# Event by Event Fluctuations

*CERN Heavy Ion Forum*
*May 24 2006*

Gunther Roland
MIT

# What can we learn from fluctuations?

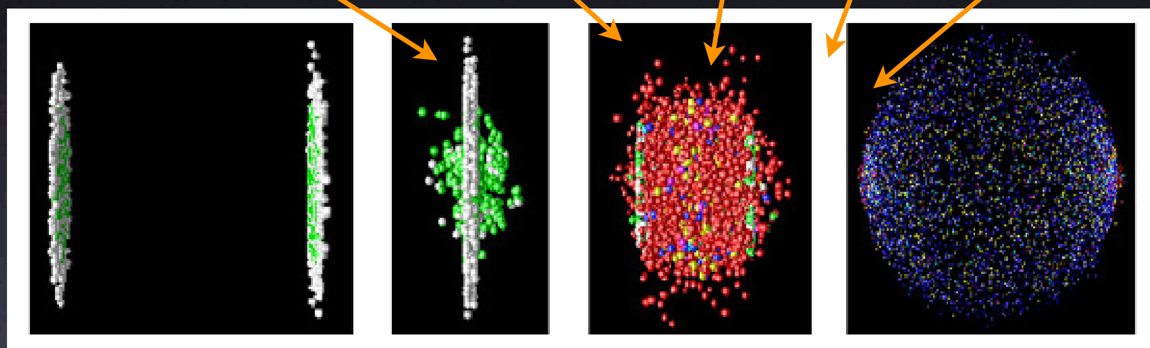
(How) Does matter thermalize?

Nature of the phase transition?

How is entropy produced?

Properties of the medium?

How are hadrons made?



Unique answers to all of these questions from fluctuations/correlations

*How far have we come trying to realize this promise?*

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**Nature of the phase transition?**

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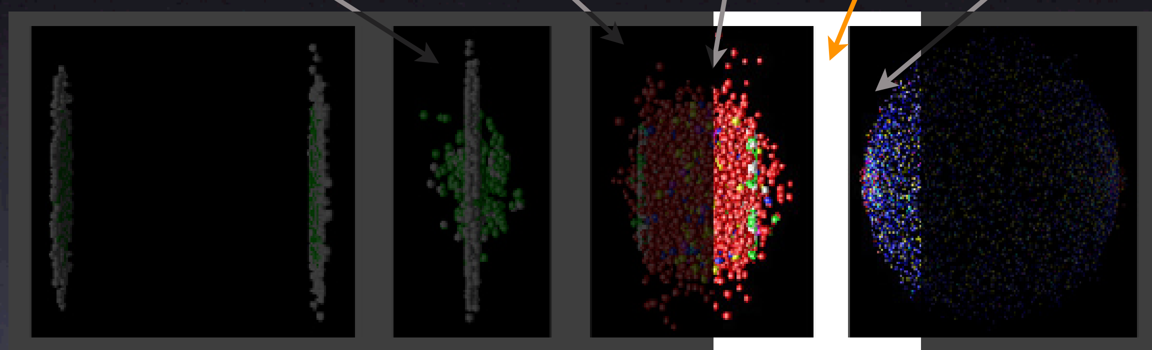
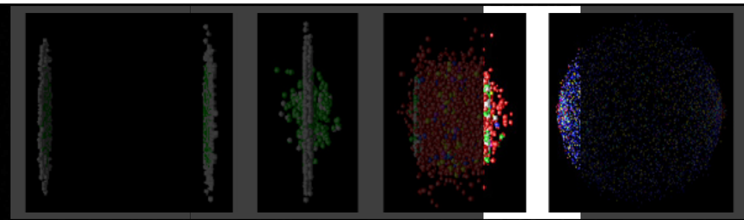
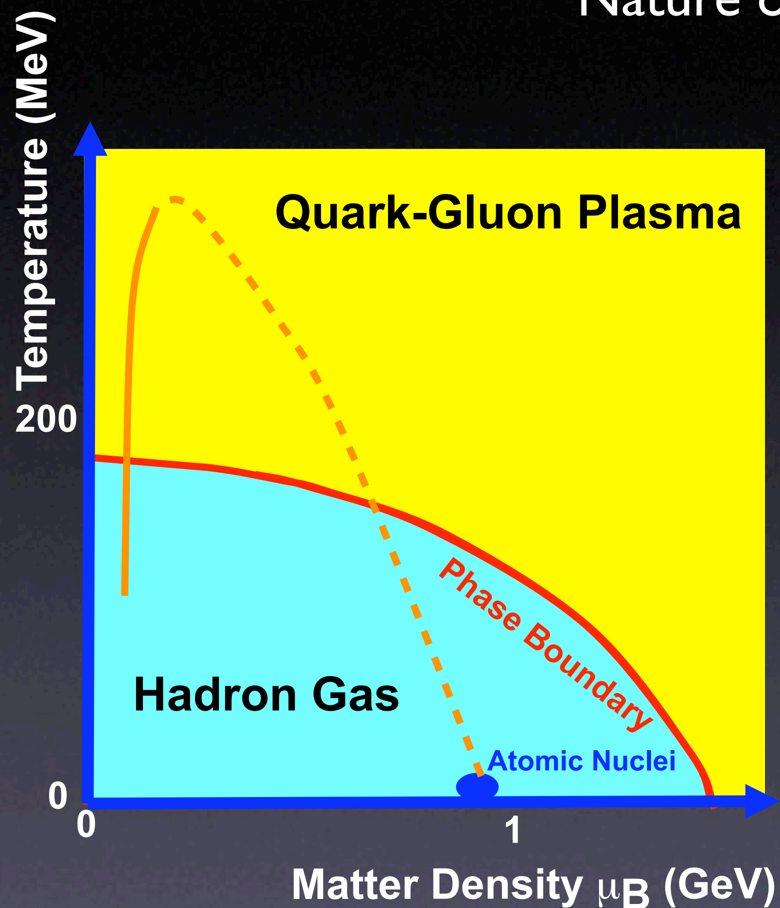
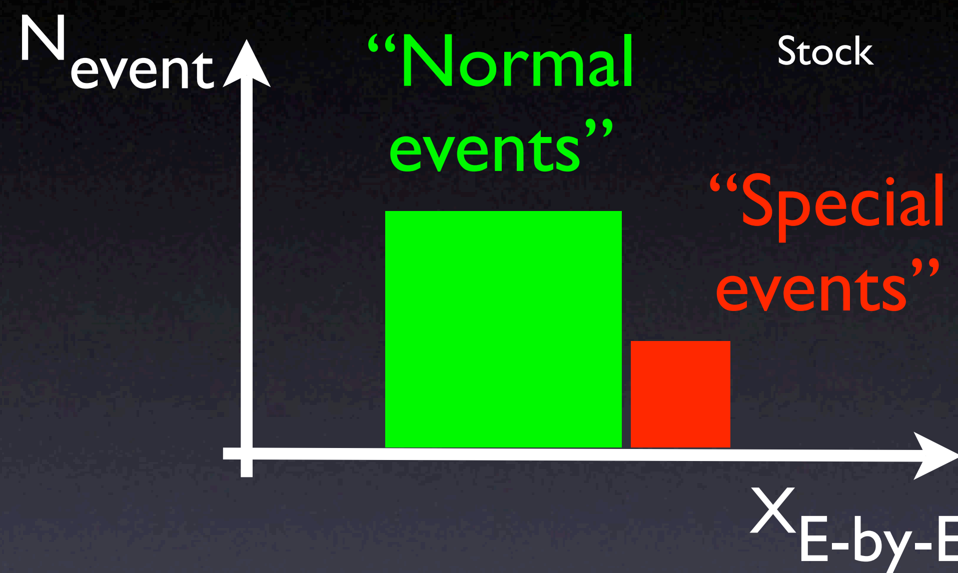


ca 1990

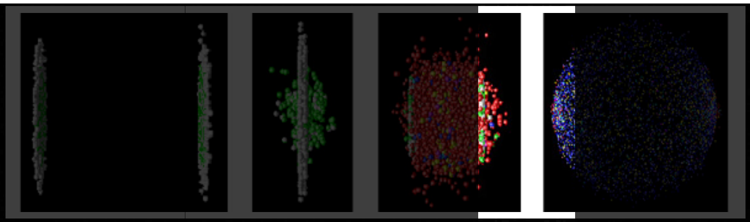


# Nature of the Phase Transition




Search for critical phenomena induced near phase transition



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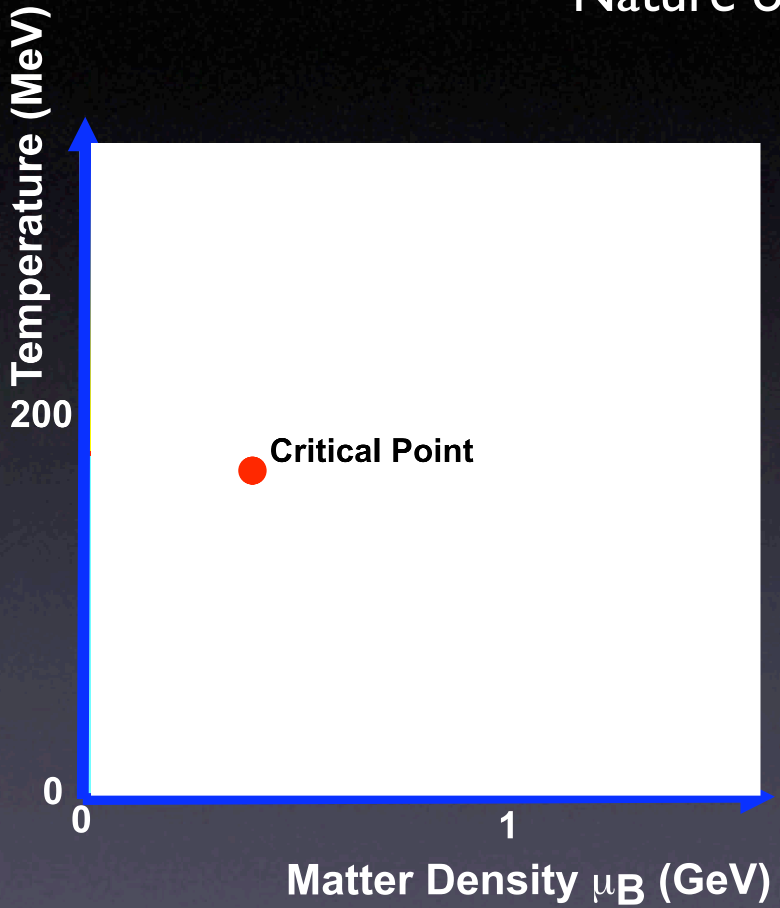
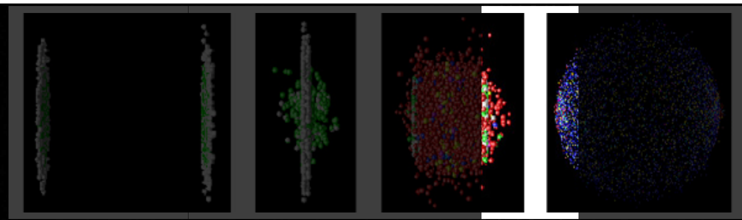



