

Femtoscscopy with Lévy sources at NA61/SHINE

19th Zimányi School Winter Workshop, Budapest, Hungary

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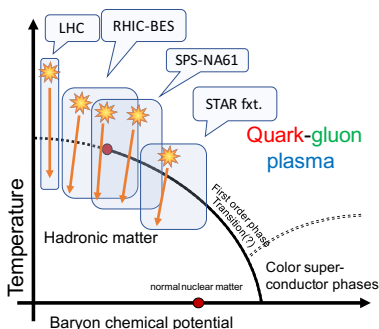
Wigner RCP, Hungary

December 3, 2019



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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-Shouk 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

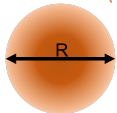
- Intensity correlations as a function of detector distance
- Measuring size of point-like sources

- Goldhaber et al: applicable in high energy physics: (for identical pions)

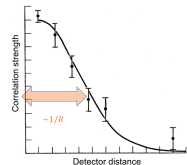
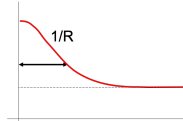
G. Goldhaber et al 1959 Phys.Rev.Lett. 3 181

- Momentum correlation $C(q)$ is related to the source $S(x)$
 $C(q) \cong 1 + |\tilde{S}(q)|^2$ where $\tilde{S}(q)$ Fourier transform of $S(q)$

Source function $S(r)$



Correlation function $C(q)$



- $S(r)$ 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

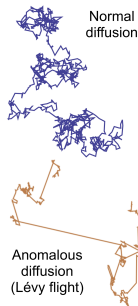
Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002

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

- Lévy distributions lead to power-law spatial correlations

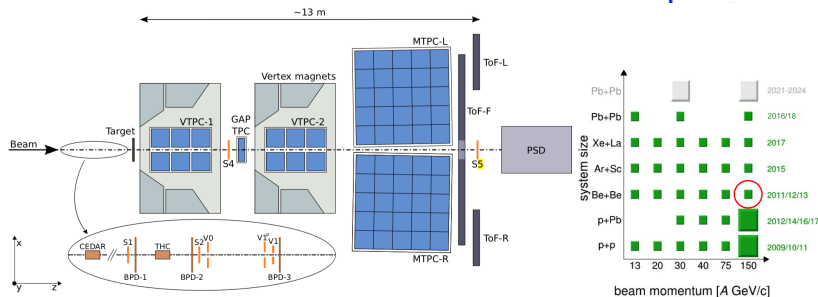
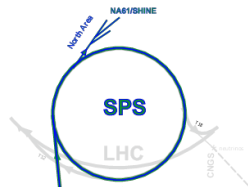
- Spatial correlation at the critical point: $\sim r^{-(d-2+\eta)}$

- Lévy-exponent α identical to correlation exponent η

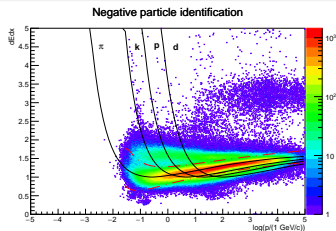
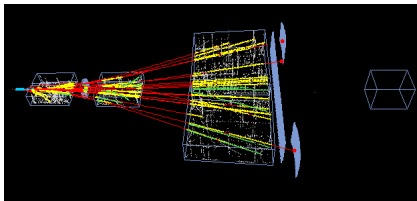


The NA61/SHINE Detector

- Located at CERN SPS, North Area
- Fixed target experiment
- Large acceptance hadron spectrometer (TPC)
 - Covering the full forward hemisphere
 - Outstanding tracking, down to $p_T = 0 \text{ GeV}/c$
- Various nuclei at multiple energies



Details of an HBT Analysis



- Be+Be @ 150A GeV/c beam momentum
- Centrality selection based on forward energy measured by PSD
- 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

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)

$$\bullet K_{Coulomb}(q) = \text{Gamow}(q) \cdot \left(1 + \frac{\pi\eta q \frac{R}{\hbar c}}{1.26 + q \frac{R}{\hbar c}}\right)$$

$$\text{where Gamow}(q) = \frac{2\pi\eta(q)}{e^{2\pi\eta(q)} - 1} \text{ and}$$

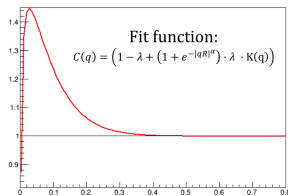
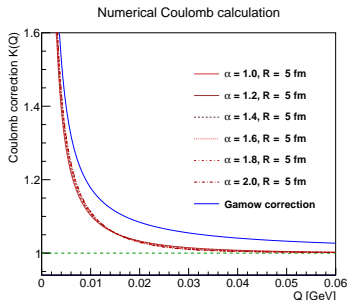
$$\eta(q) = \alpha_{QED} \cdot \frac{\pi}{q}$$

