Energy and System Size Dependence of Fluctuations: NA49 results and NA61 plans
Outline

• Fluctuations as a Signature of Phase Transition and Critical Point?
• NA49 Results on Energy and System Size Dependence of Fluctuations:
  - Charge Fluctuations
  - $<p_T>$ Fluctuations
  - Multiplicity Fluctuations
  - Hadron Ratio Fluctuations
• Search for the Critical Point at SPS: The NA61/SHINE Experiment
  - Plans
  - Status
Introduction

• Inclusive observables at SPS energies indicate the onset of deconfinement

• Can fluctuations convey more information
  - About the onset of deconfinement?
  - At the phase transition, 2 distinct event classes or mixed phase may be reflected in larger event-by-event fluctuations
  - On the nature of the phase transition and in particular about the critical point?
  - Diverging susceptibilities near the critical point are directly connected to fluctuations

(cf. e.g. Stephanov, Rajagopal, Shuryak, Phys.Rev.D60:114028; Gorenstein, Gazdzicki, Zozulya Phys.Lett. B585 237)

Setup details relevant to fluctuation analysis:

- Large volume **Time Projection Chambers (TPCs):**
  - Tracking in magnetic field: 
    → momentum, charge
  - Specific energy loss $dE/dx$: 
    → PID of $p$, $K$, $\pi$, ... : Resolution 3-4%

- Acceptance:
  - Mainly $y > 0$
  - Full $p_T$ range
  - Limited $\phi$ acceptance; $p_T$, $y$ dependent
  - Acceptance is changing with energy

→ Has to be taken into account in model comparisons!
Setup details relevant to fluctuation analysis:

- **Veto Calorimeter (VCAL):**
  - Measurement of projectile spectator energy: $\rightarrow$ centrality of collision

- **Volume fluctuations must be controlled**
  - Fluctuations of extensive quantities (e.g. $N$) are directly affected
  - Fluctuations of intensive quantities are indirectly affected
# Experiment

## NA49 Data Sets

Data sets analyzed for the shown fluctuation results

<table>
<thead>
<tr>
<th>Energy</th>
<th>$\sqrt{s_{NN}}$</th>
<th>System</th>
<th>Centrality</th>
<th>Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>158 AGeV</td>
<td>17.3</td>
<td>Pb+Pb</td>
<td>10%, 23%</td>
<td>800k, 3M</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>min. bias</td>
<td>410k</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C+C, Si+Si</td>
<td>15%, 12%</td>
<td>220k, 300k</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p+p</td>
<td>min. bias</td>
<td>6.8M</td>
</tr>
<tr>
<td>80 AGeV</td>
<td>12.3</td>
<td>Pb+Pb</td>
<td>7%</td>
<td>300k</td>
</tr>
<tr>
<td>40 AGeV</td>
<td>8.7</td>
<td>Pb+Pb</td>
<td>7%</td>
<td>600k</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>min. bias</td>
<td>750k</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C+C, Si+Si</td>
<td>66%, 29%</td>
<td>240k, 130k</td>
</tr>
<tr>
<td>30 AGeV</td>
<td>7.6</td>
<td>Pb+Pb</td>
<td>7%, 35%</td>
<td>440k, 230k</td>
</tr>
<tr>
<td>20 AGeV</td>
<td>6.3</td>
<td>Pb+Pb</td>
<td>7%, 35%</td>
<td>360k, 330k</td>
</tr>
</tbody>
</table>

+ stricter centrality selection
NA49 Results

Net-Charge Fluctuations

• Original idea: Significantly smaller fluctuations in QGP

• Fluctuation measure

\[ \Phi = \sqrt{\frac{\langle Z^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z}^2} \]

- \( \Phi = 0 \) for independent particle production
- independent of volume and multiplicity fluctuations

\[ Z = \sum_{i=1}^{N} (x_i - \overline{x}) \]

\[ z = x - \overline{x} \]
NA49 Results

Net-Charge Fluctuations

- Subtract influence of global charge conservation (acceptance dependence)
  \[ \Delta \Phi_q = \Phi_q - \Phi_q,_{GCC} \]

- NA49 data: Predicted suppression not observed

- No strong energy or acceptance dependence of \( \Delta \Phi_q \)

- QGP signatures may be shadowed by rescattering in the hadronic stage and resonance decay

Onset of deconfinement? No sensitivity
Critical point? No predictions
NA49 Results

\(<p_T> Fluctuations\)

- Enhanced fluctuations in \(<p_T>\) expected near the critical point
  (e.g. Stephanov, Rajagopal, Shuryak Phys.Rev.D60:114028)

