Bose-Einstein correlation measurement with symmetric Lévy source at NA61/SHINE

22[nd] Zimányi School Winter Workshop on Heavy Ion Physics, Budapest, Hungary

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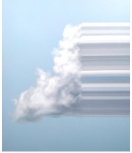
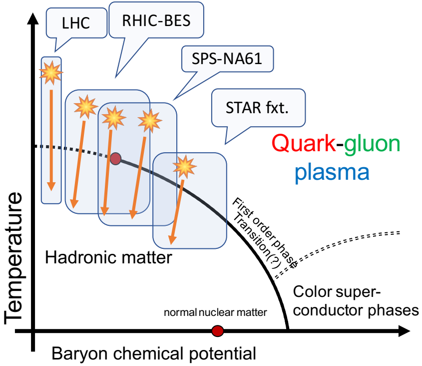


Search for the CEP: Spatial Correlations?

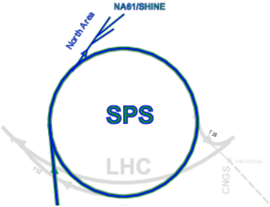


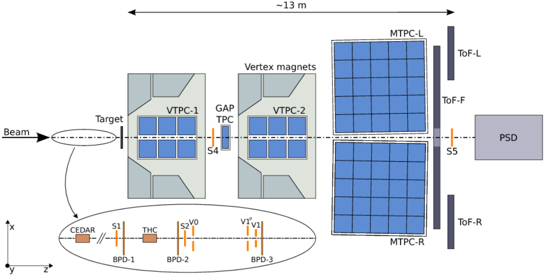
- At the critical point:fluctuations at all scales
- Power-law in spatial correlations
- Critical exponent η
- QCD universality class $\leftrightarrow$ 3D Ising:
  Halasz et al., Phys.Rev.D58 (1998) 096007
  Stephanov et al., Phys.Rev.Lett.81 (1998) 4816
  - 3D Ising: $\eta = 0.03631(3)$
    El-Showk et al., J.Stat.Phys.157 (2014): 869
  - Random field 3D Ising $\eta = 0.50(5)$
    Rieger, Phys.Rev.B52 (1995) 6659

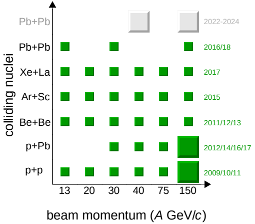
- Spatial correlation exponent near **C**ritical **E**nd **P**oint?
- Possible to measure η with Lévy HBT via measuring Lévy stability exponent
  Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042
- Scan progress: Be+Be, Ar+Sc, next Pb+Pb

The NA61/SHINE Detector

- Located at CERN SPS, North Area
- Fixed target experiment
- Large acceptance hadron spectrometer (TPC)
  - Covering the full forward hemisphere
  - Outstanding tracking, down to $p_T = 0\ GeV/c$
- Different systems scanned in beam energy

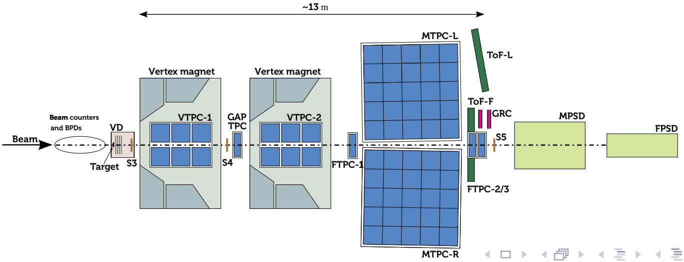






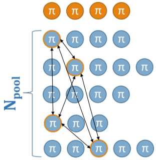
The NA61/SHINE Detector Post LS2

- 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



Correlation Function Measurement Details

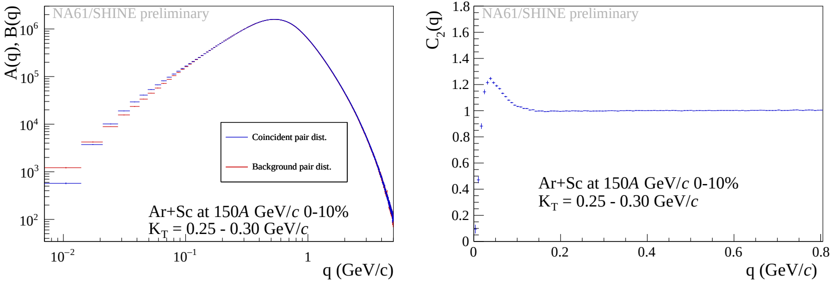
- Be+Be @ 150A GeV/c beam momentum, 0 - 20% centrality
- Ar+Sc @ 150A GeV/c beam momentum, 0 - 10% centrality
- Track cuts: Track quality, vertex, TPC
- Pair cuts: merging and splitting of tracks
- PID: dE/dx method π^-, π^+
    - A(q) - Pairs from same event
    - B(q) - Pairs from mixed events
    - C(q) - Correlation function, C(q) = A(q)/B(q)



