PHENIX results on centrality and beam energy dependent Levy HBT analysis

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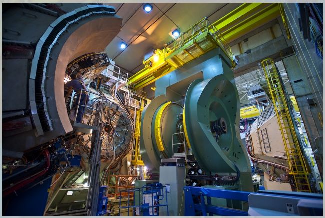
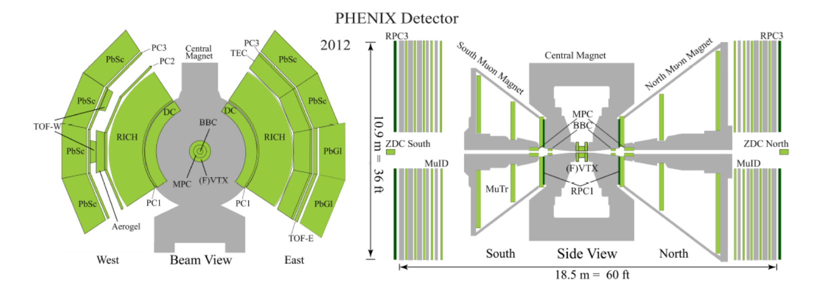
Outline

- The PHENIX experiment
- Bose-Einstein correlations
- Lévy-type distributions and the critical point
- Centrality dependent results at $\sqrt{s_{NN}} = 200$ GeV, 62 GeV and 39 GeV
- Summary

PHENIX experiment

- Observing collision of p+p, p+Al, p+Au, d+Au, h+Au, Cu+Cu, Cu+Au, Au+Au, U+U
- Charged pion ID from ∼ 0.2 to 2 GeV
- Typical Au+Au: $\sqrt{s_{NN}}$ = 130 GeV, **200 GeV**
- Beam energy scan program: **62.4**, **39.0**, 27.0, 19.6, 14.5, 7.7 GeV





Beam Energy Scan program

	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
510.0												p+p	p+p			
500.0									p+p		p+p					
200.0		Au+Au, p+p	d+Au, p+p	Au+Au, p+p	Cu+Cu, p+p	p+p	d+Au	(black), p+p	p+p	Au+Au	Au+Au	U+U, p+p, Cu+Au		Au+Au, He+Au	p+Au, p+Al, p+p	Au+Au, d+Au
130.0	Au+Au															
62.4				Au+Au	Cu+Cu	p+p				Au+Au						d+Au
39.0										Au+Au						d+Au
27.0											Au+Au					
22.5					Cu+Cu											d+Au
19.6		Au+Au									Au+Au					
14.6														Au+Au		
11.5										Au+Au						
7.7										Au+Au						
5.0								Au+Au								

○ p+p ● Au+Au ● d+Au ● Cu+Cu ● U+U ● Cu+Au ● He+Au ● p+Au ● p+Al

See details at http://www.rhichome.bnl.gov/RHIC/Runs/

Bose-Einstein correlations

- Correlation function from one- and two-particle invariant momentum distributions:

$$C_2(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_2(p_2)}$$

- $N_1(p)$ norm., $N_2(p_1, p_2) = \int S(x_1, p_1)S(x_2, p_2)|\Psi_2(x_1, x_2)|^2 d^4x_1 d^4x_2$
- $S(x, p)$ usually assumed Gaussian $\rightarrow$ we assumed it Lévy
- Ψ_2 – interaction free case – $|\Psi_2|^2 = 1 + \cos(qx)$
- Introducing $q = p_1 - p_2$ and $K = (p_1 + p_2)/2$
- If $k_1 \approx k_2 \rightarrow$ inverse Fourier-trf of the S source function

$$C_2(q, K) = 1 + \frac{|\tilde{S}(q, K)|^2}{|\tilde{S}(q = 0, K)|^2}$$

Effects on correlation functions

Several effect could modify the correlation functions

- Like-charged pions → Coulomb corr. needed: $C_{B-E} = K(q) \cdot C_m(q)$
- Strong final state interaction
- Effect of the resonance pions → core-halo model:
  - Split the source into two part: $S = S_{\text{core}} + S_{\text{halo}}$
  - Long-lived resonances contribute to the halo
  - In-medium η' mass modification → specific, m_T dependent suppression
- Partial coherence (see the next presentation)
- Squeezed states
- Aharonov-Bohm-like effect
  - The hadron gas around the pair could reduce the strength of the correlation
  - Could be treated as an Aharonov-Bohm-like effect

