Critical fluctuations of the proton density in A+A collisions at 158 AGeV

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Motivation

- Find suitable observables for detection of the **QCD Critical Point** in the particle system produced in ion-ion collisions [1-5].
- Perform a scan of the QCD phase diagram by varying the size of the colliding nuclei to explore the neighborhood of the Critical Point.

The order parameter of the QCD phase transition

- We consider **local observables** directly related to the order parameter of the QCD phase transition, the **chiral condensate**:

$$\sigma(\vec{x}) = \langle \bar{q}(\vec{x}) q(\vec{x}) \rangle, \tag{1}$$

where $\sigma(\vec{x})$ is the sigma-field and $q(x)$ the quark field.

- In a medium (finite baryon density), the sigma field mixes with the net baryon density, transferring critical fluctuations to it [6]. Therefore, **net-proton density fluctuations** can be used to detect the Critical Point [5].
- For a critical system, sigma (dipion) and proton density fluctuations are expected to obey **power-laws** with critical exponents determined by the corresponding universality class (3-D Ising) [3,5].

Intermittency analysis

- **Self-similar density fluctuations** in transverse configuration space correspond to **power-law dependence** of density-density correlation functions in transverse momentum space. These can be revealed through **intermittency analysis**.
- The quantity of interest is the **second factorial moment (F_2)**, in transverse momentum space, for net protons at mid-rapidity, as a function of the number M of momentum sub-divisions in each dimension:

$$F_2(M) = \langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i - 1) \rangle / \langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i \rangle^2, \tag{2}$$

where we average over momentum cells (sub-divisions) and events.

- For critical data with no background, critical QCD predicts [4,5]:

$F_2(M) \sim (M^2)^{\phi_{2,cr}}, \quad \phi_{2,cr}^{(p)} = \frac{5}{6}, \quad \phi_{2,cr}^{(\sigma)} = \frac{2}{3} \quad (p : \text{protons}, \sigma : \text{dipions})$

Analysed experimental data

- We analyse data recorded by the NA49 experiment [7] in A+A collisions at maximum CERN SPS energy of 158*A* GeV ($\sqrt{s_{NN}} = 17.3$ GeV).
- Datasets used: "C"(C,N), "Si"(Si,Al,P) and Pb nuclei on C, Si and Pb targets, respectively, for 12.5% most central collisions. We restrict analysis to protons, because of negligible number of anti-protons. Past analysis has been performed on dipions, also.
- Mid-rapidity region used, $-0.75 < y_{CM} < 0.75$, because of almost constant density of protons there. Standard NA49 event & track cuts were applied [8]. Identification of protons was achieved via measurements of particle energy loss dE/dx [8].
- The event statistics amounted to 210k events for "C"+C, 176k events for "Si"+Si and 1480k events for Pb+Pb.

Dealing with non-critical background

- To reveal any potential power-law present in the data, we have to subtract backround due to uncorrelated protons and contamination by particles mis-identified as protons.
- We use **mixed events** technique: Construction of artificial events where correlations have been eliminated, simulating just the background.
- Theoretical analysis then shows that critical behaviour should be restored in the corrected correlator, $\Delta F_2(M) = F_2^{(d)}(M) - F_2^{(m)}(M)$, where (d) denotes data and (m) mixed events [4].

