Quark Gluon Plasma and the LHC Revolution

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Quark Gluon Plasma and the LHC Revolution

Lessons from the cosmos
Earth based experiments
Discoveries and new challenges
Towards the most fundamental questions
Nuclear Physics: How Did Matter Form?

Theory: Quark Gluon Plasma
Accelerators: LHC, RHIC, FAIR
Nuclear Physics: How Did Matter Form?

Theory: Quark Gluon Plasma
Accelerators: LHC, RHIC

Theory: Nucleosynthesis
Accelerators: RHIC, F-RIB, FAIR
Geneva with Large Hadron Collider Superimposed

First beam in 2009
High Energy Collision
“Quark Soup”
quarks and gluons

“Ordinary Particles”
protons, neutrons, etc.
“Quark Soup”
quarks and gluons

Experiment:
quark gluon fluid
flows like a liquid

“Ordinary Particles”
protons, neutrons, etc.
Quarks are Confined

Quarks

- Electromagnetism
- Strong force: Quantum Chromodynamics

**Baryons** = $qqq^*$

<table>
<thead>
<tr>
<th>Baryon</th>
<th>Quarks</th>
<th>Electric Charge</th>
<th>Mass</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>uud</td>
<td>+1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>\bar{p}</td>
<td>\bar{u}d</td>
<td>-1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>udd</td>
<td>0</td>
<td>0.940</td>
<td>1/2</td>
</tr>
<tr>
<td>\Lambda</td>
<td>uds</td>
<td>0</td>
<td>1.116</td>
<td>1/2</td>
</tr>
<tr>
<td>\Omega^-</td>
<td>sss</td>
<td>-1</td>
<td>1.672</td>
<td>3/2</td>
</tr>
<tr>
<td>\Sigma^c</td>
<td>uuc</td>
<td>+2</td>
<td>2.455</td>
<td>1/2</td>
</tr>
<tr>
<td>Many others!!</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Mesons** = $q\bar{q}$

<table>
<thead>
<tr>
<th>Meson</th>
<th>Quarks</th>
<th>Electric Charge</th>
<th>Mass</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>\pi^+</td>
<td>u\bar{d}</td>
<td>+1</td>
<td>0.140</td>
<td>0</td>
</tr>
<tr>
<td>K^-</td>
<td>s\bar{u}</td>
<td>-1</td>
<td>0.494</td>
<td>0</td>
</tr>
<tr>
<td>K^0</td>
<td>d\bar{s}</td>
<td>0</td>
<td>0.498</td>
<td>0</td>
</tr>
<tr>
<td>\rho^+</td>
<td>u\bar{d}</td>
<td>0</td>
<td>0.770</td>
<td>1</td>
</tr>
<tr>
<td>D^+</td>
<td>c\bar{d}</td>
<td>+1</td>
<td>1.869</td>
<td>0</td>
</tr>
</tbody>
</table>

\eta_c | c\bar{c} | 0 | 2.980 | 0    |
Generating a deconfined state

Present understanding of Quantum Chromodynamics (QCD)
- heating
- compression
→ deconfined color matter!
Expectations from Lattice QCD

$\frac{\epsilon}{T^4} \sim \# \text{ degrees of freedom}$

confined: few d.o.f.

dehconfined: many d.o.f.

$T_c \approx 173 \text{ MeV} \approx 2 \times 10^{12} \text{ K} \approx 130,000 \times T[\text{Sun's core}]$

$\epsilon_C \approx 0.7 \text{ GeV/fm}^3$
Phase Transitions

ICE  →  WATER  →  STEAM

Add heat  Add heat

Quark Gluon Plasma is another phase of matter!
A Familiar Phase Diagram
The phase diagram of QCD

- Critical point question.
- Early universe.
- Neutron stars.
- Vacuum.
- Color superconductor.
- CFL.
- Quark-gluon plasma.
- Hadron gas.
- Nucleon gas.
- Nuclei.
Baryon fluctuations and the QCD phase transition

David Bower and Sean Gavin

Department of Physics and Astronomy, Wayne State University, Detroit, Michigan 48202

(Received 5 June 2001; published 1 October 2001)

The dynamic separation into phases of high and low baryon density in a heavy ion collision can enhance fluctuations of the net rapidity density of baryons compared to model expectations. We demonstrate that event-by-event proton and antiproton measurements can be used to observe this phenomenon. We then perform real-time lattice simulations to show how these fluctuations arise and how they can survive through freeze-out.

