What have we learned from event-by-event fluctuations at RHIC?

Gunther Roland/MIT
Exploring the QCD Phase Diagram
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- Pre-equilibrium
- Initial stage
- Phase transition
- Mixed Phase
- Chemical Freeze-out
- Thermal Freeze-out
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Observables:
- Initial energy/entropy density
- Properties of (partonic) medium
- Order of transition
- Critical fluctuations
- Temperature
- Chemical potentials
- Temperature, time
- Expansion velocity
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Temperature, chemical potentials
What can we learn from fluctuations?

• **Chiral Symmetry Restoration**
  - Disoriented Chiral Condensates
  - Charge/neutral event-by-event fluctuations

• **Deconfinement**
  - Charge/DoF different in QGP vs Hadron gas
  - N+/N-event-by-event fluctuations

• **Critical fluctuations at phase transition**
  - Critical endpoint in QCD phase diagram
    - 1.5-2% $\frac{\Delta T}{T}$
  - $\langle p_T \rangle$ event-by-event fluctuations
Experiments

J. Mitchell
Observables at RHIC

- Global/local multiplicity fluctuations
  - Brahms/Phenix/Phobos/Star
- Charge/neutral fluctuations
  - Phenix/Star
- $<E_T>, <p_T>$ fluctuations
  - Phenix/Star
- $<p_T>$ subevent

- Charge ratio/difference fluctuations
  - Phenix/Star
- $K/\pi, \pi/p$ fluctuation
  - Star
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Charge fluctuations

Define variables to measure variance of charge ratio and charge difference distribution

$Q = N_+ - N_-$
Charge fluctuations - $D^\sim$

\[ D^\sim = \frac{\langle \delta R \rangle^2 \cdot \langle N_{ch} \rangle_{acc}}{(C_y \cdot C_\mu)} \]

$D^\sim = 4$  : pion gas with global charge conservation

$D^\sim \approx 1$ (or 2 Heinz)  : frozen QGP fluctuations with global charge conservation

$D^\sim \approx 2.8$  : gas with resonances and with global charge conservativ

(if both particles fall in the acceptance, e.g. $\Delta y$ window)

V. Koch, S. Jeon, hep-ph / 0003168
M. Bleicher, V. Koch, S. Jeon, hep-ph / 0006201
No sign of QGP suppression of charge fluctuations
Charge fluctuations at RHIC - PHENIX

No sign of QGP suppression of charge fluctuations.

\[
\frac{(\langle R^2 \rangle - \langle R \rangle^2)}{N_{ch}} \times N_{ch} \quad (R = \frac{N_+}{N_-})
\]

\[
4 \left( \frac{\langle Q^2 \rangle - \langle Q \rangle^2}{N_{ch}} \right) \quad (Q = N_+ - N_-)
\]

No sign of QGP suppression of charge fluctuations.
Charge fluctuations at SPS

Consistent with RHIC results!
Where's the QGP?

- Results at RHIC (STAR, PHENIX) and SPS (NA49) $>>$ QGP limit
- Diffusion wins? (Shuryak/Stephanov, hep-ph/00010100)
Measuring $<p_T>$ fluctuations

STAR single event
It's not a Gaussian...

...it's a Gamma-fur

(M. Tannenbaum, Phys.Lett.B 498)
Results on $<p_T>$-SPS, part I

\[ \bar{N}\sigma_{<p_T>}^2 - \sigma_{p_T}^2 \approx 2\sigma_{p_T} (\sqrt{\bar{N}\sigma_{<p_T>}} - \sigma_{p_T}) \equiv 2\sigma_{p_T} \Delta \sigma_{p_T} \]

Inclusive Event-by-event

\[ \Phi_{p_T} = 0.6 \pm 1.0 \text{ MeV} \]

