Energy scan results with Lévy type femtoscopy at NA61/SHINE

XVII$^{\text{th}}$ Workshop on Particle Correlations and Femtoscopy

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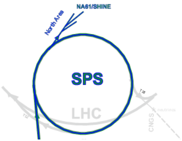
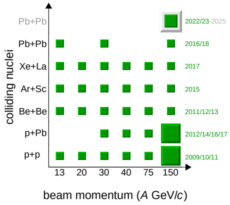
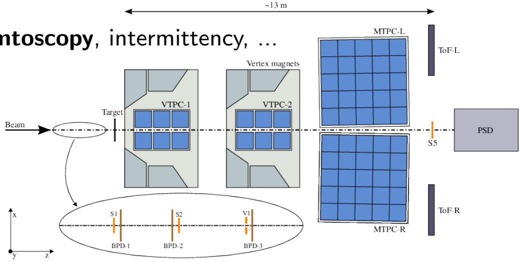
WPCF 2024 welcomes you in Toulouse France

The NA61/SHINE Detector

- Located at CERN SPS, North Area
- Fixed target experiment; upgrade during LS2
- Large acceptance hadron spectrometer (TPC)
  - Covering the full forward hemisphere
  - Outstanding tracking, down to $p_T \approx 0$ GeV/c
- Different systems scanned in beam energy
- Strong interaction program:
  - Search for Critical Point: **femtoscopy**, intermittency, ...



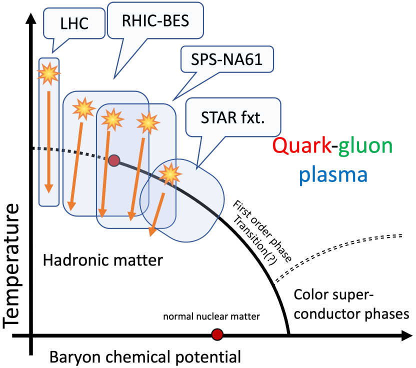




Detector layout during Ar+Sc data taking

Critical Point Search Using Femtoscopy

- System size scan progress at 150(8)A GeV/c: $p+p$, ^{7}Be+^{9}Be, ^{40}Ar+^{45}Sc, ^{129}Xe+^{139}La (in progress)
  Be+Be: NA61/SHINE, EPJC 83 (2023) 10, 919; Ar+Sc: Universe 9 (2023) 7, 298;
  arXiv:2406.02242, 2410.13975; this analysis



- Energy scan in Ar+Sc:
  150A GeV/c, 75A GeV/c, 40A GeV/c
  30A GeV/c, 19A GeV/c, 13A GeV/c
- Critical Point - fluctuations at all scales
- Power-law in spatial correlations with
  Critical exponent η,
  near **C**ritical **P**oint?
- QCD universality class $\leftrightarrow$ 3D Ising:
  Halasz et al., Phys.Rev.D58 (1998) 096007
  Stephanov et al., Phys.Rev.Lett.81 (1998) 4816
  - 3D Ising: $\eta = 0.03631(3)$
    El-Showk et al., J.Stat.Phys.157 (2014) 869
  - Random field 3D Ising $\eta = 0.50(5)$
    Rieger, Phys.Rev.B52 (1995) 6659

Bose-Einstein Correlations in Heavy-Ion Physics

Tool to measure spatial correlations: Bose-Einstein relative mom. correlations

- R. Hanbury Brown, R. Q. Twiss observed Sirius with two optical telescopes

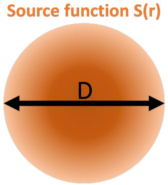
  R. Hanbury Brown and R. Q. Twiss Nature 178 (1956)

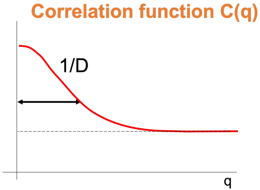
  - Intensity correlations as a function of detector distance
  - Measuring apparent angular diameter of point-like sources

- Goldhaber, Goldhaber, Lee and Pais: applicable in high energy physics: (for identical pions)

  Goldhaber, Goldhaber, Lee and Pais Phys.Rev.Lett.3 (1959) 181

  - Momentum correlation $C(q)$, $q = |p_1 - p_2|$, is related to the source $S(x)$
    $C(q) \cong 1 + |\widetilde{S}(q)|^2$ where $\widetilde{S}(q)$ Fourrier transform of $S(q)$





- S(r) frequently assumed to be Gaussian $\rightarrow$ Gaussian C(q)
  $\rightarrow$ Exp. data not supporting $\rightarrow$ CLT not satisfied?

