Properties of the space-time evolution of relativistic heavy-ion collisions observed by PHENIX

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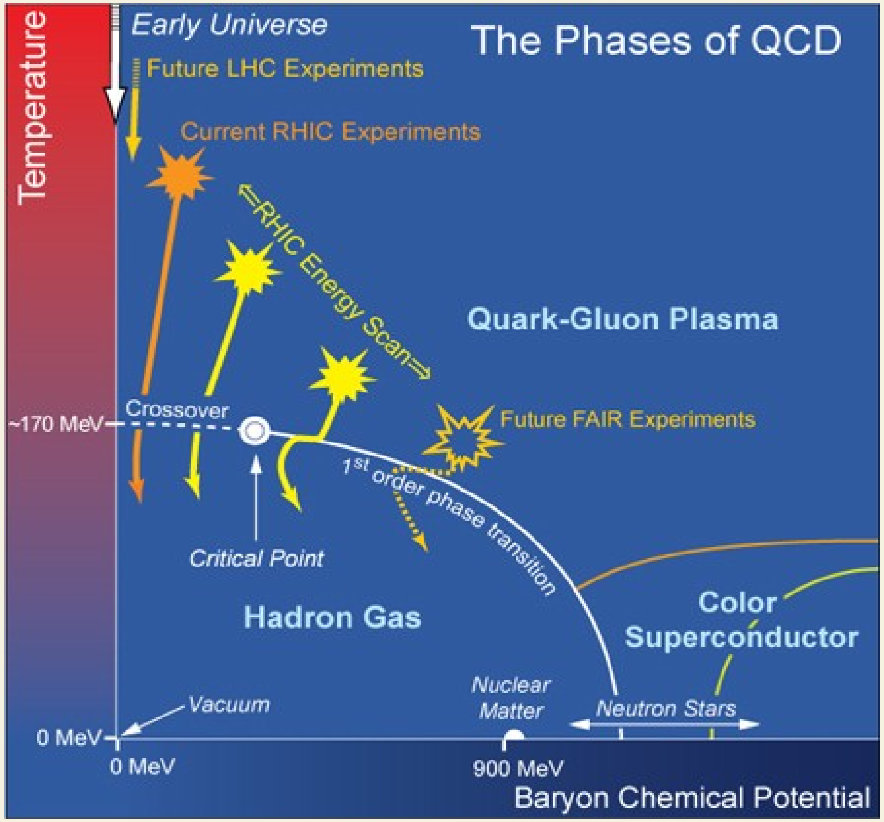
Outline

- Physics motivation
- Flows (v2, v4 and v3)
- Fluctuations
- Femtoscopy
- Spectra
- Summary

Physics motivation



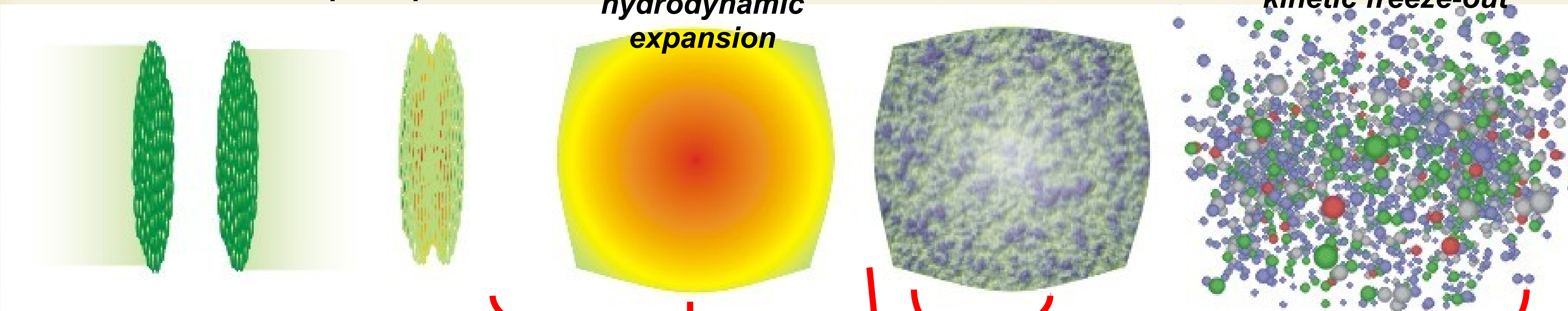
Quark Gluon Plasma (QGP) state

Experiments at Relativistic Heavy-Ion Collider (RHIC) created QGP in Au+Au at 200GeV per nucleon and theoretical calculations (e.g hydrodynamics model) are describing the QGP state quantitatively in terms of:

- ***how hot and dense the matter is***
- ***how opaque the matter is against jets***
- ***how strongly the matter is coupled***

Question: How fast the extremely hot and dense matter therm alizes and freezes-out, how much the system size grows, what is the nature of the phase transition that occurs at RHIC? Is it different from AGS, SPS energies?
What are the nature parameters to describe the state?

Space-time evolution

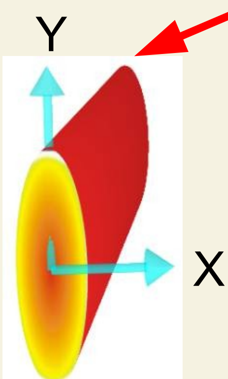


Study charge-asymmetry (P-odd Domains)

➢ Study expansion dynamics and space-time extent

$\tau, R_{o,s,l}, \eta, T_f$ *etc.*

Spectra, Femtoscopy



➢ Study how matter expands/flows under its own pressure?

Flow

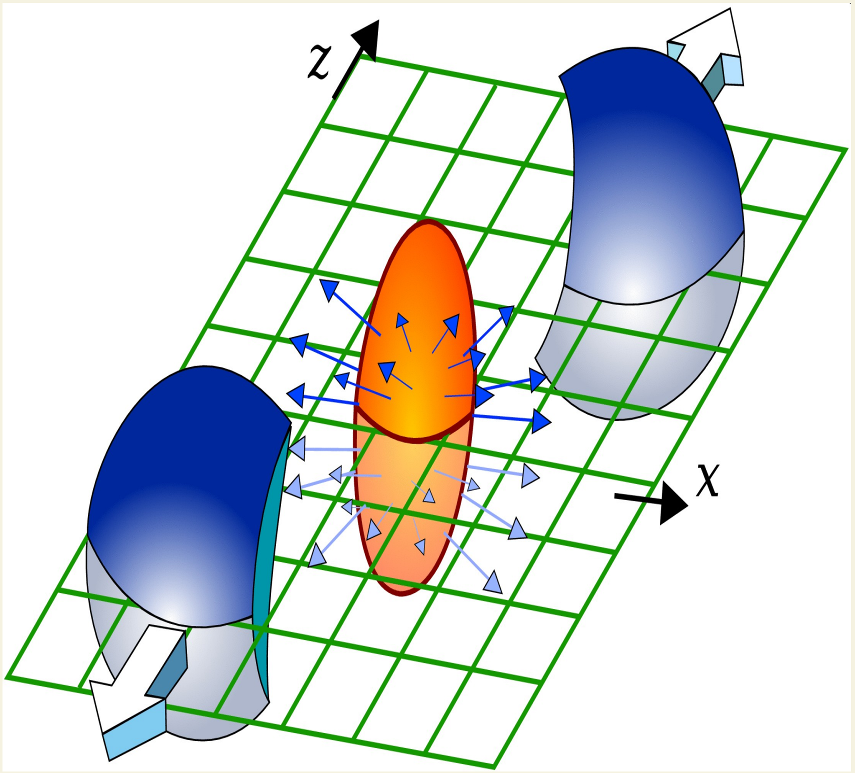
η, ξ, c_s, T_f

➢ Search for the critical end point. Study the critical behavior, phase boundary, transition order.

k, ξ *etc.*

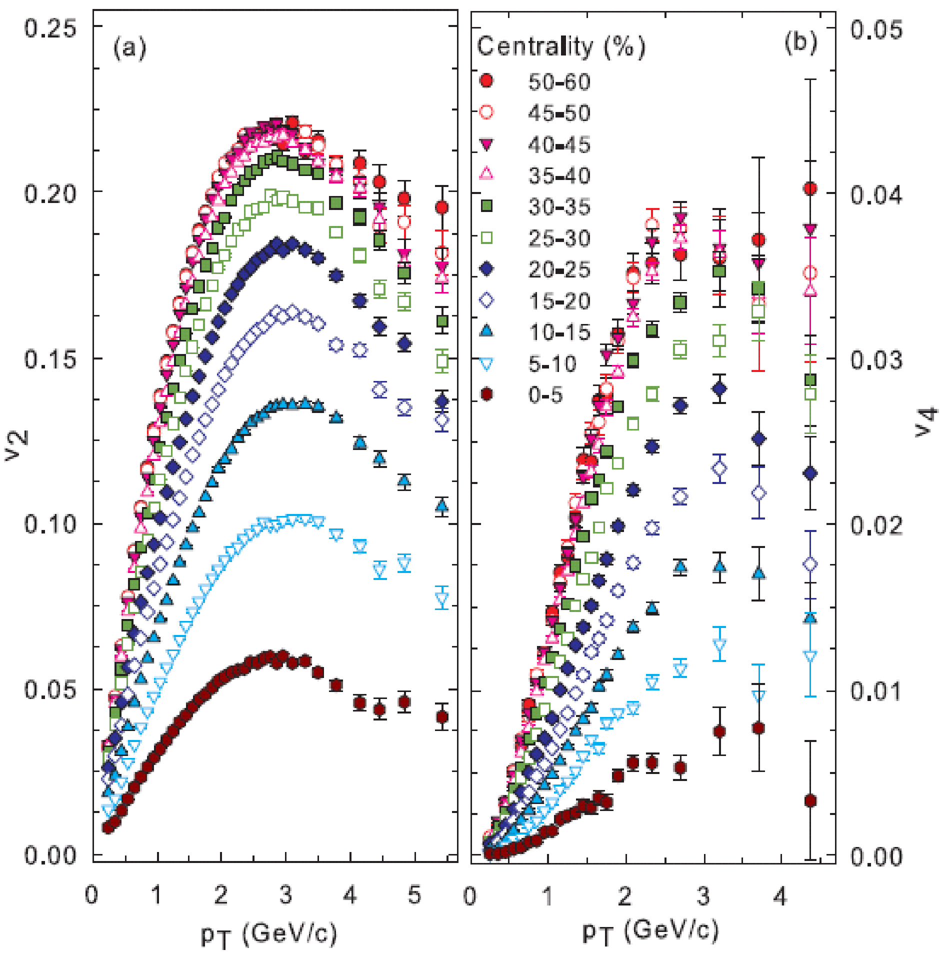
Fluctuation

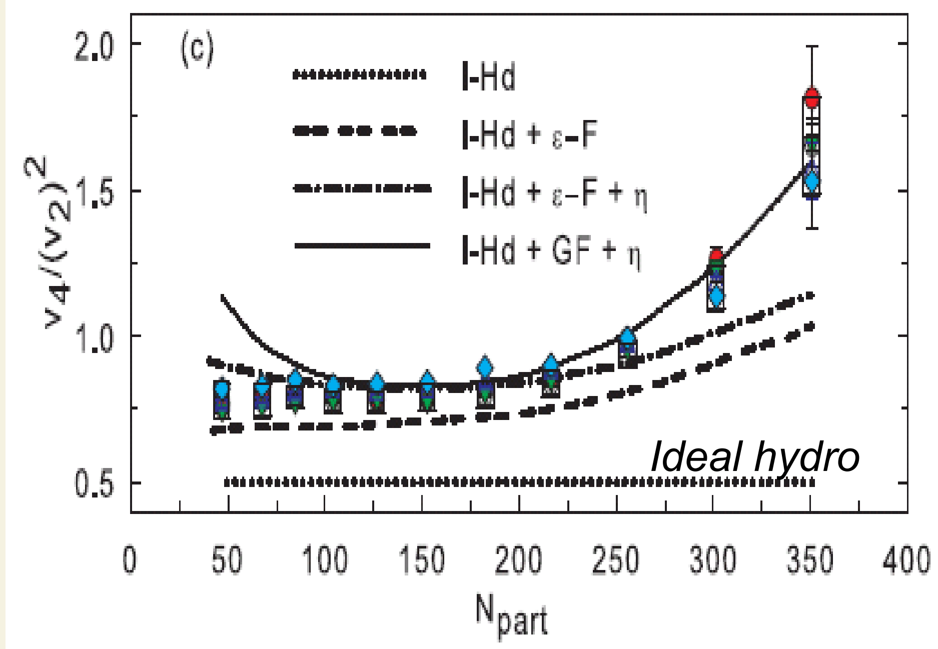
Flows



v2 and v4 in Au+Au 200GeV

Phys. Rev. Lett. 105, 062301 (2010)