Susceptibilities diverge near critical point

Locate the critical point using correlation/fluctuation measurements

ca 1998

Rajagopal, Shuryak, Stephanov



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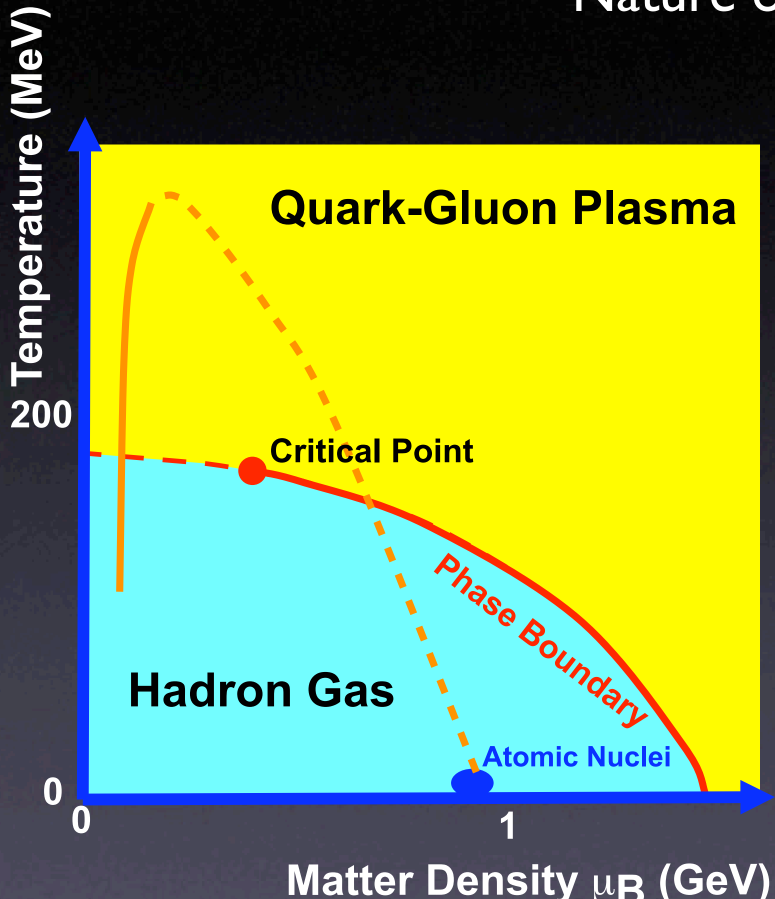
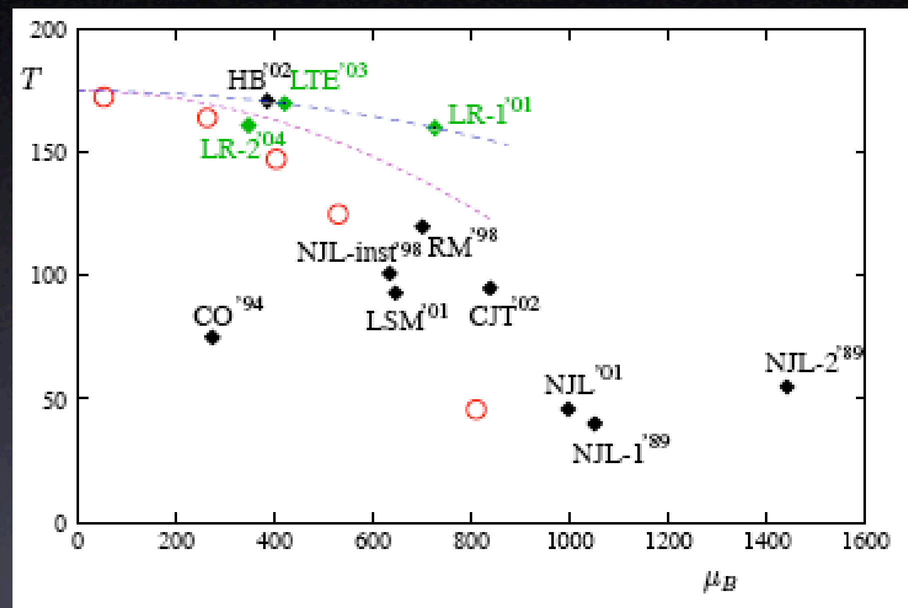
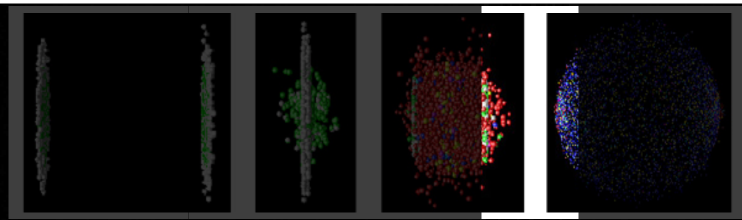


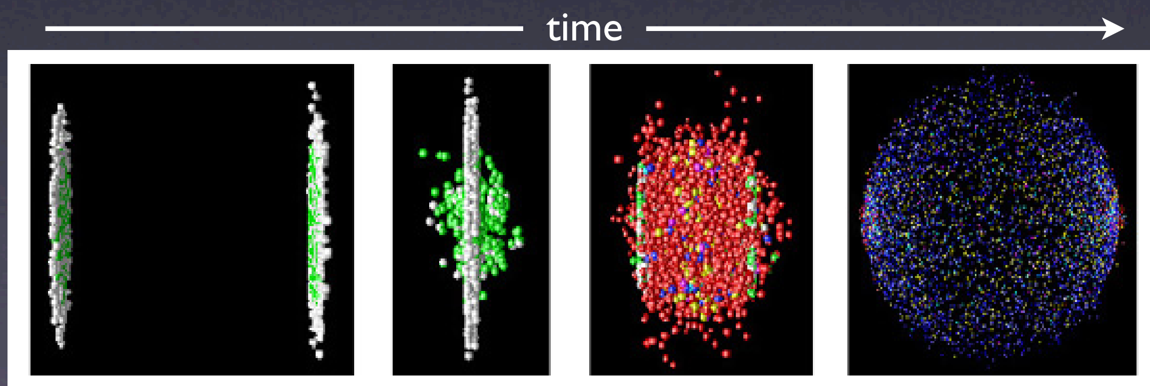



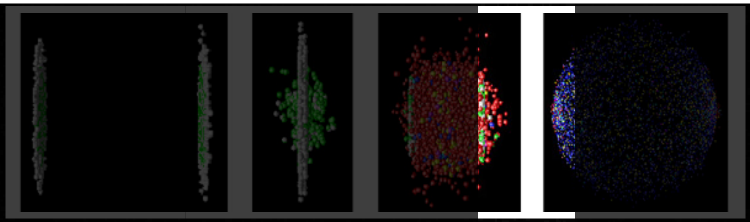

Plot from M. Stephanov, Correlations '05



Nature of the Phase Transition

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





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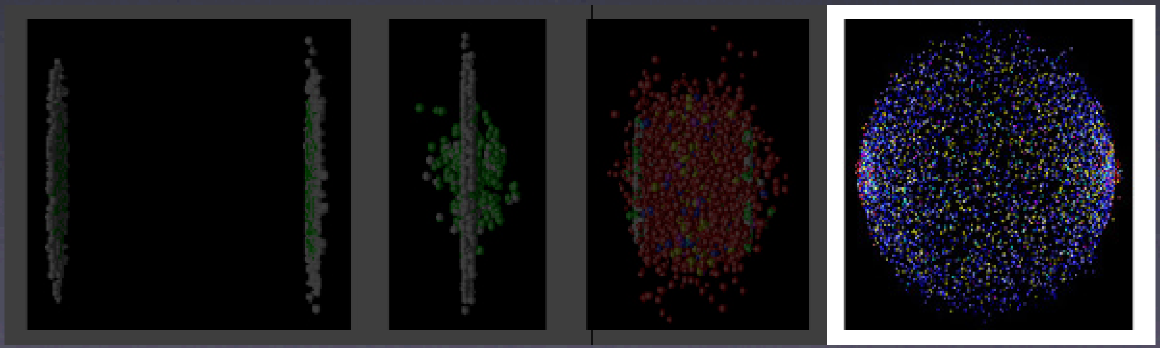
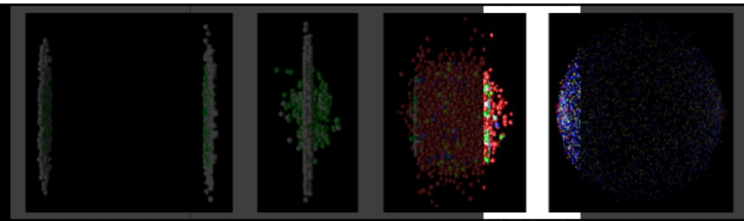