Results-analysis

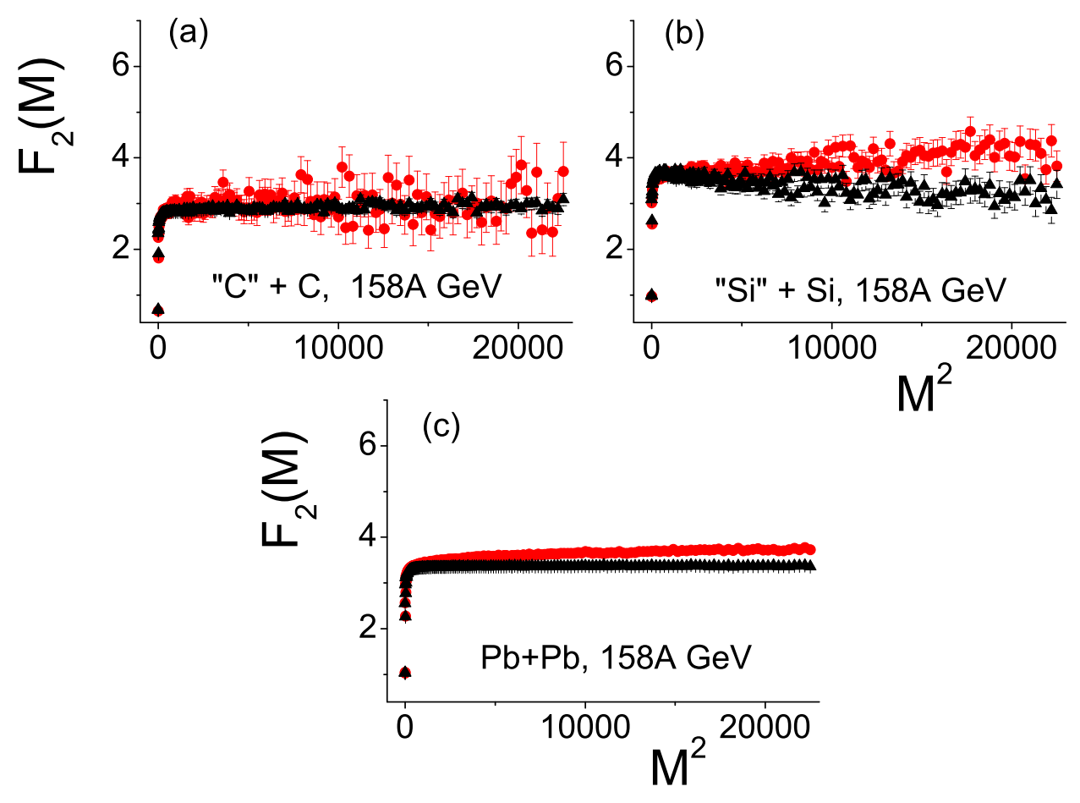

Figure 1: $F_2(M)$ for protons at midrapidity (central collisions). (a) "C"+C, (b) "Si"+Si and (c) Pb+Pb. Red circles : data , Black triangles : mixed events. In (b,c): $F_2(M)$ for data exceeds that for mixed events at increasing M → intermittent behaviour. Effect absent in (a).