<table>
<thead>
<tr>
<th>No. of events</th>
<th>98426</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\langle N \rangle$</td>
<td>$270.13 \pm 0.07$</td>
</tr>
<tr>
<td>$(\langle N^2 \rangle - \langle N \rangle^2)^{\frac{1}{2}}$</td>
<td>$23.29 \pm 0.05$</td>
</tr>
<tr>
<td>$p_T$</td>
<td>$376.75 \pm 0.06$ MeV/c</td>
</tr>
<tr>
<td>$(p_T^2 - \bar{p_T}^2)^{\frac{1}{2}}$</td>
<td>$282.2 \pm 0.1$ MeV/c</td>
</tr>
</tbody>
</table>
Results on $\langle p_T \rangle$-STAR

\[ \Delta \sigma_{pt} \sim 35 \text{ MeV} \]
Results on $<p_T>$-SPS, part II

Results from CERES TPC for central Pb+Pb

<table>
<thead>
<tr>
<th>$N_{\text{events}}$</th>
<th>$&lt;N_{\text{tracks}}&gt;$</th>
<th>$\Phi_{p_T\text{real}}$ (MeV)</th>
<th>$\Phi_{p_T\text{mix}}$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 AGeV</td>
<td>216881</td>
<td>5.5 ± 0.7</td>
<td>0.0 ± 0.2</td>
</tr>
<tr>
<td>80 AGeV</td>
<td>56464</td>
<td>3.7 ± 0.9</td>
<td>-0.5 ± 0.8</td>
</tr>
<tr>
<td>158 AGeV</td>
<td>57819</td>
<td>7.8 ± 0.9</td>
<td>1.0 ± 0.9</td>
</tr>
</tbody>
</table>

$0.05 < p_T < 1.5$ GeV
Results on $<p_T>$-PHENIX

PHENIX Preliminary

Gamma Distribution Calculation

Centrality: 0-5%

J. Mitchell (APS Wash.)
Results on $<p_T>$-SPS, part III

$\Phi_{p_T}$ vs number of wounded nucleons

- $p+p$
- $C+C$
- $Pb+Pb$

$2.9 < y < 4.0$
$4.0 < y < 5.5$
$2.9 < y < 5.5$

$f_{p_T} = 25$ MeV near $y=0$

$f_{p_T} = 1$ MeV near $y=1$
Results on $<p_T>$-STAR, part II

Centrality dependence small (similar to SPS)
Summary E-by-E $<p_T>$

- Strong rapidity dependence?
- Small centrality dependence in Au+Au
- Different azimuthal coverage – (SPS)results
Experimental summary

- No sign for QGP-suppression of charge fluctuations
- Consistent at RHIC (STAR/PHENIX) and SPS (NA49)
- Large $<p_T>$ fluctuations near mid-rapidity
  - $DT/T \sim 1-1.5\%$
- Seen at RHIC (STAR) and SPS (NA45,NA49)
- Magnitude comparable
- But not compatible with PHENIX data
- $<p_T>$ fluctuations small in forward region at SPS
What have we really learned from fluctuations at RHIC?

• Assume $DT/T \sim 1\%$ true

• Residual correlations from pp?
  • Thermalization (elliptic flow)
  • Forward data at SPS
  • pp at SPS

• (Mini-) Jets?
  • No change between SPS mid-y and RHIC

• Critical point?
  • $m_B$ (RHIC) $\sim 45$ MeV vs 270 at SPS

• Difficult measurement!
  • More experimental studies
What does it mean?

- Data consistent with **dynamical-fluctuations** simulation

*I. Ray (UTA) and R. Longacre (BNL)*

Non-statistical variation in temperature $\sim 1.2\%$
Fluctuations and Correlations

Same parent distribution

Different particle correlations

Independent production:

$$\text{RMS}_{\text{e-by-e}} = \frac{\text{RMS}_{\text{parent}}}{\sqrt{N}}$$

Central limit theorem
Where are the resonances?

Heavy resonances (>500 MeV) invisible in 'small' acceptance
What have we really learned from fluctuations at RHIC?

- Search for non-statistical fluctuations
- Relative to a reference (CLT)
  - Usually mixed event distributions
- Many 'equivalent' techniques
  - E-by-E mean values
  - Subevent correlations
- Detector effects hard to simulate
  - Can't use 'embedding'
  - Measurements very sensitive
  - Physics dependent