Search for the critical behavior at NA61/SHINE

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NA61/SHINE Experiment

- NA61/SHINE (SPS Heavy Ion and Neutrino Experiment) is a particle physics fixed-target experiment at CERN SPS
- Scan in beam momenta (13A - 150/158A GeV/c) and system size (p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb)
- Large acceptance hadron spectrometer - full coverage in the forward hemisphere (down to $p_T = 0$ GeV/c)
- Centrality selection in A+A collisions by measuring of forward energy with Projectile Spectator Detector (PSD)

Schematic picture of the NA61/SHINE experiment NA61 JINST 9: 06005

Strong interactions programme at NA61/SHINE

- study the properties of the onset of deconfinement
- search for the critical point (CP) of strongly interacting matter

Sketch of the phase diagram of strongly interacting matter

Data taking schedule

What is the CP signal amplitude?
What if it is shadowed by volume fluctuations?
Search for the critical behavior at NA61/SHINE

1. Multiplicity and transverse momentum fluctuations (p+p @20 – 158 GeV/c, $^7$Be+$^9$Be @150A GeV/c)

2. Femtoscopy studies ($^7$Be+$^9$Be @150A GeV/c)

3. Intermittency analysis (NA49, $^7$Be+$^9$Be and Ar+Sc 150/158A GeV/c)

4. Two-particle correlations ($^7$Be+$^9$Be @13A – 150A GeV/c)

Search for non-monotonic behavior of CP signatures via pseudorapidity dependence study

Measure spatial correlations within Bose-Einstein momentum correlations with Levy source

Study of local power-law fluctuations of baryon density

Study in $\Delta\eta$ - $\Delta\phi$ space to disentangle different sources of correlations
Fluctuation studies: proper measures

**Intensive** fluctuation measure: independent of the number of sources or the system volume $\omega[N] = 1$ for the Poisson distribution of $A$, $\omega[N] = 0$ in the absence of $A$ fluctuations

**Strongly intensive** fluctuation measures:
- Independent of the volume and its fluctuations in Ideal Boltzmann gas in Grand Canonical Ensemble (IBG GCE)
- $\Sigma[P_T, N] = \Delta[P_T, N] = 1$ for independent particle model
- $\Sigma[P_T, N] = \Delta[P_T, N] = 1$ for the IBG in GCE and CE
- $\Sigma[P_T, N] = \Delta[P_T, N] = 0$ in the absence of fluctuations

**Possible sensitivity:** nucleon system with van der Waals EOS in GCE formulation in the vicinity of the Critical Point

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

Gazdzicki et al. PRC 88:024907

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

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

Vovchenko, Gorenstein, Stoecker, PRL 118: 182301, Vovchenko, et al., JPA 48: 305001
No prominent structures which could be related to the critical point. Should we extend the analysis?

Since each rapidity is associated with a different value of $\mu$ and therefore probes a different part of the $(\mu-T)$ phase diagram.

Becattini F, Manninen J and Gazdzicki M PRC 73 044905

and the ratio of $p$ and $\bar{p}$ in inelastic $p+p$ at the SPS energies changes significantly with rapidity.

Let’s study pseudorapidity dependence of fluctuations.
Fluctuation studies: pseudorapidity dependence

Conclusion:
check for all energies and different pseudorapidity intervals in p+p and Be+Be did not reveal any specific structure,

however, important: similar behavior for p+p and Be+Be data, significant discrepancy with EPOS1.99 in both for $\Delta[P_T, N]$
Femtoscopy: critical exponents

History:
R. Hanbury Brown, R.Q.Twiss observed Sirius with radiotelescopes

In high energy physics (G. Goldhaber): momentum $q$ correlation of pions maps source $S(q)$ at femto-scale
$C(q) \cong 1 + |\tilde{S}(q)|^2$

Heavy ions: expanding medium, increasing mean free path: anomalous diffusion (Csanad et al., Braz.J.Phys. 37 (2007) 1002)

Levy-stable distribution:
$$L(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$$

Levy parameters appearing in correlation function:
$$C(q) = 1 + \lambda \cdot e^{-(qR)^\alpha}$$

- **Levy scale $R$** - determines length of homogeneity
- **Correlation strength $\lambda$** - describes core-halo ratio
  (core: primordial pions, halo: resonance decay products and general background)
- **Levy exponent $\alpha$** - stability exponent determines source shape:
  - $\alpha = 2$: Gaussian, predicted from simple hydro
  - $\alpha < 2$: anomalous diffusion, generalized limit theorem
  - $\alpha = 0.5$: conjectured value at the critical point (CEP)

