Fluctuations and Correlations in Relativistic Heavy Ion Collisions

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(Brookhaven National Laboratory)

Outline:

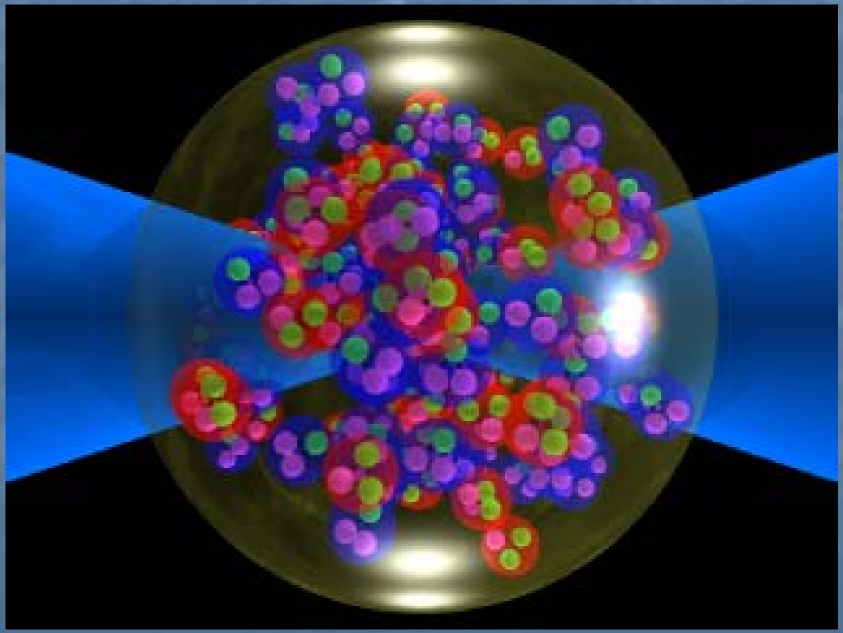
- Charge Fluctuations
- Balance Functions
- Event-by-event $<p_T>$ Fluctuations
- Looking Ahead
- Conclusions, Credits, Apologies

Charge Fluctuations

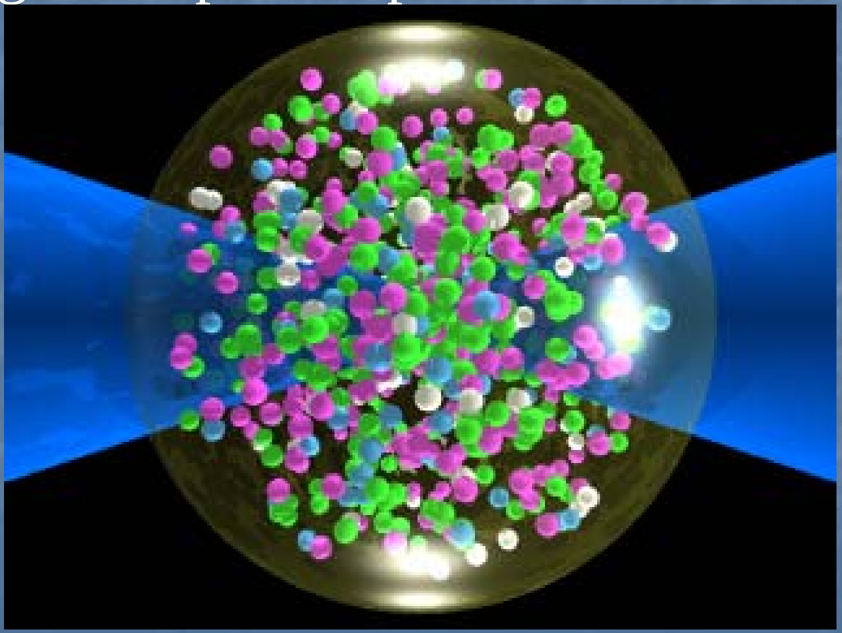
Hypothesis: Fluctuations in net charge and net baryon number may be significantly reduced if a QGP is formed in the collisions

Asakawa, Heinz, Müller PRL 85(2000)2072; Jeon & Koch PRL 85(2000)2076

Fractional electric charges of the quarks ==>
Charges more evenly spread in a plasma ==> Reduced net charge fluctuations in a small region of phase-space



Hadron Gas Scenario



Quark-Gluon Plasma Scenario

Summary of Charge Fluctuation Measures

$$Variance \left\langle \delta X^2 \right\rangle = \left\langle X^2 \right\rangle - \left\langle X \right\rangle^2$$

$$v(Q) \equiv \left\langle \delta Q^2 \right\rangle / \left\langle N_{CH} \right\rangle$$

PHENIX

$$N_{CH} = N_+ + N_-$$

$$Q = N_+ - N_-$$

$$R = \frac{\left\langle N_+ \right\rangle}{\left\langle N_- \right\rangle}$$

$$D \equiv \left\langle N_{ch} \right\rangle \left\langle \delta R^2 \right\rangle = 4 \frac{\left\langle \delta Q^2 \right\rangle}{\left\langle N_{CH} \right\rangle}$$

STAR

$$\nu_{+-,dyn} = \nu_{+-} - \nu_{+-,stat}$$

$$\nu_{+-} = \left\langle \left(\frac{N_+}{\left\langle N_+ \right\rangle} - \frac{N_-}{\left\langle N_- \right\rangle} \right)^2 \right\rangle$$

$$\nu_{+-,stat} = \frac{1}{\left\langle N_+ \right\rangle} + \frac{1}{\left\langle N_- \right\rangle}$$

$$v(Q) \approx 1 + \frac{\left\langle N_+ + N_- \right\rangle}{4} \nu_{+-,dyn}$$

$$D \approx 4 + \left\langle N_+ + N_- \right\rangle \nu_{+-,dyn}$$

$$D = 4v(Q)$$

$$\Phi_q \approx \frac{\left\langle N_+ \right\rangle^{3/2} \left\langle N_- \right\rangle^{3/2}}{\left\langle N_{CH} \right\rangle^2} \nu_{+-,dyn}$$

$$\Gamma = v(Q)$$

$$\overline{z^2} = 4 \frac{\left\langle N_+ \right\rangle \left\langle N_- \right\rangle}{\left\langle N_{CH}{}^2 \right\rangle}$$

$$Z = Q - \frac{\left\langle Q \right\rangle}{\left\langle N_{CH} \right\rangle} N_{CH}$$

NA49

$$\Phi_q = \sqrt{\frac{\left\langle Z^2 \right\rangle}{\left\langle N_{CH} \right\rangle}} - \sqrt{\overline{z^2}}$$

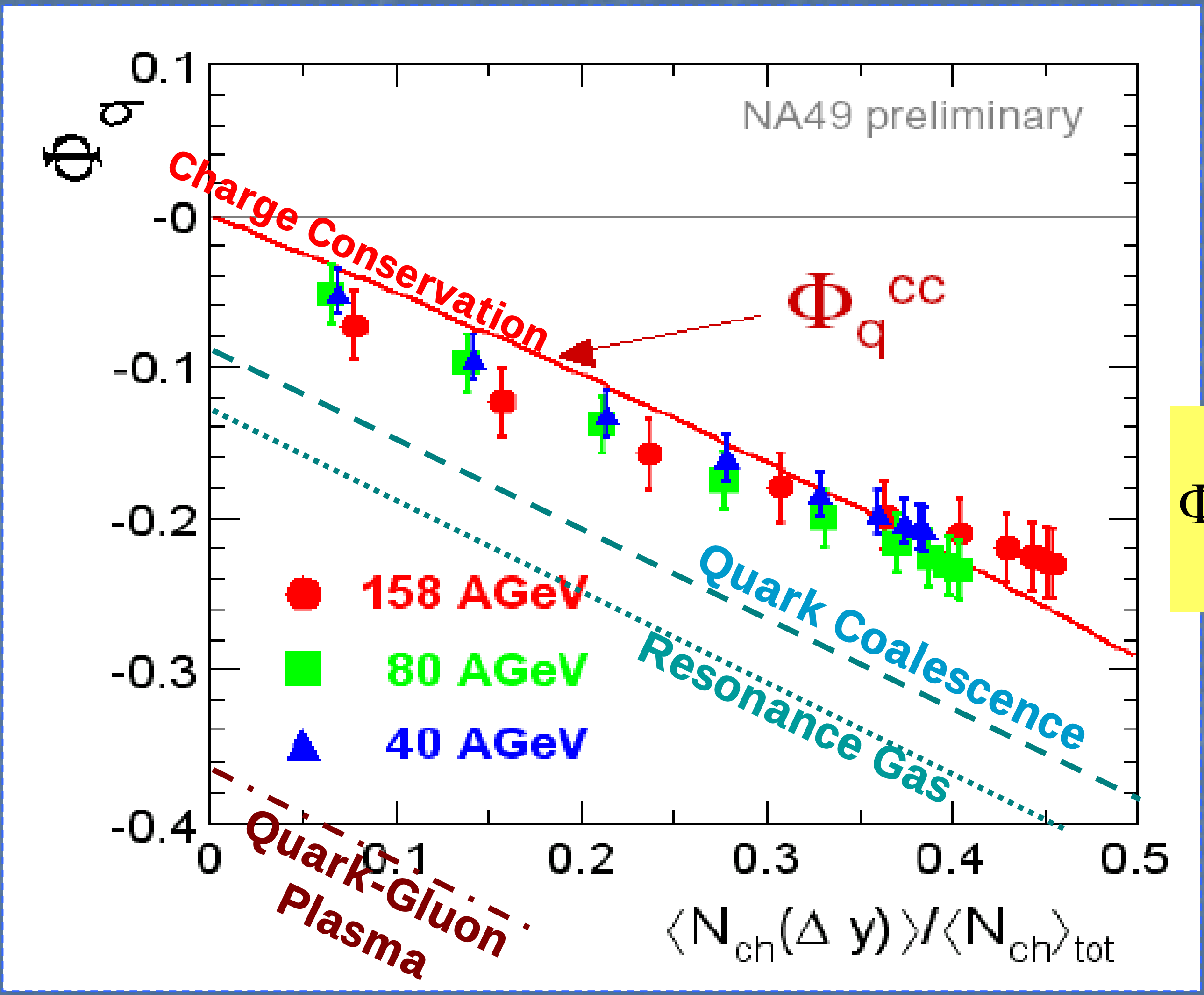
Quoted in this presentation

$$\Gamma \equiv \frac{1}{\left\langle N_{CH} \right\rangle} \left\langle \left(Q - \frac{\left\langle Q \right\rangle}{\left\langle N_{CH} \right\rangle} N_{CH} \right)^2 \right\rangle$$

Charge Fluctuation Magnitude Expectations

	v(Q)	D	$\nu_{+-,dyn}$ (STAR)	$\nu_{+-,dyn}$ (PHENIX)	Φ_q (NA49)
Independent Particle Emission	1.0	4.0	0.0	0.0	0.0
Resonance Gas	0.75	3.0	-0.0013	-0.006	-0.125
Quark-Gluon Plasma	0.25	1.0	-0.0038	-0.019	-0.375
Quark Coalescence	0.83	3.33	-0.0008	-0.004	-0.084

