Recent topics in relativistic heavy ion collisions and QGP

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RHIC Scientists Serve Up 'Perfect' Liquid

New state of matter more remarkable than predicted — raising many new questions

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TAMPA, FL — The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) — a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory — say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the billions of trillions of RHIC-created particles coalesce into a nearly uniform state of quark and gluon plasma that is so dense that it may be more like the nuclear material that fills the interior of the sun than any previous state of matter on Earth.

The scientists will present their findings this week at the American Physical Society meetings in Chicago.
Trends in high energy nuclear collisions

Discovery of QGP at RHIC

- Various collision energies
  - RHIC beam energy scan (BES) program
  - Onset of the QGP formation?
  - Investigation of super-dense matter

- Small colliding systems
  - QGP created even in small size?
  - Collectivity in small colliding systems

- Energy frontier
  - QGP at the highest collision energy at LHC
  - Precision measurements and analyses

Precision study, new findings, … ~2005
Physics of the QGP

Fukushima and Sasaki (2013)

Investigation of matter under extreme conditions
- Order of phase transition
- Location of critical point and 1\text{st} order phase transition line
- Equation of state
- Transport coefficients
- Structure of “vacuum”
- ...

High-energy nuclear collisions: Unique approach to create matter under extreme conditions on the Earth
Bottom-up approach

3-D event display from STAR
- Momentum distribution
- Particle species
- Correlation
- ...

Physics properties of the QGP
- Equation of state
- Transport coefficients
- Stopping power
- Phase structure

Phenomenological approach

Top-down approach
Results from lattice QCD, …
Standard picture of dynamics in high-energy nuclear collisions

- Color glass condensate
- Dilute parton gas
- Fragmentation
- Recombination
- QGP fluid
- Glasma
- Hadron gas
- Soft
- Hard

Interaction
Energy frontier

Anisotropic flow and precision QGP physics
Lessons from observational cosmology

Energy budget and lifetime of the Universe, inflation, …
One can reach eras before decoupling through these analyses.
Response to initial fluctuations of geometry

TH et al. (2013)

CMS Collaboration (2013)

$n = 2$ (quadrupole)
Elliptic flow
Ollitrault (1993)

$n = 3$ (hexapole)
Triangular flow
Alver, Roland (2010)

$n = 4$ (octapole)
Quadrangular flow
Kolb (2003)

How does the system respond to initial deformation?

$\ell_n = 2$ (quadrupole)

$\ell_n = 3$ (hexapole)

$\ell_n = 4$ (octapole)

Entropy density distribution

Initial deformation $\epsilon_n$

Response $v_n$

Contain information about transport properties of the QGP
Precision QGP physics using Bayesian parameter estimation

Experimental data $\rightarrow$ Posterior probability of parameters
$\leftrightarrow$ Comparison with results from lattice QCD

\textbf{Sound velocity vs. Temperature}

\begin{align*}
\text{Unconstrained} & \quad \text{Constrained by data} \\
\text{Hadron gas} & \quad \text{Lattice}
\end{align*}

Pratt \textit{et al.} (2015)

\begin{align*}
\frac{\text{Shear viscosity}}{\text{Entropy density}}
\end{align*}

\begin{align*}
0.6 & \\
0.4 & \\
0.2 & \\
0.0
\end{align*}

\begin{align*}
0.15 & \\
0.20 & \\
0.25 & \\
0.30
\end{align*}

\textbf{Comparison with results from lattice QCD}

Bernhard \textit{et al.} (2016)
Correlation of initial conditions along collision axis

Heavy ion collision as a chromoelectric capacitor

- Formation of color flux tubes \(\sim\) Approximate boost invariance
- Correlation of initial conditions in rapidity space
(De-)Correlation of elliptic flow along rapidity

- Ideal and viscous hydro $\rightarrow$ Hard to break up correlations
- Random force from thermal (hydrodynamic) fluctuations in QGP $\rightarrow$ break up correlations
- New channel to constrain transport coefficients

A. Sakai* (QM2017)
*Winner of Nuclear Physics A Young Scientist Awards
Energy frontier

Medium response and hard probes
Di-jet asymmetric event

$E \sim 200$ GeV jet dragged by medium with $T \sim 300$ MeV in a few femtometer

→ Where the lost energy goes?
→ Change of jet structure as a function of $r$?
Large angle emission of soft particles

Mach-cone like medium response at large angle from jet axis

Jet structure at large $r$: A new channel to constrain transport properties of QGP?

