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

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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. Scan the phase diagram for the existence and location of the CP by varying the energy and size of the collision system.

Global vs. local observables

- Two classes of observables: (i) Global and (ii) Local.
- Global $\Rightarrow$ 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*, PL**B 675**, 32 (2009).])
- Local $\Rightarrow$ self-similar density fluctuations of the order parameter in transverse configuration space (random fractal) $\Rightarrow$ power-law dependence of the density-density correlation functions in transverse momentum space $\Leftrightarrow$ intermittency analysis (critical opalescence, correlation length vs. size [F.K. D., N.G. Antoniou and G. Mavromanolakis, PoS(CPOD2006)010, Florence]).
  Necessary and (may be?) also **sufficient** condition for **critical** behaviour.
- Global observables are sensitive to experimental acceptance while local observables not.

Local observables

- 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 at midrapidity, k, k' are transverse momenta.

- The σ-density fluctuations $\Rightarrow$ density fluctuations of (π^+, π^-) pairs with invariant mass close to $2m_\pi$.

  [N.G. Antoniou, Y.F. Contoyiannis, F.K. D. and G. Mavromanolakis , NP**A 761**, 149 (2005); N.G. Antoniou, F.K. D., A.S. Kapoyannis and K.S. Kousouris, PRL**97**, 032002 (2006).]

- The coupling of the (isospin zero) σ-field with protons transfers critical fluctuations to the net proton density [Y. Hatta and M. A. Stephanov, PRL**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^2=number of cells in transverse momentum space,

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

(predictions of critical QCD).

Analysis scheme

- **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 vertical second factorial moment (VSFM) 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 VSFM 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

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

  $(d) \equiv$ 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:

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

with:

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

Measures for critical fluctuations

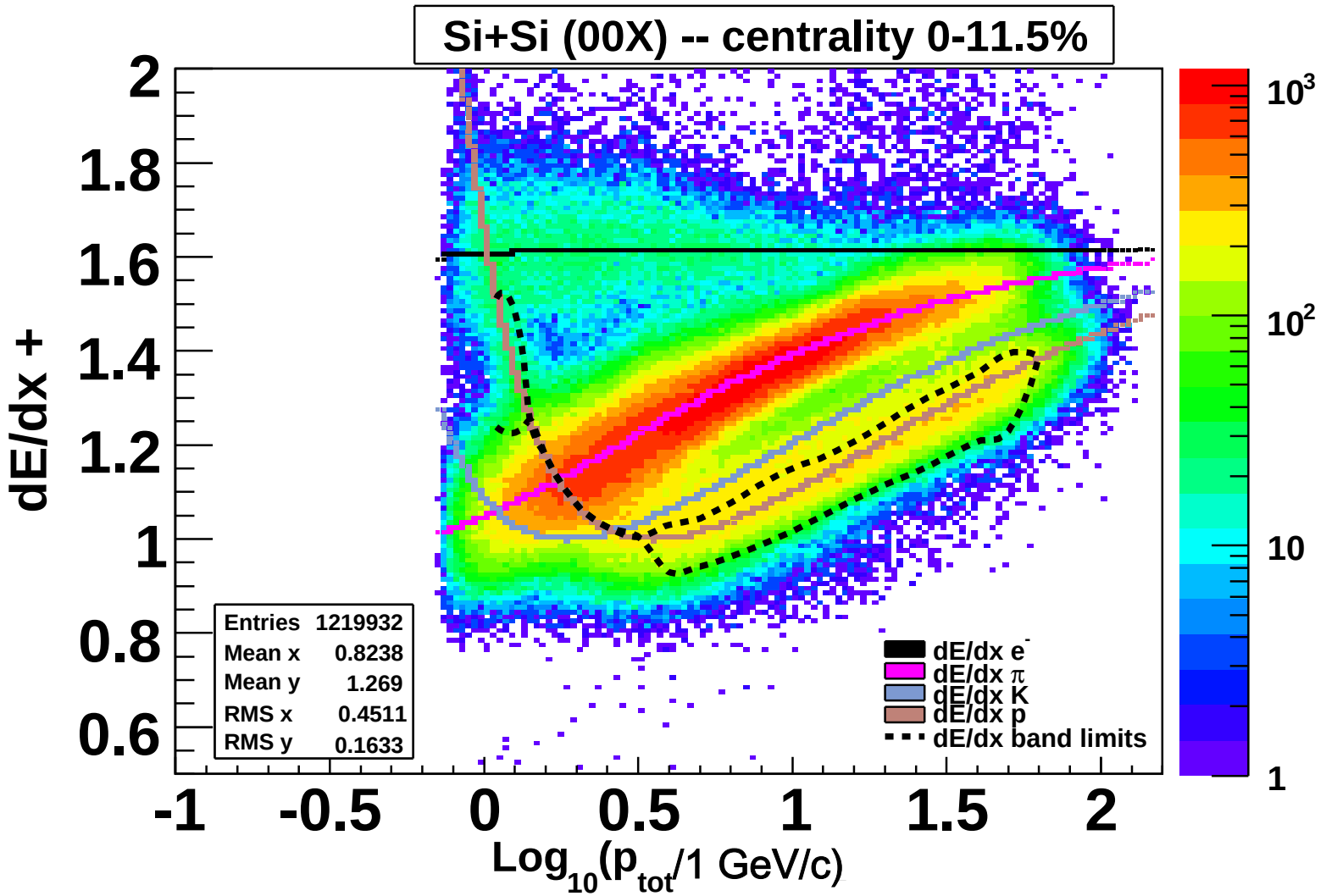
- The intermittency index ϕ_2 carries information for the critical fluctuations (universality class).
- It can be calculated through a power-law fit of $\Delta F_2(M) \Rightarrow$ exponent of the power-law.
- The distance of the freeze out state of a system from the critical point can be measured with 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

