Energy and μ_B dependence of Event-by-event Fluctuations

BNL Users Meeting workshop
June 5 2006

Gunther Roland
MIT

Event-by-event Fluctuations

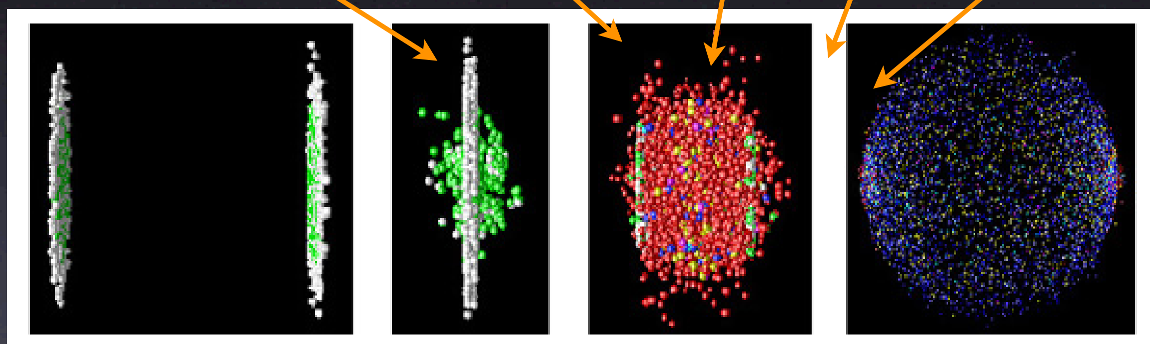
(How) Does
matter thermalize?

Nature of the
phase transition?

How is entropy
produced?

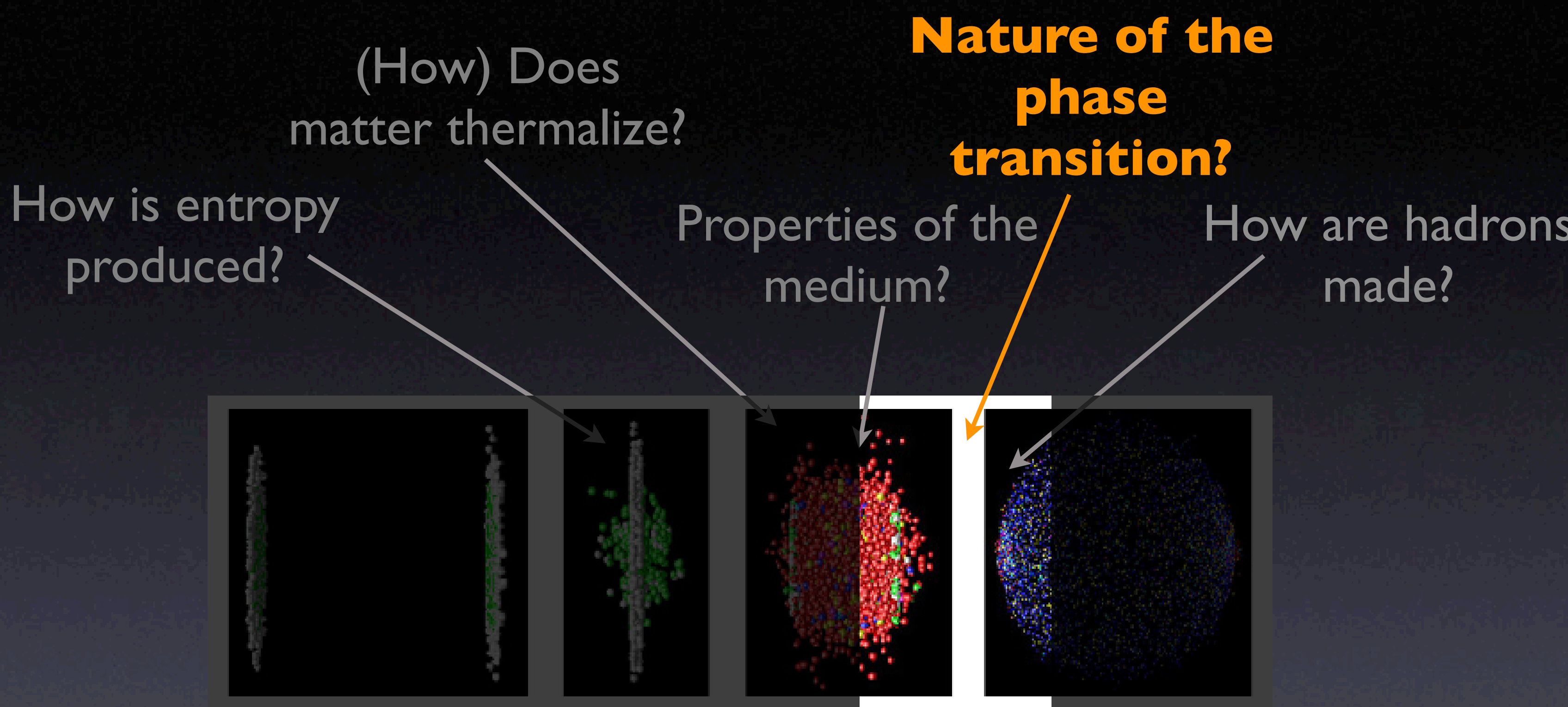
Properties of the
medium?

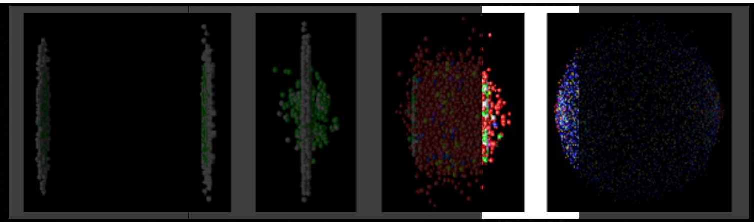
How are hadrons
made?



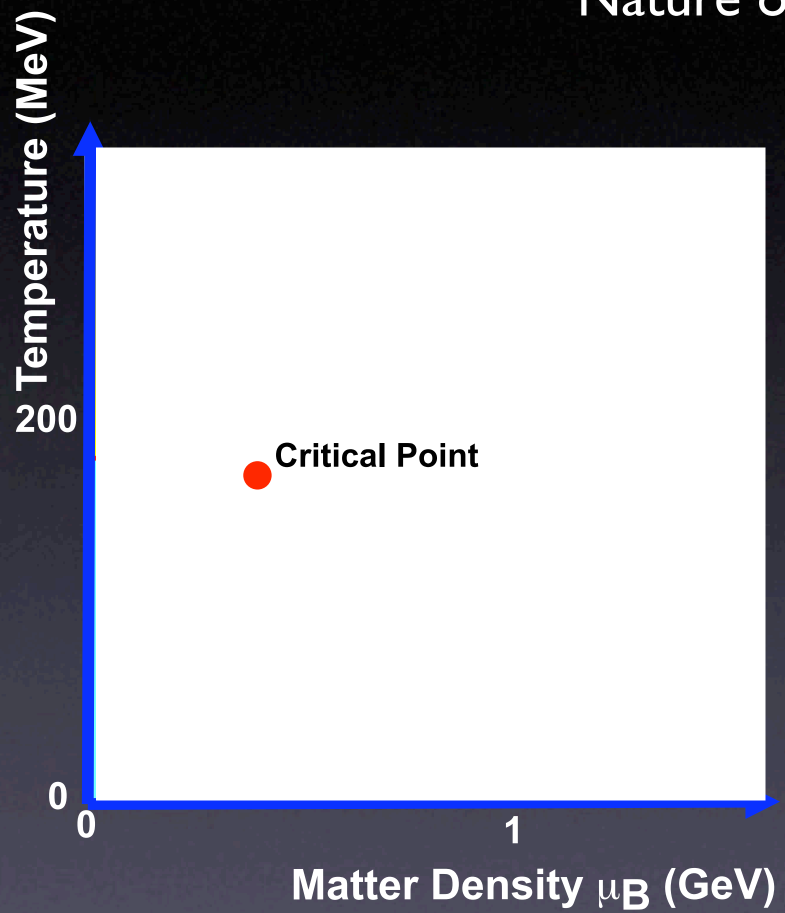
Answers to all of these questions
from fluctuations/correlations

Event-by-event Fluctuations





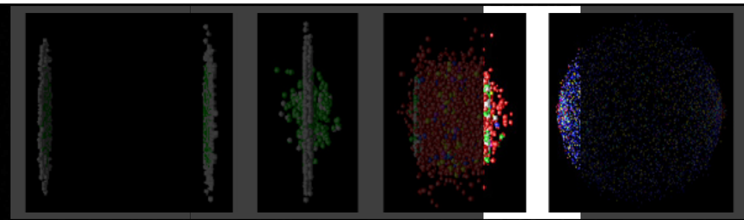
Nature of the Phase Transition



Correlation length diverges near critical point

Locate the critical point using correlation/fluctuation measurements

Rajagopal, Shuryak, Stephanov



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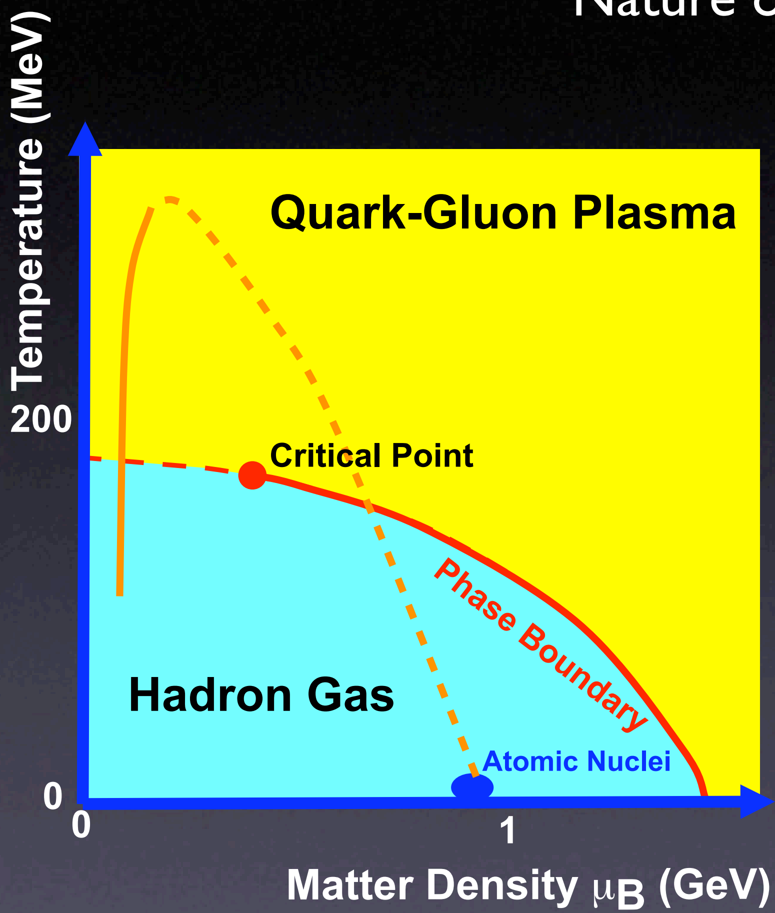
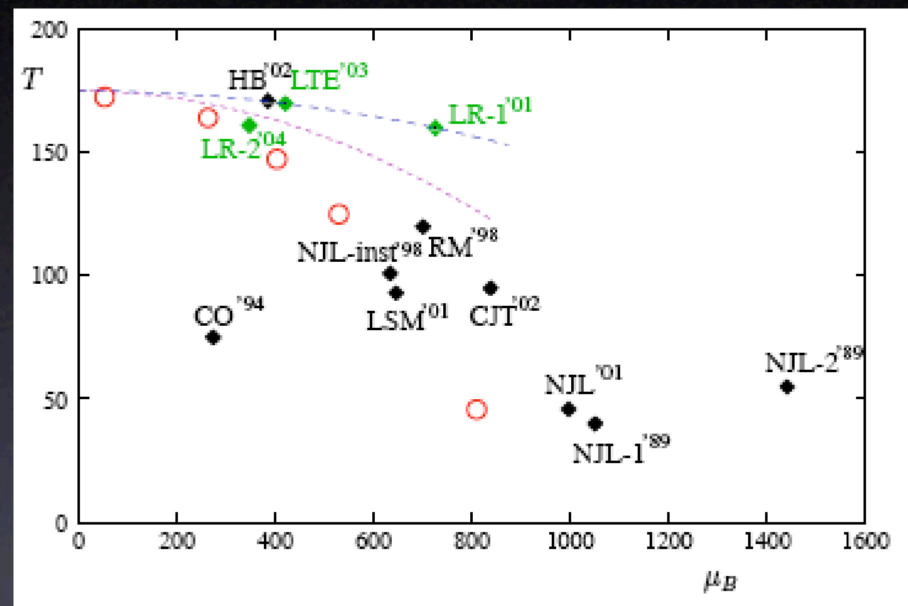
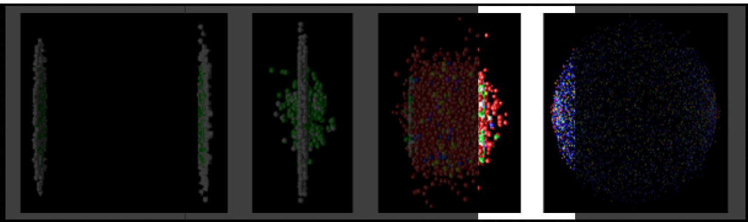
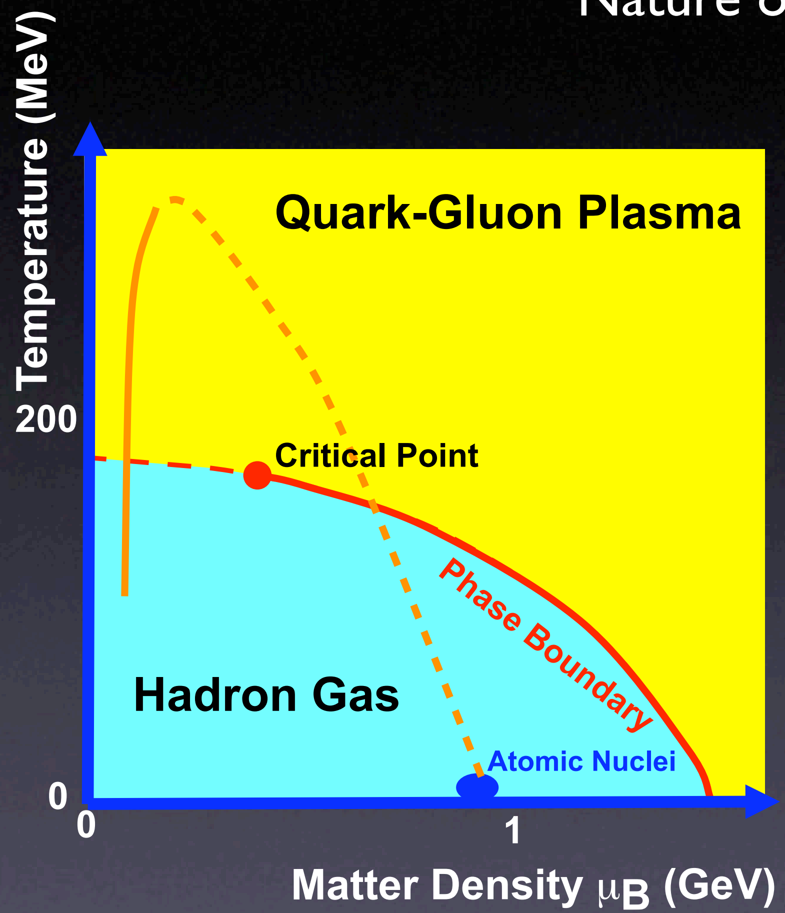


