


XIV International Conference
on New Frontiers in Physics
17-31 July 2025, OAC, Kolymbari, Crete, Greece

Centrality dependence of Lévy-stable two-pion
Bose-Einstein correlations
in $\sqrt{s_{NN}} = 200$ GeV Au+Au collisions at 

Tamás Novák

(For the PHENIX Collaboration)

MATE KRC, Gyöngyös, Hungary

BGE, Budapest, Hungary



BGE

Based on: [arXiv:2407.08586](https://arxiv.org/abs/2407.08586), [Phys.Rev.C 110 \(2024\) 6, 6](https://doi.org/10.1103/PhysRevC.110.064906)

Outline

- Introduction
- Bose-Einstein Correlations with Lévy source
- Centrality and m_T dependence of α , λ , λ/λ_{\max} , R
- Indirect observation of $U_A(1)$ symmetry restoration by PHENIX
- Summary and conclusions

1974: „...vacuum... resembles a medium whose properties can be changed”

PHYSICAL REVIEW D

VOLUME 9, NUMBER 8

15 APRIL 1974

Vacuum stability and vacuum excitation in a spin-0 field theory*

T. D. Lee and G. C. Wick

Columbia University, New York, New York 10027

(Received 17 January 1974)

The theoretical possibility that in a limited domain in space the expectation value $\langle \phi(x) \rangle$ of a neutral spin-0 field may be abnormal (that is to say quite different from its normal vacuum expectation value) is investigated. It is shown that if the ϕ^3 coupling is sufficiently large, then such a configuration can be metastable, and its physical size may become substantially greater than the usual microscopic dimension in particle physics. Furthermore, independent of the strength of the ϕ^3 coupling, if $\phi(x)$ has sufficiently strong scalar interaction with the nucleon field, the state that has an abnormal $\langle \phi(x) \rangle$ inside a very heavy nucleus can become the minimum-energy state, at least within the tree approximation; in such a state, the “effective” nucleon mass inside the nucleus may be much lower than the normal value. Both possibilities may lead to physical systems that have not yet been observed.

I. INTRODUCTION

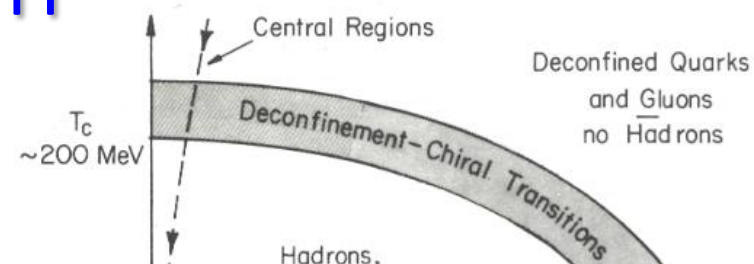
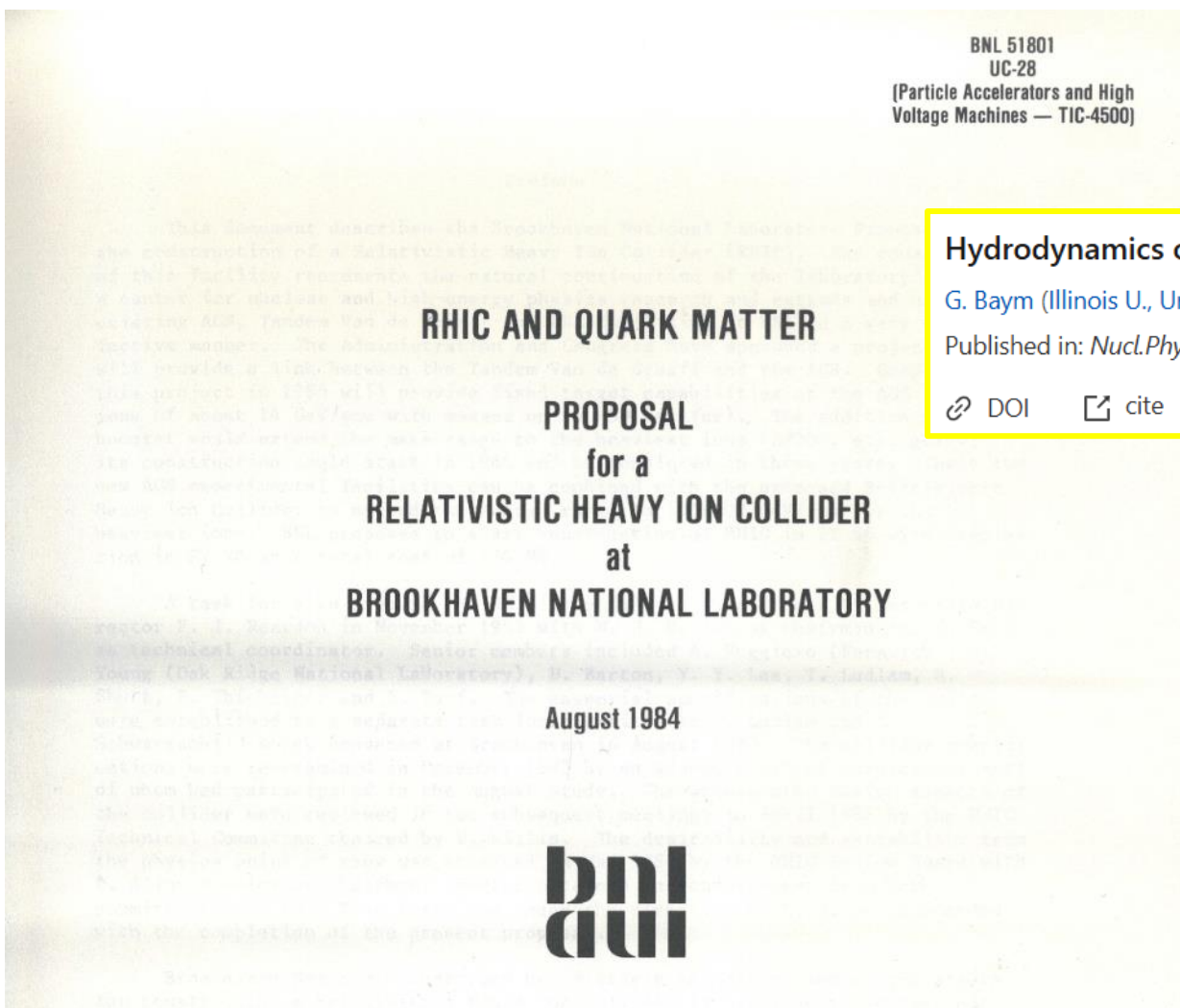
In a relativistic field theory, the vacuum state is defined to be the lowest energy level of the system. In analogy with other quantum-mechanical systems, however, a relativistic field may possess a degenerate lowest state. Perhaps the best known and simplest analogy is to Heisenberg’s infinite ferromagnet, in which case the degeneracy of the ground state is due to rotational invariance. The assumption of a degeneracy of the vacuum state, connected with a symmetry

(a) The Lagrangian of the system is invariant (or sometimes nearly invariant) under a certain group of transformations of the field variables.

(b) In the (observed) lowest state of the system, some of the field variables have expectation values which are not invariant under all transformations of the symmetry group. Because of (a) we must envisage the existence of other possible lowest states, or nearly lowest states, in which the expectation values of some of the fields are different; such states represent the abnormal vacuum states.

If the spin-0 field has a large ϕ^3 coupling constant b , then the function $U(\phi)$, defined by (1.2), can have another local minimum at $\phi = \phi_{\text{vac}} \neq 0$. In this case, even *without* the presence of nuclear matter, there could be the possibility of a pure vacuum excitation state, in which the expectation value $\langle \phi(x) \rangle \cong \phi_{\text{vac}}$ over an extended region in space. This leads naturally to the physical picture that the so-called vacuum actually more resembles a medium whose properties can be changed. If this is true, which of course we do not know at present, it must ultimately lead to rather striking physical consequences.

1984: RHIC Proposal: One or two transitions on the phase diagram



Hydrodynamics of Ultrarelativistic Heavy Ion Collisions

#2

G. Baym (Illinois U., Urbana), B.L. Friman (Illinois U., Urbana), J.P. Blaizot (Saclay), M. Soyeur (Saclay), W. Czyz (Cracow, INP) (1983)

Published in: *Nucl.Phys.A* 407 (1983) 541-570

[DOI](#) [cite](#) [claim](#)

[reference search](#) [256 citations](#)

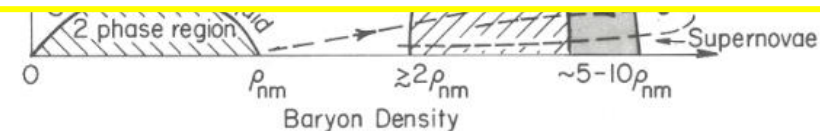


Fig. II.1 Phase diagram of Nuclear Matter (G. Baym, ref. 3). Temperature is plotted vs. net baryon density for an extended volume of nuclear matter in thermal equilibrium. Normal nuclear matter appears at the point ρ_{nm} at zero temperature, and this is the neighborhood explored by low energy nuclear physics. The region of the phase transitions corresponding to deconfinement (at temperature T_C) and chiral symmetry restoration is indicated T_F . The two critical temperatures may well be coincident. The confinement force couples quarks to form hadrons. The chiral force binds the collective excitation to Goldstone bosons. Above T_C , hadrons dissolve into quarks and gluons. Above T_F quarks are massless. The indicated trajectories show two avenues for probing the quark-gluon plasma with high energy nucleus-nucleus collisions: by reaching high baryon densities among the hot, compressed fragments of the colliding nuclei, and at very high temperatures in the central rapidity region among thermally produced particles where conditions may approximate those of the early universe.