- Correlation function q_{LCMS} 1D variable
- LCMS: Longitudinally CoMoving System
- 4 m_T bin Be+Be, $m_T \equiv \sqrt{m^2 + (K_T/c)^2}$; $K = (p_1 + p_2)/2 >> q$; $K_T = \frac{1}{2}\sqrt{K_x^2 + K_y^2}$
- 8 m_T bin Ar+Sc

Bose–Einstein Correlation Function

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



- Like charged pairs: Coulomb interaction → Coulomb correction
  - Calc: complicated numerical integral
  - Numerically possible: look-up table→ physical parameter parametrization

Csanád, M. and Lökös, S. and Nagy, M., Universe 5 (2019) 6, 133

- Meas.: LCMS, Coulomb corr.: PCMS (pair center of mass)

  → Gen. negligible, BUT
- 1D spher. symm. source LCMS not spherical PCMS

$$R \to R_{\mathrm{PCMS}} = \sqrt{\frac{1-\frac{2}{3}\beta_T^2}{1-\beta_T^2}} \cdot R_{\mathrm{LCMS}},\ \beta_T = \frac{K_T}{m_T}$$ Bálint Kurgyis: Proc. ISD (2020) 677

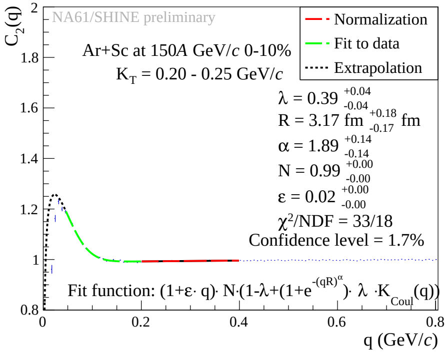
Parameters of Lévy-source

- Fit function: Bowler-Sinyukov

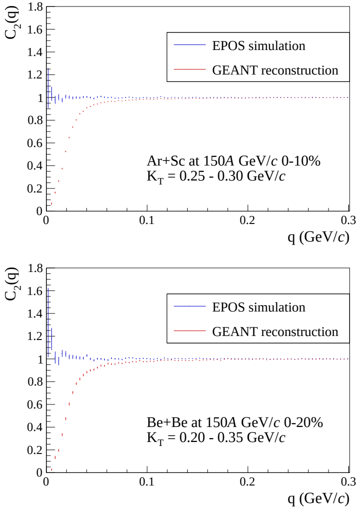
$$C(q) = 1 - \lambda + (1 + e^{-|qR|^\alpha}) \cdot \lambda \cdot K(q)$$

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

- R Lévy-scale parameter:
  - Length of homogeneity
  - From simple hydro calc.: $R_{HBT} = R/\sqrt{1 + (m_T/T_0) \cdot u_T^2}$
- λ correlation strength:
  - Core-halo ratio: $\lambda = \left(\frac{N_{\text{core}}}{N_{\text{core}} + N_{\text{halo}}}\right)^2$
  - Core: primordial pions
  - Halo: long lived resonances
- α Lévy-stability index
  - $\alpha = 2$: Gauss shape, simple hydro
  - $\alpha < 2$: Gen. cent. limit theorem
  - $\alpha = 0.5$: Value at CEP



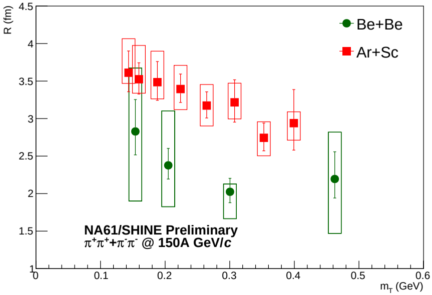
- B-E and Coul. effect not present in EPOS sim.
  - $C_2(q) \approx$ const.
- Low-q range behavior in data:
  - Fits overestimate data
  - Theor. corr. func. cannot describe
  - Observed in Be+Be, Ar+Sc
- Strong cutoff observable
  - Several possibilites...
  - Might be experimental artefact?
- Visible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



