

Fluctuations and Correlations in Relativistic Heavy Ion Collisions

Jeffery T. Mitchell
(Brookhaven National Laboratory)

Outline:

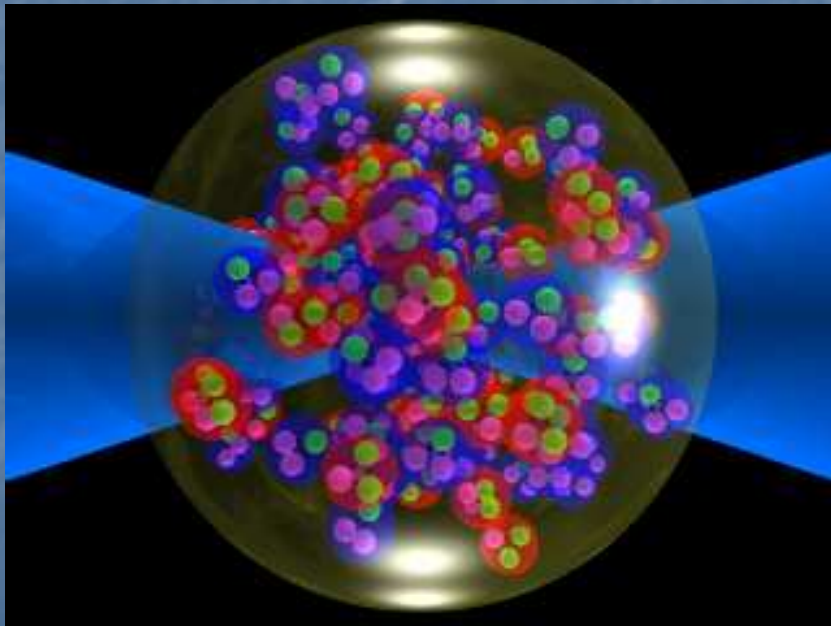
- Charge Fluctuations
- Balance Functions
- Event-by-event $\langle p_T \rangle$ Fluctuations
- Looking Ahead
- Conclusions, Credits, Apologies



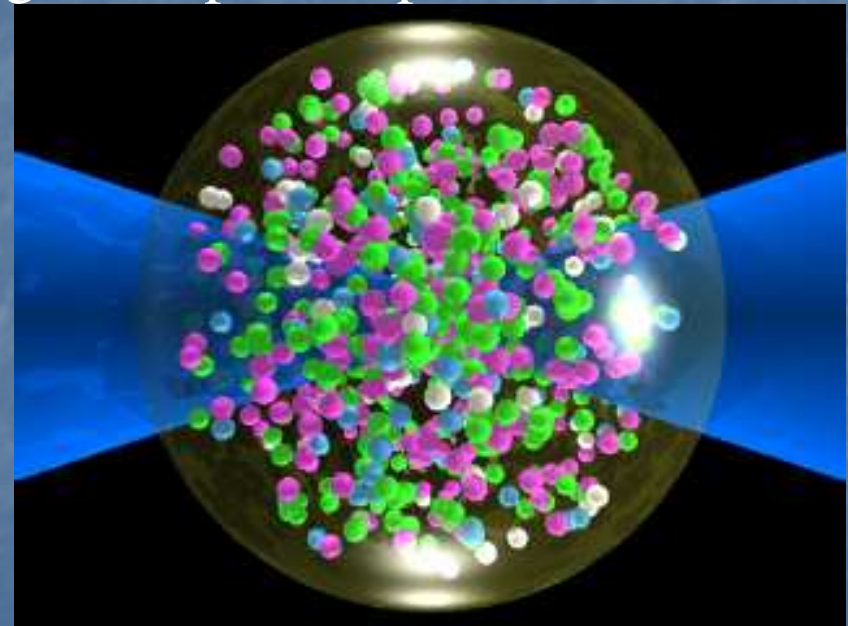
Charge Fluctuations

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

$$\text{Variance} \langle \delta X^2 \rangle = \langle X^2 \rangle - \langle X \rangle^2$$

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

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



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

$$Q = N_+ - N_-$$



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

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

$$D \approx 4 + \langle N_+ + N_- \rangle v_{+-,dyn}$$

$$D = 4v(Q)$$

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

$$\Gamma = v(Q)$$

$$v_{+-,dyn} = v_{+-} - v_{+-,stat}$$

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

$$v_{+-,stat} = \frac{1}{\langle N_+ \rangle} + \frac{1}{\langle N_- \rangle}$$

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

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



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

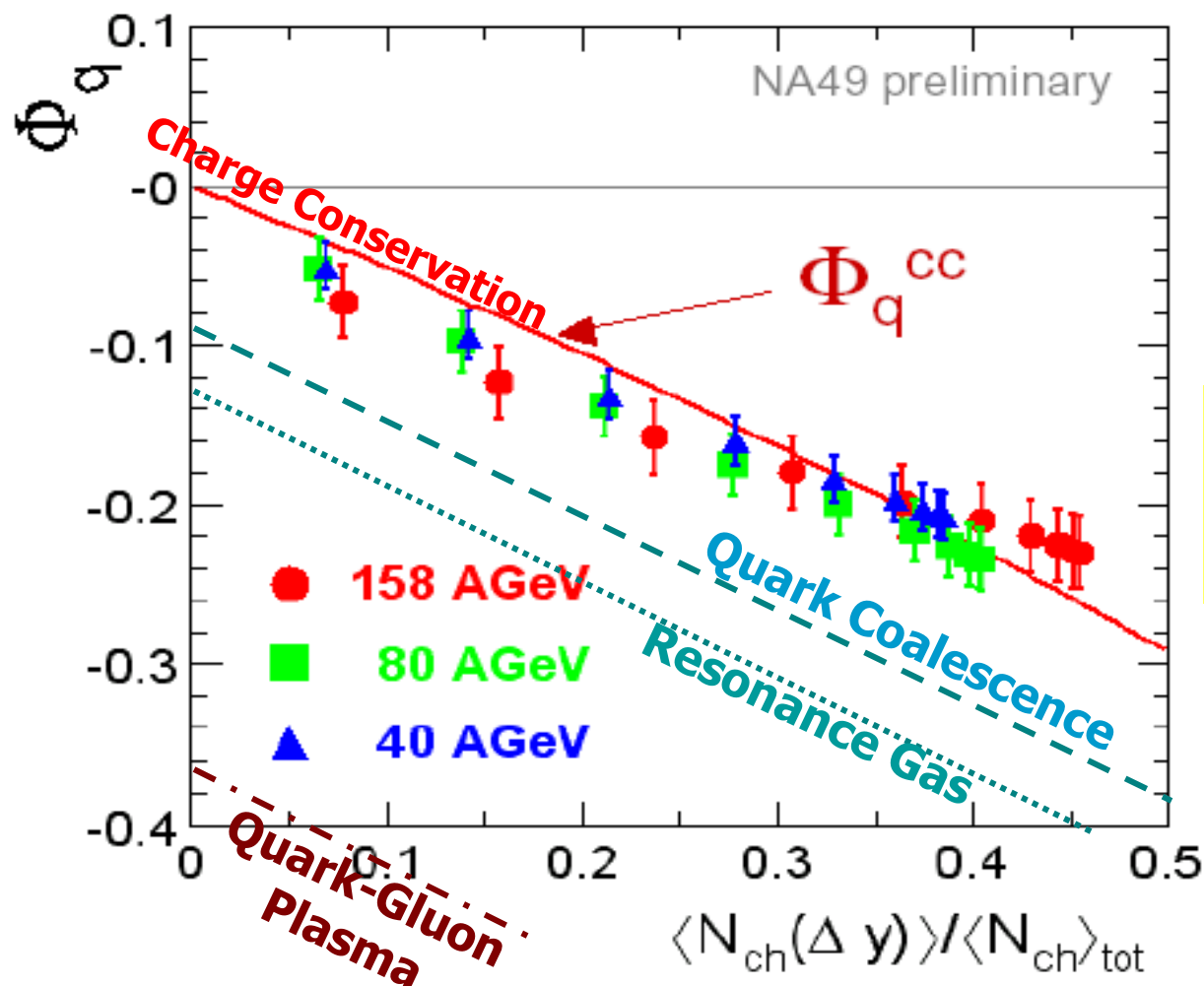
Quoted in this presentation

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

Charge Fluctuation Magnitude Expectations

	$v(Q)$	D	$V_{+-,\text{dyn}}$ (STAR)	$V_{+-,\text{dyn}}$ (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



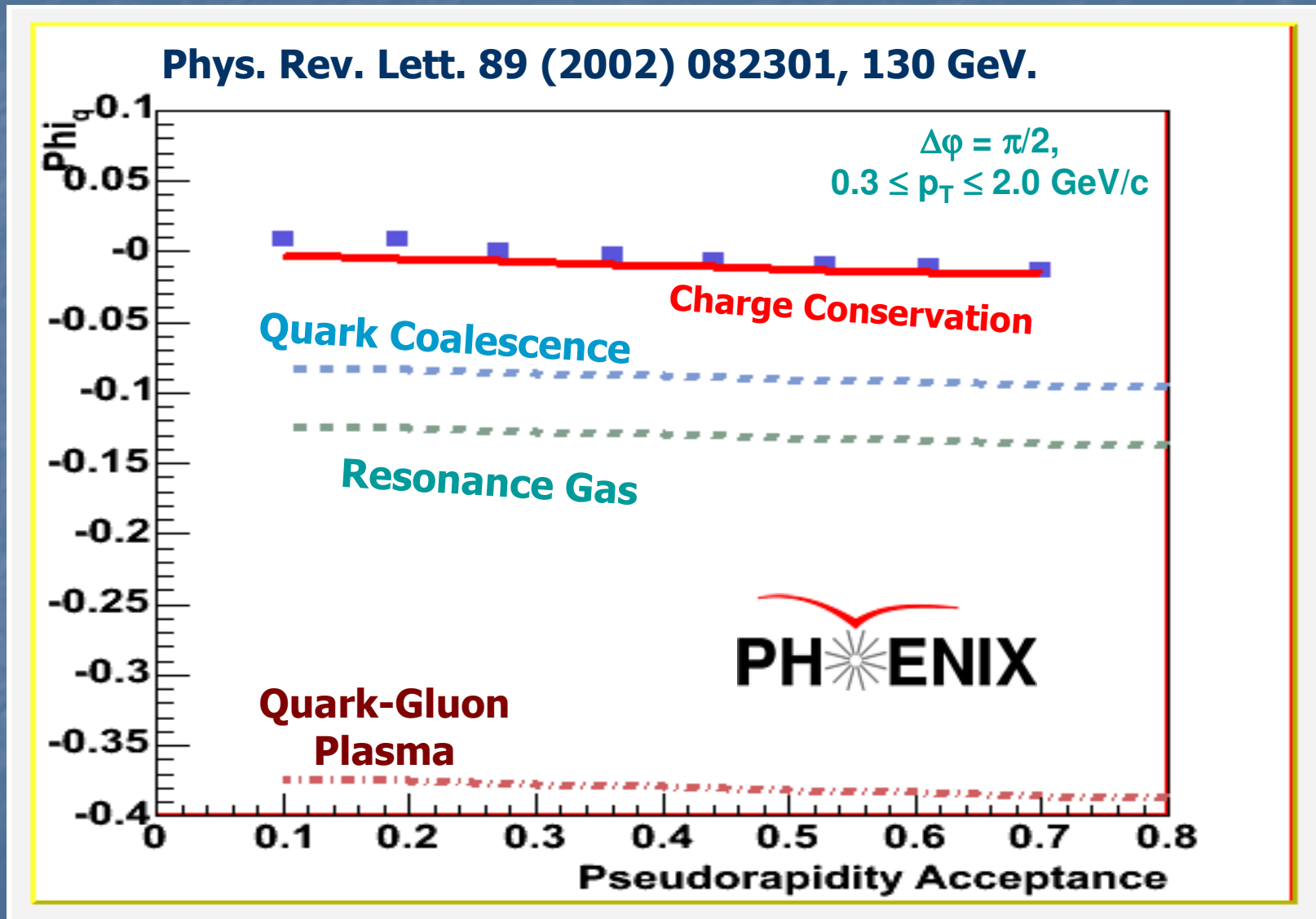
$$\Phi_q^{cc} = \sqrt{1 - \frac{\langle N_{CH}(\Delta y) \rangle}{\langle N_{CH} \rangle_{tot}} - 1}$$