1989: „Nuclei, as heavy as bulls, through collision
Generate new states of matter” /T.D. Lee/



[Courtesy of the Tsung Dao \(T.D.\)
Lee Library](#)

Poem by Prof. T. D. Lee,
Nobel Laureate in Physics

Painting by Li Keran, 1989

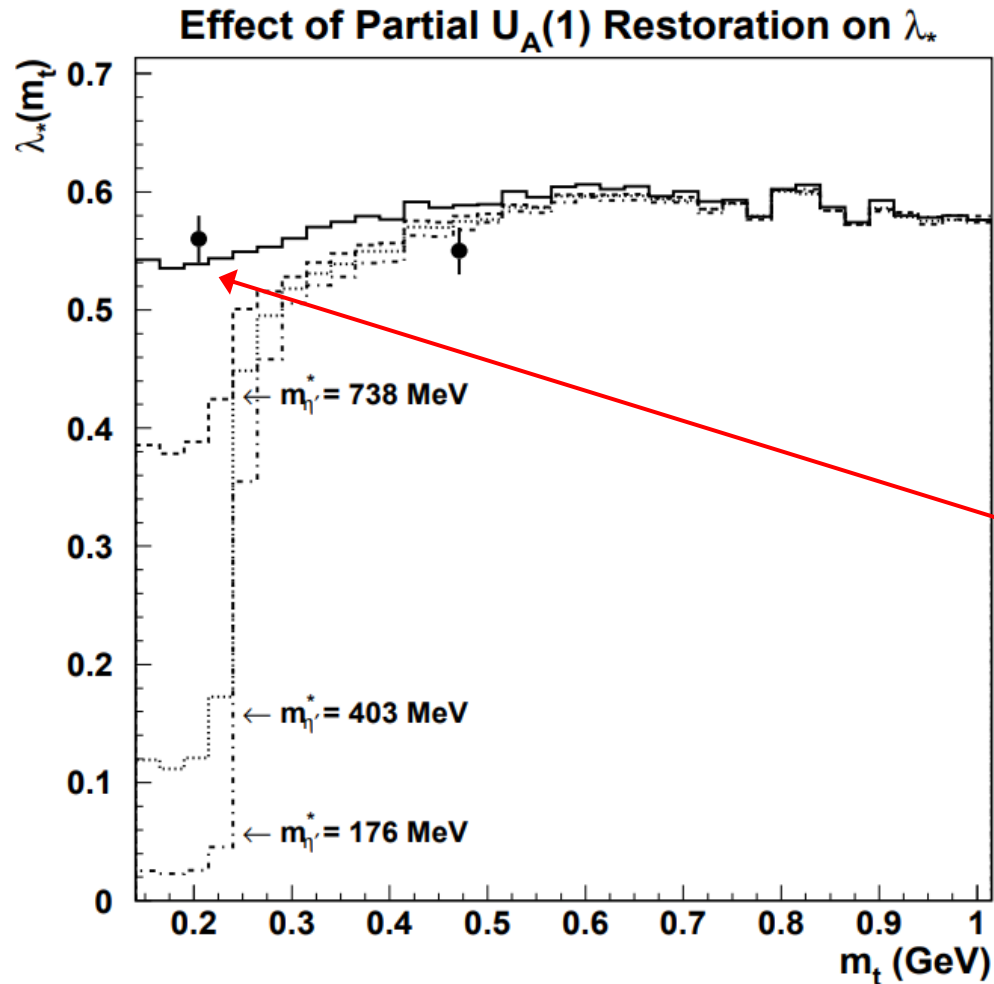
Copyright: © 1989 CCAST:
Chinese Center for Advanced Science
and Technology
© 2012 Shanghai Jiao Tong University,
Shanghai, China: All Rights Reserved

[Special thanks to: UNT Digital Library](#)

**New emphasis:
on plural of state**

At least two new states!

1998: Sensitive to in-medium η' mass modification⁶



NA44 S+Pb data + Monte Carlo,

PHENIX Phys. Rev. C 97
(**2018**) 064911:

NA44 $E_{\text{lab}} = 200$ AGeV (SPS)

S+Pb data sensitive to

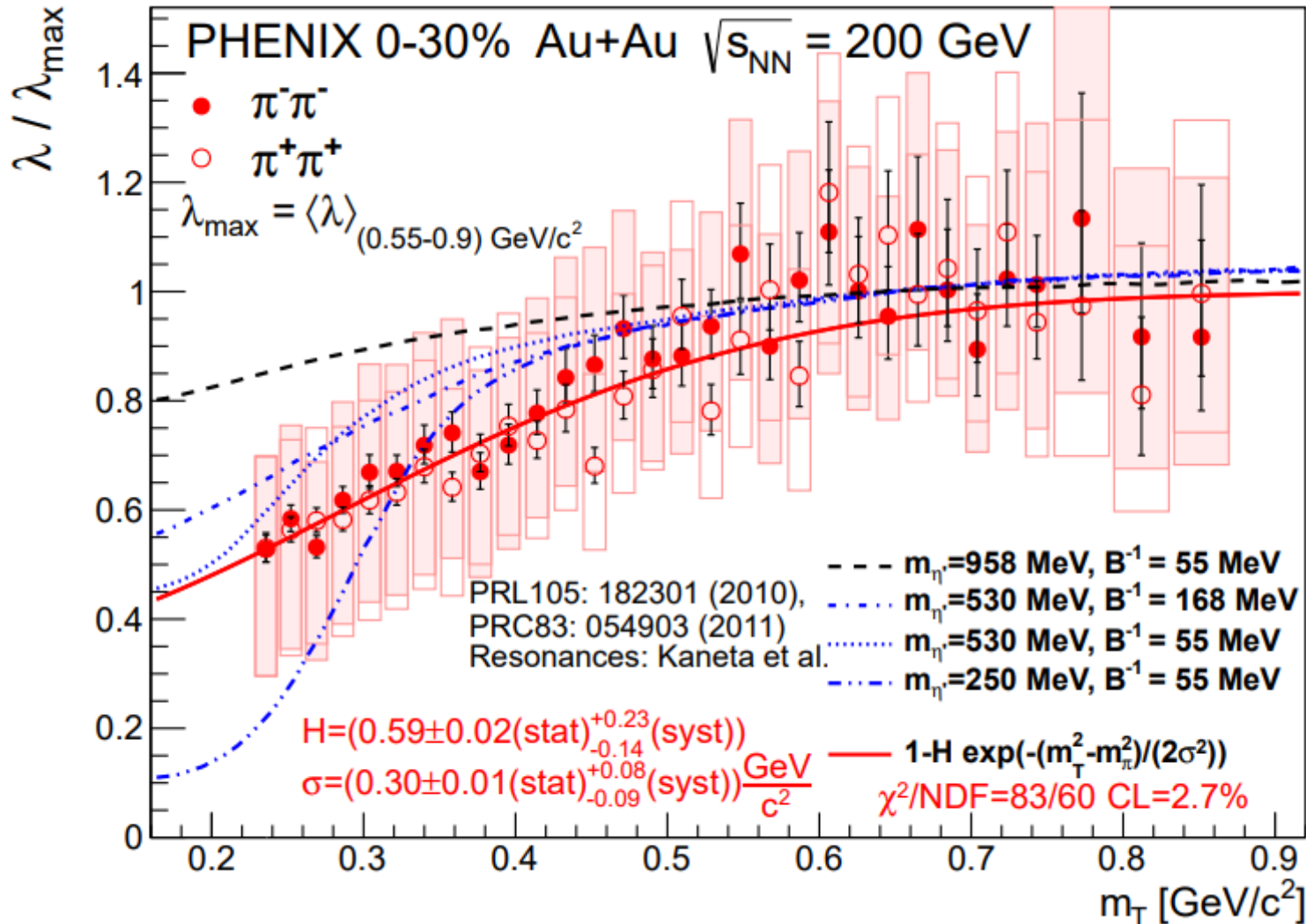
in-medium η' modification, but

**NO EFFECT
@ CERN SPS**

S. Vance, T. Cs, D. Kharzeev,
Phys.Rev.Lett. 81 (1998) 2205-2208
e-Print: [nucl-th/9802074](https://arxiv.org/abs/nucl-th/9802074) [nucl-th]

In-medium η' modification: can it be switched on?
Centrality? Energy? System size?

2018: Sensitive to in-medium η' mass modification⁷



PHENIX data + Monte Carlo,
 PHENIX Phys. Rev. C 97
 (2018) 064911:

0-30 % Au+Au @ 200 GeV
Lévy Bose-Einstein

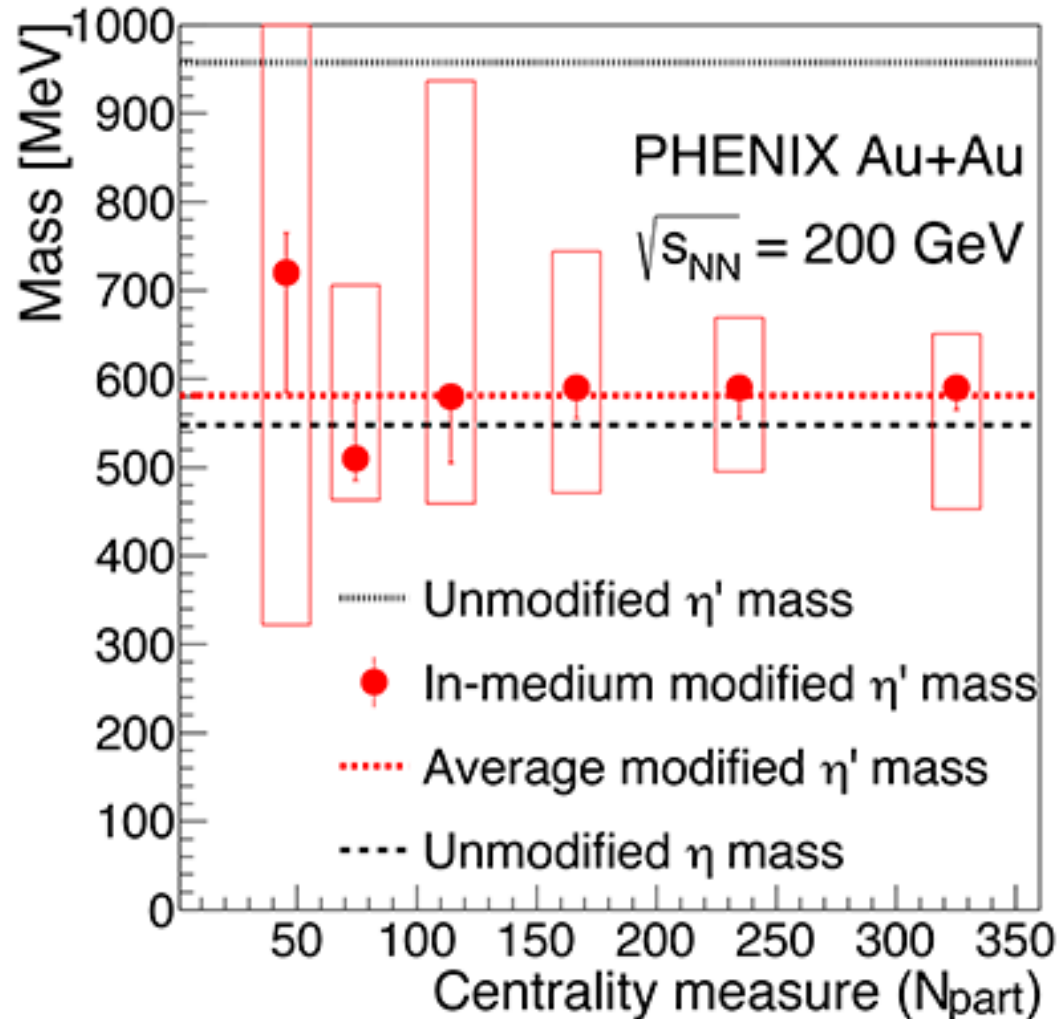
PHENIX data sensitive to

in-medium η' modification

centrality
dependence = ?

