Scaling Properties of Fluctuation and Correlation Results from PHENIX

Quark Matter 2006 – 11/18/06
Jeffery T. Mitchell
(Brookhaven National Laboratory)
for the PHENIX Collaboration

<u>Outline</u>

- **Multiplicity Fluctuations**
- **$<p_T>$ Fluctuations**
- **Azimuthal Correlations at Low p_T**

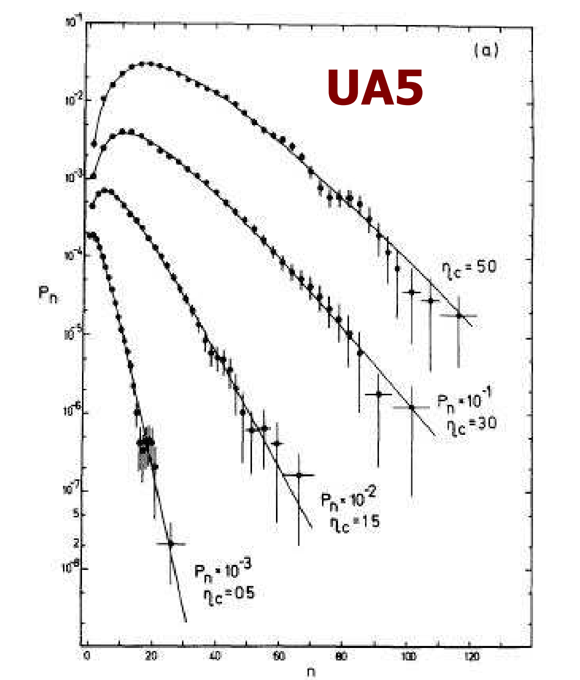
Multiplicity Fluctuations

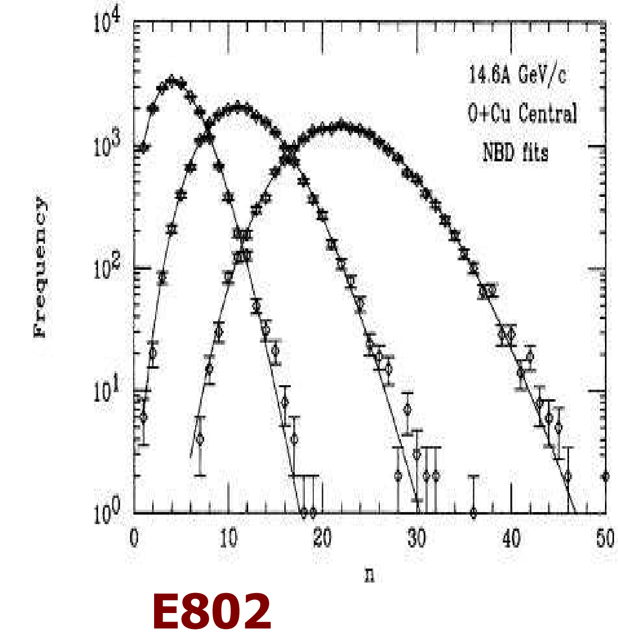
- A survey of multiplicity fluctuations in the following systems:
  - 200 GeV Au+Au
  - 62 GeV Au+Au
  - 200 GeV Cu+Cu
  - 62 GeV Cu+Cu
  - 22 GeV Cu+Cu
- Survey completed as a function of centrality and p_T

- Objective: To search for signatures of critical behavior and gain insights on the location of the QCD critical point.

Measuring Multiplicity Fluctuations with Negative Binomial Distributions

Multiplicity distributions in hadronic and nuclear collisions can be well described by the Negative Binomial Distribution.



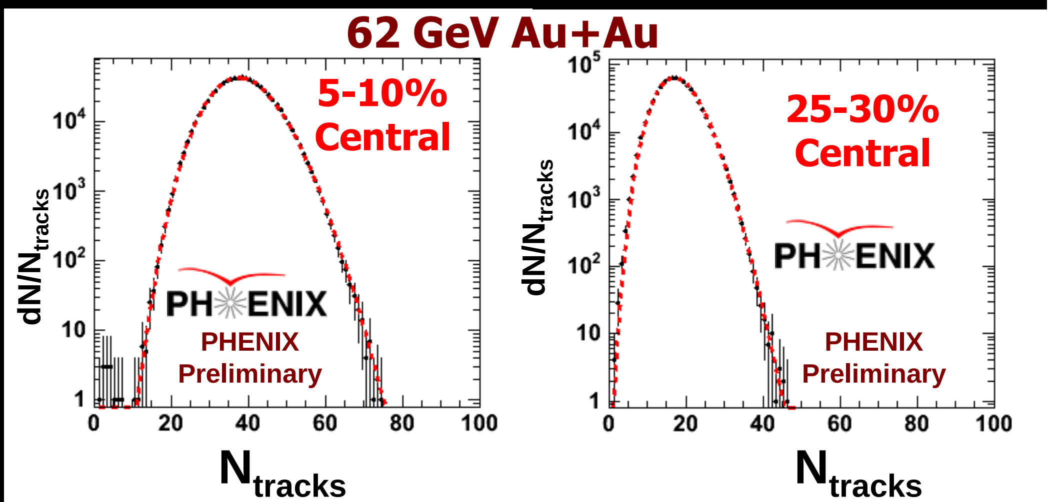


UA5: sqrt(s)=546 GeV p-pbar, Phys. Rep. 154 (1987) 247.

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

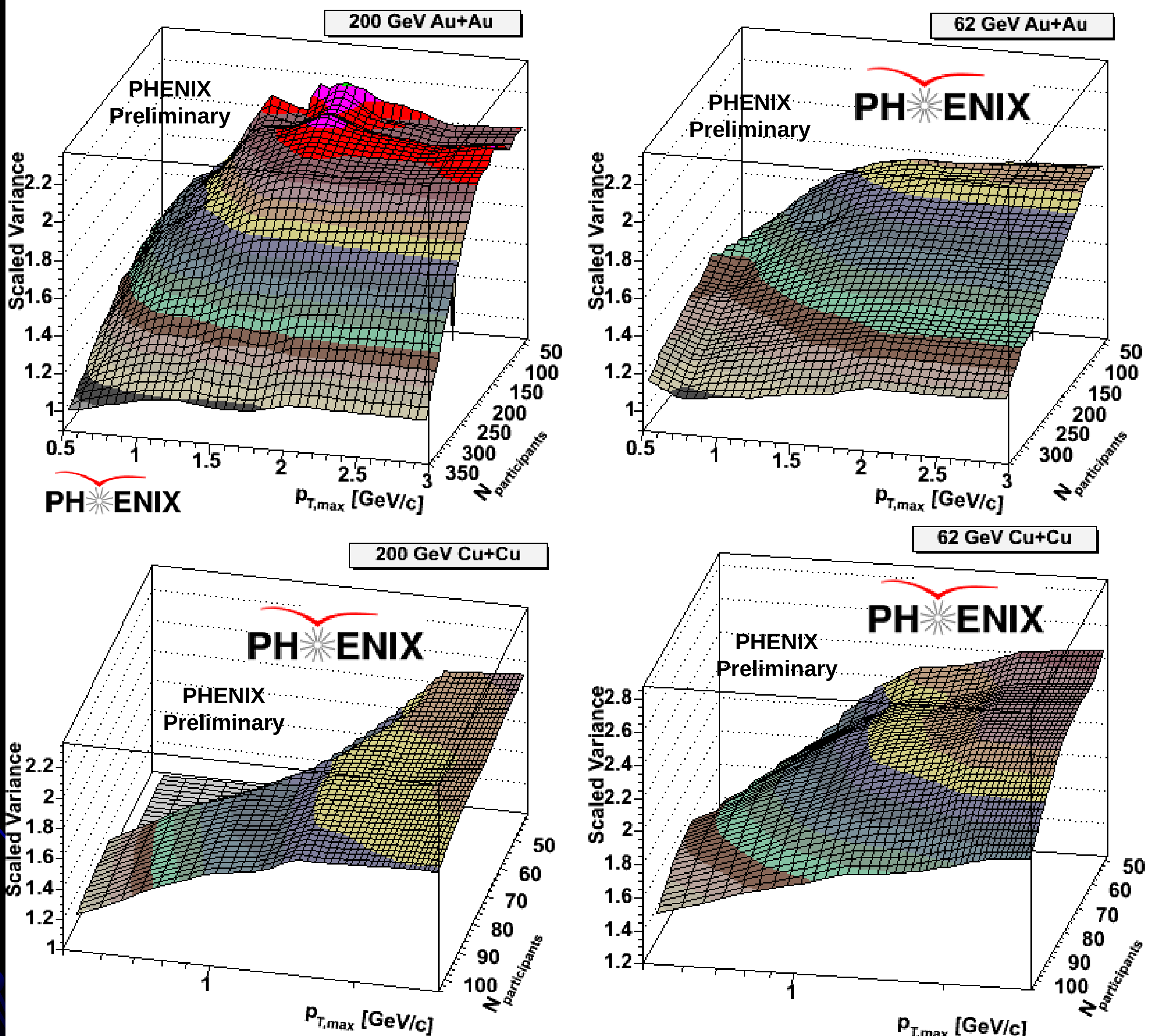
$$P(m) = \frac{(m+k-1)!}{m!(k-1)!} \frac{\left(\mu/k\right)^m}{\left(1+\mu/k\right)^{m+k}}$$

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



A Survey of Scaled Variance, σ^2/μ

- Inclusive charged hadron fluctuations.
- $0.2 < p_T < p_{T,max}$ GeV/c
- These values are corrected to remove the contribution due to impact parameter (geometrical) fluctuations and projected to 2π in azimuth for direct comparisons to other experiments.
- The Poissonian (random) limit is 1.0.
- Large non-random fluctuations are observed that increase with p_T and decrease with centrality.



