

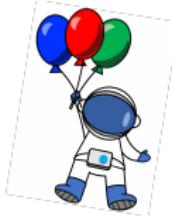
Correlation analyses at NA61/SHINE

30th Conference on Ultra-Relativistic Nucleus-Nucleus Collisions
Houston, Texas, USA

Barnabás Pórty for the NA61/SHINE Collaboration

Wigner RCP, Hungary

5 September, 2023



1 Experiment

2 Femtoscopy analysis details

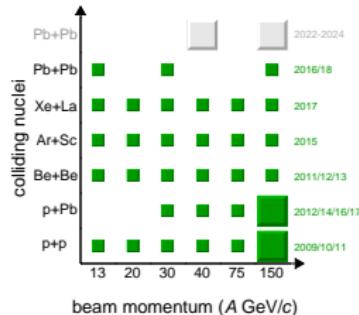
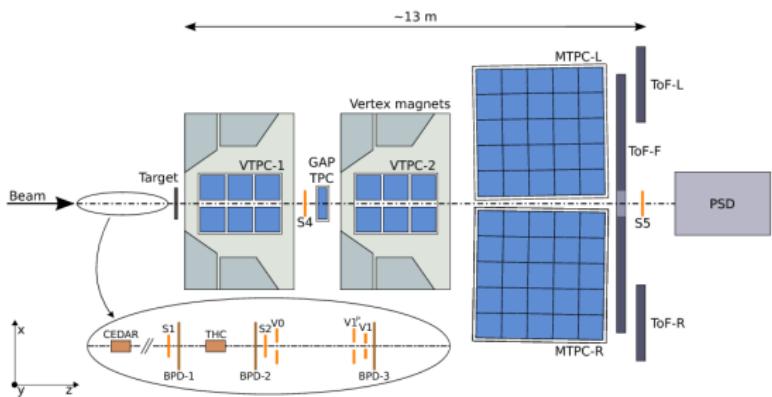
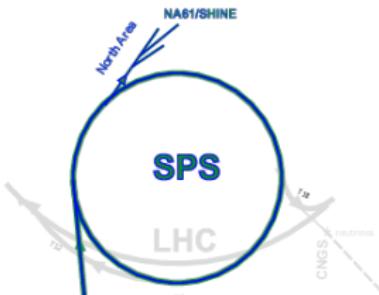
3 Lévy HBT results

4 Intermittency analysis

5 Conclusion

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 $p_T = 0 \text{ GeV}/c$
- Different systems scanned in beam energy
- Strong interactions programme:
 - ▶ Search for Critical Point: **femtoscopy, intermittency, fluctuations, ...**



1 Experiment

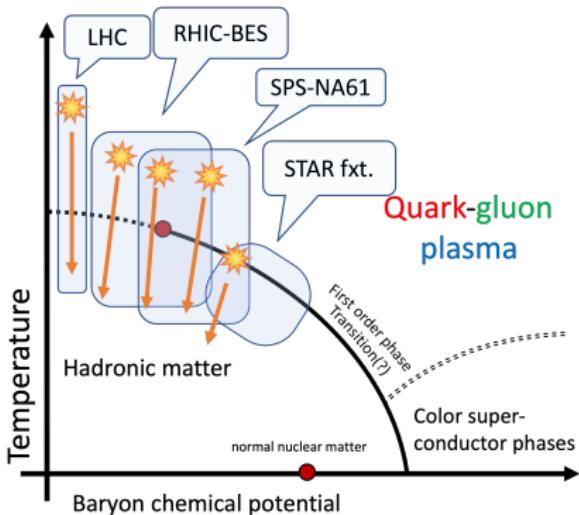
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Critical Point Search Using Femtoscopy



- At 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 **Critical Point?**
- 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

Be+Be: NA61/SHINE, arXiv:2302.04593 (accepted by EPJC), and this talk

Bose-Einstein Correlations in Heavy-Ion Physics

A tool to measure spatial correlations:

Bose-Einstein relative momentum correlations

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

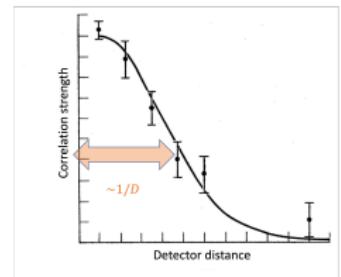
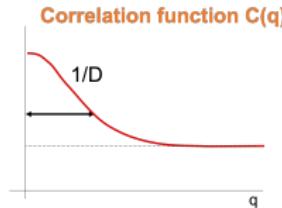
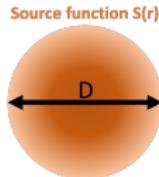
R. Hanbury Brown and R. Q. Twiss Nature 178 (1956)

- ▶ 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 Phys.Rev.Lett.3 (1959) 181

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



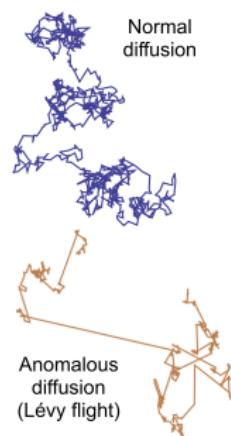
- $S(r)$ frequently assumed to be Gaussian \rightarrow Gaussian $C(q)$

Lévy Distribution in Heavy-Ion Physics

- Measurements not fully supporting Gaussian → Generalized CLT

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

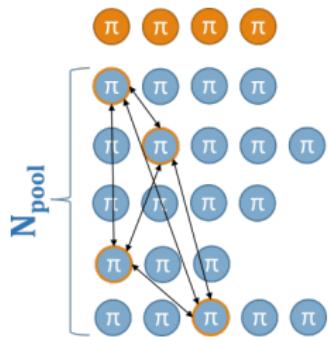
- From generalization of Gaussian, power-law tail: $\sim r^{-(d-2+\alpha)}$
 - $\alpha = 1$ Cauchy, $\alpha = 2$ Gaussian
- The shape of the correlation function with Lévy source: $C(q) = 1 + \lambda \cdot e^{-|qR|^\alpha}$
 - $\alpha = 1$: Exponential, $\alpha = 2$: Gaussian Csörgő, Hegyi, Zajc, Eur.Phys.J.C36 (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
Kincses, Stefaniak, Csanád, Entropy 24 3 (2022) 308
Kórodi, Kincses, Csanád, arXiv:2212.02980
- 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



Correlation Function Measurement Details

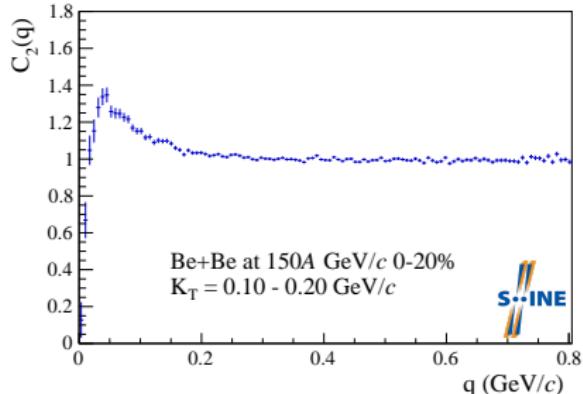
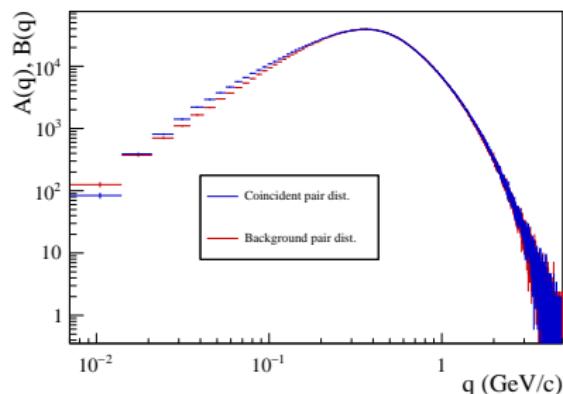
- Be+Be at 150A GeV/c beam momentum, 0 - 20% centrality
- Ar+Sc at 150A GeV/c beam momentum, 0 - 10% centrality
- Track and pair cuts
- Particle Identification via dE/dx method π^- , π^+