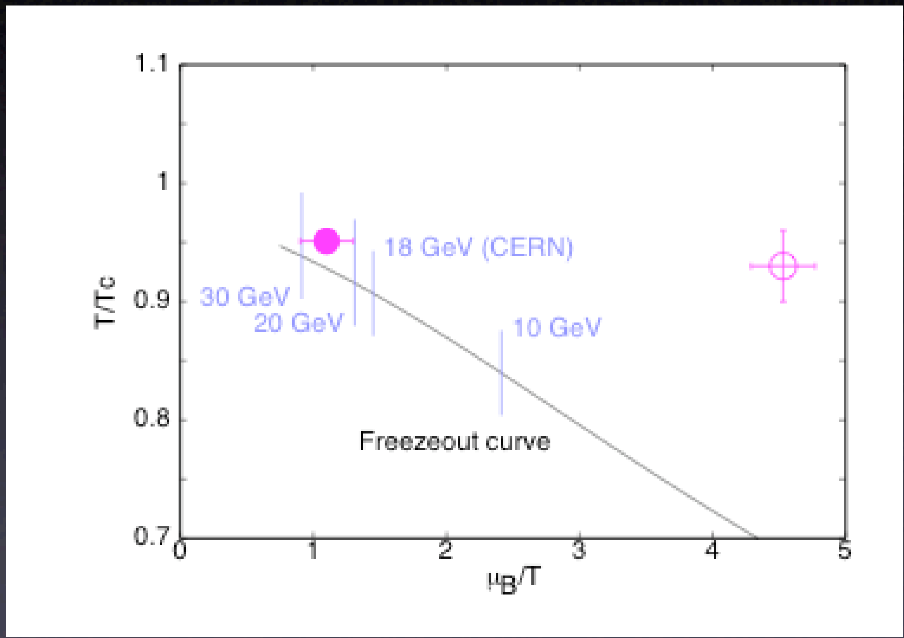


Plot from M. Stephanov, Correlations '05

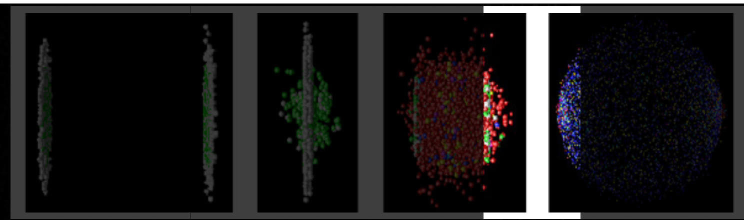


Nature of the Phase Transition



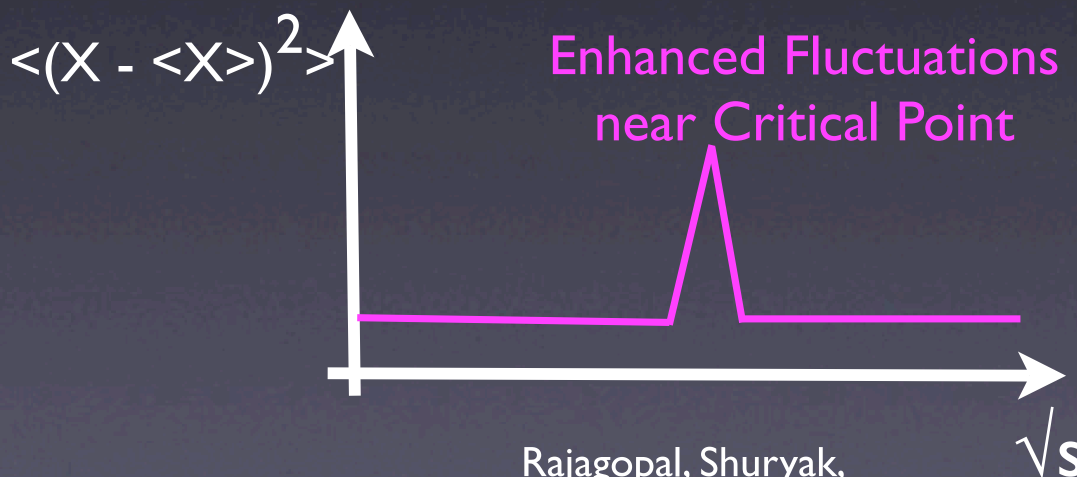


Plot from S. Gupta,
CERN HIF, May '06



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

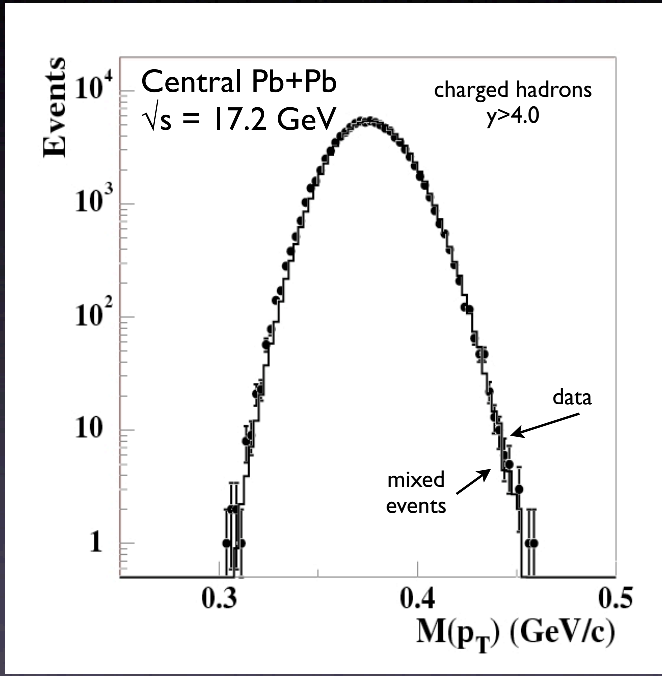


Rajagopal, Shuryak,
Stephanov

First result on <p_T> fluctuations (1999)

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

NA49, Phys Lett B459 (1999) 679

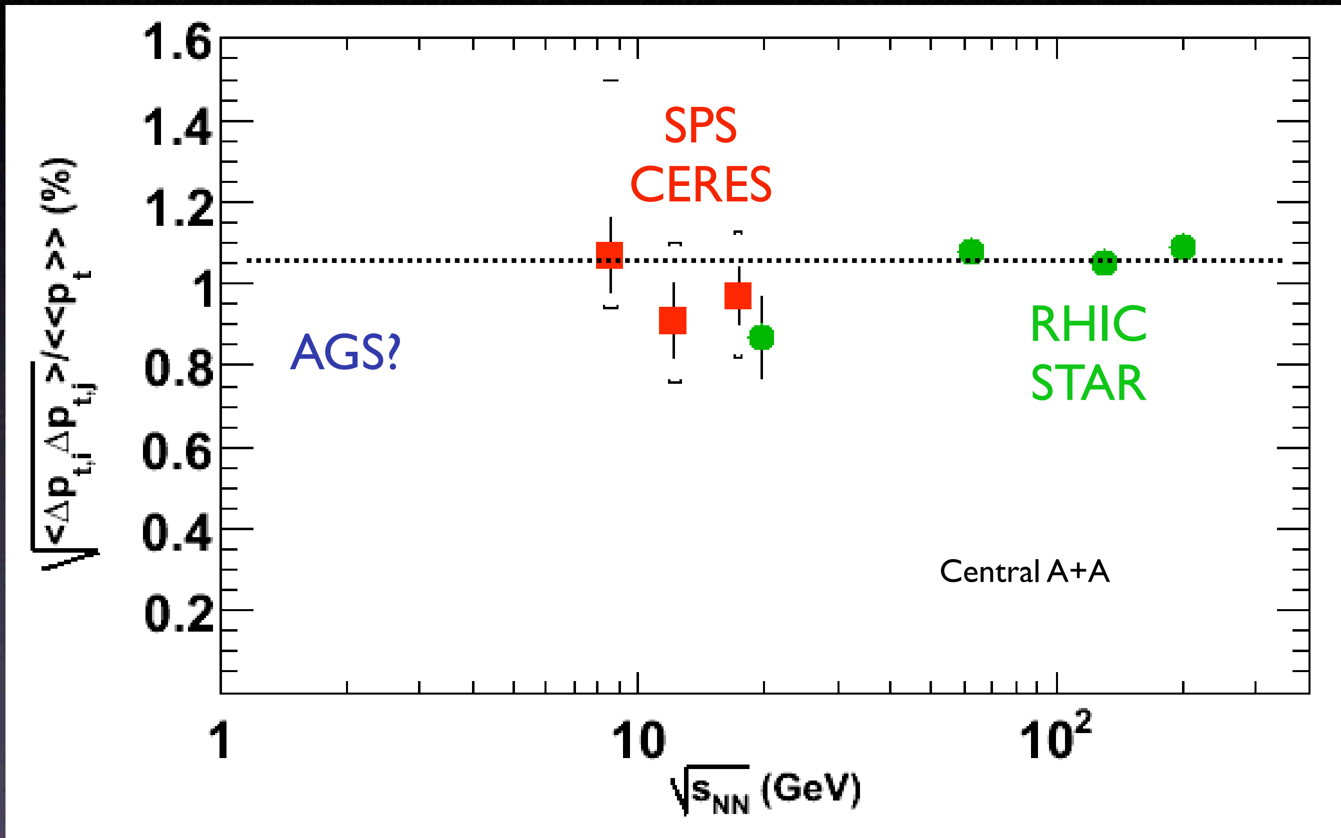


Event-by-event <p_T> compared to stochastic reference (mixed events)

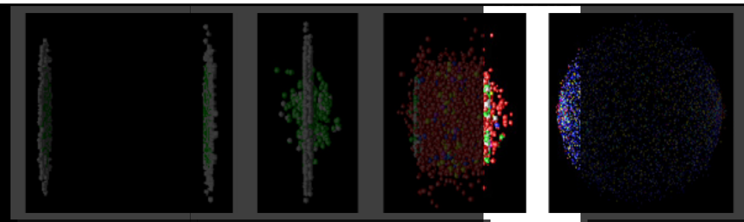
Dynamical Fluctuations: "$\sigma^2_{p_T,dyn} = \sigma^2_{M(p_T)} - \sigma^2_{M(p_T),mixed}$"

Excitation Function: Momentum Fluctuations

Compilation by STAR
STAR PRC 72 044902 (2005)



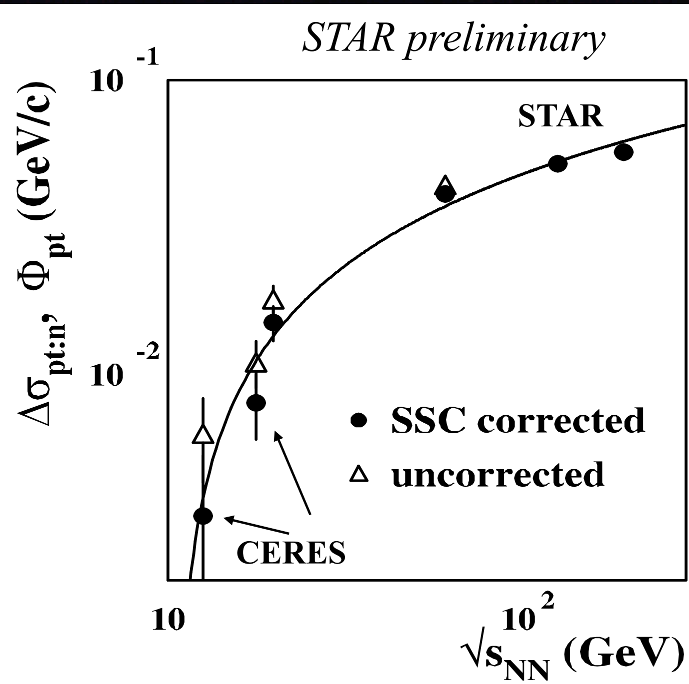
Monotonic energy dependence over measured range



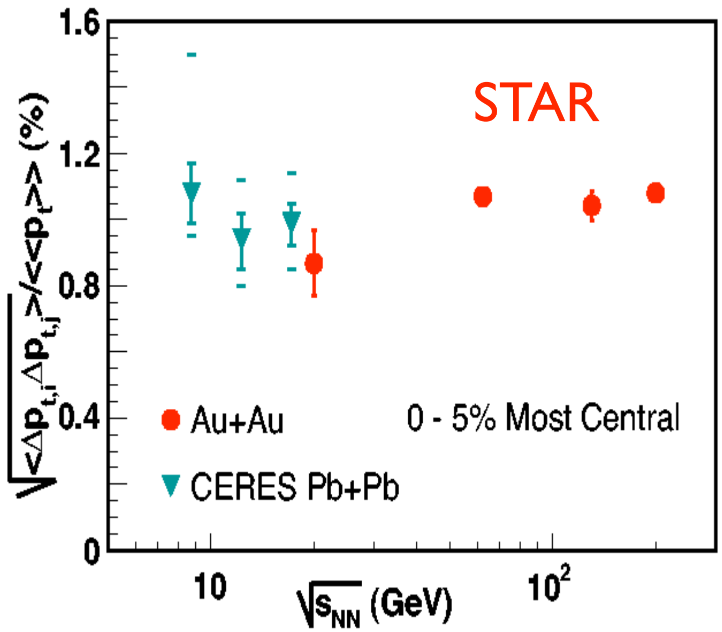
Nature of the Phase Transition

$\langle p_T \rangle$ Fluctuations

Scaling: Connection between <pT>, N, fluctuations?



