Femtoscopy at NA61/SHINE using symmetric Lévy sources

23rd Zimányi School Winter Workshop On Heavy Ion Physics

Barnabás Pórfy for the NA61/SHINE Collaboration

Wigner RCP, Hungary
Eotvos Lorand University, Hungary

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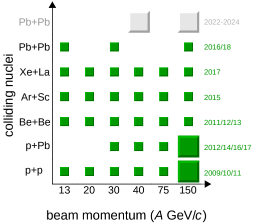
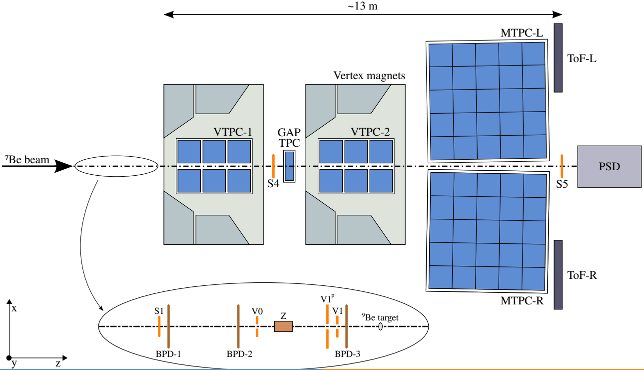
The NA61/SHINE Detector

- 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 interactions programme:
  - Search for Critical Point: **femtoscopy**, intermittency, fluctuations, ...

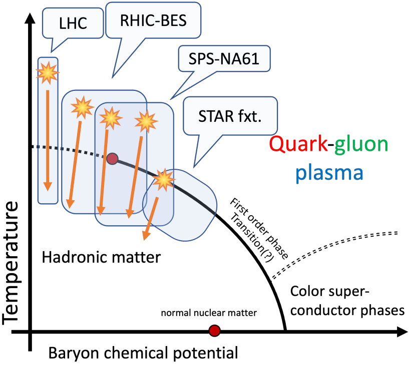




Critical Point Search Using Femtoscopy

- System size scan progress at 150(8)A GeV/c: $p+p$, Be+Be, Ar+Sc, Xe+La or Pb+Pb

  Be+Be: NA61/SHINE, Eur.Phys.J.C 83 (2023) 10, 919; Ar+Sc: Universe 2023, Volume 9, Issue 7, 298



- Energy scan ongoing in Ar+Sc: 150A, GeV/c, 75A GeV/c, 40A GeV/c 30A GeV/c, 19A GeV/c, 13A GeV/c
- At 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

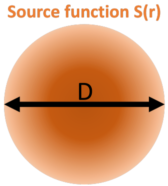
Bose-Einstein Correlations in Heavy-Ion Physics

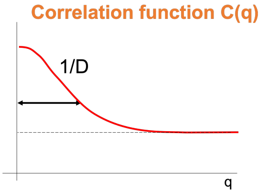
Tool to measure spatial correlations: Bose-Einstein relative mom. correlations

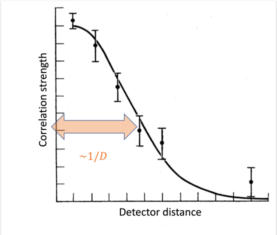
- R. Hanbury Brown, R.Q.Twiss observed Sirius with two optical telescopes

  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 → Gaussian C(q)

Lévy Distribution in Heavy-Ion Physics

- Measurements not fully supporting Gaussian source $\rightarrow$ Generalized CLT
- 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: $\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^{\alpha}}$

- From generalization of Gaussian, power-law tail: $\sim r^{-(d-2+\alpha)}$
  - $\alpha = 1$ Cauchy, $\alpha = 2$ Gaussian
- Why Lévy source:
  - QCD jets; Anomalous diffusion; Critical phenomena; ...

