Fluctuation Results from PHENIX:

Universal Scaling

QNP '06 – 6/7/06

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Outline

- **Multiplicity Fluctuations**
- **Correlation Lengths**

    (using multiplicity fluctuations)
- **<p_T> Fluctuations**

Why Study Fluctuations at RHIC?

Movie by the University of Minnesota Physics Department

Movie of a sealed container containing freon on a hot plate at the critical point.
The image is projected onto a wall.

Common Analogy: Critical Opalescence

Light is strongly scattered from a mixed phase with droplets of size on the order of the wavelength of light.

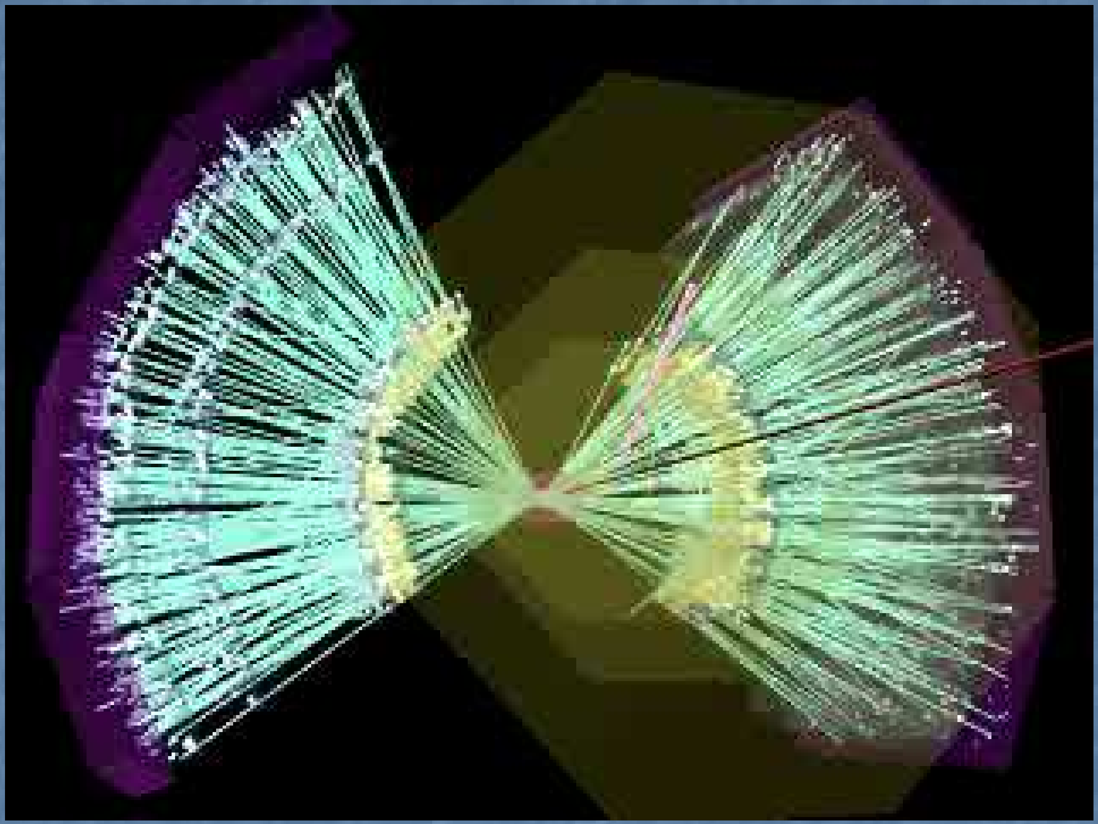
To search for direct evidence of critical behavior from a phase transition from normal hadronic matter to the sQGP phase.

Near a tri-critical end-point in the QCD phase diagram, event-by-event fluctuations in charged particle multiplicity and average p_T could increase significantly. *H. Heiselberg and A. Jackson, Phys. Rev. C63 (2001) 064904, M. Stephanov et al., Phys. Rev. Lett. 81 (1998) 4816*

The PHENIX Detector

Central 200 GeV Au+Au event display

Two "central arm" spectrometers anchored by drift chambers and pad chambers for 3-D track reconstruction within a focusing magnetic field.



Acceptance:

$|\eta| \sim 0.35$

$|\Delta\phi| \sim \pi$

Although the PHENIX acceptance is traditionally considered small for event-by-event measurements, the acceptance is large enough to provide a competitive sensitivity to most observables.

Measuring Multiplicity Fluctuations with Negative Binomial Distributions

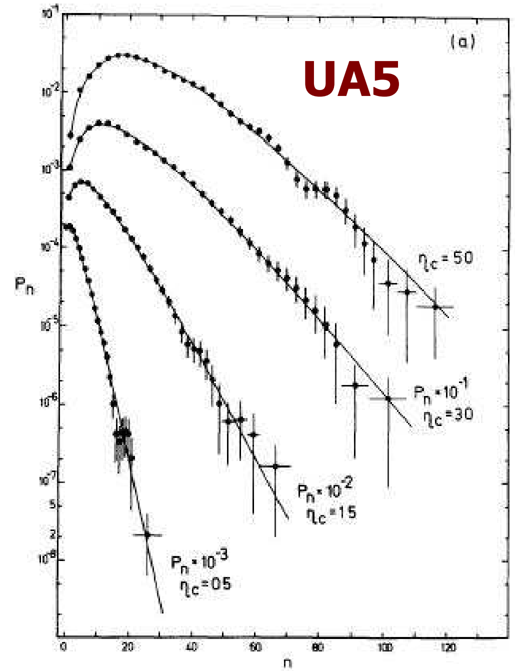
Multiplicity distributions in hadronic and nuclear collisions can be described by the Negative Binomial Distribution. The magnitude of the parameter k describes the deviation from a Poisson distribution → higher k means more Poissonian.

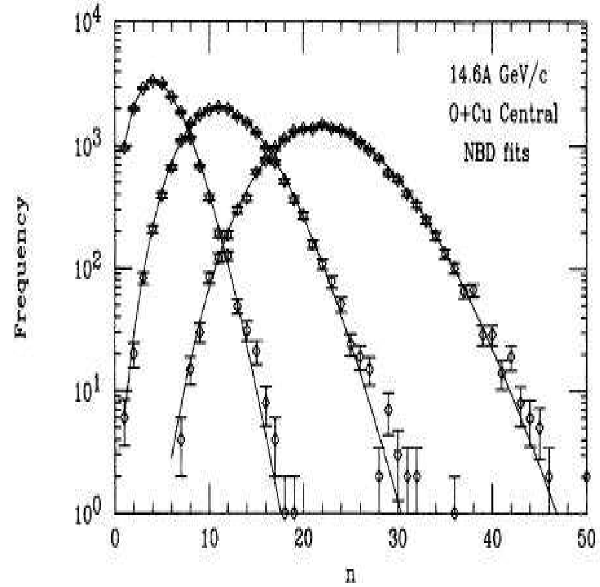
UA5: sqrt(s)=546 GeV p-pbar, Phys. Rep. 154 (1987) 247.

E802: 14.6A GeV/c O+Cu, Phys. Rev. C52 (1995) 2663.

$$P(m) = \frac{(m+k-1)!}{m!(k-1)!} \frac{\left(\mu/k\right)^{m}}{\left(1+\mu/k\right)^{m+k}}$$

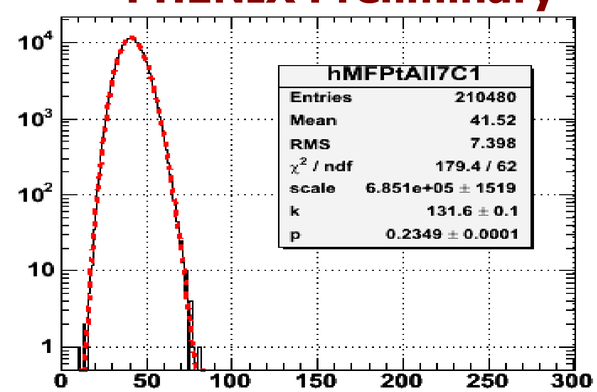
$$\frac{1}{k} = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu}$$





E802

PHENIX Preliminary



Central 62 GeV Au+Au

Thermodynamically Motivated Observables: Relating distributions to compressibility

- In the Grand Canonical Ensemble, the variance in particle number N (with μ=<N>) is related to the compressibility, k_T, via

$$\sigma^2 / \mu = \frac{k_B T \mu}{V} k_T$$

- The N.B.D. k parameter is related to the scaled variance via

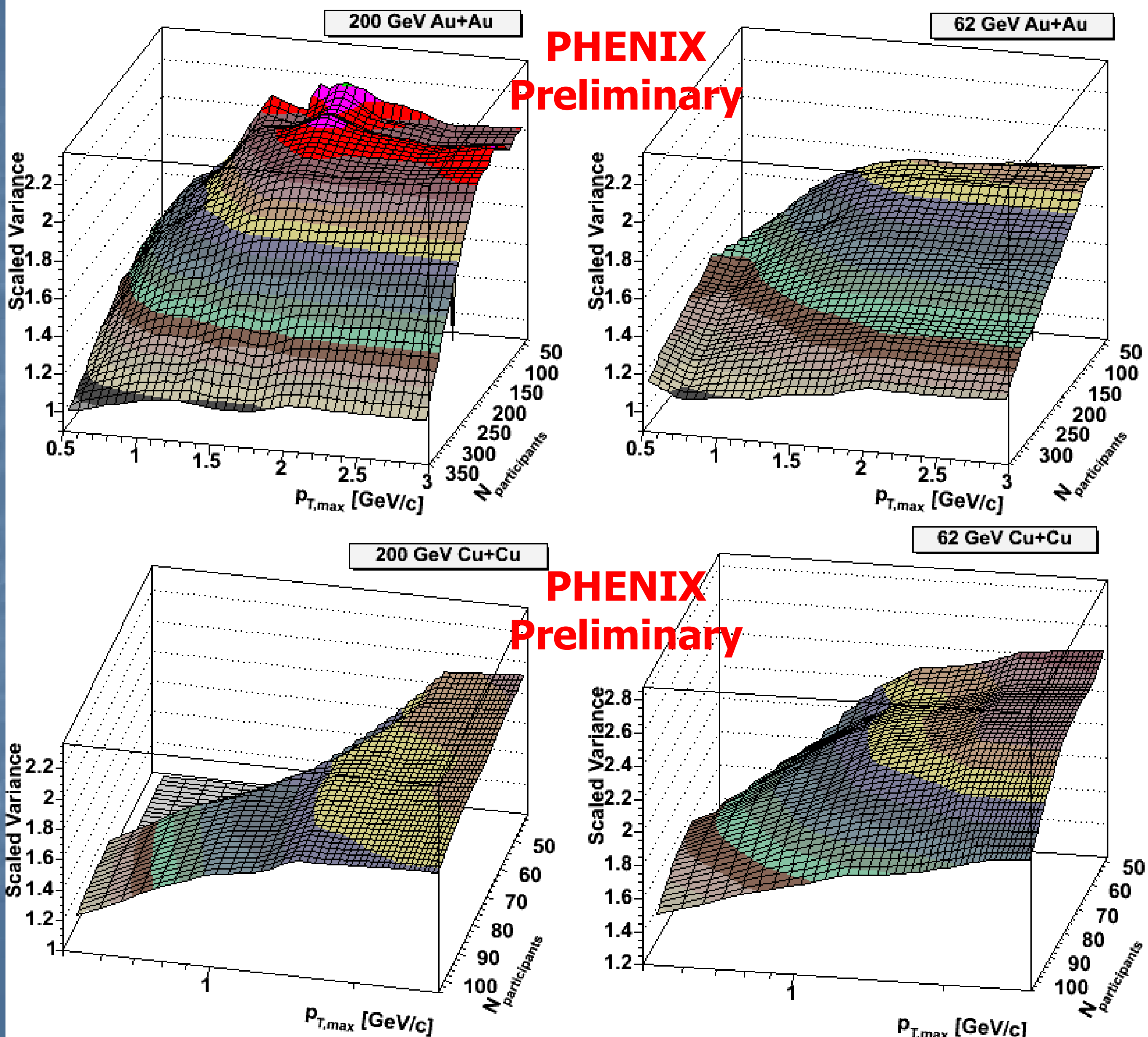
$$\sigma^2 / \mu = 1 + \mu / k_{NBD}$$

- N.B.D. k can then be related to compressibility:

$$1 / k_{NBD} = \frac{k_B T}{V} k_T - 1 / \mu$$

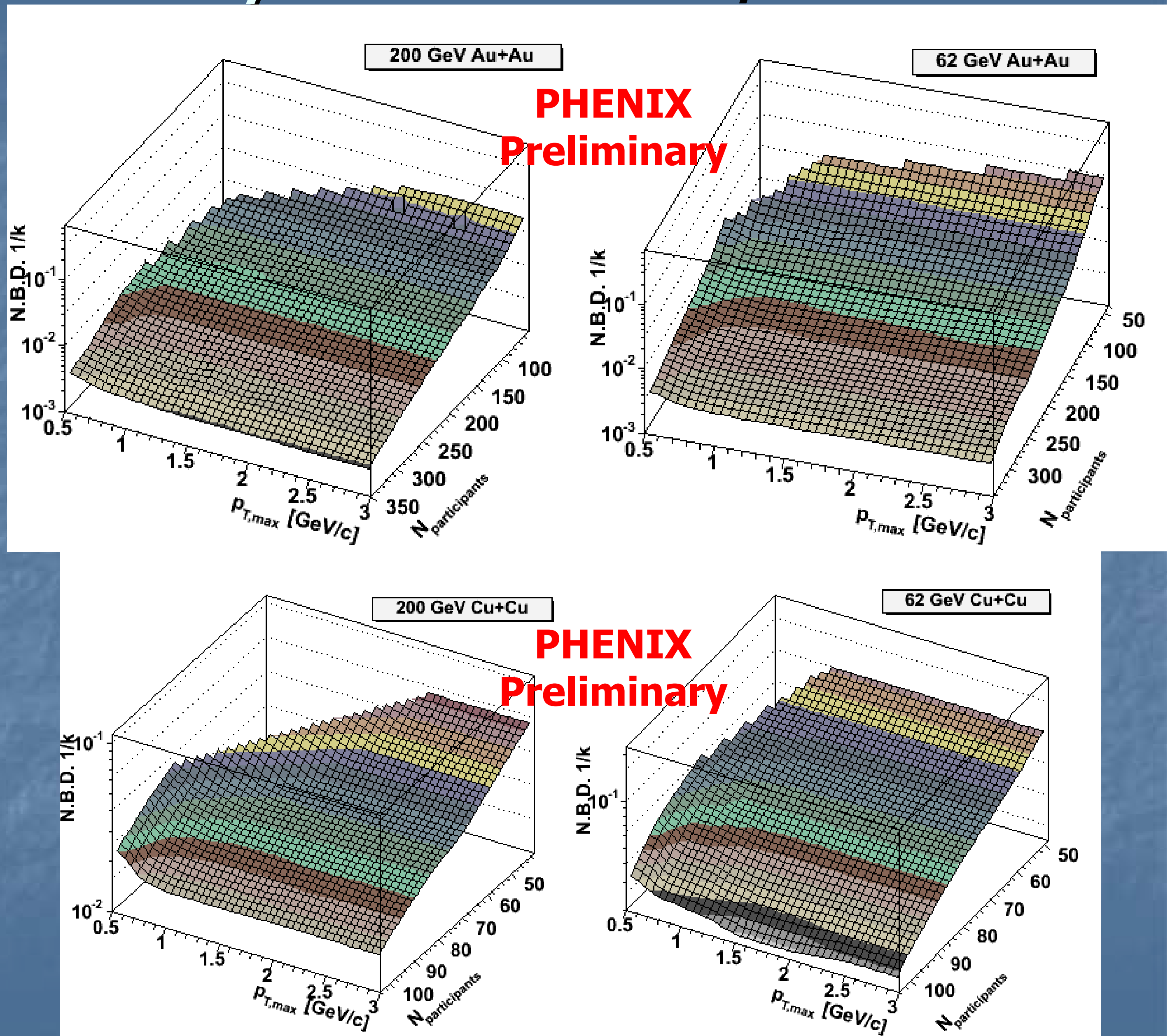
A Survey of Scaled Variance, σ^2/μ

- **Inclusive charged hadron fluctuations.**
- **These values are corrected to remove the contribution due to impact parameter (geometrical) fluctuations and projected to 2π in azimuth for direct comparisons to NA49 and other experiments.**
- **Here, the Poissonian (random) limit is 1.0.**
- **Large non-random fluctuations are observed that increase with p_T and decrease with centrality.**

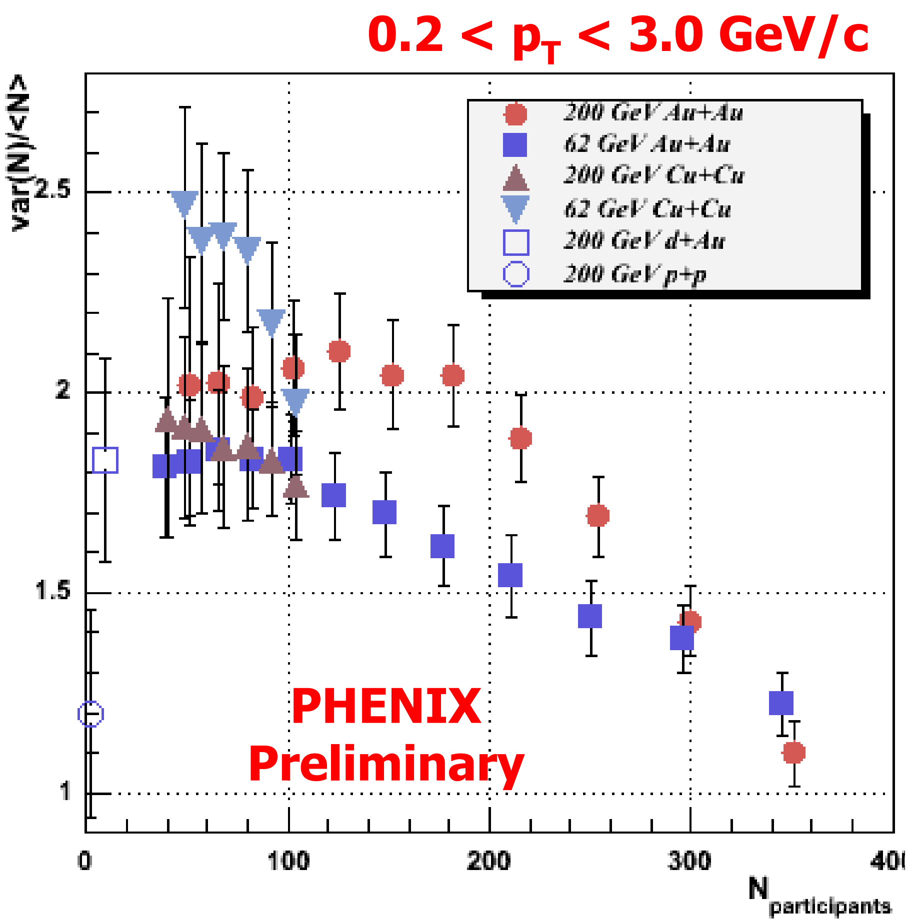


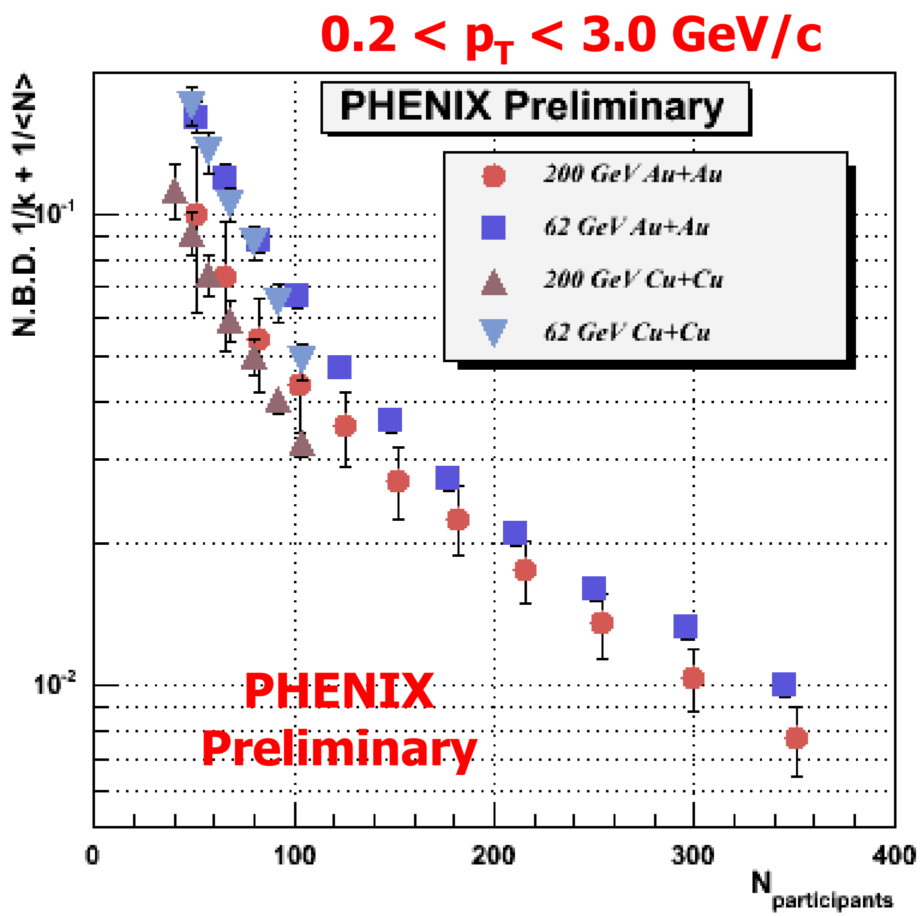
A Survey of N.B.D. 1/k

- Inclusive charged hadron fluctuations.
- These values are corrected to remove the contribution due to impact parameter (geometrical) fluctuations and projected to 2π in azimuth for direct comparisons to NA49.
- Here, the Poissonian (random) limit is $1/k \rightarrow 0$.
- Large non-random fluctuations are observed that decrease with centrality.



Fluctuations over the entire p_T range





Inclusive charged hadron fluctuations. All points are projected to 2π azimuthal acceptance, corrected for detector occupancy and efficiency. All points are corrected for non-dynamical geometry fluctuations due to the finite width of the centrality bins. Errors include time-dependent systematic errors, azimuthal extrapolation systematic errors, and impact parameter correction systematic errors. p+p fluctuations are consistent with projections of UA5 results to sqrt(s)=200 GeV.

A Critical Exponent analysis of the centrality-dependent fluctuations

- Let's assume that the increased fluctuations are indicative of critical behavior. Then, it is expected that a) the system can be described by critical exponents, and b) all systems can be described by the same set of critical exponents. Recall that

$$\frac{\left(\sigma^2/\mu\right)}{\mu} = \frac{1}{k_{NBD}} + \frac{1}{\mu} = \frac{k_B T}{V} k_T$$

- The critical exponent for compressibility is represented by the symbol γ and is described by $\frac{k_T}{k_T^c} = A'\left(\frac{T-T_c}{T_C}\right)^{-\gamma}$

- Replacing and solving for $1/k_{NBD}$ gives (A=constant, T=Temperature, V=volume)

$$\frac{1}{k_{NBD}} + \frac{1}{\mu} = \frac{\left(\sigma^2/\mu\right)}{\mu} = A\left(\frac{T}{V}\right)\left(\frac{T-T_c}{T_C}\right)^{-\gamma}$$

N.B.D. $1/k+1/\mu$

All systems have been scaled to match the 200 GeV Au+Au points for emphasis.

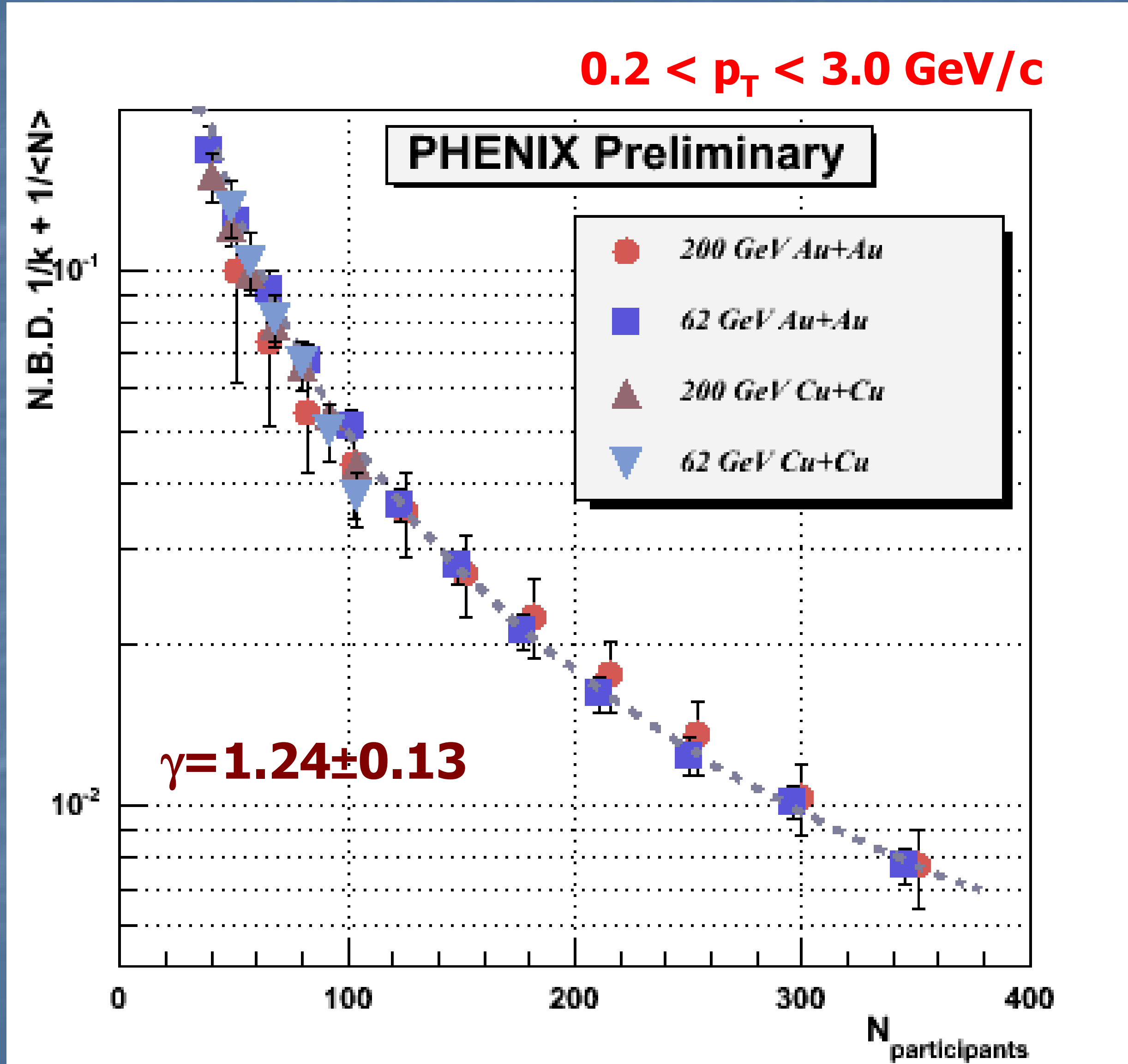
All four systems exhibit a power law behavior with respect to N_{part}. All systems appear to follow a universal curve within errors.

