

Search for critical fluctuations in A+A collisions at 158A GeV

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- 1 Theoretical background
- 2 Method of analysis
- 3 Results for NA49 data analysis
- 4 Conclusions

Observables for critical fluctuations

- Detection of “chiral” critical point (CP) \Rightarrow **critical fluctuations** of the **order parameter**
- Order parameter = “chiral” condensate

$$\sigma(x) = \langle \bar{q}(x)q(x) \rangle$$

($q(x)$ = quark field, sigma-field $\sigma(x)$ =quantum state (wave function) describing the “chiral” condensate)

- In medium (finite baryon density) sigma-field **mixes** with net baryon density
- **(Critical) fluctuations** of the sigma field transferred to the **net baryon density**
- Look for observables tailored for CP search in ion collisions.

Global vs. local observables

- Two classes of observables: (i) **Global** and (ii) **Local**.
- Global = **non-monotonic** dependence of event-by-event fluctuations in **integrated measures** (charge, net proton number susceptibilities) on control parameters (beam energy, size of colliding nuclei).
Necessary but **not sufficient** condition for **critical** behaviour (analytical crossover, [M. He *et al*, **PLB** **675**, 32 (2009).])
- Local = **self-similar** density fluctuations of the order parameter in transverse configuration space (local **fractal** geometry) \Rightarrow **power-law** dependence of the density-density correlation functions in transverse momentum space \Leftrightarrow intermittency analysis (**critical opalescence**, correlation length smaller than the size).
Necessary and **sufficient** condition for **critical** behaviour [N.G. Antoniou *et al*, **NPA** **761**, 149 (2005); **PRL****97**, 032002 (2006).]
- Global observables are sensitive to experimental acceptance while local observables not.

- **Power-law exponents** are determined by **universality class (critical exponents)**. For $3 - D$ Ising:

$$\langle n_\sigma(k) n_\sigma(k') \rangle \sim |k - k'|^{-4/3} \quad ; \quad \langle n_B(k) n_B(k') \rangle \sim |k - k'|^{-5/3}$$

$n_\sigma(k) = \sigma^2(k)$, $n_B =$ net baryon density, k, k' are transverse momenta.

- The **σ -density fluctuations** \Leftrightarrow **density fluctuations of (π^+, π^-) pairs** with invariant mass close to $2m_\pi$.
- The coupling of the (isospin zero) σ -field with protons transfers **critical fluctuations** to the **net proton density** [Y. Hatta and M. A. Stephanov, Phys. Rev. Lett. **91**, 102003 (2003).]

Local observables (ideal case)

- Search for critical power-law fluctuations \Rightarrow Calculation of **second factorial moments (F_2) in transverse momentum** space for:
 - (π^+, π^-) **pairs close to their production threshold**
 - **net protons at mid-rapidity**
- Expected behaviour in the absence of background (**intermittency**):

$$F_2^{(\sigma)}(M) \sim (M^2)^{\phi_{cr}^{(\sigma)}} \quad ; \quad F_2^{(p)}(M) \sim (M^2)^{\phi_{cr}^{(p)}}$$

M =number of cells in transverse momentum space,

$$\phi_{cr}^{(\sigma)} = \frac{2}{3}, \quad \phi_{cr}^{(p)} = \frac{5}{6}$$

(predictions of critical QCD).

- **For dipions** (π^+ , π^-):

- Event-by-event form (π^+ , π^-) pairs with invariant mass (IM) close to $2m_\pi$ reconstructing the isoscalar sigma-field fluctuations.
- Calculate the horizontal second factorial moment (HSFM) of these pairs in transverse momentum space.
- Main background: Coulomb correlations (shift by ≈ 5 MeV of the IM window), combinatorial due to fake "sigmas" (simulated and subtracted using mixed events).

- **For net protons:**

- Neglect antiprotons (much less than protons).
- Calculate the HSFM in transverse momentum of protons in the central rapidity region:

$$-0.75 \leq y_{CM} \leq 0.75$$

where y_{CM} =proton center of mass rapidity

- Main background: Uncorrelated and/or misidentified protons (simulated and subtracted using mixed events).

