NA61/SHINE results on fluctuations and correlations at CERN SPS energies

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NA61/SHINE is a fixed target experiment located at SPS CERN. Two dimensional system size - energy scan of the ion program is focused on:

- the study of the onset of deconfinement (OD)
- search for the critical point (CP)

Large acceptance (≈ 50% of produced charged particles) combined with precise forward energy measurements makes NA61/SHINE perfect place to measure fluctuations and correlations.
New results on fluctuations and correlations

- net-charge/multiplicity fluctuations $\rightarrow$ CP

  - $\xi$ 
  - $\langle N^2 \rangle \sim \xi^2 \langle N^4 \rangle \sim \xi^7$

  Stephanov, J.Phys.G 38,124147

- HBT analysis $\rightarrow$ CP

  The shape of the correlation function with Lévy source:

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

  Lévy distribution leads to power-law correlation functions where Lévy-exponent $\alpha$ identical to correlation exponent $\eta$

  Csörgő et al., EPJC36

  Expected value of $\alpha$ for CP $\approx 0.5$

- intermittency $\rightarrow$ CP

  2nd order phase transition $\rightarrow$ scale invariance $\rightarrow$ power-law form of correlation function for large distances

  $\leftrightarrow$ small momentum transfer $\Delta \vec{k}$


- flow $\rightarrow$ OD

  Csernai, Rohrich, PLB458,454; Stoecker, NPA750,121; Brachmann et al. PRC61,02909
Fluctuations - Intensive quantities

Independent of volume $V$ in Ideal Boltzmann Grand Canonical Ensample (IB-GCE)

$$\omega[N] = \frac{\kappa_2[N]}{\kappa_1[N]}, \quad S\sigma[N] = \frac{\kappa_3[N]}{\kappa_2[N]}, \quad \kappa_2\sigma^2[N] = \frac{\kappa_4[N]}{\kappa_2[N]}$$

where $\kappa_i$ stands for $i^{th}$ order cumulant

There are two reference values:

- 1 for Poisson distribution (e.g. IB-GCE)
- 0 for no fluctuations

Begun and MMP, arxiv:1705.01110[nucl-th]

Experimentally we are only able to narrow centrality of the registered events and consider events from a given centrality class. Thus, intensive quantities contain also fluctuations of the system size.

Remarks:

- For net-charge reference distribution is Skellam not Poisson
- Centrality selection differs between experiments and for not the most central events it leads to different sets of events
- The simplest dependence is for $\omega[N] = \omega[N]_V + \langle n \rangle \frac{\text{Var}[V]}{\langle V \rangle}$, where $n$ stands for particle density
Fluctuations at 150/158A GeV/c - system size dependence

- $K^+/\pi^+$ rapid change between Be+Be and Ar+Sc
- similar change visible in fluctuations at top SPS not reproduced by EPOS1.99
- possible phenomena:
  - percolation
    Baym, Physica 96A,131; Celik, et al., PLB 97:128; Armesto et al.PRL 77:3736
  - AdS/QCD correspondence
    Shuryak, Prog.Part.Nucl.Phys.62:48; Lin, Shuryak, PRD 79: 124015

EPOS1.99: Werner, et al., PRC74:044902
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\[ \langle K^+ / \pi^+ \rangle \]

\[ \langle W \rangle \]

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Presented results refers to charged hadrons produced in strong and electromagnetic processes. For 150/158 A GeV/c the following results are available:

- **p+p** - minimum bias interactions corrected for trigger bias, detector inefficiency and feed-down
  ω - NA61/SHINE, EPJC(2016)76:635; MMP, CPOD2016

- **Be+Be** - 1% most central collisions uncorrected with estimate of systematic bias
  ω - Seryakov, WPCF2017

- **Ar+Sc** - 1% most central collisions corrected results with systematic uncertainty under study
  ω - Seryakov, WPCF2017

All considered results have statistical uncertainty obtained either via subsample method or with bootstrap method.

Acceptance: forward rapidity with $p_T < 1.5$:

- **p+p** acceptance - full acceptance of NA61/SHINE
  [link](https://edms.cern.ch/document/1549298/1)

- **Be+Be/Ar+Sc** acceptance: NA61/SHINE p+p acceptance with additional rapidity cut: $0 < y_{\pi} < y_{beam}$. 

![Graph](image.png)
Fluctuations - net-charge

- $p+p \approx Be+Be$ in $\kappa_3/\kappa_2$ and $\kappa_4/\kappa_2$
- EPOS 1.99 predictions agree with the measured data
- no indications of CP
- stay tuned for Ar+Sc results

Remarks:
statistical uncertainty of each data point - black dashed lines
systematic uncertainty/estimation of systematic bias - solid line of the same color as marker
Multiplicity fluctuations - higher order moments

\[ \frac{\kappa_3}{\kappa_2} : p+p > Be+Be \]

- EPOS predicts qualitatively system size dependence of \( \frac{\kappa_3}{\kappa_2} \) but predicted decrease in EPOS is too weak
- stay tuned for Ar+Sc results

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- statistical uncertainty of each data point - black dashed lines
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central A+A at 150/158A GeV/c

\[ h^- \quad h^+ \]

- \( h^+ \) EPOS 1.99
- \( h^- \) EPOS 1.99
- Poisson

\[ \langle W \rangle \]

\[ \frac{k_2}{k_1} \]

\[ 1 \quad 10 \quad 10^2 \]

