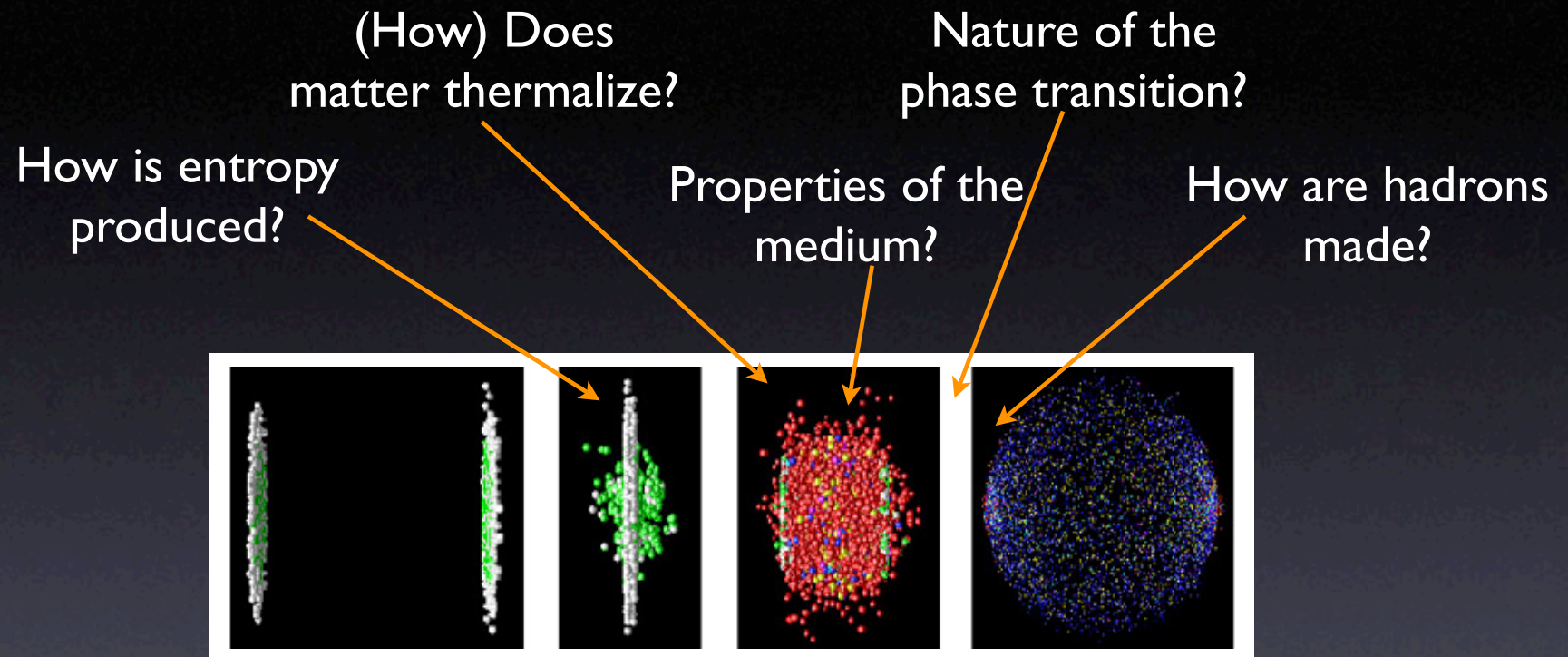


Energy and μ_B dependence of Event-by-event Fluctuations

*BNL Users Meeting workshop
June 5 2006*

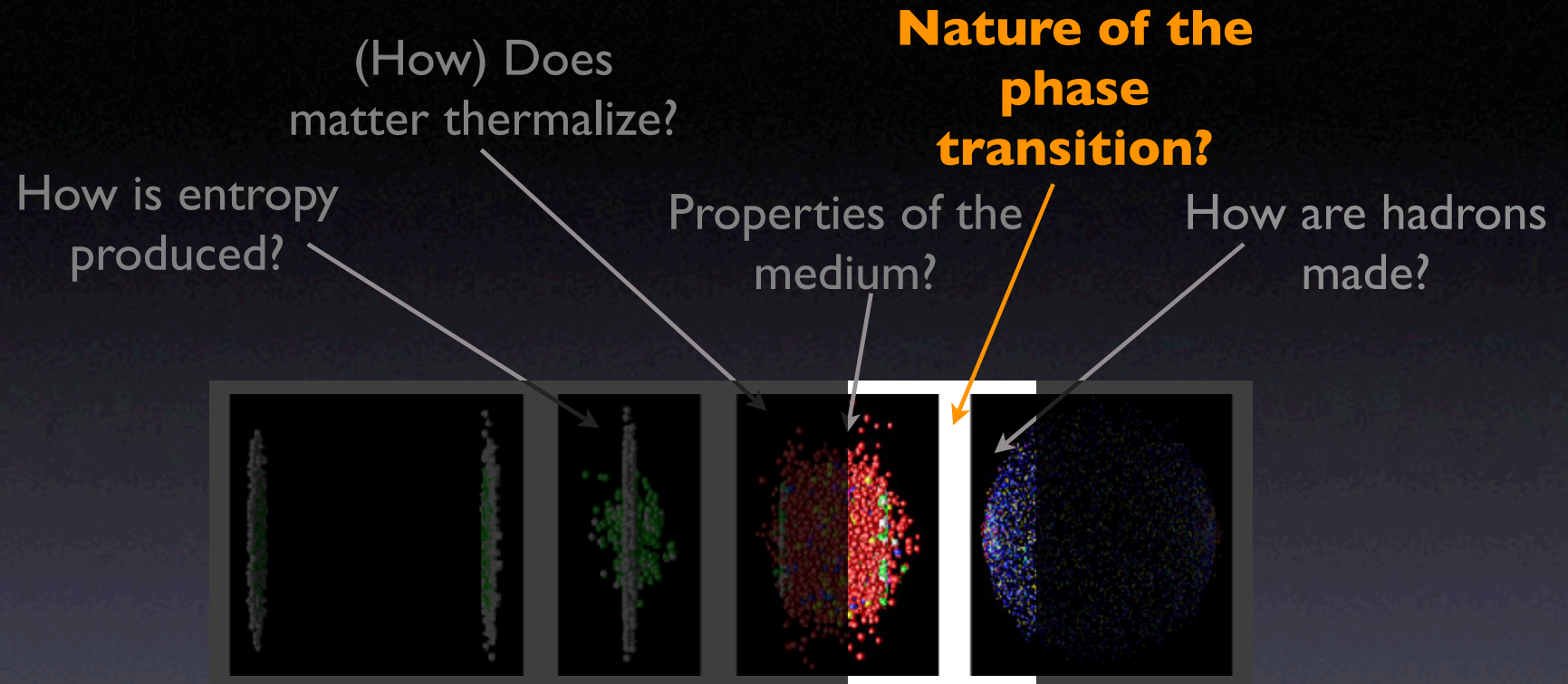
Gunther Roland
MIT

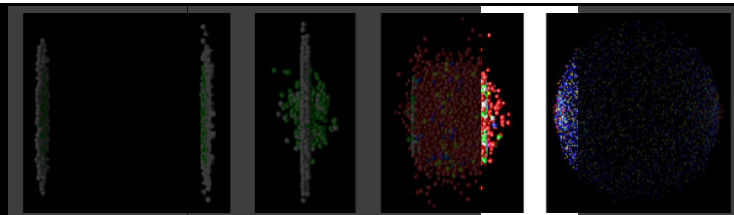
Event-by-event Fluctuations



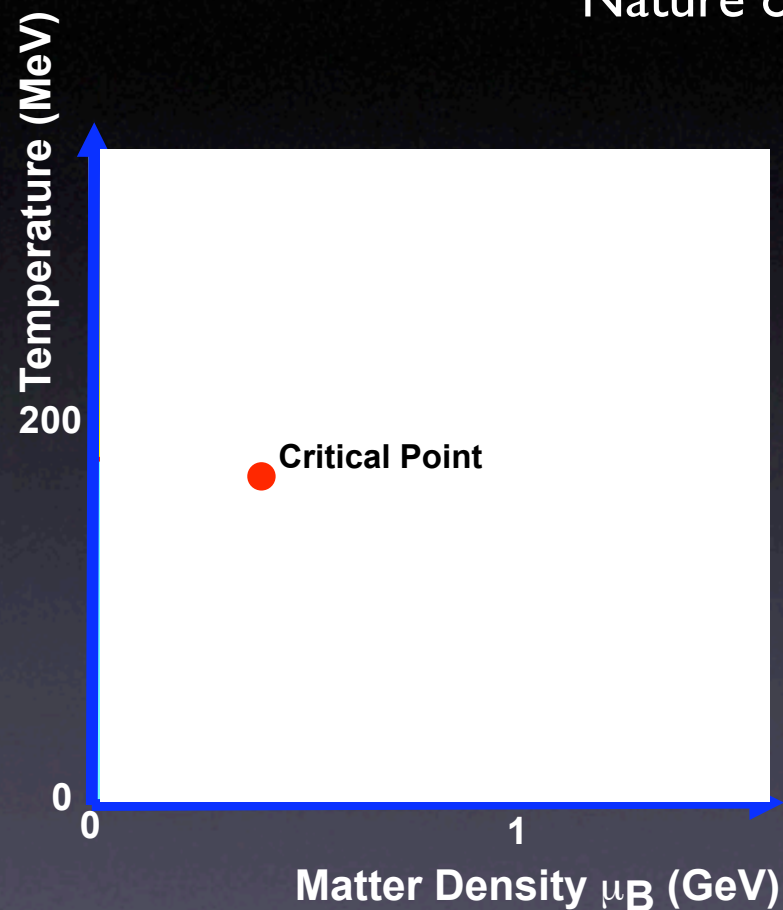
Answers to all of these questions
from fluctuations/correlations

Event-by-event Fluctuations





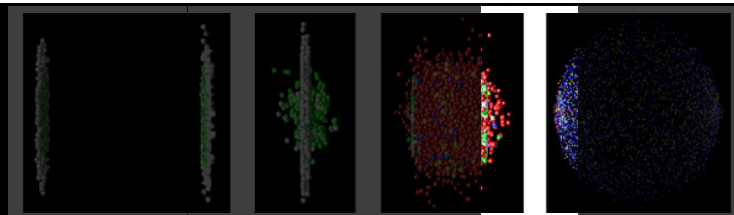
Nature of the Phase Transition



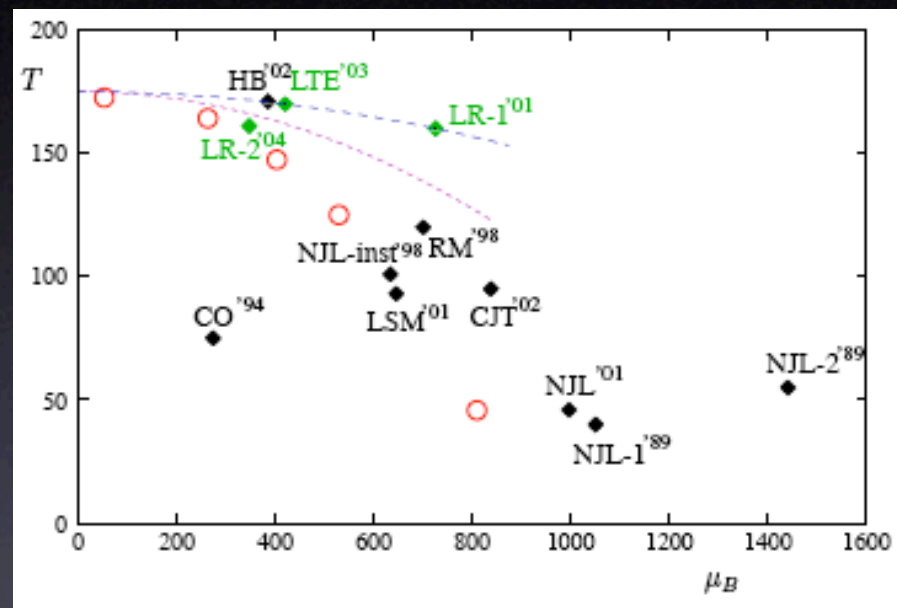
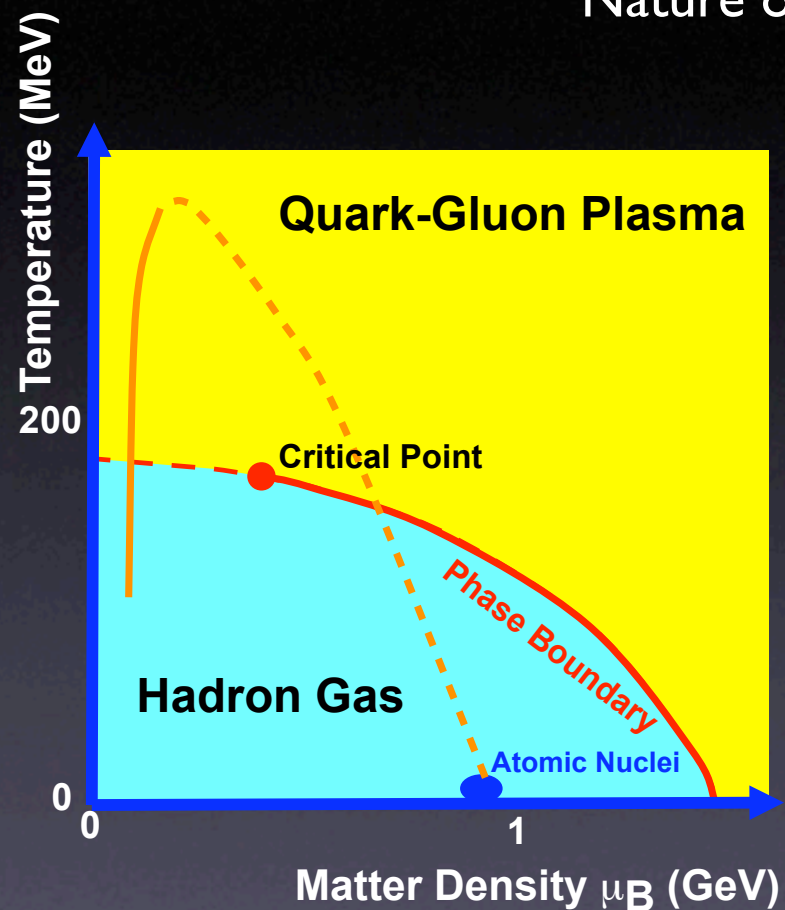
Correlation length diverges near critical point

