Femtoscopy with Levy HBT at NA61/SHINE

17th International Scientific Days, Gyöngyös, Hungary

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Wigner RCP, Hungary

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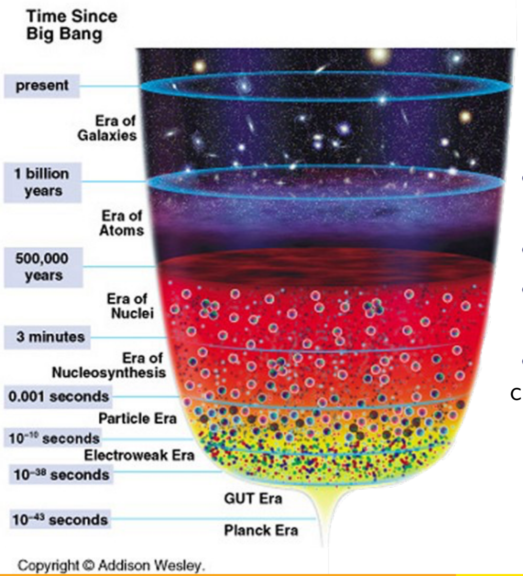
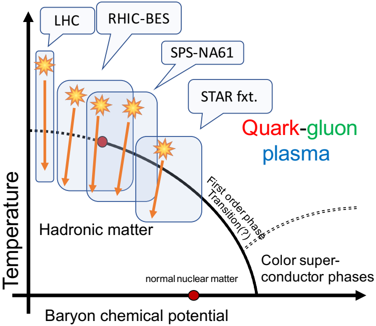
High Energy Physics and the Big Bang



- Big Bang 0 s,
  Present 13,7 billion years after
- First μs $\rightarrow$ sQGP
- How can we observe?
  Heavy ion-collisions
- Strongly interacting matter created (sQGP)
  QCD phasediagram

Search for the CEP: Spatial Correlations?



- At the critical point CEP: fluctuations at all scale
- 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

- Possible to measure η with Lévy HBT
  Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042

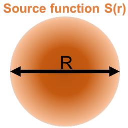
Bose-Einstein Correlations in Heavy-Ion Physics

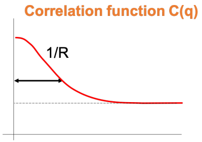
A way to measure spatial correlations: Bose-Einstein mom. correlations

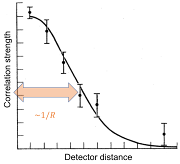
- R. Hanbury Brown, R.Q.Twiss observed Sirius with optical telescopes

  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: (for identical pions)

  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) frequently assumed to be Gaussian, leads to Gaussian C(q)

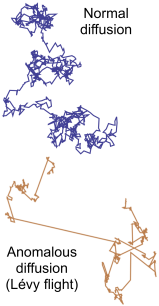
Lévy Distribution in Heavy-Ion Physics

- Measurements not fully supporting Gaussian $\rightarrow$ 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, ...

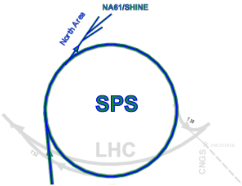
    Csörgő, Hegyi, Novák, Zajc, AIP Conf. Proc. 828 (2006) 525-532
    Csörgő, Hegyi, Novák, Zajc, Acta Phys.Polon. B36 (2005) 329-337
    Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002
    Metzler, Klafter, Physics Reports 339 (2000) 1-77