NA61/SHINE preliminary

\[ p+p \quad Be+Be \]
Multiplicity fluctuations - higher order moments

- $h^+$ and $h^-$ results indicate different system size dependence
- System size dependence predicted by EPOS 1.99 is different than in the data for both $h^+$ and $h^-$
- Stay tuned for Ar+Sc results

Remarks:
- Statistical uncertainty of each data point - black dashed lines
- Systematic uncertainty/estimation of systematic bias - solid line of the same color as marker
Bose-Einstein correlations allow to measure spatial correlations

- usually assumed Gaussian shape of source but it can be generalized to Lévy-stable distribution

\[
\mathcal{L}(\alpha, R, r) = \frac{1}{2\pi} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^{\alpha}},
\]

where \(\alpha = 1\) Cauchy, \(\alpha = 2\) Gaussian, \(\alpha < 2\) e.g. anomalous diffusion (Lévy flight)

- \(R\) weakly decreases with \(m_T\) (transverse flow) comparable with RHIC and LHC \(p+p\) data

- \(\lambda\) independent of \(m_T\) with given statistics

\(\pi\) HBT in 20\% Be+Be at 150\%A GeV/c
$\pi$ HBT in 20% Be+Be at 150A GeV/c

- $\alpha$ does not indicate CP in Be+Be (far from 0.5)
- $\alpha$ between Gaussian or Cauchy shape might be the sign of anomalous diffusion
Intermittency

Nature of CP should lead to local, **power-law fluctuations of baryon density**, which can be calculated by scaling of 2nd factorial moments with cell size $\Leftrightarrow$ cells $M$ in $p_T$ space (intermittency)

Antoniou et al., Phys. Rev. Lett. 97, 032002

- **for critical system** $F_2(M) \sim (M^2)^{\phi_2,cr}$,
  $\phi_2,cr = 5/6$
- **for noisy system** non-critical background moments must be subtracted. Then the correlator

$$\Delta F_2(M) = F_2^{\text{data}}(M) - F_2^{\text{mix}}(M),$$

should scale according to power-law for $M \gg 1$

In 2018 we have reported indications of intermittency signal at Ar+Sc 150A GeV/c

Davis, CPOD2018
Intermittency measurements with larger statistics did not improve the significance of the measured $\Delta F_2$ - no indication of CP
See poster of E. Kashirin, O. Golosov, I. Selyuzhenkov and V. Klochkov

- **SPS** beam momentum scan covers OD
- Large particle acceptance and $\Psi_{RP}$ estimation with transverse energy projectile spectators

- Pb+Pb at 40A GeV/c measured by NA49
  - $v_1$ measured at 13A GeV/c from 30/40A GeV/c differs in the region of sign change
  - Elliptic flow of $\pi^-$ and $p$ is different but it does not show any energy dependence
Conclusions

Search for the critical point

- fluctuations of net-charge in p+p and Be+Be at 150/158A GeV/c do not show indication of CP
- pion HBT in Be+Be at 150A GeV/c - no indications of CP
- intermitency measurements with larger statistics in Ar+Sc at 150A GeV/c did not improve the significance of the measured $\Delta F_2$ - no indication of CP
- multiplicity fluctuations of different charges show interesting dependence which is often not reproduced by the EPOS model - more systematic measurements needed in order to understand observed dependencies

Properties of the onset of deconfinement:

- direct flow in Pb+Pb collisions at 13A GeV/c differs from 30/40A GeV/c
Thank you.

For other results from NA61/SHINE see also A. Tefelska poster SS 41 on $K^*$ measurements in $p+p$. 
Acknowledgements

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Bose-Einstein correlations allow to measure spatial correlations usually assumed Gaussian shape of source but it can be generalized to Lévy-stable distribution

\[ \mathcal{L}(\alpha, R, r) = \frac{1}{2\pi} \int d^3q e^{iqr} e^{-\frac{1}{2} |qR|^{\alpha}}, \]

where \( \alpha = 1 \) Cauchy, \( \alpha = 2 \) Gaussian, \( \alpha < 2 \) anomalous diffusion (Lévy flight)

shape of the correlation function with Lévy source:

\[ C(q) = 1 + \lambda \cdot e^{-(qR)^\alpha} \]

Lévy distributions leads to power-law correlation functions with Lévy-exponent \( \alpha \) identical to correlation exponent \( \eta \)

Csörgő et al., EPJC36
Parameters of the Lévy Correlation Function

Fit parameters:

- $\lambda$ correlation strength
  - ratio of primordial pions to sum of primordial pions and resonance decay products
- from hydrodynamical picture:
  \[ R_{HBT} = \frac{R}{\sqrt{1 + \frac{m_T}{T_0} u_T^2}} \]

- $\alpha$ exponent:
  - $\alpha = 2$ simple hydrodynamical picture
  - $\alpha < 2$ anomalous diffusion $\rightarrow$ generalized limit theorem
  - $\alpha = 0.5$ conjectured value at the critical point

$\lambda = 0.495 \pm 0.092$
$R = 2.335 \text{ fm} \pm 0.444 \text{ fm}$
$\alpha = 1.018 \pm 0.155$

Full range goodness-of-fit:
$\chi^2/\text{NDF} = 40.611/40$
Confidence level = 44.3%

Peak range (0.018-0.350 GeV/c):
$\chi^2/\text{NDF} = 40.611/40$
Confidence level = 44.3%

Fit function: $N \cdot \left(1 + \lambda \cdot e^{-(qR)^\alpha}\right) \cdot K_{\text{Coulomb}}(q)$

Be+Be @ 150 AGeV/c
NA61/SHINE preliminary

B. Porfy, WPCF2018