# PHENIX results on the Lévy stable Bose-Einstein correlation functions

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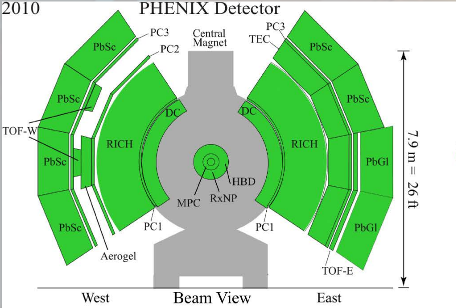
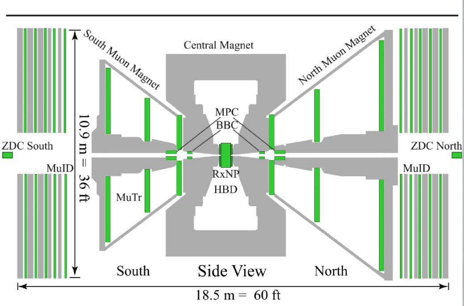
# Outline

# The PHENIX Experiment




- Versatile detector, operating until 2016
- Tracking via Drift Chambers and Pad Chambers
- Charged pion ID with TOF, from $\sim$ 0.2 to 2 GeV/c
- This analysis: PID also with EMCal

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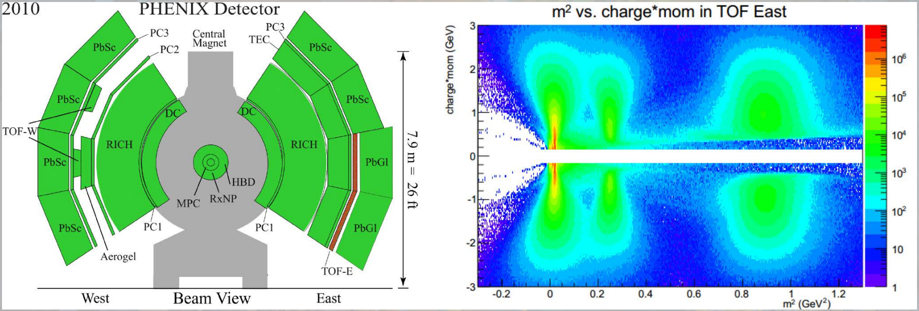


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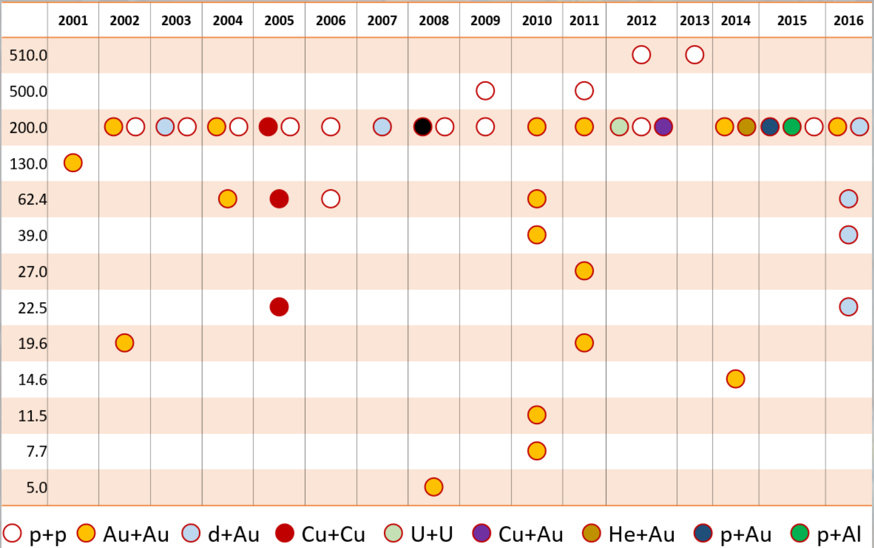
# PHENIX runs at a glance




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

# Outline

# Bose-Einstein correlations

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

$$C_2(p_1, p_2) = \frac{N_2(p_1, p_2)}{N_1(p_1)N_2(p_2)} \rightarrow C_2(q, K) = 1 + \frac{|\tilde{S}(q, K)|^2}{|\tilde{S}(q = 0, K)|^2}$$

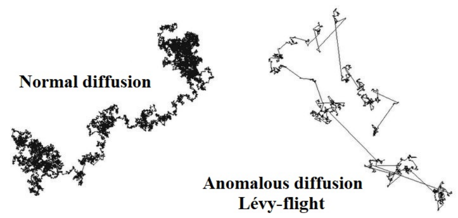
where $q = p_1 - p_2$ and $K = (p_1 + p_2)/2$