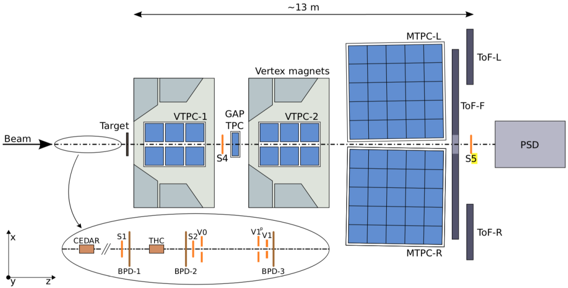


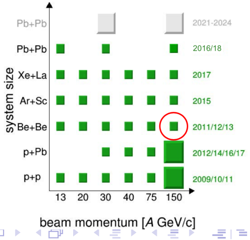
- Lévy distributions lead to power-law spatial correlations
- Spatial correlation at the critical point: $\sim r^{-(d-2+\eta)}$
- Lévy-exponent α identical to correlation exponent η

The NA61/SHINE Detector

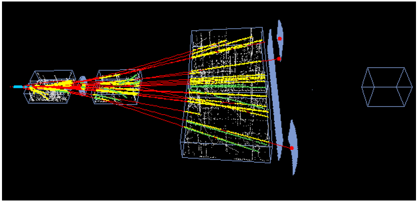
- Located at CERN SPS, North Area
- Fixed target experiment
- Large acceptance spectrometer (TPC)
  - Covering the full forward hemisphere
  - Outstanding tracking, down to $p_T = 0\ GeV/c$
- Light to heavy collisions at multiple energies
- Centrality selection based on forward energy measured by PSD

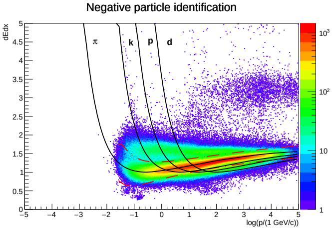






Event and Track Selection

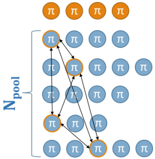




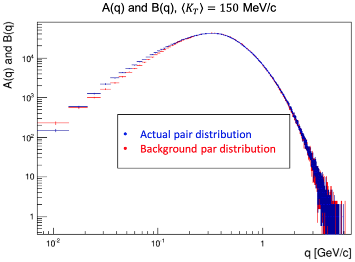
- Be+Be @ 150A GeV/c beam momentum
- Track selection:
  - Track quality and vertex cut applied
- Pair selection:
  - Reduce track merging and track splitting
- Particle identification:
  - Done via dE/dx method
  - Negative π pairs and positive π pairs
  - Works well for π

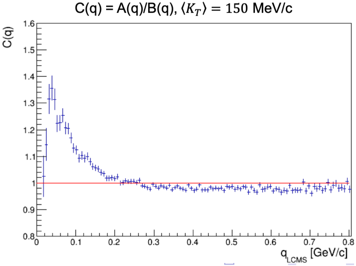
Bose–Einstein-correlation function

- A(q) - Pairs from same event
- B(q) - Pairs from mixed event
- C(q) - Correlation function, C(q) = A(q)/B(q)



- $C(q)$ corr. func. as a function of q_{LCMS} $q = |p_1 - p_2|$
- LCMS: Longitudinally CoMoving System
- In 4 m_T intervals from 0 to 600 MeV/c; $m_T \equiv \sqrt{m^2 + (K_T/c)^2}$
- $C(q)$: B–E effect and Coulomb-hole at low q values:





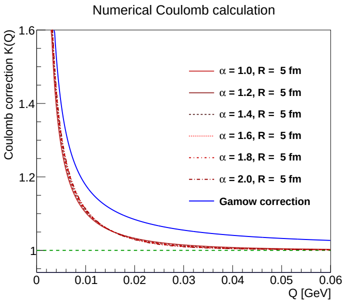
Handling the Coulomb Interaction

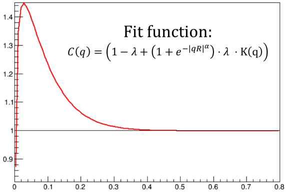
- Same charge pairs: Coulomb repulsion
  - Standard handling method: Coulomb corr.
  - Calculation: complicated numerical integral
  - Does not depend strongly on α, see plot $\rightarrow$
  - Small effect in Be+Be
- Approximate formula (for $\alpha = 1$) from CMS:
  Sirunyan et al. (CMS Collab.), arXiv:1712.07198 (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 $\eta(q) = \alpha_{QED} \cdot \frac{\pi}{q}$