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

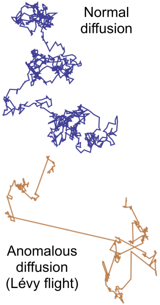
    Csanád, Csörgő, Nagy, Braz.J.Phys.37 (2007) 1002

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

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

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

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



- 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

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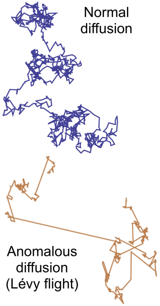

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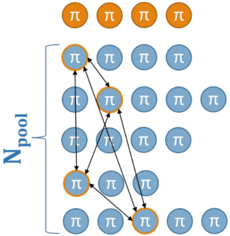
Correlation Function Measurement Details

- Be+Be, 0-20% $150A$ GeV$/c$ beam momentum,($\sqrt{s_{\mathrm{NN}}} = 16.8$ GeV)
- Ar+Sc, 0-10% $150A$ GeV$/c$, $75A$ GeV$/c$, $40A$ GeV$/c$ ($\sqrt{s_{\mathrm{NN}}} = 16.8, 11.9, 8.8$ GeV)
- Event and track cuts (centrality, vertex, rapidity, ...)
- Momentum dependent pair cut
- Particle Identification via d$E/$dx method to select π^-, π^+

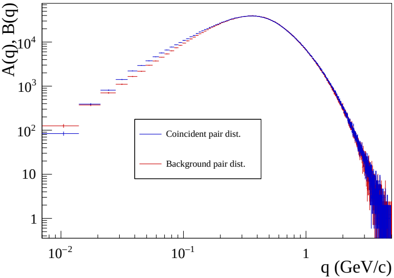
Correlation function measurement via mixed event background:

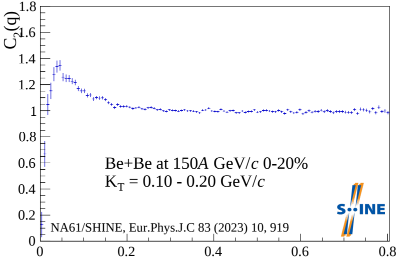
- A(q) - Pairs from same event
- B(q) - Pairs from mixed events
- C(q) - Correlation function, C(q) = A(q)/B(q)
  - Correlation function q_{LCMS} 1D variable
  - LCMS: Longitudinally CoMoving System
  - $m_{\mathrm{T}} \equiv \sqrt{m^2 + (K_{\mathrm{T}}/c)^2}$; $K = (p_1 + p_2)/2$; $K_{\mathrm{T}} =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

    Nagy, M., Purzsa, A., Csanád, M. and Kincses, Dániel, Eur.Phys.J.C 83 (2023) 11, 1015
  - Parametrization used before
- Meas.: LCMS, CC.: PCMS (pair center of mass) negligible, BUT 1D spher. symm. source LCMS not spherical PCMS

  B. Kurgyis, D. Kincses, M. Nagy, and M. 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:

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

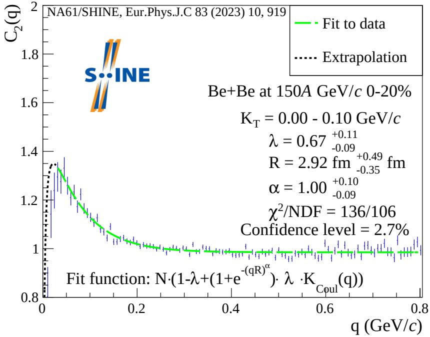
    Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996)