Multiplicity Fluctuation Universal Scaling

Grand Canonical Ensemble

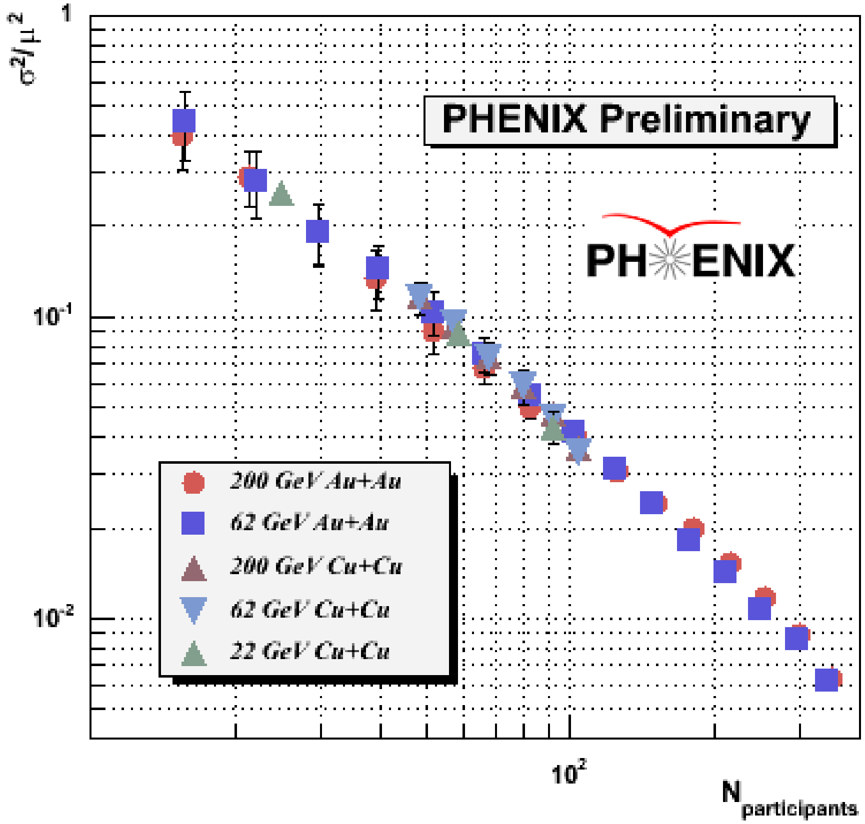
$$\frac{\left(\sigma^2/\mu\right)}{\mu} = \frac{1}{k_{NBD}} + \frac{1}{\mu} = \frac{k_B T}{V} k_T$$

All points are scaled to match the 200 GeV Au+Au data curve to illustrate the scaling.

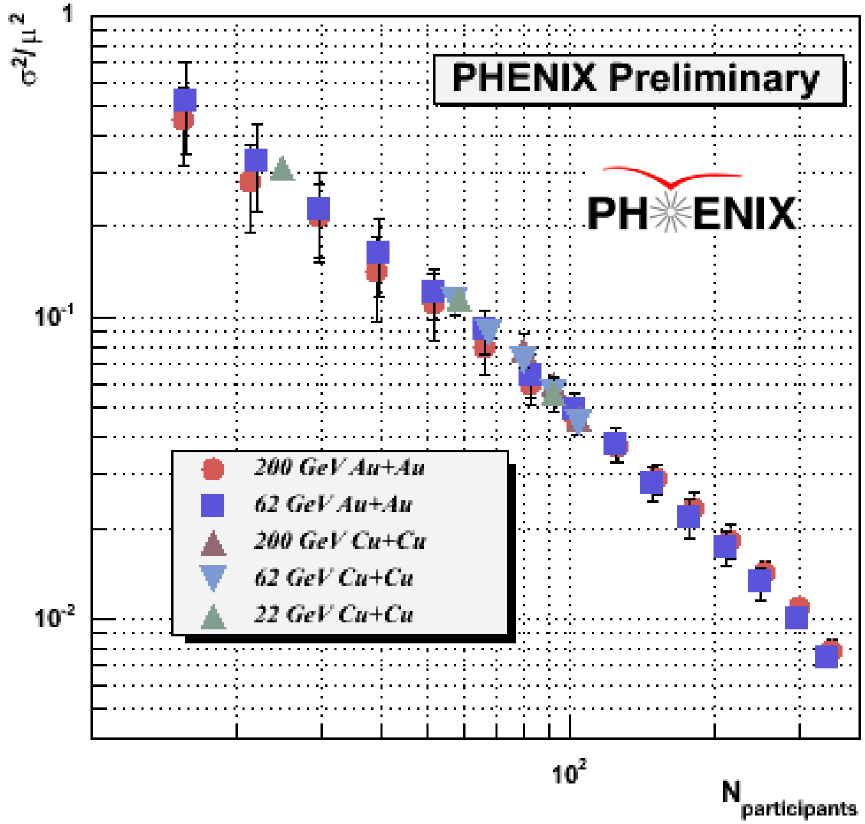
Data can be described by a power law in N_{part}:

$$\sigma^2/\mu^2 \propto N_{part}^{-1.40\pm0.03}$$

0.2<p_T<2.0 GeV/c



0.2<p_T<0.75 GeV/c



Event-by-Event Mean p_T Fluctuations

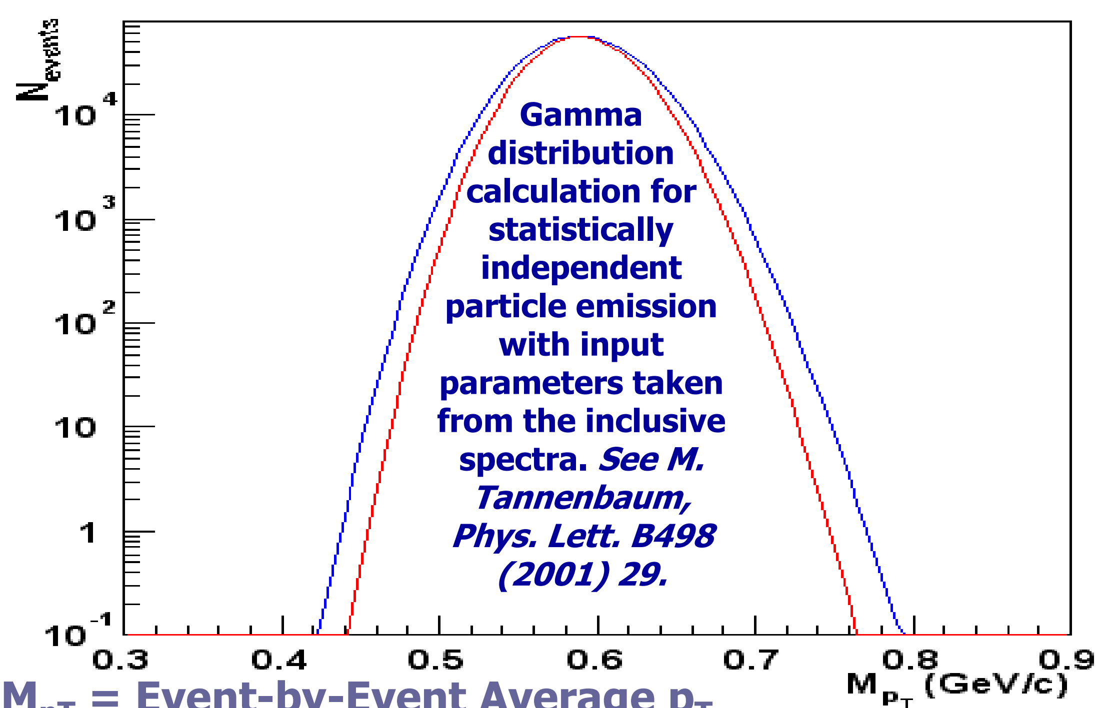
- A survey of multiplicity fluctuations in the following systems:
  - 200 GeV Au+Au
  - 62 GeV Au+Au
  - 200 GeV Cu+Cu
  - 62 GeV Cu+Cu
  - 22 GeV Cu+Cu
- Survey completed as a function of centrality and p_T

- Objective: To search for signatures of critical behavior and gain insights on the location of the QCD critical point.