Experiments only see final state particles



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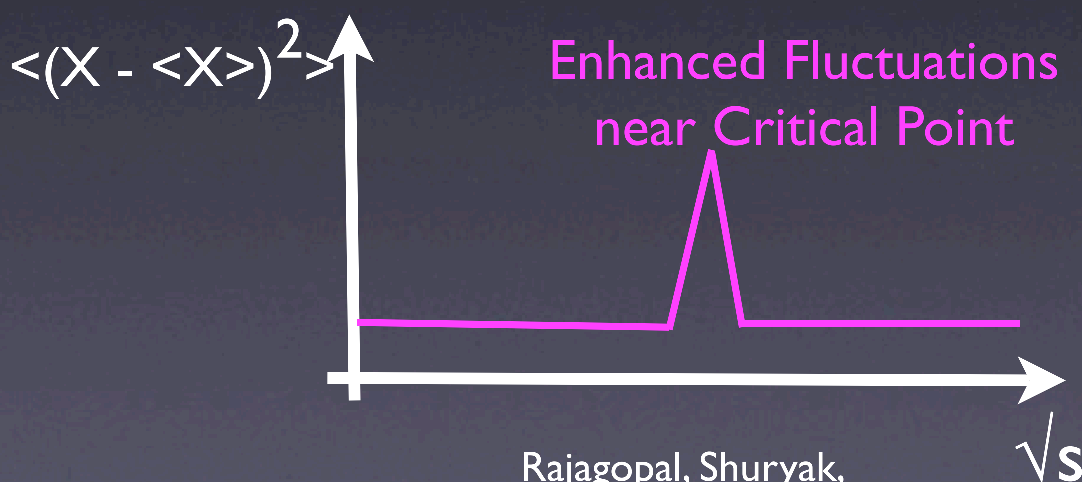
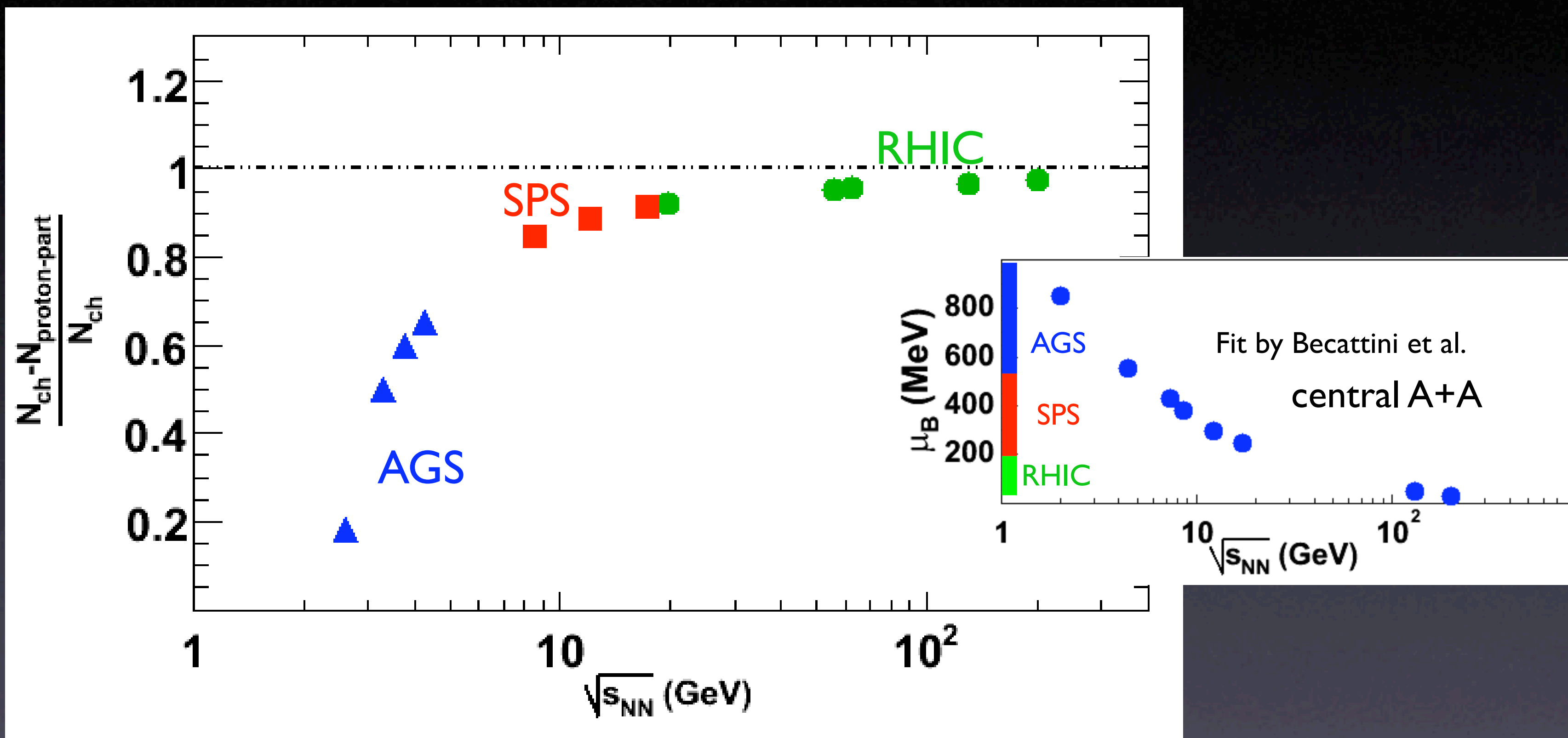



Rajagopal, Shuryak, Stephanov

# Energy Regimes and Accelerators




Change from baryon- to meson dominated system

# First result on $\langle p_T \rangle$ 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**

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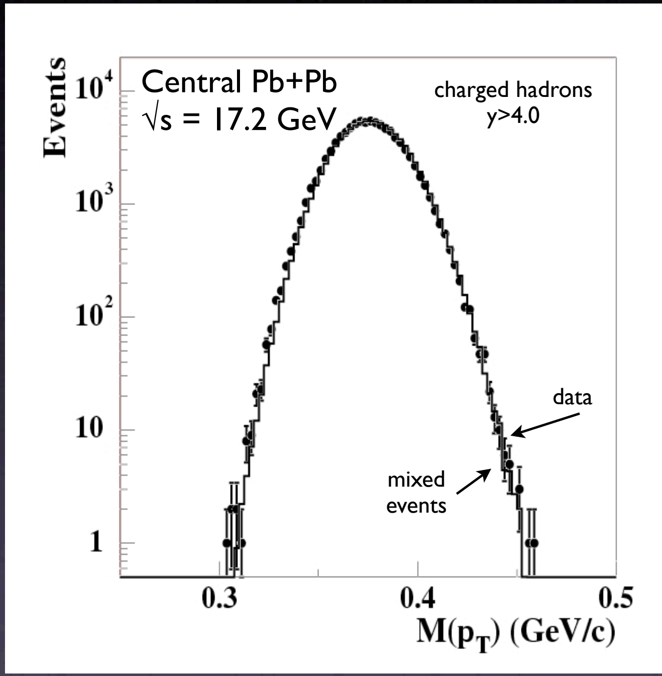
NA49, Phys Lett B459 (1999) 679

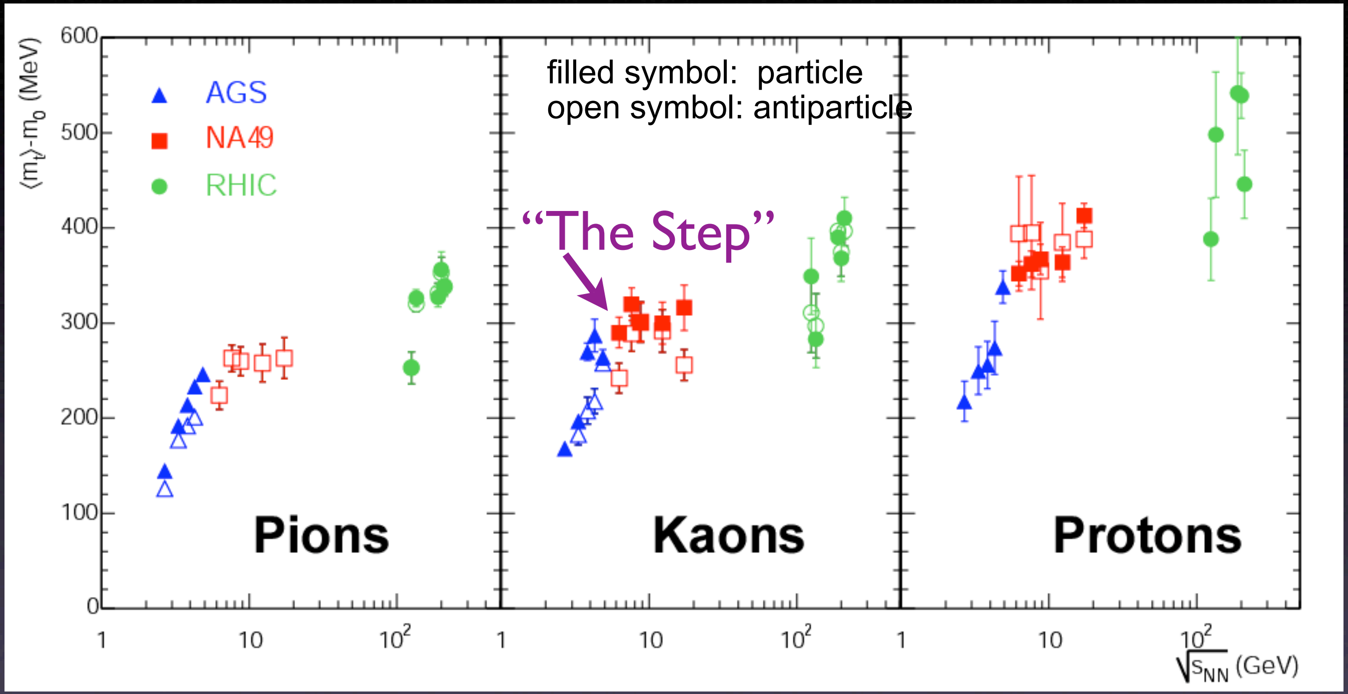



Event-by-event $\langle p_T \rangle$ compared to stochastic reference (mixed events)

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

# Excitation Function: Momentum Spectra

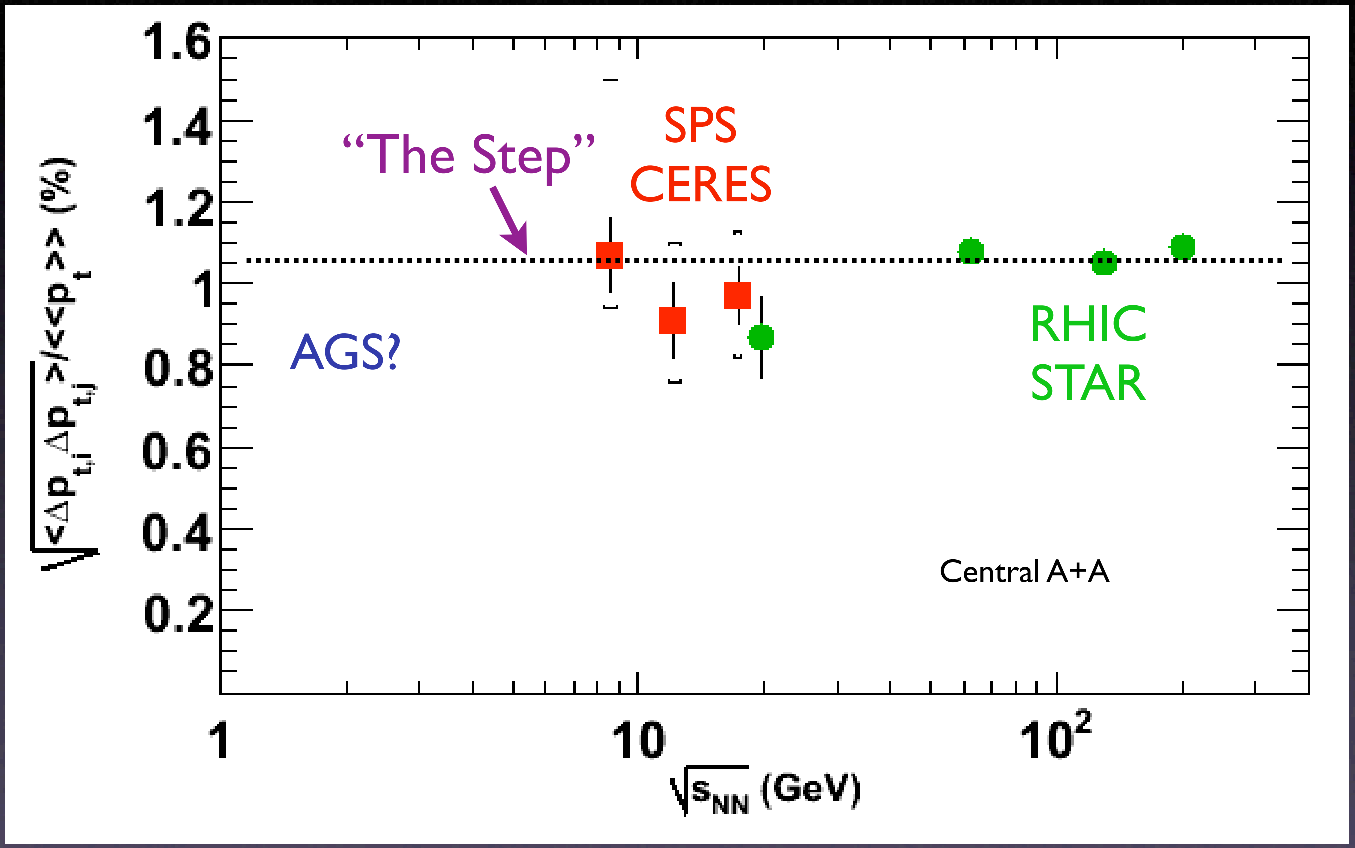
Compilation by NA49
Plot from Claudia Hoehne, QM'05



