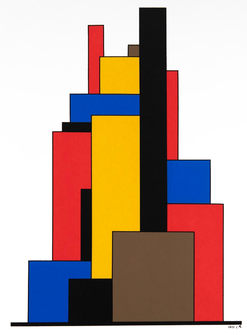
# Energy scan results using Lévy femtoscopy at NA61/SHINE

24th Zimányi School, Winter Workshop on Heavy Ion Physics

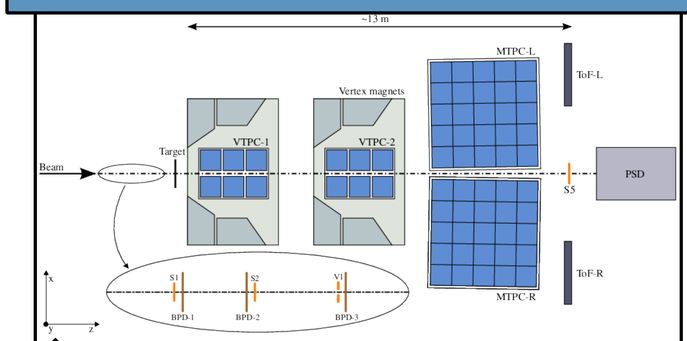
Barnabás Pórfy, HUN-REN Wigner Research Centre for Physics,
Eötvös Loránd University
for the NA61/SHINE Collaboration



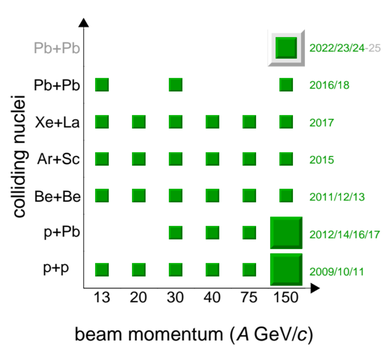
## Summary


- 1D two particle pion femtoscopy
- $^{7}$Be+$^{9}$Be, $^{40}$Ar+$^{45}$Sc
  $13A\,\mathrm{GeV}/c, 19A\,\mathrm{GeV}/c, 30A\,\mathrm{GeV}/c,$
  $40A\,\mathrm{GeV}/c, 75A\,\mathrm{GeV}/c, 150A\,\mathrm{GeV}/c$
- Non Gaussian source shape
  Symmetric Lévy assumption valid
- Small non-monotonicity,
  no clear indication of the Critical Point


## NA61/SHINE




- Large acceptance hadron spectrometer
  - Covering the full forward hemisphere
- Energy and system size scan
  - Search for the critical point
- Upgrade LS2 – data taking rate up by 20x




## FEMTOSCOPY

- Tool to measure spatial correlations in heavy ion and hadron collisions

D. A. Brown and P. Danielewicz. Phys. Lett. B 398 (1997), pp. 252–258.
S. S. Adler et al., PHENIX Coll. Phys. Rev. Lett. 98 (2007), p. 132301.

- Femtometer scale study of momentum difference correlations of identical bosons
- Pair source distribution:

$$D(r,K) = \int S\left(\rho + \frac{r}{2}, K\right) S\left(\rho - \frac{r}{2}, K\right) d^4\rho$$

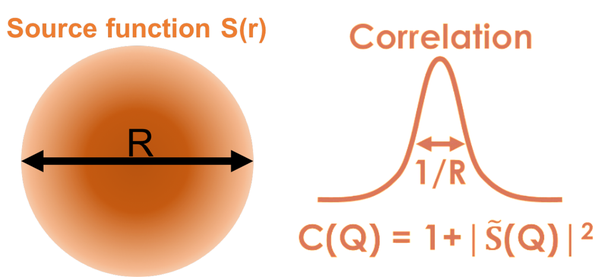
($\rho$: Pair centre of mass; $r$: Pair separation)

- Correlation function:

$$C(Q,K) = \int d^4r D(r,K)\,|\psi_Q(r)|^2$$

($K$: Average pair momentum; $Q$: Relative pair momentum; $|\psi_Q(r)|^2$: Pair wave function (FSI incl.))