Measuring <p_T> Fluctuations

- Σ_{pT} = (event-by-event p_T variance) – [(inclusive p_T variance)/(mean multiplicity per event)], normalized by the inclusive mean p_T. Random = 0.0.
- Σ_{pT} is the mean of the covariance of all particle pairs in an event normalized by the inclusive mean p_T.
- Σ_{pT} can be simply related to the heat capacity:

$$4\Sigma_{pT}^{\;2} = 1/C_V$$



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

Red: Random Expectation

(Γ distribution)

Blue: STAR acceptance fluctuation of:

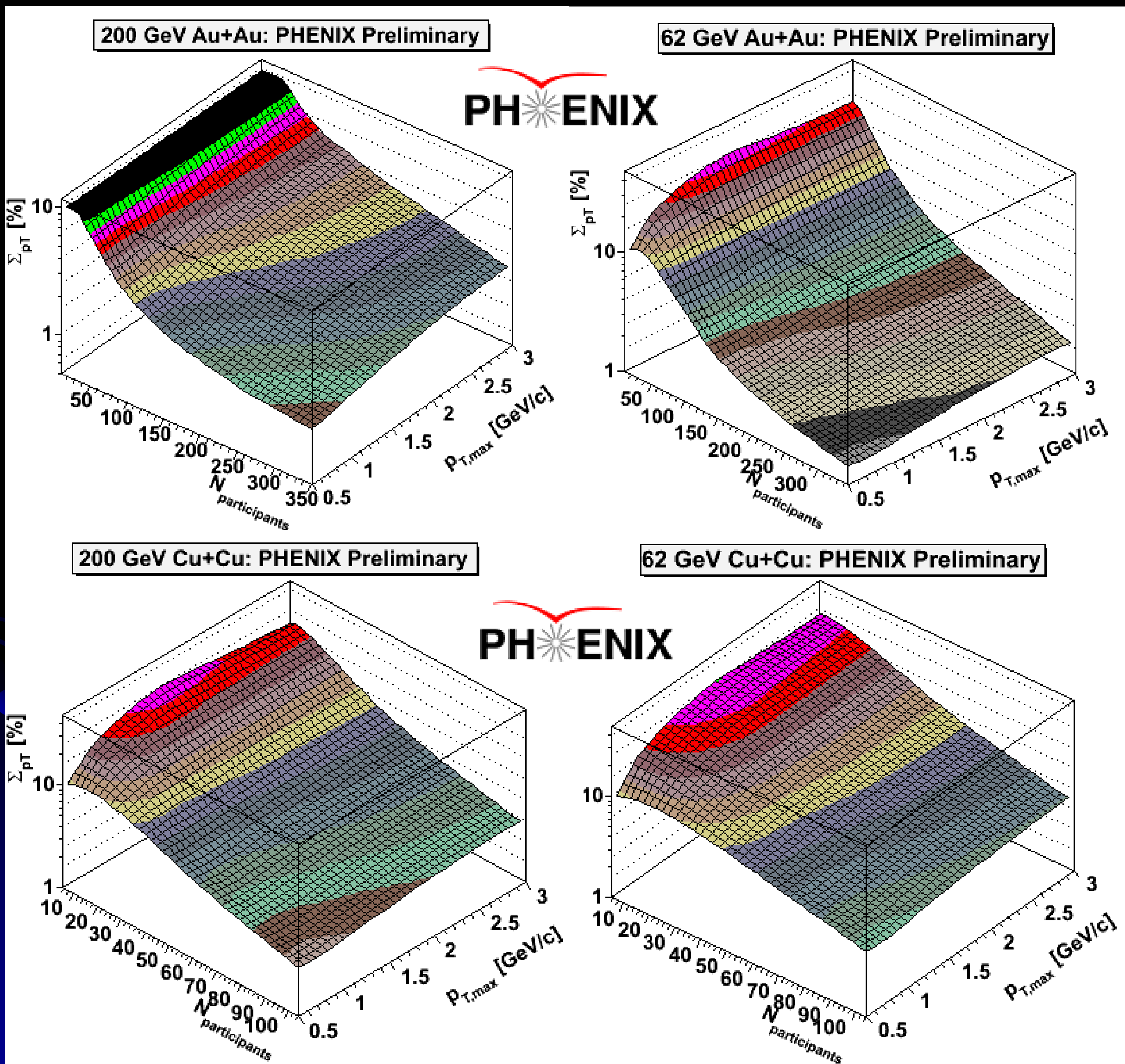
ϕ_{pT}=52.6 MeV,

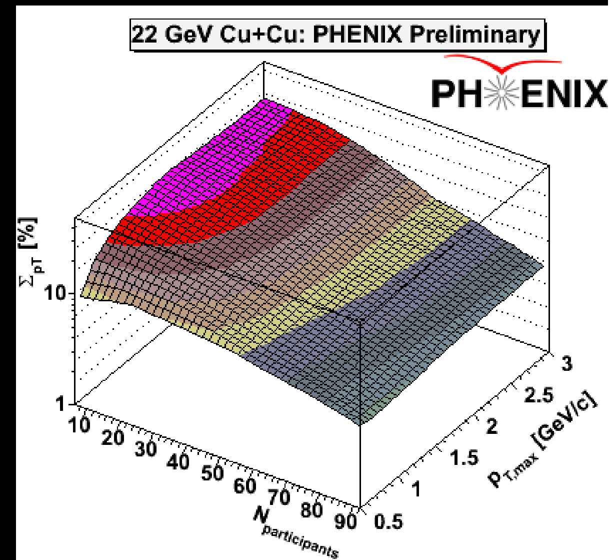
F_{pT}=14%,

$\sigma^2_{pT,dyn}$=52.3 (MeV/c²),

Σ_{pT}=9.8%

<p_T> Fluctuations Survey



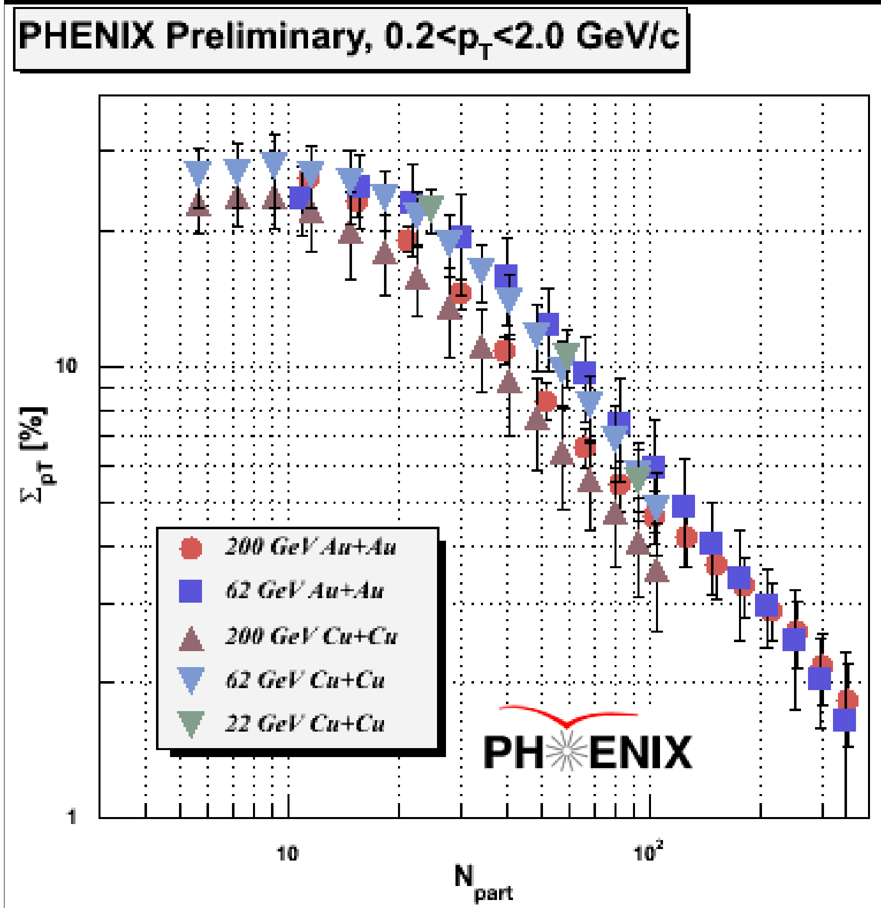


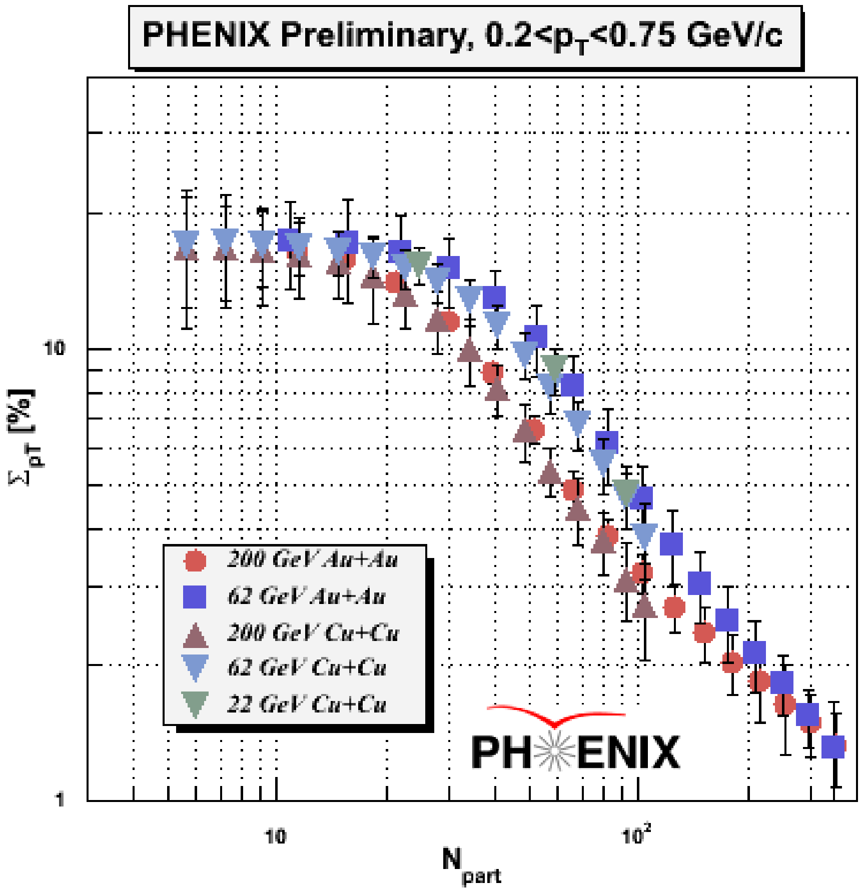
Features: Σ_{pT} **increases with decreasing centrality. Similar trend to multiplicity fluctuations (σ^2/μ^2). Increases with increasing p_T. Same behavior for all species, including 22 GeV Cu+Cu.**

NOTE: Random fluctuations, Σ_{pT}=0.0.

$\langle p_T \rangle$ Fluctuations vs. Centrality

