Search for the critical point via intermittency analysis in NA61/SHINE at CERN

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for NA61/SHINE collaboration

(NCN Grant No. 2020/39/O/ST2/00277 and RID/SP/0015/2024/01)

24th ZIMÁNYI SCHOOL WINTER WORKSHOP ON HEAVY ION PHYSICS
Budapest, Hungary – December 3, 2024

Outline

1. **Introduction**

2. **Results for proton intermittency for Ar+Sc energy scan**

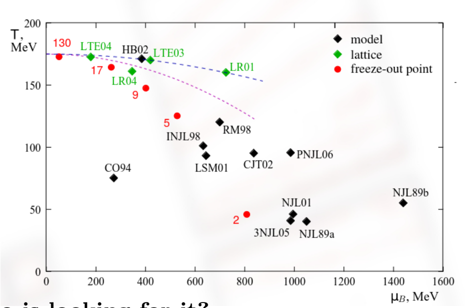
3. **Results for negatively charged hadrons intermittency in Xe+La collisions at 150A GeV/c**

Introduction

The search for the Critical Point

What is it?

- Critical Point (CP): Hypothetical endpoint of the first-order QGP-HM transition, with second-order phase properties.
- 2nd Order Transition: Scale-invariant power-law correlations; CP existence, location, and fluctuations are model-dependent.



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

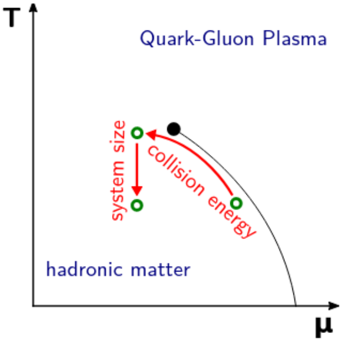
Stephanov, PoS LAT2006 (2006) 024

Who is looking for it?

- *Past:* NA49 experiment at CERN. proton intermittency, pion intermittency
- *Present*
  - NA61/SHINE at CERN: proton intermittency, h^- intermittency
  - STAR Collaboration at RHIC: $h^{\pm}$intermittency

Intermittency analysis in high energy physics

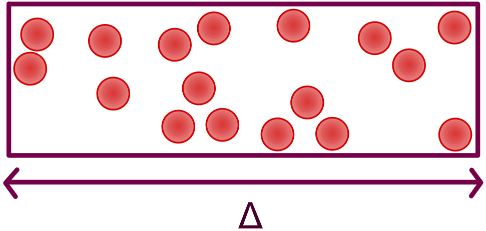
- QCD Critical Point Search: Explored via collision energy and nuclear mass adjustments, affecting freeze-out parameters T_c and μ_c.
- Intermittency Analysis: Examines momentum distribution fluctuations using scaled factorial moments to probe second-order phase transitions.



Intermittency

Intermittency: random deviations from smooth or regular behavior.

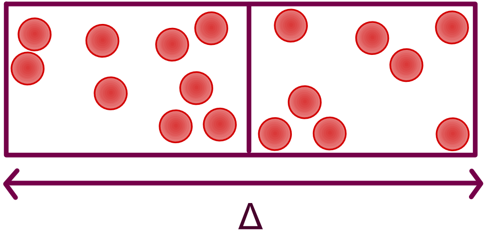
If we consider a container, a box of size Δ, and we fill it with N balls:



(Bialas and Peschanski: Nucl. Phys. B 273 (1986),1496 pp. 703–718)

Intermittency

What can happen when we vary the number of cells (M) but the length of the box Δ and the total number of balls (N) remain fixed?



Intermittency

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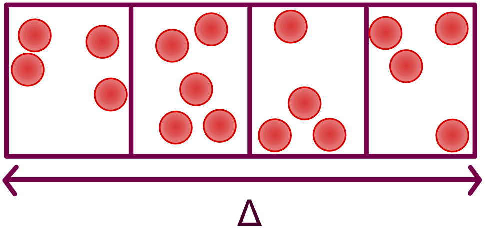
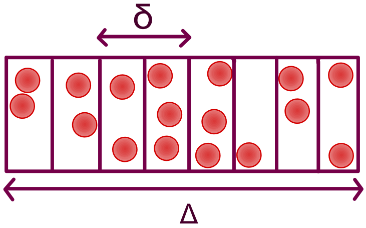


The idea of intermittency is repeating this scenario: divide the box into smaller cells of the same size δ, keeping the main size of the box and the number of balls fixed.

