Femtoscopy with Lévy sources at NA61/SHINE

XVI Workshop on Particle Correlations and Femtoscopy
IV Resonance Workshop
Catania, Italy

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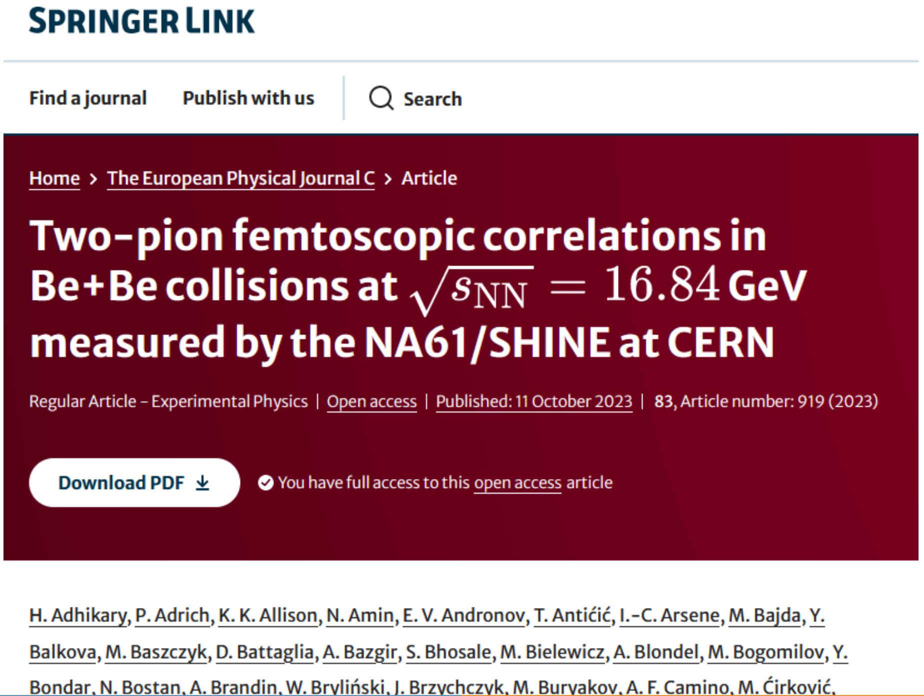
9 November, 2023



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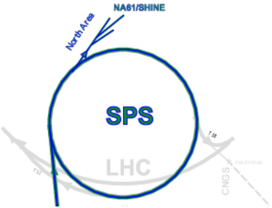
Two-pion femtoscopic correlations in Be+Be collisions at $\sqrt{s_{\mathrm{NN}}} = 16.84$ GeV measured by the NA61/SHINE at CERN

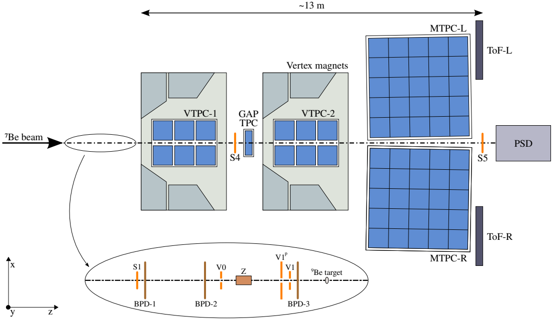
Regular Article – Experimental Physics | Open access | Published: 11 October 2023 | **83**, Article number: 919 (2023)

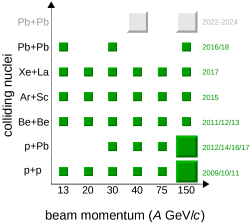
H. Adhikary, P. Adrich, K. K. Allison, N. Amin, E. V. Andronov, T. Antićić, I.-C. Arsene, M. Bajda, Y. Balkova, M. Baszczyk, D. Battaglia, A. Bazgir, S. Bhosale, M. Bielewicz, A. Blondel, M. Bogomilov, Y. Bondar, N. Bostan, A. Brandin, W. Bryliński, J. Brzychczyk, M. Buryakov, A. F. Camino, M. Ćirković,