Lévy Distribution in Heavy-Ion Physics

- Generalized CLT? $\rightarrow$ Lévy-stable distribution
- Shape of correlation function with Lévy source: $C(q) = 1 + \lambda \cdot e^{-|qR|^{\alpha}}$
  - $\alpha = 1$: Exponential, $\alpha = 2$: Gaussian Csörgő, Hegyi, Zajc, Eur.Phys.J.C36 (2004) 67, nucl-th/0310042

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

- From generalization of Gaussian, power-law tail: $\sim r^{-(d-2+\alpha)}$
  - $\alpha = 1$ Cauchy, $\alpha = 2$ Gaussian
- Why Lévy source: - detailed in talk of **D. Kincses, E. Árpási, L. Kovács**
  - QCD jets; Lévy walk; Critical phenomena; ...?

    Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon.B36 (2005) 329-337

    Csanád, Csörgő, Nagy, Braz.J.Phys.37 (2007) 1002

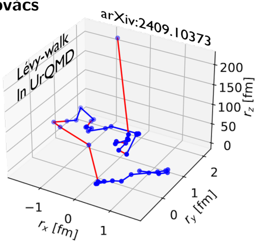
    Metzler, Klafter, Physics Reports 339 (2000) 1-77

    Kincses, Stefaniak, Csanád, Entropy 24 3 (2022) 308

    Kórodi, Kincses, Csanád, Phys.Lett.B 847 (2023)

    Kincses, Nagy, Csanád, arXiv:2409.10373

    Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc.828 (2006) 525-532



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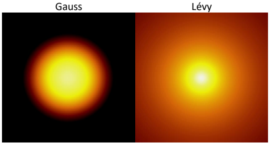
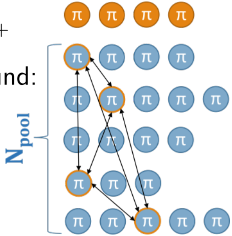
- Why Lévy source:
  QCD jets; Lévy walk; Critical phenomena; ...?
- Lévy distribution leads to power-law spatial correlation
- Spatial correlation at the Critical Point: $\sim r^{-(d-2+\eta)}$
  - Lévy-exponent α identical to correlation exponent η



Correlation Function Measurement Details

- Be+Be, 0-20% $\sqrt{s_{NN}} = 16.8$ GeV
- Ar+Sc, 0-10% $\sqrt{s_{NN}} = 16.8, 11.9, 8.8, 7.7, 6.2, 5.3$ GeV
- Event and track cuts (centrality, vertex, rapidity, ...)
- Momentum dependent pair cut
- Particle Identification via dE/dx method to select π^-, π^+

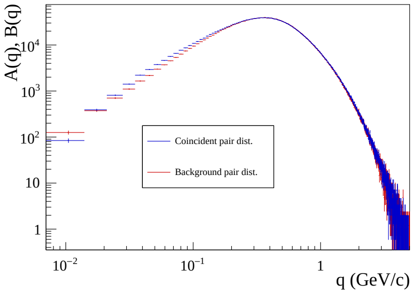


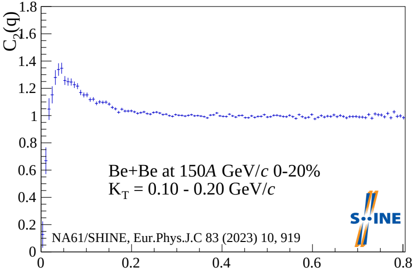
Correlation function measurement via mixed event background:

- A(q) - Pairs from same event
- B(q) - Pairs from mixed events
- C(q) - Correlation function, C(q) = A(q)/B(q)
  - Correlation function q_{LCMS} 1D variable
  - LCMS: Longitudinally CoMoving System
  - $m_{\mathrm{T}} \equiv \sqrt{m^2 + (K_{\mathrm{T}}/c)^2}$; $K = (p_1 + p_2)/2$; $K_{\mathrm{T}} = \sqrt{K_x^2 + K_y^2}$
  - No. m_{T} bins: **8** - Ar+Sc 150A GeV/c, **7** - Ar+Sc 75A GeV/c, 40A GeV/c,
    6 - Ar+Sc 30A GeV/c
    4 - Ar+Sc 19A GeV/c, 13A GeV/c, Be+Be 150A GeV/c