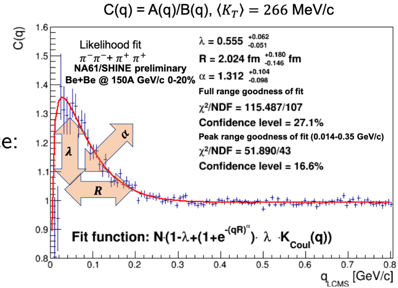
Fit function: Bowler-Sinyukov
$C(q) = 1 - \lambda + (1 + e^{-|qR|^{\alpha}}) \cdot \lambda \cdot K(q)$

Yu. Sinyukov et al., Phys. Lett. B432 (1998) 248,
M.G. Bowler, Phys. Lett. B270 (1991) 69





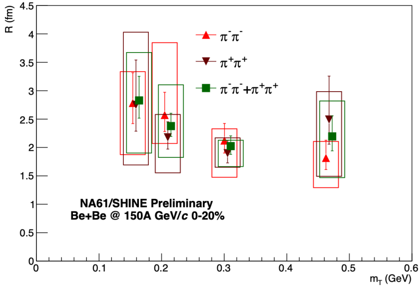
Parameters of the Lévy Correlation Function

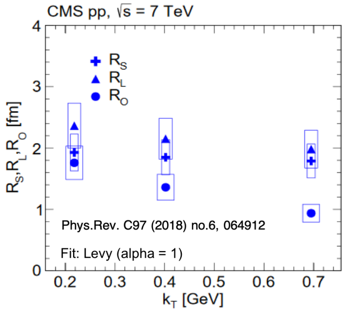


- Lévy scale R:
  - Determines length of homogeneity
  - Simple hydro picture suggests transverse velocity (u_T) dependence:
    $R_{HBT} = R/\sqrt{1 + (m_T/T_0) \cdot u_T^2}$
- Correlation strength λ:
  - Describes core-halo ratio:
    $\lambda(m_T) = \left(\frac{N_{core}}{N_{core}+N_{halo}}\right)^2$
  - 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
  - $\alpha < 2$: Generalized CLT, maybe anomalous diffusion
  - $\alpha = 0.5$: Conjectured value at the critical point (CEP)

Correlation Radius R vs m_T

- Describes length of homogeneity
- From hydro: $R \sim 1/\sqrt{m_T}$
- Slight decrease with m_T
  Sign of transverse flow?
- Similar results to RHIC p+p, LHC p+p and p+Pb





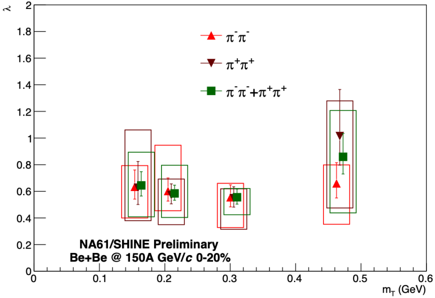
A.N, Makhlin and Yu. M. Sinyukov, Z.Phys. C39 (1988) 69
Csörgő, Lörstad, Phys.Rev.C54 (1996) 1390

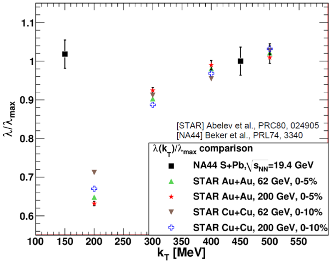
S. Chapman, P. Scotto and U. Heinz, Phys.Rev.Lett. 74 (1995) 4400-4403