- 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
- $m_T \equiv \sqrt{m^2 + (K_T/c)^2}$; $K = (p_1 + p_2)/2$; $K_T = \frac{1}{2} \sqrt{K_x^2 + K_y^2}$
- 4 m_T bins Be+Be, 8 m_T bins Ar+Sc



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: complicated numerical integral
 - ▶ Numerically possible: look-up table → physical parameter parametrization
Nagy, M., Purzsa, A., Csanad, M. and Kincses, Daniel, arXiv:2308.10745
- Meas.: LCMS, CC.: PCMS (pair center of mass) negligible, BUT
- 1D spher. symm. source LCMS not spherical PCMS

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

B. Kurygis, D. Kincses, M. Nagy, and M. Csanad, Universe 2023, 9(7), 328

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

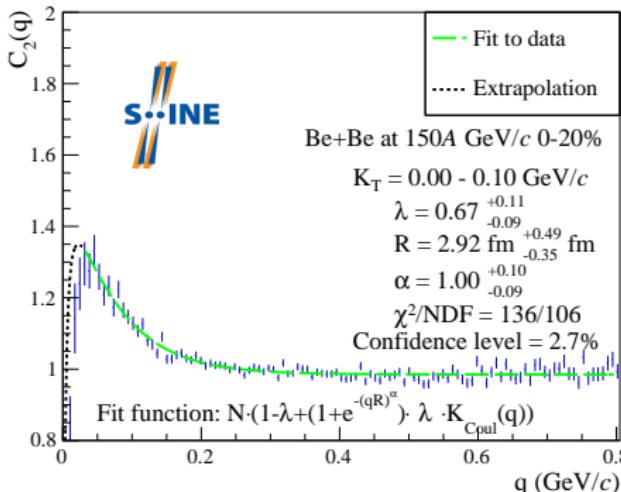
- Halo: pions from long-lived resonances

- α Lévy-stability index

- $\alpha = 2$: Gauss shape, simple hydro

- $\alpha < 2$: Generalized central limit theorem

- $\alpha = 0.5$: Conjectured value at CP



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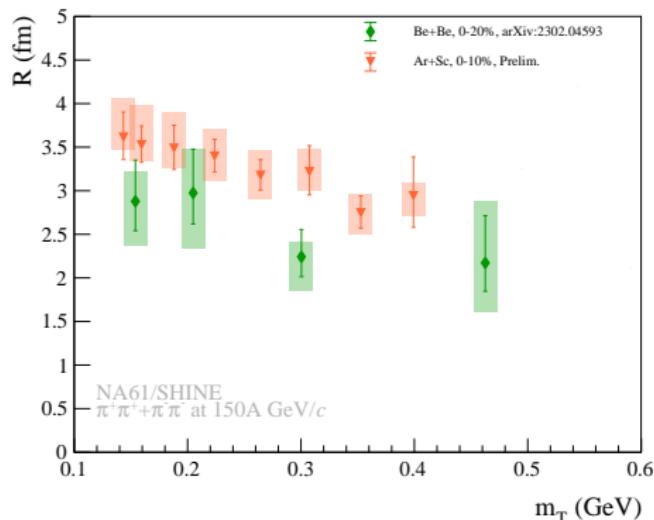
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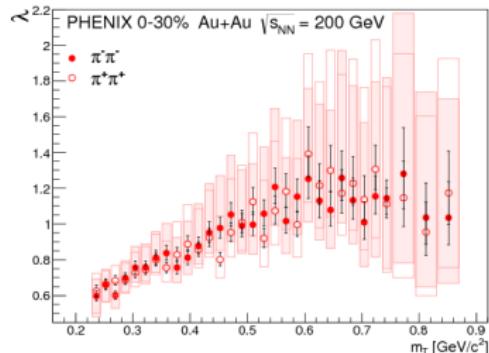
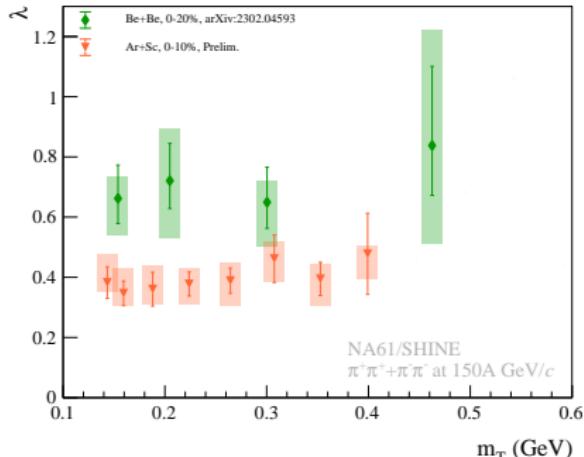
Lévy-scale parameter R vs. m_T

