XIII International Conference
on New Frontiers in Physics
26 Aug - 4 Sep 2024, OAC, Kolymbari, Crete, Greece

PHENIX Heavy Ion Overview

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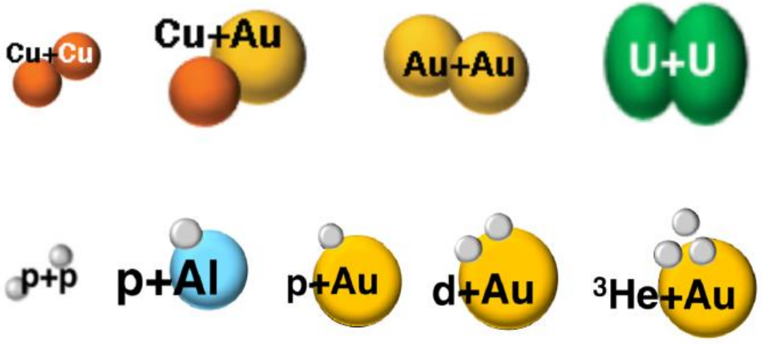
XIII International Conference
On New Frontiers in Physics

Progresses from larger systems to smaller systems

PHENIX Run History

Accomplished 16 years of operation with 9 collision species and 9 collision energies

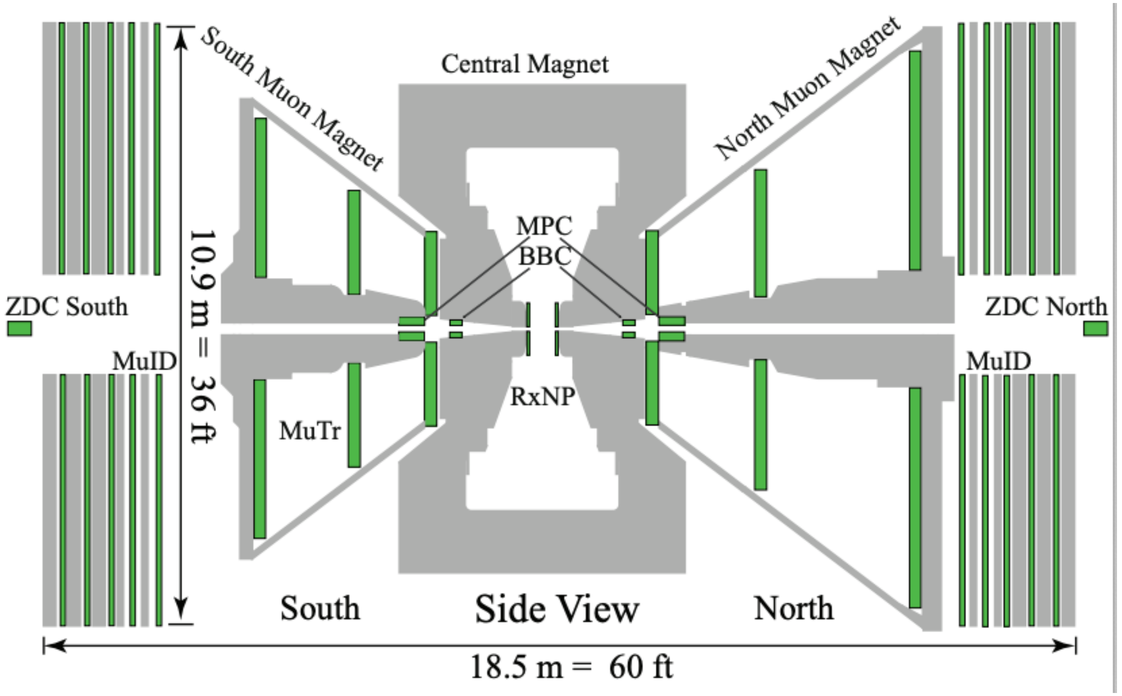


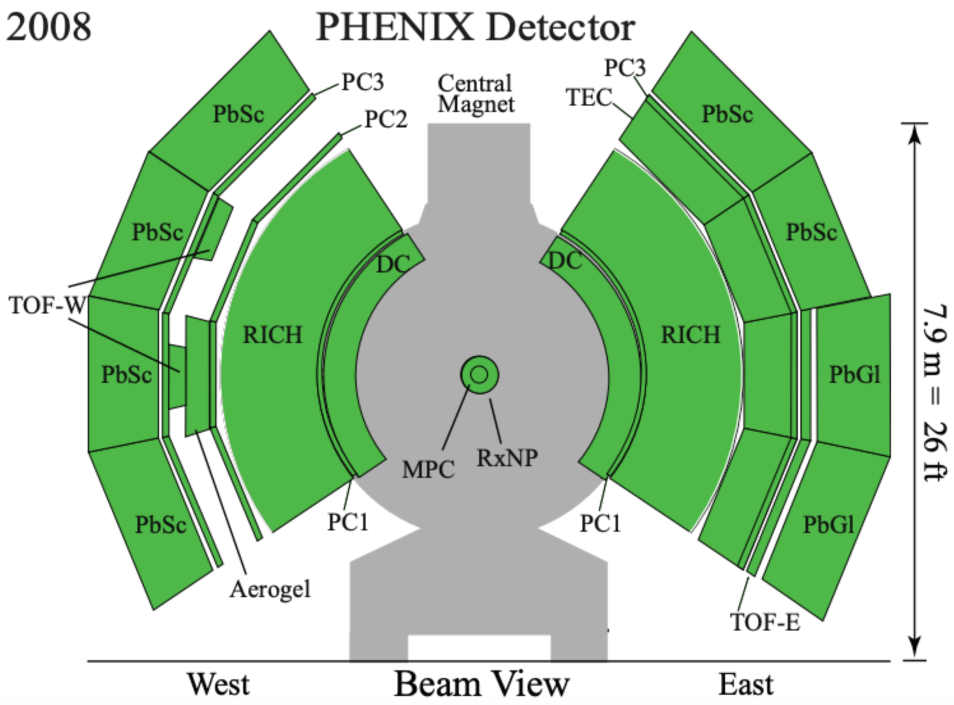
Although PHENIX is no longer actively recording data, analysis continues with the primary focus on these most recent data sets.

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
^{3}He+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

Small Systems Results

CNM Effects

- Gluon Shadowing/Anti-Shadowing:

Modification (suppression/enhancement) of heavy quark cross section due to modifications of the gluon structure function

- Parton Energy Loss:

The projectile gluon experiences multiple scattering while passing through the target before J/ψ production, reducing the rapidity of the J/ψ

- Cronin Effect:

Modification of the J/ψ p_T distribution due to multiple elastic scattering of partons

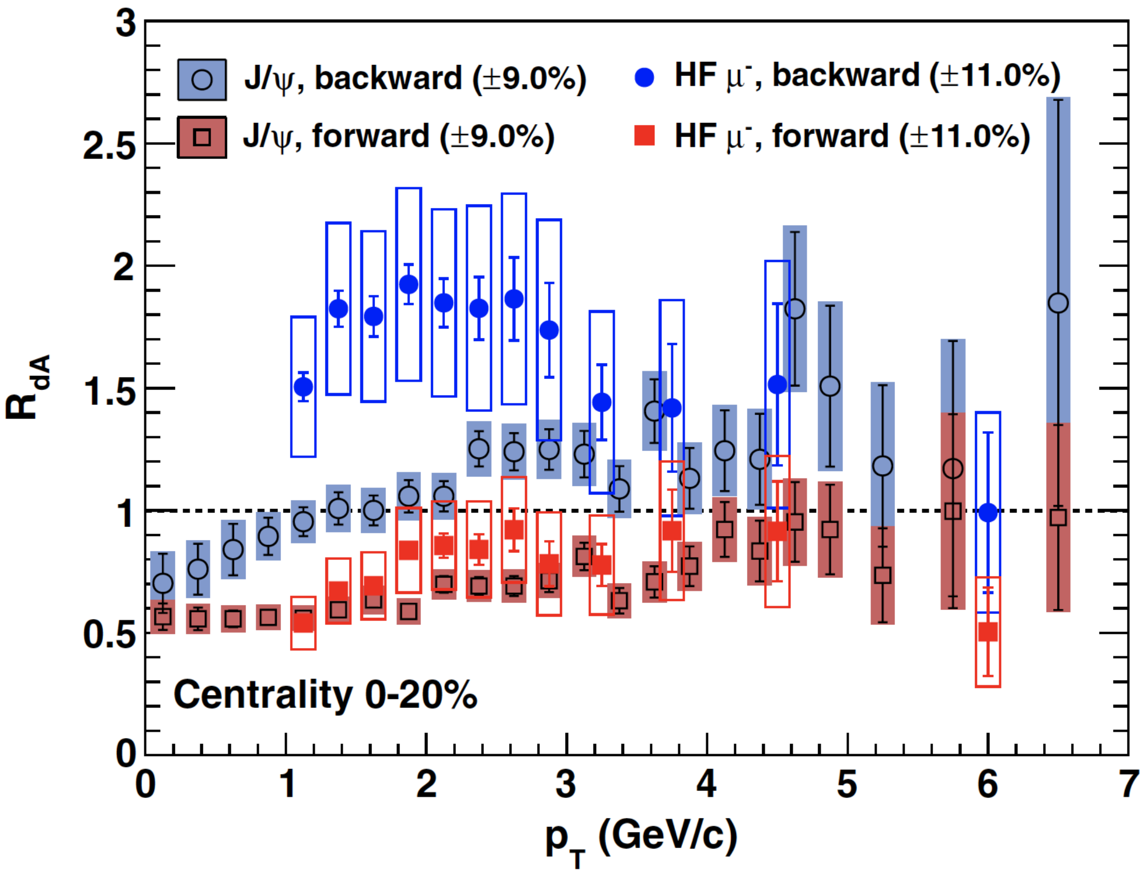
- Nuclear Break-Up:

The break up of the bound J/ψ (or precursor state) in collisions with other target nucleons that pass through J/ψ production point

- Co-Movers Break-Up:

Final state break up of the J/ψ through interactions with produced partons

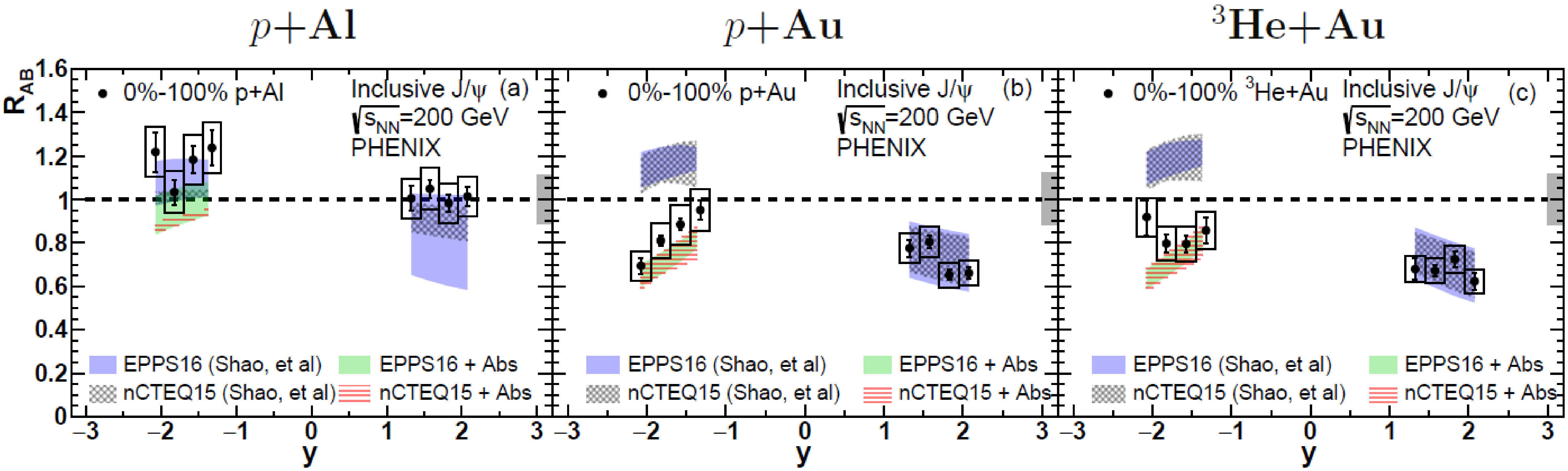
J/ψ Nuclear Modification (2014)



- Forward rapidity: J/ψ suppression similar to open charm suppression
  - Consistent with shadowing and/or parton energy loss
- Backward rapidity: J/ψ suppressed relative to open charm
  - Expect open charm enhanced by anti-shadowing
  - J/ψ suppression consistent with absorption from collisions with nucleons in target
  - Possible contribution also from co-movers

Phys. Rev. Letters 112, 252301 (2014)

J/ψ Nuclear Modification (2020)

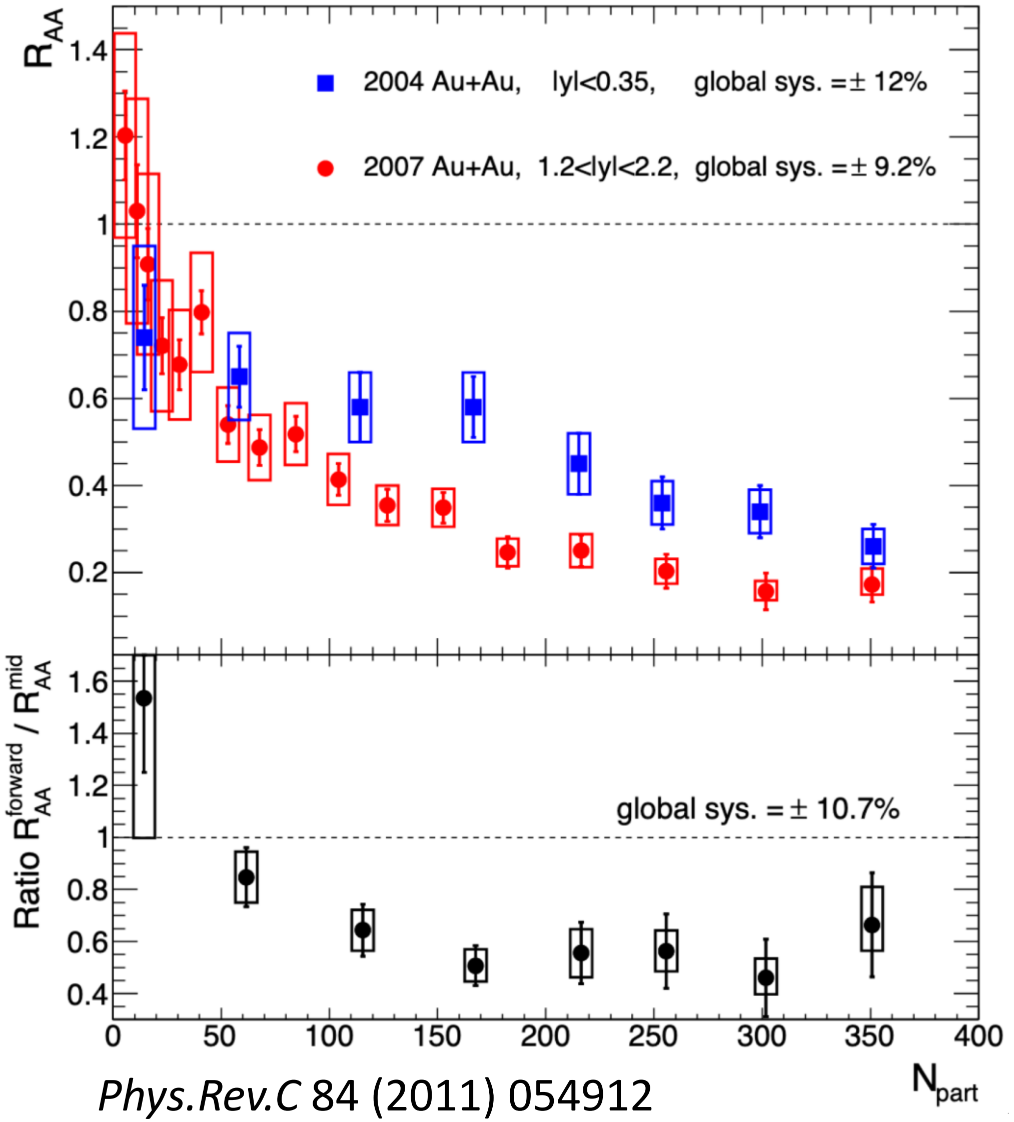


Phys. Rev. C 102, 014902 (2020)

- **Predictions for *p*/^{3}He+Au based on Bayesian reweighting method using J/*ψ* constraints from *p*+Pb data at the LHC**
- **Added PHENIX nuclear absorption estimate at backward rapidity**

Large Systems Results

J/ψ Suppression puzzle

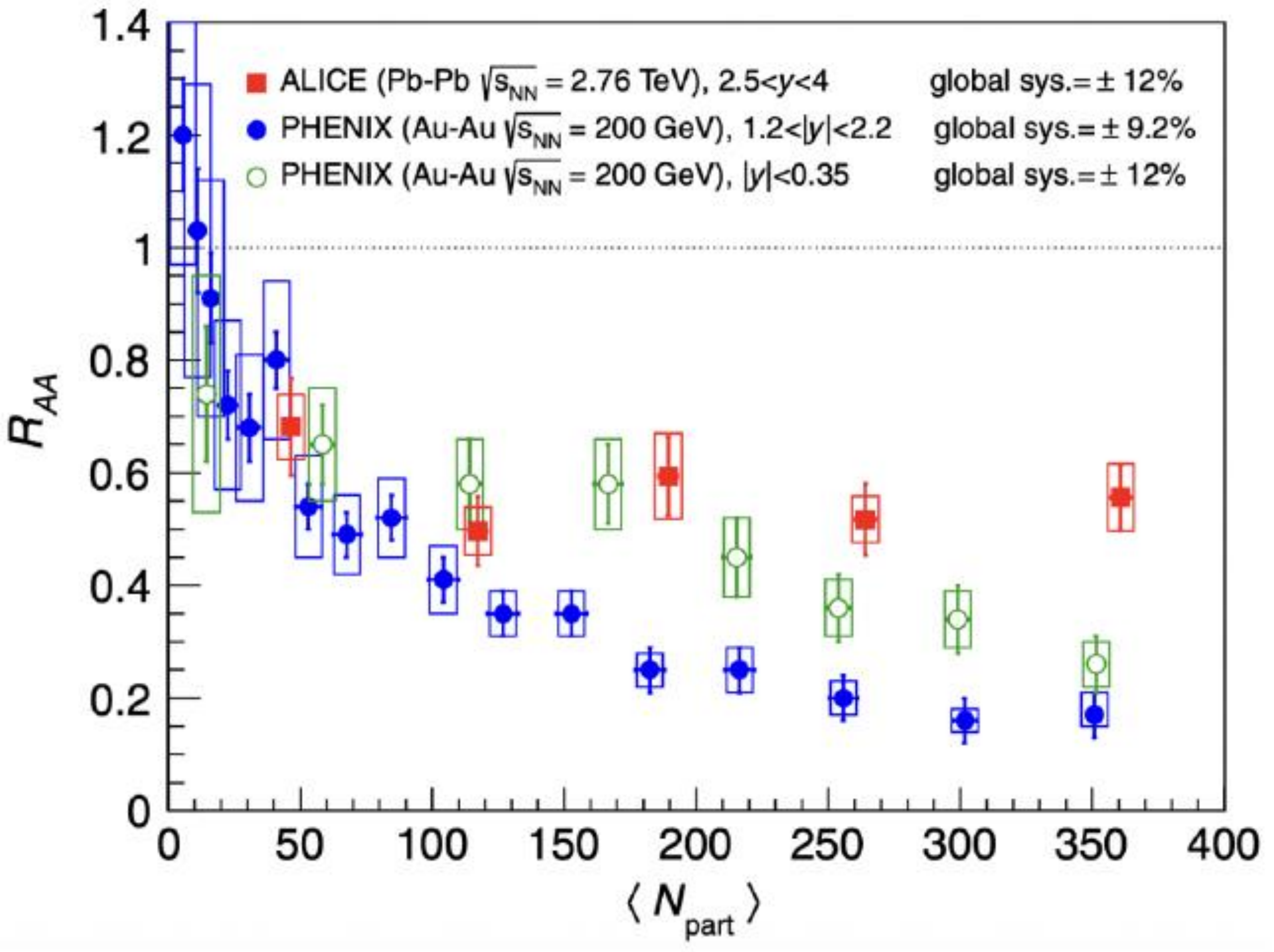


Phys.Rev.C 84 (2011) 054912

- $R_{AA}^{\mathrm{Fwd}} < R_{AA}^{\mathrm{mid}}$, **contrary to expectation**
- **~20 $c\bar{c}$ pairs in collisions at RHIC (mostly at mid-rapidity)**

