Recent results from the search for the critical point of strongly interacting matter at the CERN SPS

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Introduction

The exploration of the phase diagram of strongly interacting matter, particularly the search for a phase transition from hadronic to partonic degrees of freedom and possibly a critical endpoint, is one of the most challenging tasks in present heavy ion physics.

NA49 data on inclusive hadron production indicate that the onset of deconfinement in central Pb+Pb collisions is located at about 30*A* GeV. It is mainly based on the observation of norrow structures in the energy dependence of hadron production in central Pb+Pb collisions which are not observed in elementary interactions [1,2].

The NA61/SHINE experiment [3] continues the ion program of NA49 with the main aim of searching for the critical point and studying in details the onset of deconfinement by performing a two dimensional scan of the phase diagram in T and μ_B. This is achieved by varying collision energy (13A-158A GeV) and size of the colliding systems (p+p, p+Pb, Be+Be, Ar+Ca, Xe+La). The data sets recorded by the NA49 and NA61/SHINE experiments and those planned to be recorded by NA61/SHINE for the ion program are presented in Fig.1 (left). The planned scan of the phase diagram is shown in Fig.1 (right).

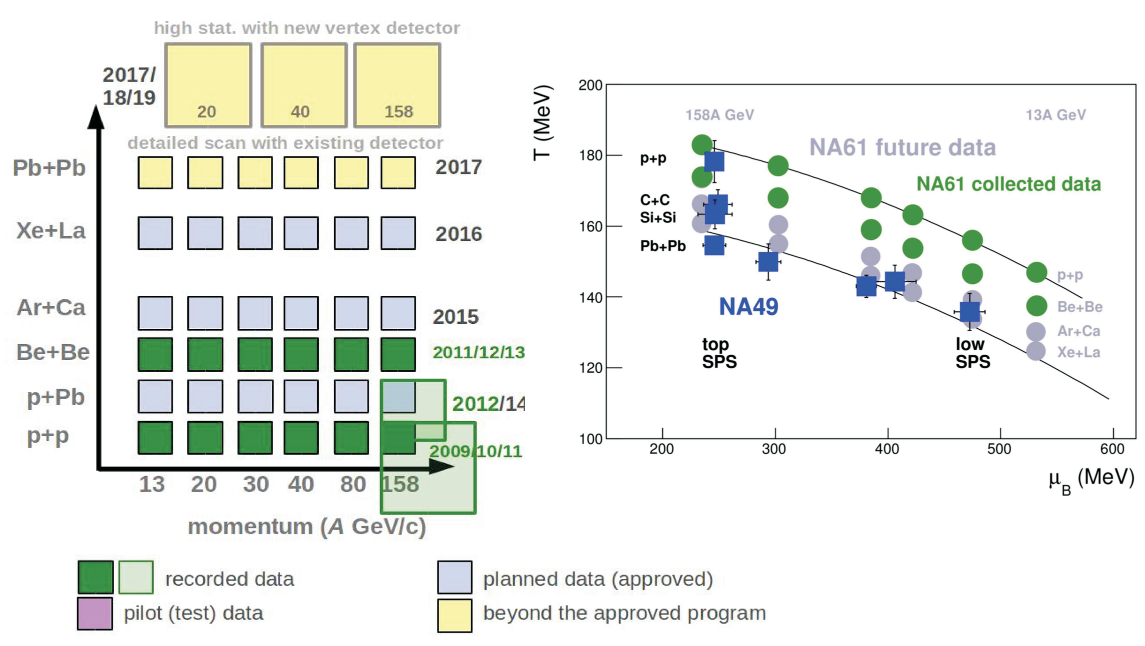

Fig.1 Left: Data sets collected and planned to be recorded by NA61/SHINE within the ion program and those recorded by NA49. **Right**:Scan of the phase diagram by varying collision energy (μ_B) and size of colliding nuclei (T). Chemical freeze-out points are taken from [4] and parametrizations therein.

An illustration of the impact of new measurements on the system size dependence of the K^+/π^+ (horn) is shown in Fig.2 (left). The presence of the predicted critical point is expected to lead to an increase of event-by-event fluctuations of many observables [5,6] provided that the freeze-out of the measured hadrons occurs close to its location in the phase diagram and the evolution of the final hadron phase does not erase the fluctuation signals.The NA61/SHINE experiment looks for a maximum of fluctuations as experimental signature for the critical point, Fig.2(right).