Spatial correlation at the critical point: $\sim r^{-(d-2+\eta)}$, ** Levy-exponent $\alpha$ is identical to correlation exponent $\eta$**

Intensity correlations as a function of detector distance to measure size of point-like sources

B. Porfy for NA61/SHINE, CPOD 2018

Daria Prokhorova for NA61/SHINE Collaboration

22-26 October 2018, ICPPA, Moscow
Femtoscopy: performance results of NA61/SHINE

- **NA61/SHINE Levy HBT measure is possible**
- Moving on to measure 0-20% identified HBT
- Next step, measuring Levy HBT in Ar+Sc

**Performance NA61/SHINE results**

- "Hole" at low \( m_T \)?
- Decreases with \( m_T \) (radial flow)?
- Distance from Gauss (\( \alpha = 2 \)), Cauchy (\( \alpha = 1 \)) or CEP conjecture (\( \alpha = 0.5 \))?  

**World data**

**Distance from Gauss (\( \alpha = 2 \)), Cauchy (\( \alpha = 1 \)) or CEP conjecture (\( \alpha = 0.5 \))?**

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Intermittency analysis: factorial moments

Experimental observation of local, power-law distributed fluctuations


Intermittency in transverse momentum space (net protons at mid-rapidity)


- Transverse momentum space is partitioned into $M^2$ cells
- Calculate second factorial moments $F_2(M)$ as a function of cell size

$⇔$ number of cells $M$
- Background of non-critical pairs must be subtracted at the level of factorial moments to clean experimental data

For $\lambda(M) < 1$, two approximations can be applied:

1. Cross term can be neglected
2. Non-critical background moments can be approximated by (uncorrelated) mixed event moments:

$$\Delta F_2(M) \simeq \Delta F_2^{(e)}(M) \equiv F_2^{\text{data}}(M) - F_2^{\text{mix}}(M)$$

And for a critical system $\Delta F_2(M)$ scales with cell size (number of cells, $M$) as:

$$\Delta F_2(M) \sim (M^2)^{q_{2}}$$
Intermittency analysis: Ar+Sc at 150A GeV/c

NA61/SHINE preliminary results

EPOS reproduces results for 5-10% centrality

EPOS does not reproduce observed effect for 10-15% centrality

N. Davis for NA61/SHINE, CPOD 2018
• Indication of intermittency effect in middle-central NA61/SHINE Ar+Sc collisions
• First possible evidence of CP signal in NA61/SHINE
• Effect quality increases with increased proton purity selection (up to 90%), EPOS does not reproduce observed effect
Two-particle correlations: $\Delta \eta$-$\Delta \phi$

Study of correlations in azimuthal angle and pseudorapidity difference between two particles in the same event:

- $\Delta \eta = | \eta_1 - \eta_2 |$
- $\Delta \phi = | \phi_1 - \phi_2 |$

\[ C^{\text{raw}}(\Delta \eta, \Delta \phi) = \frac{N^\text{pairs}_{\text{bkg}}}{N^\text{pairs}_{\text{signal}}} \cdot \frac{S(\Delta \eta, \Delta \phi)}{B(\Delta \eta, \Delta \phi)}; \]
\[ S(\Delta \eta, \Delta \phi) = \frac{d^2 N^\text{signal}}{d \Delta \eta d \Delta \phi}; \quad B(\Delta \eta, \Delta \phi) = \frac{d^2 N^\text{bkg}}{d \Delta \eta d \Delta \phi} \]

Note:

- To improve statistics azimuthal angle distribution is folded: if $\Delta \phi > \pi$ then $\Delta \phi$ becomes $\Delta \phi = 2\pi - \Delta \phi$
- Signal and background distributions are calculated and normalized in restricted $\Delta \eta$ region: $0 < \Delta \eta < 3$
- Correlation functions are mirrored around $(\Delta \eta, \Delta \phi) = (0, 0)$ point in order to emphasize the trend
- Event and track cuts select the 5% most violent collisions with particles produced in strong and EM processes within the NA61/SHINE acceptance

Preliminary results for $^7\text{Be}+^9\text{Be}$ are obtained for all charge combinations (all, like-sign, unlike-sign, positively charged, negatively charged) and for the full momentum range (13A – 150A GeV/c). Comparison (not shown) with published p+p NA61/SHINE data revealed an increase of quantum statistics contribution in higher beam momenta in Be+Be.
Two-particle correlations: some Be+Be NA61/SHINE data

Preliminary NA61/SHINE results

NA61/SHINE data

- Maximum at \((\Delta \eta, \Delta \phi) = (0, \pi)\) – probably resonance decays and momentum conservation
- A hill at \((0, 0)\) in unlike-sign is Coulomb attraction (products of photons conversion were rejected during analysis)
- EPOS reproduces data qualitatively well except of Coulomb peak at \((\Delta \eta, \Delta \phi) = (0, 0)\)

