The Smallest Drops of the Hottest Matter
Exploring the Small Size Limit of the Quark Gluon Plasma

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how hot?
how hot?

80 ° F
how hot?

80 ° F

2000 ° F
how hot?

80 °F

2000 °F

28M °F
how hot?

- 80 ° F
- 2000 ° F
- 28M ° F
- 150B ° F
how hot?

- 80 °F
- 2000 °F
- 28M °F
- 150B °F
- 5T °F

quark-gluon plasma
no photo available
The nucleus

- >99% of the mass of atoms, and thus normal matter, is in the nucleus
- composed of protons and neutrons, nucleons
- these nucleons are held together by the strong force
- one of the 4 fundamental forces of nature
- characterized by very strong short range interactions
and what’s inside protons and neutrons?

fundamental particles which interact via the strong force

**quarks** and **gluons**

**valence** quarks define the hadron
also a **sea** of (anti)quarks & gluons
and what’s inside protons and neutrons?

fundamental particles which interact via the strong force

**quarks and gluons**

**confinement**
quarks & gluons are bound inside color neutral particles

**valence** quarks define the hadron
also a **sea** of (anti)quarks & gluons
and what’s inside protons and neutrons?

fundamental particles which interact via the strong force

**quarks and gluons**

confinement
quarks & gluons are bound inside color neutral particles

valence quarks define the hadron
also a sea of (anti)quarks & gluons

confinement makes the strong force hard to study because the details are locked inside the protons and neutrons
strong force at high temperature

a system that’s hot and dense enough for the quarks and gluons to not be confined anymore
strong force at high temperature

a system that’s hot and dense enough for the quarks and gluons to not be confined anymore

nucleus
(many protons & neutrons)
strong force at high temperature

a system that’s hot and dense enough for the quarks and gluons to not be confined anymore

nucleus
(many protons & neutrons)

+ energy
strong force at high temperature

to create a system that’s hot and dense enough for the quarks and gluons to not be confined anymore: the **quark gluon plasma**
Colliders at BNL and CERN

**RHIC**

0.200 TeV collision energy
Au+Au

**LHC**

2.76 TeV collision energy
Pb+Pb
relativistic heavy ion collisions

Quark Gluon Plasma
relativistic heavy ion collisions

Quark Gluon Plasma

lasts for a billionth of a trillionth of a second
and billion times smaller than a pixel on an iPhone display
relativistic heavy ion collisions

Quark Gluon Plasma

lasts for a billionth of a trillionth of a second and billion times smaller than a pixel on an iPhone display

when two individual nuclei collide they create a droplet of this matter this process happens thousands of times a second
relativistic **heavy** ion collisions

**Quark Gluon Plasma**

lasts for a billionth of a trillionth of a second
and billion times smaller than a pixel on an iPhone display

when two individual nuclei collide they create a droplet of this matter
this process happens thousands of times a second

we watch the collisions, we cannot do anything external to it
what do we see?

hundreds or thousands of **new** particles are created in each collision

$$E = mc^2$$

these particles provide the only window into the earlier stages of the collision
we look at each collision individually, but measure billions of collisions!
RHIC @ Brookhaven

- RHIC
- NSRL
- LINAC Booster
- AGS
- Tandems
- EBIS
- BLIP
- PHENIX 8:00 o'clock
- STAR 6:00 o'clock
PHENIX Detector
PHENIX Detector
the aftermath of a collision
the aftermath of a single collision
collision geometry

view: one nuclei going into the screen and one coming out
collision geometry

view: one nuclei going into the screen and one coming out

varying the distance between the nuclei, changes the shape and size of the region where the nuclei overlap
collision geometry

view: one nuclei going into the screen and one coming out

varying the distance between the nuclei, changes the shape and size of the region where the nuclei overlap

the parts of the nuclei that don’t overlap continue on and don’t play a role
counting particles

\[ \sum \cos(\phi) \]