The magnitude of Σ_{pT} varies little as a function of sqrt(s_{NN}) and species. In a simple model that embeds PYTHIA hard scattering events into inclusively parametrized events, the jet fraction necessary to reproduce the fluctuations does not scale with the jet cross section.

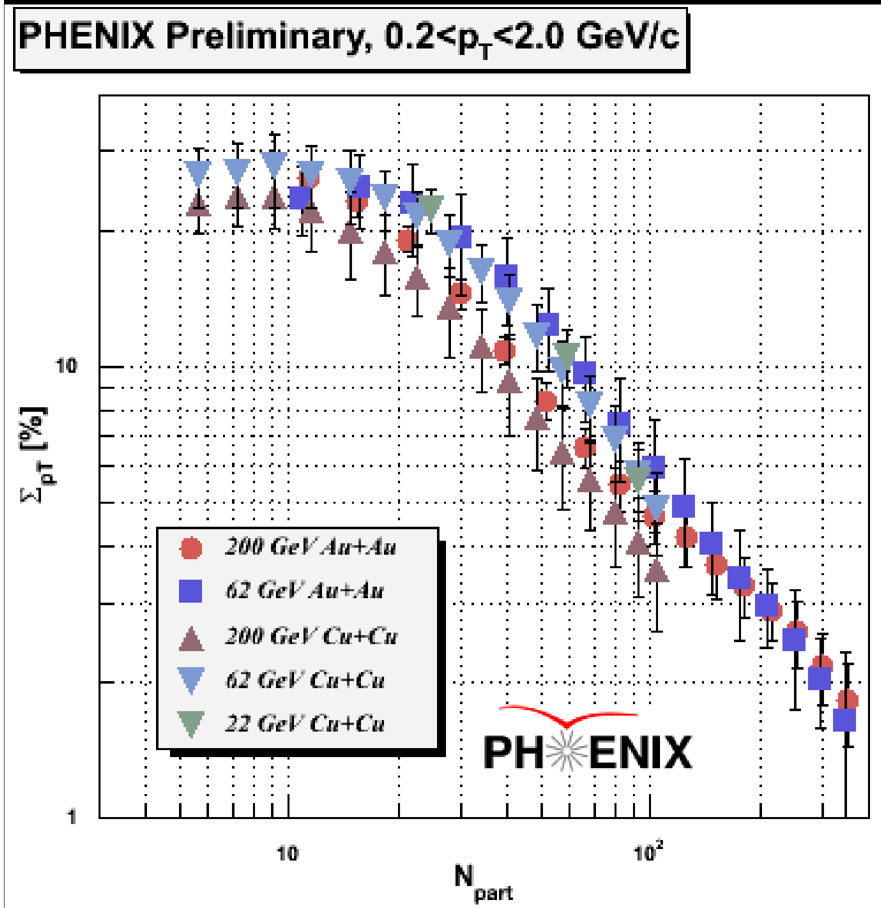


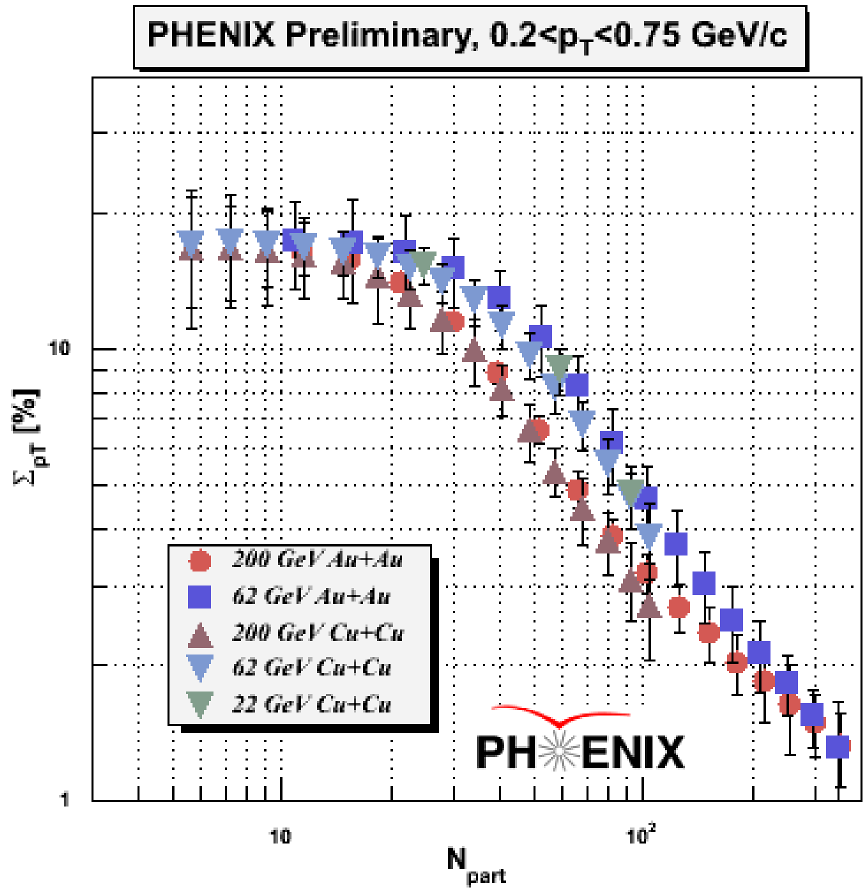


<p_T> Fluctuations vs. Centrality

Above N_{part}~30, the data can be described by a power law in N_{part}, independent of the p_T range down to $0.2<p_T<0.5$ GeV/c:

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





Critical Exponents: A Handle on the Critical Point

Near the critical point, several properties of a system diverge. The rate of the divergence can be described by a set of critical exponents. For systems in the same universality class, all critical exponent values should be identical.

- The critical exponent for compressibility, γ:

$$k_T \propto \left(\frac{T - T_c}{T_C}\right)^{-\gamma}$$

- The critical exponent for heat capacity, α:

$$C_V \propto \left(\frac{T - T_c}{T_C}\right)^{-\alpha}$$

- The critical exponent for correlation functions, η:

$$C(R) \propto R^{-(d-2+\eta)}$$

(d=3)

We can directly measure the critical exponent η on HBT correlations in azimuth.

