NA61/SHINE prospects for Bose-Einstein correlation measurements
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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 $\eta$
- QCD universality class $\leftrightarrow$ 3D Ising:
  - 3D Ising: $\eta = 0.03631$
  - Random field 3D Ising $\eta = 0.50 \pm 0.05$

- Search for the crit. point with SPS beam momentum/species scan
- Spatial correlation exponent near Critical End Point?
- Possible to measure 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
  - Intensity correlations as a function of detector distance
  - Measuring size of point-like sources

- Goldhaber et al: applicable in high energy physics:
  - Momentum correlation $C(q)$ is related to the source $S(x)$
    $C(q) \approx 1 + |\tilde{S}(q)|^2$ where $\tilde{S}(q)$ Fourrier transform of $S(q)$

- $S(r)$ usually assumed to be Gaussian, leads to Gaussian $C(q)$
Levy Distribution in Heavy-Ion Physics

- Expanding medium, increasing mean free path: anomalous diffusion
  Metzler, Klafter, Physics Reports 339 (2000) 1-77

- **Levy-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 Levy source:
  \( C(q) = 1 + \lambda \cdot e^{-(qR)^\alpha} \)
  - \( \alpha = 2 \): Gaussian
  - \( \alpha = 1 \): Exponential

- Levy distributions lead to power-law correlation functions
- Spatial correlation at the critical point: \( \sim r^{-(d-2+\eta)} \)
- Levy-exponent \( \alpha \) identical to correlation exponent \( \eta \)
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)
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 $E_F < 730\text{GeV}$
- In our analysis, we mistakenly selected $E_F > 730\text{GeV}$
- 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**

- **Event mixing method:**
  - $A(q)$ - Actual event relative momentum distribution
    - Pairs from same event
  - $B(q)$ - Background event relative momentum 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:

  ![Plot A(q) and B(q) at $\langle K_T \rangle = 284$ MeV]

  ![Plot C(q) = A(q)/B(q) at $\langle K_T \rangle = 284$ MeV]

  - 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 $\chi^2$
- Fit parameters:
  - $\lambda$ Correlation strength related to core/halo ratio
  - $R$ Levy scale parameter similar to a HBT size
  - $\alpha$ Lévy index of stability possibly related to the CEP

$$C(q) = A(q)/B(q) \text{ at } \langle K_T \rangle = 284 \text{ MeV}$$

$\lambda = 0.57^{+0.06}_{-0.05}$, $R = 1.65 \text{ fm}^{+0.13}_{-0.11}$, $\alpha = 1.38^{+0.11}_{-0.10}$

Full range goodness-of-fit
$\chi^2/\text{NDF} = 86.8/108$
Confidence level = 93.4%

Peak range (0.014 - 0.35 GeV/c)
$\chi^2/\text{NDF} = 39.4/44$
Confidence level = 67.1%

Fit function: $N \left( 1 - \lambda + (1 + e^{-(qR)^\alpha}) \right) \cdot e^{-\frac{q}{\lambda \cdot K_{\text{Coul}}(q)}}$
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:
    \[ R_{HBT} = R / \sqrt{1 + \left( \frac{m_T}{T_0} \right) \cdot u_T^2} \]
- Correlation strength \( \lambda \):
  - 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 \( \alpha \):
  - 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)
Cocrrrelation 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: \( \lambda \) vs \( m_T \)

- Correlation strength \( \lambda \): 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: $\alpha$ vs $m_T$

- Lévy index $\alpha$: 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

![Graph showing $\alpha$ vs $m_T$ for Gaussian, Cauchy, and CEP conjecture.](image)
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 ↔ Critical Exponent

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

\[ \alpha \equiv \eta \]


- QCD universality class ↔ (random field) 3D Ising:
  - 3D Ising: \( \eta = 0.03631 \)
  - Random field 3D Ising \( \eta = 0.50 \pm 0.05 \)

- Lévy exponent \( \alpha \) change near Critical End Point?
Core-Halo Model

- Hydrodynamically expanding core, emits pions at the freeze-out
- This results in a two component source: $S(x) = S_c(x) + S_h(x)$
- Core $\approx 10$ fm size, halo ($\omega, \eta \ldots$) $\approx 50$ fm size
- Halo unresolvable experimentally
- True $q \rightarrow 0$, limit $C(q = 0) = 2$

Results show $C(q \rightarrow 0) = 1 + \lambda$, where $\lambda = \left(\frac{N_{\text{core}}}{N_{\text{halo}} + N_{\text{core}}^2}\right)^2$

Handling the Coulomb Interaction

- Same charge pairs: Coulomb repulsion
  - Standard handling method: Coulomb corr.
  - Calculation: complicated numerical integral
  - Does not depend strongly on $\alpha$, see plot →
  - Small effect in Be+Be
- Approximate formula (for $\alpha = 1$) from CMS: Sirunyan et al. (CMS Collab.), arXiv:1712.07198 (PRC 2018)
  - $K_{Coulomb}(q) \equiv \text{Gamow}(q) \cdot \left(1 + \frac{\pi \eta q \frac{R}{\hbar c}}{1.26 + q \frac{R}{\hbar c}}\right)$
  - where $\text{Gamow}(q) = \frac{2 \pi \eta(q)}{e^{2\pi \eta(q)} - 1}$ and $\eta(q) = \alpha_{\text{QED}} \cdot \frac{\pi}{q}$
  - 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 \((Q_{\text{min}}, Q_{\text{max}})\) 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 \(\alpha\) and \(R\)
  - For \(\lambda\), any visible effect is in \(m_{T,0}\)