EPOS1.99 with NA61/SHINE acceptance

B. Maksiak for NA61/SHINE, QM 2018
Two-particle correlations: some Be+Be NA61/SHINE data

Preliminary NA61/SHINE results

NA61/SHINE data

- Almost no away-side enhancement: low multiplicity of double-negative resonances
- Peak at $(\Delta \eta, \Delta \varphi) = (0, 0)$ prominent – Bose-Einstein statistics

EPOS1.99 with NA61/SHINE acceptance

- EPOS does not reproduce peak at $(\Delta \eta, \Delta \varphi) = (0, 0)$ due to lack of implementation of quantum statistics
Summary and outlook

- Results on system size vs. energy dependence of $N$ and $[P_T, N]$ fluctuations for particles produced in strong processes within the NA61/SHINE acceptance show no indication of the critical point so far.

- Pseudorapidity dependence of fluctuation measures revealed a significant discrepancy between $p+p$ and $Be+Be$ data and EPOS1.99 for $\Delta[P_T, N]$ measure.

- Two-particle correlations revealed two main structures:
  - away-side enhancement due to momentum conservation and resonance decays
  - near-side peak due to Coulomb attraction in unlike-sign pairs of particles and quantum statistics in like-sign ones (problematic in EPOS1.99 simulations)

- First measurements of Levy HBT within NA61/SHINE acceptance – performance results!

- Indication of intermittency effect in middle-central NA61/SHINE $Ar+Sc$ collisions: First possible evidence of CP signal at NA61/SHINE?
Stay tuned and have a SHINY day!
Back up slides
First released Intermittency results of preliminary analysis in Ar+Sc at 150A GeV/c at CPOD 2018, details:

Intermittency analysis: details

## Event & Track cuts

### Event cuts
- Target IN/OUT,
- BPD status,
- WFA particles (4.5 μs),
- WFA interaction (25 μs),
- BPD3X(Y) charge,
- S5 (0 → 170),
- T2 trigger (eAll),
- Vertex track fitted to the main vertex,
- Vertex fit quality = ePerfect,
- Fitted vertex position $-580 \pm 10$ cm,
- PSD Module Energy Sum cut (inner/outer),
- Centrality 0-20% (based on PSD),
- $n_{\text{TracksFit}} / n_{\text{TracksAll}} > 0.25$ if $n_{\text{TracksFit}} \leq 50$ (Andrey)

### Track cuts
- Track status,
- Charge ±1,
- Impact point [$\pm 4$cm; $\pm 2$cm],
- Total number of clusters $\geq 30$,
- VTPCs clusters $\geq 15$,
- NO GTPC clusters,
- dE/dx clusters $\geq 30$,
- $0.5 \leq \frac{\#\text{Points}}{\#\text{Potential Points}} \leq 1.0$
- TTD cut $> 2$ cm
- dE/dx $\leq 1.8$ (dE/dx fit issue)
- proton selection (scan)
- $3.98$ GeV/c $\leq p_{\text{tot}} \leq 126$ GeV/c (for dE/dx proton ID – scan)
# Intermittency analysis: details

## Event & Track cuts – EPOS

**Event cuts**
- Target IN/OUT,
- BPD status,
- Vertex track fitted to the main vertex,
- Vertex fit quality = ePerfect,
- Fitted vertex position $-580 \pm 10$ cm,
- Centrality 10% (based on nFSpec)

**Track cuts**
- Track status,
- Charge ±1,
- Impact point $[\pm 4\text{cm}; \pm 2\text{cm}]$,
- Total number of clusters $\geq 30$,
- VTPCs clusters $\geq 15$,
- NO GTPC clusters,
- TTD cut $> 2$ cm,
- Proton selection – matching closest simTrack,
- $3.98\text{ GeV/c} \leq p_{\text{tot}} \leq 126\text{ GeV/c}$
  (to match effect of $dE/dx$ $p_{\text{tot}}$ cut),
- Acceptance cut

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Intermittency analysis: details

Split tracks & the $q_{inv}$ cut

- Events may contain **split tracks**: sections of the same track erroneously identified as a pair of tracks that are close in momentum space.