Locate the critical point using correlation/fluctuation measurements

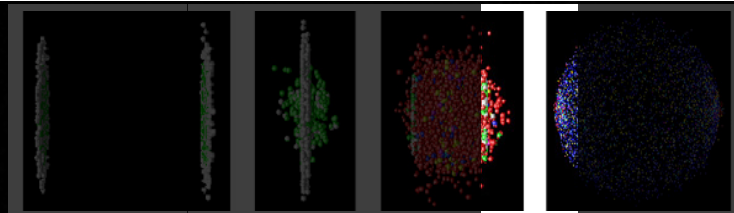
Rajagopal, Shuryak,
Stephanov



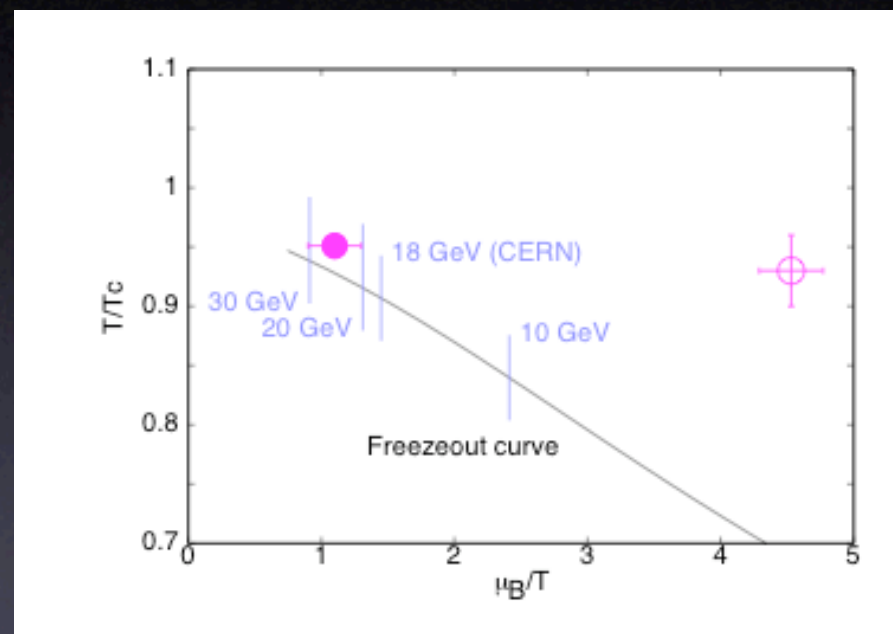
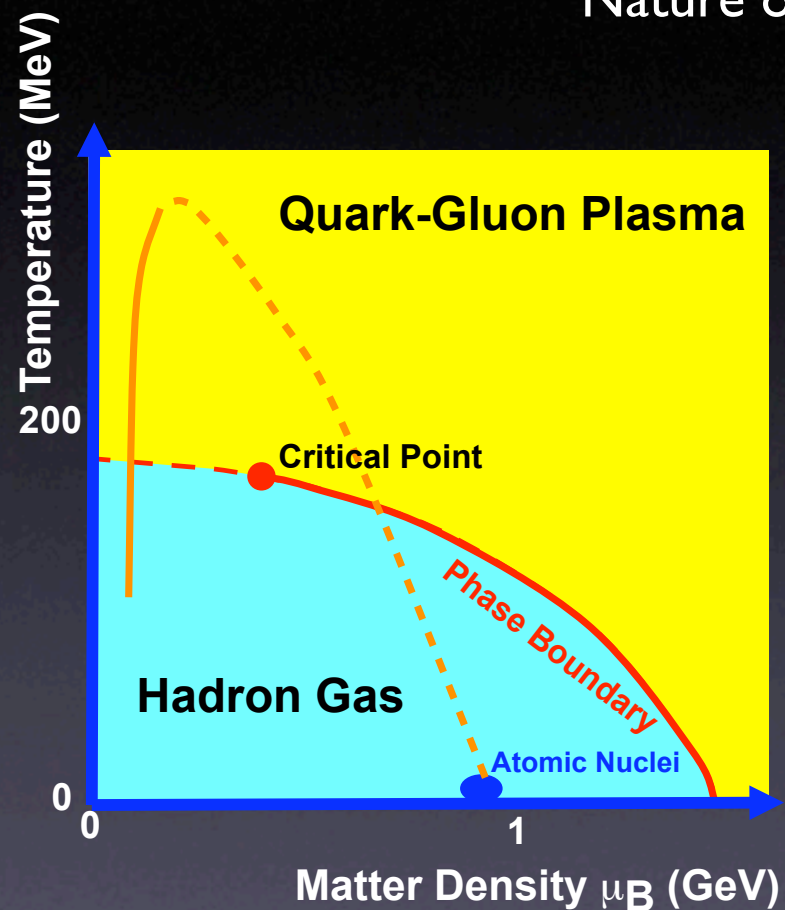
Nature of the Phase Transition



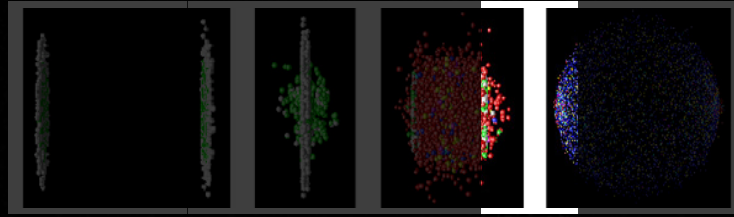
Plot from M. Stephanov,
Correlations '05



Nature of the Phase Transition

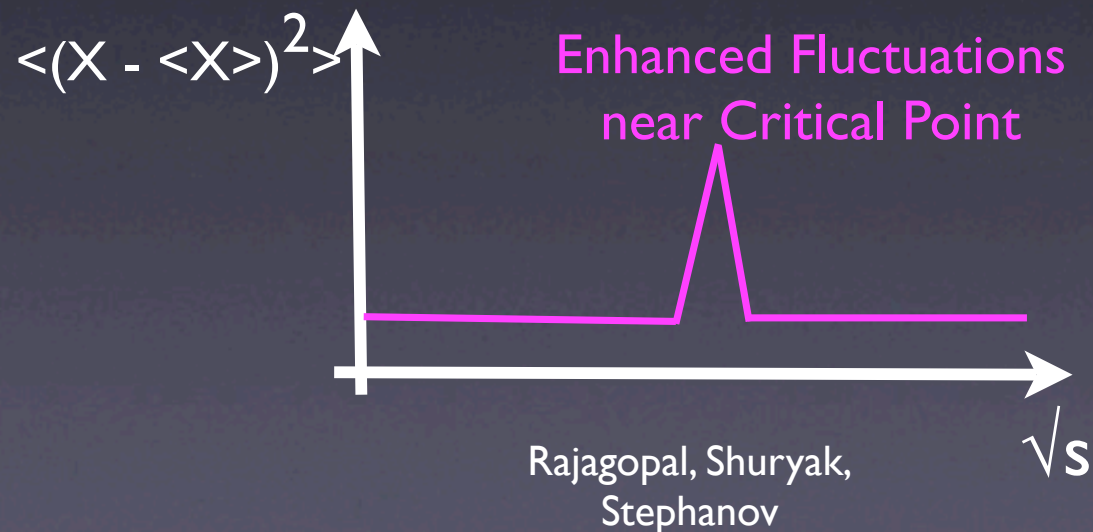


Plot from S. Gupta,
CERN HIF, May '06



Nature of the Phase Transition

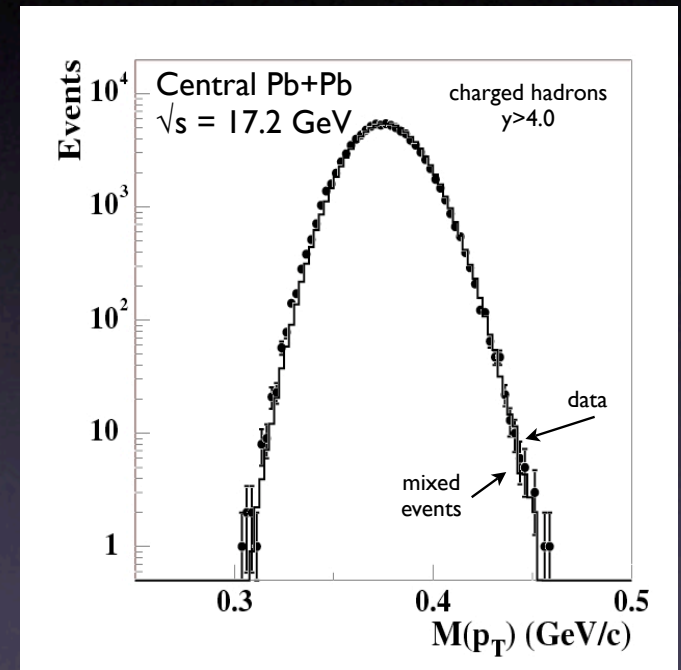
- Theoretical guidance is limited
- Experimental strategy:
 - Search in different observables, correlate observables
 - Fine grained exploration of μ_B , T space



First result on $\langle p_T \rangle$ fluctuations (1999)

- p_T - simple observable (supposedly...)
- High statistical precision:
 - $\sigma_{p_T}/\langle p_T \rangle_{inc} < 0.1\%$
- Sensitive to many interesting scenarios
 - Critical Point
 - DCC production
 - Droplet formation
 - **Any non-statistical, momentum-localized process**

NA49, Phys Lett B459 (1999) 679

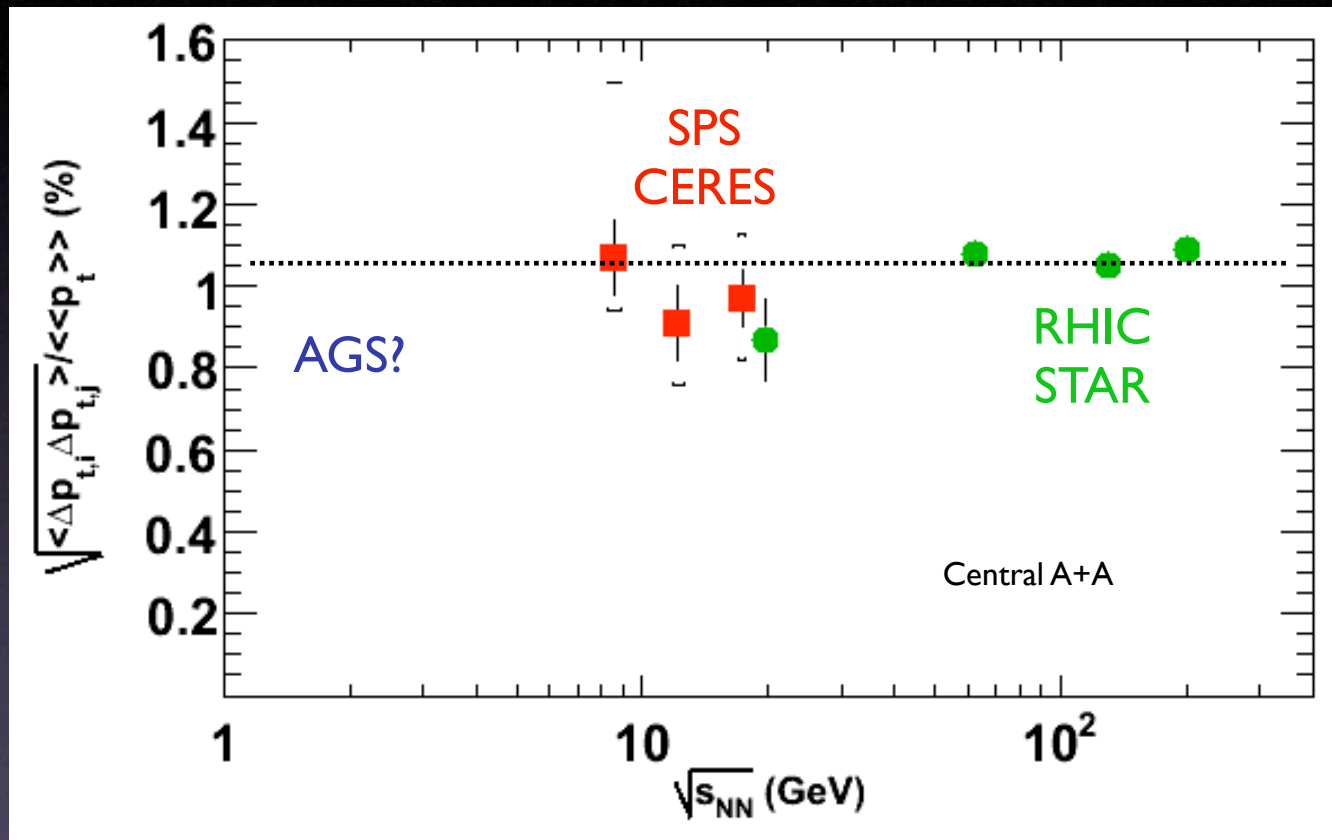


Event-by-event $\langle p_T \rangle$ compared to stochastic reference (mixed events)

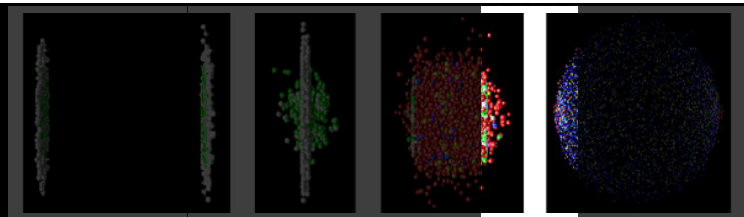
Dynamical Fluctuations: $\sigma_{p_T, \text{dyn}}^2 = \sigma_{M(p_T)}^2 - \sigma_{M(p_T), \text{mixed}}^2$

Excitation Function: Momentum Fluctuations

Compilation by STAR
STAR PRC 72 044902 (2005)



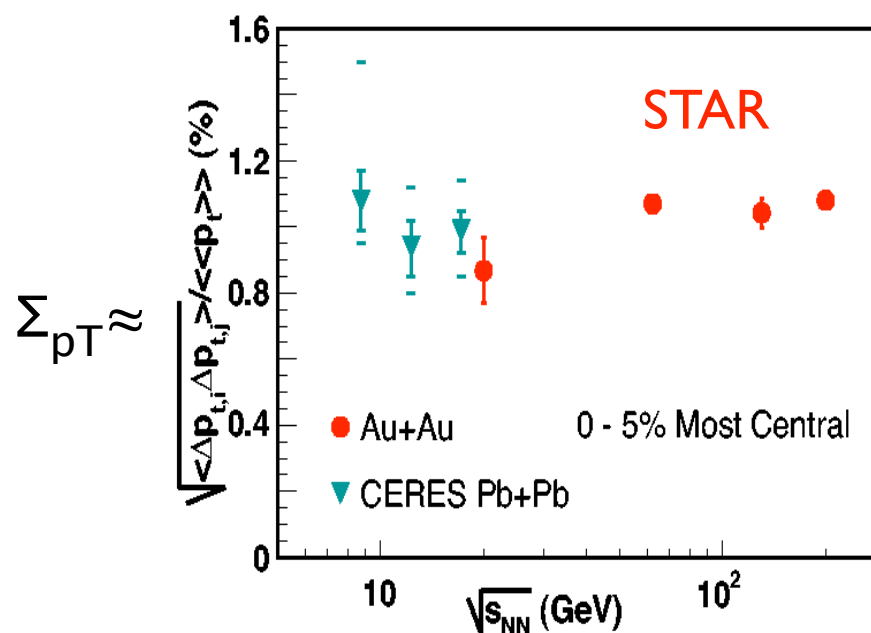
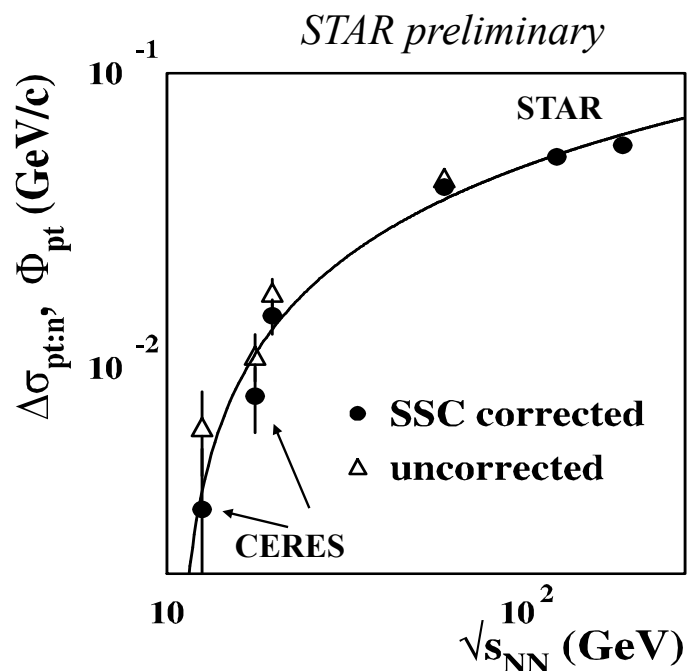
Monotonic energy dependence over measured range



Nature of the Phase Transition

$\langle p_T \rangle$ Fluctuations

Scaling: Connection between $\langle p_T \rangle$, N , fluctuations?