- 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.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
 - ▶ α anticorrelates with R , λ ; increase in $\alpha \rightarrow$ decrease in R



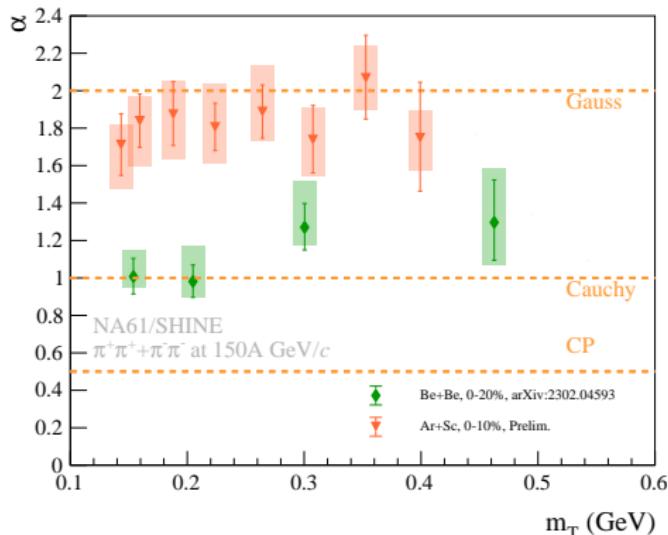
Correlation Strength λ vs. m_T

- Describes core-halo ratio 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 no m_T dependence



Lévy-stability index α vs. m_T

- Lévy-stability index α : shape of spatial correlation
- 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, close to Gaussian
- NA61/SHINE: $\alpha \approx 0.9 - 1.5$, $\sqrt{s_{NN}} = 16.82$ GeV, Be+Be, arXiv:2302.04593
- PHENIX: $\alpha = 1.2$ $\sqrt{s_{NN}} = 200$ GeV, Au+Au, Phys.Rev.C97 (2018) no.6, 064911
- CMS: $\alpha = 1.6-1.9$ $\sqrt{s_{NN}} = 5$ TeV, Pb+Pb arXiv:2306.11574



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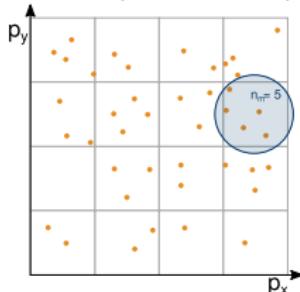
Critical Point Search Using Intermittency

