Scaling Properties of Azimuthal Correlation and Fluctuation Results from PHENIX

BNL-RIKEN Lunch Seminar – 5/24/07
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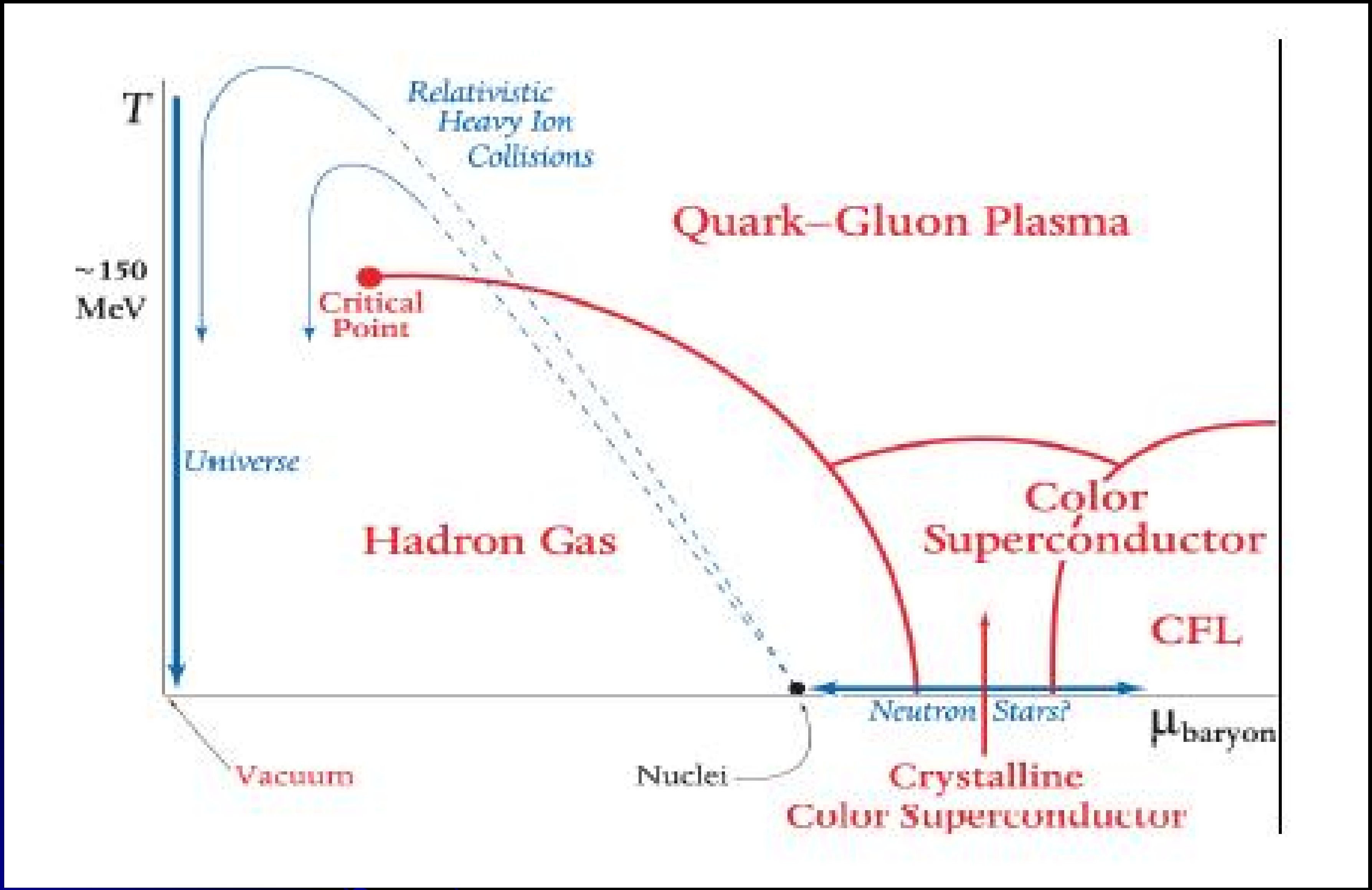
for the PHENIX Collaboration

Outline

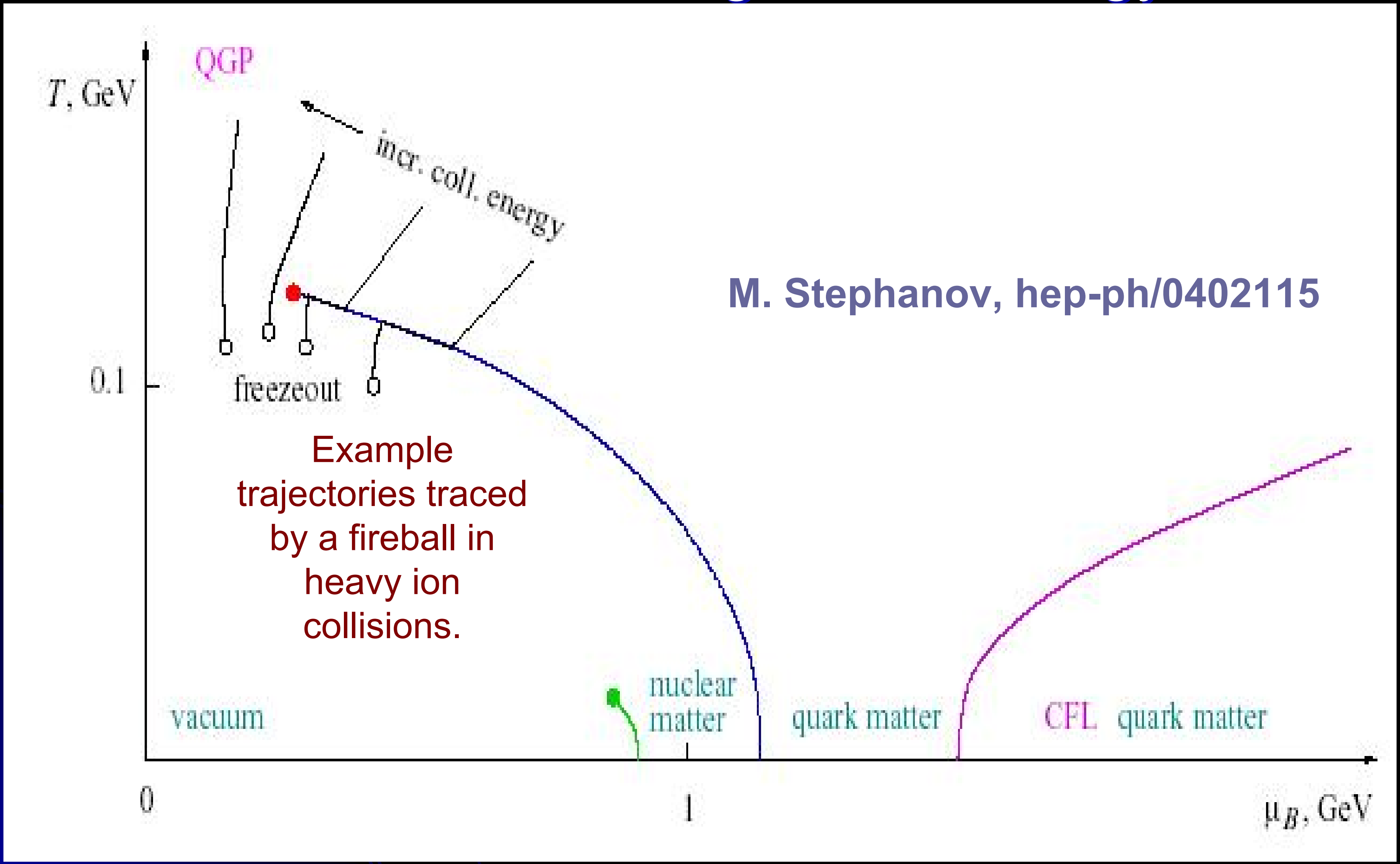
- **Searching for Critical Behavior**
  - **Multiplicity Fluctuations**
  - **<p_T> Fluctuations**
  - **Azimuthal Correlations**
- **p_T-dependence of azimuthal correlations**

Motivating a Search for Critical Behavior at RHIC

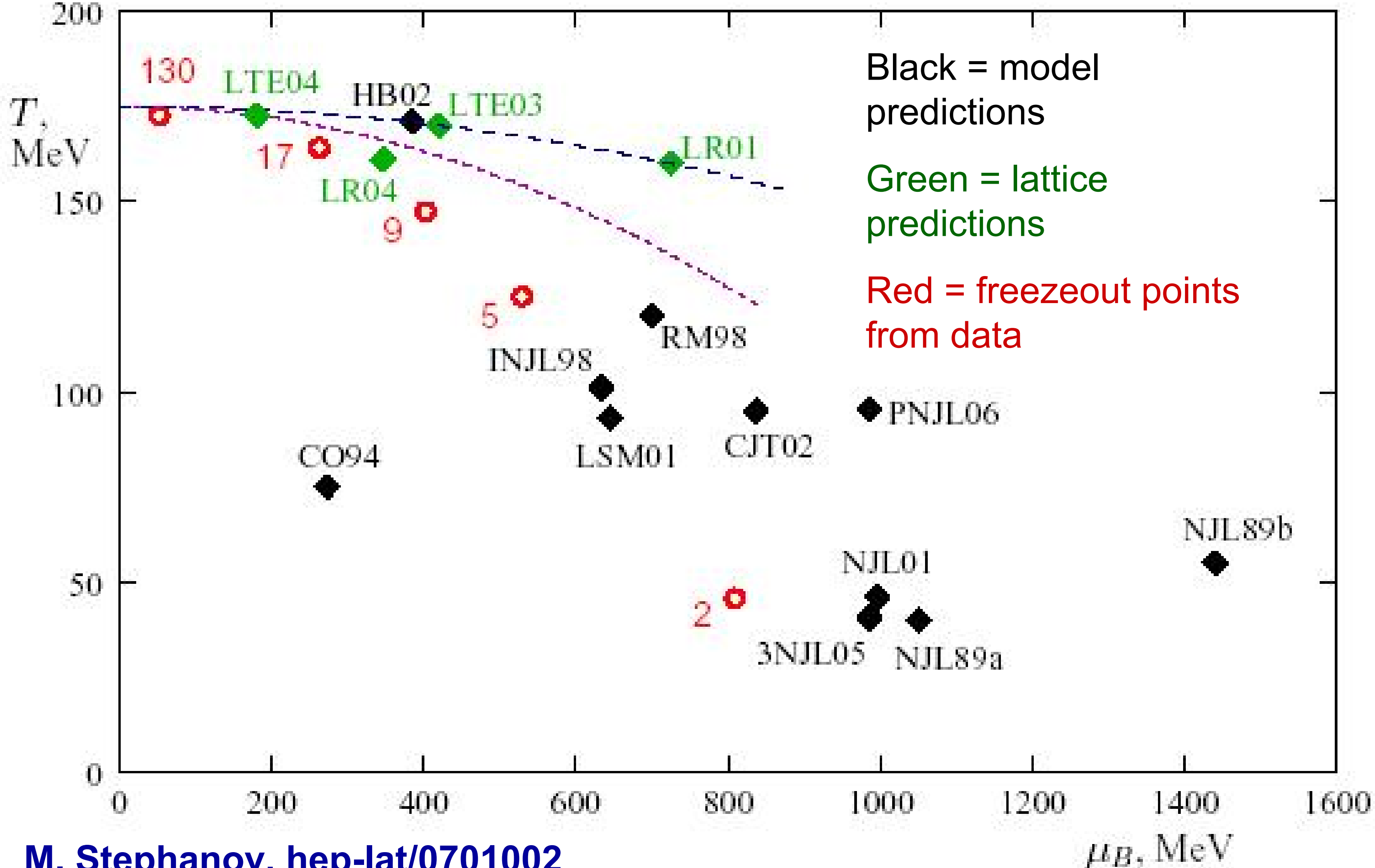


From BNL-77334-2006-IR, "Future Science at the Relativistic Heavy Ion Collider"

Motivating a Search for Critical Behavior at RHIC: Scan the Colliding Beam Energy



Where is the Critical Point?

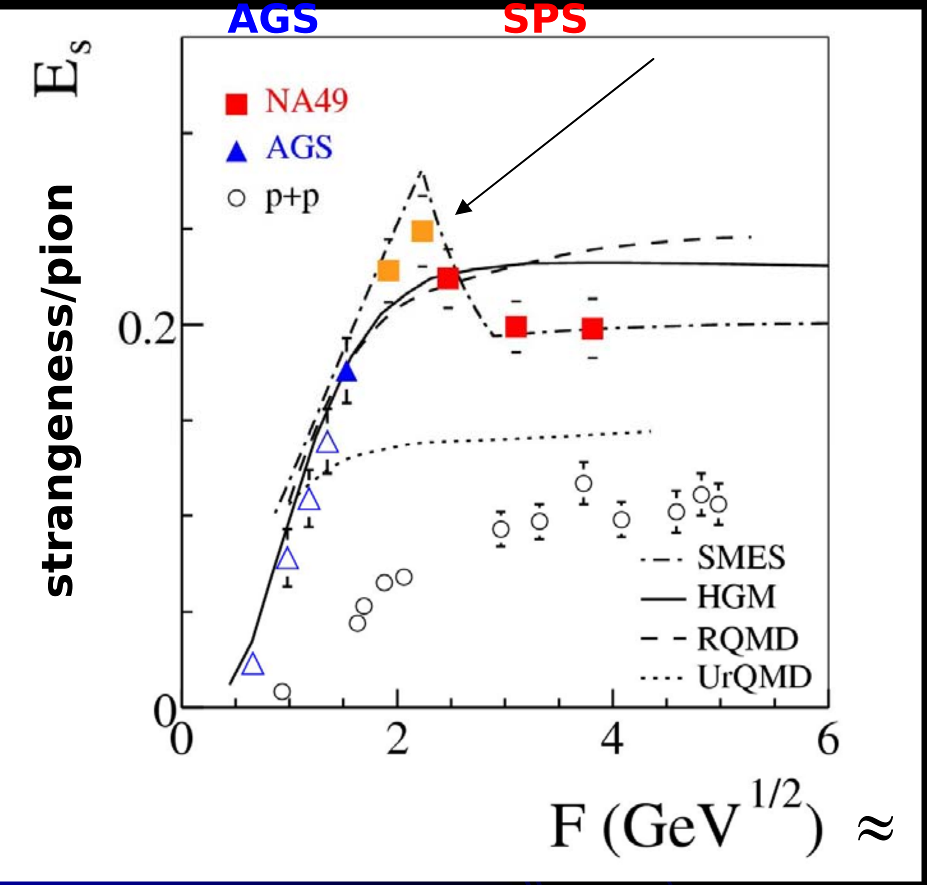


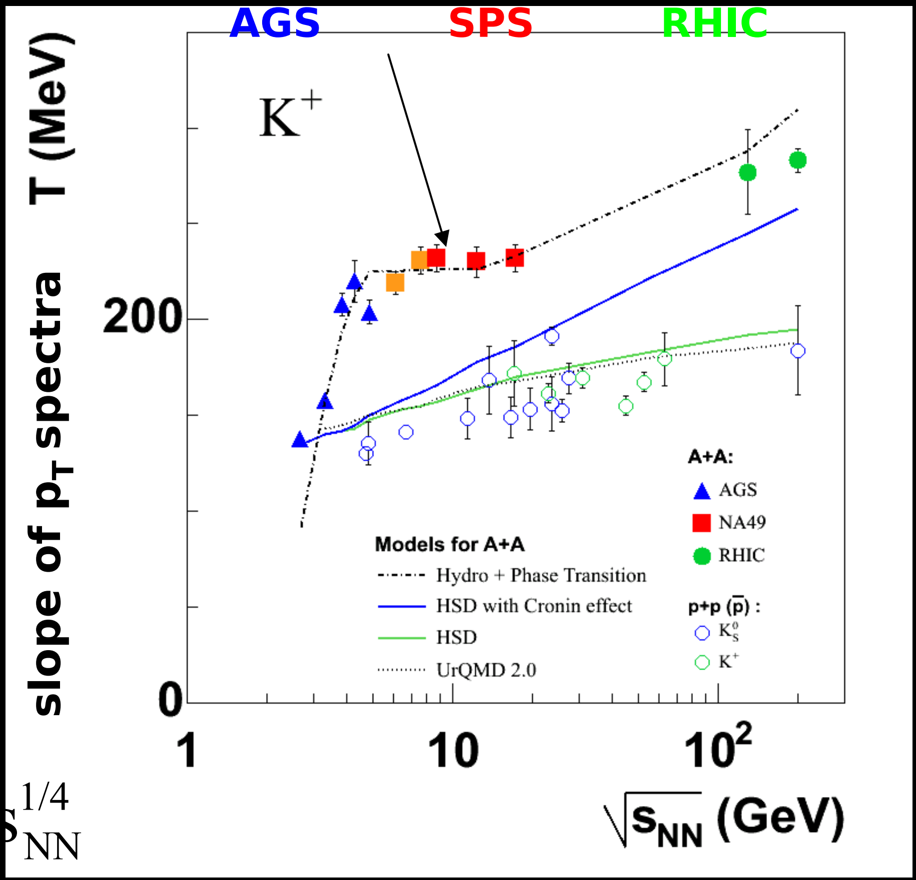
M. Stephanov, hep-lat/0701002

Critical Behavior at the SPS?

NA49 (Talk by P. Seyboth)

Changes of hadron production properties in central Pb+Pb collisions at the CERN SPS energies are not reproduced by models without onset of deconfinement at low SPS energies





Critical Exponents: An Experimental 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:

  <N_{ch}> Fluctuations.

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

- The critical exponent for heat capacity, α:

  <p_T> Fluctuations.

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

- The critical exponent for correlation functions, η:

  HBT correlations in azimuth and Q_{inv}.