Connection to
2-particle
correlations

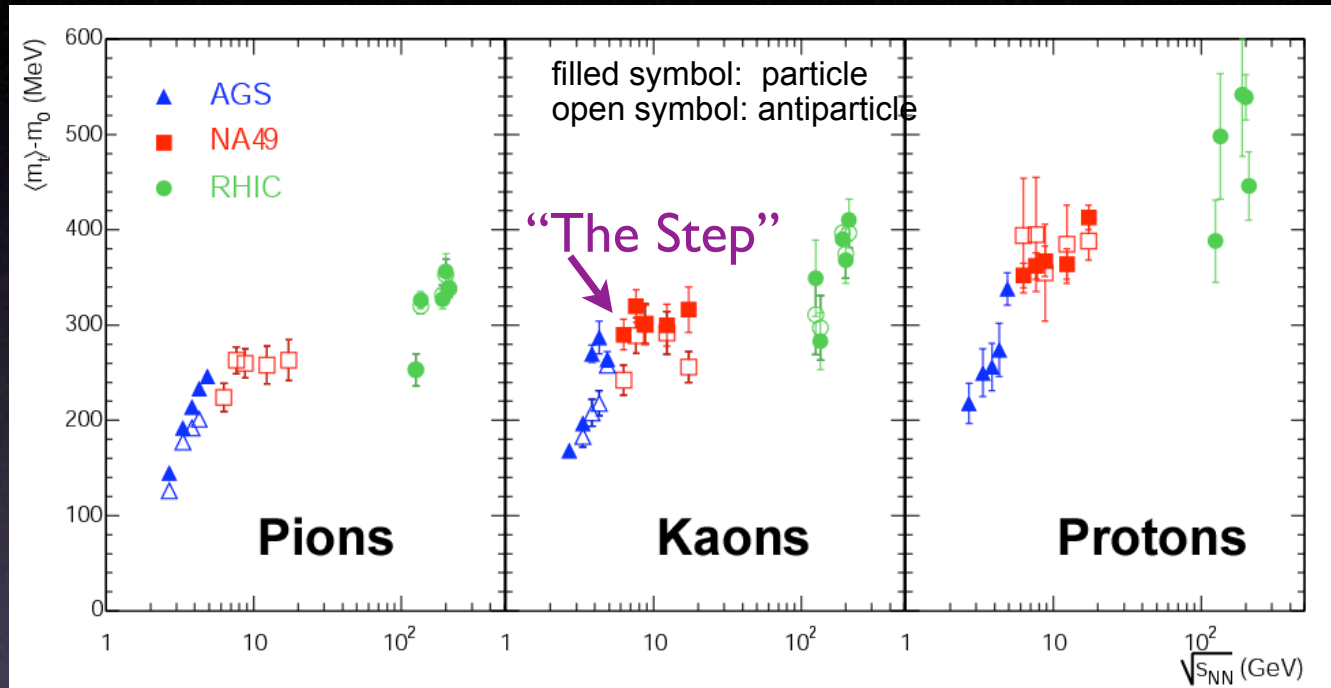
Normalization to $\langle p_T \rangle$

Normalization per particle
Linear or quadratic measures

$$\Sigma_{pT} \simeq \sqrt{\frac{2\Phi_{pT} \sqrt{\sigma_{\hat{p}_T}^2}}{N \bar{p}_T^2}}$$

Excitation Function: Momentum Spectra

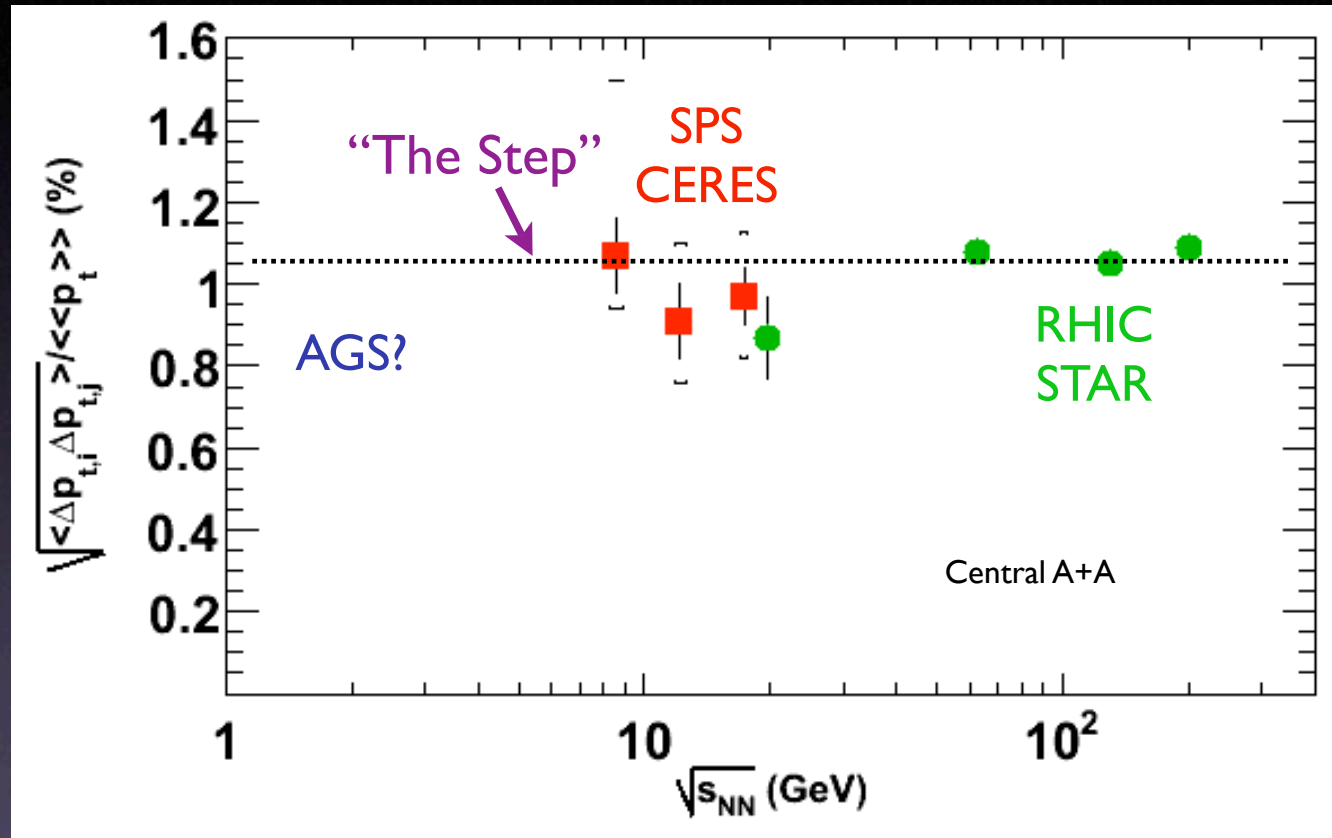
Compilation by NA49
Plot from Claudia Hoehne, QM'05



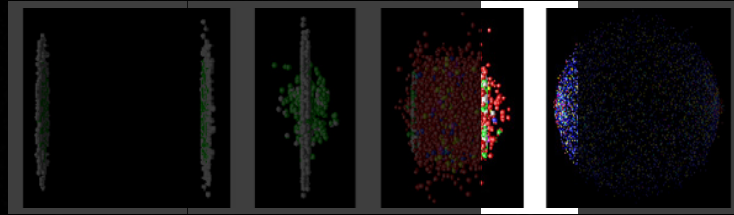
- Structure in energy dependence of $\langle m_T \rangle$
- Reminiscent of Van Hove's T vs ϵ prediction (1982)
- Surprisingly difficult measurement
 - Decay corrections, PID acceptance

Excitation Function: Momentum Fluctuations

Compilation by STAR
STAR PRC 72 044902 (2005)



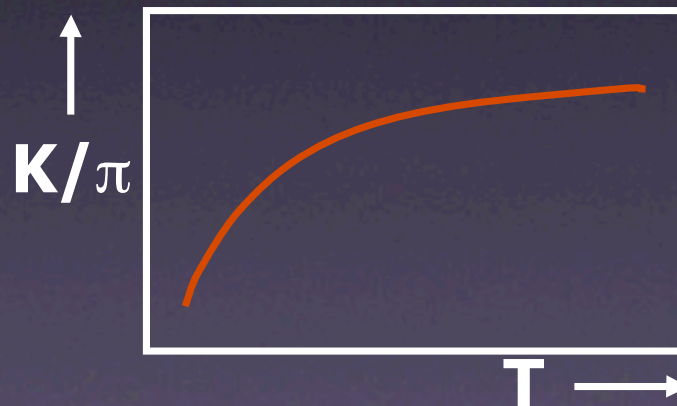
Monotonic energy dependence over measured range
No results near “step” region

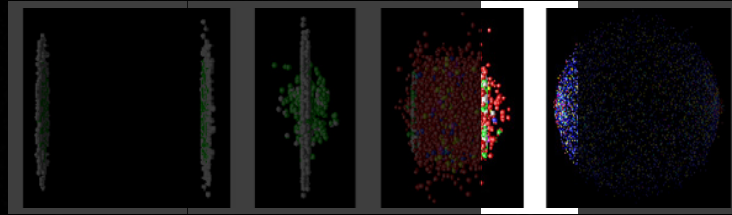


Nature of the Phase Transition

K/π Fluctuations

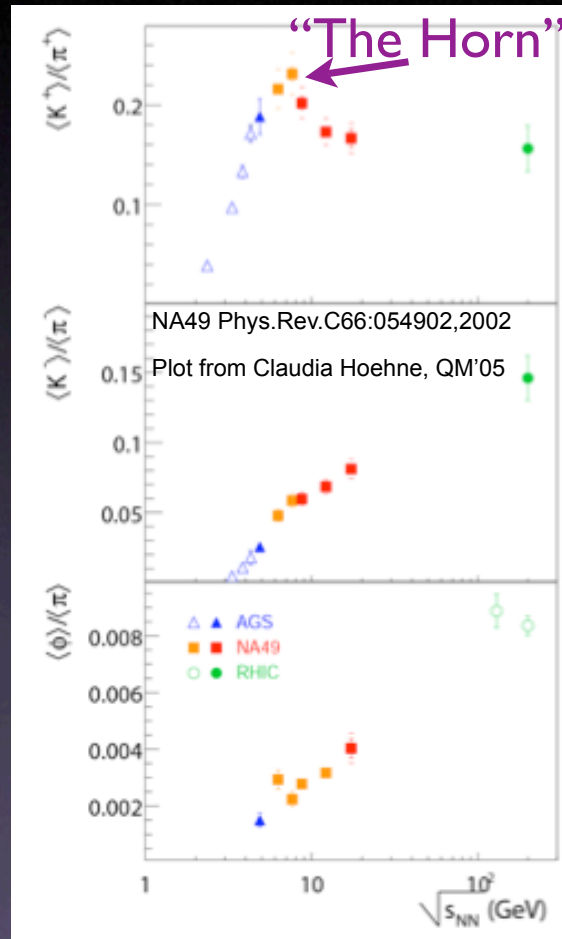
- Is strangeness enhanced in every event?
- Can we see signs of super-cooling below T_{crit} ?