The fit assumes that $N_{part,c}$~0 and (see e.g. *hep-ph/0502174*)

$$T \propto N_{part}^{1/3}$$

The value of the critical exponent is γ=1.24±0.13 for all species.

This is consistent with γ for common gas-liquid phase transitions, which are typically between 1.2 and 1.3.

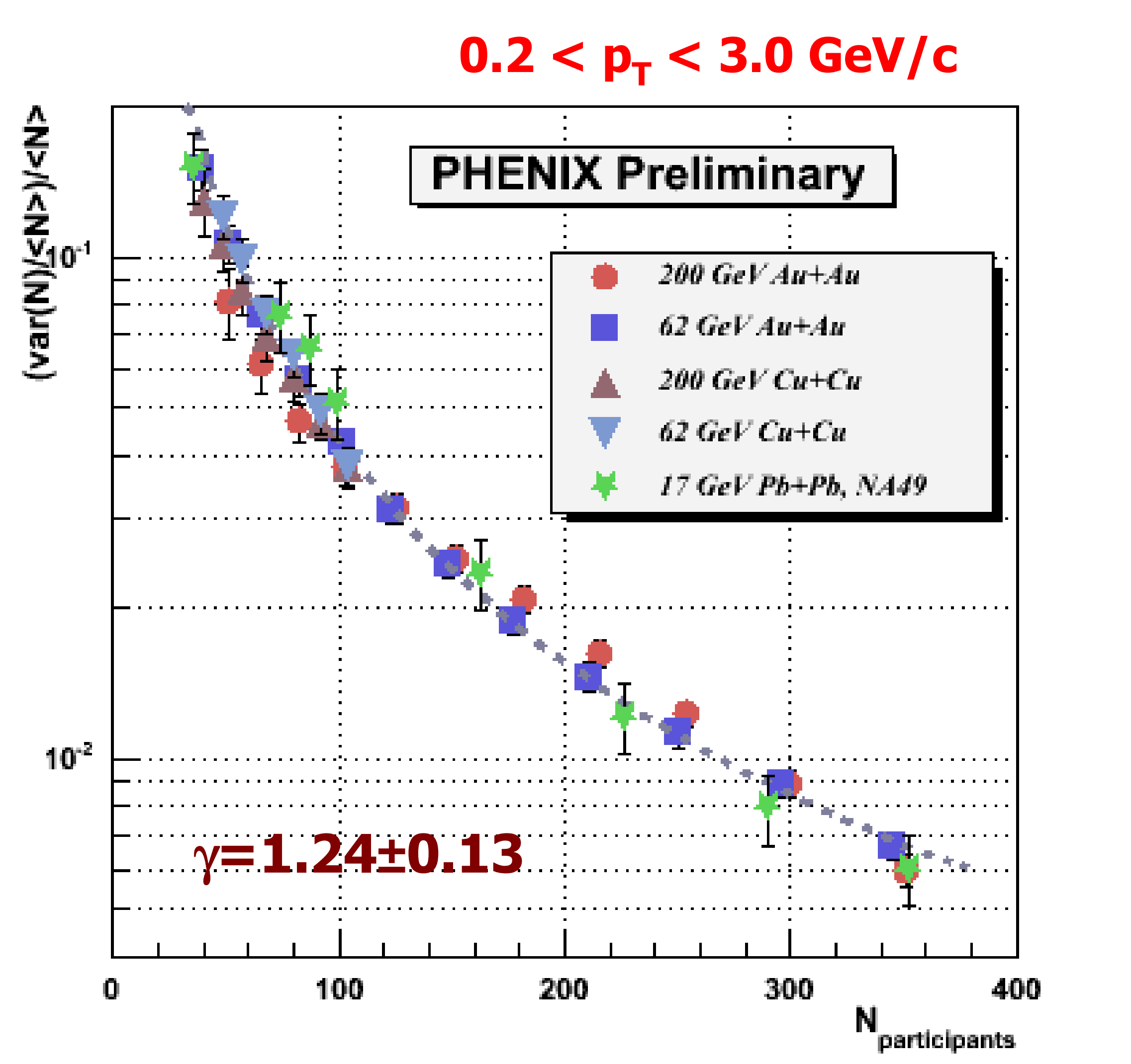


Scaled Variance Direct comparison to NA49 (17 GeV Pb+Pb)

$$\frac{\left(\sigma^2/\mu\right)}{\mu} = \frac{k_B T}{V} k_T$$

$$T \propto N_{part}^{1/3}$$

Includes a comparison to NA49 measurements at SPS energies. The NA49 scaled variance data have been corrected for impact parameter fluctuations from their 10% wide centrality bins and scaled up by 15% to lie on the 200 GeV Au+Au curve. The fits use γ=1.24. The NA49 data amazingly exhibit the same universal behavior!



Multiplicity Fluctuations: Extracting a Correlation Length

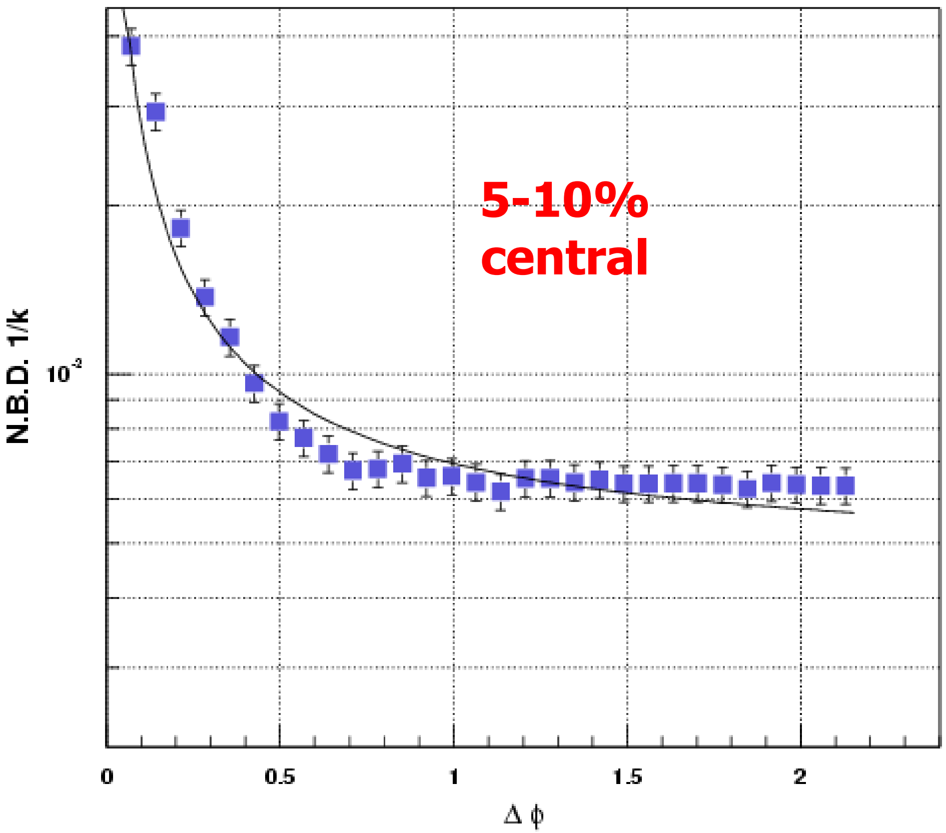
- **The correlation length, ξ, is expected to diverge at the critical point.**
- **To extract ξ, the N.B.D. k parameter is extracted by fitting the multiplicity distribution in successive ranges of $\delta\eta$ or $\delta\phi$.**
- **NBD k can be related to a correlation length as follows (see *E802, Phys. Rev. C52 (1995) 2663*):**

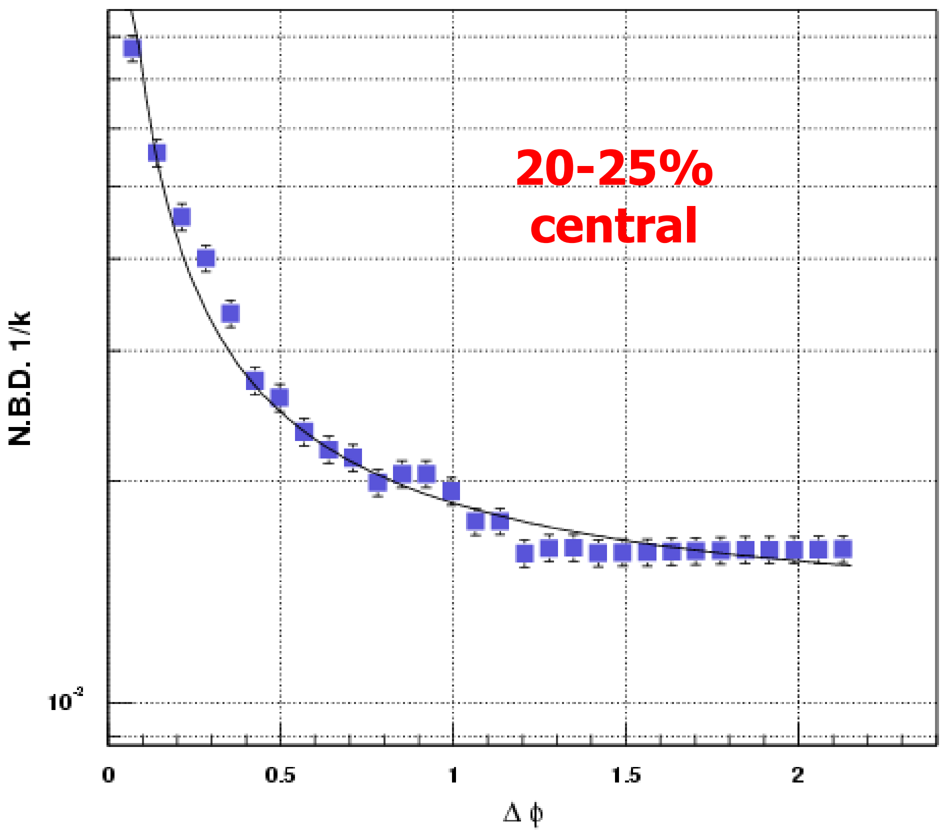
$$1/k = \frac{2\alpha\xi^2\left(\delta\eta/\xi - 1 + e^{-\delta\eta/\xi}\right)}{\delta\eta^2} + \beta$$

Here, α is fixed to 0.5 (based on PHENIX preliminary correlation function measurements). β, and ξ are free parameters.