In-medium η' modification: It can be switched on/off with \sqrt{s} and/or system size

2024: „This implies a second transition in QCD...” /PRC Editors/



EDITORS' SUGGESTION

Centrality dependence of Lévy-stable two-pion Bose-Einstein correlations in $\sqrt{s_{NN}} = 200 \text{ GeV}$ Au + Au collisions

20 DECEMBER, 2024

Color deconfinement and chiral-symmetry restoration have long been predicted by QCD theory. Color deconfinement in the form of a nearly perfect fluid of quarks was reported by all four RHIC experiments in 2005. Now, the PHENIX Collaboration details two-pion Lévy-stable Bose-Einstein correlation data in Au+Au collisions at the top RHIC energy. They report a significant reduction of the mass of the η' meson in hot and dense hadronic, color-confining matter. This implies a second transition in QCD by the return of the so-called prodigal Goldstone boson—a specific kind of partial chiral-symmetry restoration—and calls for further, challenging experimental studies, aiming at direct measurements of identified η' spectra in high-energy heavy-ion collisions.

N. J. Abdulameer *et al.* (PHENIX Collaboration)

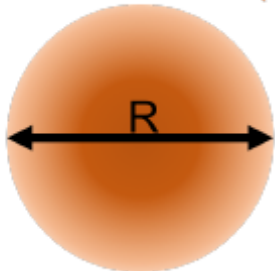
[Phys. Rev. C **110**, 064909 \(2024\)](#)

The HBT-effect in Femtoscopy

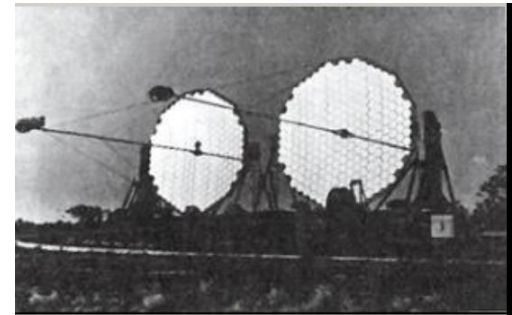
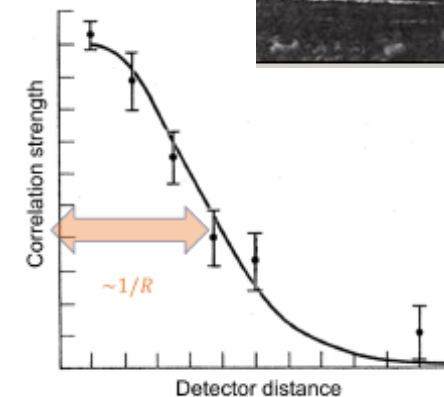
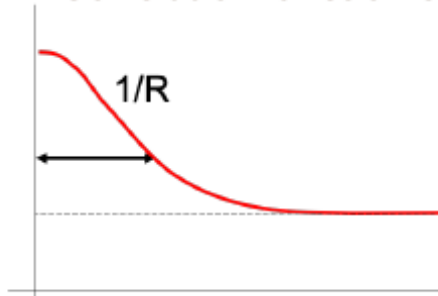
- R. Hanbury Brown, R.Q. Twiss observed Sirius with radio telescopes
- R. Hanbury Brown and R.Q. Twiss 1956 Nature 178
 - Intensity correlations as a function of detector distance
 - Measuring size of point-like sources
- Goldhaber et al: applicable in high energy physics: (for identical pions)
- G. Goldhaber et al 1959 Phys.Rev.Lett. 3 181
 - Momentum correlation $C(q)$ is related to the source $S(x)$:

$$C(q) \cong 1 + |\tilde{S}(q)|^2, \text{ where } \tilde{S}(q) \text{ is Fourier transform of } S(q).$$

Source function $S(r)$



Correlation function $C(q)$

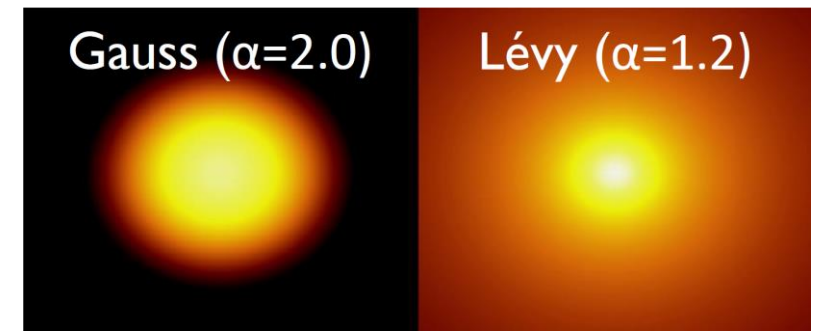


Lévy Distributions in Heavy Ion Physics

- Usual assumption that $S(r)$ is Gaussian \rightarrow Gaussian $C(q)$
- Measurements suggest phenomena beyond Gaussian distribution

- Lévy stable distribution: $\mathcal{L}(\alpha, R; r) = (2\pi)^{-3} \int d^3q e^{iqr} e^{-1/2|qR|^\alpha}$

- From generalized central limit theorem, power law tail $\sim r^{-(1+\alpha)}$
- Special cases: $\alpha = 2$ Gaussian, $\alpha = 1$ Cauchy



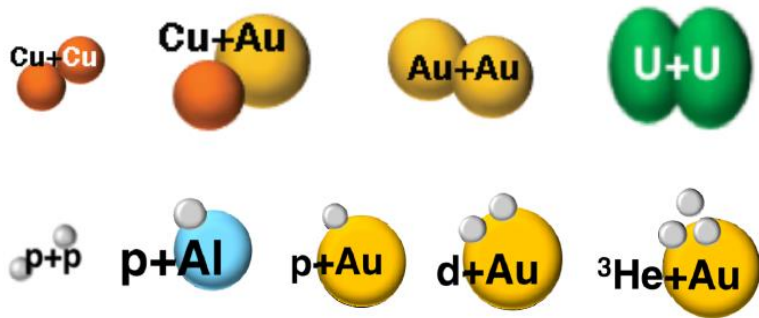
- Shape of the correlation functions with Lévy source:

$$C_2(q) = 1 + \lambda \cdot e^{-|qR|^\alpha}; \quad \alpha=2: \text{Gaussian}; \quad \alpha=1: \text{exponential}$$

- A possible reason for Lévy source: criticality, anomalous diffusion, many others

PHENIX Run History

Accomplished 16 years of operation with 9 collision species and 9 collision energies. Both **geometry** and **beam energy scan**.



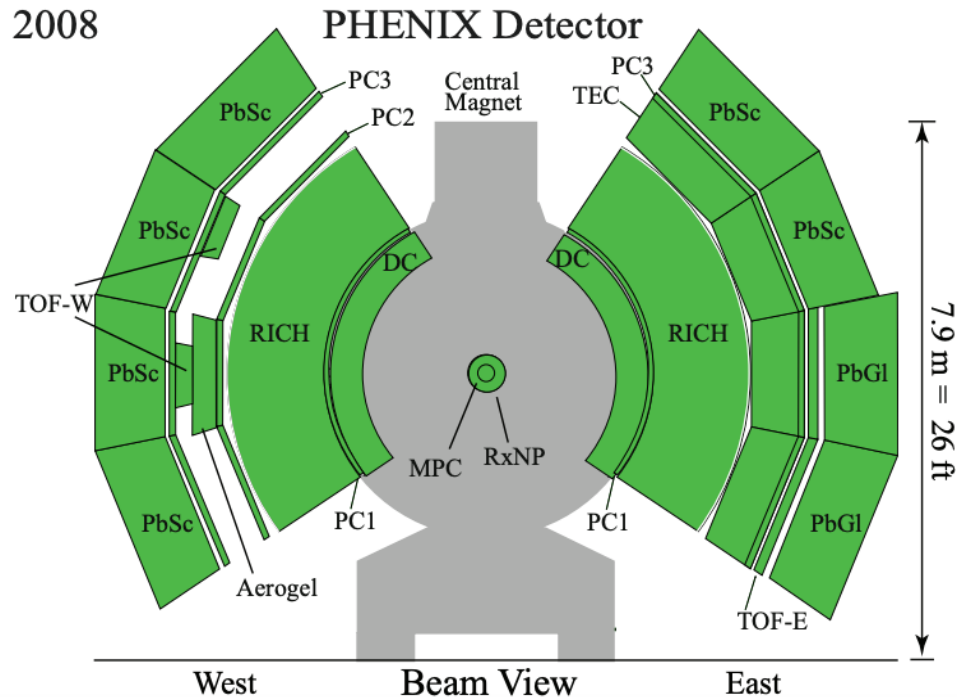
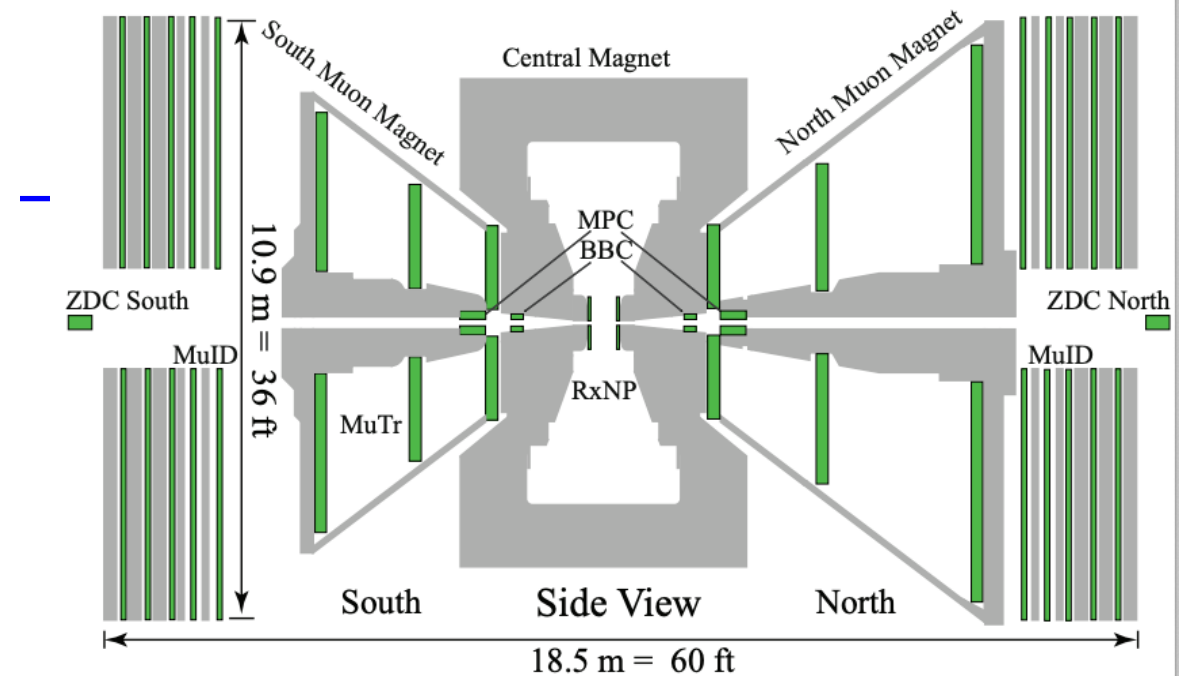
Although PHENIX is no longer actively recording data, analysis continues, exploiting the **discovery potential** of PHENIX.

