Quantifying properties of liquid nuclei

Christine Nattrass, University of Tennessee, Knoxville
How to make a Quark Gluon Plasma

1. Heat the nucleus
2. Compress the nucleus
3. The result is a Quark Gluon Plasma (QGP)

nucleon boundary
irrelevant
The phase transition in the laboratory

Initial State

QGP

Freeze-out

Hydrodynamical flow

Jet quenching

K, O’Hara, S. Hemmer, M. Gehm, S. Granade, J. Thomas
Science 298 2179 (2002)

https://physics.aps.org/articles/v7/97
Relativistic Heavy Ion Collider

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

Large Hadron Collider

- **Geneva, Switzerland**
  - 8.6km diameter
  - \( p+p, p+Pb, Pb+Pb \)
  - \( \sqrt{s_{NN}} = 2.76 \text{ GeV, 5.5 TeV} \)
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
Pb+Pb collisions

Pb+Pb @ sqrt(s) = 2.76 ATeV
2010-11-08 11:29:42
Fill : 1482
Run : 137124
Event : 0x000000271EC893
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
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

\[ R_{AA} = \frac{d^2N_{AA}/dp_Td\eta}{T_{AA}d^2\sigma_{pp}/dp_Td\eta} \]
Nuclear modification factor

![Graph showing nuclear modification factor](image-url)
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!

**RHIC**

$R_{AA} = 200 \text{ GeV, 0-10\% most central}$

- $\gamma$ (PRL109, 152302)
- $J/\psi$ 0-20\% cent. (PRL98, 232301)
- $\pi^0$ (PRL101, 232301)
- $\omega$ 0-20\% cent. (PRC84, 044902)
- $\eta$ (PRC82, 011902)
- $\phi$ (PRC83, 024904)
- $K^-$ (PRC83, 064903)
- $\rho$ (PRC83, 064903)

**LHC**

$R_{AA} = 2.76 \text{ TeV}$

- $0-10\%$ $\gamma$ EPJC 72 (2012) 1945
- $0-10\%$ $Z$ JHEP 03 (2015) 022

**ALICE**

- $0-5\%$ $\pi^0$ Phys. Rev. C 93 (2016) 034913
- $0-10\%$ $\gamma$ PLB 710 (2012) 256

**CMS**

- $0-10\%$ $h^1$ JHEP 03 (2016) 081

Christine Nattrass, University of Tennessee, Knoxville, 26 Sept. 2022
D^0-tagged jets

ALICE Preliminary
0-10% Pb–Pb \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \)
charged jets, anti-\(k_T\)

D^0-jet, \( R = 0.3 \)
\( 3 < p_{T,D} < 36 \text{ GeV/c} \)
Inclusive jets, \( R = 0.2 \)
Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles.

Christine Nattrass, University of Tennessee, Knoxville, 26 Sept. 2022
Jet reconstruction

- Identify all of the particles in the jet → parton energy, momentum
- Difficult in heavy ion collisions – but possible!
Di-hadron correlations

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

Associated

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

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

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

\[ \text{Au+Au Central} \]

\text{STAR}

\text{Phys.Rev.Lett.93:252301,2004}
Method development

Sharma, Mazer, Stuart, & Nattrass, Phys. Rev. C 93 (2016), 044915
Nattrass & Todoroki, Phys. Rev. C 97 (2018), 054911
Sharma, Perez, Castro, Kumar, & Nattrass, Phys. Rev. C 98 (2018), 014914

Christine Nattrass, University of Tennessee, Knoxville, 26 Sept. 2022
Di-hadron correlations

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

Nattrass, Sharma, Mazer, Stuart, Bejnood

\[
\frac{1}{N} dN d\Delta\phi
\]

\[ v_1, \tilde{v}_3 \]

\[ v_1, \tilde{v}_3 \]

\[ \Delta\phi \]

\[ d+Au, \text{arXiv:1010.0690} \]
Jet-hadron correlations vs reaction plane

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


Trigger

Associated

Joel Mazer
Jet-hadron correlations vs reaction plane

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

Trigger

Charles Hughes

Associated
Towards quantitative understanding
There is no partionic energy loss.
There is only partionic energy redistribution.
Signal vs Background: The standard paradigm

Background

Combinatorial jets

Signal

*Some gray areas

More work in progress
Adopted by all major experiments (PHENIX)

HEPMC

Rivet

Comparison to data

Now standard! See HEPMC in HI Workshop

1-week workshop for implementing analyses in Rivet
**Undergraduates!***

- 5 semesters
- 20 students
- 10 women
- 5 minorities
- 3 non-traditional

All Rivet students

- 35 students
- 14 women
- 10 minorities
- 5 non-traditional

Left to right: Ricardo Santos (Berea), James Neuhaus, Jerrica Wilson, Mariah McCreary, Christine Nattrass, Austin Schmier (UTK)

*And one beginning graduate student*
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
Christopher Nattrass, University of Tennessee, Knoxville, 26 Sept. 2022

Bayesian Statistical Analysis
Models and Data Analysis Initiative
http://madai.us

**Monte Carlo models**

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

**Data**

- ALICE Preliminary

**Prior**

- Optimization

- Constraint of QGP properties
First online workshop in heavy ion physics?

- Over >180 participants (was: ~20)
- Recorded and posted lectures online → resource for community
- Broadened participation
- Increased software downloads, citations
Bayesian Parameter Estimation - $\hat{q}$


Still only includes single hadrons!
Take home messages

- If we get nuclear matter dense enough, we make a new phase of matter, which we produce in high energy heavy ion collisions.
- This medium is opaque to colored probes and translucent to electromagnetic probes.
- We can quantify its properties with realistic models.
Event Generator + Bayesian Statistical analysis

Realistic theoretical calculations

Bayesian Statistical Analysis

Constraint of QGP properties

Data

Christine Nattrass, University of Tennessee, Knoxville, 26 Sept. 2022
Course-based undergraduate research experience

Ask me if you want more info!

Phys 494 – Course-based Undergraduate Research Experience in Relativistic Heavy Ion Physics

Instructor:
Dr. Christine Nattrass
Office: SERF 609
Phone: 974-6211
Email: christine.nattrass@utk.edu
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.

3 semesters
15 students
8 women
3 minorities
3 non-traditional

All Rivet students
22 students
11 women
7 minorities
4 non-traditional

Christine Nattrass, University of Tennessee, Knoxville, 26 Sept. 2022