NA61/SHINE prospects for Bose-Einstein correlation measurements

Day of Femtoscopy 2018, Gyöngyös

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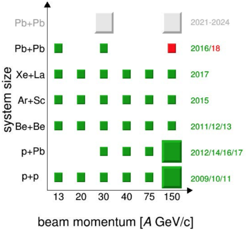
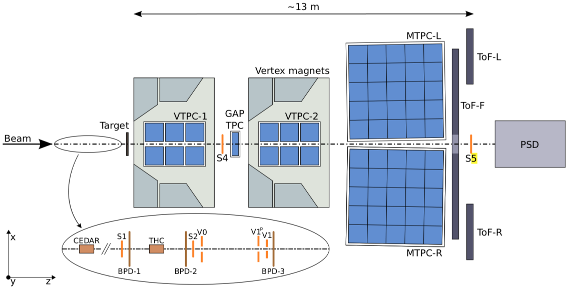
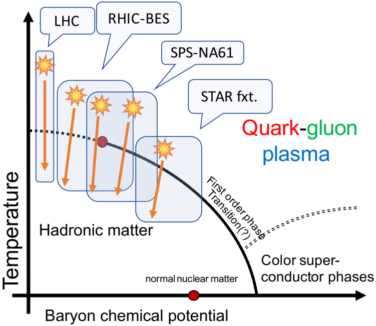
The NA61/SHINE Detector

- 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





Search for the CEP: Spatial Correlations?



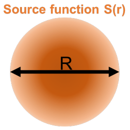
- At the critical point: fluctuations at all scales
- Power-law in spatial correlations
- Critical exponent η
- QCD universality class $\leftrightarrow$ 3D Ising:
  Halasz et al., Phys.Rev.D58 (1998) 096007
  Stephanov et al., Phys.Rev.Lett.81 (1998) 4816
  - 3D Ising: $\eta = 0.03631$
    El-Showk et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

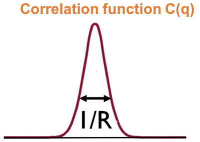
- Search for the crit. point with SPS beam momentum/species scan
- Spatial correlation exponent near **C**ritical **E**nd **P**oint?
- Possible to measure η with Lévy HBT

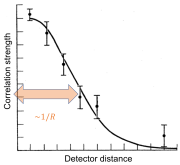
Bose-Einstein Correlations in Heavy-Ion Physics

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

- 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 $S(q)$







- S(r) usually assumed to be Gaussian, leads to Gaussian C(q)

Lévy Distribution in Heavy-Ion Physics

- Expanding medium, increasing mean free path: anomalous diffusion

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

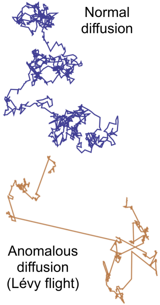
  Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002

- **Lévy-stable distribution:** $\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3} \int d^3 q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$
  - From generalization of Gaussian, power-law tail: $\sim r^{-(1+\alpha)}$
  - $\alpha = 1$ 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
- Spatial correlation at the critical point: $\sim r^{-(d-2+\eta)}$
- Lévy-exponent α identical to correlation exponent η

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

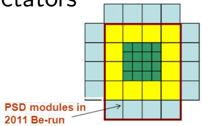


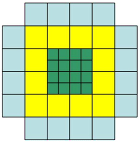
Details of an HBT Analysis

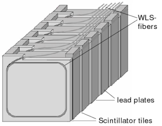
- Be+Be @ 150A GeV/c beam momentum
- Centrailty selection based on forward energy measured by PSD
- Track selection:
  - Track quality and vertex cut applied
  - Negative hadrons selected, these are mostly pions ($\pi/K < 2\%$ in EPJC77(2017)10 671)
  - Particle identification possible via dE/dx method
- Pair selection:
  - Random member of pairs with distance < 0.8 cm was dropped
  - Reduces track splitting (already small effect in Be+Be)