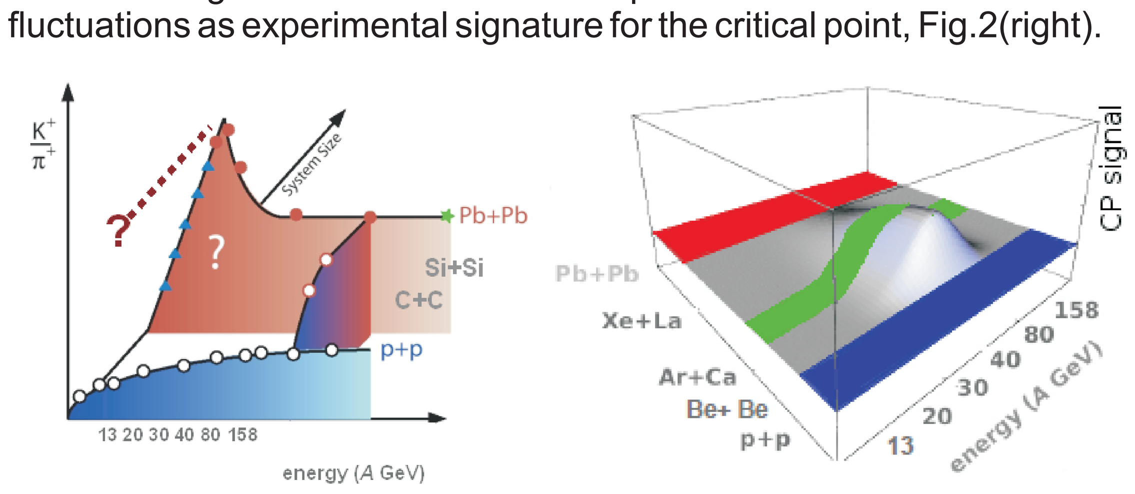

Fig.2 Left: An ilustration of the impact of the NA61 measurements on clarifying the system size dependence of the K^+/π^+ (horn) observed in central Pb+Pb collisions at low SPS energies. **Right**: The hill of fluctuations as a signature for the critical point.

Event-by-event fluctuations

In the NA49 and NA61/SHINE experiments event-by-event fluctuations of the particle multiplicity are measured by the scaled variance ω which is intensive measure (independent of volume) and defined as

$$\omega = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle}$$

The transverse momentum fluctuations are measured by the Φ quantity proposed in [7] which was also succesfully employed by the NA49 experiment to study charge and azimuthal angle fluctuations. Recently new strongly intensive fluctuation measures (independent of volume and volume fluctuations) Δ and Σ were proposed in [8]. Whereas $\Sigma[P_T,N]$ is closely related to Φ_{PT} the quantity $\Delta[P_T,N]$ is sensitive to fluctuations of p_T and N in a different combination thus these measures can be sensitive to various physics effects. All mentioned measures are formulated below

$$\Delta[P_T,N] = \left[\langle N\rangle\omega[P_T] - \langle P_T\rangle\omega[N]\right]\frac{1}{\langle N\rangle\omega[p_T]}$$

$$\Sigma[P_T,N] = \left[\langle N\rangle\omega[P_T] - \langle P_T\rangle\omega[N] - 2\left(\langle P_T,N\rangle - \langle P_T\rangle\langle N\rangle\right)\right]\frac{1}{\langle N\rangle\omega[p_T]}$$

$$\Phi_{pT} = \sqrt{\overline{p_T}\,\omega[p_T]}\left[\sqrt{\Sigma[P_T,N]} - 1\right]$$

where

$$P_T = \Sigma_i^N p_{Ti} \qquad \omega[P_T] = \frac{\langle P_T^2\rangle - \langle P_T\rangle^2}{\langle P_T\rangle} \qquad \omega[N] = \frac{\langle N^2\rangle - \langle N\rangle^2}{\langle N\rangle}$$

Fig.3 shows the dependence of multiplicity fluctuations quantified by scaled variance ω and fluctuations of the average transverse momentum measured by Φ_{PT} as well as $\Delta[P_T,N]$ and $\Sigma[P_T,N]$ as a function of chemical freeze-out temperature T_{chem} (from statistical model fits [4]) in p+p interactions and central C+C, Si+Si and Pb+Pb collisions. All quantities show a possible maximum of fluctuations at T_{chem}=160-170 MeV reached in collisions of medium-size nuclei. It agrees with expectations for the critical point represented by curves for ω and Φ_{PT}[9].