Lévy-scale parameter R vs. m_T

- Describes length of homogeneity
- From hydro: $R \sim 1/\sqrt{m_T}$ (For Gaussian source)
  Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390-1403
  S. V. Akkelin and Yu. M. Sinyukov, Phys.Lett.B 356 (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
- Ar+Sc similar trend to Be+Be arXiv:1904.08169 [nucl-ex]
  - expected R $\approx$ 1.6x of Be+Be
  - α anticorrelates with **R**, $\lambda \rightarrow$ decrease in R

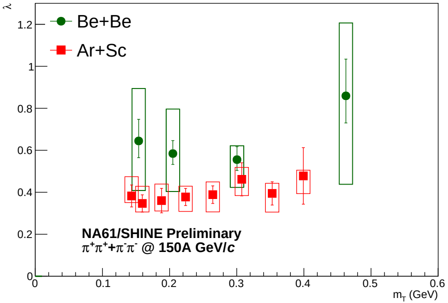


Correlation Strength λ vs. m_T

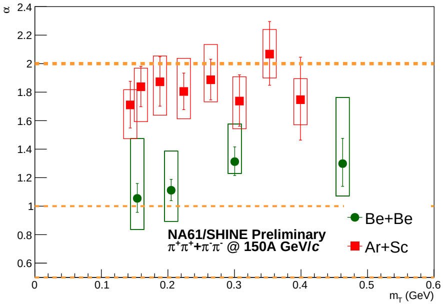
- Describes core-halo ratio

  Core-Halo model: Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996)
  Bolz et al, Phys.Rev. D47 (1993) 3860-3870
- Comparing with SPS and RHIC results:
  - Low m_T values show no decrease (sim. to my previous and 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 weak m_T dependence



- Lévy-stability index α: shape of spatial correlation
- Ar+Sc: $\alpha \approx 1.5$ and 2.0 - higher values compared to Be+Be ($\approx 1 - 1.5$)
- Compatible with Lévy assumption
  - Ar+Sc: close to Gaussian ($\alpha = 2$), far from Cauchy ($\alpha = 1$)
  - Be+Be: far from Gaussian, close to Cauchy
- Far from CEP ($\alpha = 0.5$)



Summary

- NA61/SHINE Lévy HBT analysis
  B.Pórfy for the NA61/SHINE Collaboration, arXiv:1904.08169 [nucl-ex] (Be+Be results)
  - 150A GeV/c beam momentum
  - Be+Be and Ar+Sc collisions
  - 0-20% centrality; 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:
  - $\alpha(m_T)$: Ar+Sc: $\approx 1.5 - 2.0$; Be+Be: $\approx 1.0 - 1.5$
  - $R(m_T)$: visible m_T dependence - sign of transverse flow
  - $\lambda(m_T)$: slight dependence, no hole
- Symmetric Lévy source is a good assumption
- Difference in parameter values between Be+Be and Ar+Sc
- MC check for low q behaviour: indication of possible residual detector effect

Outlook:

- Paper on Be+Be analysis in final stages
- Energy scan with Ar+Sc

Thank you for your attention!

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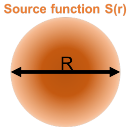
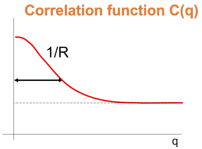
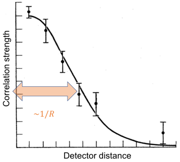
Bose-Einstein Correlations in Heavy-Ion Physics

A way to measure spatial correlations:
Bose-Einstein relative momentum correlations

- R. Hanbury Brown, R.Q.Twiss observed Sirius with two optical telescopes
  R. Hanbury Brown and R. Q. Twiss 1956 Nature 178
  - Intensity correlations as a function of detector distance
  - Measuring angular size of point-like sources
- Goldhaber, Goldhaber, Lee and Pais: applicable in high energy physics: (for identical pions)
  Goldhaber, Goldhaber, Lee and Pais 1959 Phys.Rev.Lett. 3 181
  - 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 $\rightarrow$ Generalized CLT

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

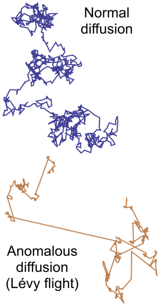
- From generalization of Gaussian, power-law tail: $\sim r^{-(d-2+\alpha)}$
  - $\alpha = 1$ Cauchy, $\alpha = 2$ Gaussian
- The shape of the correlation function with Lévy source: $C(q) = 1 + \lambda \cdot e^{-(qR)^\alpha}$
  - $\alpha = 1$: Exponential, $\alpha = 2$: Gaussian Csörgő, Hegyi, Zajc, Eur.Phys.J.C36(2004)67-78
- Reasons for Lévy source:
  - QCD jets; Anomalous diffusion; Critical phenomena, ...