Lévy-type distribution and the critical point

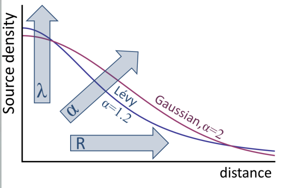
- Generalized Gaussian – Lévy-distribution

  –Anomalous diffusion
  –Generalized central limit th.

$$\mathcal{L}(\alpha, R, \mathbf{r}) = \frac{1}{(2\pi)^3} \int d^3 q e^{i\mathbf{q}\mathbf{r}} e^{-\frac{1}{2}|\mathbf{q}R|^\alpha}$$

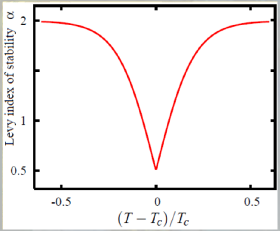
- $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy, $0 < \alpha \leq 2$ Lévy
- The C_2 from a symmetric Lévy-source:

$$C_2(Q) = 1 + \lambda \cdot e^{-(RQ)^\alpha}$$



- Spatial corr. $\sim r^{-1-\eta}$ in 3D → defines η exponent
- Symmetric stable distribution (Lévy) → spatial corr. $\sim r^{-1-\alpha}$
- α identical to η!
- For details see e.g.:
  - [1] Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67, nucl-th/0310042
  - [2] Csörgő, Hegyi, Novák, Zajc, AIP Conf.Proc. 828 (2006) 525, nucl-th/0512060
  - [3] Csörgő, PoS HIGH-pTLHC08:027 (2008), nucl-th/0903.0669
  - [4] Csanád, Csörgő, Nagy, Braz.J.Phys. 37 (2007) 1002-1013

Searching for the critical point



- QCD universality class ↔ 3D Ising [5],[6]
- At the critical point:
  - random field 3D Ising model [7]: $\eta = 0.5 \pm 0.05$
  - 3D Ising [8]: $\eta = 0.03631(3)$
- Change in $\alpha \rightarrow$ vicinity of the CEP
- Motivation for precise HBT measurements ...
  - ... with different multiplicity → centrality dependence
  - ... with different energy: now 200 GeV, 62 GeV, 39 GeV

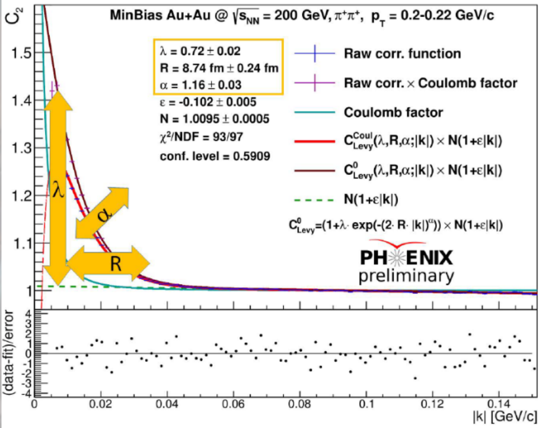
- [5] Halasz et al., Phys.Rev.D58 (1998) 096007, hep-ph/9804290
- [6] Stephanov et al., Phys.Rev.Lett.81 (1998) 4816, hep-ph/9806219
- [7] Rieger, Phys.Rev.B52 (1995) 6659, cond-mat/9503041
- [8] El-Showk et al., J.Stat.Phys.157 (4-5): 869, hep-th/1403.4545

Analysis details

- Data used for the centrality dependent analysis:
  - Run-10, Au+Au at $\sqrt{s_{NN}} = 200$ GeV
  - 18 m_T bin, 6 cent.bin by 10% steps