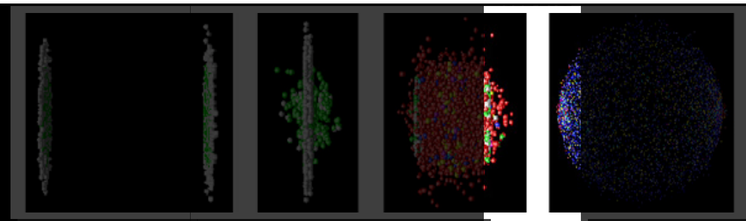

- Structure in energy dependence of $<m_T>$
- Reminiscent of Van Hove's T vs ϵ prediction (1982)
- Surprisingly difficult measurement
  - Decay corrections, PID acceptance

# Excitation Function: Momentum Fluctuations

Compilation by STAR
STAR PRC 72 044902 (2005)



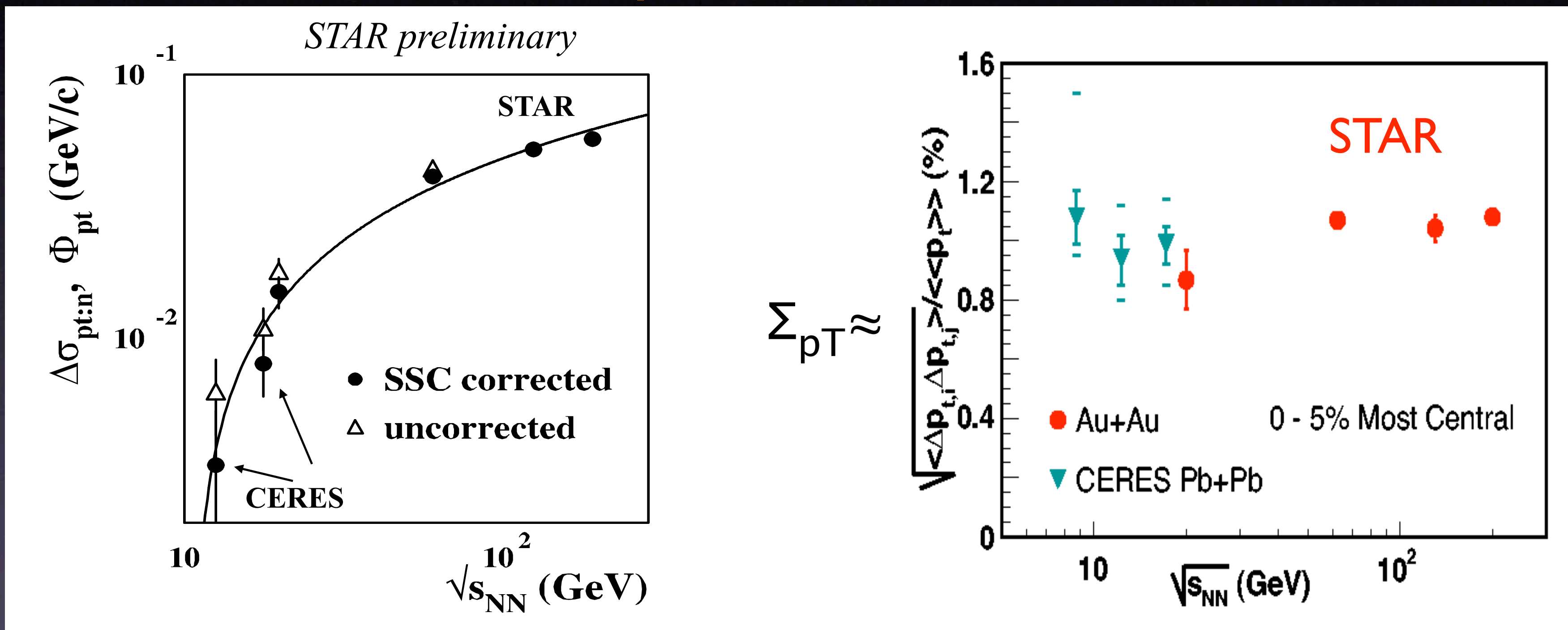

Monotonic energy dependence over measured range
No results near "step" region



Nature of the Phase Transition

# <pT> Fluctuations

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




Connection to 2-particle correlations

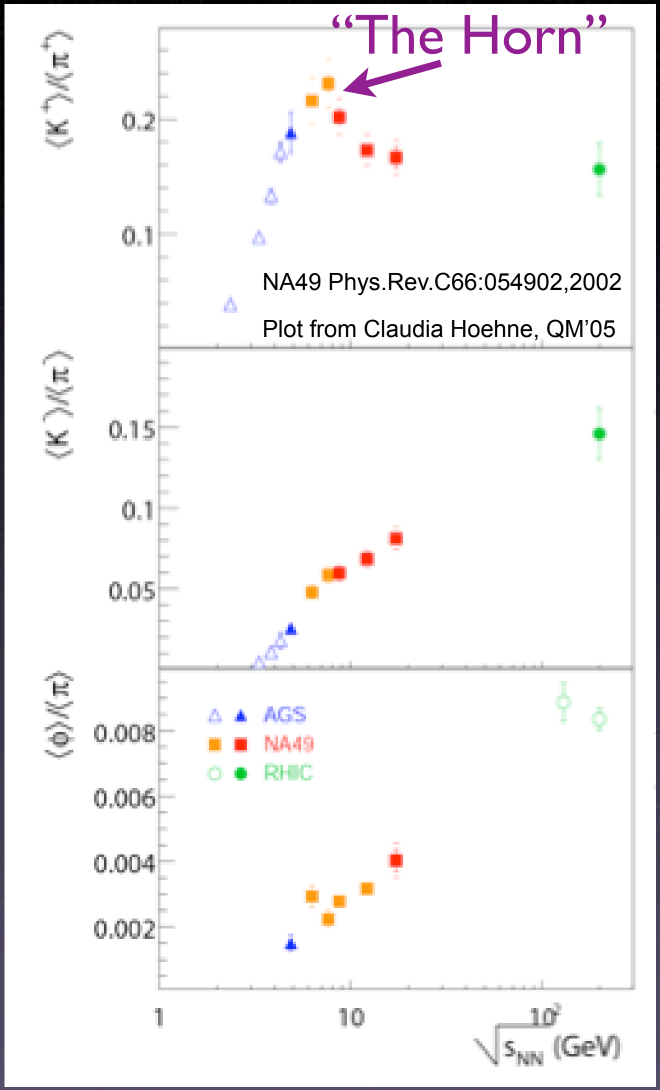
Normalization to <pT>

Normalization per particle

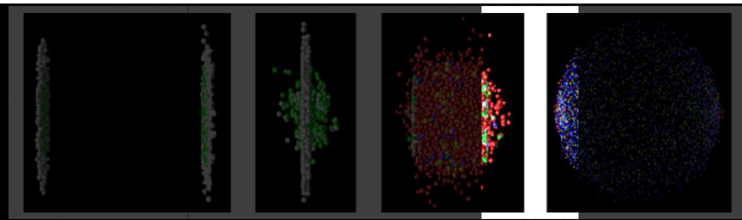
Linear or quadratic measures

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

# Particle Ratios



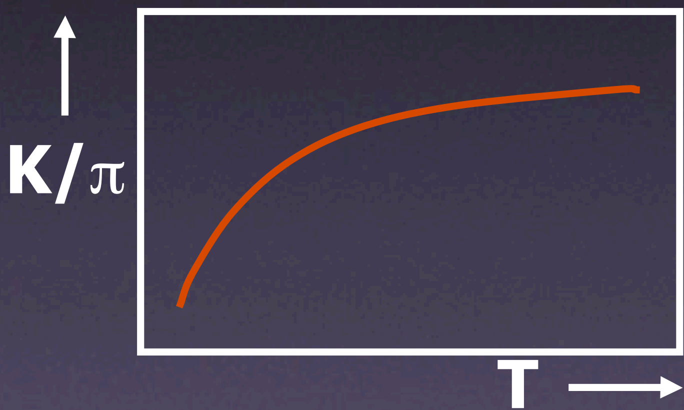

Non-monotonic behavior at AGS/SPS boundary



Nature of the Phase Transition

# K/π Fluctuations

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

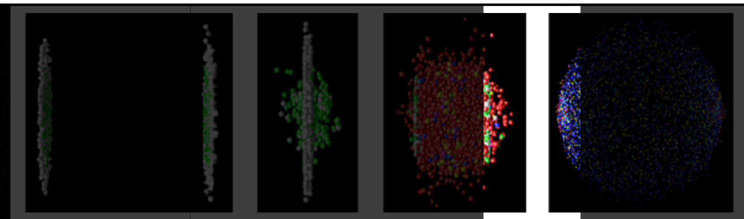



NA49 Measurement

- Use dE/dx to identify π,K,p event-by-event

- Do Max Likelihood fit to extract K/π ratio event-by-event

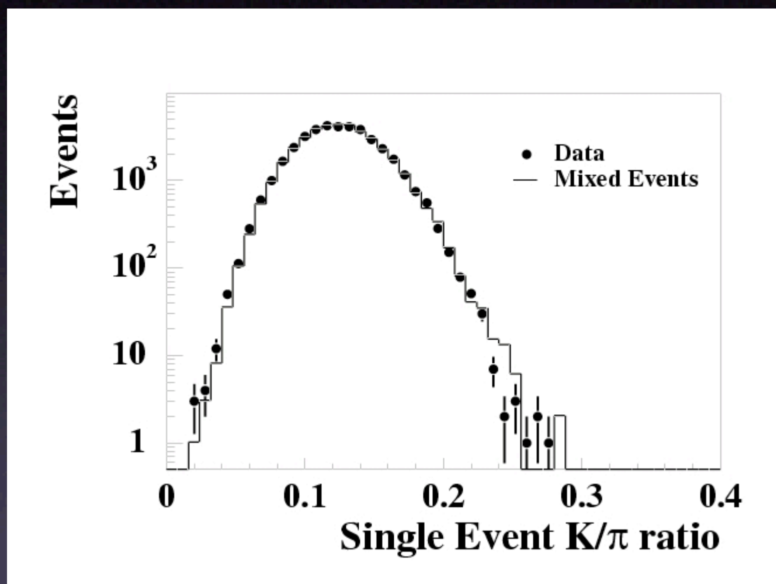
- Required 2 years of detector calibration to eliminate dE/dx – multiplicity correlation