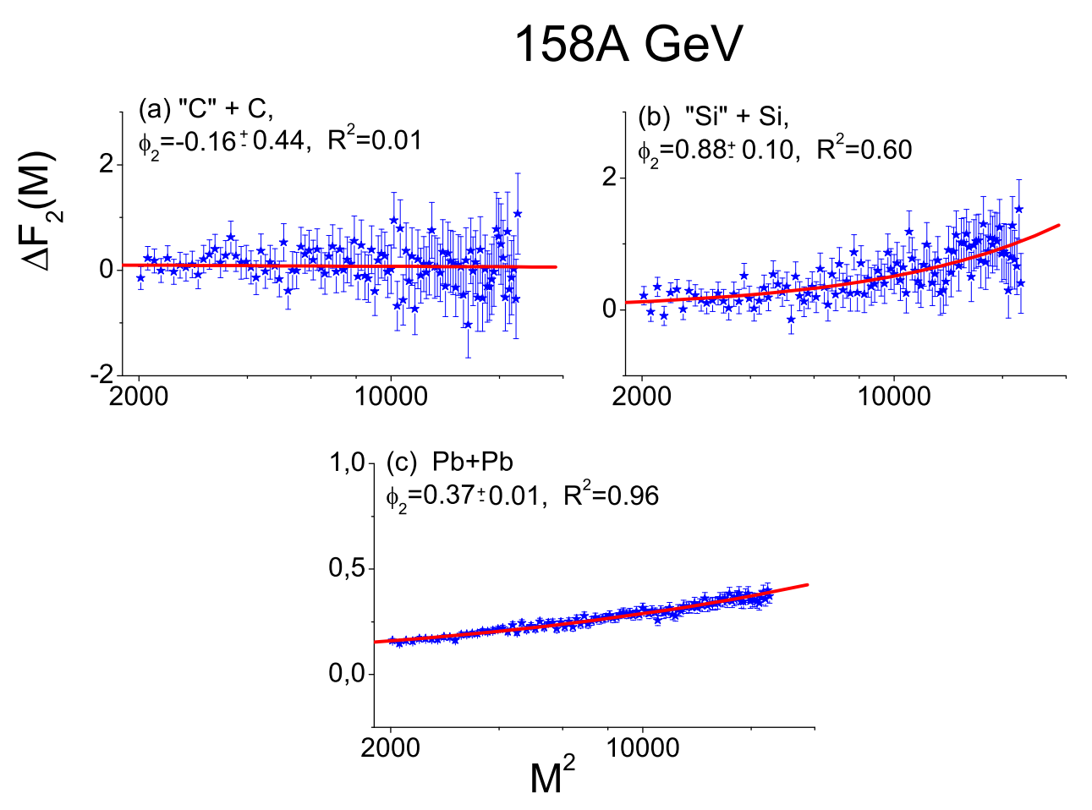

Figure 2: Corrected correlator $\Delta F_2(M)$, shown in log-linear scale, corresponding to the moments of Fig. 1. (a) "C"+C , (b) "Si"+Si and (c) Pb+Pb. Red solid lines: direct power-law fit.

Results-analysis

- [Fig.2] After subtraction of background, the corrected correlator $\Delta F_2(M)$ for "Si"+Si and Pb+Pb is well-described, in the region of large $M^2 (> 2000)$, by a power-law fit (coefficient of determination $R^2 > 0.5$).
- [Fig.2] For the "C"+C system, we get very poor fit quality, $R^2 \sim 0.01$, and a negative exponent due to negative values resulting from statistical fluctuations in data & mixed events. We conclude that the "C"+C system does **not** follow a power-law.

Dependence of intermittency index on system size

- Both "Si"+Si and Pb+Pb systems have intermittency indices that approach the QCD predicted value.They appear to freeze out near the Critical Point. In [Fig.3], we plot the fitted intermittency indices ϕ_2 as a function of the size A of the nuclei for all 3 systems ("C"+C included for completeness).
- The estimated error of ϕ_2 values is obtained from the variation of results obtained by using 4 different fit methods: Direct power law fit (DPF), correlated χ^2 fit [9], independent bins [10] and sparse binning [11].