The NA61/SHINE Detector

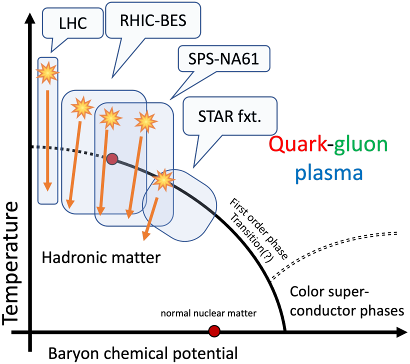
- Located at CERN SPS, North Area
- Fixed target experiment; upgrade during LS2
- Large acceptance hadron spectrometer (TPC)
  - Covering the full forward hemisphere
  - Outstanding tracking, down to $p_\mathrm{T} = 0\ \mathrm{GeV}/c$
- Different systems scanned in beam energy
- Strong interactions programme: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







Critical Point Search Using Femtoscopy



- At Critical Point - fluctuations at all scales
- Power-law in spatial correlations
- Critical exponent η
- QCD universality class ↔ 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 **P**oint?
- Lévy sources applicable in HBT

  Csörgő, Hegyi, Zajc, Eur.Phys.J.C36 (2004) 67, nucl-th/0310042
- System size scan progress at 150A GeV/c: Be+Be, Ar+Sc

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

  next Xe+La or Pb+Pb
- Energy scan ongoing in Ar+Sc

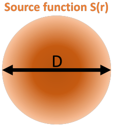
Bose-Einstein Correlations in Heavy-Ion Physics

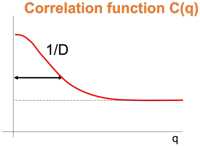
A tool to measure spatial correlations:
Bose-Einstein relative momentum correlations

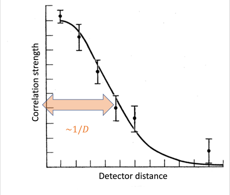
- R. Hanbury Brown, R.Q.Twiss observed Sirius with two optical telescopes

  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 $S(x)$
    $C(q) \cong 1 + |\widetilde{S}(q)|^2$ 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 → Generalized CLT

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
- 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, Acta Phys.Polon.B36 (2005) 329-337

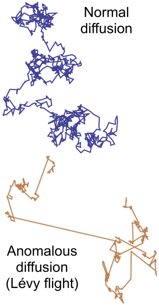
    Csanád, Csörgő, Nagy, Braz.J.Phys.37 (2007) 1002

    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, 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

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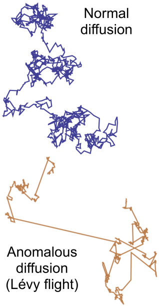

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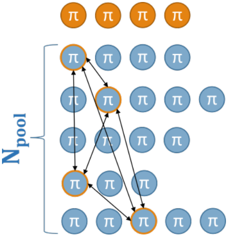
Correlation Function Measurement Details

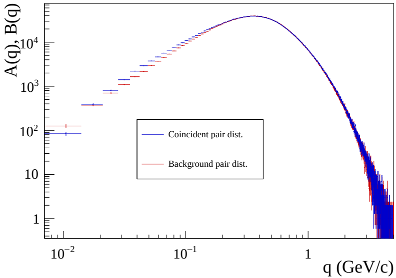
- Be+Be at $150A$ GeV$/c$ beam momentum, 0 - 20% centrality
- Ar+Sc at $150A$ GeV$/c$ beam momentum, 0 - 10% centrality
- Track and pair cuts
- Particle Identification via d$E/$dx method π^-, π^+
  - A(q) - Pairs from same event
  - B(q) - Pairs from mixed events
  - C(q) - Correlation function, C(q) = A(q)/B(q)