Bose–Einstein Correlation Function

- $C_2(q)$: B–E peak and Coulomb hole, at low q values:





- Like charged pairs: Coulomb interaction → Coulomb correction (CC)
  - Calc: numerical integral possible - detailed in talk of **M. Nagy**

    Nagy, Purzsa, Csanád, Kincses, Eur.Phys.J.C 83 (2023) 11, 1015
  - Parametrization used before Csanád, Lökös, Nagy, Phys.Part.Nucl. 51 (2020) 238
- Meas.: LCMS, CC.: PCMS (pair center of mass) negligible, BUT 1D spher. symm. source LCMS not spherical PCMS Kurgyis, Kincses, Nagy, Csanád, Universe 2023, 9(7), 328

$$R \to R_{\mathrm{PCMS}} = \sqrt{\frac{1-\frac{2}{3}\beta_T^2}{1-\beta_T^2}} \cdot R_{\mathrm{LCMS}},\ q_{\mathrm{inv}} \approx \sqrt{1-\beta^{2/3}} \cdot q_{\mathrm{LCMS}},\ \beta_T = \frac{K_T}{m_T}$$

Parameters of Lévy-source

- R Lévy-scale parameter:
  - Length of homogeneity
  - From simple hydro calc.:
    $$R_{\mathrm{HBT}} = R/\sqrt{1 + (m_{\mathrm{T}}/T_0) \cdot u_{\mathrm{T}}^2}$$
- λ correlation strength:
  - Core-halo ratio:
    $$\lambda = \left(\frac{N_{\mathrm{core}}}{N_{\mathrm{core}} + N_{\mathrm{halo}}}\right)^2$$
    Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996)

    Bolz et al, Phys.Rev.D47 (1993) 3860-3870
  - Core: primordial pions
  - Halo: pions from long-lived resonances
- α Lévy-stability index
  - $\alpha = 2$: Gauss shape, simple hydro
  - $\alpha < 2$: Generalized central limit theorem
  - $\alpha = 0.5$: Conjectured value at CP

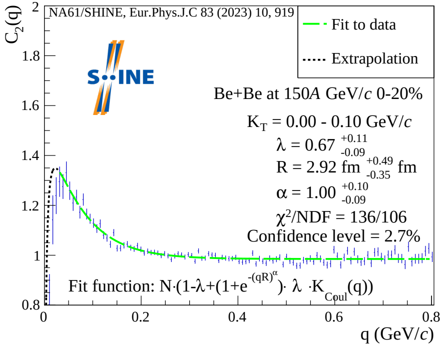
Bowler-Sinyukov

$$C(q) = 1 - \lambda + (1 + e^{-|qR|^{\alpha}}) \cdot \lambda \cdot K(q; \alpha, R)$$

$K(q; \alpha, R)$ calculated numerically: see talk of **M. Nagy**

Yu. Sinyukov et al., Phys.Lett.B432 (1998) 248,

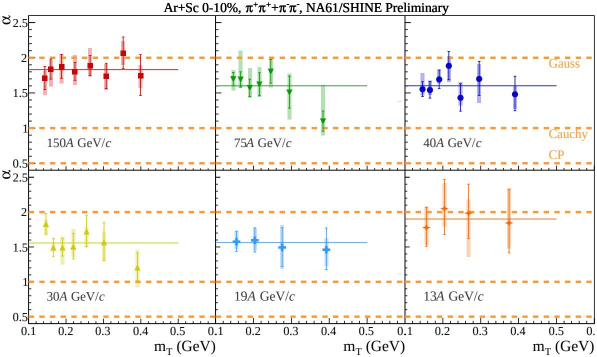
M.G. Bowler, Phys.Lett.B270 (1991) 69



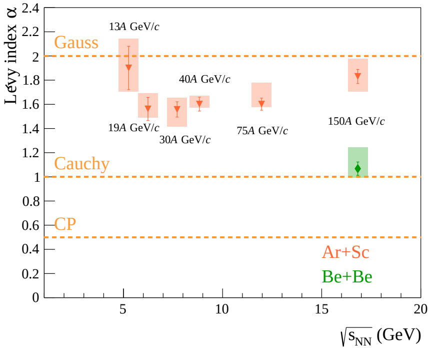
Lévy-stability index α

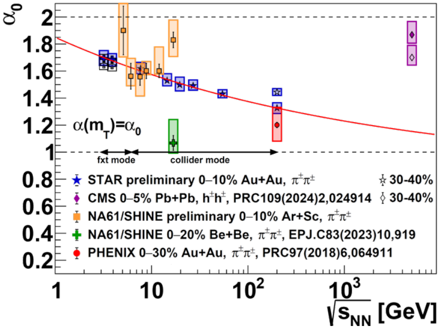
- Shape of spatial correlation
- Compatible with Lévy assumption ($\alpha < 2$),
  - Ar+Sc: far from Cauchy, Decreases from "close to Gaussian" far from CP ($\alpha = 0.5$)

