NA61/SHINE results on Lévy analysis of HBT correlation functions

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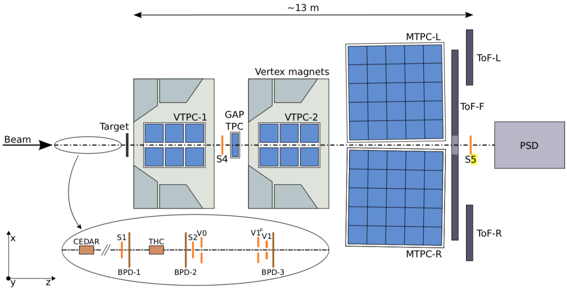
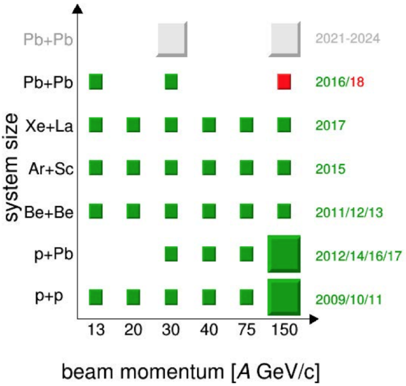
Outline

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 $p_T = 0\ GeV/c$
- Various nuclei at multiple energies

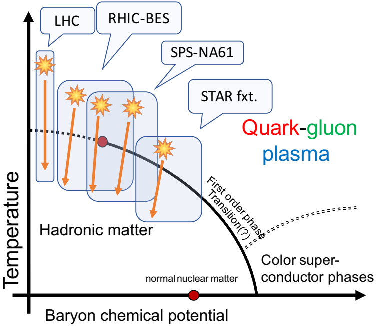


NA61/SHINE Data



- Taken data(green)
- Approved for 2018(red)
- Proposed extension(grey)
- Bigger squares → better statistics w/ new detector
- Various collision systems (p+p,p+Pb,Be+Be,Ar+Sc,Xe+La,Pb+Pb)
- Wide beam momentum range
- Allows phase diagram investigation

Search for the CEP: Spatial Correlations?



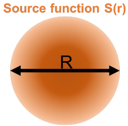
- At the critical point: fluctuations at all scales
- Power-law in spatial correlations
- Critical exponent η
- QCD universality class $\leftrightarrow$ 3D Ising:
  Halasz et al., Phys.Rev.D58 (1998) 096007
  Stephanov et al., Phys.Rev.Lett.81 (1998) 4816
  - 3D Ising: $\eta = 0.03631$
    El-Showk et al., J.Stat.Phys.157 (4-5): 869
  - Random field 3D Ising $\eta = 0.50 \pm 0.05$
    Rieger, Phys.Rev.B52 (1995) 6659

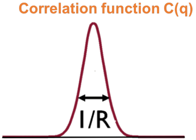
- Particle distributions helps with the behavior of quark matter
- Search for the crit. point with SPS beam momentum/species scan
- Spatial correlation exponent near **C**ritical **E**nd **P**oint?

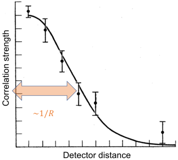
Bose-Einstein Correlations in Heavy-Ion Physics

A way to measure spatial correlations: Bose-Einstein mom. correlations
Short recap:

- R. Hanbury Brown, R.Q.Twiss observed Sirius with radiotelescopes
  R. Hanbury Brown and R. Q. Twiss 1956 Nature 178
    - Intensity correlations as a function of detector distance
    - Measuring size of point-like sources
- Goldhaber et al: applicable in high energy physics:
  G. Goldhaber et al 1959 Phys.Rev.Lett. 3 181
    - Momentum correlation $C(q)$ is related to the source $S(x)$
      $C(q) \cong 1 + |\widetilde{S}(q)|^2$ where $\widetilde{S}(q)$ Fourrier transform of $S(q)$







- High energy physics: momentum correlation of pions
- We can map the source on a femtometer scale

Lévy Distribution in Heavy-Ion Physics

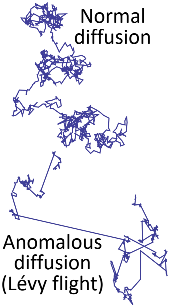
- Usually the assumed shape of the source is Gaussian
- Expanding medium, increasing mean free path: anomalous diffusion

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

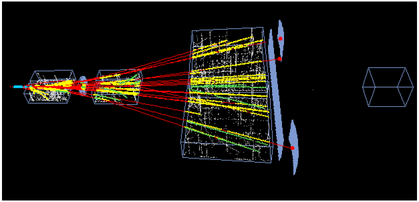
  Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002
- **Lévy-stable distribution:** $\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$
  - Generalization of Gaussian
  - $\alpha = 1$ Cauchy, $\alpha = 2$ Gaussian, $\alpha < 2$ Anomalous diffusion