Correction for
fluctuations due to
charge conservation.

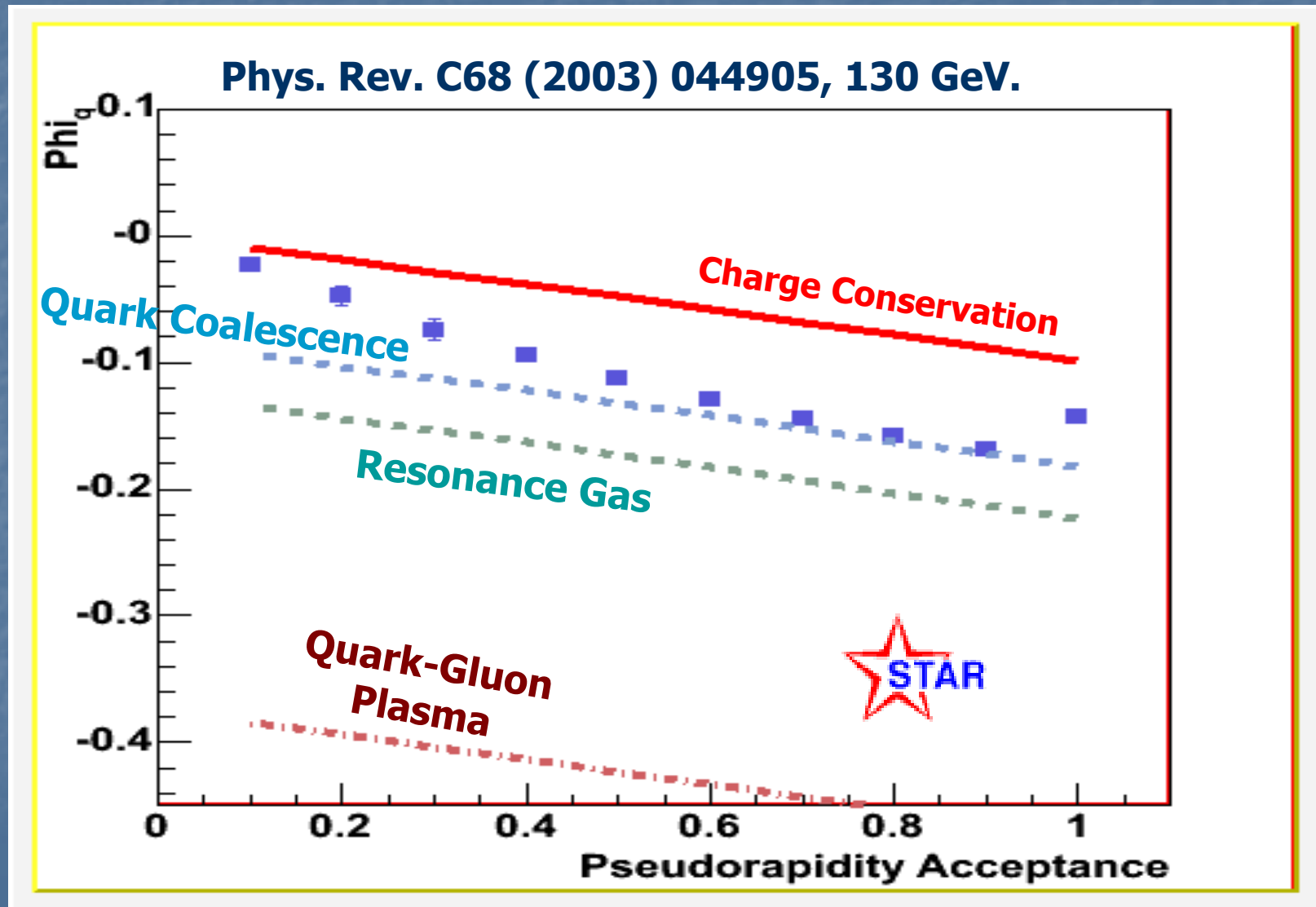
See poster by P. Chrisakogiou

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)

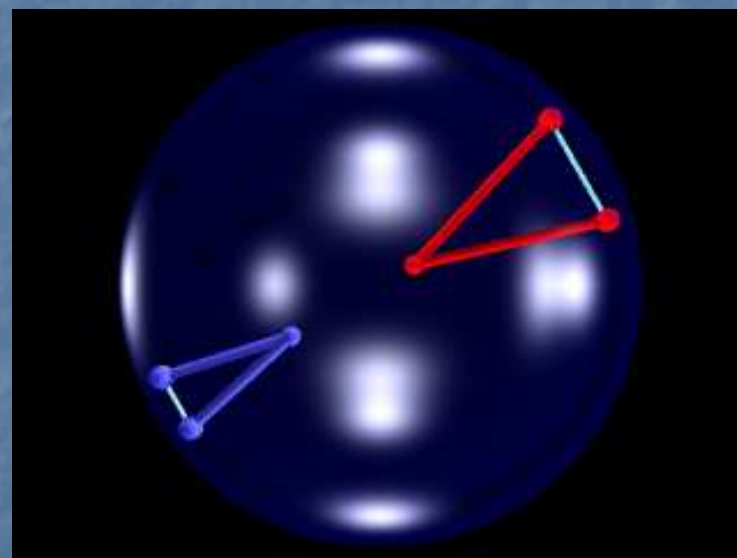
$$B(\Delta y) = \frac{1}{2} \left\{ \frac{N_{+-}(\Delta y) - N_{++}(\Delta y)}{N_{+}} + \frac{N_{-+}(\Delta y) - N_{--}(\Delta y)}{N_{-}} \right\}$$

$N_{+-}(\Delta y)$ = 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.

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

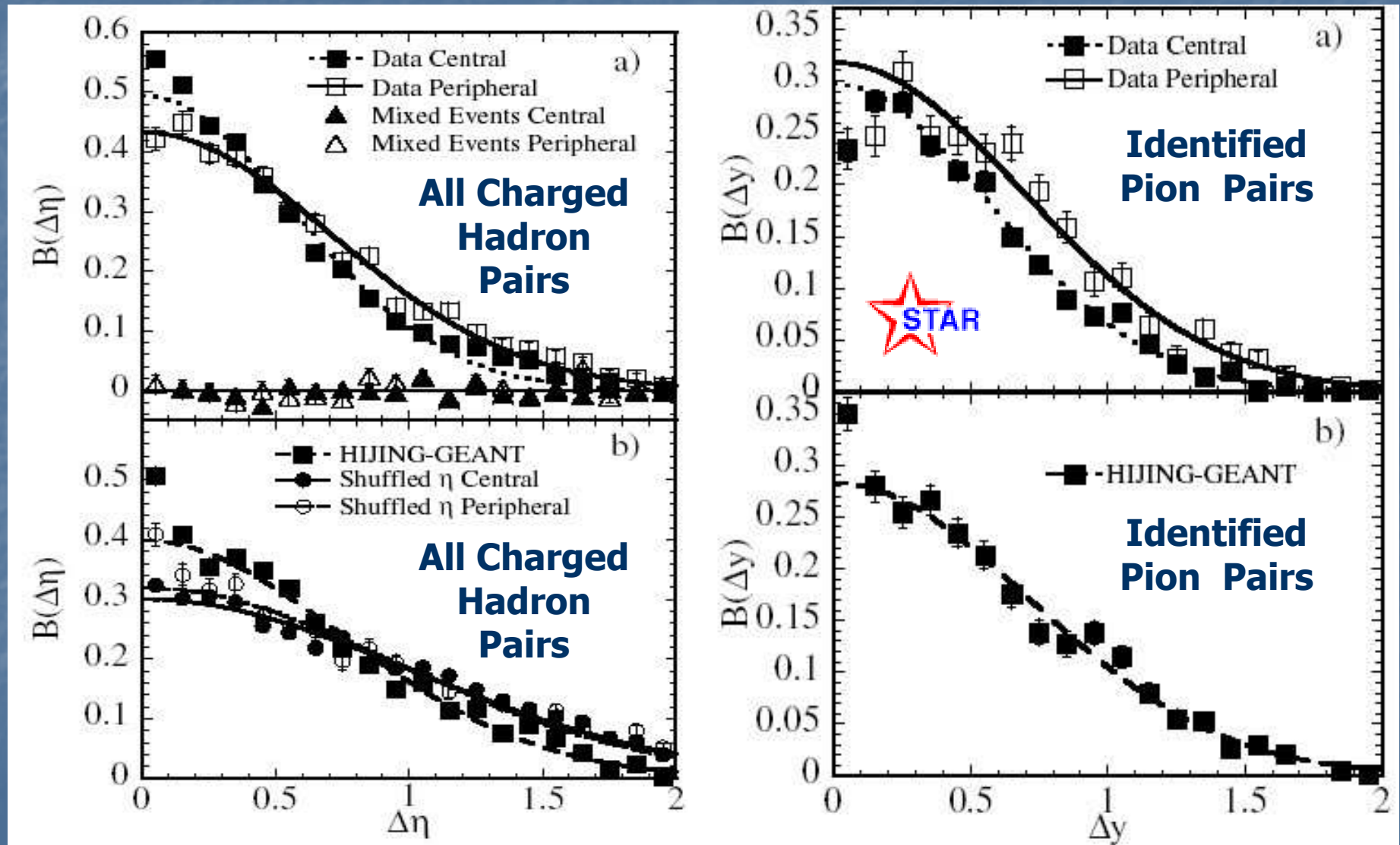
Early hadronization scenario: Pairs separate in rapidity due to expansion and rescattering.