Charge Fluctuations vs. Rapidity Acceptance (Excitation Function): NA49



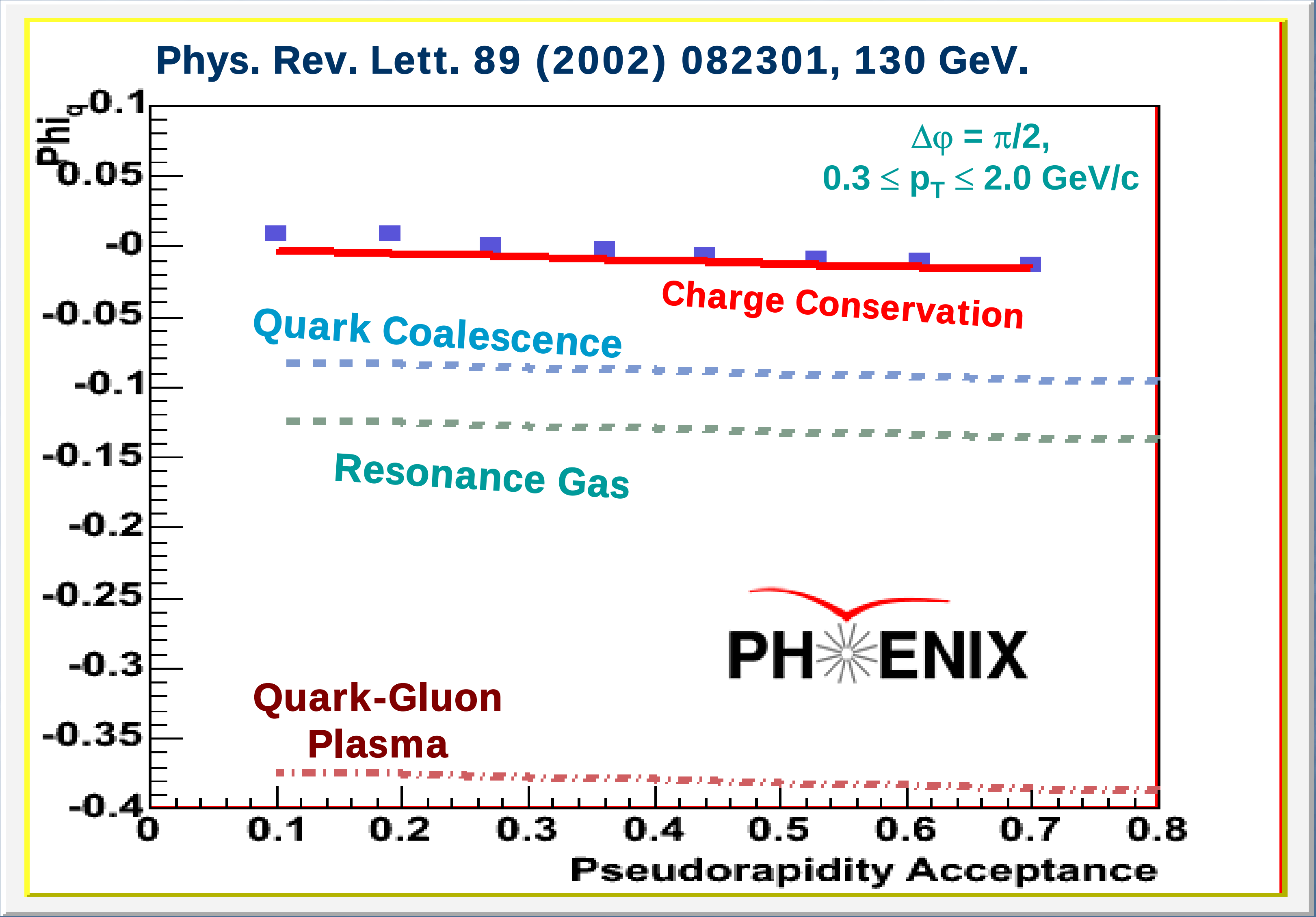
$$\Phi_q^{cc} = \sqrt{1 - \frac{\langle N_{CH}(\Delta y)\rangle}{\langle N_{CH}\rangle_{tot}}} - 1$$

Correction for fluctuations due to charge conservation.

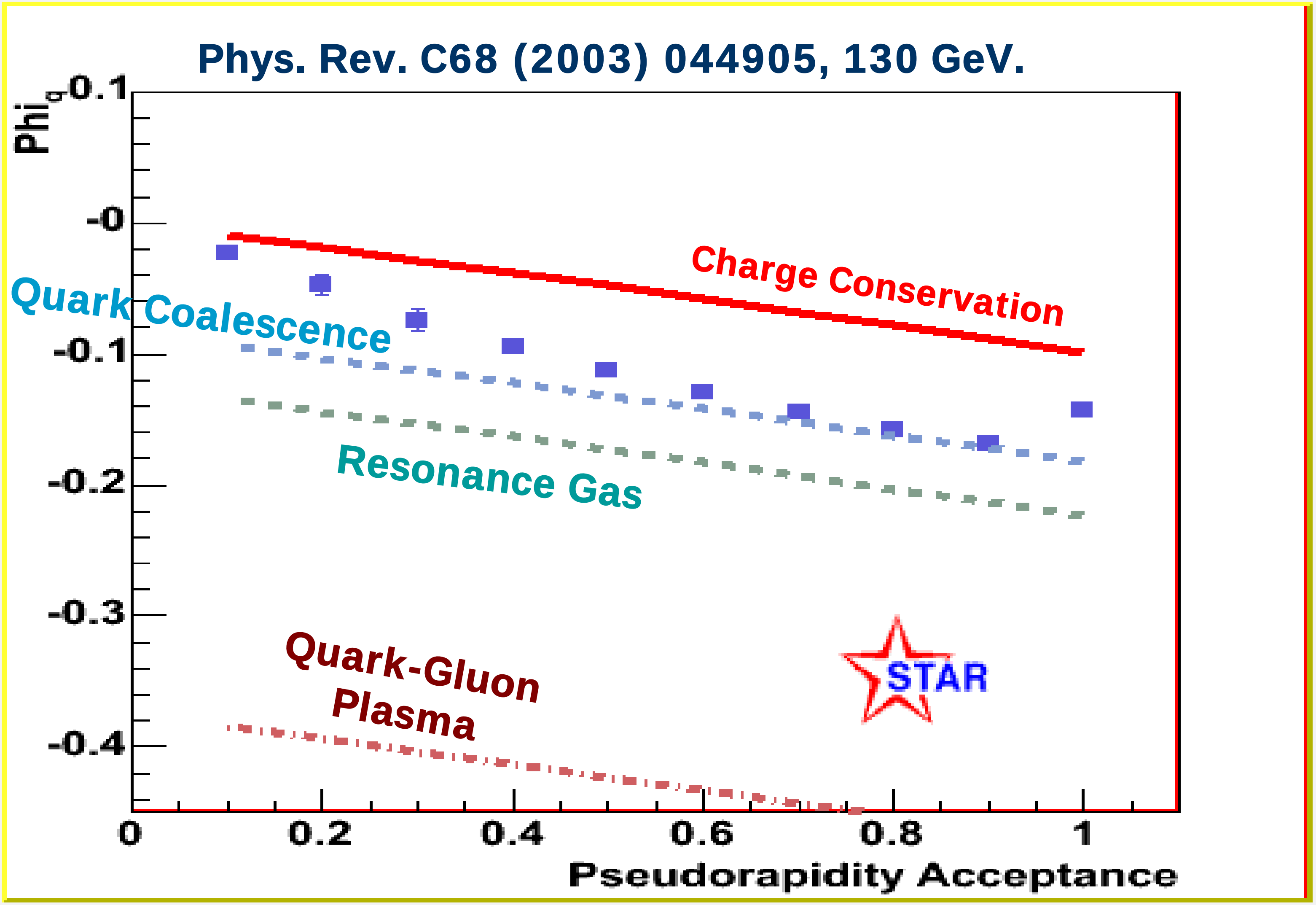
See poster by P. Chrisakogiou

Also see talk by H. Sako for new CERES results.

Charge Fluctuations vs. Rapidity Acceptance



Charge Fluctuations vs. Rapidity Acceptance



Balance Functions

Bass, Danielewicz, & Pratt, Phys. Rev. Lett. **85**, 2689 (2000)

$$B(\Delta y) = \frac{1}{2}\left\{ \frac{N_{+-}(\Delta y) - N_{++}(\Delta y)}{N_{+}} + \frac{N_{-+}(\Delta y) - N_{--}(\Delta y)}{N_{-}} \right\}$$

$N_{+-}(\Delta y)$ = Histogram of | $y(\pi^+)$ - $y(\pi^-)$ |, for all possible pairs within an event. This histogram is summed over all events.

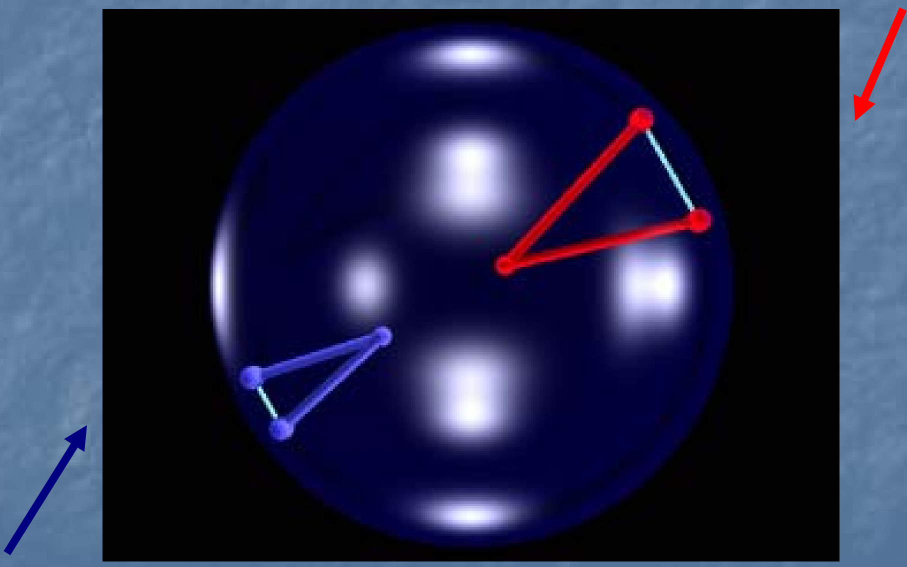
- Designed to determine whether hadronization from a QGP occurs early (<1 fm/c) or late.

- Based upon the fact that charge is conserved locally, and produced pairs are initially correlated in coordinate space.

- **Bottom line**: The balance function is narrower in the delayed hadronization scenario.

$$\sigma^2_{\delta y} = \sigma^2_{\delta\eta} + \sigma^2_{thermal}$$

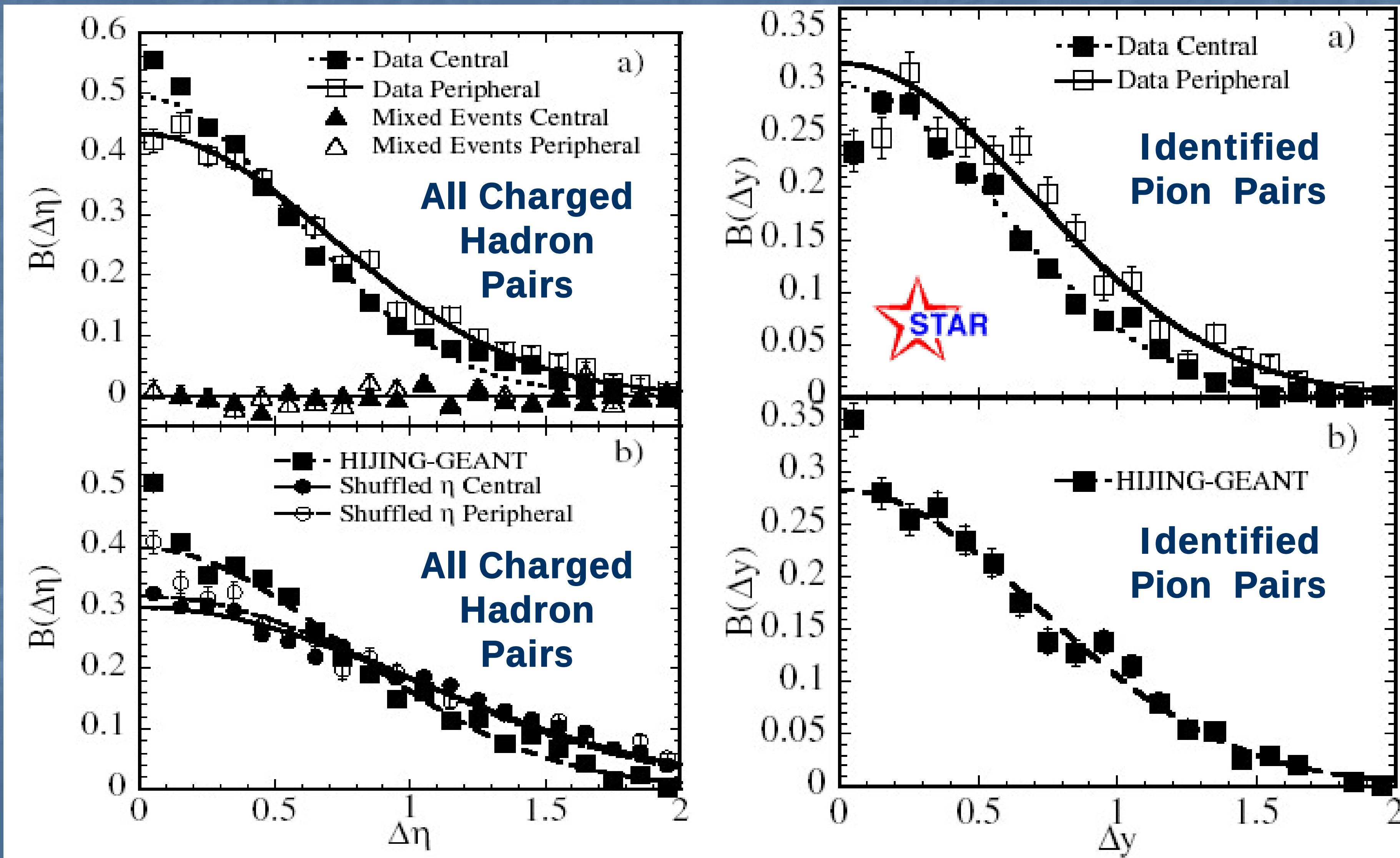
Early hadronization scenario: Pairs separate in rapidity due to expansion and rescattering.