- The shape of the correlation function with Lévy source: $C(q) = 1 + \lambda \cdot e^{-(qR)^\alpha}$
  - $\alpha = 2$: Gaussian
  - $\alpha = 1$: Exponential
- Lévy distributions lead to power-law correlation functions
- Lévy-exponent α identical to correlation exponent η

  Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042

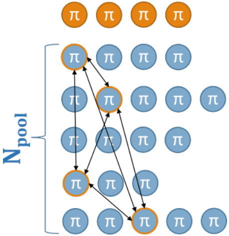


HBT Measurement setup with NA61/SHINE



- Be+Be collision sample from NA61/SHINE

- Event mixing method:
  - A(q) - Actual event relative momentum distribution
    - Pairs from same event
  - B(q) - Background event relative mom. distribution
    - Pairs from mixed event
- Correlation function:
  - C(q) = A(q)/B(q)

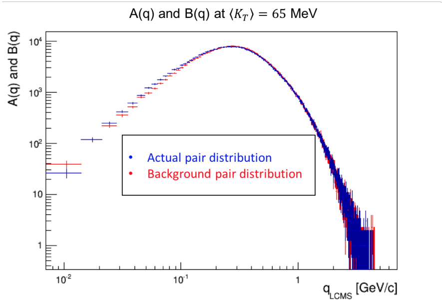


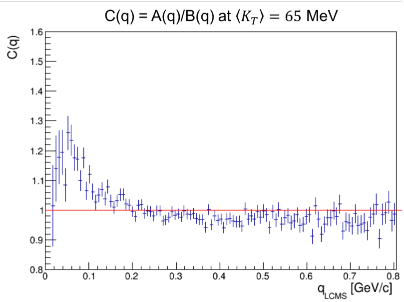
Details of this HBT Analysis

- Used dataset:
  - Be+Be @ 150 AGeV/c with $20 - 47\%$ cent.
    Centrality selection based on forward energy measured by PSD, peripheral event selection prone to trigger bias
  - Neg. charged particles $\rightarrow$ not only π^- $\rightarrow$ particle contamination
    - Observation: $\pi^-/K^- < 2\%$ $\rightarrow$ small K^- contamination
      NA61/SHINE, Eur.Phys.J. C77 (2017) 10, 671 [arXiv:1705.02467]
    - Pos. charged particles would result higher contamination in Be+Be
  - Track selection:
    - Track quality and vertex cut applied
  - Pair selection:
    - Random member of pairs with distance < 0.8 cm was dropped
- 1D correlation function as function of q_{LCMS} in 4 m_T bins
  - Bins: (0-100, 100-200, 200-400, 400-600) MeV/c
  - $\langle K_T \rangle$: (65, 150, 284, 478) MeV/c
- Systematic uncertainties:
  - Q bin width choice
  - Various values for Q_{min}, Q_{max}
  - Various track cut settings

Example Bose-Einstein Correlation Function

- Example plot, showing B-E effect at very low q values

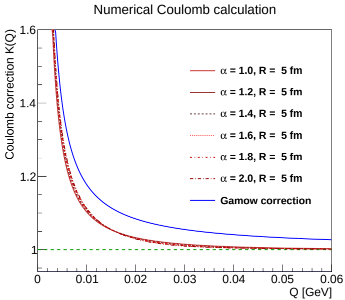


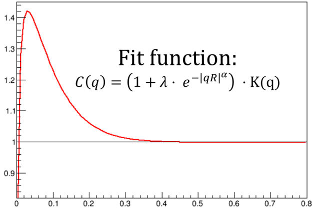


- Coulomb-hole appearing at small q

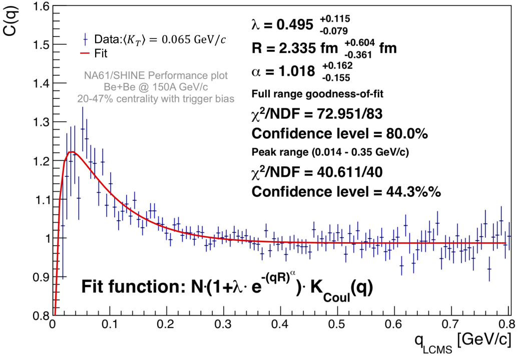
Handling the Coulomb Interaction

- Same charge pairs: Coulomb repulsion
  - Standard handling method: Coulomb corr.
  - Calculation: complicated numerical integral
  - Does not depend strongly on α, see plot $\rightarrow$
  - Small effect in Be+Be
- Approximate formula (for $\alpha = 1$) from CMS: Sirunyan et al. (CMS Collab.), arXiv:1712.07198 (PRC 2018)
  - $K_{Coulomb}(q) = \text{Gamow}(q) \cdot \left(1 + \frac{\pi\eta q \frac{R}{\hbar c}}{1.26 + q\frac{R}{\hbar c}}\right)$
    where $\text{Gamow}(q) = \frac{2\pi\eta(q)}{e^{2\pi\eta(q)} - 1}$ and $\eta(q) = \alpha_{QED} \cdot \frac{\pi}{q}$
  - Fit function: $C(q) = (1 + \lambda e^{-|qR|^\alpha}) \cdot K(q)$



