PROCEEDINGS OF SCIENCE

Femtoscopy using Lévy-distributed sources at NA61/SHINE

Barnabás Pórfy[a,b,*] **for the NA61/SHINE Collaboration**

[a] *Eötvös Loránd University, Budapest, Hungary*

[b] *HUN-REN Wigner Research Centre for Physics Budapest, Hungary*

E-mail: barnabas.porfy@cern.ch, porfy.barnabas@wigner.hun-ren.hu

In the recent years, research studies in high-energy physics have confirmed the creation of the strongly interacting quark-gluon plasma (sQGP) in ultra-relativistic nucleus-nucleus collisions. NA61/SHINE at CERN SPS investigates hadronic matter properties by varying collision energy ($\sqrt{s_{\rm NN}} \approx 5.3, 6.2, 7.7, 8.8, 12,$ and 16.8 GeV) and systems (such as p+p, p+Pb, Be+Be, Ar+Sc, Xe+La, Pb+Pb). Utilizing femtoscopic correlations, we can unveil the space-time structure of the hadron emitting source. Our focus is on femtoscopic correlations in small to intermediate systems, comparing measurements with source calculations based on Lévy-distributed sources, to explore the pair transverse mass dependence of the Lévy source parameters. The Lévy exponent α is of particular significance, which characterizes the shape of the source and may be connected to the critical exponent η near the critical point. Our analysis will reveal that the Lévy shape parameter, α, has a slight non-monotonic behaviour as a function of collision energy and that we see a deviation from Gaussian sources. Finally, it will be shown that there is no indication of the critical point at any of the investigated energies.

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*Speaker

1. Introduction

The NA61/SHINE experiment, located on the CERN SPS H2 beam line, is a fixed target experiment, using multiple Time Projection Chambers (TPCs) for large-acceptance hadron spectroscopy [1]. Its detector setup allows tracking down to $p_T \approx 0$ GeV/c. NA61/SHINE primarily aims to explore the phase diagram of strongly interacting matter across various temperatures and baryon-chemical potentials through system and beam energy scans. This work focuses on ^{40}Ar+^{45}Sc collisions at the three lowest available energies (13, 19, and 30A GeV/c) at 0–10% centrality, and comparing with previous results [2–4] using femtoscopy correlations with spherically symmetric Lévy distributions:

$$\mathcal{L}(\alpha, R, \boldsymbol{r}) = \frac{1}{(2\pi)^3} \int \mathrm{d}^3\zeta \mathrm{e}^{\mathrm{i}\zeta \boldsymbol{r}} \mathrm{e}^{-\frac{1}{2}|\zeta \mathrm{R}|^\alpha}, \tag{1}$$

where R is the Lévy scale parameter, α is the Lévy stability index, $\boldsymbol{r}$ is the vector of spatial coordinates. Bose-Einstein momentum correlations are related to the particle source function $S(x)$ via the equation $C(q) \cong 1 + |\tilde{S}(q)|^2$, see Ref. [2] for details. The Lévy distribution generalizes Gaussian distributions ($\alpha = 2$) and captures effects like critical fluctuations [5]. For $\alpha < 2$, the Lévy distribution exhibits a power-law tail $\sim r^{-(1+\alpha)}$. Critical behavior is related to the exponent η, which also follows a power-law tail and has been linked to the 3D Ising model, where $\eta = 0.03631 \pm 0.00003$ [6] and to the 3D Ising model with random external field, resulting in $\eta = 0.50 \pm 0.05$ [7]. Other phenomena could have influences on the source shape, such as QCD jets, anomalous diffusion, and others, as discussed in Refs. [8–13]. For overview of recent results, see Ref. [14].

The Lévy exponent can be measured utilizing the following femtoscopic correlation function to data:

$$C_2^0(q) = 1 + \lambda \cdot e^{-(qR)^\alpha}, \tag{2}$$

where $C_2^0(q)$ is the correlation function in absence of interaction and λ is the correlation strength, often interpreted through the core-halo model [15, 16] and is related to the core and halo pion multiplicities (denoted by N):

$$\lambda = (N_{\mathrm{core}}/N_{\mathrm{total}})^2 . \tag{3}$$

We investigate the combination of positive ($\pi^+\pi^+$) and negative ($\pi^-\pi^-$) pion pairs, identified via energy loss in the TPCs ($\mathrm{d}E/\mathrm{d}x$) and comparison with the Bethe-Bloch curves. Track merging was eliminated with momentum-based two-track distance cuts [17]. Centrality was selected via forward energy measurements. Pion pairs were grouped into four to eight (energy dependent) K_T bins (0-500 MeV/c). We address Coulomb repulsion effects on like-charged pairs using the correction factor $K_{\mathrm{Coulomb}}(q)$:

$$K_{\mathrm{Coulomb}}(q) = \frac{C_2^{\mathrm{Coulomb}}(q)}{C_2^0(q)}, \tag{4}$$

where $C_2^{\mathrm{Coulomb}}(q)$ is calculated numerically [18, 19]. We are utilizing a novel method in our analysis for estimating the effect of Coulomb repulsion, presented in Ref. [20]. The correlation function, corrected for Coulomb interaction, using the Bowler-Sinyukov method [21], takes the form:

$$C_2(q) = N \cdot (1 + \epsilon \cdot q) \cdot \left[1 - \lambda + \lambda \cdot \left(1 + e^{-|qR|^\alpha}\right) \cdot K_{\mathrm{Coulomb}}(q)\right], \tag{5}$$

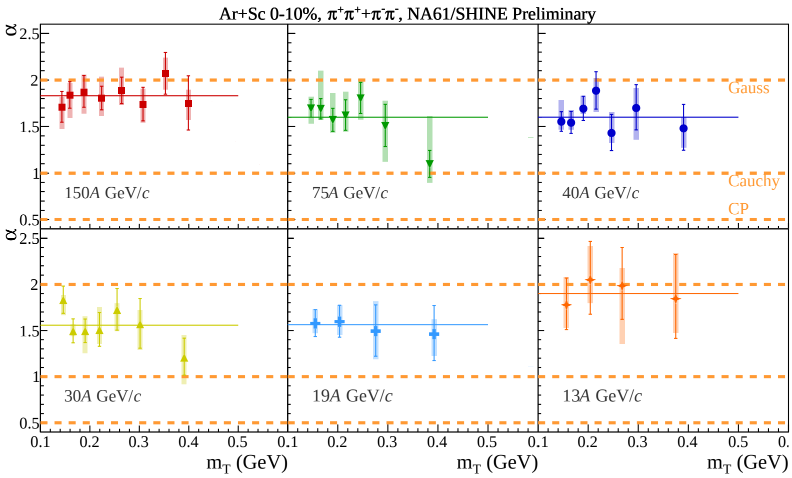

Figure 1: The fit parameters, for 0–10% central Ar+Sc at all available energies, as a function of m_{T}. Special cases corresponding to a Gaussian ($\alpha = 2$) or a Cauchy ($\alpha = 1$) source are shown, as well as $\alpha = 0.5$, the conjectured value corresponding to the critical endpoint, while the constant α fit is shown with a solid line. Boxes denote systematic uncertainties, bars represent statistical uncertainties.

where N is introduced as normalization parameter and ε is introduced to describe the residual background in the form of $(1 + \varepsilon \cdot q)$. The Coulomb correction is applied in the pair-center-of-mass system (PCMS), with corrections for the longitudinally co-moving system (LCMS) [22].

2. Results

The physical parameters α, R, and λ were measured in bins of pair transverse momentum, K_{T}, at 13, 19, and 30A GeV/c by fitting the measured correlation functions using Eq.(5). Their dependence on transverse mass $m_{\mathrm{T}} = \sqrt{m^2c^4 + K_{\mathrm{T}}^2c^2}$ was studied and compared to previous NA61/SHINE results, taken from Refs. [2–4]. The stability exponent α indicates the strength of the source tail, with results ranging from 1.5 to 2.0, with the lowest energy being comparable to 150A GeV/c, implying sources that are closer to Gaussian (Fig. 1). These values are higher than the conjectured value at the critical endpoint ($\alpha \approx 0.5$), with a non-monotonic trend emerging around $\sqrt{s_{\mathrm{NN}}} \approx 6-8$ GeV. It is interesting to compare our α values to results from other experiments, see details in Ref. [14].

The Lévy scale parameter R is related to the homogeneity scale of the pion source. A slight decrease in R with m_{T} was observed, compatible with $R \sim 1/\sqrt{m_{\mathrm{T}}}$, consistently with hydrodynamical predictions [23, 24] for Gaussian sources, based on transverse flow. It is particularly interesting that this results holds for Lévy sources as well. A similar behavior was observed at RHIC and LHC energies [25, 26] and in simulations as well [11].

The correlation strength λ shows a moderate m_{T} dependence but remains mostly constant, as shown in Fig. 3. Our λ values are lower than unity, suggesting a significant fraction of pions are decay products of long-lived resonances. At RHIC, a decrease of λ at low m_{T} was seen and attributed to in-medium mass modification of η' [25, 27]. We do not see this effect in our results.