The dependence of all fluctuation measures on μ_B (from statistical model fits [4]) in p+p interactions (NA61) and central Pb+Pb collisions (NA49) is shown in Fig.4. Here the data don't support a maximum as might be expected for the critical point (curves for ω and Φ_{PT}[9]).

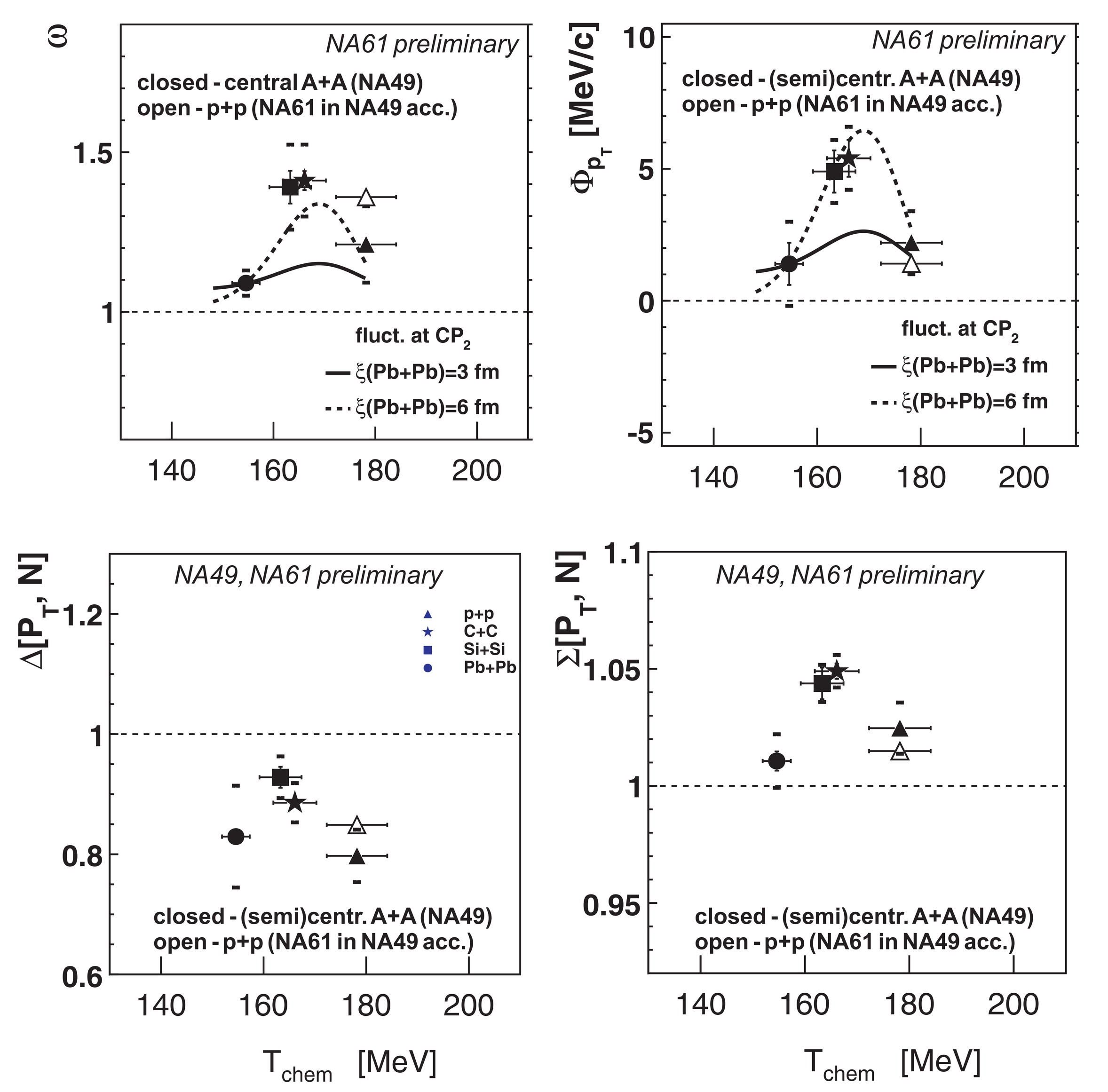

Fig.3 The dependence of the Φ_{pT}, Δ and Σ measures and the scaled variance of multiplicity fluctuations ω on T_{chem} (system size) for charged hadrons in central A+A collisions and p+p interactions. Curves indicate the estimated effects of the critical point (T=178MeV, μ_B=250MeV) for two values of the correlation length ξ.