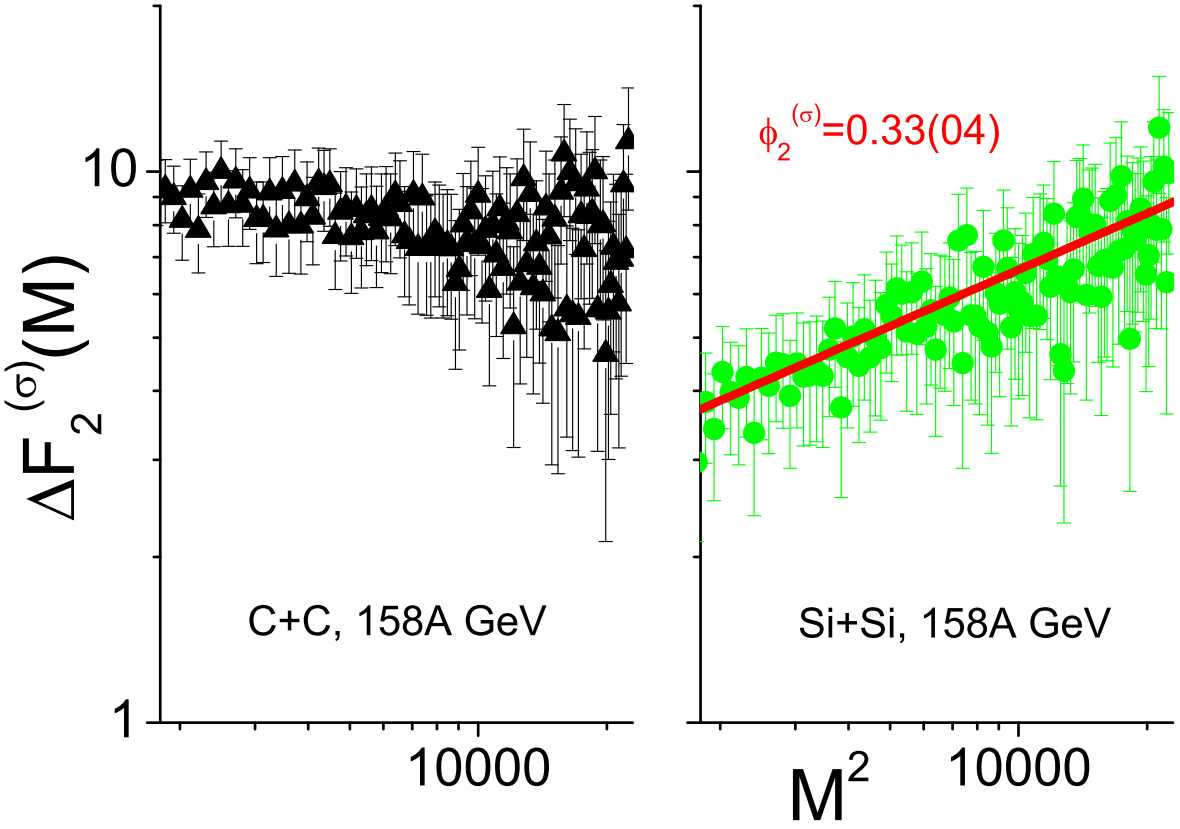
	A+C (A=C,N)	**A+Si** (A=Si,Al,P)	**Pb+Pb**
beam energy	158 A GeV		40, 158 A GeV
centrality range	$0 \rightarrow 11.5\%$		$0 \rightarrow 12.5\%$
# of events	33 560	175 943	1 480 587