- Several effect could modify the correlation functions
  - Like-charged pions → Coulomb correction needed: $C_{B-E} = K(q) \cdot C_m(q)$
  - Strong final state interaction
  - Effect of the resonance pions → core-halo model:
    - $S = S_{\text{core}} + S_{\text{halo}}$
    - Long-lived resonances contribute to the halo
    - In-medium $\eta'$ mass modification → specific, $m_T$ dependent suppression
  - Partial coherence
  - Squeezed states

# Lévy-type of distribution and anomalous diffusion

- Expanding medium, increasing mean free path: anomalous diffusion
- Lévy-distribution from generalized central limit theorem could be valid

$$S(x,p) = \frac{1}{(2\pi)^3}\int d^3q e^{i\mathbf{qx}} e^{-\frac{1}{2}|\mathbf{x}R|^\alpha}$$



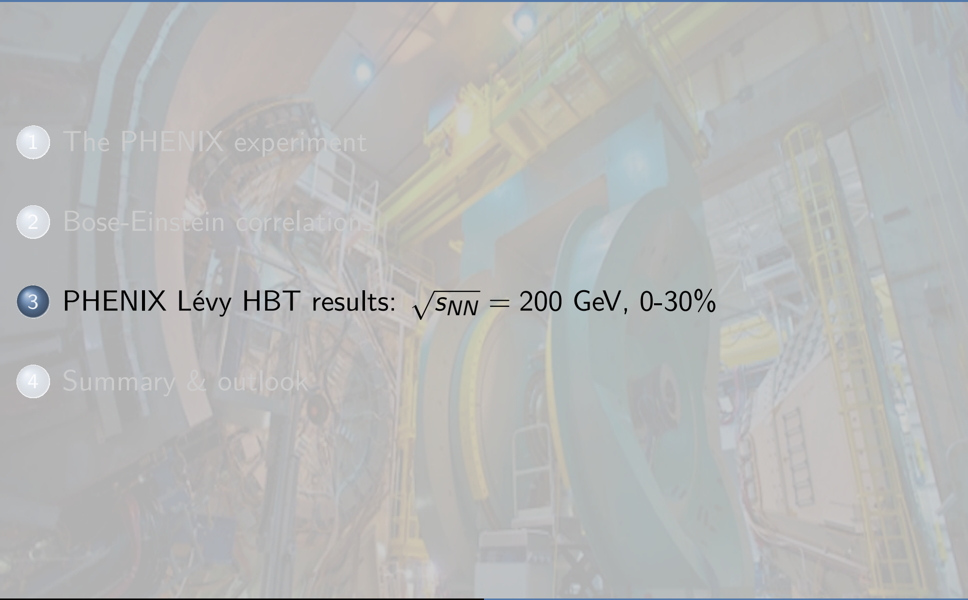

- $C_2$ with Lévy source:

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

$$\text{Lévy index} \Rightarrow \begin{cases} \alpha = 2 \ \text{Gaussian} & \rightarrow \quad \text{normal diffusion} \\ 0 < \alpha \leq 2 \ \text{Lévy} & \rightarrow \quad \text{anomalous diffusion} \end{cases}$$