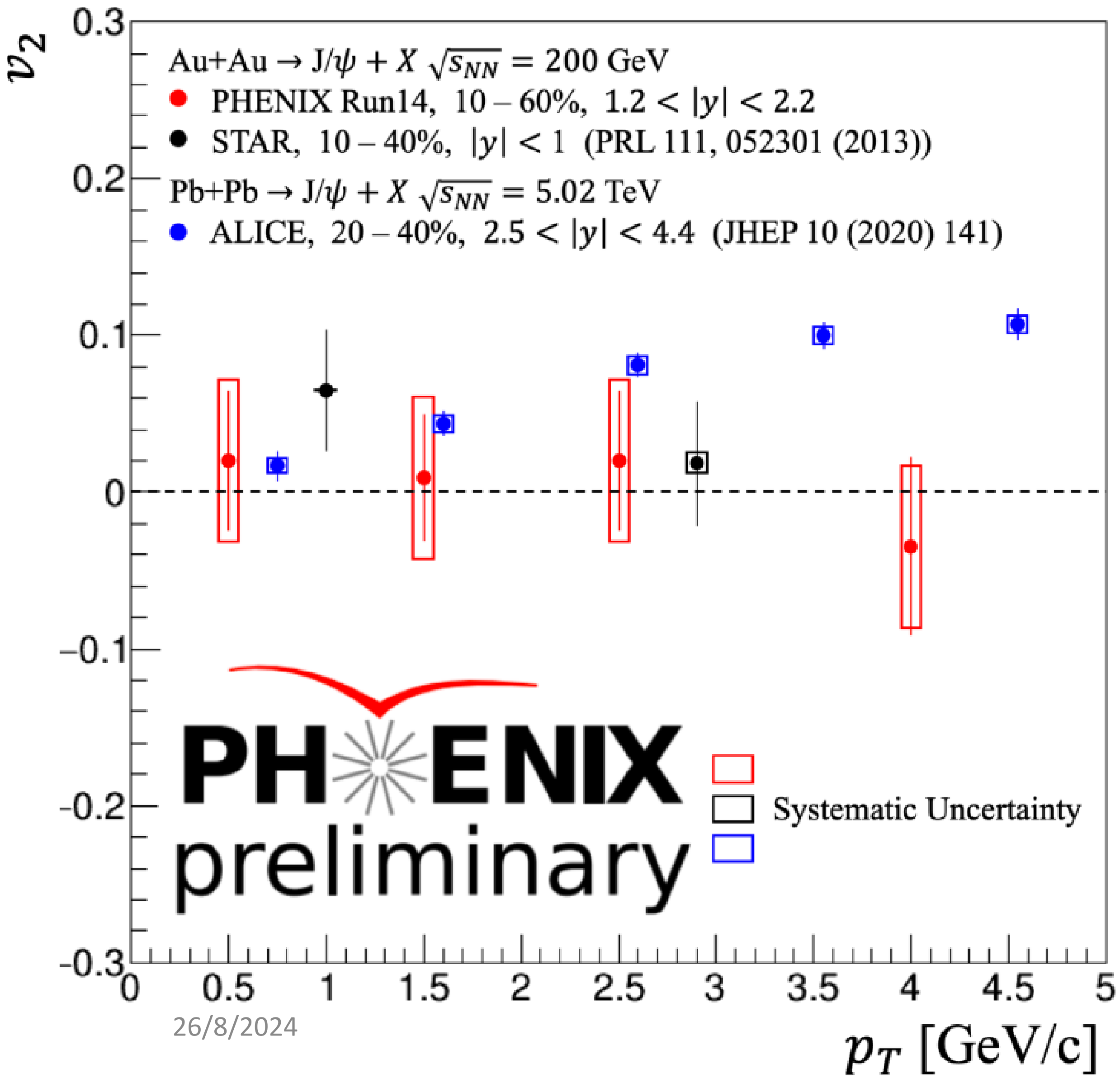
Can we attribute this significant difference in J/ψ R_{AA} to regeneration of J/ψ from $c\bar{c}$ pairs at mid-rapidity?

Coalescence as the solution



- $R_{AA}^{\mathrm{LHC}} > R_{AA}^{\mathrm{RHIC}}$
- **Greater J/ψ suppression predicted at higher T**
- **PHENIX J/ψ shows stronger suppression at both forward and mid-rapidity compared to ALICE**

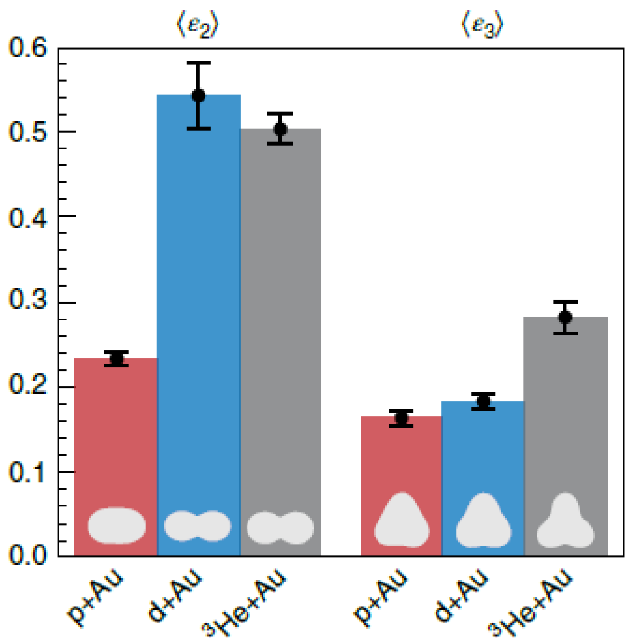
J/ψ v_2 measurement

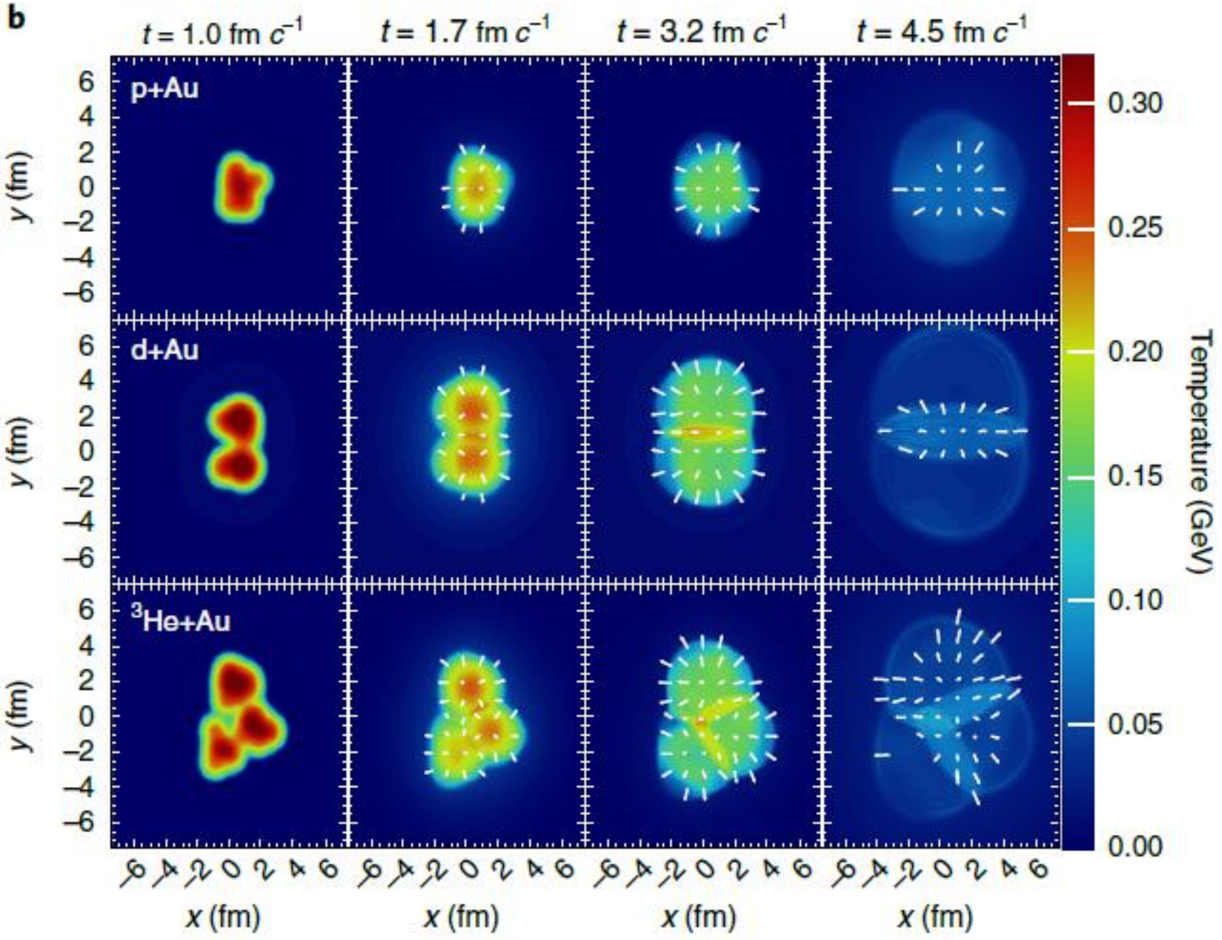


- **PHENIX J/ψ v_2 at forward rapidity is consistent with zero**
- **Forward and mid-rapidity results at RHIC are consistent, but the uncertainties are large**
- **The ALICE nonzero result is different from our measurement**
- **At RHIC energies, regeneration not as significant**