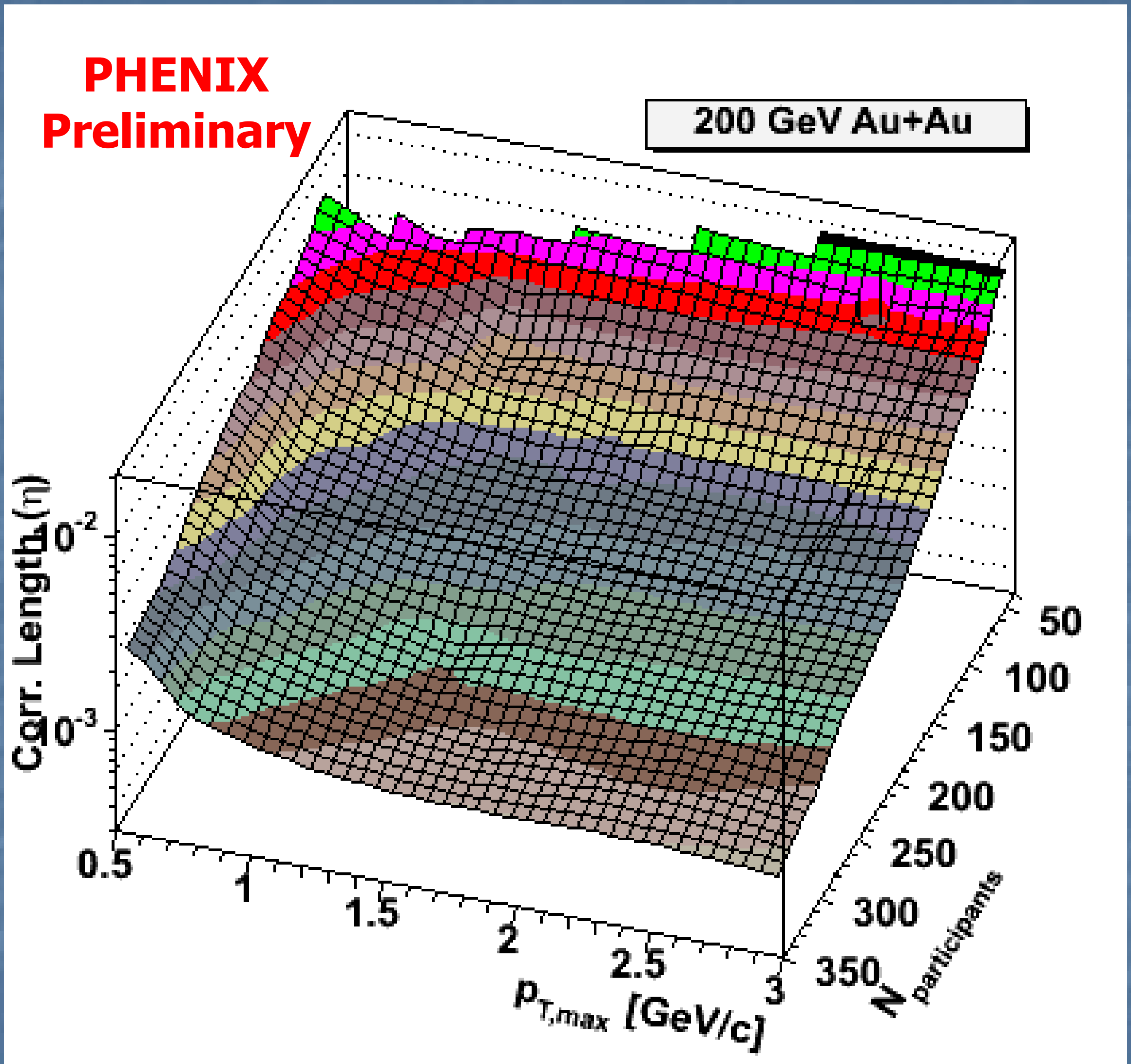
Example: NBD 1/k vs. $\Delta\phi$

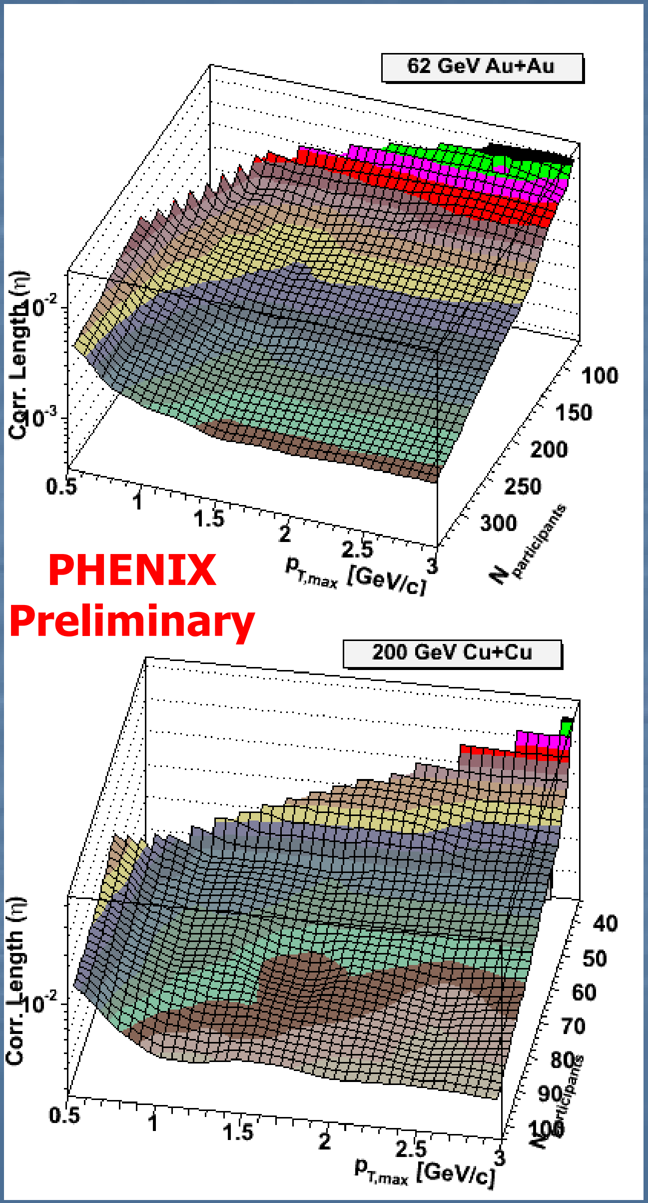
$$1/k = \frac{2\alpha\xi^2\left(\delta\phi/\xi - 1 + e^{-\delta\phi/\xi}\right)}{\delta\phi^2} + \beta$$





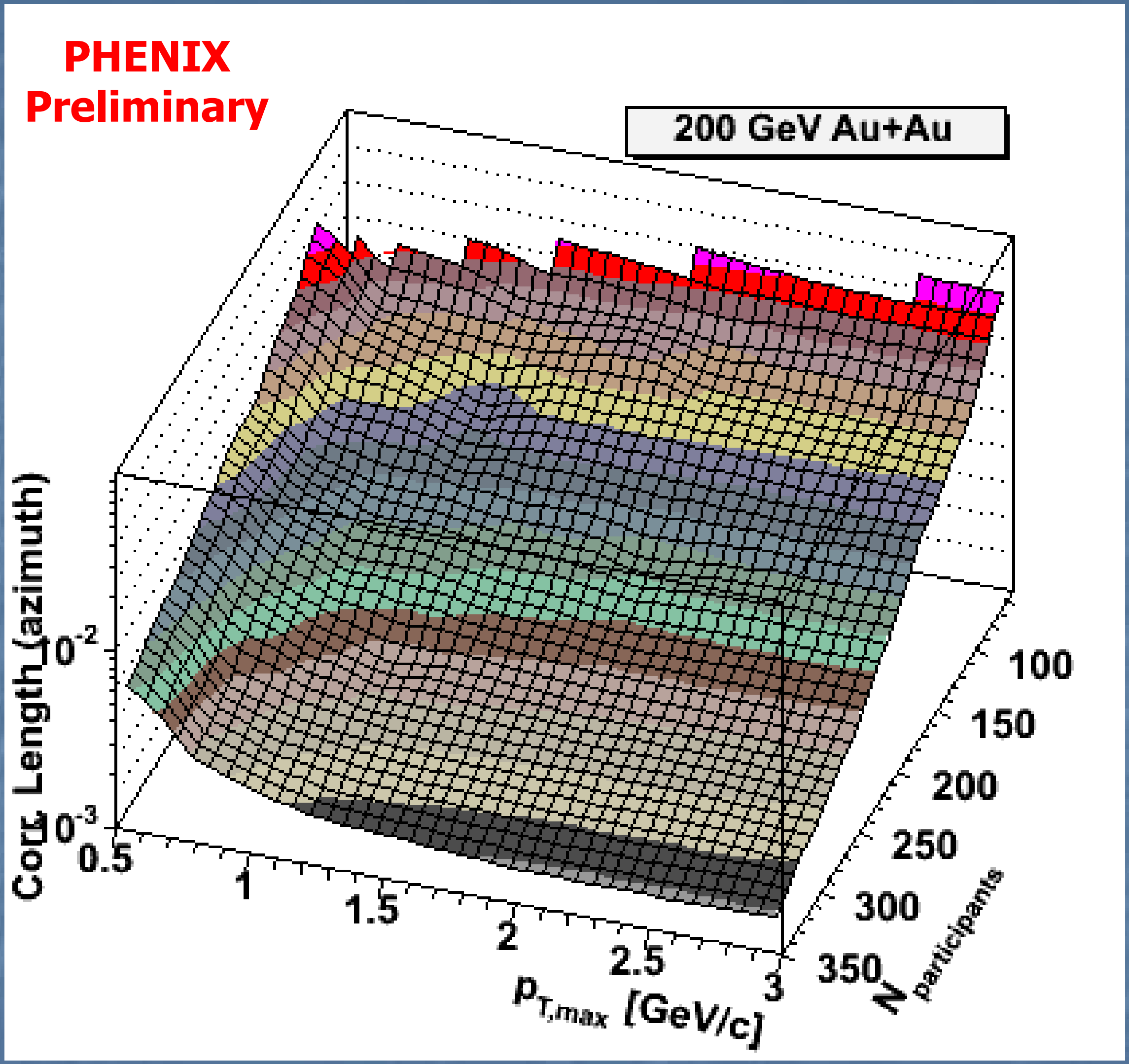
Correlation length (η) in centrality and $p_{T,max}$

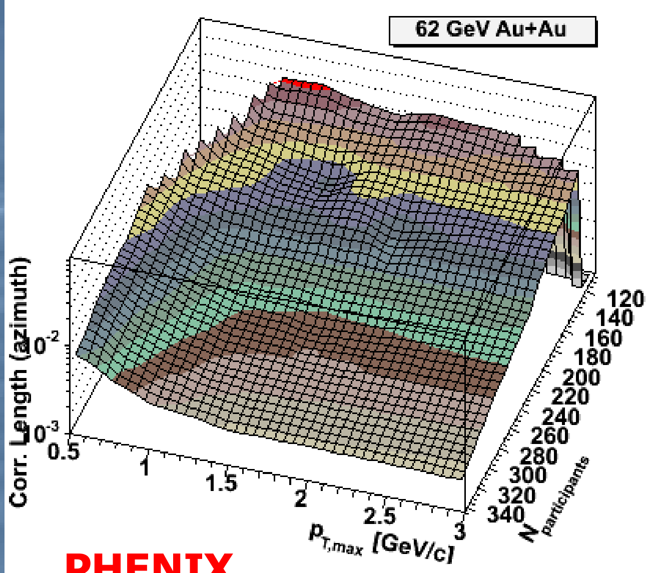




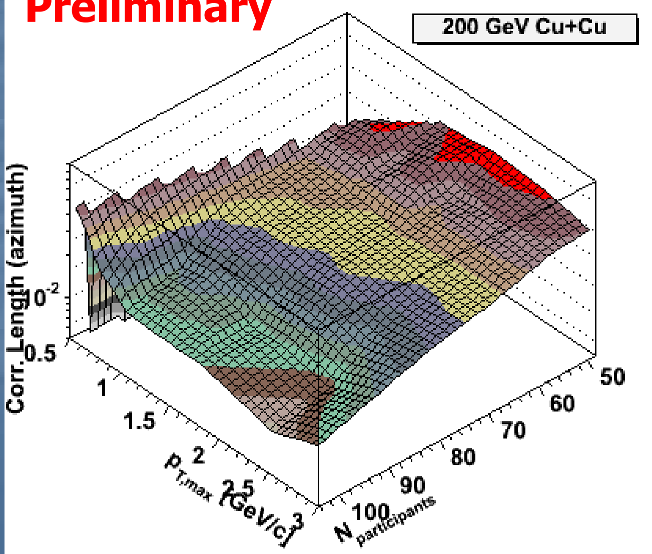
All species show the same increasing trend as N_{part} and $p_{T,max}$ decrease.