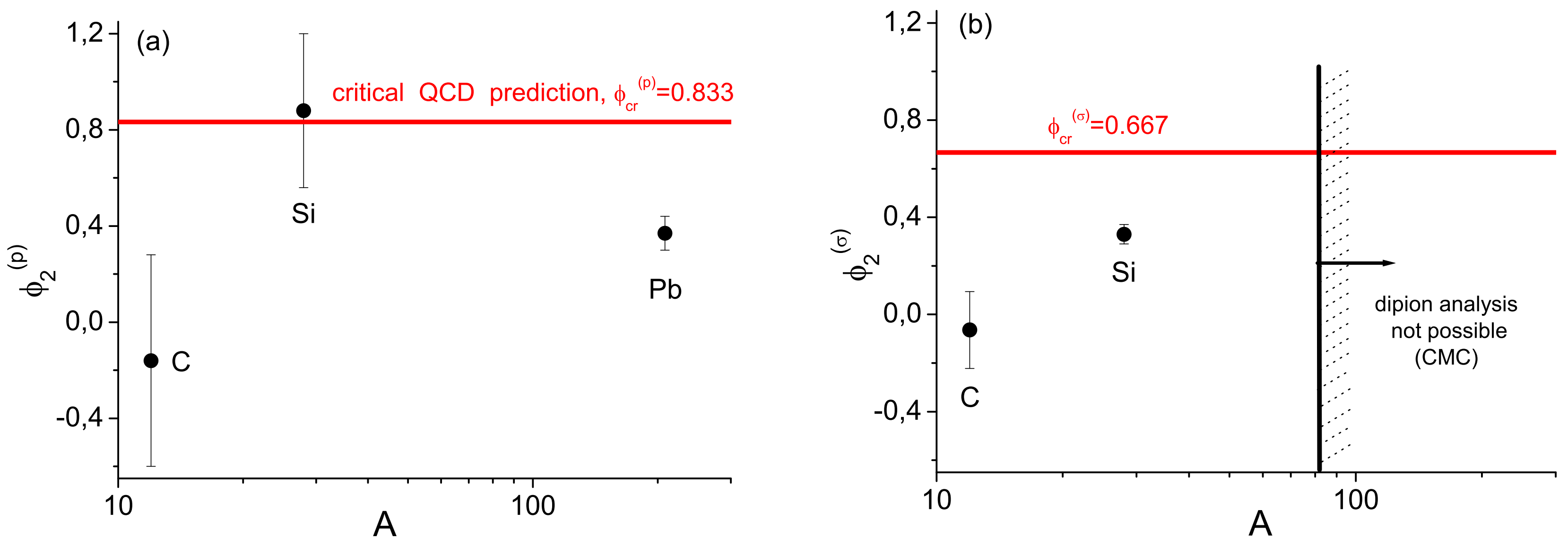

Figure 3: (a) The intermittency index $\phi_2^{(p)}$ calculated using proton tracks at midrapidity and (b) the corresponding intermittency index $\phi_2^{(\sigma)}$ for dipions as calculated in [12]. In each plot the red lines indicate the corresponding QCD predictions: $\phi_2^{(p)} = \frac{5}{6}$ and $\phi_2^{(\sigma)} = \frac{2}{3}$.

Dependence on rapidity range and beam energy

- Intermittency is suppressed outside the mid-rapidity region [Fig.4, Ref.5], and at energies lower than the maximum beam energy [Fig.5]

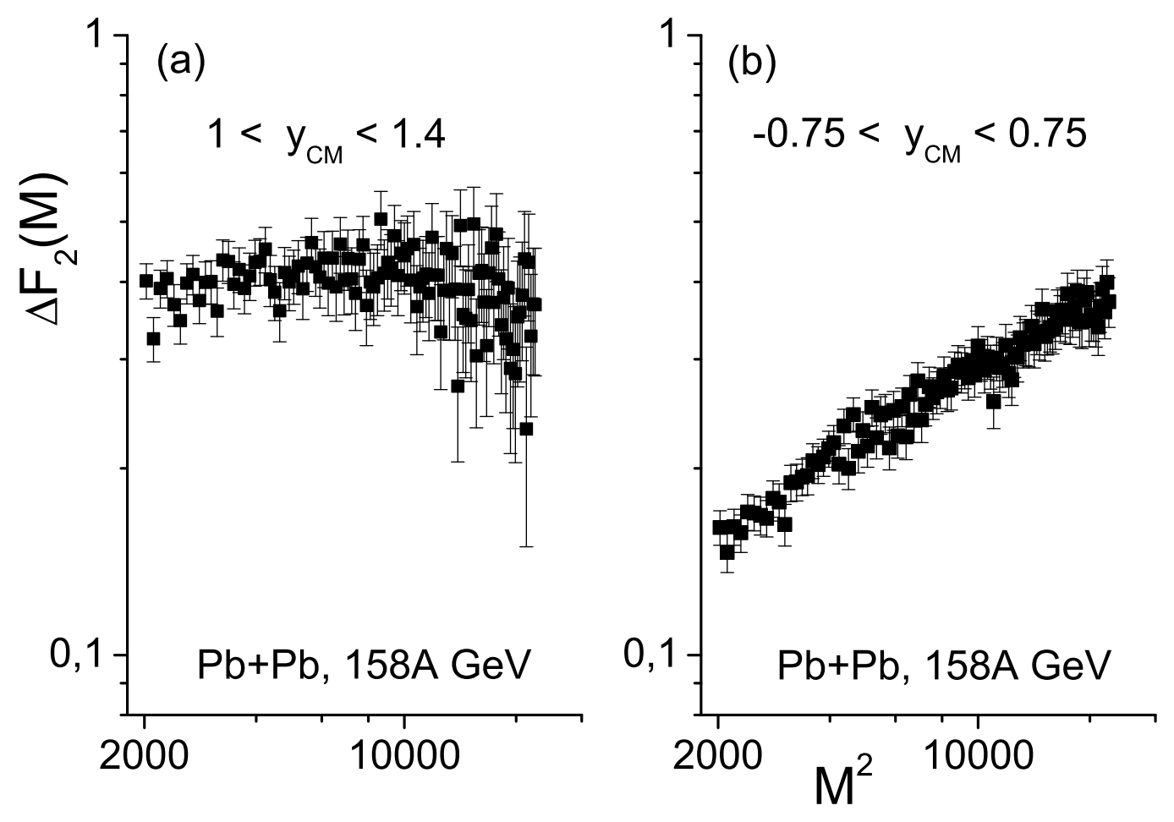

Figure 4: The correlator ΔF_2 for the 12.5% most central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV using tracks with (a) $1 < y_{CM} < 1.4$ and (b) $-0.75 < y_{CM} < 0.75$ plotted in a double logarithmic scale.