NA61/SHINE, arXiv:2305.07557 (accepted by EPJC), and this talk

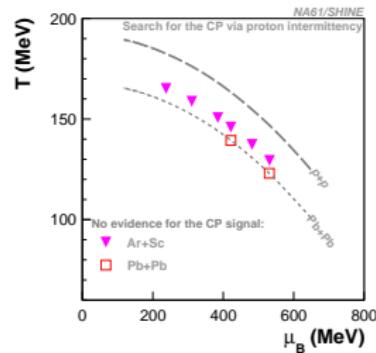
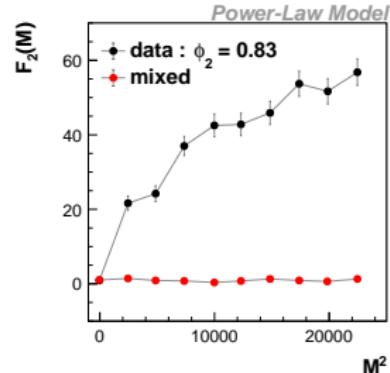
- Ar+Sc $\sqrt{s_{\text{NN}}} \approx 5.1 - 16.8$ GeV, proton intermittency
- Pb+Pb $\sqrt{s_{\text{NN}}} \approx 5.1, 7.6$ GeV, proton intermittency
 h^- intermittency

Scaled Factorial Moment:

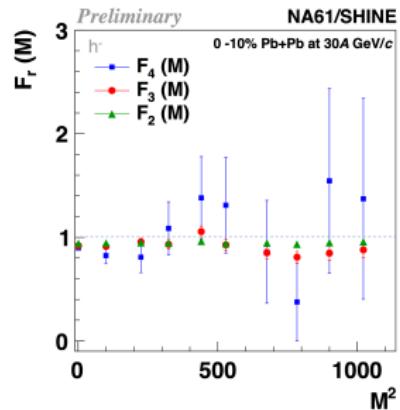
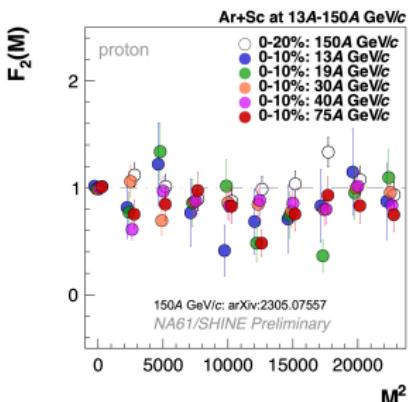
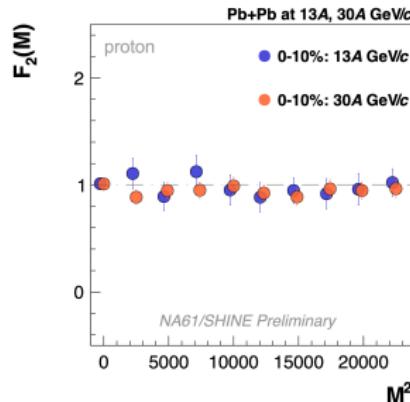
$$F_r(M) = \frac{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m(n_m-1)\dots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M^2} \sum_{m=1}^{M^2} n_m \right\rangle^r}$$



- Preserves power-law momentum correlation's power: $F_r(M) \sim (M^2)^{\phi_r}$
- System freeze-out near Critical Point:
 $F_2(M)$ power-law dependence, $\phi_2 = 5/6$
N. Antoniu et al., Phys. Rev. Lett. 97 (2006) 032002



Intermittency Results



Using cumulative transverse-momentum variable

A. Bialas and M. Gazdzicki Phys.Lett.B252 (1990)
483–486

and statistically independent points

NA61/SHINE, arXiv:2305.07557 (accepted by EPJC)

- No structure indicating a power-law

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Summary

- NA61/SHINE Lévy HBT analysis
 - ▶ 150A 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: $\approx 0.9 - 1.5$; Ar+Sc: $\approx 1.5 - 2.0 \longrightarrow$ far from CP
 - ▶ $R(m_T)$: visible m_T dependence - sign of transverse flow
 - ▶ $\lambda(m_T)$: no dependence, no hole
- Symmetric Lévy source is a good assumption

Ongoing, Outlook:

- Energy scan with Ar+Sc; Pb+Pb analysis

Intermittency analysis:

- No indication of Critical Point

Thank you for your attention!

Supported by the ÚNKP-22-3 New National Excellence Program of the Ministry for Culture and Innovation
from the source of the National Research, Development and Innovation Fund.

