Search for critical point in NA61/SHINE

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for the **NA61/SHINE Collaboration**

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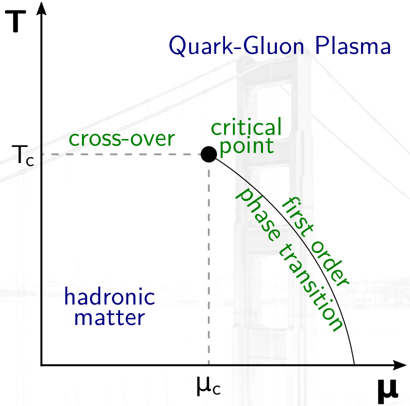
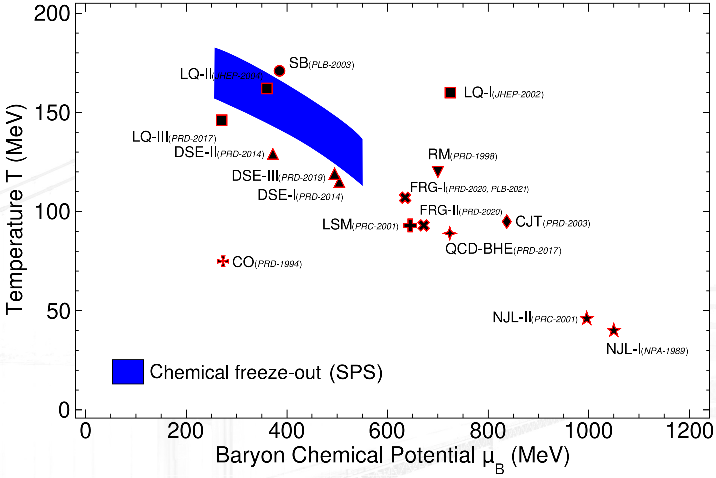


Critical point (CP) – a hypothetical end point of first order phase transition line (QGP-HM) that has properties of second order phase transition.

2[nd] order phase transition ⟶ scale invariance ⟶ power-law form of correlation function.
These expectations are for fluctuations and correlations in the configuration space which are expected to be projected to the momentum space via quantum statistics and/or collective flow.

Asakawa, Yazaki NPA 504 (1989) 668
Barducci, Casalbuoni, De Curtis, Gatto, Pettini, PLB 231 (1989) 463

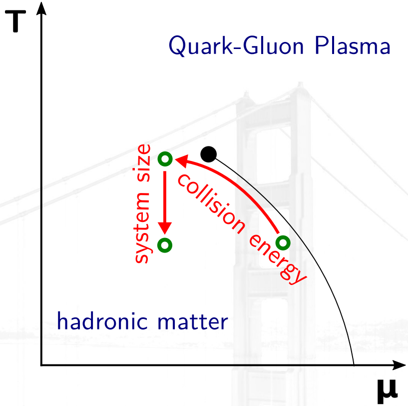
Critical Point of QGP



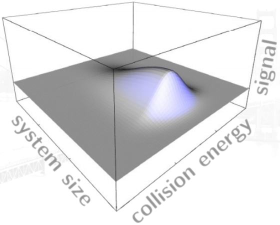
Predictions on the CP existence, its location and what and how should fluctuate are model-dependent.

Pandav, Mallick, Mohanty, Prog.Part.Nucl.Phys. 125 (2022) 103960
Becattini, Manninen, Gazdzicki, Phys. Rev.C73 2006

Exploring the phase diagram with heavy-ion collisions



Search for the critical end point in heavy-ion collisions is performed by a scan in the parameters controlled in laboratory (collision energy and nuclear mass number, centrality).
Conjecture is, that by changing them, we change freeze-out conditions (T, μ_B).

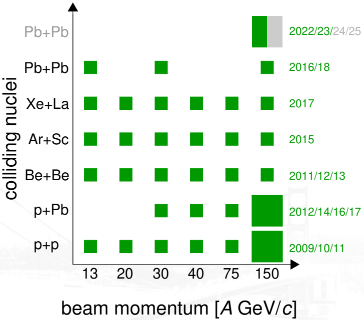


The experimental search for the critical point requires a two-dimensional scan in collision energy and size of the colliding nuclei (centrality).