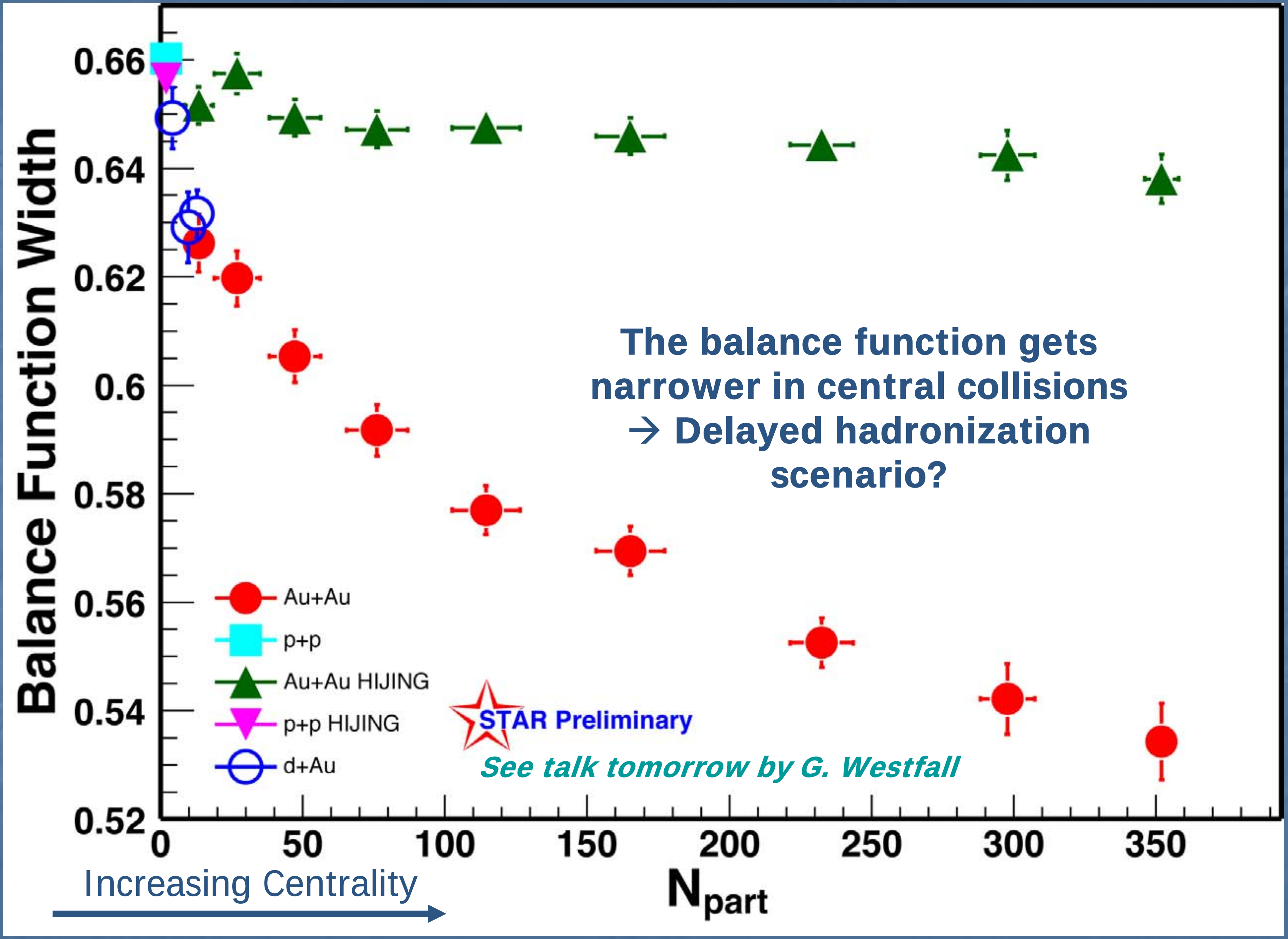
Delayed hadronization scenario: Pairs are more strongly correlated in rapidity.

STAR 130 GeV Balance Function Results

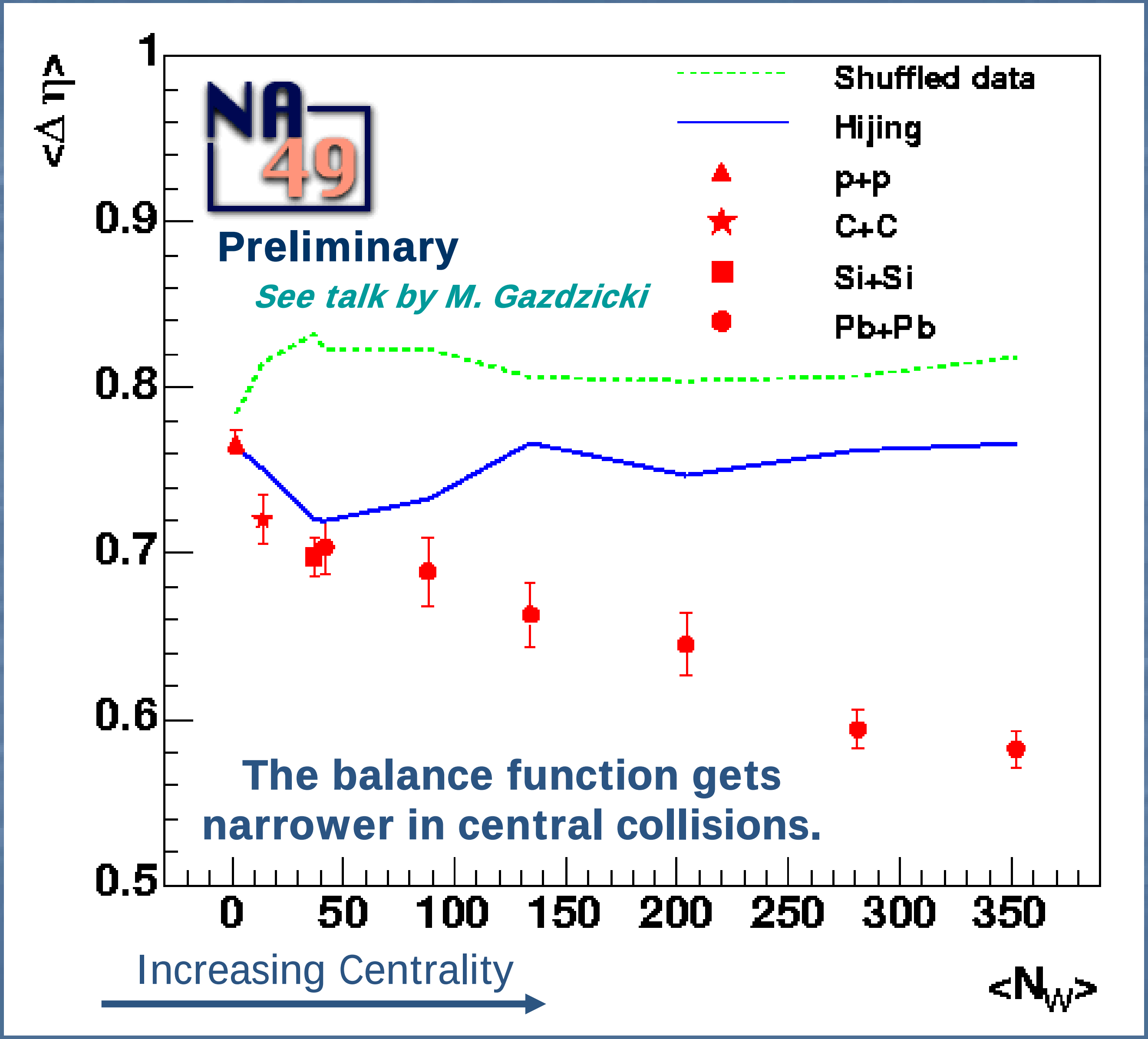
Phys. Rev. Lett. 90 (2003) 172301.



STAR 200 GeV Balance Function Widths



NA49 17 GeV Balance Function Widths



A similar behavior AND narrowing magnitude is observed compared to the STAR data!

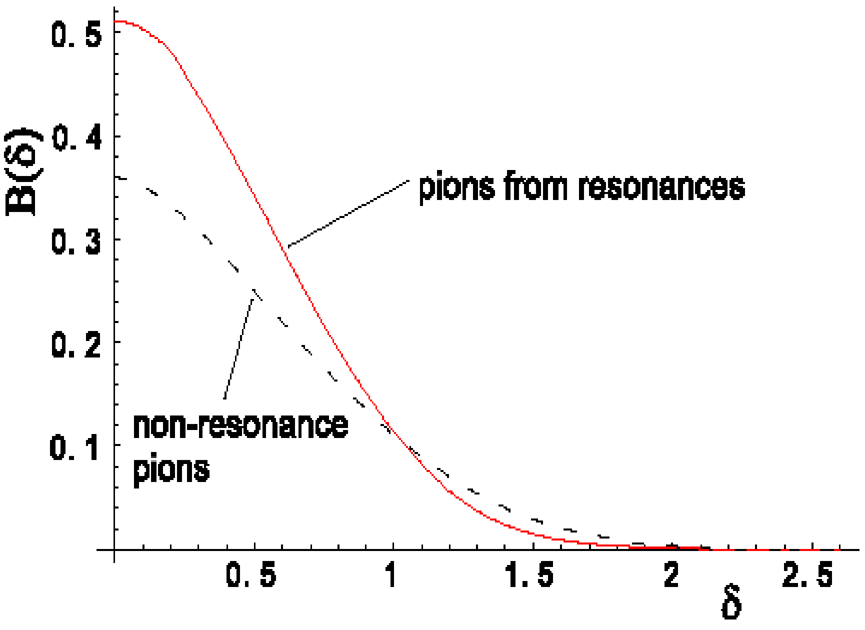
Other explanations for the broadening of the balance function

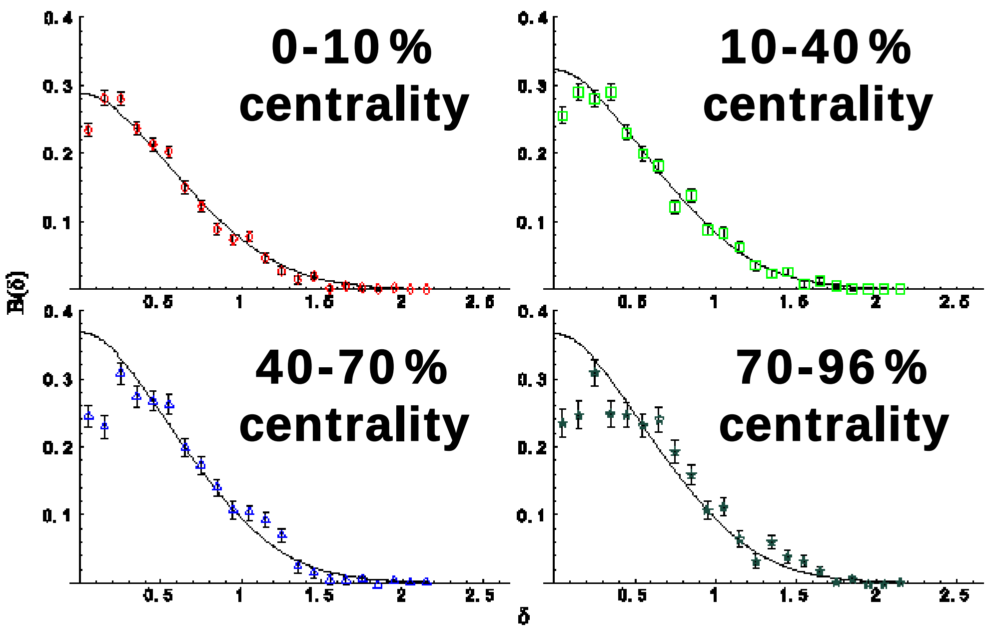
Resonance contributions

P. Bozek, W. Broniowski, and W. Florkowski, nucl-th/0310062

Computing balance functions in a thermal model with neutral resonance decay.

The calculations including resonances are consistent with the STAR results.