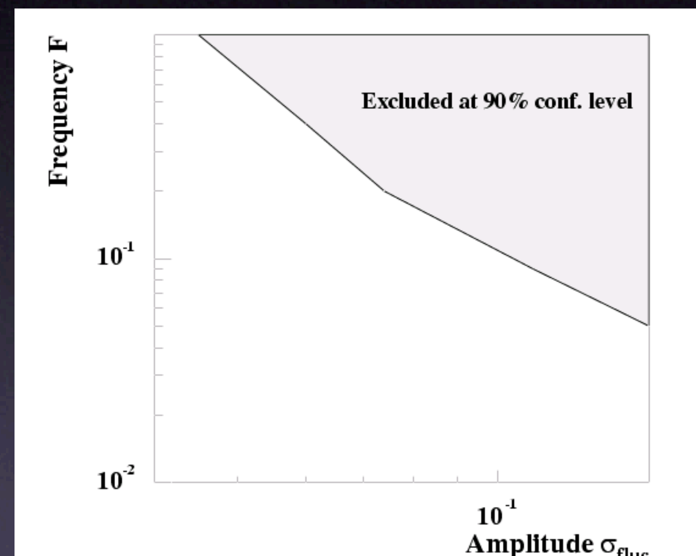


Nature of the Phase Transition

# K/π Fluctuations

**Pb+Pb, 17.2 GeV**
**NA49, PRL 86 (2001) 1965**



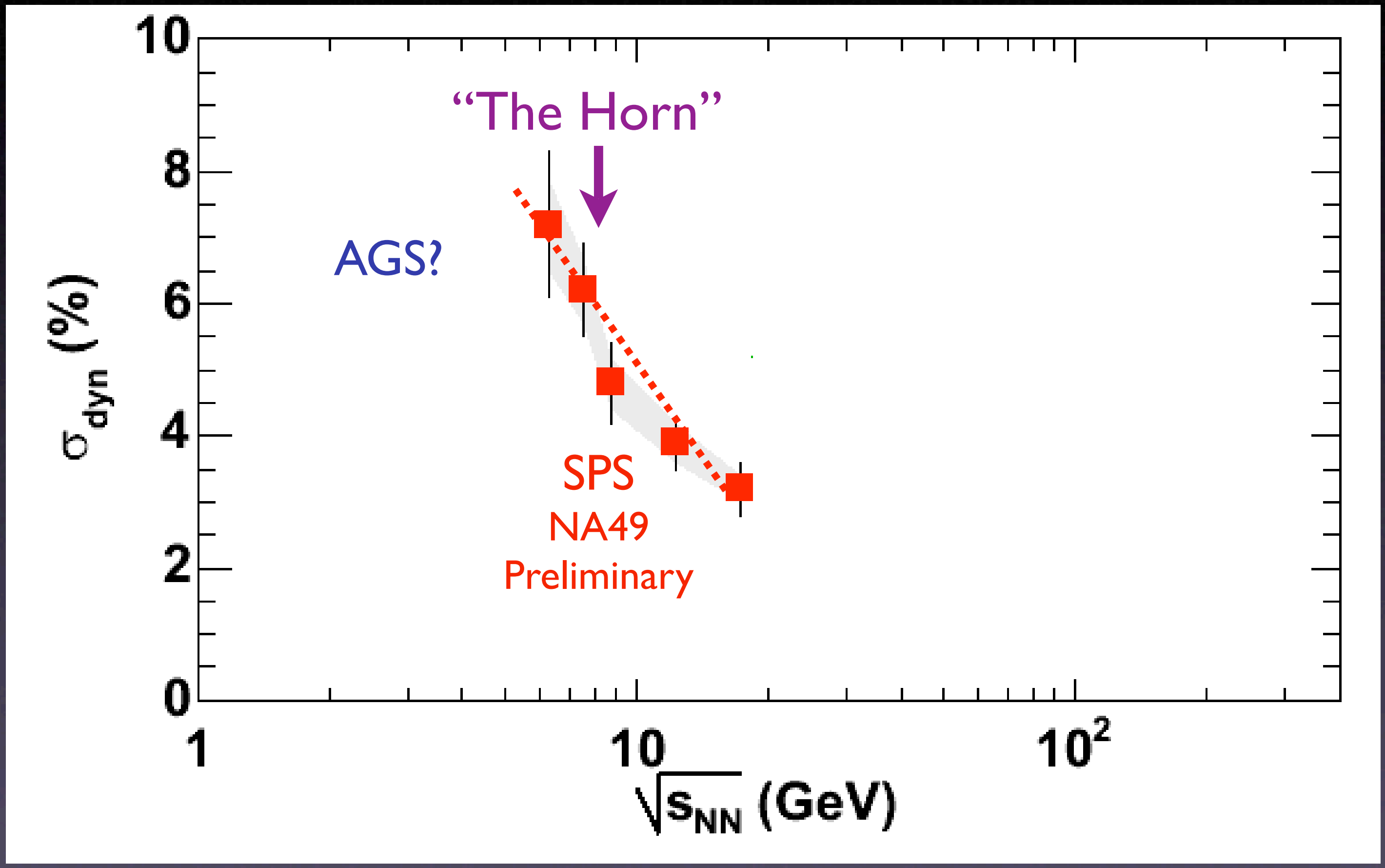




PhD thesis Christof Roland, 2000

- Dynamical fluctuations are small ( < ~5%)
- Compatible with resonance gas (Jeon, Koch; nucl-th/9906074)
- Strangeness enhancement in every event
- Chemical freeze-out at same T in every event

# Excitation Function: K/π Fluctuations

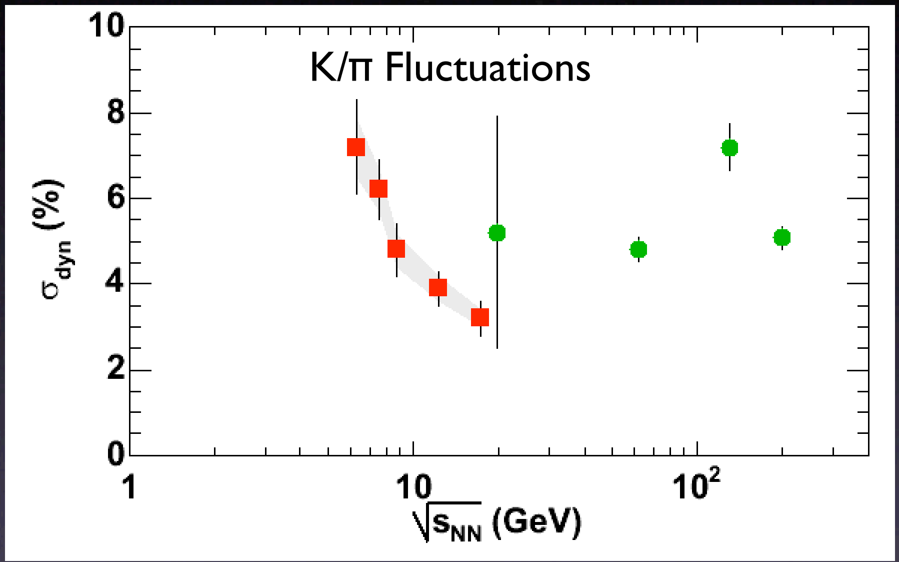
NA49, Christof Roland, QM'04    STAR, Supriya Das, VI Workshop '05