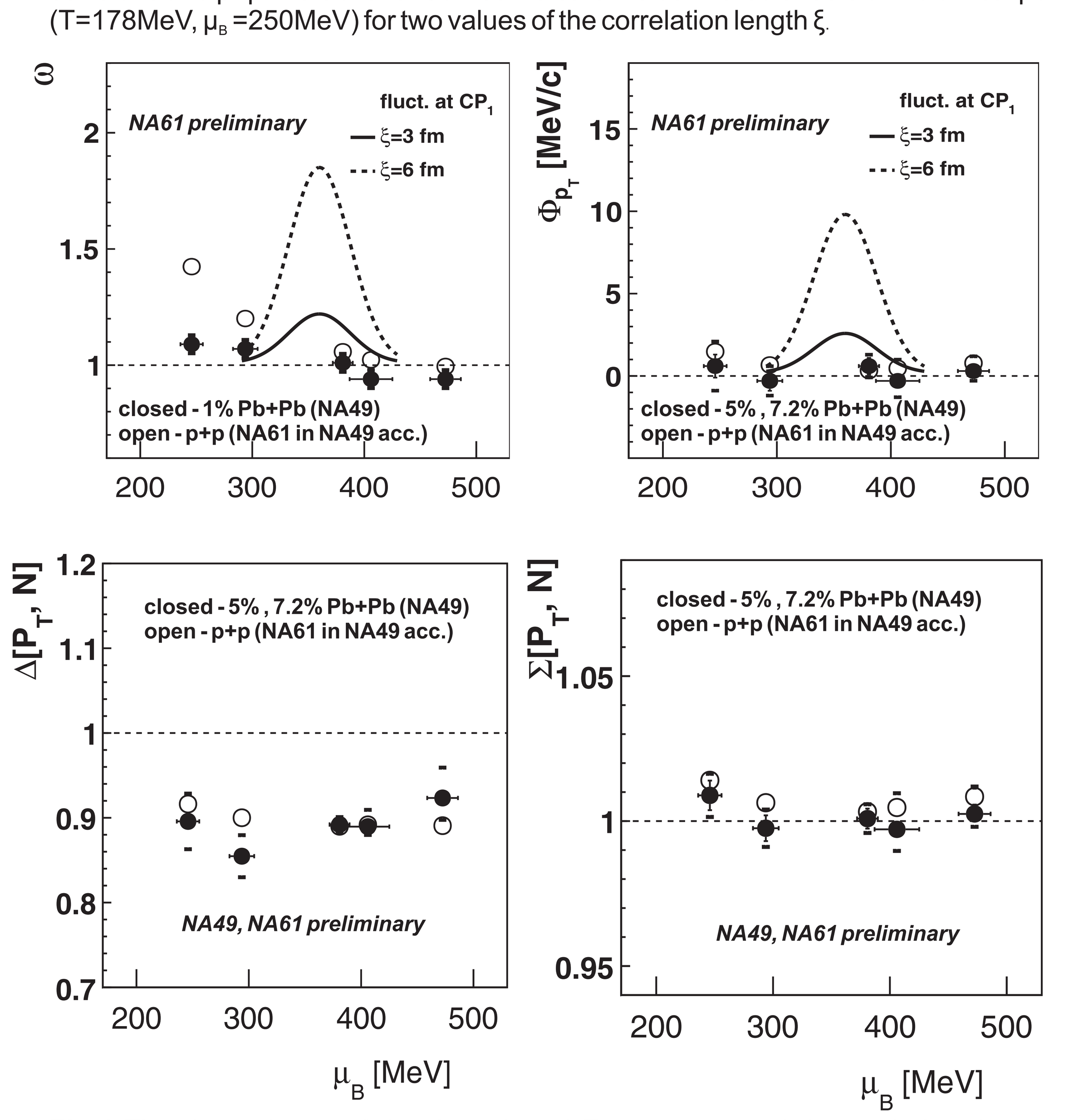

Fig.4 The dependence of the Φ_{pT}, Δ and Σ measures and the scaled variance of multiplicity fluctuations ω on μ_B (collision energy) for charged hadrons in central Pb+Pb collisions and p+p interactions. Curves indicate the estimated effects of the critical point (T=147MeV, μ_B=360MeV) for two values of the correlation length ξ.