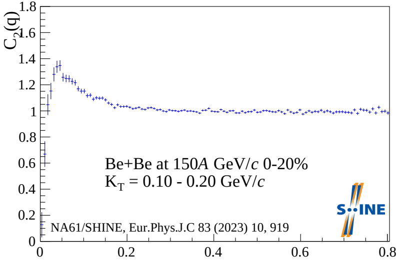


- Correlation function q_{LCMS} 1D variable
- LCMS: Longitudinally CoMoving System
- $m_\mathrm{T} \equiv \sqrt{m^2 + (K_\mathrm{T}/c)^2}$; $K = (p_1 + p_2)/2$; $K_\mathrm{T} = \frac{1}{2}\sqrt{K_x^2 + K_y^2}$
- 4 m_T bins Be+Be, 8 m_T bins Ar+Sc

Bose–Einstein Correlation Function

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





Be+Be at 150A GeV/c 0-20%
K_T = 0.10 - 0.20 GeV/c

NA61/SHINE, Eur.Phys.J.C 83 (2023) 10, 919

- Like charged pairs: Coulomb interaction → Coulomb correction (CC)
  - Calc: complicated numerical integral
  - Numerically possible: look-up table→ physical parameter parametrization
    Nagy, M., Purzsa, A., Csanád, M. and Kincses, Dániel, arXiv:2308.10745
- Meas.: LCMS, CC.: PCMS (pair center of mass) negligible, BUT
- 1D spher. symm. source LCMS not spherical PCMS

$$R \to R_{\mathrm{PCMS}} = \sqrt{\frac{1-\frac{2}{3}\beta_{\mathsf{T}}^2}{1-\beta_{\mathsf{T}}^2}} \cdot R_{\mathrm{LCMS}},\ q_{\mathrm{inv}} \approx \sqrt{1-\beta^{2/3}} \cdot q_{\mathrm{LCMS}},\ \beta_{\mathsf{T}} = \frac{K_{\mathsf{T}}}{m_{\mathsf{T}}}$$

B. Kurgyis, D. Kincses, M. Nagy, and M. Csanád, Universe 2023, 9(7), 328

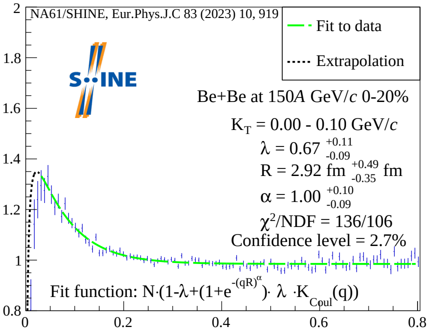
Parameters of Lévy-source

- 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.: $R_{\mathrm{HBT}} = R/\sqrt{1 + (m_{\mathrm{T}}/T_0) \cdot u_{\mathrm{T}}^2}$
- λ correlation strength:
  - Core-halo ratio: $\lambda = \left(\frac{N_{\mathrm{core}}}{N_{\mathrm{core}} + N_{\mathrm{halo}}}\right)^2$
  - 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

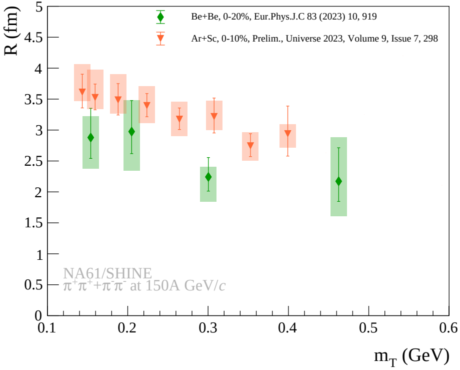


1. Experiment
2. Femtoscopy analysis details
3. **Lévy HBT results**
4. Intermittency analysis
5. Conclusion

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

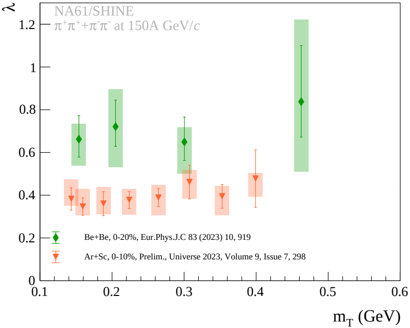
  S. Chapman, P. Scotto and U. W. Heinz, Phys.Rev.Lett.74 (1995) 4400-4403
- Visible m_T dependence - sign of transverse flow
  - α anticorrelates with R, λ; increase in $\alpha \rightarrow$ decrease in R