In this talk: centrality dependence of Bose-Einstein correlations in a **2010** RHIC run ¹¹ for **Au+Au** at $\sqrt{s_{NN}} = 200$ GeV

Species	Run Year
Au+Au	2001, 2002, 2004, 2007, 2008, 2010 , 2011, 2014, 2016
d+Au	2003, 2008, 2016
Cu+Cu	2005
U+U	2012
Cu+Au	2012
3He+Au	2014
p+Au	2015
p+Al	2015

Muon Arms

- Rapidity coverage: $1.2 < |y| < 2.2$
- Muon Tracking followed by Muon Identifier
 - *Stainless steel and copper absorbers for hadron rejection*
- BBC measures collision vertex along beam axis



Central Arms

- Rapidity coverage: $|y| < 0.35$
- Charged particle tracks and momentum – pad and drift chambers
- Ring Imaging Cherenkov detector for pion rejection
- Energy / momentum matching of charged particles using EMCal clusters

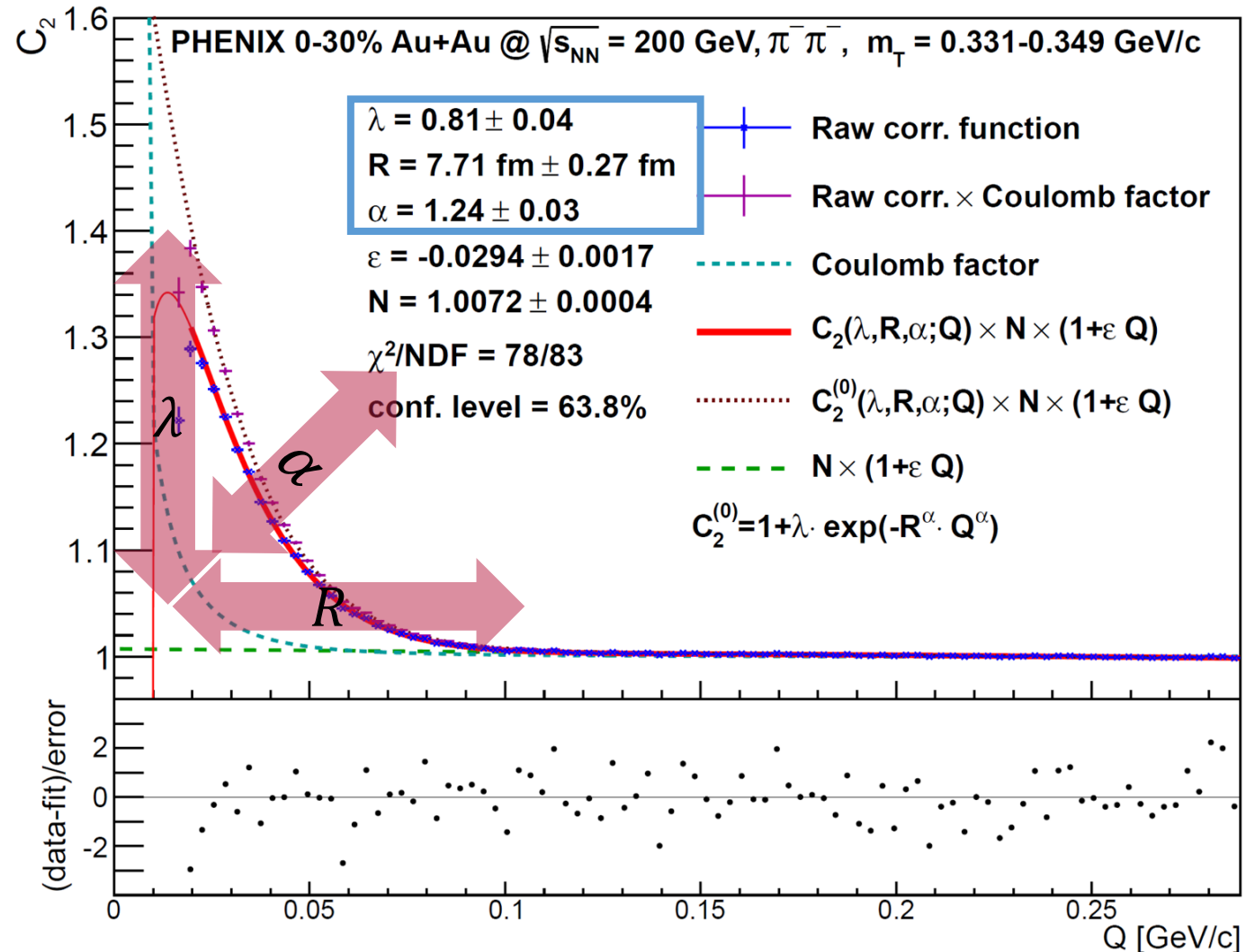
Data sample

- $\sqrt{s_{NN}} = 200$ GeV Au+Au, half field in PHENIX central magnet allows pion id down to transverse momentum $p_T > 0.16$ GeV
- Min. bias data sample ~ 7.3 billion events.
- 0 – 60 % centrality selection ~ 4.4 billion events. Centrality vs N_{part} determination with PHENIX Glauber calculations.
- Six centrality classes: 0-10%, 10-20%, 20-30%, 30-40%, 40-50% and 50-60%
- In each centrality class: 23 bins in $m_T = \sqrt{(m^2 + p_T^2)}$, from 0.248 GeV to 0.876 GeV
- Due to broader central range, more stringent pair cuts, as compared to our 0-30 % results published in Phys. Rev. C 97 (2018) 064911. Other details similar.

Example Correlation Function

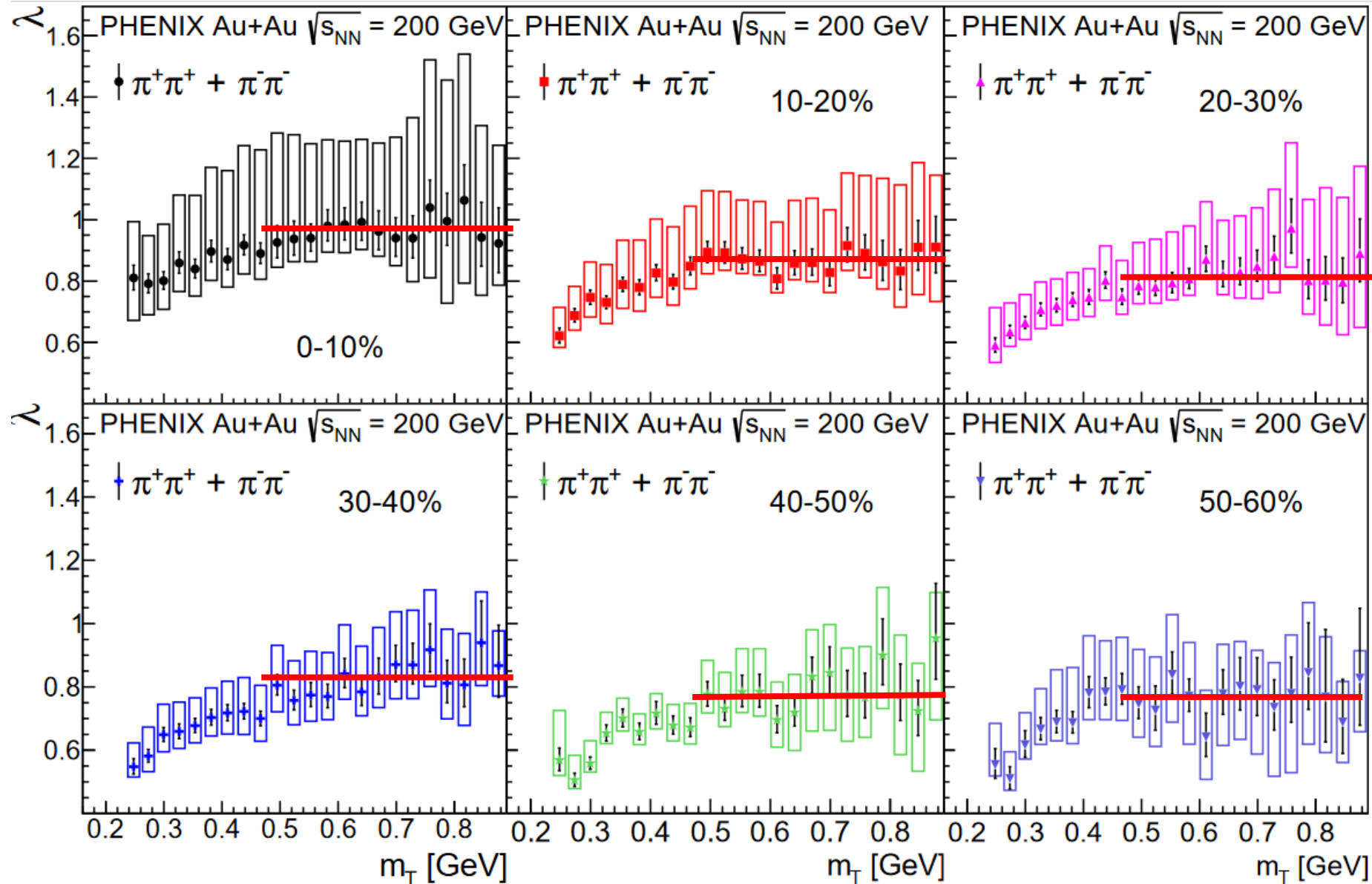
- Fit with calculation based on Lévy distribution
- Physical parameters: R , α , λ measured versus pair m_T
- R : homogeneity length, dynamics, sizes
- α : shape, criticality, anomalous diffusion
- λ : particle creation mechanisms, in-medium mass modification