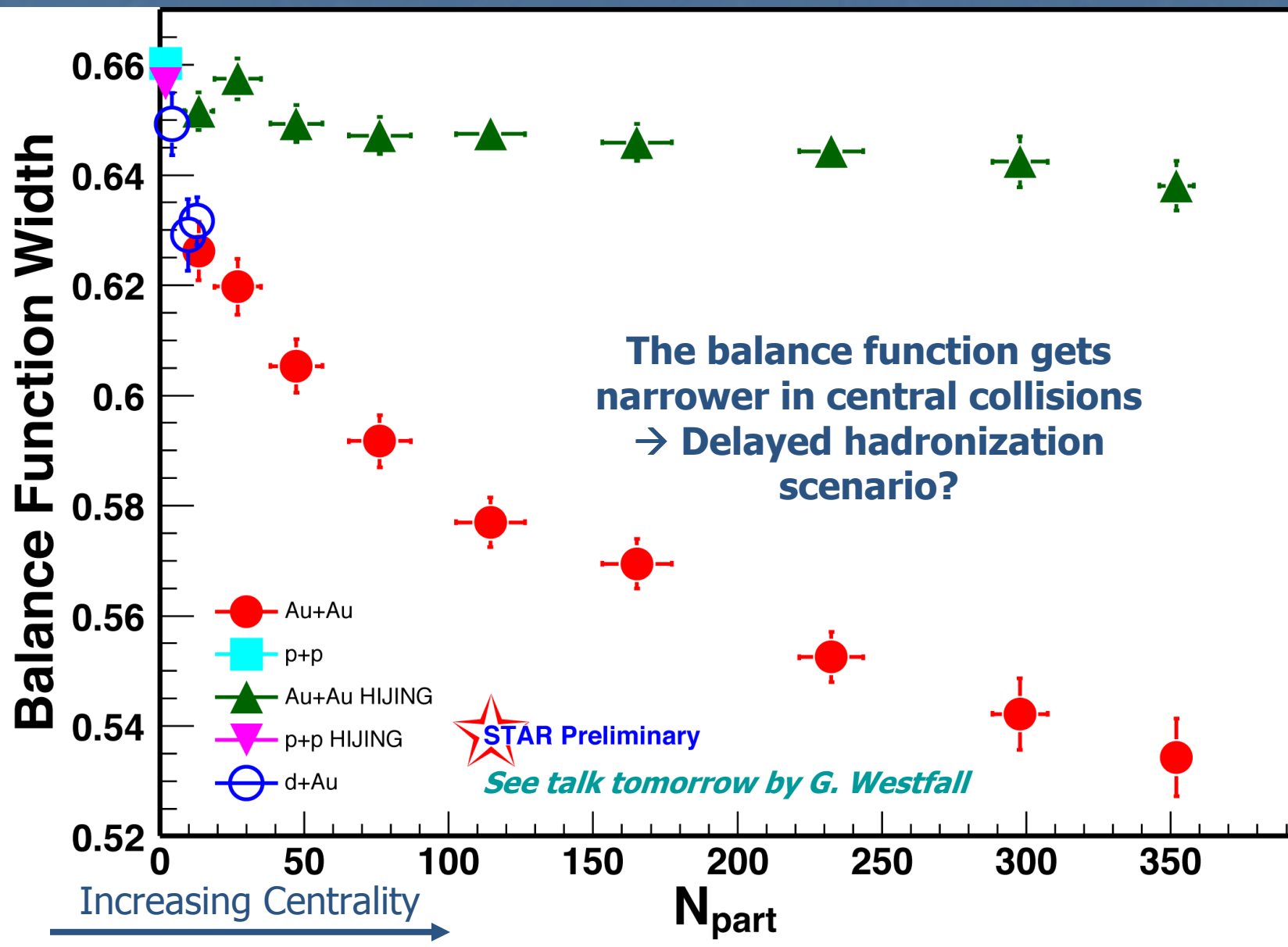
Delayed hadronization scenario: Pairs are more strongly correlated in rapidity.

STAR 130 GeV Balance Function Results

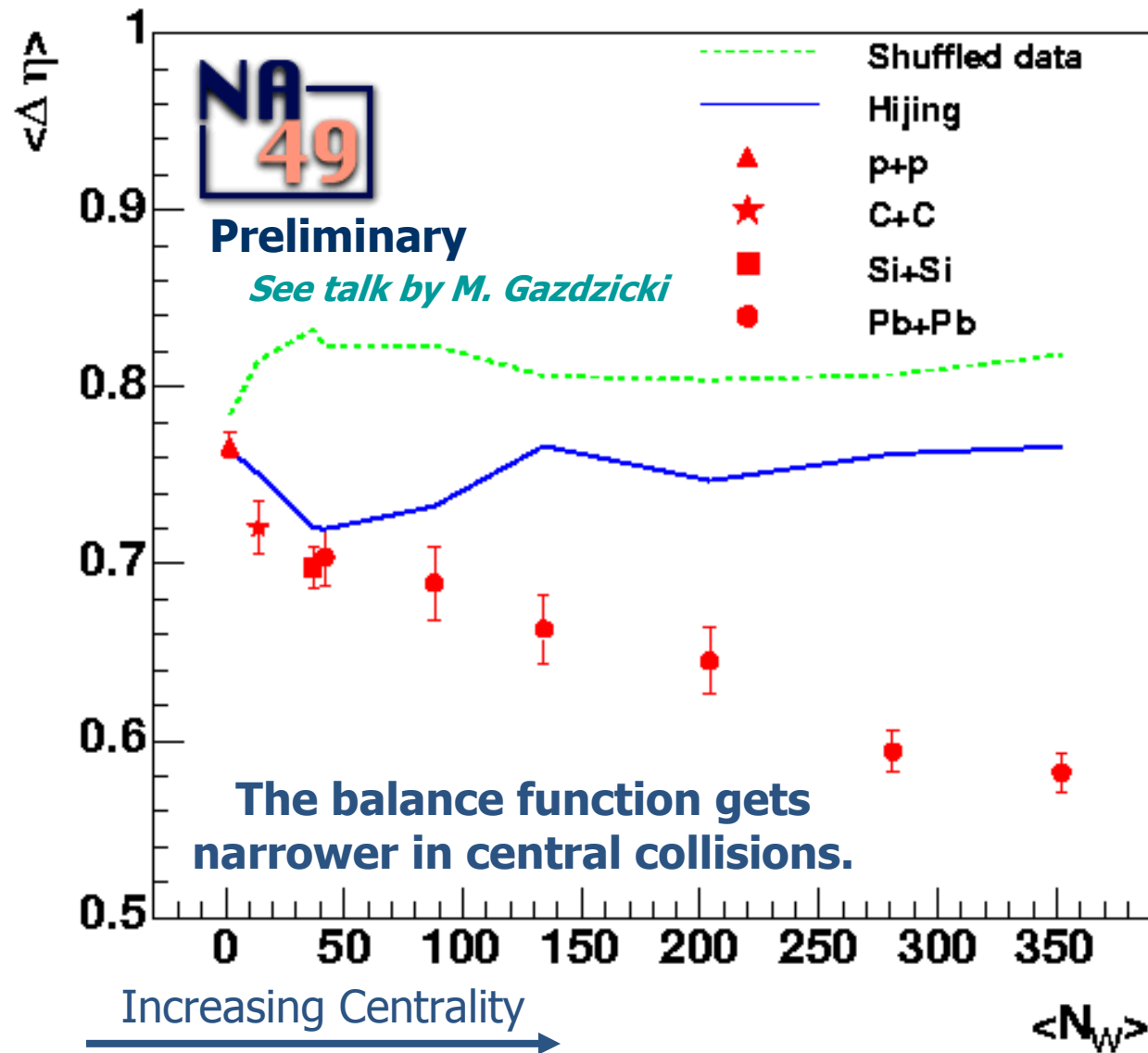
Phys. Rev. Lett. 90 (2003) 172301.



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 narrowing of the balance function

Resonance contributions

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

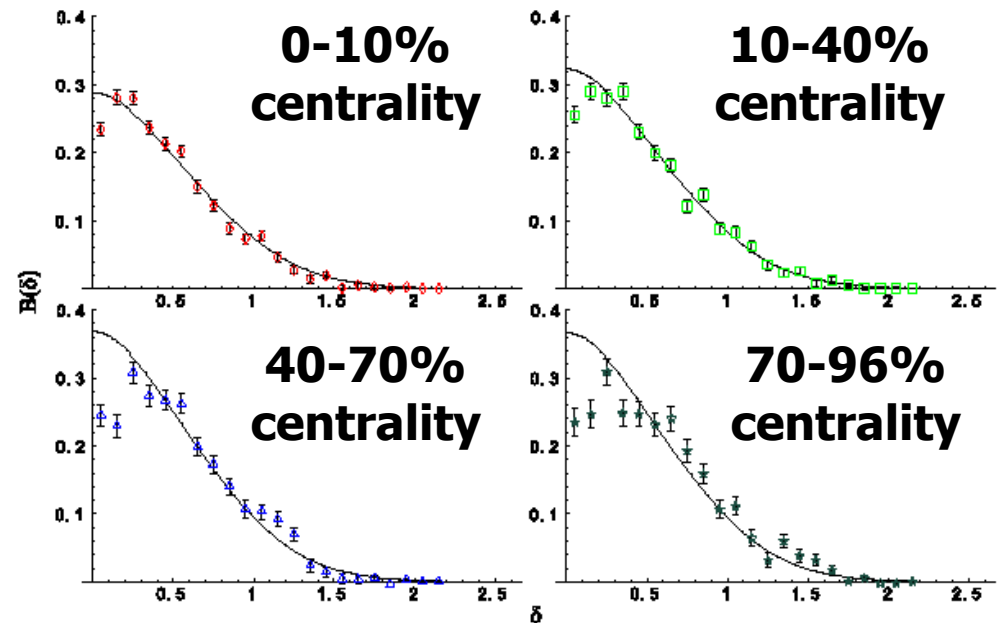
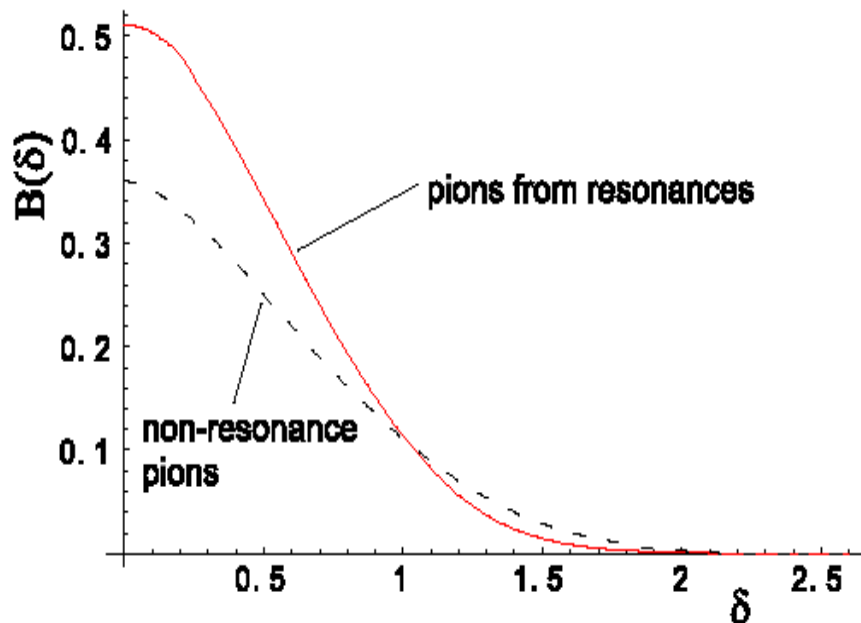
Computing balance functions in a thermal model
with neutral resonance decay.

