Fluctuations and Correlations in Relativistic Heavy Ion Collisions

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Outline:
- Charge Fluctuations
- Balance Functions
- Event-by-event $<p_T>$ Fluctuations
- Looking Ahead
- Conclusions, Credits, Apologies
Hypothesis: Fluctuations in net charge and net baryon number may be significantly reduced if a QGP is formed in the collisions


Fractional electric charges of the quarks ==> Charges more evenly spread in a plasma ==> Reduced net charge fluctuations in a small region of phase-space
Summary of Charge Fluctuation Measures

\[ \text{Variance} \langle \delta X^2 \rangle = \langle X^2 \rangle - \langle X \rangle^2 \]

\[ R = \frac{\langle N_+ \rangle}{\langle N_- \rangle} \]

\[ D \equiv \left \langle N_{ch} \right \rangle \left \langle \delta R^2 \right \rangle = 4 \frac{\left \langle \delta Q^2 \right \rangle}{\left \langle N_{CH} \right \rangle} \]

\[ \overline{z}^2 = 4 \frac{\left \langle N_+ \right \rangle \left \langle N_- \right \rangle}{\left \langle N_{CH} \right \rangle^2} \]

\[ Z = Q - \frac{\langle Q \rangle}{\left \langle N_{CH} \right \rangle} N_{CH} \]

\[ \Phi_q = \sqrt{\frac{\langle Z^2 \rangle}{\langle N_{CH} \rangle}} - \sqrt{\overline{z}^2} \]

\[ \nu(Q) \equiv \frac{\left \langle \delta Q^2 \right \rangle}{\left \langle N_{CH} \right \rangle} \]

\[ N_{CH} = N_+ + N_- \]

\[ Q = N_+ - N_- \]

PHENIX

\[ \nu(Q) \approx 1 + \frac{\langle N_+ + N_- \rangle}{4} \nu_{++,-,dyn} \]

\[ D \approx 4 + \langle N_+ + N_- \rangle \nu_{++,-,dyn} \]

\[ \Phi_q \approx \frac{\left \langle N_+ \right \rangle^{3/2} \left \langle N_- \right \rangle^{3/2}}{\left \langle N_{CH} \right \rangle^2} \nu_{++,-,dyn} \]

\[ \Gamma = \nu(Q) \]

\[ \nu_{++,-,dyn} = \nu_{++} - \nu_{++,-,stat} \]

\[ \nu_{++} = \left \langle \left( \frac{N_+}{\left \langle N_+ \right \rangle} - \frac{N_-}{\left \langle N_- \right \rangle} \right)^2 \right \rangle \]

\[ \nu_{++,-,stat} = \frac{1}{\left \langle N_+ \right \rangle} + \frac{1}{\left \langle N_- \right \rangle} \]

\[ \Gamma \equiv \frac{1}{\left \langle N_{CH} \right \rangle} \left \langle \left( Q - \frac{\langle Q \rangle}{\left \langle N_{CH} \right \rangle} N_{CH} \right)^2 \right \rangle \]

Quoted in this presentation

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# Charge Fluctuation Magnitude Expectations

<table>
<thead>
<tr>
<th></th>
<th>$v(Q)$</th>
<th>$D$</th>
<th>$v_{+-,\text{dyn}}$ (STAR)</th>
<th>$v_{+-,\text{dyn}}$ (PHENIX)</th>
<th>$\Phi_q$ (NA49)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Independent Particle Emission</td>
<td>1.0</td>
<td>4.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Resonance Gas</td>
<td>0.75</td>
<td>3.0</td>
<td>-0.0013</td>
<td>-0.006</td>
<td>-0.125</td>
</tr>
<tr>
<td>Quark-Gluon Plasma</td>
<td>0.25</td>
<td>1.0</td>
<td>-0.0038</td>
<td>-0.019</td>
<td>-0.375</td>
</tr>
<tr>
<td>Quark Coalescence</td>
<td>0.83</td>
<td>3.33</td>
<td>-0.0008</td>
<td>-0.004</td>
<td>-0.084</td>
</tr>
</tbody>
</table>
Charge Fluctuations vs. Rapidity Acceptance
(Excitation Function): NA49

\[ \Phi_{q}^{cc} = \sqrt{1 - \frac{\langle N_{CH} (\Delta y) \rangle}{\langle N_{CH} \rangle_{tot}}} - 1 \]

Correction for fluctuations due to charge conservation.

See poster by P. Chrisakogiou

Also see talk by H. Sako for new CERES results.
Charge Fluctuations vs. Rapidity Acceptance

$\Delta \phi = \pi/2$

$0.3 \leq p_T \leq 2.0$ GeV/c

Charge Fluctuations vs. Rapidity Acceptance


Charge Conservation
Quark Coalescence
Resonance Gas
Quark-Gluon Plasma

Pseudorapidity Acceptance
Balance Functions


\[ B(\Delta y) = \frac{1}{2} \left\{ \frac{N_{+-}(\Delta y) - N_{++}(\Delta y)}{N_+} + \frac{N_{-+}(\Delta y) - N_{--}(\Delta y)}{N_-} \right\} \]

\( N_{+-}(\Delta y) = \text{Histogram of } |y(\pi^+) - y(\pi^-)|, \text{ for all possible pairs within an event. This histogram is summed over all events.} \)

- Designed to determine whether hadronization from a QGP occurs early (<1 fm/c) or late.

