Trimming

Pruning

Mass-drop tagger (MDT, aka BDRS)


Courtesy to Gavin Salam
Utilize tools developed for pp 😊 - Jet Grooming: the systematic removal of a subset of the jet constituents → remove soft and wide-angle radiation from the jet

large-angle soft radiation and bkg removed by grooming!

\[
Z_g = \frac{\min(p_{T,i}, p_{T,j})}{p_{T,i} + p_{T,j}} \geq Z_{\text{cut}} \left( \frac{\Delta R_{ij}}{R_0} \right)^\beta,
\]

Check out HP 2018 Raghav Kunnawalkam Elayavalli’s talk on Thursday

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Utilizing Jet Grooming

Momentum sharing between two leading subjets
Modification of branch splitting of inclusive jet measurements!
Utilizing Jet Grooming

No clear message from model comparisons
→ Need more precise and differential data

Courtesy to Marta Verweij

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$S_{NN} = 5.02$ TeV, pp $27.4$ pb$^1$, PbPb $404$ μb$^{-1}$

- Centrality: 0-10%
  - $140 < p_{T,\text{jet}} < 160$ GeV
  - $160 < p_{T,\text{jet}} < 180$ GeV
  - $180 < p_{T,\text{jet}} < 200$ GeV

- anti-$k_T$, $R = 0.4$, $|\eta_{\text{jet}}| < 1.3$

- Soft Drop, $\beta = 0$, $z_{\text{cut}} = 0.1$, $\Delta R_{12} > 0.1$

- CMS

- JEWEL
  - Coherent antenna BDMPS
  - $g = 1$ GeV/fm$^2$, $L = 5$ fm
  - $g = 2$ GeV/fm$^2$, $L = 5$ fm

- SCET
  - Chien-Vitev
  - HT $g = 4$ GeV/fm$^2$

- $g = 1.8$
- $g = 2.2$
- Incoherent
Utilizing Jet Grooming at RHIC with di-jets

Hard Core – Dijet Selection

No observable difference in AuAu in comparison to pp

Courtesy to Kolja Kauder
Groomed Jet Mass

Grooming Independent of angular separation

Core of the jet stays the same.

Grooming for larger angular separation

The periphery of the jet is sensitive to interactions of partons with the medium during the parton shower evolution.
Jet Mass w/o grooming

Fig. 10: Fully-corrected jet mass distribution for anti-$k_T$ jets with $R = 0.4$ in the 10% most central Pb–Pb collisions compared to PYTHIA with tune Perugia 2011 and predictions from the jet quenching event generators (JEWEL and Q-PYTHIA). Statistical uncertainties are not shown for the model calculations.

No apparent change in jet mass.

Jet Mass dependence on Jet Shape

Raghav Kunnawalkam Elayavalli

Esha Rao (CEU-DNP16-EA96 Poster Session)

Jet Shape flattens with larger jet masses. Mass and Shape are convoluted variables!
Precision Studies:
Power of global data analysis

- Global fitting leverage information and differential power from individual data/observable to extract optimal amount of information
- Require large efforts in simultaneously describing background and jetty probes
  - “Standard model(s)” of HI
  - forward folding in experiments
  - quantifying contribution from individual measurement
- Cautious models’ validity and systematic bias on interpretation used in global fit

Jet Structure Observables

Courtesy of Shuzhe Shi
Why is JETSCAPE a potential solution ... 

A. Majumder, Hard Probes ‘15

- Multi-Stage Energy Loss
- … no one group can do it all
- Mission Statement: **Extensive, extensible event generator**
- Note: Framework is agnostic to “multi-stage”, ”energy loss”

**JETSCAPE**: Theoretical and experimental physicists, computer scientists, statisticians

Courtesy to Joern Putschke
Why is JETSCAPE a potential solution ...

A. Majumder, Hard Probes '15

JETSCAPE:
Theoretical and experimental physicists, computer scientists, statisticians

Note: Framework is agnostic to "multi-stage", "energy loss"

Use MC to study detector performance/sensitivity to quenching observables.

Courtesy to Joern Putschke
Jets are useful probes to study QGP. We have learned a lot about QGP w/o & w reconstructing jets. Reconstructed jets with its structure evolution allow us to do global data analysis.
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Treatment of background & fakes need to be handled carefully. Choice of measurement regions could affect physics interpretation.
Jets are useful probes to study QGP.  
We have learned a lot about QGP w/o & w reconstructing jets.  
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Treatment of background & fakes need to be handled carefully.  
Choice of measurement regions could affect physics interpretation.  

Conclusions  
● We need to talk about background  
● We should try to measure the same things  
● We should report correlations between uncertainties  
● We should ask whether we’re learning something  
● We should think about what we’re not seeing  

So the thing is, you should do it the way I do it because your way is wrong.  

http://www.memes.com/searchresults/sex/205126  

Courtesy to Christine Nattrass