$\Sigma_{pT} \approx$



Connection to 2-particle correlations

Normalization to $\langle p_T \rangle$

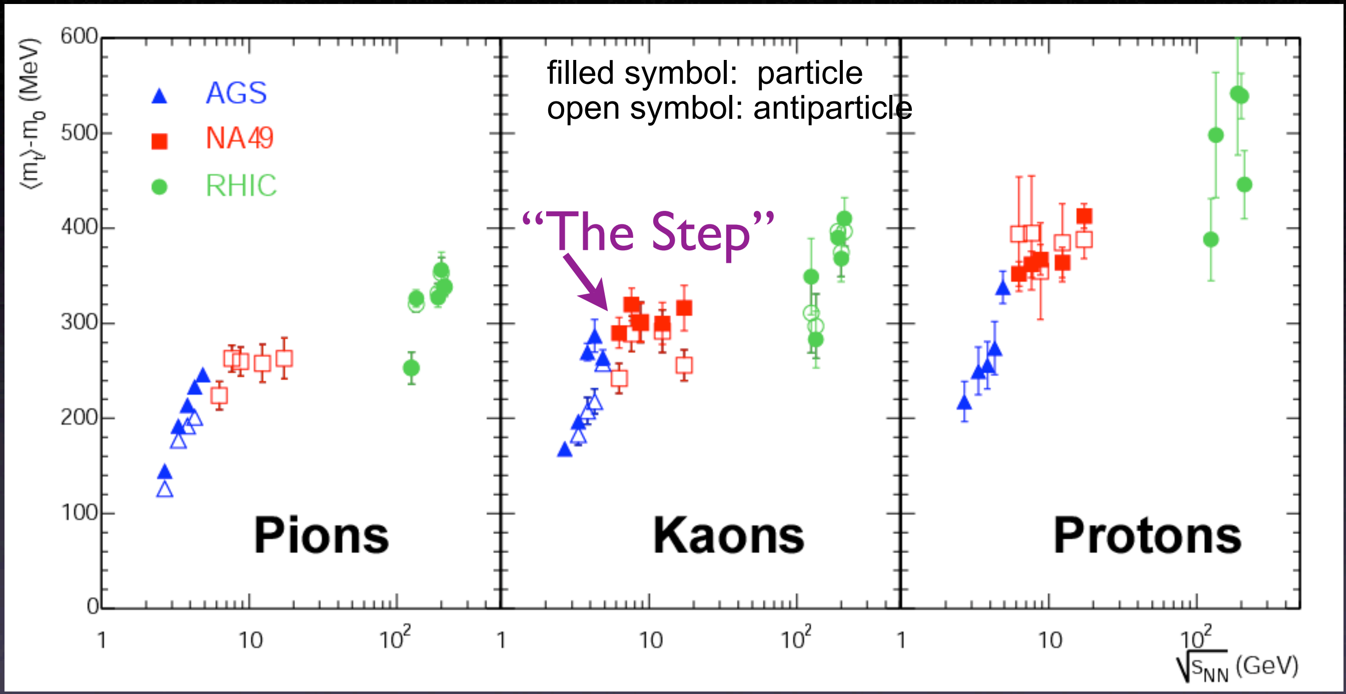
Normalization per particle

Linear or quadratic measures

$$\Sigma_{p_T} \simeq \sqrt{\frac{2\Phi_{p_T}\sqrt{\sigma^2_{\hat{p}_T}}}{\overline{N}\overline{p}_T^2}}$$

Excitation Function: Momentum Spectra

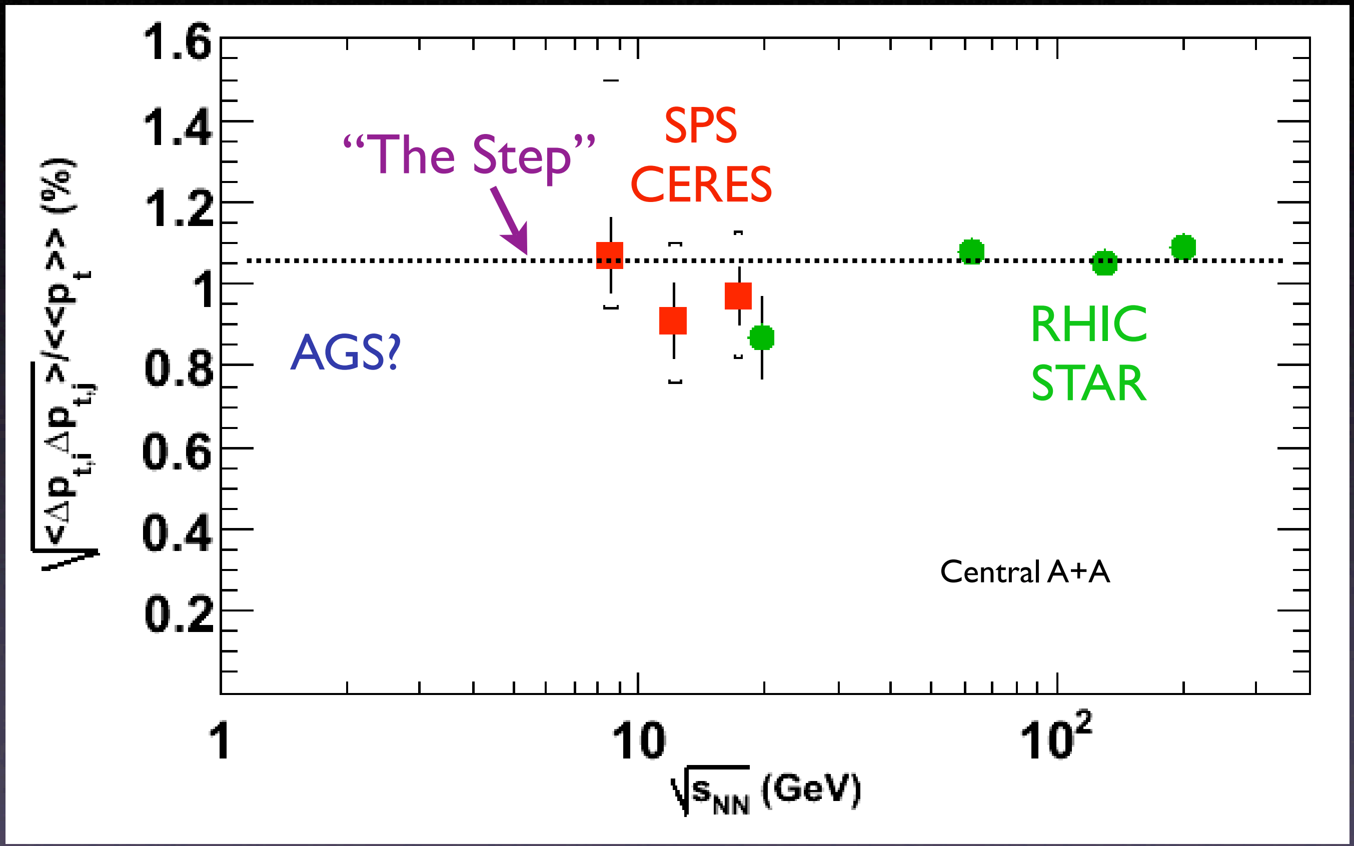
Compilation by NA49
Plot from Claudia Hoehne, QM'05



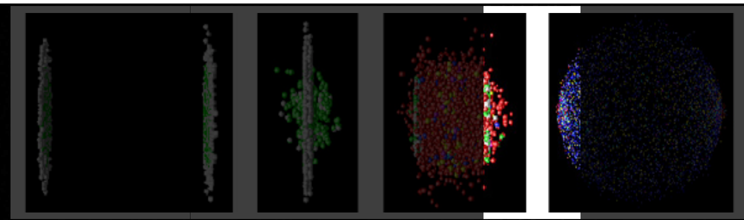
- Structure in energy dependence of $<m_T>$
- Reminiscent of Van Hove's T vs ϵ prediction (1982)
- Surprisingly difficult measurement
  - Decay corrections, PID acceptance

Excitation Function: Momentum Fluctuations

Compilation by STAR
STAR PRC 72 044902 (2005)



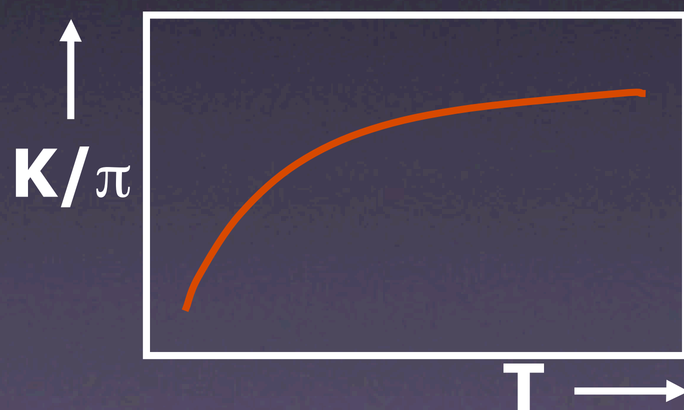
Monotonic energy dependence over measured range
No results near “step” region

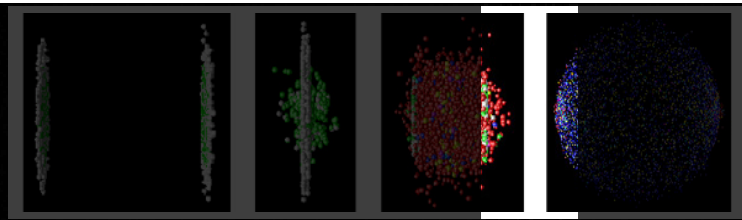


Nature of the Phase Transition

K/π Fluctuations

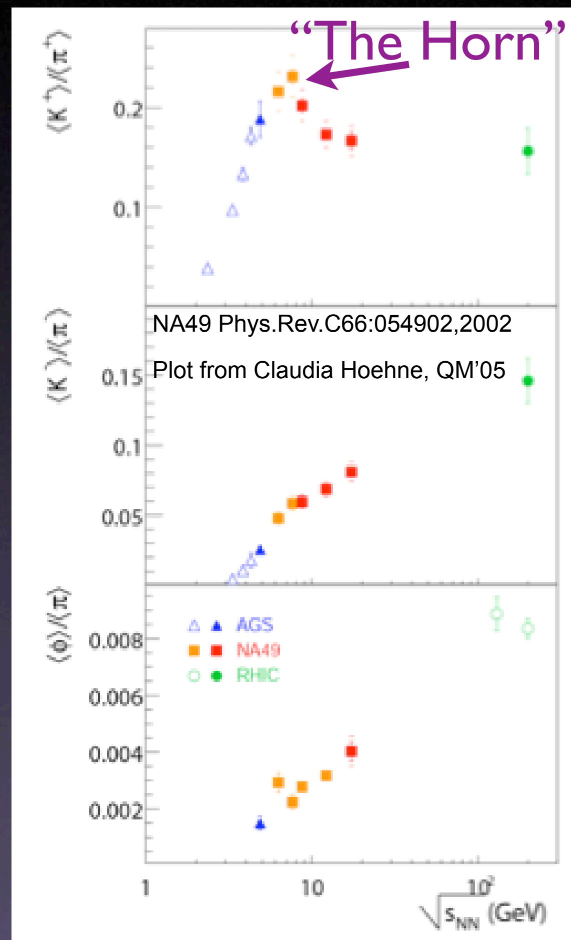
- Is strangeness enhanced in every event?
- Can we see signs of super-cooling below T_{crit}?



