Search for the critical point in NA61/SHINE

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for NA61/SHINE collaboration

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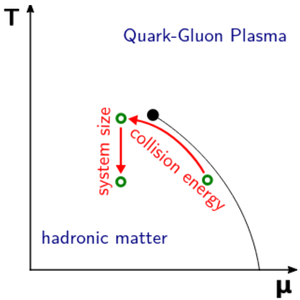
Outline

1. **The search for the critical point**
2. **Multiplicity fluctuations and Net-electric charge fluctuations**
3. **Femtoscopy (HBT correlations)**
4. **Intermittency analysis of scaled factorial moments**

The search for the critical point

The search for the Critical Point

- Critical Point (CP): Hypothetical endpoint of the first-order QGP-HM transition, with second-order phase properties.
- What to expect?: 2nd Order Transition → Scale-invariance → power-law form 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.



Who is looking for it?

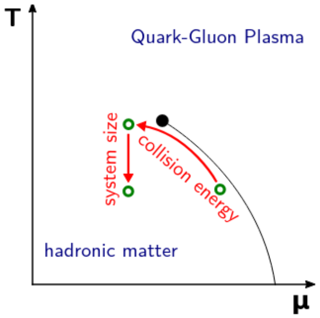
- *Present*
  - NA61/SHINE at CERN
  - STAR Collaboration at RHIC
- *Future*
  - CBM at FAIR
  - MPD at NICA

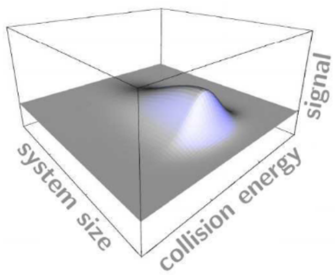
Asakawa, Yazaki NPA 504 (1989) 668
Barducci, Casalbuoni, De Curtis, Gatto, Pettini, PLB 231 (1989) 463

Stephanov, PoS LAT2006 (2006) 024

The search for the Critical Point

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





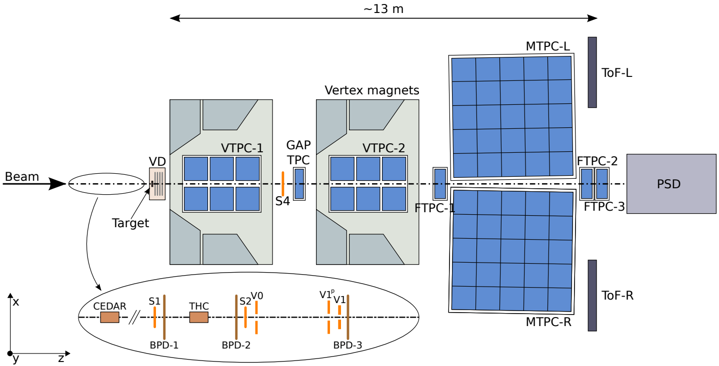
What do we do to search for the critical point? We perform a scan of the parameters controlled in the laboratory (collision energy and nuclear mass number, centrality). The idea is that by changing them, we change the freeze-out conditions (T, μ_B).

The NA61/SHINE experiment

→ Multipurpose fixed target spectrometer with unique capabilities

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

- Strangeness in quark matter: $K^+, K^-, K^0_S, K^*, \Lambda, \phi$
- Heavy quarks: D^0 and $\bar{D}^0$
- Correlations, fluctuations, HBT, intermittency...



$$p_{\text{beam}} = 13A \text{ - } 150A \text{ GeV}/c \quad \Rightarrow \quad \sqrt{s_{NN}} \approx 5 - 17 \text{ GeV}$$

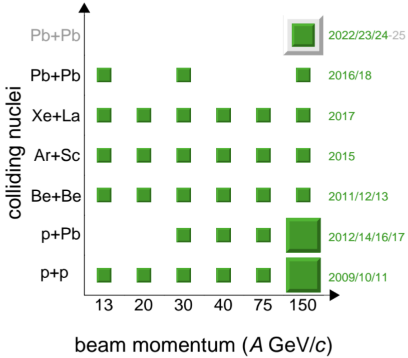
The physics program

Strong interactions physics:

- Study the onset of deconfinement
- Search for the critical point
- Measurement of open charm

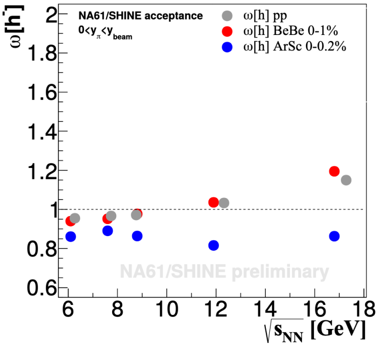
Neutrino and cosmic-ray physics

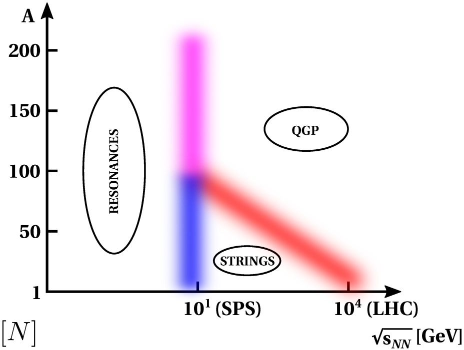
- measurements for neutrino programs at J-PARC and Fermilab
- measurements of nuclear fragmentation cross-section for cosmic rays physics



Multiplicity fluctuations and Net-electric charge fluctuations

Multiplicity fluctuations



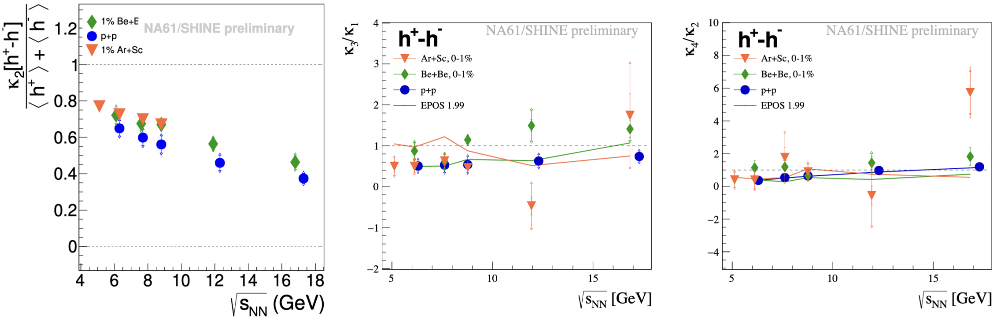


$$\omega[N] = \frac{Var[N]}{\langle N \rangle}$$

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

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

Net-electric charge fluctuations



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

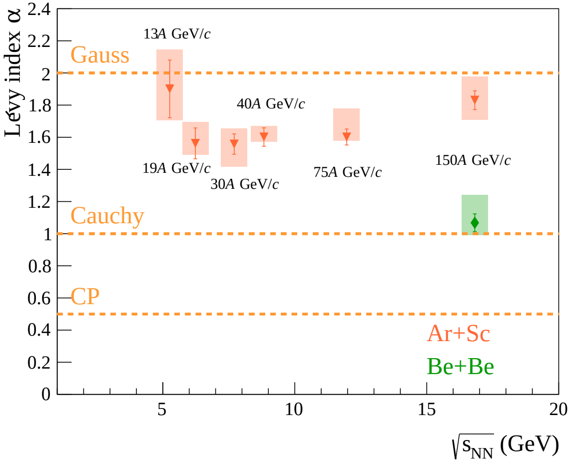
$$\langle N_2 \rangle \sim \xi^2$$
$$\langle N_4 \rangle \sim \xi^7$$

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

No significant non-monotonic signal observed

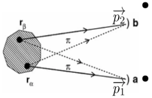
Femtoscopy (HBT correlations)

Bose-Einstein (HBT) correlations (femtoscopy)



Ar+Sc, 0-10% central, NA61/SHINE preliminary
Be+Be, 0-20% central, NA61/SHINE, EPJC 83 (2023) 919

- Femtoscopy reveals the space-time structure of hadron production
- The **Levy parameter** α describes the shape of the source and is sensitive to the system freezing out at the CP
- The new Ar+Sc results are close to Gaussian and far from the CP



Levy-shaped source (1-D):

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

where $q = |\vec{p}_1 - \vec{p}_2|_{LCMS}$, λ describes correlation strength, R determines the length of homogeneity.