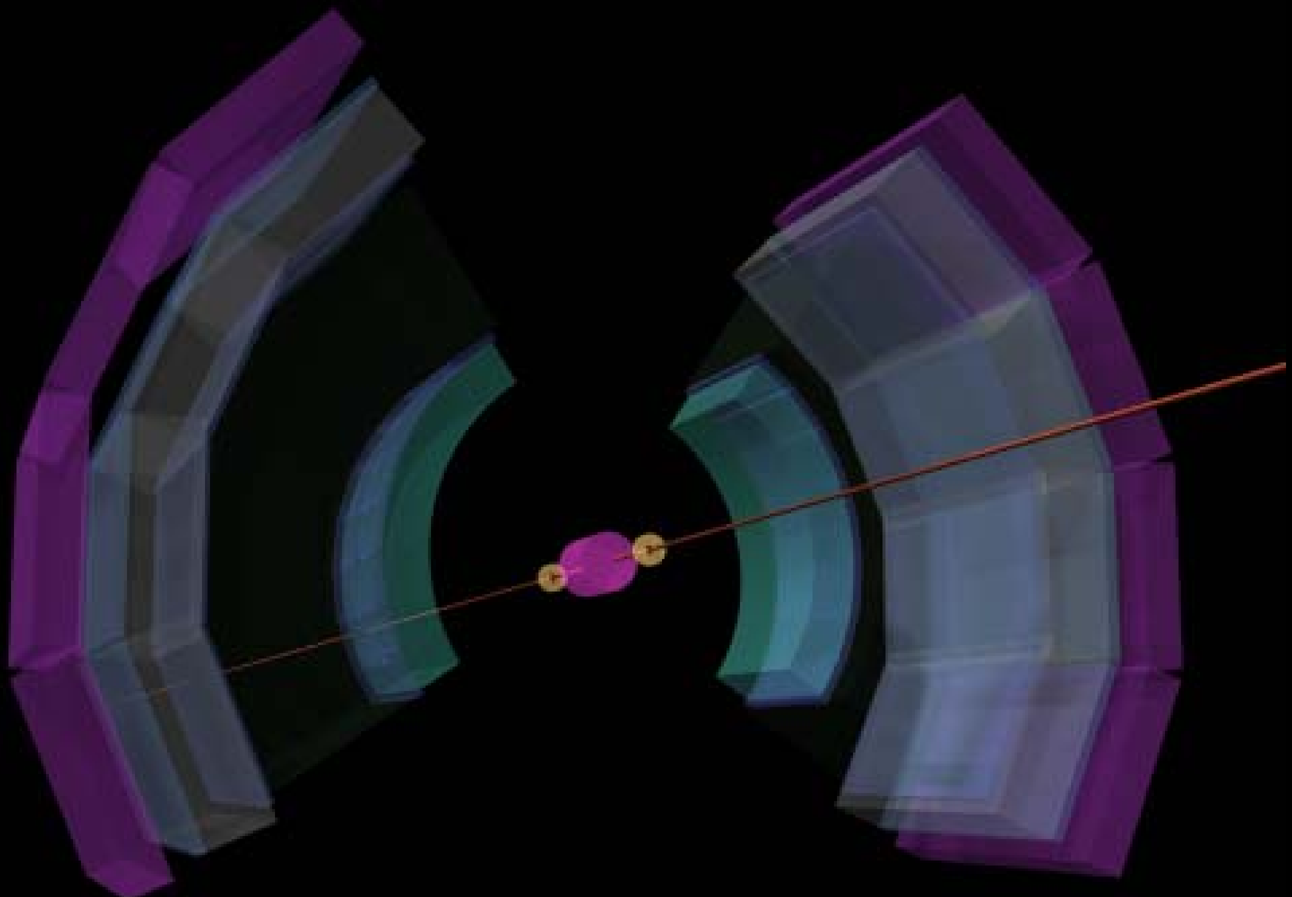
$$C(R) \propto R^{-(d-2+\eta)}$$ (d=3)

The PHENIX Detector

Acceptance:

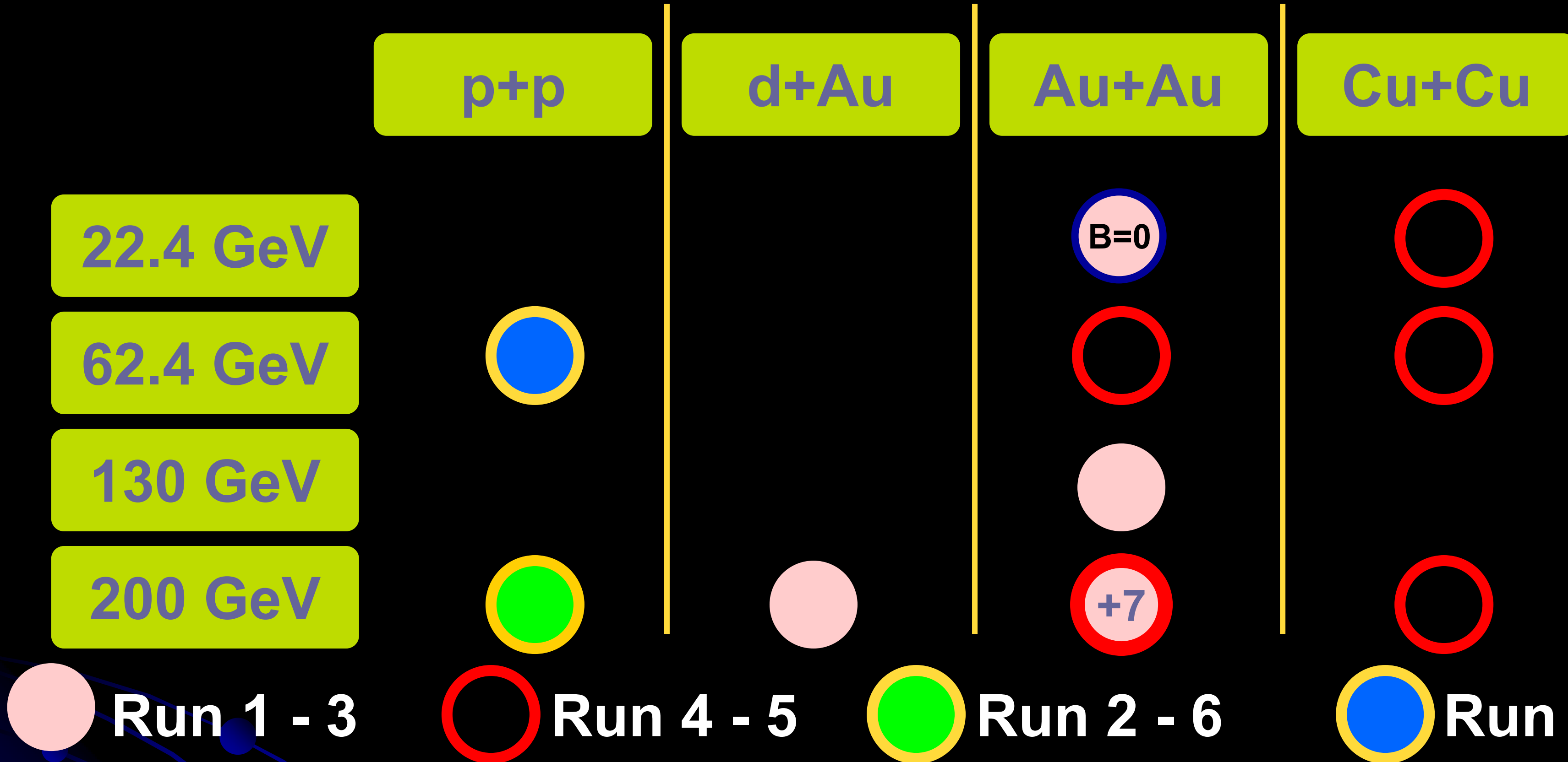
$|\eta| \sim 0.35$

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



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.

Current PHENIX Datasets



CuCu	200GeV	1.08 Billion Events	157TB on tape
CuCu	62.4GeV	630 Million Events	42TB on tape
CuCu	22GeV	48 Million Events	3TB on tape
p-p	200GeV	6.8 Billion Events	286TB on tape

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488 TB on tape for Run 5

Advances in data logging and the implementation of "multi-event buffering" increased our Event rate dramatically in Runs 4 and 5

Multiplicity Fluctuations

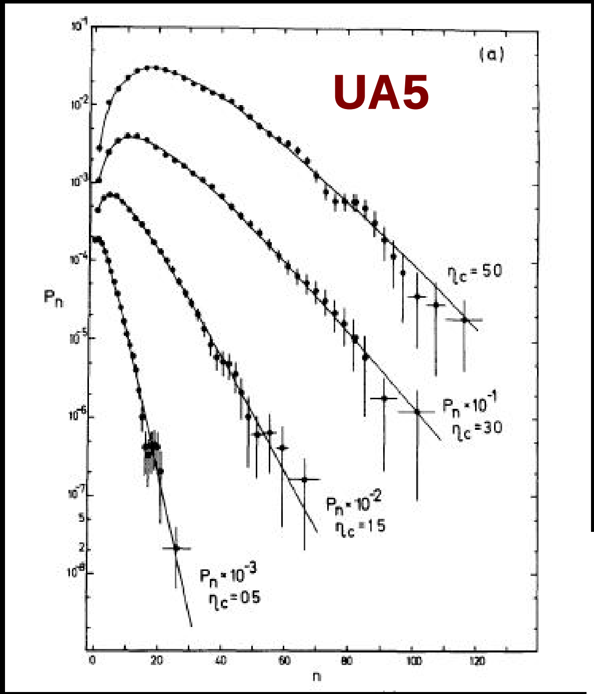
- A survey of multiplicity fluctuations has been completed in the following systems:
  - 200 GeV Au+Au
  - 62.4 GeV Au+Au
  - 200 GeV Cu+Cu
  - 62.4 GeV Cu+Cu
  - 22.5 GeV Cu+Cu
- Survey completed as a function of centrality and p_T

- 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

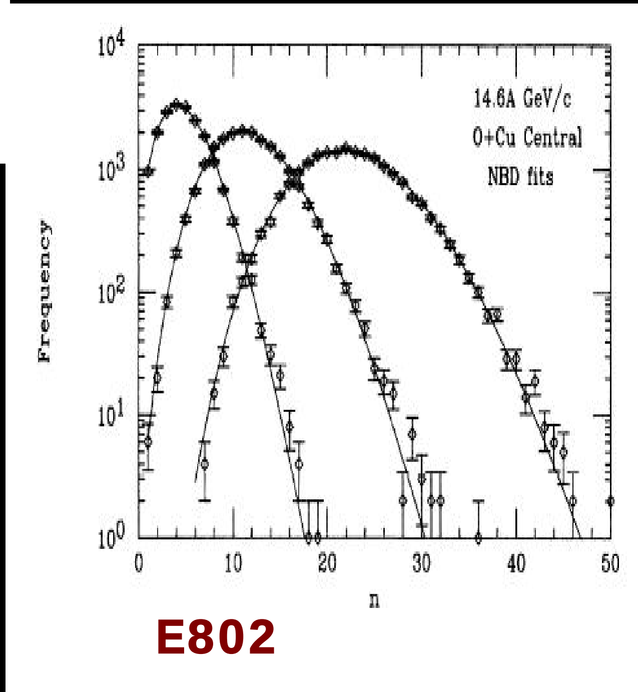
Multiplicity distributions in hadronic and nuclear collisions can be well described by the Negative Binomial Distribution.

For 1/k→0, the N.B.D. becomes a Poisson 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.

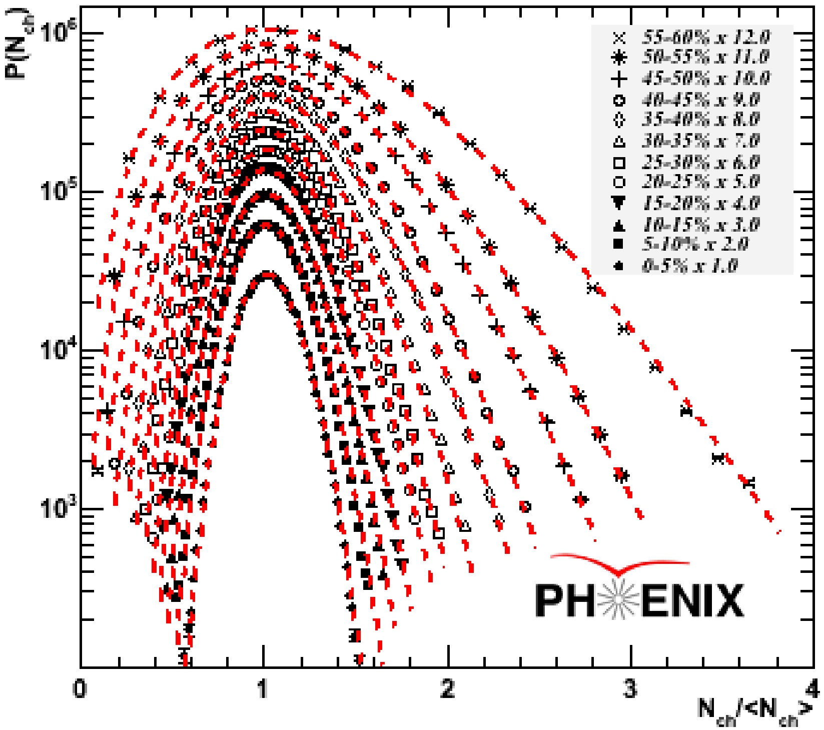


$$P(m) = \frac{(m+k-1)!}{m!(k-1)!} \frac{\left(\mu/k\right)^m}{\left(1+\mu/k\right)^{m+k}}$$

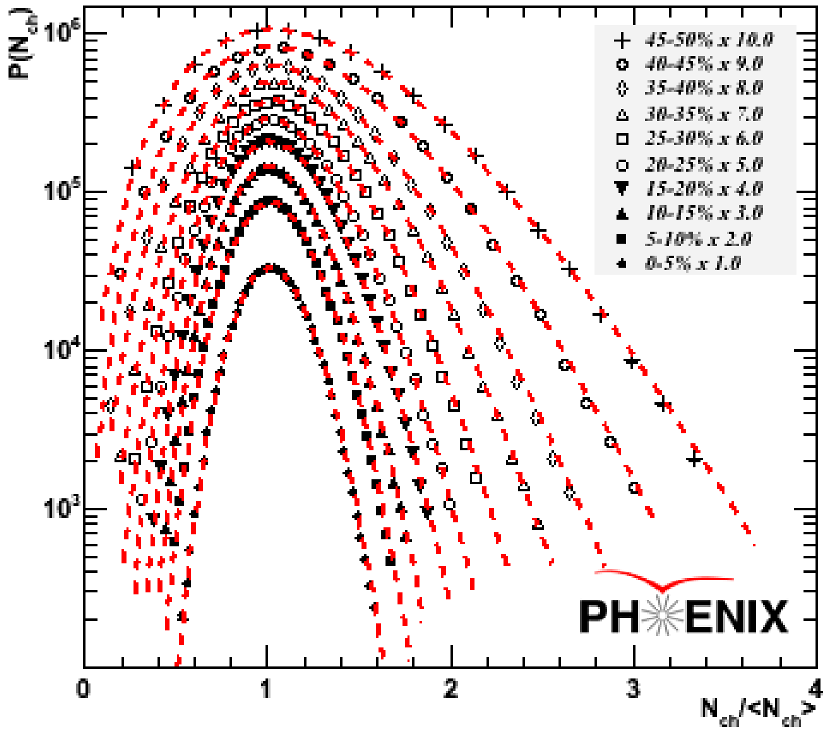
$$\frac{1}{k} = \frac{\sigma^2}{\mu^2} - \frac{1}{\mu}$$

Au+Au Centrality-Dependent Multiplicity Distributions

200 GeV Au+Au



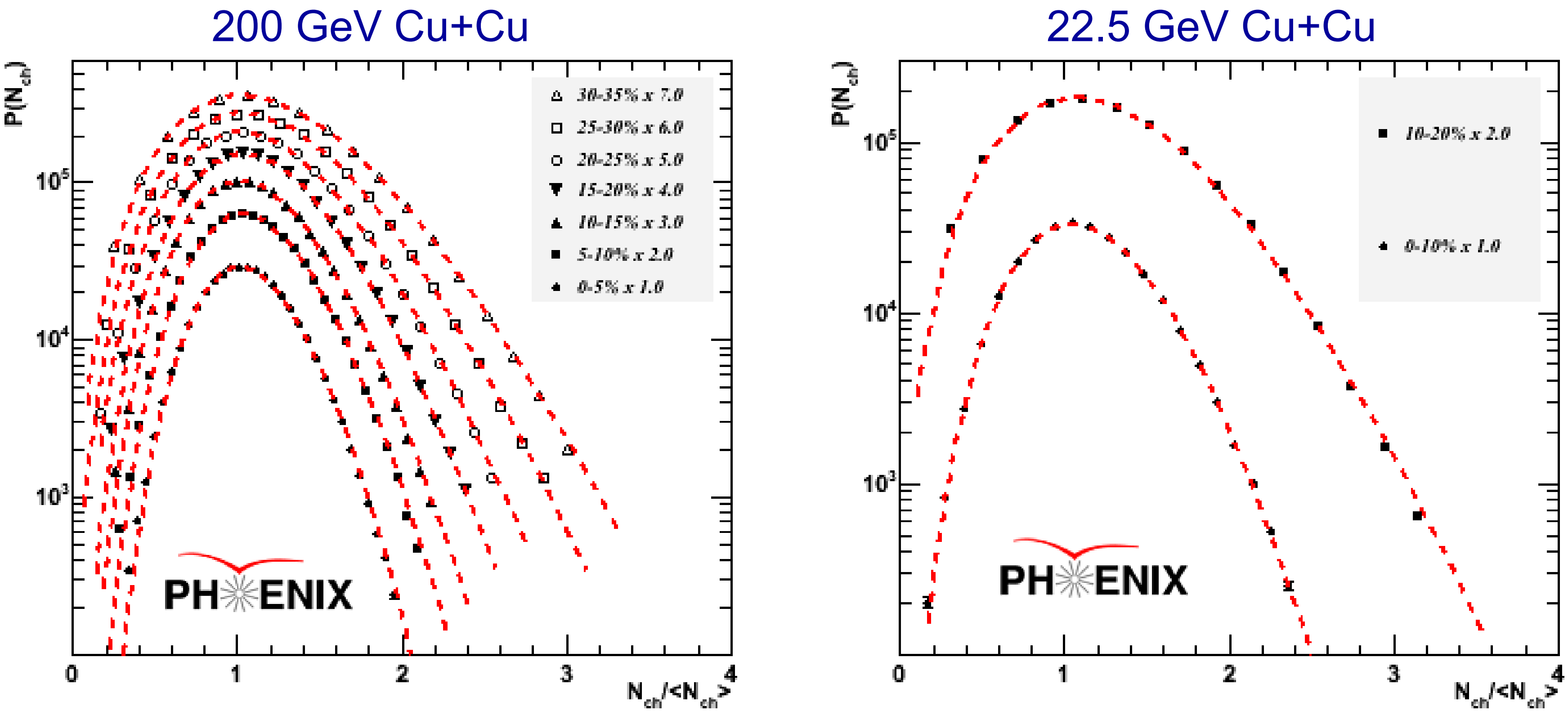
62.4 GeV Au+Au



PHENIX Preliminary

Multiplicity distributions are scaled horizontally to $N/\langle N_{ch} \rangle$. They are scaled vertically in order of decreasing centrality.

Cu+Cu Centrality-Dependent Multiplicity Distributions



PHENIX Preliminary

Multiplicity distributions are scaled horizontally to $N/\langle N_{ch}\rangle$. They are scaled vertically in order of decreasing centrality.

Comparisons to the Wounded Nucleon Model

- In the Wounded Nucleon Model, multiplicity fluctuations are given by:

$$\omega_N = \omega_n + \langle N \rangle \omega_{Np}$$

$\omega = \sigma^2/\mu$. ω_N = total fluctuation, ω_n = fluctuation of each source (e.g. hadron-hadron collision), ω_{Np} = fluctuation in number of sources (participants).