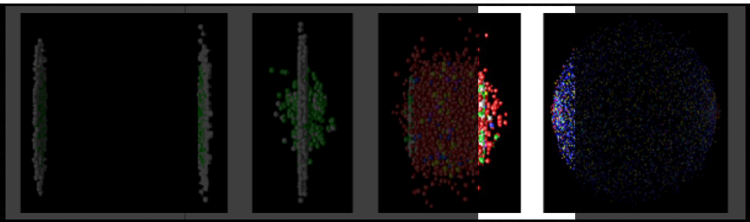


Nature of the Phase Transition

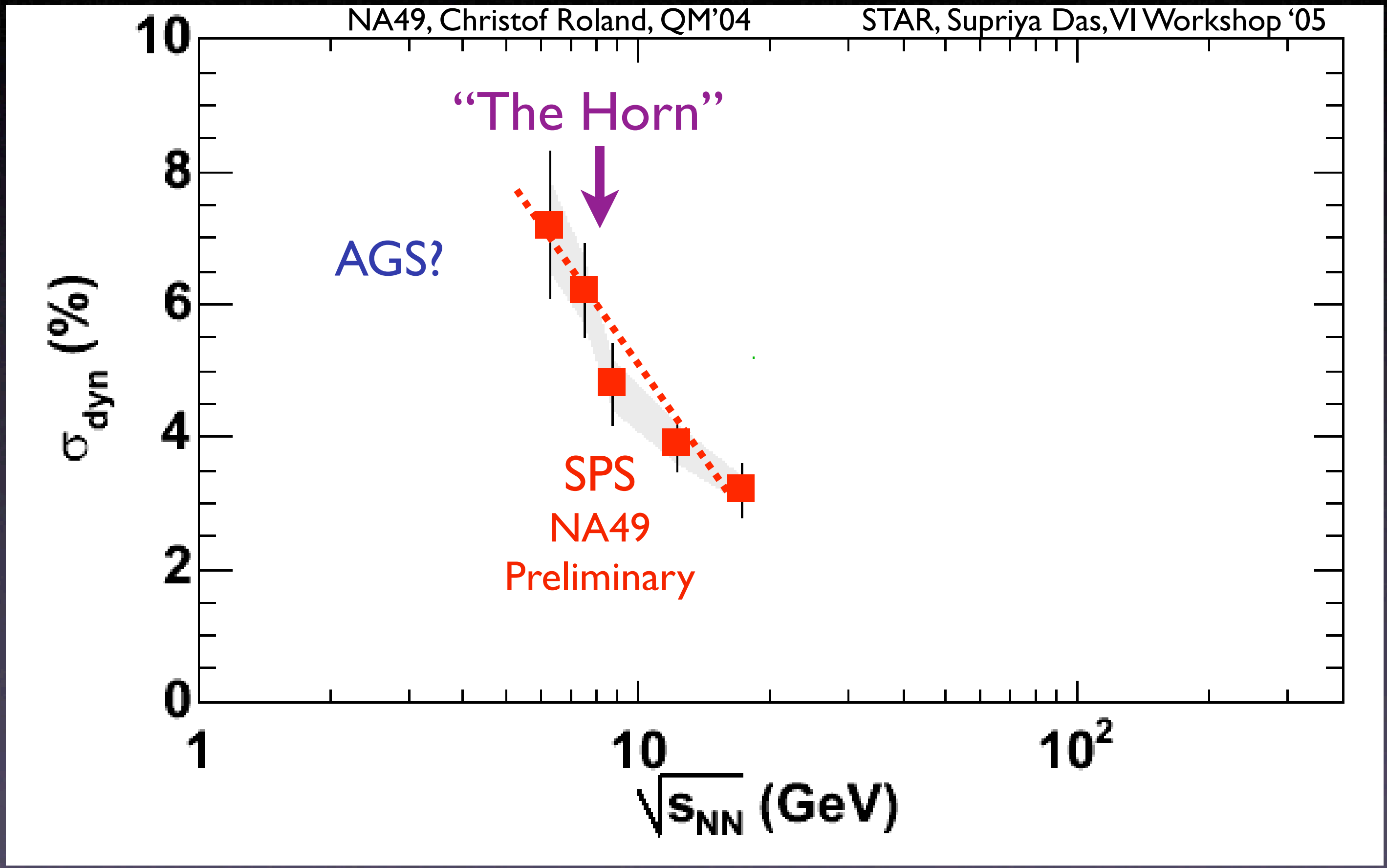
Average K/π ratio



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

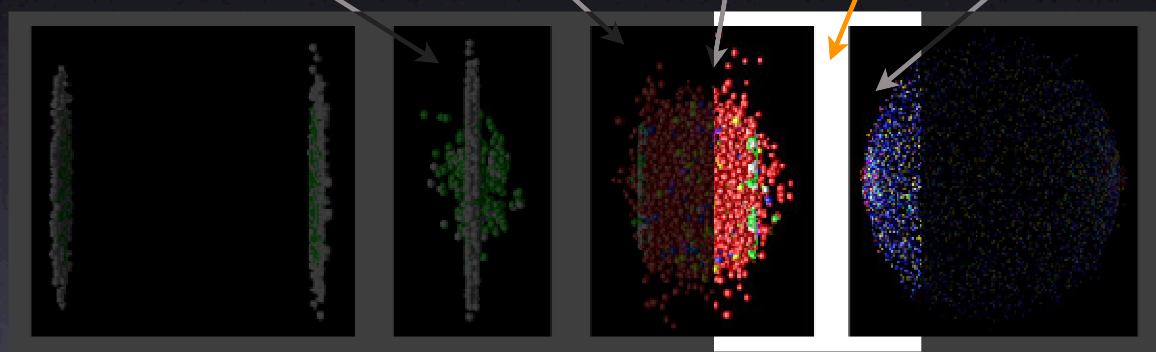
(How) Does matter thermalize?

Nature of the phase transition?

How is entropy produced?

Properties of the medium?

How are hadrons made?



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

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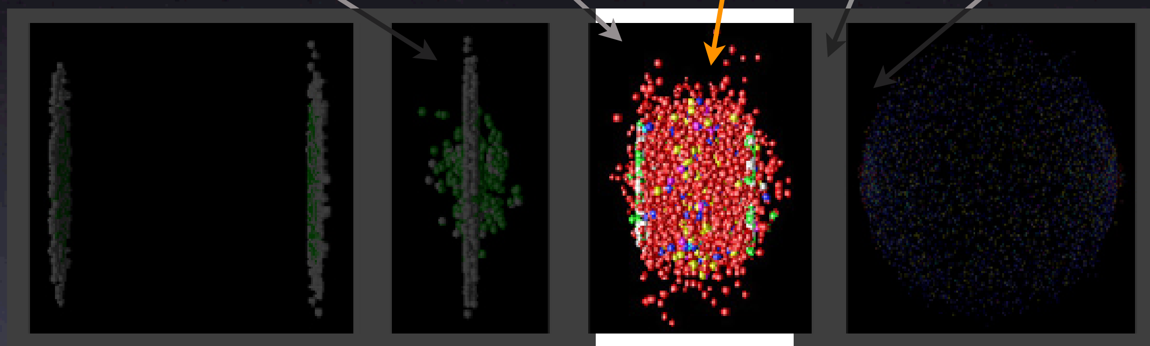
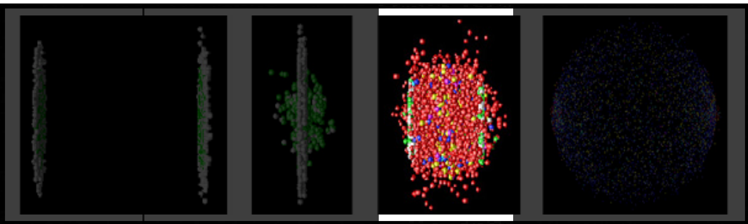


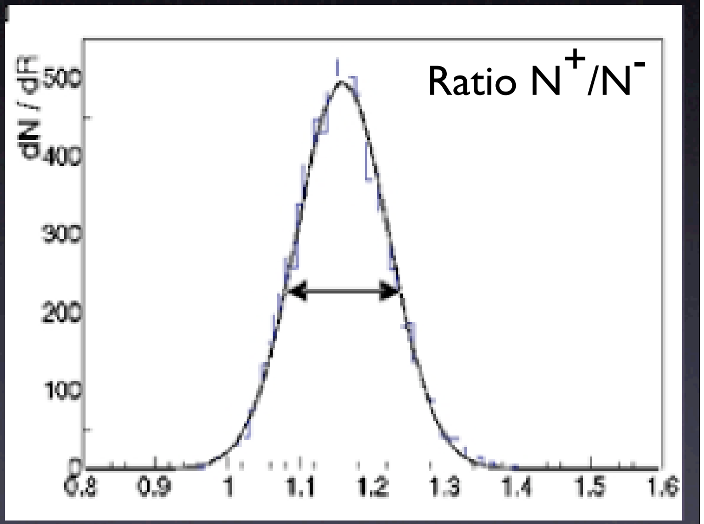
ca 2000



Properties of the Medium

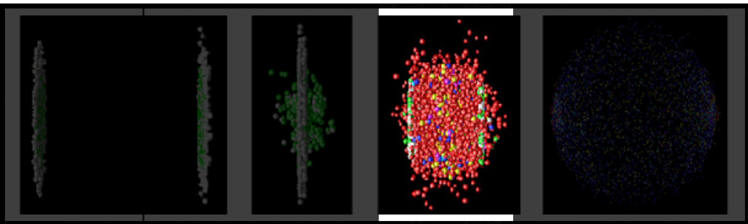
- Net Charge/Δy Fluctuations ⇔ Charge/DoF
  - Fluc's change from 1-2 (QGP) to 4 (Pion Gas)
- Fluctuations frozen b/c charge conservation
  - Diffusion vs Expansion timescale

Jeon, Koch PRL (2000) hep-ph/0003168
Asakawa, Heinz, Mueller PRL (2000) hep-ph/0003169



Event-by-event distribution of net charge ratio

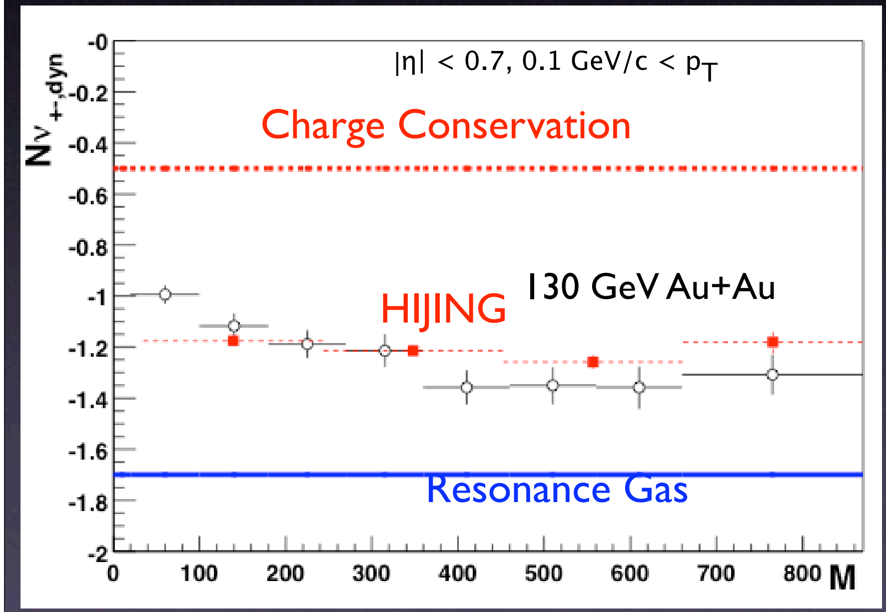
Note:
* Similar for net baryon number
* Connection to quark number susceptibilities
* Connection to Critical point



Properties of the Medium

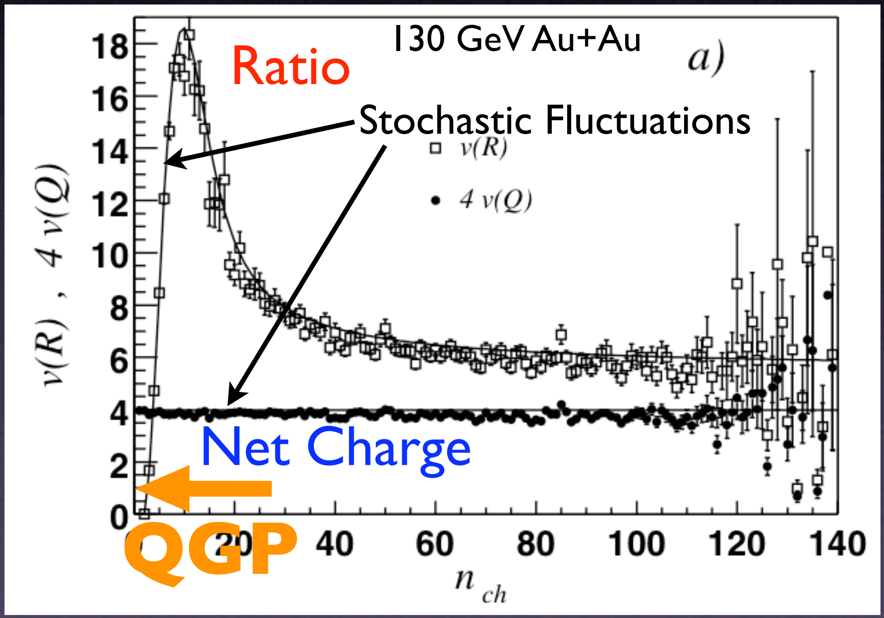
Net Charge Fluctuations

STAR PRC 68 (2003)



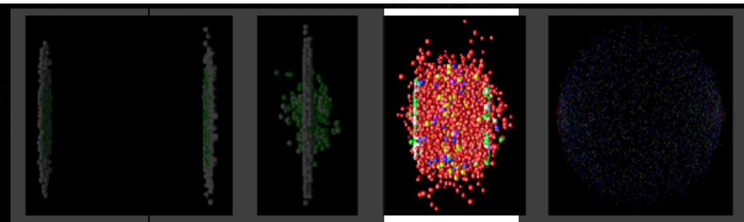
Centrality ⟶

PHENIX PRL 89 (2002)



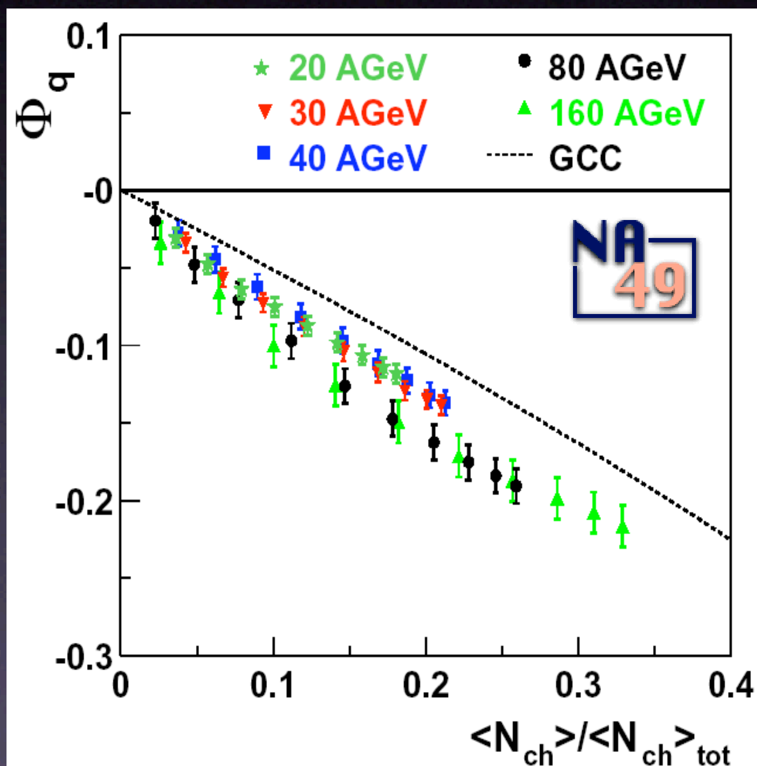
Centrality ⟶

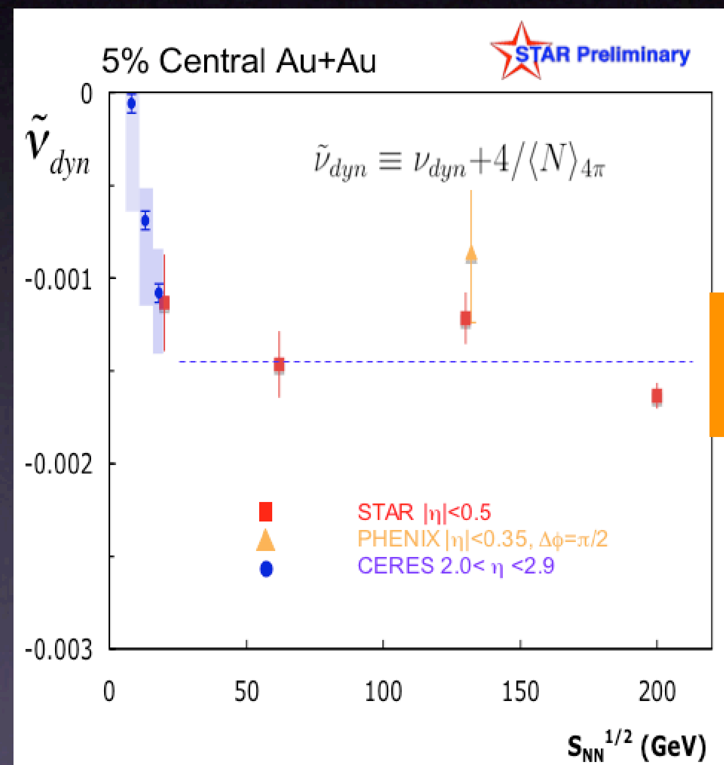
Fluctuations agree with stochastic distributions of *Hadrons*