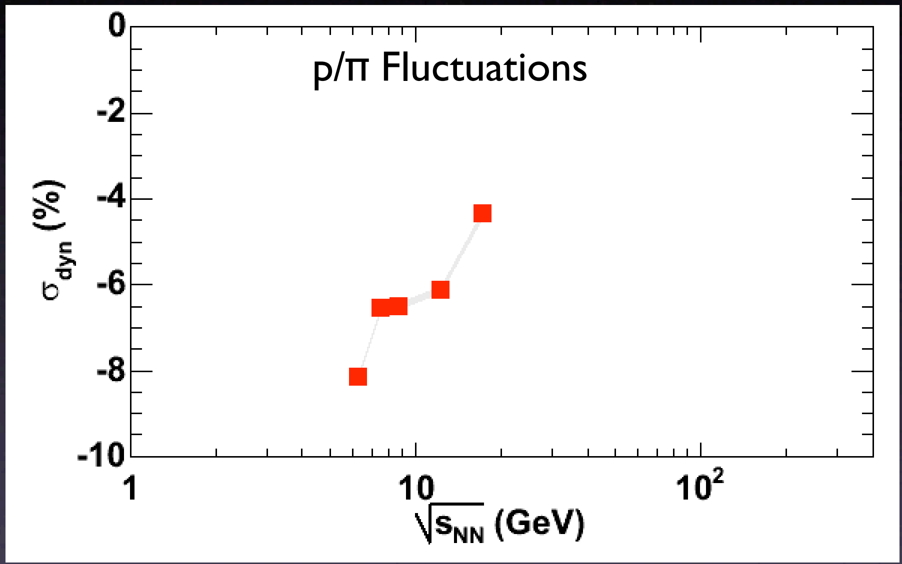



Strong increase at low energy
Comparison between experiments difficult

# Proton-number fluctuations?

NA49, Christof Roland, QM'04



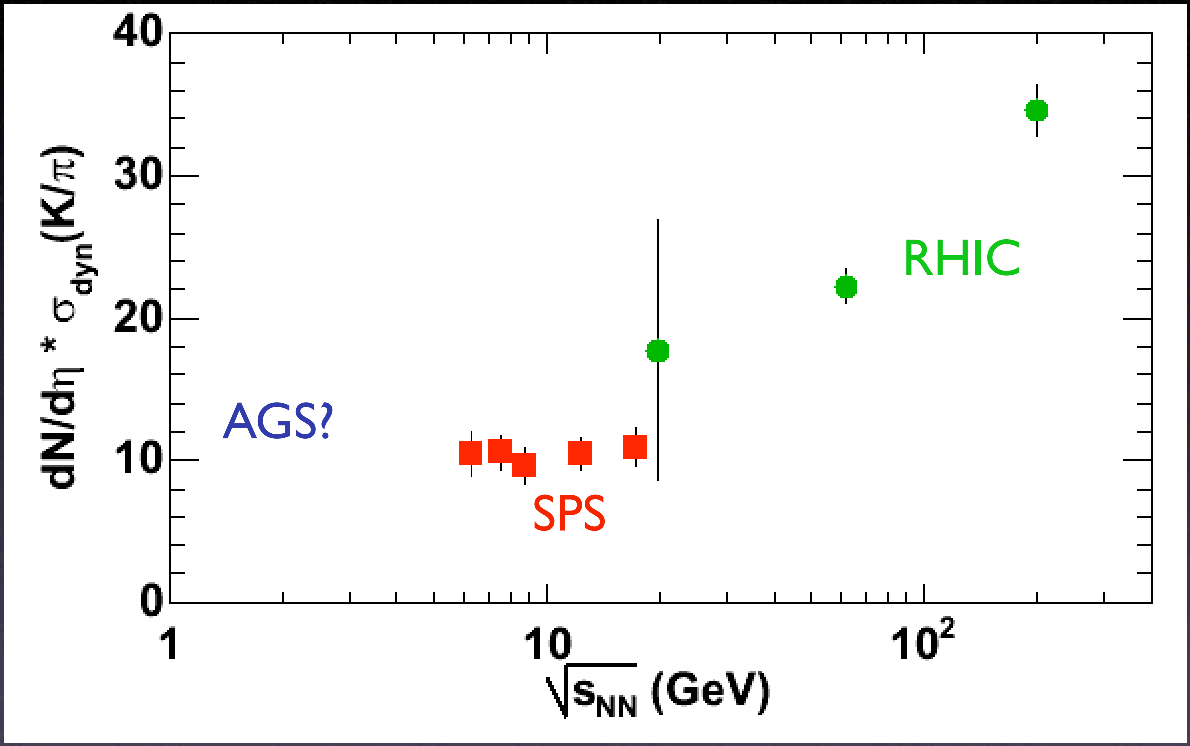




Proton/π fluctuations negative

➡ Correlated production of protons and pions

# 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

# What can we learn from fluctuations?

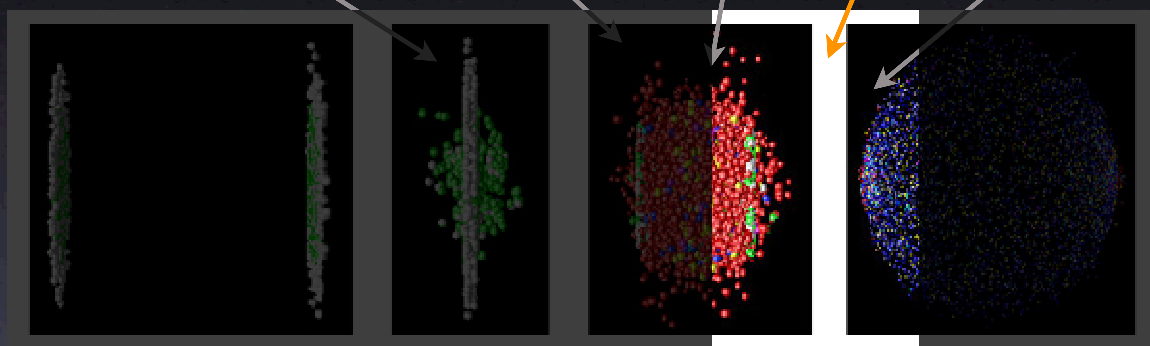
How is entropy produced?

(How) Does matter thermalize?

Properties of the medium?

**Nature of the phase transition?**

How are hadrons made?



Monotonic √s evolution of global fluctuations

Magnitude of fluctuations moderate

Scaling of relative fluctuations

Increase in K/π fluctuations at low √s

→

Equilibrium evolution?

Small latent heat?

Kinetic freeze-out far from critical point?

Connection to PT/CP?

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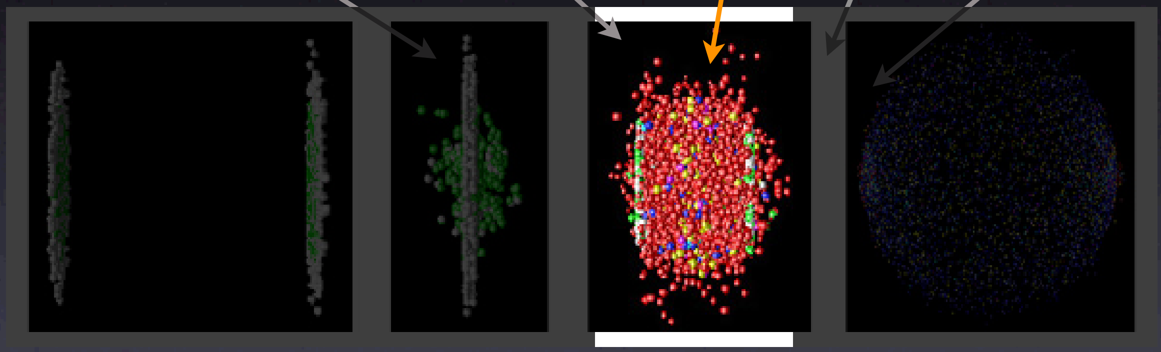
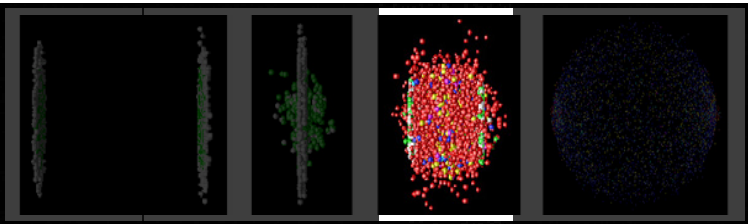


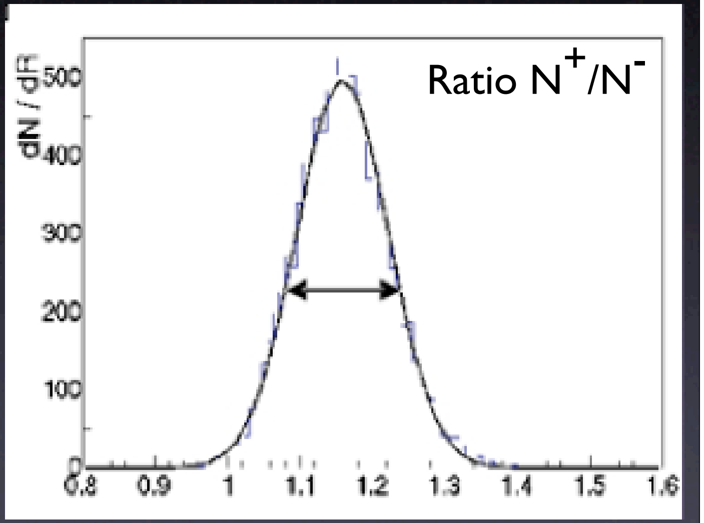
ca 2000



# Properties of the Medium

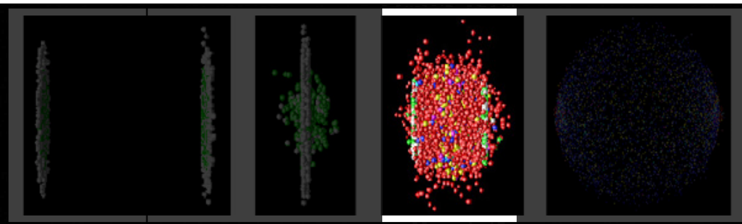
- Net Charge/Δy Fluctuations ⇔ Charge/DoF
  - Fluc's change from 1-2 (QGP) to 4 (Pion Gas)
- Fluctuations frozen b/c charge conservation
  - Diffusion vs Expansion timescale

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




Event-by-event distribution of net charge ratio

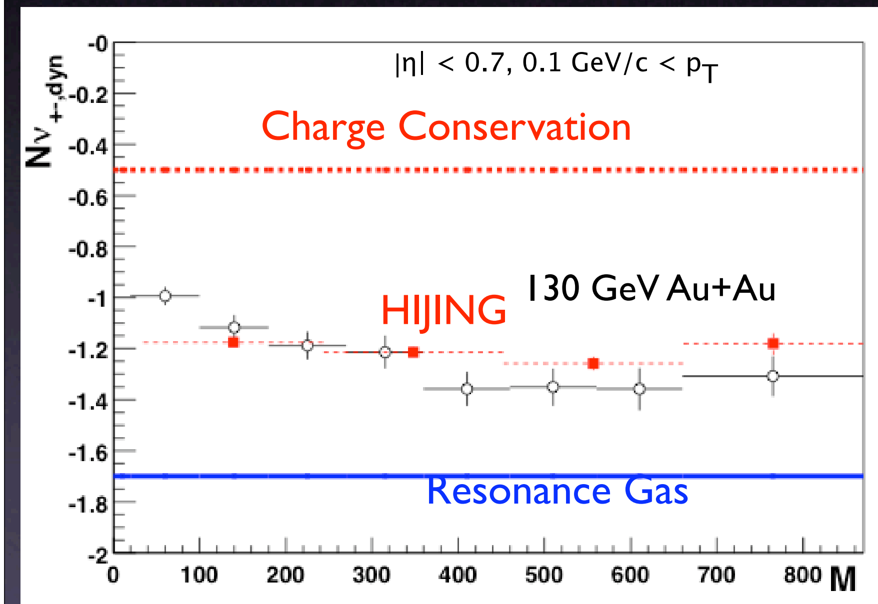
Note:
* Similar for net baryon number
* Connection to quark number susceptibilities
* Connection to Critical point



Properties of the Medium

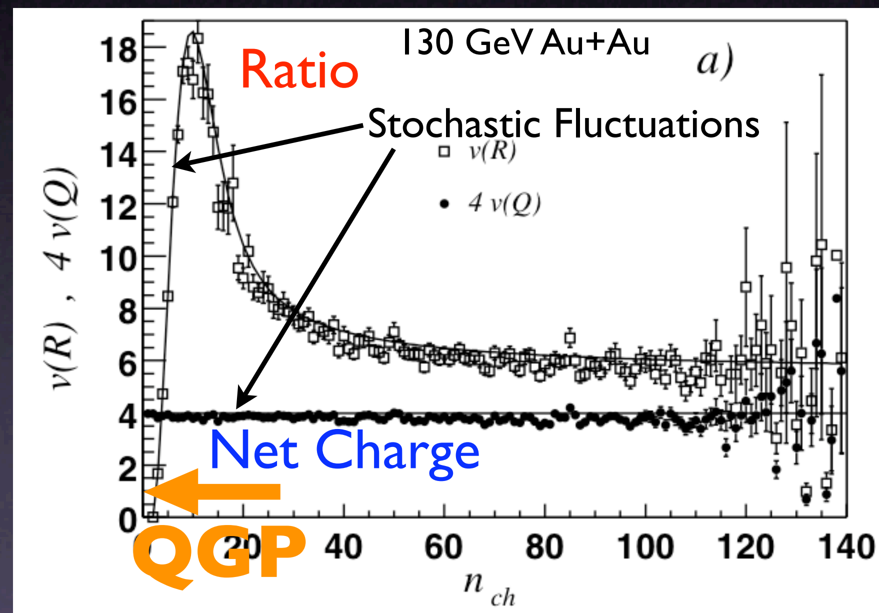
# Net Charge Fluctuations

STAR PRC 68 (2003)



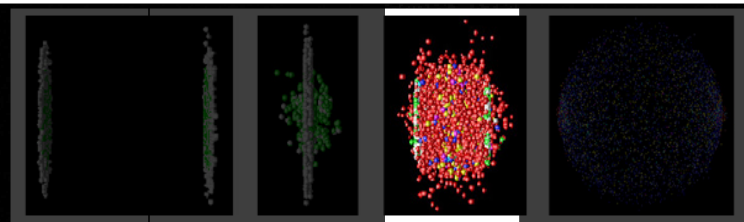

Centrality ⟶

PHENIX PRL 89 (2002)