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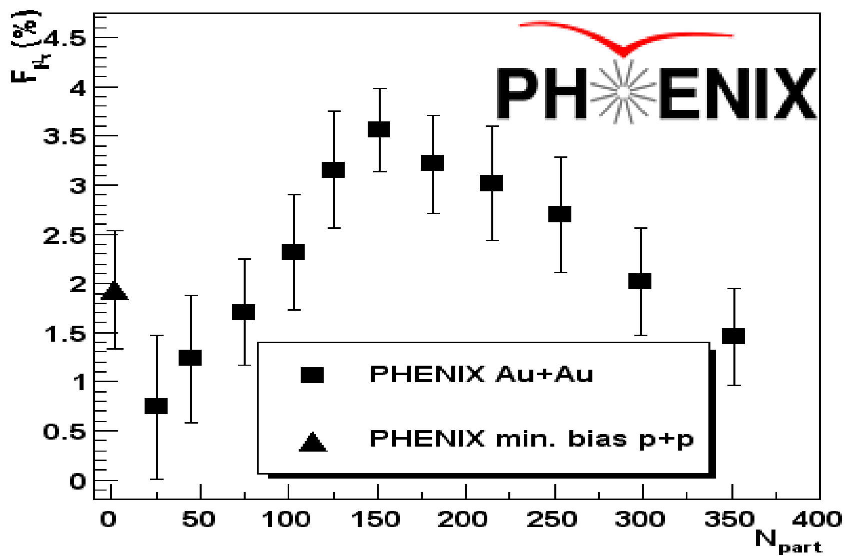
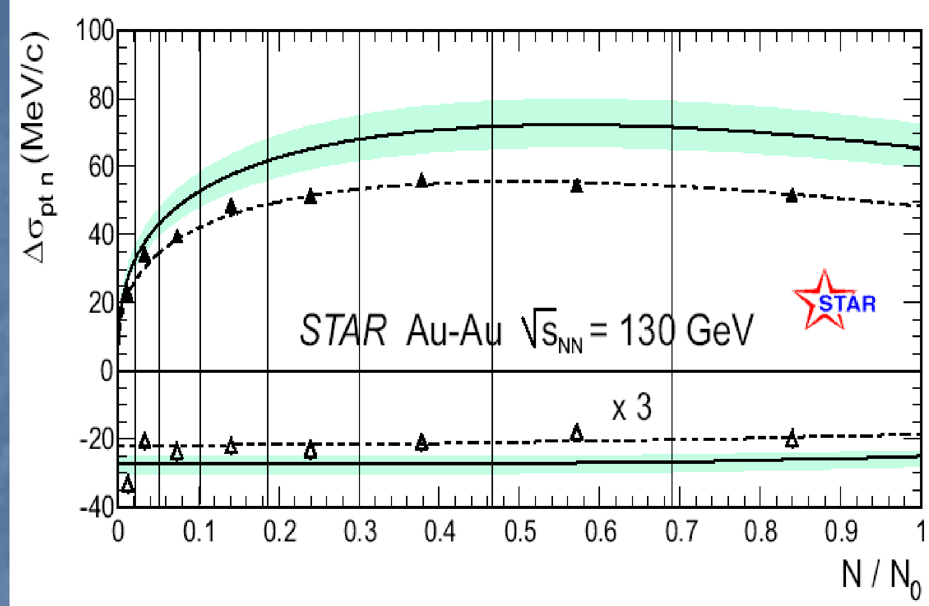
Quark Coalescence Model Predictions

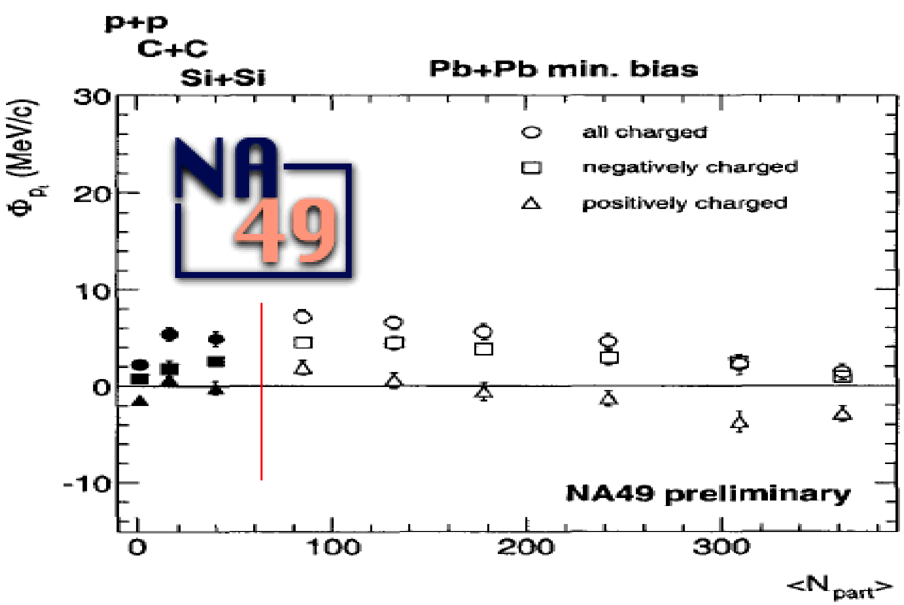
A. Bialas, hep-ph/0308245.

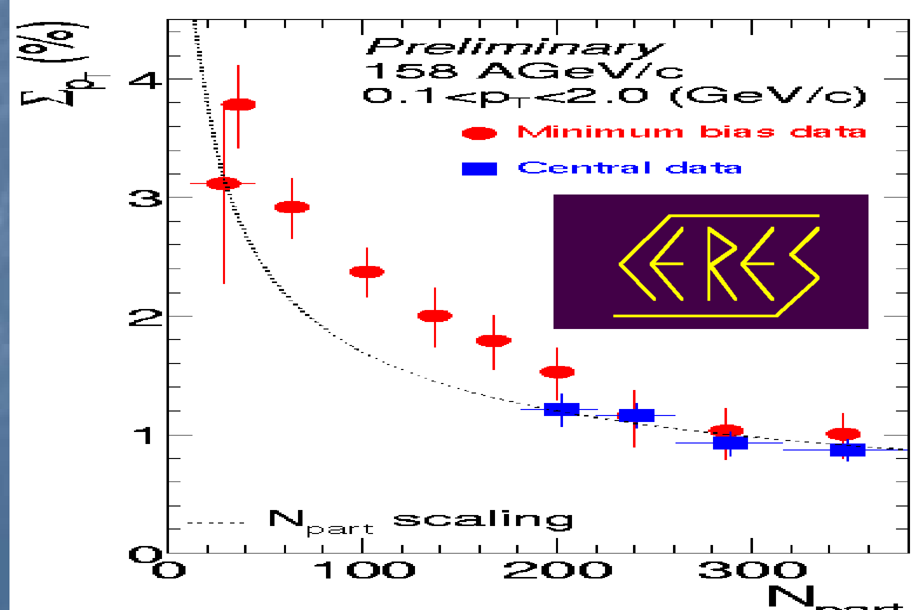
Predicts a width consistent with the STAR result for central collisions with a transverse flow velocity below 0.5c.

Behold The $\langle P_T \rangle$ Fluctuation Signal!









Summary of Event-by-event <p_T> Fluctuation Measures

Goal of the observables:

State a comparison to the expectation of statistically independent particle emission.

F_{pT}

$$F_{p_T} \approx \frac{\Phi_{p_T}}{\sigma_{p_T,incl.}}$$

$\sigma^2_{pT,dyn}$

$$\sigma^2_{p_T,dyn} \cong \frac{2\Phi_{p_T}\sqrt{\overline{\Delta p_T^2}}}{\langle N \rangle}$$

$\Delta\sigma_{pT,n}$

$$\Delta\sigma_{p_T,n} \cong \sqrt{\left(\Phi_{p_T} + \sigma_{p_T,incl}\right)^2 - \sigma^2_{p_T,incl}}$$

$$\sigma_{p_T,incl.} = \sqrt{\langle p_T^2 \rangle - \langle p_T \rangle^2}$$

$$\overline{\Delta p_T^2} \equiv \overline{p_T^2} - \overline{p_T}^2$$

$$\Sigma_{p_T} = \frac{\sigma_{p_T}}{\overline{p_T}}\sqrt{\frac{2F_{p_T}}{< N >}}$$

$$\Sigma_{p_T} \equiv \mathrm{sgn}\left(\sigma^2_{p_T,dyn}\right)\frac{\sqrt{|\sigma^2_{p_T,dyn}|}}{\overline{p}_T}$$

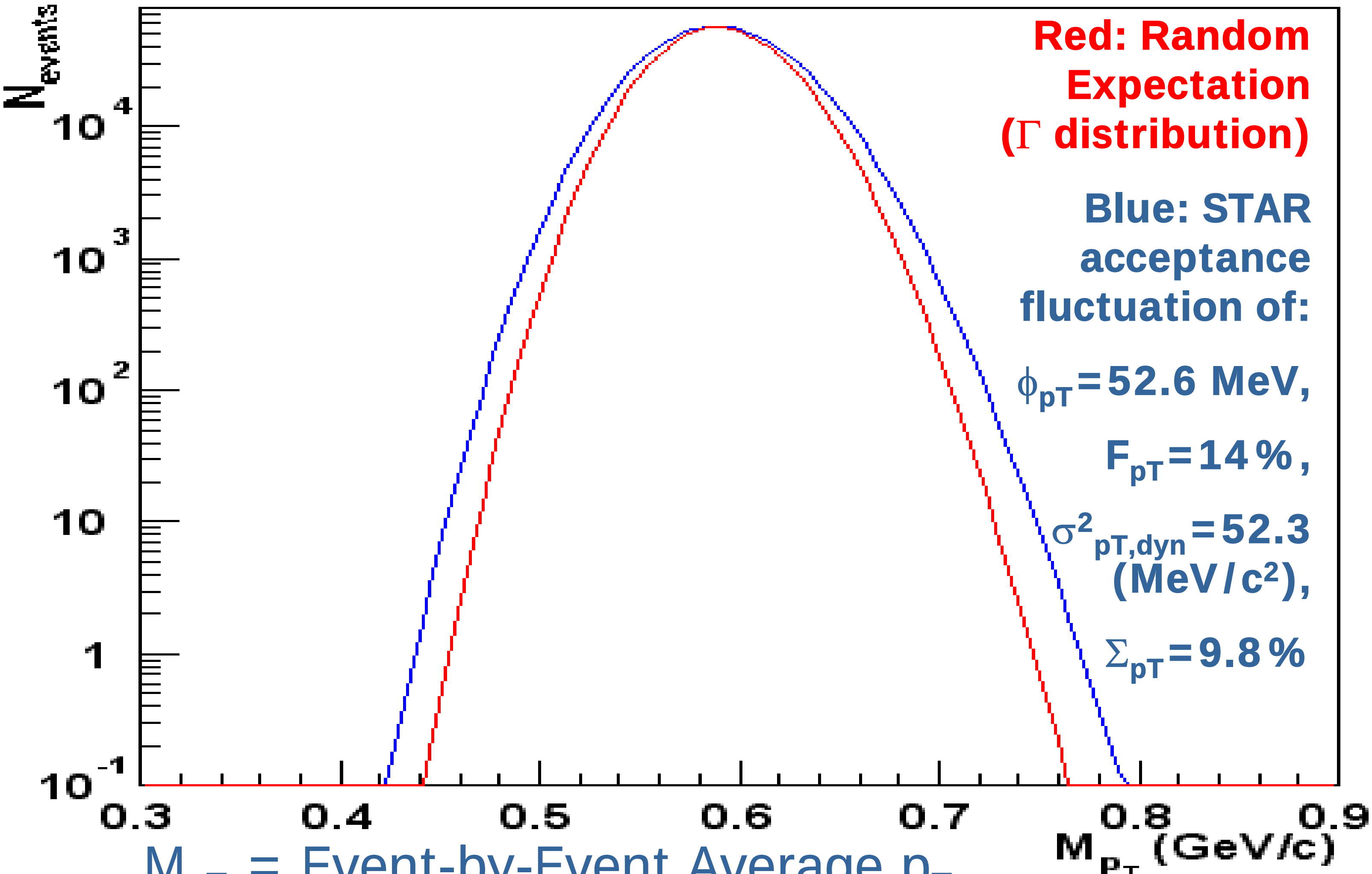
Quoted in this presentation

Φ_{pT}

Σ_{pT}

How To Measure A Fluctuation

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

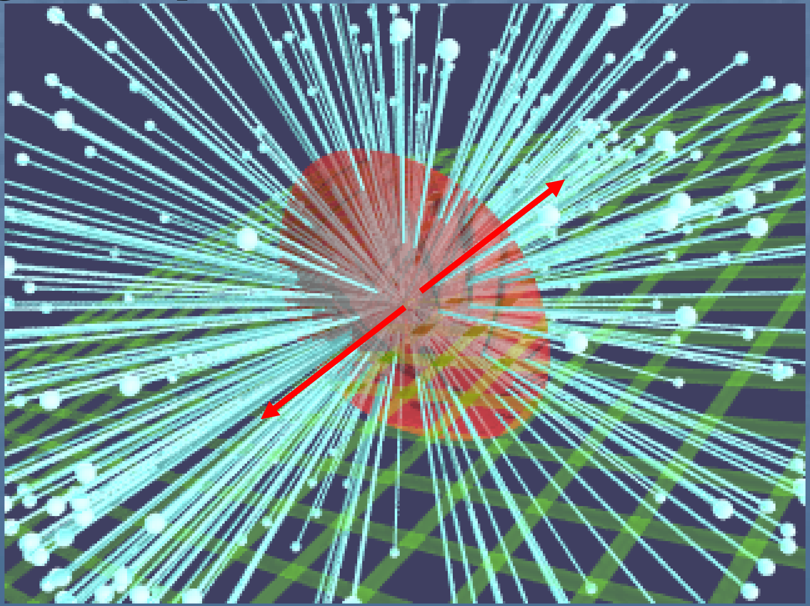


M_{pT} = Event-by-Event Average p_T

A Positive Signal is Observed! Known contributions to the $<p_T>$ fluctuation signal should be subtracted.