Local observables (real experiment)

- **Dipions** (π^+ , π^-): \Rightarrow Calculate the **correlator**

$$\Delta F_2^{(\sigma)}(M) = F_2^{(d)}(M) - x_M^2 F_2^{(m)}(M) - 2x_M(1-x_M) ; \quad x_M = \frac{\langle n^{(m)} \rangle_M}{\langle n^{(d)} \rangle_M}$$

(d) \equiv data, (m) \equiv mixed events, M^2 = number of cells in transverse momentum space, n = dipion multiplicity

- **Protons:** Calculate the **correlator**

$$\Delta F_2^{(p)}(M) = F_2^{(d)}(M) - F_2^{(m)}(M)$$

Expected behaviour for the **critical freeze-out state**:

$$\Delta F_2^{(\sigma)}(M) \sim (M^2)^{\phi_{2,cr}^{(\sigma)}} ; \quad \Delta F_2^{(p)}(M) \sim (M^2)^{\phi_{2,cr}^{(p)}}$$

with:

$$\phi_{2,cr}^{(\sigma)} = \frac{2}{3} ; \quad \phi_{2,cr}^{(p)} = \frac{5}{6}$$

Measures for critical fluctuations

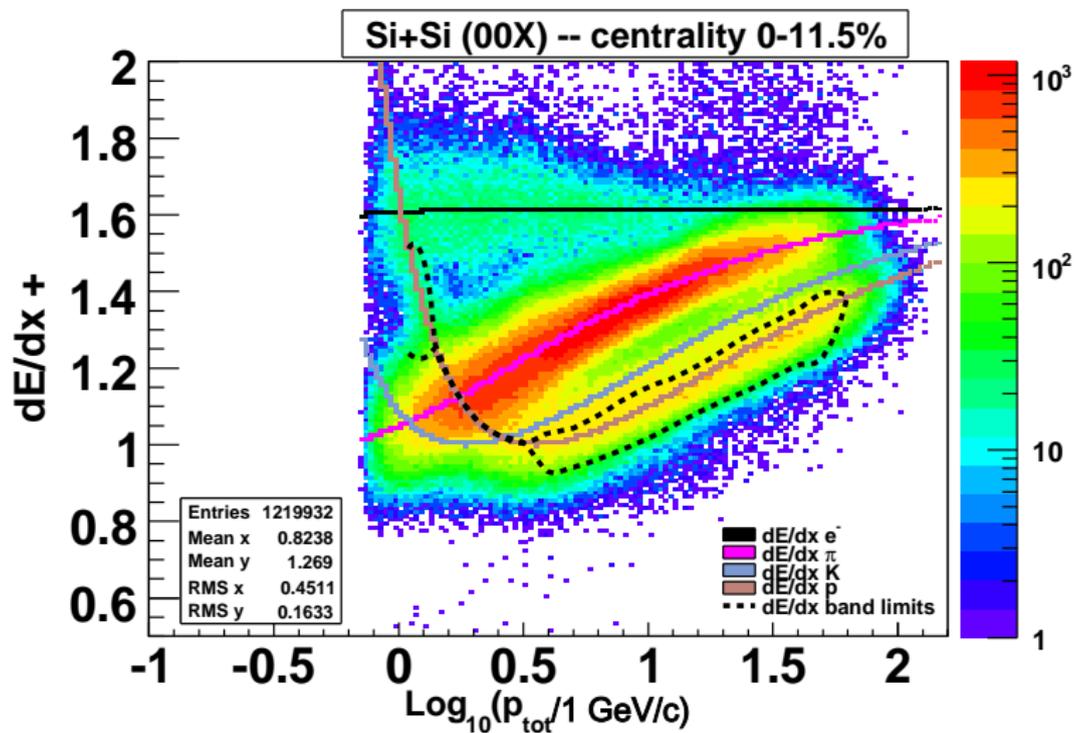
- The **intermittency index ϕ_2** carries information for the critical fluctuations (universality class).
- It can be calculated through a **power-law fit of $\Delta F_2(M)$** \Rightarrow exponent of the power-law.
- The **distance of the freeze out state** of a system **from the critical point** can be **measured with ϕ_2** obtained from the power-law fit (and R^2 =coefficient of determination).
- The difference $|\phi_2 - \phi_{2,cr}|$ expresses the distance from the critical point. The quantity $1 - R^2$ is sensitive to statistics but it can also measure this distance.