The calculations including resonances are
consistent with the STAR results.

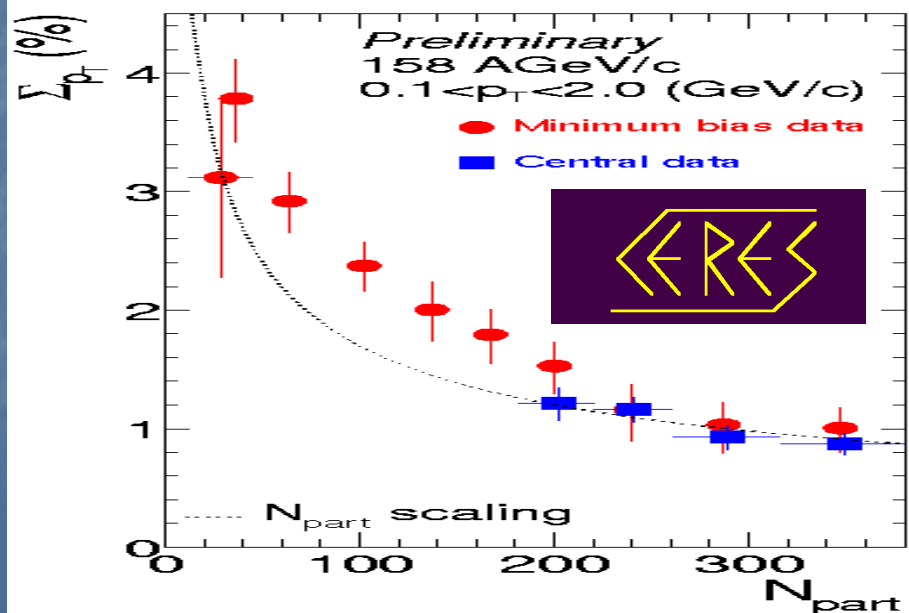
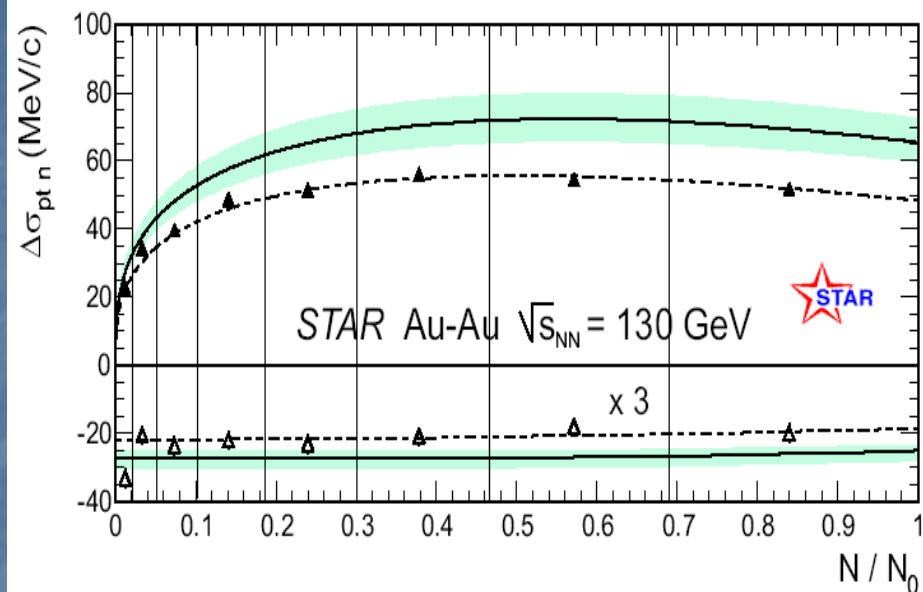
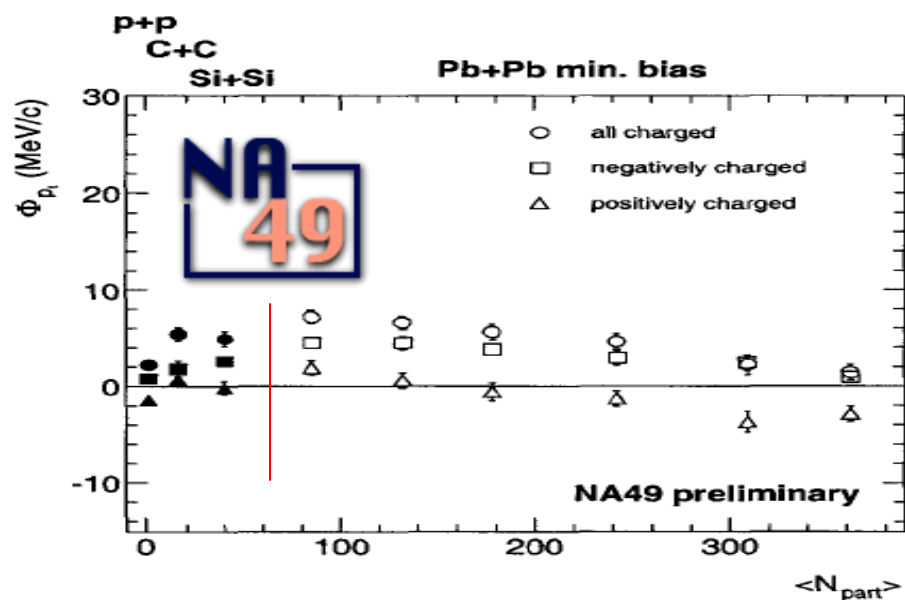
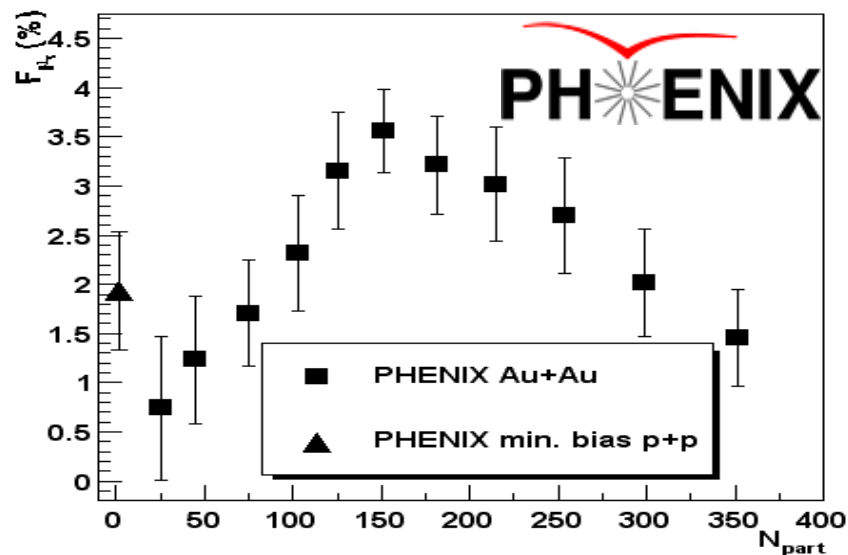
Quark Coalescence Model Predictions

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 $\langle p_T \rangle$ Fluctuation Measures

Goal of the observables:

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



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



Quoted in this presentation



Φ_{p_T}

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

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

$$\Delta\sigma_{p_T, n} \cong \sqrt{(\Phi_{p_T} + \sigma_{p_T, incl.})^2 - \sigma_{p_T, incl.}^2}$$

$\Delta\sigma_{p_T, n}$



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

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

$$\Sigma_{p_T} = \frac{\sigma_{p_T}}{p_T} \sqrt{\frac{2F_{p_T}}{\langle N \rangle}}$$

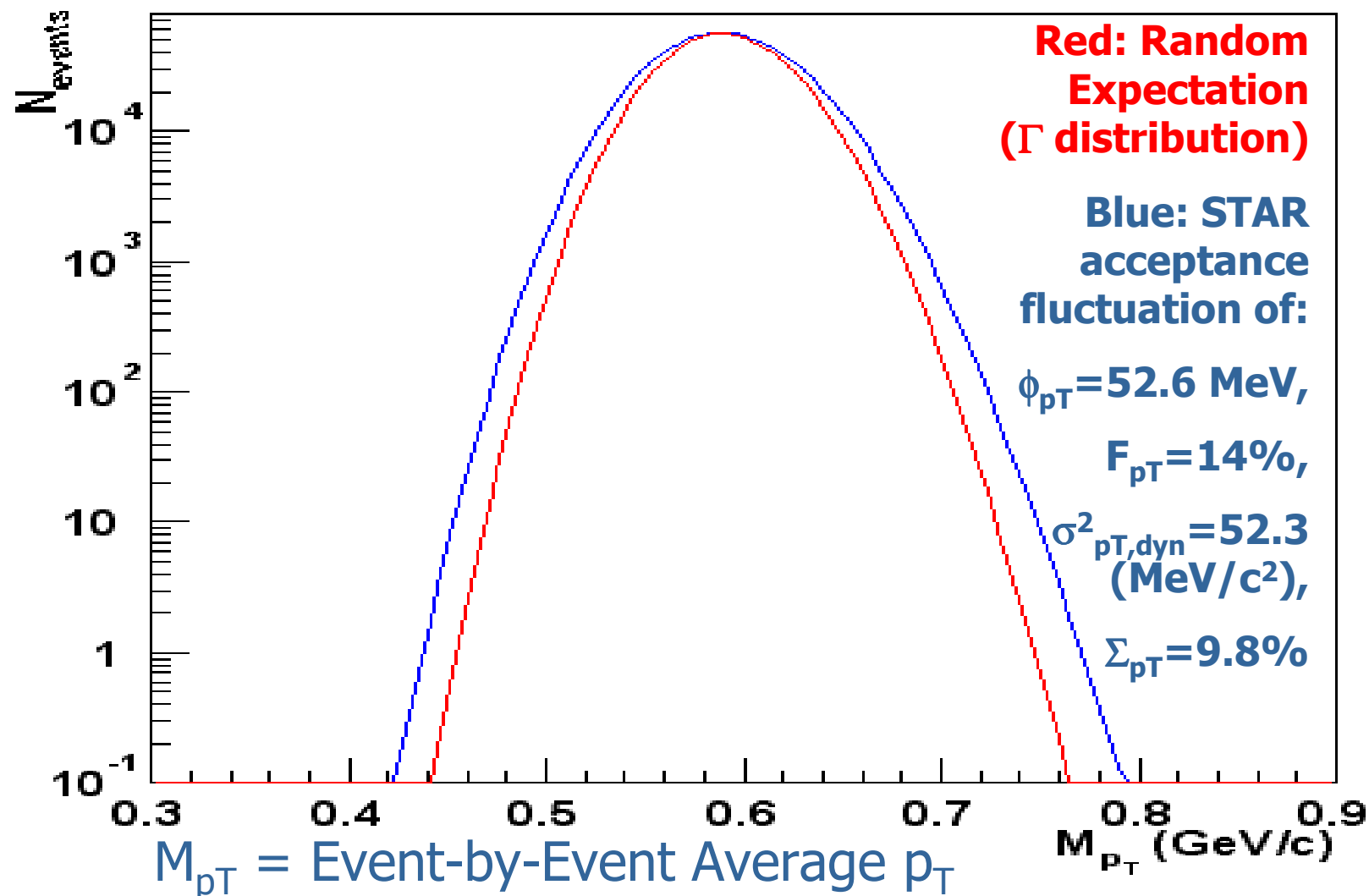
$$\Sigma_{p_T} \equiv \text{sgn}(\sigma^2_{p_T, dyn}) \frac{\sqrt{|\sigma^2_{p_T, dyn}|}}{\bar{p}_T}$$