- 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 :

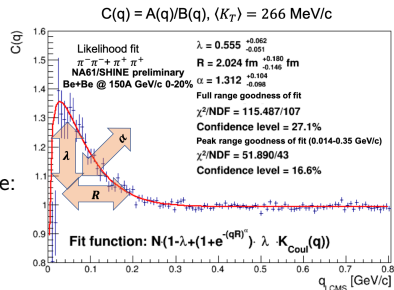
- Describes core-halo ratio:

$$\lambda(m_T) = \left(\frac{N_{core}}{N_{core} + N_{halo}} \right)^2$$

- Core: primordial pions
- Halo: resonance decay products and general background

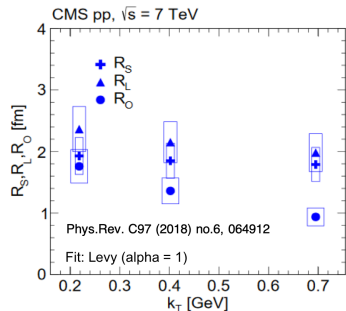
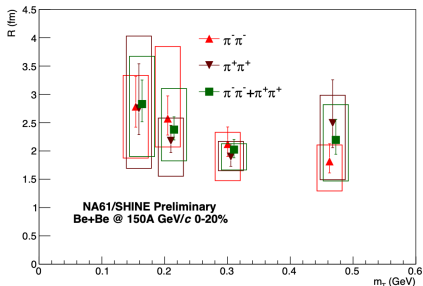
- Lévy exponent α :

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



Correlation Strength λ vs m_T

- Describes core-halo ratio

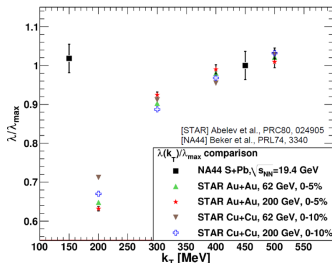
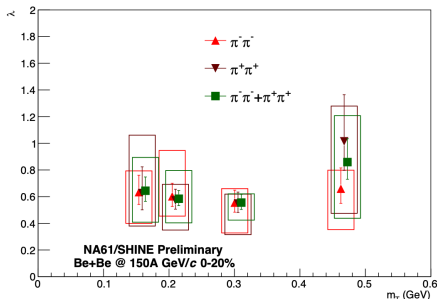
Core-Halo model: Csörgő, Lörstad, Zimányi, Z.Phys.C71 (1996)

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

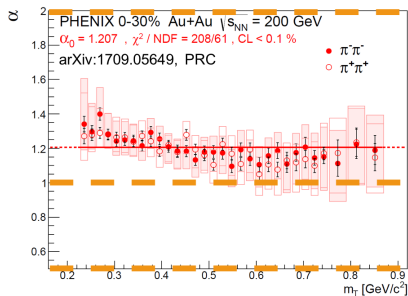
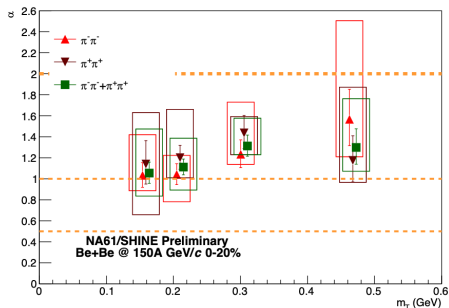
A. Adare for PHENIX Collaboration, Phys.Rev. C97 (2018) no.6, 064911