- Standard event and track selection cuts of NA49 experiment [T. Anticic *et al*, PR**C 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

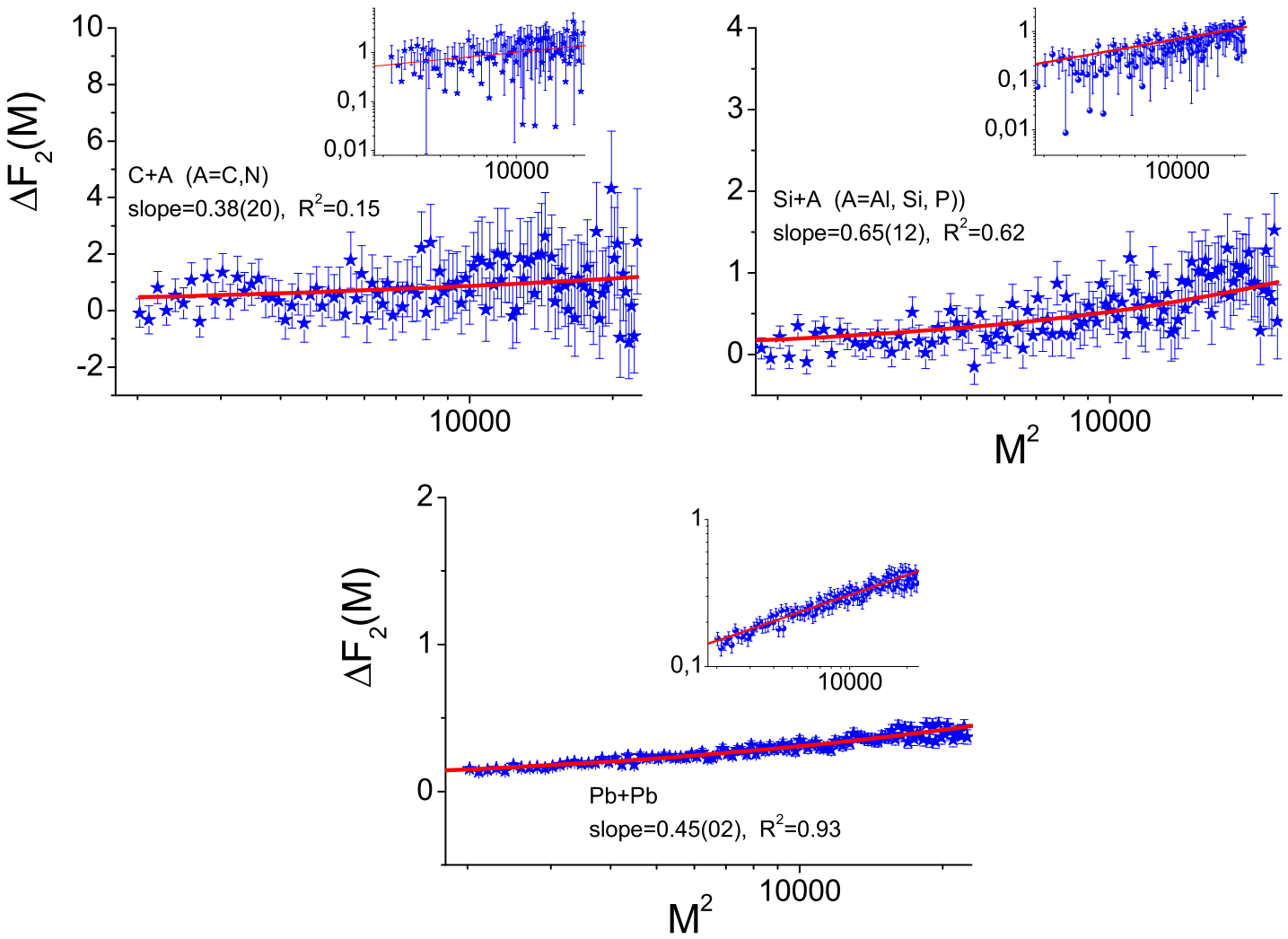