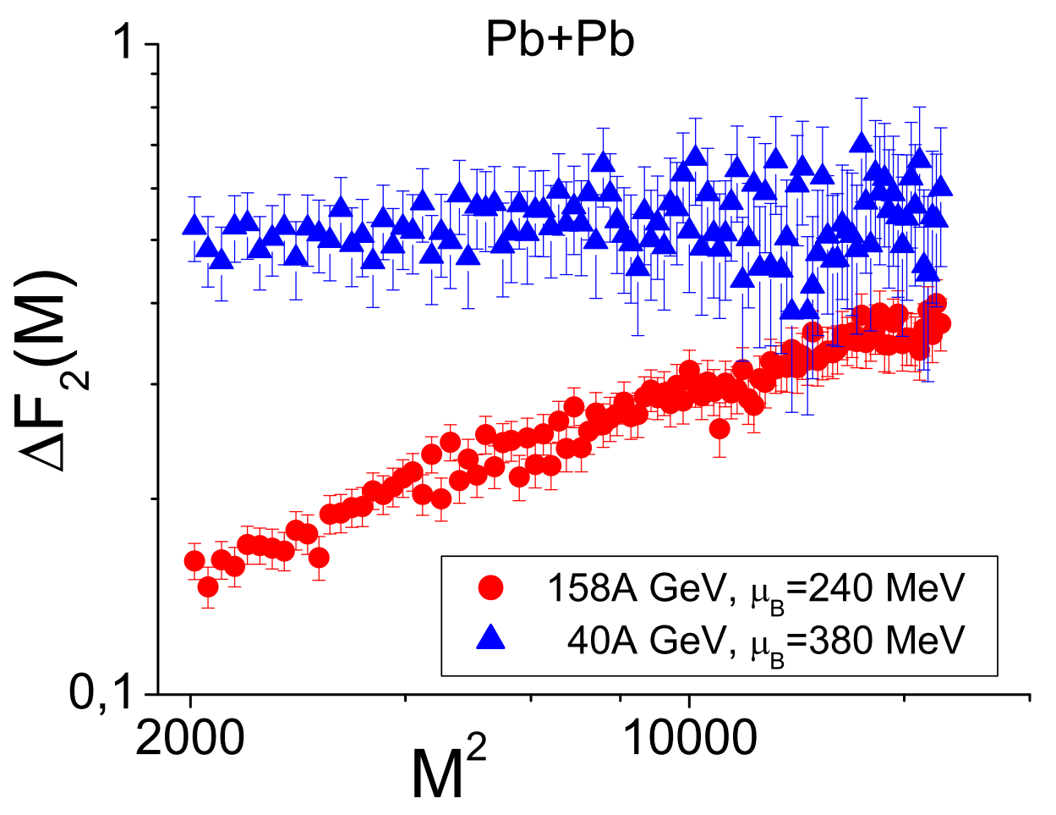

Figure 5: Correlator ΔF_2 for the 12.5% most central Pb+Pb collisions at $\sqrt{s_{NN}} = 17.3$ GeV (red circles) and $\sqrt{s_{NN}} = 8.8$ GeV (blue triangles) in the midrapidity region.

Conclusions

- We find a **strong intermittency effect** for the "Si"+Si and the Pb+Pb systems at midrapidity. The intermittency index ϕ_2 for the "Si"+Si system approaches in size the QCD prediction for the critical point.
- **First strong** experimental indication for the existence of the QCD critical point in the neighbourhood of the Si+Si and Pb+Pb freeze-out states in the phase diagram ($T \simeq 150 - 160$ MeV, $\mu_B \simeq 200 - 250$ MeV).
- Further restrictions on the location of the Critical Point may be provided by measurements in the **NA61 experiment**, studying A+A collisions with small and intermediate size nuclei. Significant new results on fluctuations may also be expected from the RHIC Beam Energy Scan program [13].

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