Intermittency: random deviations from smooth or regular behaviour



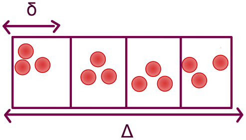
N is the total number of balls
Δ: is the size of the box
δ is the size of each cell
$M = (\Delta/\delta)$: is the number of cells
n_i: number of balls put into i$^{\text{th}}$ cell such that
$\sum_i n_i = N$

The r-order factorial moment for a given configuration (a given distribution of the balls) is defined as:

$$f_r(M) = \frac{\left[\frac{1}{M}\sum_{i=1}^{M} n_i^r\right]}{\left[\frac{1}{M}\sum_{i=1}^{M} n_i\right]^r} = M^{r-1} N^{-r} \sum_{i=1}^{M} n_i^r$$

Intermittency: example of two extreme cases

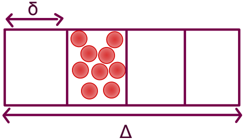
Case 1: equidistribution (N/M balls in each box)



$$n_i = N/M, \quad \forall i$$

$$f_r(M) = 1, \quad \forall i$$

Case 2: all balls in one cell (for an extreme fluctuation from a thermodynamic point of view)



$$n_i = N \quad for \quad i = 2$$

$$n_i = 0 \quad for \quad i \neq 2$$

$$f_r(M) = M^{r-1}$$

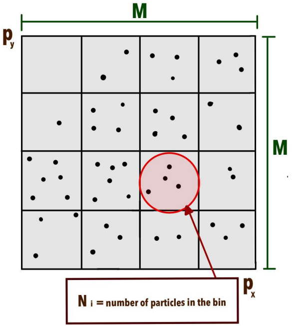
We say that it is intermittent behaviour if: $log(f_r(M))$ varies linearly with $log(\delta)$

Scaled factorial moments

- In NA61/SHINE at CERN SPS, intermittency analysis is performed in 2D transverse momentum plane.
- At the second order phase transition (critical point), the system becomes scale invariant.
- This phenomenon leads to enhanced multiplicity fluctuations with special properties that can be revealed by scaled factorial moments:

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

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



When the system is a simple fractal, $F_q(M)$ follows a power law dependence: $F_q(M) = F_q(\Delta)(M^2)^{\phi_q}$ where the critical exponent or intermittency indices ϕ_q obey the relation: $\phi_q = (q-1)d_q$ where the anomalous fractal dimension d_q is independent of q.

Wosiek, APPB 19 (1988) 863

Satz, NPB 326 (1989) 613 Bialas, Peschanski, NPB 273 (1986) 703

Current methodologies

$F_r(M)$ depends on the shape of inclusive single particle p_T distribution. In order 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

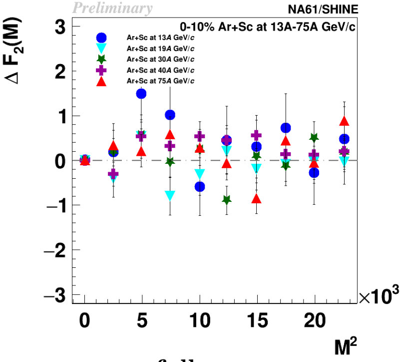
[2] Bialas; Gazdzicki. In: Physics Letters B 252.3 (1990), pp. 483–486

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

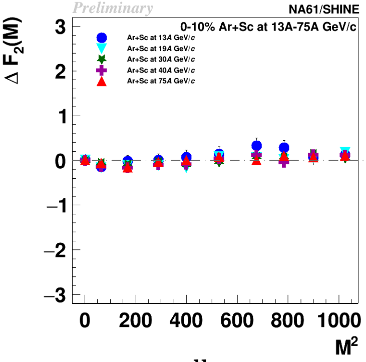
Results for proton intermittency for Ar+Sc energy scan