Collectivity in Small Systems

Geometry Scan : 3 different shapes





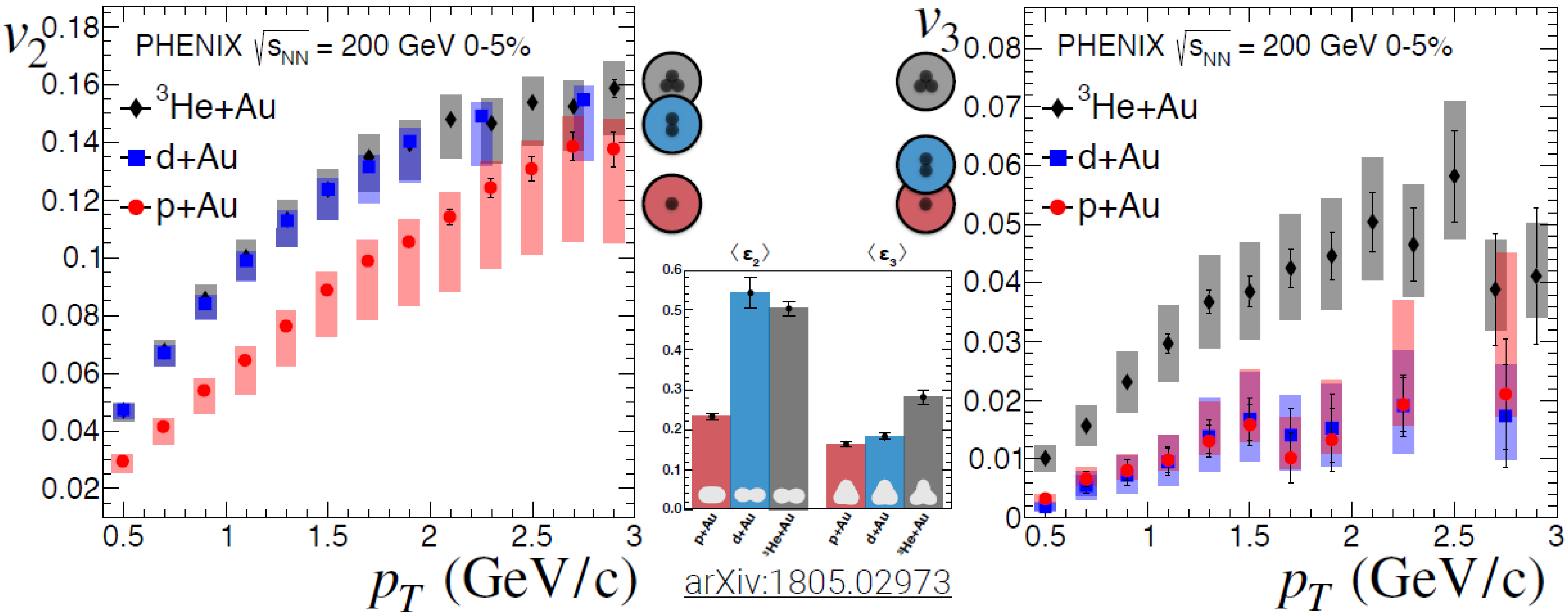
$$\varepsilon_2^{p+\mathrm{Au}} < \varepsilon_2^{d+\mathrm{Au}} \approx \varepsilon_2^{^3\mathrm{He}+\mathrm{Au}}$$

$$\varepsilon_3^{p+\mathrm{Au}} \approx \varepsilon_3^{d+\mathrm{Au}} < \varepsilon_3^{^3\mathrm{He}+\mathrm{Au}}$$

$$\varepsilon_n = \frac{\sqrt{\langle r^n \cos(n\phi)\rangle^2 + \langle r^n \sin(n\phi)\rangle^2}}{\langle r^n \rangle}$$

Hydrodynamics (SONIC, LQCD EoS, 1+2d):
Different initial geometry /energy deposition translated by ∇p
to *different* final state momentum space correlations

Flow in Small Systems: Geometric Ordering



arXiv:1805.02973

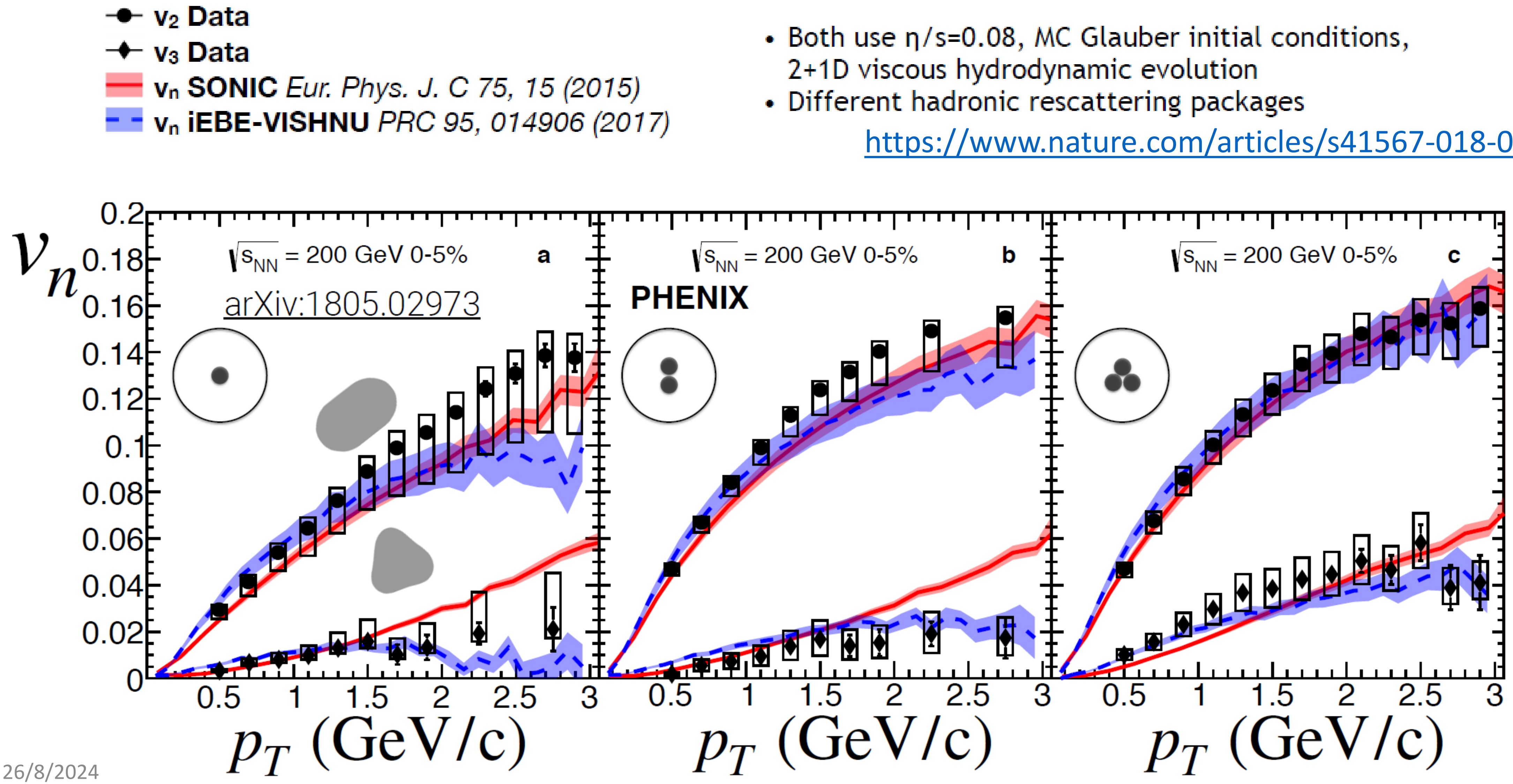
v_2, v_3 results beautifully consistent with hydro ordering

Collective motion of system translates the initial geometry into the final state

Comparison to Hydro Calculations

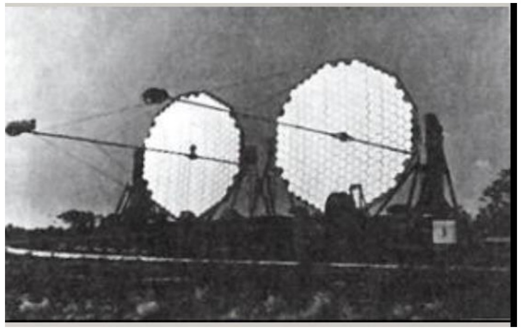
- Both use η/s=0.08, MC Glauber initial conditions, 2+1D viscous hydrodynamic evolution
- Different hadronic rescattering packages

https://www.nature.com/articles/s41567-018-0360-0



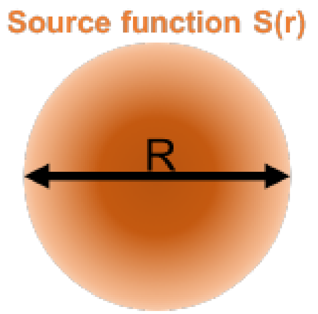
Femtoscopy in Au+Au

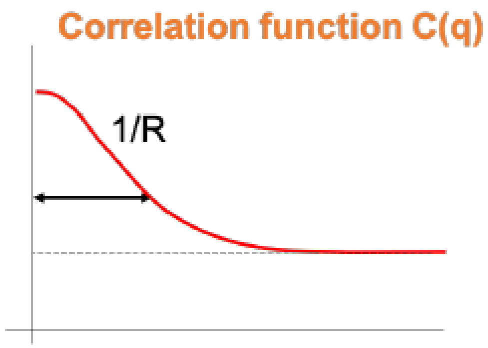
The HBT-effect in Femtoscopy

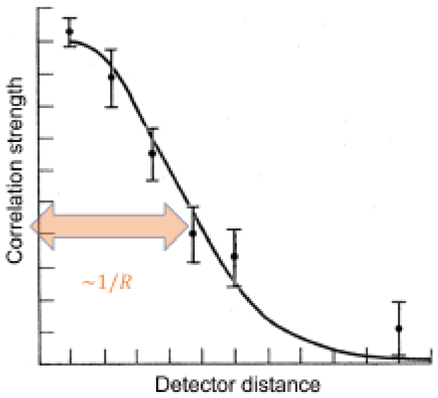


- **R. Hanbury Brown, R.Q.Twiss observed Sirius with radio telescopes**
- **R. Hanbury Brown and R. Q. Twiss 1956 Nature 178**
  - **Intensity correlations as a function of detector distance**
  - **Measuring size of point-like sources**
- **Goldhaber et al: applicable in high energy physics: (for identical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