Analysed data sets - technical issues

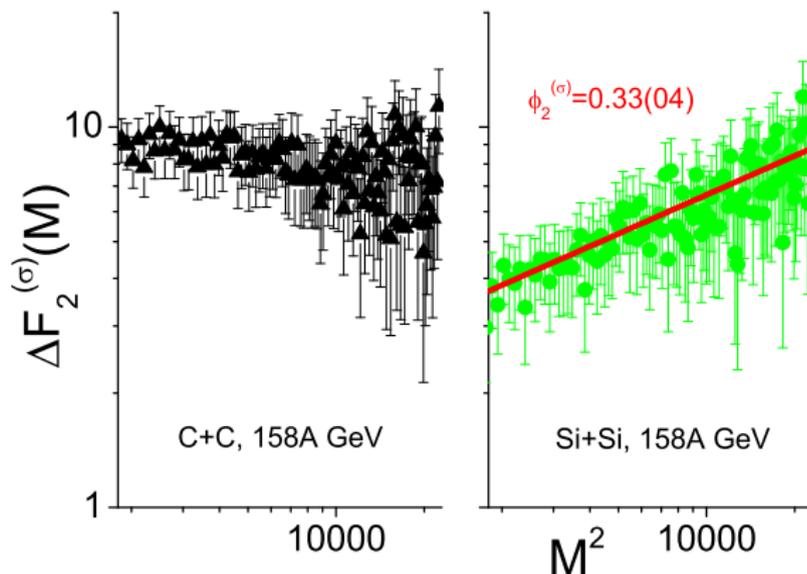
	A+C (A=C,N)	A+Si (A=Si,Al,P)	Pb+Pb
beam energy	158 A GeV		40, 158 A GeV
centrality range	0 \rightarrow 11.5%		0 \rightarrow 12.5%
# of events	33 560	175 943	1 480 587

- Standard event and track selection cuts of NA49 experiment [T. Anticic *et al*, *PRC* **81**, 149 (2010)].
- Particle (protons, pions) identification with purity $> 80\%$.
- Correlations between $\Delta F_2(M)$ for nearby M 's were checked and taken into account.

Analysed data sets - proton identification

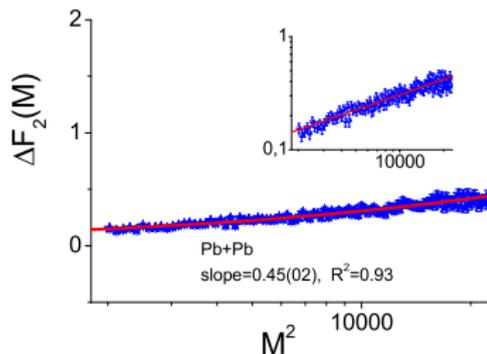
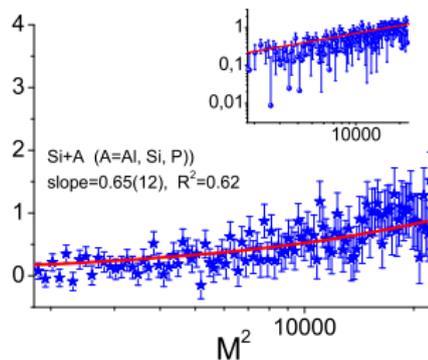
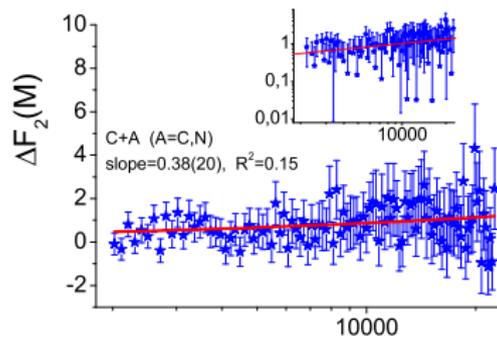