- 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

# Outline

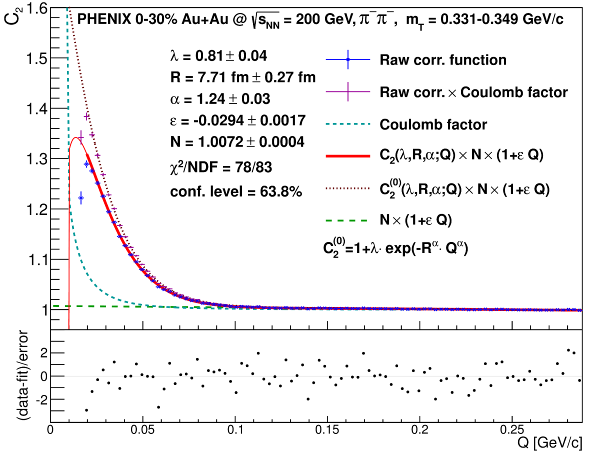


# PHENIX Lévy HBT analysis

- Dataset used for the analysis:
  - Run-10, Au+Au, $\sqrt{s_{NN}} = 200$ GeV, $7.3{\cdot}10^9$ events
  - 0-30% centrality was used
  - Additional offline requirements: collision vertex position less than $\pm 30$ cm
  - Particle identification:
    - time-of-flight data from PbSc e/w, TOF e/w, momentum, flight length
    - 2 $\sigma$ cuts on $m^2$ distribution
  - Correlation variable $Q = \sqrt{(p_{1x} - p_{2x})^2 + (p_{1y} - p_{2y})^2 + q^2_{\text{long,LCMS}}}$, where $q^2_{\text{long,LCMS}} = \frac{4(p_{1z}E_2 - p_{2z}E_1)}{(E_1+E_2)^2 - (p_{1z}+p_{2z})^2}$
  - Single track cuts: $2\sigma$ matching cuts in TOF & PbSc for pions
  - Pair-cuts:
    - A random member of pairs assoc. with hits on same tower were removed
    - customary shaped cuts on $\Delta\varphi - \Delta z$ plane for PbSc e/w, TOF e/w
- 1D corr. func. as a function of $Q$ in various $m_T$ bins
  - Lévy fits for 31 $m_T$ bins ($m_\text{T}$ from $\sim 0.280$ GeV/c$^2$ to $\sim 0.870$ GeV/c$^2$)
  - Coulomb effect incorporated in fit function

# Example $C(Q)$ measurement result

Measured in 31 $m_T^2 = m^2 + p_T^2$ bins for $\pi^+\pi^+$ and $\pi^-\pi^-$ pairs




arxiv:1709.05649 (accepted for publication in Phys.Rev.C)
Physical parameters: $R, \lambda, \alpha$; measured versus pair $m_T$

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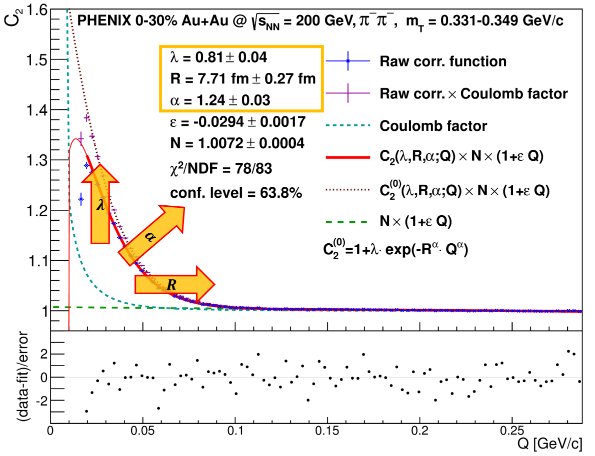


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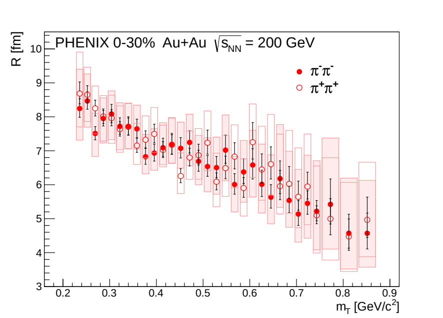
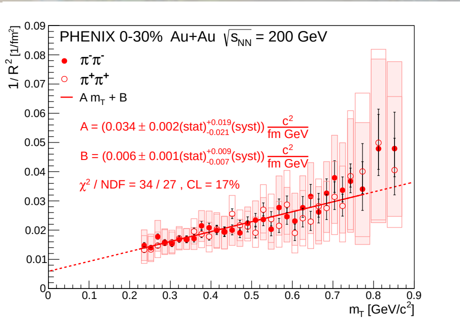
# Lévy scale parameter $R$

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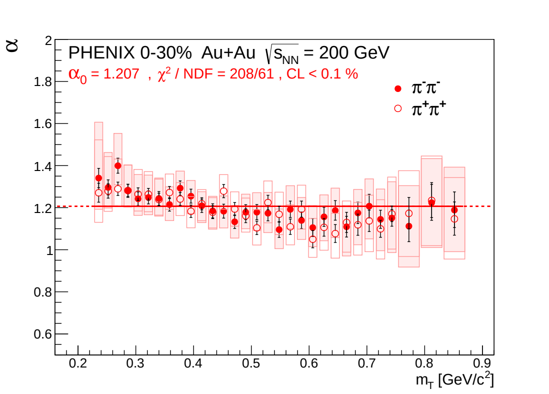
- Similar decreasing trend as Gaussian HBT radii
- Hydro predicts $1/R^2_{\text{Gauss}} = a + bm_{\text{T}}$
- Hydro behavior not invalid for $R_{\text{Lévy}}$!
- The linear scaling of $1/R^2$ breaks for high $m_T$