Azimuthal Correlations at Low p_T

- This study will quote correlation amplitudes in a given centrality, p_T, and $\Delta\phi$ bin with no trigger particle determined using the mixed event method via:

$$C(\Delta\phi) = (dN/d\phi_{data}/dN/d\phi_{mixed})*(N_{events,mixed}/N_{events,data})$$

- There is no trigger particle. All particle pairs are included in the correlation function calculation.
- Red dashed lines are fits to the following equation:

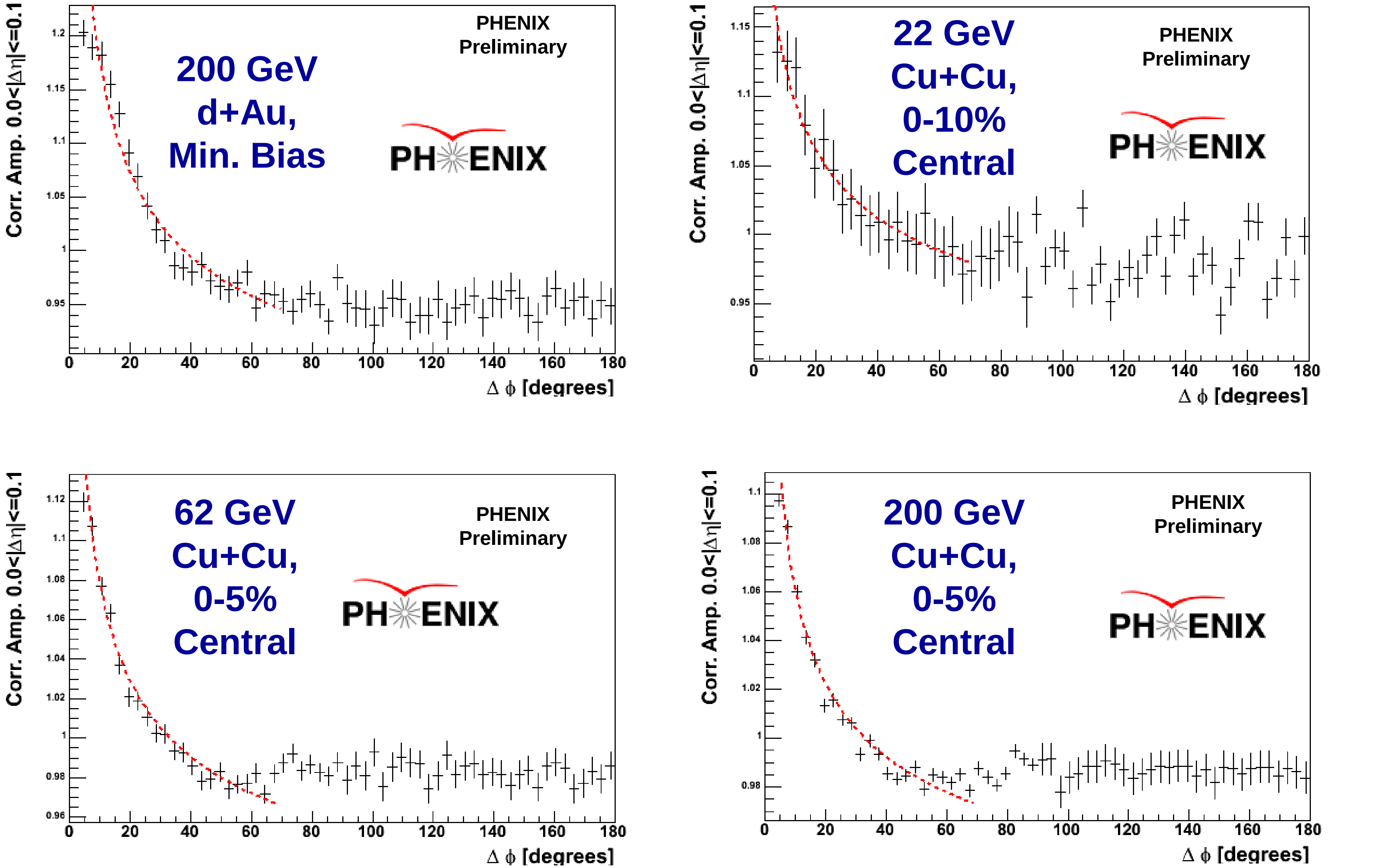
$$C(\Delta\phi) \propto \Delta\phi^{-(1+\eta)}$$

- Shown are results for the following systems:
  - 200 GeV Au+Au
  - 62 GeV Au+Au
  - 200 GeV Cu+Cu
  - 62 GeV Cu+Cu
  - 22 GeV Cu+Cu
  - 200 GeV d+Au

Assuming that QCD belongs in the same universality class as the (d=3) 3-D Ising model, the expected value of η is 0.5 (Reiger, Phys. Rev. B52 (1995) 6659 .

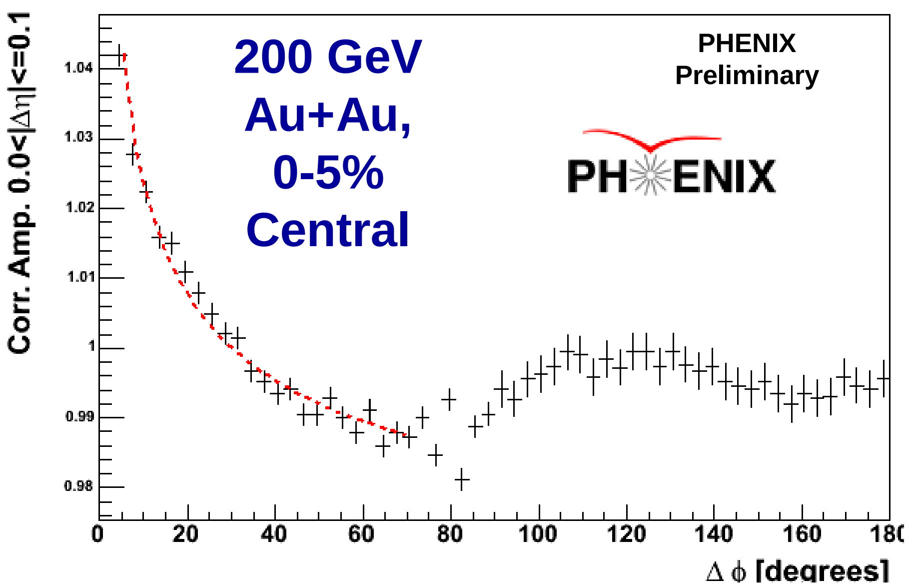
Like-Sign Pair Azimuthal Correlations: d+Au, Cu+Cu

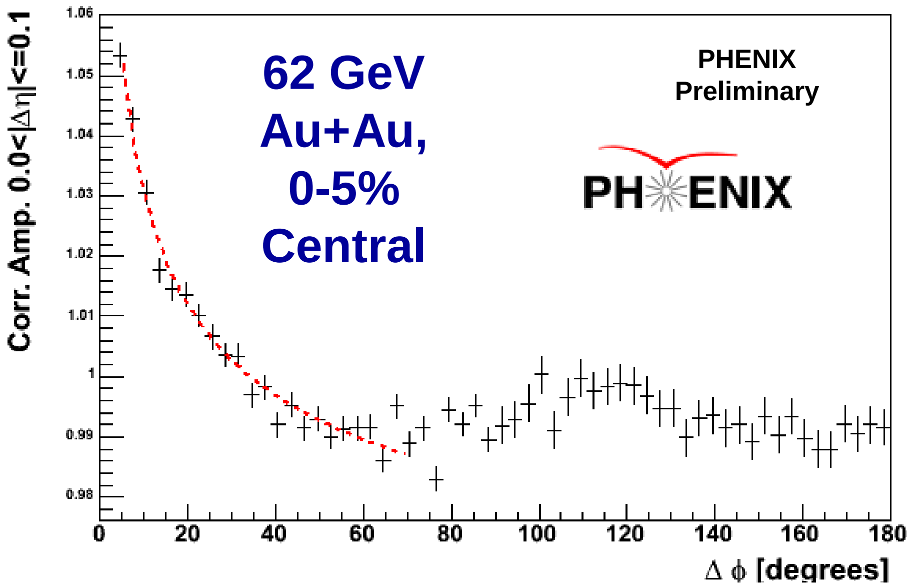
$0.2 < p_{T,1} < 0.4$ GeV/c, $0.2 < p_{T,2} < 0.4$ GeV/c, $|\Delta\eta|<0.1$