- Experiments: measure C(Q), gather info on D(r) and FSI




## LÉVY DISTRIBUTIONS

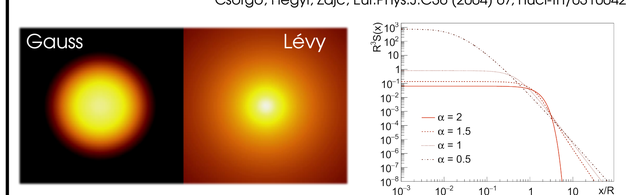
- S(r) is frequently assumed to be Gaussian
- Gaussian C(Q) → experimental data not supporting
- **C**entral **L**imit **T**heorem not satisfied?
- Generalized **C**entral **L**imit **T**heorem?
  - Leads to Lévy distribution

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

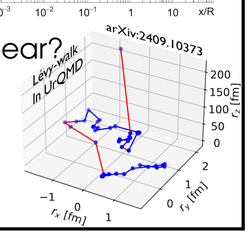
  - $\alpha = 2 \rightarrow$ Gaussian  $\alpha < 2 \rightarrow$ power-law tail
    $\alpha = 1 \rightarrow$ Cauchy  $\sim r^{-(1+\alpha)}$
- Correlation func. with Lévy shaped source

$$C(Q) = 1 + \lambda \cdot e^{-|QR|^{\alpha}}$$

Csörgő, Hegyi, Zajc, Eur.Phys.J.C36 (2004) 67, nucl-th/0310042




- Why does Lévy shape appear?
  - Lévy walk — Braz.J.Phys.37 (2007) 1002; Physics Reports 339 (2000) 1-77; Entropy 24 3 (2022) 308; Phys.Lett.B 847 (2023); arXiv:2409.10373
  - QCD jets — Acta Phys.Polon.B36 (2005) 329-337
  - Criticality — AIP Conf.Proc.828 (2006) 525-532




## CRITICALITY

- Fluctuations appear at all scales near Critical Point
- Spatial correlations exhibit power-law near CP

$$\sim r^{-(d-2+\eta)}$$

- QCD universality class ↔ 3D Ising

Halasz et al., Phys.Rev.D58 (1998) 096007
Stephanov et al., Phys.Rev.Lett.81 (1998) 4816

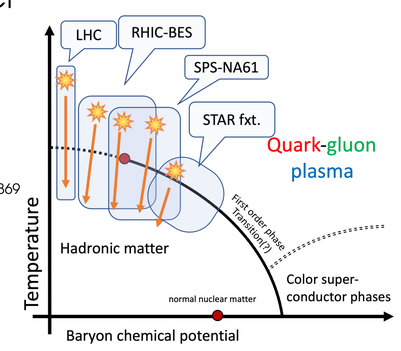
$$\begin{cases} \eta = 0.03631 \pm 0.00003 \leftrightarrow \text{3D Ising} \\ \eta = 0.5 \pm 0.05 \leftrightarrow \text{rfd. 3D Ising} \end{cases}$$

El-Showk et al., J.Stat.Phys.157 (2014) 869
Rieger, Phys.Rev.B52 (1995) 6659

- Lévy power-law tail + spatial correlations

$$\alpha \simeq \eta$$

- Possible to measure shape & CP proximity!




## FINAL STATE INTERACTIONS

- Like charged pion pairs → Coulomb interaction → Coulomb correction

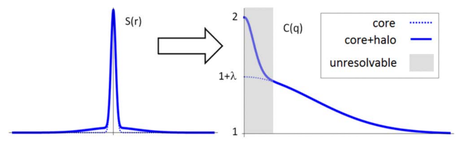
$$K_{\mathrm{Coul}}(Q;\alpha,R) = \frac{C_2^{\mathrm{Coulomb}}(Q)}{C_2^0(Q)}$$

Csanád, Lökös, Nagy, Phys.Part.Nucl. 51 (2020) 238
Nagy, Purzsa, Csanád, Kincses, Eur.Phys.J.C 83 (2023) 11, 1015
Kurgyis, Kincses, Nagy, Csanád, Universe 2023, 9(7), 328

→ FSI free

- Resonance pions reduce correlation → Two component pion source
- $S_{\mathrm{core}}$- primordial pions, size $\leq 10$ fm
- $S_{\mathrm{halo}}$ - long lived resonances, large size
- Formula with all FSI included:

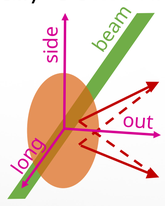
$$C(Q) = 1 - \lambda + \left(1 + e^{-|QR|^{\alpha}}\right) \cdot \lambda \cdot K_{\mathrm{Coul}}(Q;\alpha,R)$$




Yu. Sinyukov et al., Phys.Lett.B432 (1998) 248,
M.G. Bowler Phys.Lett.B270 (1991) 69