Analysis results - Dipions

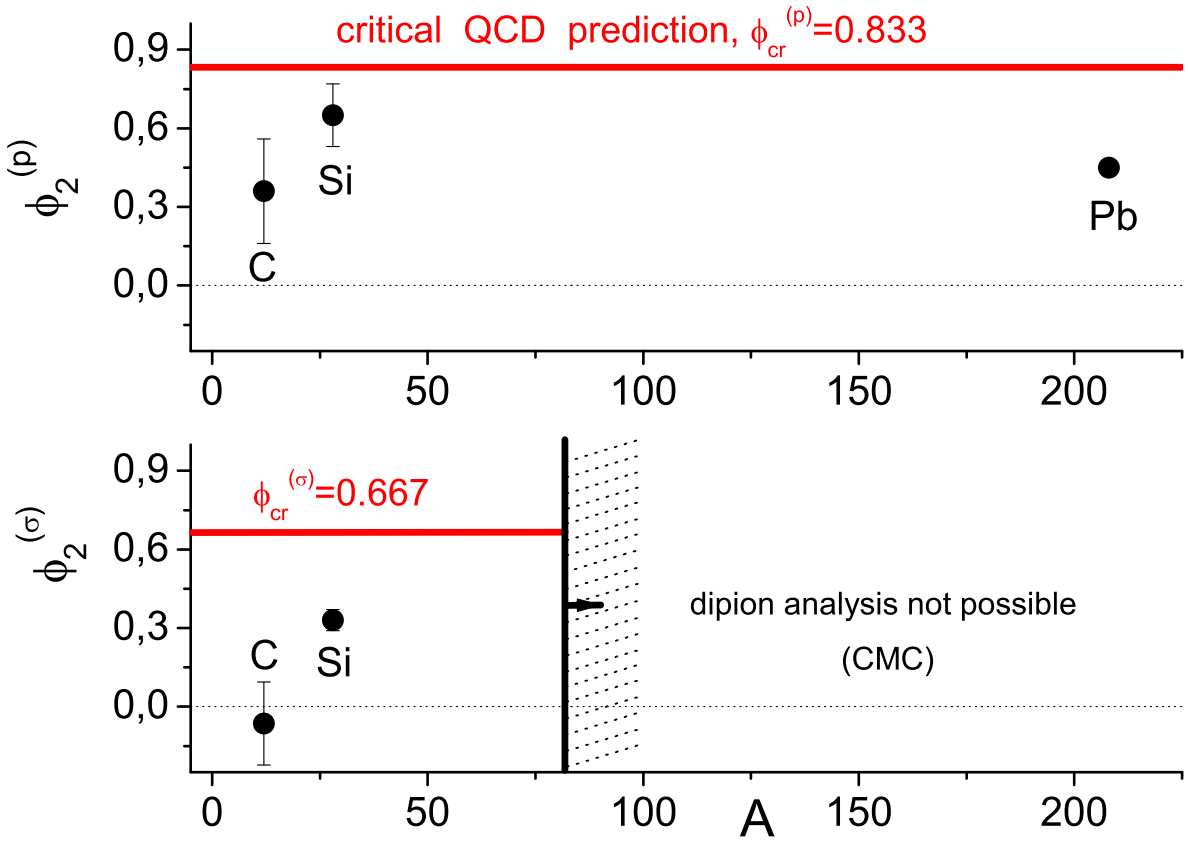


Reconstruction of critical isoscalar fluctuations does not work for large systems (Pb+Pb) [T. Anticic *et al*, PR**C 81**, 149 (2010).]