- Measure studied in NA49: \(\Phi_{pT}\)
  - defined as in \(\Phi_q\), but for \(x = p_T\)
• No significant energy dependence
• Trend reproduced by hadronic model (UrQMD, v1.3)
NA49 Results

\(<p_T> \text{ Fluctuations}\)

- Anticipated effect of critical point in NA49 acceptance:
  (large systematic error on prediction)
  
  \[ \Delta \Phi_{p_T} \approx 1.5 \text{ MeV/c} \] (for negative/positive particles separately)
  
  \[ \Delta \Phi_{p_T} \approx 3 \text{ MeV/c} \] (for all charged particles)

- Onset of deconfinement?
  No predictions

- Critical point?
  No signal observed

\(\mu_B\) from hadron gas fit:
F. Becattini et al,

Amplitude of effect:
Stephanov, Rajagopal, Shuryak,
Phys.Rev.D60:114028
and private communication

Position of critical point:
Z. Fodor and S. Katz,
JHEP 0404, 050, 2004

Width of critical point:
Y. Hatta and T. Ikeda,

NA49 data:
arXiv:0805.2245 [nucl-ex]
• $n$ is an extensive quantity!
  - Avoid volume fluctuations
  → Strict centrality selection: 1%

• Measure used in NA49: scaled variance

  $\omega = \frac{\text{Var}(n)}{\langle n \rangle} = \frac{\langle n^2 \rangle - \langle n \rangle^2}{\langle n \rangle}$

  - Measured width compared to Poissonian
  - $h^-$: data narrower than Poisson, $\omega < 1$
NA49 Results  Multiplicity Fluctuations

• Energy dependence: Trend reproduced by the hadronic transport model UrQMD v1.3

![Graph showing energy dependence of multiplicity fluctuations](image)

NA49 Data:
arXiv:0712.3216 [nucl-ex]
(submitted to Phys. Rev. C)

UrQMD:
B. Lungwitz and M. Bleicher,
arXiv:0707.1788 [nucl-th]

• Predicted increase due to onset of deconfinement: 0.02 (smaller than systematic errors)
NA49 Results

Multiplicity Fluctuations

- Predicted increase due to critical point:
  \( \Delta \omega (h^{-}) \approx 0.25 \) in \( 4\pi \) and \( \Delta \omega (h^{-}) \approx 0.075 \) in NA49 acceptance
  (large systematic error of prediction)

Onset of deconfinement?  No sensitivity
Critical point?  No signal observed
• Original idea:
  - Change of strangeness production at the phase transition
  - Two event classes
  - Larger fluctuations in the mixed phase

• Lattice calculations show change in quark number susceptibilities
  - For light and strange quarks
  - Smooth transition at $\mu_B = 0$
  - Divergence at the critical point
• Extract event-by-event hadron ratios (e.g. K/π) from
  
  - real measured events (●)
  - mixed events (—)

• Extract *dynamical* fluctuations as quadratic difference of relative widths:

\[
\sigma_{\text{dyn}}^2 = \text{sign} \left( \sigma_{\text{data}}^2 - \sigma_{\text{mix}}^2 \right) \sqrt{\left| \sigma_{\text{data}}^2 - \sigma_{\text{mix}}^2 \right|}
\]
NA49 Results

Particle Ratio Fluctuations

\( \frac{(p + \bar{p})}{\pi} \)

- \( p/\pi \): Negative dynamical fluctuations
  - Can be understood in terms of resonance decay
  - Energy dependence reproduced in hadronic model (UrQMD)

arXiv:0808.1237 [nucl-ex]
Submitted to Phys. Rev. C
NA49 Results

Particle Ratio Fluctuations

- $K/\pi$: Positive dynamical fluctuations
  - Steep rise towards low SPS energies
  - Cannot be reproduced in hadronic model (UrQMD)
  - No variation from top SPS energy to RHIC energy

Submitted to Phys. Rev. C

STAR data: S. Das, J. Phys. G32 S541

Onset of deconfinement?
Critical point?