- λ value shows weak m_T dependence



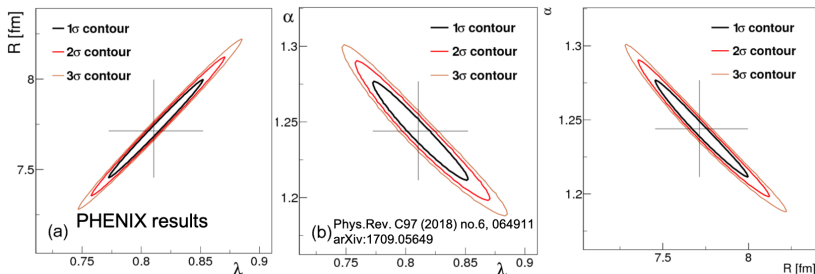
Lévy Stability Index α vs m_T

- 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



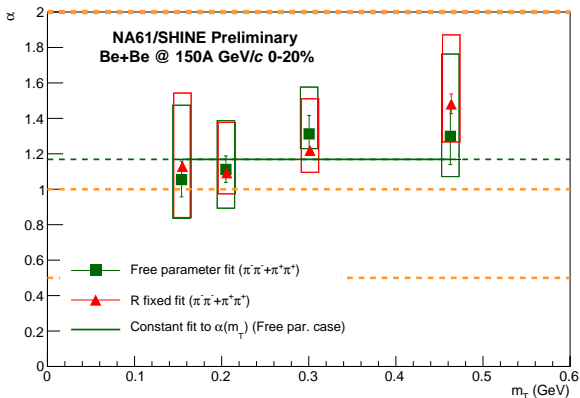
Fixed Parameter Fitting

- 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)
 $A/\sqrt{1 + m_T/B}$



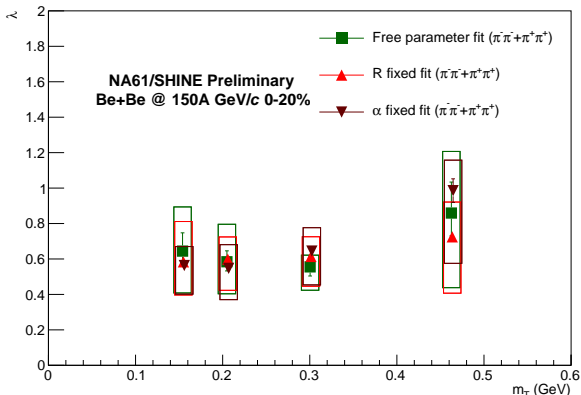
Lévy Exponent α vs. m_T

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



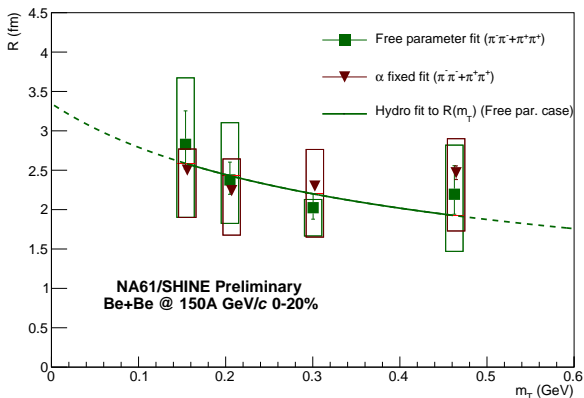
Correlation Strength λ vs. m_T

- 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

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



Summary

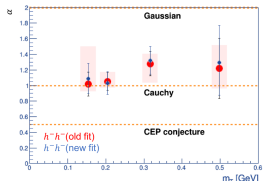
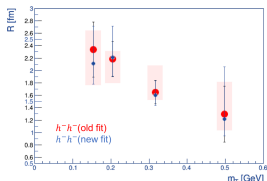
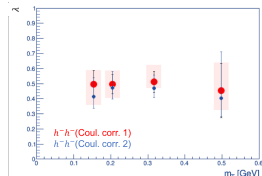
- First NA61/SHINE Lévy HBT analysis
- Measured momentum correlations of identical pion pairs
- Fitted them with correlation functions from Lévy source
- Investigated parameter m_T dependencies for free par. fit
 - $R(m_T)$: Decreasing trend, hadron transverse flow?
 - $\lambda(m_T)$: Slight dependence 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!