Properties of the Medium

Net Charge Fluctuations





Quark-Coalescence

Bialas, 2003

QGP

Little (no) √s dependence of charge fluctuations

Energy dependence of charge fluctuations

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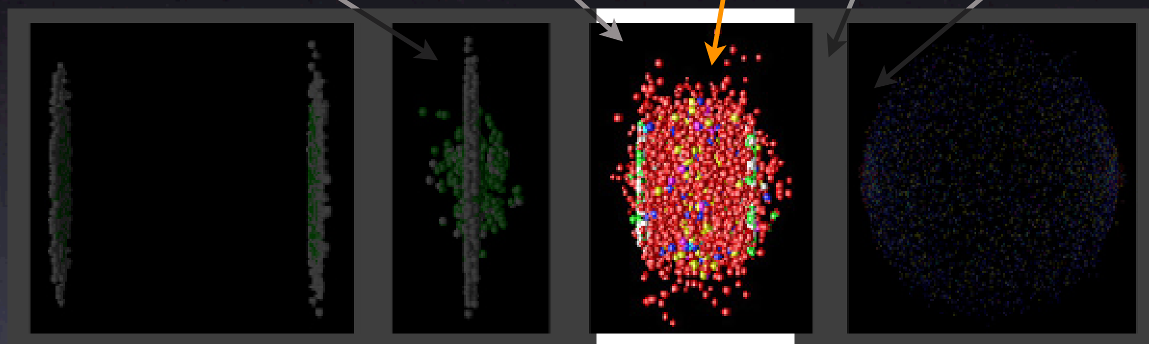

Net charge fluctuations large (~ hadron gas)

Small/no √s dependence

→

Quark coalescence?

Property of Hadronization?

Diffusion?

Bound states?

Energy dependence of charge fluctuations

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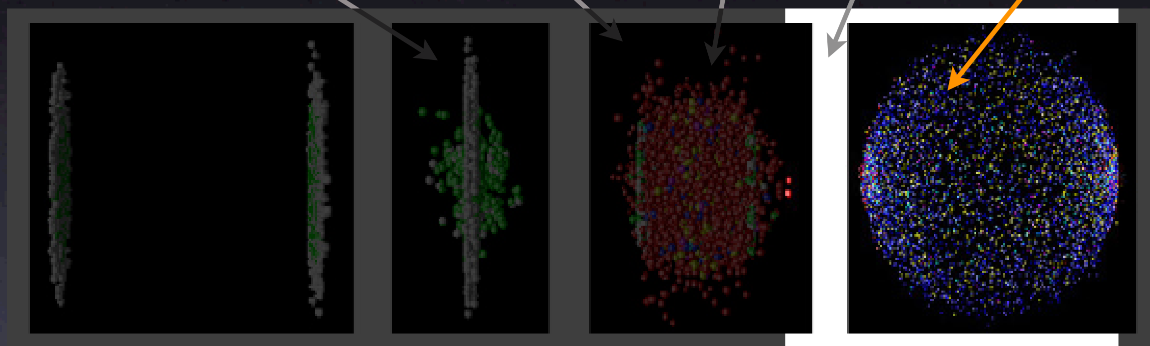

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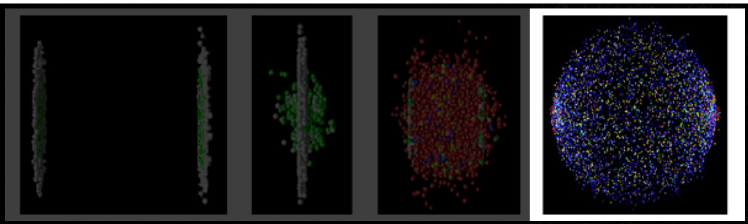
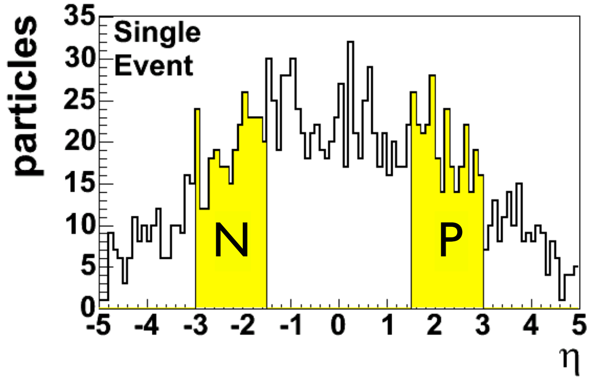


Hadronization

Forward/backward multiplicity correlations



$$C = \frac{P - N}{\sqrt{P + N}}$$

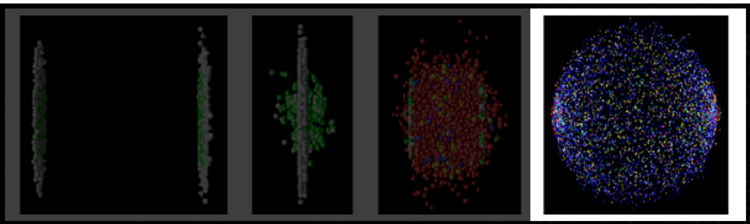
Use variance σ^2_C

Particles produced independently:

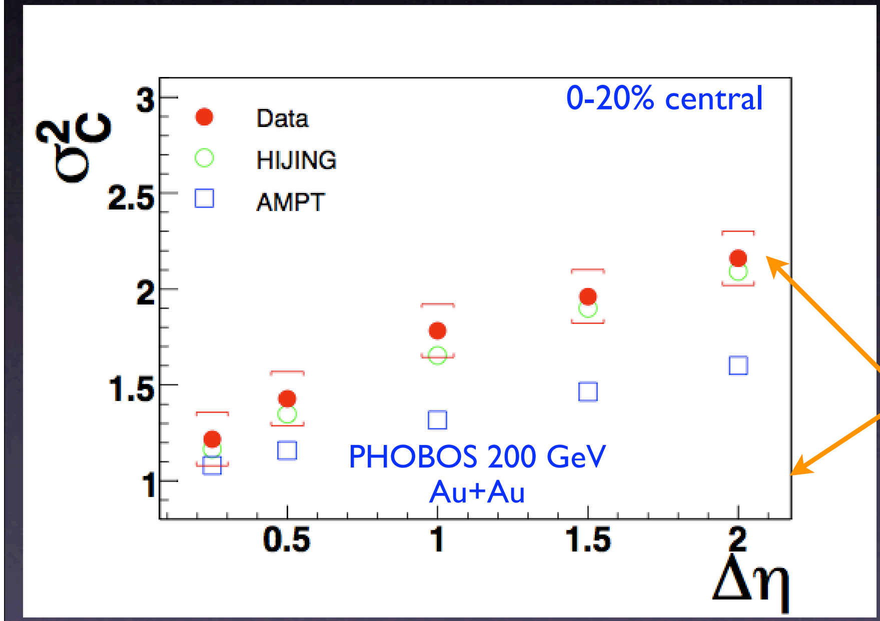
$\sigma^2_C = 1$

Particles produced in clusters of size *K*:

$$C \rightarrow \sqrt{K} C$$
$$\sigma^2_C \rightarrow K \sigma^2_C$$



Forward/backward multiplicity correlations



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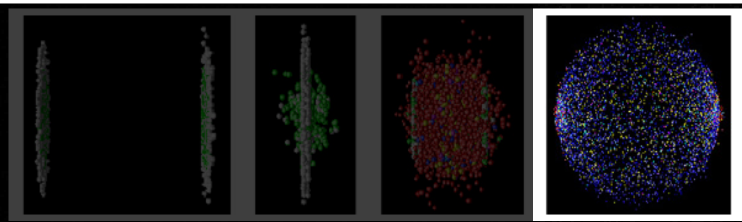
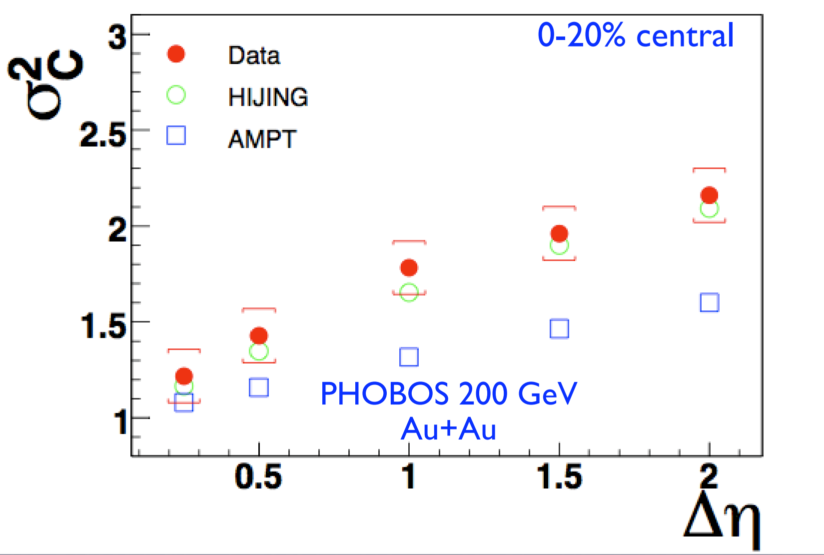
$$C \rightarrow \sqrt{K}C$$
$$\sigma_C^2 \rightarrow K\sigma_C^2$$

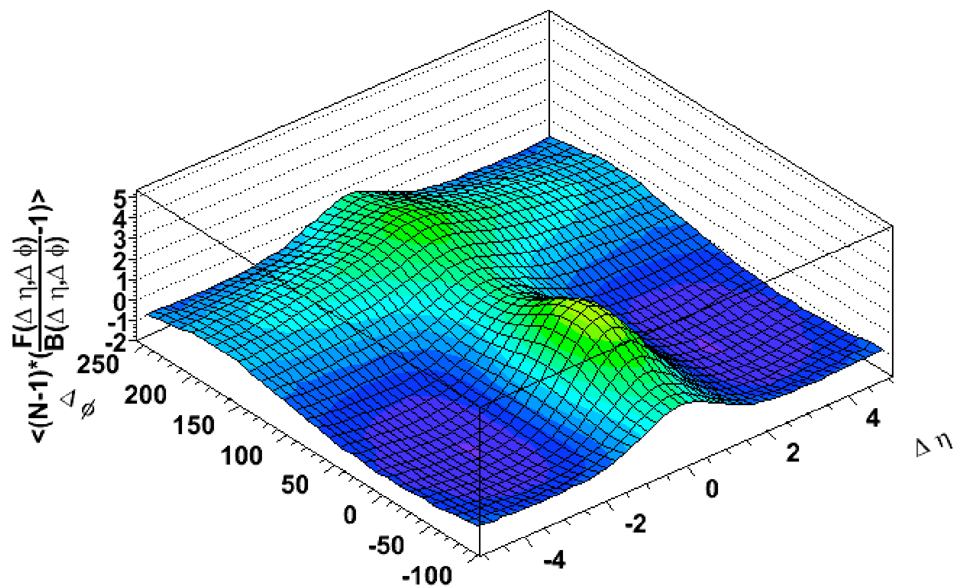
effective cluster size ≈ 2-2.5 for 200 GeV Au+Au