- After correcting for fluctuations due to impact parameter, $\omega_N = \omega_n$ independent of centrality.
- Multiplicity fluctuations are also dependent on acceptance:

$$\omega_n = 1 - f + f\omega_\nu$$

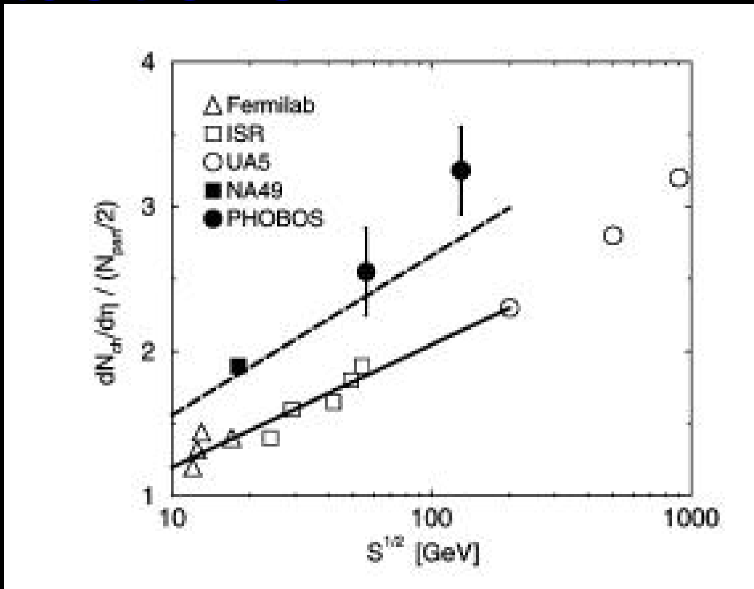
$f = N_{accepted}/N_{total}$. ω_n = fluctuations from each source in 4π

Wounded Nucleon Model Fluctuations in PHENIX

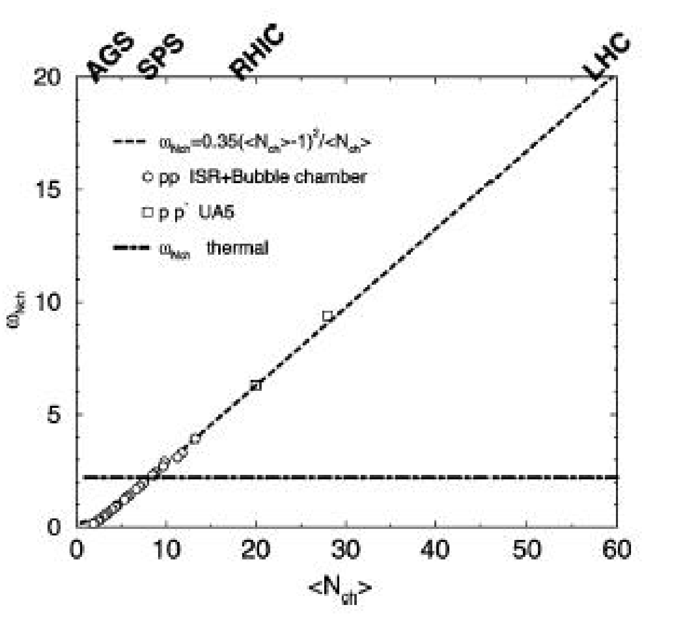
- From p+p data, the scaled variance, ω_{ch}, can be parametrized as follows:

$$\omega_{ch} \approx 0.35 \frac{\left(\langle N_{ch} \rangle - 1\right)^2}{\langle N_{ch} \rangle}$$

$$\langle N_{ch} \rangle \approx -4.2 + 4.69 \left(\frac{s}{GeV^2} \right)^{0.155}$$



H. Heiselberg / Physics Reports 351 (2001) 161–194



200 GeV:

$\langle N_{ch} \rangle = 20.04$, $\omega_{ch} = 6.33$.

62 GeV:

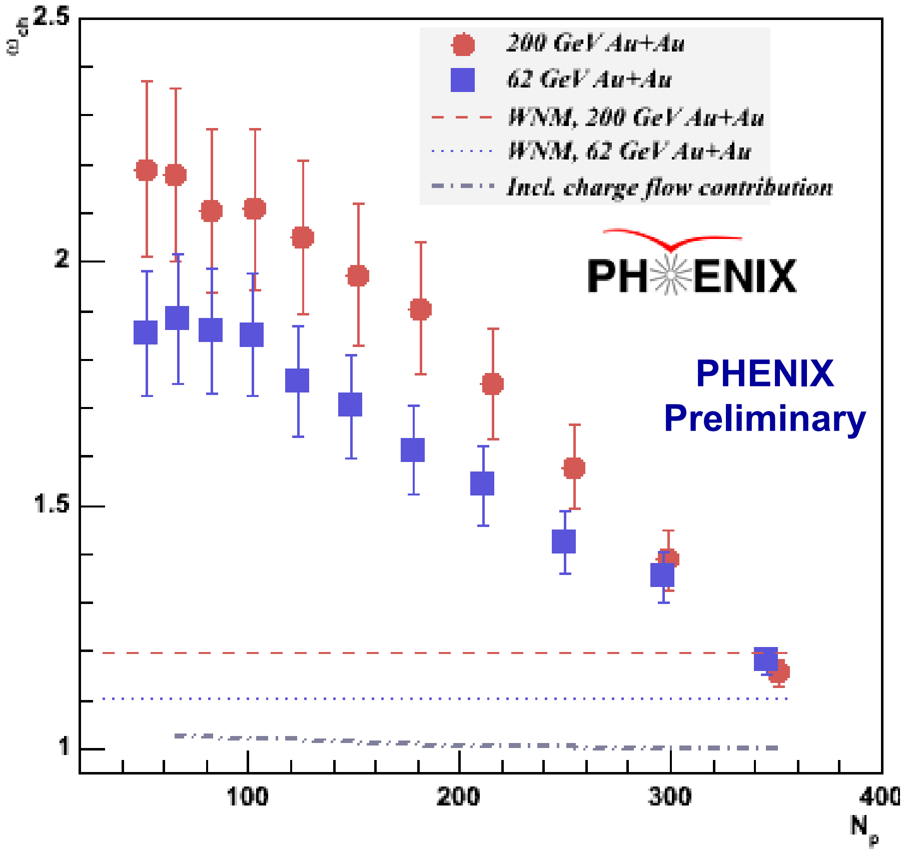
$\langle N_{ch} \rangle = 12.66$, $\omega_{ch} = 3.75$.

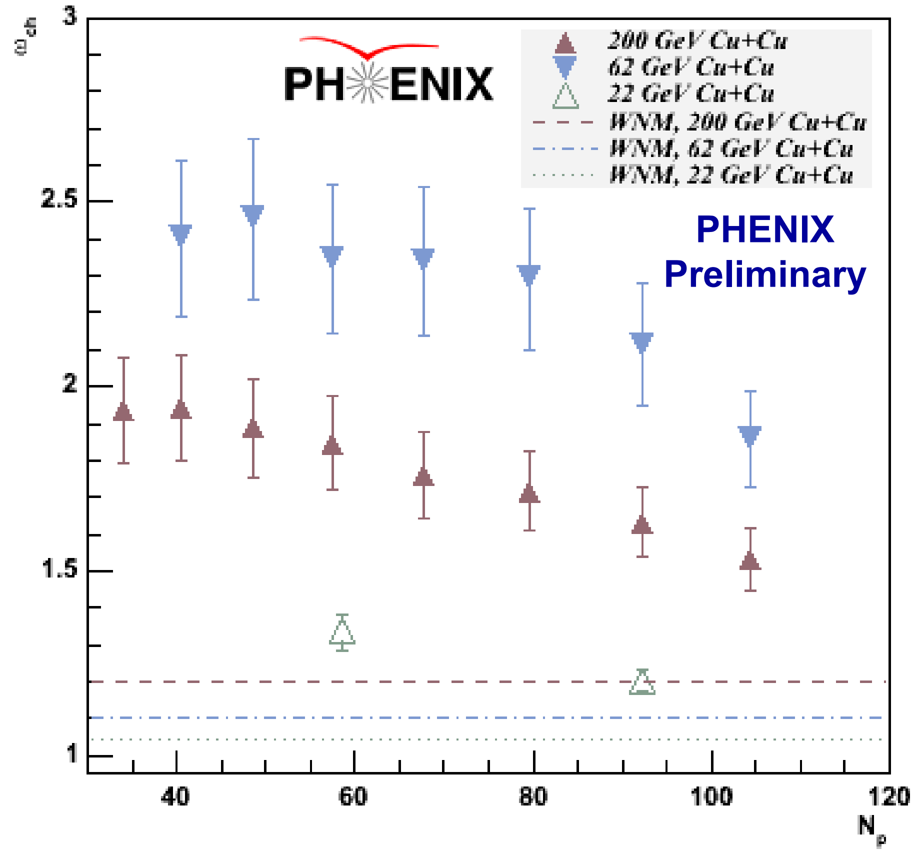
22 GeV:

$\langle N_{ch} \rangle = 8.03$, $\omega_{ch} = 2.15$.

- Wounded Nucleon model in PHENIX 2π acceptance (f=0.037): $\omega_n = 1 - f + f\omega_n$
  - 200 GeV: $\omega_N = 1.20$
  - 62 GeV: $\omega_N = 1.10$
  - 22 GeV: $\omega_N = 1.04$

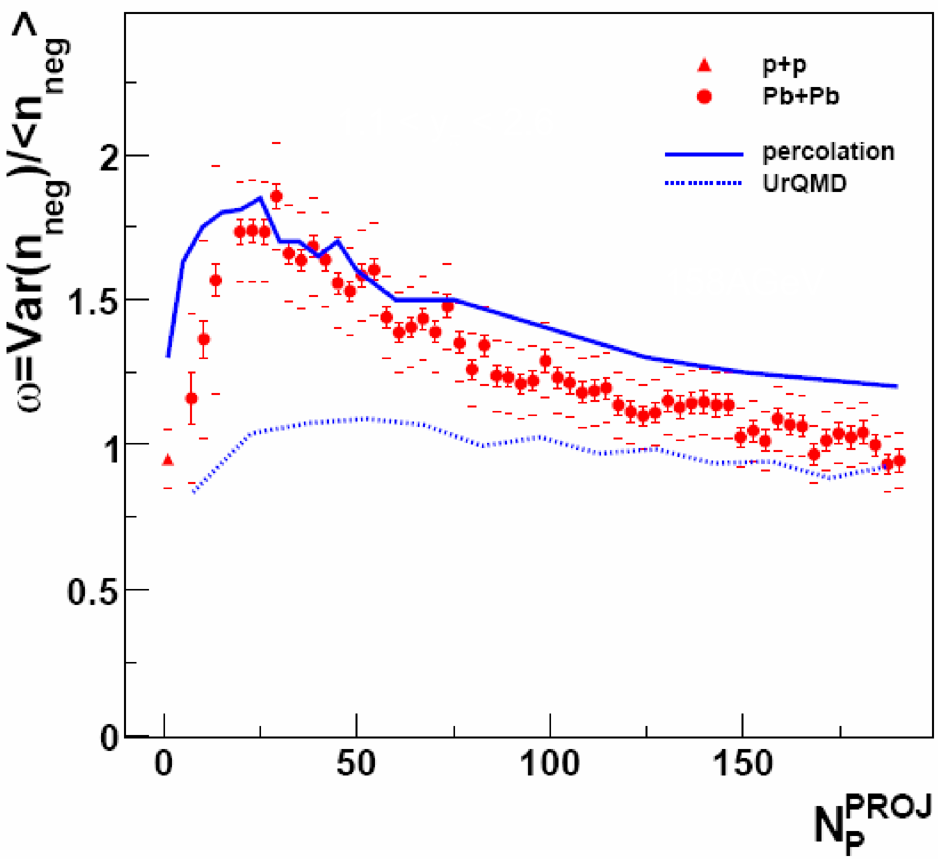
A Survey of Scaled Variance, $\omega_{ch} = \sigma^2/\mu$

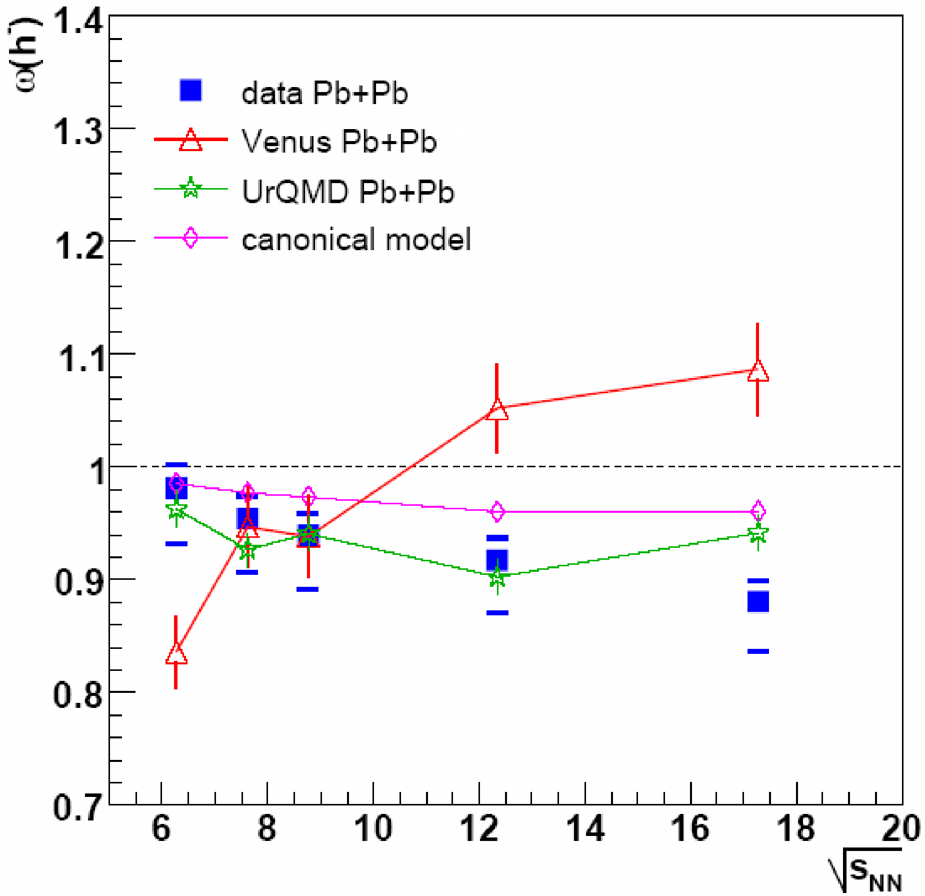




- Inclusive charged hadron fluctuations. $0.2 < p_T < p_{T,max}$ GeV/c
- These values are corrected to remove the contribution due to impact parameter (geometrical) fluctuations and projected to 2π in azimuth for direct comparisons to other experiments.
- The Poissonian (random) limit is 1.0.
- Large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

NA49 Results, 17 GeV Pb+Pb: Event-by-event fluctuations of negative hadron multiplicity





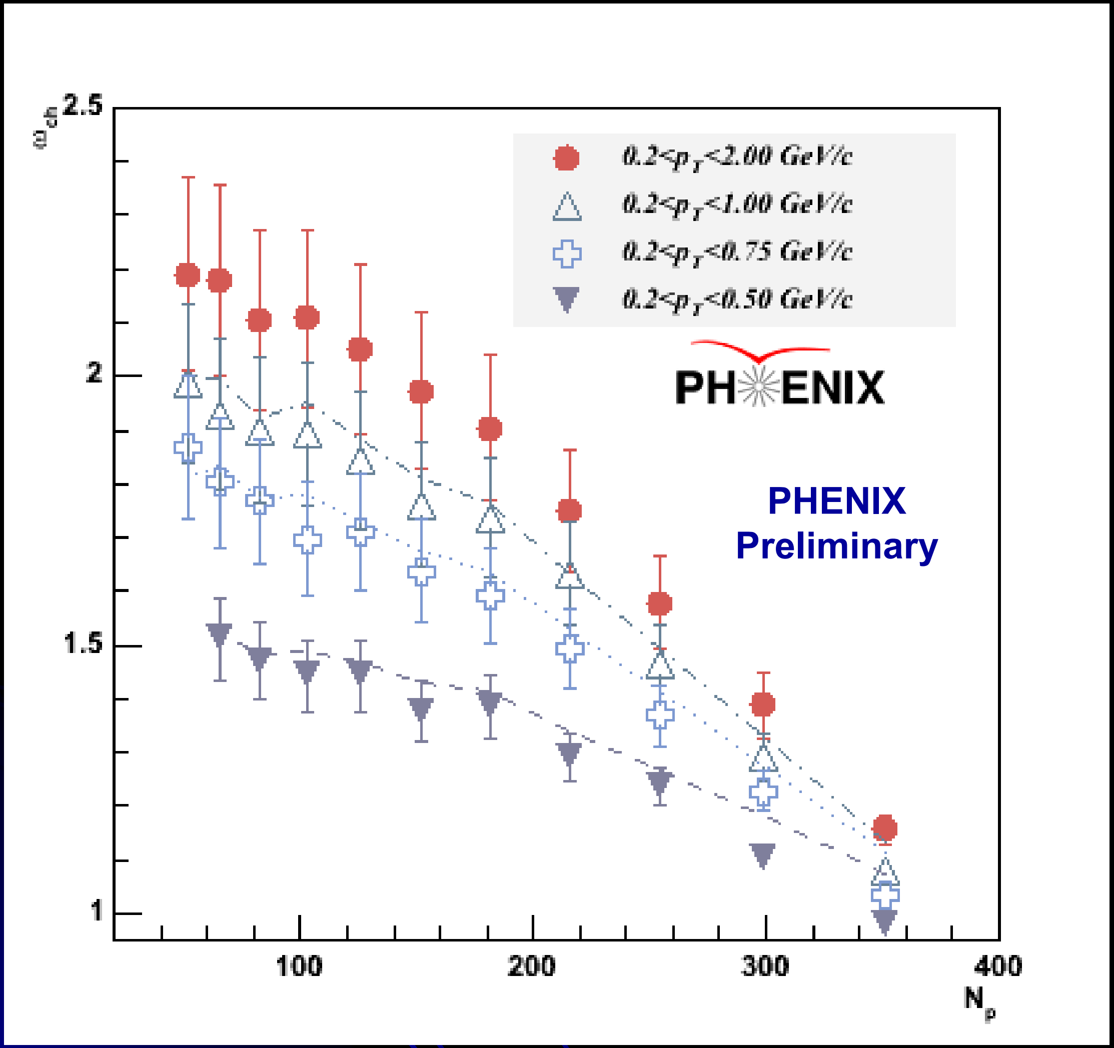
- reproduced by string models with string fusion (QGSM+fusion)

P. Seyboth

L.Cunqueiro et al.,PRC69 (2005) 024907

- fluctuations in central Pb+Pb small and nearly energy independent
- trend in statistical models is due to conservation laws

Scaled Variance vs. p_T



The curves represent the $0.2<p_T<2.0$ GeV/c data scaled as follows:

$\omega_n = 1 - f + f\omega_n$

where f = $\langle N\rangle_{0.2<pT<2.0} / \langle N\rangle_{0.2<pT<pT,2}$

Conclusion: No additional dynamical fluctuations as a function of p_T.

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 and the scaled variance can then be related to compressibility:
$$1 / k_{NBD} + 1 / \mu = \sigma^2 / \mu^2 = \frac{k_B T}{V} k_T$$

Multiplicity Fluctuations: Universal Scaling?