Contributions from Known Processes

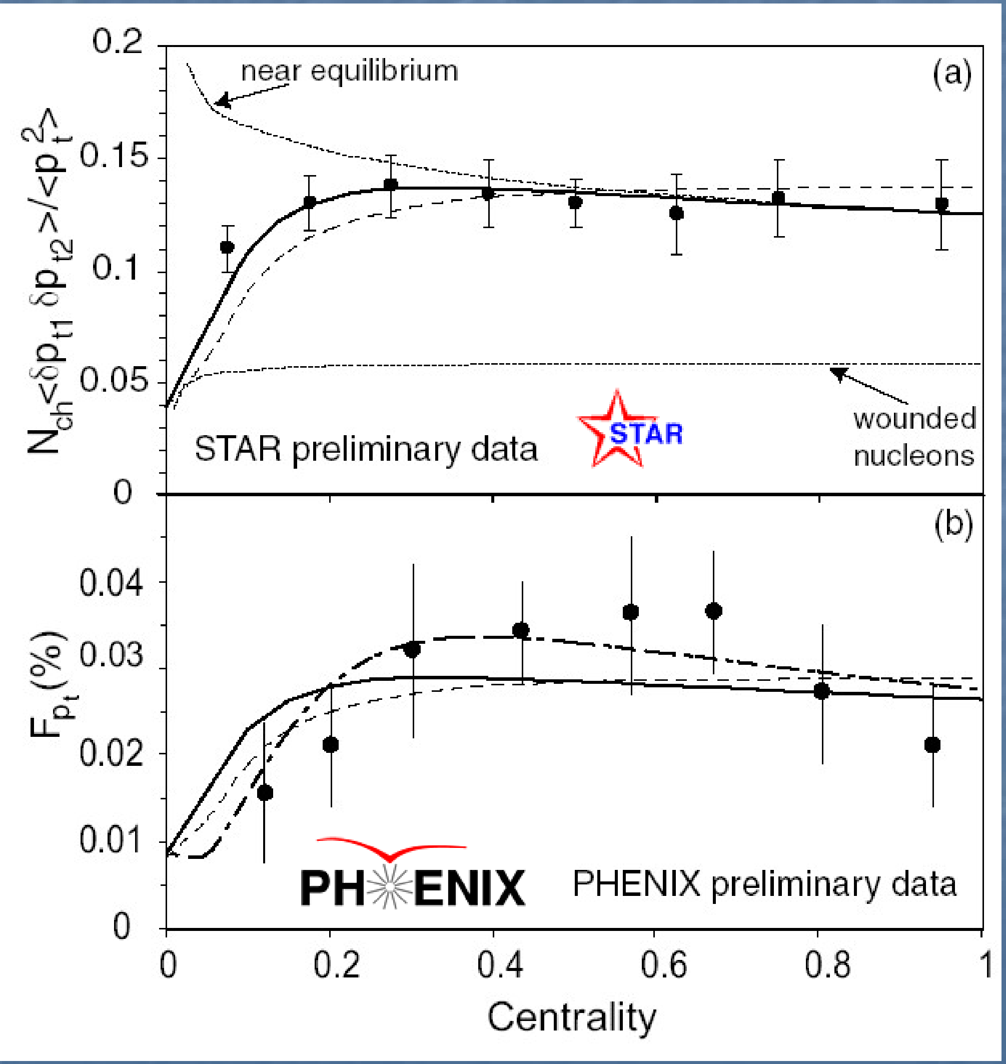
- **HBT – too small (NA49, STAR, CERES)**
- **Resonances – too small (NA49, STAR)**
- **Elliptic Flow – too small/negligible (PHENIX, CERES, NA49)**
- **Hard Processes…**
- **Or onset of thermalization…**

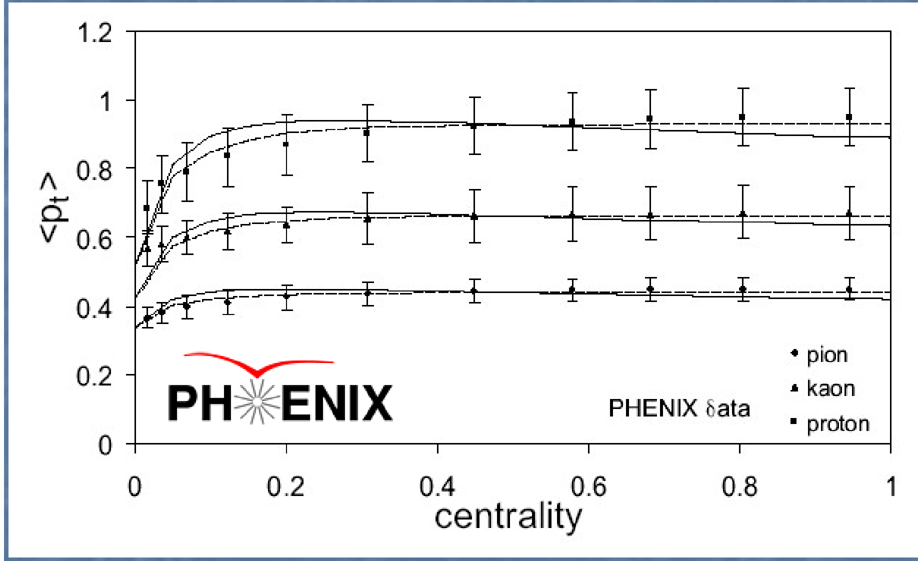


A Schematic Illustration of Elliptic Flow

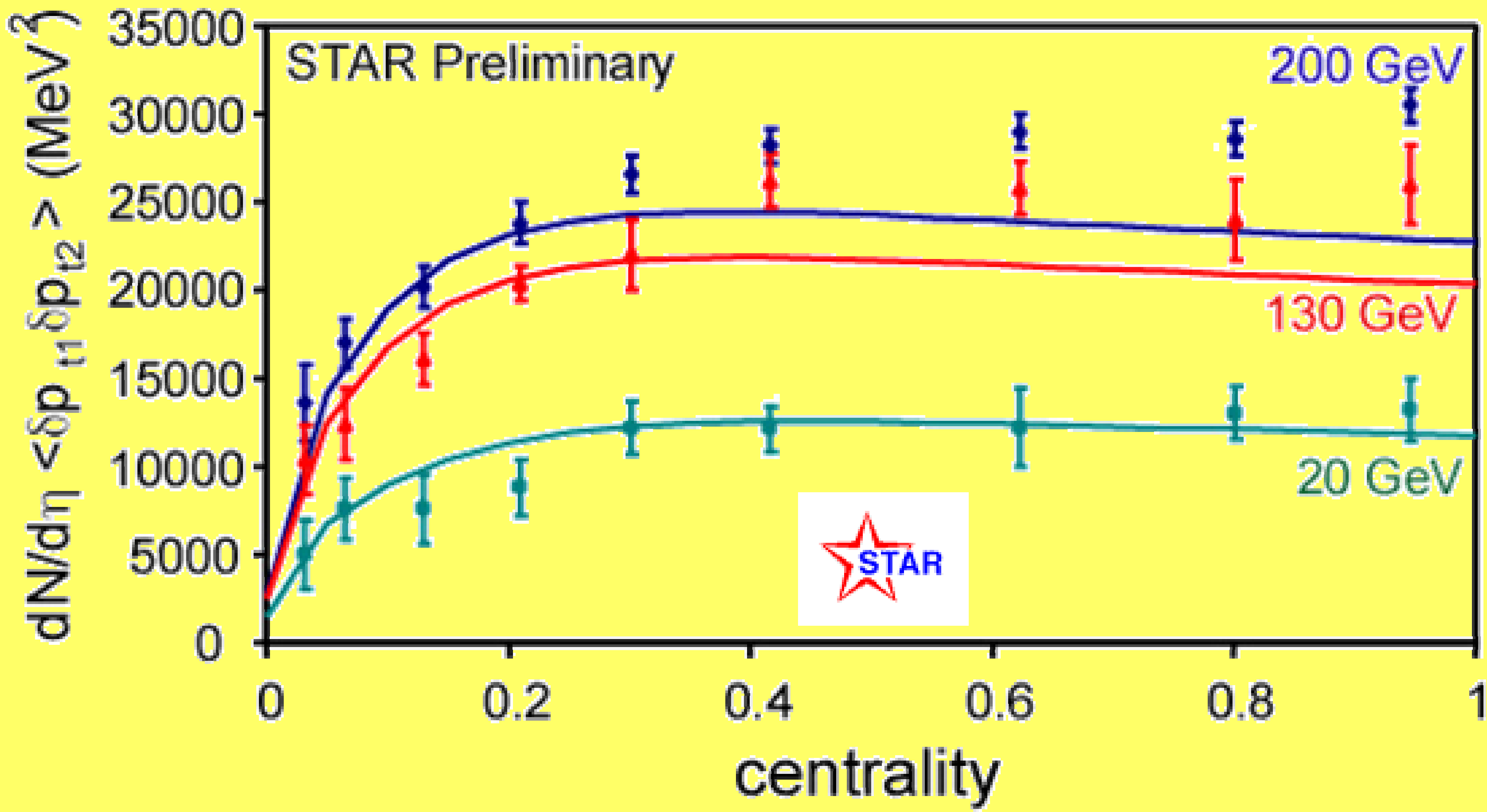
A Possible Explanation of the Signal: A System in Near-local Thermal Equilibrium

Sean Gavin, nucl-th/0308067, see his talk tomorrow for more details.





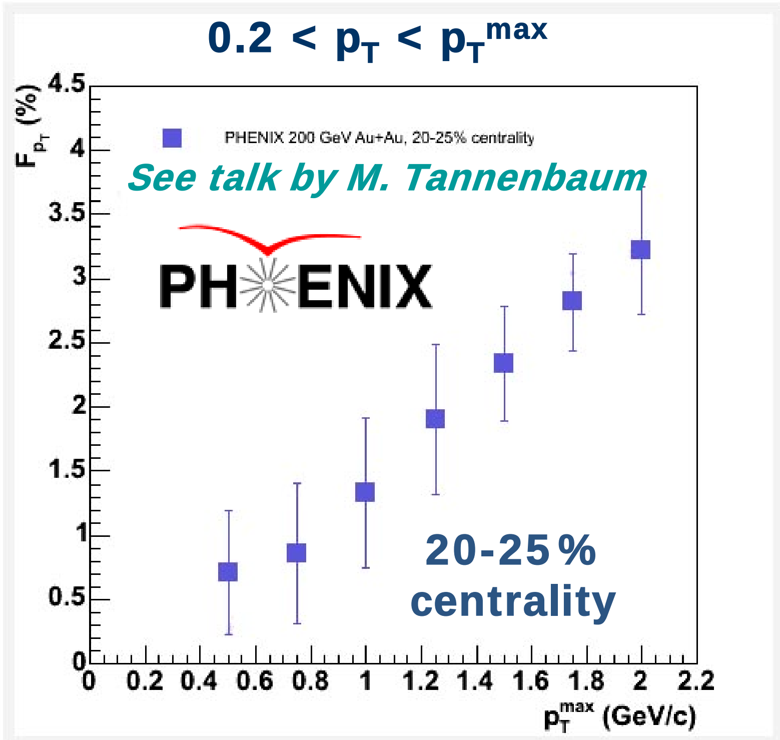
The onset of thermalization?

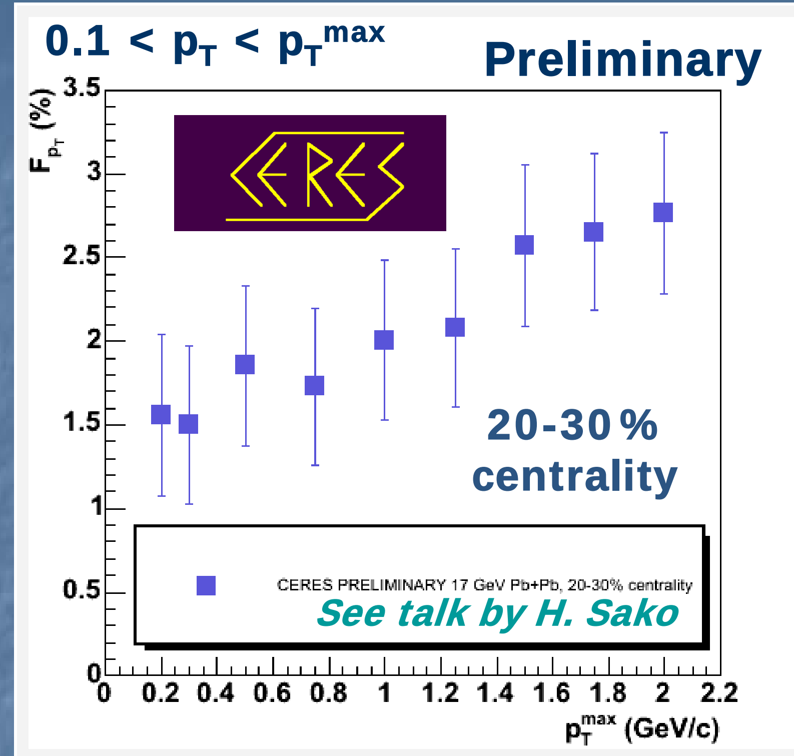


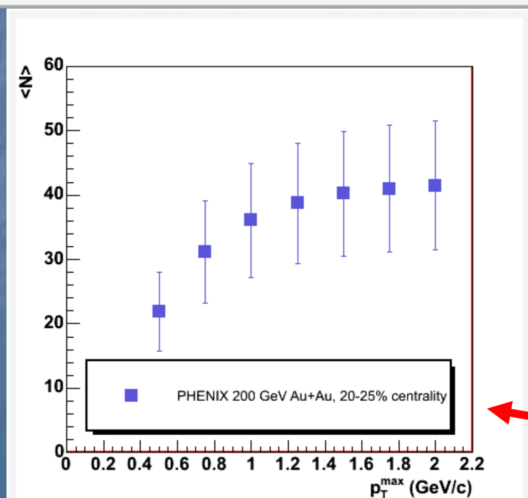
$$\frac{dN}{d\eta}\left\langle \delta p_{t1}\delta p_{t2}\right\rangle \propto \Phi_{p_t}$$

See talks tomorrow by S. Gavin (model) and G. Westfall (data)

A Large Fluctuation Contribution at high p_T







This trend is observed at all centralities.