Hadronization

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



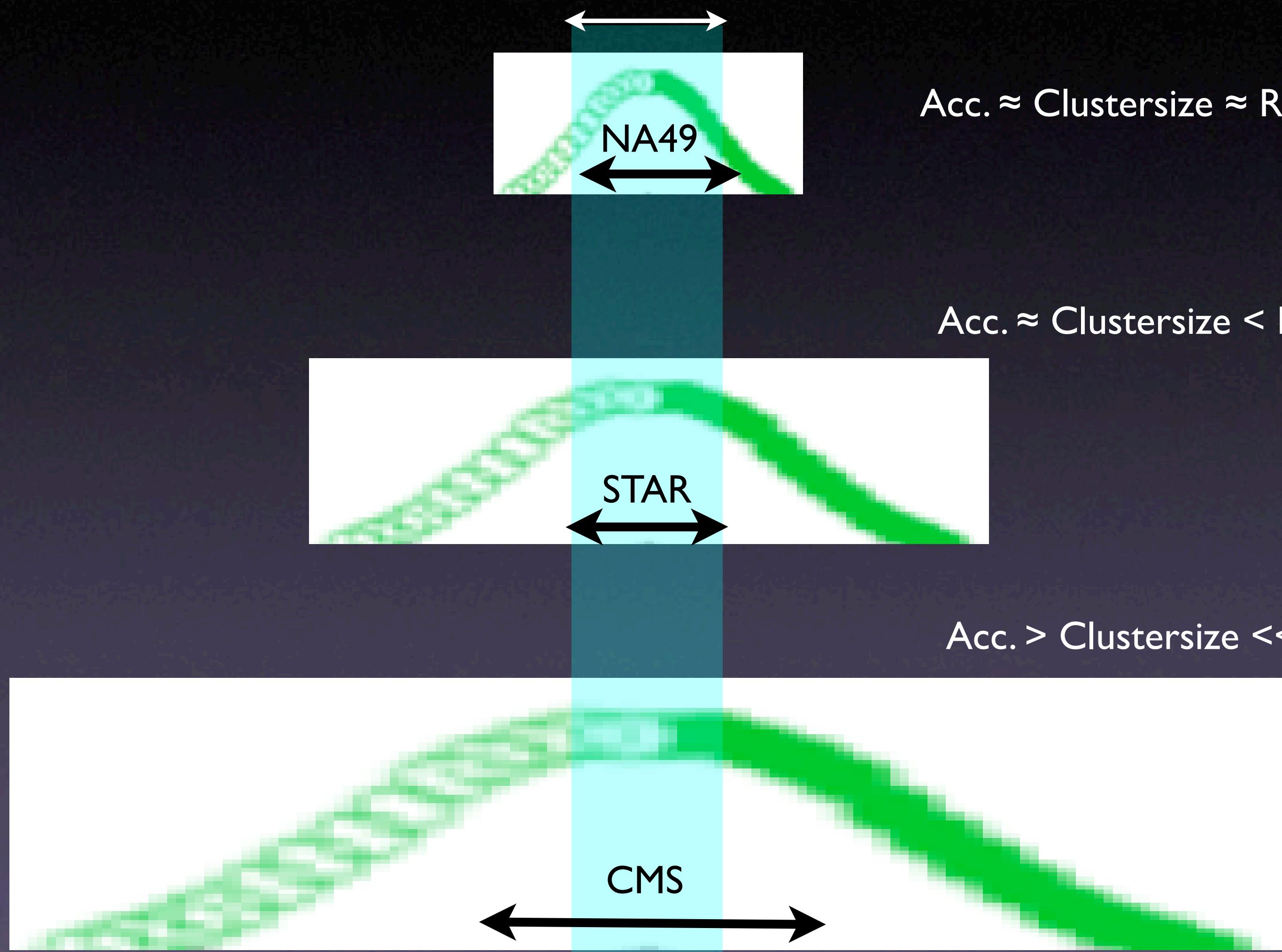


effective cluster size ≈ 2-2.5 for 200 GeV Au+Au

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

Measuring global charge fluctuations

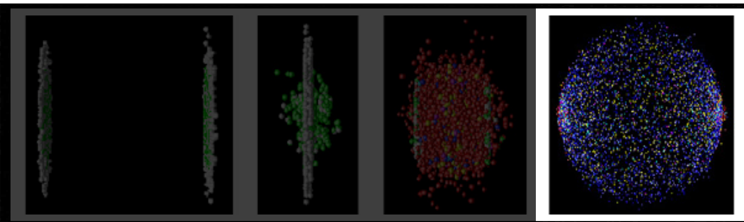
"Clustersize" $\Delta y \approx 2$



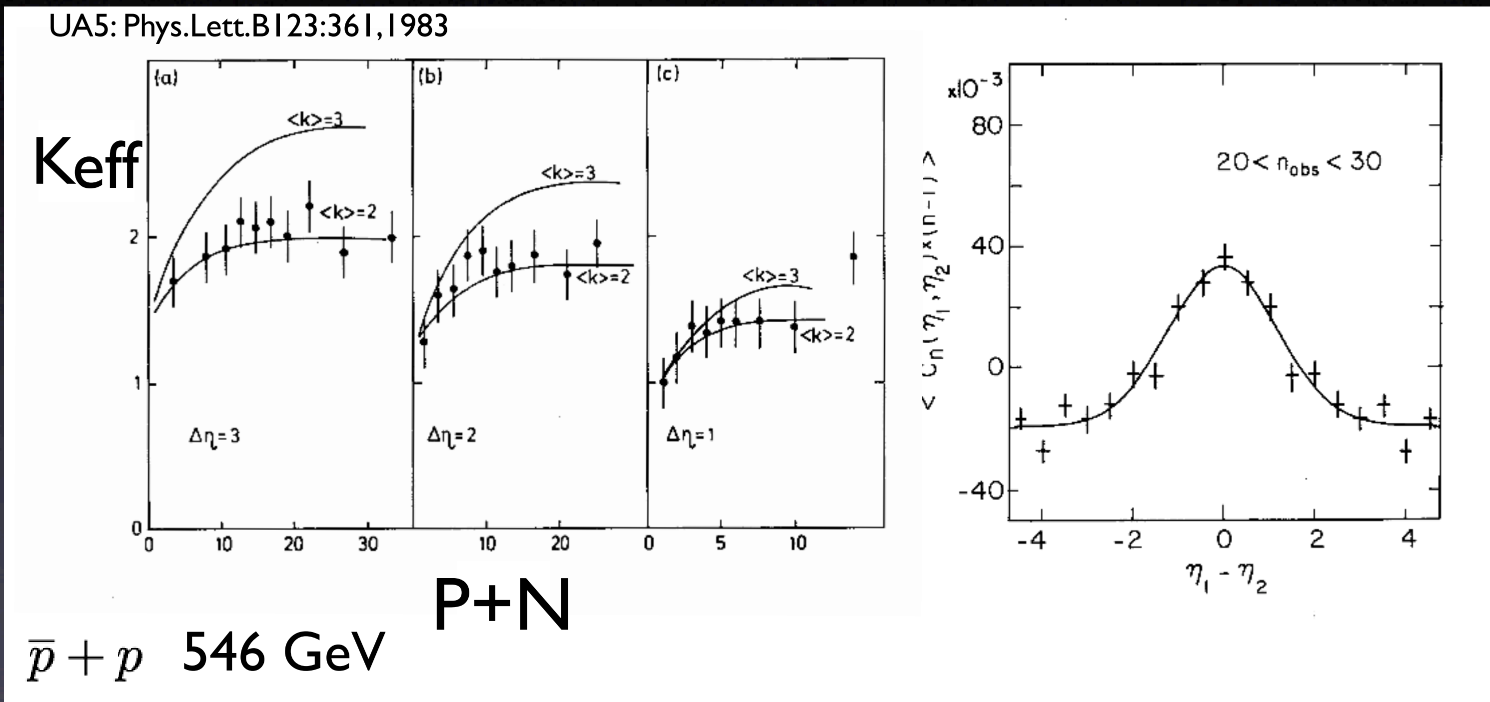
SPS — Acc. ≈ Clustersize ≈ Rapidity gap

RHIC — Acc. ≈ Clustersize < Rapidity gap

LHC — Acc. > Clustersize << Rapidity gap



Hadronization

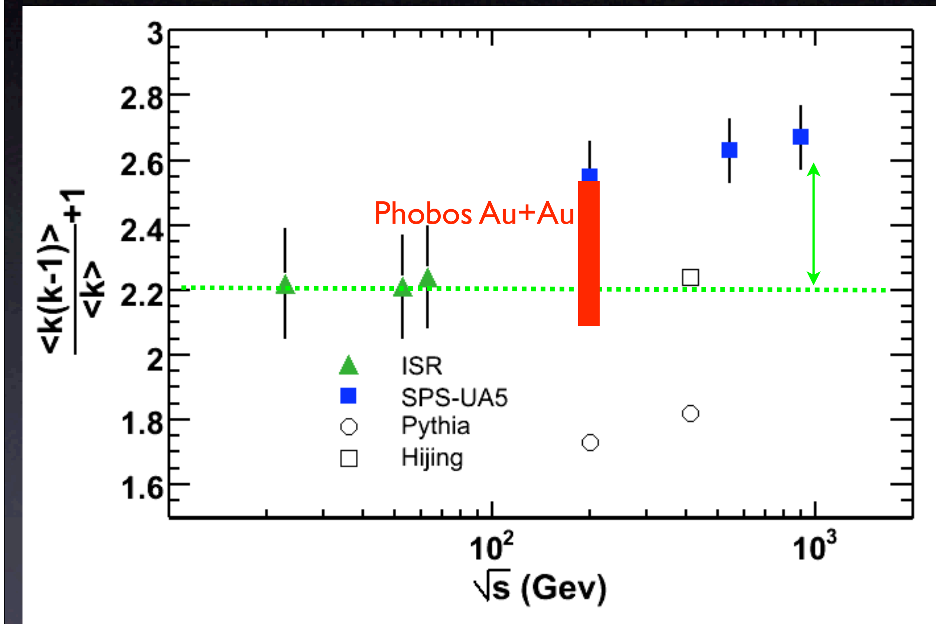


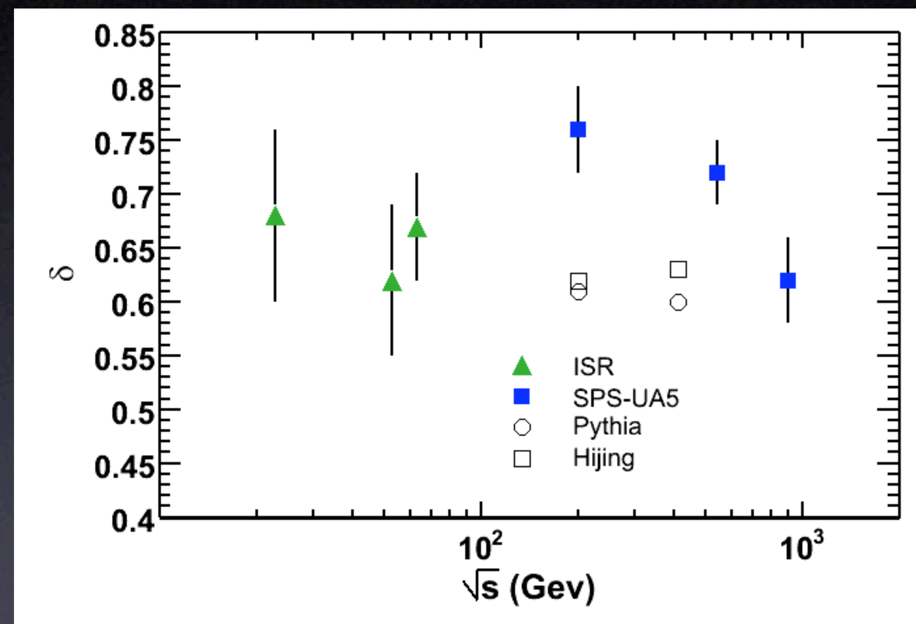
Clusters in Au+Au reminiscent of results from $p+\bar{p}$

p+p clusters vs √s

Origin of p+p clusters?

Plots from Wei Li

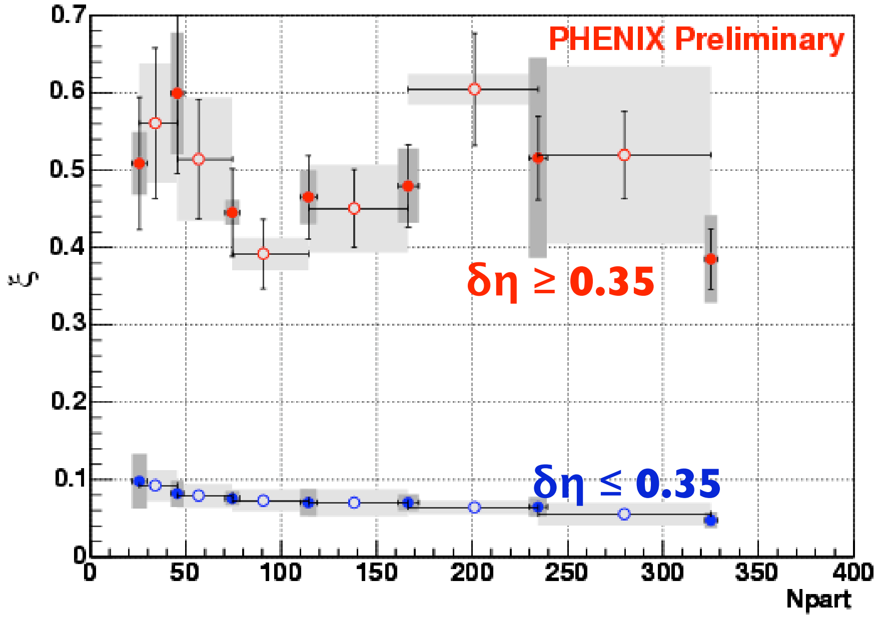


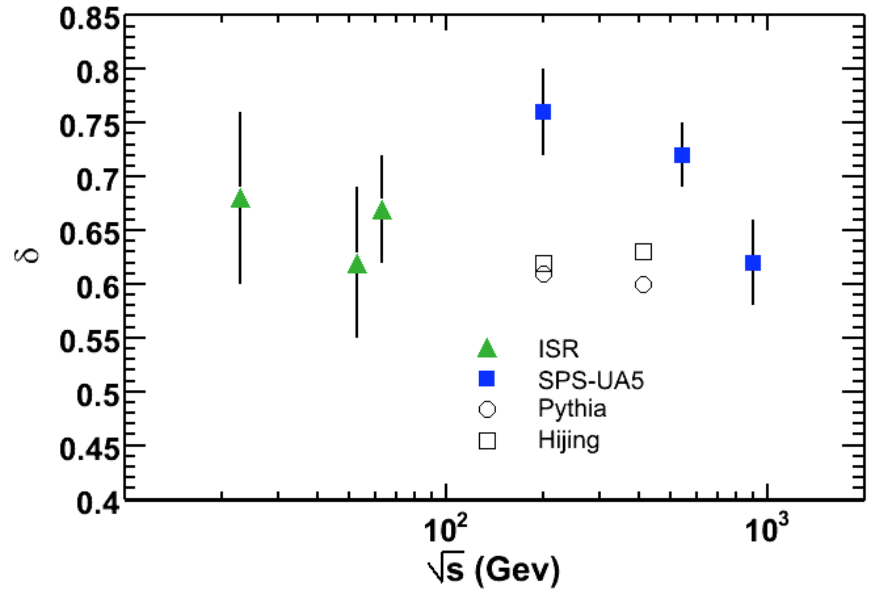


* Resonances?
* String fragmentation?
* (mini-) Jets?

Clusterwidth in A+A vs p+p

Au+Au 200 GeV, no magnetic field
Δη<0.7, ΔΦ<π/2 rad





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

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

Clusters and Correlations

(How) Does matter thermalize?

Nature of the phase transition?