Lévy works well: CL=63.8%



m_T and centrality dependent results

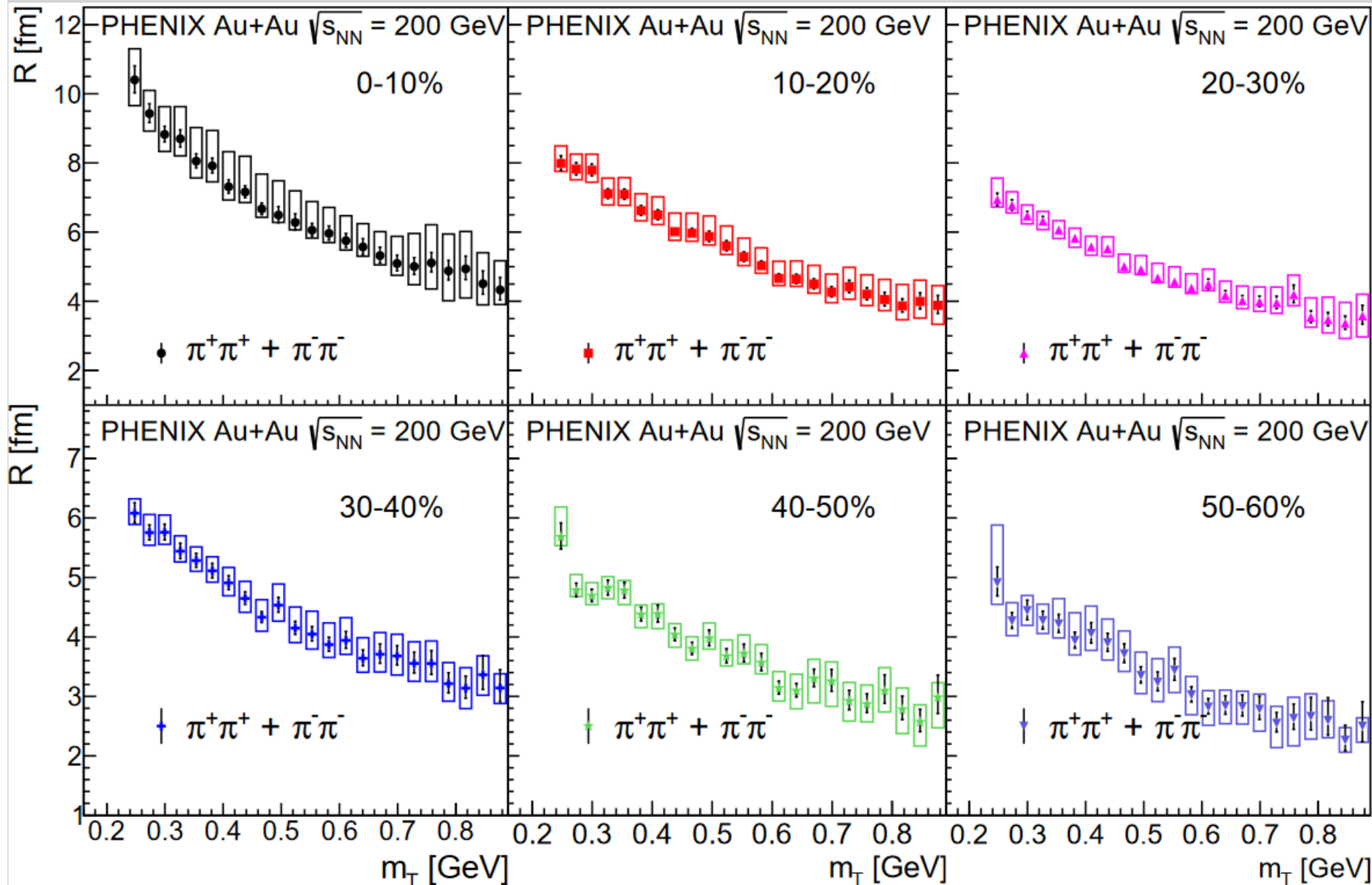
m_T and centrality dependence of Lévy λ



Results for Lévy λ
 saturation at large m_T
 and
 suppression at low m_T
 IN EACH
 CENTRALITY CLASS