An increase in observed fluctuations grows primarily in a p_T region where number fluctuations vary little.

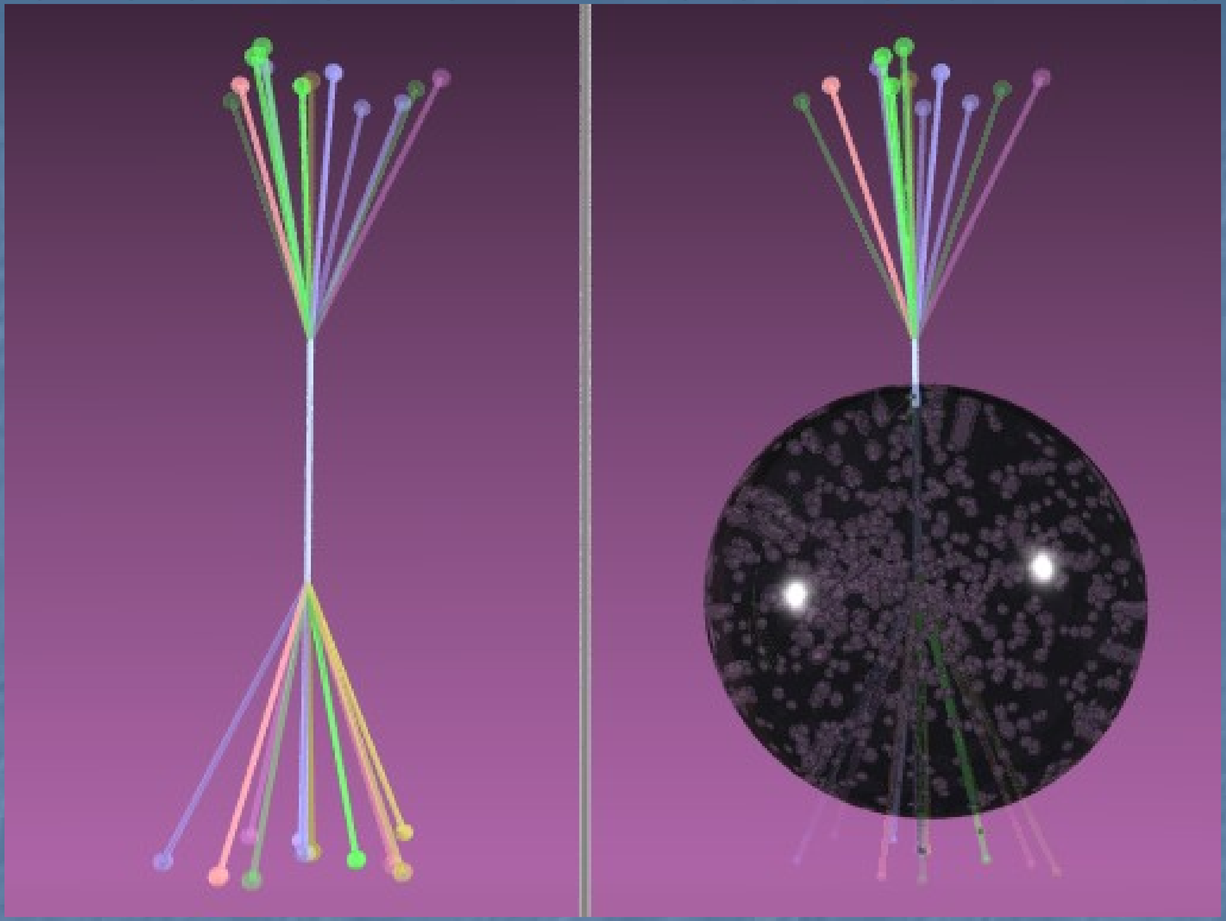
Increases from p_T^{max}=1.0 to 2.0 GeV/c

PHENIX Fluctuations: 243%

CERES Fluctuations: 34%

<N>: < 15%

Fluctuations: A Jet Contribution?



A Schematic Illustration of Jet Suppression

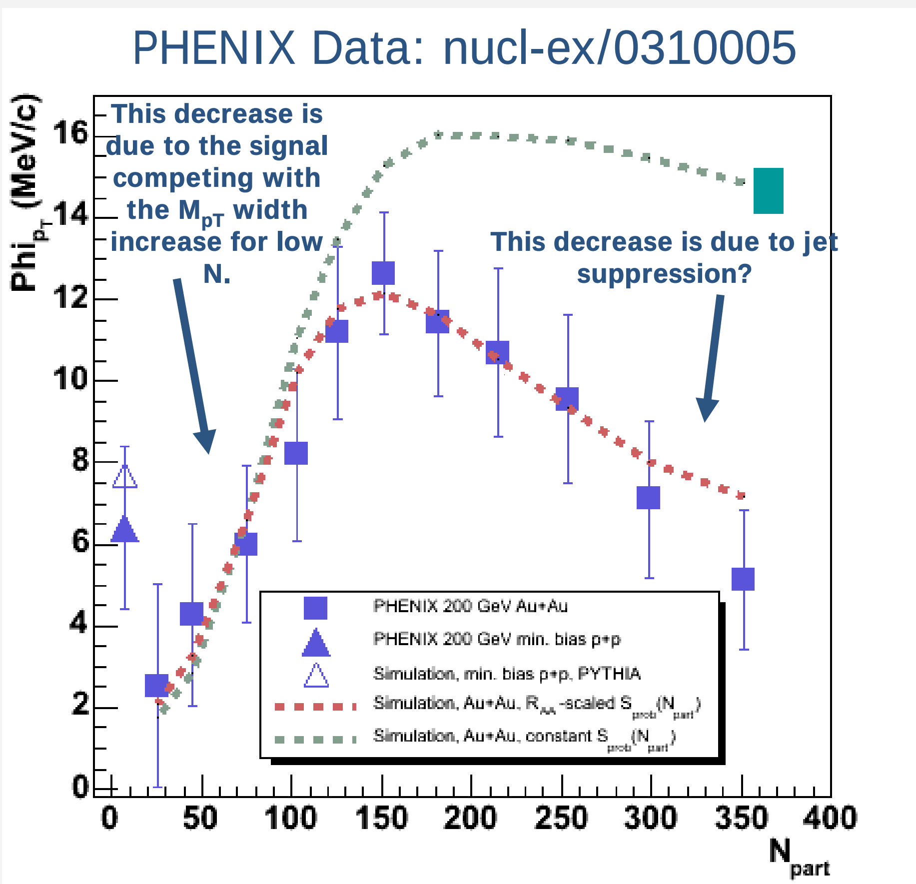
Jets inherently add particles that are correlated in p_T to the event, so a contribution due to hard processes is expected, but how much? What about jet suppression?

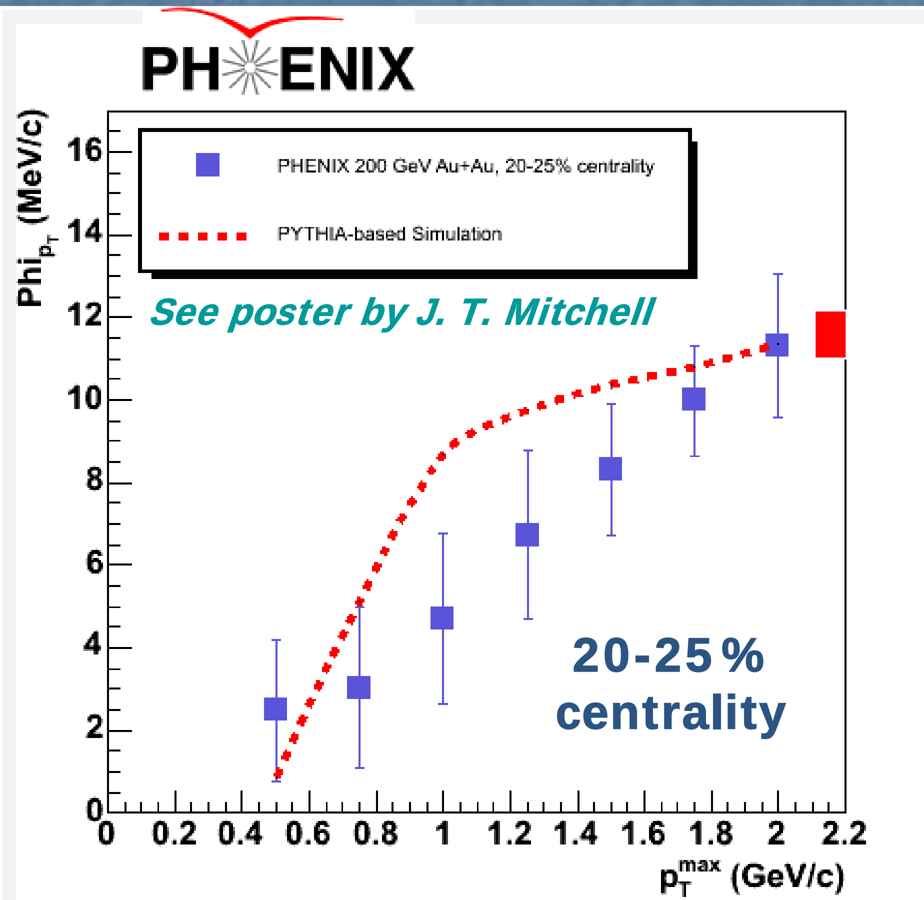
Jet Simulation Results: PHENIX at 200 GeV

Results from a 2-component hybrid simulation.

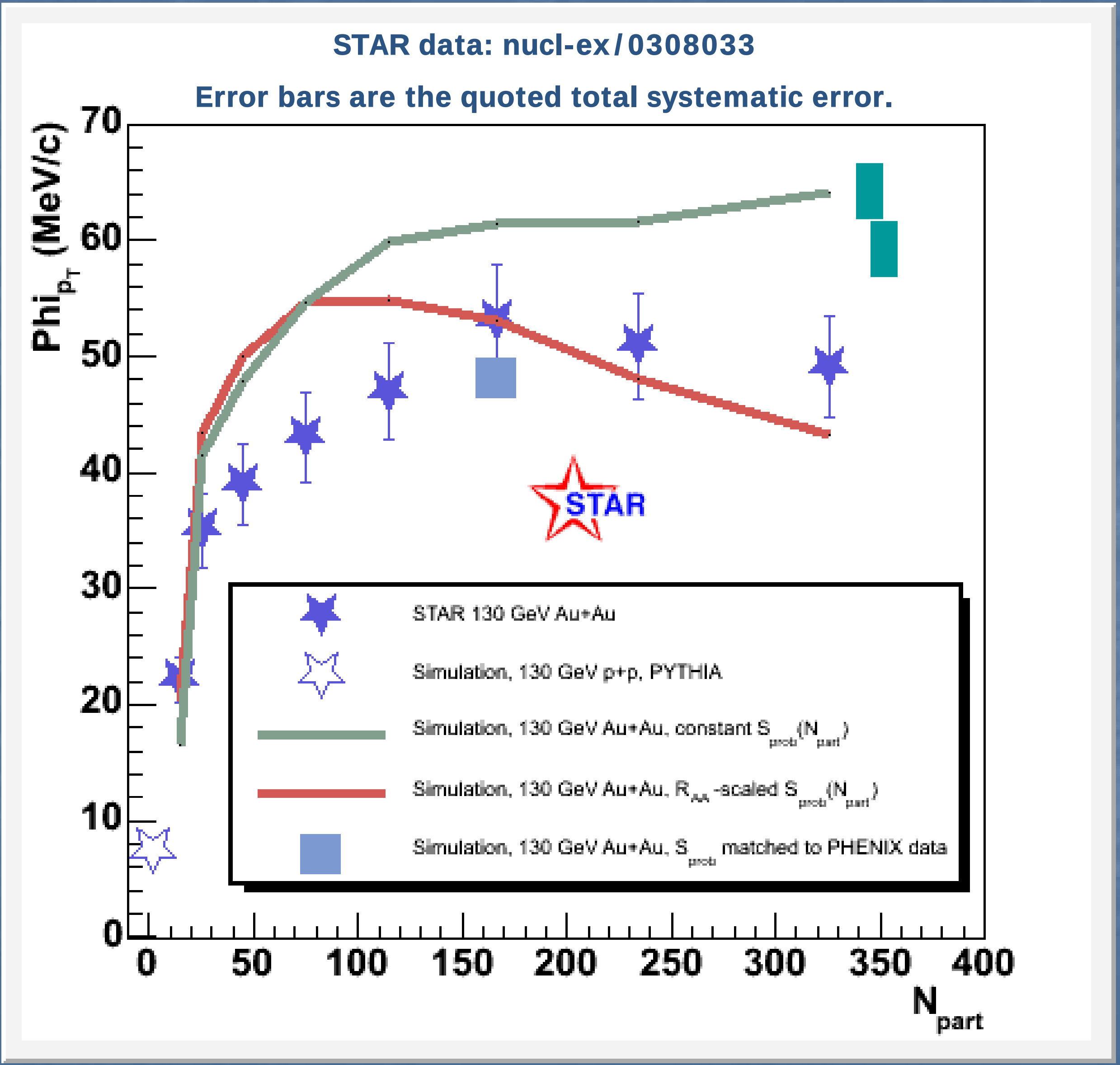
Component 1: Reproduce soft processes by sampling the inclusive p_T and N data distributions.