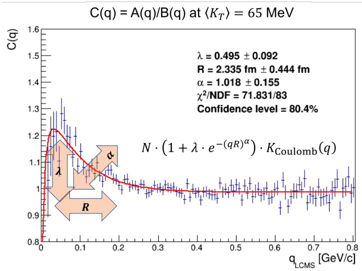


Example Lévy HBT Fit



- Log-likelihood fit (conventional χ^2)
- Assuming no corr among q points
- Goodness-of-fit analyzed in full range and peak range as well
- Fit parameters:
  - λ Correlation strength
    related to core/halo ratio
  - R Levy scale parameter
    similar to a HBT size
  - α Lévy index of stability
    possibly related to the CEP

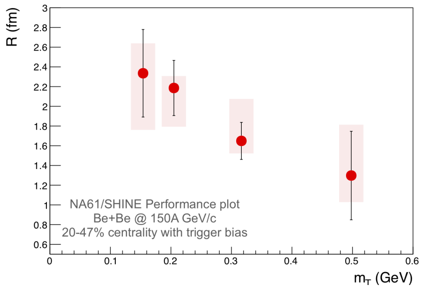
Parameters of the Lévy Correlation Function

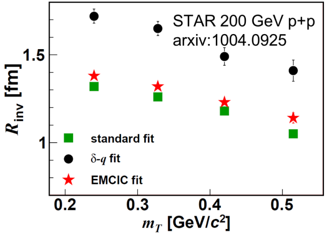


- The shape of the correlation function with Lévy source: $C(q) = 1 + \lambda \cdot e^{-(qR)^\alpha}$
- Lévy scale R:
  - Determines correlation length
  - Got this from simple hydro picture: $R_{HBT} = \frac{R}{\sqrt{1+\frac{m_T}{T_0} u_T^2}}$
  - Decreasing with m_T caused by transverse flow
- Correlation strength λ:
  - Describes core-halo ratio: $\lambda(m_T) = \left(\frac{N_{core}}{N_{core}+N_{halo}}\right)^2$
  - Core: primordial pions; Halo: resonance decay products
- Lévy exponent α:
  - Stability exponent determines source shape
  - $\alpha = 2$: Gaussian, predicted from simple hydro
  - $\alpha < 2$: Anomalous diffusion, generalized limit theorem
  - $\alpha = 0.5$: Conjectured value at the critical point (CEP)

Correlation Radius R vs m_T

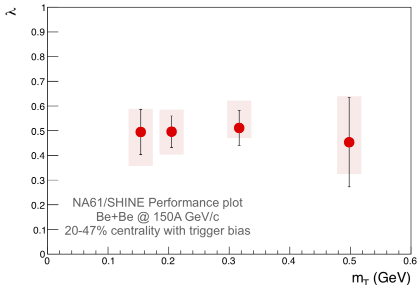
- Spatial scale R: describes homogeneity length
- What to look for: decrease with m_T (radial flow)?
- Compare to: RHIC p+p, LHC p+p and p+Pb results
- Below results are performance plots and not to be interpreted, they were measured in an event class prone to trigger bias

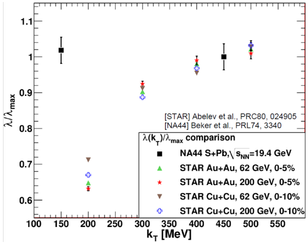


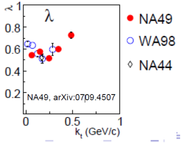


Correlation Strength λ vs m_T

- Correlation strength λ: describes core-halo ratio
- What to look for: "hole" at low m_T?
- Compare to: SPS and RHIC results
- Below results are performance plots and not to be interpreted, they were measured in an event class prone to trigger bias