- Based upon the fact that charge is conserved locally, and produced pairs are initially correlated in coordinate space.

- **Bottom line**: The balance function is narrower in the delayed hadronization scenario.

\[ \sigma_{\delta y}^2 = \sigma_{\delta \eta}^2 + \sigma_{\text{thermal}}^2 \]

**Early hadronization scenario**: Pairs separate in rapidity due to expansion and rescattering.

**Delayed hadronization scenario**: Pairs are more strongly correlated in rapidity.
STAR 130 GeV Balance Function Results


Identified Pion Pairs

All Charged Hadron Pairs

Identified Pion Pairs

All Charged Hadron Pairs
The balance function gets narrower in central collisions → Delayed hadronization scenario?

STAR Preliminary
See talk tomorrow by G. Westfall
The balance function gets narrower in central collisions.

A similar behavior AND narrowing magnitude is observed compared to the STAR data!
Other explanations for the broadening of the balance function

Resonance contributions

P. Bozek, W. Broniowski, and W. Florkowski,
nucl-th/0310062

Computing balance functions in a thermal model with neutral resonance decay.

The calculations including resonances are consistent with the STAR results.
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Quark Coalescence Model Predictions

Predicts a width consistent with the STAR result for central collisions with a transverse flow velocity below 0.5c.
Behold The $<p_T>$ Fluctuation Signal!

**PHENIX**

**STAR Au-Au $\sqrt{s_{NN}} = 130$ GeV**

**NA49 preliminary**

**CERES**

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Summary of Event-by-event $<p_T>$ Fluctuation Measures

Goal of the observables:
State a comparison to the expectation of statistically independent particle emission.

\begin{align*}
\sigma_{p_T,dyn}^2 &\equiv 2\Phi_{p_T} \sqrt{\Delta p_T^2} \frac{\langle N \rangle}{\langle N \rangle} \\
\sigma_{p_T,\text{incl.}}^2 &\equiv \sqrt{\langle p_T^2 \rangle - \langle p_T \rangle^2} \\
\Sigma_{p_T} &\equiv \sigma_{p_T} \sqrt{\frac{2 F_{p_T}}{p_T} \langle N \rangle} \\
\Phi_{p_T} &\equiv \text{sgn}(\sigma_{p_T,dyn}^2) \sqrt{\frac{\sigma_{p_T,dyn}^2}{p_T}} \\
F_{p_T} &\approx \frac{\Phi_{p_T}}{\sigma_{p_T,\text{incl.}}} \\
\Delta \sigma_{p_T,n} &\equiv \sqrt{\left(\Phi_{p_T} + \sigma_{p_T,\text{incl.}}\right)^2 - \sigma_{p_T,\text{incl.}}^2} \\
\Delta p_T &\equiv p_T^2 - p_T^2 \quad \text{Quoted in this presentation}
\end{align*}
How To Measure A Fluctuation


\[ M_{pT} = \text{Event-by-Event Average } p_T \]

Red: Random Expectation (\( \Gamma \) distribution)

Blue: STAR acceptance fluctuation of:

\[ \phi_{pT} = 52.6 \text{ MeV}, \]
\[ F_{pT} = 14\%, \]
\[ \sigma^2_{pT, \text{dyn}} = 52.3 \text{ (MeV/} c^2\text{)}, \]
\[ \Sigma_{pT} = 9.8\% \]
A Positive Signal is Observed!
Known contributions to the $<p_T>$ fluctuation signal should be subtracted.

**Contributions from Known Processes**
- **HBT** – too small (NA49, STAR, CERES)
- **Resonances** – too small (NA49, STAR)
- **Elliptic Flow** – too small/ negligible (PHENIX, CERES, NA49)
- **Hard Processes**…
- **Or onset of thermalization**…

*A Schematic Illustration of Elliptic Flow*
A Possible Explanation of the Signal: A System in Near-local Thermal Equilibrium

Sean Gavin, nucl-th/0308067, see his talk tomorrow for more details.
The onset of thermalization?

\[ \frac{dN}{d\eta} \langle \delta p_{t1} \delta p_{t2} \rangle \propto \Phi_{p_t} \]

See talks tomorrow by S. Gavin (model) and G. Westfall (data)
A Large Fluctuation Contribution at high $p_T$

An increase in observed fluctuations grows primarily in a $p_T$ region where number fluctuations vary little.