[Csörgo, Hegyi, Novak, Zajc, AIP Conf. Proc. 828 (2006) 525]

Intermittency analysis of scaled factorial moments

Fluctuations as a function of the momentum bin size

Scaled factorial moments $\mathrm{F_r(M)}$ of the order r

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

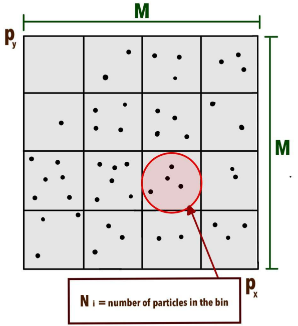
M – sub-division intervals
N_i – number of particles in i-th bin

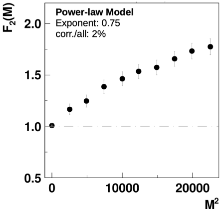
When the system freezes out near or at CP, its properties are expected to be different from an ideal gas

- System represents a simple fractal
- Scaled factorial moments $\mathrm{F_r(M)}$ are expected to follow a **power-law** behaviour

$$F_r(M) \sim (M^2)^{\phi_r}$$

N. Antoniu et al., Phys.Rev.Lett.97 (2006) 032002





Bialas, Peschanski, NPB 273 (1986) 703
Wosiek, APPB 19 (1988) 863
Asakawa, Yazaki, NPA 504 (1989) 668
Barducci et al., PLB 231 (1989) 463
Satz, NPB 326 (1989) 613
Antoniou et al., PRL 97 (2006) 032002
Czopowicz, arxiv:2309.13706

Current methodologies

$F_r(M)$ depends on the shape of inclusive single particle p_T distribution. To eliminate this dependence, we have two approaches

p_T binning

Instead of studying $F_2(M)$ we study ΔF_2. The quantity defined as:[1]

$$\Delta F_2(M) = F_2^{data}(M) - F_2^{mixed}(M)$$

Cumulative p_T binning

Instead of using p_x, p_y we use cumulative quantities Q_x, Q_y:

$$Q_x = \int_{x_{min}}^{x} \rho(x)dx / \int_{x_{min}}^{x_{max}} \rho(x)dx$$

$$Q_y = \int_{y_{min}}^{y} P(x,y)dy/P(x)$$

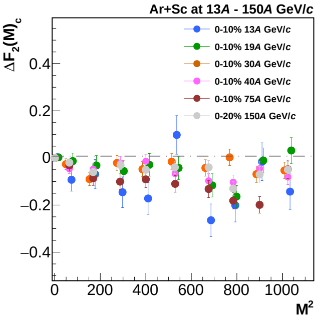
- Transforms any distribution into uniform [2] and removes the dependence of F_r on the shape of single particle distribution.
- Intermittency index of an ideal power law correlation function remain invariant [3]
- Results are displayed in:
  - $\Delta F_r(M)_c = F_r(M) - F_r(1)$ (where $F_r(M)$ and $F_r(1)$ by employing the cumulative p_T binning. $F_r(1) = F_r(M)$ for uncorrelated particles in p_T)

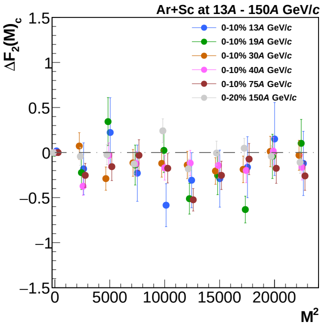
[1] NA49 collaboration. In: Eur. Phys. J. C 75.2 (2015), p. 587m

