Measurements of jets in heavy ion collisions

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Largely based on Connors, Nattrass, Reed, & Salur
arxiv:1705.01974, accepted in RMP
How to make a Quark Gluon Plasma

1. Heat
2. Compress
3. Nucleon boundary irrelevant

nucleus
The phase transition in the laboratory

Initial State

QGP

Freeze-out

Hydrodynamical flow

Jet quenching

Initial State


https://physics.aps.org/articles/v7/97


https://physics.aps.org/articles/v7/97

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Relativistic Heavy Ion Collider

Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, U+U
\( \sqrt{s_{NN}} = 9 - 200 \text{ GeV} \)

Geneva, Switzerland
8.6km diameter
Pb, Pb+Pb
2.76 GeV, 5.5 TeV
Trigger detectors: When do we have a collision?
Tracking detectors: Where did the particle go?
Identification detectors: What kind of particle is it?
Calorimeters: How much energy does the particle have?
p+p collisions

3D image of each collision
Pb+Pb collisions
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
What is a jet?
What is a jet?

\[ p+p \rightarrow \text{dijet} \]
What is a jet?

\[ p+p \rightarrow \text{dijet} \]

“I know it when I see it”

US Supreme Court Justice Potter Stewart,

Jacobellis v. Ohio
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.
A jet is what a jet finder finds.
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
- Large, fluctuating, correlated background
- Sensitive to methods to suppress combinatorial jets and correct energy
- Focus on narrow/high energy jets
Energy loss
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

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

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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
Nuclear modification factor $R_{AA}$

- **Electromagnetic probes** – consistent with no modification – medium is transparent to them
- **Strong probes** – significant suppression – medium is opaque to them - even heavy quarks!
Jet $R_{AA}$

- Jet $R_{AA}$ also demonstrates suppression
Di-hadron correlations

\[ p+p \rightarrow \text{dijet} \]

Associated

\[ \text{nucleus} \rightarrow \text{nucleus} \]

Trigger

\[ 1/N_{\text{Trigger}} \frac{dN}{d(\Delta \phi)} \]

\[ \Delta \phi \text{ (radians)} \]

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\[ \text{p+p min. bias} \]

\[ \text{Au+Au Central} \]
Di-hadron correlations

\[ p+p \rightarrow \text{dijet} \]

Updated to include latest information about background
**Di-hadron correlations**

"Too many to list"

*Phys. Rev. C84* :024906, 2011,
*Phys. Lett. B* 712 (2012) 176,
*Phys. Rev. Lett.* 105:252303, 2010,

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**γ-jet correlations**

*Phys. Rev. C80* :024908, 2009,
*Phys. Rev. D82*:072001, 2010,
*Phys. Rev. C82*:034909, 2010

*Physics Letters B* 760 (2016)

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**Jet $v_2$**

*Phys. Lett. B* 753 (2016) 511-525,

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**High-$p_T$ hadron $v_2$**

*too many to list*

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**γ-jet correlations**

*Phys. Rev. C84*:024906, 2011,
*Phys. Lett. B* 712 (2012) 176,
*Phys. Rev. Lett.* 105:252303, 2010,

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**Dijet asymmetry**

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Fragmentations from $\gamma$-hadron correlations

- Enhancement at low $z$
- Slight suppression at high $z$

$$z = \frac{p_T}{E_\gamma}$$

$5 < p_T^\gamma < 9$ GeV/c $\times 0.5 < p_T^h < 7$ GeV/c

- Global sys = $\pm 6\%$

0-40% Au+Au @ 200 GeV
Modified fragmentation

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

$z = \frac{p_T}{E_y}$
Jet-hadron correlations vs reaction plane

Full jets
1) signal+bkgd
2) bkgd dominated
3) bkgd RPF fit

Trigger

- No modification of constituents relative to reaction plane
  → Jet-by-jet fluctuations more important than path length [PLB 735 157(2014)]
  - Also needed to explain high $p_T \nu_2$ [PRL 116 252301 (2016)]
Jet-hadron correlations

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

Fragmentation functions with jets

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

Di-hadron correlations

[Lots of papers]

Jet shapes


Jet-hadron correlations

Di-jet asymmetry

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

Kolja Kauder,
RHIC/AGS
User's Meeting
2016
Jet structure
Christine Nattrass (UTK), Prague, May 2019

\[ g = \sum_{i \in \text{jet}} \frac{p_T^i}{p_T^{\text{jet}}} r_i \]

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

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

Jets are slightly more collimated than in pp

Agrees with PYTHIA
Theory
Data

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

QGP brick + jet

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

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

200 GeV Au+Au

2.76 TeV Pb+Pb
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

Constraint of QGP properties
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
Event Generator + Bayesian Statistical analysis

Realistic theoretical calculations

Data

Bayesian Statistical Analysis

Constraint of QGP properties

Christine Nattrass (UTK), Prague, May 2019
Undergraduates!*  

*And one beginning graduate student with no programming experience. We acknowledge substantial support from the US NSF and the JETSCAPE Collaboration.
Early Engagement in Course-Based Research Increases Graduation Rates and Completion of Science, Engineering, and Mathematics Degrees

Stacia E. Rodenbusch, Paul R. Hernandez, Sarah L. Simmons, and Erin L. Dolan

Published Online: 13 Oct 2017 | https://doi.org/10.1187/cbe.15-03-0117

Abstract

National efforts to transform undergraduate biology education call for research experiences to be an integral component of learning for all students. Course-based undergraduate research experiences, or CUREs, have been championed for engaging students in research at a scale that is not possible through apprenticeships in faculty research laboratories. Yet there are few if any studies that examine the long-term effects of participating in CUREs on desired student outcomes, such as graduating from college and completing a science, technology, engineering, and mathematics (STEM) major. One CURE program, the Freshman Research Initiative (FRI), has engaged thousands of first-year undergraduates over the past decade. Using propensity score–matching to control for student-level differences, we tested the effect of participating in FRI on students’ probability of graduating with a STEM degree, probability of graduating within 6 yr, and grade point average (GPA) at graduation. Students who completed all three semesters of FRI were significantly more likely than their non-FRI peers to earn a STEM degree and graduate within 6 yr. FRI had no significant effect on students’ GPAs at graduation. The effects were similar for diverse students. These results provide the most robust and best-controlled evidence to date to support calls for early involvement of undergraduates in research.
Phys 494 – Course-based Undergraduate Research Experience in Relativistic Heavy Ion Physics

Instructor:
Dr. Christine Nattrass
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Office hours: TBA

Teaching assistant: N/A

Class time & Location: TR 12:40-1:55 SERF 210

Course Description:
This course will incorporate undergraduates into a research project in high energy nuclear physics in a course setting. Each student will be responsible for implementing a heavy ion analysis in the program RIVET so that it can be used by the JETSCAPE collaboration to make comparisons between Monte Carlo models and data. Each student’s project will be incorporated into a public software repository so that it is available to the field and, if possible, it will be validated by the relevant experiment and incorporated into the official RIVET software.
Analyses (almost) implemented in UTK copy of RIVET

https://github.com/cnattras/rivet-hi

Need to be finalized! Hold me to it!
What have we accomplished?
- Qualitative confirmation of partonic energy loss models
- Quantitative constraints of $\hat{q}$
- Lots of measurements

What do we still have to do?
- Understand bias
- Make quantitative comparisons to theory
- Make more differential measurements
- We need an accord on how to treat background

Connors, Nattrass, Reed, SalurarXiv:1705.01974 [nucl-ex]