Quark Gluon Plasma created at RHIC and LHC

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Outline

Heavy ion collision experiment

Quark gluon plasma

Elliptic flows

Viscous hydrodynamics

Dijet anisotropy

Conclusion
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What we see

Events recorded by the ALICE experiment from the first lead ion collisions, at a centre-of-mass energy of 2.76 TeV per nucleon pair.
What happened

Centrality = $\frac{\pi b^2}{\pi (2R_A)^2}$

$R_A \sim 5 \text{ fm}$
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QCD predicts phase transitions in strongly interacting matter at high temperatures.

Above the critical temperature, ordinary hadronic matter, where protons and neutrons are composed of quarks and gluons confined in a colour-neutral state, melts during the deconfinement phase transition.

The energy density and pressure by $T^4$ of QCD computed with $N_T = 8$ lattice data. 0903.4379.
Gas vs. Liquid

The spectators continue down the beam pipe leaving an excited oval shape which expands preferentially along the short axis of the ellipse, since the pressure gradient is large along the short axis.

Almond shaped interaction volume after a non-central collision of two nuclei. 1102.3010
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Some definitions

Reaction plane angle: $\psi_{RP}$

Asymmetry parameter: 
$$\epsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$$

Elliptic flow: $v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle$

A schematic of the transverse plane in a heavy ion event.
Anisotropic flow harmonics

Fourier expansion of differential distribution:

\[ E \frac{d^3 N}{d^3 p} = \]
\[ \frac{1}{2\pi} \frac{d^2 N}{p_t dp_t dy} \left( 1 + 2 \sum_{n=1}^{\infty} \nu_n \cos[n(\phi - \psi_{RP})] \right) \]

For example:

\[ \frac{dN}{d\phi} = \frac{N_0}{2\pi} \left( 1 + 2\nu_2 \cos[2(\phi - \psi_{RP})] + \ldots \right) \]

Then the elliptic flow is the second Fourier coefficient, \( \nu_2 \) of the azimuthal distribution.

Additional constraints on the parameters can be obtained by measurements of the other anisotropic flow harmonics \( \nu_3, \nu_4 \) and \( \nu_5 \).
Elliptic flow

The scaled elliptic flow $v_2/\epsilon$ measures the response of the medium to the initial geometry.

So the collective expansion of QGP has occurred.

Elliptic flow $v_2(p_T)$ as measured by the STAR collaboration\textsuperscript{39,40} for different centralities. \textsuperscript{0905.2433}
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Relativistic hydrodynamics

Energy momentum tensor:

\[ T^\mu_\nu = \begin{pmatrix} e \\ p \\ p \\ p \end{pmatrix} \]

(In the rest frame of volume element)

In general:

\[ T^\mu_\nu = (e + p)u^\mu u^\nu + pg^\mu_\nu \]

Conservation law:

\[ \partial_\nu T^\nu_\mu = 0 \]

Equation of state:

\[ p = p(e) \]

For viscous effect, we modify the energy-momentum tensor:

\[ T^\mu_\nu = T_{\text{ideal}}^\mu_\nu + \eta(\pi^\mu_\nu) \]

where \( \pi \) is the traceless shear tensor,

\[ \pi = \nabla^\mu u^\nu + \nabla^\nu u^\mu - 2/3(g^\mu_\nu + u^\mu u^\nu)\nabla_\lambda u^\lambda \]
The transverse momentum dependence of $v_2$ compared to the viscous hydrodynamic calculations.
A perfect liquid

Specific shear viscosity estimations. Grey bands are for RHIC (200 A GeV Au+Au collisions) and dark green band are for LHC (2.76 A TeV Pb+Pb collisions). 1210.5778

Theoretical works on strongly coupled quantum field theories using tools from superstring theory, established a lower limit around $\eta/s = 1/4\pi$. So QGP is a perfect liquid with almost lowest viscosity.
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Event display of a highly asymmetric dijet event, with one jet with $E_T > 100\,\text{GeV}$ and no evident recoiling jet and with high-energy calorimeter cell deposits distributed over a wide azimuthal region. PhysRevLett.105.252303
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Theoretical understanding is improving.

High quality data from LHC, additional measurements of anisotropy flow harmonics.

Effects from bulk viscousity

Will increase our understanding of this new state of matter, ultra-relativistic quark gluon plasma.
Transverse momentum spectra

Charged particle spectra

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