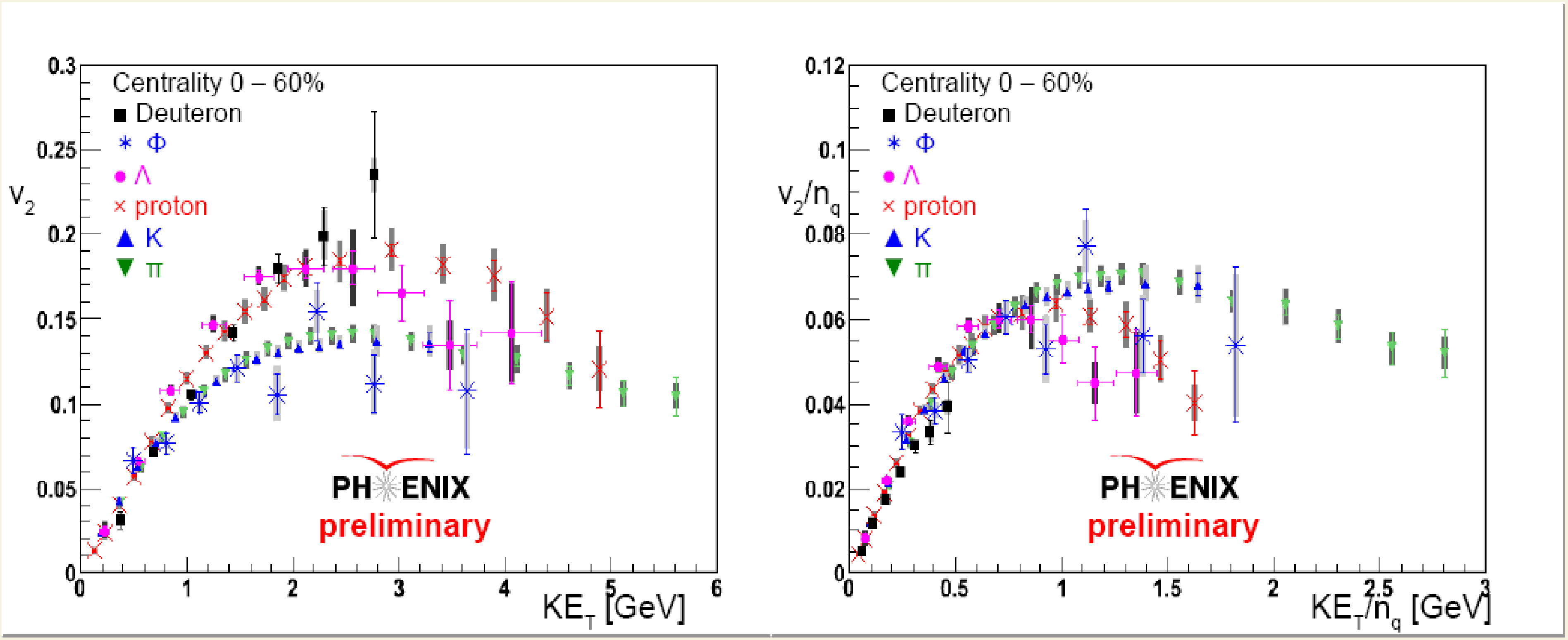


- $v4/(v2)^2$ is independent of centrality.
- $v4/(v2)^2$ is ~0.8 for N_{part}<200, which is larger than the ideal hydro (~0.5).
- Adding an eccentricity fluctuation and small viscosity well reproduces the data (need an additional fluctuation for central collision).

Estimate → 4π(η/s) ~ 1-2

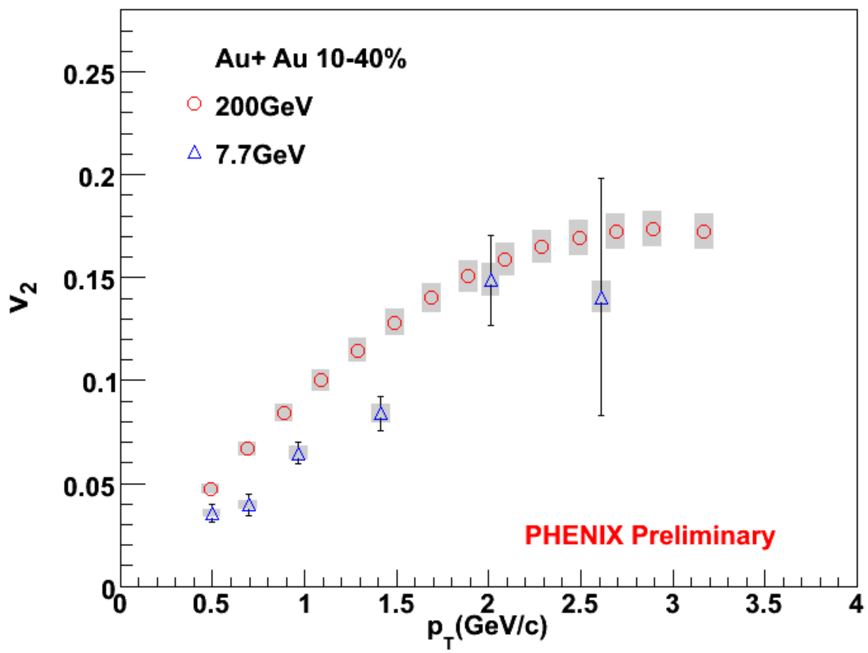
High precision double differential Measurements are pervasive

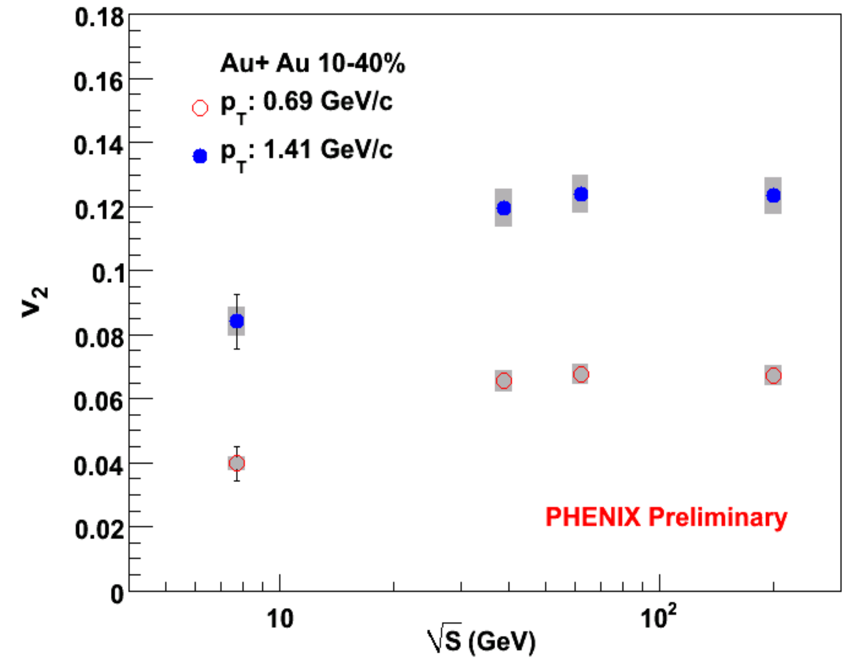
Scaling property of PID v2



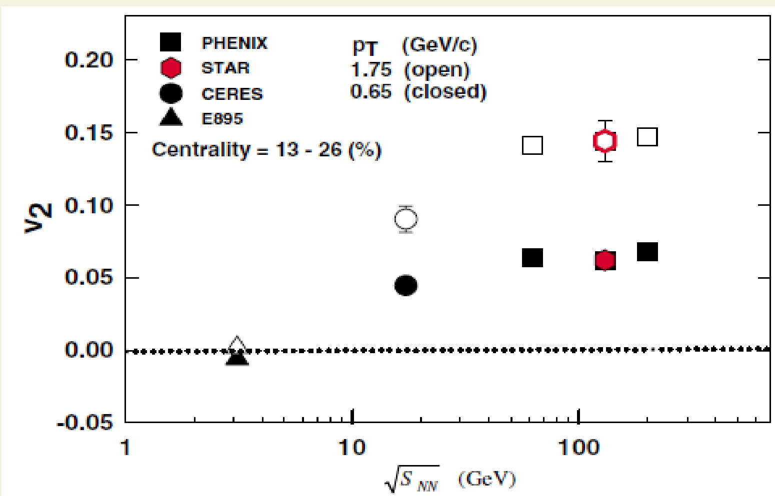
- v2 are consistent between mesons, or baryons as a function of KE_T (= M_T - M_0)
- Universal quark scaling works fine up to KE_T/n_q ~ 1 GeV but deviate at higher KE_T region.
  - Mechanism could be changed from soft to hard process.

Energy dependence of v2



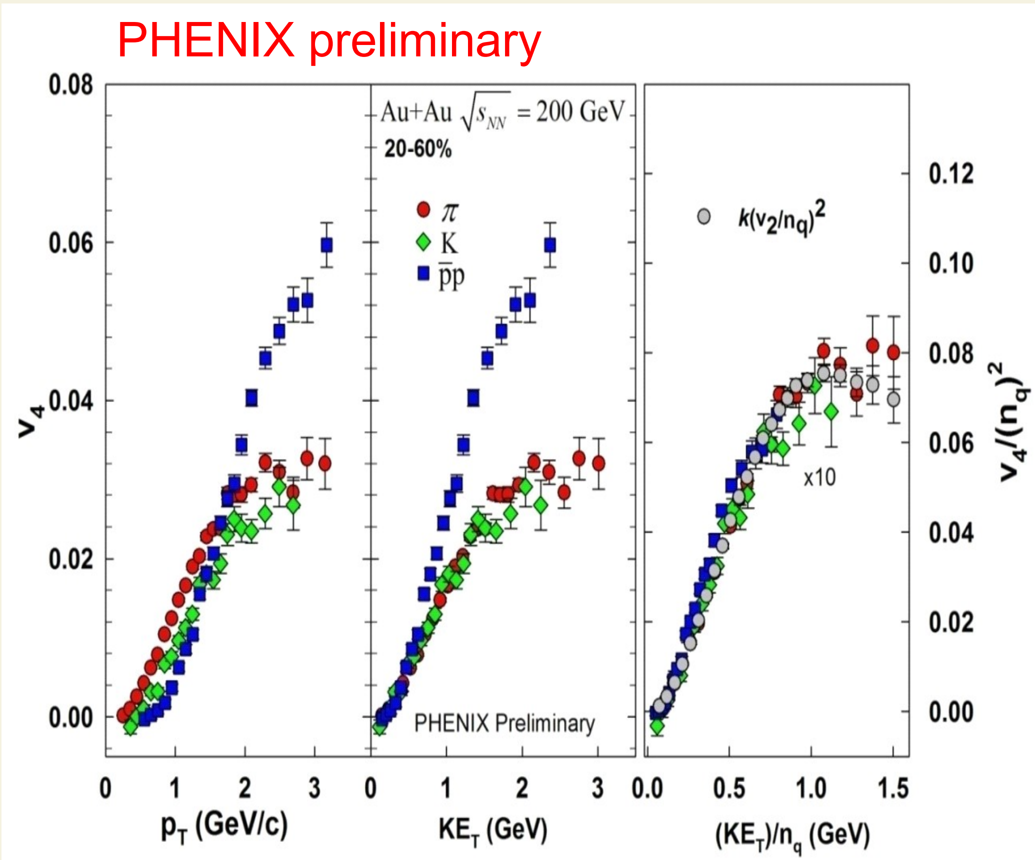


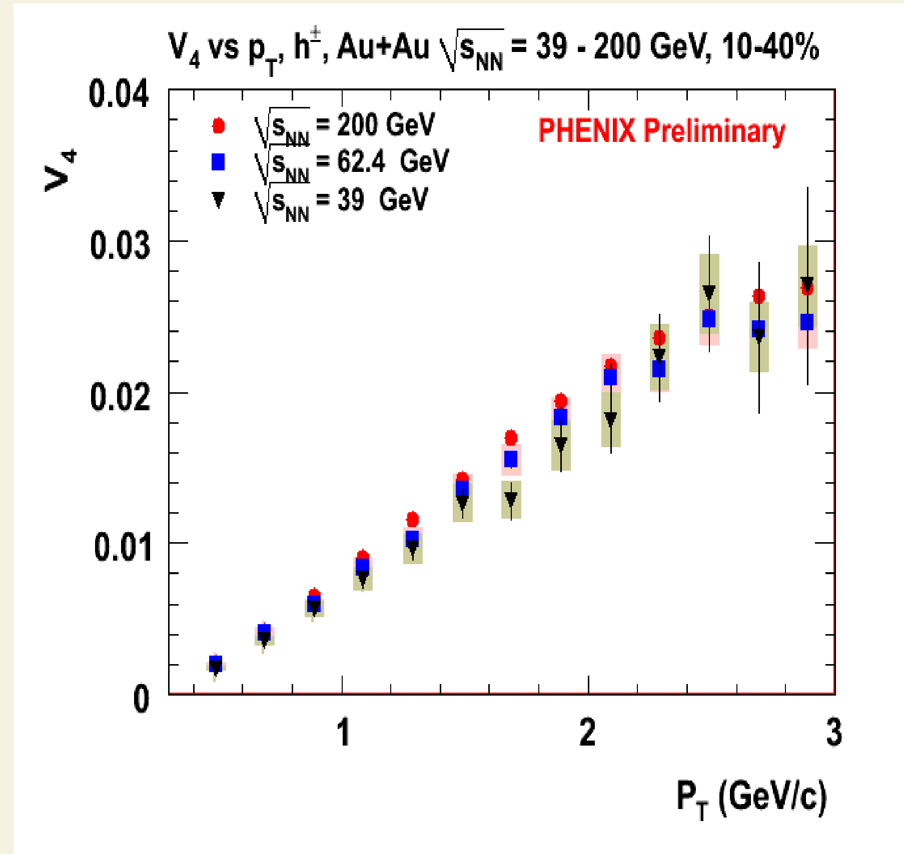
- v2 is saturated and flat at 39 GeV to 200 GeV in Au+Au collisions.
- v2 at 7.7 GeV is lower than 39 GeV (partonic → hadronic flow?)
- Next step will be to investigate the universal scaling of v2 (KE_T/n_q) at the lower energies.