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

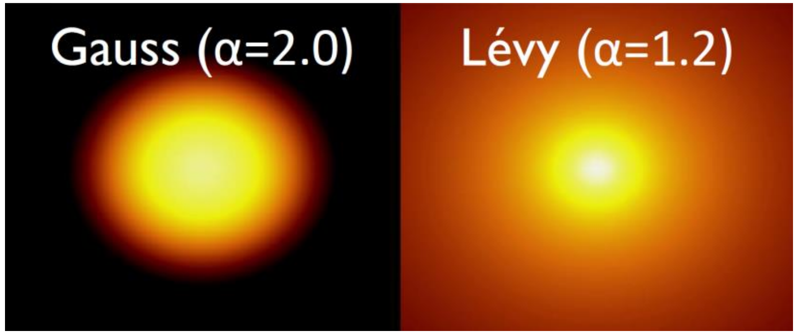






Lévy Distributions in Heavy Ion Physics

- **Usual assumption that *S*(*r*) is Gaussian → 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 ~ $r^{-(1+\alpha)}$**
  - **Special cases: α = 2 Gaussian, α = 1 Cauchy**



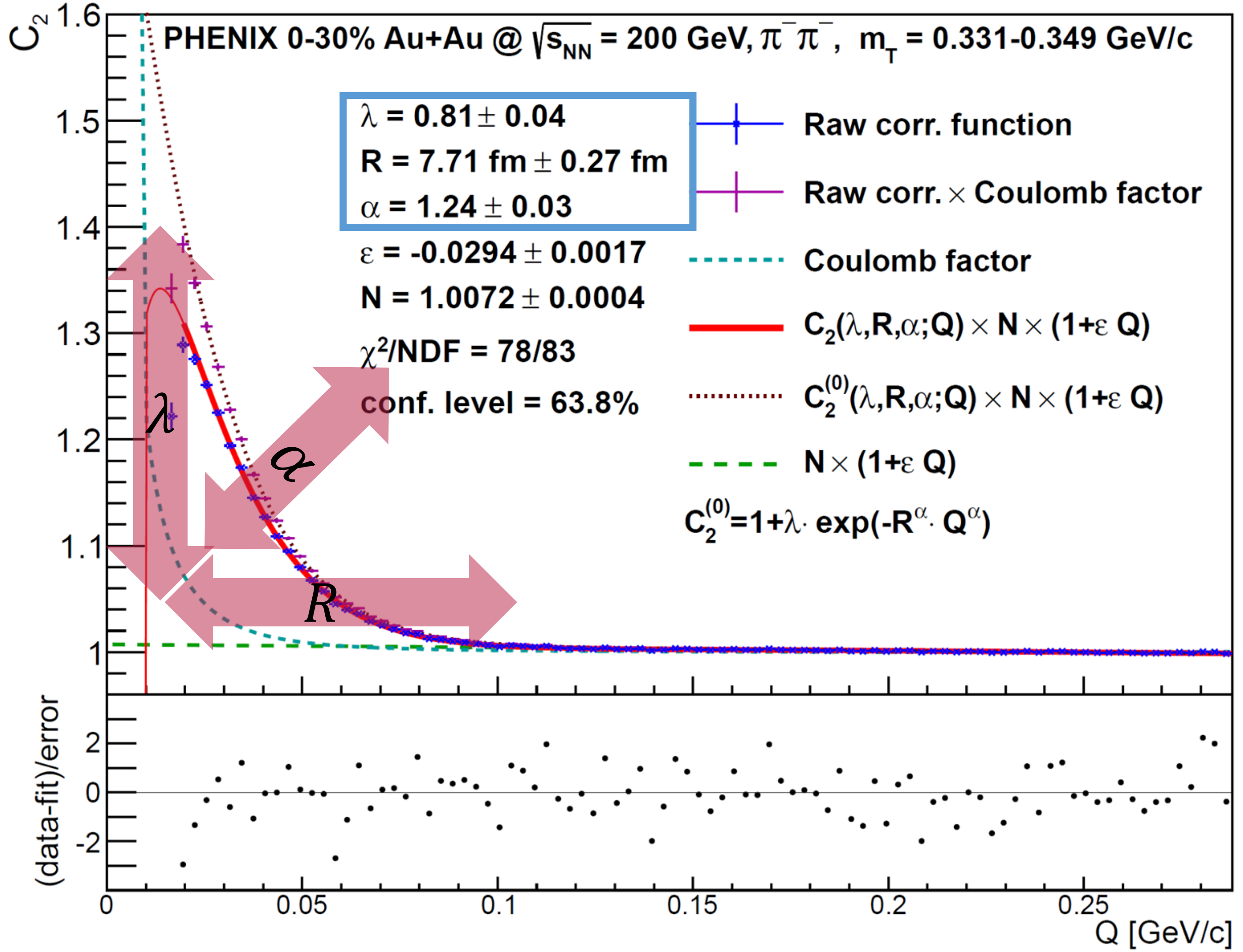
- **Shape of the correlation functions with Lévy source:**

  $C_2(q)=1+\lambda\cdot e^{-|qR|^{\alpha}}$; α=2:Gaussian; α=1:exponential Csörgő, Hegyi, Zajc, Eur.Phys.J. C36 (2004) 67 78
- **A possible reason for Levy source: criticality, anomalous diffusion, many others**

Example Correlation Function

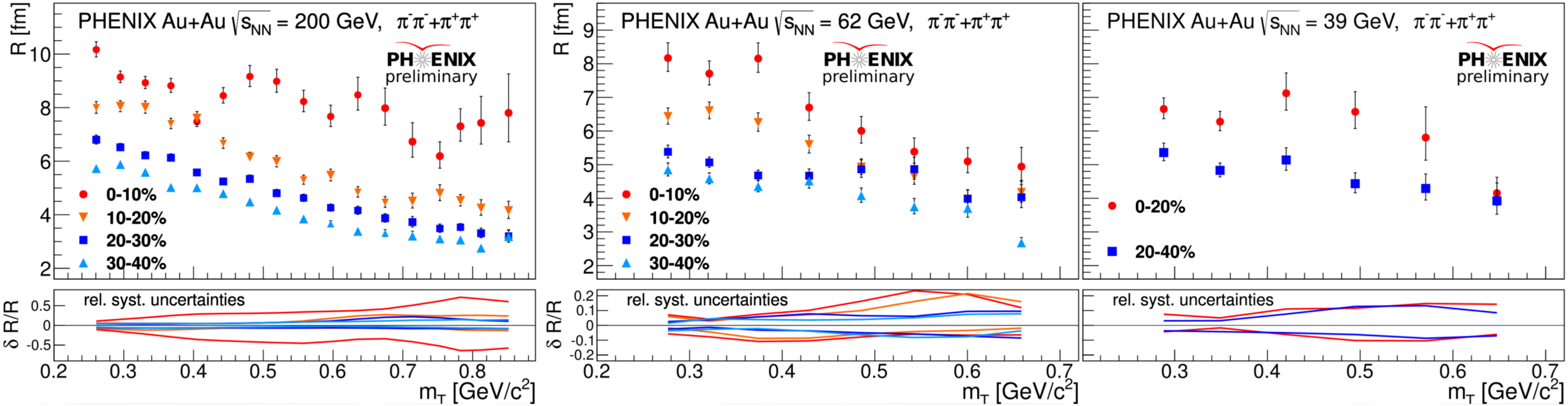
- **Fit with calculation based on Lévy distribution**
- **Physical parameters: *R, α, λ* measured versus pair m_T**
- ***R*: homogeneity length, dynamics, sizes**
- ***α*: shape, criticality, anomalous diffusion**
- ***λ*: particle creation mechanisms, in-medium mass modification**

Lévy works well



R – Centrality and m_T dependence

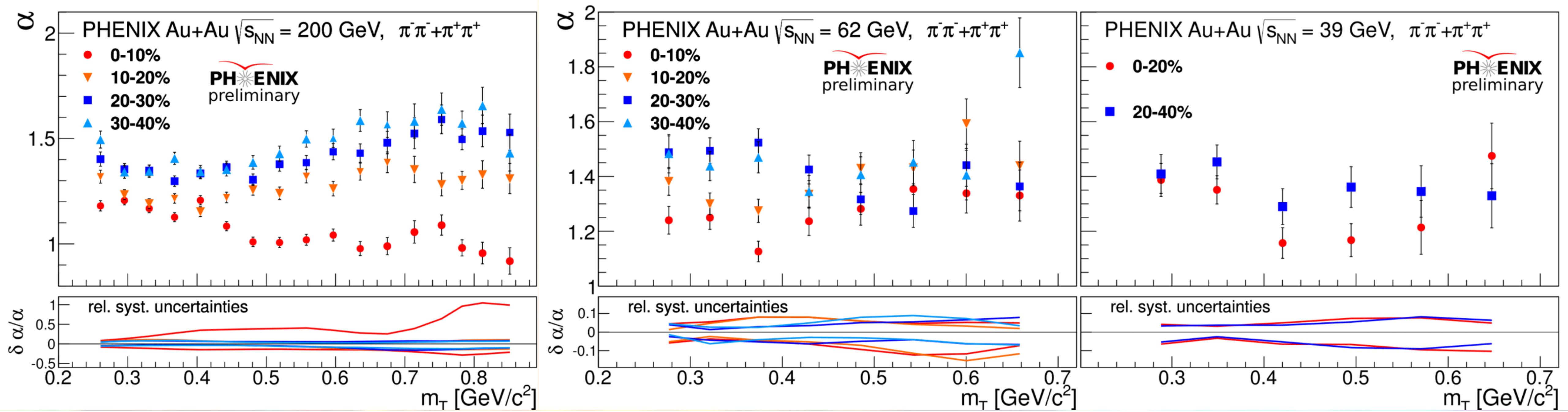
D. Kincses, Universe 4 (2018) 11



- **Geometrical centrality dependence**
- **Usual decrease with *m_T* is present**