NA61/SHINE

Strong interactions physics:

- search for the **critical point** of strongly interacting matter
- study the **diagram of high-energy nuclear collisions**
- direct measurement of **open charm**



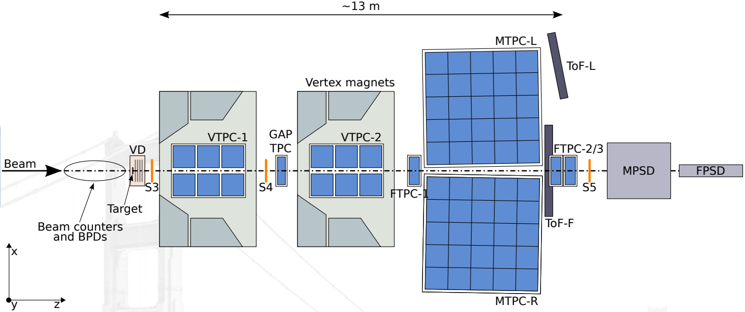
And more:

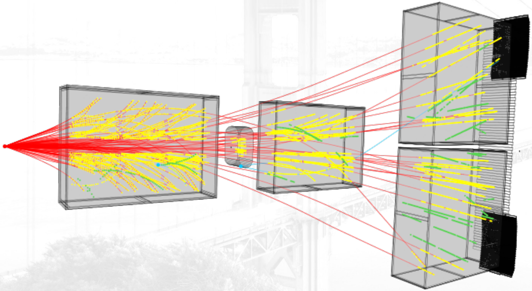
- measurements for **neutrino programs** at J-PARC and Fermilab
- measurements of **nuclear fragmentation** cross section for cosmic rays physics

NA61/SHINE

Be, Ar, Xe, Pb:
$13A - 150A$ GeV/c

p, π, K:
$13 - 400$ GeV/c





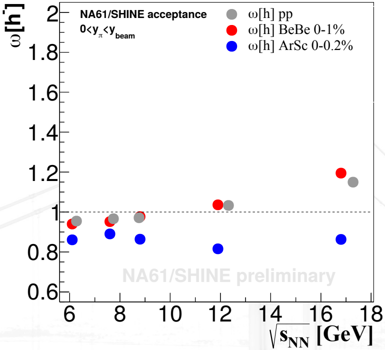
coverage up to 50% of produced charged particles starting from $p_T \approx 0$

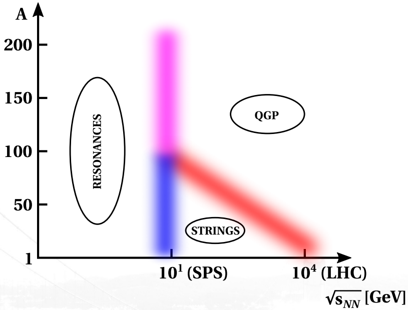
$$p_{beam} = 13A - 150A \text{ GeV}/c$$

$$\Downarrow$$

$$\sqrt{s_{NN}} \approx \mathbf{5 - 17\ GeV}$$

Multiplicity fluctuations



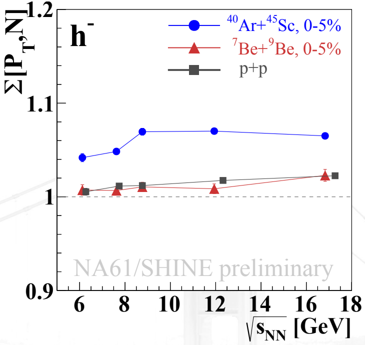


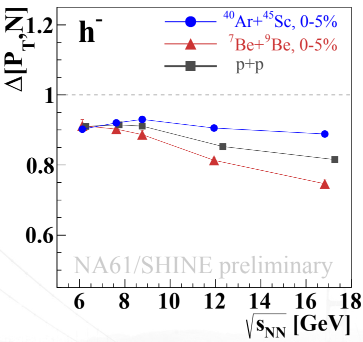
$$\omega[N] = \frac{Var[N]}{\langle N \rangle}$$