Results for proton intermittency for Ar+Sc energy scan

p_T binning



full range



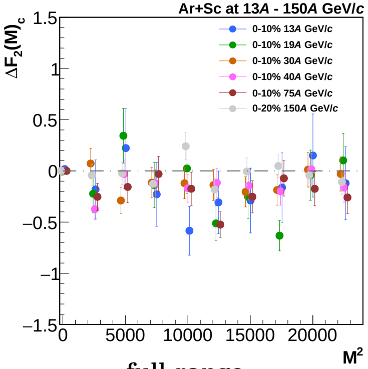
small range

No indication of power law increase with bin size

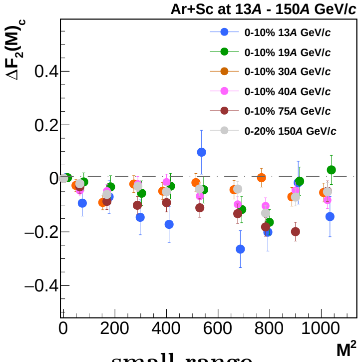
H. Adhikary et.al (NA61/SHINE Collaboration), Eur.Phys.J.C 83 (2023) 9, 881
H. Adhiakry (for NA61/SHINE Collaboration), EPJ Web Conf. 274 (2022) 06008

Results for proton intermittency for Ar+Sc energy scan

cumulative p_T binning



full range



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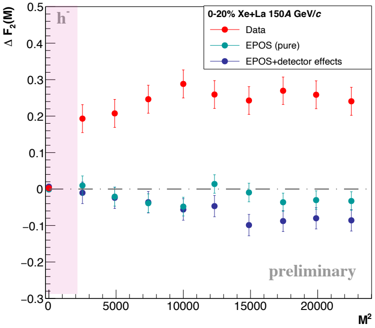
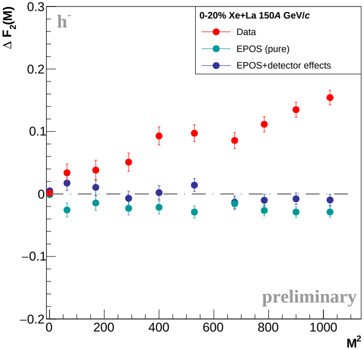
Results for negatively charged hadrons intermittency in Xe+La collisions at 150A GeV/c

h^- intermittency: an unexpected increase



full range – p_T binning



small range – p_T binning

An unexpected increase was found when analyzing negatively charged hadrons in central Xe+La collisions at 150A GeV/c. (A similar increase was reported by STAR collaboration in 2023, but the physics form was not explained)

Short range correlations

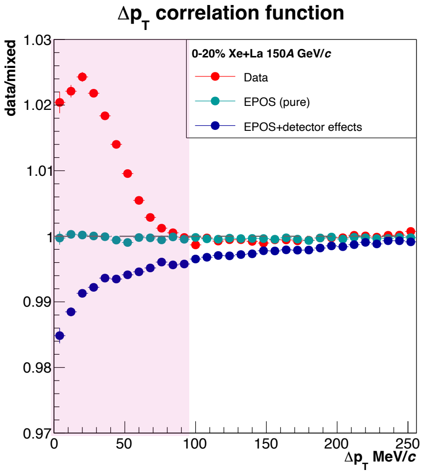
- A strong increase of ΔF_2 with M is observed for results in p_T binning.
- EPOS model does not show this increase
- In the case of protons, no increase of ΔF_2 results, neither in data nor in EPOS, was observed.

Is there a physics correlation which is present for h^- data, and absent in protons and EPOS h^-, that can explain this behavior?

Yes, short-range correlations of Bose-Einstein type

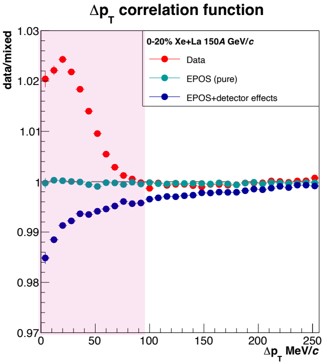
So we studied the h^--h^- correlation.