Saturated region:
 $0.45 \leq m_T \leq 0.9$ GeV
 average value: λ_{\max}

m_T and centrality dependence of Lévy R

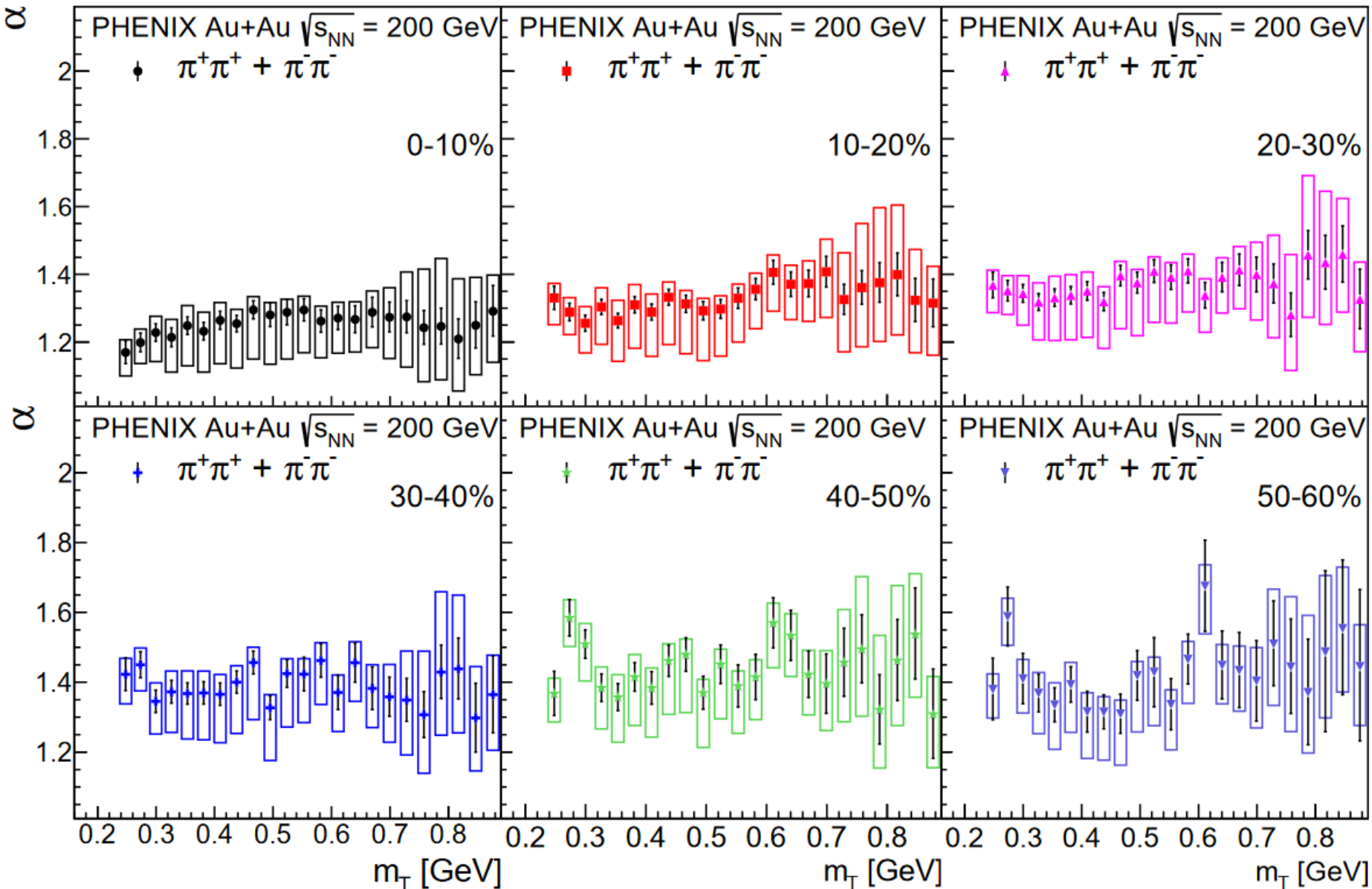


Results for Lévy R

monotonic decrease
with increasing m_T

IN EACH
CENTRALITY CLASS

m_T and centrality dependence of Lévy α



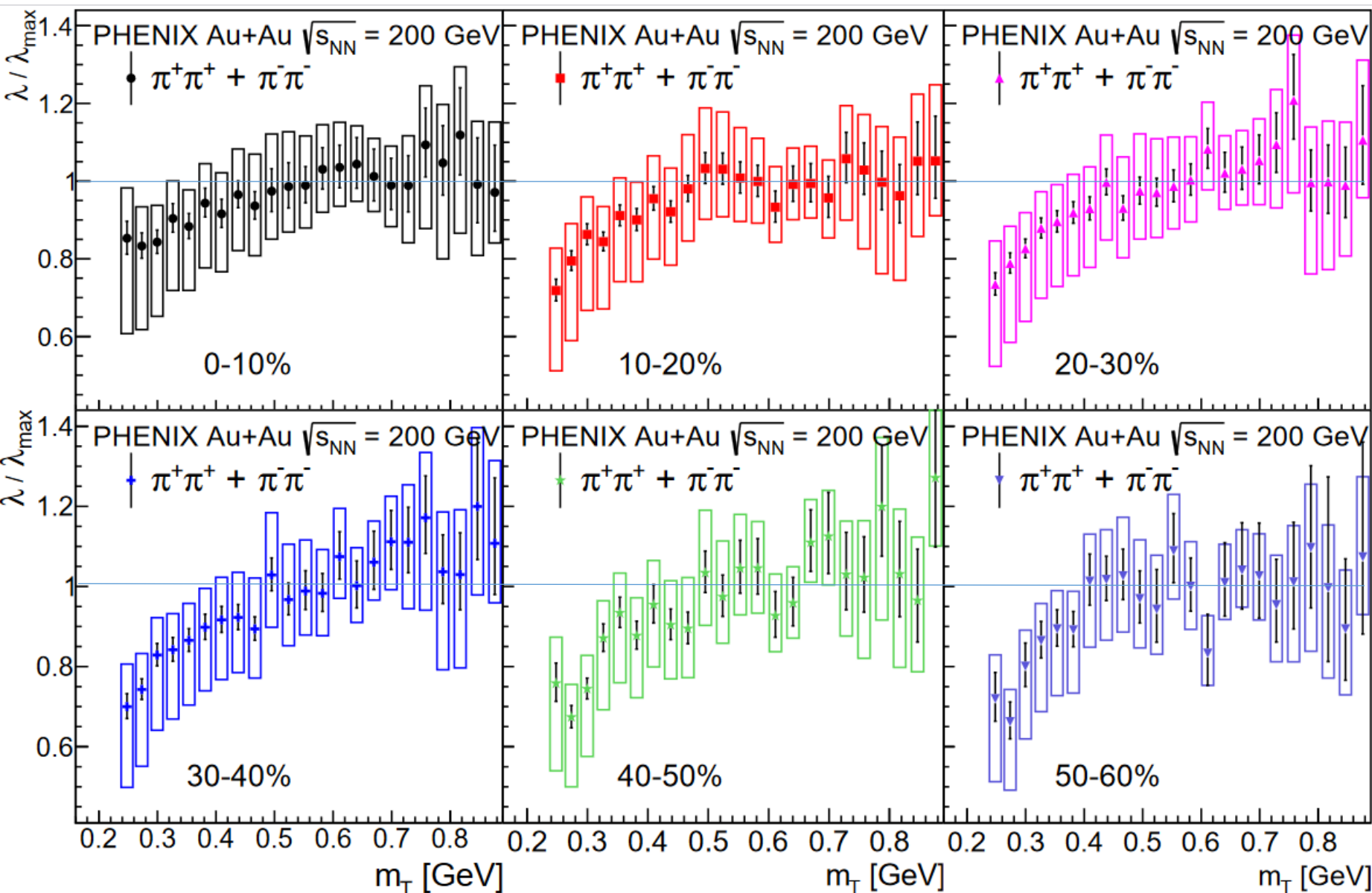
Results for Lévy α

m_T independent
constant α_0 value

IN EACH
CENTRALITY CLASS

Parametrization of m_T dependence

m_T and centrality dependence of Lévy λ/λ_{\max}



$0.45 \leq m_T \leq 0.9$ GeV
 average value: λ_{\max}

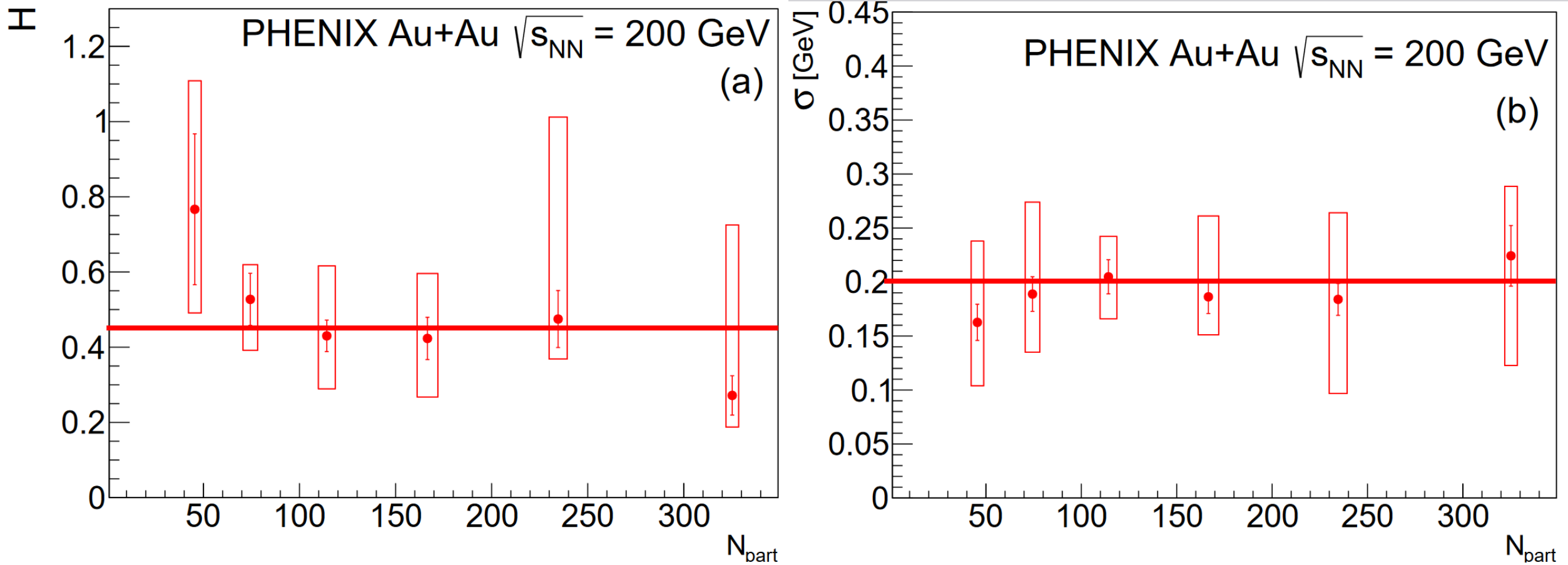
**Unexpected,
 centrality
 independent scaling**

IN EACH
 CENTRALITY CLASS

$$\frac{\lambda}{\lambda_{\max}} = 1 - H \exp\left(-\frac{m_T^2 - m_\pi^2}{2\sigma^2}\right)$$

Values of
 σ and H are expected
 to be independent
 of centrality

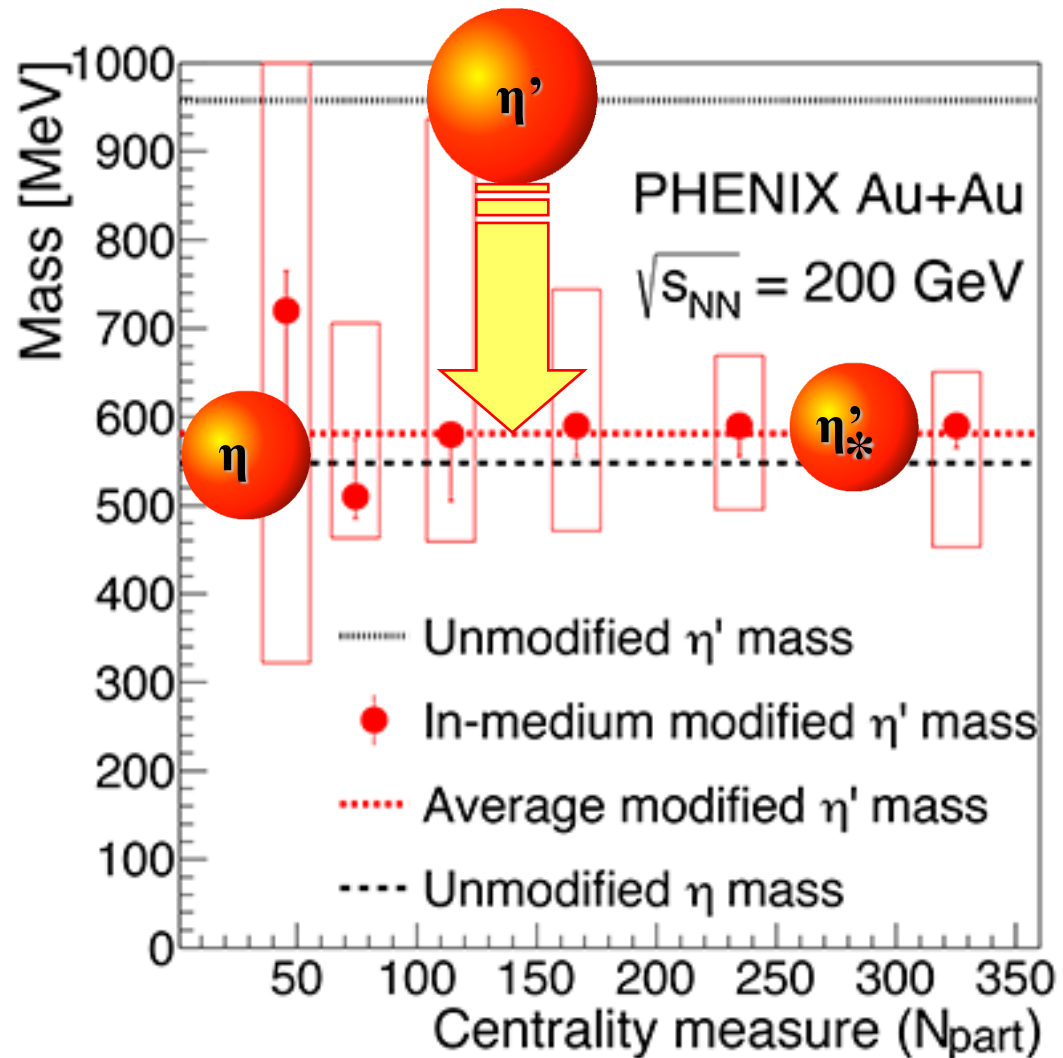
Centrality dependence of Lévy σ and H



$$\frac{\lambda}{\lambda_{\text{max}}} = 1 - H \exp\left(-\frac{m_T^2 - m_\pi^2}{2\sigma^2}\right)$$

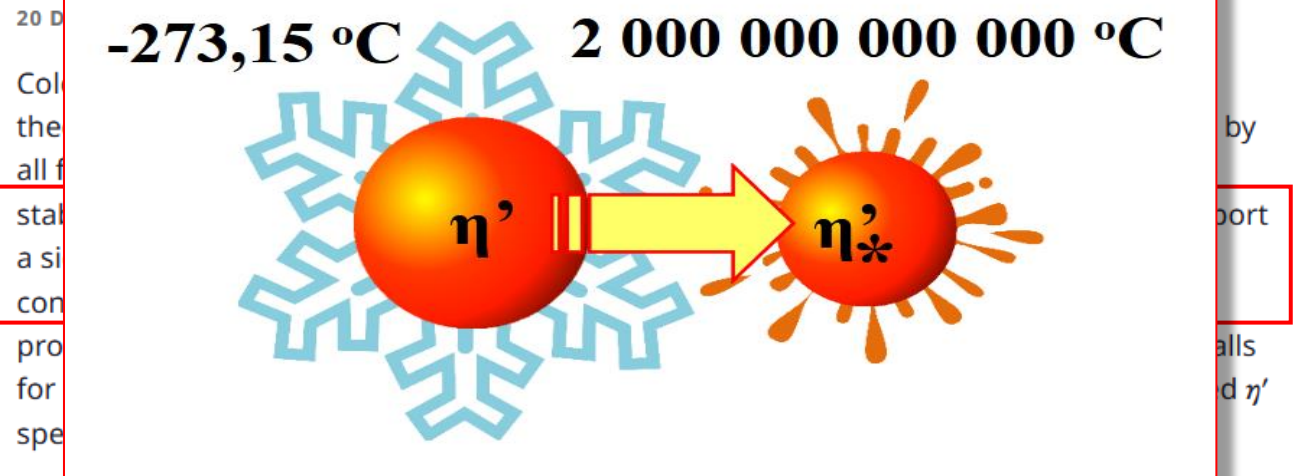
Values of σ and H are (within errors) independent of centrality, with a CL > 0.1 %