Be+Be similar to p+p, Ar+Sc different → onset of fireball (?).
No collision energy dependence that could be related to the critical point observed in Ar+Sc

NA61/SHINE, PoS CPOD2017 (2018) 012
Andronov, Kuich, Gazdzicki, Universe 9 (2023) 2, 106

Multiplicity-transverse momentum fluctuations



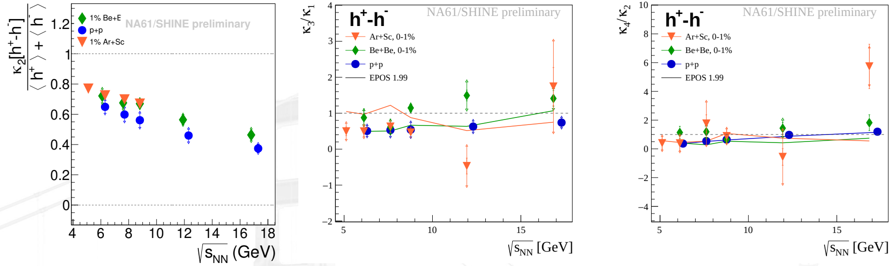


$$\Sigma[A,B] = \frac{1}{C_\Sigma}\left[\langle B\rangle\omega[A] + \langle A\rangle\omega[B] - 2\Big(\langle AB\rangle - \langle A\rangle\langle B\rangle\Big)\right] \qquad \Delta[A,B] = \frac{1}{C_\Delta}\Big[\langle B\rangle\omega[A] - \langle A\rangle\omega[B]\Big]$$

$$P_T = \sum_{i=1}^{N} p_{T_i}, \quad C_\Delta = C_\Sigma = \langle N\rangle\omega[p_T]$$

Be+Be similar to p+p, Ar+Sc different → onset of fireball (?).
No collision energy dependence that could be related to the critical point observed in Ar+Sc

NA61/SHINE, Acta Phys.Polon.Supp. 10 (2017) 449



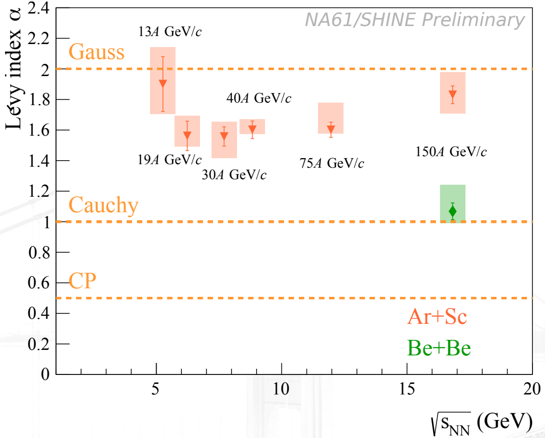
$$\kappa_1 = \langle N \rangle$$
$$\kappa_2 = \left\langle (\delta N)^2 \right\rangle$$
$$\kappa_3 = \left\langle (\delta N)^3 \right\rangle$$
$$\kappa_4 = \left\langle (\delta N)^4 \right\rangle$$

$$\langle N_2 \rangle \sim \xi^2$$
$$\langle N_4 \rangle \sim \xi^7$$

No significant non-monotonic signal observed

NA61/SHINE, PoS(PANIC2021)238
NA61/SHINE, Status Report 2022

Short-range correlations



Lévy-shaped source (1-D):

$$C(q) \cong 1 + \lambda \cdot e^{(-qR)^{\alpha}}$$

where $q = |\vec{p_1} - \vec{p_2}|_{\text{LCMS}}$,
λ describes correlation strength,
R determines the length of homogeneity and Lévy exponent α determines source shape:

- $\alpha = 2$: Gaussian, predicted from simple hydro
- $\alpha = 1$: Cauchy
- $\alpha = 0.5$: conjectured value at the critical point

No indication of the critical point so far

NA61/SHINE, EPJC 83 (2023) 10, 919
NA61/SHINE, Universe 9 (2023) 7, 298

Scaled factorial moments $F_r(M)$ of order r

$$F_r(M) = \frac{\left\langle \frac{1}{M} \sum_{i=1}^{M} n_i(n_i-1)\ldots(n_i-r+1) \right\rangle}{\left\langle \frac{1}{M} \sum_{i=1}^{M} n_i \right\rangle^r}$$

