New results from fluctuation analysis in NA49 at the CERN SPS

Maja Maćkowiak-Pawłowska for the NA49 Collaboration

Frankfurt University, IKF, Frankfurt
WUT, Faculty of Physics, Warsaw

November 7, 2011
1 Motivation

2 NA49 experiment

3 Measures of fluctuations
   - Chemical fluctuations $N$ and average $p_T$
   - Azimuthal angle fluctuations

4 Summary

Intermittency analysis will be presented by F. Diakonos
Contents

1 Motivation

2 NA49 experiment
Contents

1 Motivation

2 NA49 experiment

3 Measures of fluctuations
Contents

1 Motivation

2 NA49 experiment

3 Measures of fluctuations
   • Chemical fluctuations
Contents

1 Motivation

2 NA49 experiment

3 Measures of fluctuations
   - Chemical fluctuations
   - $N$ and average $p_T$ fluctuations
Motivation

NA49 experiment

Measures of fluctuations
- Chemical fluctuations
- $N$ and average $p_T$ fluctuations
- Azimuthal angle fluctuations
1 Motivation

2 NA49 experiment

3 Measures of fluctuations
   - Chemical fluctuations
   - $N$ and average $p_T$ fluctuations
   - Azimuthal angle fluctuations
   - Intermittency analysis will be presented by F. Diakonos
Contents

1 Motivation

2 NA49 experiment

3 Measures of fluctuations
   - Chemical fluctuations
   - $N$ and average $p_T$ fluctuations
   - Azimuthal angle fluctuations
   - Intermittency analysis will be presented by F. Diakonos

4 Summary
Motivation
Fluctuations study for OD and CP

Onset of Deconfinement:
- early stage hits transition line,
- observed signals: kink, horn, step

Critical Point:
- freeze-out close to critical point,
- and system large enough,
- expected signal: a hill in fluctuations

E(CP) > E(OD)

Fluctuations/correlations may serve as an additional evidence of OD

Fluctuations/correlations are basic signal of the critical point.
NA49 experiment
NA49 (fixed target) experiment at CERN SPS

- Data taking 1994–2002
- p+p, C+C, Si+Si, Pb+Pb interactions at √s_{NN} ∈ (6.3 − 17.3)GeV

- **Hadron spectrometer**
  - Four TPCs; two VTPCs (1/2) in the B field and two others MTPCs (R/L) outside; for a precise measurement of p and dE/dx

- **Large acceptance ~ 50%**

- **High momentum resolution**
  \[ \frac{\sigma(p)}{p^2} \sim 10^{-4} \left( \frac{GeV}{c} \right)^{-1} \]

- **PID by dE/dx, TOF, decay topology, invariant mass**
  \[ \frac{\sigma(dE/dx)}{<dE/dx>} \sim 5\% \]
  \[ \sigma(TOF) \sim 60\text{ps} \]
  \[ \sigma(m_{inv}) \sim 5\text{MeV} \]

- **Good centrality determination**
  - Forward Calorimeter (energy of projectile spectators)
E-by-e identified hadron multiplicities in NA49

Fit dE/dx spectra in each phase-space bin:

11.00 < p < 13.23 GeV/c, $\pi < \phi < 5\pi$/4
0.4 < $p_{T}$ < 0.6 GeV/c, $q = 1$

Fit multiplicities of identified hadrons with maximum likelihood method in each event.

Correct fluctuation results for misidentification using mixed events method.
Measures of fluctuations
Fluctuation measures studied in NA49

\( \sigma_{\text{dyn}} \) - measure of dynamical particle ratio fluctuations \((K/p, K/\pi, p/\pi)\)

- E-by-e fit of particle multiplicities required in NA49
- Mixed events used as reference
- \( \sigma_{\text{dyn}}^2 \approx \frac{1}{N_W} \), \( \sigma_{\text{dyn}} \approx \nu_{\text{dyn}} \)

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

\[ \sigma = \sqrt{\frac{\text{Var}(A/B)}{\langle A/B \rangle}} \cdot 100[\%] \]

\( \omega \) - scaled variance of multiplicity distribution

- Intensive measure
- For Poissonian multiplicity distribution \( \omega = 1 \)
- In wounded nucleon model: \( \omega(AA) = \omega(NN) + \frac{1}{2} < n > \omega_W \)
  - Where \( w(NN) \) and \( < n > \) are scaled variance and mean multiplicity in NN interactions; respectively
  - \( \omega_W \) - scaled variance of the number of wounded nucleons, \( N_W \)
  - \( \omega \) depends on \( N_W \) fluctuations

\[ \omega = \frac{n^2}{<n>^2} - \frac{n^2}{<n>} \]

\( \Phi_x \) - strongly intensive fluctuation measure \((x= p_T, \phi, Q)\)

- In superposition model \( \Phi_x(AA) = \Phi_x(NN) \)
- For independent particle emission \( \Phi_x = 0 \)
- \( \Phi_x \) is independent of volume and volume fluctuations (strongly intensive)

\[ \Phi_x = \sqrt{\frac{n^2}{<n>}} - \sqrt{z^2}, \quad z_x = x - \bar{x}, \quad \bar{x} - \text{incl. aver.}, \]

\[ Z_x = \sum_{i=1}^{N} (x - \bar{x}) \]