Phys.Rev.Lett.94:232302,2005

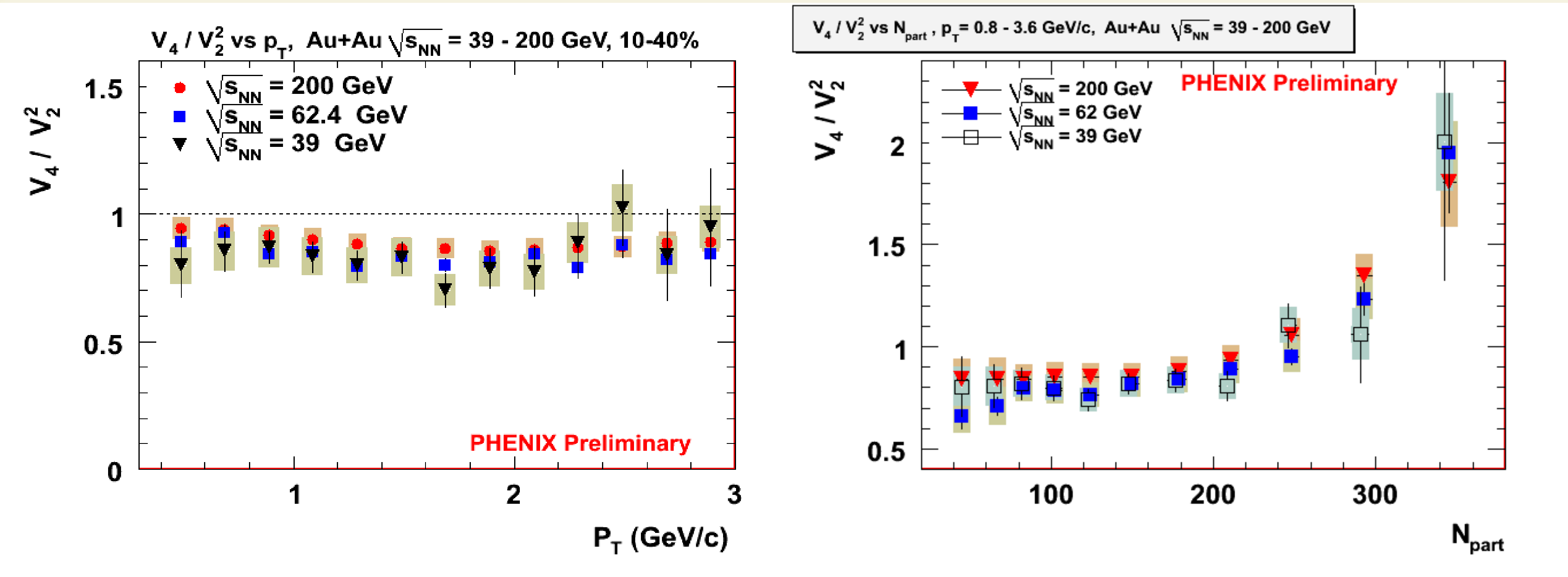
Scaling, energy dependence of v4

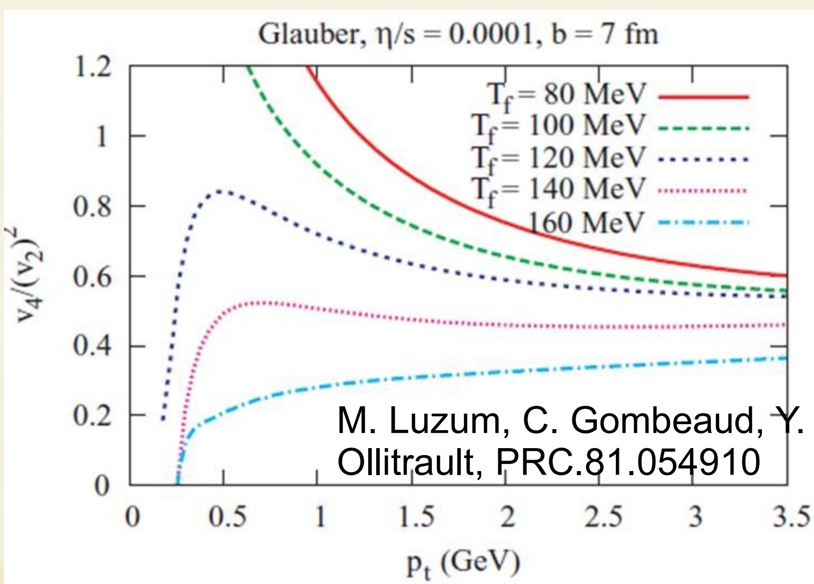




- v4 also flow the KE_T/n_q scaling
- v4 is less varied in Au+Au collision energy from 39 to 200 GeV
  - v4 is also saturated at 39 GeV.

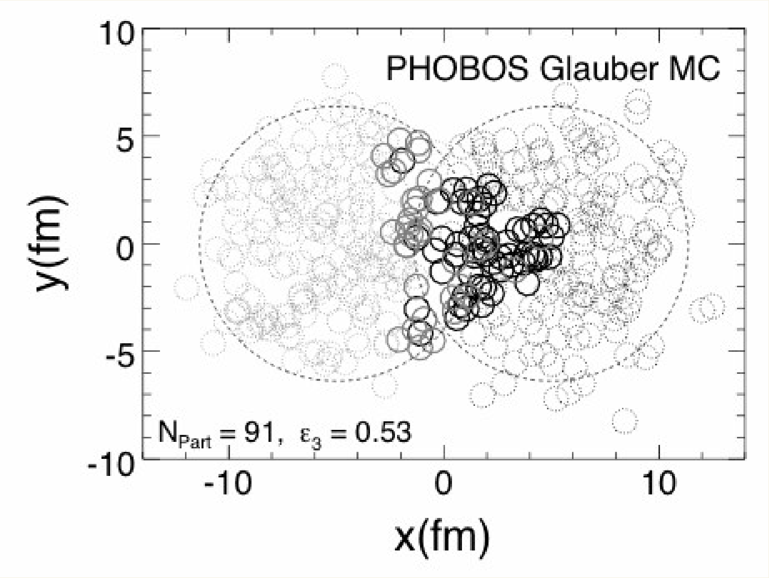
v4/(v2)^2





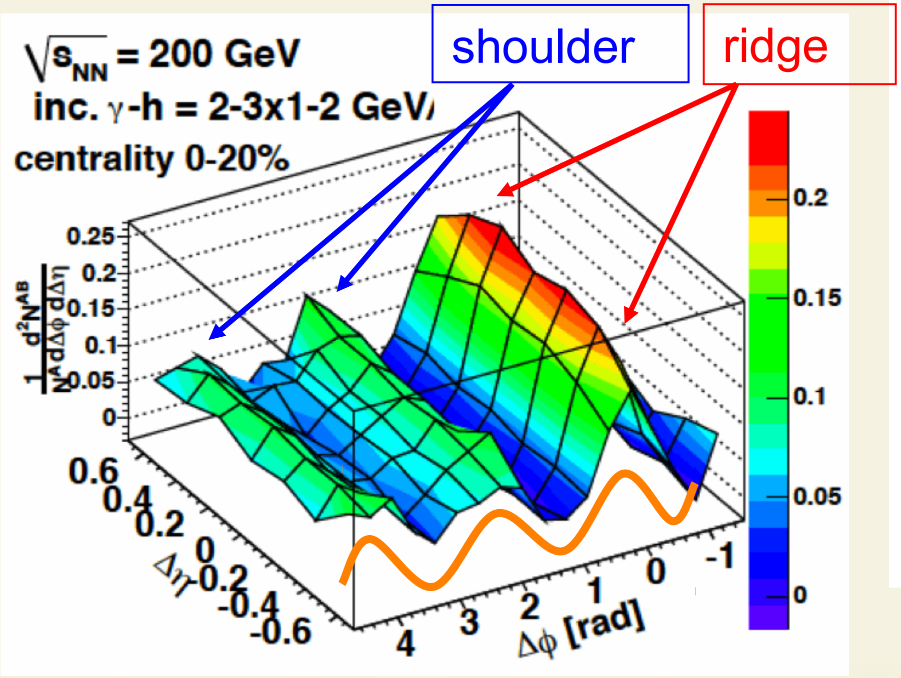
- $v4/(v2)^2$ is sensitive to hydrodynamics freeze-out temperature, viscosity.
- $v4/(v2)^2$ is flat as a function of p_T, and similar from 39 GeV to 200 GeV at different N_{part} in Au+Au collisions
  - Hydrodynamics paremeters (freeze-out temperature, η/s) don't change between the energy region.

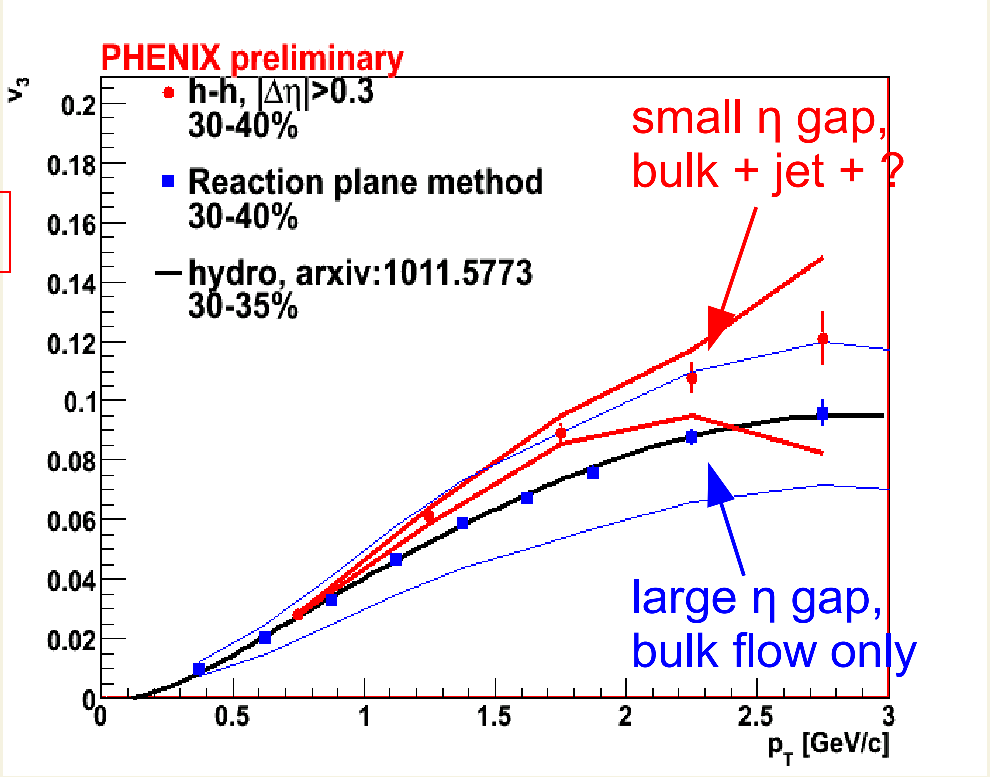
v3



- v3 could be observed if the overlapped nuclei is not perfectly elliptical shape.