Component 2: Embed PYTHIA hard scattering events at a given rate per particle produced in Part 1. Keep the rate fixed, or scale it by R_{AA}.

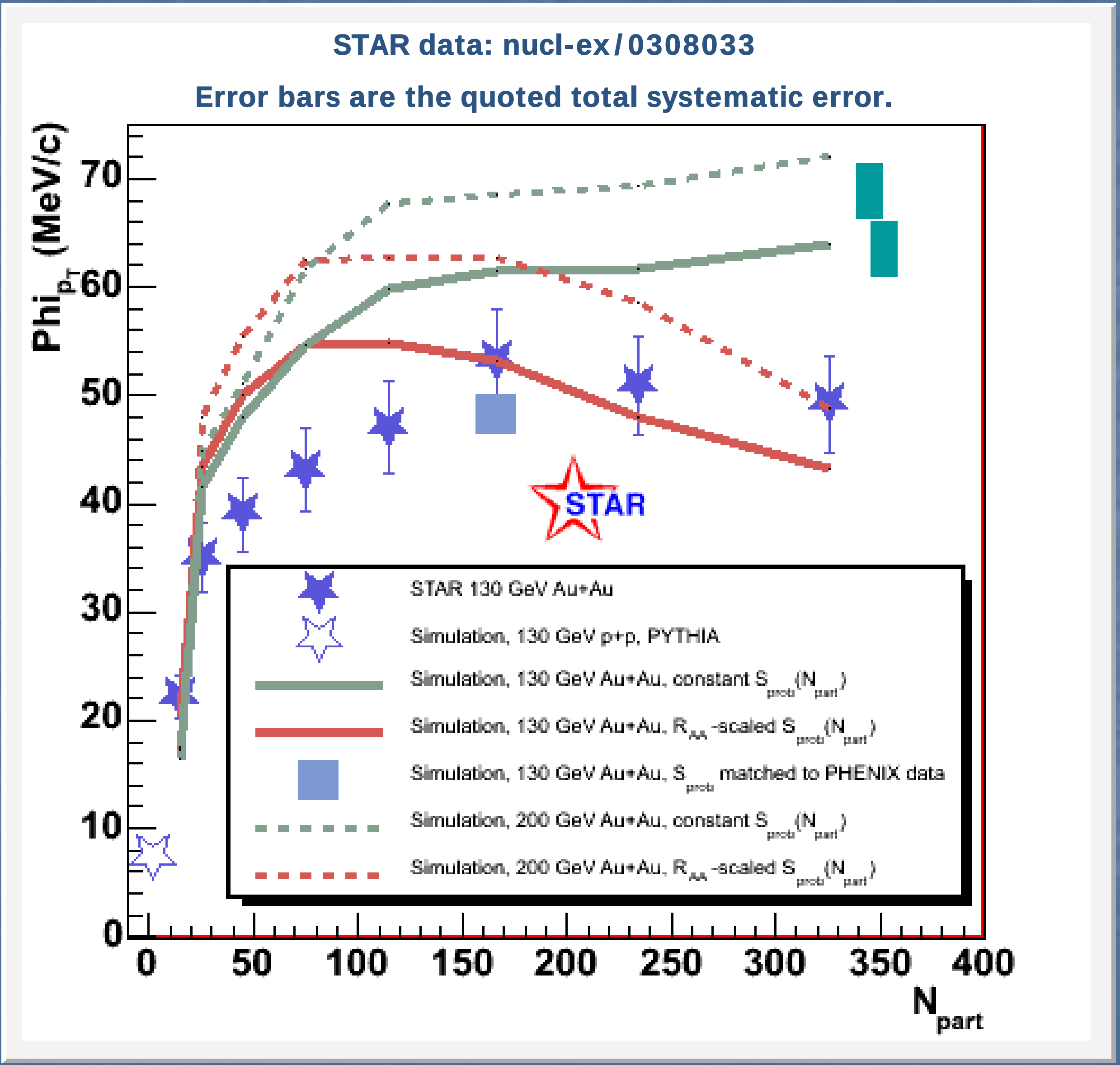




Jet Simulation Results: STAR at 130 GeV

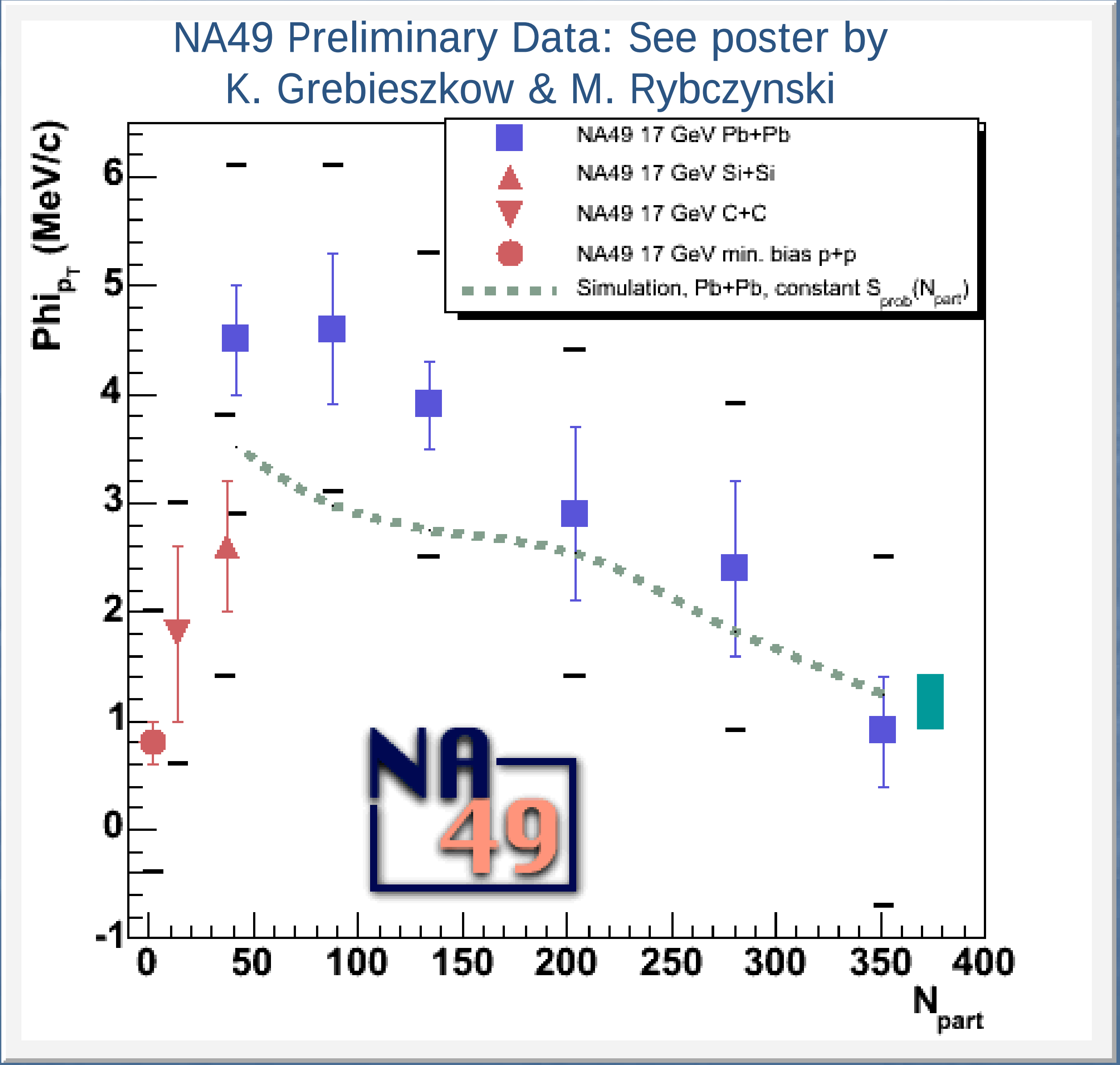


Jet Simulation Results: STAR at 130 GeV



The simulation predicts ~15-20% increase when going from 130 to 200 GeV

Jet Simulation Results: NA49 at 17 GeV



Estimate of the Magnitude of Residual Event-by-Event Temperature Fluctuations

$$\frac{\sigma_T}{<T>} = \sqrt{\frac{2F_{p_T}}{p(<N>-1)}}$$

p → inclusive p_T, $\Gamma(p,b)$, p~1

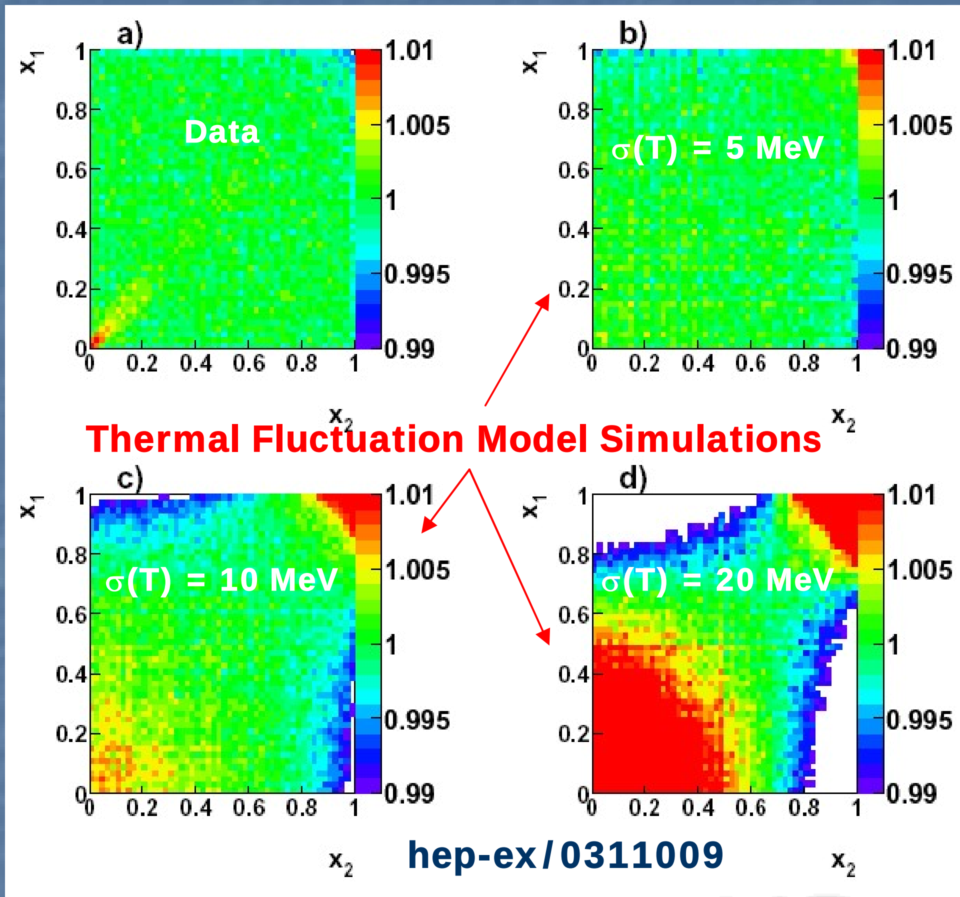
R. Korus and S. Mrowczynski,

Phys. Rev. C64 (2001) 054908.

