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

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for NA61/SHINE collaboration

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New Trends in High-Energy and Low-x Physics
Sfantu Gheorghe, Romania
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Outline

1. **Introduction**

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

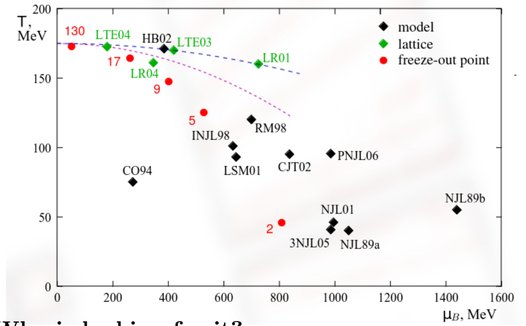
3. **Results for negatively charged hadrons intermittency in Xe+La collisions at 150A GeV/c**

Introduction

The search for the Critical Point

What is it?

- Critical point (CP) – a hypothetical end point of first order phase transition line (QGP-HM) that has properties of second order phase transition.
- 2nd order phase transition – scale invariance power-law form of correlation function. Predictions on the CP existence, its location and what and how should fluctuate are model-dependent.



Who is looking for it?

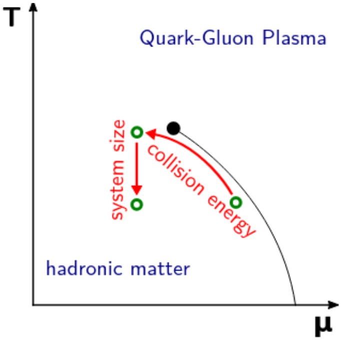
- *Past:* NA49 experiment at CERN. proton intermittency, pion intermittency
- *Present*
  - NA61/SHINE at CERN: proton intermittency, h^- intermittency
  - STAR Collaboration at RHIC: $h^{\pm}$intermittency

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

Stephanov, PoS LAT2006 (2006) 024

Intermittency analysis in high energy physics

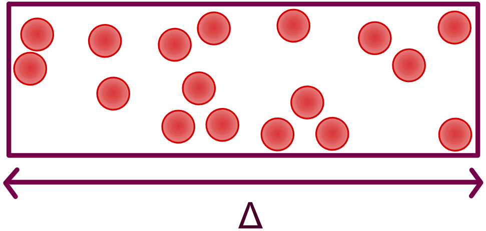
- The **search for the QCD Critical Point** in heavy ion collisions is performed by scan in the parameter controlled in laboratory (collision energy and nuclear mass number, by changing them we change freeze-out parameters (T_c, μ_c)
- Intermittency analysis was introduced in to study fluctuations in 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.



Intermittency

Intermittency: random deviations from smooth or regular behaviour.

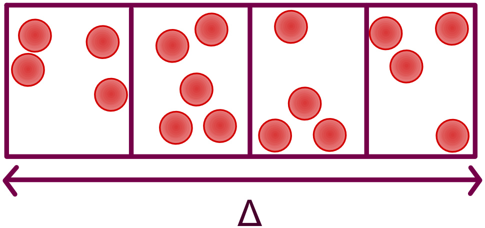
If we consider a container, a box of size Δ, and we fill it with N balls:



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

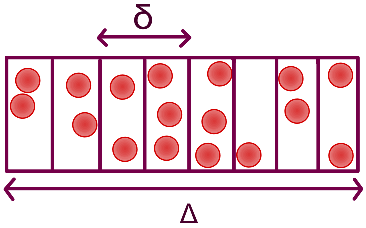
Intermittency

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?