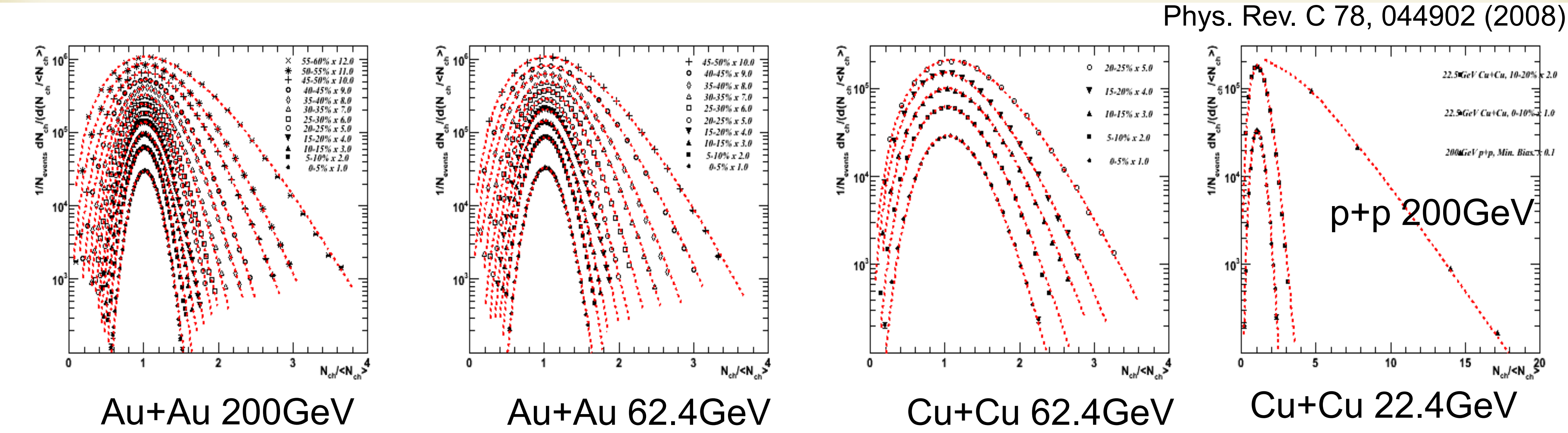
- v3 measured with large η gap (bulk effect only) shows a good agreement with hydro calculation.





Fluctuations

Multiplicity fluctuation



Multiplicity distribution is well described by the negative binomial distribution (NBD).

$$P(n) = \frac{\Gamma(n+k_{NBD})}{\Gamma(n+1)\Gamma(k_{NBD})} \frac{(\mu_{ch}/k_{NBD})^n}{(1+\mu_{ch}/k_{NBD})^{n+k_{NBD}}}$$

μ_{ch} : Average multiplicity

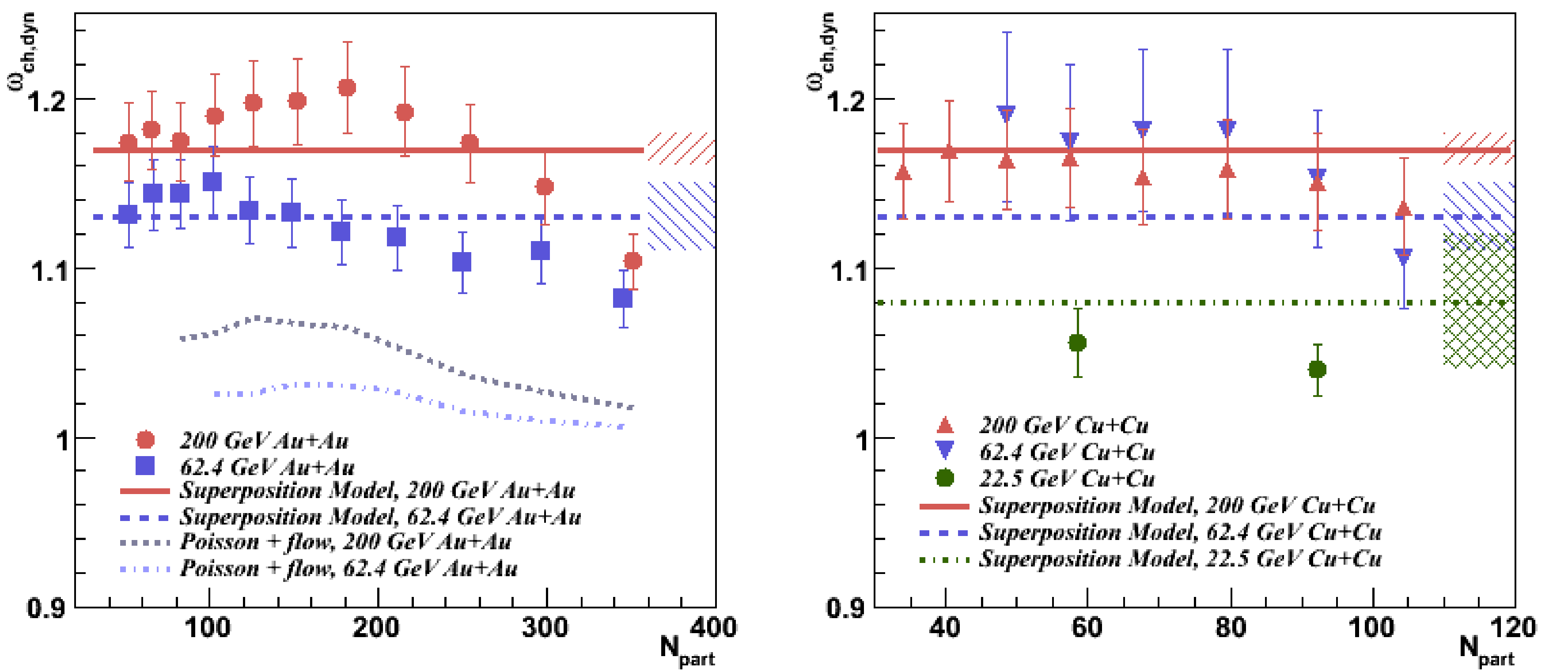
$1/k_{NBD}$: Deviation from Poison distribution

$$\frac{1}{k_{NBD}} = \frac{\sigma_{ch}^2}{\mu_{ch}^2} - \frac{1}{\mu_{ch}}$$

$$\frac{\sigma_{ch}^2}{\mu_{ch}} = \omega_N = \frac{k_{NBD}}{\mu_{ch}} + 1$$

Multiplicity fluctuation

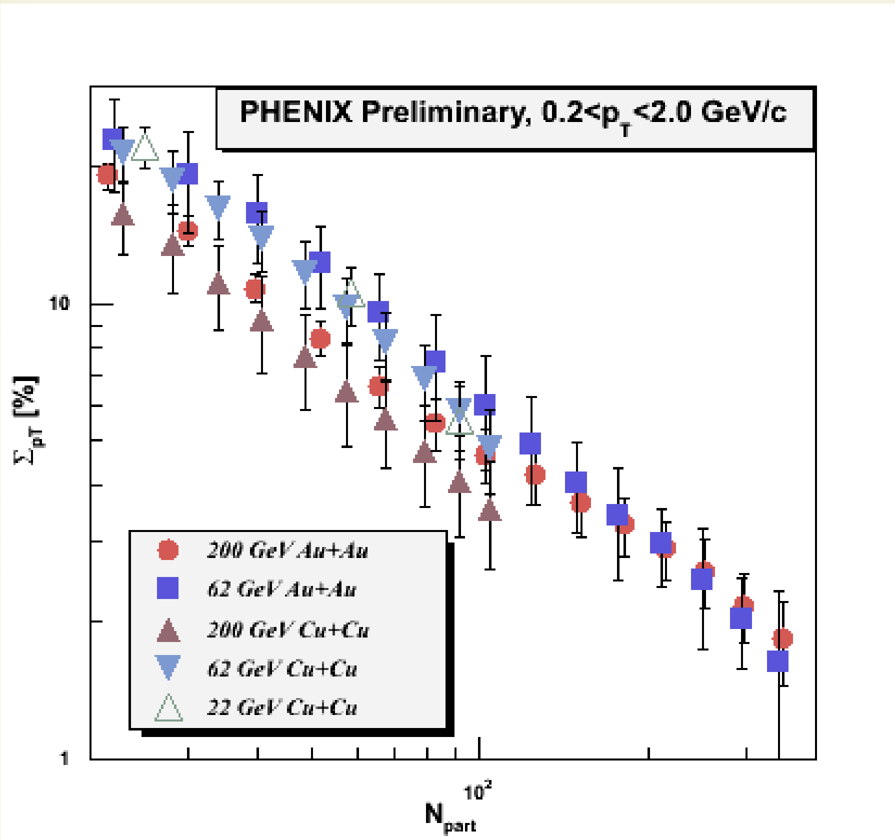
Phys. Rev. C 78, 044902 (2008)



"scaled variance" $\omega_{ch} = \frac{\sigma_{ch}^2}{\mu_{ch}} = \frac{k_{NBD}}{\mu_{ch}} + 1$

- Near the critical point, the multiplicity fluctuations should exceed the superposition model expectation.
  - No significant evidence for critical behavior is observed.