Y. Tachibana et al. (2017)
$Z^0$-jet correlations as a new probe

$qq \to qZ$ and $\bar{q}g \to \bar{q}Z$
less background than $qq \to q\gamma$ or $\bar{q}g \to \bar{q}\gamma$

$x_{jZ} \sim 1 \rightarrow$ Balance btw. jet and Z
Peak shifted to lower $x_{jZ}$
$\rightarrow$ New probe for jet tomography
Discovery of top quarks in p+Pb collisions

e.g.) $gg \rightarrow t\bar{t} \rightarrow W^+bW^-\bar{b}$

- Constraint on nPDFs
  $5 \cdot 10^{-3} < x < 0.05$
  $Q^2 \sim 3 \cdot 10^4$ GeV$^2$

- b-quark energy loss in heavy ion collision case
  $c\tau$ of top quarks $\sim 0.15$ fm
  $<<$ Dimension of the medium $\sim$ several fm

$\rightarrow$ New channel to probe the QGP
Small colliding systems

New challenge to models
To be QGP or not to be?

That is THE question!

RHIC
p+Au

LHC
p+p

p+Pb

d+Au

\[ {^{3}\text{He}}+\text{Au} \]

2003~2010: Control experiment \(\rightarrow\) Initial state effects such as Cronin effect, (anti-)shadowing and saturation

2010~today: Discussion of possibility to create QGP in small colliding systems

* “Collectivity” = Correlated particle emission ≠ flow
Everything starts from CMS findings

What is “Ridge”?
Correlation of two particle emission with
the same azimuthal angle but large rapidity
gap ($\Delta \eta \sim 2-4$)

Ridge in heavy ion collisions
$\leftrightarrow$Interpreted as collective flow

First ridge observation in high-multiplicity pp
collisions at $\sqrt{s} = 7$ TeV!
Collectivity in pp and pPb collisions at LHC

Guilbaud for CMS (2017)
Collectivity in p,d,He+Au collisions at RHIC

PHENIX Collaboration (2017)

Large elliptic flow measured at RHIC
- Mass ordering
- Consistent with hydrodynamic calculations

\[ \frac{\eta}{s} = 0.08 \]

The same hydro models reproduce experimental results in both large and small systems at RHIC.
Strangeness enhancement in pp

$h_s/\pi$ increase with multiplicity
Multi-strange hadrons increase more rapidly
← Commonly seen in heavy ion data from SPS to LHC

Violation of “jet universality”?
QGP formation (EPOS, 2015)
Rope hadronization (DIPSY, 2015, 2016)
Thermodynamical string model (Fischer, Sjöstrand, 2017)
→ Need more studies in final stage
Initial or Initial + Final?

Large system: Final state effect
Small system: Initial or Initial + Final state effect

→ Necessity for sophisticated modeling in small systems
→ Thermalization, hydrodynamization, …
Short summary of small colliding systems

Experimental data in pp and pA:
  Collectivity (ridge, finite $v_2, \cdots$)
  Strangeness enhancement
← How small can the QGP be?
← Collectivity or fluidity?
Interpretation not settled:
  Final state effects: QGP fluid, rope + shove, themodynamical string frag, color reconnection, \cdots
  Initial state effects: Color glass condensate
Various collision energies

RHIC-Beam Energy Scan program and beyond
Scanning phase diagram

Chemical freezeout parameters from particle yields in Au+Au collisions at various energies
Centrality dependence of $\mu_B$ at low energies $\leftrightarrow$ Baryon stopping

Control baryon density and initial energy density
Scan broad regions of phase diagram

STAR Collaboration (2017)
Collision energy evolution of third harmonics

Au+Au or Pb+Pb

Response of the system

→ Minimum at $\sqrt{s_{NN}} \sim 20$ GeV (mostly seen in semi-central collisions)

→ Indication of softest point (minimum sound velocity) in equation of state?