Correlation length (ϕ) in centrality and $p_{T,max}$



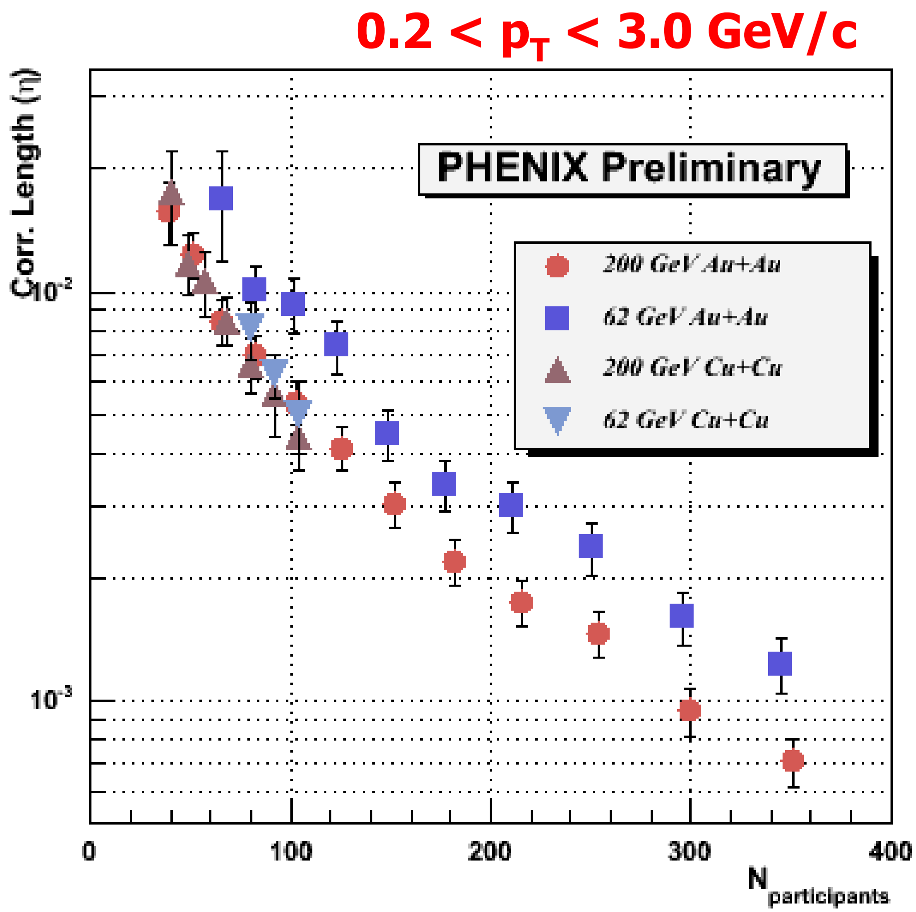


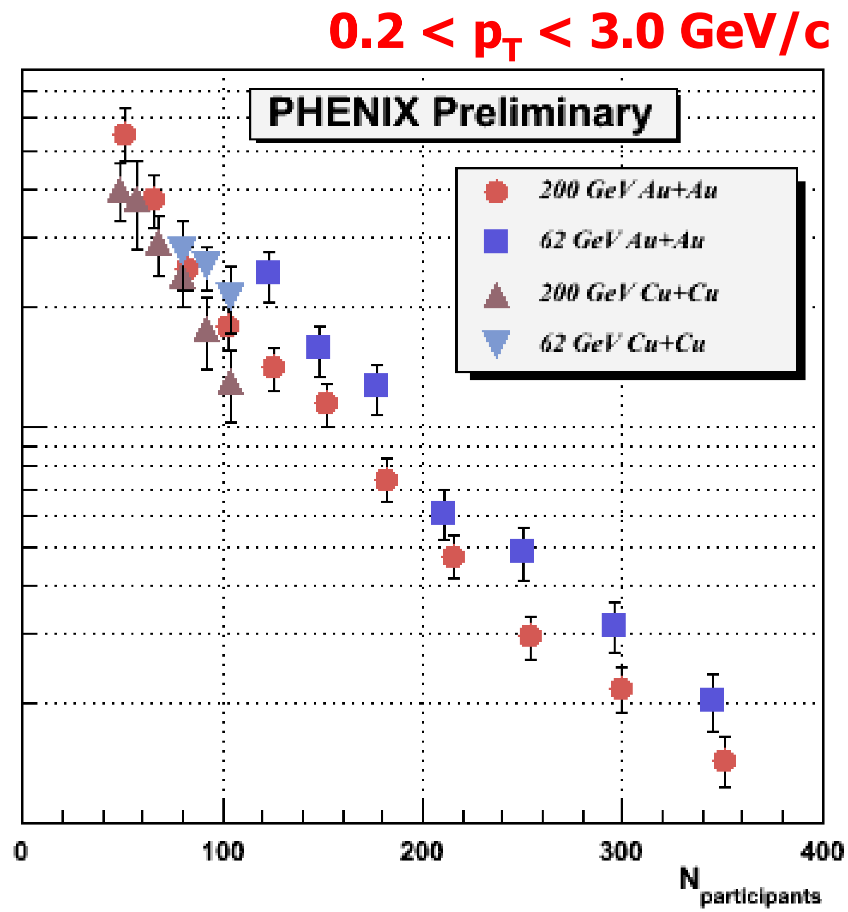
PHENIX
Preliminary



All species show the same increasing trend as N_{part} and $p_{T,max}$ decrease.

Correlation Length vs. Centrality



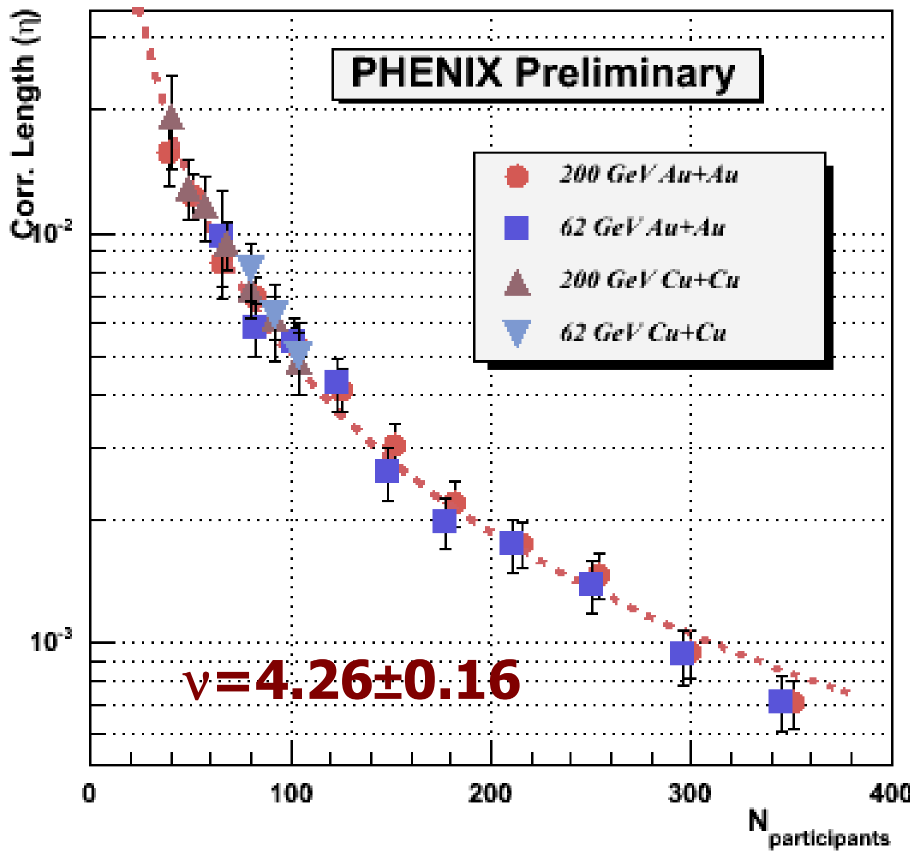


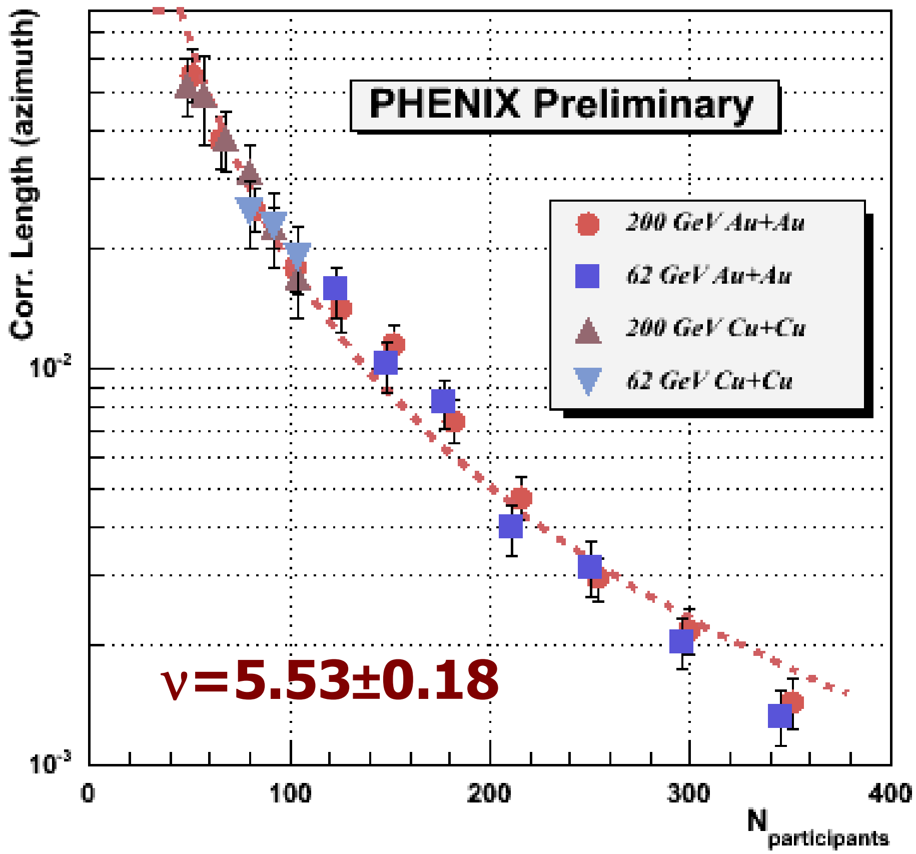
These points have not been scaled. Notice that the correlation lengths also appear to exhibit a universal behavior as a function of centrality. A critical exponent analysis can be performed on the correlation length:

$$\xi = \left(\frac{T - T_C}{T_C}\right)^{-\nu}, T > T_C$$

$$T \propto N_{part}^{1/3}$$

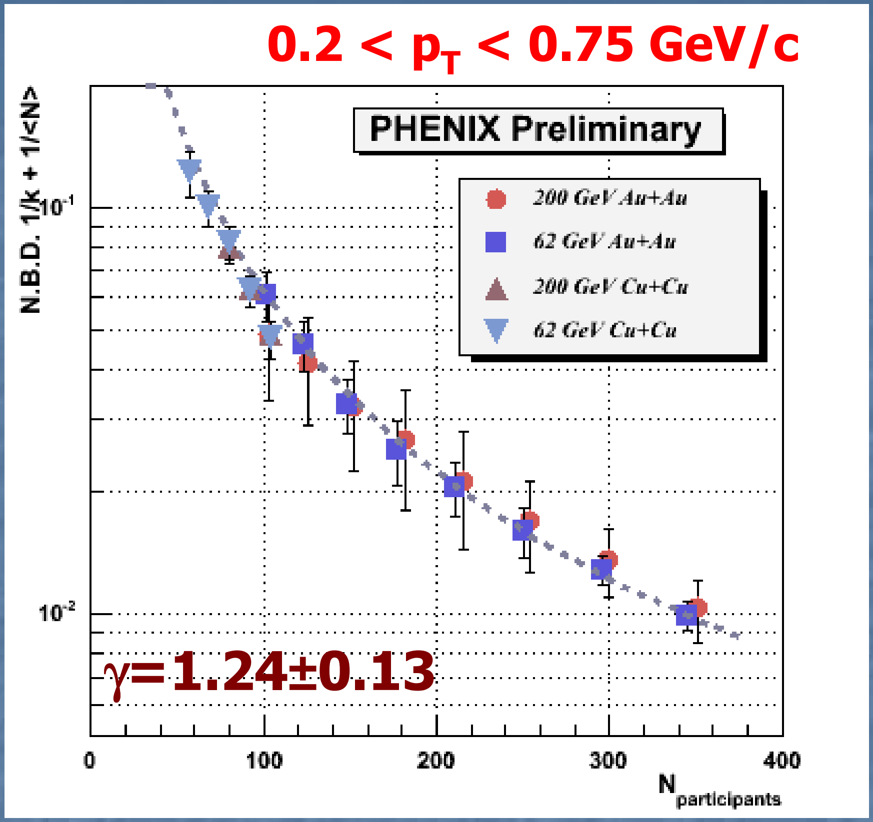
Correlation Lengths: Critical Exponent Analysis

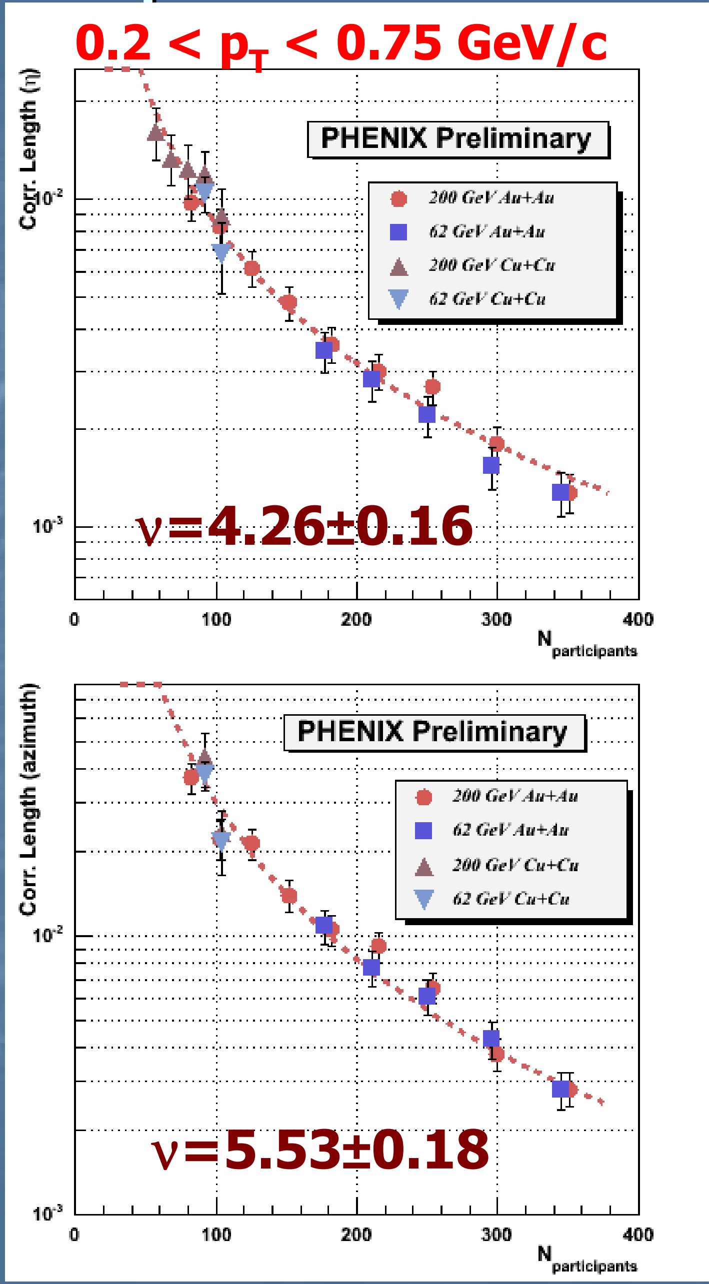




The data from other systems have been scaled to lie on top of the 200 GeV Au+Au points for emphasis. The fits yield ν=4.26 for pseudorapidity and ν=5.53 for azimuth. The typical value for ν in common systems is 0.5.