## ANALYSIS

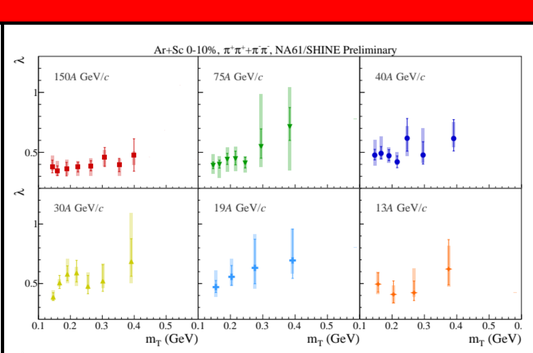
- Two particle pion femtoscopy
- System size scan at $150A\,\mathrm{GeV}/c$ :
- $^{7}$Be+$^{9}$Be, $^{40}$Ar+$^{45}$Sc,
  $^{129}$Xe+$^{139}$La (ongoing)
- Energy scan in Ar+Sc completed:
- $13A\,\mathrm{GeV}/c, 19A\,\mathrm{GeV}/c, 30A\,\mathrm{GeV}/c,$
  $40A\,\mathrm{GeV}/c, 75A\,\mathrm{GeV}/c, 150A\,\mathrm{GeV}/c$
- Particle identification via $\mathrm{d}E/\mathrm{d}x$
- 1D momentum difference $q$ in **L**ongitudinally **Co**-**M**oving **S**ystem




- Be+Be at 0-20% centrality
  NA61/SHINE, EPJC 83 (2023) 10, 919
- Ar+Sc at 0-10% centrality
  Universe 9 (2023) 7, 298;
  arXiv:2406.02242, 2410.13975

$$K_{\mathrm{T}} = \sqrt{K_{\mathrm{x}}^2 + K_{\mathrm{y}}^2}$$
$$m_{\mathrm{T}} \equiv \sqrt{m_{\pi}^2 + (K_{\mathrm{T}}/c)^2}$$

## ENERGY SCAN RESULTS

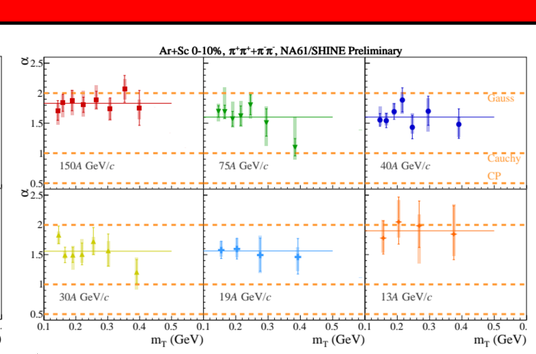



- Correlation strength

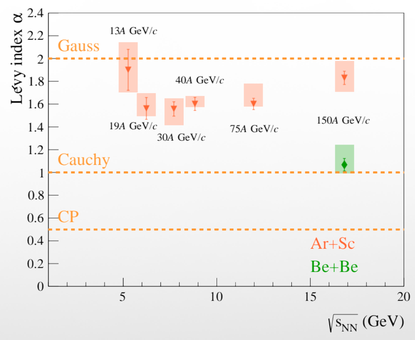
$$\lambda = \left(\frac{N_{\mathrm{core}}}{N_{\mathrm{core}} + N_{\mathrm{halo}}}\right)^2$$

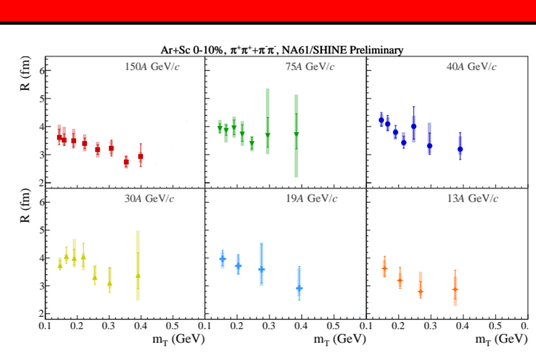
Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996)
Bolz et al, Phys.Rev.D47 (1993) 3860-3870

- No clear $m_{\mathrm{T}}$ dependence
- No visible hole at low-$m_{\mathrm{T}}$
  - Seen at RHIC (STAR, PHENIX)
    S. E. Vance et al, Phys.Rev.Lett.81 (1998) 2205-2208
    T. Csörgő et al, Phys.Rev.Lett.105 (2010) 182301
    Abdulameer, N. J. and others for PHENIX Collaboration, arXiv:2407.08586
  - Possibly turned off at SPS
    this results and NA44 results
    Beker et al., PRL74, 3340




- Lévy stability index $\alpha$
- Shape of spatial correlation &
- related to CP
- No clear $m_{\mathrm{T}}$ dependence
  fit with constant → interesting trend




- Lévy scale parameter *R*
  - Length of homogeneity
- $m_{\mathrm{T}}$ dependence → collective flow
- Hydro prediction:
  $R \approx 1/m_{\mathrm{T}}$ (for non power-law tail)
  Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390-1403
  S. V. Akkelin and Yu. M. Sinyukov, Phys.Lett.B356 (1995) 525-530
  S. Chapman, P. Scotto and U. W. Heinz, Phys.Rev.Lett.74 (1995) 4400-4403
  → interesting for $\alpha < 2$
- When does Lévy shape appear?
  - After hydro phase?
- Why does it follow hydro prediction?