Small $\leftrightarrow$ Initial energy density $\rightarrow$ Large
Collision energy evolution of jet quenching

Yield at high $p_T$ is suppressed at the top RHIC energy as an evidence for QGP formation

$\Rightarrow$ Monotonic change with $\sqrt{s_{NN}}$

$\Rightarrow$ Null results on onset of QGP formation?

Hard to disentangle jet quenching from Cronin effect (random transverse kicks in the initial collision)

STAR Collaboration (2017)
Higher order fluctuations of conserved quantity

Asakawa, Ejiri, Kitazawa (2009), Stephanov (2009, 2011), ...

Non-monotonic behavior expected around critical point

\[ \kappa \sigma^2 = \frac{\chi_4}{\chi_2} \]

\[ \chi_n = \frac{\partial^n \hat{\rho}}{\partial \hat{\mu}^n} \]

\[ \hat{\rho} = \frac{p}{T^4}, \hat{\mu} = \frac{\mu}{T} \]

Critical Signature
Collision energy dependence of $\kappa \sigma^2$

$$\kappa \sigma^2 = \frac{\langle (\delta N_B)^4 \rangle}{\langle (\delta N_B)^2 \rangle} = \frac{\chi_4}{\chi_2}$$

*In actual experimental data, not net baryon, but net proton

Expected non-monotonic behavior seen in experimental data → Signature of critical point!?
Future study of Super-dense nuclear/quark matter

Binary neutron star merger

M. Shibata, talk at QM2015
Outlook (instead of Summary)

- Construct robust models against precision data
  - Correlation measurement and its analysis
  - New (hard) probes
  - Interplay between soft and hard
- Need much more studies even in pp collisions!
  - Initial state: Particle production, thermalization?

Final question: Everything flows?
παντα ῥει! Everything flows!

Even cats flow!
The 2017 Ig Nobel Prize in Physics: M.A. Fardin for using fluid dynamics to probe the question "Can a Cat Be Both a Solid and a Liquid?"
(https://www.improbable.com/ig)

Spontaneous rotation

Figures taken from M.A.Fardin, On the rheology of cats, Rheology Bulletin, 83(2) July 2014
Correlation of elliptic flow parameter between different rapidity

\[ -\eta_a < \eta_b < 4.0: \text{Reference flow} \]

Same quadrupole emission pattern across rapidity?
Rope + shove model
Bierlich et al. (2014, 2016)

Strings overlapping in transverse plane
⇒ ”Rope” formation (with larger string tension)

Schwinger mechanism

\[ P \propto \exp \left( -\frac{\pi m_q^2}{\kappa} \right) \]

\( \kappa \to \kappa' (> \kappa) \) expected to enhance yields of strange hadrons

Ridge appears in central pp events shoveing model \sim \text{hydro?}
**QGP as the most vortical fluid**


\[
\omega \sim \frac{1}{2} \nabla \times \mathbf{v} \quad |v_z^+ - v_z^-| \sim 0.1c \quad d \sim 10\text{fm}
\]

Protons from \(\Lambda\) carry information about polarization

\[
P_\Lambda + P_{\bar{\Lambda}} = \frac{\hbar \omega}{k_BT} \quad \omega = (9 \pm 1) \times 10^{21}\text{s}^{-1}
\]

Beccatini *et al.* (2017)  
STAR Collaboration (2017)

\[
\omega \sim 10^{22}\text{s}^{-1}
\]
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