Correlation Strength λ vs m_T

- Describes core-halo ratio

  Core-Halo model: Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996)
- Comparing with SPS and RHIC results:
  - Low m_T values show no decrease in λ (sim. to other SPS results)
  - Halo component increases at RHIC (e.g. In-medium mass mod.)
- λ value shows weak m_T dependence



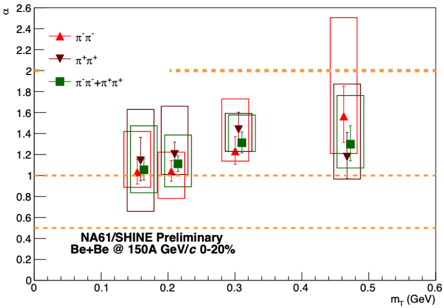


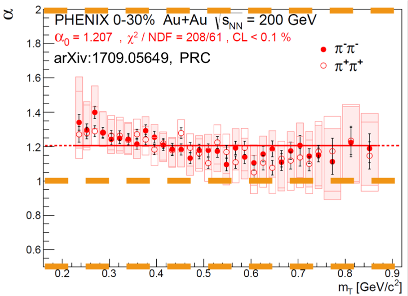
S. E. Vance et al, Phys.Rev.Lett. 81 (1998) 2205-2208
T. Csörgő et al, Phys.Rev.Lett. 105 (2010) 182301

A. Adare for PHENIX Collaboration, Phys.Rev. C97 (2018) no.6, 064911

Lévy Stability Index α vs m_T

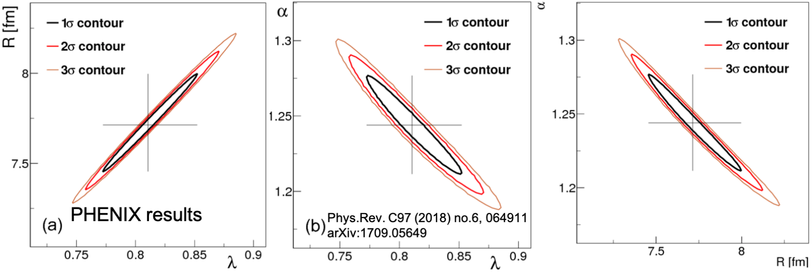
- Lévy-stability index α:
  - Shape of spatial correlation
- Between $\alpha \approx 1$ and 1.5
- Far from Gaussian ($\alpha = 2$), near Cauchy ($\alpha = 1$)
- Far from CEP($\alpha = 0.5$)
- Similar results to RHIC Au+Au $\sqrt{s_{NN}} = 200$ GeV results





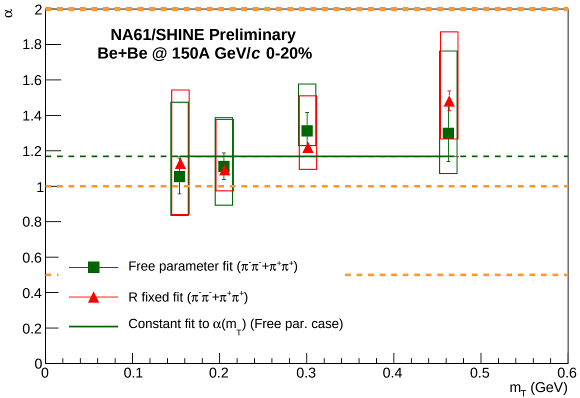
Fixed Parameter Fitting

- Interparameter correlations:
  - Known characteristic of Lévy fit
  - Observed in PHENIX (see below)
- To reduce the correlation one can fix a parameter
  - Fixing α, fitting R and λ (Constant to all m_T)
  - Fixing R, fitting α and λ (m_T dependent fit, based on hydro) $A/\sqrt{1+m_T/B}$