Analysis results - Protons

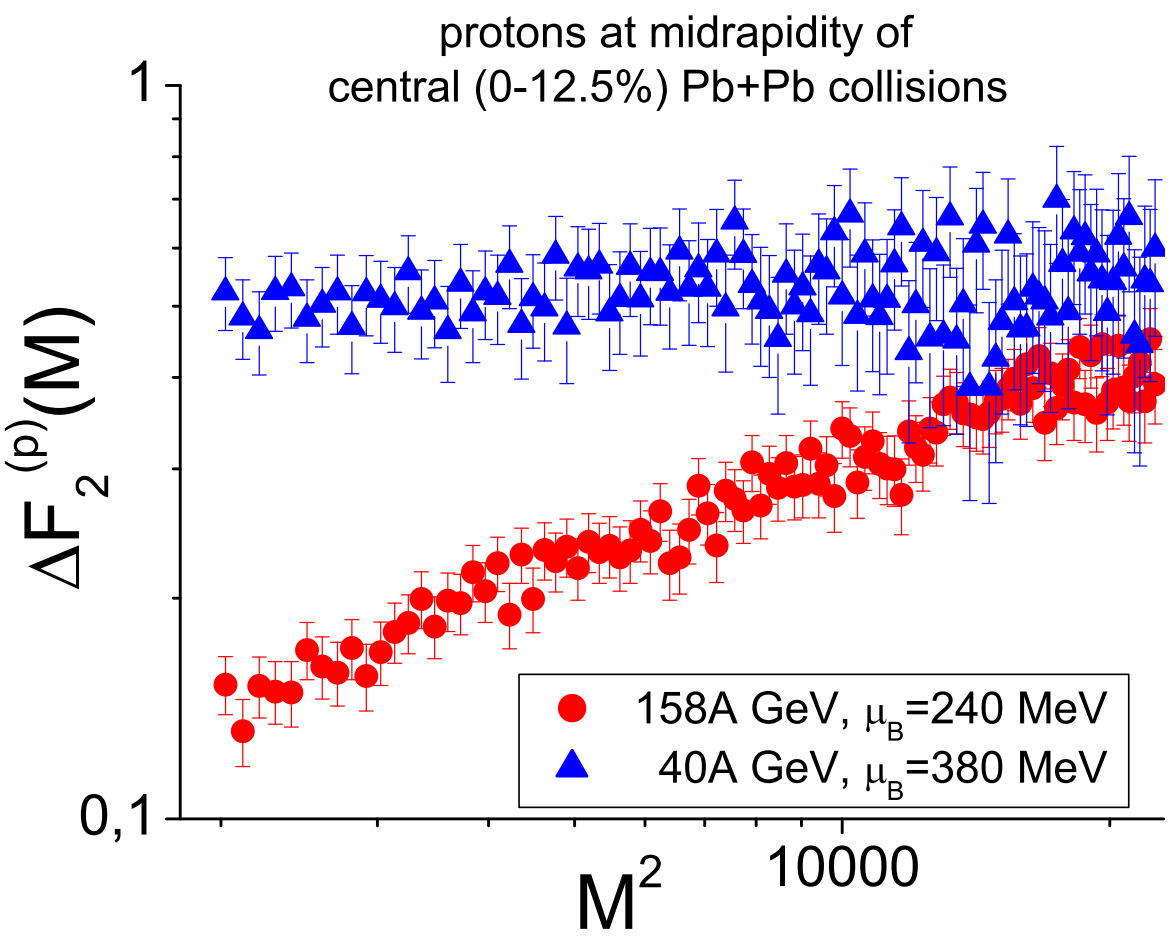


Analysis results - Size dependence of ϕ_2



Significant power-law fluctuations for Si and Pb systems at 158A GeV. The intermittency index ϕ_2 for **Si is closest** 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 conditions.

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.