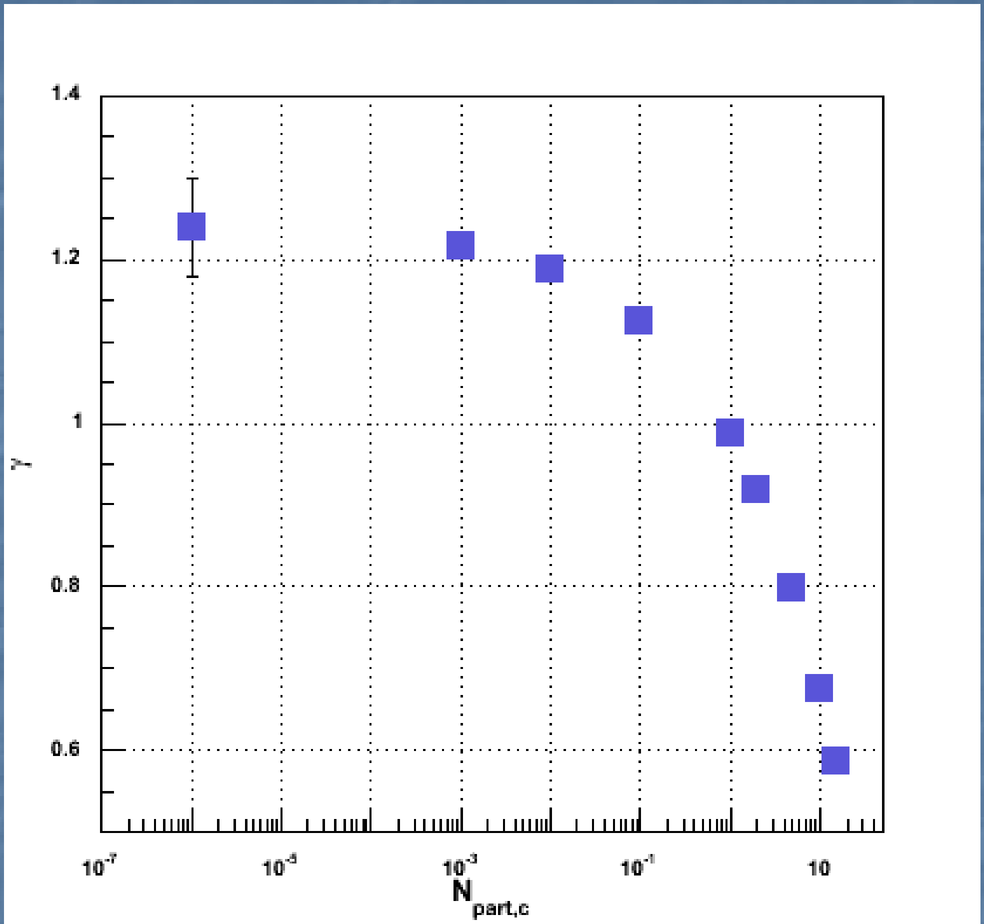
Critical Exponents: p_T-independent

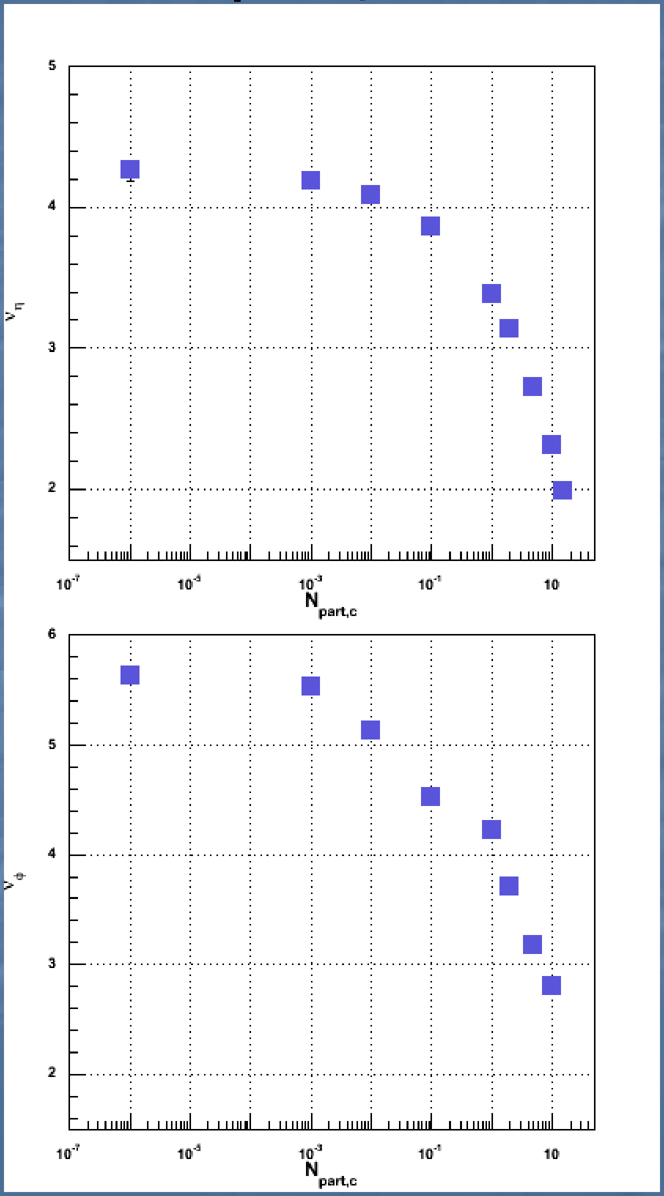




The critical exponents describing the data are independent of p_T range. The scaling appears to be driven by low p_T processes.

Critical Exponents vs. $N_{part,c}$

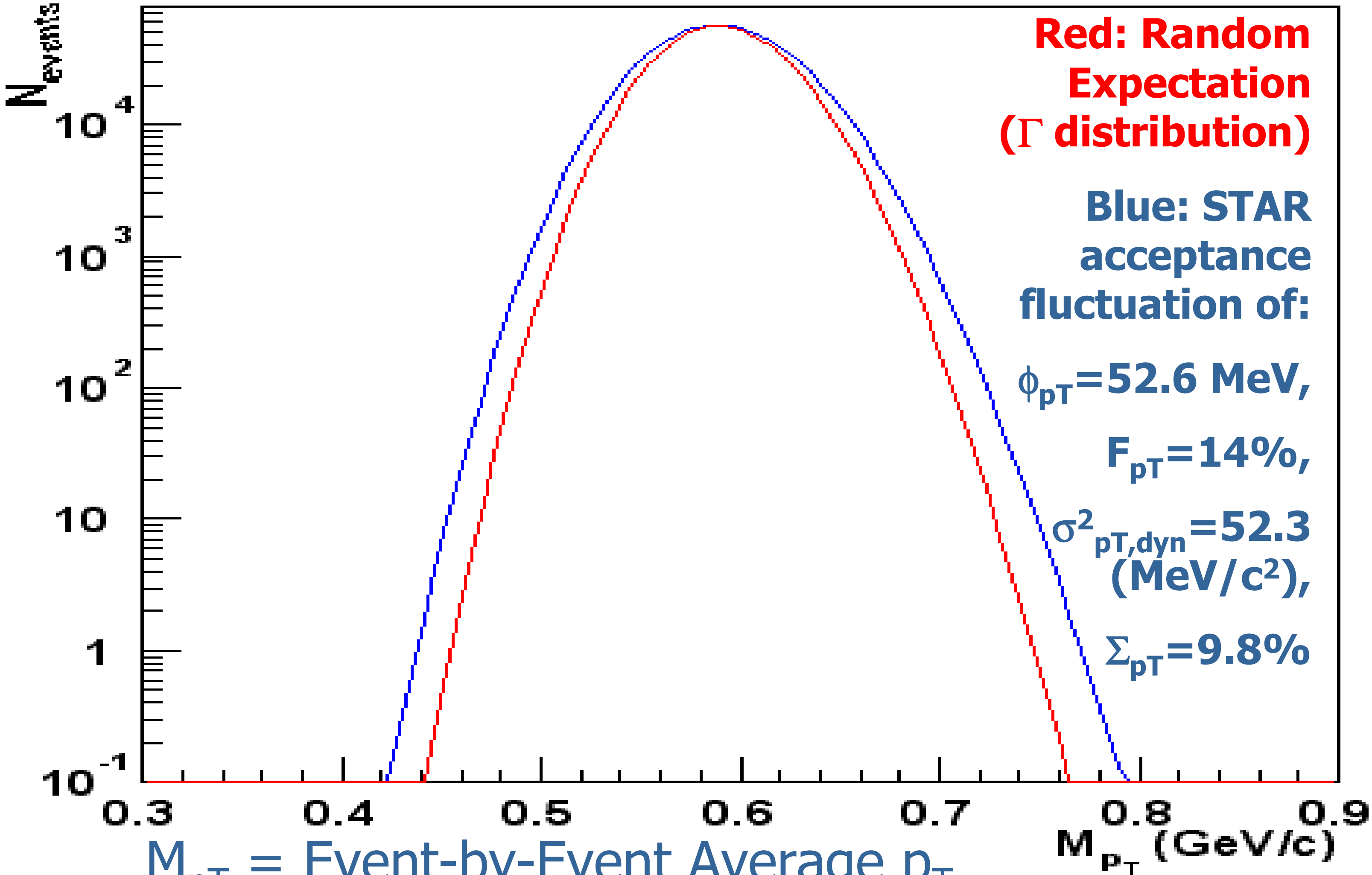




The critical exponents from the fits are sensitive to $N_{part,c}$ above about 0.1