α – Centrality and m_T dependence

D. Kincses, Universe 4 (2018) 11

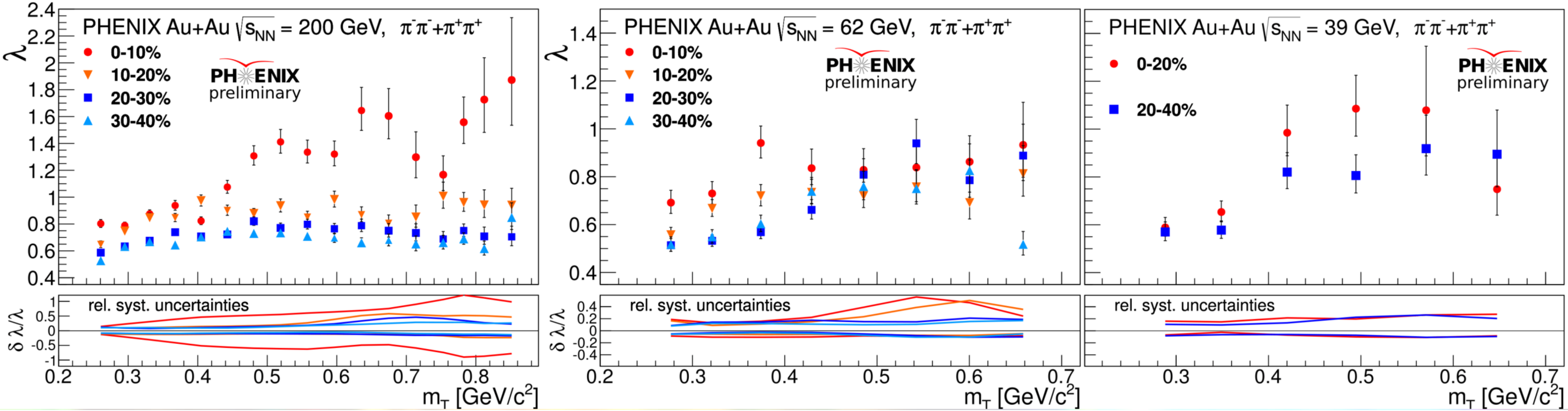


- **Measured value far from Gaussian (α = 2), inconsistent with expo. (α =1)**
- **Far from random field 3D Ising value at CEP (α = 0.5)**
- **Approximately constant (at least within systematic uncertainties)**

λ – Centrality and m_T dependence

See T. Csörgő talk
Wed. 12:00PM – 12:20PM

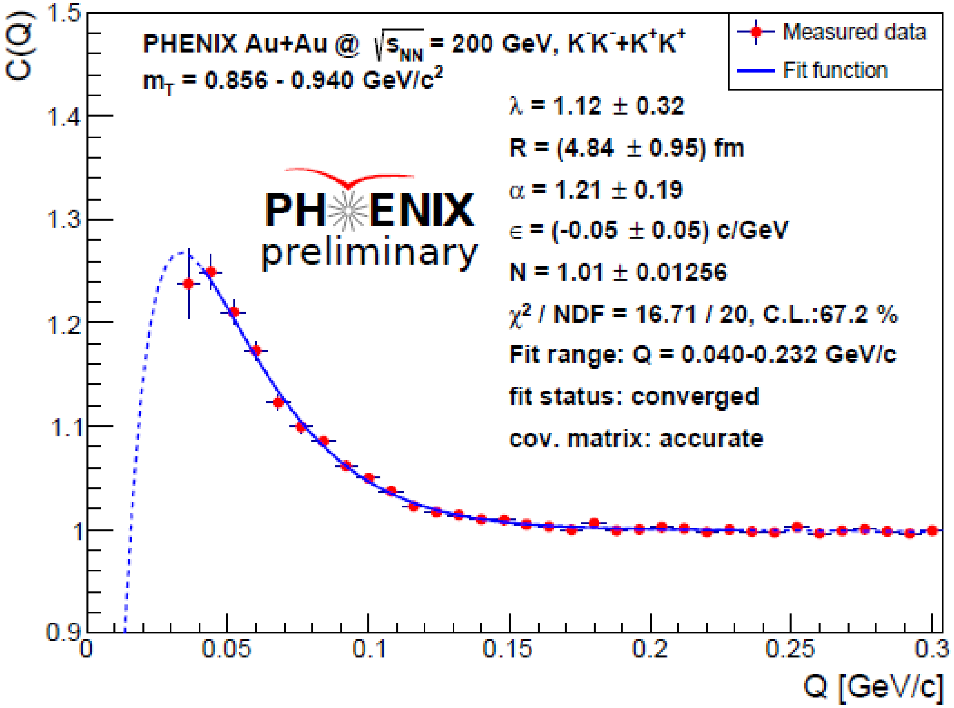
S. Lökös, Universe 4 (2018) 31

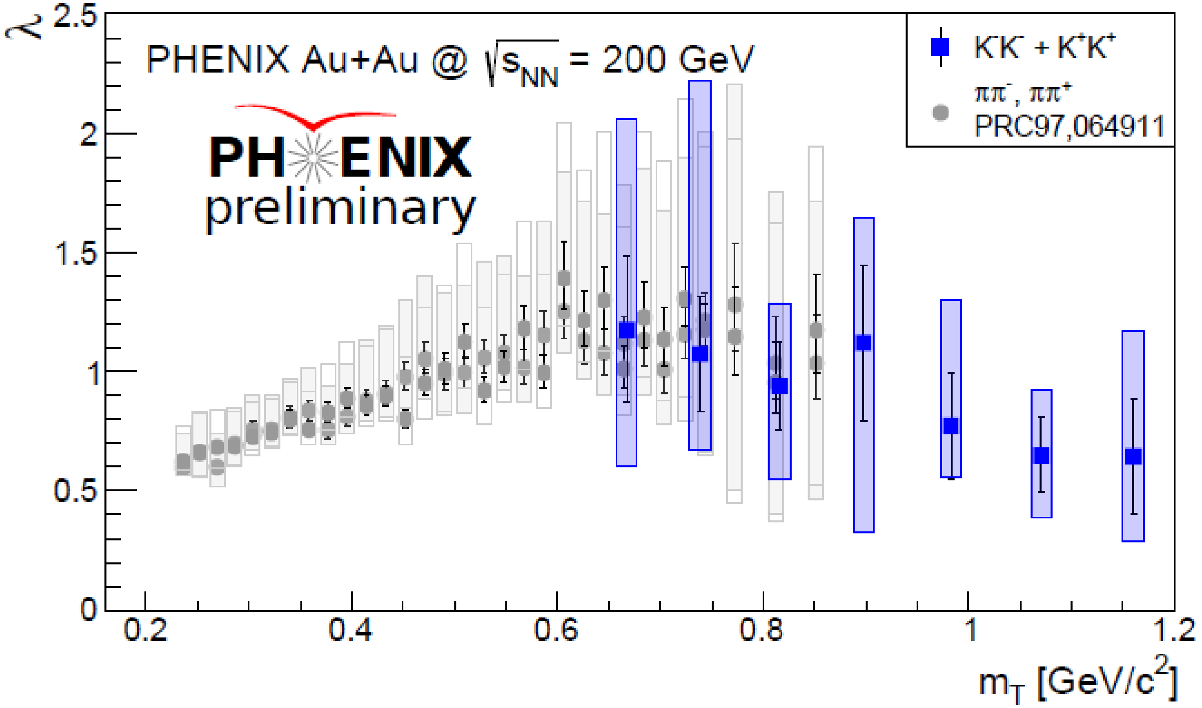


- **From the Core-Halo model, measure the core-halo fraction: $\lambda = \left(\frac{N_C}{N_C+N_H}\right)^2$**
- **Observed suppression at small m_T increase of halo fraction**

Kaon Femtoscopy in Au+Au

arxiv.org/pdf/2307.09573





- Femtoscopy with $K^{\pm}$ and assuming Lévy source
- λ describes strength of correlation
- α describes shape of distributions—$\alpha = 2$ is Gaussian, $\alpha = 1$ is Cauchy
- R is width parameter (similar to but not same as standard Gaussian radius)

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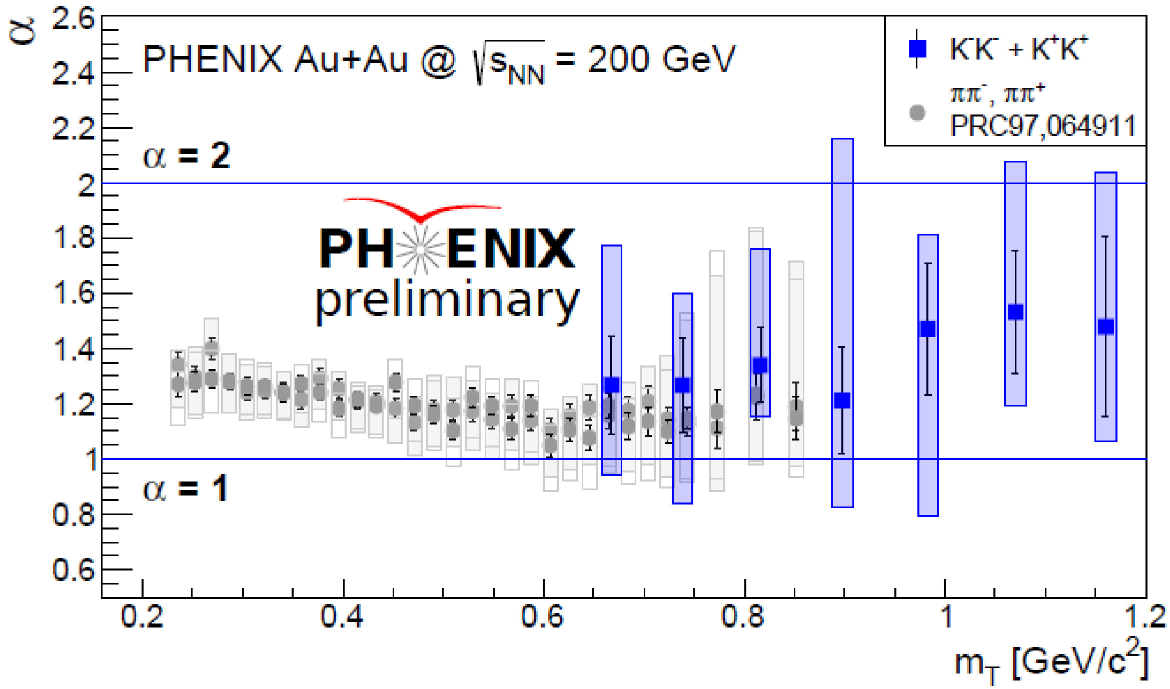