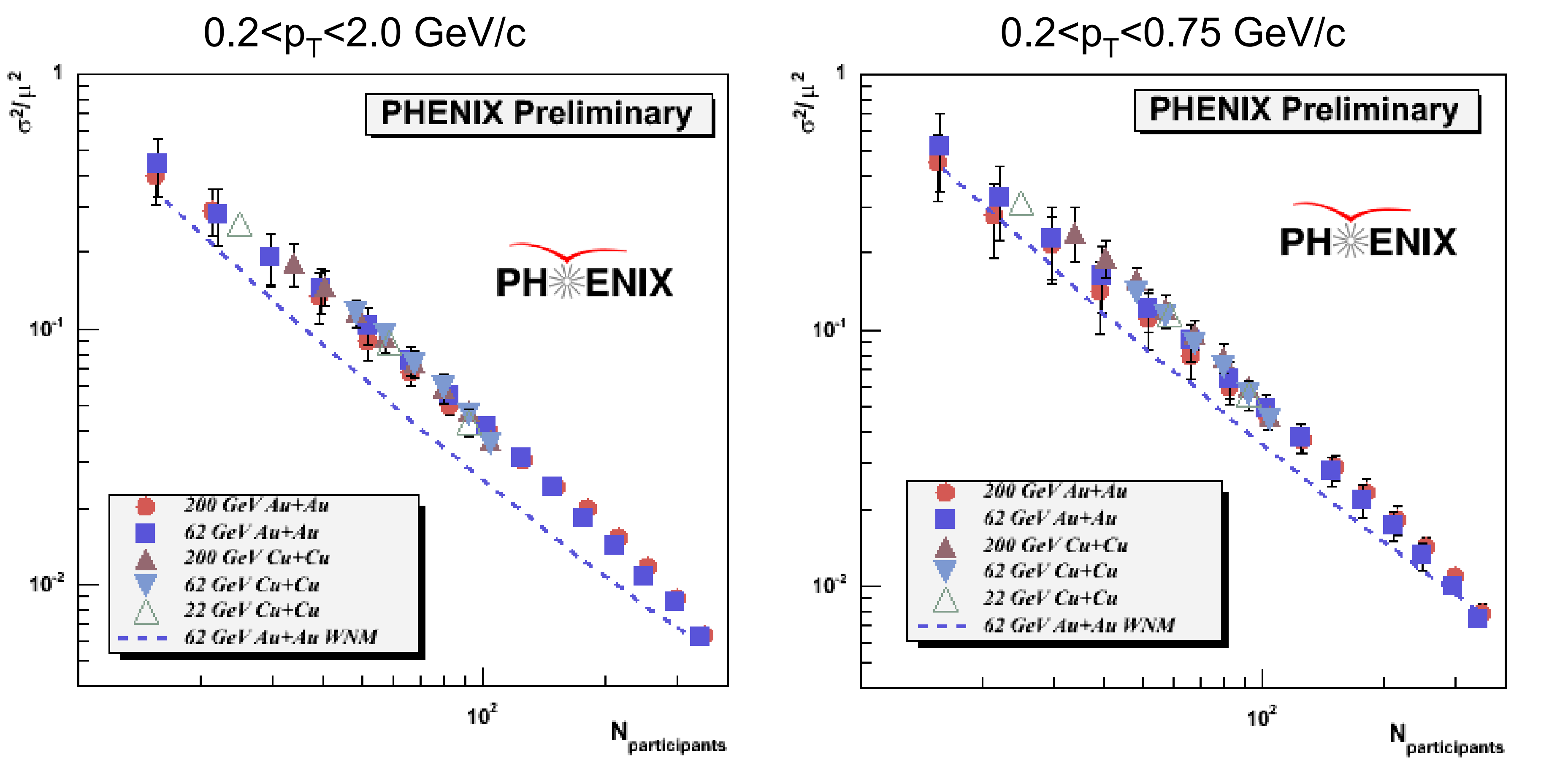
Grand Canonical Ensemble

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

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

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

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



Event-by-Event Mean p_T Fluctuations

- A survey of multiplicity fluctuations in the following systems:
  - 200 GeV Au+Au
  - 62.4 GeV Au+Au
  - 200 GeV Cu+Cu
  - 62.4 GeV Cu+Cu
  - 22.5 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.

Quantifying <p_T>Fluctuations

- The community consensus to quantify dynamical p_T fluctuations
  - Define the quantity <$\Delta p_{T,1}\Delta p_{T,2}$>.
  - 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

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

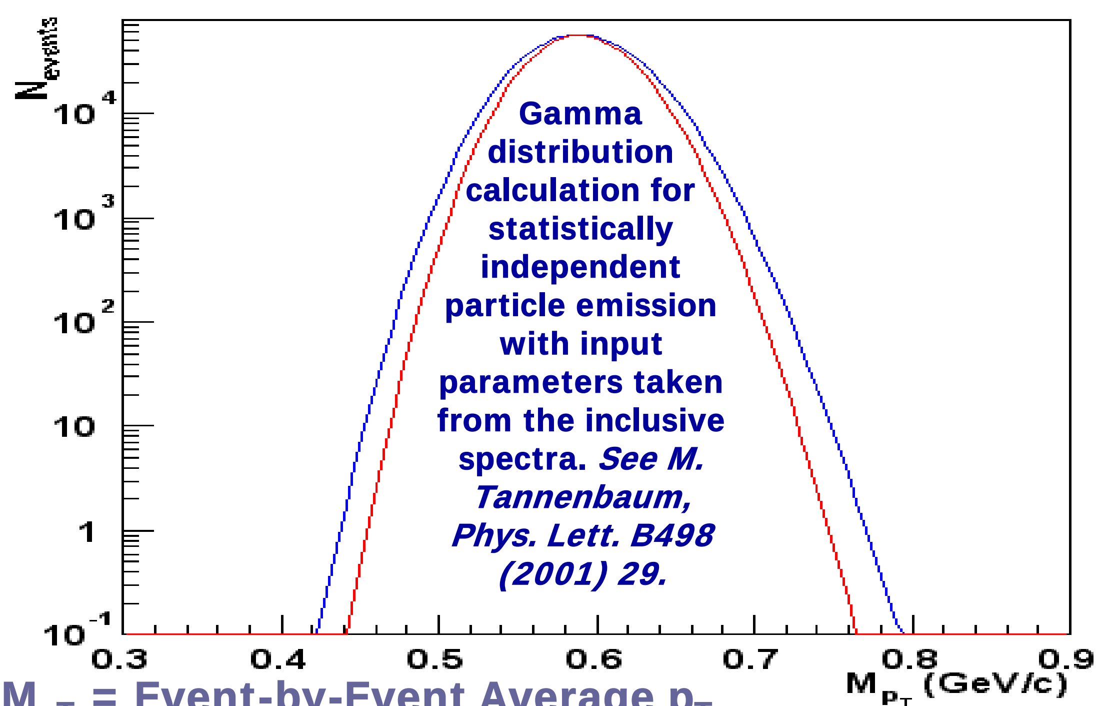
and $\langle\langle p_t \rangle\rangle = \left(\sum_{k=1}^{N_{event}} \langle p_t \rangle_k \right) / N_{event}$ and $\langle p_t \rangle_k = \left(\sum_{i=1}^{N_k} p_{t,i} \right) / N_k$

Then normalize as follows for a dimensionless quantity:

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

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} is related to the inverse of the heat capacity.



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

Red: Random Expectation (Γ distribution)

Blue: STAR acceptance fluctuation of:

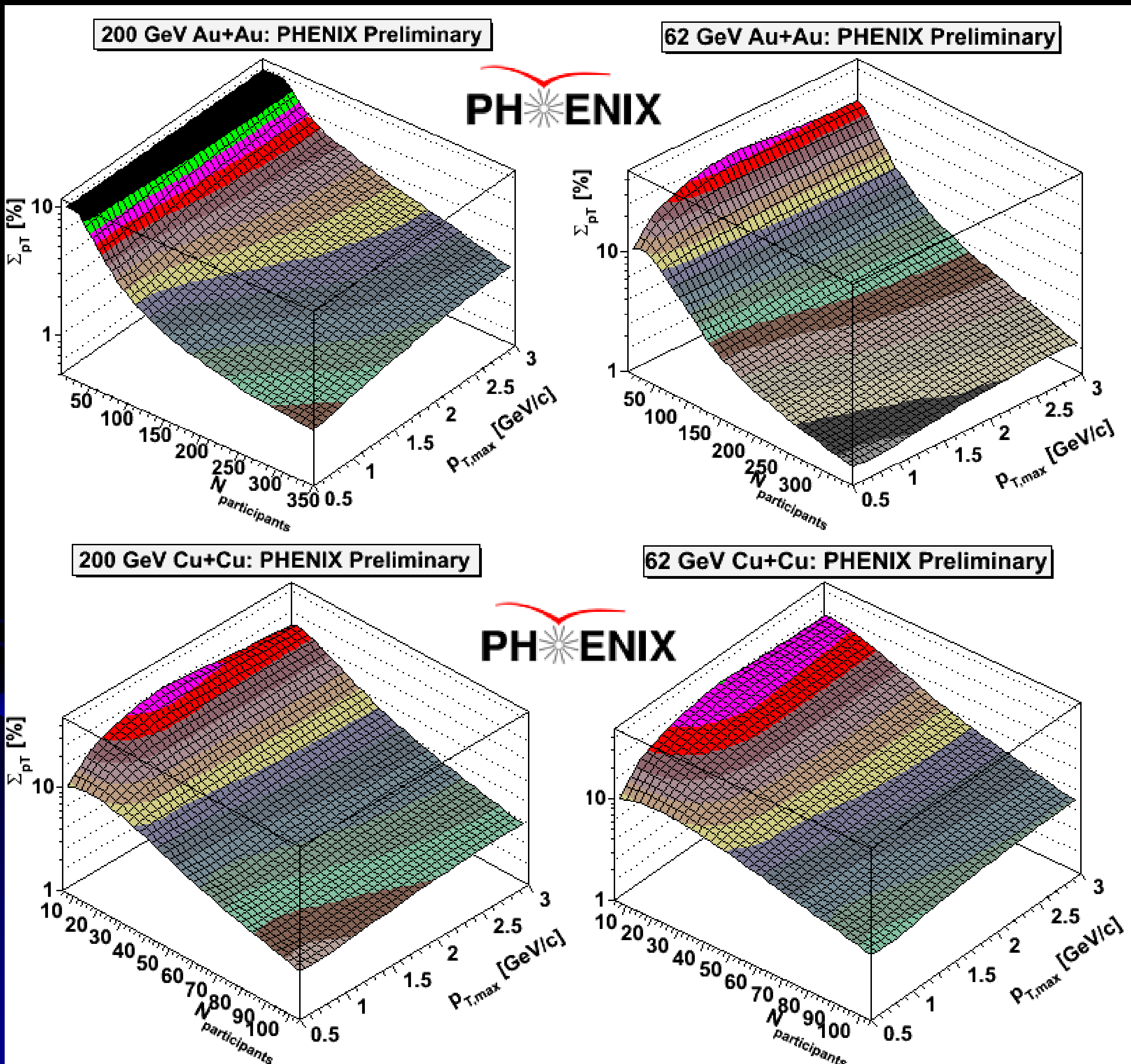
ϕ_{pT} = 52.6 MeV,

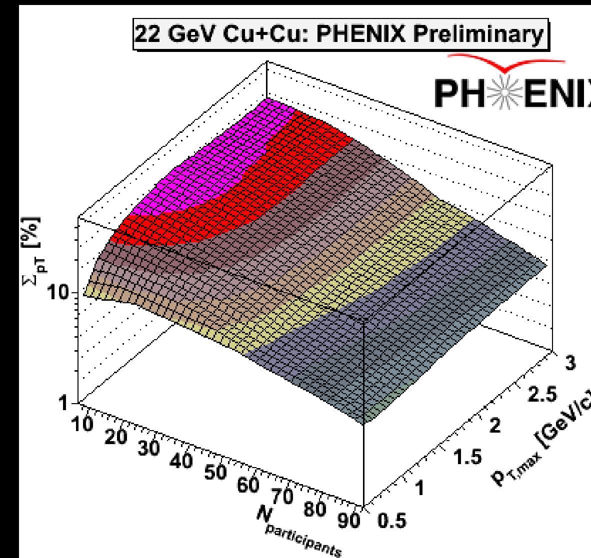
F_{pT} = 14 %,

$\sigma^2_{pT,dyn}$ = 52.3 (MeV/c^2),

Σ_{pT} = 9.8 %

<p_T> Fluctuations Survey



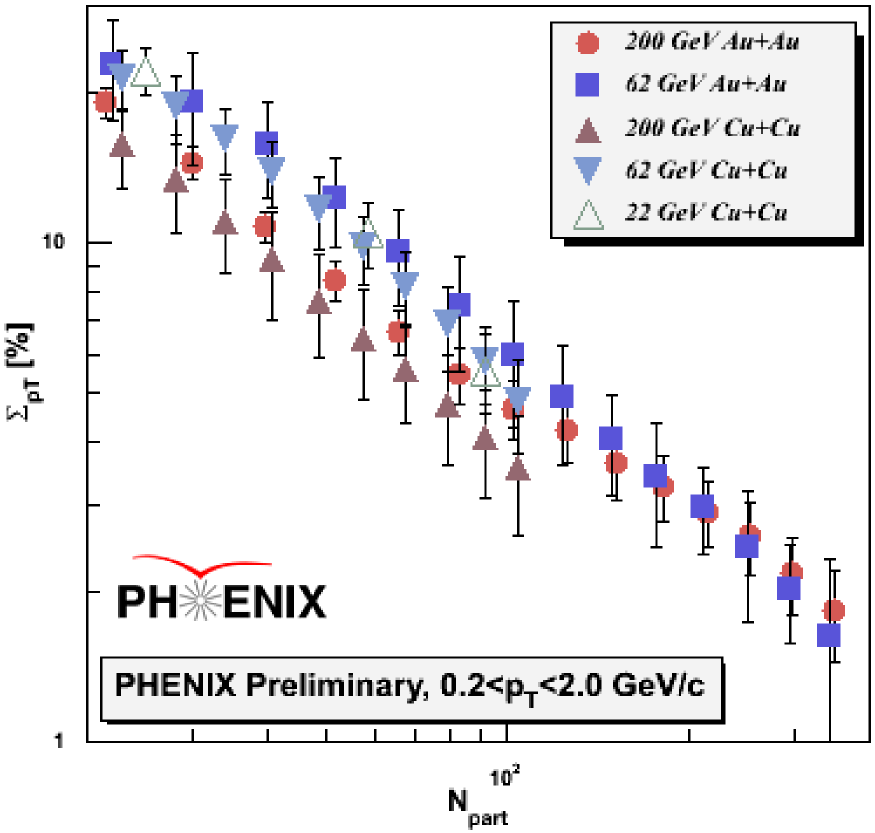


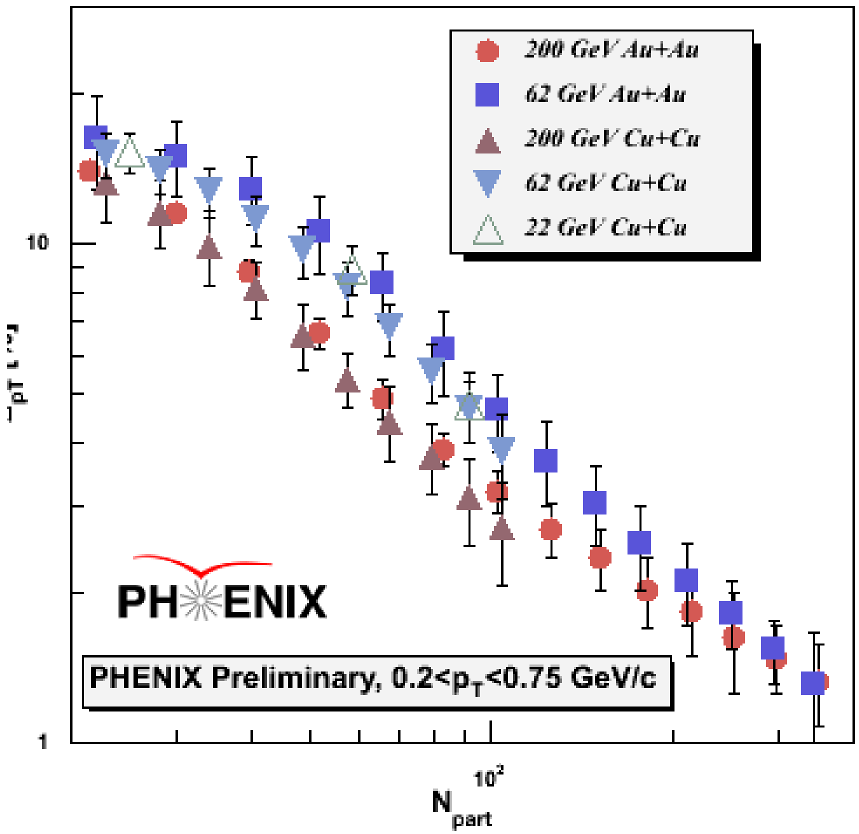
<u>Features:</u> Σ_{pT} increases with decreasing centrality. Similar trend to multiplicity fluctuations (σ^2/μ^2). Increases with increasing p_T. Same behavior for all species, including 22 GeV Cu+Cu.

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

<p_T> 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.