\[ \sum \sin(\phi) \]

\[ \phi \quad [\text{rad}] \]

\[ \text{Fig. 1.} \]

\[ \Psi \]

\[ \text{Fig. 2.} \]

\[ \sum dp \]

\[ \sum p \]

\[ E_\text{cal} \]

\[ \eta \]

\[ \Delta \]

\[ \phi \]

\[ n \]

\[ v \]

\[ \sin \theta \]

\[ \cos \theta \]

\[ \alpha \]

\[ \alpha_\text{corr} \]

\[ \text{Fig. 3.} \]

\[ \eta \]

\[ \Delta \]

\[ \phi \]

\[ \Psi \]

\[ \text{Fig. 4.} \]

\[ \eta \]

\[ \Delta \]

\[ \phi \]

\[ \Psi \]

\[ \text{Fig. 5.} \]
collision geometry

\[
\begin{align*}
\text{Correlation of individual track azimuthal angles with the event plane, in eight centrality intervals. These distributions are meant to illustrate the observed correlation relative to the event plane, and are not used in the quantitative estimates of the final state momentum anisotropy. The modulation is largest in the 20–50% centrality intervals, and decreases for the more central and peripheral events. In the central 1–2 GeV, there is a clear sinusoidal modulation at all centralities. The final state momentum anisotropy can be quantified by the $F_{\text{Cal}}$ distribution divided into 10% centrality intervals (black).}
\end{align*}
\]
collision geometry

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![Diagram of collision geometry](image)

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The collision geometry illustrates the observed correlation relative to the event plane, and are not used in the full FCal analysis, due to the relatively large uncertainties in determining the appropriate selection criteria. To verify that this does not bias the measurement, we have extracted the odd amplitudes from this subsample have been found to be stable for the full data. In Ref. 98%, with an uncertainty of 2%. This is similar to estimates given by the trigger and event selection has been estimated to be primarily reflects fluctuations in the initial-state collision geometry.
collision geometry

more particles come out the long side than the short side!
interactions are important
interactions are important
liquid rather than a gas
liquid rather than a gas

steep pressure change
liquid rather than a gas
liquid rather than a gas

gradual pressure change
characterizing a liquid

• liquids flow
characterizing a liquid

- liquids flow

  low viscosity
characterizing a liquid

- liquids flow

low viscosity  

high viscosity
liquid QGP
Of events with the smallest FCal average number of reconstructed tracks in each interval. The 20% analysis, due to the relatively large uncertainties in determining the correlation with data on an event-by-event basis, according to the scheme outlined in a previous ATLAS publication.

Fig. 1. Distribution of the azimuthal angle of individual tracks relative to the measured event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are meant to estimate the event plane, in eight centrality intervals. These distributions are mean
liquid QGP

QGP flows well!

low viscosity

\[ \eta/s > 25 \ (1/4\pi) \]
liquid QGP

QGP flows well!

\[ \eta/s(\text{QGP}) < 5 \ (1/4\pi) \]

\[ \eta/s > 25 \ (1/4\pi) \]

low viscosity
QGP flows well!

low viscosity

\[ \eta/s(QGP) < 5 \ (1/4\pi) \]

string theory calculation: universal minimum
\[ \eta/s > 1/4\pi \]

\[ \eta/s > 25 \ (1/4\pi) \]
liquid QGP

QGP flows well!

\[ \eta/s(QGP) < 5 \, (1/4\pi) \]

string theory calculation:
universal minimum
\[ \eta/s > 1/4\pi \]

determining \( \eta/s(QGP) \) is very important

\[ \eta/s > 25 \, (1/4\pi) \]

low viscosity
shape changes and particle distributions
isolating shape effects

RHIC

number of produced particles
isolating shape effects

LHC

15x bigger collision energy

RHIC

number of produced particles
characterizing particle distributions
characterizing particle distributions

\[ v_2 \text{ is the strength of the modulation} \]
$v_2$ in heavy ion collisions