    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

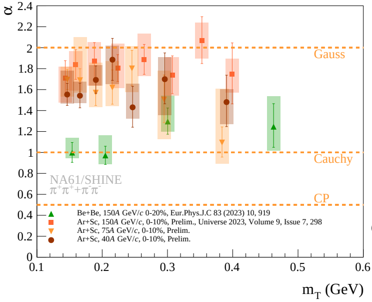
Bowler-Sinyukov

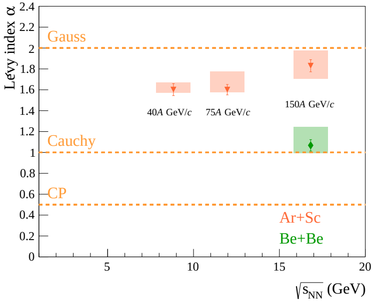
$$C(q) = 1 - \lambda + (1 + e^{-|qR|^{\alpha}})\cdot\lambda\cdot K(q)$$

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



Lévy-stability index α





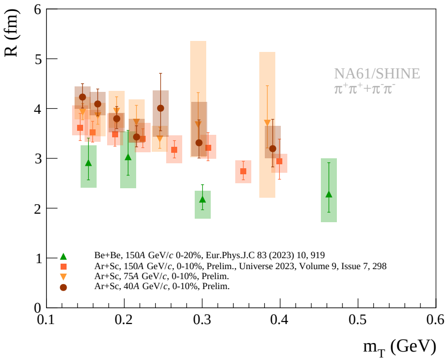
- Compatible with Lévy assumption, far from CP ($\alpha = 0.5$)
  - Be+Be: far from Gaussian ($\alpha = 2$), close to Cauchy ($\alpha = 1$)
  - Ar+Sc: far from Cauchy, Decreases from „close to Gaussian"

Constant fit to α unravels interesting trend

- NA61/SHINE: α
  ≈ 1.1 Be+Be, $\sqrt{s_{NN}} = 16.82$ GeV
  Eur.Phys.J.C 83 (2023) 10, 919
  ≈ 1.8 Ar+Sc, $\sqrt{s_{NN}} = 16.82$ GeV
  ≈ 1.6 Ar+Sc, $\sqrt{s_{NN}} = 11.97$ GeV
  ≈ 1.6 Ar+Sc, $\sqrt{s_{NN}} = 8.83$ GeV
- PHENIX: $\alpha = 1.2$ $\sqrt{s_{NN}} = 200$ GeV, Au+Au, $p_T > 0.2$ GeV Phys.Rev.C97 (2018) no.6, 064911
- CMS: $\alpha = 1.6$-1.9 $\sqrt{s_{NN}} = 5$ TeV, Pb+Pb, $p_T > 0.5$ GeV arXiv:2306.11574

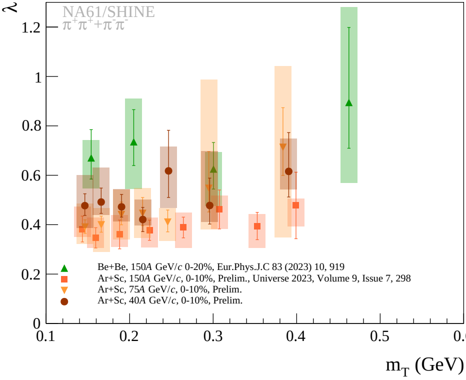
Lévy-scale parameter R vs. m_T

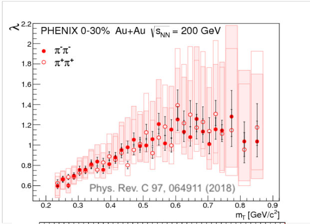
- Describes length of homogeneity
- From hydro: decrease with m_T
  $R \approx 1/\sqrt{m_T}$ (For non power-law tail)
  Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390-1403
  S. V. Akkelin and Yu. M. Sinyukov, Phys.Lett.B356 (1995) 525-530
  S. Chapman, P. Scotto and U. W. Heinz, Phys.Rev.Lett.74 (1995) 4400-4403
- Visible m_T dependence
  sign of transverse flow
  Interesting for $\alpha < 2$
  - α anticorrelates with R, λ;
    increase in $\alpha \rightarrow$ decrease in R