Constant fit to α unravels interesting trend



Lévy-stability index α





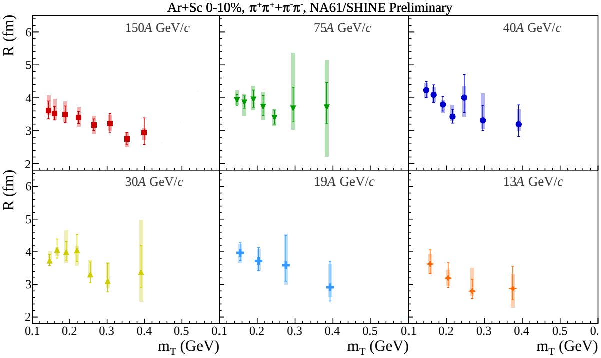
Min. around $\sqrt{s_{NN}} = 6\text{-}8$ GeV?
Slightly nonmonotonic trend?

Eur.Phys.J.C 83 (2023) 10, 919
Universe 2023, Volume 9, Issue 7, 298;
arXiv:2406.02242; arXiv:2410.13975

- New PHENIX results:
  see talk of **S. Lökös**
  $\alpha = 1.2\text{-}1.6$ Au+Au, $\sqrt{s_{NN}} = 200$ GeV
  $p_T > 0.2$ GeV$/c$ arXiv:2407.08586

- From hydro: decrease with m_T: $R \approx 1/\sqrt{m_T}$ (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
  Visible m_T dependence $\rightarrow$ sign of collective flow
  $R \approx 1/\sqrt{m_T}$ $\rightarrow$ interesting for $\alpha < 2$
  BUT: when does Lévy shape appear (after hydro phase?) &
  why does it follow hydro prediction?



Correlation Strength λ

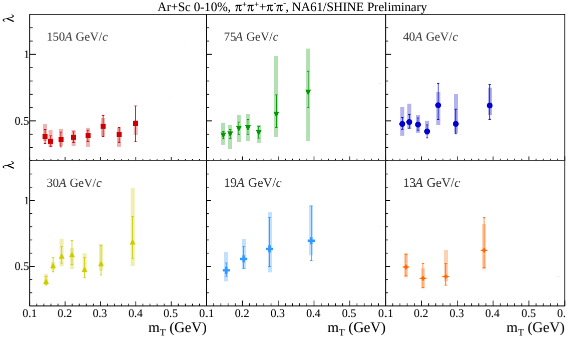
- Describes core-halo ratio
- Compared to RHIC results:
  - Low m_T values show no decrease (sim. to other SPS results)
  - Halo component increases at RHIC (e.g. In-medium mass mod.)

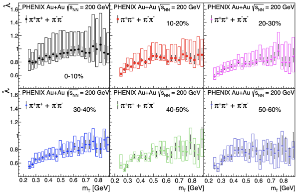
    S. E. Vance et al, Phys.Rev.Lett.81 (1998) 2205-2208

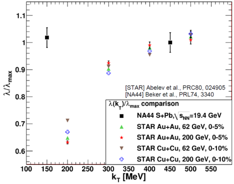
    T. Csörgő et al, Phys.Rev.Lett.105 (2010) 182301