![Graph showing $v_2$ vs. number of produced particles for Au+Au and Pb+Pb collisions at RHIC and LHC.](image)

- **Au+Au** $\sqrt{s}=0.200$ TeV at RHIC
- **Pb+Pb** $\sqrt{s}=2.76$ TeV at LHC

The graph illustrates the evolution of $v_2$ with the number of produced particles for different collision energies and systems.
quantifying shapes

eccentricity ($\varepsilon_2$) is related to how elongated any shape is

\[ \varepsilon_2 = 0 \quad \varepsilon_2 = 0.17 \quad \varepsilon_2 = 0.50 \quad \varepsilon_2 = 1 \]
ratio: $v_2 / \varepsilon_2$

\[ v_2 / \varepsilon_2 \]

\[ \text{number of produced particles} \]

\[ \text{LHC} \]

\[ \text{RHIC} \]

\[ \text{Au+Au } \sqrt{s} = 0.200 \text{ TeV} \]

\[ \text{Pb+Pb } \sqrt{s} = 2.76 \text{ TeV} \]

\[ \text{=0.200 TeV } \]

\[ \text{=2.76 TeV } \]
ratio: $v_2 / \varepsilon_2$

The relationship between geometry ($\varepsilon_2$) and $v_2$ is a signature of small viscosity QGP.

![Graph showing $v_2 / \varepsilon_2$ vs. number of produced particles for RHIC and LHC experiments.](image)
How Small can the Quark Gluon Plasma Be?
why take something so small and make it smaller?

- changing the shape and size of the QGP help to measure the viscosity
why take something so small and make it smaller?

- is a QGP this small possible?
- could be an extreme variation of the size and time evolution from heavy ion collisions
v2 in p+Pb collisions @ the LHC

\[ v_2 / \varepsilon_2 \] vs. number of produced particles

- ATLAS p+Pb \( \sqrt{s}=5 \) TeV
- ALICE p+Pb \( \sqrt{s}=5 \) TeV
big vs small collisions

large $\varepsilon_2$

small $\varepsilon_2$
big vs small collisions

can we have a collision with large eccentricity, but similar size to p+Pb?
varying the small nucleus

d+Au
large $\varepsilon_2$

p+Pb
small $\varepsilon_2$

deuteron (d): 1 proton and 1 neutron
which way does the ellipse go?

in any given event, we can’t control it and it’s hard to measure for these small systems
looking for v2 in d+Au

correlations between pairs of particles
each particle knows something about the collision orientation, but the precision is low

also, there are lots of reasons for particles to be correlated
looking for v2 in d+Au

correlations between pairs of particles
each particle knows something about the collision orientation, but the precision is low

also, there are lots of reasons for particles to be correlated

signal + background
looking for v2 in d+Au

correlations between pairs of particles

each particle knows something about the collision orientation, but the precision is low

also, there are lots of reasons for particles to be correlated

![Graph showing Δφ correlations between pairs of particles](image)

\[ [0.5,0.75] \times [0.75,1.0] \text{ GeV/c} \]
\[ |\Delta \eta| \in [0.48,0.7] \]

- Y_c 0-5% d+Au
- Y_p 50-88% d+Au

signal + background

background
hunting down the signal

correlations between pairs of particles
each particle knows something about the collision orientation, but the precision is low

$Y(\Delta \phi), \Delta Y(\Delta \phi)$

d+Au $s_{_{NN}} = 200$ GeV $|\Delta \eta| \in [0.48,0.7]$

signal - background
hunting down the signal

correlations between pairs of particles

each particle knows something about the collision orientation, but the precision is low

$\Delta \phi$

$v_2^2 \cos 2\Delta \phi$

signal - background
\( v_2 / \varepsilon_2, \) expectations in d+Au

![Graph showing the relationship between \( v_2 / \varepsilon_2 \) and the number of produced particles for different collisions.](attachment:image.png)