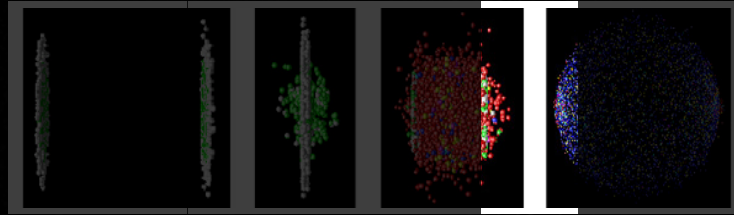


Nature of the Phase Transition

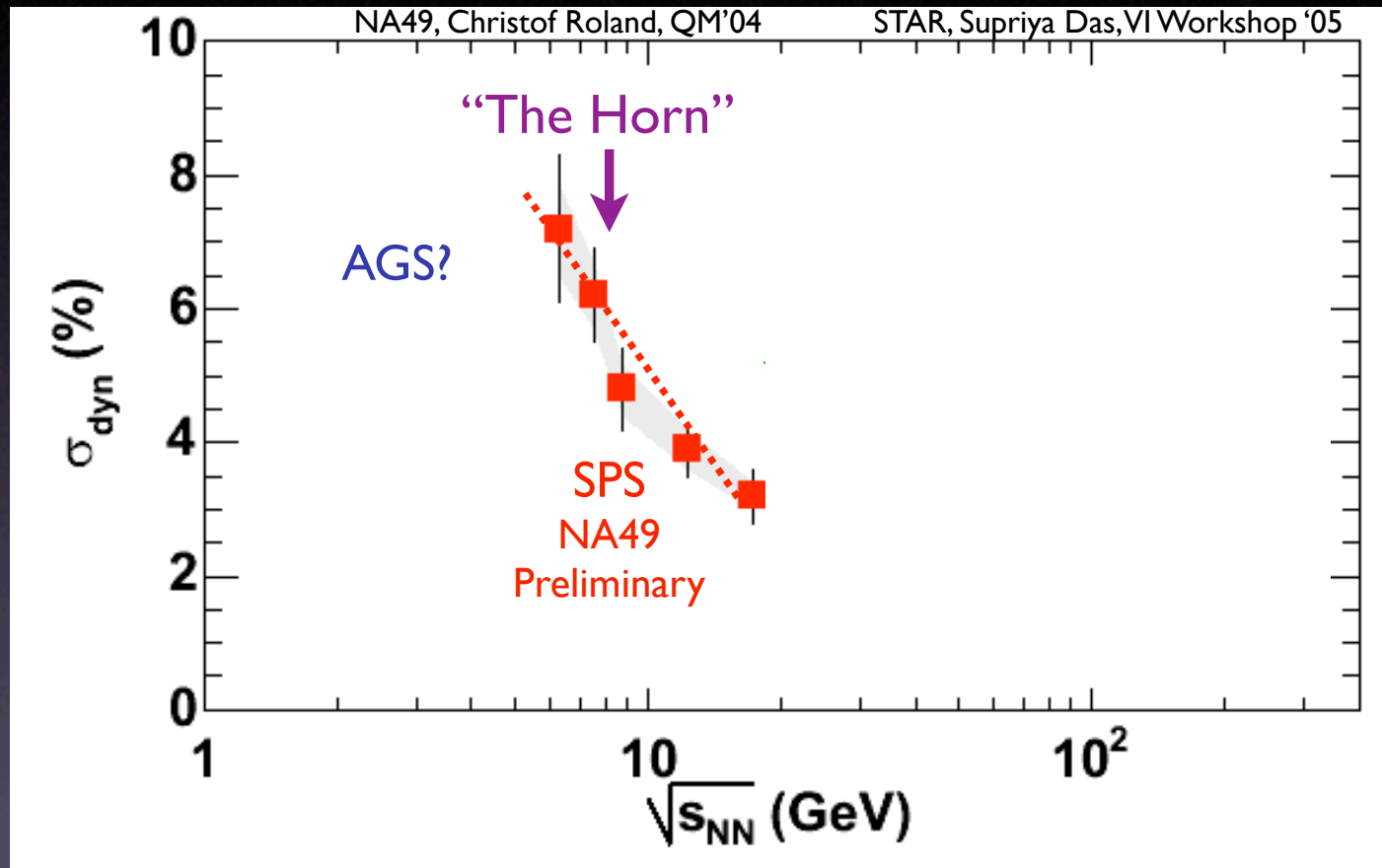
Average K/π ratio



Non-monotonic behavior at AGS/SPS boundary

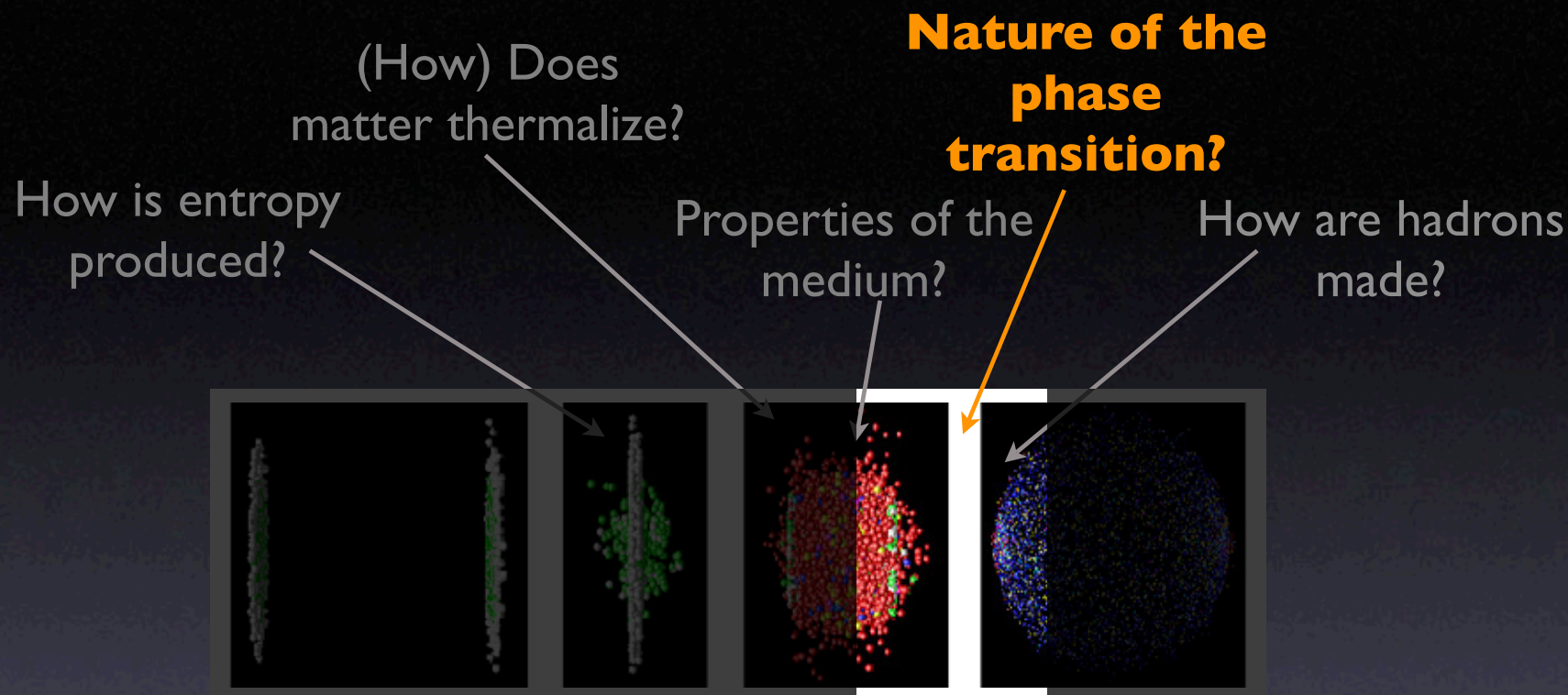


Nature of the Phase Transition



Strong increase at low energy
Comparison between experiments difficult

Fluctuations and the Phase Transition



Monotonic $\sqrt{s}$ evolution
of global fluctuations

Magnitude of fluctuations moderate

Scaling of relative fluctuations

Increase in K/π fluctuations at low $\sqrt{s}$

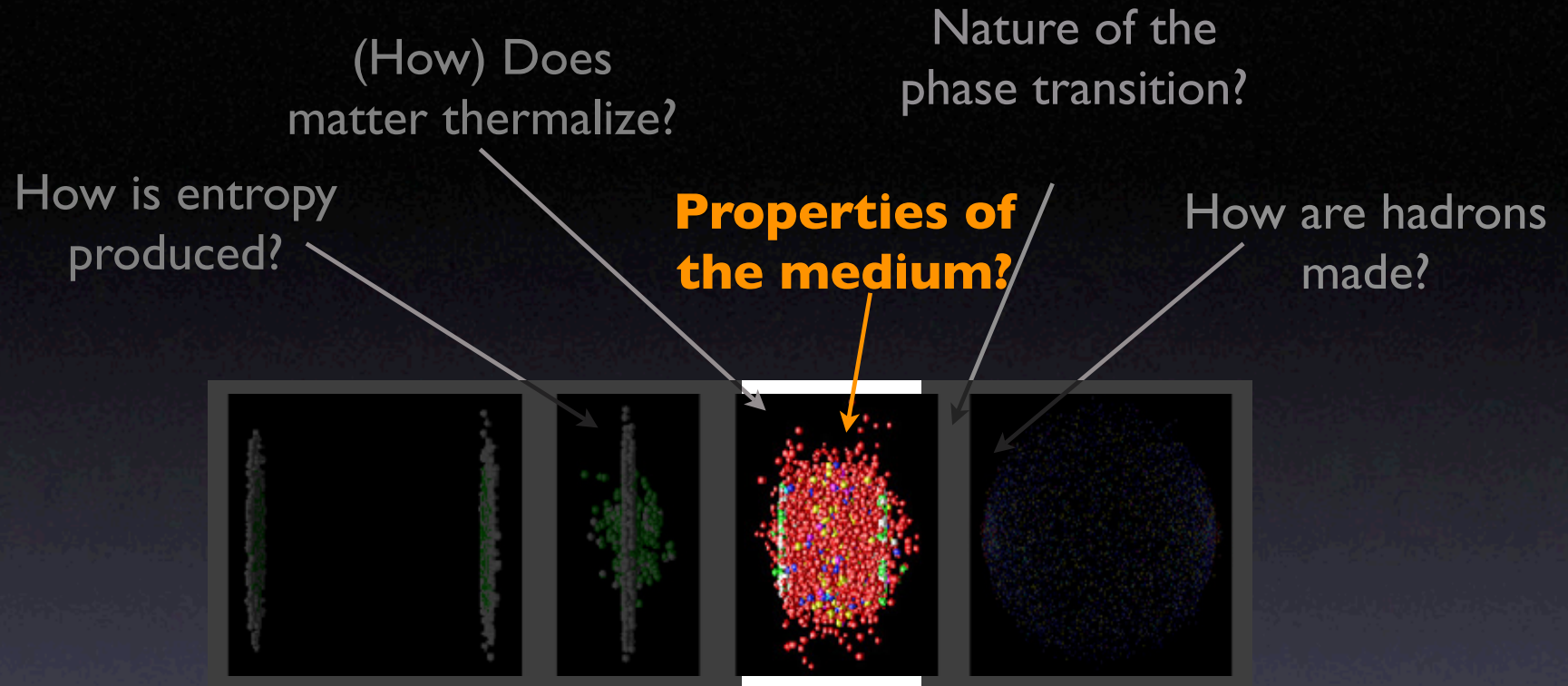
Equilibrium evolution?

Small latent heat?

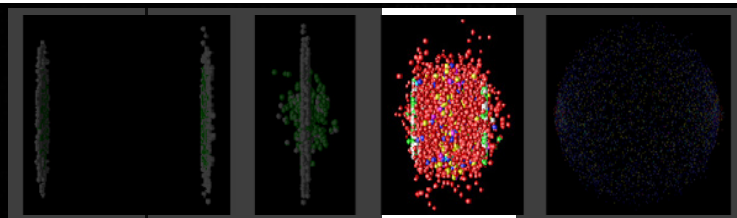
Kinetic freeze-out far from
critical point?

Connection to PT/CP?

Fluctuations and the Phase Transition



ca 2000

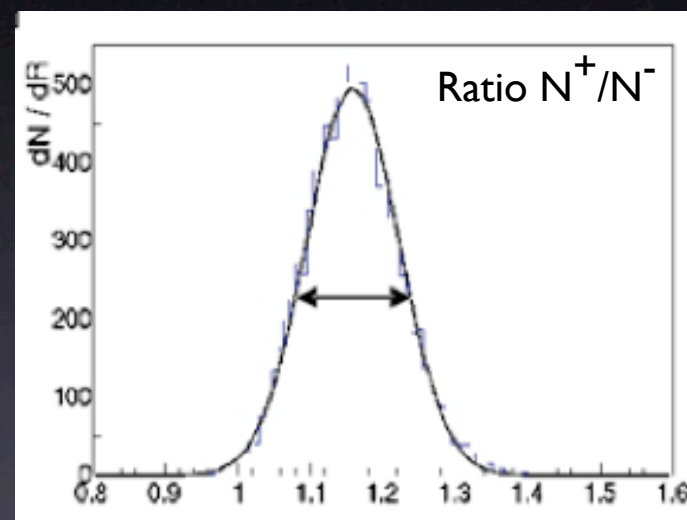


Properties of the Medium

- **Net Charge/ Δy Fluctuations $\Leftrightarrow$ Charge/DoF**
 - Fluc's change from **1-2 (QGP)** to **4 (Pion Gas)**
- **Fluctuations frozen b/c charge conservation**
 - Diffusion vs Expansion timescale

Jeon, Koch PRL (2000) hep-ph/0003168

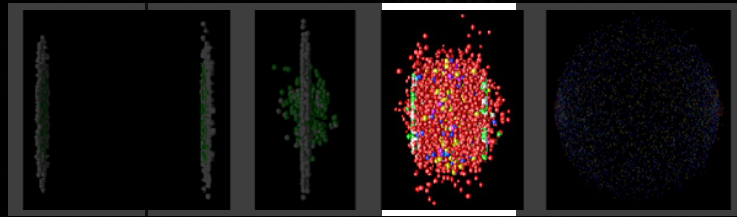
Asakawa, Heinz, Mueller PRL (2000) hep-ph/0003169



Event-by-event distribution of net charge ratio

Note:

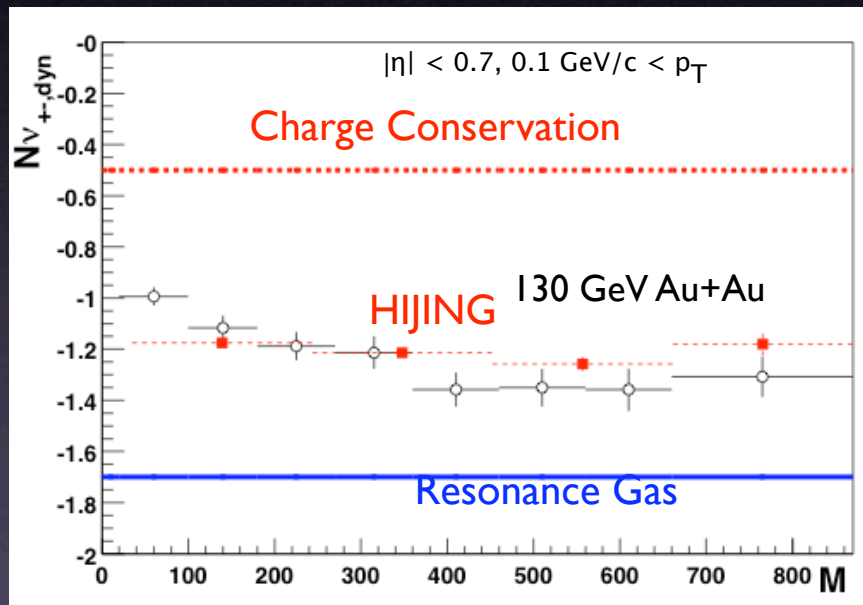
- * Similar for net baryon number
- * Connection to quark number susceptibilities
- * Connection to Critical point



Properties of the Medium

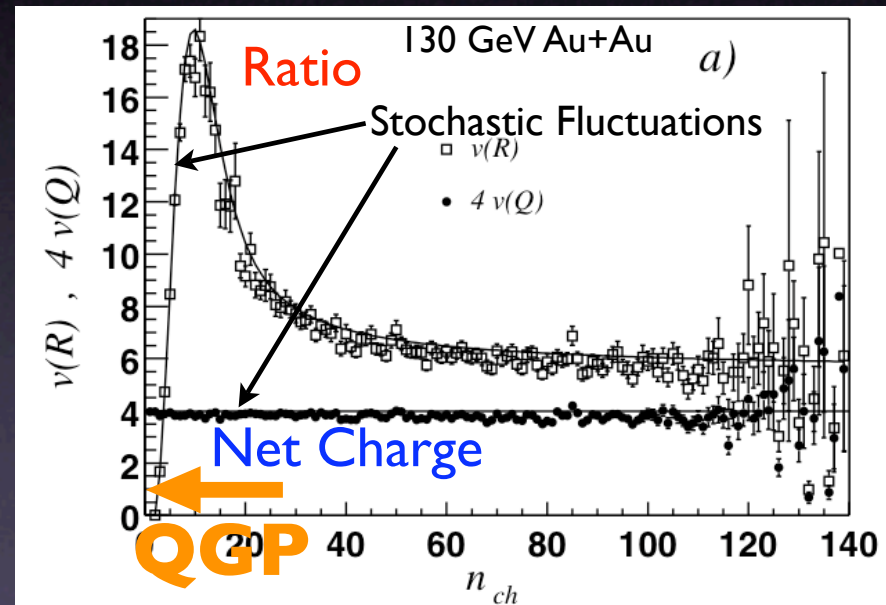
Net Charge Fluctuations

STAR PRC 68 (2003)



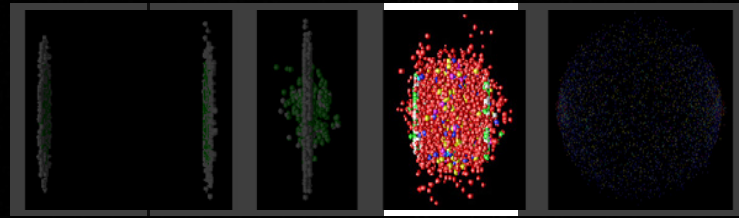
Centrality →

PHENIX PRL 89 (2002)



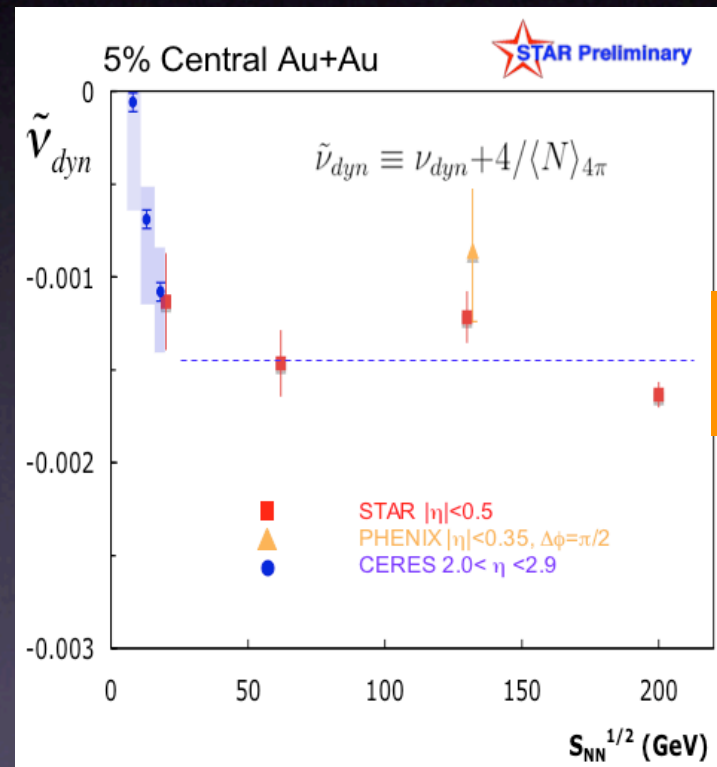
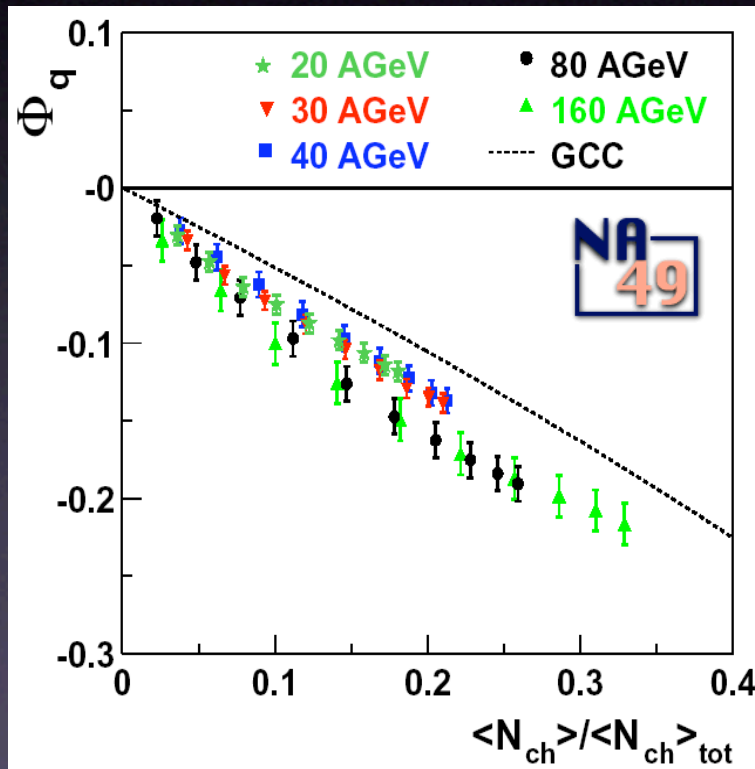
Centrality →