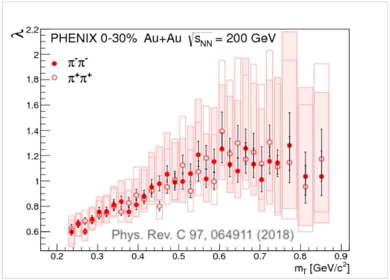


Correlation Strength λ vs. m_T

- 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: - also see talk of **D. Kincses**
  - 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

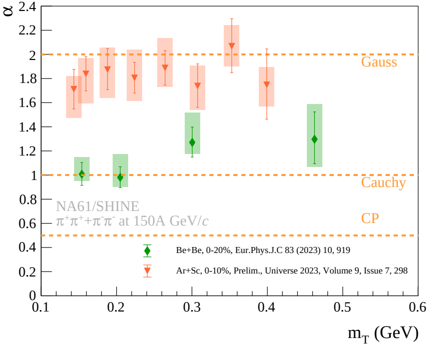
    A. Adare for PHENIX Collaboration, Phys.Rev.C97 (2018) no.6, 064911
- λ value shows no m_T dependence





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, Eur.Phys.J.C 83 (2023) 10, 919
- 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

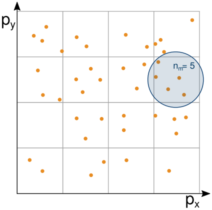


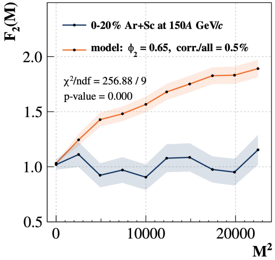
Cricial Point Search Using Intermittency

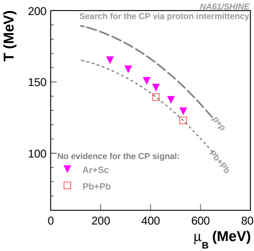
NA61/SHINE, arXiv:2305.07557 (accepted by EPJC), and this talk

- 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
  h^- intermittency
  Scaled Factorial Moment:

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

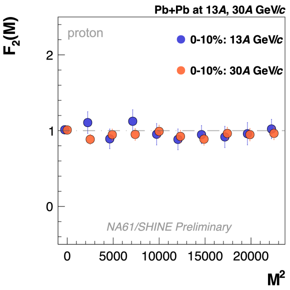


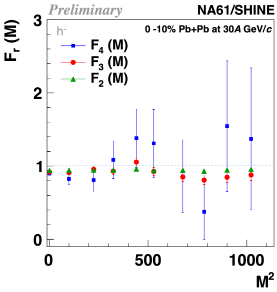


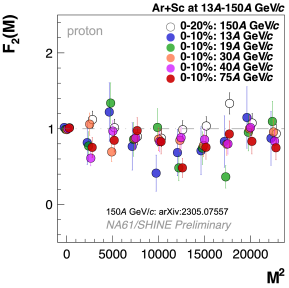


- Preserves power-law momentum correlation's power: $F_r(M) \sim \left(M^2\right)^{\phi_r}$
- System freeze-out near Critical Point: $F_2(M)$ power-law dependence, $\phi_2 = 5/6$
  N. Antoniu et al., Phys.Rev.Lett.97 (2006) 032002

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:
  - $\alpha(m_\mathrm{T})$: Be+Be: $\approx 0.9 - 1.5$; Ar+Sc: $\approx 1.5 - 2.0 \longrightarrow$ far from CP
  - $R(m_\mathrm{T})$: visible m_T dependence - sign of transverse flow
  - $\lambda(m_\mathrm{T})$: no dependence, no hole
- Symmetric Lévy source is a good assumption

Ongoing, Outlook:

- Energy scan with Ar+Sc; Larger system analysis

Intermittency analysis:

- No indication of Critical Point

Thank you for your attention!