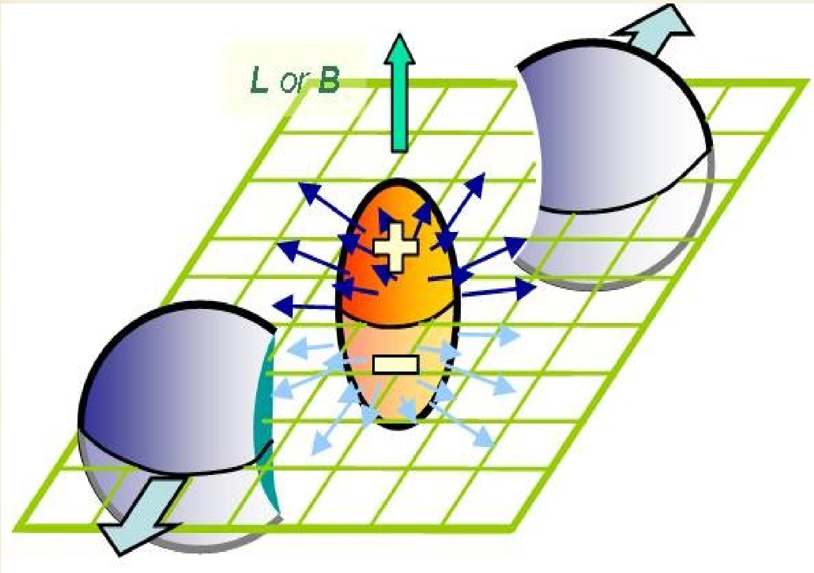
Mean p_T fluctuation

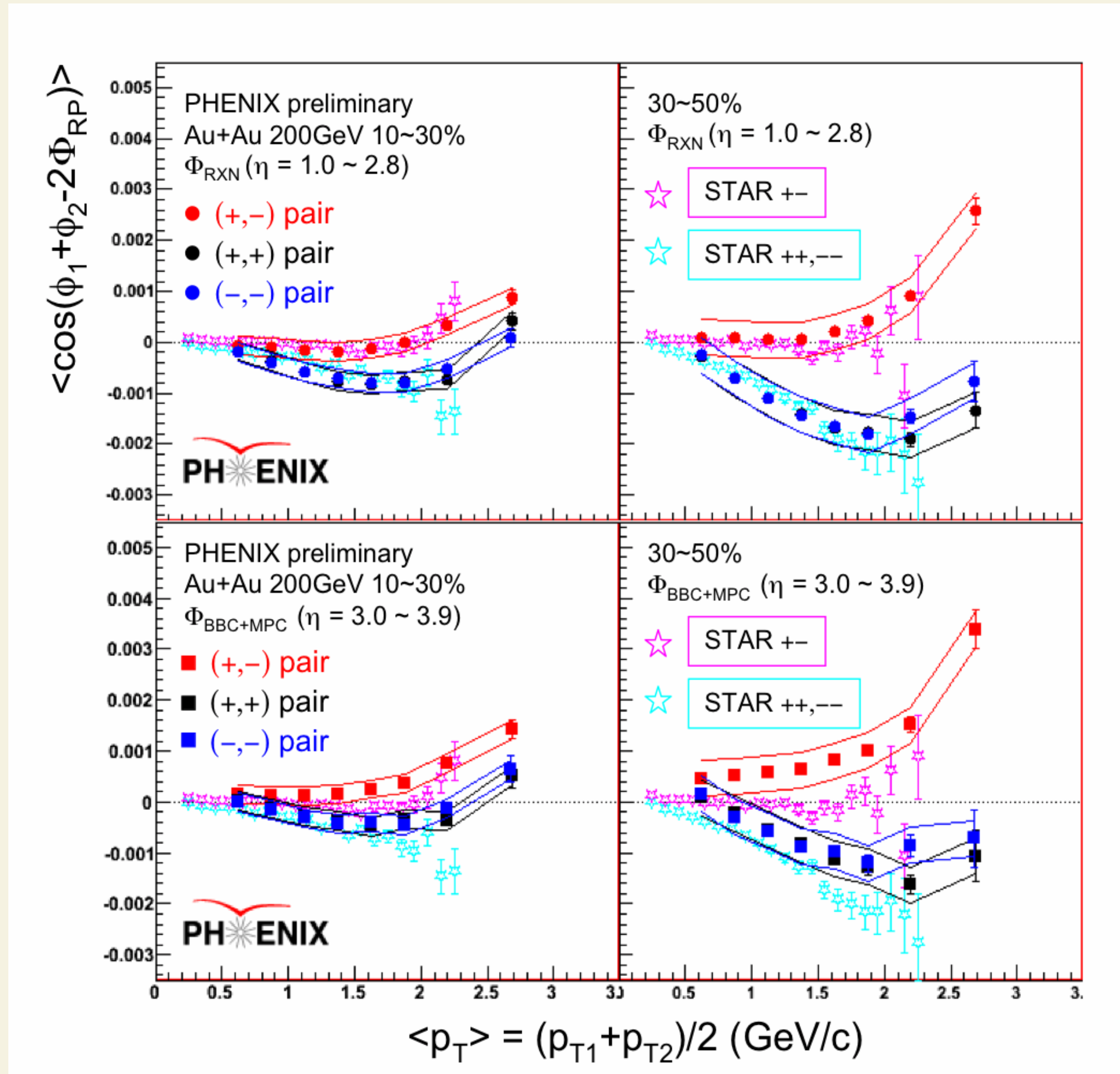


$$\Sigma_{p_T} \propto N_{part}^{-1.02\pm0.10}$$

- Σ_{pT} is the mean of the covariance of all particle pairs in an event normalized by the inclusive mean p_T.
  - Can be related to the inverse of the heat capacity.
  - Random fluctuation: $\Sigma_{pT} = 0$
- The magnitude of Σ_{pT} is less changed from Cu+Cu 22.4 GeV up to Au+Au 200 GeV.
  - All data can be expressed by the power row function of N_{part}.

Local parity violation

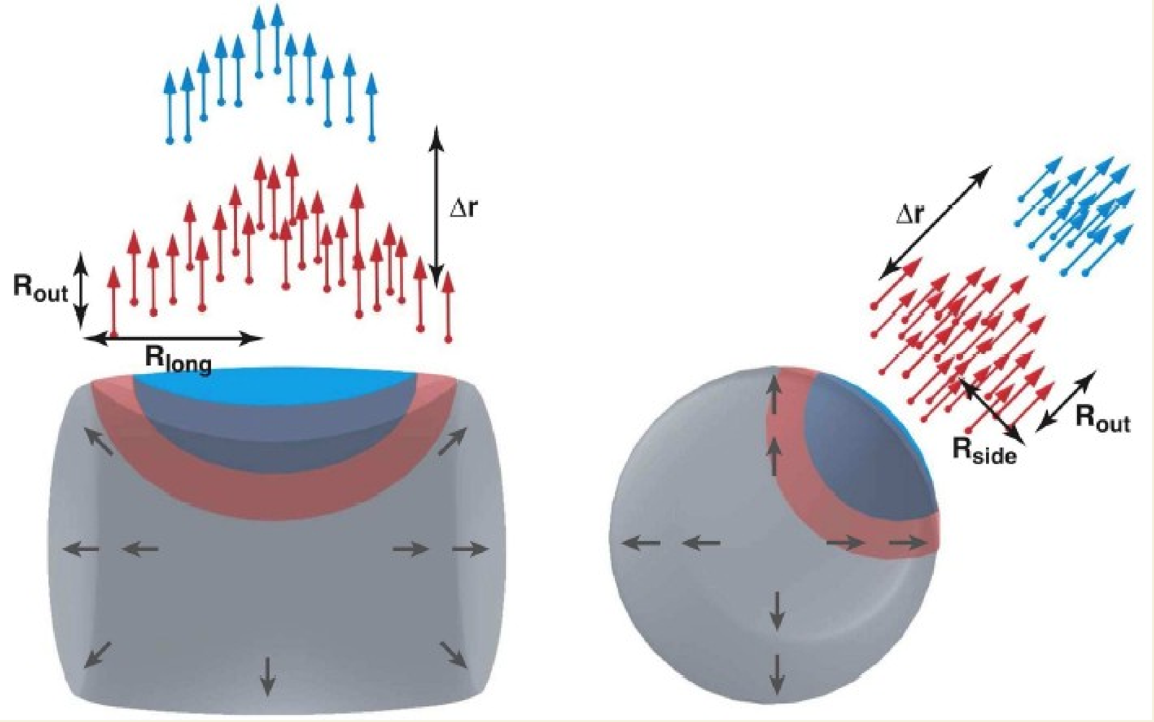




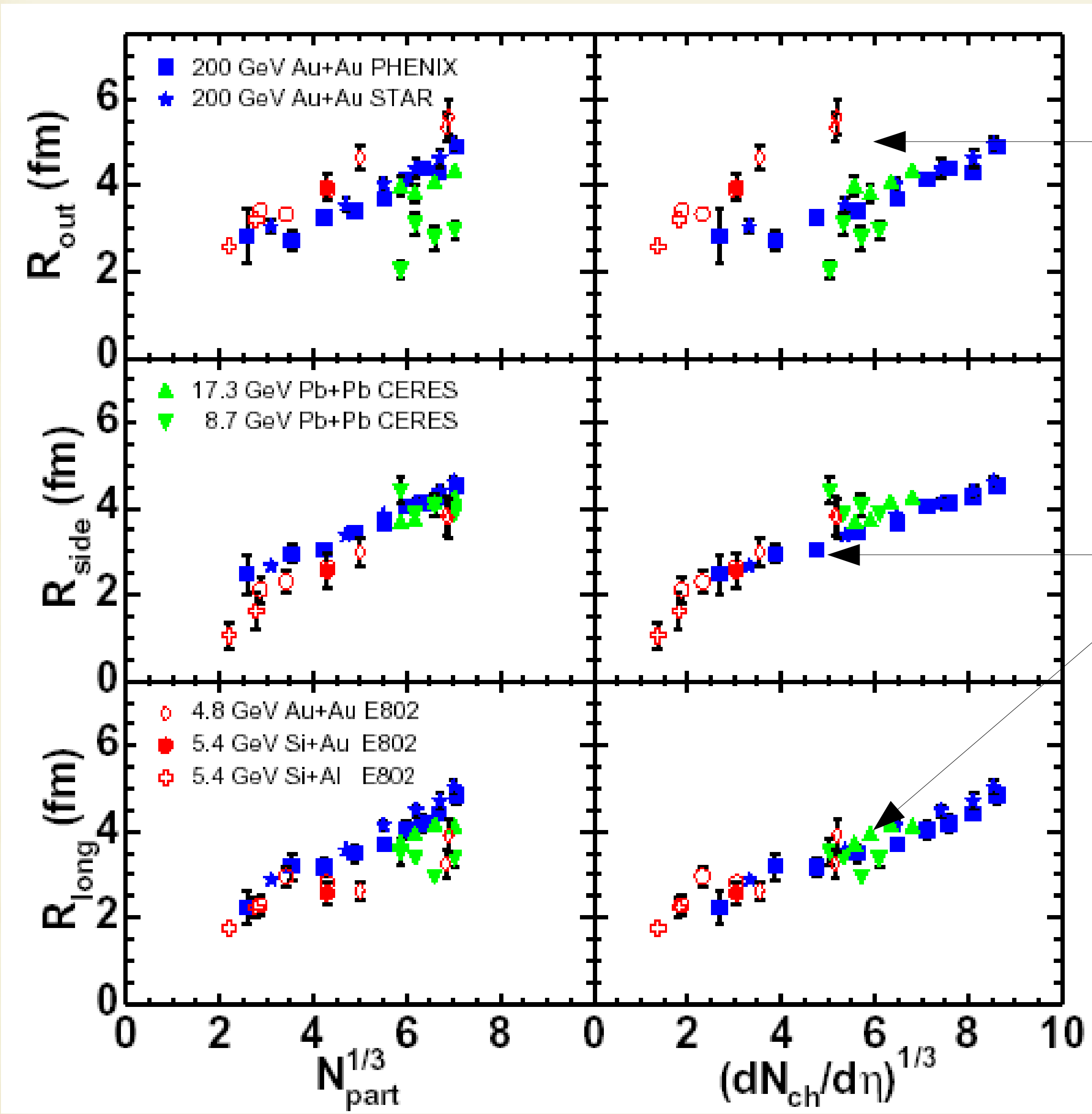
It has been proposed that in heavy ion collisions, a combination of a net chirality of quarks within a domain and the extremely strong magnetic field could lead to the manifestation of parity violation as a separation of charges along the angular momentum vector of the collision system.

Signal grows with centrality and pT, which agrees with STAR's result.

Femtoscopy (aka HBT)



Energy versus HBT radius



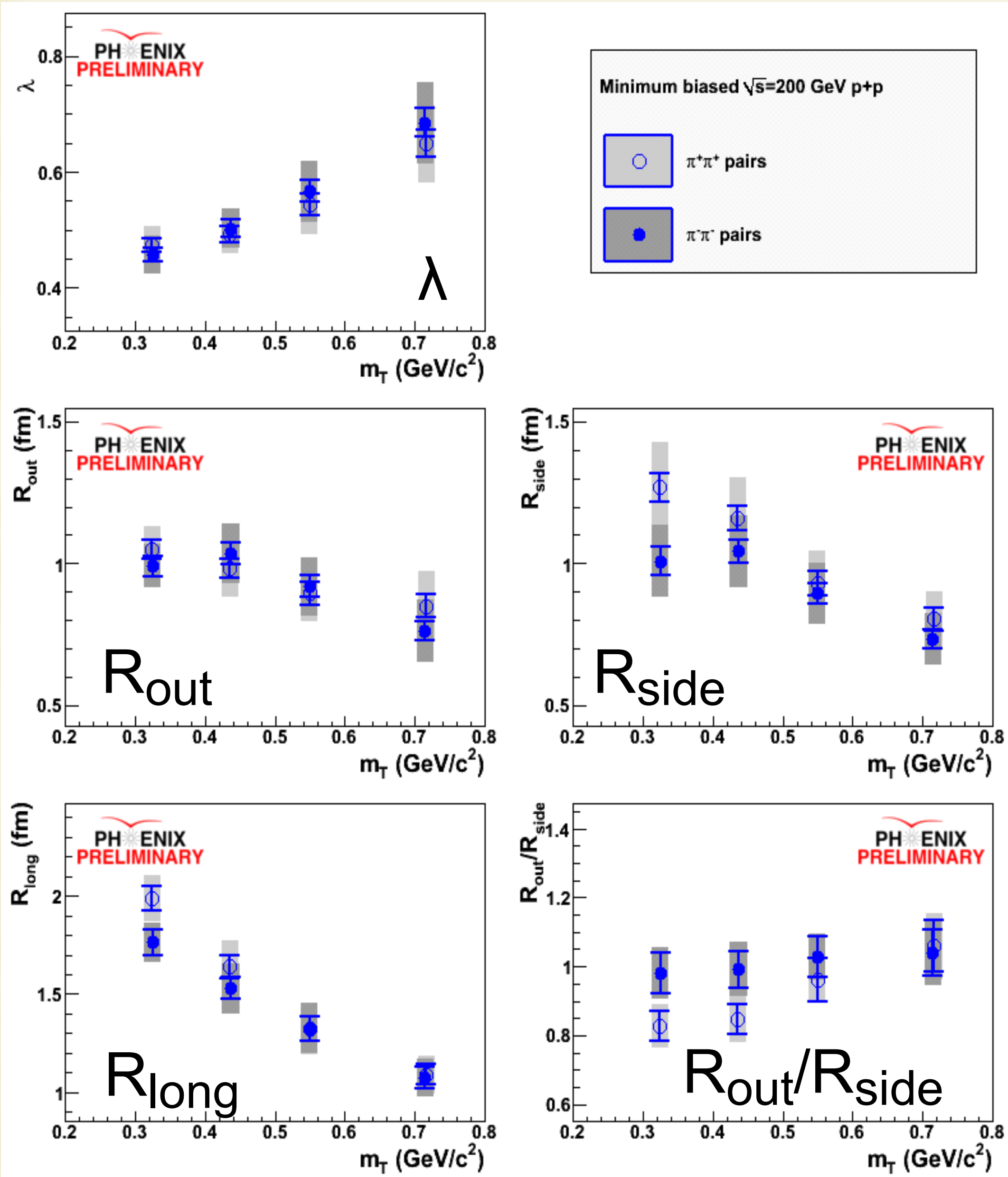
R_{out} is not scaled with dN/dy from AGS to SPS energy. Emission duration is significantly changed from AGS to SPS?