M - number of subdivision intervals of the transverse momentum region Δ

n_i - number of particles in i-th bin

$\langle \ldots \rangle$ - averaging over events

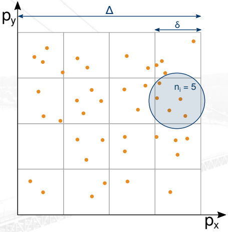
When the system is a simple fractal, $F_r(M)$ follows a power-law dependence:

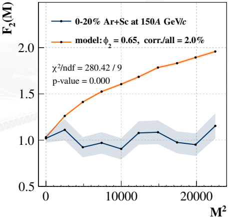
$$F_r(M) = F_r(\Delta) \cdot (M^2)^{\varphi_r}.$$

Additionally, the exponent (intermittency index) φ_r obeys the relation:

$$\varphi_r = (r-1)/2 \cdot d_r,$$

where the anomalous fractal dimension d_r is independent of r.





Bialas, Peschanski, NPB 273 (1986) 703
Wosiek, APPB 19 (1988) 863
Asakawa, Yazaki NPA 504 (1989) 668
Barducci, Casalbuoni, De Curtis, Gatto, Pettini, PLB 231 (1989) 463
Satz, NPB 326 (1989) 613
Czopowicz, arXiv:2309.13706

Cumulative transformation and independent points

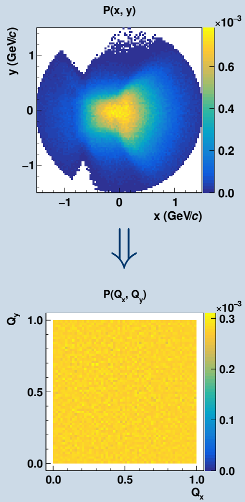
Fluctuations as a function of momentum bin size

Instead of using p_x and p_y, one can use cumulative quantities:

$$Q_x = \int_{min}^{x} \rho(x)dx \Big/ \int_{min}^{max} \rho(x)dx \qquad Q_y(x) = \int_{y_{min}}^{y} P(x,y)dy/P(x)$$

- transform any distribution into uniform one (0,1)
- remove the dependence of F_2 on the shape of the single-particle distribution
- the intermittency index of an ideal power-law system described in two dimensions in momentum space was proven to remain approximately invariant after the transformation

Additionally, $F_2(M)$ data points are independent – each one was calculated using separate sub-samples of the total available statistics.

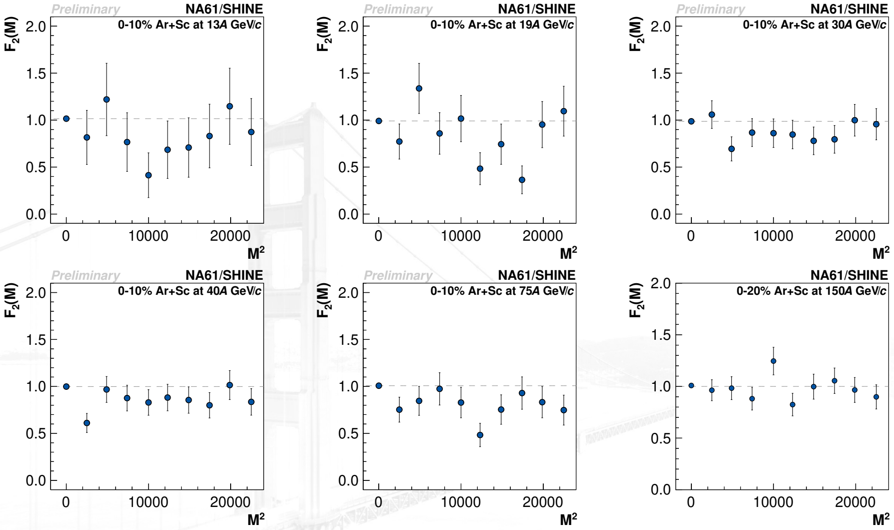


(example for 0-5% Ar+Sc at 150*A* GeV/*c*)