    Abdulameer, N. J. and others for PHENIX Collaboration, arXiv:2407.08586

    more details - talk of **S. Lökös**
- λ values show no clear m_T dependence

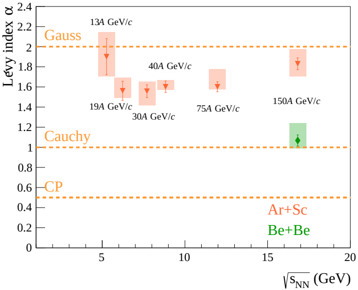






Summary

- NA61/SHINE Lévy HBT analysis
  - ^{7}Be+^{9}Be collisions, 0-20% centrality at 150A GeV/c beam momentum
  - ^{40}Ar+^{45}Sc collisions, 0-10% centrality at 150A, 75A, 40A, 30A, 19A, 13A GeV/c beam momentum
- Using $\pi^+\pi^+ + \pi^-\pi^-$
- Fit using symmetric Lévy source
- Parameter m_T dependence:
  - $\alpha(m_T)$:
    - ★ Be+Be ≈ 1
    - ★ Ar+Sc $\approx 1.6 - 1.8$
  - $R(m_T)$: m_T dependence - transverse flow
  - $\lambda(m_T)$: no dependence, no hole
  - Minimum in $\langle\alpha\rangle$ around 6-8 GeV
- $\alpha < 2 \rightarrow$ Symmetric Lévy source good assumption



Ongoing:

- Analysis with ^{129}Xe+^{139}La

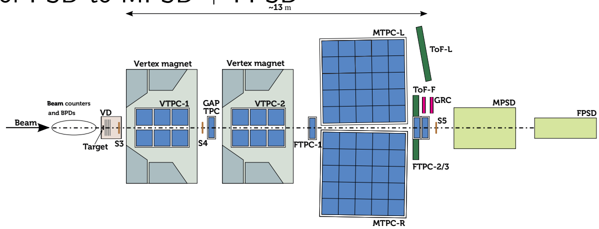
Thank you for your attention!

Supported by the DKOP-23 Doctoral Excellence Program of the Ministry for Culture and Innovation from the source of the National Research, Development and Innovation Fund.

Backup

The NA61/SHINE Detector Post LS2

- Upgrade of DAQ + new trigger system (TDAQ)
  - Detector readouts replaced → data taking rate up by 20x
  - TPCs - ALICE; other detectors - DRS4
- Construction of:
  - Vertex Detector - open-charm measurements
  - ToF-F wall
  - Multi-gap Resistive Plate Chamber based ToF-L (ToF-R under constr.)
  - Beam Position Detector
  - Geometry Reference Chamber - drift velocity measurements
- Upgrade of PSD to MPSD + FPSD



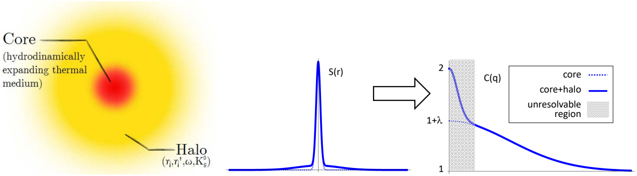
Stable distributions

- If a lin. comb. of two indep. random variables with this distribution has the same distribution
- $f(x) = \frac{1}{2\pi}\int_{-\infty}^{\infty}\varphi(q)e^{-ixq}dq$, where the characteristic func.:
- $\varphi(q;\alpha,\beta,R,\mu) = \exp(iq\mu - |Rq|^{\alpha}(1-\beta\text{sgn}(q)\Phi)$
  α: stability index
  β: skewness, distribution symmetric if $= 0$
  R: scale parameter
  μ: location parameter, if $\beta = 0 \rightarrow$ median
  $$\Phi = \begin{cases} \tan(\frac{\pi\alpha}{2}, \alpha \neq 1 \\ -\frac{2}{\pi}\log|t|, \alpha = 1 \end{cases}$$
- Sum of two random variables from a stable distribution gives something with the same values of α and β (with possibly different values of μ and R...)
- $\beta = 0 \rightarrow$ Lévy symmetric alpha-stable distribution

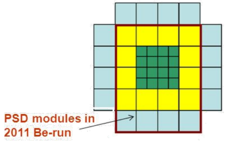
Core-Halo Model

- Hydrodinamically increasing core $\rightarrow$ pion emission
- Results in two component source: $S(x) = S_M(x) + S_G(x)$
- Core $\cong$ 10 fm size, halo$(\omega, \eta \ldots) >$ 50 fm size
- Halo not seen due to detector resolution
- Real q$\rightarrow$ 0, at $C(q = 0) = 2$
- Results show $C(q \rightarrow 0) = 1 + \lambda$, where $\lambda = \left(\frac{N_m}{N_g + N_m}\right)^2$

Bolz et al, Phys.Rev.D47 (1993) 3860-3870
Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996) 491-497



Projectile Spectator Detector



- Centrality measurement with PSD
- Located on beam axis
- measures forward energy (E_F) from spectators
- Intervals in E_F allows to select centrality classes