R_{side}, R_{long} are scaled well with multiplicity dN/dy rather than N_{part}.

Nature of phase transition could be changed at energy between AGS to SPS region. Detailed studies by energy scan is being performed at RHIC.

M.A. Lisa, S. Pratt, R. Soltz, U. Wiedemann
Ann.Rev.Nucl.Part.Sci.55:357-402,2005

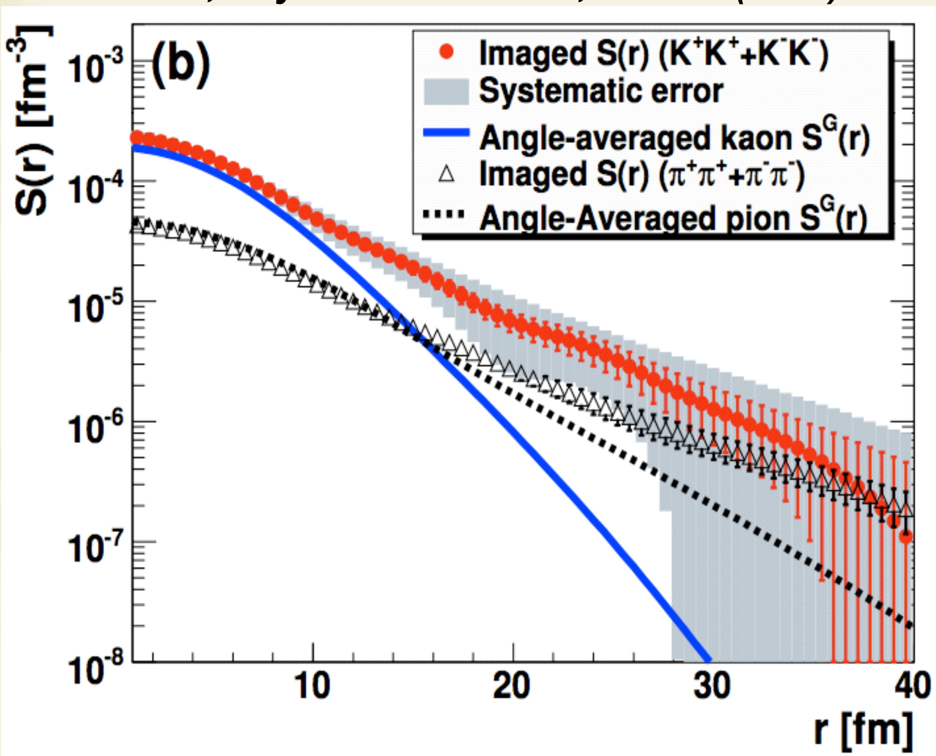
Corrective flow in p+p?



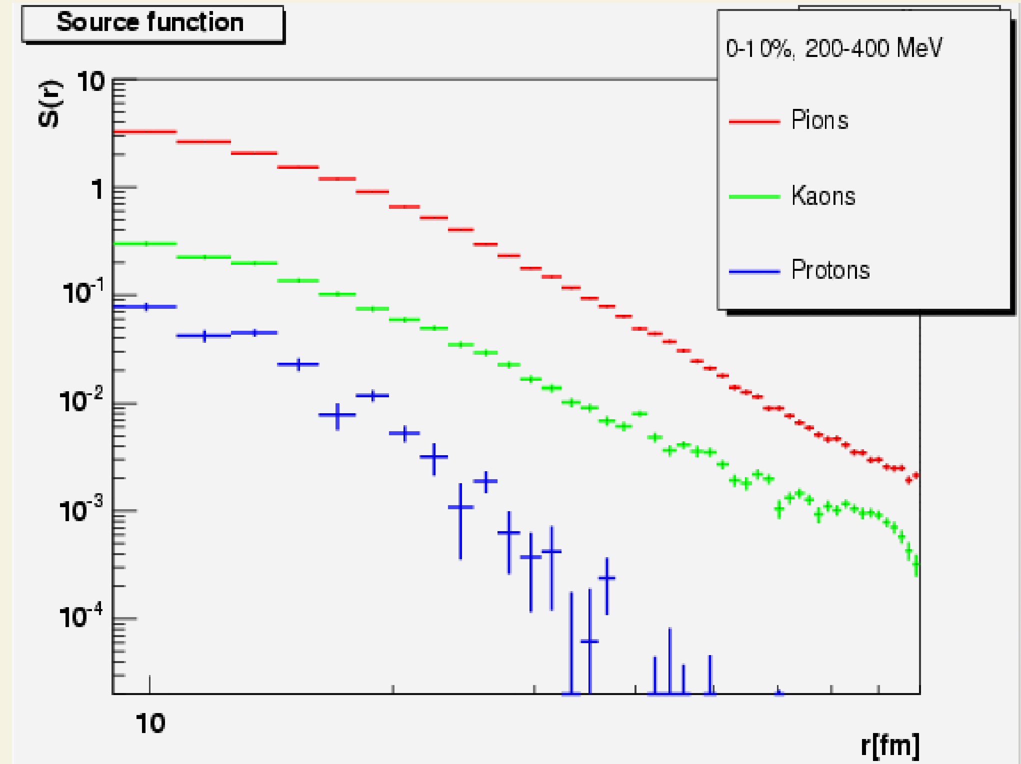
- Charged pion HBT transverse radius (R_{side}) measured in p+p collisions also show the m_T dependence.
  - Collective flow in p+p collision??
- Recent analysis by ALICE showed less p_T dependence after subtracting non-flat baseline.

HBT-imaging analysis

PHENIX, Phys. Rev. Lett. 103, 142301 (2009)



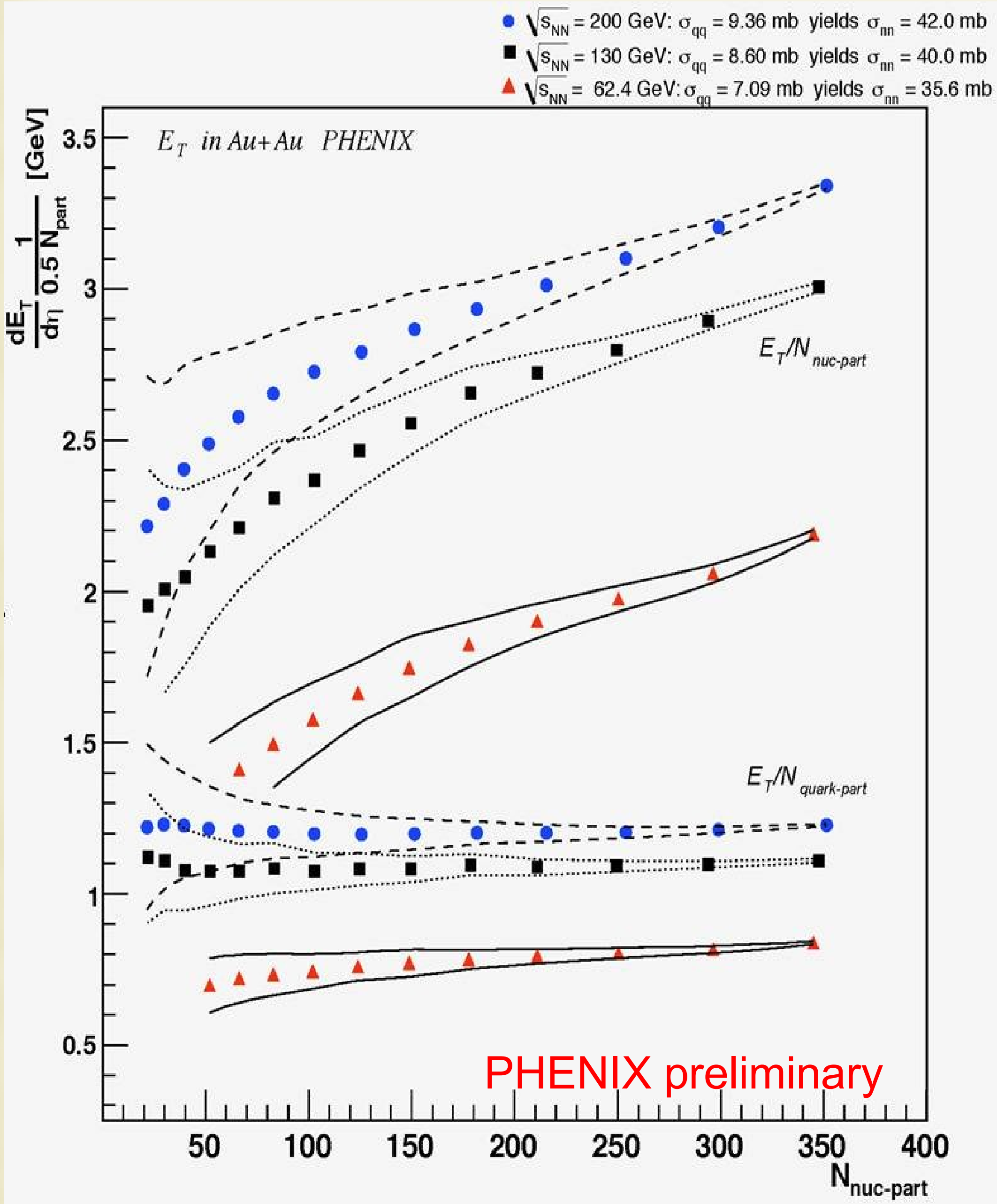
M. Csanád, T. Csörgő and M. Nagy, hep-hp/0702032



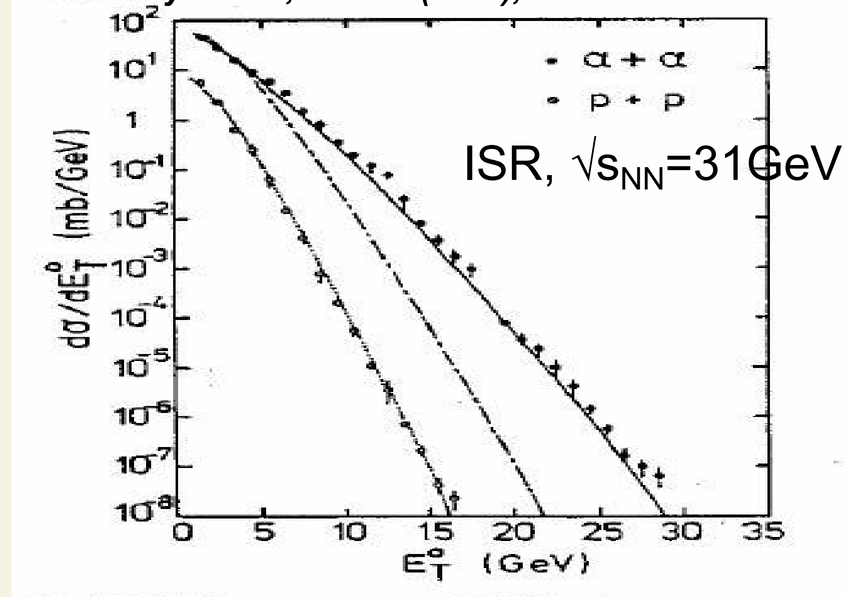
- The result shows a non-Gaussian structure in kaon emission function, as well as pion. Systematic errors are still big and we need to study with high statistics data.
- The magnitude of anomalous diffusion depends on particle's mean free path. Kaon has the smallest cross-section among pi, K, p, therefore shows the largest exponential tail.

Spectra

E_T spectra (WNM vs AQM?)