  Data used for the $\sqrt{s_{NN}}$ dependent analysis:
  - Run-10, Au+Au at
    - $\sqrt{s_{NN}} = 62$ GeV with 8 m_T bin, 4 cent.bin by 10% steps
    - $\sqrt{s_{NN}} = 39$ GeV with 8 m_T bin, 2 cent.bin by 20% steps
- Yield the m_T and centrality dependence of the Lévy-parameters
- Estimate the systematical uncertainties (in progress):
  - Effect of single and pair cuts
  - Choice of PID arm (East or West)
  - Systematics from fit: choice of the $Q_{\min}$ and $Q_{\max}$
  - In Coulomb correction $q_{\text{inv}} \leftrightarrow Q$ change

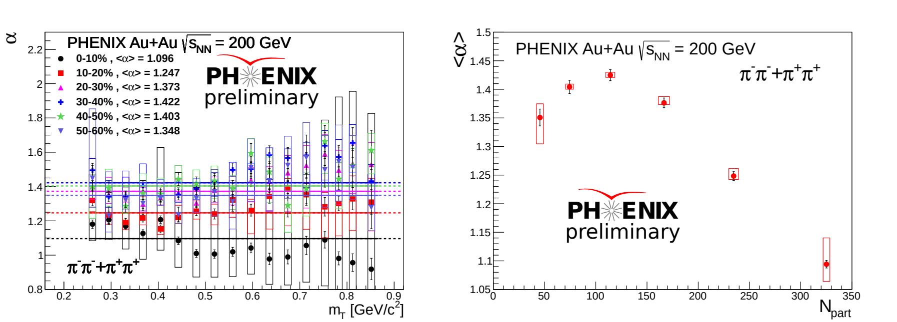
Example fit



- Fitted with Coulomb-corrected function
- All fits converged and the conf.levels are acceptable
- Lévy parameters are measured versus m_T

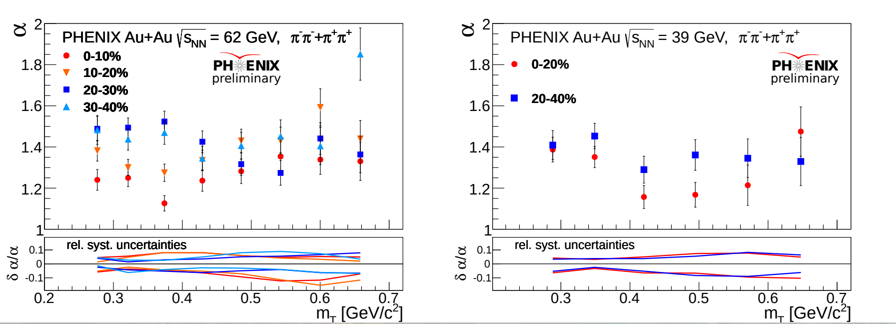
Lévy exponent α at 200 GeV

- Slightly non-monotonic behavior as a function of m_T
- Average has non-monotonic behavior at 200 GeV
- $\alpha = \langle\alpha\rangle$ constant fits were performed with centrality bin dependent value



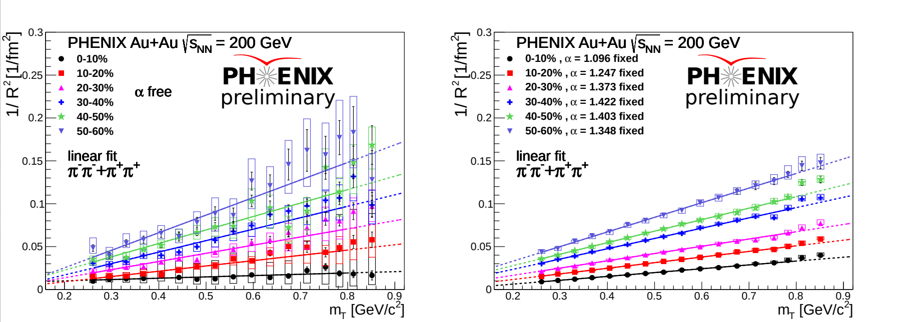
Lévy exponent α at 62 and 39 GeV

- Lévy exponent α does not seem to depend on $\sqrt{s_{NN}}$
- Fewer centrality bins have to be used due to the statistics
- $\alpha = \langle\alpha\rangle$ constant fits were not done