Backup

Intermittency Summary

- Intermittency analysis measuring Scaled Factorial Moments in
 - ▶ Ar+Sc $\sqrt{s_{NN}} \approx 5.1 - 16.8$ GeV, proton intermittency
 - ▶ Pb+Pb $\sqrt{s_{NN}} \approx 5.1, 7.6$ GeV, proton intermittency, negatively charged hadrons (h^-) intermittency
- Analysis was based on statistically independent data points
- Cumulative variables
 - ▶ remove dependence on the shape of the single-particle distribution
 - ▶ preserve critical behaviour
- No signal of a power-law increase was observed
 - ▶ in Second Scale Factorial Moment Ar+Sc, Pb+Pb proton intermittency,
 - ▶ in Second, Third and Fourth Scale Factorial Moment Pb+Pb negatively charged hadrons (h^-) intermittency,
- on the cumulative momentum bin size

Intermittency Methodology

In NA61/SHINE, intermittency analysis is performed at mid-rapidity, and particle fluctuations are studied in the transverse momentum plane.

$$F_r(M) = \frac{\left\langle \frac{1}{M^D} \sum_{m=1}^{M^D} n_m(n_m-1)\dots(n_m-r+1) \right\rangle}{\left\langle \frac{1}{M^D} \sum_{m=1}^{M^D} n_m \right\rangle^r}$$

- ▶ M^D : number of equally sized cells in D-dimensional space
 - ▶ n_m : number of particles in m^{th} bin
 - ▶ $\langle \dots \rangle$: averaging over events
- At the second order phase transition, the system is a simple fractal, and the factorial moment exhibits a power law dependence: $F_r(M) = F_r(\Delta) \cdot (M^D)^{\phi_q}$
 - ϕ_r are predicted to follow the pattern: $D \cdot \phi_r = (r - 1) \cdot d_r$,
where d_r : anomalous fractal dimension

Wosiek, Acta Phys.Polon.B19, 863 (1988)

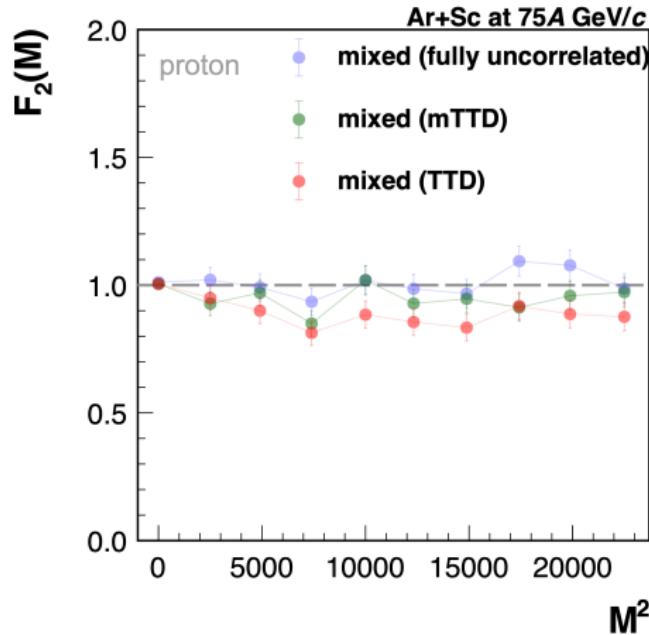
Bialas, Hwa, Phys.Lett.B253 (1991) 436

Bialas, Peschanski, NPB 273(1986) 703

Intermittency - Effect of mTTD cut

Possible explanation:

anti-correlation by momentum based Two-Track Distance cut
necessary to account for close-in-space tracks