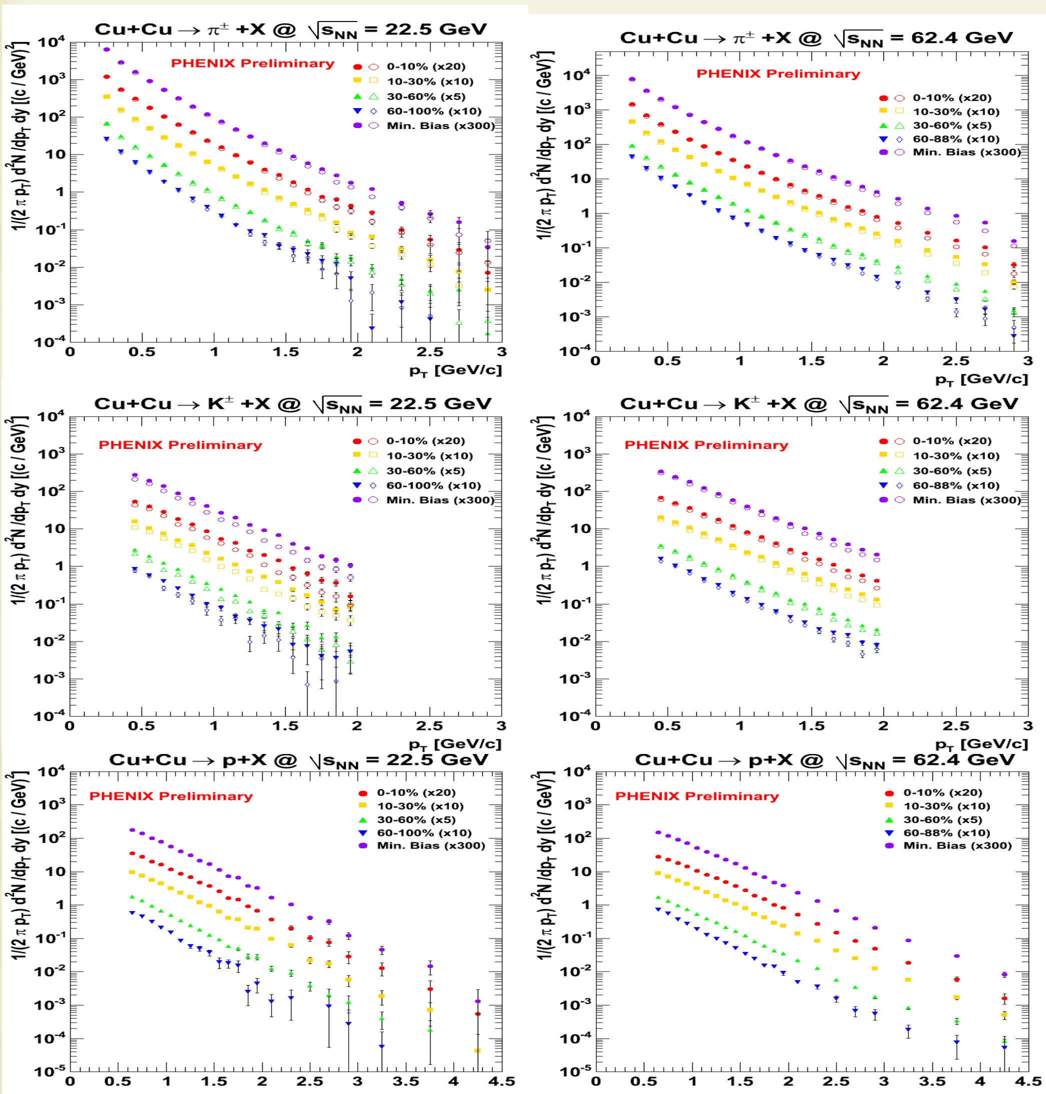


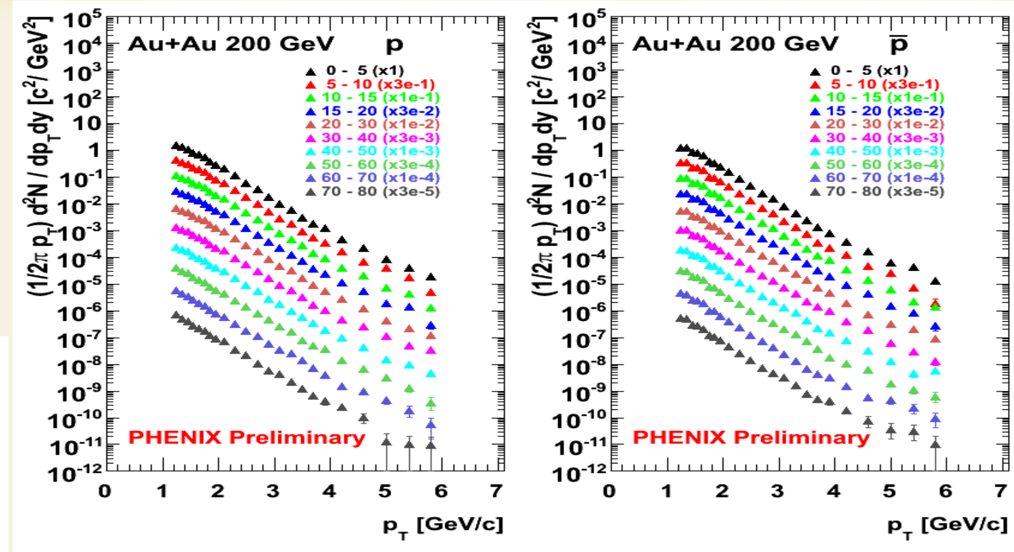
Z. Phys. C 35, 209214 (1987), T. Ochiai

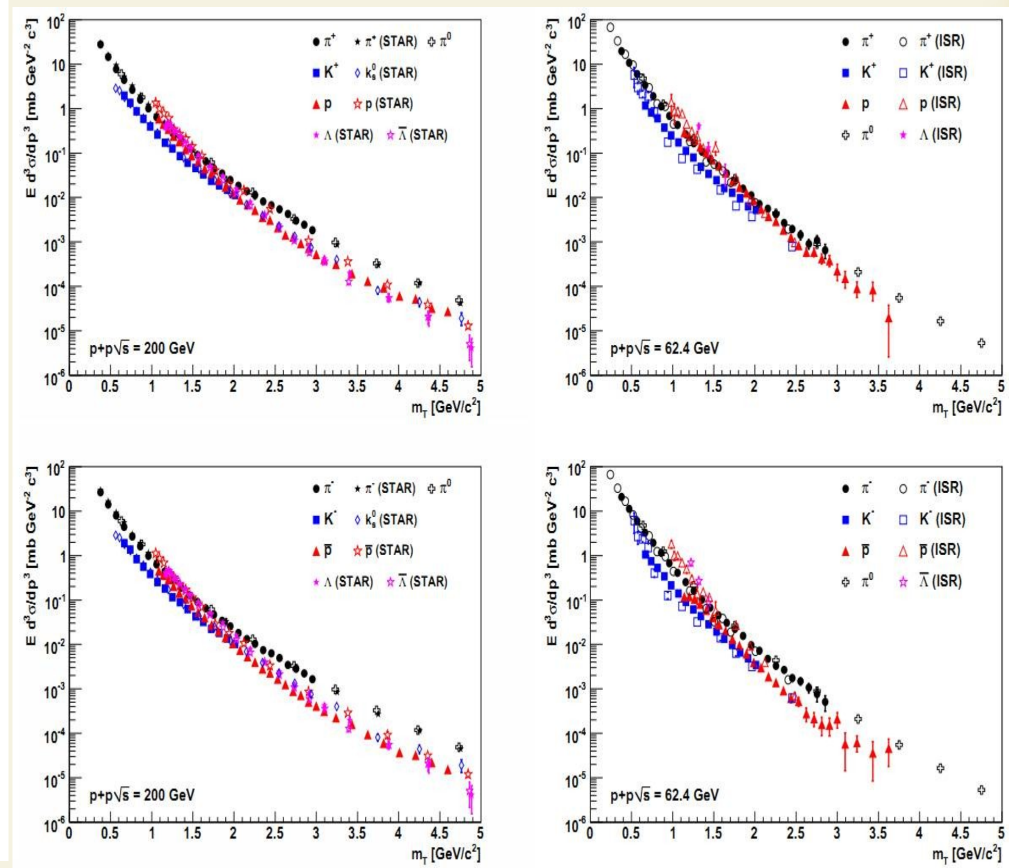


- PHENIX E_T measurement showed the AQM works in Au+Au at 62.4-200 GeV.
  - AQM works for $\sqrt{s_{NN}}$ > ~20 GeV
  - WNM works for $\sqrt{s_{NN}}$ < ~20 GeV
- A systematic study using lower collision energy, smaller system data is on-going to investigate the onset of the transition.

PID spectra

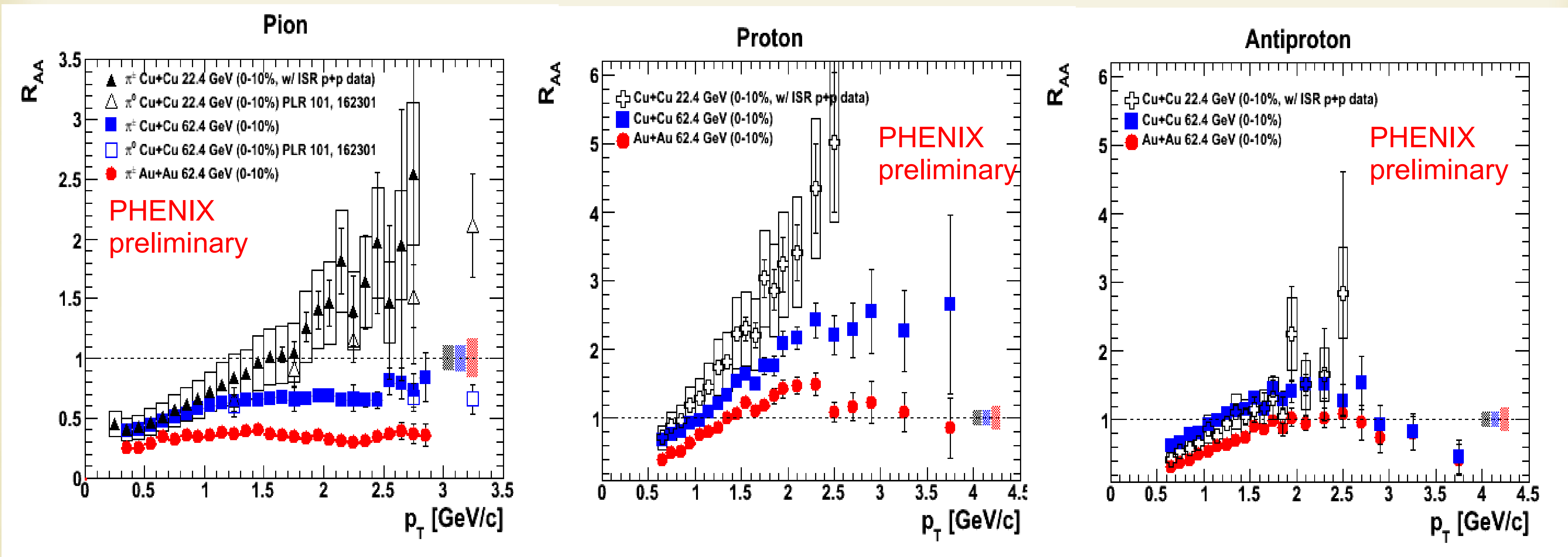






PHENIX collaboration, arXiv:1102.0753

R_{AA}



- Pion suppression is observed in Au+Au and Cu+Cu at 62.4 GeV
- Proton is enhanced, and the enhancement is most magnified in Cu+Cu at 22.4 GeV
  - Baryon transport in the mid-rapidity
- Anti-proton is less sensitive to the collision system/energy for Au+Au/Cu+Cu at 22.4 – 62.4 GeV.

Summary

- Large amount of data in Au+Au at 200GeV allowed us to investigate and deliver the detailed picture of space-time evolution of HI collisions through soft observables.
- Observables are well consistent (or linearly scaled) between Au+Au/Cu+Cu 39 ~ 200 GeV data, but not for the lower energies (Au+Au 7.7 GeV and Cu+Cu 22.4 GeV).
- So far, no significant sign of the critical point has been observed through fluctuation measurements with the available data sets.
- More PHENIX results with low-energy data sets describing the onset of the transition between quark and hadronic pictures will be coming out soon!