Σ_{p_T}

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*.

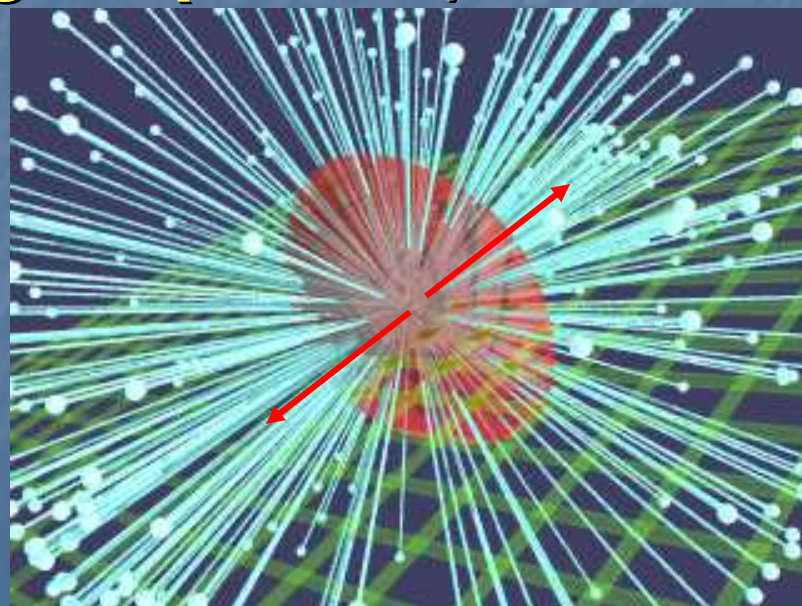


A Positive Signal is Observed!
Known contributions to the $\langle p_T \rangle$ fluctuation
signal should be subtracted.

Contributions from Known Processes

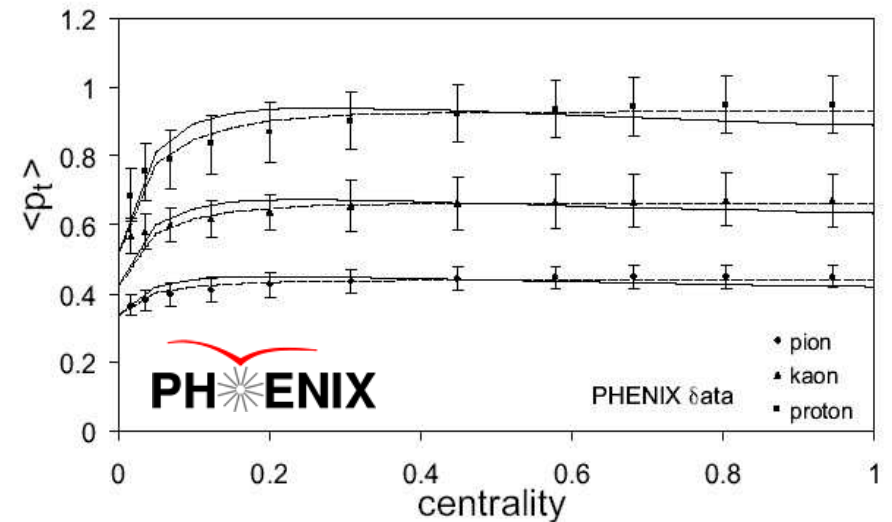
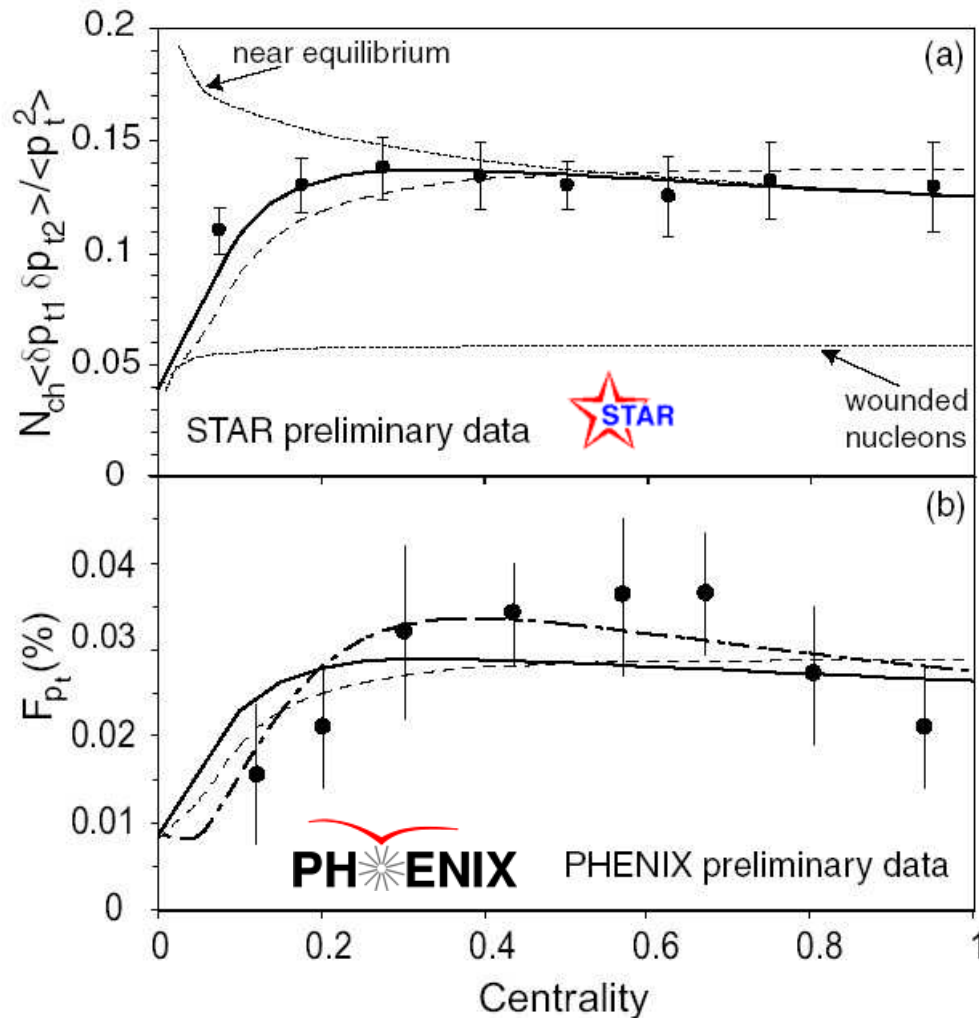
- HBT – too small (NA49, STAR, CERES)
- Resonances – too small (NA49, STAR)
- Elliptic Flow – too small/negligible (PHENIX, CERES, NA49)
- Hard Processes...
- Or onset of thermalization...