A new identification procedure (identity method [10]) allowed to measure the energy dependence of fluctuations of identified proton, kaon and pion multiplicities in p+p and Pb+Pb collisions. As in the case of charged particle multiplicites no indication of the critical point was found.

Chemical (particle type) fluctuations were analysed using Φij measure [11] defined as:

$$\Phi_{ij} = \left[\sqrt{\Sigma^{ij}} - 1\right]\frac{\langle N_i\rangle\langle N_j\rangle}{\langle N_i + N_j\rangle}$$

where

$$\Sigma^{ij} = \left[\langle N_i\rangle\omega_j + \langle N_j\rangle\omega_i - 2\left(\langle N_{ij}\rangle - \langle N_i\rangle\langle N_j\rangle\right)\right] / \langle N_i + N_j\rangle$$

and *i,j* indicate two different particle types.

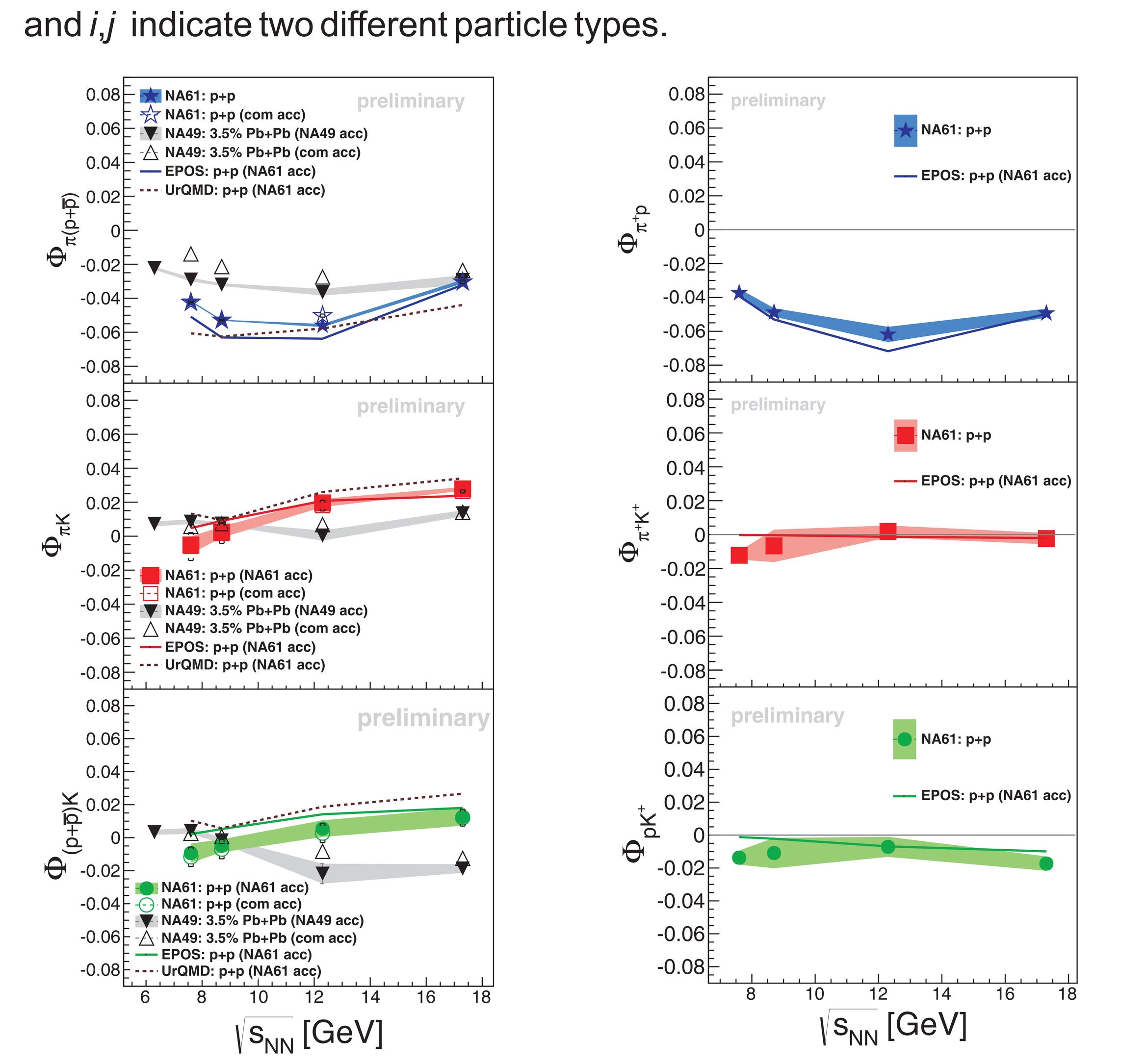

Fig5. Chemical (particle type) fluctuations in inelastic p+p interactions at 30, 40, 80, and 158GeV/c. NA61 p+p data are compared to those obtained by NA49 in Pb+Pb collisions [12]. See [13] for NA49, NA61 acceptance and common phase space region.

Fig.5 shows two particle chemical fluctuations as a function of interaction energy. The fluctuations cannot be corrected for the limited acceptance thus the results are presented both for the NA49, NA61 acceptance and a common NA49/NA61 phase space region. The left panel of Fig.5 shows combinations of both charges, the right panel only of positively charged particles. The values of Φ for pions and protons