

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 ($\sqrt{s_{NN}} \approx 5.3, 6.2, 7.7, 8.8, 12$, 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.

*42nd International Conference on High Energy Physics (ICHEP2024)
18-24 July 2024
Prague, Czech Republic*

*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 $^{40}\text{Ar}+^{45}\text{Sc}$ 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:

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

where R is the Lévy scale parameter, α is the Lévy stability index, \mathbf{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:

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

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):

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

We investigate the combination of positive ($\pi^+\pi^+$) and negative ($\pi^-\pi^-$) pion pairs, identified via energy loss in the TPCs (dE/dx) 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 $K_{\text{Coulomb}}(q)$:

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

where $C_2^{\text{Coulomb}}(q)$ 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:

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

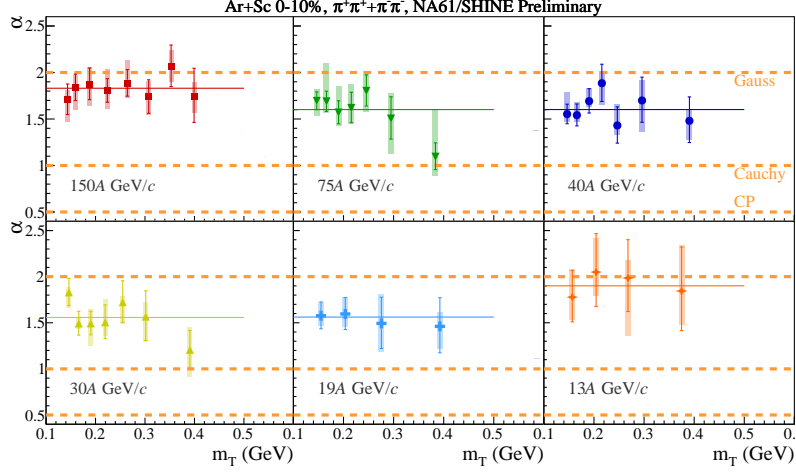


Figure 1: The fit parameters, for 0–10% central Ar+Sc at all available energies, as a function of m_T . Special cases corresponding to a Gaussian ($\alpha = 2$) or a Cauchy ($\alpha = 1$) source are shown, as well as $\alpha = 0.5$, the conjectured value corresponding to the critical endpoint, while 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 $m_T = \sqrt{m^2 c^4 + K_T^2 c^2}$ 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 $\sqrt{s_{NN}} \approx 6 - 8$ 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 $R \sim 1/\sqrt{m_T}$, 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.

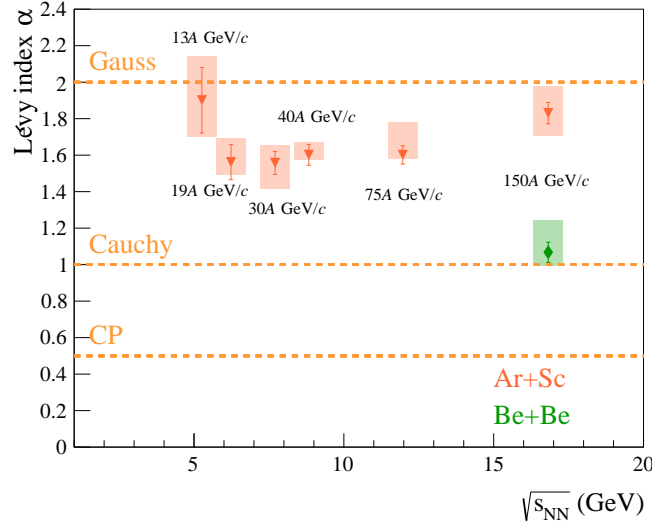


Figure 2: The constant fit to α , for 0–20 % central Be+Be at 150A GeV/c and 0–10% central Ar+Sc at all available energies, as a function of $\sqrt{s_{NN}}$. Special cases corresponding to a Gaussian ($\alpha = 2$) or a Cauchy ($\alpha = 1$) source are shown, as well as $\alpha = 0.5$, the conjectured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

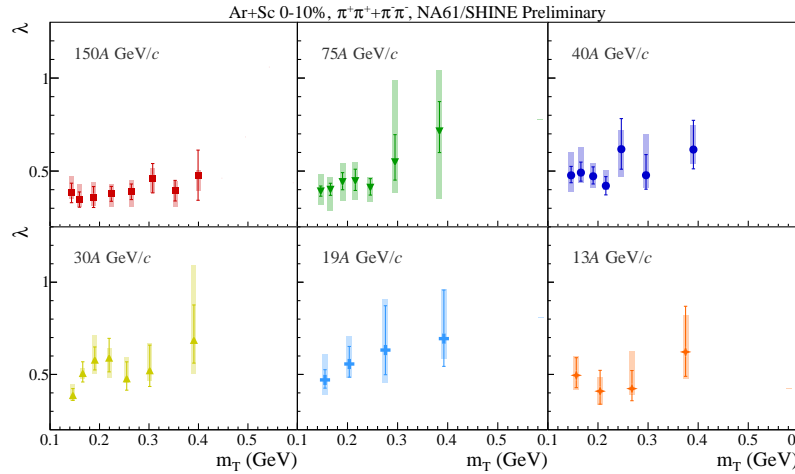


Figure 3: The fit parameters, for 0–10% central Ar+Sc at all available energies, as a function of m_T . Boxes denote systematic uncertainties, bars represent statistical uncertainties.