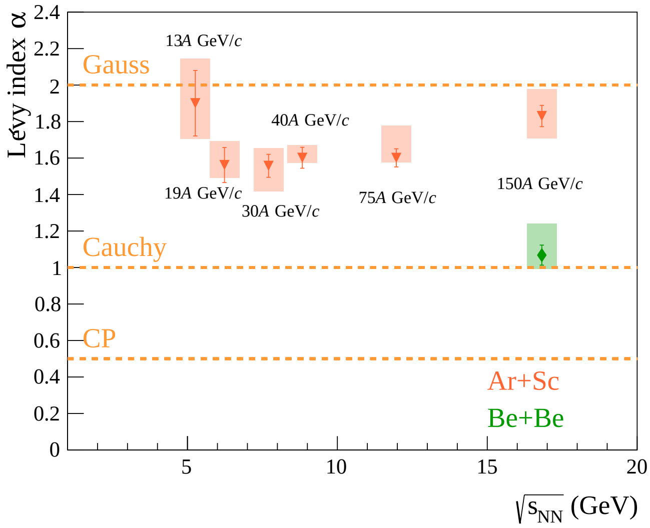

Figure 2: The constant fit to α, for 0–20 % central Be+Be at 150A GeV/c and 0–10% central Ar+Sc at all available energies, as a function of $\sqrt{s_{NN}}$. Special cases corresponding to a Gaussian ($\alpha = 2$) or a Cauchy ($\alpha = 1$) source are shown, as well as $\alpha = 0.5$, the conjectured value corresponding to the critical endpoint. Boxes denote systematic uncertainties, bars represent statistical uncertainties.

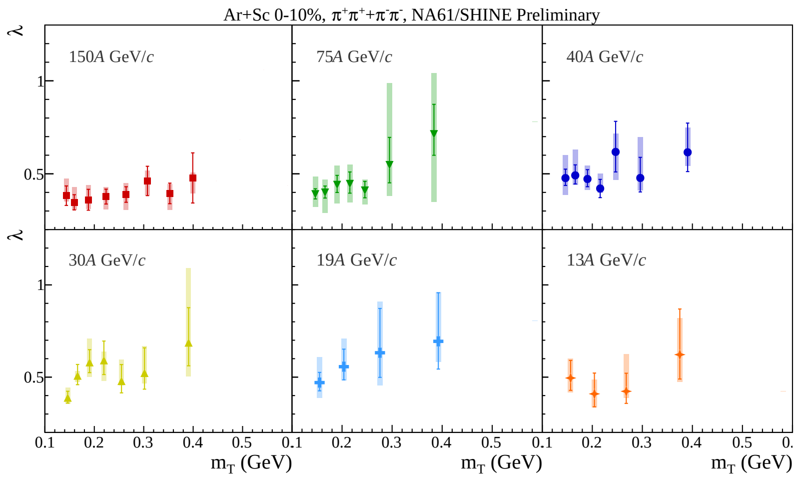

Figure 3: The fit parameters, for 0–10% central Ar+Sc at all available energies, as a function of m_T. Boxes denote systematic uncertainties, bars represent statistical uncertainties.

3. Conclusion

In this proceedings, we presented the NA61/SHINE measurements of one-dimensional two-pion femtoscopic correlation functions in Ar+Sc collisions at 13, 19, and 30A GeV/c beam momenta in 0-10% centrality collisions. We fitted these correlation functions based on Lévy-shaped source distributions, and investigated the transverse mass dependence of the source parameters. We furthermore compared them to previous NA61/SHINE results. Additionally, the Lévy scale parameter, R, exhibits a noticeable decrease with m_T. Finally, the correlation strength parameter, λ, shows no

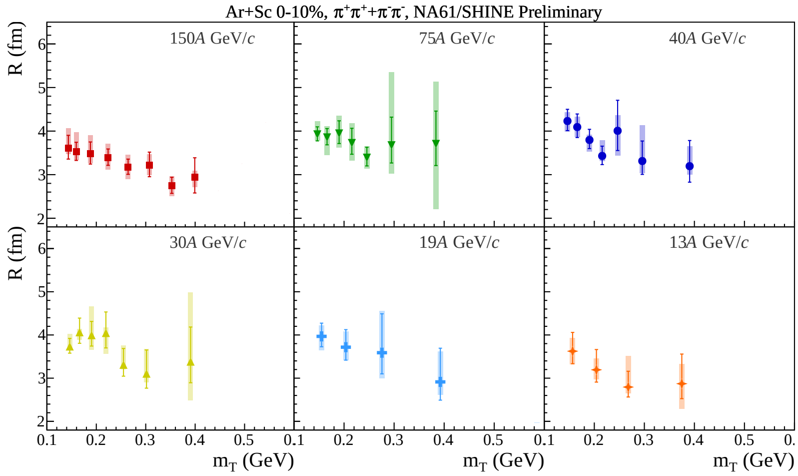

Figure 4: The fit parameters, for 0–10% central Ar+Sc at all available energies, as a function of m_T. Boxes denote systematic uncertainties, bars represent statistical uncertainties.

significant dependence on m_T, unlike RHIC results but consistent with earlier SPS measurements. In future studies, we plan to measure Bose-Einstein correlations in larger systems and at lower energies to further investigate the phase diagram of strongly interacting matter.