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

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

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

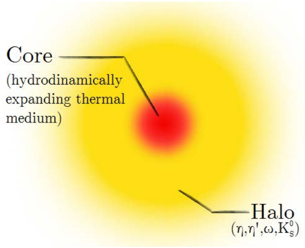
    Metzler, Klafter, Physics Reports 339 (2000) 1-77
- Lévy distributions lead to power-law spatial correlations
- Spatial correlation at the critical point: $\sim r^{-(d-2+\eta)}$
- Lévy-exponent α identical to correlation exponent η

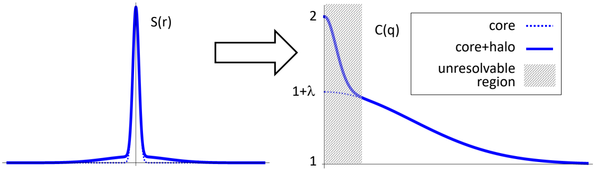


Core-Halo Model

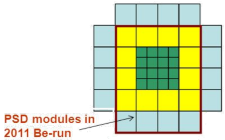
- Hydrodinamically increasing core $\rightarrow$ emits pions during hadronization
- Results in two component source: $S(x) = S_M(x) + S_G(x)$
- Core $\cong$ 10 fm size, halo$(\omega, \eta \ldots) >$ 50 fm size
- Halo not seen due to detector resolution
- Real q$\rightarrow$ 0, at $C(q = 0) = 2$
- Results 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

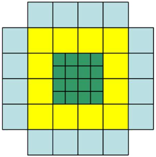


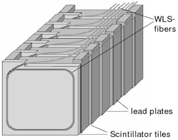


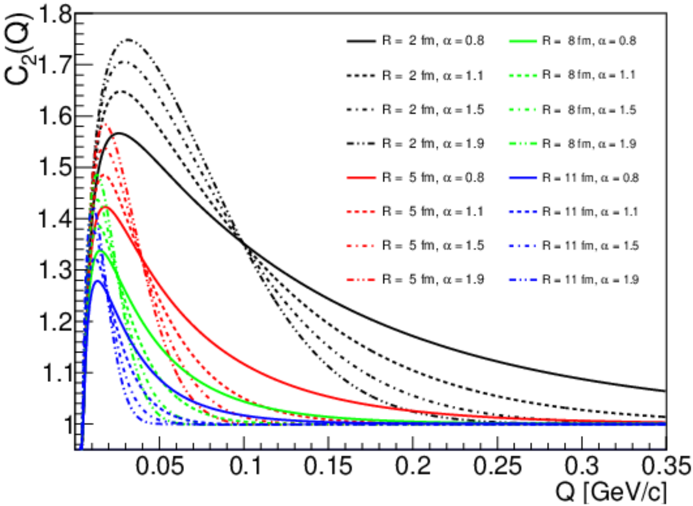
Projectile Spectator Detector



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







$C_2(Q)$
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.05
0.1
0.15
0.2
0.25
0.3
0.35
Q [GeV/c]
R = 2 fm, α = 0.8
R = 2 fm, α = 1.1
R = 2 fm, α = 1.5
R = 2 fm, α = 1.9
R = 5 fm, α = 0.8
R = 5 fm, α = 1.1
R = 5 fm, α = 1.5
R = 5 fm, α = 1.9
R = 8 fm, α = 0.8
R = 8 fm, α = 1.1
R = 8 fm, α = 1.5
R = 8 fm, α = 1.9
R = 11 fm, α = 0.8
R = 11 fm, α = 1.1
R = 11 fm, α = 1.5
R = 11 fm, α = 1.9

Centrality Selection

- $0 - 20\%$ corresponds to $E_F < 730 GeV$ in Be+Be
- $0 - 10\%$ corresponds to $E_F < 2276 GeV$ in Ar+Sc