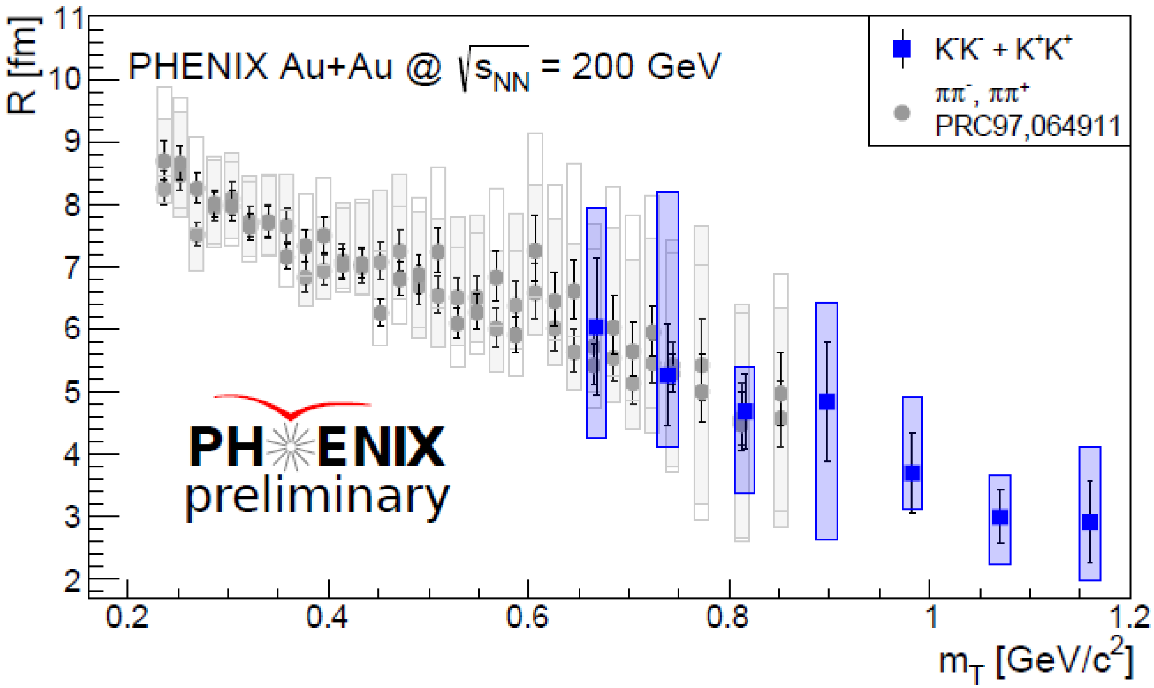

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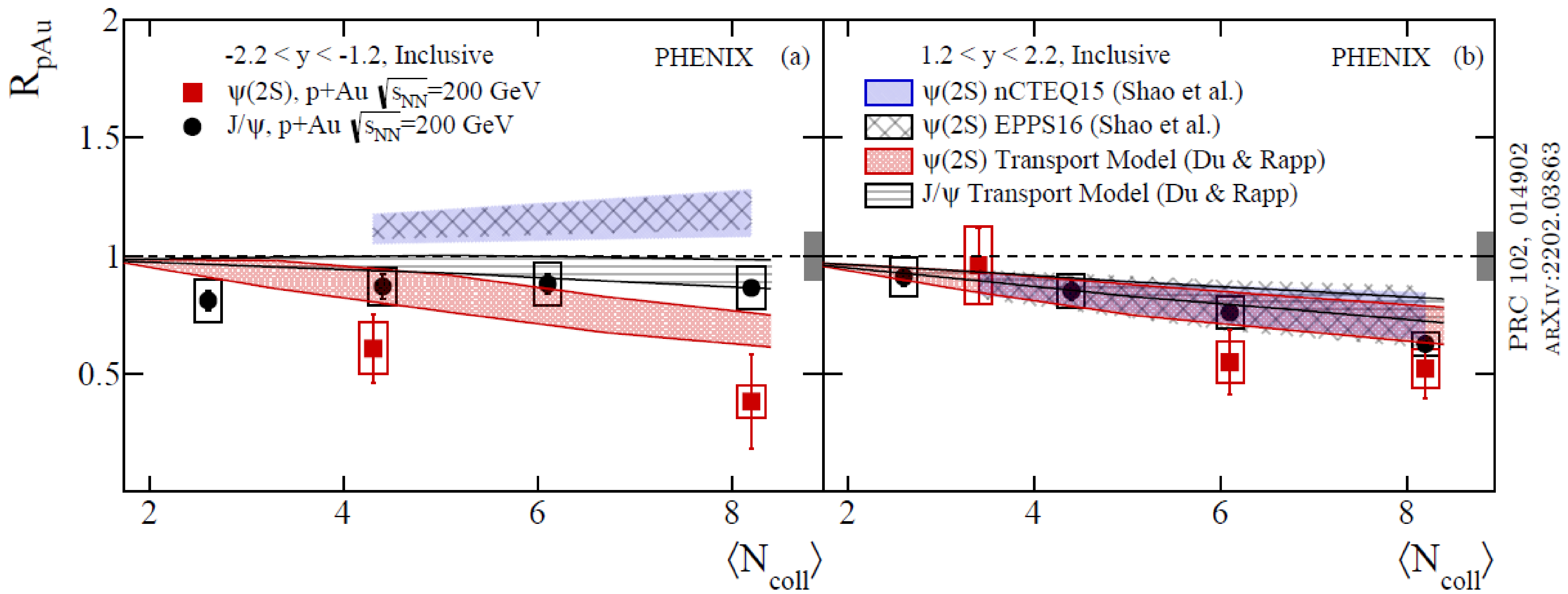
Summary

- Large enhancement seen in open heavy flavor decays at backward rapidity
- J/ψ R_{AA} suppression at backward rapidity consistent with nuclear absorption effects
- Data at forward rapidity suggests little to no coalescence effects
- J/ψ v_2 measurements consistent with zero (and stronger suppression compared to LHC)
- Strong evidence for QGP droplets in small systems
- New results on femtoscopy with charged kaons

Thank you for your attention!

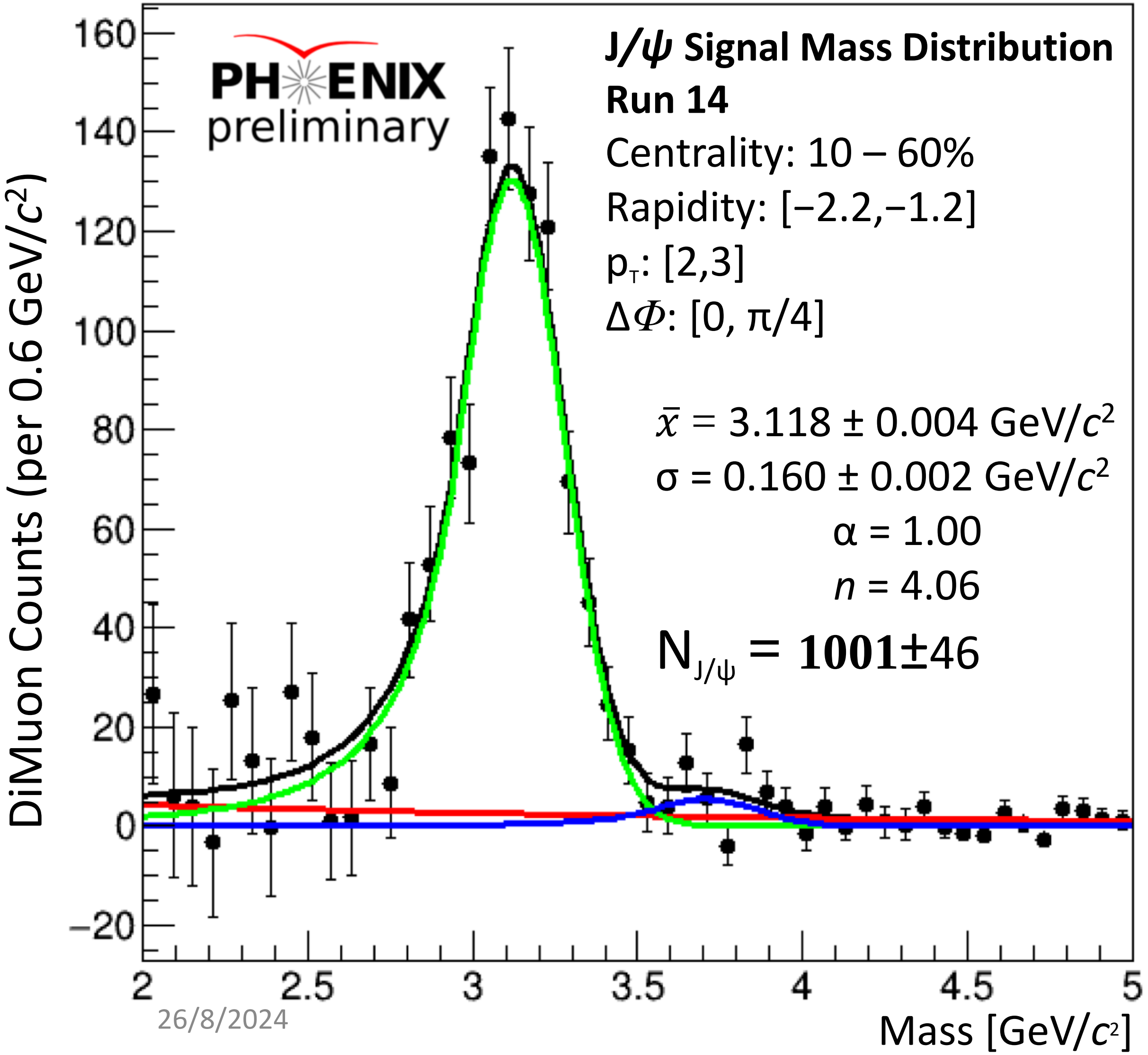
Back up

Charmonia Nuclear Modification in *p*+Au Collisions



- At forward rapidity, J/ψ and $\psi(2S)$ modification well described by shadowing models
  - Consistent with cold nuclear matter effects
- At backward rapidity, charmonium modification inconsistent with shadowing effects alone