*A Schematic
Illustration of
Elliptic Flow*

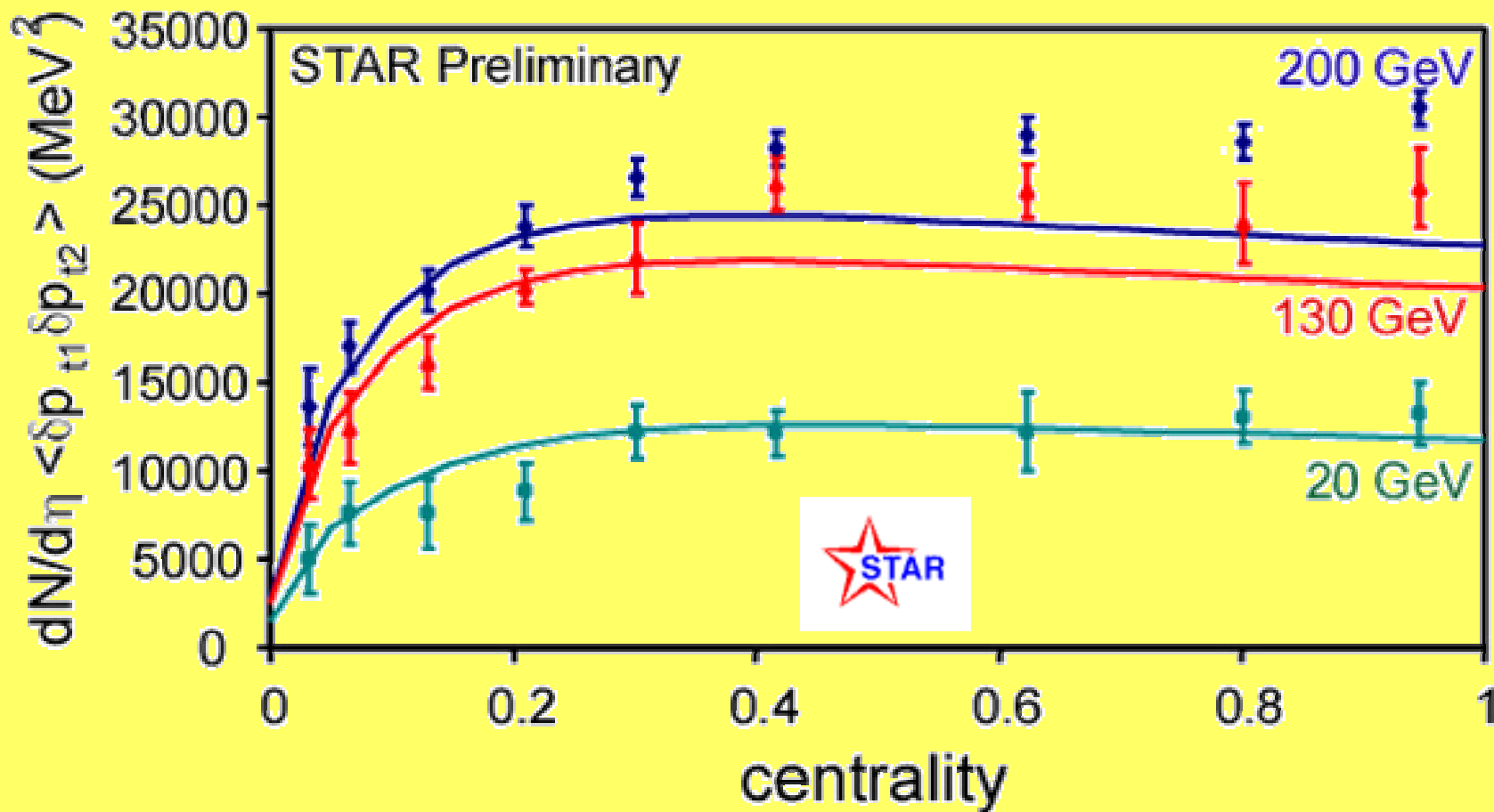


A Possible Explanation of the Signal: A System in Near-local Thermal Equilibrium

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



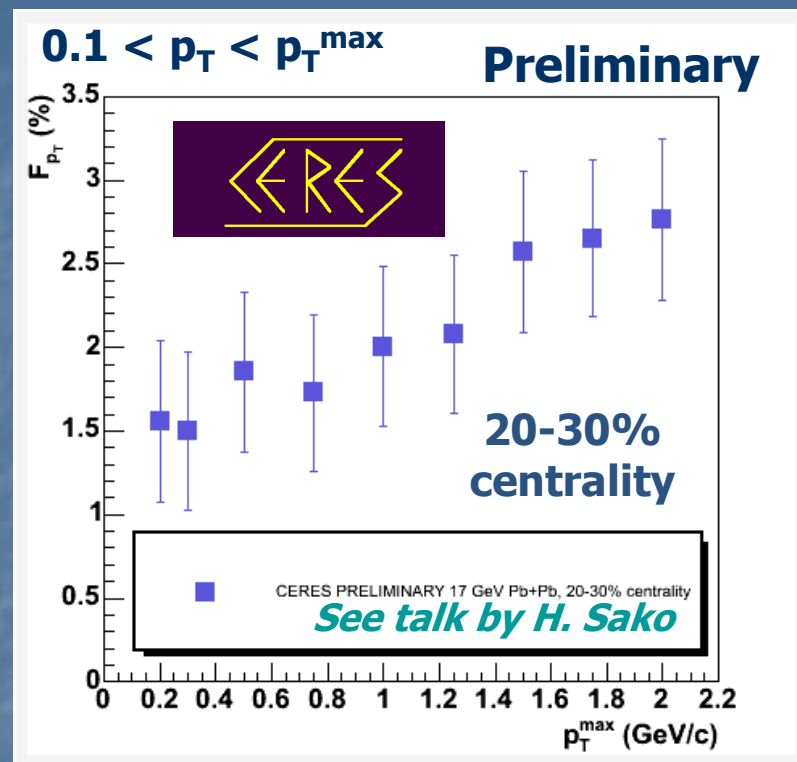
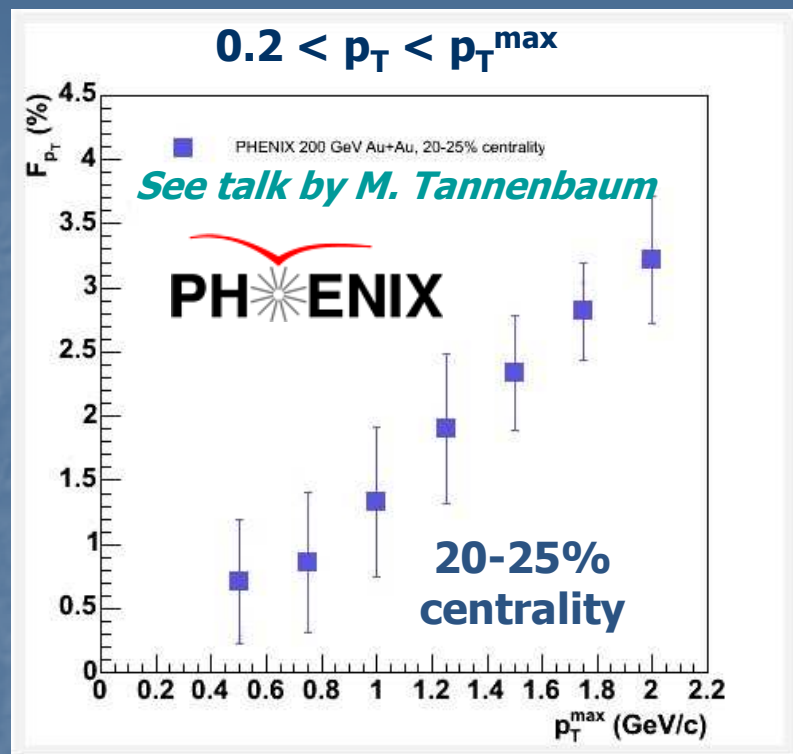
The onset of thermalization?



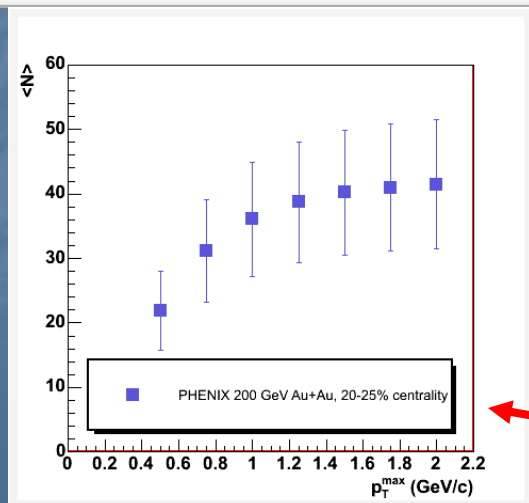
$$\frac{dN}{d\eta} \langle \delta p_{t1} \delta p_{t2} \rangle \propto \Phi_{p_t}$$

*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.

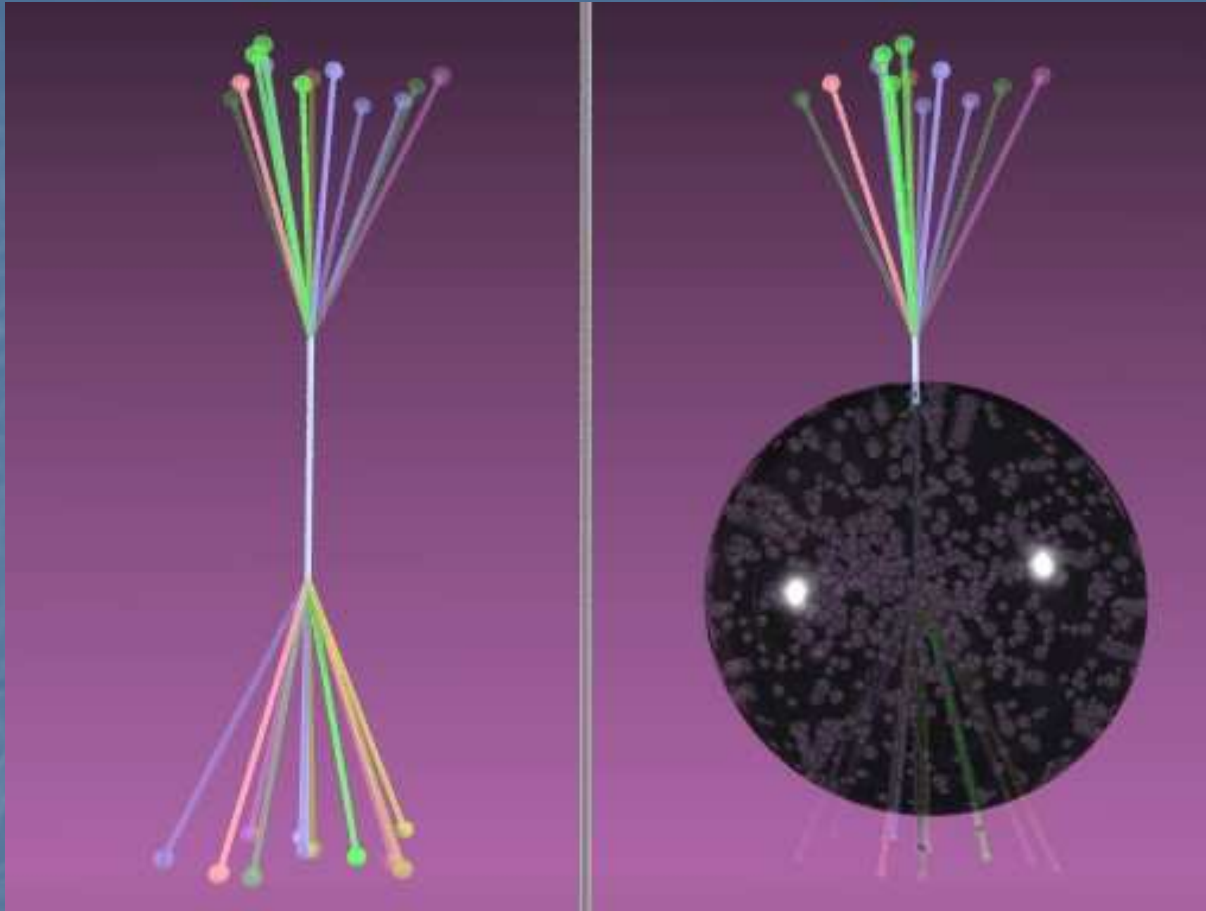
Increases from $p_T^{\max} = 1.0$ to $2.0 \text{ GeV}/c$

PHENIX Fluctuations: 243%

CERES Fluctuations: 34%

$\langle N \rangle: < 15\%$

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?