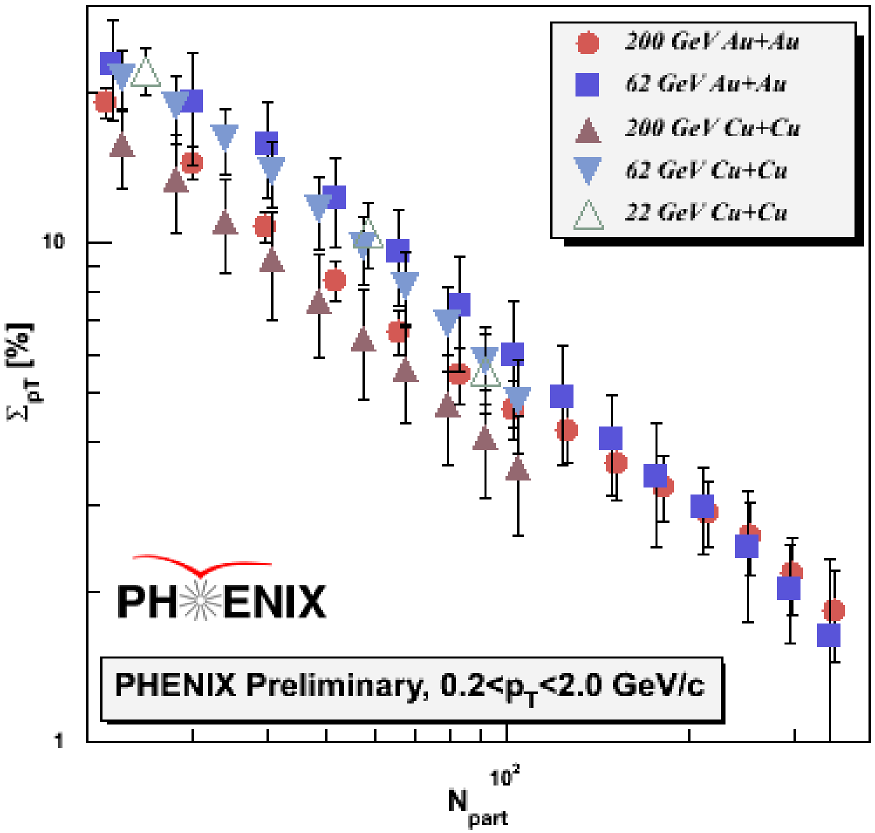


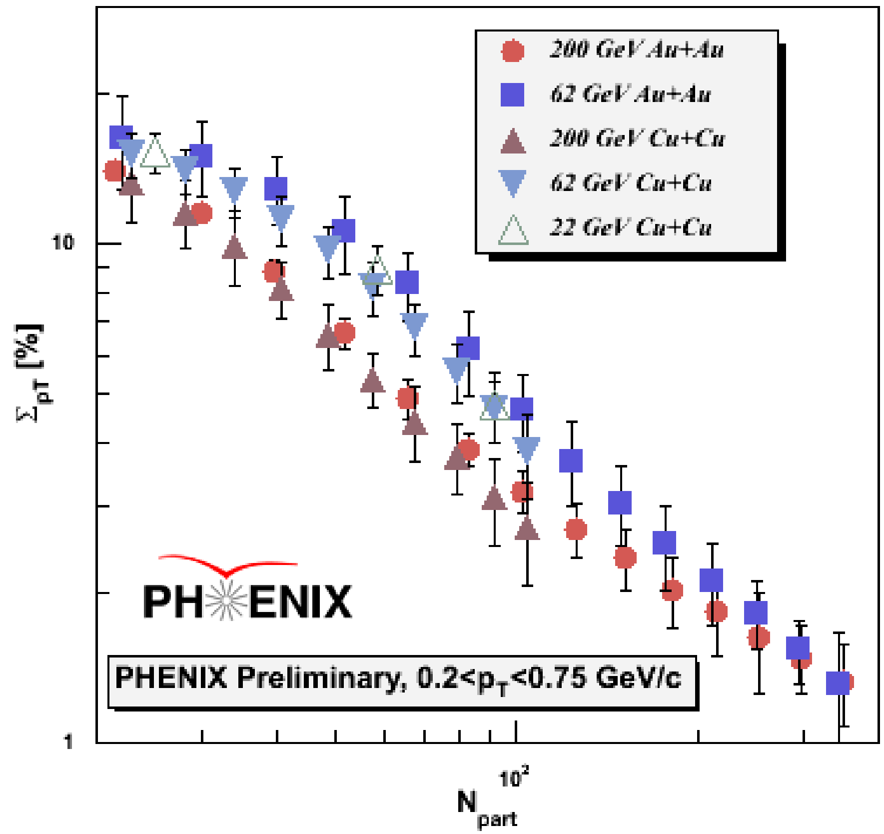


$<p_T>$ Fluctuations vs. Centrality

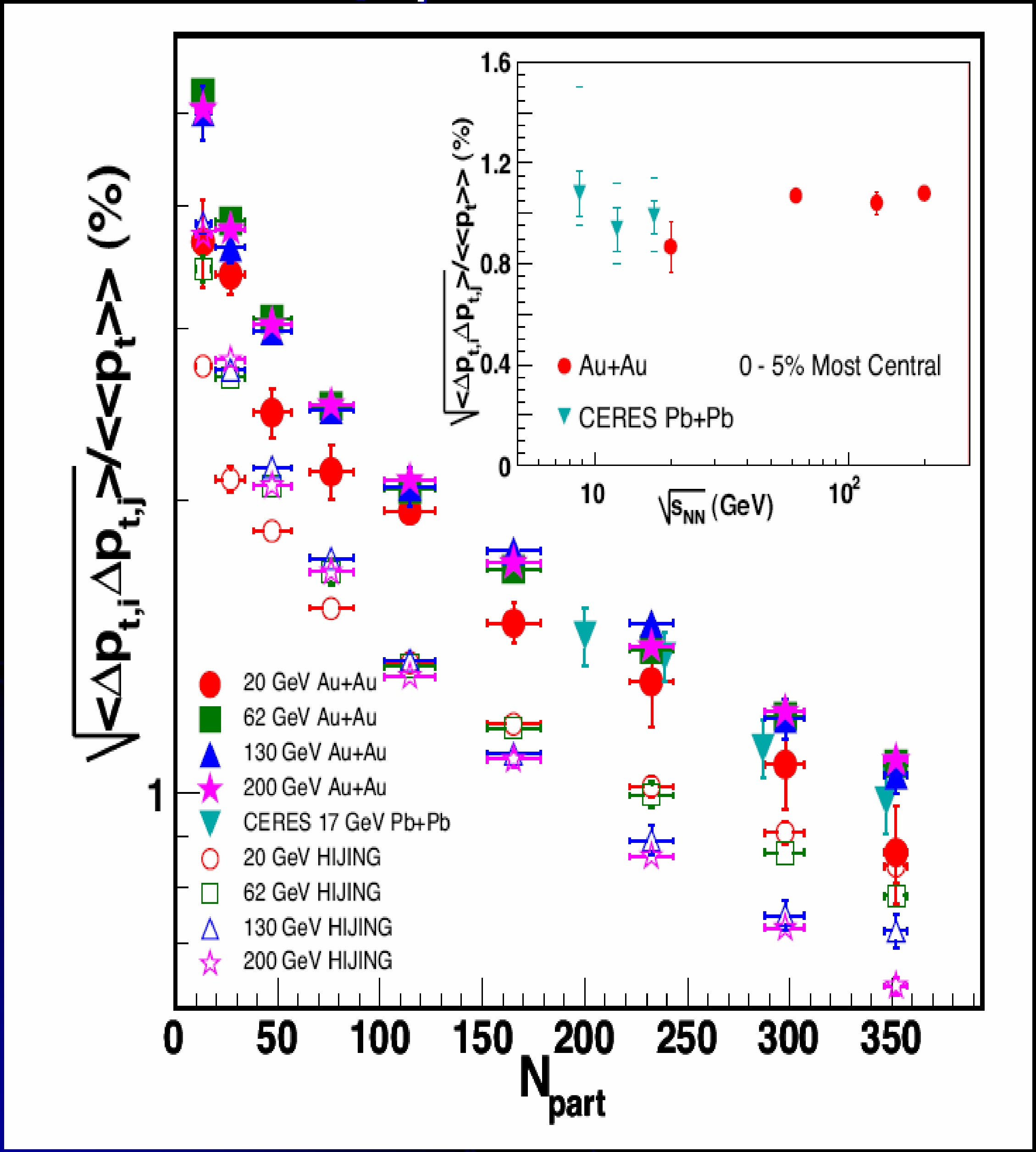
Above N_{part}~30, the data can be described by a power law in N_{part}, independent of the p_T range down to $0.2<p_T<0.5$ GeV/c:

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





STAR $\langle p_T \rangle$ Au+Au Fluctuation Results



Similar N_{part} scaling is observed in STAR's larger acceptance.

$\langle p_T \rangle$ fluctuations are independent of collision energy.

Correlation signals at the critical point

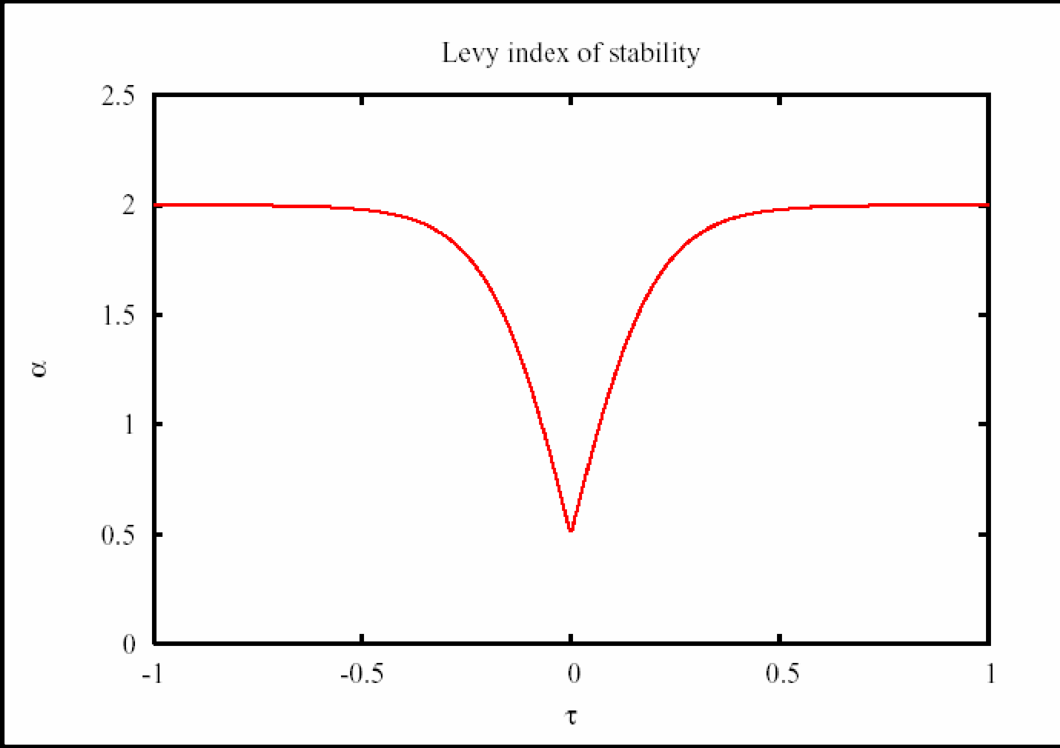
T. Csorgo, S. Hegyi, T. Novák, W.A. Zajc,
Acta Phys. Pol. B36 (2005) 329-337

- If the source distribution at the critical point is a Lévy distribution, it decays as:

$$\rho(R) \propto R^{-(1+\alpha)}$$

- at the critical point, the tail decreases as:

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



Excitation function of a as a function of $\tau = |T - T_c| / T_c$

T. Csorgo

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:**

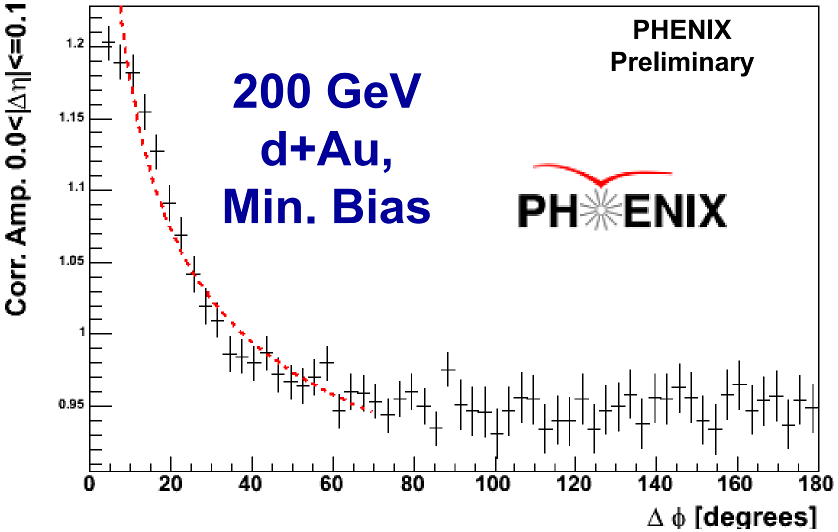
$$C(\Delta\phi) \propto \Delta\phi^{-(1+\eta)}$$

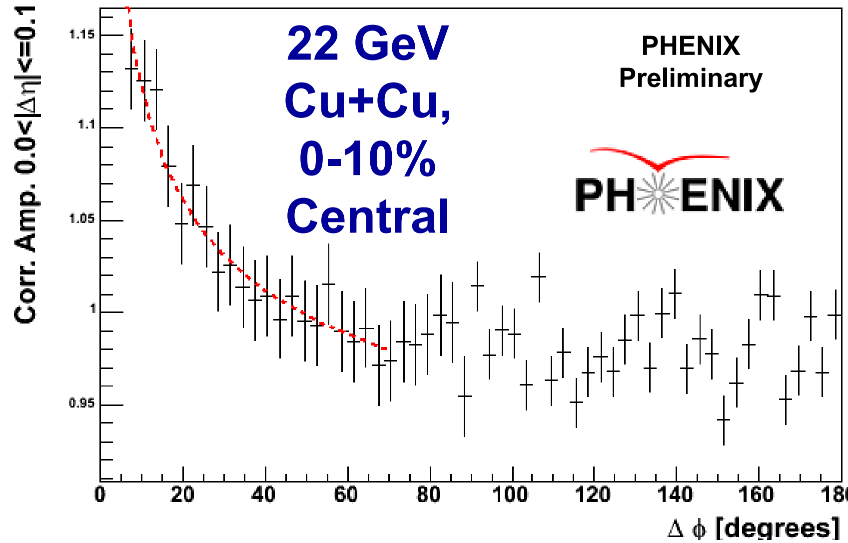
- **Shown are results for the following systems:**
  - **200 GeV Au+Au**
  - **62.4 GeV Au+Au**
  - **200 GeV Cu+Cu**
  - **62.4 GeV Cu+Cu**
  - **22.5 GeV Cu+Cu**
  - **200 GeV d+Au**
  - **200 GeV p+p**

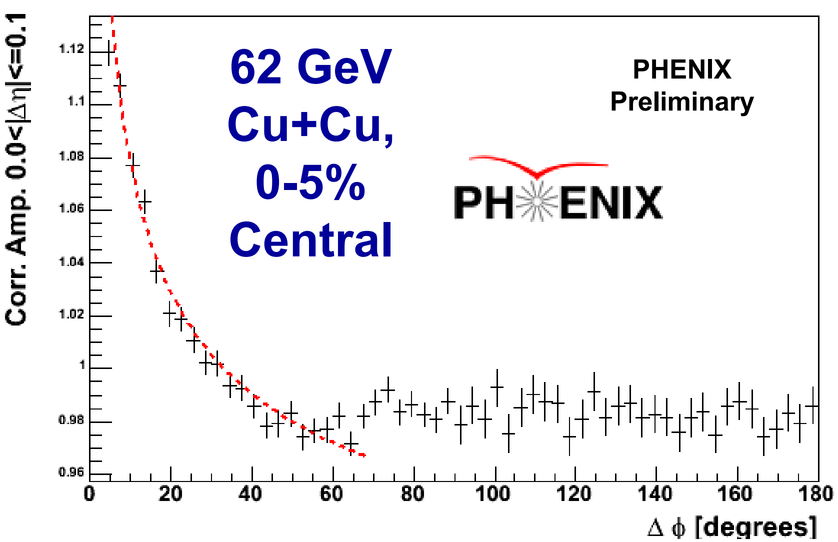
Assuming that QCD belongs in the same universality class as the (d=3) 3-D Ising model, the expected value of η is 0.5 (Reiger, Phys. Rev. B52 (1995) 6659 .

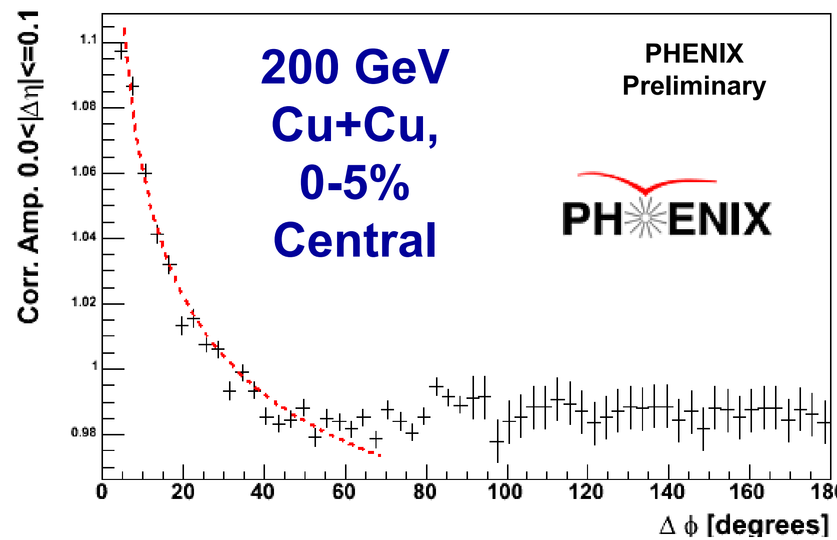
Like-Sign Pair Azimuthal Correlations: d+Au, Cu+Cu

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



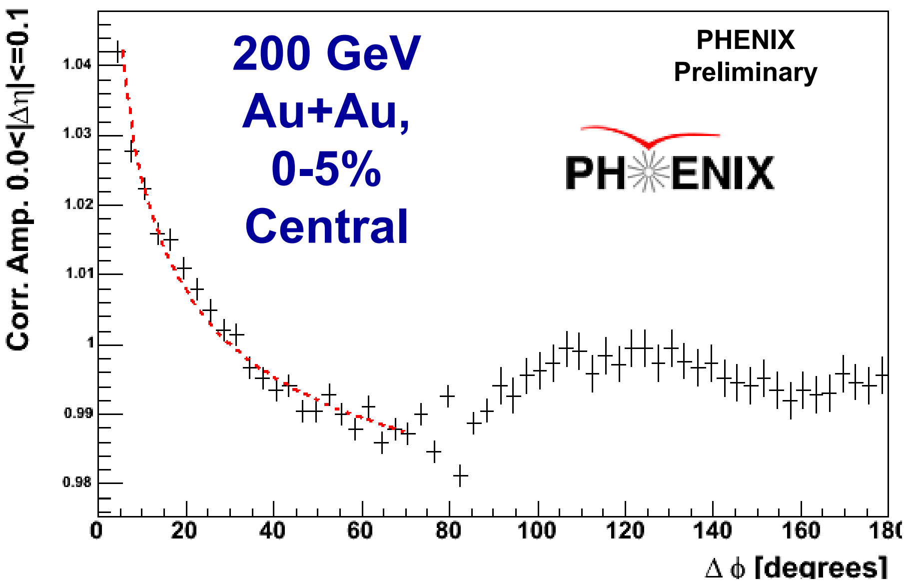


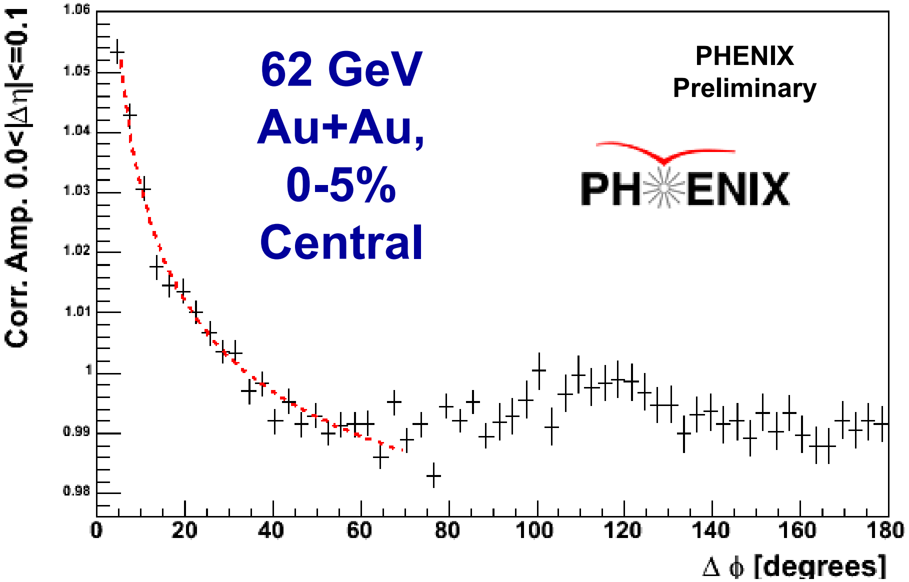




Like-Sign Pair Azimuthal Correlations: Au+Au

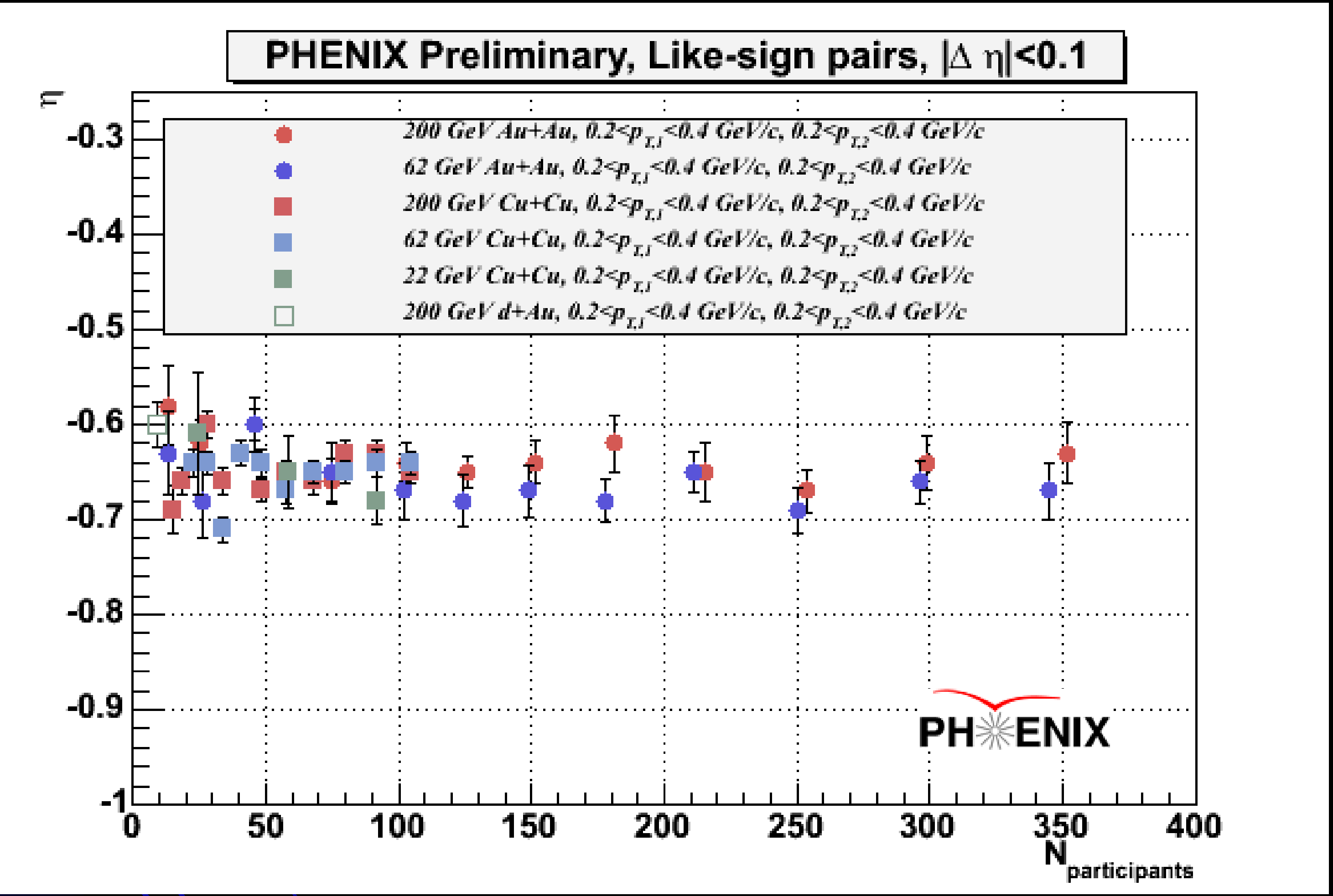
$0.2 < p_{T,1} < 0.4$ GeV/c, $0.2 < p_{T,2} < 0.4$ GeV/c, $|\Delta\eta|<0.1$





- The power law function fits the data well for all species and centralities.