- ATLAS p+Pb, \( \sqrt{s} = 5 \text{ TeV} \)
- ALICE p+Pb, \( \sqrt{s} = 5 \text{ TeV} \)
$v_2 / \varepsilon_2$, expectations in d+Au

number of produced particles

$QGP$
\( \frac{v_2}{\varepsilon_2} \)

- **d+Au** \( \sqrt{s}=0.200 \) TeV
- **ATLAS** p+Pb \( \sqrt{s}=5 \) TeV
- **ALICE** p+Pb \( \sqrt{s}=5 \) TeV
a small QGP?

continuous behavior from big to small collisions

\[
\frac{V_2}{\varepsilon_2} = 0.200 \text{ TeV for } s = 0.200 \text{ TeV}
\]

\[
\text{ATLAS p+Pb } \sqrt{s} = 5 \text{ TeV}
\]

\[
\text{ALICE p+Pb } \sqrt{s} = 5 \text{ TeV}
\]

\[
\text{d+Au } \sqrt{s} = 0.200 \text{ TeV}
\]

\[
\text{Au+Au } \sqrt{s} = 0.200 \text{ TeV}
\]

\[
\text{Pb+Pb } \sqrt{s} = 2.76 \text{ TeV}
\]

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number of produced particles

continuous behavior from big to small collisions
a small QGP?

![Graph showing continuous behavior from big to small collisions](image)

**Number of produced particles**

**Continuous behavior from big to small collisions**
a small QGP?

continuous behavior from big to small collisions

\begin{align*}
\epsilon \left/ \varepsilon_2 \right. &= 0.200 \text{ TeV} \\
\sqrt{s} &= 0.200 \text{ TeV} \\
\sqrt{s} &= 2.76 \text{ TeV} \\
\sqrt{s} &= 5 \text{ TeV} \\
p+Pb, \ d+Au \\
\text{Au+Au, Pb+Pb}
\end{align*}
a small QGP?

![Graph showing continuous behavior from big to small collisions](Diagram)

- d+Au $\sqrt{s}=0.200$ TeV
- Au+Au $\sqrt{s}=0.200$ TeV
- Pb+Pb $\sqrt{s}=2.76$ TeV
- ATLAS p+Pb $\sqrt{s}=5$ TeV
- ALICE p+Pb $\sqrt{s}=5$ TeV

**PHENIX PRL 111 212301 (2013)**

- number of produced particles
- continuous behavior from big to small collisions
particle distributions reflect initial shape

in big & small collisions…
each nucleus is a little different

- 200 protons and neutrons move around within the nucleus
each collision is unique
each collision is unique
each collision is unique
shape control

small $\varepsilon_2$

large $\varepsilon_2$
Sensitivity of $v_n$ on viscosity and fluctuations


more sensitive

more sensitive

Au+Au $p_s = 200$ A GeV

viscous to ideal results

smoother to more granular results

Viscosity decreases anisotropic flow (it's friction)

Smoother initial conditions decrease anisotropic flow

Sensitivity to viscosity and initial state structure increases with

Björn Schenke (BNL)

BNL, March 2013

17/45
shape control

small $\varepsilon_2$

large $\varepsilon_2$

small $\varepsilon_3$

Björn Schenke (BNL)
BNL, March 2013

Sensitivity of $v_n$ on viscosity and fluctuations

$\frac{v_n(\text{viscous})}{v_n(\text{ideal})}$

$\frac{v_n(\eta/s=0.08)}{v_n(\text{ideal})}$

$\frac{v_n(\eta/s=0.16)}{v_n(\text{ideal})}$

$\frac{v_n(\sigma_0A)}{v_n(\sigma_0B)}$

$\frac{v_n(\sigma_0=0.4)}{v_n(\sigma_0=0.2)}$

$\frac{v_n(\sigma_0=0.8)}{v_n(\sigma_0=0.2)}$

more sensitive

more sensitive

Au+Au $p_s = 200$ A GeV

viscous to ideal results

smoother to more granular results

Viscosity decreases anisotropic flow (it's friction)