Intermittency analysis will be presented by F. Diakonos
Chemical fluctuations
E-b-e hadron ratios

Fitted event-by-event hadron ratios (e.g., K/p) from

\[ \sqrt{s_{NN}} = 6.3 \text{ GeV} \]

- data events
- mixed events:
  - event mixing + maximum likelihood PID

Calculate from data and mixed events:

\[ \sigma = \frac{\sqrt{\text{Var}(A/B)}}{<A/B>} \cdot 100[\%] \]

\[ \sigma_{dyn} = \text{sign}(\sigma_{data}^2 - \sigma_{mix}^2) \sqrt{|\sigma_{data}^2 - \sigma_{mix}^2|} \]
Energy dependence for central Pb+Pb

\[ \frac{K}{\pi}: \sigma_{\text{dyn}} > 0 \]

\[ \frac{p}{\pi}: \sigma_{\text{dyn}} < 0 \]

\( \sigma_{\text{dyn}} \) rises towards low SPS energies which is not reproduced by UrQMD. HSD catches the trend but over-predicts points at high SPS energies. Data are reproduced by multiplicity scaling.

NA49: PRC79, 044910 (2009)
HSD: PRC79, 024907 (2009)

Multiplicity scaling is expected in thermodynamic models for \( \mu_B, T_{\text{chem}} = \text{const} \) [Koch, Schuster PRC81,034910(2010)]
Energy dependence for central Pb+Pb

\[ \frac{(K^+ + K^-)}{(p + \overline{p})} \]

\( \sigma_{dyn} \) changes sign

The sign change is not reproduced by hadronic models (UrQMD and HSD) and by the multiplicity scaling.

NA49: PRC83, 061902 (2011) [arXiv:1101.3250]; HSD: J.Phys. G36, 125106 (2009)
Centrality dependence of Pb+Pb at 17.3 GeV

\[ \sigma_{dyn} \text{ does not change sign for } K/p, \ K/\pi, \ p/\pi \]
Direct multiplicity scaling

\[
\sigma_{\text{dyn}} \propto \sqrt{\frac{1}{\langle A \rangle} + \frac{1}{\langle B \rangle}}
\]

works for \( K/\pi \) and \( p/\pi \) fluctuations

The same scaling does not work for \( K/p \)
Comparison between NA49 and STAR

Energy dependence for central Pb+Pb (Au+Au) collisions.

\[ \nu_{\text{dyn}} = \text{sign}(\sigma_{\text{dyn}}) \cdot \sigma_{\text{dyn}}^2 \]

STAR results do not show increase towards low SPS energies for \( K/\pi \) and \( K/p \).

Figures from T. Tarnowsky (STAR, SQM2011) conversion via:

CPOD2011, Wuhan, China
Maja Maćkowiak-Pawłowska for the NA49 Collaboration
Possible sources of the difference

Analysis procedures were carefully checked, no problems found

NA49 and STAR acceptance and centrality selection differ significantly

Further steps

- further checks of the used analysis methods
- a new analysis method (identity $PRC_{83},054907(2011),PRC_{84},024902(2011)$) and strongly intensive fluctuation measures will be used by NA49
$N$ and average $p_T$ fluctuations
Large fluctuations of multiplicity and mean transverse momentum expected at CP \[\text{[Stephanov, Rajagopal, Shuryak, PRD60, 114028 (1999)]}\]

**Maximum of $\Phi_{p_T}$ and $\omega$ for C+C and Si+Si**

**Weak, if any, energy dependence**

Maja Maćkowiak-Pawłowska for the NA49 Collaboration
Multiplicity and mean transverse momentum fluctuations

For the search of CP it is more convenient to use \( (T_{\text{chem}}, \mu_B) \) instead of \( (N_w, \sqrt{s_{NN}}) \)

Chemical freeze-out points
[Beccattini et al., PRC73, 044905 (2006)]
Comparing with critical point predictions

All charged:

Maximum of $\Phi_{p_T}$ and $\omega$ observed for C+C and Si+Si

Data are consistent with the $CP_2$ predictions

---

1 Stephanov et al., PRD60 114028 (1999), Hatta, Ikeda et al., PRD67 014028 (2003) for details see Grebieszkow et al., NPA830, 547C-550C (2009)
Results for same charged particles

Increase about two times larger for all charged than for same charged particles (as predicted for CP)
$3^{rd}$ moment of average $p_T$ fluctuations

Higher moments are expected to be more sensitive to the CP fluctuations.

$$\Phi_{p_T}^{(3)} = \sqrt{\frac{3<Z_{p_T}^3>}{<N>}} - \sqrt{\frac{3<\bar{Z}_{p_T}^3>}{<\bar{N}>}}$$

No quantitative predictions for fluctuations at CP.
Azimuthal angle fluctuations
Azimuthal angle fluctuations may be sensitive to:

- plasma instabilities \cite{PLB314, 118 (1993)}
- flow fluctuations \cite{APPB34, 4241 (2003); arXiv:nucl-ex/0312008}

Central Pb+Pb:

\[ \Phi_\phi (\text{negative}) > 0 \]
- different than in UrQMD (1.3)

\[ \Phi_\phi (\text{positive}) \text{ consistent with zero} \]
System size dependence at 17.3 GeV of azimuthal angle fluctuations

NA49 preliminary:

- $\Phi_\phi > 0$ for peripheral Pb+Pb
- UrQMD(3.3) does not reproduce the data
- the magnitude of $\Phi_\phi$ reproduced by the effect of $v_1$ and $v_2$
Energy and system size dependence of $K/\pi$ and $p/\pi$ fluctuations can be described in a simple multiplicity scaling model.

$K/p$ fluctuations show a deviation from this scaling; is the underlying correlation physics changing with energy?

The energy dependence of event-by-event $K/p$ and $K/\pi$ fluctuations measured by NA49 and STAR in central Pb+Pb/Au+Au is different. Both collaborations work on clarification of the observed differences.

Fluctuations of average $p_T$ and multiplicity are maximal in Si+Si collisions at 17.3 GeV. This might be connected with the critical point at SPS energies → strong motivation for future experiments.
Back-up slides
Details of acceptance in NA49 and STAR

NA49:

![Graph showing acceptance in NA49](image1)

STAR:

![Graph showing acceptance in STAR](image2)
Test of the method

artificial correlations introduced by the fit procedure are quantified by applying the same analysis procedure to mixed events and subtracted

$$
\sigma_{\text{dyn}} = \text{sign}(\sigma^2_{\text{data}} - \sigma^2_{\text{mix}})\sqrt{|\sigma^2_{\text{data}} - \sigma^2_{\text{mix}}|}, \quad \sigma = \frac{\sqrt{\text{Var}(A/B)}}{\langle A/B \rangle}
$$

UrQMD simulation demonstrates validity of the method:

- differences mostly insignificant, taken into systematic errors

- equivalence of $\sigma_{\text{dyn}}$ and $\nu_{\text{dyn}}$

$$
\sigma_{\text{dyn}}^2 \approx \left( \frac{\langle A(A-1) \rangle}{\langle A^2 \rangle} + \frac{\langle B(B-1) \rangle}{\langle B^2 \rangle} - 2 \frac{\langle AB \rangle}{\langle A \rangle \langle B \rangle} \right) = \nu_{\text{dyn}}
$$

- generic multiplicity dependence

Koch, Schuster PRC81, 034910(2010)
Calculate $\nu_{dyn}$ in NA49

\[ \nu = \frac{\langle A^2 \rangle}{\langle A \rangle^2} + \frac{\langle B^2 \rangle}{\langle B \rangle^2} - 2 \frac{\langle AB \rangle}{\langle A \rangle \langle B \rangle} \]

The definition of $\nu_{dyn}$ assumes uncorrelated background

\[ \nu_{stat} = \frac{1}{\langle A \rangle} + \frac{1}{\langle B \rangle} \quad \nu_{dyn} = \nu - \nu_{stat} \]

To subtract correlation present in mixed events, we instead define

\[ \Delta \nu = \nu_{data} - \nu_{mix} \]
**K/\pi in central Pb+Pb**

**K/\pi fluctuations**

**Results for $v_\Delta$**

![Graphs showing K/\pi fluctuations](image)

CPOD2011, Wuhan, China

Maja Maćkowiak-Pawłowska for the NA49 Collaboration
$K/\pi$ in central Pb+Pb

Calculate $\nu_{\text{dyn}}$ in NA49

Compare to $\sigma_{\text{dyn}}$ results
Multiplicity and mean transverse momentum fluctuations

Strategy to look for critical point in NA49:

- Energy scan (beams 20A-158A GeV) with central Pb+Pb collisions - $\mu_B$ extracted from the fits to particles multiplicities
- System size dependence (different ions) at 158A GeV (top SPS energy) - $T_{chem}$ depends on system size
Estimates of effects due to the critical point

Correlation length $\xi$ at the critical point not divergent but limited by finite size and lifetime of the fireball.

parameterization: $\xi = \min(c_1 A^{1/3}, c_2 A^{1/9})$

size lifetime

Suggesting: $\xi(Pb + Pb) = 3 \to 6\text{ fm}$

$\xi(p + p) = 1 \to 2\text{ fm}$

Range of correlation effect estimated from QCD calculations (Hatta, Ikeda, PRD67, 014028(2003):

$\sigma(\mu_B) = 30\text{ MeV}, \sigma(T) = 10\text{ MeV}$

considered examples:

- CP1 - $\mu_B = 360\text{ MeV}$ (lattice QCD, Fodor-Katz)
  $T = 147\text{ MeV}$ (chem. freeze-out line)

- CP2 - $\mu_B = 250\text{ MeV}$ (data 158A GeV)
  $T = 178\text{ MeV}$ (fit of p+p data)