Bialas, Gazdzicki, PLB 252 (1990) 483
Antoniou, Diakonos, `https://indico.cern.ch/event/818624/`

Proton intermittency results for Ar+Sc

Fluctuations as a function of momentum bin size

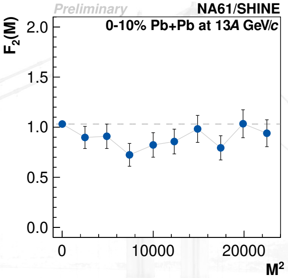


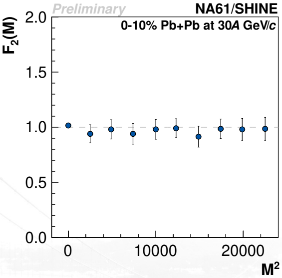
No indication for power-law increase with bin size

NA61/SHINE, EPJC 83 (2023) 9, 881

Proton intermittency results for Pb+Pb

Fluctuations as a function of momentum bin size

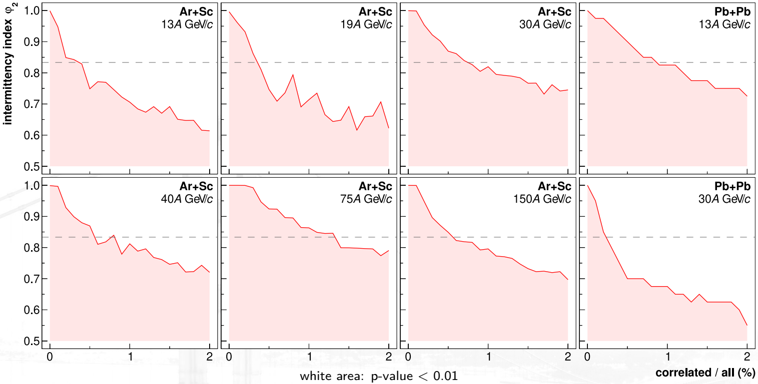




No indication for power-law increase with bin size

Exclusion plots

Fluctuations as a function of momentum bin size



Exclusion plots for parameters of simple power-law model:

- power-law exponent ϕ in $\left|\Delta\overrightarrow{p_T}\right|$ correlation function $\rho\left(\left|\Delta\overrightarrow{p_T}\right|\right) = \left|\Delta\overrightarrow{p_T}\right|^{-\phi}$, $\varphi_2 = (\phi+1)/2$,
- fraction of correlated particles

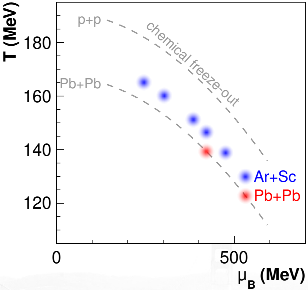
The intermittency index φ_2 for a system freezing out at the QCD critical endpoint is expected to be $\varphi_2 = 5/6$ assuming that the latter belongs to the 3-D Ising universality class.

Summary

- Results on **net-charge fluctuations** in p+p, Be+Be and Ar+Sc energy scans show **no non-monotonic signal**
- Obtained exponents from the Lévy-shaped source fit in the **HBT analyses** of pions produced in Be+Be at $\sqrt{s_{NN}} \approx 17$ GeV and Ar+Sc energy scan ares **far from the values predicted for the critical point**
- Results on the dependence of **scaled factorial moments** of multiplicity distribution on cumulative momentum bin size, analyzed using independent data points for:
  - protons in Pb+Pb at $\sqrt{s_{NN}} \approx 5$ GeV
  - protons in Pb+Pb at $\sqrt{s_{NN}} \approx 7.5$ GeV
  - protons in Ar+Sc at $\sqrt{s_{NN}} \approx 5 - 17$ GeV

  show **no indication of a power-law increase**
- **Exclusion plots** for parameters of a simple model (ratio of correlated to background particles and power-law exponent) were presented

Status of NA61/SHINE CP search via proton intermittency



Points indicate analyzed reactions with no evidence for CP. They are placed at T-μ_B values calculated from Becattini, Manninen, Gazdzicki, Phys. Rev. C73 2006

Thank You!