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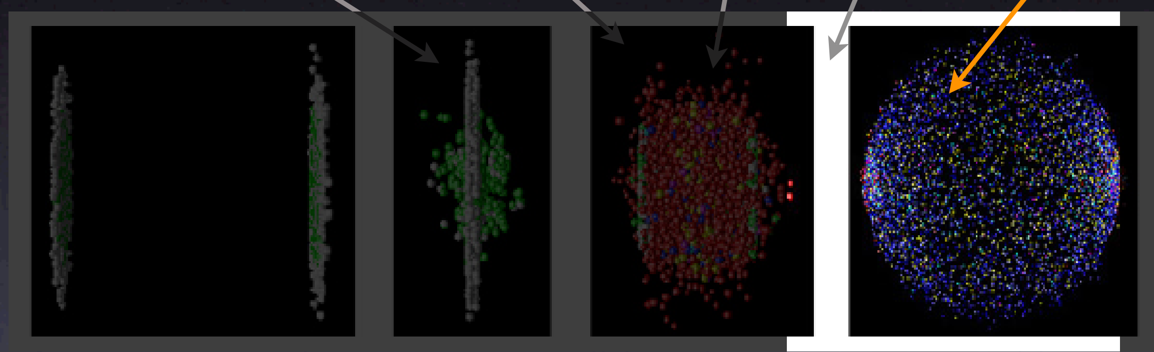

Large multiplicity fluctuations

Strong change in underlying correlation structure

→

Particles produced in large ‘clusters’

Understanding of hadronization essential

Collision dynamics reflected in correlation structure

Future Measurements

(How) Does matter thermalize?

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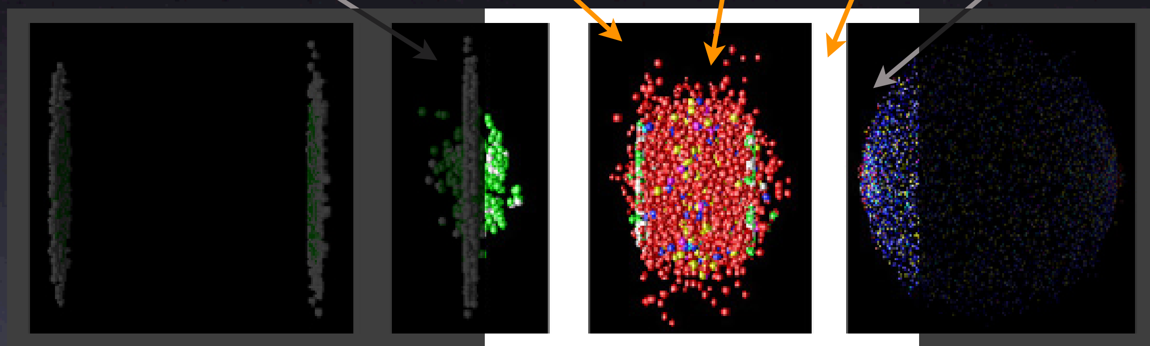
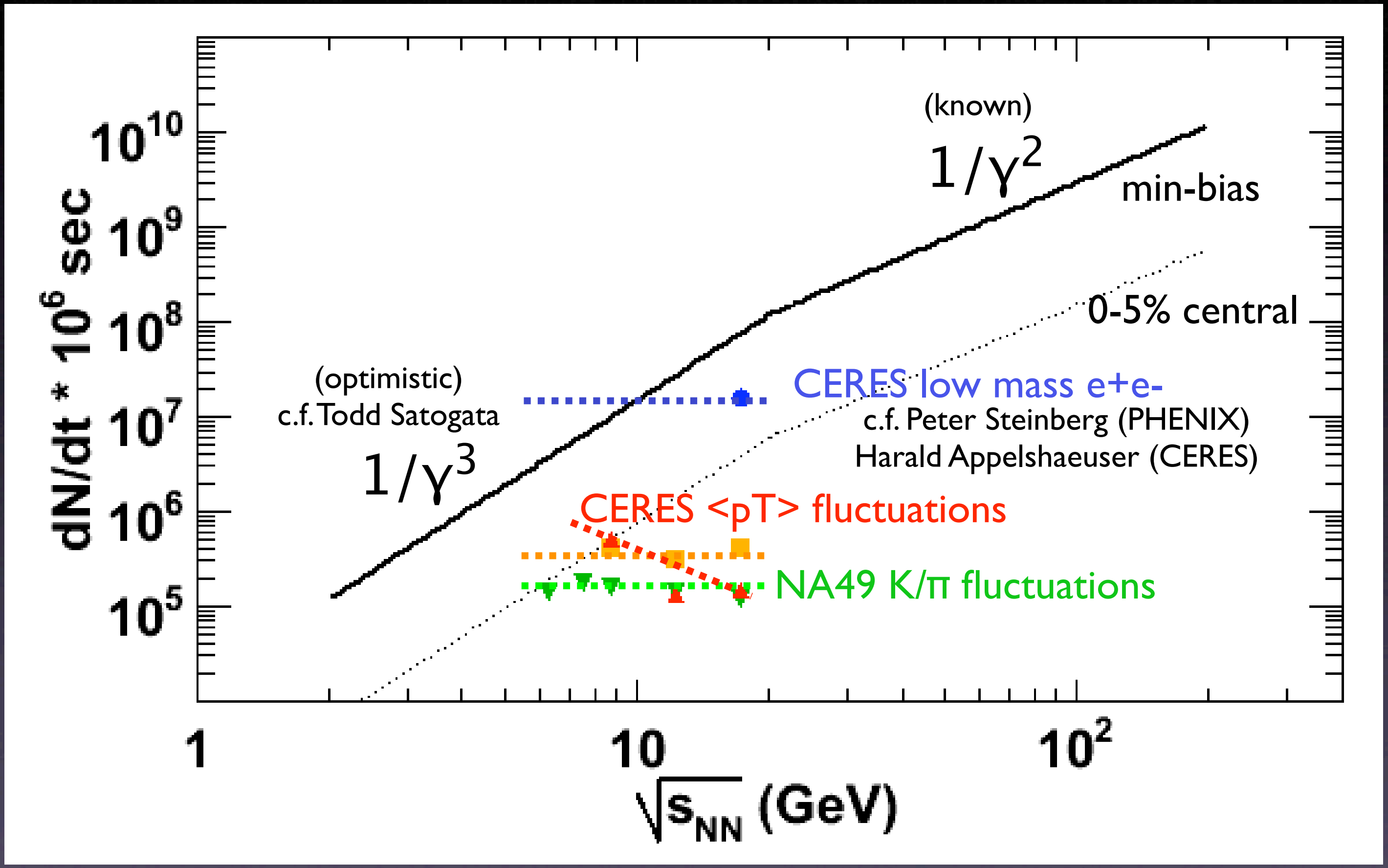


Some remarks on future measurements

Low energy running at RHIC

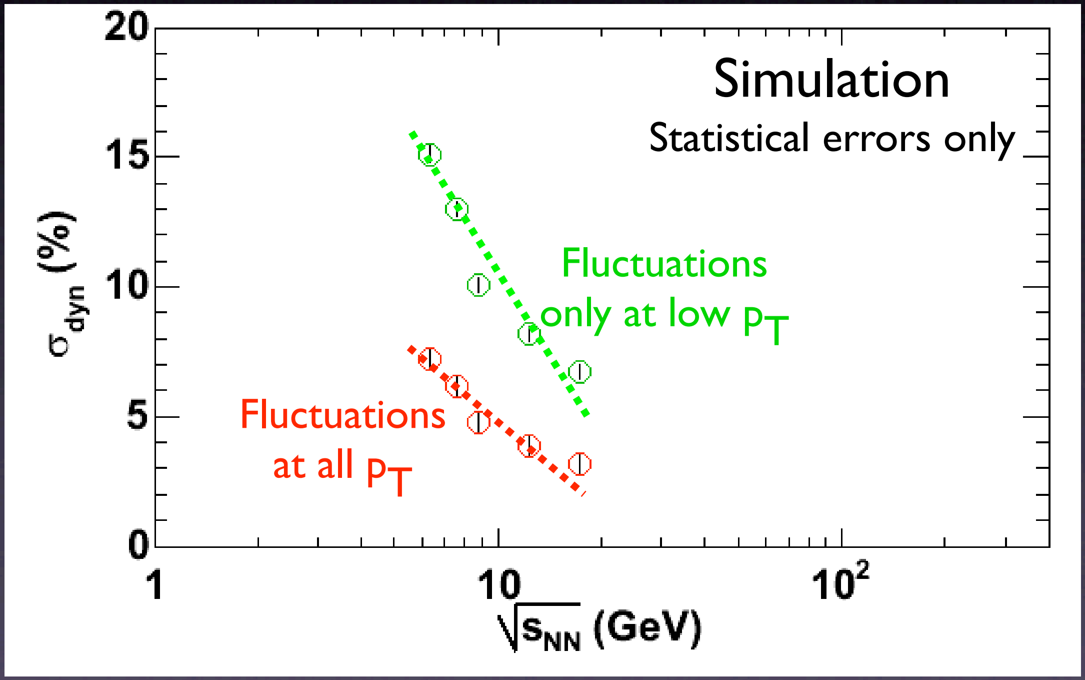


If rates O(1Hz) or greater:
√s scan of hadronic observables feasible

Low energy running at RHIC

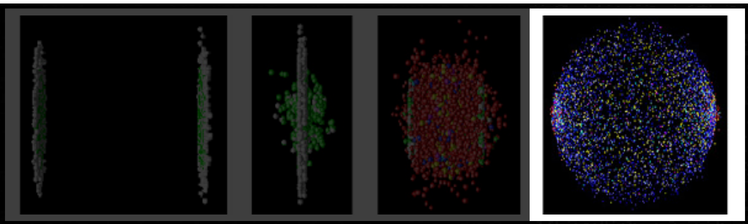
Assumptions:
* Ideal RHIC detector
* 100k central Au+Au at each √s
* K/π Fluctuations from NA49 are correct
* $0.1 < p_T < 0.5$ GeV/c

Strangeness Fluctuations vs √s



Opportunity with possible low-E run at RHIC

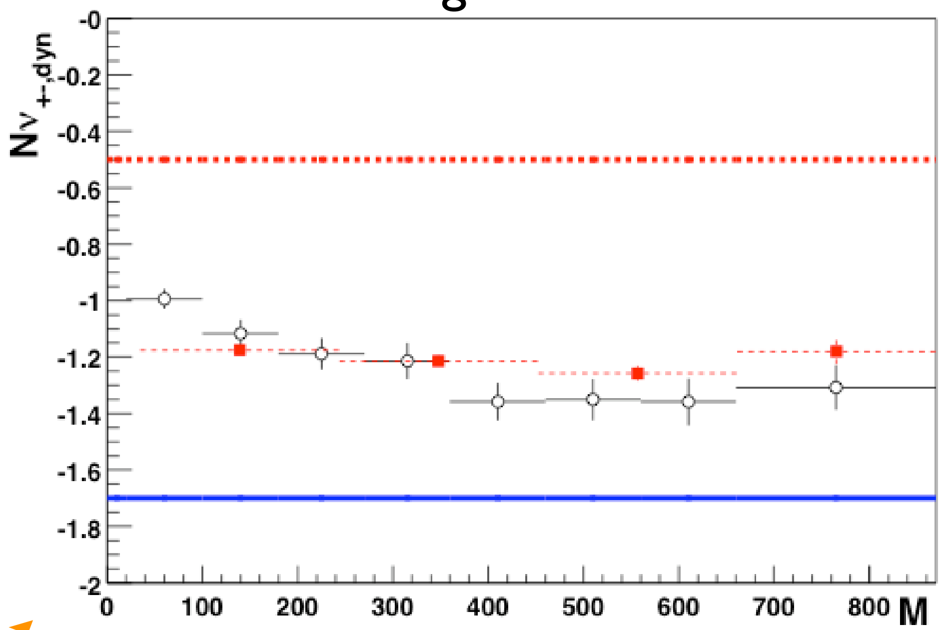
STAR with ToF/Si-VTX upgrade is ideal place



Hadronization

Correlations and Fluctuations, revisited

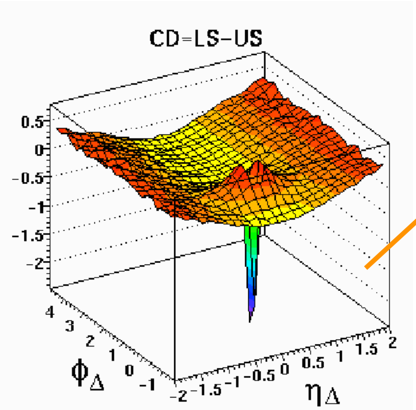
Net-charge Fluctuations



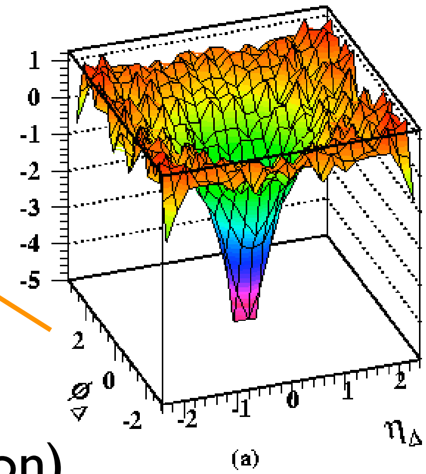
centrality →

Global scaling, even though underlying correlations change

p+p



Central A+A



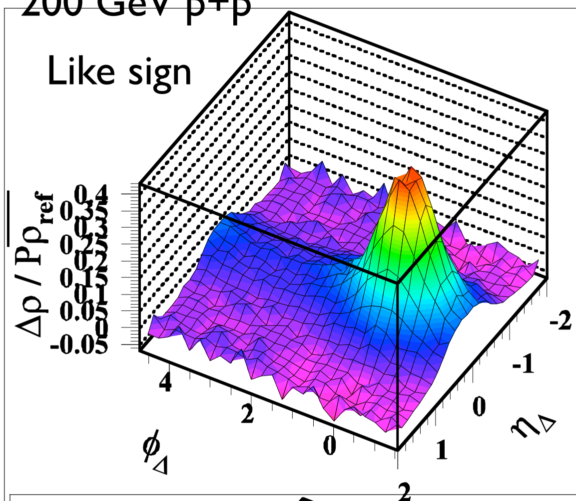
Net-charge correlations (c.f. Balance Function)