Like-Sign Pair Azimuthal Correlations: Au+Au

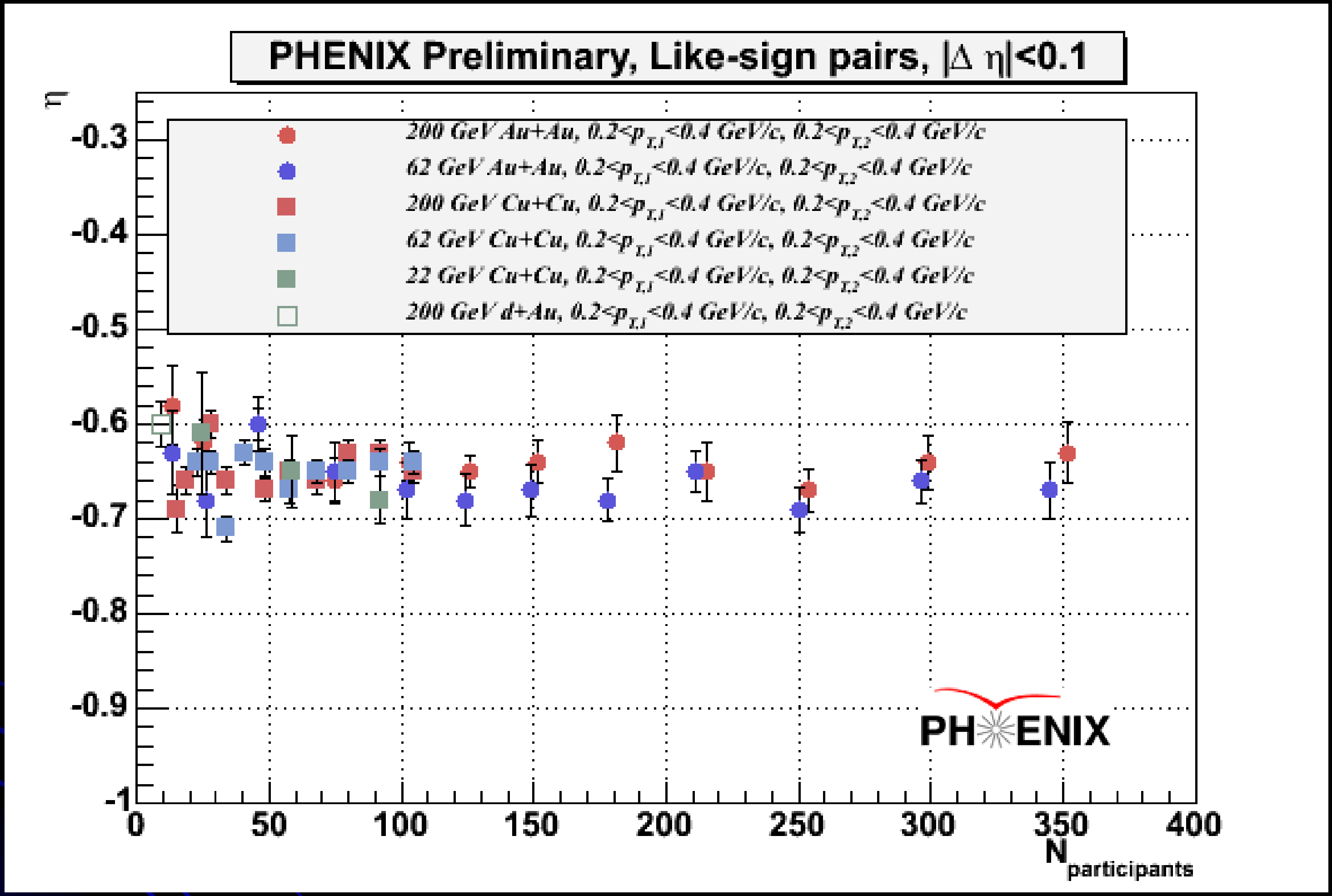
$0.2 < p_{T,1} < 0.4$ GeV/c, $0.2 < p_{T,2} < 0.4$ GeV/c, $|\Delta\eta|<0.1$





- The power law function fits the data well for all species and centralities.
- A displaced away-side peak is observed in the Au+Au correlation functions.

Exponent η vs. Centrality

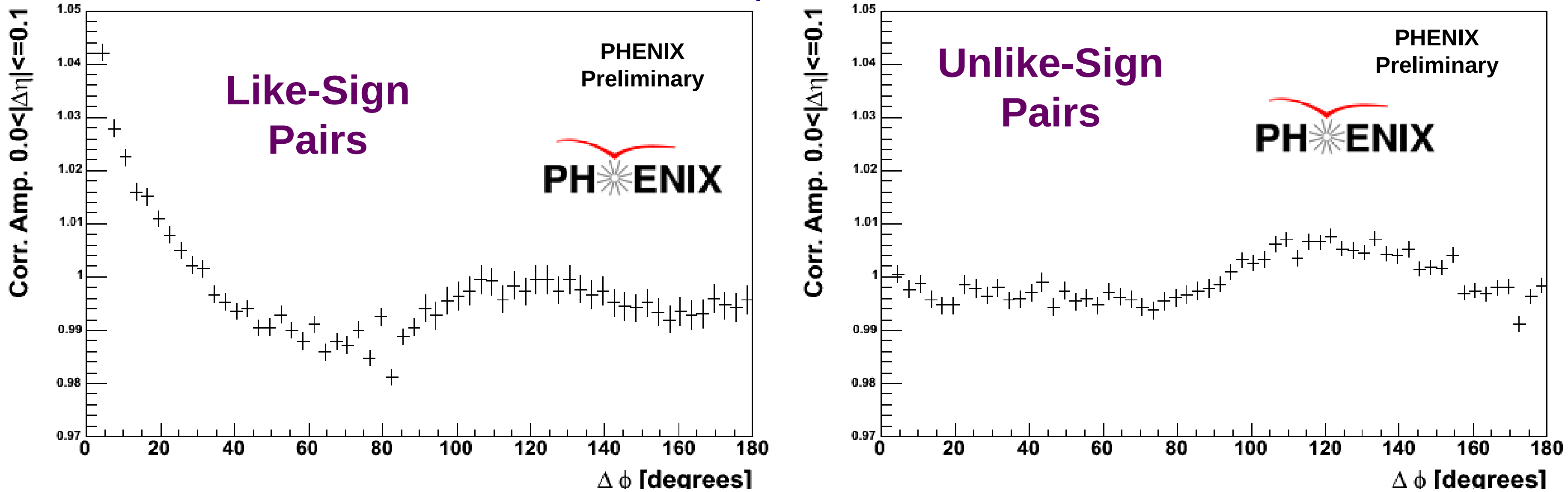


The exponent η is independent of species, centrality, and collision energy.

The value of η is inconsistent with the d=3 expectation at the critical point.

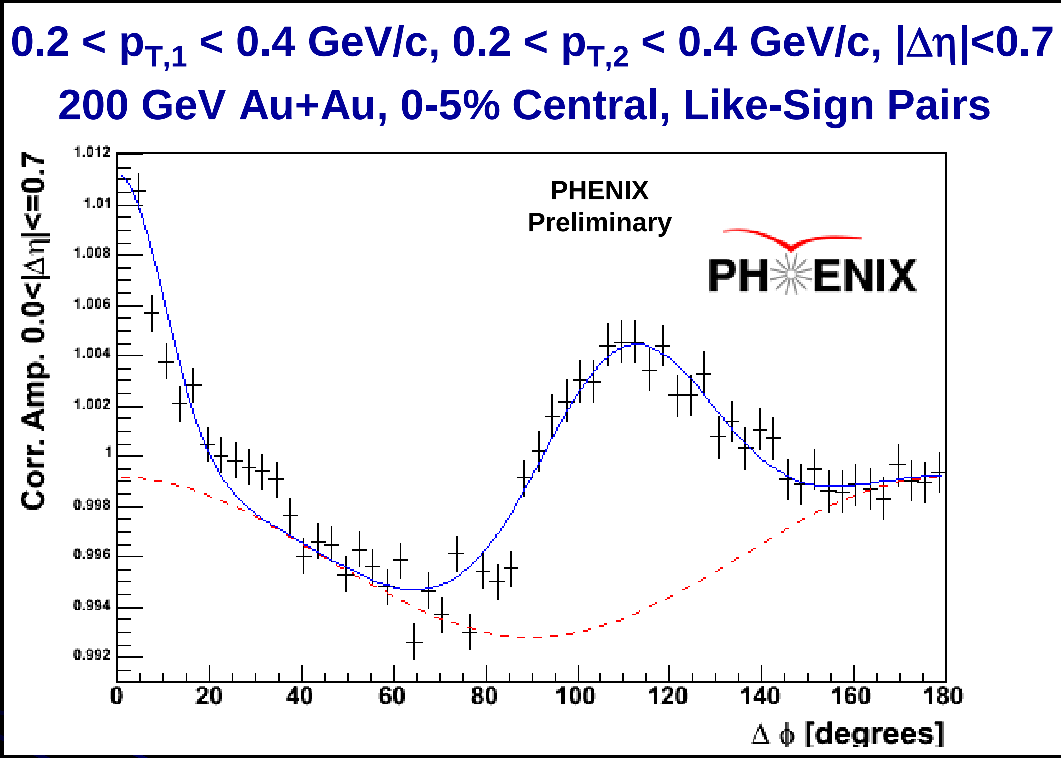
Controlling HBT: LS vs. US Pairs

$0.2 < p_{T,1} < 0.4$ GeV/c, $0.2 < p_{T,2} < 0.4$ GeV/c, $|\Delta\eta|<0.1$
200 GeV Au+Au, 0-5% Central



- The HBT peak apparent in like-sign pair correlations disappears in unlike-sign pair correlations.
- The displaced away-side peak persists both like-sign and unlike-sign pair correlations.
- The displaced away-side peak extends across the PHENIX acceptance in $\Delta\eta$.