DOI: 10.1103/PhysRevC.64.0419XX

PACS number(s): 25.75.–q, 24.85.+p, 25.70.Mn, 24.60.Ky
Fate of jets in heavy ion collisions?

idea: jets in p+p collisions

ask: what happens in Au+Au to jets which pass through medium?

Prediction: scattered quarks radiate energy (~ GeV/fm) in the colored medium:
→ decreases their momentum (fewer high $p_T$ particles)
→ “kills” jet partner on other side
Long range correlations and the soft ridge in relativistic nuclear collisions

Sean Gavin, ¹ Larry McLerran, ² and George Moschelli¹

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(Received 10 July 2008; published 19 May 2009)

Relativistic Heavy Ion Collider experiments exhibit correlations peaked in relative azimuthal angle and extended in rapidity. Called the ridge, this peak occurs both with and without a jet trigger. We argue that the untriggered ridge arises when particles formed by flux tubes in an early Glasma stage later manifest transverse flow. Combining a blast wave model of flow fixed by single-particle spectra with a simple description of the Glasma, we find excellent agreement with current data.
Long range correlations and the soft ridge in relativistic nuclear collisions

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(Received 19 May 2009; published 19 May 2009)

Soft contribution to the hard ridge in relativistic nuclear collisions

George Moschelli, Sean Gavin

Fluctuation probes of early-time correlations in nuclear collisions

Sean Gavin and George Moschelli

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(Received 25 July 2011; published 11 January 2012)

Flow fluctuations from early-time correlations in nuclear collisions

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Perfect Liquid

Off-center collisions between gold nuclei produce an elliptical region of quark-gluon medium. The pressure gradients in the elliptical region cause it to explode outward, mostly in the plane of the collision (arrows).

Sergei Voloshin, STAR

![Graph showing elliptic flow and event reconstruction](image-url)
Measuring Shear Viscosity

Elliptic and radial flow suggest small shear viscosity

Problem: initial conditions & EOS unknown

Additional viscosity probes?

What does shear viscosity do? \textbf{It resists shear flow.}

flow $v_x(z) \Rightarrow T_{zx} = -\eta \frac{\partial v_x}{\partial z}$

shear viscosity $\eta$
How Perfect?


Measuring Shear Viscosity Using Transverse Momentum Correlations in Relativistic Nuclear Collisions

Sean Gavin\textsuperscript{1} and Mohamed Abdel-Aziz\textsuperscript{2}

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(Received 30 June 2006; published 19 October 2006)

Elliptic flow measurements at the Brookhaven National Laboratory Relativistic Heavy Ion Collider suggest that quark-gluon fluid flows with very little viscosity compared to weak-coupling expectations, challenging theorists to explain why this fluid is so nearly “perfect.” It is therefore vital to find quantitative experimental information on the viscosity of the fluid. We propose that measurements of transverse momentum fluctuations can be used to determine the shear viscosity. We use current data to estimate the viscosity-to-entropy ratio in the range from 0.08 to 0.3 and discuss how future measurements can reduce this uncertainty.
Measuring Shear Viscosity Using Transverse Momentum Correlations in Relativistic Nuclear Collisions

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(Received 30 June 2006; published 19 October 2006)

Elliptic flow measurements at the Brookhaven National Laboratory Relativistic Heavy Ion Collider

PHYSICAL REVIEW C 70, 034905 (2004)

Causal diffusion and the survival of charge fluctuations in nuclear collisions

Mohamed Abdel Aziz and Sean Gavin

Physics and Astronomy Department, Wayne State University, 666 W Hancock, Detroit, Michigan 48201, USA

(Received 22 April 2004; published 28 September 2004)

Fluctuating Hydrodynamics Confronts the Rapidity Dependence of Transverse Momentum Fluctuations

Rajendra Pokharel\textsuperscript{a}, Sean Gavin\textsuperscript{a} and George Moschelli\textsuperscript{b}

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The future is bright

A three prong approach:
lower energy
better facility
higher energy

FAIR:
Facility for Antiproton & Ion Research

RHIC:
RHIC upgrade with higher luminosity and upgraded detectors

LHC:
Large Hadron Collider with ALICE, CMS, ATLAS