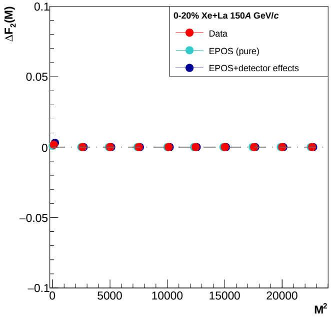
$$\Delta p_T = \sqrt{(p_{2,x} - p_{1,x})^2 + (p_{2,y} - p_{1,y})^2}$$



Short range correlations

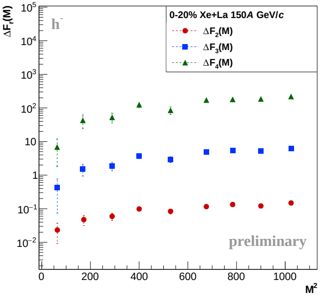
If we remove the region with Δp_T <100 MeV/c, the ΔF_2 is independent of M^2 for both experimental data and EPOS.



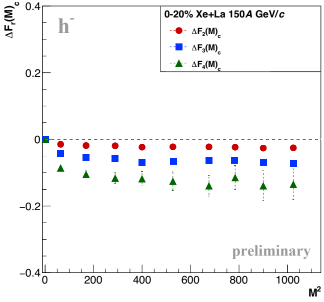


This suggests that the increase of ΔF_2 of the data was cause by this short range correlations
However, this removal of Δp_T region may also affect possible correlations due to CP.

h^- intermittency results for Xe+La 150*A* GeV/*c*



p_T binning



cumulative p_T binning

- The removal of these short-range correlations might be too drastic. Cumulative p_T transformation preserves the scale-invariant power-law correlations and destroys other types of non-scale invariant correlations.
- Statistics of Xe+La at 150*A* GeV/*c* allow us to explore higher order moments of intermittency.

Summary

The results of intermittency analysis in NA61/SHINE were discussed

- Proton intermittency analysis for central Ar+Sc collisions (13A-150A GeV/c)
  - ✓ No signs of a power-law increase with bin size were found in proton intermittency analysis, nor using p_T or cumulative p_T
- Negatively charged hadrons intermittency for central Xe+La collisions at 150A GeV/c
  - ✓ The experimental data on ΔF_2 for p_T binning exhibits an increase, but it does not follow a power law, the increase can be explained by short range correlations (HBT).
  - ✓ No indication of power law increase with bin size observed in cumulative p_T distribution. Since cumulative transformation preserves the scale-invariant power-law correlations but destroys other types of non-scale invariant correlations.
  - ✓ This might be a potential explanation to the increase seen by other collaborations.

Thanks

Appendix

History of intermittency analysis in high energy physics

- The concept of intermittency was originally developed in the study of turbulent flow. (Ya.B. Zeldovich et al., Usp. Fiz. Nauk 152 3)
- Bialas and Pschanski, introduced after that intermittency analysis could be used to study fluctuations in high energy physics. It was proposed to study the scaled factorial moments of rapidity distribution of particles produced in high energy collisions as a function of the size of the rapidity interval. (Bialas, A. and Peschanski, R. (1986) Nuclear Physics B, 273, 703-718.)
- After, Wosiek's work showed indications of intermittent behavior in the critical region of the 2D Ising model. This raised the general question of whether or not intermittency and critical behavior were related.
- Satz showed that the critical behavior of the Ising model indeed leads to intermittency, with indices determined by the critical exponents (Satz: Nucl. Phys. B 326 (1989), pp. 613–618)
- And Bialas and Hwa reported that intermittency parameters could serve as a signal of second-order phase transition using scaled factorial moments (Bialas and Hwa: Phys.Lett. B253 (1991), pp. 436–438)
- And at this point, experiments begin to use this approach...

Intermittency analysis in high energy physics

- The **search for the QCD Critical Point** in heavy ion collisions is performed by scan in the parameter controlled in the laboratory (collision energy and nuclear mass number, by changing them we change freeze-out parameters (T_c, μ_c)
- Intermittency analysis was introduced in to study fluctuations in particle production by examining the scaled factorial moments of momentum distributions. These moments, dependent on the momentum interval size, may indicate a second-order phase transition.