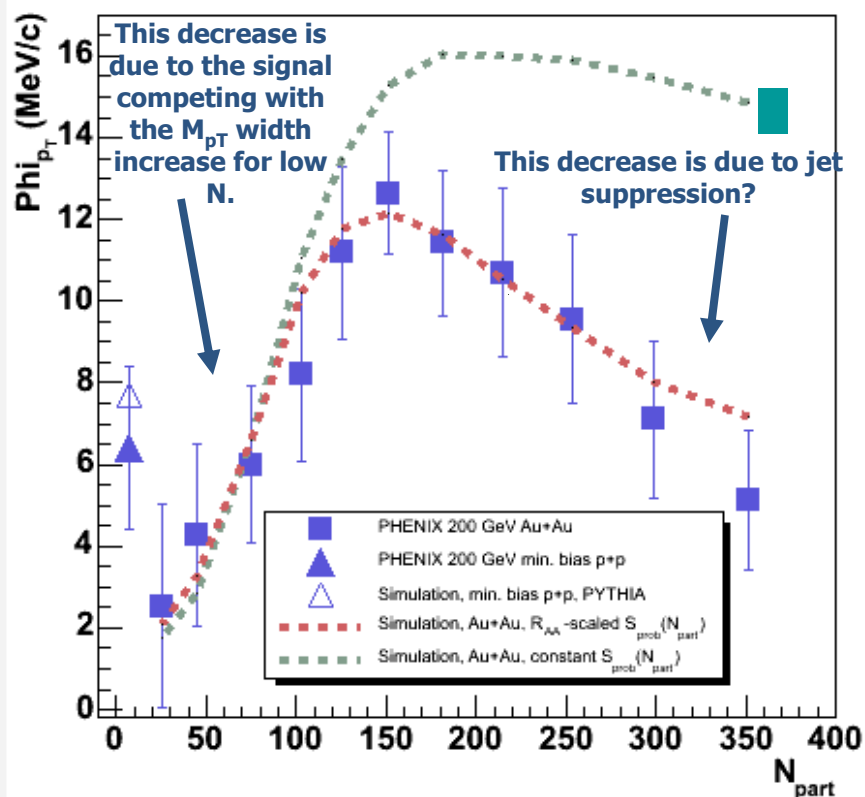
Jet Simulation Results: PHENIX at 200 GeV

Results from a 2-component hybrid simulation.

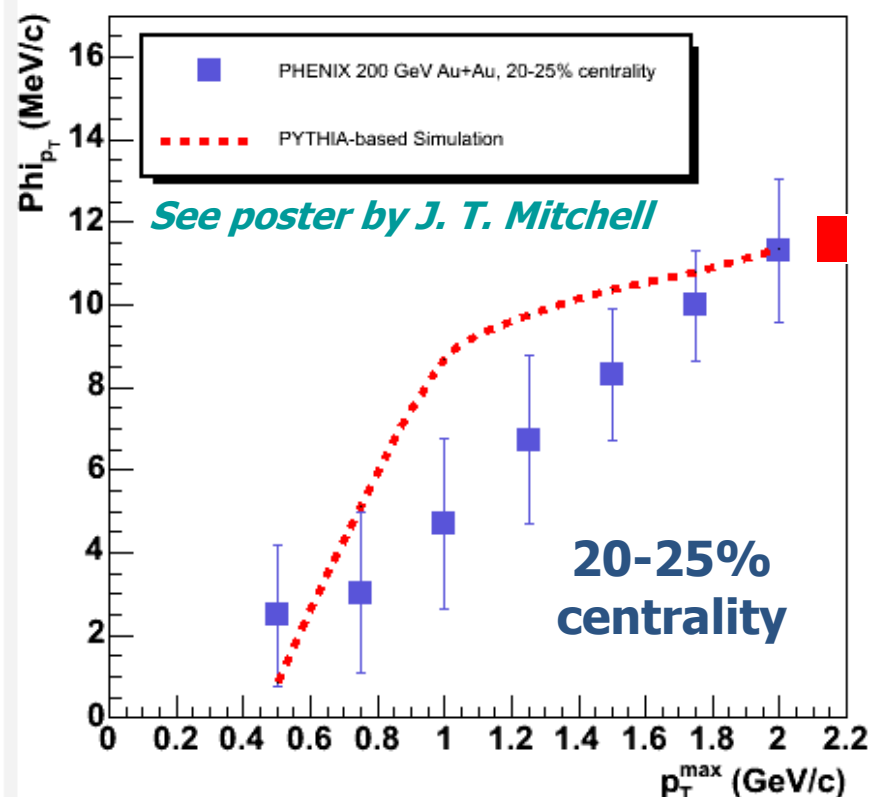
Component 1: Reproduce soft processes by sampling the inclusive p_T and N data distributions.

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} .