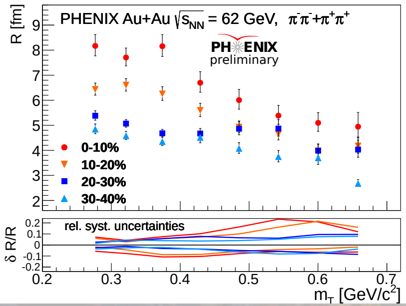
Lévy scale R at 200 GeV

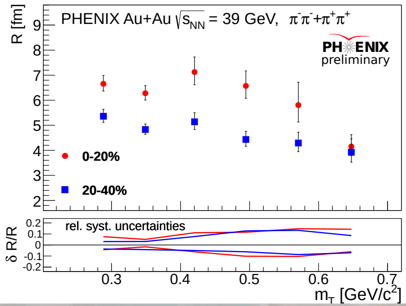
- Not equivalent with the Gaussian width but show similar trends
- Linear scaling behavior is seen in $1/R^2(m_T)$
- α fix fits reduce the systematic uncertainties



Lévy scale R at 62 and 39 GeV

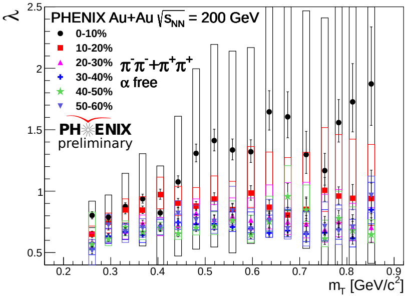
- Similar decreasing trends with m_T as in the Gaussian case
- Similar trends as at 200 GeV
- Fewer centrality bins have to be used due to statistics

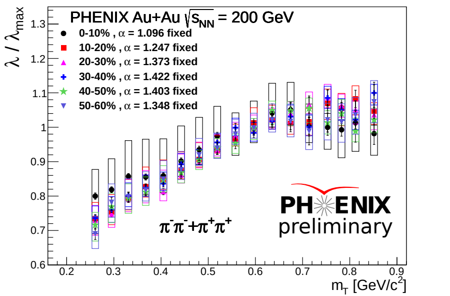




Lévy strength λ at 200 GeV

- Decreasing tendency at lower m_T not depend on centrality (as in [9])
- Can be observed clearly in $\lambda/\lambda_{\text{max}}$ with α fix (r.h.s. figure)
- Partial coherence predicts strong centrality dependence
- No centrality dependence of the "hole"