# Lévy exponent $\alpha$

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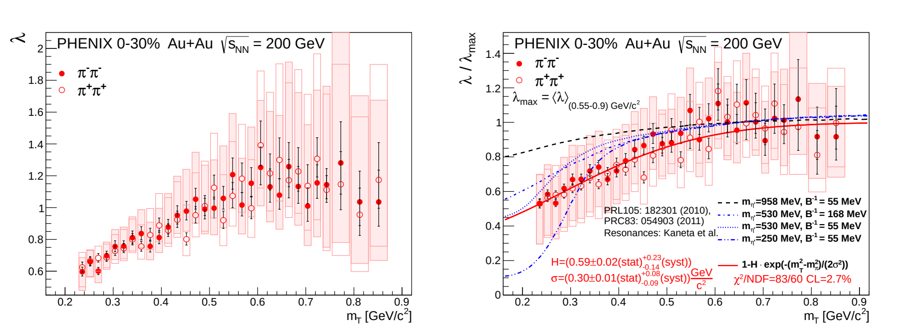
- Measured value is far from Gaussian ($\alpha = 2$), also not expo. ($\alpha = 1$)
- More or less constant (at least within systematic errors)
- Note: $\alpha(m_T) =$ const. fit statistically not acceptable (only with syst.)

# Correlation strength $\lambda$

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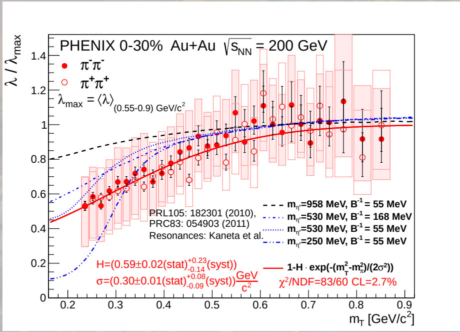
- From the Core-Halo model, measure the core-halo fraction: $\lambda = \left(\frac{N_C}{N_C+N_H}\right)^2$
- Observed suppression at small $m_T$ $\rightarrow$ increase of halo fraction
- Different effects can cause change in $\lambda$
- Resonance effects, partially coherent pion production
- $\lambda/\lambda_{\mathrm{max}}$ with smaller systematic uncertainties
- Precise measurement may help extract physics info

# A possible interpretation of $\lambda(m_T)$

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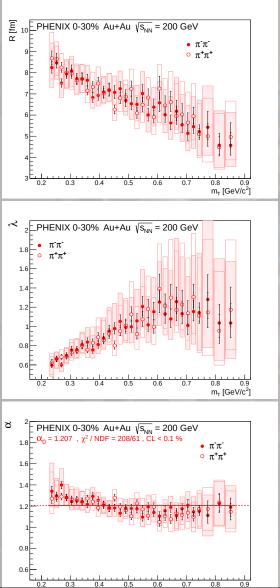
- May be connected to mass modifications (c.f. $U_A(1)$ chiral restoration)
  - Decreased $\eta'$ mass $\rightarrow$ $\eta'$ enhancement $\rightarrow$ halo enhancement
  - Kinematics: $\eta'$s low $m_T$ decay pions $\rightarrow$ decreased $\lambda$ at small $m_T$
- The results are not inconsistent with modified $m_\eta$

Kapusta, Kharzeev, McLerran, Phys.Rev. D53 (1996) 5028, hep-ph/9507343
Vance, Csörgő, Kharzeev, Phys.Rev.Lett. 81 (1998) 2205, nucl-th/9802074
Csörgő, Vértesi, Sziklai, Phys.Rev.Lett. 105 (2010) 182301, arXiv:0912.5526

# Interesting scaling parameter $\widehat{R}$

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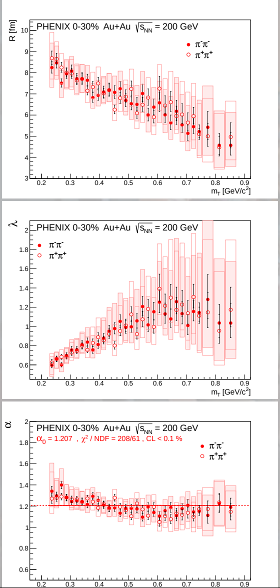