No quantitative predictions for $\sigma_{\text{dyn}}$
**NA49 Results**

**Summary Energy Dependence**

- NA49 Results on the energy dependence of fluctuations:

<table>
<thead>
<tr>
<th></th>
<th>Onset of deconfinement</th>
<th>Critical Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charge Fluctuations:</td>
<td>No sensitivity</td>
<td>No predictions</td>
</tr>
<tr>
<td>$&lt;p_T&gt;$ Fluctuations:</td>
<td>No predictions</td>
<td>No signal observed</td>
</tr>
<tr>
<td>Multiplicity Fluctuations:</td>
<td>No sensitivity</td>
<td>No signal observed</td>
</tr>
<tr>
<td>Hadron Ratio Fluctuations:</td>
<td>No quantitative predictions</td>
<td></td>
</tr>
</tbody>
</table>

but the structure seen in the energy dependence of $K/\pi$ fluctuations cannot be explained in a hadronic scenario!
NA49 Results

Centrality Dependence

- Centrality dependence at $E_{\text{Beam}} = 158A$ GeV:
  - Enhanced fluctuations in peripheral collisions not reproduced by transport models

![Graph showing centrality dependence](image_url)

Phys. Rev. C70 034902, 2004

NA61 Plans

Future SPS Ion Program

NA61 / SHINE:
A new SPS Ion Program based on NA49 detector

5 Main Physics Goals:

Study the properties of the Onset of Deconfinement

Discover the QCD Critical Point

Increase range for High $p_T$ measurements at SPS

Provide important input for Cosmic Ray and Neutrino physics
Onset of Deconfinement

How do “horn” position and amplitude vary with system size?

→ Extend the original SPS energy and system size scan

NA49 energy and system size scan

NA61/SHINE plan

= 2M events
• Small systems freeze out at higher temperatures:
  - A 2-D scan \((T, \mu_B)\) is possible by varying \((A, \sqrt{s})\)

• UrQMD simulation of fluctuations visible in the NA49 acceptance

• Anticipated critical fluctuations:
  \(\approx 8 \text{ MeV/c} \)
  (Stephanov, Rajagopal, Shuryak Phys.Rev.D60:114028 and Stephanov priv. comm.)

Added to the S+S @ 80A GeV point
<table>
<thead>
<tr>
<th>Year</th>
<th>Reaction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>p+Pb</td>
<td>Test run</td>
</tr>
<tr>
<td>2007</td>
<td>p+C</td>
<td>Neutrino physics detector R&amp;D</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>1 month p beam successfully completed, results are coming</em></td>
</tr>
<tr>
<td>2008</td>
<td>p+C, p+p</td>
<td>high $p_T$, cosmic ray &amp; neutrino physics</td>
</tr>
<tr>
<td></td>
<td></td>
<td><em>Approved, will start end of August</em></td>
</tr>
</tbody>
</table>

**proposed future runs:**

<table>
<thead>
<tr>
<th>Year</th>
<th>Reaction</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>p+Pb at 158A GeV</td>
<td>high $p_T$</td>
</tr>
<tr>
<td></td>
<td>p+p at 6 energies</td>
<td></td>
</tr>
<tr>
<td>2010</td>
<td>p+Pb at 6 energies</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>S+S at 6 energies</td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td>C+C at 6 energies</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>In+In at 6 energies</td>
<td></td>
</tr>
</tbody>
</table>

*Energy and system size scan for onset of deconfinement and critical point*
• **2007**: Installation of forward TOF detector complete

• **2008**: Replacement of the TPC readout and DAQ by an ALICE-like system: Increase event rate to $\approx 100$ Hz ($= 10 \times \text{NA49}$)

• **2011**: Replacement of the Veto Calorimeter by a Projectile Spectator Detector (PSD):
  - Increase the resolution to $\Delta E/E \approx 50\% / \sqrt{(E/1\text{GeV})}$
  - Possibly determine the reaction plane

• **2011**: Installation of He beam pipe in Vertex TPCs:
  - Reduce background from $\delta$ electrons

R&D with CERN Gas Detector Development group on GEM detectors for centrality determination in p+A

Successful tests of PSD and GEM prototypes in 2006 test beam
Summary

- NA49 Results on Fluctuations show interesting results that still await an explanation:
  - Energy dependence of $K/\pi$ ratio fluctuations
  - Centrality dependence of multiplicity and $<p_T>$ fluctuations

- Search for the Critical Point at SPS: NA61/SHINE
  - NA61 will extend the NA49 energy/system size scan to study the onset of deconfinement and search for the critical point
  - Comparison to other worldwide efforts to scan the phase diagram:
    - RHIC energy scan: Systematic study with energy independent acceptance over a wide energy range ($5 < \sqrt{s_{NN}} < 200$ GeV)
    - CBM at FAIR: Measurement of rare probes at lower energies
    - NA61 adds a complementary system size scan and larger rapidity coverage
  - Start of ion beams in SPS in 2011
End.
Energy dependence of $\Delta \Phi_q$

NA49 Phys. Rev. C 70 064903, 2004
Comparison to CERES and STAR results

NA49 preliminary