plus anti-protons are negative for all studied energies. This is most probably due to charge conservation and resonance decays. In p+p collisions $\Phi_{\pi K}$ is higher than zero probably due to strangeness conservation. It slightly increases with interactions energy for p+p interactions which is not observed for Pb+Pb collisions. For both systems $\Phi_{(p+\bar{p})K}$ crosses zero at medium SPS energies. Finally, we observe no significant energy dependence of Φ_{pK+} in the NA61 data. The EPOS and UrQMD model predictions reproduce p+p data resonably well.

Density fluctuations of protons and low-mass $\pi^+\pi^-$ pairs.

Theoretical investigation [14] predict near the critical point the appearance of local density fluctuations for protons [15] and low-mass $\pi^+\pi^-$ pairs of power-law nature with known critical exponents [16]. This can be studied by the intermittency analysis method in transverse momentum space using second factorial moments $F_2(M)$, where M is the number of subdivisions in each p_T direction. After combinatorial background subtraction the exponents φ_2 are obtained from a power-law fit to the corrected moments $\Delta F_2(M) \approx M^{2\varphi_2}$. The resulting values of φ_2 obtained for central C+C, Si+Si and Pb+Pb collisions at 158GeV are plotted in Fig.6. Remarkably, φ_2 seems to reach a maximum for Si+ Si collisions which is consistent with the theoretical expectations for the critical point.