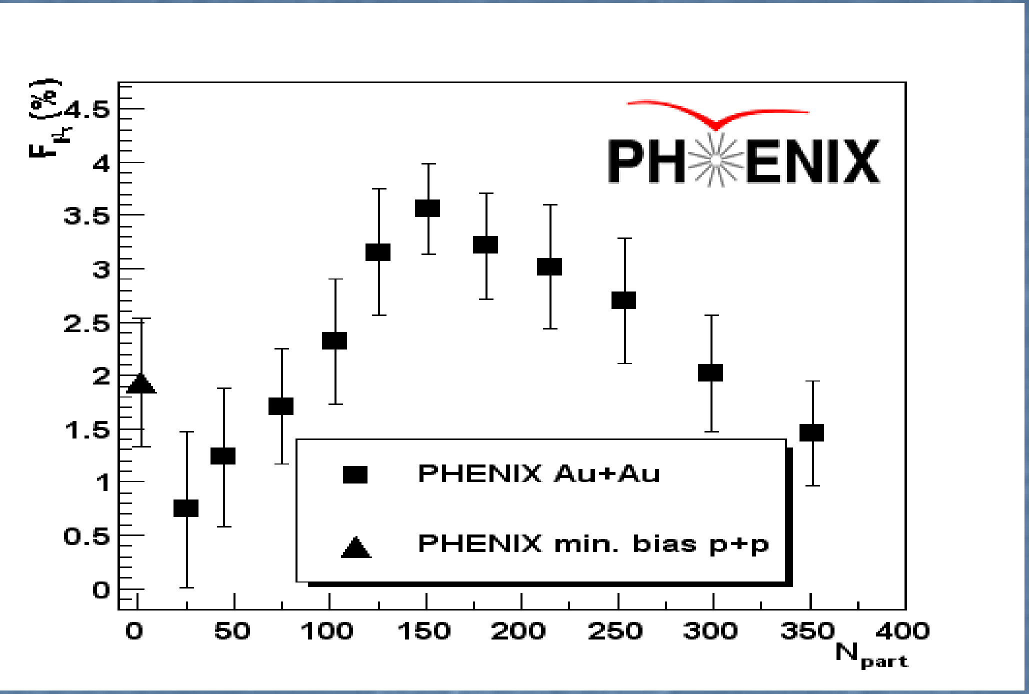
Measuring <p_T> Fluctuations

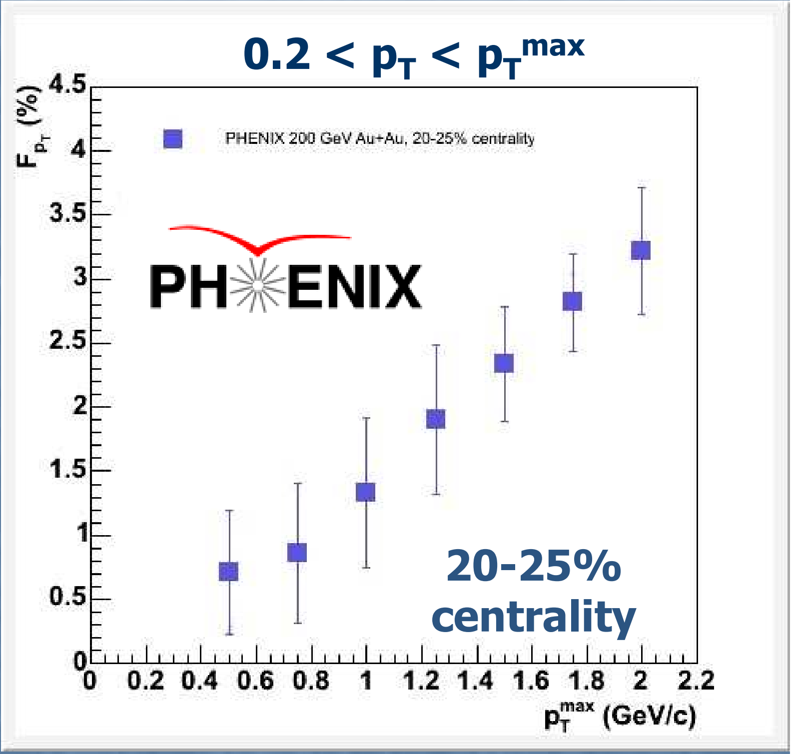
Gamma distribution calculation for statistically independent particle emission with input parameters taken from the inclusive spectra. *See M. Tannenbaum, Phys. Lett. B498 (2001) 29.*



M_{pT} = Event-by-Event Average p_T

PHENIX Event-by-Event <p_T> Fluctuation Results





Highlights: Non-random fluctuations are observed. Non-monotonic centrality-dependence. Strong p_T-dependence. p_T fluctuations appear to be driven by high p_T particles. The shape can be explained using a PYTHIA-based simulation by the contribution of correlations due to jets.

S. Adler et al., Phys. Rev. Lett. 93 (2004) 092301.

Thermodynamically Motivated Observables: Relating p_T Fluctuations to Heat Capacity

- **Let's switch p_T fluctuation measures to the commonly used Σ_{pt} = (event-by-event p_T variance) – (inclusive p_T variance)/(mean multiplicity per event) normalized by the inclusive mean p_T. For random particle emission, this variable is 0.**

- **From *R. Korus et al., Phys. Rev. C64 (2001) 054908*, this variable can be related to the heat capacity by:**

$$\Sigma_{p_T} = 2\sqrt{2}\left(\frac{\sqrt{\overline{\Delta p_T^2}}}{\overline{p_T}}\right)\frac{\langle T\rangle}{C_V}$$

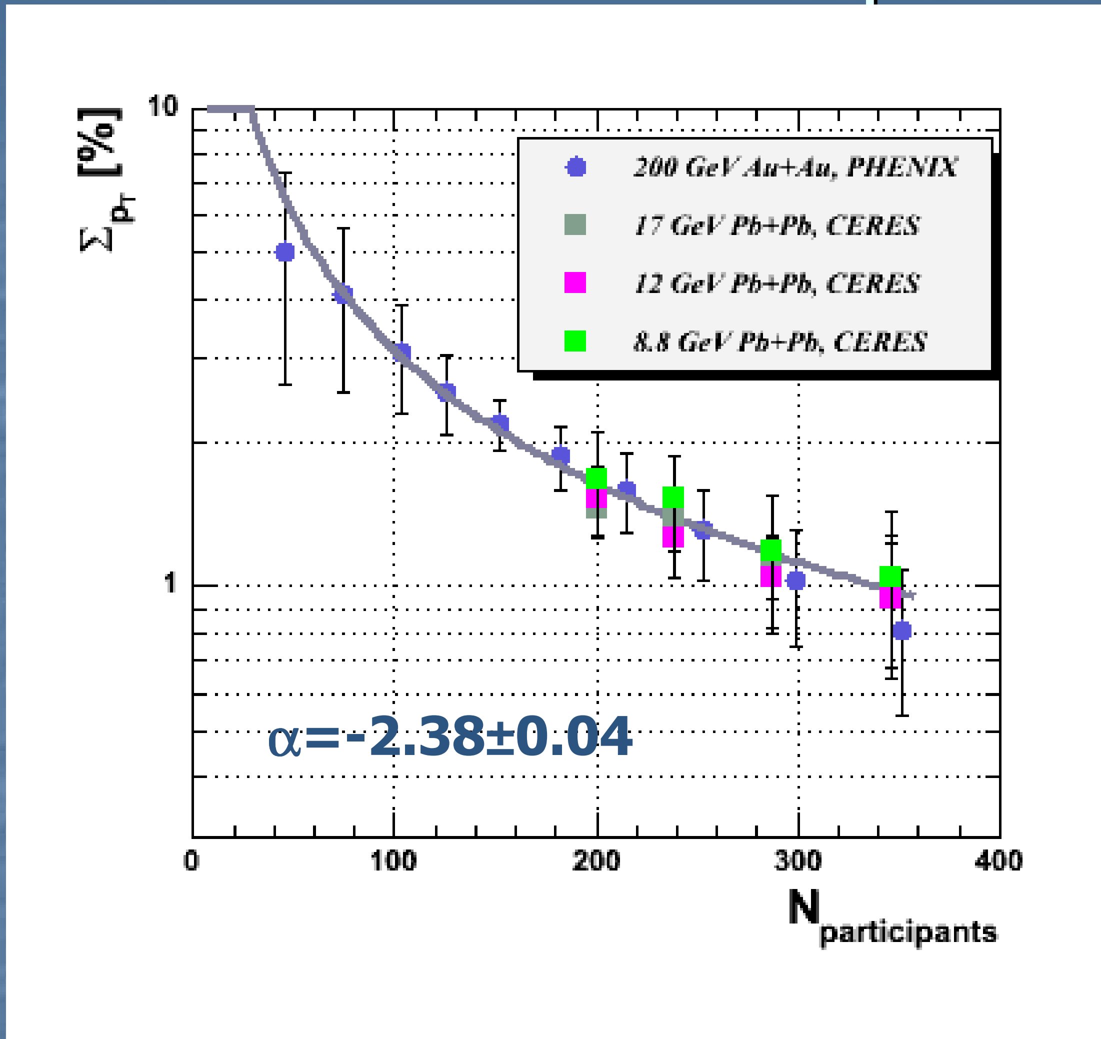
- **The critical exponent for the heat capacity is given by:**

$$C_V = \left(\frac{T - T_C}{T_C}\right)^{-\alpha}, T > T_C$$

- **Substituting gives:**

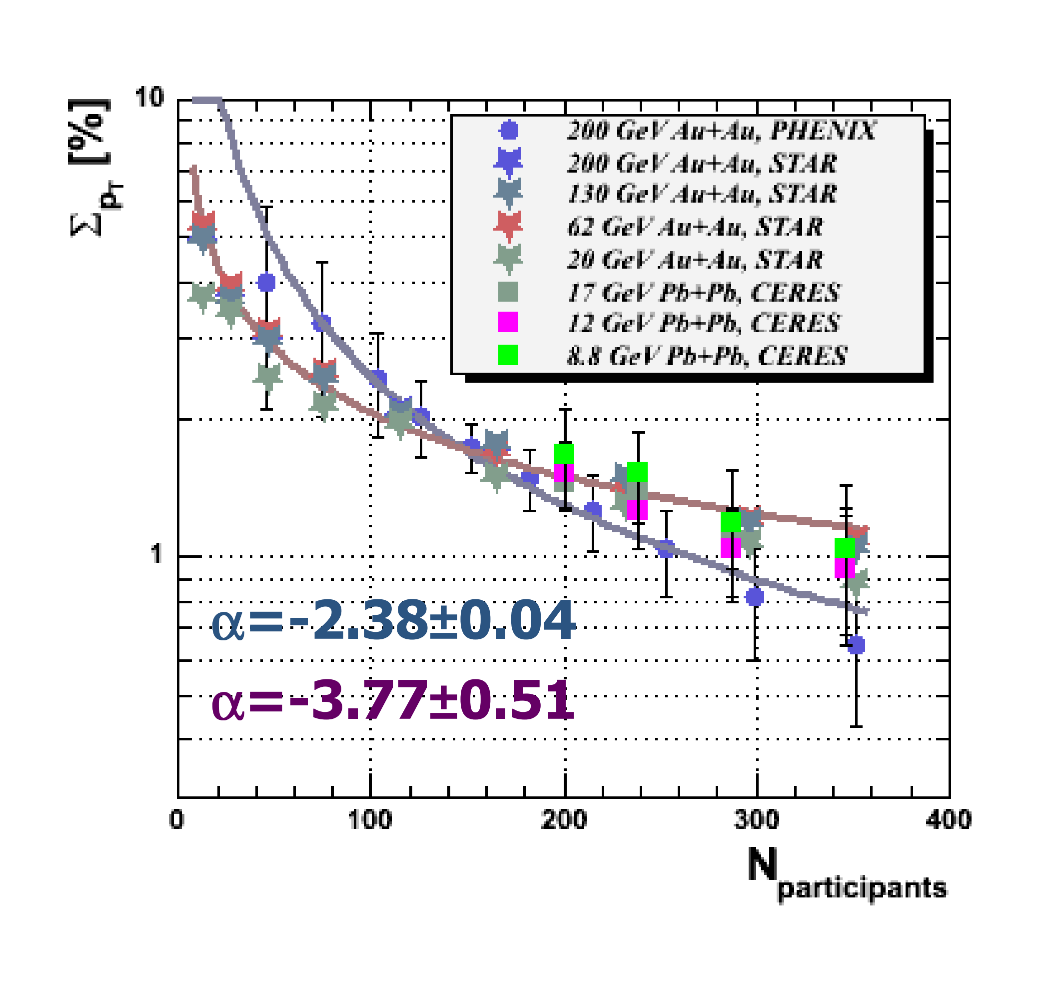
$$\Sigma_{p_T} = A\langle T\rangle\left(\frac{\sqrt{\overline{\Delta p_T^2}}}{\overline{p_T}}\right)\left(\frac{(T - T_C)}{T_C}\right)^{\alpha}$$

$\langle p_T \rangle$ Fluctuations: Critical Exponent Analysis



The CERES data has been scaled to the match the PHENIX data. Within the (large) errors, the various species lie on a universal curve. The fit to the PHENIX data yields α=-2.38. Typical values are α=0.1.

<p_T> Fluctuations: Critical Exponent Analysis



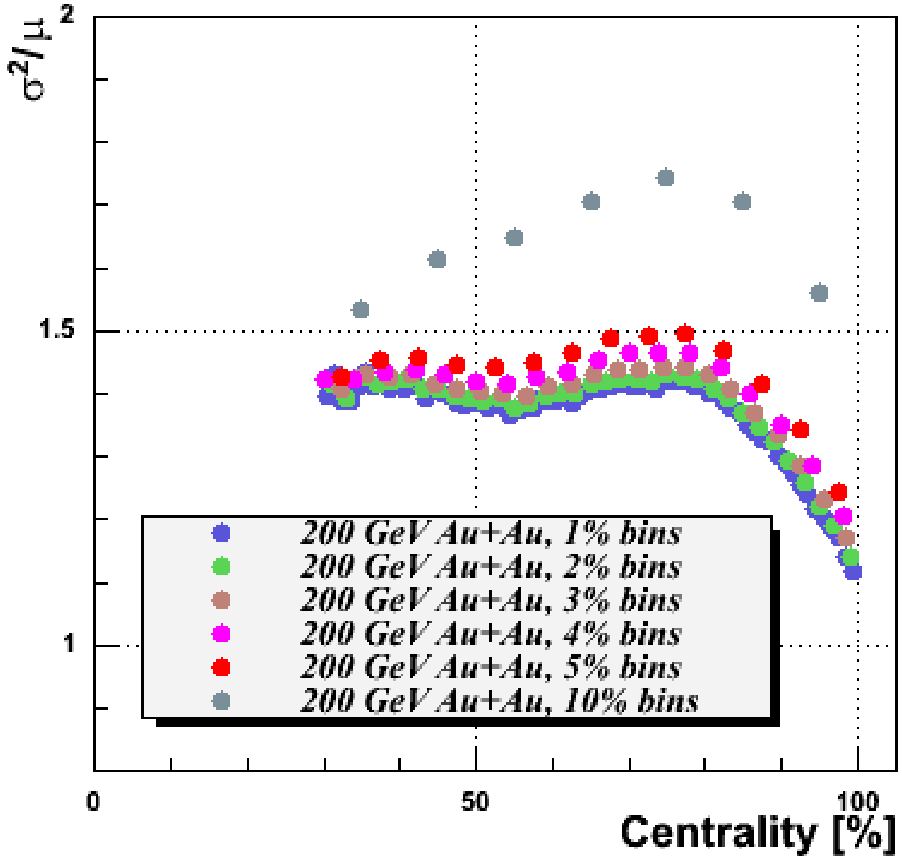
The CERES and PHENIX data has been scaled to match the STAR 200 GeV Au+Au data. Within the smaller STAR errors, the various species lie on a universal curve. The fit to the STAR data yields α=-3.77. Typical values are α=0.1.