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



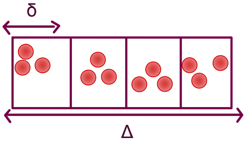
N is the total number of balls
Δ: is the size of the box
δ is the size of each cell
$M = (\Delta/\delta)$: is the number of cells
n_i: number of balls put into i^{th} cell such that
$\sum_i n_i = N$

The r-order f 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: we can have two cases

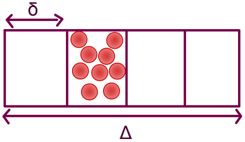
Case 1: equidistribution (N/M balls in each box)



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

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

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



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

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

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

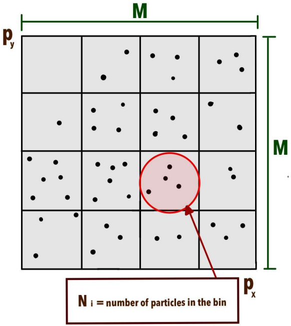
We say that it is intermittent behaviour if: $log(f_r(M))$ varies linearly with $log(\delta)$

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:
  - $F_2(M)$ for proton intermittency
  - $\Delta F_r(M)_c = F_r(M) - F_r(1)$ for h^- (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)

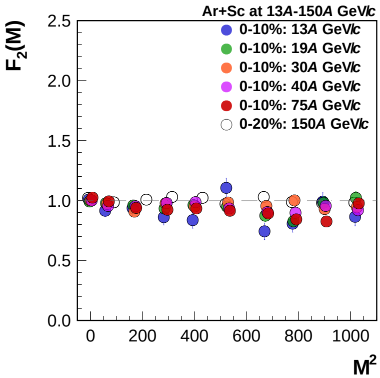
[1] NA49 collaboration. In: Eur. Phys. J. C 75.2 (2015), p. 587m

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

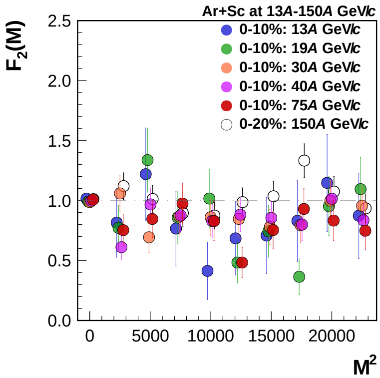
[3] Antoniou; Diakonos. url: https://indico.cern.ch/event/818624

Results for proton intermittency for Ar+Sc energy scan

Results for proton intermittency for Ar+Sc energy scan



cumulative p_T binning



cumulative p_T binning

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

Power-law Model: What if we actually have a signal?

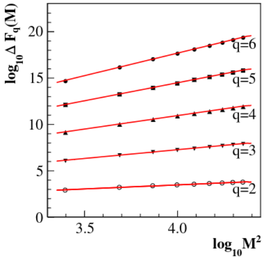
Developer: Tobiasz Czopowicz (arXiv:2309.13706)

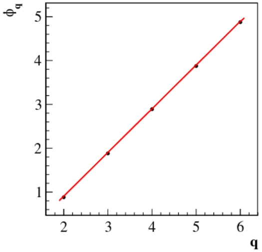
Purpose of model: to test different experimental effects and quantify negative intermittency results (inspired by the power-law correlations between particles near the QCD CP)

This model introduces a power-law correlation near the CP, demonstrating the expected scaling behavior of $F_q(M)$ in M^2 and a linear relationship between intermittency indices.

model is capable of generating particle correlations independent of the form of transverse momentum or multiplicity distributions. Additionally, the model can be used to study the impact of detector effects on scaled factorial moments.

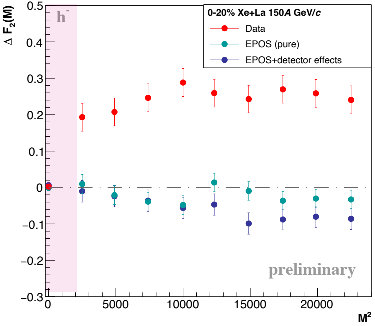
Key feature: Generates momenta of uncorrelated and correlated particles with a given single-particle p_T distribution in events with a given multiplicity distribution.