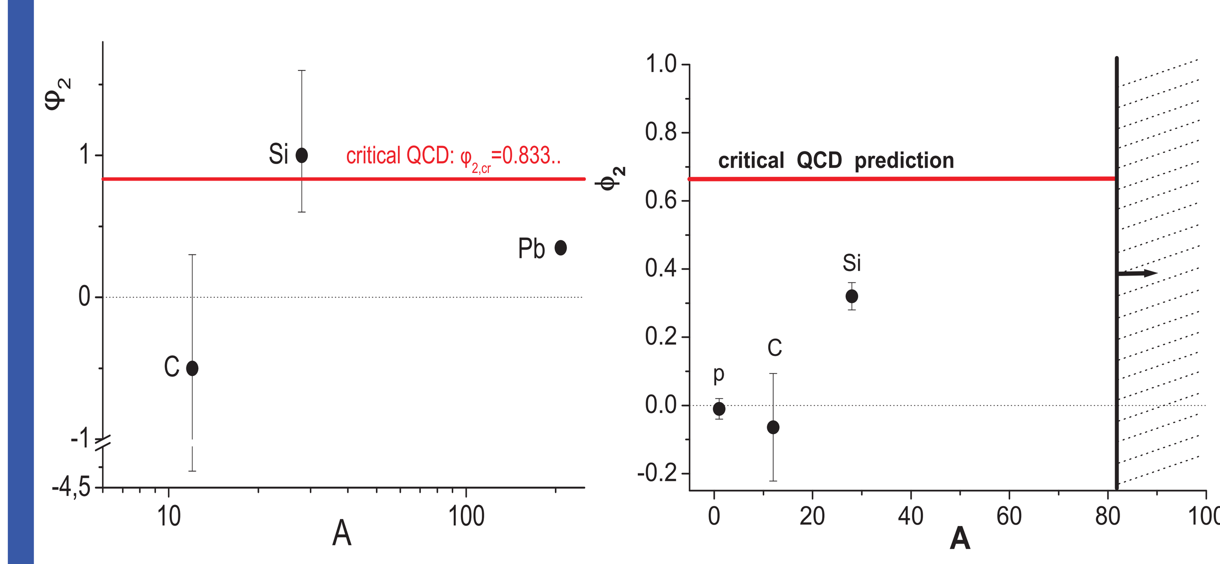

Fig.6 Exponent φ_2 obtained from power-law fits to second scaled factorial moments of protons (left) and low-mass $\pi^+\pi^-$ pairs (right) for several collision systems at 158AGeV.

Spectra of π^- mesons.

Transverse mass spectra of π^- were obtained by so called h^- method. The method exctracts the non-identified hadron spectrum and subtracts the small (≈ 10%) contribution of particles other than pions based on Monte-Carlo model simulations. The transverse mass spectra of π^- in p+p, Be+Be and central Pb+Pb collisions at 158A GeV are shown on Fig.7 (left). Spectra of π^- in Be+Be collisions exhibit similar concave shape as in Pb+Pb while spectra in p+p interactions show exponential behavior.

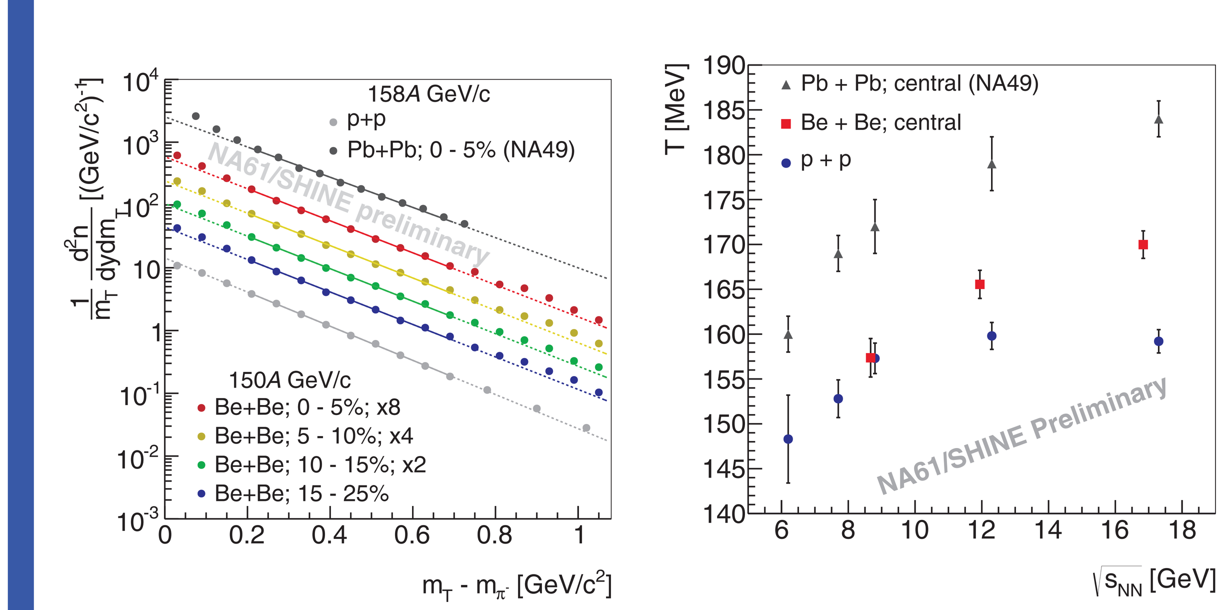

Fig.7 Left: Transverse mass spectra of π^- in p+p, Be+Be and central Pb+Pb collisions. **Right:** Energy dependence of the inverse slope parameter.

The inverse slope parameter T exhibits strong energy dependence. At lower collision energy T behaves similarly in pp and Be+Be collisions, while at high energies Berylium data lie between p+p and Pb+Pb results.

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