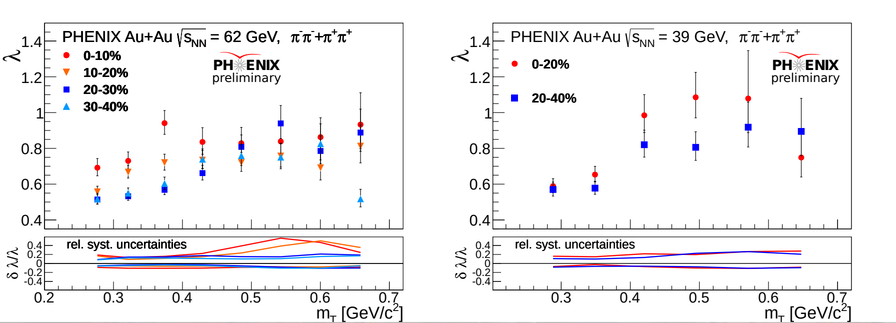




[9] Abelev et al. [STAR collaboration] PRC80, 024905

Lévy strength λ at 62 and 39 GeV

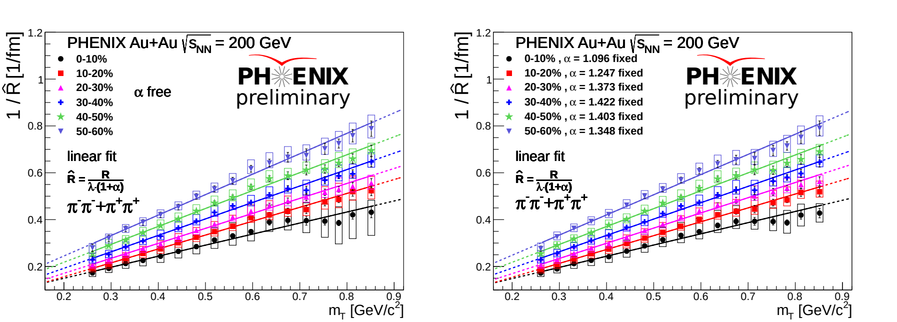
- Similar trends as at 200 GeV
- The characteristics of the "hole" do not depend strongly on $\sqrt{s_{NN}}$
- At $\sqrt{s_{NN}} \approx 19.4$ GeV the effect seems to disappear in S+Pb (see [10])



[10] Beker et al. [NA44 collaboration], PRL74, 3340

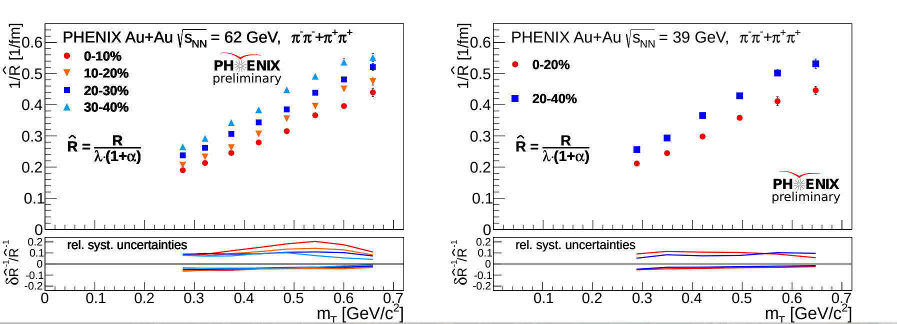
New scaling parameter $\hat{R}$ at 200 GeV

- $\frac{1}{\hat{R}} = \frac{\lambda(1+\alpha)}{R}$ scales with m_T
- Not sensitive to the α fixation
- May correspond to the area under the correlation function
- Experimentally observed, no theoretical explanation as far as we know



New scaling parameter $\hat{R}$ at 62 and 39 GeV

- Surprisingly good behavior at lower energy
- Linear behavior does still hold

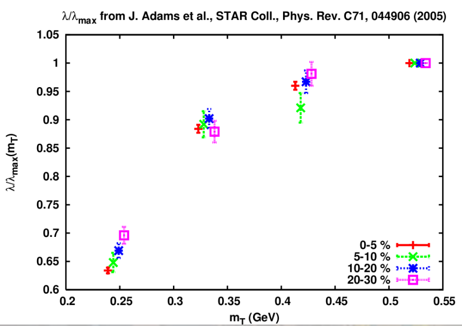


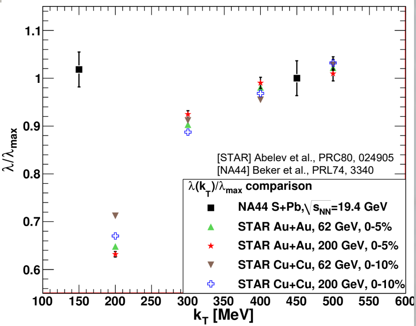
Summary

- Experimentally, a significant deviation from the Gaussian ($\alpha = 2$) case
- Symmetric Lévy shape is a statistically acceptable description
- Lévy parameters connected to rescattering, core/halo model and size
- Lévy exponent α: non-monotonic in N_{part}, almost independent of $\sqrt{s_{NN}}$
- Lévy scale R: geometric/hydro scaling, similar to Gaussian
- Lévy strength: low-m_T "hole" for $\sqrt{s_{NN}} \geq 39$ GeV, weak centrality dep.
- New par $\hat{R}$: linear scaling for $\sqrt{s_{NN}} \geq 39$ GeV, all investigated centrality

Thank you for your attention!

Backup slides





STAR centrality dependent results (left) and the comparison of STAR results in different $\sqrt{s_{NN}}$ with NA44 data (right)