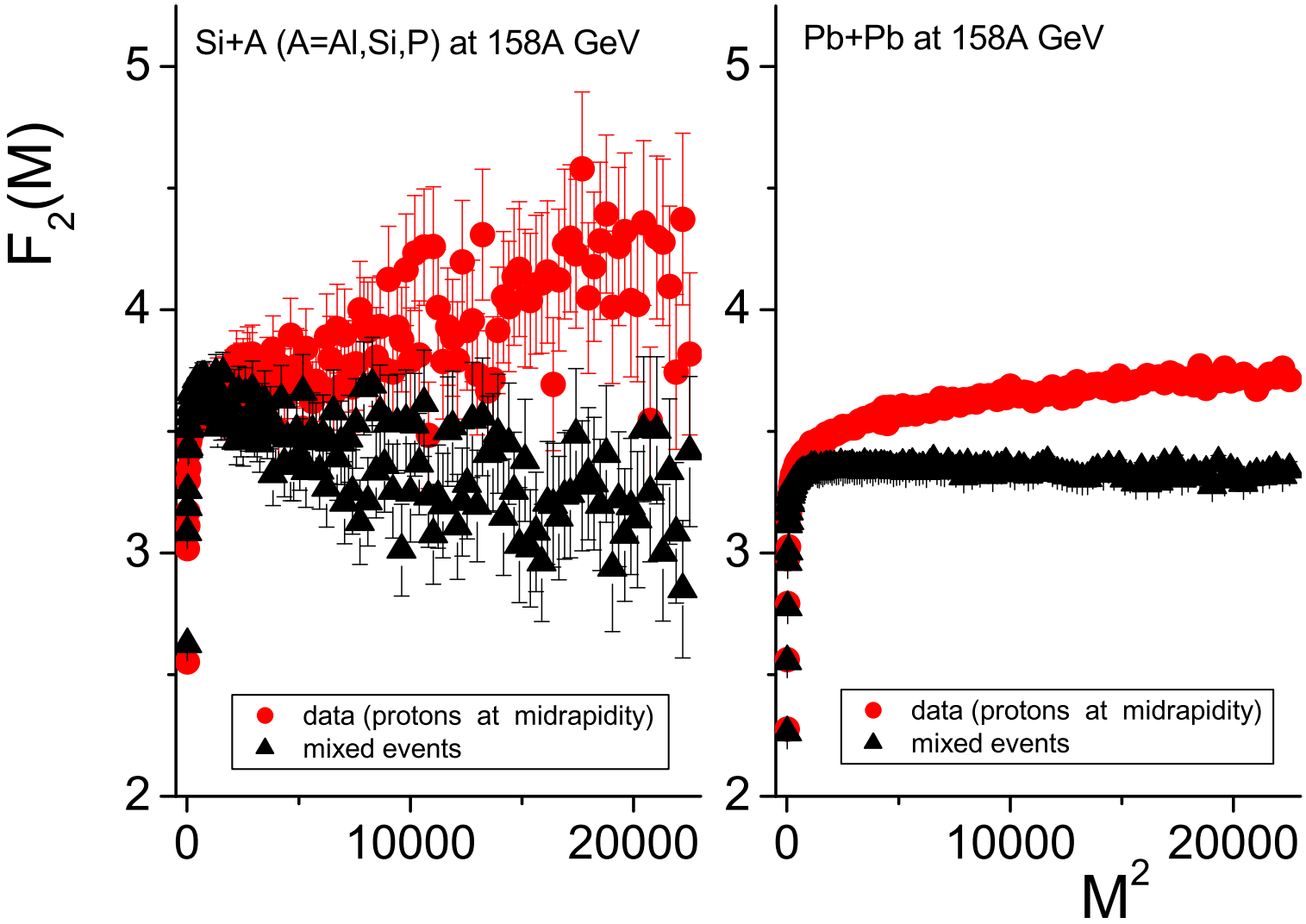
- For (π^+, π^-) pairs (dipions) with invariant mass close to $2m_\pi$ we have found significant power-law fluctuations in Si at 158A GeV.
- For protons at midrapidity we have found significant power-law fluctuations in Si and Pb at 158A GeV.
- The **intermittency index ϕ_2** for the **Si system approaches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

Factorial moments for protons in Si+A and Pb+Pb



Correlator of protons, Pb+Pb