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References

[1] N. Abgrall *et al.*, [NA61/SHINE Collab.] *JINST* **9** (2014) P06005, `arXiv:1401.4699 [physics.ins-det]`.

[2] H. Adhikary *et al.*, [NA61/SHINE Collab.] *Eur. Phys. J. C* **83** no. 10, (2023) 919, `arXiv:2302.04593 [nucl-ex]`.

[3] B. Porfy, [NA61/SHINE Collab.] *Universe* **9** no. 7, (2023) 298, `arXiv:2306.08696 [nucl-ex]`.

[4] B. Porfy, [NA61/SHINE Collab.], "Femtoscopy at NA61/SHINE using symmetric Lévy sources in central ^{40}Ar+^{45}Sc from 40*A* GeV/*c* to 150*A* GeV/*c*," in *23rd Zimanyi School Winter Workshop*. 6, 2024. `arXiv:2406.02242 [nucl-ex]`.

[5] T. Csörgő *PoS* **HIGH-PTLHC08** (2008) 027, `arXiv:0903.0669 [nucl-th]`.

[6] S. El-Showk *et al.* *J. Stat. Phys.* **157** (2014) 869, `arXiv:1403.4545 [hep-th]`.

[7] H. Rieger *Physical Review B* **52** no. 9, (1995) 6659.
`http://link.aps.org/doi/10.1103/PhysRevB.52.6659`.

[8] R. Metzler, E. Barkai, and J. Klafter *Phys. Rev. Lett.* **82** (1999) 3563–3567.

[9] T. Csörgő, S. Hegyi, and W. A. Zajc *Eur. Phys. J. C* **36** (2004) 67–78, `arXiv:nucl-th/0310042`.

[10] T. Csörgő, S. Hegyi, T. Novak, and W. A. Zajc *Acta Phys. Polon. B* **36** (2005) 329–337.

[11] D. Kincses, M. Stefaniak, and M. Csanád *Entropy* **24** no. 3, (2022) 308, `arXiv:2201.07962 [hep-ph]`.

[12] B. Kórodi, D. Kincses, and M. Csanád *Phys. Lett. B* **847** (2023) 138295, `arXiv:2212.02980 [nucl-th]`.

[13] D. Kincses, M. Nagy, and M. Csanád `arXiv:2409.10373 [nucl-th]`.

[14] M. Csanád and D. Kincses *Universe* **10** no. 2, (2024) 54, `arXiv:2401.01249 [hep-ph]`.

[15] T. Csörgő and B. Lörstad *Phys. Rev. C* **54** (1996) 1390–1403, `arXiv:hep-ph/9509213`.

[16] T. Csörgő *Acta Phys. Hung. A* **15** (2002) 1–80, `arXiv:hep-ph/0001233`.

[17] T. Czopowicz, [NA61/SHINE Collab.] *PoS* **CPOD2021** (2022) 039.

[18] D. Kincses, M. I. Nagy, and M. Csanád *Phys. Rev. C* **102** no. 6, (2020) 064912, `arXiv:1912.01381 [hep-ph]`.

[19] M. Csanád, S. Lökös, and M. Nagy *Phys. Part. Nucl.* **51** no. 3, (2020) 238–242, `arXiv:1910.02231 [hep-ph]`.

[20] M. Nagy, A. Purzsa, M. Csanád, and D. Kincses *Eur. Phys. J. C* **83** no. 11, (2023) 1015, `arXiv:2308.10745 [nucl-th]`.

[21] Y. Sinyukov *et al.* *Phys. Lett. B* **432** (1998) 248–257.

[22] B. Kurgyis, D. Kincses, M. Nagy, and M. Csanád *Universe* **9** no. 7, (2023) 328, `arXiv:2007.10173 [nucl-th]`.

[23] Y. M. Sinyukov *Nucl. Phys. A* **566** (1994) 589C–592C.

[24] Y. M. Sinyukov *Hot Hadronic Matter: Theory and Experiment* (1995) 309–322.

[25] A. Adare *et al.*, [PHENIX Collab.] *Phys. Rev. C* **97** no. 6, (2018) 064911, `arXiv:1709.05649 [nucl-ex]`.

[26] D. Kincses, [STAR Collab.] *Universe* **10** no. 3, (2024) 102, `arXiv:2401.11169 [nucl-ex]`.

[27] N. J. Abdulameer *et al.*, [PHENIX Collab.] `arXiv:2407.08586 [nucl-ex]`.