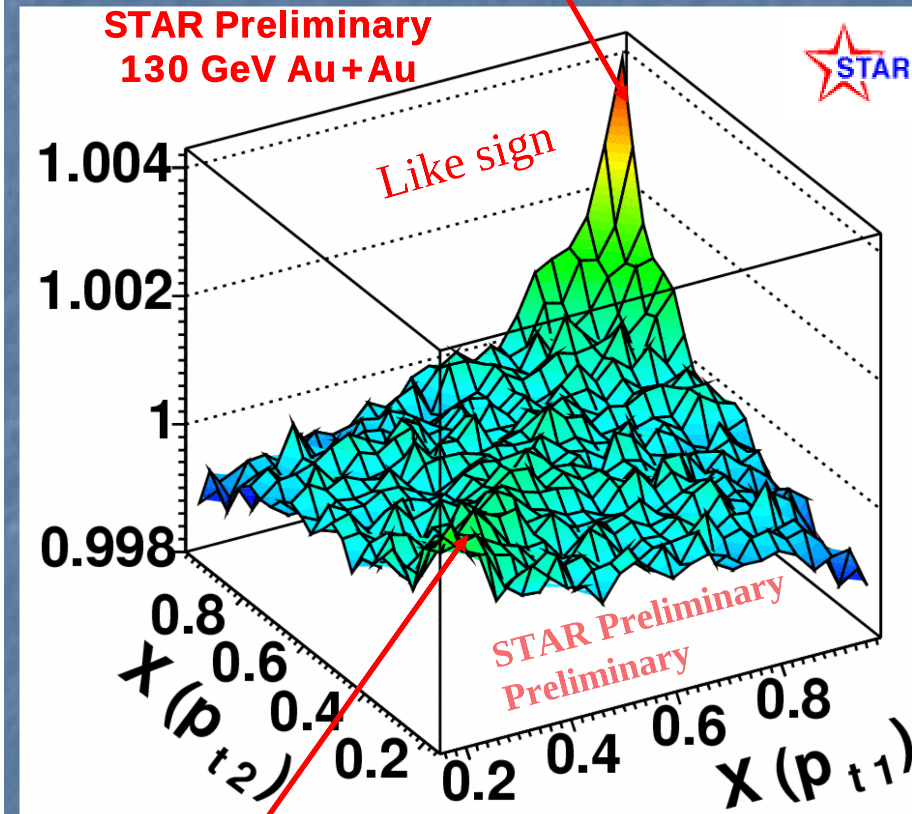
Measurement	**sqrt(s_{NN})**	**σ_T / <T>, Most central**	**σ_T / <T>, At the peak**
PHENIX	200	1.8%	3.7%
STAR	130	1.7%	3.8%
CERES	17	1.3%	2.2%
NA49	17	0.6%	1.7%

Add a dimension: 2-point transverse momentum correlations

NA49 17 GeV Pb+Pb



Higher p_t pairs from hard scattering ?



L. Ray, DNP 2003, see his poster

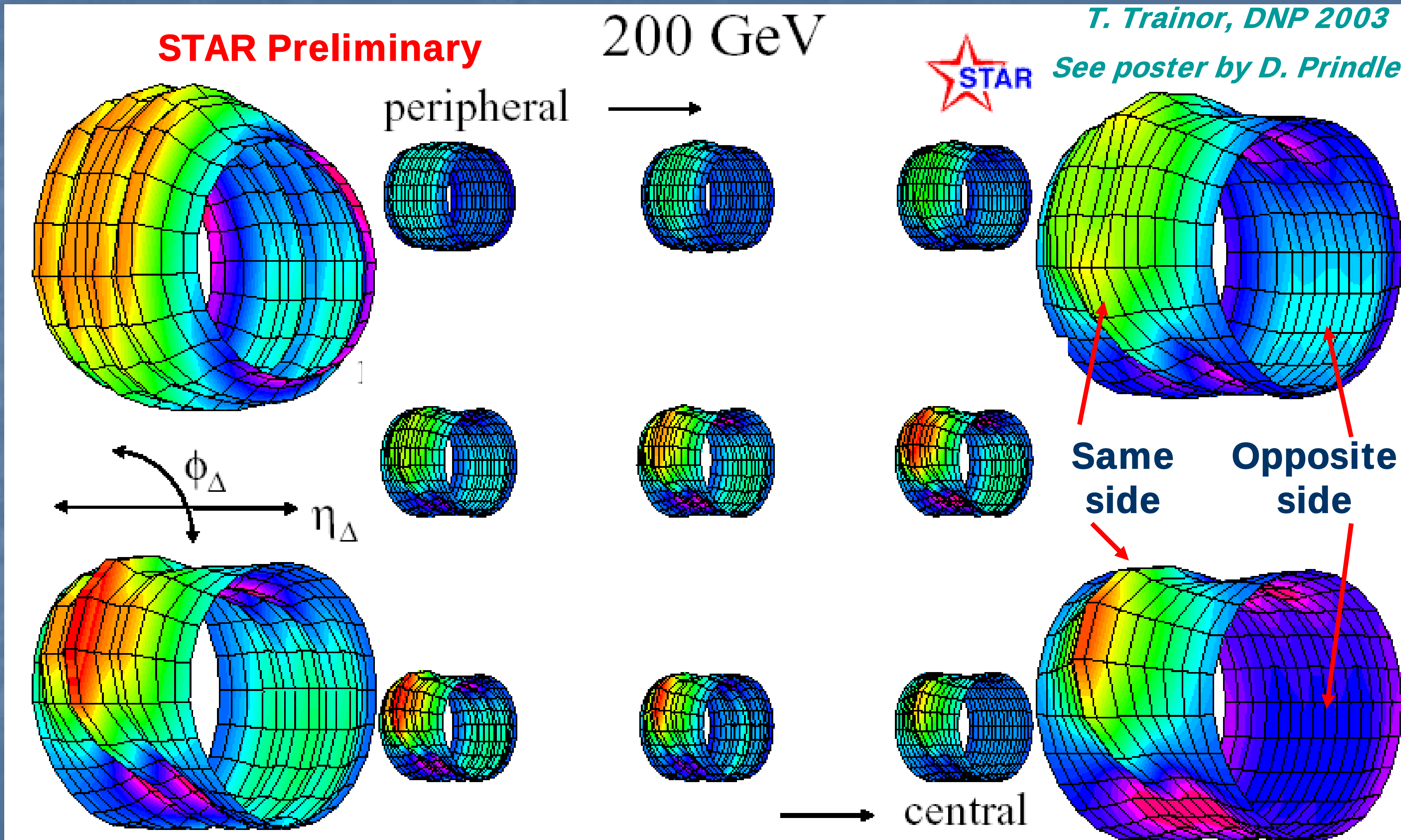
$$x(p_T) = \frac{\int_0^{p_T} \frac{dN}{dp_T} dp_T}{\int_0^{\infty} \frac{dN}{dp_T} dp_T}$$

HBT and Coulomb interaction

In PHENIX, x(1.5 GeV/c) ~ 0.93

Coming Soon: A Multi-dimensional Analysis

(centrality, $p_{T,1}$, $p_{T,2}$, pseudorapidity, azimuth)



Elliptic flow has been removed.

Synopsis

- Charge fluctuations:
  - SPS results and RHIC-PHENIX results are close to the random expectation after correcting for charge conservation.
  - RHIC-STAR results are consistent with a quark coalescence model prediction in central collisions.
- Balance Functions:
  - Both SPS (NA49) and RHIC (STAR) results show a narrowing of the balance function in central collisions.
  - The narrowing is indicative of delayed hadronization.
  - The narrowing may also be explained within the quark coalescence picture, or by resonance decay contributions.
- $\langle p_T \rangle$ Fluctuations:
  - A positive fluctuation signal that decreases for more central collisions is seen at the SPS and at RHIC.
  - The signal can be explained within a model that simulates jet production, however, a jet suppression scenario must be introduced to describe the most central collisions at RHIC.
  - The signal can also be explained within a thermalization onset scenario.
- Stay tuned for more exciting results soon!

But wait! There's more!

The following topics could not be covered in this presentation.

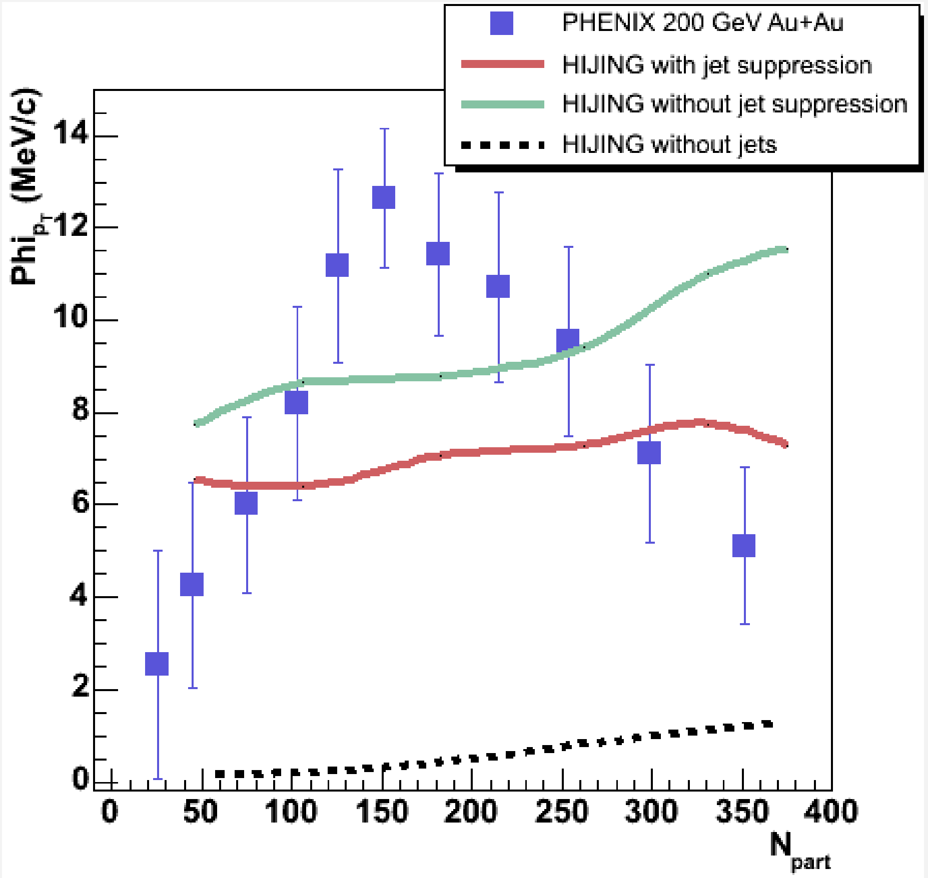
- **Multiplicity Fluctuations**
- **Spatial Fluctuations, or "Event Texture"**
- **Charge/Neutral (Isospin) Fluctuations**
- **Particle Ratio Fluctuations**

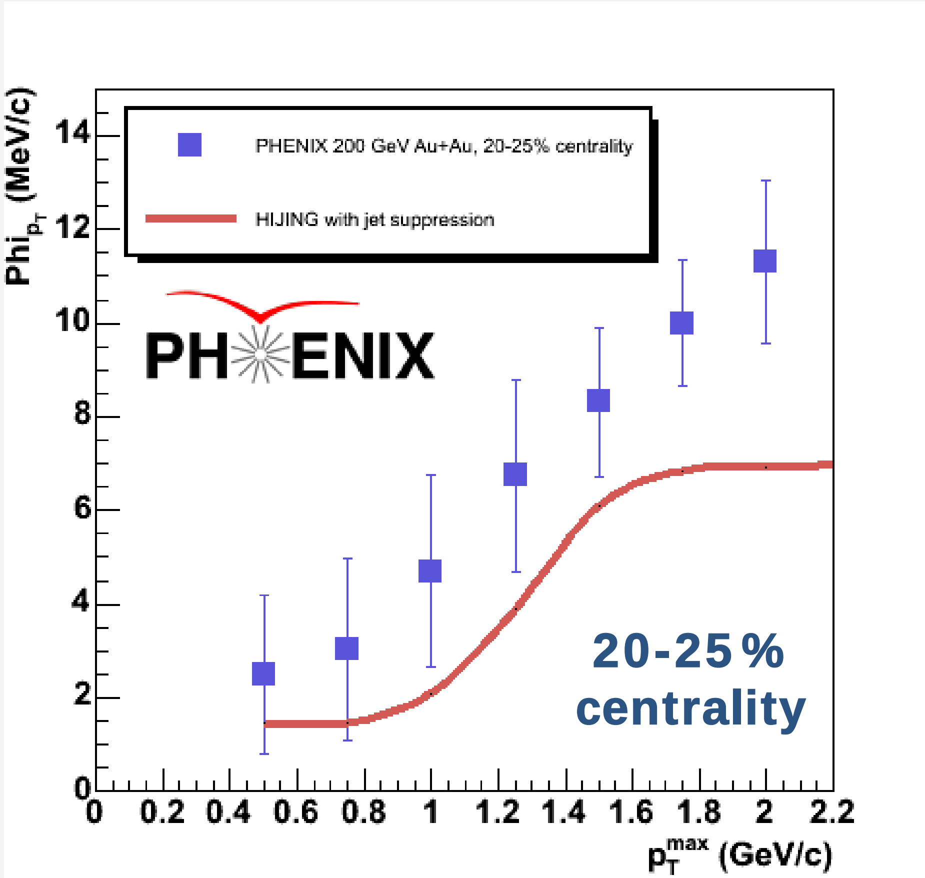
Acknowledgements

Many thanks to H. Appelshauser (CERES), M. Gazdzicki (NA49), S. Gavin, D. Prindle (STAR), L. Ray (STAR), C. Roland (NA49), H. Sako (CERES), T. Trainor (STAR), G. Westfall (STAR), for providing input into this presentation.

Auxiliary Slide

Fluctuations According to HIJING





HIJING cannot reproduce the centrality dependence of the fluctuations.

One problem is that <N> changes depending on the HIJING settings – not matched to the observed dataset.

Example for 0-5% centrality: <N> = 93.0 for jet suppression, 76.6 without suppression, and 51.2 without jets.