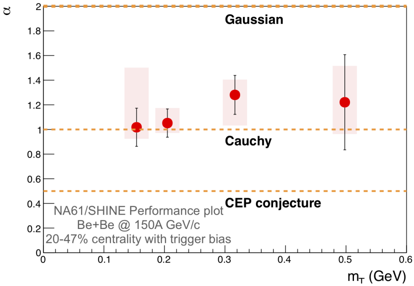


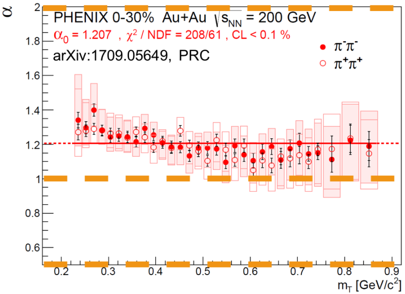




Lévy Stability Index α vs m_T

- Lévy index α: spatial source shape, $\alpha < 2$ for anomalous diffusion
- What to look for: distance from Gauss ($\alpha = 2$), Cauchy ($\alpha = 1$) or CEP conjecture ($\alpha = 0.5$)
- Compare to: RHIC Au+Au results at $\sqrt{s_{NN}} = 200$ GeV
- Below results are performance plots and not to be interpreted, they were measured in an event class prone to trigger bias





Systematic Uncertainties

Investigated sources of uncertainties

- Track settings
- Pair cuts
- Q bin width choice
- Fit range (Q_{min}, Q_{max}) choice (for each K_T)

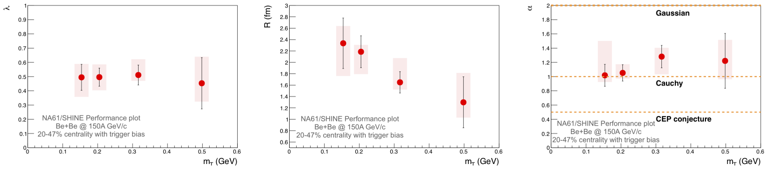
Typical effects and results:

- # of points for reconstruction in all TPC
  - Does not depend on m_T
  - For every param. always the largest syst. err.
- Fit limits are strongly dependent on K_T
- Ratio of clusters has low impact
- Q bin width has very low impact
- Track proximity to the main vertex
  - Has slight effect in $m_{T,2}, m_{T,3}$ for α and R
  - For λ, any visible effect is in $m_{T,0}$

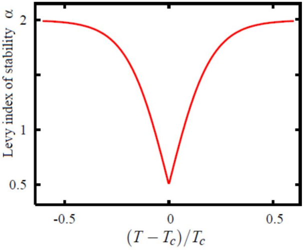
Summary

- First NA61 HBT analysis, in Be+Be collisions at 150 AGeV/c
- Lévy distribution valid? $\rightarrow$ anomalous diffusion
- Correlation function Lévy parameters
  - R weakly decreasing with m_T $\rightarrow$ hydro scaling?
  - λ nearly constant
    - sim. to earlier SPS results
    - different from RHIC results (low-m_T "hole")
  - α nearly constant, far from 2, CEP, near 1, similar to RHIC results

Thank you for your attention!



Lévy Exponent $\leftrightarrow$ Critical Exponent



- Power-law in spatial correlations: $\sim r^{-(1+\alpha)}$
- Spatial corr. at the crit. point: $\sim r^{-(d-2+\eta)}$

$$\alpha \equiv \eta$$

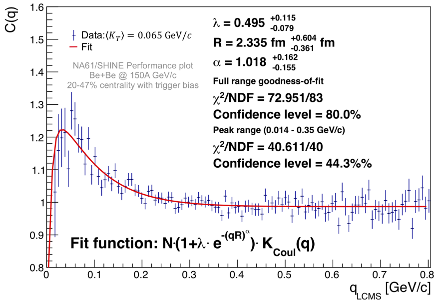
Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042

- QCD universality class $\leftrightarrow$ (random field) 3D Ising:
  Halasz et al., Phys.Rev.D58 (1998) 096007 Stephanov et al., Phys.Rev.Lett.81 (1998) 4816
  - 3D Ising: $\eta = 0.03631$
    El-Showk et al., J.Stat.Phys.157 (4-5): 869
  - Random field 3D Ising $\eta = 0.50 \pm 0.05$
    Rieger, Phys.Rev.B52 (1995) 6659

- Lévy exponent α change near **C**ritical **E**nd **P**oint?

χ^2,NDF,Conf.lvl values

K_T	χ^2	NDF	Conf. level
0_{peak}	40.611	40	44.3%
0_{full}	71.831	83	80.4%
1_{peak}	38.165	41	59.7%
1_{full}	81.989	85	54.2%
2_{peak}	30.446	38	80.3%
2_{full}	59.786	74	88.4%
3_{peak}	41.953	36	22.8%
3_{full}	93.563	107	82.0%



Core-Halo Model

- Hydrodinamically expanding core, emits pions at the freeze-out
- This results in a two component source: $S(x) = S_c(x) + S_h(x)$
- Core $\cong$ 10 fm size, halo$(\omega, \eta \dots) >$ 50 fm size
- Halo unresolvable experimentally
- True q$\to$ 0, limit $C(q = 0) = 2$
- Results show $C(q \to 0) = 1 + \lambda$, where $\lambda = \left(\frac{N_{core}}{N_{halo}+N_{core}}\right)^2$

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