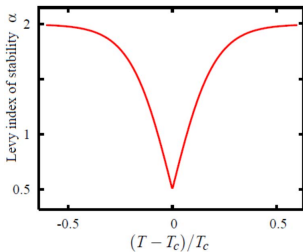
arXiv:1904.08169 [nucl-ex] arXiv:1906.06065 [nucl-ex]

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 \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

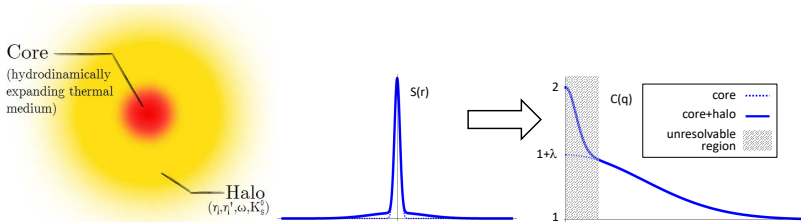
- Lévy exponent α change near **Critical End Point?**

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 \cong 10 fm size, halo($\omega, \eta \dots$) $>$ 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

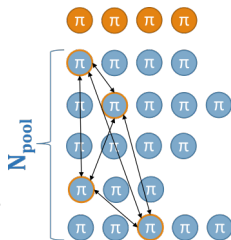
- Track settings
- Pair cuts
- Q bin width choice
- Fit range (Q_{min} , Q_{max}) choice (for each K_T)
- PID cuts

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 $m_{T,0}$

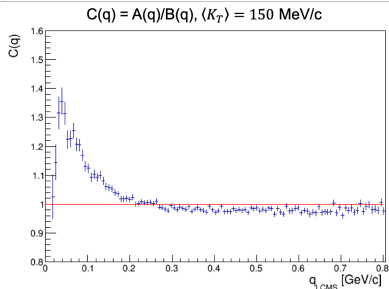
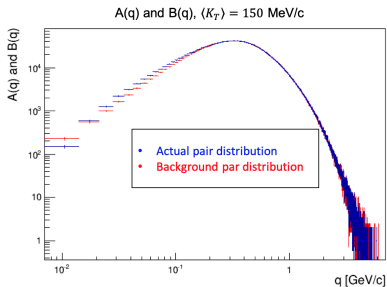
HBT Measurement setup with NA61/SHINE

- Event mixing method:
 - $A(q)$ - Actual event relative momentum distribution
 - Pairs from same event
 - $B(q)$ - Background event relative 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 K_T bins
 - Bins: (0-100, 100-200, 200-400, 400-600) MeV/c
 - $\langle K_T \rangle$: (65, 150, 266, 441) MeV/c
 - $m_T \equiv \sqrt{m^2 + (K_T/c)^2}$



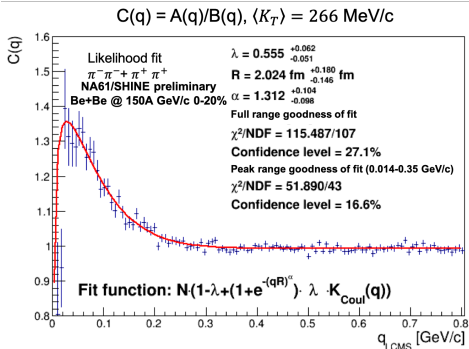
Example Bose-Einstein Correlation Function

- 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

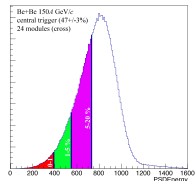
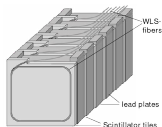
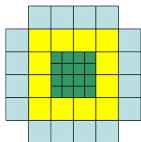
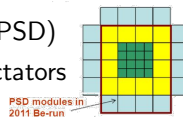
Example Lévy HBT Fit



- Log-likelihood fit
- Assuming no corr. among q points
- Goodness-of-fit analyzed: 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 $E_F < 730\text{GeV}$

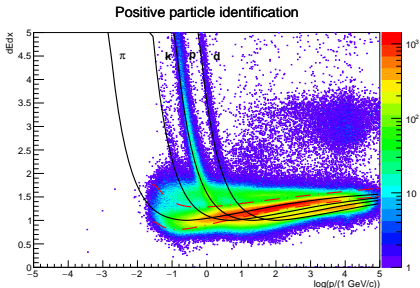
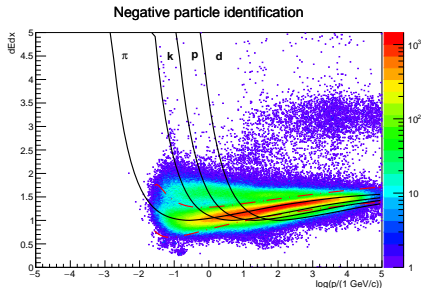


Track and Pair Selection

- 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 reconstructed 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 EPJCF77(2017)10 671)