Exponent η vs. Centrality

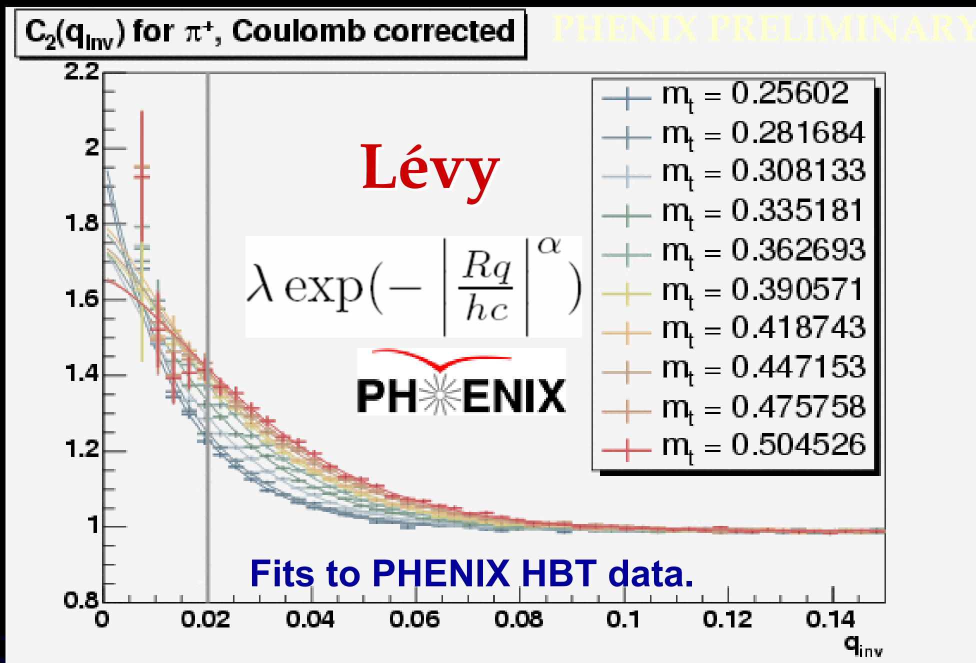


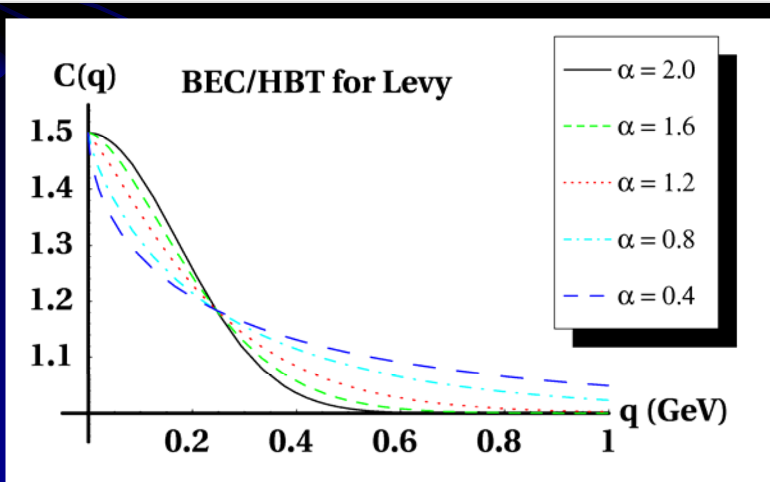
The exponent η is independent of species, centrality, and collision energy.

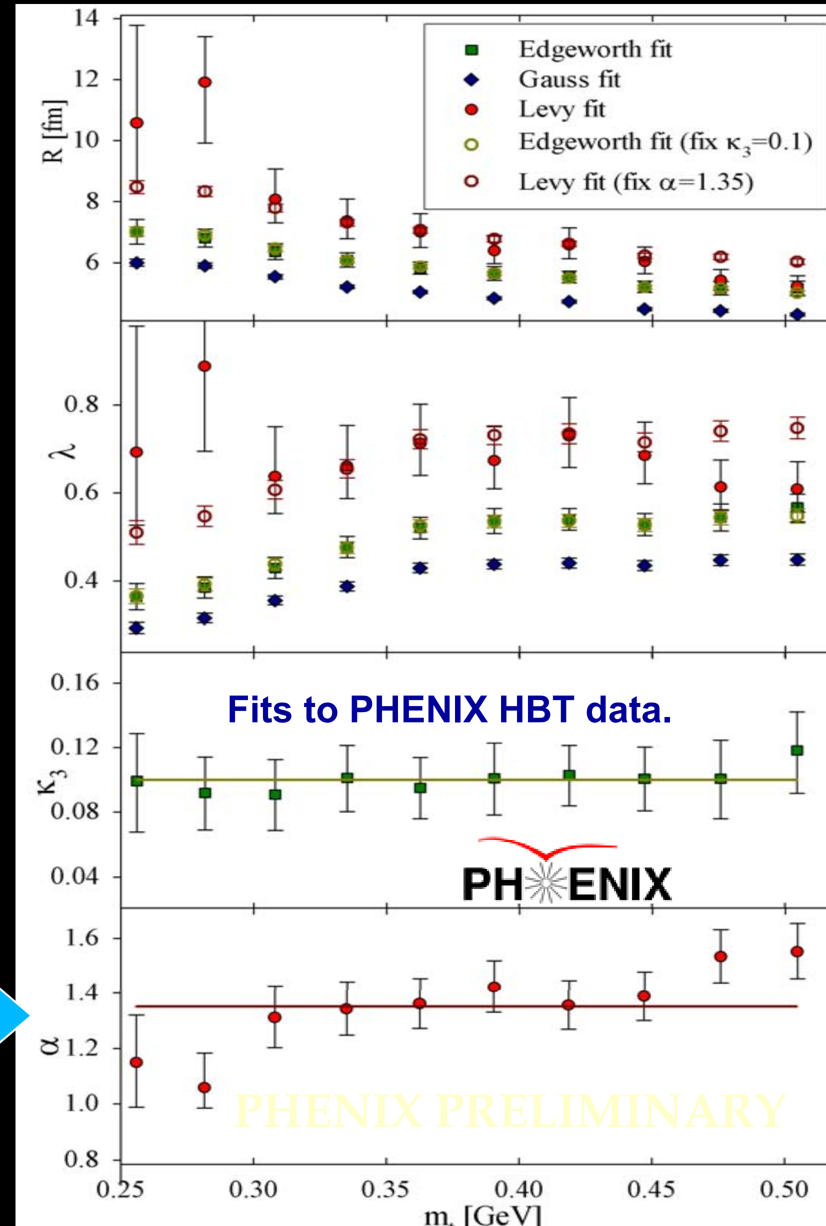
The value of η is inconsistent with the d=3 expectation at the critical point.

Exponents from Q_{inv} Distribution Fits

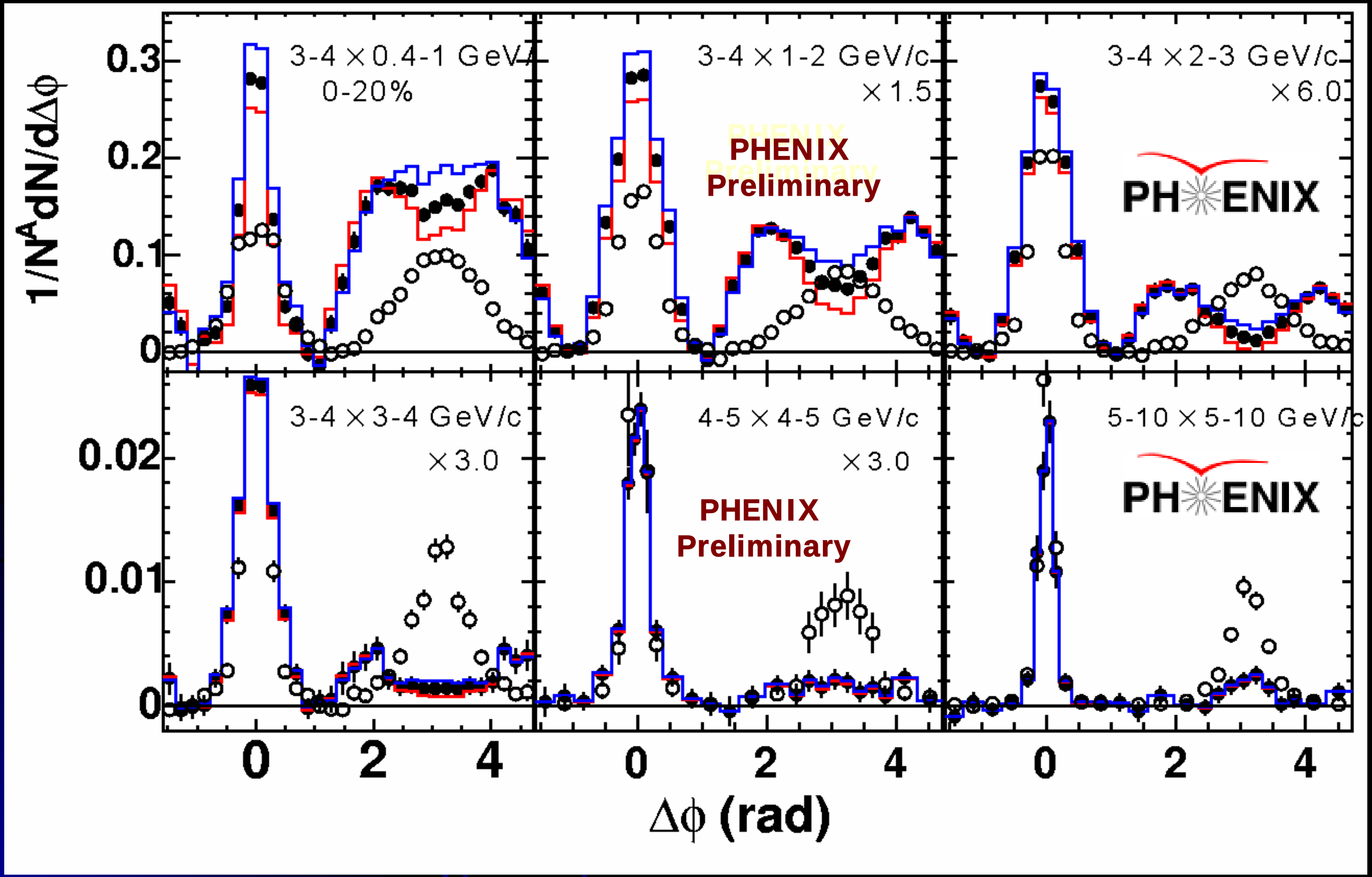
T. Csorgo, M. Csanad







Medium Modificaton: Triggered Analysis - Evolution with $p_{T,1}$,$p_{T,2}$

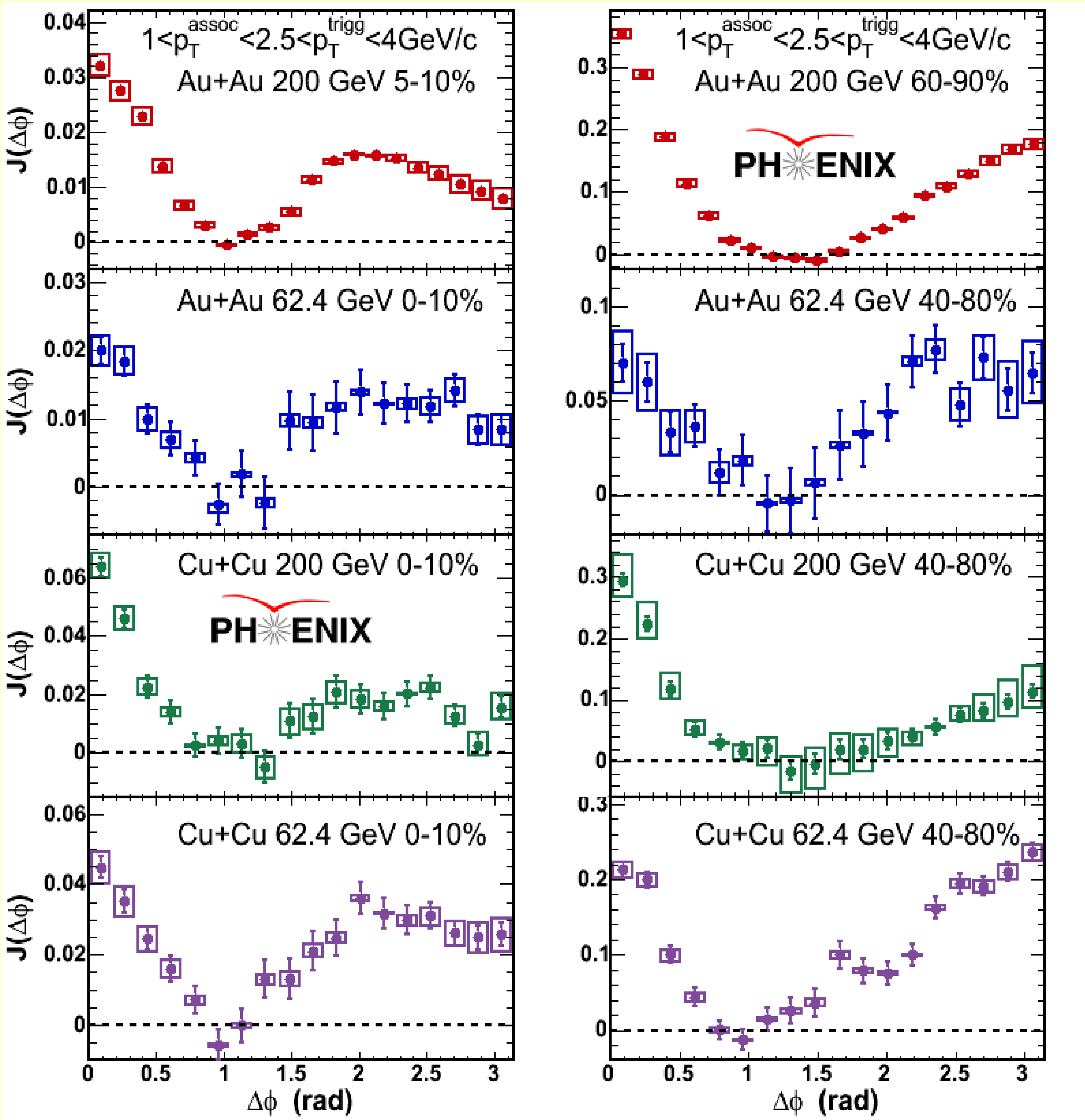


Dip persists for all p_T ranges

Jet emerges at high p_T

J. Jia

Triggered Correlations: System and Energy Scan



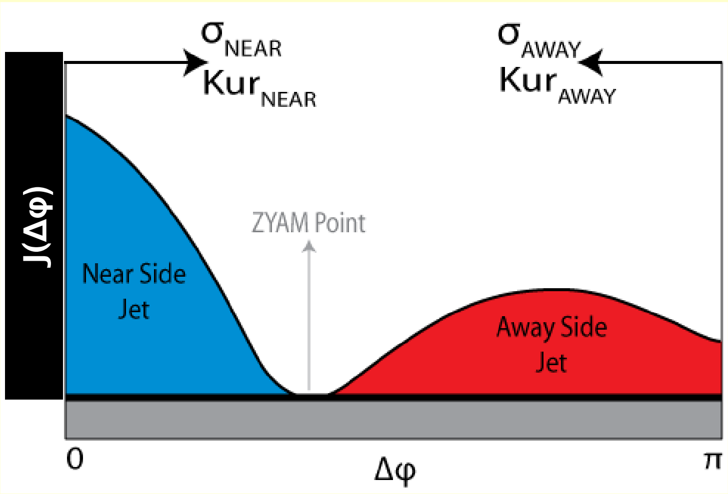
Away-side structure vs. beam species, beam energies, and centrality