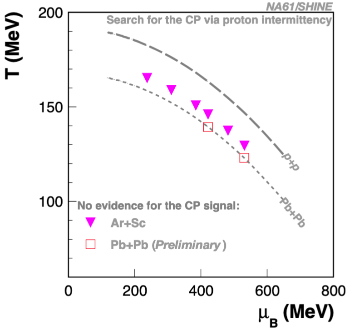
[2] Bialas; Gazdzicki. In: Physics Letters B 252.3 (1990), pp. 483–486

[3] Antoniou; Diakonos. url: https://indico.cern.ch/event/818624

Proton intermittency results for Ar+Sc



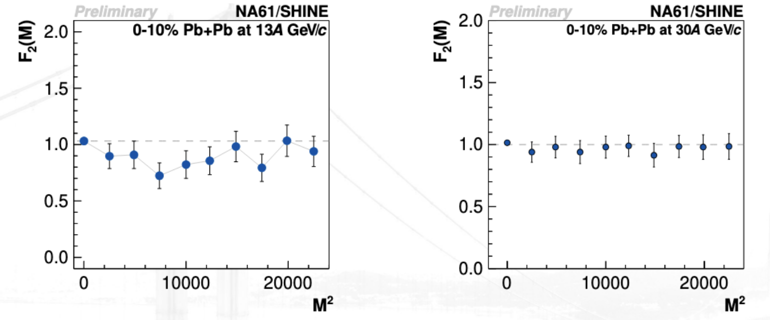




No indication for power-law increase with cumulative p_T binning

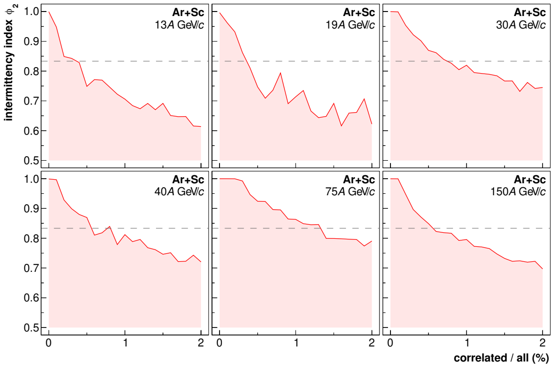
NA61/SHINE, EPJC 83 (2023) 881
NA61/SHINE, EPJC 84 (2024) 7, 741

Proton intermittency results for Pb+Pb



No indication for power-law increase with cumulative p_T binning

Exclusion plots



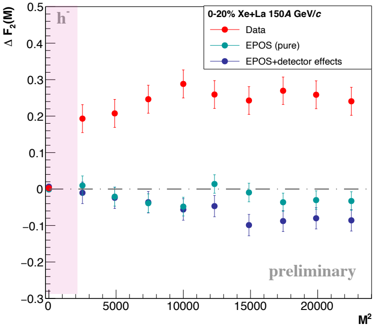
white are: p-value < 0.01

Exclusion plots for parameters of simple power-law model:

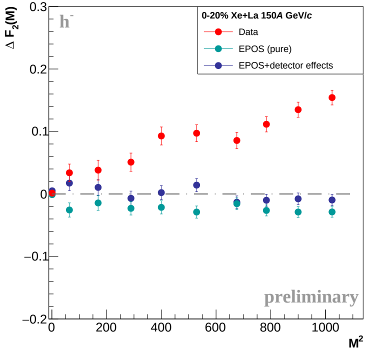
- power-law exponent ϕ in $|\Delta\vec{p}_T|$ correlation function $\rho(|\Delta\vec{p}_T|) = |\Delta\vec{p}_T|^{-\phi}$, $\varphi_2 = (\phi + 1)/2$
- fraction of correlated particles

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 3D Ising universality class.