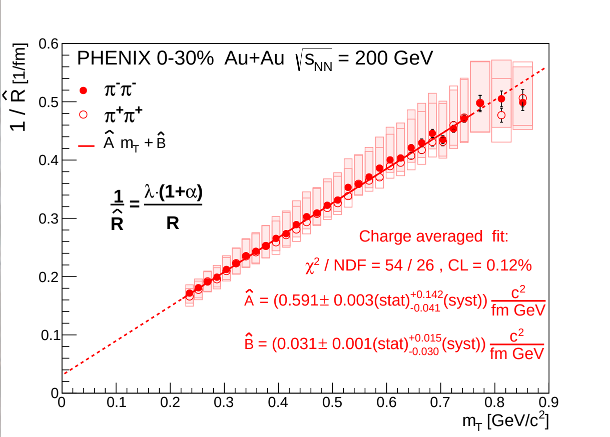


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- Empirically found scaling parameter
- Remarkably linear in $m_T$
- Physical interpretation → open question

# Outline

1. The PHENIX experiment
2. Bose-Einstein correlations
3. PHENIX Lévy HBT results: $\sqrt{s_{NN}} = 200$ GeV, 0-30%
4. Summary & outlook

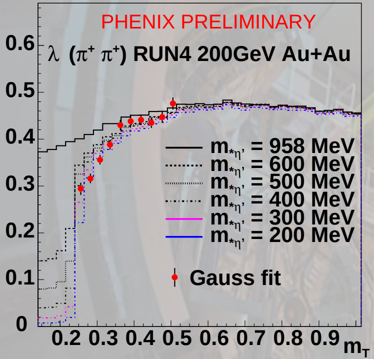
# Summary & outlook

- Lévy fits gives acceptable description $\leftrightarrow$ anomalous diffusion?
- Nearly constant $\alpha$, away from 2, 1 and 0.5 $\leftrightarrow$ distance to CEP?
- Linear scaling of $1/R^2(m_T)$ $\leftrightarrow$ hydro?
- Low-$m_T$ decrease in $\lambda(m_T)$ $\leftrightarrow$ resonances, $\eta'$ in-medium mass?
- Empirically found scaling parameter $\widehat{R} = R/(\lambda \cdot (1+\alpha))$
- Current projects and plans:
  - Centr. and coll. en. dependence: Dániel Kincses's talk on Saturday
  - 3D HBT analysis: Máté Csanád's talk on Wednesday
  - 3-particle analysis: Máté Csanád's talk on Wednesday
  - kaon-kaon correlation, Lévy HBT in p+p collision, ...

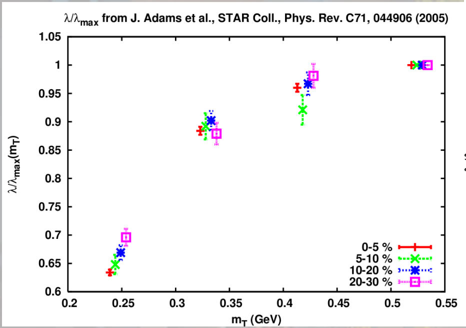
Thank you for your attention!

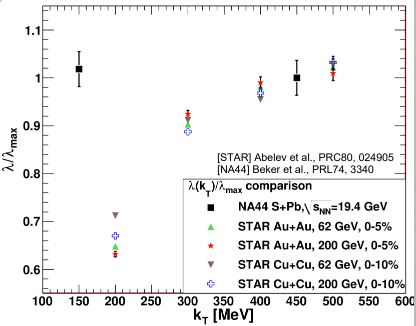
# Outline

# Run4 preliminary&Gauss → Run10 preliminary&Lévy



# Backup slides




STAR centrality dependent results (left) and the comparison of STAR results in different energy with NA44 data (right)

# Lévy source function and kinematic variables

## Basic two-particle variables

$$K^\mu = \frac{p_1^\mu + p_2^\mu}{2}, \qquad q^\mu = p_1^\mu - p_2^\mu, \qquad q_{inv} = \sqrt{-q^\mu q_\mu}$$

- $C_2(q_{inv})$ - Lorentz invariant 1 dimensional function
- $|k| = \frac{1}{2}\sqrt{q_{out}^2 + q_{side}^2 + q_{long}^2}$ instead of $q_{inv}$ - better
- $C_2(|k|)$ - 1 dim. function
- Generalized Gaussian - Lévy-distribution
  - Anomalous diffusion
  - Generalized limit theorem $\mathcal{L}(\alpha, R, r) = \frac{1}{(2\pi)^3}\int d^3q e^{iqr} e^{-\frac{1}{2}|qR|^\alpha}$

$$S(r) = (1-\sqrt{\lambda})\mathcal{L}(\alpha, R_H, r) + \sqrt{\lambda}\cdot\mathcal{L}(\alpha, R_C, r) \tag{1}$$

- Shape of the correlation functions with Lévy source ($R_H \to \infty$):

$$C_2(|k|) = 1 + \lambda \cdot e^{-(2R|k|)^\alpha} \tag{2}$$