J/ψ Reconstruction



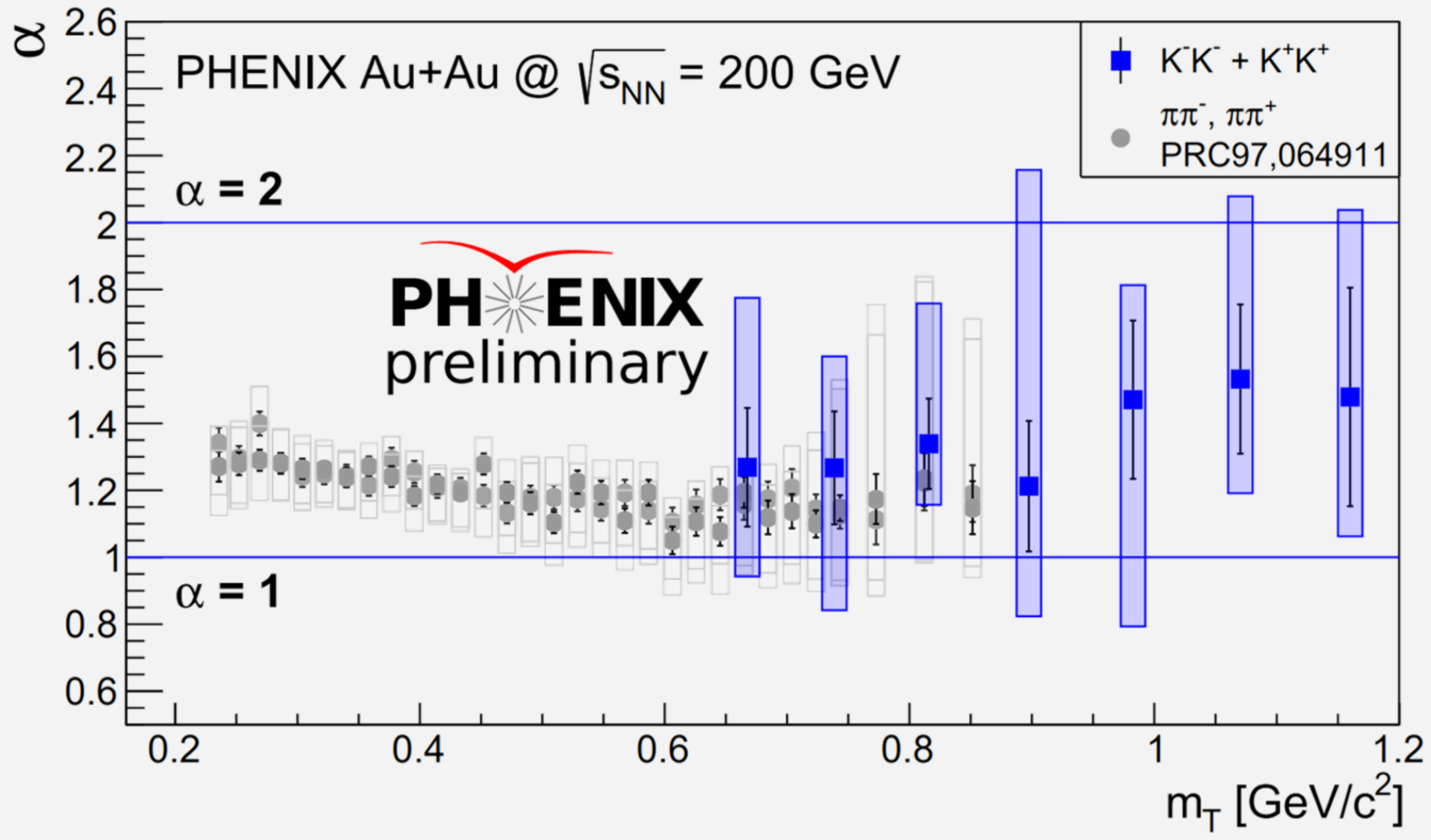
J/ψ simulated with PYTHIA embedded in Au+Au data

- Obtain Crystal Ball fit parameters

Constructing the signal and fit

- Crystal Ball function (J/ψ)
- Crystal Ball function (ψ(2S))
- Exponential (residual background)

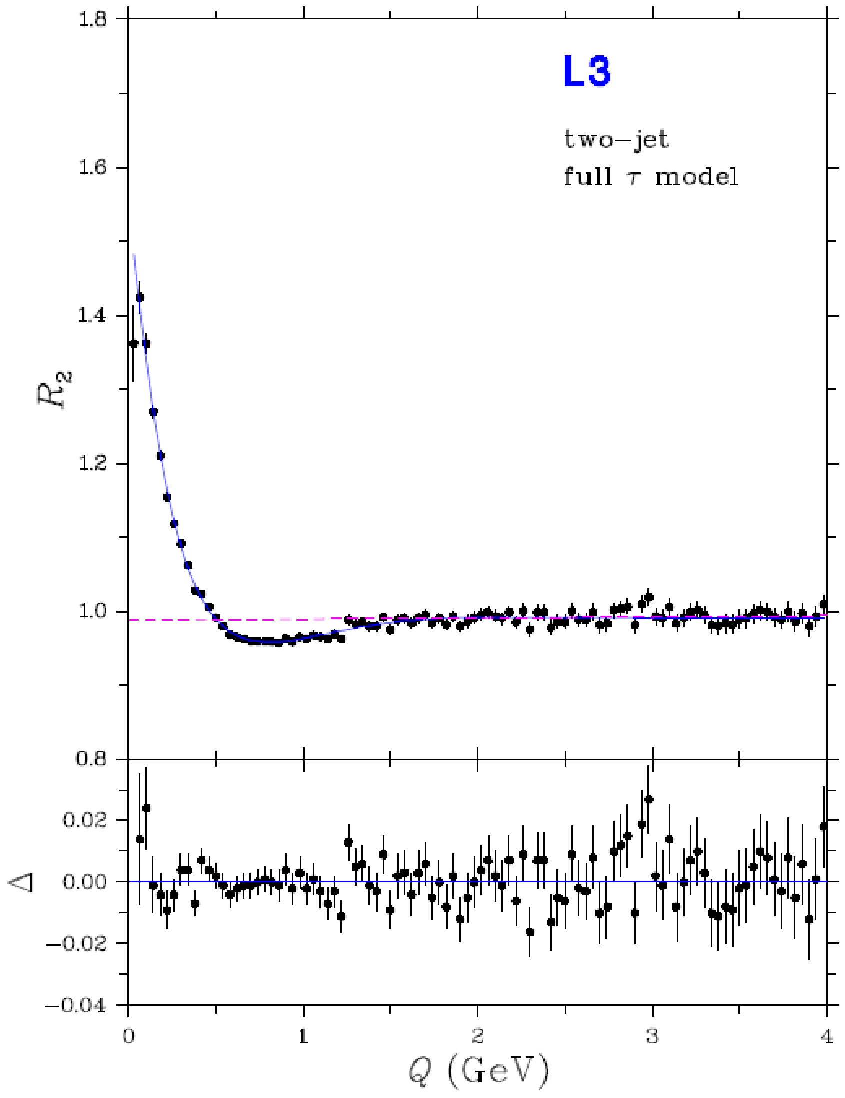
Kaon Lévy shape - α

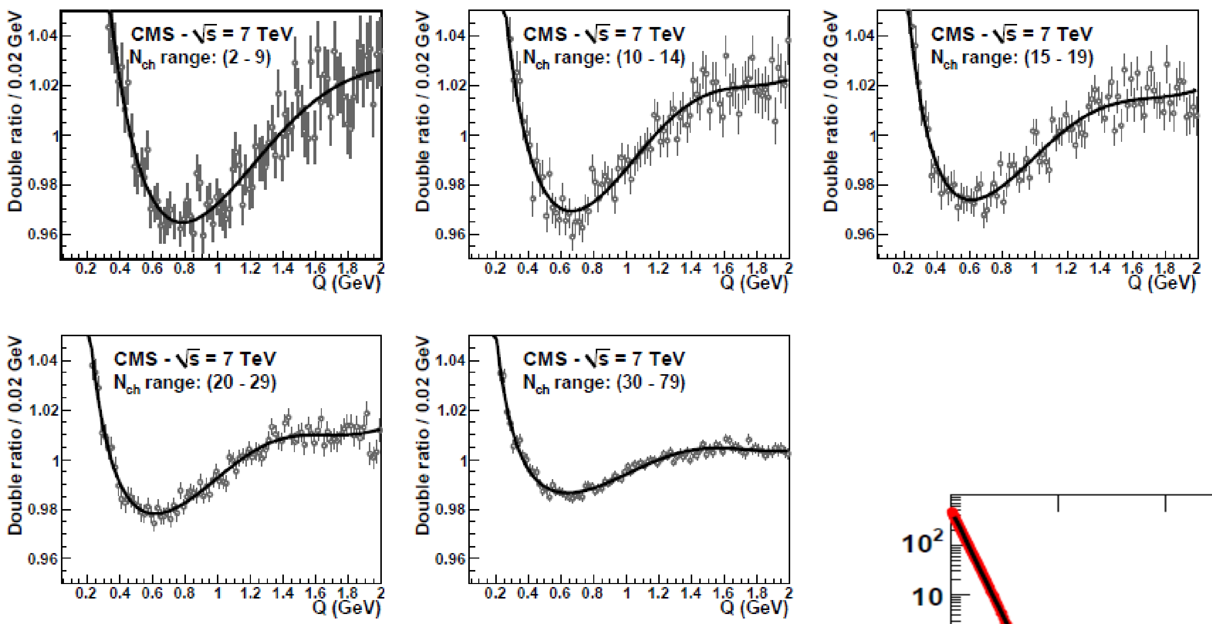


- Does not exhibit strong dependence on transverse mass
- Kaon α consistent with pions, weak $\alpha(K) \geq \alpha(\pi)$ indication
- Anomalous diffusion suggests $\alpha(K) < \alpha(\pi)$

[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**