Extracting the properties of the correlations

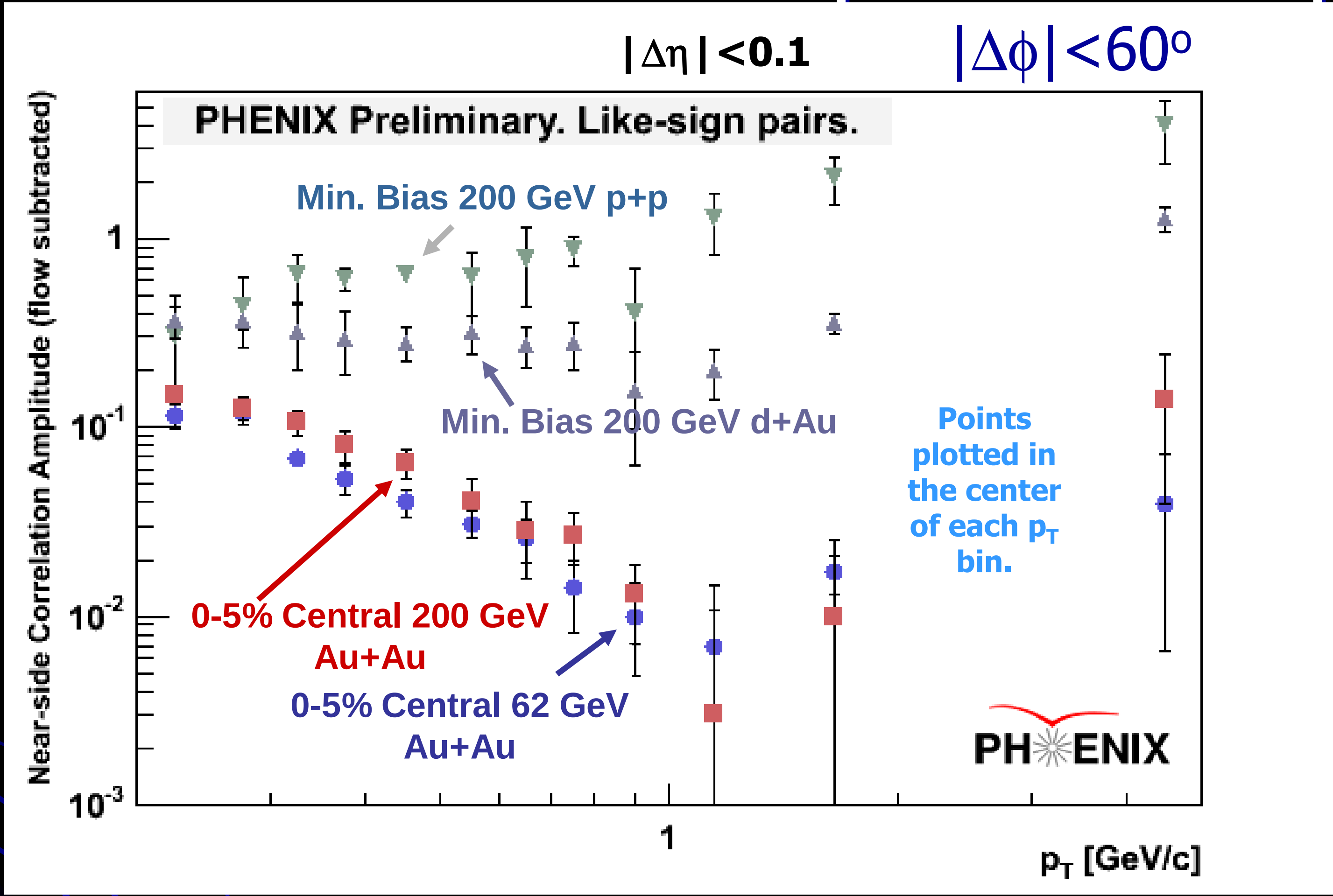


- The blue line is a fit to a function with a v_2 component, a near-side Gaussian at $\Delta\phi=0$ and an away-side Gaussian at $\Delta\phi=\pi-D$
- The dashed red line is the v_2 component.

$$\boxed{C(\Delta\varphi) = B\left(1 + 2c_2\cos(2\Delta\varphi)\right) + Gauss_{Near,1}(\Delta\varphi;\sigma_{Near}) + AJ(\Delta\varphi - \pi)}$$

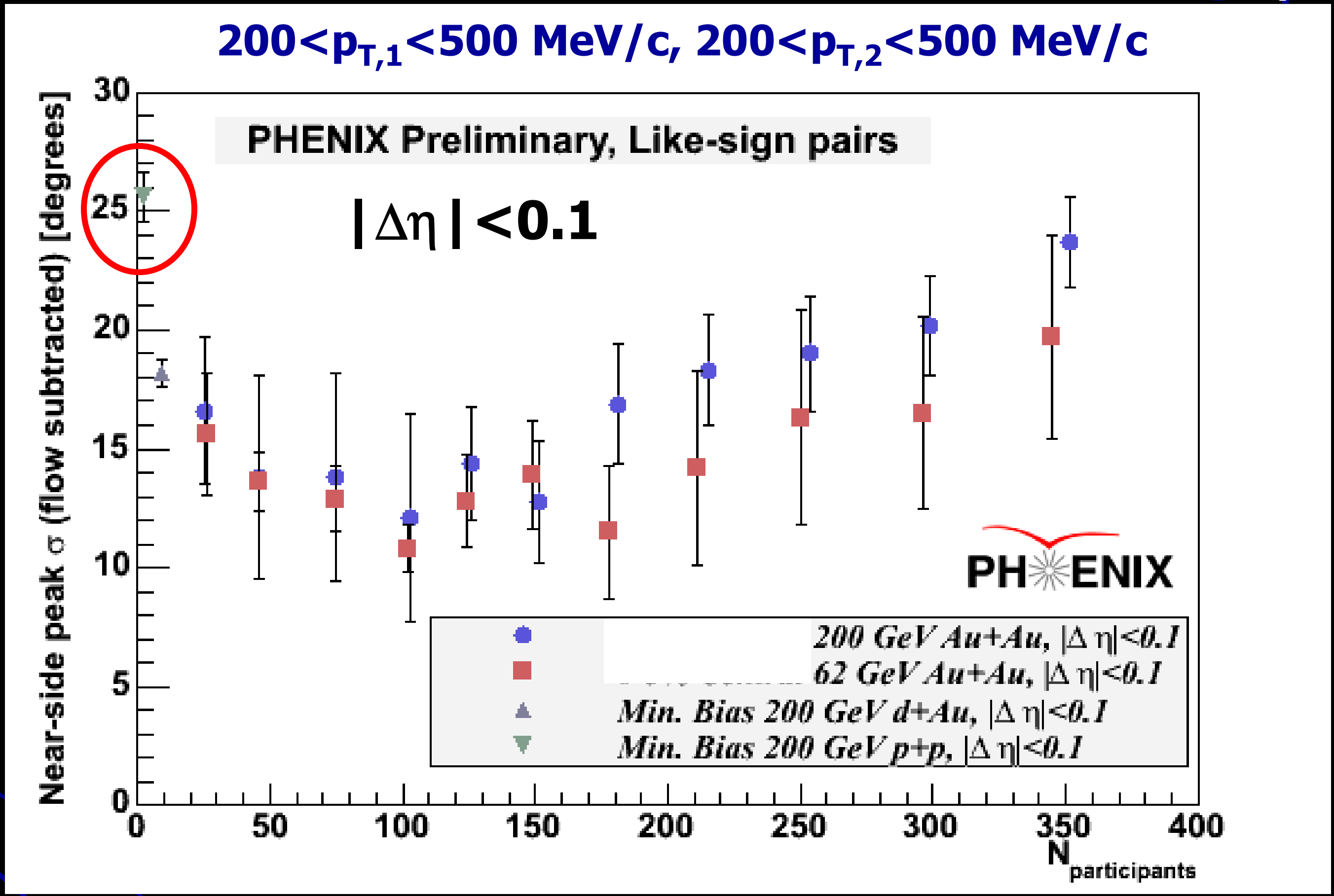
$$\boxed{AJ(\Delta\varphi - \pi) \equiv \frac{S_A}{\sqrt{2\pi}\sigma_A}\left[\exp\left\{-\frac{(\Delta\varphi - \pi - D)^2}{2\sigma_A^2}\right\} + \exp\left\{-\frac{(\Delta\varphi - \pi + D)^2}{2\sigma_A^2}\right\}\right]}$$

Near-Side Peak Amplitude vs. p_T



- The p_T bins have been chosen so that there are equal numbers of particles per event in each bin to offset the effects of statistical dilution of the correlation amplitudes.
- The Au+Au amplitudes for p_T<1 GeV/c show a power law decrease with p_T not seen in p+p or d+Au.
- The increase in amplitudes for p_T>1 GeV/c are due to the onset of the jet peak.