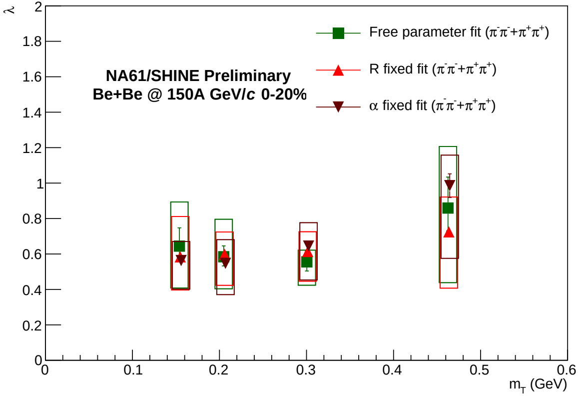
Lévy Exponent α vs. m_T

- Stability exponent determines source shape
- Comparing free par. results with fixed parameter fits:
  - Fitting with R fixed yields similar results, maybe smaller α



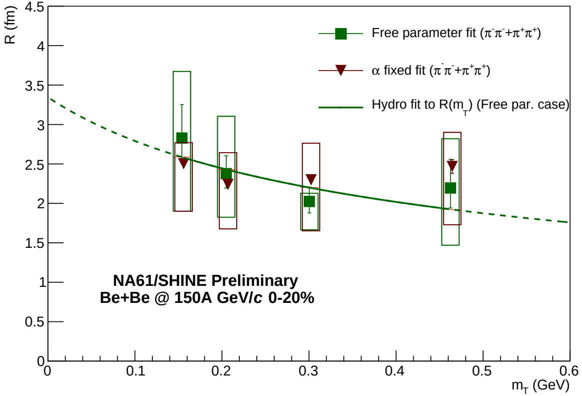
Correlation Strength λ vs. m_T

- Correlation strength describes core/halo ratio
- Both R fixed and α fixed fitting show similar results
- Results are within free par. statistical uncertainty



Lévy Scale R vs. m_T

- Levy HBT scale determines correlation length
- Parameter results similar
- Trend a bit different for fixed α case



Summary

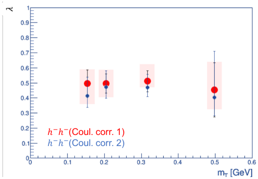
- First NA61/SHINE Lévy HBT analysis
- Measured momentum correlations of identical pion pairs
- Fitted them with correlation functions from Lévy source
- Investigated parameter m_T dependencies for free par. fit
  - $R(m_T)$: Decreasing trend, hadron transverse flow?
  - $\lambda(m_T)$: Slight dependence with m_T, no "hole"
  - $\alpha(m_T)$: Not Gaussian, nearly Cauchy, around 1.0-1.5
- Investigated parameter m_T dependencies for fixed par. fit
  - Statistical uncertainties reduced

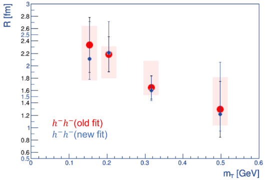
Thank you for your attention!

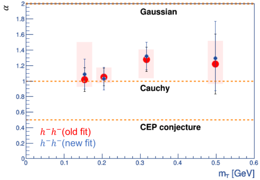
arXiv:1904.08169 [nucl-ex] arXiv:1906.06065 [nucl-ex]

Bowler-Sinyukov Fit Formula Comparison

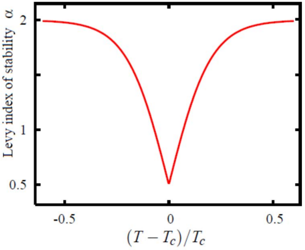
- Coul. corr. 1: $C(q) = (1 + \lambda e^{-|qR|^{\alpha}}) \cdot K(q)$
- Coul. corr. 2: $C(q) = (1 - \lambda + (1 + e^{-|qR|^{\alpha}}) \cdot \lambda \cdot K(q))$