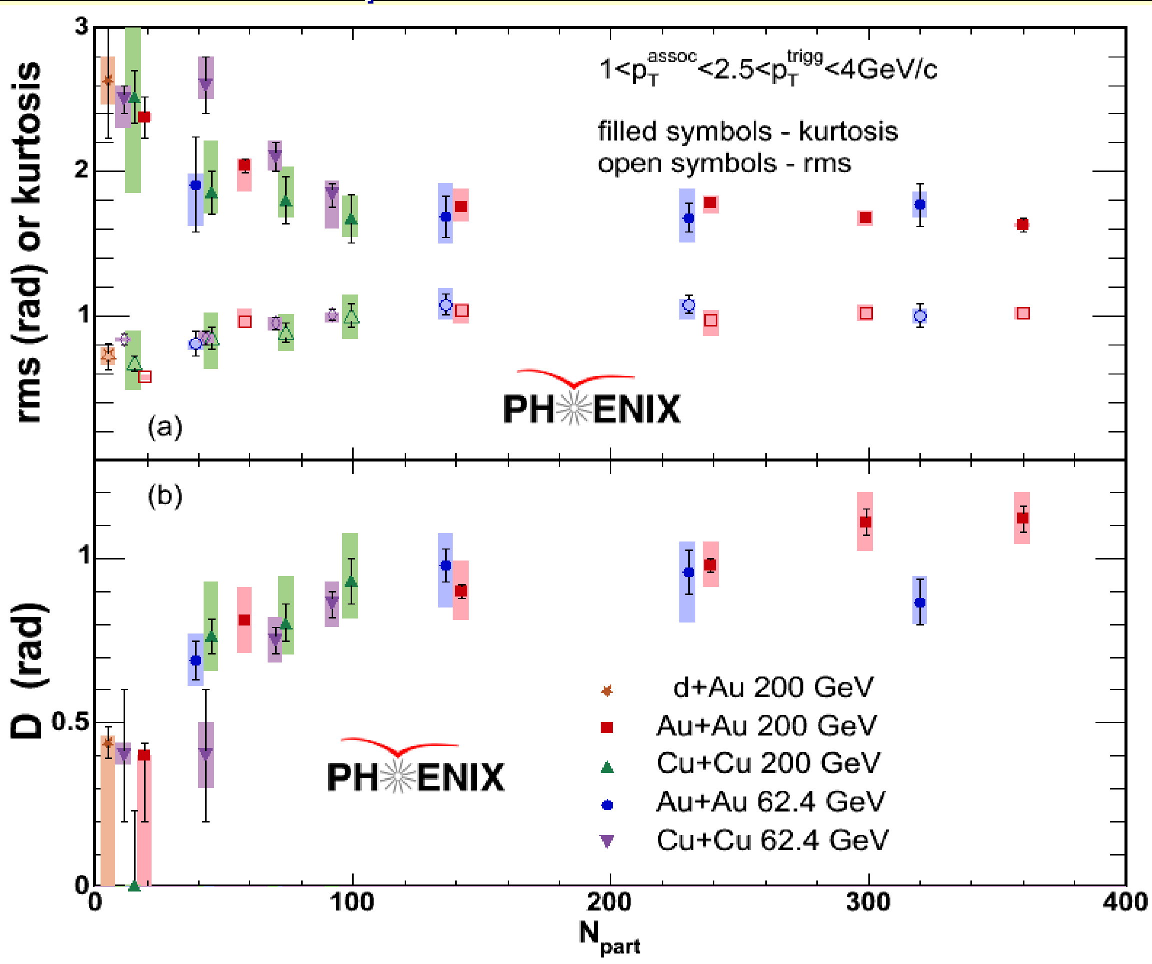
<u>All cases:</u>

- Peripheral similar to p-p
- Central shows development of “lobe”-like structure

M. McCumber

Triggered Correlations: N_{part} Shape Scaling





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$$RMS = \sqrt{\mu_2}$$

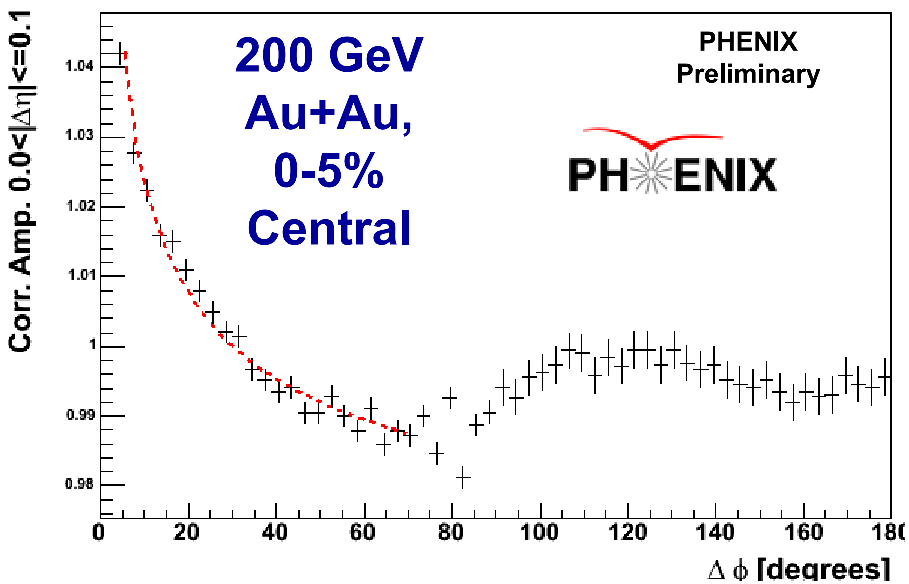
$$Kur = \frac{\mu_4}{\mu_2^2}$$

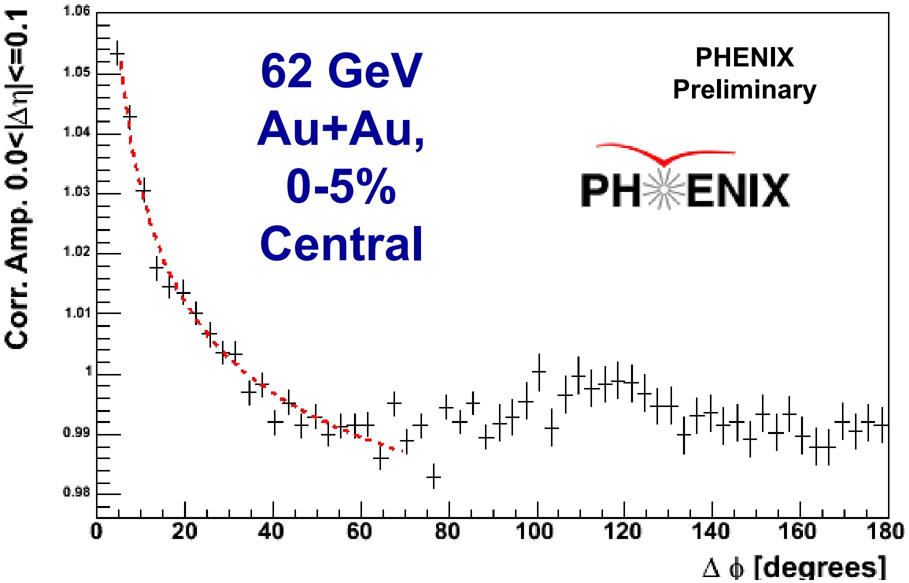
- Shape saturates above 100 N_{part}

$$J(\Delta\phi) = Gaus(A_{near}, \sigma_{near}, x) + Gaus(A_{away}, \sigma_{away}, \Delta\phi - \pi + D) + Gaus(A_{away}, \sigma_{away}, \Delta\phi - \pi - D)$$

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, $|\Delta\eta|<0.1$

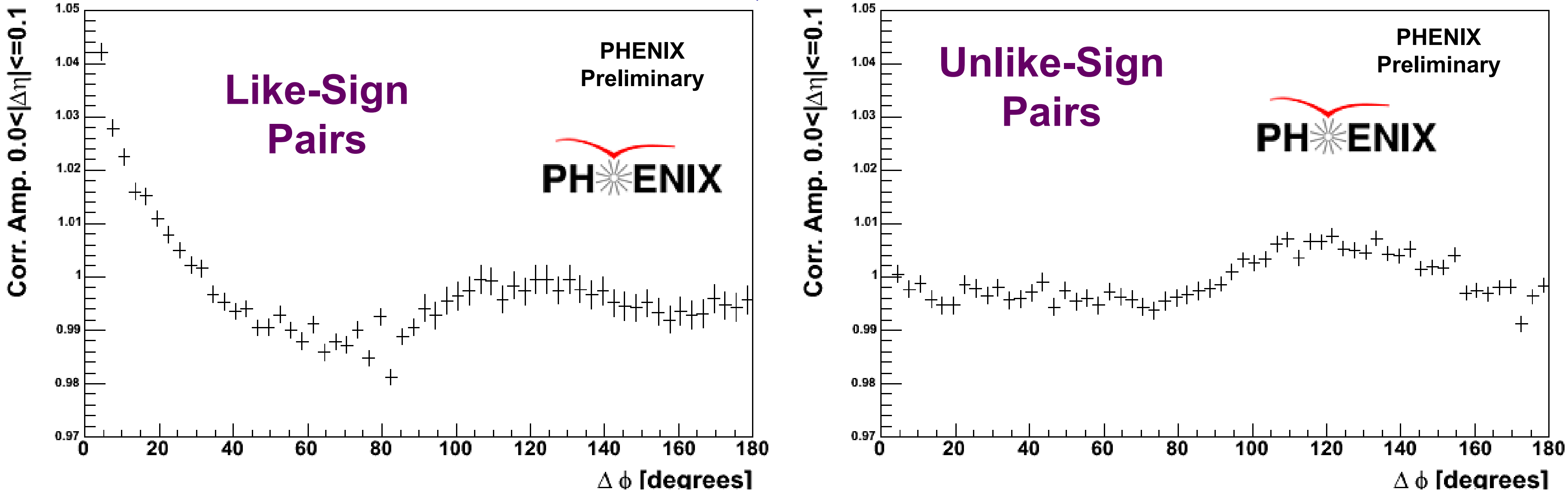




- The power law function fits the data well for all species and centralities.
- A displaced away-side peak is observed in the Au+Au correlation functions.

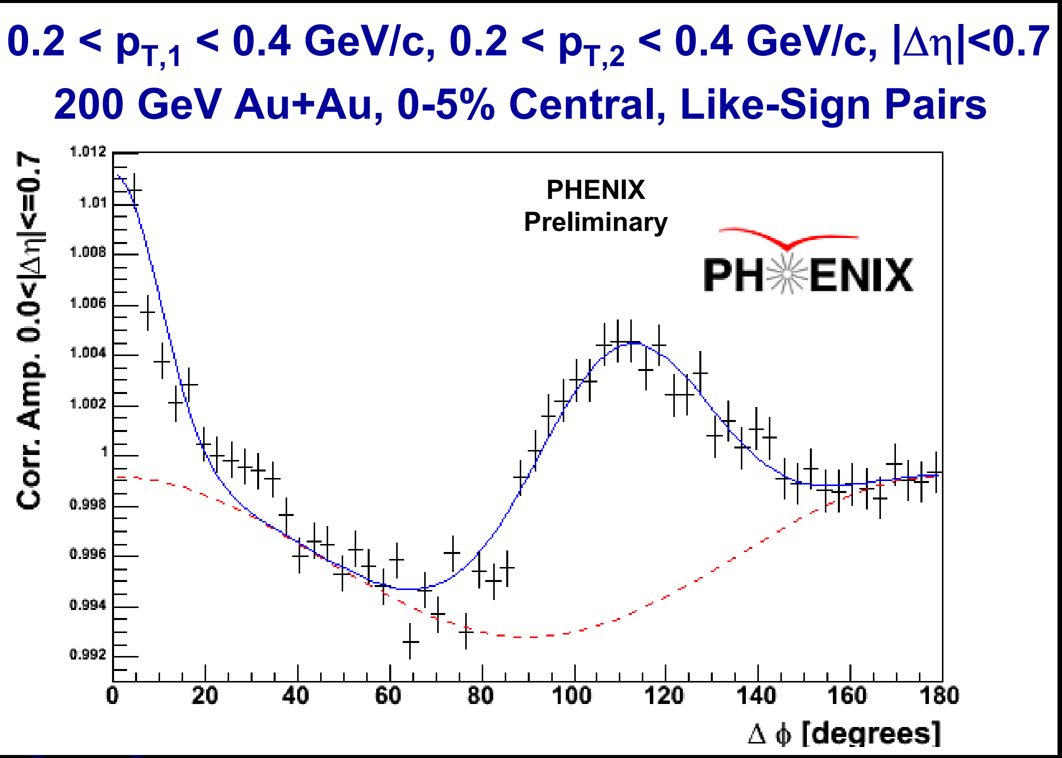
Controlling HBT: LS vs. US Pairs

$0.2 < p_{T,1} < 0.4$ 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

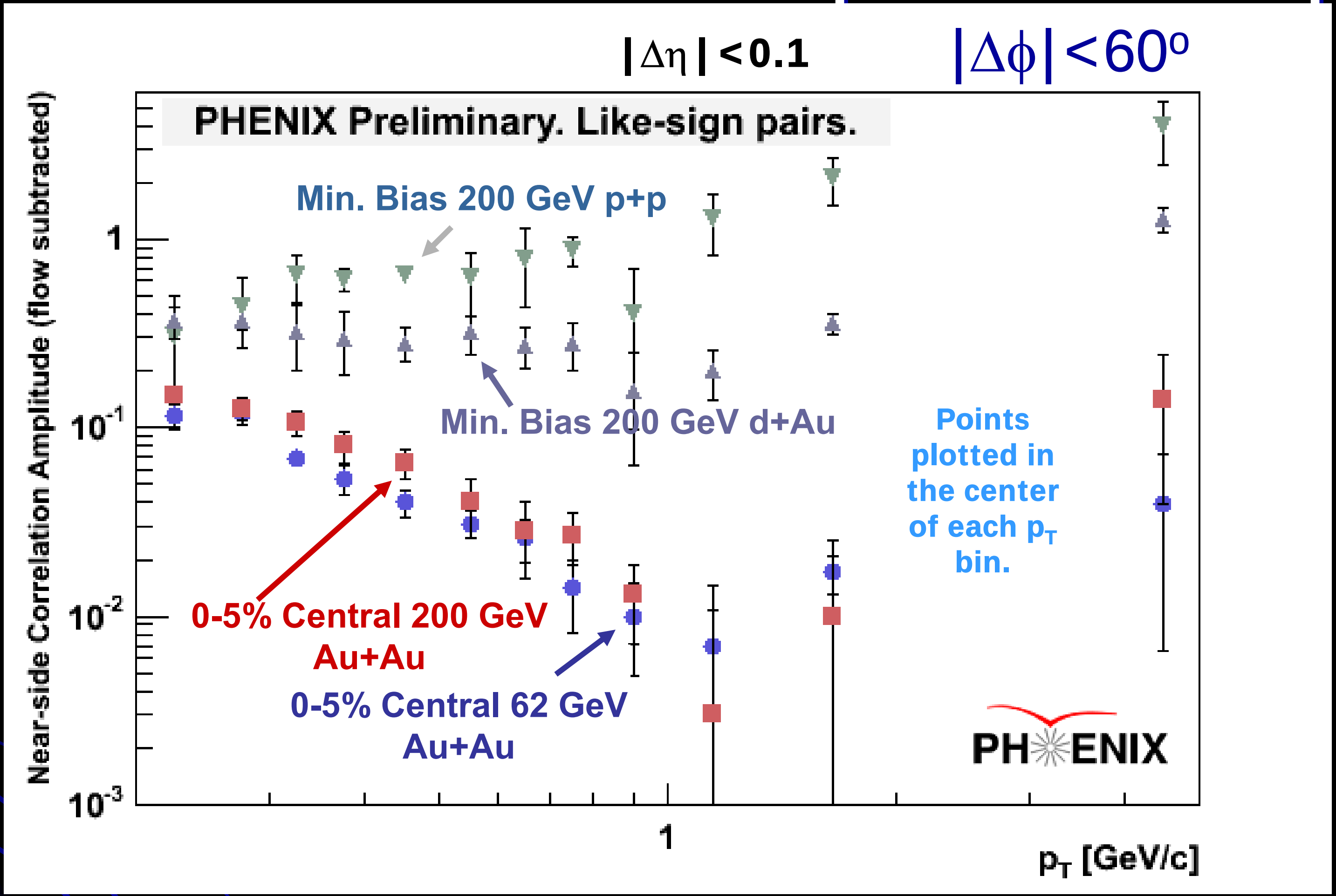


- The blue line is a fit to a function with a v_2 component, a near-side Gaussian at $\Delta\phi=0$ and an away-side Gaussian at $\Delta\phi=\pi$-D
- The dashed red line is the v_2 component.

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

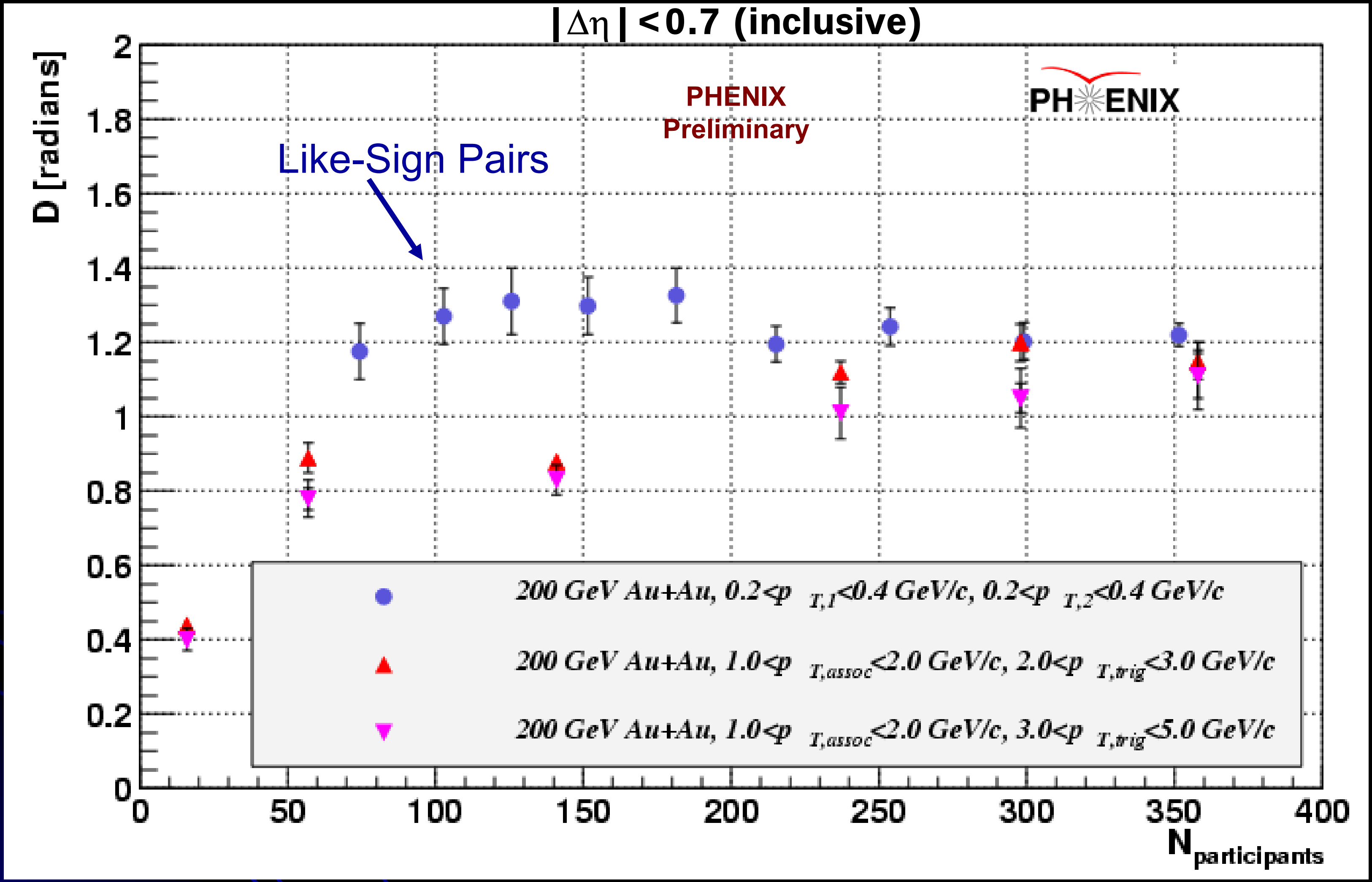
$$AJ(\Delta\varphi - \pi) \equiv \frac{S_A}{\sqrt{2\pi}\sigma_A}\left[\exp\left\{-\frac{(\Delta\varphi - \pi - D)^2}{2\sigma_A^2}\right\} + \exp\left\{-\frac{(\Delta\varphi - \pi + D)^2}{2\sigma_A^2}\right\}\right]$$

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.