Increases from $p_T^{max} = 1.0$ to $2.0 \text{ GeV/c}$

PHENIX Fluctuations: 243%
CERES Fluctuations: 34%

$\langle N \rangle$: $< 15\%$

This trend is observed at all centralities.
Jets inherently add particles that are correlated in $p_T$ to the event, so a contribution due to hard processes is expected, but how much? What about jet suppression?
Jet Simulation Results: PHENIX at 200 GeV
Results from a 2-component hybrid simulation.

**Component 1:** Reproduce soft processes by sampling the inclusive $p_T$ and $N$ data distributions.

**Component 2:** Embed PYTHIA hard scattering events at a given rate per particle produced in Part 1. Keep the rate fixed, or scale it by $R_{AA}$.

PHENIX Data: nucl-ex/0310005

This decrease is due to the signal competing with the $M_{pT}$ width increase for low $N$.

This decrease is due to jet suppression?

See poster by J. T. Mitchell
Jet Simulation Results: STAR at 130 GeV

STAR data: nucl-ex/0308033

Error bars are the quoted total systematic error.
Jet Simulation Results: STAR at 130 GeV

STAR data: nucl-ex/0308033

Error bars are the quoted total systematic error.

The simulation predicts ~15-20% increase when going from 130 to 200 GeV.
Jet Simulation Results: NA49 at 17 GeV

NA49 Preliminary Data: See poster by K. Grebieszkow & M. Rybczynski
Estimate of the Magnitude of Residual Event-by-Event Temperature Fluctuations

\[
\frac{\sigma_T}{<T>} = \sqrt{\frac{2F_{p_T}}{p(<N> - 1)}}
\]

\(p \rightarrow \text{inclusive } p_T, \Gamma(p,b), p \sim 1\)


<table>
<thead>
<tr>
<th>Measurement</th>
<th>sqrt(s_{NN})</th>
<th>(\sigma_T/ &lt;T&gt;), Most central</th>
<th>(\sigma_T/ &lt;T&gt;), At the peak</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHENIX</td>
<td>200</td>
<td>1.8%</td>
<td>3.7%</td>
</tr>
<tr>
<td>STAR</td>
<td>130</td>
<td>1.7%</td>
<td>3.8%</td>
</tr>
<tr>
<td>CERES</td>
<td>17</td>
<td>1.3%</td>
<td>2.2%</td>
</tr>
<tr>
<td>NA49</td>
<td>17</td>
<td>0.6%</td>
<td>1.7%</td>
</tr>
</tbody>
</table>

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Add a dimension: 2-point transverse momentum correlations

NA49 17 GeV Pb+Pb

Higher $p_T$ pairs from hard scattering?

STAR Preliminary
130 GeV Au+Au

Like sign

NA49

Thermal Fluctuation Model Simulations

$$x(p_T) = \frac{\int_0^{p_T} dN dp_T}{\int_0^{\infty} dN dp_T}$$

In PHENIX, $x(1.5 \text{ GeV}/c) \sim 0.93$

L. Ray, DNP 2003, see his poster

HBT and Coulomb interaction
Coming Soon: A Multi-dimensional Analysis

(centrality, $p_{T,1}$, $p_{T,2}$, pseudorapidity, azimuth)

**STAR Preliminary**

![3D diagrams showing peripheral and central regions with ellipses indicating flow removal.]

Elliptic flow has been removed.

T. Trainor, DNP 2003
See poster by D. Prindle

See poster by D. Prindle

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Synopsis

- **Charge fluctuations:**
  - SPS results and RHIC-PHENIX results are close to the random expectation after correcting for charge conservation.
  - RHIC-STAR results are consistent with a quark coalescence model prediction in central collisions.

- **Balance Functions:**
  - Both SPS (NA49) and RHIC (STAR) results show a narrowing of the balance function in central collisions.
  - The narrowing is indicative of delayed hadronization.
  - The narrowing may also be explained within the quark coalescence picture, or by resonance decay contributions.

- **$<p_T>\ >$ Fluctuations:**
  - A positive fluctuation signal that decreases for more central collisions is seen at the SPS and at RHIC.
  - The signal can be explained within a model that simulates jet production, however, a jet suppression scenario must be introduced to describe the most central collisions at RHIC.
  - The signal can also be explained within a thermalization onset scenario.

- Stay tuned for more exciting results soon!
But wait! There’s more!

The following topics could not be covered in this presentation.

- Multiplicity Fluctuations
- Spatial Fluctuations, or “Event Texture”
- Charge/Neutral (Isospin) Fluctuations
- Particle Ratio Fluctuations

Acknowledgements

Many thanks to H. Appelshauser (CERES), M. Gazdzicki (NA49), S. Gavin, D. Prindle (STAR), L. Ray (STAR), C. Roland (NA49), H. Sako (CERES), T. Trainor (STAR), G. Westfall (STAR), for providing input into this presentation.
HIJING cannot reproduce the centrality dependence of the fluctuations.

One problem is that $<N>$ changes depending on the HIJING settings – not matched to the observed dataset.

Example for 0-5% centrality: $<N> = 93.0$ for jet suppression, 76.6 without suppression, and 51.2 without jets.