Smoother initial conditions decrease anisotropic flow

Sensitivity to viscosity and initial state structure increases with
shape control

small $\varepsilon_2$

large $\varepsilon_2$

small $\varepsilon_3$

large $\varepsilon_3$


Sensitivity of $v_n$ on viscosity and fluctuations

Viscosity decreases anisotropic flow (it's friction)

Smoother initial conditions decrease anisotropic flow

Sensitivity to viscosity and initial state structure increases with $n$

Visit Björn Schenke (BNL)

BNL, March 2013

17/45
a triangular nucleus?

deuteron: 1 proton, 1 neutron
helium 3 ($^3$He): 2 protons, 1 neutron
a triangular nucleus?

deuteron: 1 proton, 1 neutron
helium 3 ($^3$He): 2 protons, 1 neutron
a triangular nucleus?

deuteron: 1 proton, 1 neutron
helium 3 ($^3$He): 2 protons, 1 neutron
a triangular nucleus?

deptron: 1 proton, 1 neutron
helium 3 ($^3$He): 2 protons, 1 neutron

very successful $^3$He+Au run concluded last week, analysis in progress!
jets in proton-proton collisions
probing the QGP with jets

\textit{p+p collisions}

hadrons

jet

jet

hadrons
probing the QGP with jets
probing the QGP with jets
probing the QGP with jets
jet quenching

ATLAS PRL 105 252303
jet quenching

ATLAS PRL105 252303
where does the energy not found in the jets end up? what does that tell us about the matter we’re studying?
Detector Overview

**sPHENIX Detector Requirements**

**Hadronic Calorimeter**

An iron-scintillator sampling calorimeter outside the cryostat. In order to minimize the mass and bulk, the calorimeter doubles as the flux return for the solenoid. A thickness of 5\( \text{in} \) combined with the electromagnetic calorimeter in front is sufficient to fully contain the energies of interest, and provide more than enough iron for the full flux return. The hadronic calorimeter is divided into two longitudinal compartments consisting of plates running parallel to the beam axis with scintillator plates interleaved, then read out via embedded wavelength shifting fiber. The hadronic calorimeter will use the same silicon photomultiplier sensors as the electromagnetic calorimeter and similar electronics. The coarser segmentation (\( D_h \times D_f \approx 0.1 \times 0.1 \)) results in an electronic channel count of about 10% that of the electromagnetic calorimeter.

**Readout electronics**

Bias voltage and analog signal processing for silicon photomultipliers in physical proximity to the sensors, with a number of options for the digitization and buffering using either commercial components or integrated circuits adapted from existing experimental projects.

Figure 2.1: Cutway view of the detector.

The detector concept that has resulted from these considerations is shown in Figure 2.1 and Figure 2.2 and will be described in detail in Chapter 3. Taking advantage of both technological developments in the era of RHIC and LHC experiments, and building on...
between RHIC & LHC initial QGP temperature is changed

what does the combination of flow and jets tell us about how the QGP works?
exploring the strong force

- creating a picture of the quark-gluon plasma by using the geometry and variations of the nuclei collided at RHIC and the LHC
- very small nuclei are providing a unique control of the geometry
- excited to be able to fully exploit this technique at RHIC with p+Au, d+Au, and 3He+Au collisions soon!
acknowledgements

• all the members of the PHENIX Collaboration
• my colleagues at BNL
• funded through DOE Office of Science
investigating initial state of the nucleus?
investigating initial state of the nucleus?
investigating initial state of the nucleus?

- electrons are point-like particles
investigating initial state of the nucleus?

- electrons are point-like particles

eRHIC upgrade to allow electrons at RHIC timescale ~ 2025