Fluctuations agree with stochastic distributions of Hadrons



Properties of the Medium

Net Charge Fluctuations

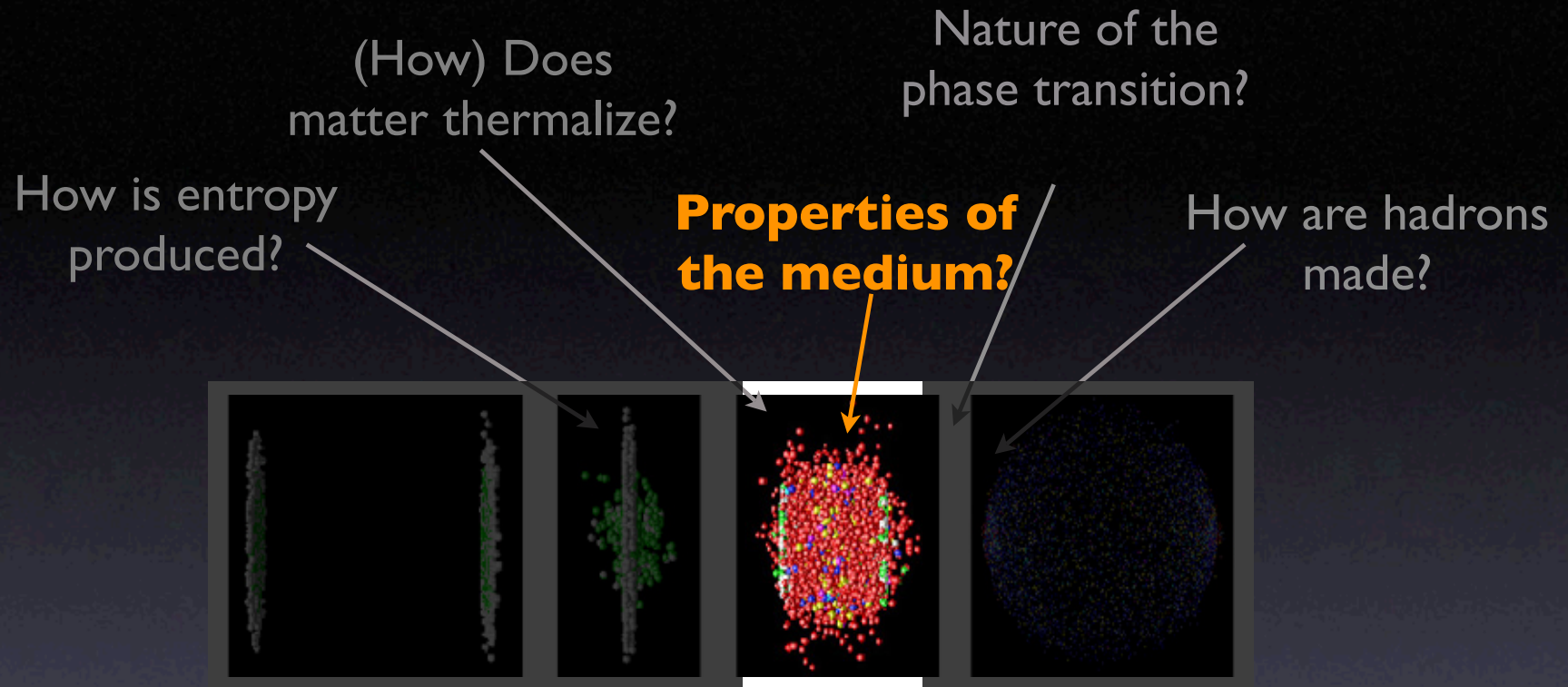


Quark-
Coalescence
Bialas, 2003

QGP
↓

Little (no) $\sqrt{s}$ dependence of charge fluctuations

Energy dependence of charge fluctuations



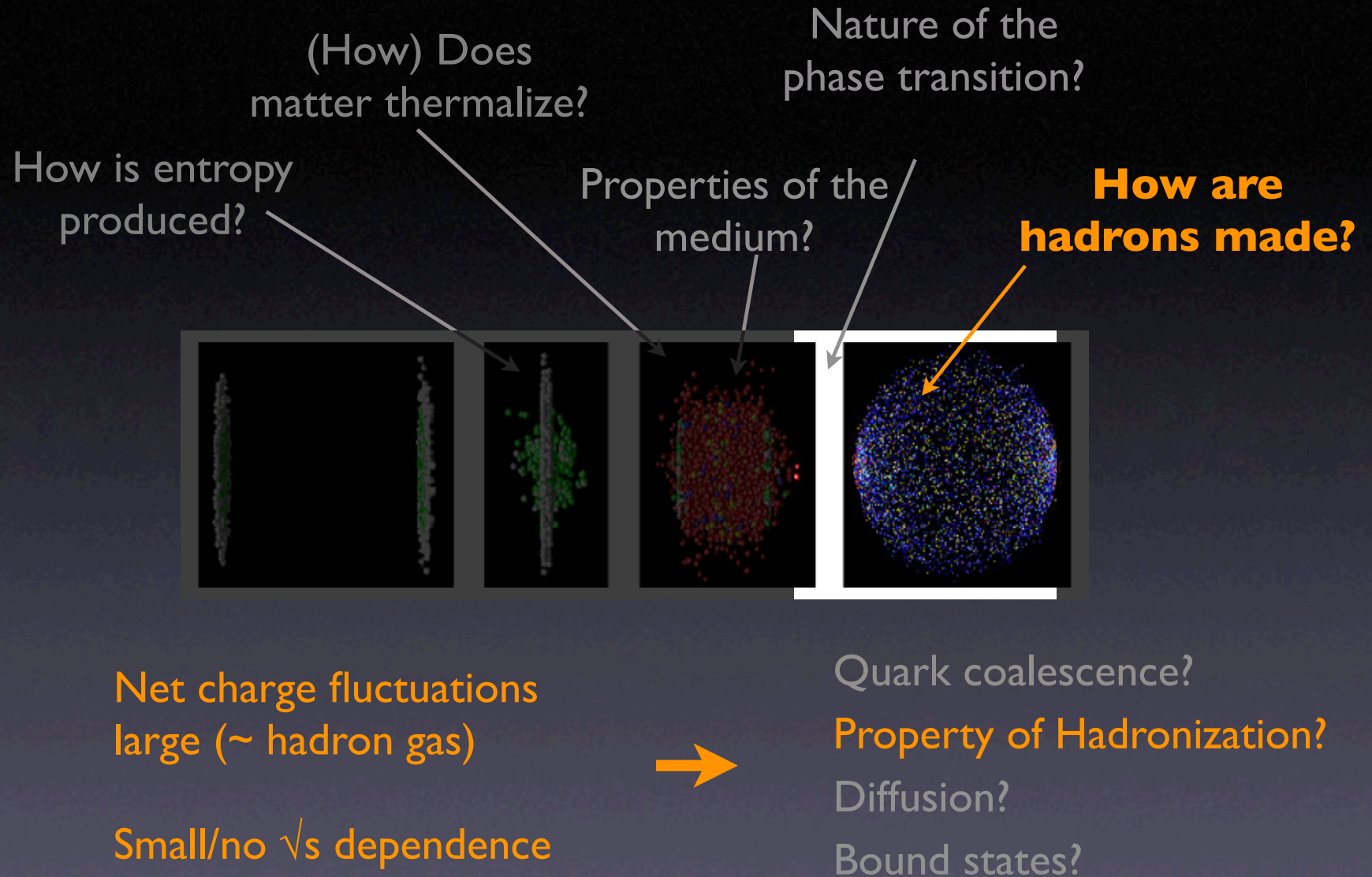
Net charge fluctuations
large ($\sim$ hadron gas)

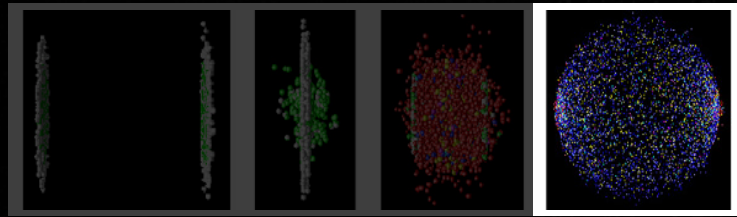
Small/no $\sqrt{s}$ dependence



Quark coalescence?
Property of Hadronization?
Diffusion?
Bound states?

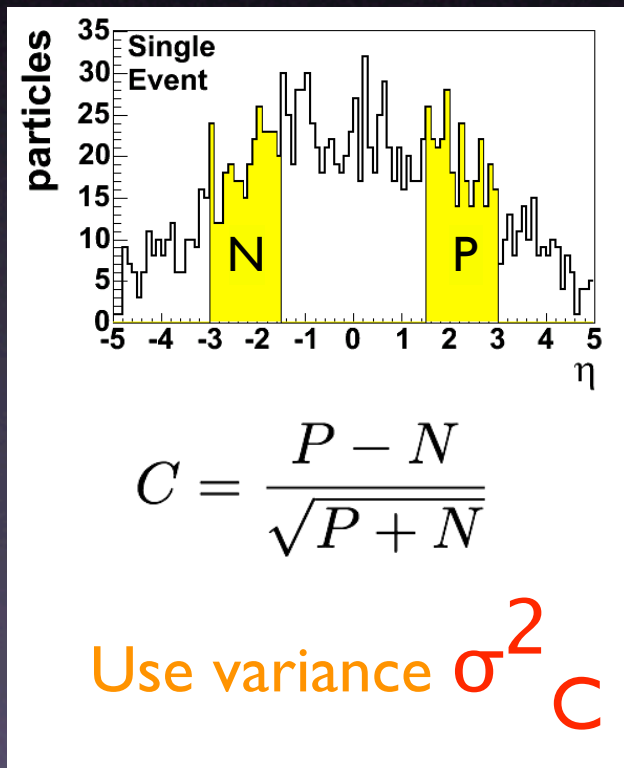
Energy dependence of charge fluctuations





Hadronization

Forward/backward multiplicity correlations



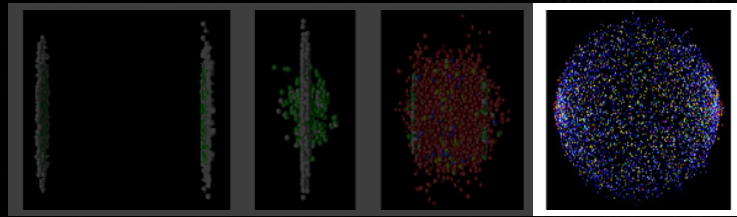
Particles produced independently:

$$\sigma_C^2 = 1$$

Particles produced in clusters of size K :

$$C \rightarrow \sqrt{K} C$$

$$\sigma_C^2 \rightarrow K \sigma_C^2$$



Hadronization

Forward/backward multiplicity correlations

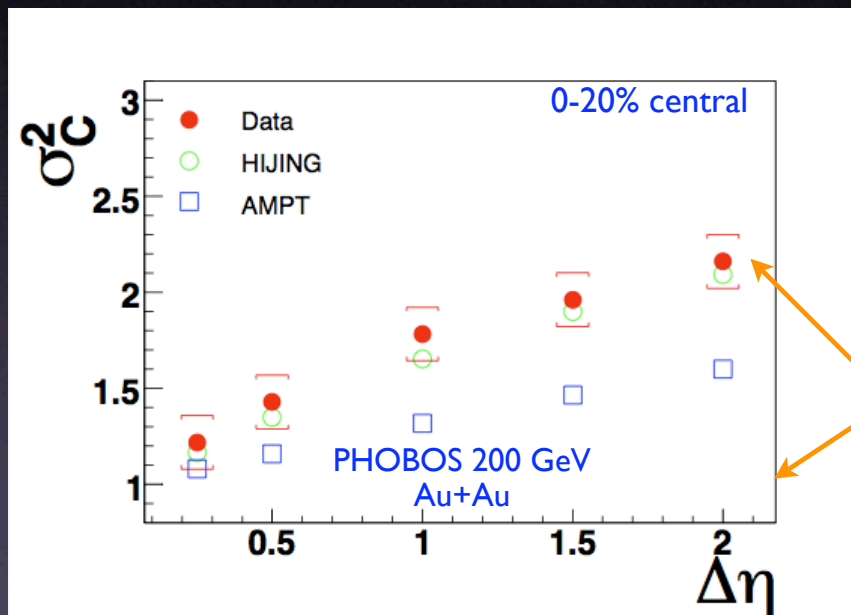
Particles produced independently:

$$\sigma_C^2 = 1$$

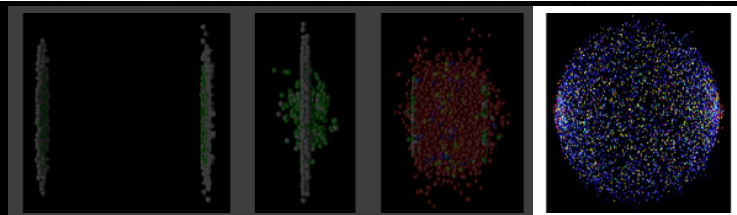
Particles produced in clusters of size K :

$$C \rightarrow \sqrt{K} C$$

$$\sigma_C^2 \rightarrow K \sigma_C^2$$

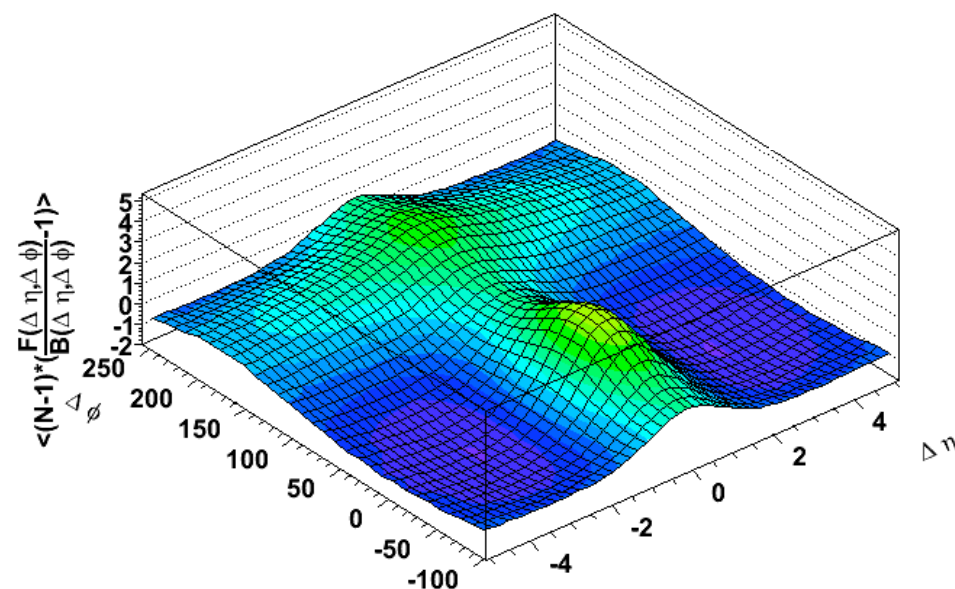
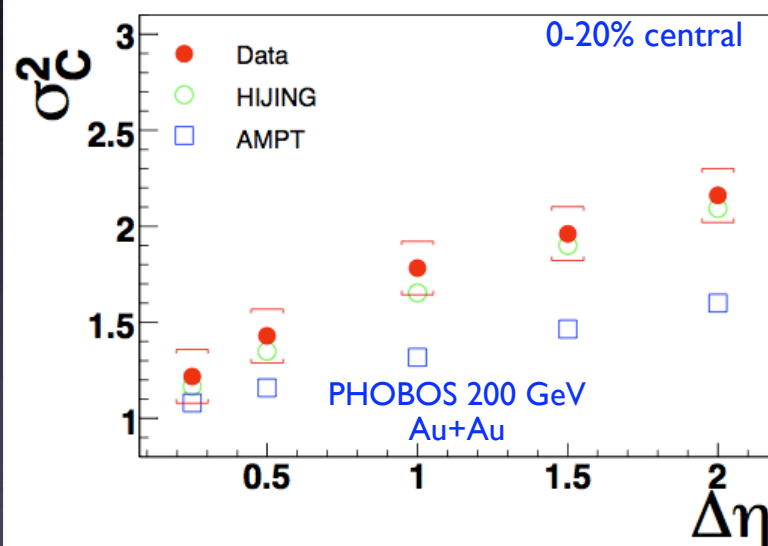


effective cluster size $\approx 2-2.5$
for 200 GeV Au+Au



Hadronization

Clusters in A+A (and p+p) collisions



effective cluster size $\approx 2-2.5$
for 200 GeV Au+Au

“Cluster” in $\Delta\eta, \Delta\phi$ space via
2-particle correlations
(pythia p+p @200 GeV, $\eta < 3$)