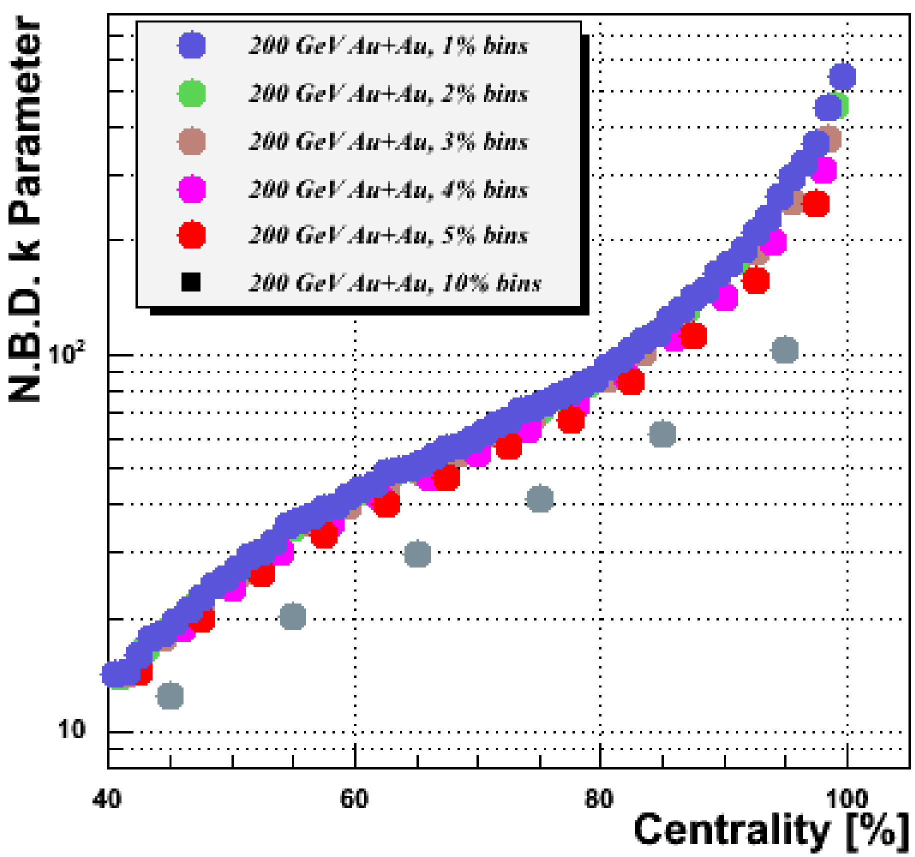
Conclusions

- PHENIX has completed a survey of multiplicity fluctuations as a function of collision species, collision energy, centrality, and p_T range. The fluctuations increase with a power law behavior as centrality decreases.
- A critical exponent analysis of the multiplicity fluctuations, correlation length extracted from multiplicity fluctuations, and $\langle p_T \rangle$ fluctuations show that:
  - The centrality dependence of all systems measured are consistent with critical behavior and critical exponents can be extracted.
  - The critical exponents extracted are independent of the p_T range over which the measurement is made.
  - When thermodynamically-driven quantities are plotted as a function of centrality, all species lie along a universal curve.
  - However, p_T fluctuations are driven by high p_T particles and $\nu \neq (2+\alpha)/3$.
- Future work with theoretical guidance can help us extract and test relations between critical exponent parametrizations.

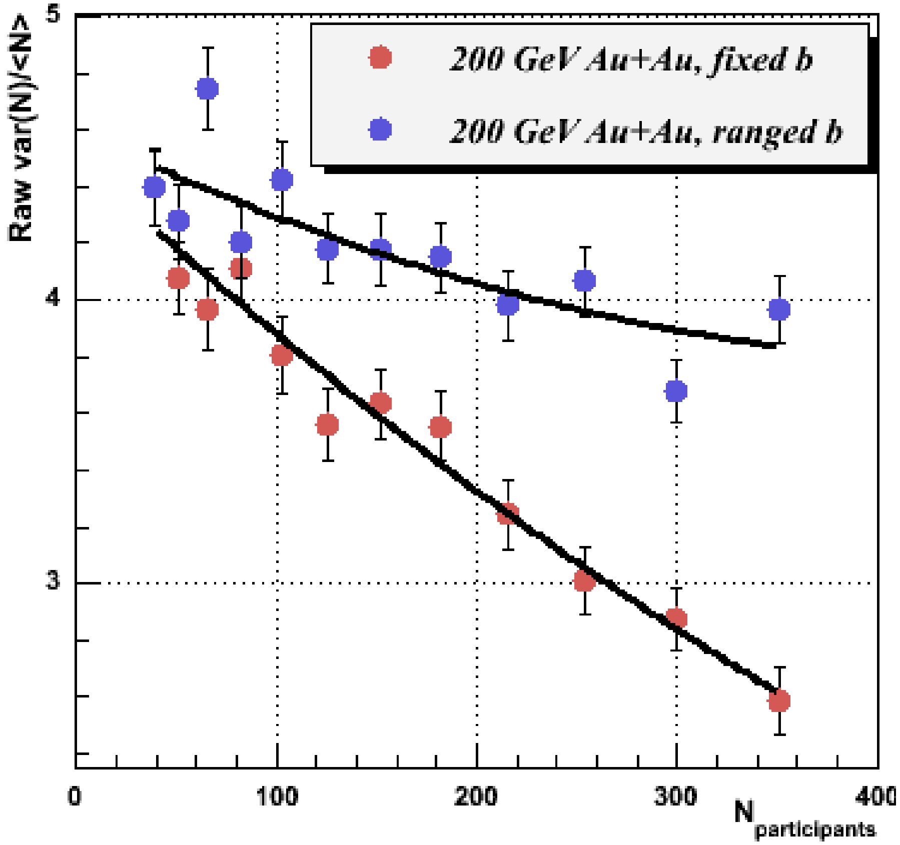
Auxiliary Slides

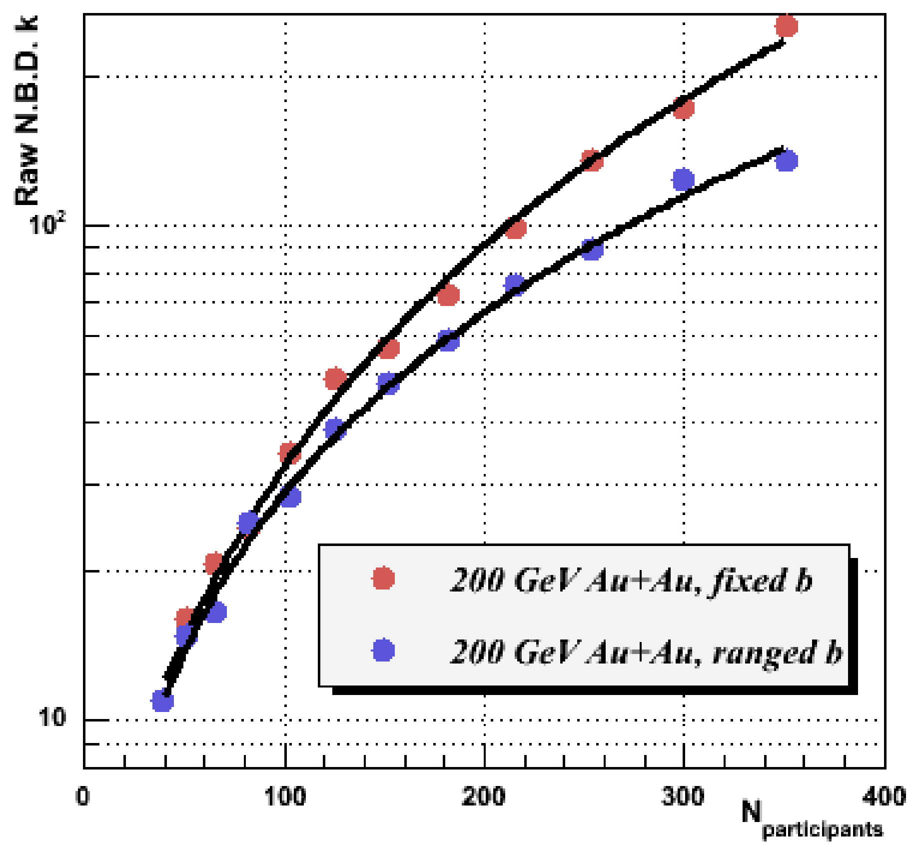
Impact Parameter Fluctuations: Data



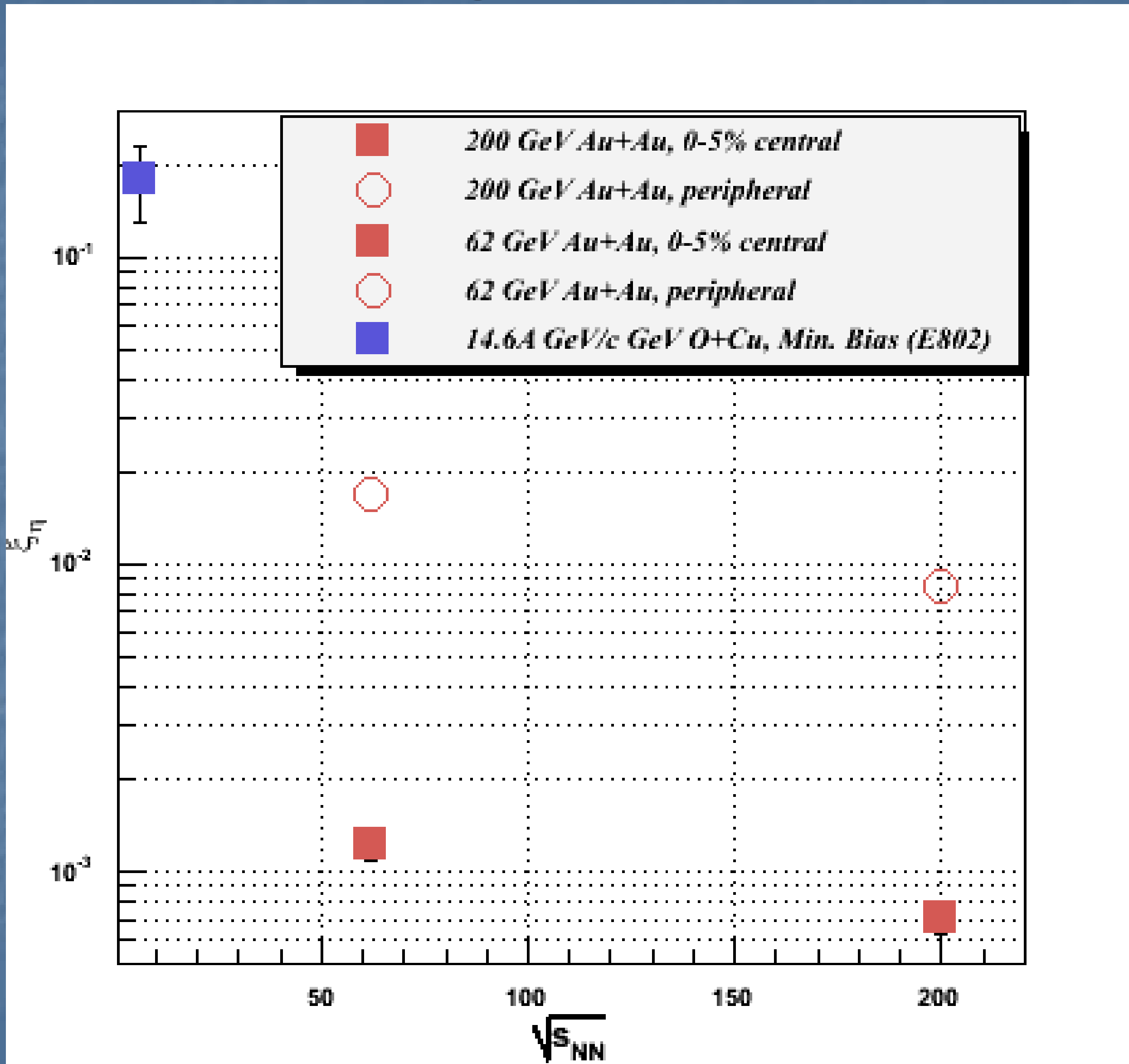


Impact Parameter Fluctuations: HIJING 1.37





Correlation Length Excitation Function



Jet Simulation Results: PHENIX at sqrt(s_{NN}) = 200 GeV

The S_{prob} parameter is initially adjusted so that F_{pT} from the simulation matches F_{pT} from the data for 20-25% centrality (circled). It is then FIXED and finally scaled by R_{AA} for all other centralities.