Lévy Exponent ↔ Critical Exponent



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

$$\alpha \equiv \eta$$

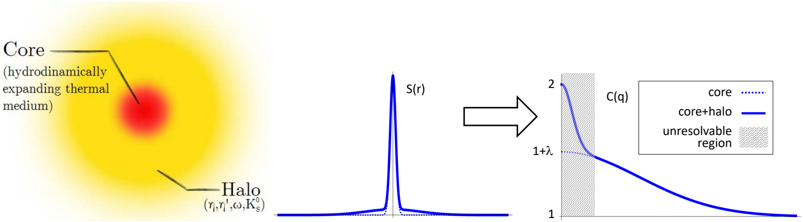
Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042

- QCD universality class ↔ (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$\rightarrow$ 0, limit $C(q = 0) = 2$
- Results show $C(q \rightarrow 0) = 1 + \lambda$, 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



Systematic Uncertainties

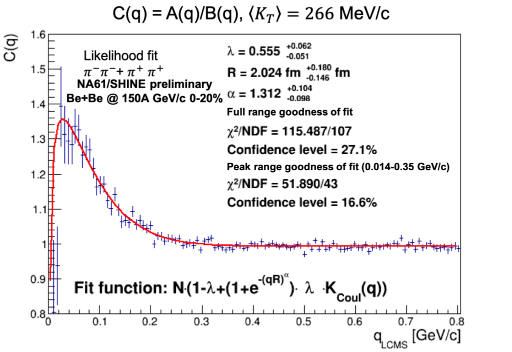
Investigated sources of uncertainties

- 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 $m_{T,0}$

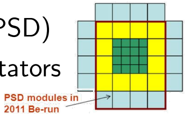
Example Lévy HBT Fit

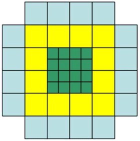


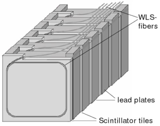
- Log-likelihood fit
- Assuming no corr. among q points
- Goodness-of-fit analyzed: conventional χ^2
  - Full range
  - Peak range
- Fit parameters:
  - λ Correlation strength
    related to core/halo ratio
  - R Lévy scale parameter
    similar to a HBT size
  - α Lévy index of stability
    possibly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

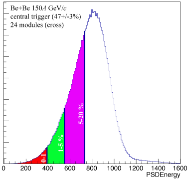
Projectile Spectator Detector

- 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 $E_F < 730 GeV$







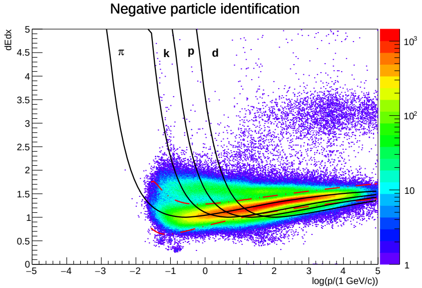


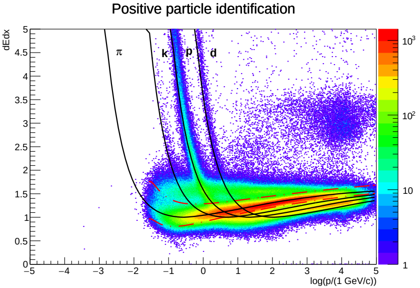
Track and Pair Selection

- Track selection:
  - Track quality and vertex cut applied
  - Particle identification possible via dE/dx method
  - Negative π pairs and positive π pairs
- Pair selection:
  - Check track pair transverse distance at several z values
    Drop one track randomly if their distance < 0.8 cm
    (pairs from actual and background events)
  - Ratio of number of recontructed to potential points > 0.5
    Reduce track splitting (already small effect in Be+Be)

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 resolution for dE/dx is 4%
- dE/dx versus $log(p)$ measured, 80 slices fitted with Gaussians
- High π multiplicity; mean of Gaussians to describe pions





Negative Hadron Results with Trigger Bias

- Negative hadrons selected, these are mostly pions ($\pi/K < 2\%$ in EPJC77(2017)10 671)