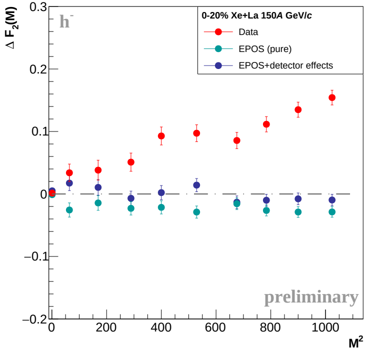


Results for negatively charged hadrons intermittency in Xe+La collisions at 150A GeV/c

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 Xe+La collisions at 150A GeV/c in central collisions. (A similar increase was reported by STAR collaboration in 2023, but the physics beyond this form was left unexplained)

Short range correlations

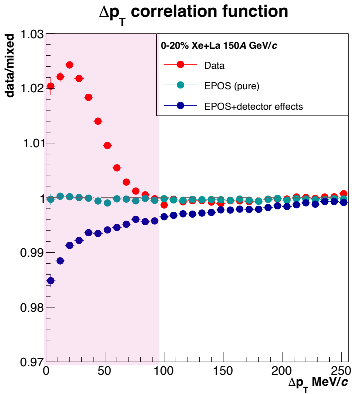
- A strong increase of ΔF_2 with M is observed for results in p_T binning.
- EPOS model does not show this increase
- In the case of protons no increase of ΔF_2 results, neither in data or EPOS observed.

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

Yes, short range correlations, of Bose-Einstein type

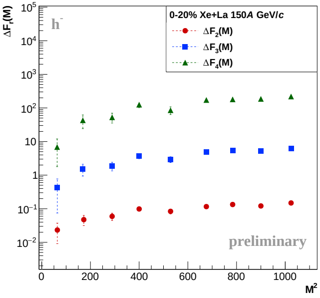
So we studied the h^--h^- correlation.

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

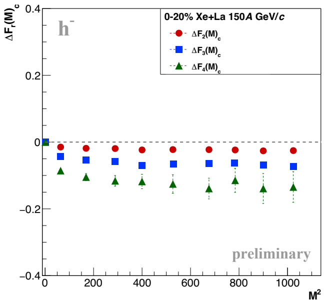


For experimental data we observe the typical expected behavior indicating the presence of short range correlations. For pure EPOS there are no correlations, and for EPOS+detector effects there are anti-correlations due to the limited two track resolution.

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



p_T binning



cumulative p_T binning

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

Summary

Results on intermittency analysis in NA61/SHINE were discussed

- proton intermittency analysis for central Ar+Sc collisions (13-150A GeV/c)
  - ✓ No signs of power law increase with bin size was found on proton intermittency analysis, nor using p_T of 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).
  - ✓ this might be a potential explanation to the increase seen by other collaborations.
  - ✓ 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 non-scale invariant correlations.

Thanks

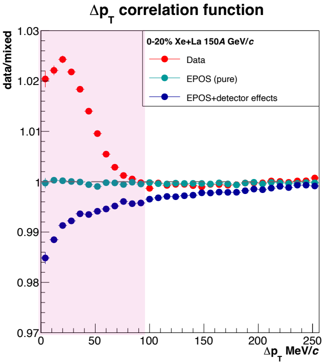
Appendix

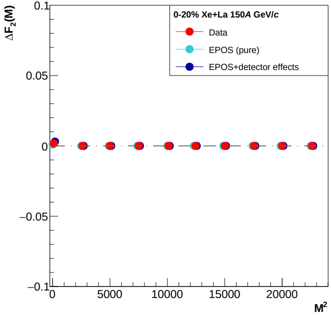
History of intermittency analysis in high energy physics

- 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 partcls produces in high energy collisions as function of the size of rapidity interval. (Bialas, A. and Peschanski, R. (1986) Nuclear Physics B, 273, 703-718.)
- After, Wosiek's work showed indications of intermittent behaviour in the critical region of the 2D Ising model. This raised the general question of wheter or not intermittency and ciritical behaviour wer 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...

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.

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 laboratory (collision energy and nuclear mass number, by changing them we change freeze-out parameters ($\mathrm{T_c}$, μ_c)
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