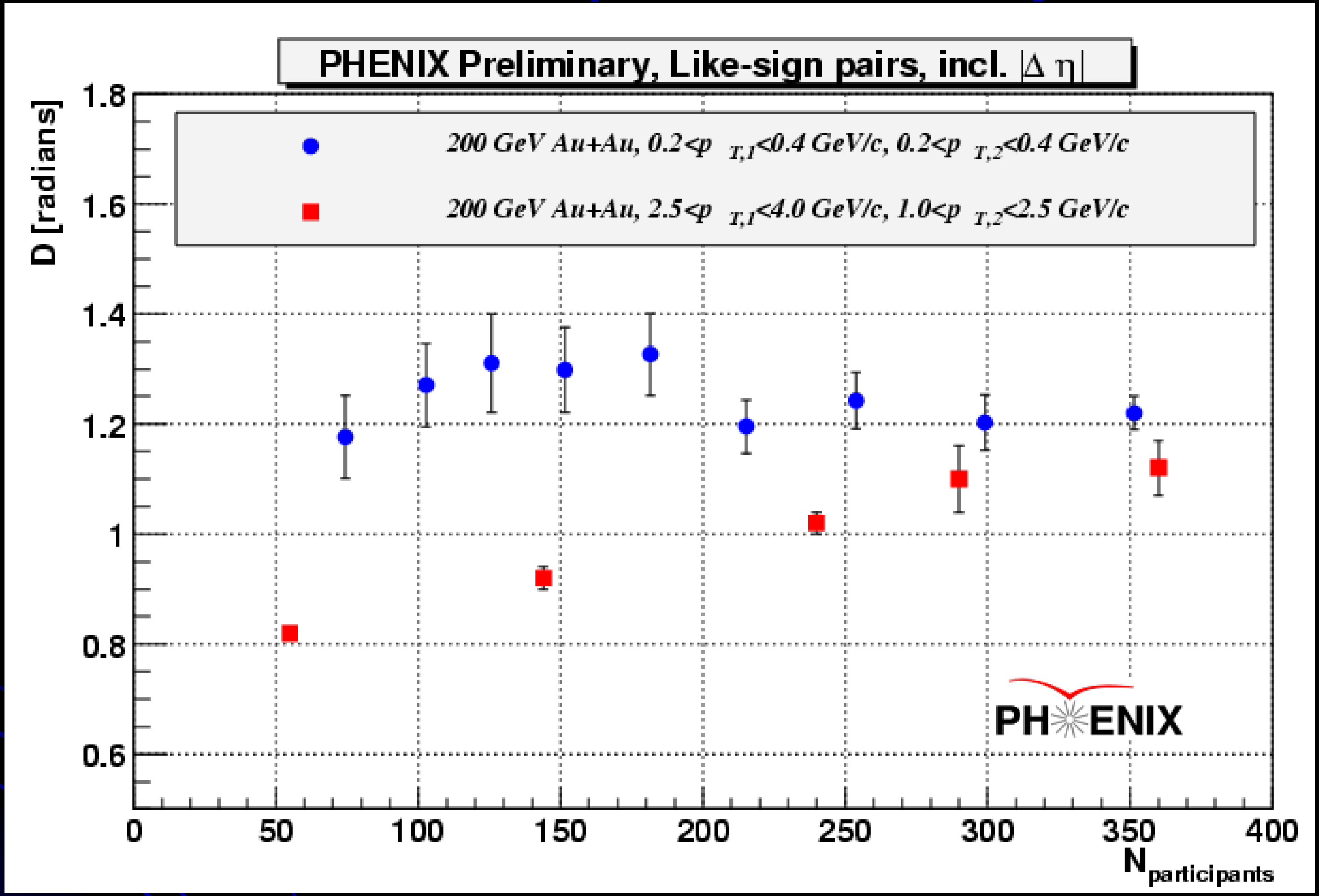
Near-Side Peak Width vs. p_T



Weak centrality dependence on the near-side peak widths.

d+Au and Au+Au widths are narrower than p+p.

Location of the Displaced Away-Side Peak



The location of the displaced peak shows little centrality dependence. The location deviates from that at high p_T in more peripheral collisions.

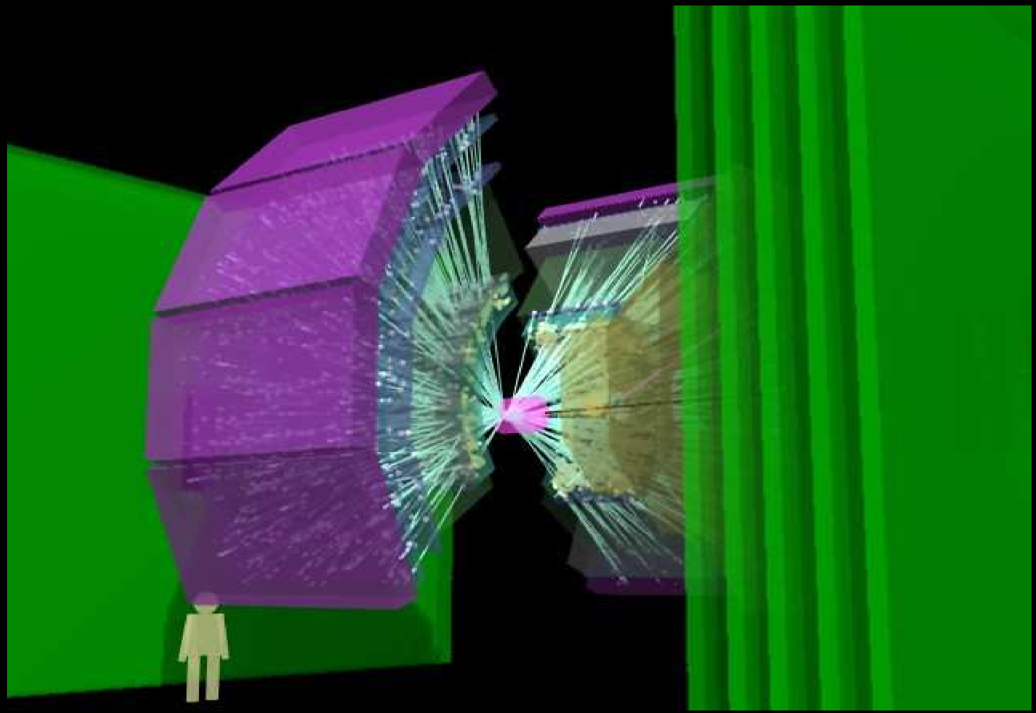
Summary

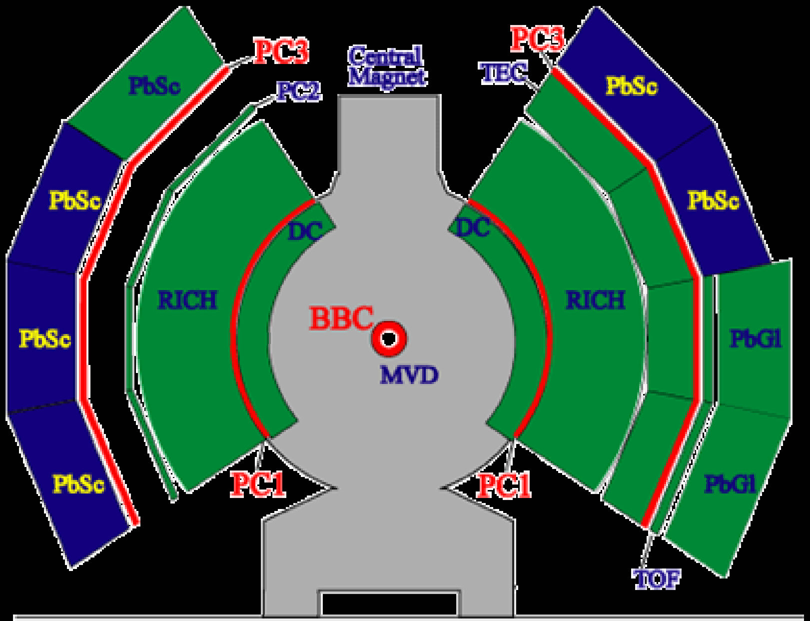
- **Multiplicity fluctuations**:
  - Exhibit a universal power law scaling as a function of N_{part}. The scaling properties are independent of p_T.
- **$\langle p_T \rangle$ fluctuations:**
  - Exhibit a universal power law scaling as a function of N_{part} in central collisions.
  - The magnitude of $\langle p_T \rangle$ fluctuations as a function of $\mathrm{sqrt}(s_{NN})$ do not scale with the jet production cross section.
- **Low-p_T Correlations**:
  - The exponent η extracted from the HBT peak is identical for all collision species.
  - A displaced away-side peak is observed in azimuthal correlations at low p_T in Au+Au collisions.
  - Further studies of this phenomenon are underway.

The analysis framework for measuring several critical exponents in RHIC collisions is in place → Bring on a RHIC low energy scan!

Auxiliary Slides

The PHENIX Detector





Acceptance:

$|\eta| \sim 0.35$, $|\Delta\phi| \sim \pi$

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

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.

p_T Fluctuations: Updating the Measure

- The consensus to quantify dynamical p_T fluctuations
  - Define the quantity $\langle \Delta p_{T,1} \Delta p_{T,2} \rangle$.
  - It is a covariance and an integral of 2-particle correlations.
  - It equals zero in the absence of dynamical fluctuations
  - Defined to be positive for correlation and negative for anti-correlation.

$$\langle \Delta p_{t,1} \Delta p_{t,2} \rangle = \frac{1}{N_{event}} \sum_{k=1}^{N_{event}} \frac{C_k}{N_k (N_k - 1)}$$

N_{event} = number of events

$\langle p_t \rangle_i$ = average p_t for i^{th} event

N_k = number of tracks for k^{th} event

$p_{t,i} = p_t$ for i^{th} track in event

where

$$C_k = \sum_{i=1}^{N_k} \sum_{j=1, i \neq j}^{N_k} \left(p_{t,i} - \langle\langle p_t \rangle\rangle \right)\left(p_{t,j} - \langle\langle p_t \rangle\rangle \right)$$

and $\langle\langle p_t \rangle\rangle = \left(\sum_{k=1}^{N_{event}} \langle p_t \rangle_k \right) / N_{event}$ and $\langle p_t \rangle_k = \left(\sum_{i=1}^{N_k} p_{t,i} \right) / N_k$

Then normalize as follows for a dimensionless quantity:

$$\Sigma_{pT} = \sqrt{\langle \Delta p_{T,1} \Delta p_{T,2} \rangle} \Big/ \langle\langle p_T \rangle\rangle$$