Measuring global charge fluctuations

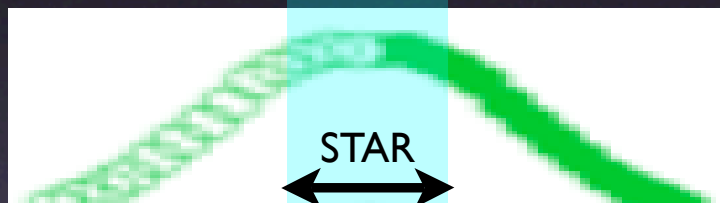
“Clustersize” $\Delta y \approx 2$

SPS



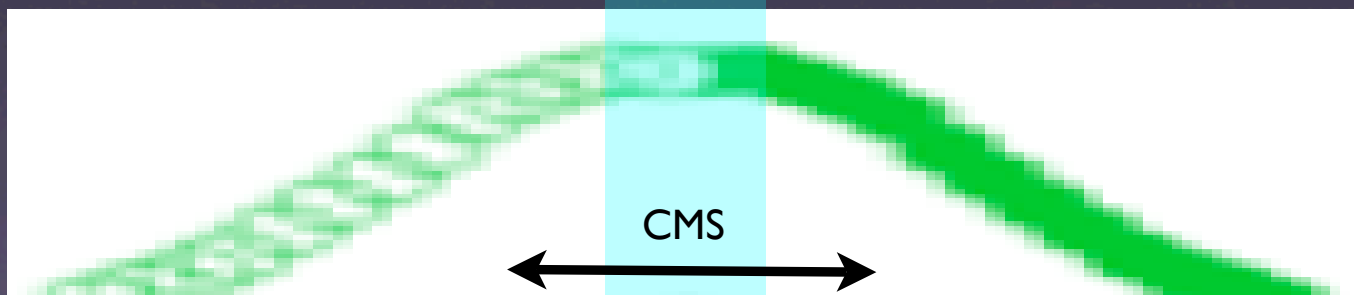
Acc. $\approx$ Clustersize $\approx$ Rapidity gap

RHIC

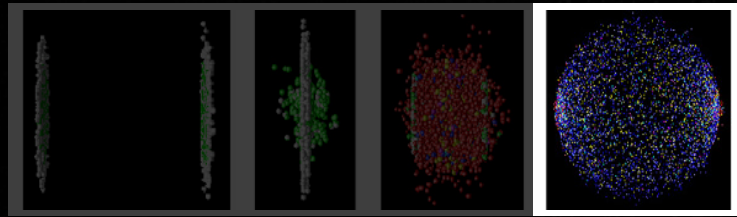


Acc. $\approx$ Clustersize $<$ Rapidity gap

LHC

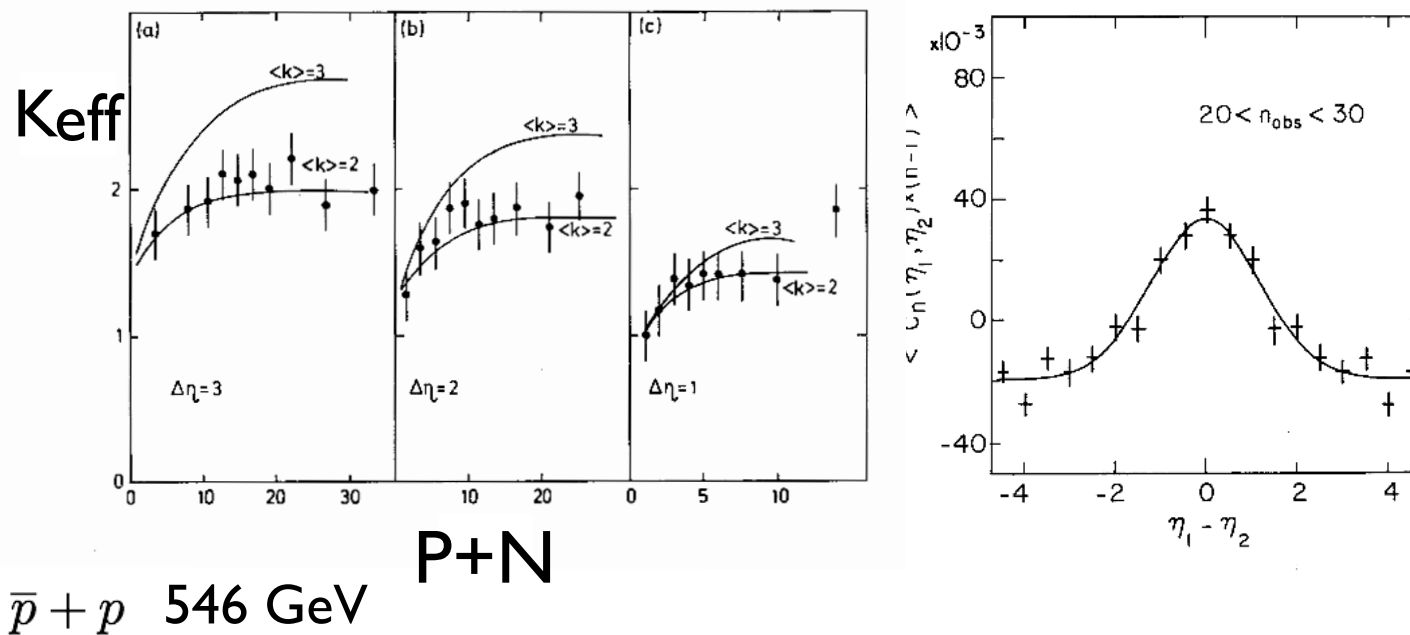


Acc. $>$ Clustersize $\ll$ Rapidity gap



Hadronization

UA5: Phys.Lett.B123:361,1983

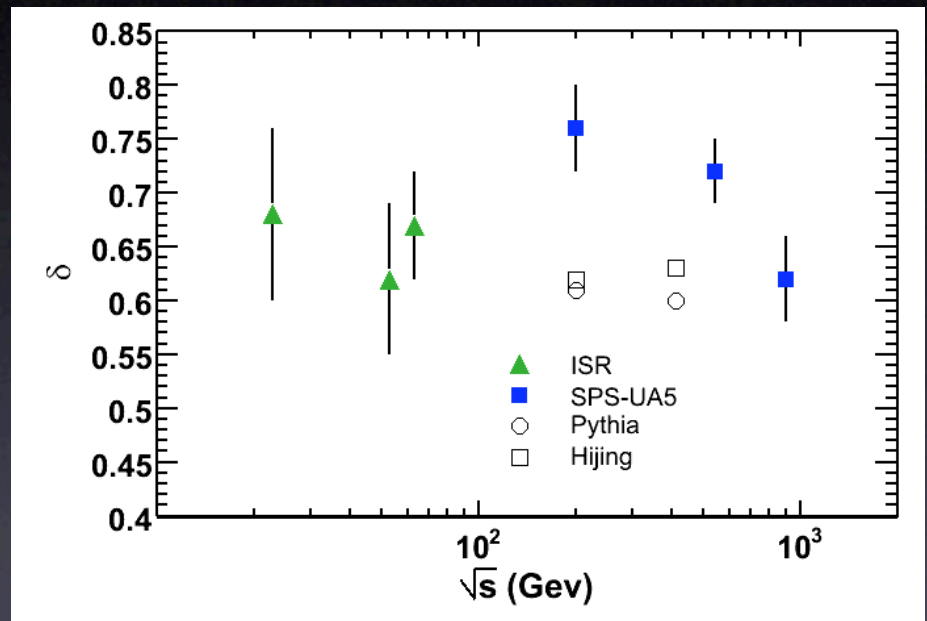
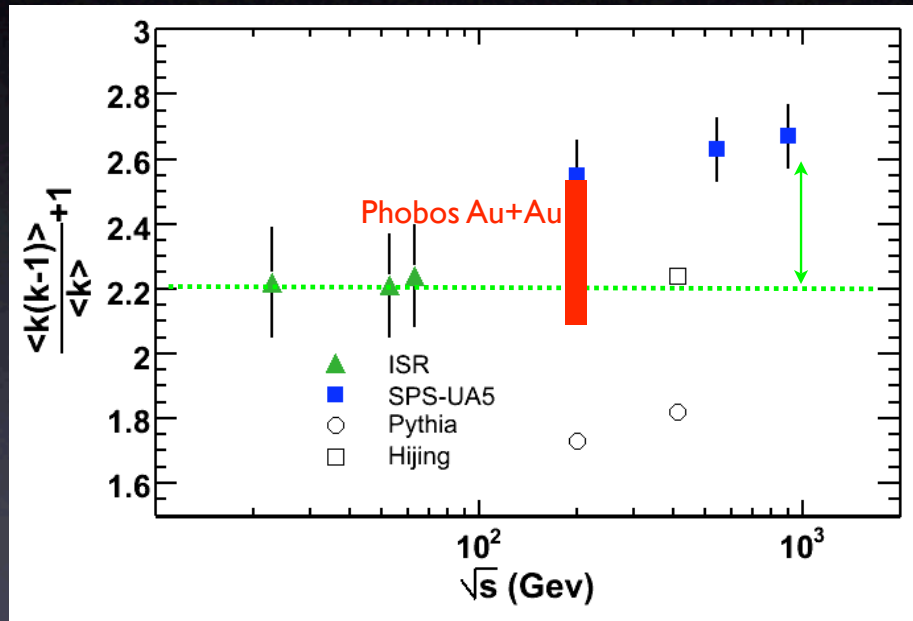


Clusters in Au+Au reminiscent
of results from $p+\bar{p}$

p+p clusters vs $\sqrt{s}$

Origin of p+p clusters?

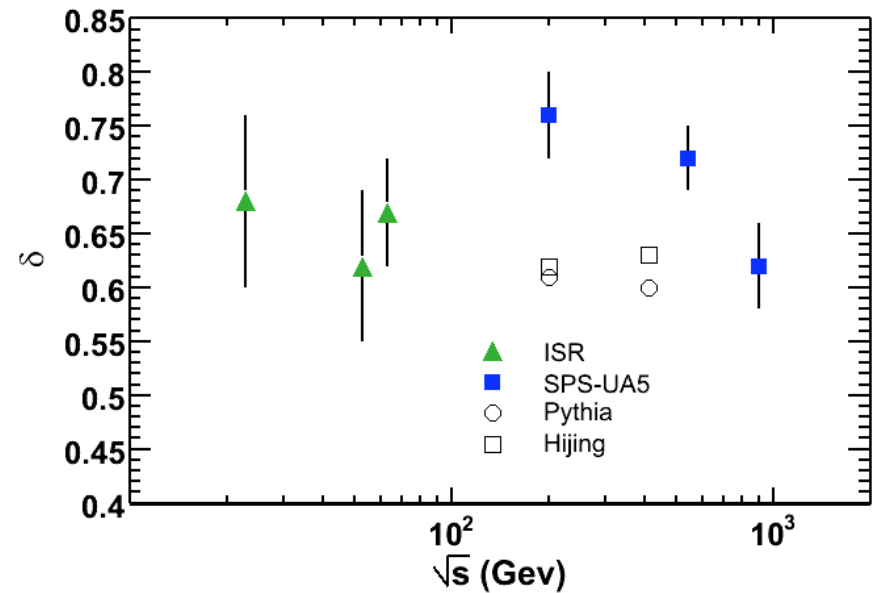
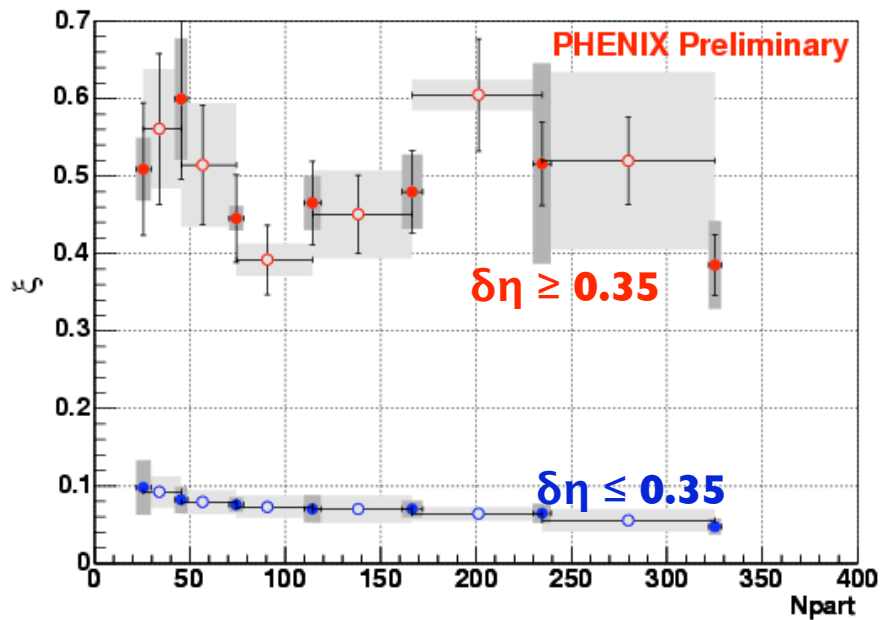
Plots from Wei Li



- * Resonances?
- * String fragmentation?
- * (mini-) Jets?

Clusterwidth in A+A vs p+p

Au+Au 200 GeV, no magnetic field
 $\Delta\eta < 0.7, \Delta\Phi < \pi/2$ rad

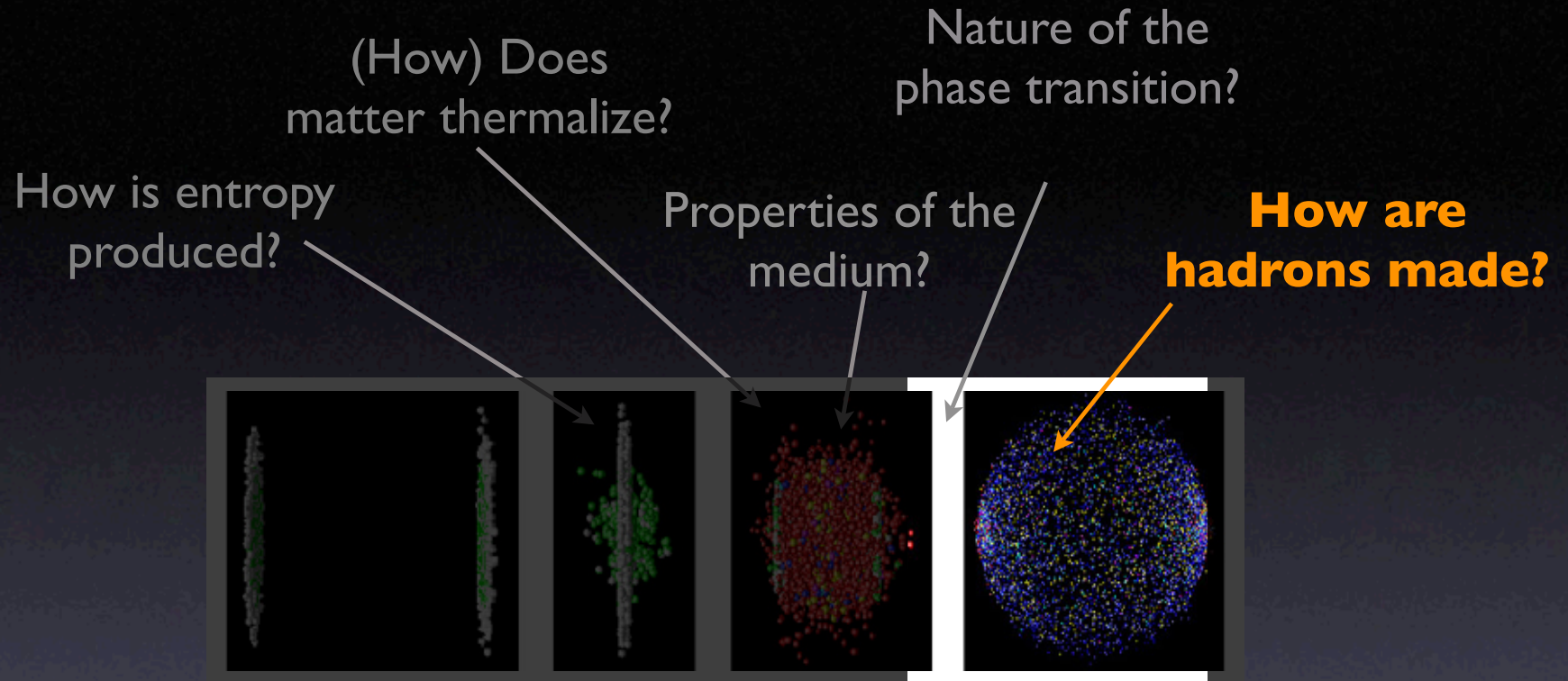


K. Homma and T. Nakamura (QM'05)

Fitted with:

