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N.B. Not a STAR talk
Quark Gluon Plasma established theoretically

Lattice calculations indicate a rapid crossover accompanied by an increase in the number of degrees of freedom.

How can QGP be studied in the lab?
Nuclear collisions and the QGP expansion

collision evolution
expansion and cooling

particle detectors

dlumpy initial energy density

QGP phase
quark and gluon degrees of freedom

hadronization

τ ~ 0 fm/c
τ0~1 fm/c
τ ~ 10 fm/c

kinetic freeze-out

distributions and correlations of produced particles

τ ~ 10^{15} fm/c
Correlations and Fluctuations

as the system expands are the correlations and fluctuations from the initial conditions carried over to the final state?
$v_2$ depends on initial deformation: fluctuations of $v_2$ can reveal information about fluctuations and correlations in the initial conditions.
Flow vector distribution

\[ q_{n,x} = \frac{1}{\sqrt{M}} \sum_{i=1}^{M} \cos(n \varphi_i) \]
\[ q_{n,y} = \frac{1}{\sqrt{M}} \sum_{i=1}^{M} \sin(n \varphi_i) \]

- q-vector and \( v_2 \) related by definition: \( v_2 = \langle \cos(2 \varphi_i) \rangle = \langle q_{2,x} \rangle / \sqrt{M} \)
- width depends on
  - non-flow: \( \delta_n = \langle \cos(n(\varphi_i - \varphi_j)) \rangle \) (2-particle correlations)
  - \( v_2 \) fluctuations: \( \sigma_v \)
- we measure dynamic width: \( \sigma_{q,\text{dyn}}^2 = \delta + 2\sigma_v^2 \)

J.-Y. Ollitrault nucl-ex/9711003; A.M. Poskanzer and S.A. Voloshin nucl-ex/9805001
correlations and the flow vector

width depends on the track sample

\[ \sigma_q^2 = \frac{1}{2} \left( 1 + M(\delta_2 + 2\sigma_{v^2}) \right) \]

differences are due to more or less non-flow in various samples

\[ \delta_2 = \langle \cos 2(\varphi_1 - \varphi_2) \rangle_{\text{correlated}} \]

smaller \( \delta_2 \) for like-sign (charge ordering) larger \( \delta_2 \) for small \( \eta \) (strong short range correlations)

also in 2-D correlations: can be fit with a \( \Delta \eta \) independent \( \cos(2\Delta \varphi) \) term + non-flow structures

N.B. relationship of measured \( \delta_2 \) from 2 particle correlations and dynamic width is not trivial: depends on ZYAM and 2-component model (see backup slides)
dynamic width from dN/dq fit

The well constrained combinations of fit parameters are:

\[
\langle v_2 \rangle^2 + \sigma_{v_2}^2 + \delta_2 = v_2 \{2\}^2 \\
\langle v_2 \rangle^2 - \sigma_{v_2}^2 = v_2 \{4\}^2
\]

The dynamic width is the difference between the above equations

\[
\sigma_{dyn}^2 = \delta + 2\sigma_{v_2}^2 = v_2 \{2\}^2 - v_2 \{4\}^4
\]

See Miller, Snellings, nucl-ex/0312008
mean and width of $f(v_2)$

analysis places an upper limit on flow fluctuations
Comparison to models

STAR Preliminary

Comparison to models:
- **confined quark MC:**
  - treats confined constituent quarks as the participants
  - decreases eccentricity fluctuations
- **color glass MC:**
  - includes effects of saturation
  - increases the mean eccentricity

Models of spatial eccentricity:

- $\sigma_{v^2}/\langle v^2 \rangle$ MC Glauber
- Nucleon $\varepsilon_{\text{standard}}$
- Nucleon $\varepsilon_{\text{part}}$
- Confined quark $\varepsilon_{\text{part}}$
- Color glass (fKLN) $\varepsilon_{\text{part}}$

Comparison to hydro (NexSPheRio): Hama et al.
arXiv:0711.4544

Eccentricity fluctuations from CGC: Drescher, Nara.

Extraction of Knudsen number: Vogel, Torrieri, Bleicher.
nucl-th/0703031

Fluctuating initial conditions: Broniowski, Bozek, Rybczynski.

First disagreement with $\varepsilon_{\text{standard}}$ and use of quark MC:
Miller, Snellings.
ucl-ex/0312008
that was ellipticity ($v_2$) fluctuations

now more about two particle correlations?
Long range correlations

structures unique to Au+Au collisions

3 < $p_T^{(trig)}$ < 6 GeV
2 < $p_T^{(assoc)}$ < $p_T^{(trig)}$

large $\Delta \eta$: the ridge

STAR Preliminary

Central Au+Au 200 GeV
J. Putschke, QM2006

D. Magestro, HP04

Winter Workshop 2008
Two particle correlation densities

Correlations of all unique pairs of charged particles

p+p

Au+Au

M. Daugherity: QM2008
Large increase in peak amplitude and longitudinal width

Narrowing in azimuth (boost?)