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

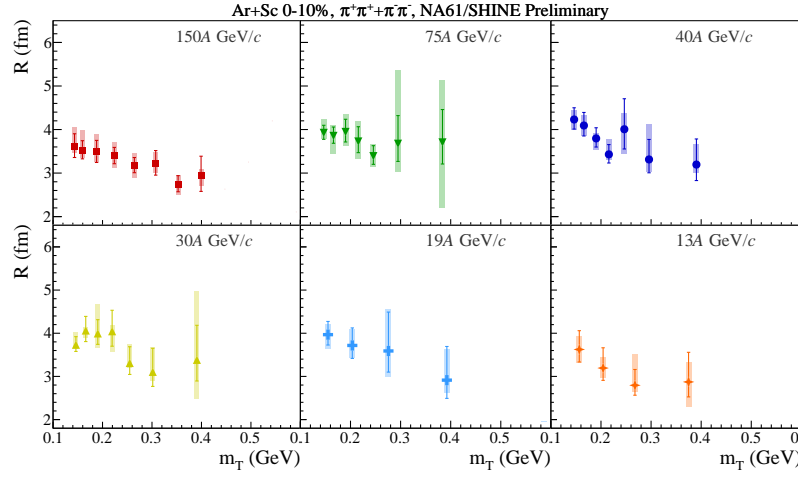


Figure 4: The fit parameters, for 0–10% central Ar+Sc at all available energies, as a function of m_T . Boxes denote systematic uncertainties, bars represent statistical uncertainties.

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.

Acknowledgments

The author acknowledges support of the DKOP-23 Doctoral Excellence Program of the Ministry for Culture and Innovation, and was furthermore supported by K-138136 and K-138152 grants of the National Research, Development and Innovation Fund.

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.], “Femtoscopia at NA61/SHINE using symmetric Lévy sources in central $^{40}\text{Ar}+^{45}\text{Sc}$ from 40A GeV/c to 150A 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:nuc1-th/0310042](https://arxiv.org/abs/nuc1-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](https://arxiv.org/abs/2201.07962) [hep-ph].
- [12] B. Kórodi, D. Kincses, and M. Csanád *Phys. Lett. B* **847** (2023) 138295,
[arXiv:2212.02980](https://arxiv.org/abs/2212.02980) [nucl-th].
- [13] D. Kincses, M. Nagy, and M. Csanád [arXiv:2409.10373](https://arxiv.org/abs/2409.10373) [nucl-th].
- [14] M. Csanád and D. Kincses *Universe* **10** no. 2, (2024) 54, [arXiv:2401.01249](https://arxiv.org/abs/2401.01249) [hep-ph].
- [15] T. Csörgő and B. Lörsstad *Phys. Rev. C* **54** (1996) 1390–1403, [arXiv:hep-ph/9509213](https://arxiv.org/abs/hep-ph/9509213).
- [16] T. Csörgő *Acta Phys. Hung. A* **15** (2002) 1–80, [arXiv:hep-ph/0001233](https://arxiv.org/abs/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](https://arxiv.org/abs/1912.01381) [hep-ph].
- [19] M. Csanád, S. Lökös, and M. Nagy *Phys. Part. Nucl.* **51** no. 3, (2020) 238–242,
[arXiv:1910.02231](https://arxiv.org/abs/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](https://arxiv.org/abs/2308.10745) [nucl-th].
- [21] Y. Sinyukov *et al.* *Phys. Lett. B* **432** (1998) 248–257.
- [22] B. Kurgiy, D. Kincses, M. Nagy, and M. Csanád *Universe* **9** no. 7, (2023) 328,
[arXiv:2007.10173](https://arxiv.org/abs/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](https://arxiv.org/abs/1709.05649) [nucl-ex].
- [26] D. Kincses, [STAR Collab.] *Universe* **10** no. 3, (2024) 102, [arXiv:2401.11169](https://arxiv.org/abs/2401.11169) [nucl-ex].
- [27] N. J. Abdulameer *et al.*, [PHENIX Collab.] [arXiv:2407.08586](https://arxiv.org/abs/2407.08586) [nucl-ex].