2024: „This implies a second transition in QCD...” /PRC Editors/



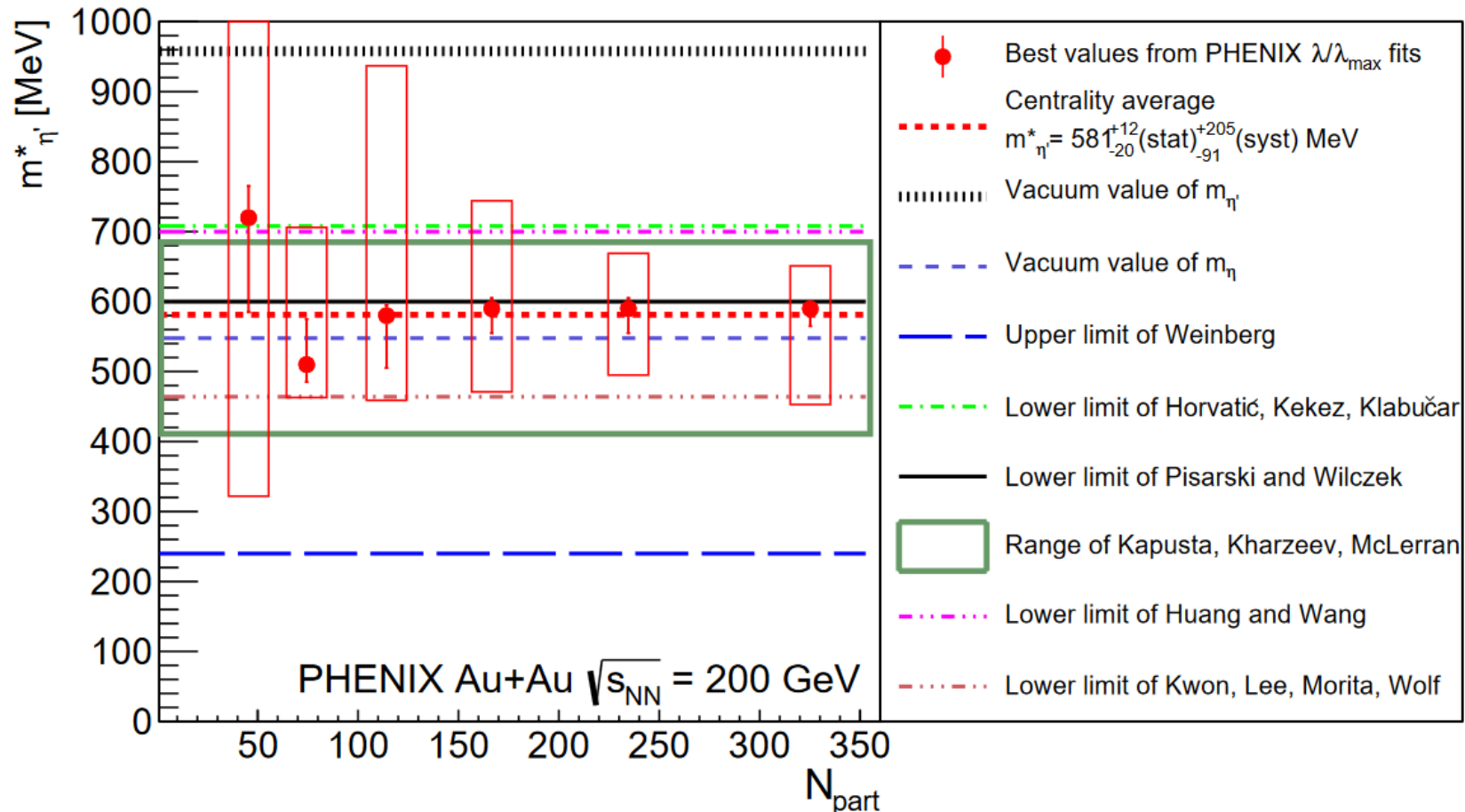
EDITORS' SUGGESTION

Centrality dependence of Lévy-stable two-pion Bose-Einstein correlations in $\sqrt{s_{NN}} = 200 \text{ GeV}$ Au + Au collisions



N. J. Abdulameer *et al.* (PHENIX Collaboration)
[Phys. Rev. C **110**, 064909 \(2024\)](#)

N_{part} dependence of in-medium mass of η'

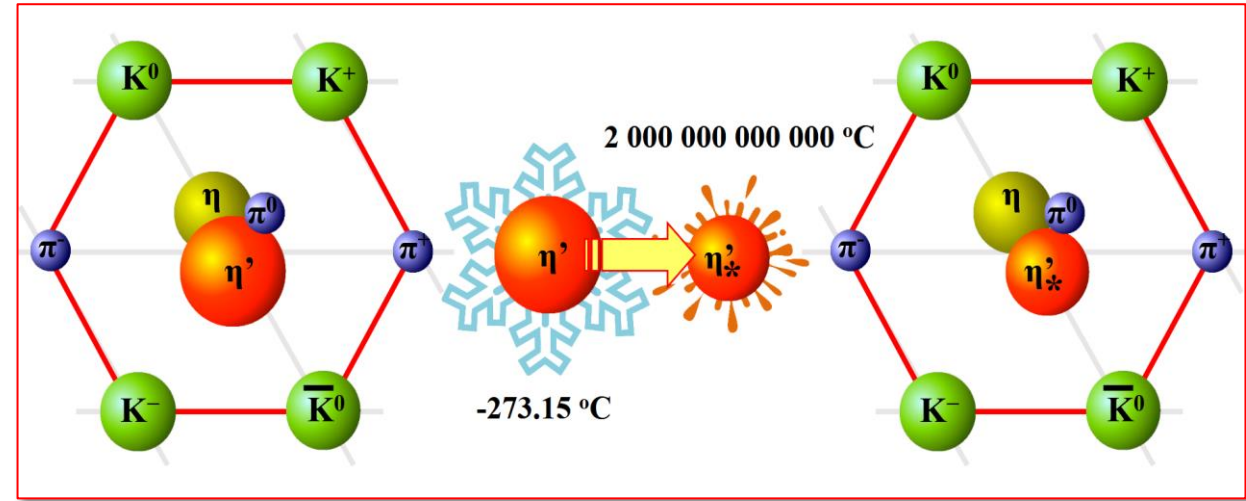


In-medium mass of η' is determined with the help of Levy Bose-Einstein correlation measurements to be similar to the vacuum mass of η in each centrality class: indirectly, return of the prodigal Goldstone boson η'

Centrality dependent selection power, successful: KHM, KLMW, PW: $m^*(\eta') \sim m(\eta)$

Summary and conclusions

- Centrality dependent BECs in $\sqrt{s_{NN}}=200\text{GeV}$ Au+Au collisions by PHENIX
- $1 < \alpha < 2$ significantly, decreasing with increasing N_{part}
- Unexpected scaling laws found
- Data not inconsistent with $U_A(1)$ symmetry restoration: in-medium mass modification of η' with indirect method
- Direct observation is particularly challenging, but also particularly rewarding:
- Challenge for sPhenix?



Thank you for your attention!

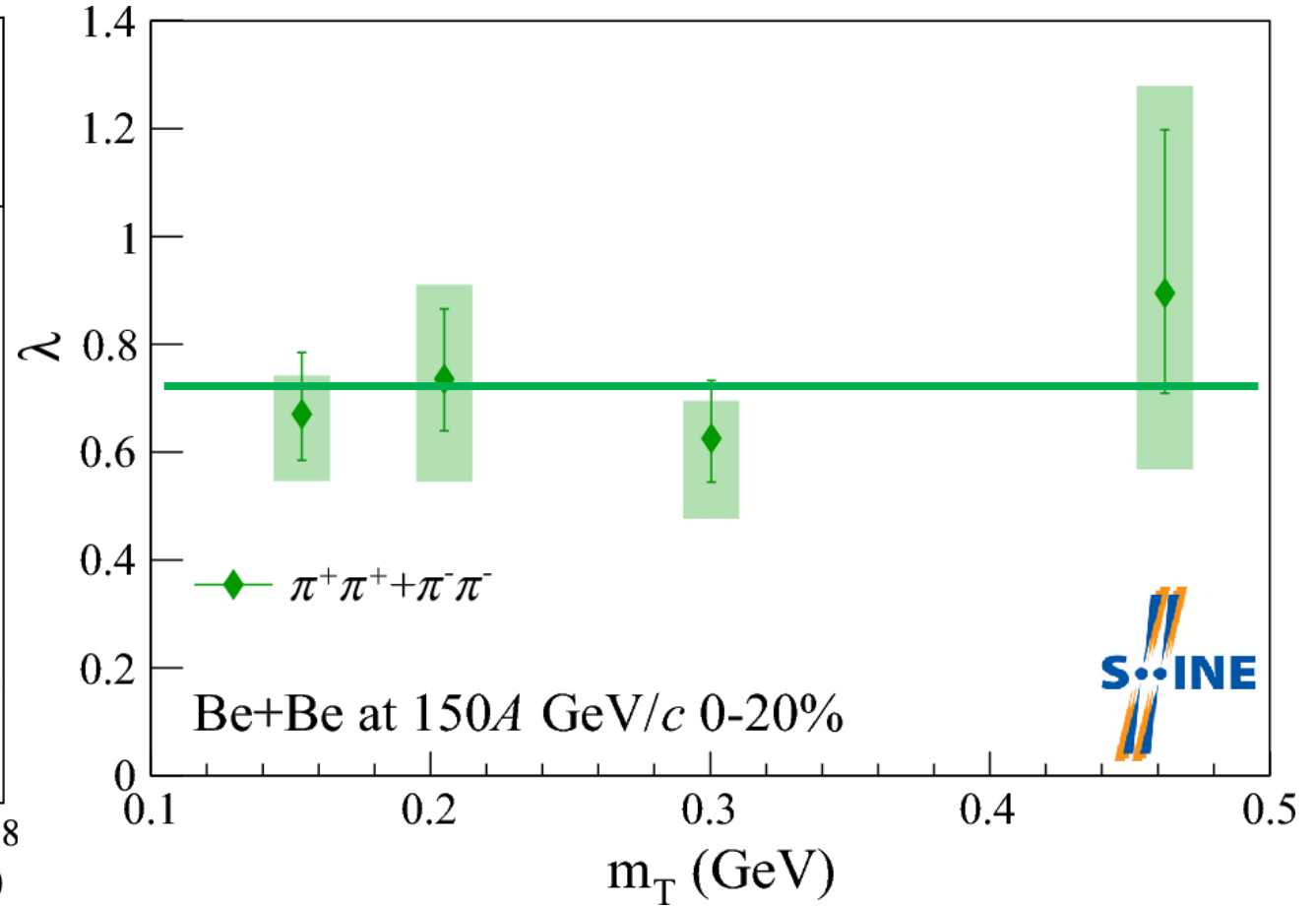
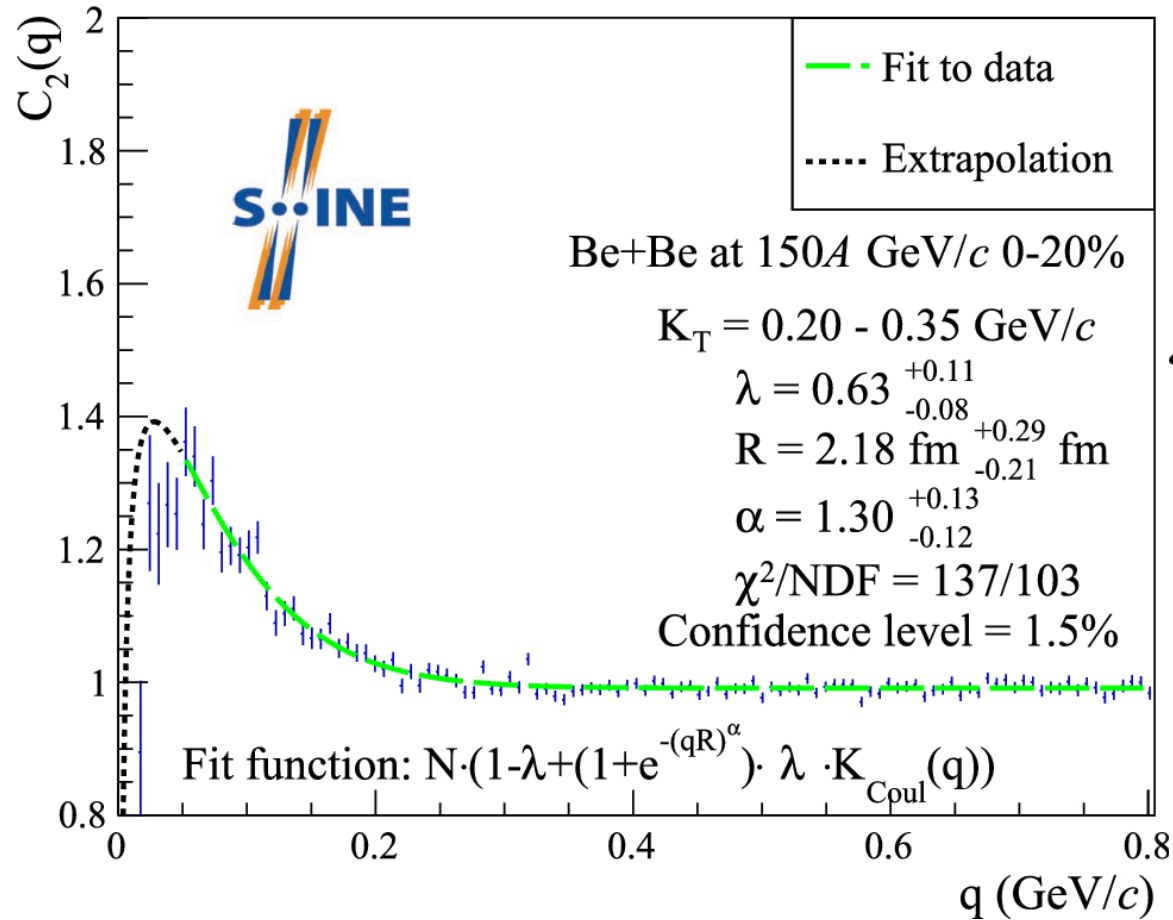
Back up

Direct and indirect observation



Can λ/λ_{\max} $U_A(1)$ restoration signal be switched off?