$$R_2 = e^{-|y_1 - y_2|/\xi} + b$$

Clusters and Correlations



Large multiplicity fluctuations

Strong change in underlying correlation structure

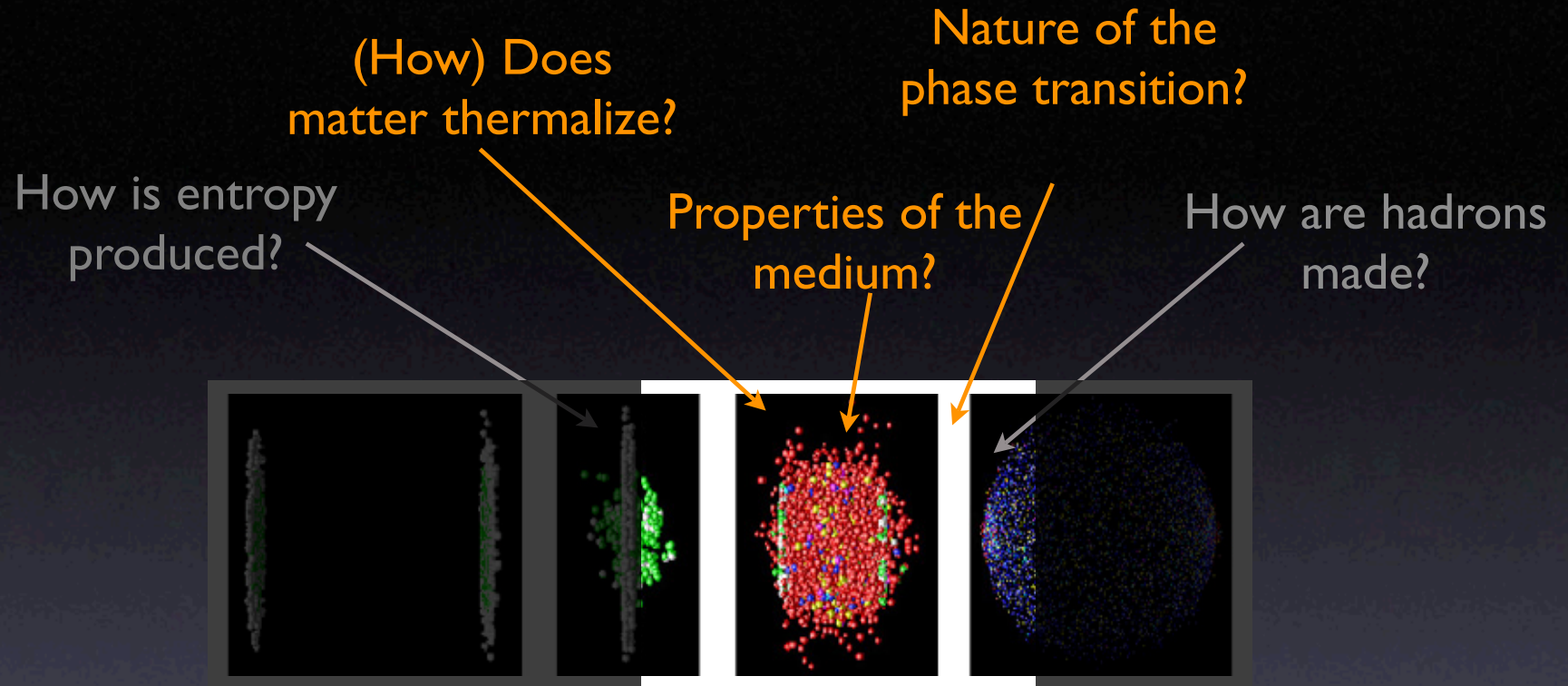


Particles produced in large 'clusters'

Understanding of hadronization essential

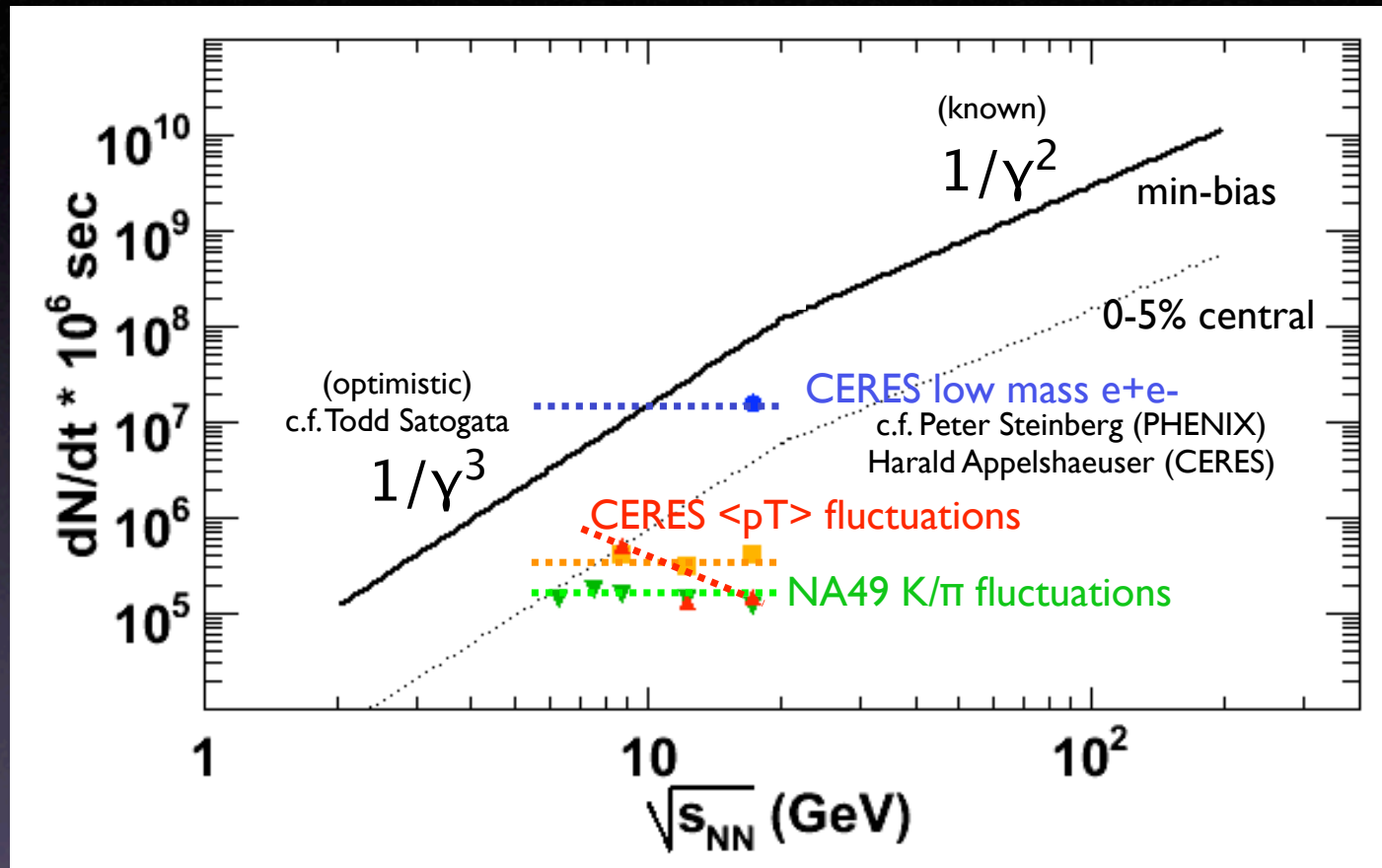
Collision dynamics reflected in correlation structure

Future Measurements



Some remarks on future measurements

Low energy running at RHIC



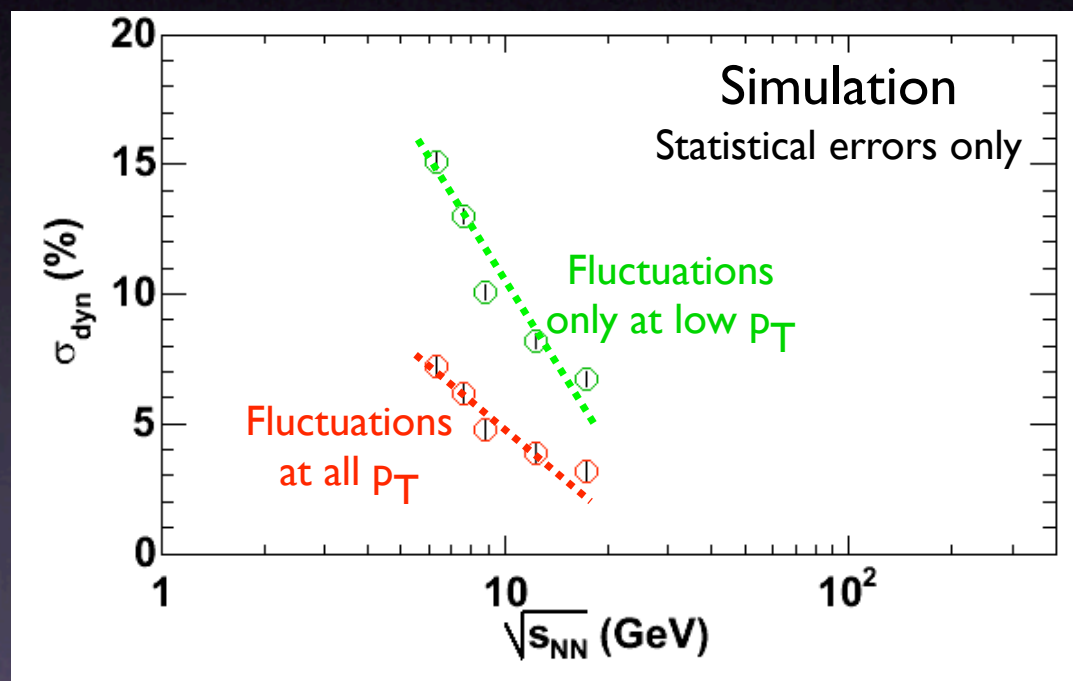
If rates $O(1\text{Hz})$ or greater:
 $\sqrt{s}$ scan of hadronic observables feasible

Low energy running at RHIC

Assumptions:

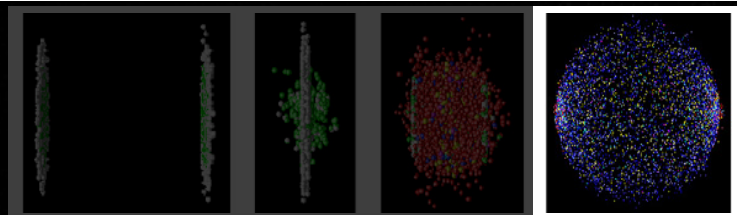
- * Ideal RHIC detector
- * 100k central Au+Au at each $\sqrt{s}$
- * K/ π Fluctuations from NA49 are correct
- * $0.1 < p_T < 0.5$ GeV/c

Strangeness Fluctuations vs $\sqrt{s}$



Opportunity with possible low-E run at RHIC

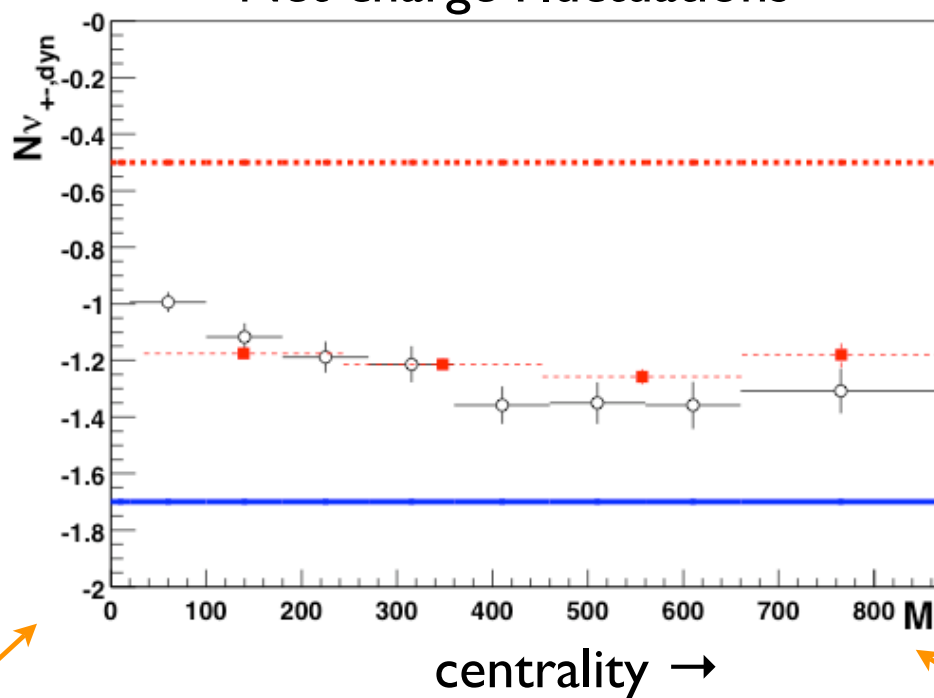
STAR with ToF/Si-VTX upgrade is ideal place



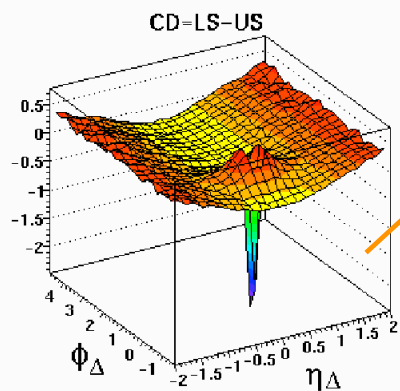
Hadronization

Correlations and Fluctuations, revisited

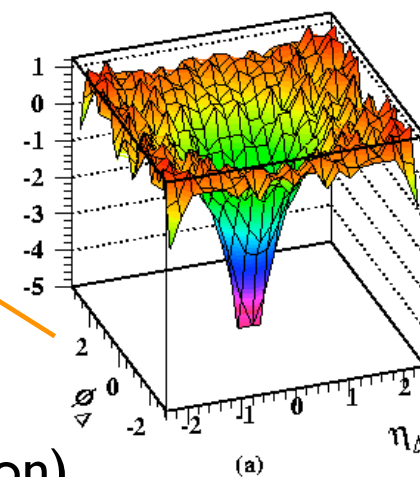
Net-charge Fluctuations



p+p



Central A+A

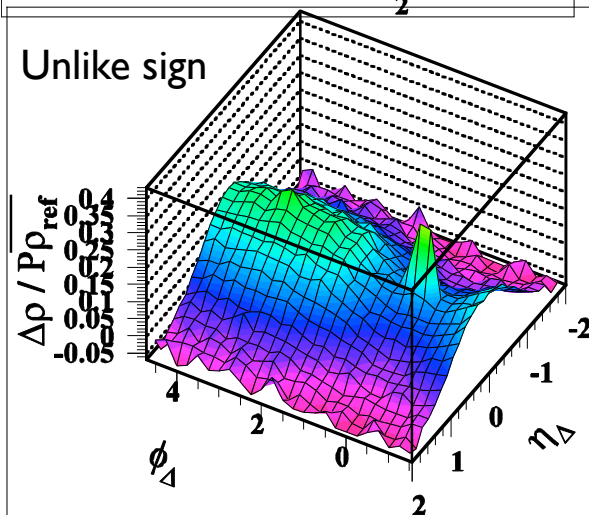
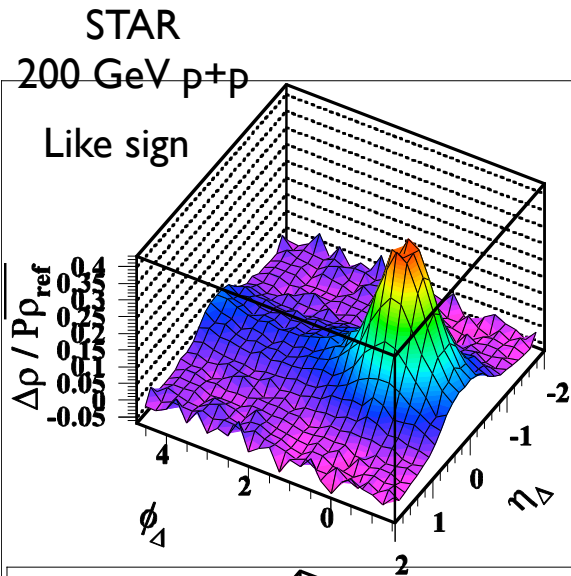


Net-charge correlations (c.f. Balance Function)