Acknowledgment

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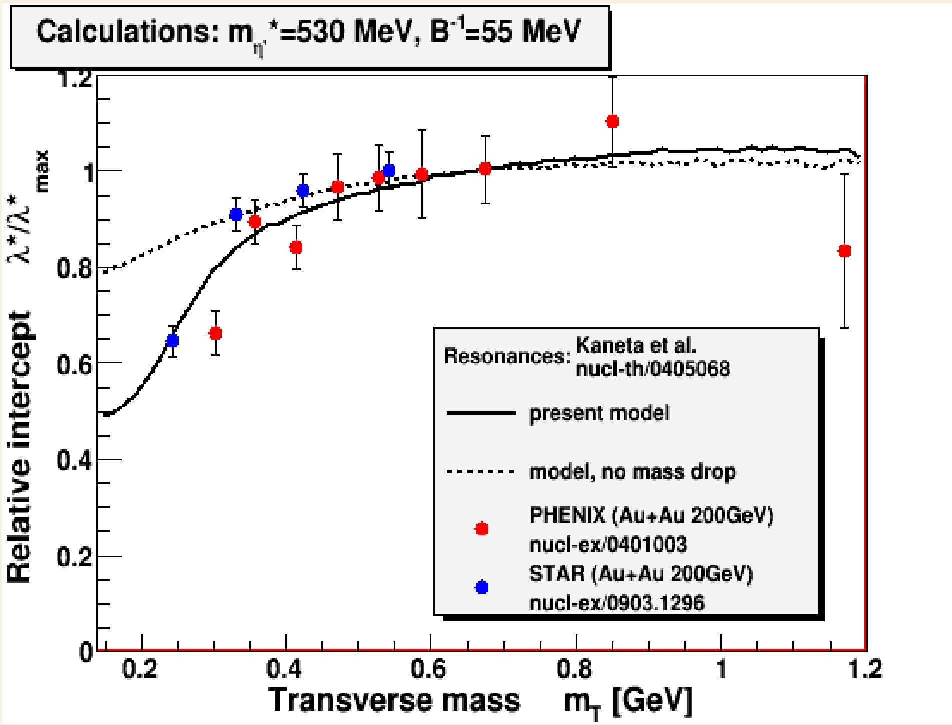
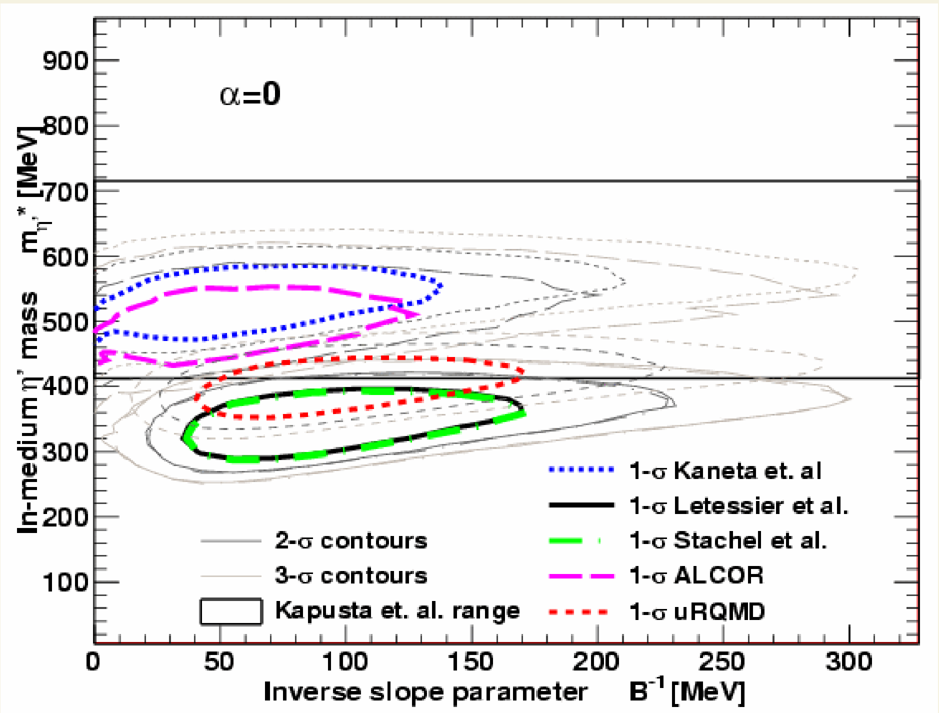
Backup slides

HBT-λ

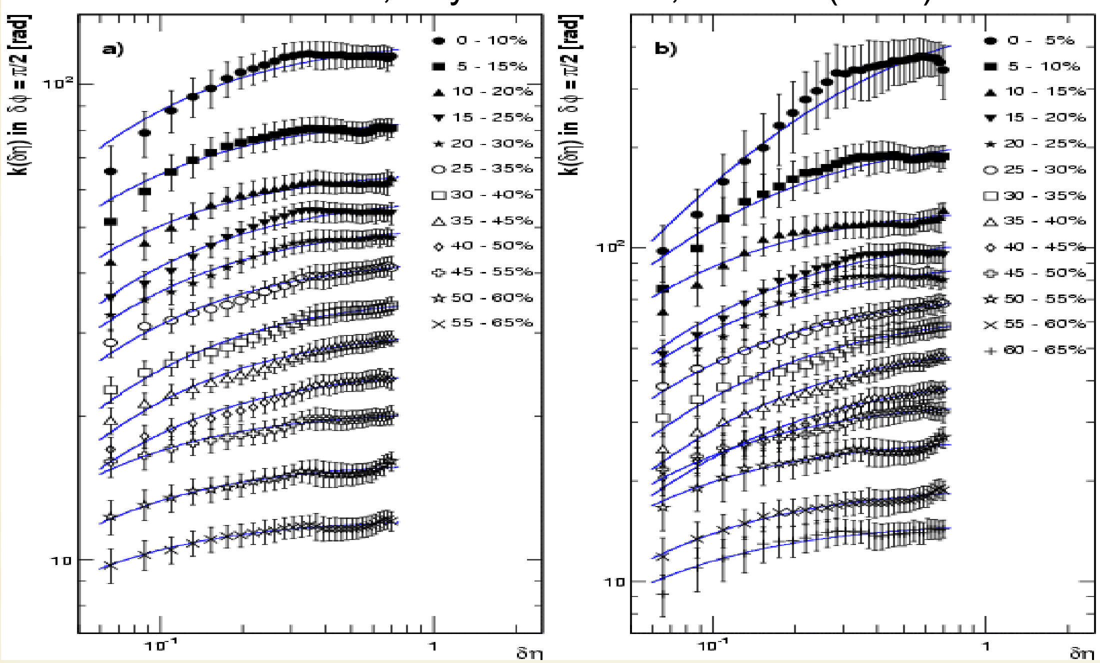




- In hot medium η' mass could be reduced to quark model mass due to UA(1) symmetry restoration mass, resulting in enhancement of mass of η' production (decrease of HBT-λ) at low p_T.
- Reliable data missing mainly at low m_T
  - Not enough restrictive on hadron production models
  - High precision low-pT HBT measurements will change this!

Susceptibility

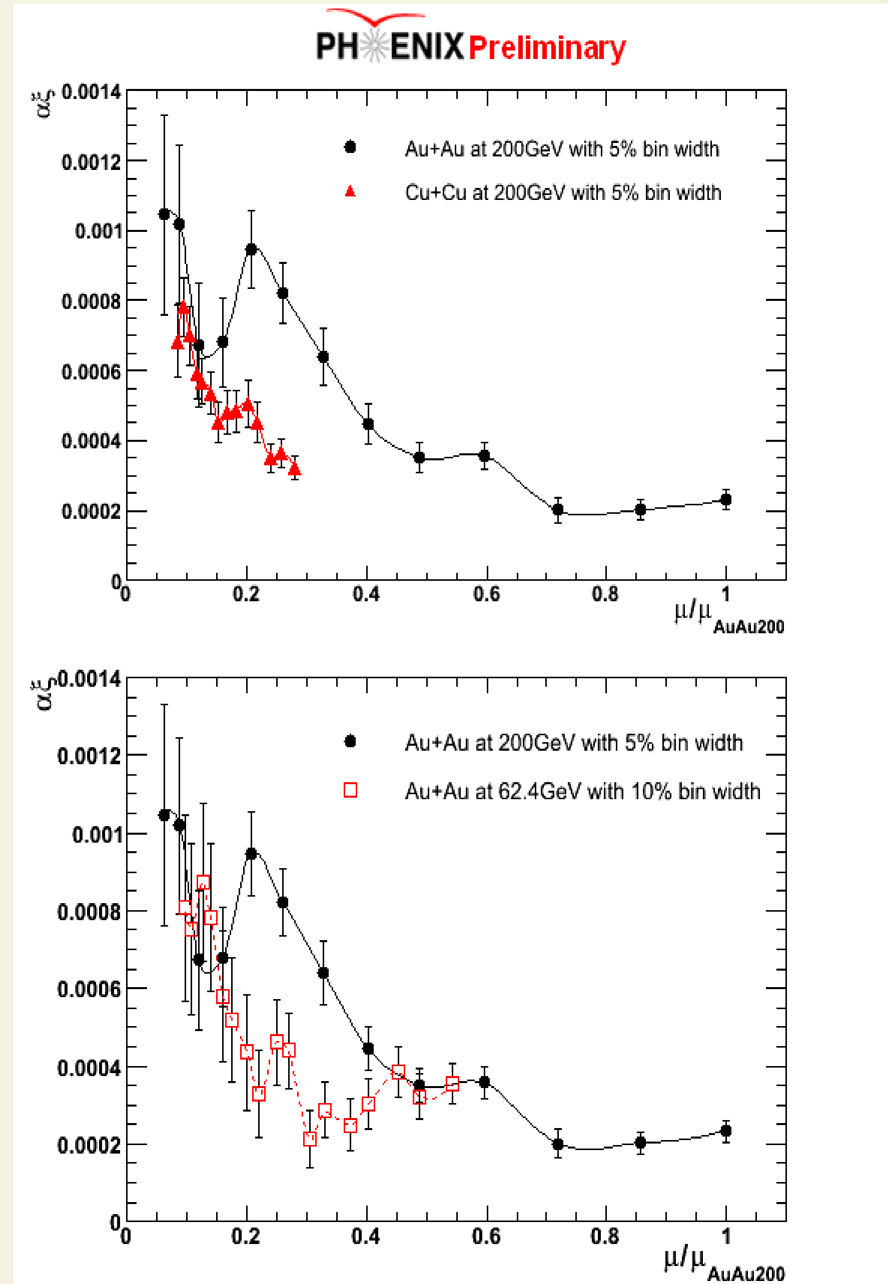
PHENIX collaboration, Phys. Rev. C 76, 034903 (2007)



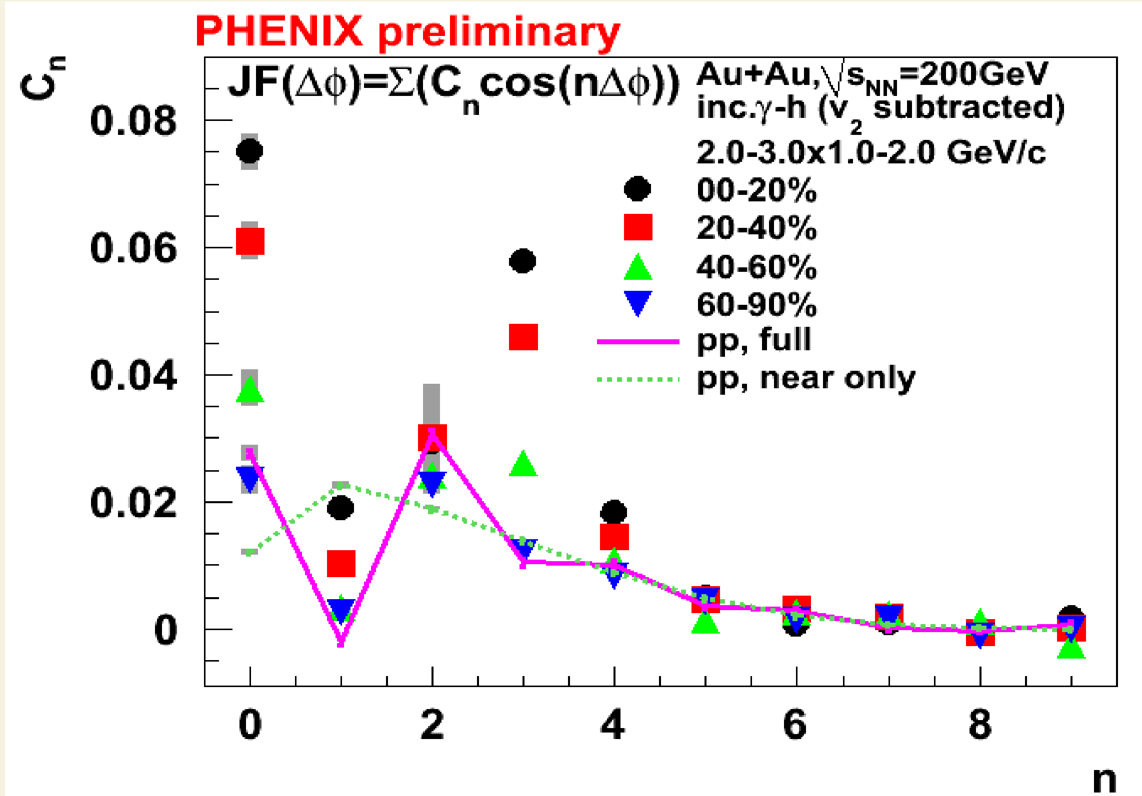
$$k^{-1}(\delta\eta) = \frac{2\alpha\xi^{2}\left(\delta\eta/\xi - 1 + e^{-\delta\eta/\xi}\right)}{\delta\eta^{2}} + \beta$$

Non-monotonic increase of αξ indicates T~Tc w.r.t. monotonically decreasing baseline as mean density μ increases.

αξ measured in Au+Au 200 GeV indicates non-monotonic behavior around N_{part}~90.



Fourier spectra of Jet Function



- No significant contribution above C_4
- Removing the away side pp enhances the C-odd terms
- The C_3 in AuAu has contributions from both jet and bulk