Backup

Intermittency Summary

- Intermittency analysis measuring Scaled Factorial Moments in
  - Ar+Sc $\sqrt{s_{\mathrm{NN}}} \approx 5.1 - 16.8$ GeV, proton intermittency
  - Pb+Pb $\sqrt{s_{\mathrm{NN}}} \approx 5.1, 7.6$ 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.

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

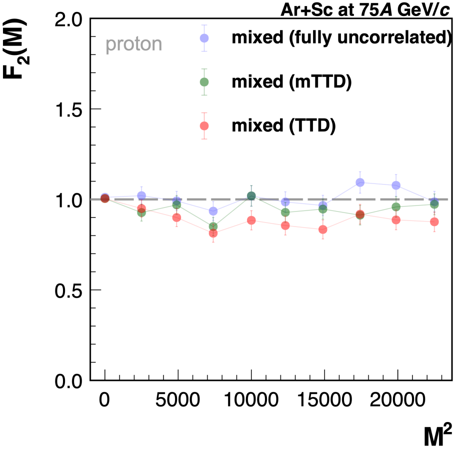
- M^D: number of equally sized cells in D-dimensional space
- n_m: number of particles in mth bin
- $\langle ... \rangle$: averaging over events

- 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

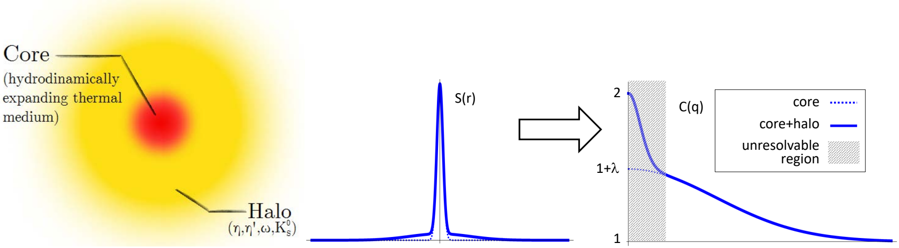
Possible explanation:
anti-correlation by momentum based Two-Track Distance cut necessary to account for close-in-space tracks



Core-Halo Model

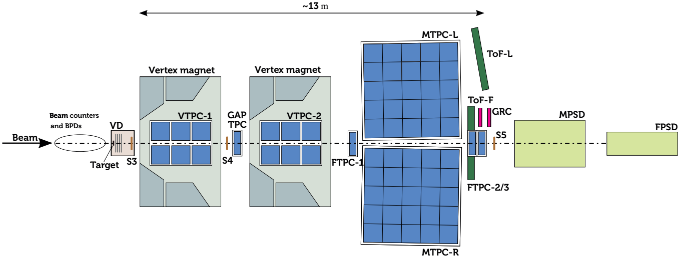
- Hydrodinamically increasing core → pion emission
- Results in two component source: $S(x) = S_M(x) + S_G(x)$
- Core $\cong$ 10 fm size, halo$(\omega, \eta \ldots) >$ 50 fm size
- Halo not seen due to detector resolution
- Real q$\rightarrow$ 0, at $C(q = 0) = 2$
- Results show $C(q \rightarrow 0) =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



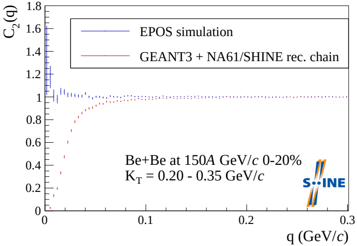
The NA61/SHINE Detector Post LS2

- 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

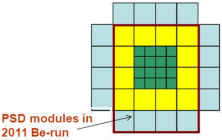


Low-q Behavior

- 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