h^- intermittency: an unexpected increase



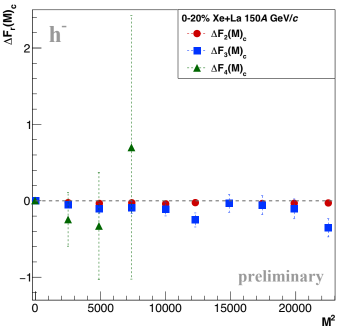
full range – p_T binning

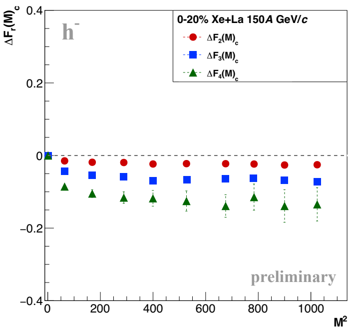


small range – p_T binning

Motivated by STAR collaborations results from 2023, we follow the NA49 methodology and found an unexpected increase when analyzing negatively charged hadrons in central Xe+La collisions at 150A GeV/c. However, this increase does not follow a proper power law.

h^- intermittency in Xe+La





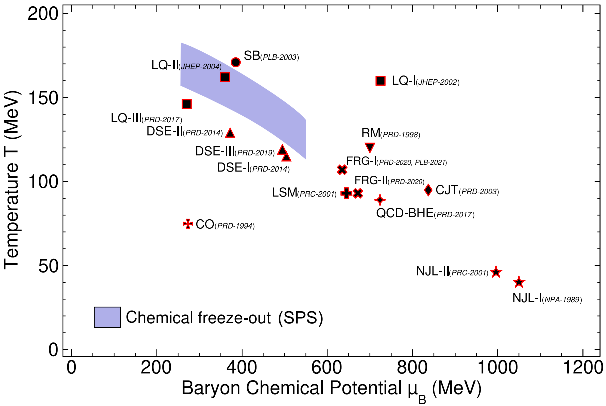
No indication for power-law increase with cumulative p_T binning

Therefore, we attribute the seen increase to short-range correlations of HBT type.

Summary

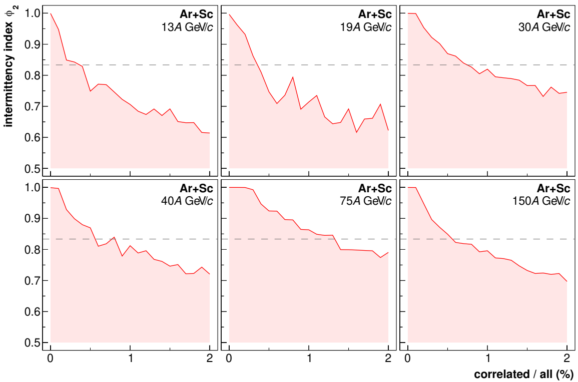
In this talk, I resumed results on:

- Multiplicity fluctuations and net-charge fluctuations in Be+Be, p+p and Ar+Sc
- Femtoscopy analysis in Be+Be and Ar+Sc
- Proton intermittency using cumulative p_T in Ar+Sc and Pb+Pb
- Negatively charged hadron intermittency using p_T binning and cumulative p_T binning in Xe+La

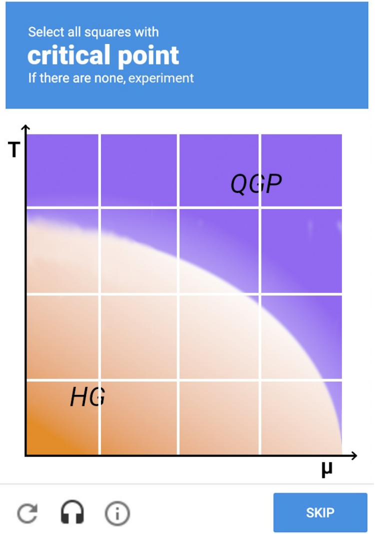


Summary

- A huge amount of data has been analyzed, resulting in better insight and physics comprehension related to the critical point
- New methods were developed
- None of the results show indication of the Critical Point
- We were able to establish exclusion limits on a simple model of the critical point
- And we are working on more...



Thanks



Select all squares with
critical point
If there are none, experiment
T
QGP
HG
μ
SKIP