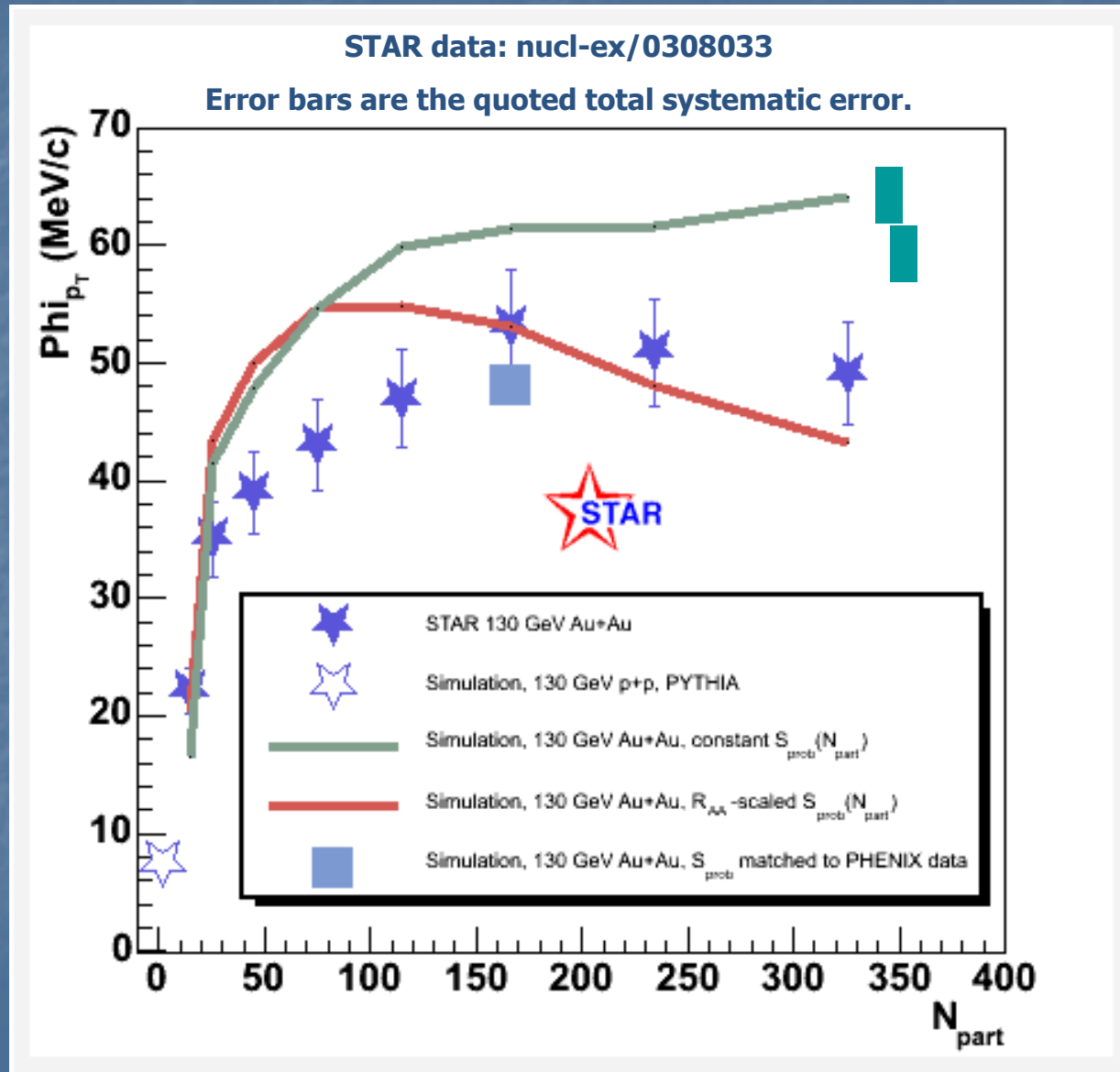
PHENIX Data: nucl-ex/0310005



PHENIX

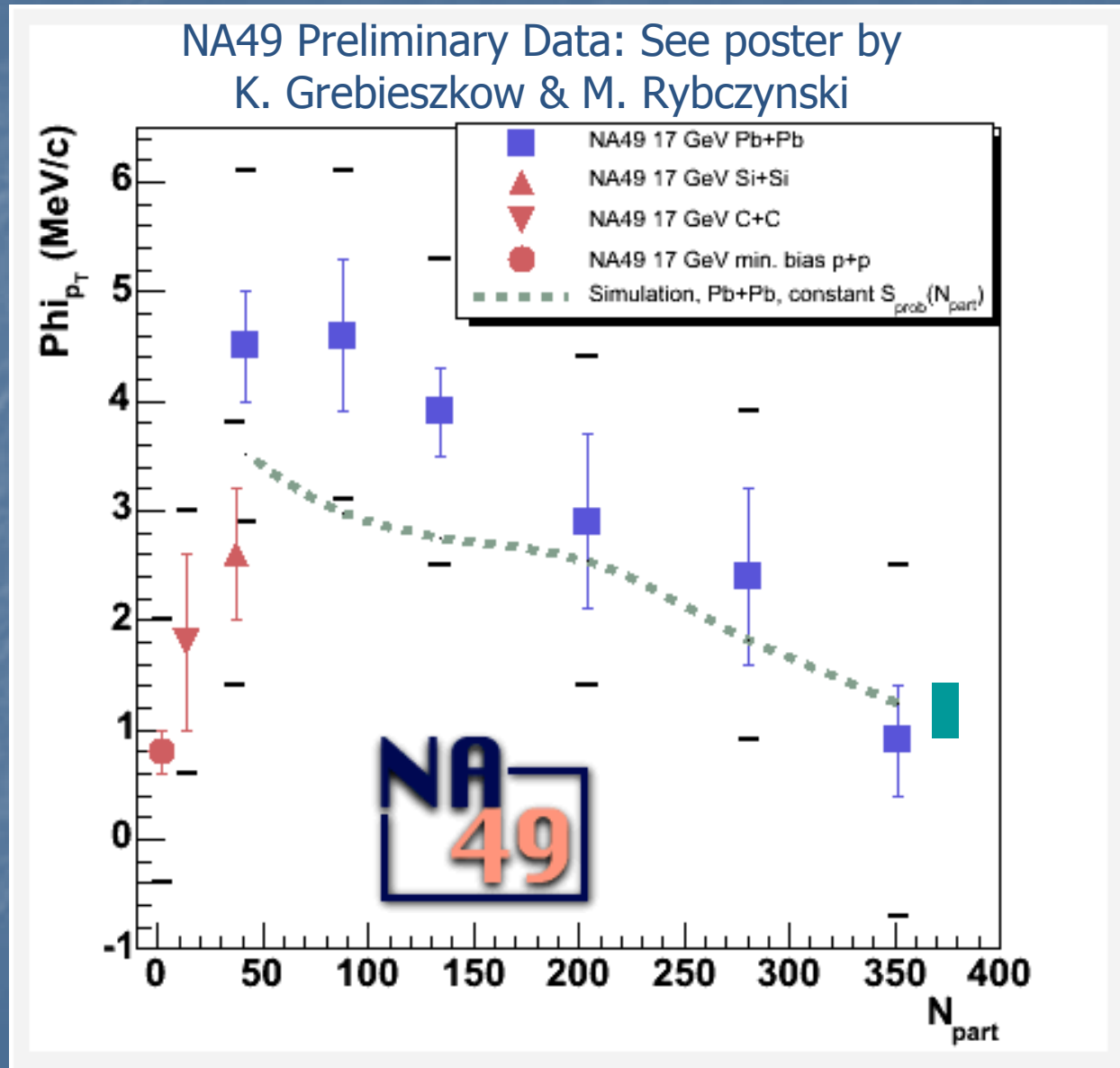


Jet Simulation Results: STAR at 130 GeV



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

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

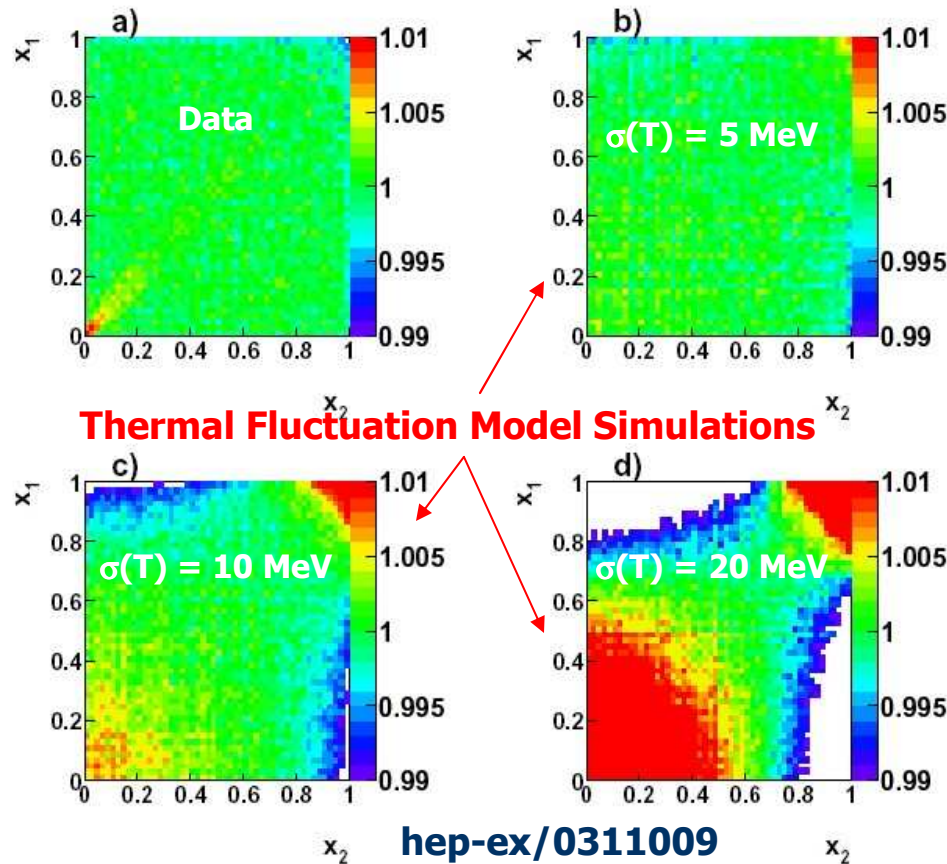
p → inclusive p_T , $\Gamma(p, b)$, $p \sim 1$

R. Korus and S. Mrowczynski,
Phys. Rev. C64 (2001) 054908.

Measurement	sqrt(s _{NN})	$\sigma_T/\langle T \rangle$, Most central	$\sigma_T/\langle T \rangle$, 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

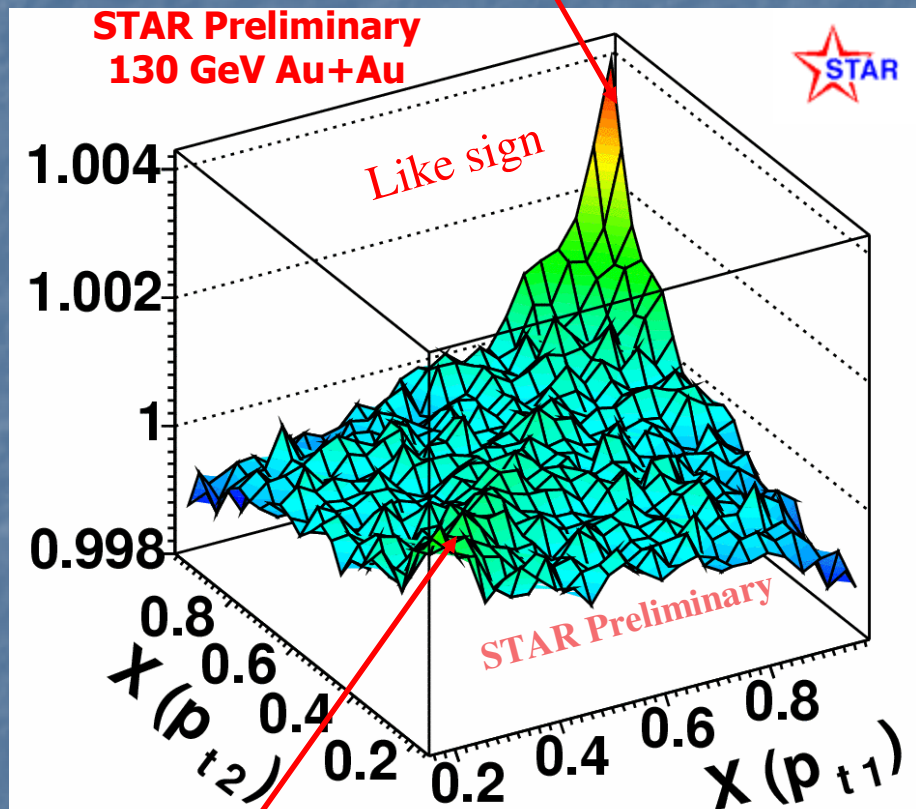


$$x(p_T) = \frac{\int_0^{p_T} \frac{dN}{dp_T} dp_T}{\int_0^\infty \frac{dN}{dp_T} dp_T}$$



Jeffery T. Mitchell (BNL) – QM2004

Higher p_t pairs from hard scattering ?



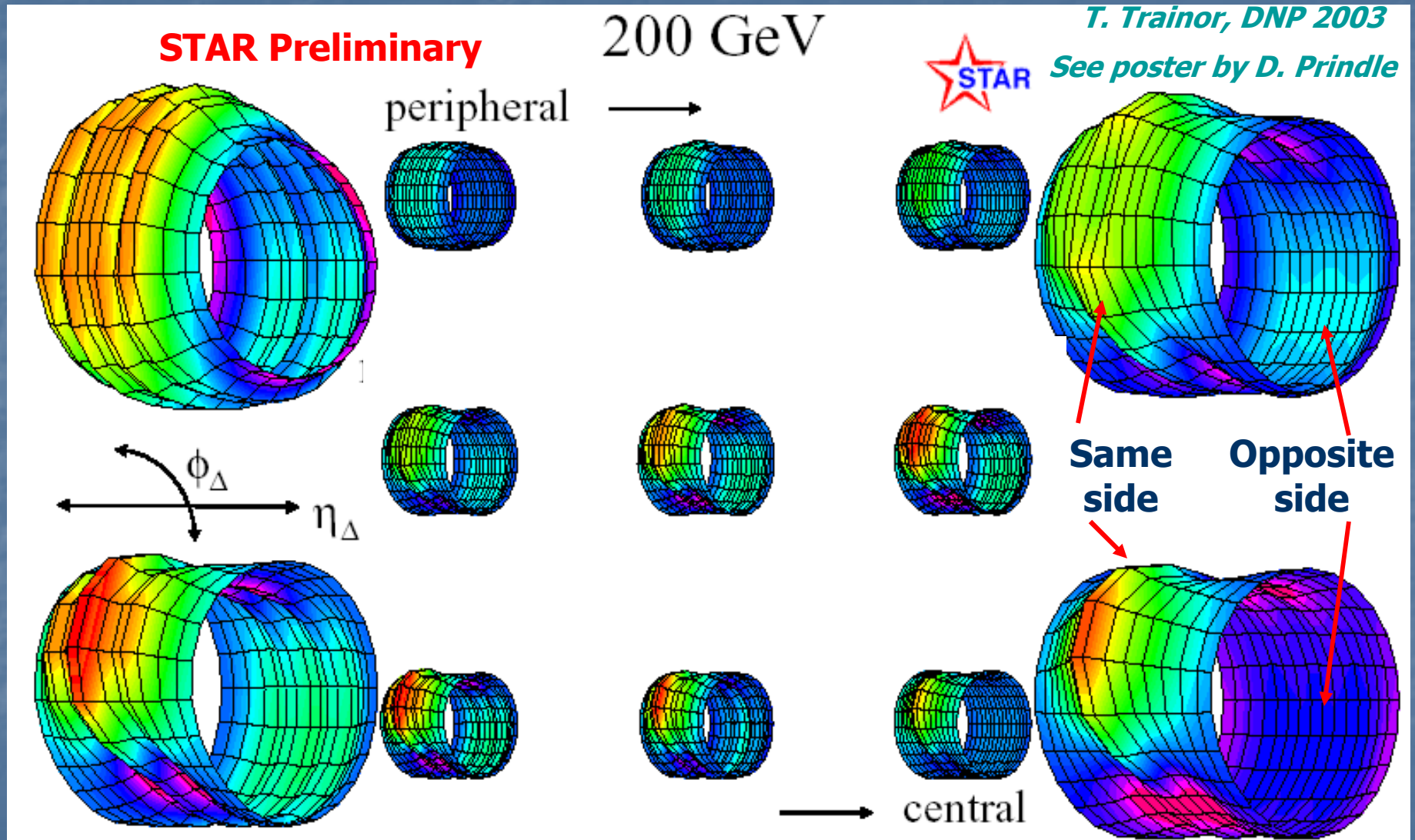
L. Ray, DNP 2003, see his poster

HBT and Coulomb interaction

In PHENIX, $x(1.5 \text{ GeV/c}) \sim 0.93$

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.