Analysis results - Dipions

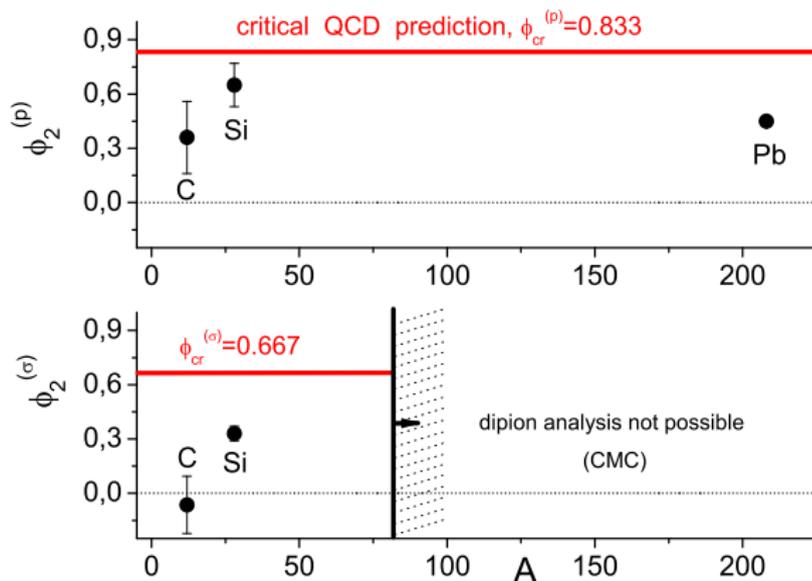


Reconstruction of critical isoscalar fluctuations does not work for large systems (Pb+Pb) [T. Anticic *et al*, PRC **81**, 149 (2010).]

Analysis results - Protons

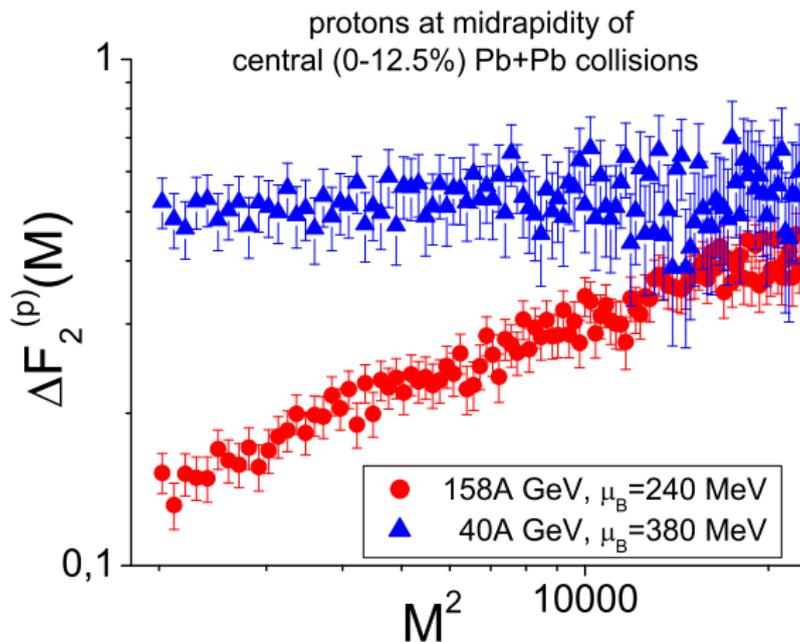


Analysis results - Size dependence of ϕ_2



Significant power-law fluctuations for Si and Pb systems at 158A GeV. The intermittency index ϕ_2 for **Si is closer** to the critical QCD prediction.

Analysis results - Energy dependence of $\phi_2^{(p)}$



No trace of power-law fluctuations in Pb+Pb at 40A GeV (not enough statistics for C+C and Si+Si) \Rightarrow CP closer to 158A GeV freeze out state.

Summary and outlook

Intermittency analysis in transverse momentum space of NA49 data from central C+A (A=C,N), Si+A (A=Al,Si,P) and Pb+Pb collisions has been performed.

- For (π^+, π^-) pairs (dipions) with invariant mass close to $2m_\pi$ we have found **significant power-law correlations in Si at 158A GeV.**
- For **protons at midrapidity** we have found **significant power-law correlations in Si and Pb at 158A GeV.**
- The **intermittency index ϕ_2** for the **Si system approaches the critical QCD prediction.**

Summary and outlook

- **First experimental evidence** for the **approach to the vicinity of the critical point**.
- **No power-law behaviour** is observed for protons of **Pb+Pb system at 40A GeV**.
- The **critical baryochemical potential closer to 240 MeV** (than to 380 MeV).

Exploring peripheral Pb+Pb collision data of NA49 at 158 A GeV and performing a systematic **intermittency study in lighter systems** (Be+Be, Ar+Ca, Xe+La) as function of energy **in NA61** will hopefully lead to an **accurate determination of the critical point location**.