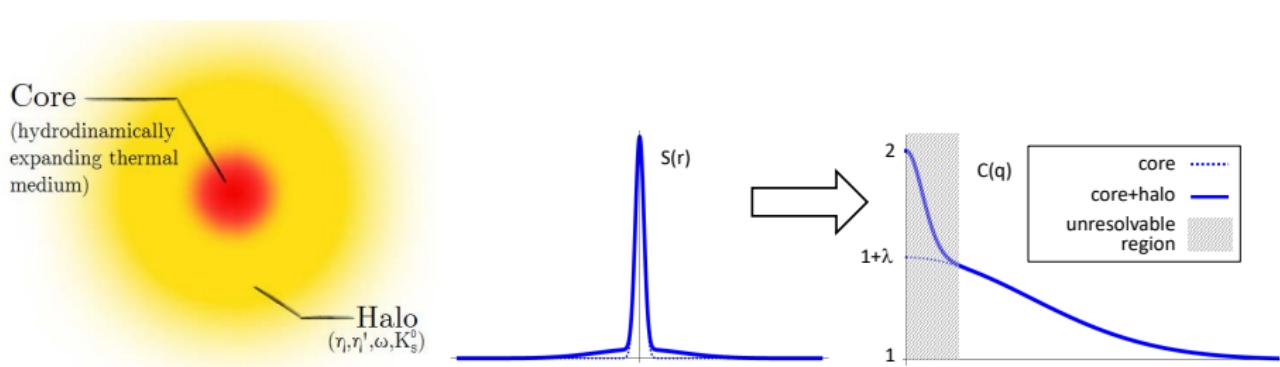


Core-Halo Model

- Hydrodynamically increasing core \rightarrow pion emission
- Results in two component source: $S(x) = S_M(x) + S_G(x)$
- Core \cong 10 fm size, halo($\omega, \eta \dots$) $>$ 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 $\lambda = \left(\frac{N_m}{N_g + N_m} \right)^2$

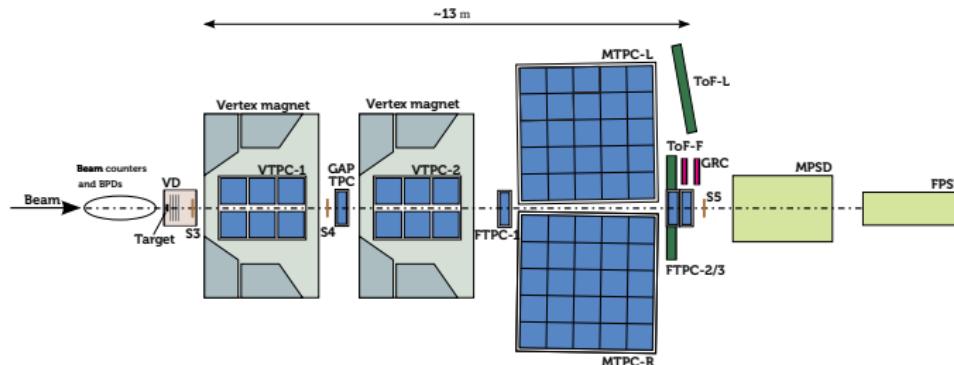
Bolz et al, Phys.Rev.D47 (1993) 3860-3870

Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996) 491-497



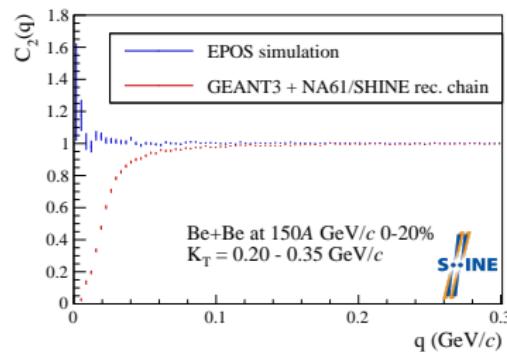
The NA61/SHINE Detector Post LS2

- 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.
 - ▶ $C_2(q) \approx \text{const.}$
- Low-q range behavior in data:
 - ▶ Fits overestimate data
 - ▶ Theor. corr. func. cannot describe
 - ▶ Observed in Be+Be, Ar+Sc
- Strong cutoff observable
 - ▶ Several possibilities...
 - ▶ 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