Location of the Displaced Away-Side Peak



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

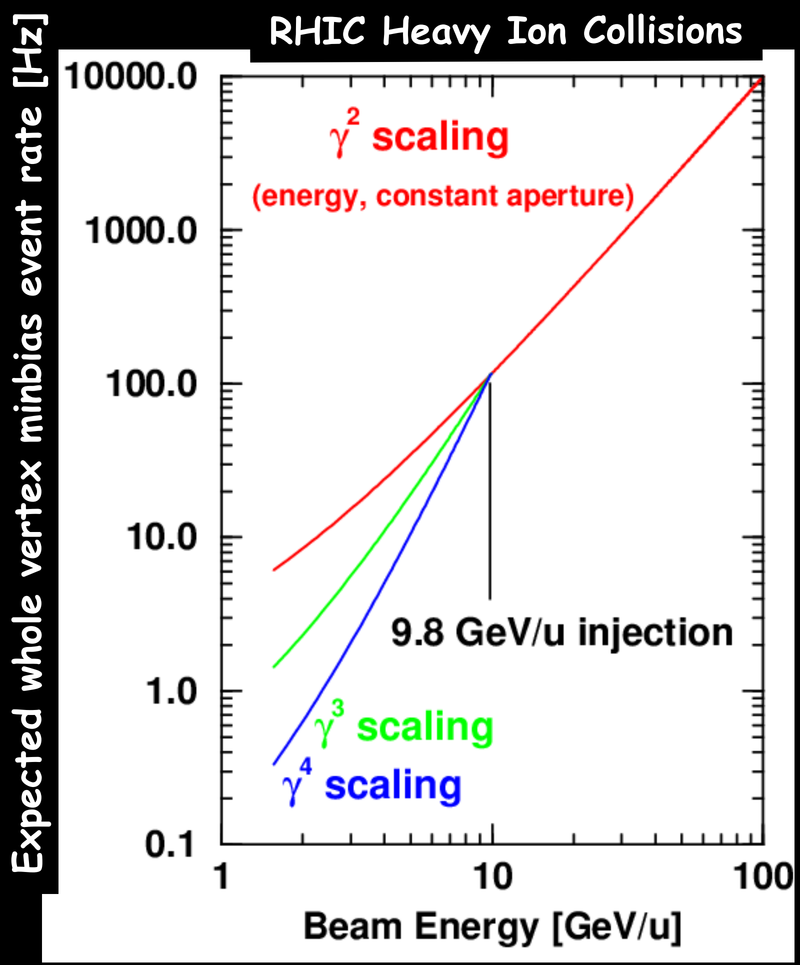
Summary

- **Multiplicity fluctuations**:
  - Significant non-random fluctuations are seen that exceed the Wounded Nucleon Model expectation for non-central collisions.
- **$\langle p_T \rangle$ 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 sqrt(s_{NN}) do not scale with the jet production cross section.
- **Low-p_T Azimuthal Correlations**:
  - The exponent η extracted from the HBT peak is identical for all collision species. It is largely independent of centrality in both azimuthal and Q_{inv} correlations.
  - A displaced away-side peak is observed in azimuthal correlations at low p_T in Au+Au collisions.
  - Further studies of the latter phenomenon are underway.

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

RHIC low-E Feasibility

- No apparent show-stoppers for RHIC collisions at E_{cm} = 5-50 GeV/n
  - Only equal energies
  - Unequal species possible only if minimum rigidity > 200 T-m
  - Without cooling → long vertex distribution
- Small set of specific energies (and species?) should be a workshop deliverable for planning:
  - 2.5,3.2,3.8,4.4… GeV/n total beam energy
- Studies that should be done soon:
  - A ~1 day study period at low total beam energy to identify power supply, lifetime, tuning issues/limitations
  - Low-current superconducting magnet measurements
- Pre-cooling in AGS → 10x luminosity ?
- Electron beam cooling would make this a fantastic facility: ~100x luminosity, small vertex distribution, long stores.



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Initial Machine Projections

Mode	Beam Energy [GeV/u]	$N_{bunches}$	Ions/bunch [10^9]	β^* [m]	Emittance [μm]	L_{peak} [$cm^{-2}s^{-1}$]
Au-Au 2001-2	9.8	55	0.6	3	15	8.0×10^{24}
Au-Au 2003-4	31.2	45	1.0	3	15-30	1.2×10^{26}
Au-Au	9.8	55	1.2	10	15-40	1.0×10^{25}
Au-Au	2.5	55	1.0	10	15-30	1.1×10^{23}
Au-Au	25	55	1.2	3	15-40	2.0×10^{26}

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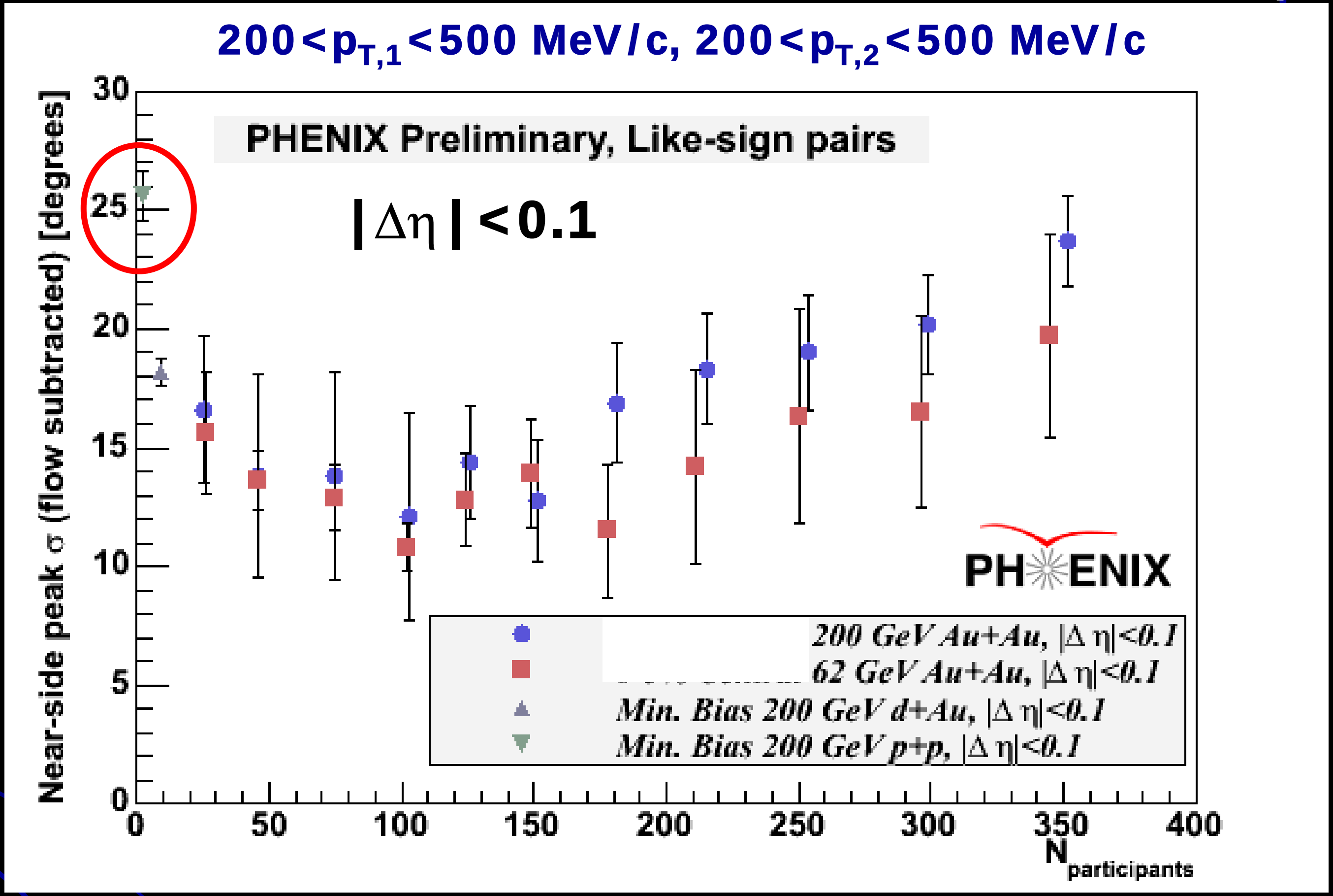
- Assumes expected luminosity scaling as γ^3 below 9.8 GeV/u
- β^*/aperture and integrated luminosity tradeoffs must be studied
- Projections do not include potential improvements
  - Electron and stochastic cooling (peak and integrated luminosity)
  - Lattice modifications to mitigate IBS (integrated luminosity)
  - Total bunch intensity from vacuum improvements (peak luminosity)

Auxiliary Slides

Near-Side Peak Width vs. p_T

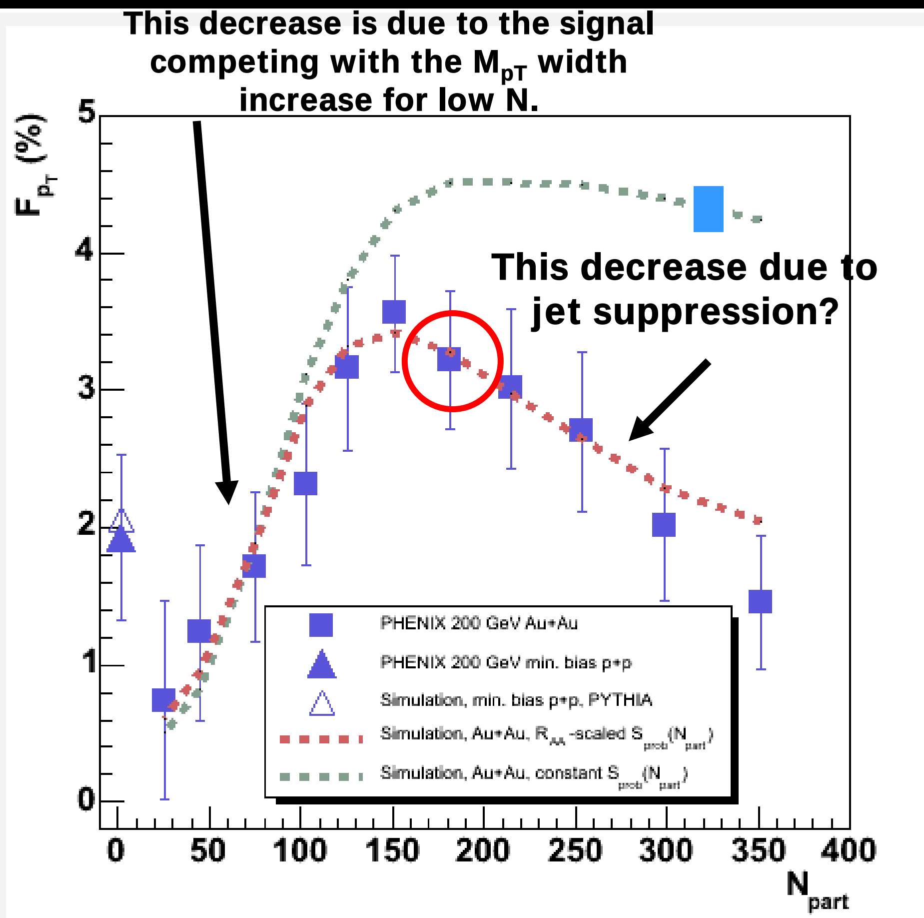


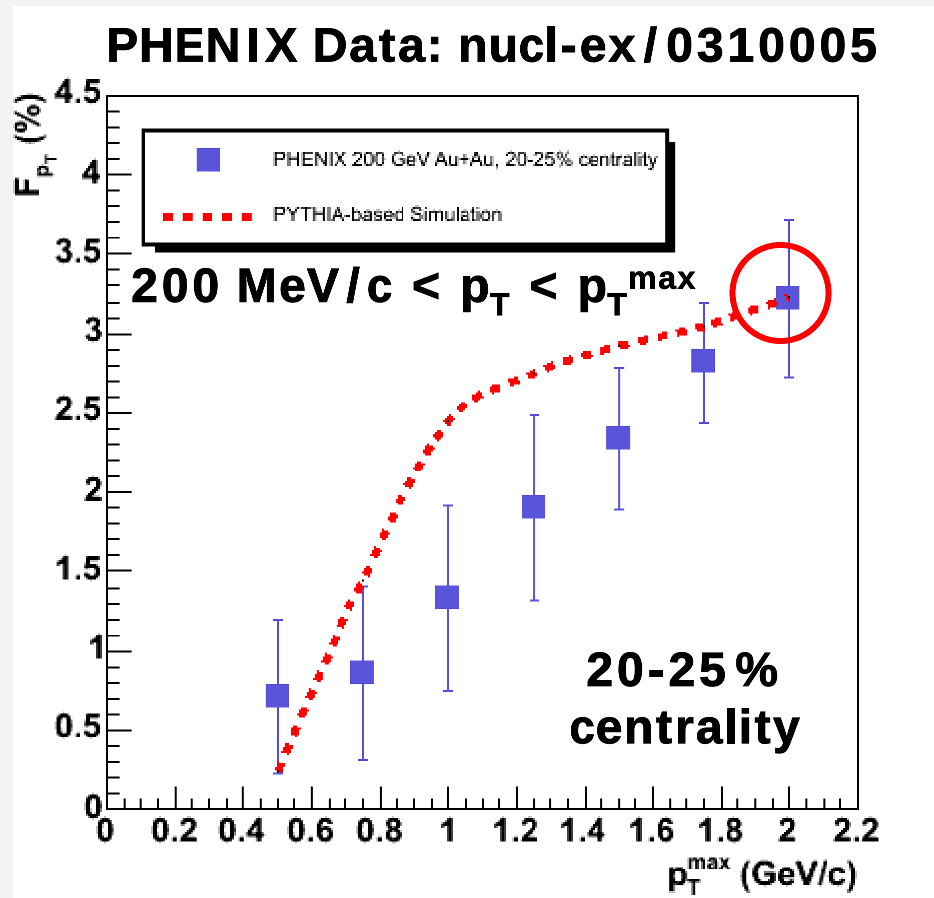
Weak centrality dependence on the near-side peak widths.

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

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

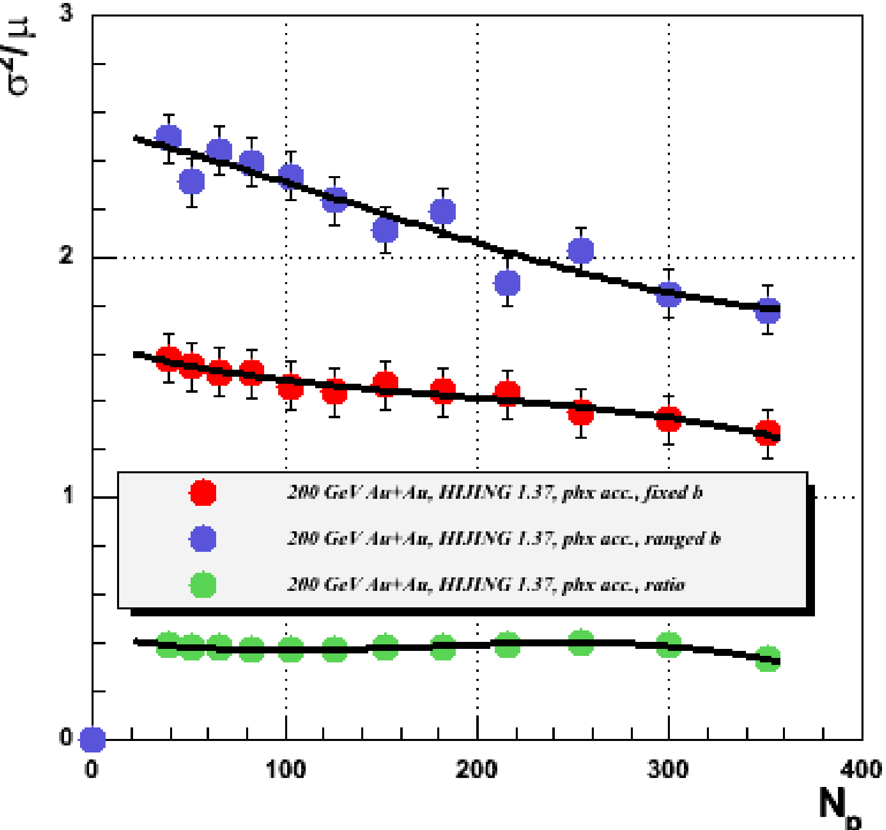
The S_{prob} parameter is initially adjusted so that F_{pT} from the simulation matches F_{pT} from the data for 20-25% centrality (circled). It is then FIXED and finally scaled by R_{AA} for all other centralities.

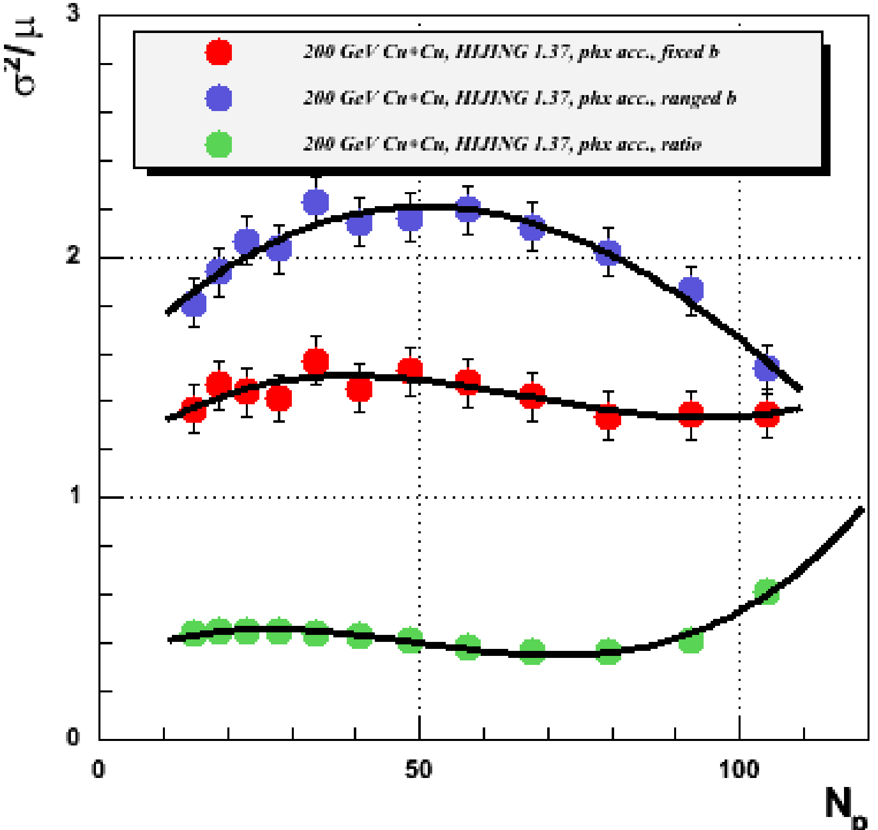




Impact Parameter Fluctuation Corrections

$$b_{correction} = \frac{\left(\sigma^2/\mu - 1\right)_{b,Fixed}}{\left(\sigma^2/\mu - 1\right)_{b,Gaussian}}$$





Corrections estimated from the ratio of the HIJING ranged impact parameter (Gaussian b distribution) to the fixed impact parameter (at the mean b estimated by the Glauber model) scaled variances. Corrections are generally flat with N_{part}.