- **Three cuts** to root them out:
  1. Ratio of points / potential points in a track (removes most)
  2. Minimum track distance in the detector (pair cut)
  3. $q_{inv}$ cut (pair cut, physics-significant)

- $q_{inv}$ distribution of track pairs probed in order to root the rest out:
  $$q_{inv}(p_i, p_j) = \frac{1}{2} \sqrt{-(p_i - p_j)^2}, \quad p_i : \text{4-momentum of } i^{th} \text{ track}.$$

- We calculate the ratio of $q_{inv}^{data} / q_{inv}^{mixed}$.
Intermittency analysis: details

Split tracks & the $q_{inv}$ cut

- A peak at low $q_{inv}$ (below 20 MeV/c) indicates a possible split track contamination that must be removed.
- Anti-correlations due to F-D effects and Coulomb repulsion must be removed before intermittency analysis $\Rightarrow$ “dip” in low $q_{inv}$, peak predicted around 20 MeV/c [Koonin, PLB 70, 43-47 (1977)]
- Universal cutoff of $q_{inv} > 7$ MeV/c applied to all sets before analysis.
Intermittency analysis: details

$\Delta p_T$ distributions: NA61 data vs EPOS

- Ar+Sc at 150A GeV/c: $\Delta p_T = \frac{1}{2} \sqrt{(p_{x_1} - p_{x_2})^2 + (p_{y_1} - p_{y_2})^2}$

  distributions of protons selected for intermittency analysis

- In NA61 data, we see strong correlations in $\Delta p_T \to 0 \Rightarrow$ indication of intermittent behaviour
Intermittency analysis: details

$\Delta p_T$ distributions & $F_2(M)$: NA61 data vs EPOS

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NA61/SHINE: Ar+Sc at 150A GeV/c: $F_2(M)$
Intermittency analysis: details

NA61/SHINE: Ar+Sc at 150A GeV/c: $\Delta F_2(M)$
# Intermittency analysis: details

**NA61/SHINE: Ar+Sc at 150A GeV/c: $\phi_2$ bootstrap dist.**

<table>
<thead>
<tr>
<th>Centrality</th>
<th>Purity</th>
<th>Distribution</th>
<th>Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5%</td>
<td>&gt;80%</td>
<td>$\phi_2$ C.I.</td>
<td>(0.298, 0.372, 0.450)</td>
</tr>
<tr>
<td>5-10%</td>
<td>&gt;85%</td>
<td>$\phi_2$ C.I.</td>
<td>(0.511, 0.724, 0.930)</td>
</tr>
<tr>
<td>10-15%</td>
<td>&gt;85%</td>
<td>$\phi_2$ C.I.</td>
<td>(0.460, 0.525, 0.593)</td>
</tr>
<tr>
<td>0-5%</td>
<td>&gt;90%</td>
<td>$\phi_2$ C.I.</td>
<td>(0.135, 0.245, 0.318)</td>
</tr>
<tr>
<td>5-10%</td>
<td>&gt;90%</td>
<td>$\phi_2$ C.I.</td>
<td>(0.203, 0.312, 0.404)</td>
</tr>
<tr>
<td>10-15%</td>
<td>&gt;90%</td>
<td>$\phi_2$ C.I.</td>
<td>(0.457, 0.515, 0.577)</td>
</tr>
</tbody>
</table>

*NA61/SHINE preliminary*
Intermittency analysis: details

Ar+Sc EPOS: $F_2(M)$, $\Delta F_2(M)$, $\phi_2$ bootstrap distribution
Intermittency analysis: details

Improving calculation of $F_2(M)$ via lattice averaging

- **Problem:** With low statistics/multiplicity, lattice boundaries may **split pairs** of neighboring points, affecting $F_2(M)$ values (see example below).

- **Solution:** Calculate moments several times on different, slightly displaced lattices (see example)

- **Average** corresponding $F_2(M)$ over all lattices. Errors can be estimated by variance over lattice positions.

- **Lattice displacement is larger than experimental resolution,** yet maximum displacement must be of the order of the finer binnings, so as to stay in the correct $p_T$ range.

![Displaced lattice — a simple example](image)
Intermittency analysis: details

Mixing for:

\[ \Delta F_2(M) \approx \Delta F_2^{(e)}(M) \equiv F_2^{\text{data}}(M) - F_2^{\text{mix}}(M) \]

1. Set of 1...N events with \( n_i \) with \( i = 1...N \) multiplicity in i-th event

2. Going through all events: label each particle with number 1 ... N_particles (N_particles = sum of \( n_i \) for \( i = 1...N \)) and associate number of the event it belongs to

3. To create mixed event with multiplicity \( n_m \) we do:
   a) Select a particle randomly from the N_particles
   b) Check that its event label is different than ALL previously selected particles for THIS mixed event
   c) If it is, add particle to this mixed event; if it is not, we have a conflict, so we reject this particle and go back to step a)
   d) Repeat until the desired multiplicity \( n_m \) has been reached

4. Repeat process until we have the desired number of mixed events (typically >10 times the original number of events)