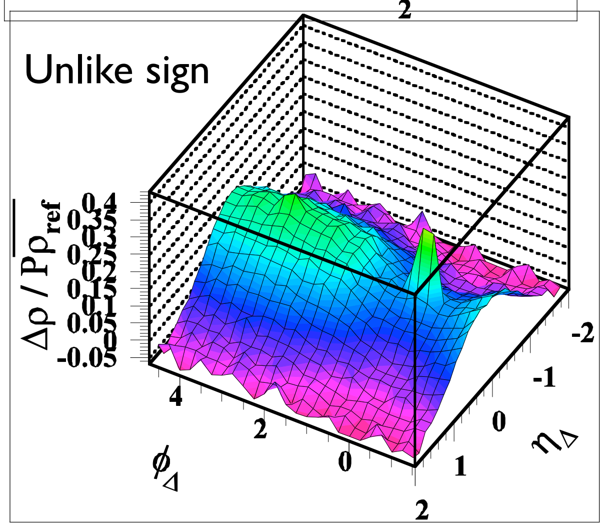
Summary

- Rich existing data set on fluctuations
  - Energy independence of global pT, charge fluctuations
  - Energy <u>dependence</u> 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 <u>improve</u> experimental results

Beyond global charge fluctuations

STAR
200 GeV p+p





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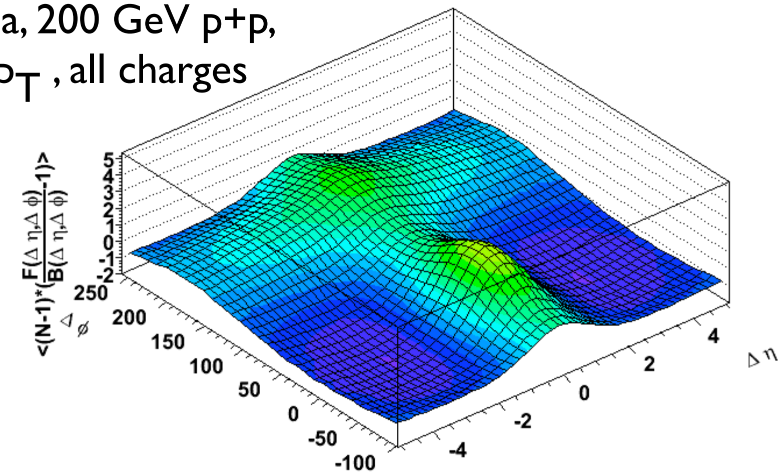
Split sample

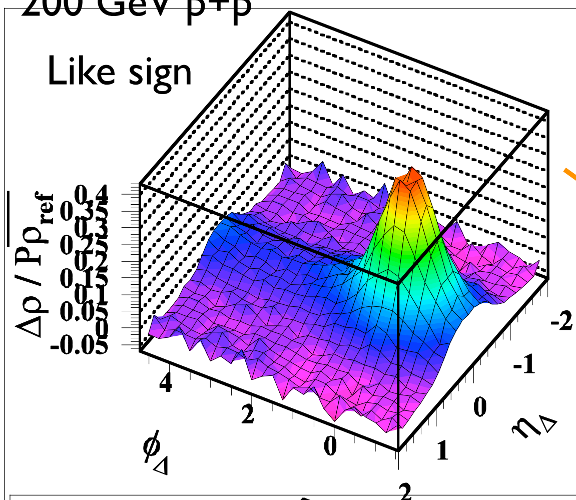
Pythia, 200 GeV p+p,
all p_T , all charges

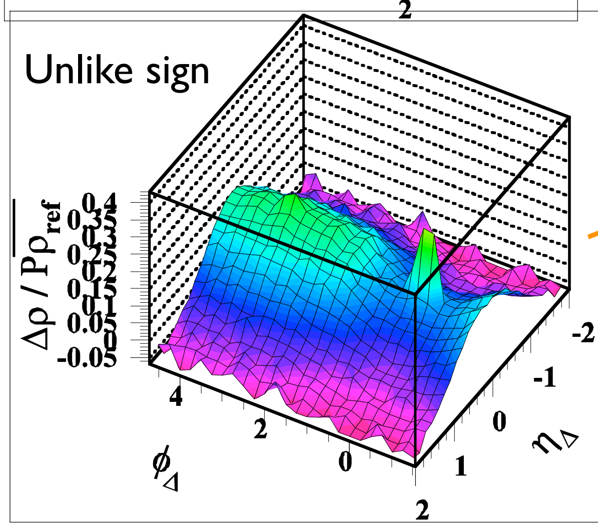


2-D angular correlation function

Charge Dependent Correlations

STAR
200 GeV p+p





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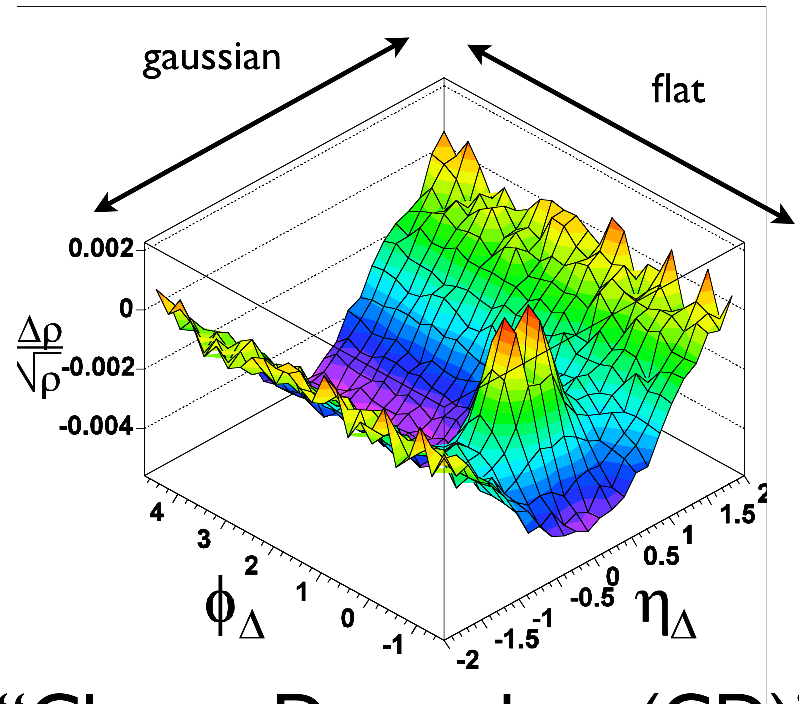
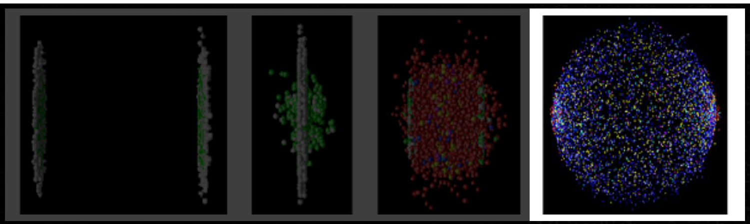
subtract

longitudinal charge ordering

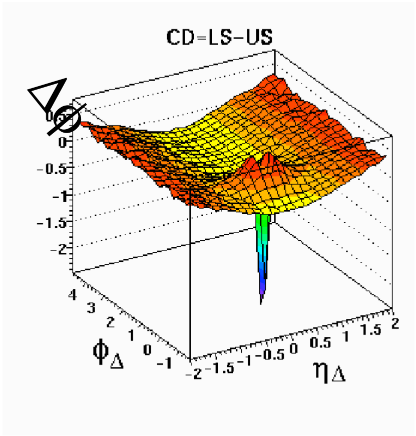


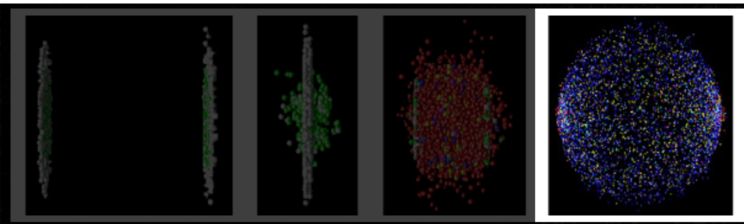
"Charge Dependent (CD)" correlations
[= like sign - unlike sign]



Hadronization

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





Hadronization

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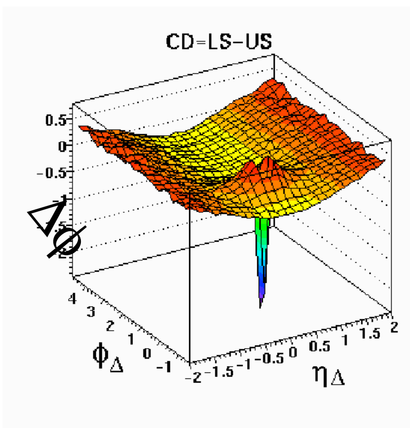
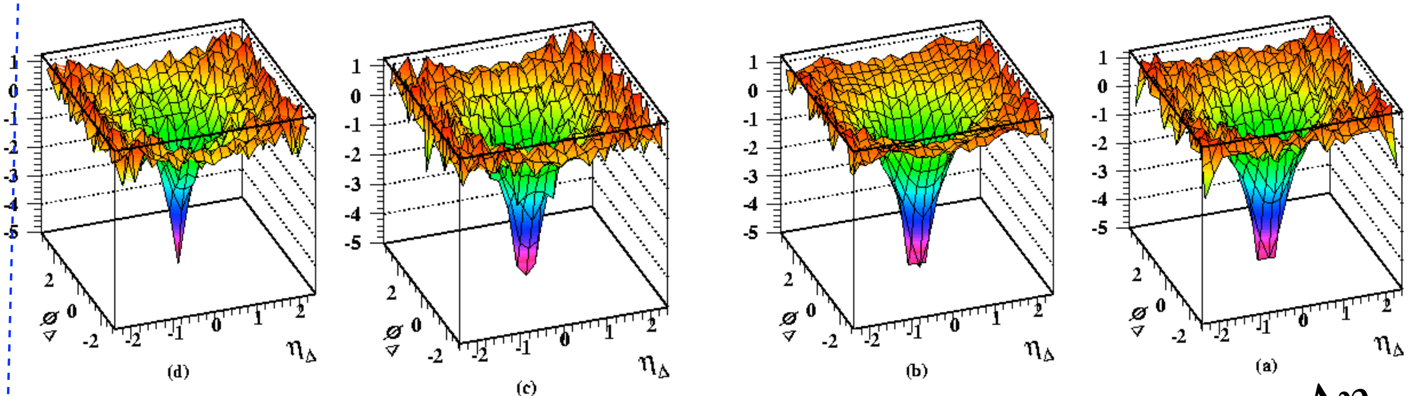


p+p

peripheral ⟷ central



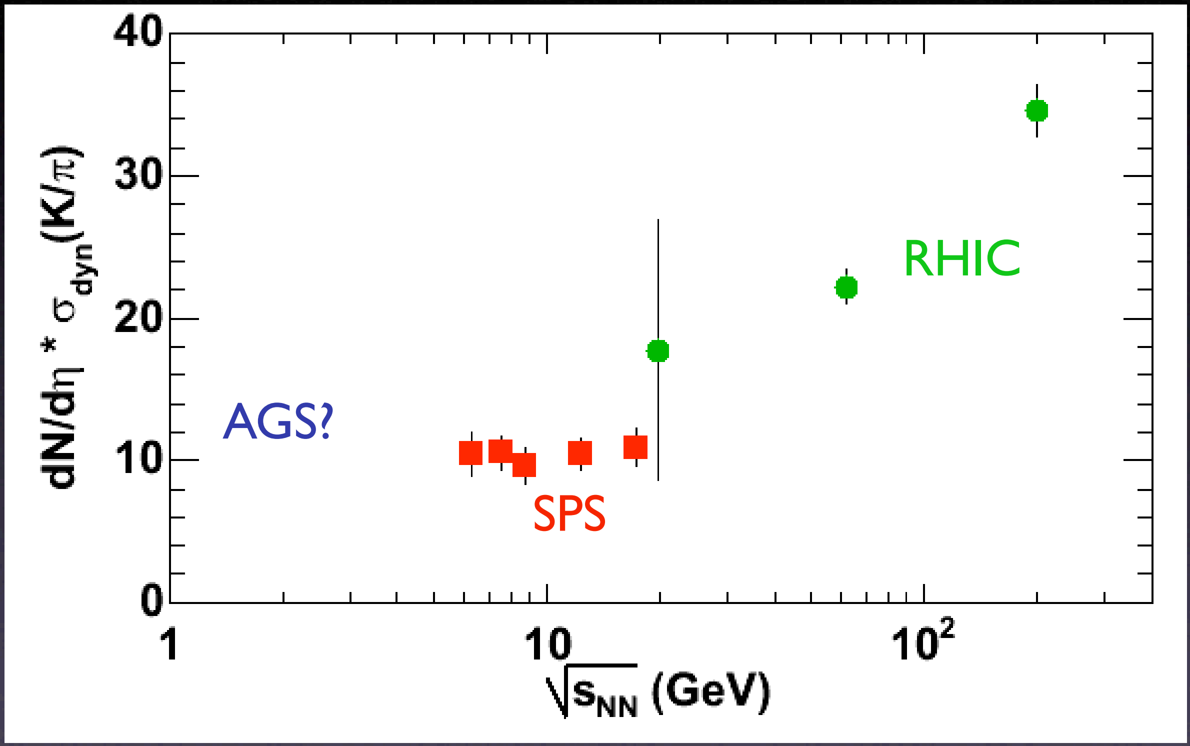
Au+Au

STAR
nucl-ex/0406035

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

$$\Phi_{p_T} = \sqrt{\frac{\frac{1}{\varepsilon}\sum_{j=1}^{\varepsilon}(N_j < p_T >_j - N_j\hat{p}_T)^2}{\overline{N}}} - \sigma_{\hat{p}_T} \quad (1)$$

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

$$\Sigma_{p_T} = \frac{\sqrt{\sigma^2_{<p_T>,dyn}}}{\overline{p}_T} \quad (3)$$

$$\sigma^2_{<p_T>,dyn} = \frac{1}{\varepsilon}\sum_{j=1}^{\varepsilon}\frac{N_j(< p_T >_j - \hat{p}_T)^2}{\overline{N}} - \frac{\sigma^2_{\hat{p}_T}}{\overline{N}} \quad (4)$$

The relationshipe between Φ_{p_T} and Σ_{p_T} when Φ_{p_T} is small and $\Phi^2_{p_T}$ term is neglected:

$$\Phi_{p_T} \simeq \frac{\sigma^2_{<p_T>,dyn}\overline{N}}{2\sqrt{\sigma^2_{\hat{p}_T}}} \quad (5)$$

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

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":

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

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

<p_t> 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

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

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

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