Summary

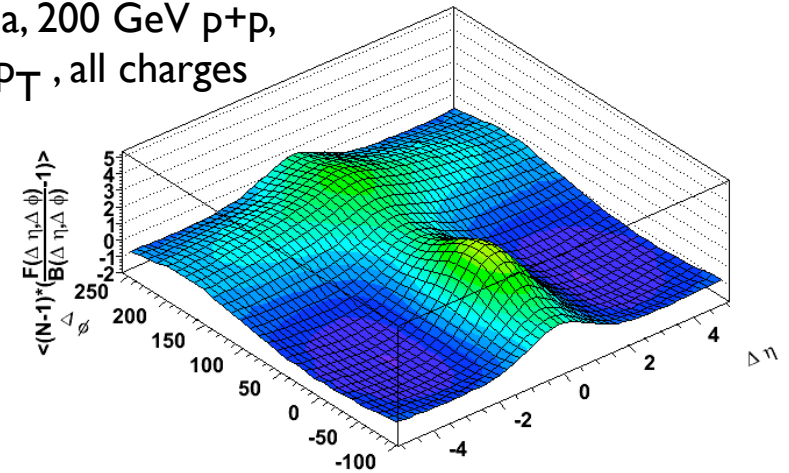
- Rich existing data set on fluctuations
 - Energy independence of global p_T , charge fluctuations
 - Energy dependence in K/π , p/π fluctuations
 - limited statistical significance
 - Non-trivial structure/change in charge correlations
- Low- $\sqrt{s}$ scan at RHIC could confirm and improve experimental results

Beyond global charge fluctuations



Tom Trainor et al (STAR)

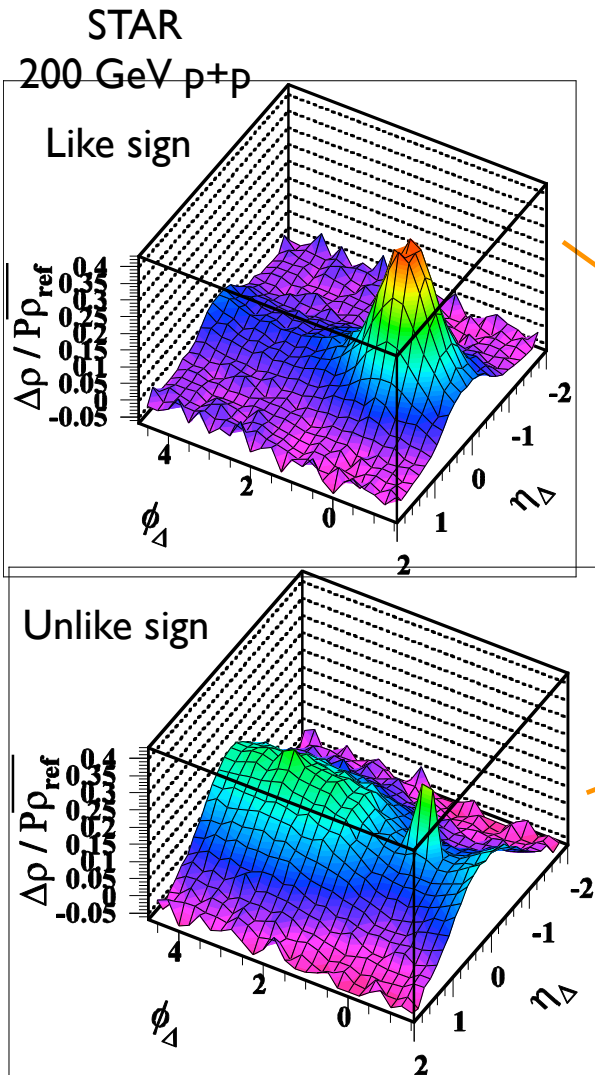
Pythia, 200 GeV p+p,
all p_T , all charges



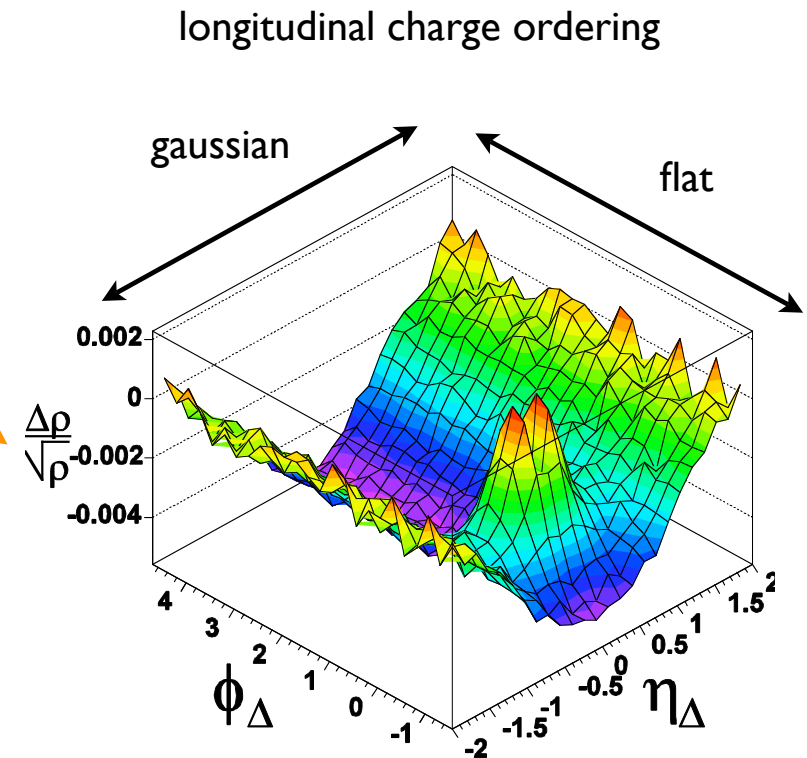
2-D angular correlation function

Split sample

Charge Dependent Correlations

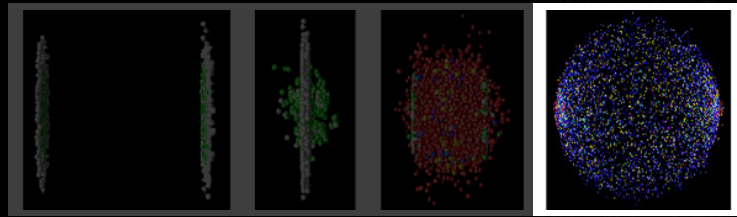


subtract



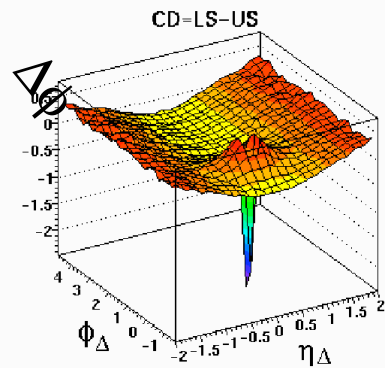
“Charge Dependent (CD)”
correlations
[= like sign - unlike sign]

Tom Trainor et al (STAR)

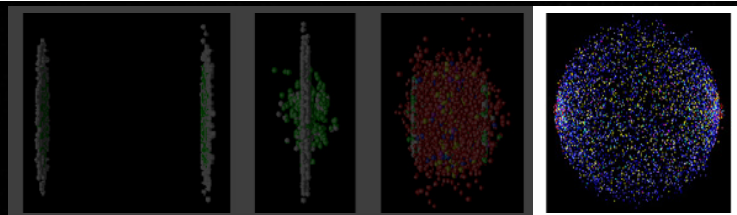


Hadronization

Difference of like-sign and unlike-sign 2-particle correlations:

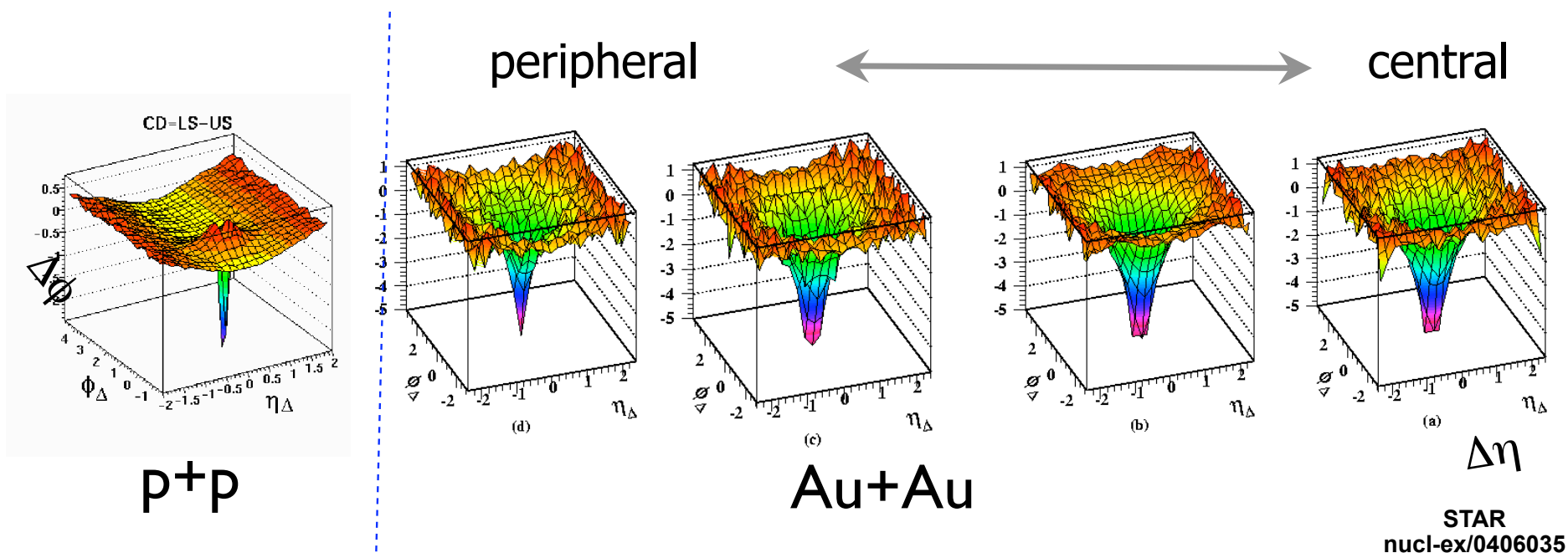


$p+p$



Hadronization

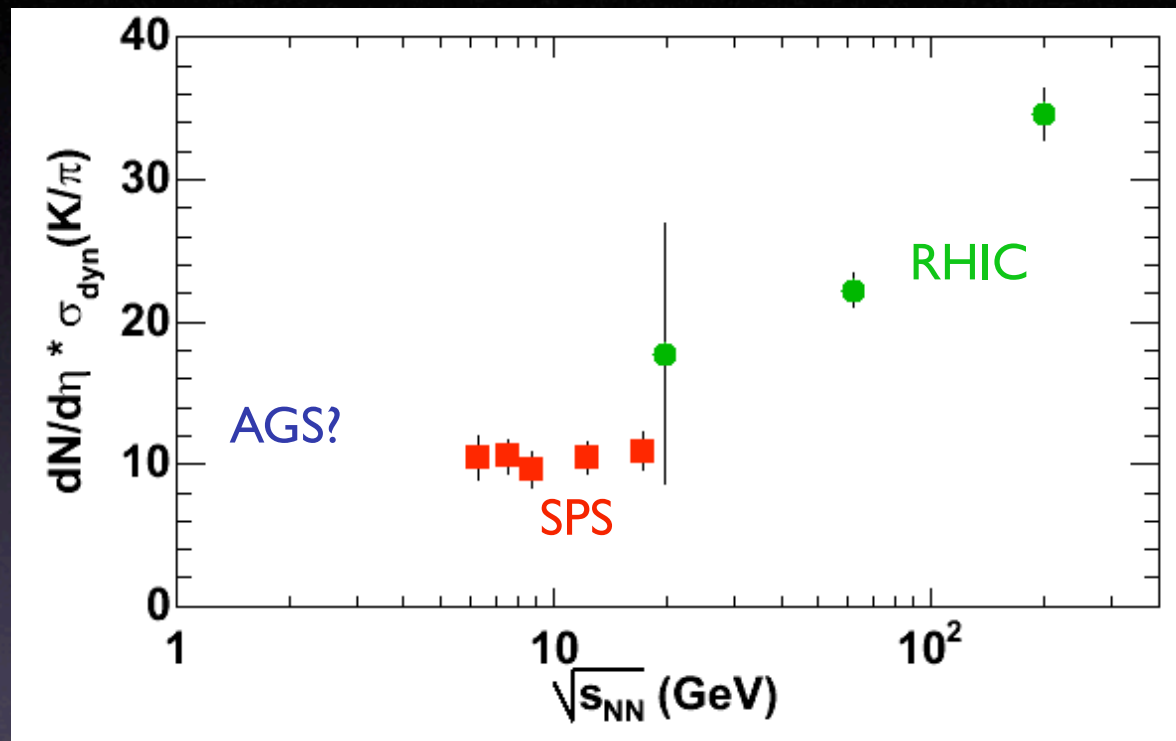
Difference of like-sign and unlike-sign 2-particle correlations:



Evolution of “cluster” properties/charge correlations

Excitation Function: K/ π Fluctuations

Normalized by dN/dy



Scaling by dN/dy or $(dN/dy)^{1/2}$ does not work over full energy range

$$\Phi_{p_T} = \sqrt{\frac{\frac{1}{\varepsilon} \sum_{j=1}^{\varepsilon} (N_j \langle p_T \rangle_j - N_j \hat{p}_T)^2}{\bar{N}}} - \sigma_{\hat{p}_T} \quad (1)$$

$$\simeq \sqrt{\frac{1}{\varepsilon} \sum_{j=1}^{\varepsilon} N_j (\langle p_T \rangle_j - \hat{p}_T)^2} - \sigma_{\hat{p}_T} \quad (2)$$

$$\Sigma_{p_T} = \frac{\sqrt{\sigma_{\langle p_T \rangle, dyn}^2}}{\bar{p}_T} \quad (3)$$

$$\sigma_{\langle p_T \rangle, dyn}^2 = \frac{1}{\varepsilon} \sum_{j=1}^{\varepsilon} \frac{N_j (\langle p_T \rangle_j - \hat{p}_T)^2}{\bar{N}} - \frac{\sigma_{\hat{p}_T}^2}{\bar{N}} \quad (4)$$

The relationship between Φ_{p_T} and Σ_{p_T} when Φ_{p_T} is small and $\Phi_{p_T}^2$ term is neglected:

$$\Phi_{p_T} \simeq \frac{\sigma_{\langle p_T \rangle, dyn}^2 \bar{N}}{2\sqrt{\sigma_{\hat{p}_T}^2}} \quad (5)$$

$$\Sigma_{p_T} \simeq \sqrt{\frac{2\Phi_{p_T} \sqrt{\sigma_{\hat{p}_T}^2}}{\bar{N}\bar{p}_T^2}} \quad (6)$$

Net Charge, and K/ π Fluctuations

Instead of measuring the variance of a yield ratio,

$$r_{12} = \frac{n_1}{n_2} \quad \rightarrow \quad \frac{\langle (\Delta r_{12})^2 \rangle}{\langle r_{12} \rangle^2} \approx \frac{\langle (\Delta n_1)^2 \rangle}{\langle n_1 \rangle^2} + \frac{\langle (\Delta n_2)^2 \rangle}{\langle n_2 \rangle^2} - 2 \frac{\langle \Delta n_1 \Delta n_2 \rangle}{\langle n_1 \rangle \langle n_2 \rangle}$$

Study the “dynamical fluctuations”:

$$v_{12,dyn} = \left\langle \left(\frac{n_1}{\langle n_1 \rangle} - \frac{n_2}{\langle n_2 \rangle} \right)^2 \right\rangle - \frac{1}{\langle n_1 \rangle} - \frac{1}{\langle n_2 \rangle} = \tilde{R}_{11} + \tilde{R}_{22} - 2\tilde{R}_{12}$$

Side Note: $D \equiv \langle n_1 + n_2 \rangle \langle (\Delta r_{12})^2 \rangle$ $\frac{D}{4} \approx 1 + \frac{(\tilde{R}_{++} + \tilde{R}_{--} - 2\tilde{R}_{+-}) \langle n_+ + n_- \rangle}{4}$

$\langle p_t \rangle$ Fluctuations

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

where

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

$$\langle \langle p_t \rangle \rangle = \left(\sum_{k=1}^{N_{event}} \langle p_t \rangle_k \right) / N_{event}$$

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