Deviations between Au+Au and p+p scaling trends
Sudden jump in width and amplitude

The abrupt transition occurs at the same energy density for two different collision energies!

\[ \varepsilon_{BJ} = \frac{dE_T/dy\big|_{y=0}}{\pi R^2 \tau_0} \]

Au+Au
200 GeV
62 GeV
Sudden jump in width and amplitude

Liberation of colored degrees of freedom near $\varepsilon = 1.5 \text{ GeV/fm}^3$?

large pressure $\rightarrow$ QGP expansion?

initial spatial correlations translated to momentum space?

interesting checks: more energies, different size nuclei, and particle composition

Frithjof Karsch, arXiv:0711.0656

M. Daugherity: QM2008
The Algebra

Venugopalan, Gelis

Frithjof Karsch, arXiv:0711.0656

Initial State Fluctuations
Quark Gluon Plasma Pressure
Large Long Range Correlations
Analogies with the early universe

**The Universe: Slow Expansion**
- Afterglow Light Pattern 400,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.
- Big Bang Expansion
- 13.7 billion years

Credit: NASA

**Heavy-ion Collisions: Rapid Expansion**
- Collision evolution
  - Expansion and cooling
- Particle detectors
  - Distributions and correlations of produced particles
- Lumpy initial energy density
- QGP phase
  - Quark and gluon degrees of freedom
- Hadronization
- Collision overlap zone
- Quantum fluctuations
- $\tau \sim 0$ fm/c
- $\tau_0 \sim 1$ fm/c
- $\tau \sim 10$ fm/c

Heavy-ion Collisions: Rapid Expansion

The Universe: Slow Expansion

The Universe: Slow Expansion

Heavy-ion Collisions: Rapid Expansion

Heavy-ion Collisions: Rapid Expansion
WMAP analogy: $\langle p_T \rangle$ fluctuations

- scale dependence of $\langle p_T \rangle$ fluctuations tells us about $p_T$ correlations
- $\langle p_T \rangle$ reflects the slope of the spectra; these measurements are the analogy to CMBR temperature fluctuations
The ridge and the valley


same data after subtraction: cylindrical format

- subtract the elliptic modulation and near side peak
- anomalous depression apparent

One interpretation: medium response to an impinging minimum-bias jet?
Multipole moments and the valley

\[ \sqrt{\frac{\ell(\ell+1)}{2\pi}} C_\ell \quad [\text{GeV}/c] \]

large scale fluctuations causally disconnected during the evolution?

See Also: Superhorizon fluctuations in HIC, Ananta P. Mishra, Ranjita K. Mohapatra, et al.
Harmonic decomposition


Valley indicates suppression of lower multipole moments

We need a model to generate a reference shape

P. Sorensen, Á. Mocsy, In Preparation

spherical harmonic decomposition

no valley

with the valley
Super-horizon fluctuations

fluctuations with large characteristic length scales remain super-horizon for a longer time because of causality and the finite lifetime ($\Delta \tau$) of the fireball. The largest modes are suppressed by the length scale

$$\lambda_{l} \approx \frac{R \{ Au \}}{\ell}$$

See Also: Superhorizon fluctuations in HIC, Ananta P. Mishra, Ranjita K. Mohapatra, et al.

$$\sqrt{\frac{\ell(\ell+1)}{2\pi}} C_{\ell} \text{ [GeV/c]}$$

P. Sorensen, Á. Mocsy, In Preparation

The Universe

200 GeV Au+Au collisions

$$\lambda_{l} > c \Delta \tau$$
Super-horizon fluctuations

fluctuations with large characteristic length scales remain super-horizon for a longer time due to causality and the finite lifetime ($\Delta \tau$) of the fireball. The largest modes cannot fully develop, and suppressed modes at large scales remain super-horizon for a longer time.

$$\lambda_\ell \approx \frac{R\{Au\}}{\ell}$$

$$\lambda_\ell > c\Delta \tau$$

200 GeV Au+Au collisions

P. Sorensen, Á. Mocsy, In Preparation
Life is short

Correct scale shows:
regions remain outside the event horizon

\[ \tau \sim 0 \text{ fm/c} \]

\[ \tau_0 \sim 1 \text{ fm/c} \]

\[ \tau \sim 10 \text{ fm/c} \]
Conclusions

Correlations show structures unique to A+A collisions
• a ridge: narrow in $\phi$, broad in $\eta$
• ridge develops suddenly near $\varepsilon=1.5$ GeV/fm$^3$
• features of $\langle p_T \rangle$ fluctuations are consistent with super-horizon fluctuations from the initial conditions

Do trends indicate sudden turn on of color degrees-of-freedom?

Future tests:
  - vary beam energy *(2010!)*
  - vary system size
  - add particle identification
  - correlate trends with other probes (J/$\psi$ suppression etc.)
Good scaling with \( \frac{dN_{ch}}{dy} \) varying the beam energy will test correct scaling.

\( dN_{ch}/dy \) and Bjorken energy density only differ by a factor of \( \langle m_T \rangle \).
The ridge and $p_T$ correlations

Ridge first seen in $p_T$ correlations for all hadrons

![Graphs showing $p_T$ correlations for different energies and collision rates.](image)

STAR data on $\langle p_T \rangle$ fluctuations show features indicative of super-horizon fluctuations.

A multipole expansion may reveal the correct interpretation of novel correlation structures in Au+Au collisions.

Valley indicates suppression of lower multipole moments.

\[
\sqrt{\frac{\ell(\ell + 1)}{2\pi}} C_{\ell} \quad [GeV/c]
\]
Relativistic Nuclear Collisions

Nucleus-nucleus collisions may probe the physics of the quark-hadron transition

\[
\sqrt{s_{NN}} = 200 \text{ GeV}
\]

\[^{197}\text{Au} \rightarrow \text{Quark-Gluon Matter?} \rightarrow \text{hadrons form} \rightarrow \text{hadronic interactions} \rightarrow \text{observed particles} \]

initial conditions

- soft bulk
- hard probes

a difficult question: CGC, Glasma, what path to thermalization, what initial energy/entropy density, what formation time

understood in pQCD

Description of the matter phase *might* be simple: hydrodynamics?

Hadronization: an unsolved problem

hadronic transport

particles detectors and data analysis

UrQMD Group – Frankfurt
Radial expansion

Data are well described by a thermally radiating radially boosted source