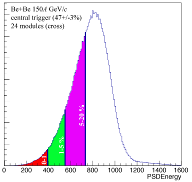
Projectile Spectator Detector

- Centrality measured using the Projectile Spectator Detector (PSD)
- Located on beam axis, measures forward energy E_F from spectators
- Intervals in E_F allows to select centrality classes
- $0 - 20\%$ corresponds to $E_F < 730 GeV$
- In our analysis, we mistakenly selected $E_F > 730 GeV$
- Our results are around $20 - 47\%$, but prone to trigger bias, as trigger efficiency is less constant for peripheral events
- Presented results are performance results and not to be interpreted



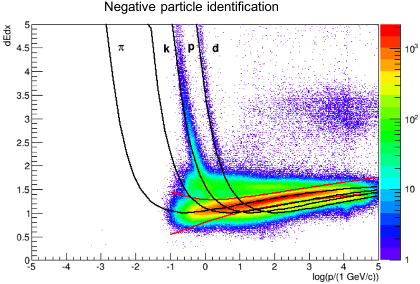


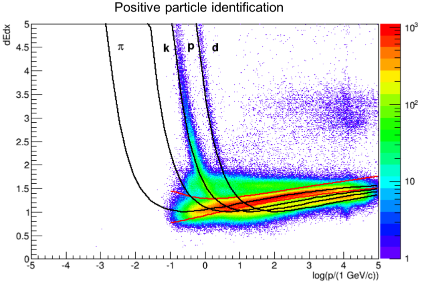




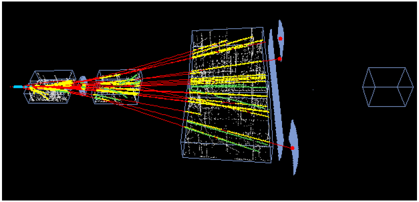
Particle Identification Method: dE/dx

- Particle identification from the energy loss in the TPC gas
- dE/dx PID works well in relativistic rise region
- PID capability for dE/dx is 4%
- Identified particle HBT is also possible
- dE/dx versus $log(p)$ measured, 80 slices fitted with Gaussians



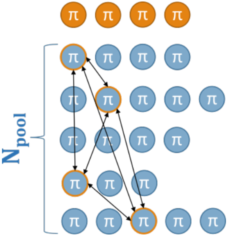


HBT Measurement setup with NA61/SHINE



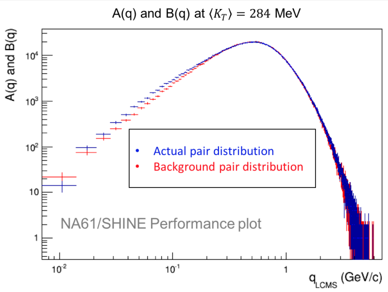
- Be+Be collision sample from NA61/SHINE

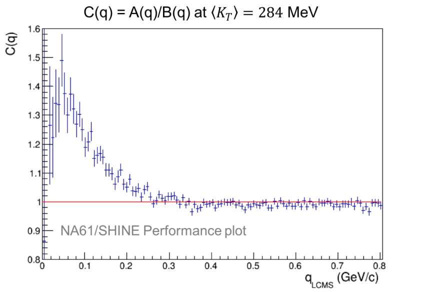
- Event mixing method:
  - A(q) - Actual event relative momentum distribution
    - Pairs from same event
  - B(q) - Background event relative mom. distribution
    - Pairs from mixed event
- Correlation function:
  - C(q) = A(q)/B(q)
- C(q) corr. function as function of $|q|_{LCMS}$ in 4 m_T bins
  - Bins: (0-100, 100-200, 200-400, 400-600) MeV/c
  - $\langle K_T \rangle$: (65, 150, 284, 478) MeV/c



Example Bose-Einstein Correlation Function

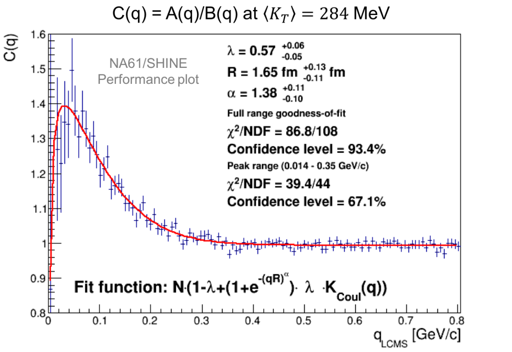
- Recall event mixing
  - $A(q)$ - q distribution of pairs from an actual event
  - $B(q)$ - q distribution of pairs from a mixed event
  - $C(q) = A(q)/B(q)$
- Example plots, showing B-E effect at low q values:





- Note Coulomb-hole appearing at small q

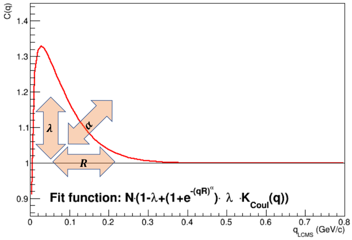
Example Lévy HBT Fit



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

Parameters of the Lévy Correlation Function

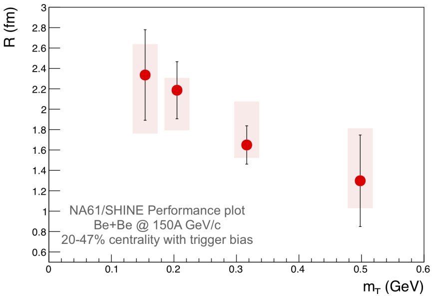
- The correlation function with Lévy source: $C^0(q) = 1 + e^{-(qR)^\alpha}$
- Coulomb effect handled via Bowler-Sinyukov $1 - \lambda + \lambda C^0(q)K(q)$
- Lévy scale R:
  - Determines length of homogeneity
  - Simple hydro picture suggests: $R_{HBT} = R/\sqrt{1 + (m_T/T_0) \cdot u_T^2}$

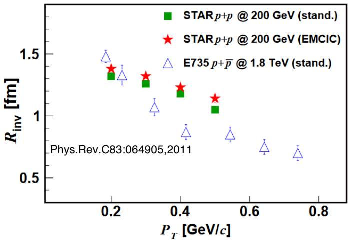


- Correlation strength λ:
  - Describes core-halo ratio: $\lambda(m_T) = \left(\frac{N_{core}}{N_{core}+N_{halo}}\right)^2$
  - Core: primordial pions
  - Halo: resonance decay products and general background
- Lévy exponent α:
  - Stability exponent determines source shape
  - $\alpha = 2$: Gaussian, predicted from simple hydro
  - $\alpha < 2$: Anomalous diffusion, generalized limit theorem
  - $\alpha = 0.5$: Conjectured value at the critical point (CEP)

Correlation Radius Example: R vs m_T

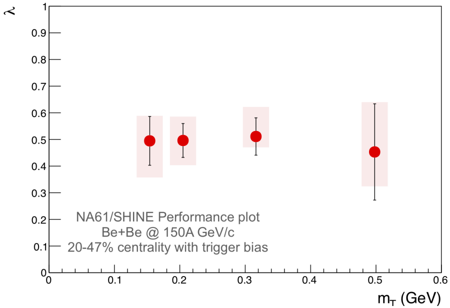
- Spatial scale R: describes homogeneity length
- What to look for: decrease with m_T (radial flow)?
- Compare to: RHIC p+p, LHC p+p and p+Pb results
- Below results are performance plots and not to be interpreted, they were measured in an event class prone to trigger bias