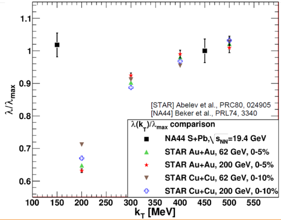


Correlation Strength λ

- Describes core-halo ratio
- Compared to RHIC results: - also see talk of **D. Kincses**
  - 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
    A. Adare for PHENIX Collaboration, Phys.Rev.C97 (2018) no.6, 064911
- λ value shows no m_T dependence







Summary

- NA61/SHINE Lévy HBT analysis
  - 150A, 75A, 40A GeV/c beam momentum
  - Be+Be collisions, 0-20% centrality
  - Ar+Sc collisions, 0-10% centrality
- Measured momentum correlations of sum of like charged π pairs
- Fit done with correlation functions from symmetric Lévy source
- Parameter m_T dependence:
  - $\alpha(m_T)$:
    - Be+Be ≈ 1
    - Ar+Sc $\approx 1.6 - 1.8$
  - $R(m_T)$: visible m_T dependence - sign of transverse flow
  - $\lambda(m_T)$: no dependence, no hole
  - Interesting trend in $\langle\alpha\rangle$ vs $\sqrt{s_{NN}} \rightarrow$ lower energies!
- $\alpha < 2 \rightarrow$ Symmetric Lévy source is a good assumption

Ongoing, Outlook:

- Energy scan with Ar+Sc; Larger system analysis

Thank you for your attention!

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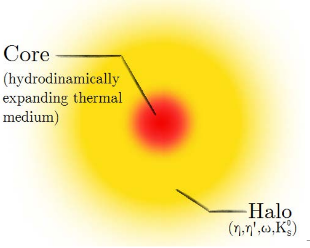
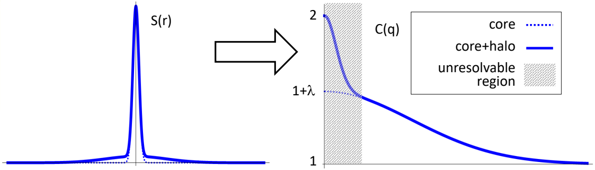
Backup

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

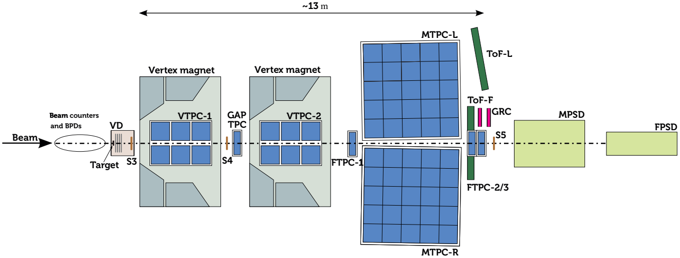
  Bolz et al, Phys.Rev.D47 (1993) 3860-3870
  Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996) 491-497





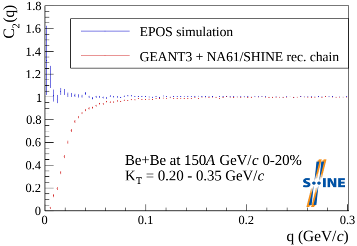
The NA61/SHINE Detector Post LS2

- 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

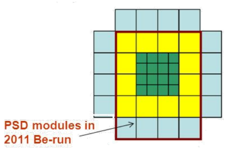


Low-q Behavior

- B-E and Coul. effect not present in EPOS sim.
  - $C_2(q) \approx$ const.
- Low-q range behavior in data:
  - Fits overestimate data
  - Theor. corr. func. cannot describe
  - Observed in Be+Be, Ar+Sc
- Strong cutoff observable
  - Several possibilites...
  - Might be experimental artefact?
- Visible deviation from generated (simulated)
  - Effects such as track merging present
- Low-q region (until reconstructed ≈ 1) can be excluded
  - Two Track Distance cut not needed



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