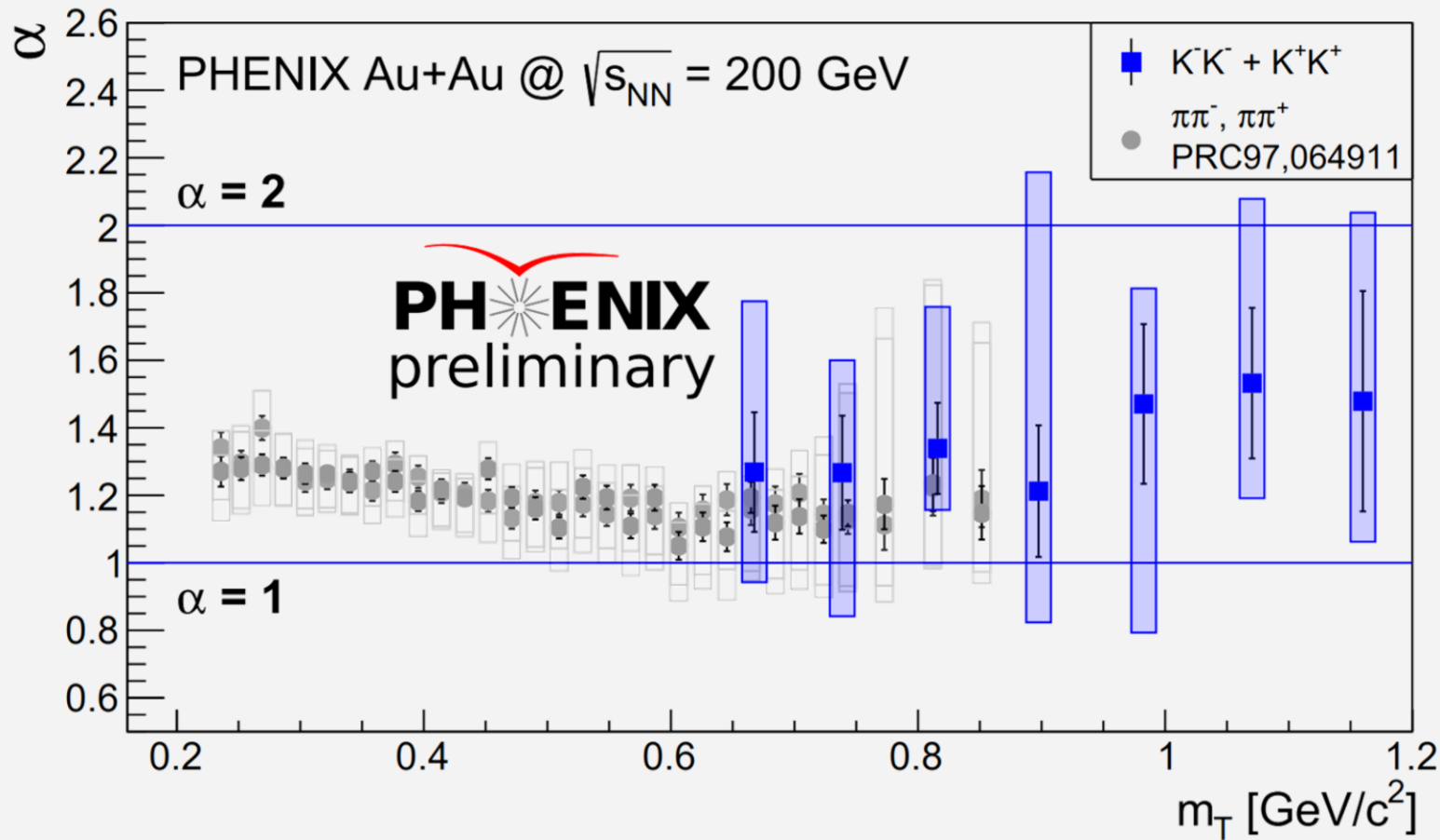
Yes, as known from the first papers, but confirmed by NA61!



NA61 data: no signal of decrease of λ/λ_{\max} for $m_T < 0.5$ GeV, no signal of $U_A(1)$ symmetry restoration
 Small systems (Be+Be) and relatively low energy, $\sqrt{s} < 20$ GeV.

NA61 data on charged $\pi\pi$ correlation in 150 AGeV Be+Be collisions
 Eur.Phys.J.C 83 (2023) 10, 919, e-Print: [2302.04593](https://arxiv.org/abs/2302.04593) [nucl-ex]

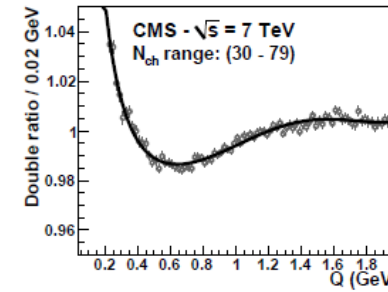
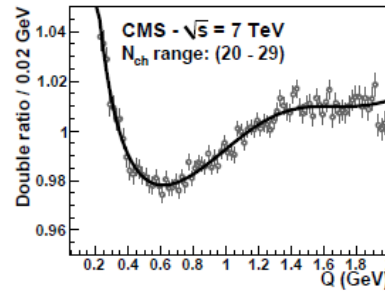
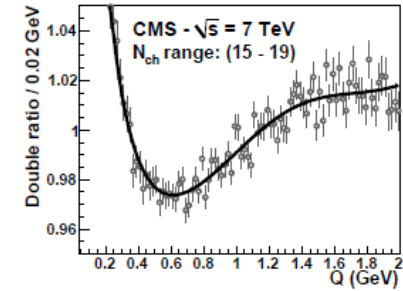
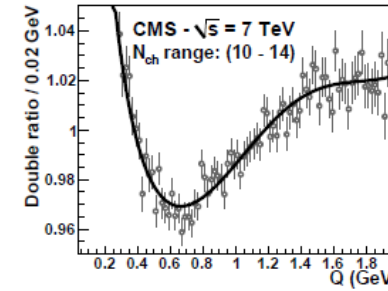
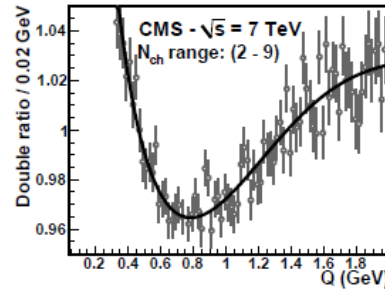
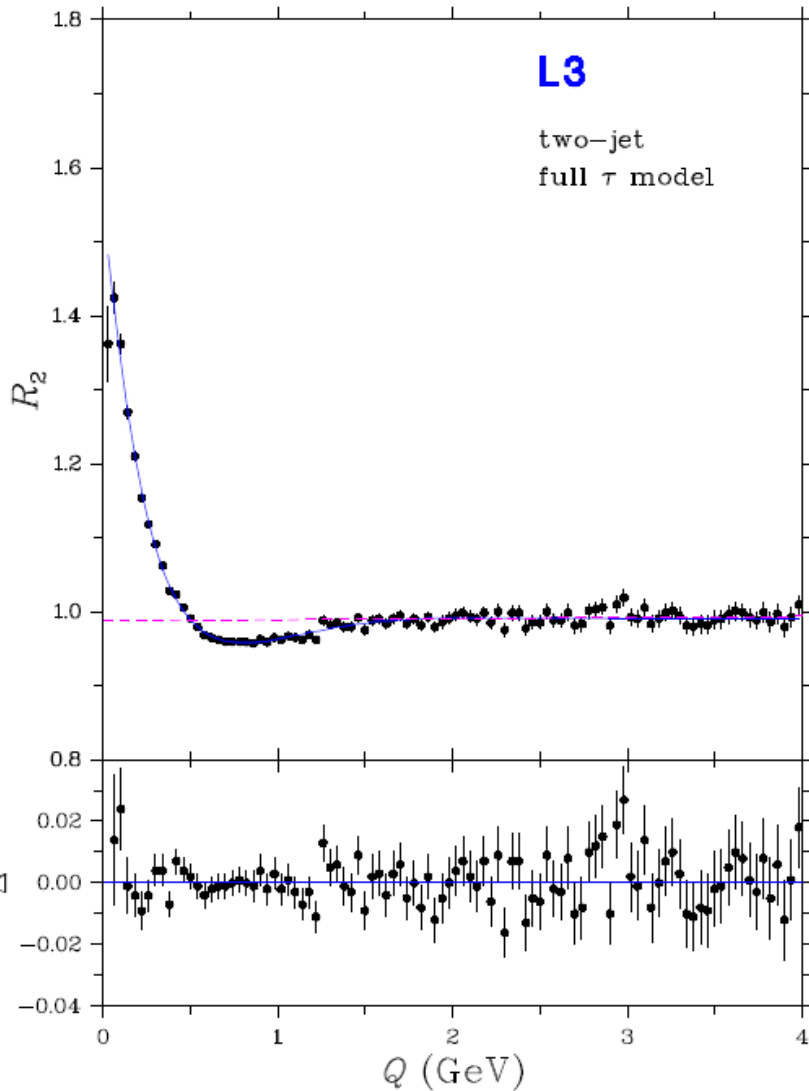
Kaon Lévy shape - α



- Does not exhibit strong dependence on transverse mass
- Kaon α consistent with pions, weak $\alpha(K) \geq \alpha(\pi)$ indication
- Anomalous diffusion suggests $\alpha(K) < \alpha(\pi)$

[M. Csanád, T. Csörgő, M. Nagy, *Braz.J.Phys.* 37 (2007) 1002]

Earlier Experimental Applications of Lévy



- Three experimental results:
 - L3 e+e-at LEP
 - CMS pp at LHC
 - TOTEM at LHC