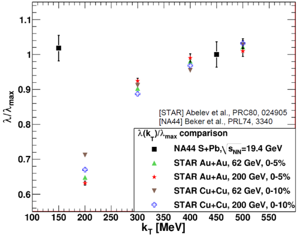


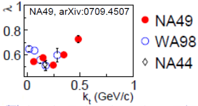


Correlation Strength Example: λ vs m_T

- 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

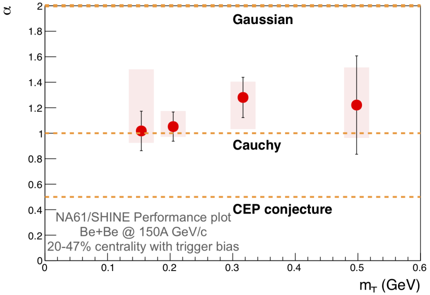


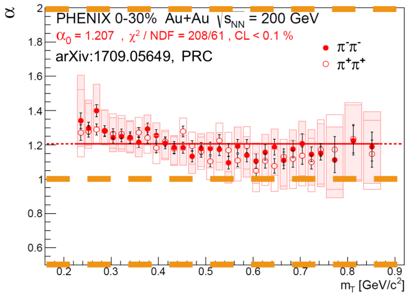




Lévy Stability Index Example: α vs m_T

- 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





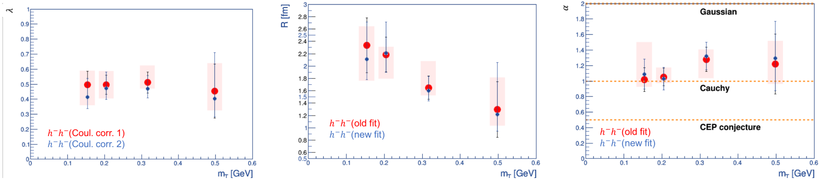
Summary

- NA61/SHINE Lévy HBT analysis possible
- For now, performance results are shown only
- Lévy HBT parameters to be measured
  - $R(m_T)$: looking for radial flow effect?
  - $\lambda(m_T)$: is there a "hole" (as seen at RHIC)?
  - $\alpha(m_T)$: Gaussian assumption valid? Proximity of CEP?
- Moving on to measure 0-20% identified HBT
- Next step, measuring Lévy HBT in Ar+Sc

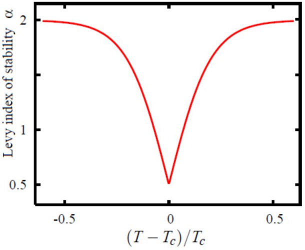
Thank you for your attention!

Bowler-Sinyukov Fit Formula Comparison

- Coul. corr. 1: $C(q) = (1 + \lambda e^{-|qR|^{\alpha}}) \cdot K(q)$
- Coul. corr. 2: $C(q) = (1 - \lambda + (1 + e^{-|qR|^{\alpha}}) \cdot \lambda \cdot K(q))$



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 $\eta = 0.50 \pm 0.05$

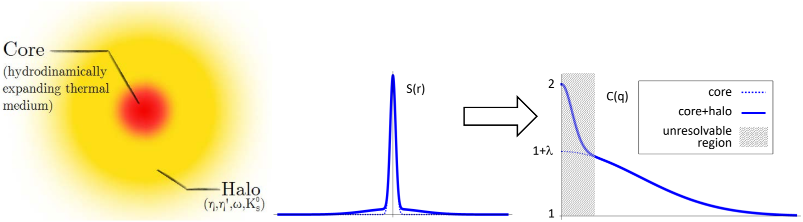
    Rieger, Phys.Rev.B52 (1995) 6659

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

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$(\omega, \eta \ldots) >$ 50 fm size
- Halo unresolvable experimentally
- True q$\to$ 0, limit $C(q=0) = 2$
- Results show $C(q \to 0) = 1 + \lambda$, where $\lambda = \left(\frac{N_{core}}{N_{halo}+N_{core}}\right)^2$

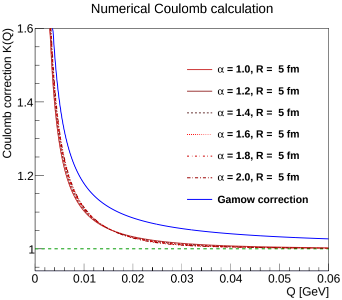
  Bolz et al, Phys.Rev. D47 (1993) 3860-3870
  Csörgő, Lörstad, Zimányi, Z.Phys. C71 (1996) 491-497

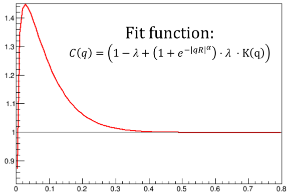


Handling the Coulomb Interaction

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





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)
- PID cuts

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 $m_{T,0}$