Centrality ⟶

**Fluctuations agree with stochastic distributions of *Hadrons***



Properties of the Medium

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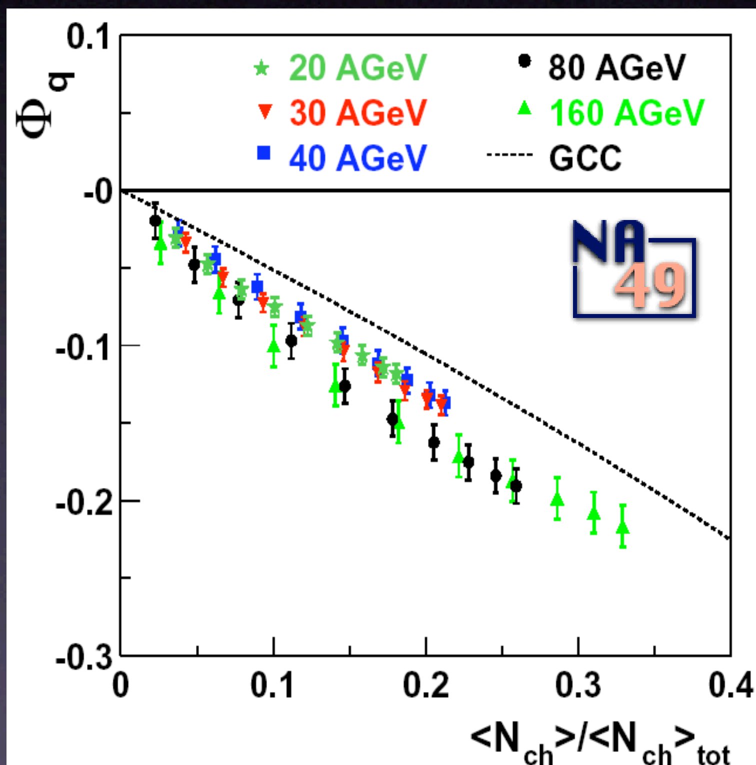


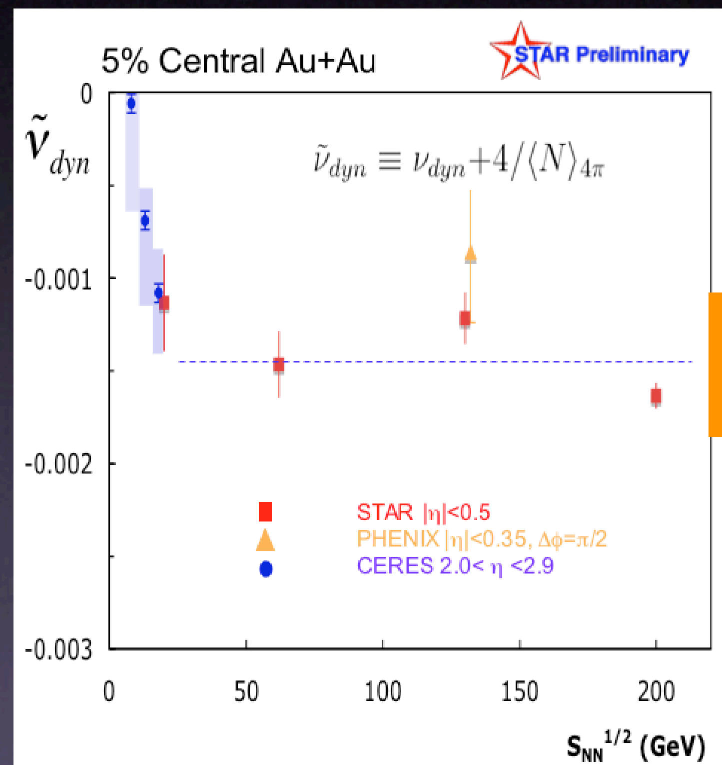


Quark-Coalescence
Bialas, 2003

QGP

Little (no) √s dependence of charge fluctuations

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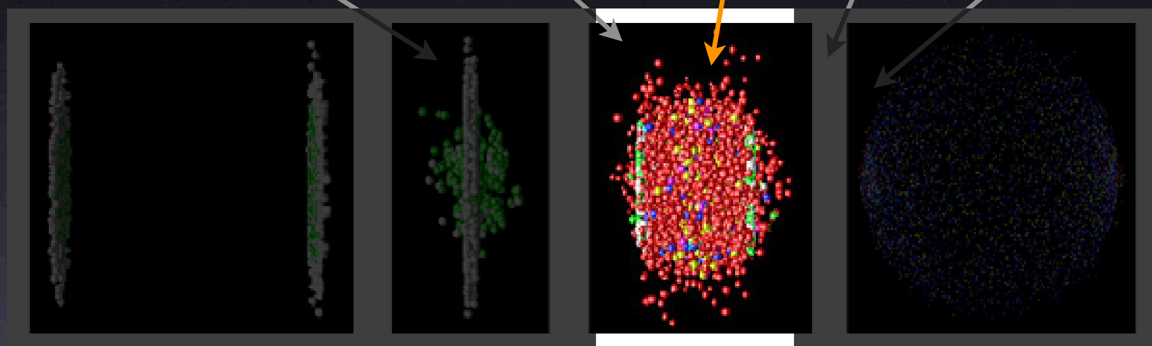

Net charge fluctuations large (~ hadron gas)

Small/no $\sqrt{s}$ dependence

→

Quark coalescence?

Property of Hadronization?

Diffusion?

Bound states?

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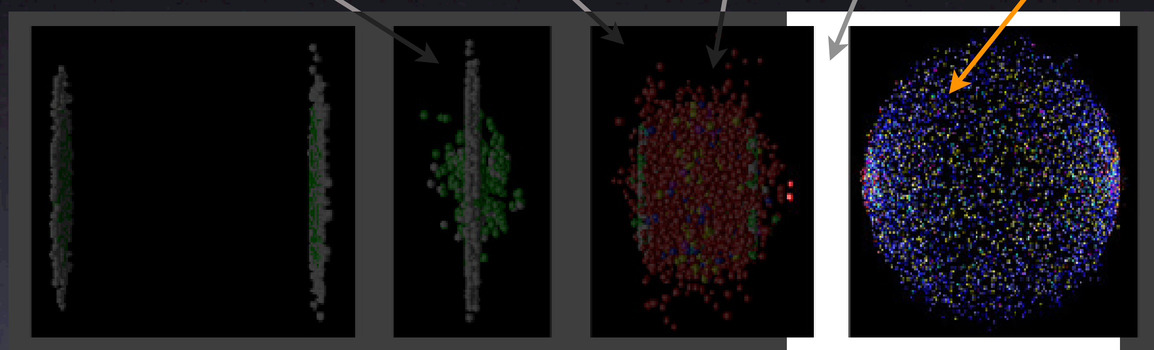

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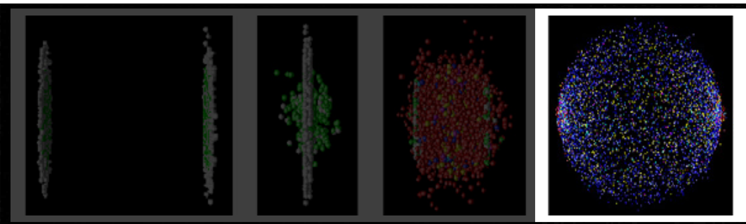
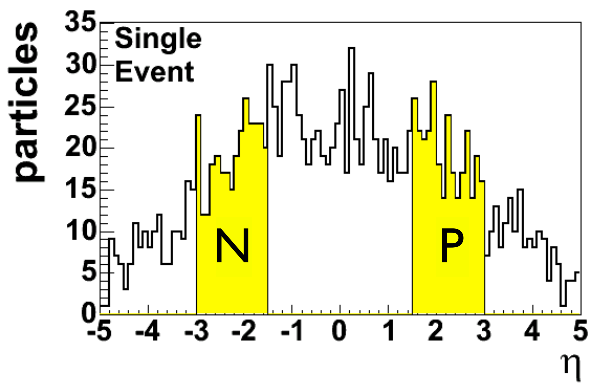


Hadronization

# Forward/backward multiplicity correlations




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

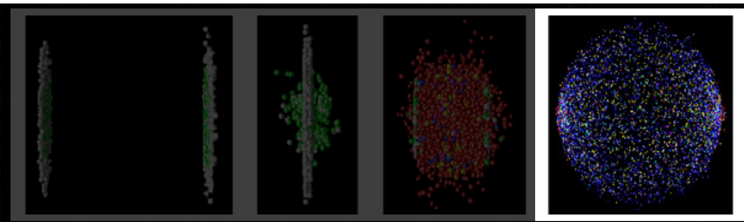
Use variance $\sigma^2_C$

Particles produced independently:

$\sigma^2_C = 1$

Particles produced in clusters of size $K$:

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



Hadronization

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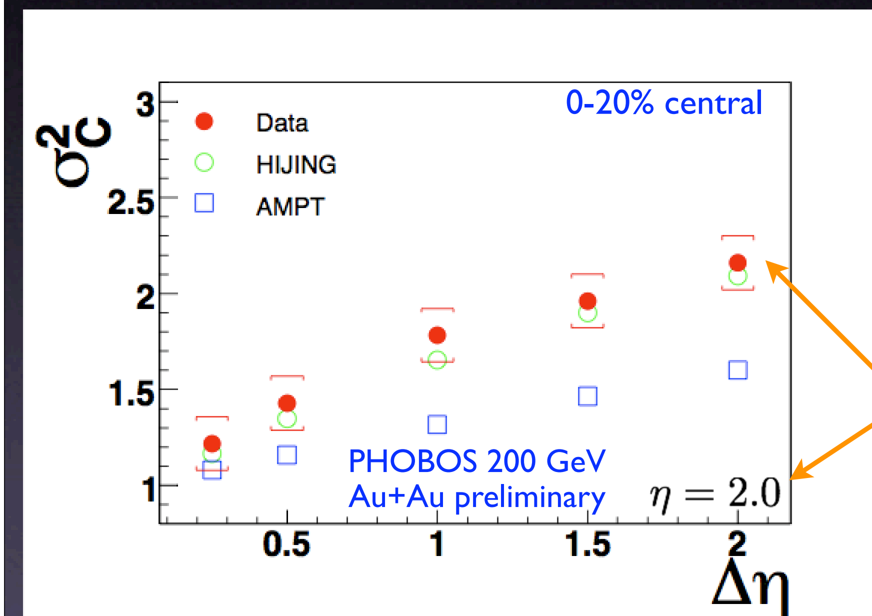


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Particles produced in clusters of size *K*:

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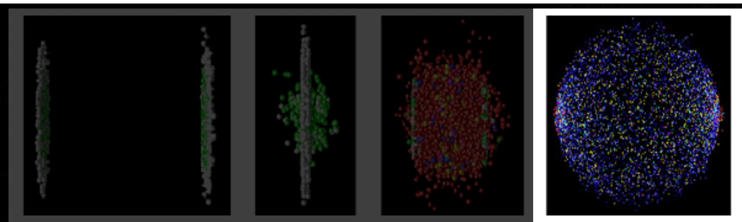
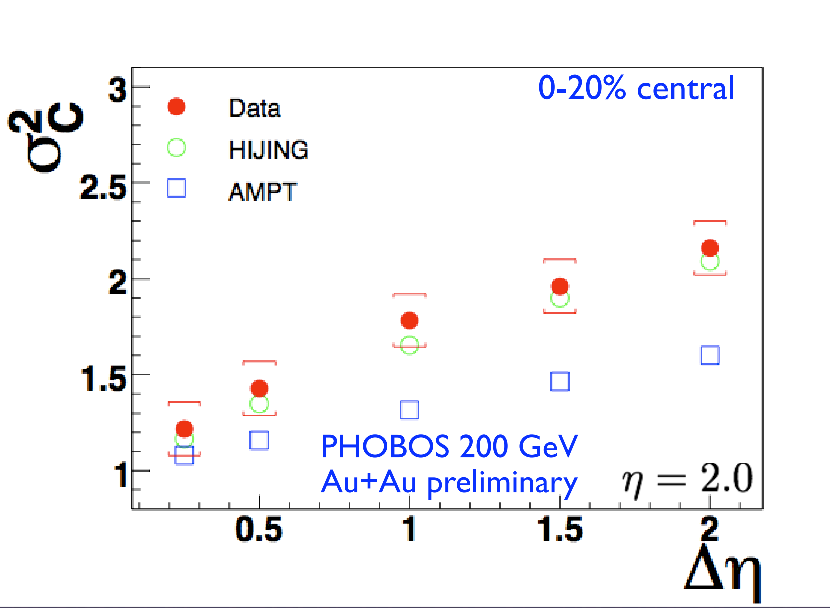
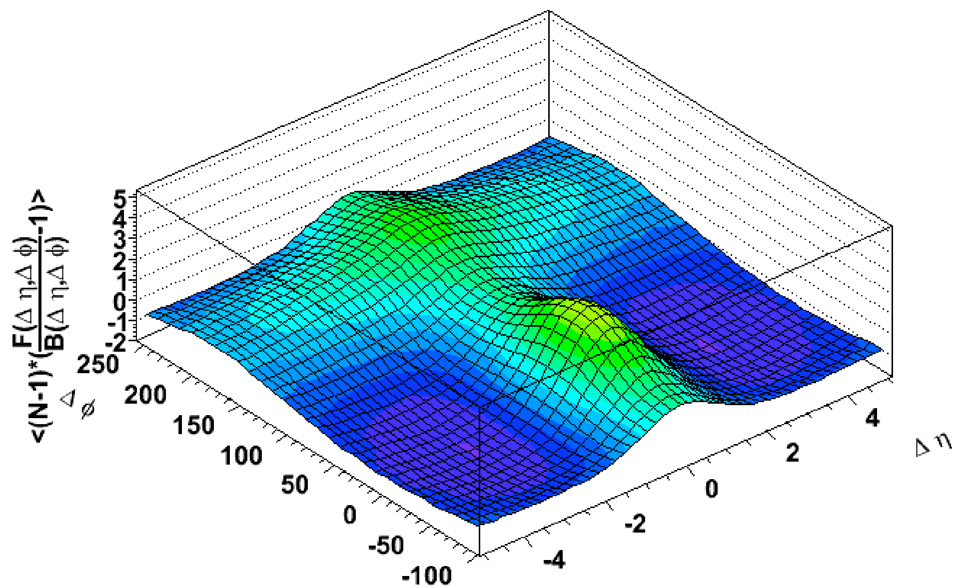
effective cluster size ≈ 2-2.5 for 200 GeV Au+Au



Hadronization

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



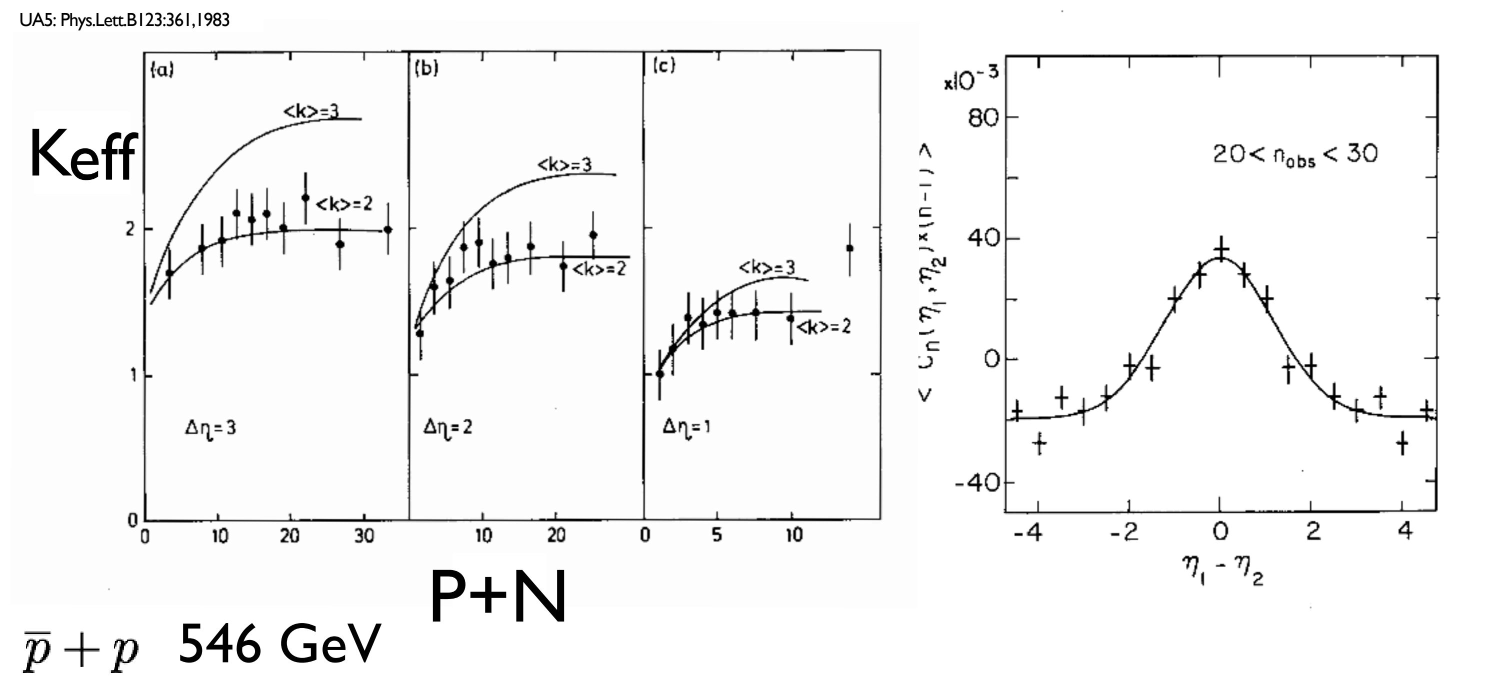




effective cluster size ≈ 2-2.5
for 200 GeV Au+Au

"Cluster" in Δη,Δφ space via
2-particle correlations
(pythia p+p @200 GeV, η<3)

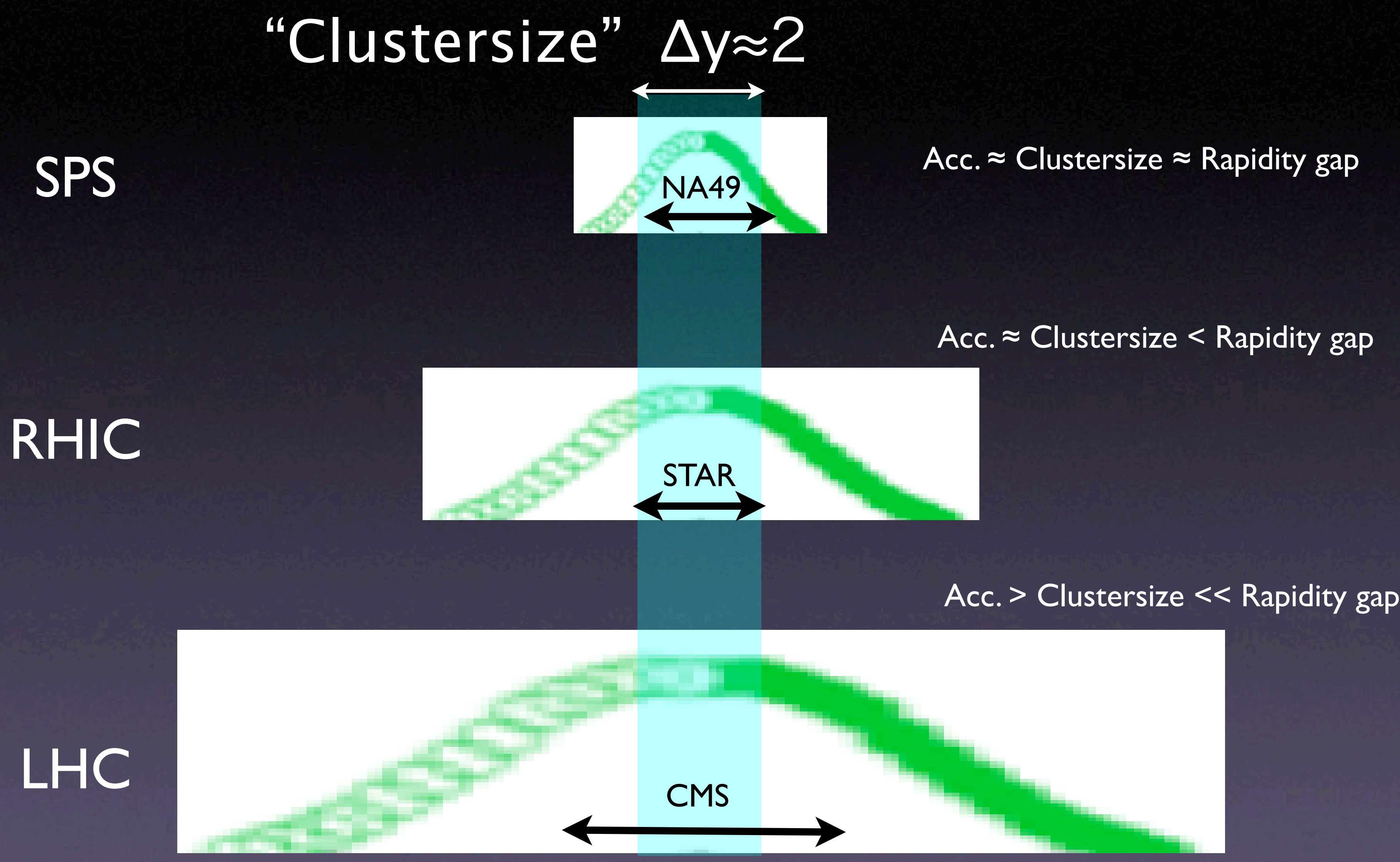
# Clusters in p+p

UA5: Phys.Lett.B123:361,1983



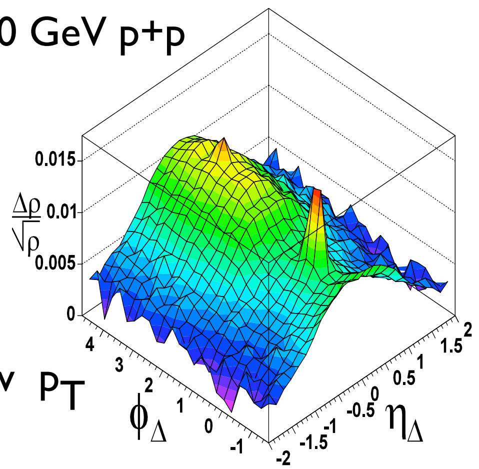

Clusters in Au+Au reminiscent of results from p+$\bar{p}$

# Measuring global charge fluctuations



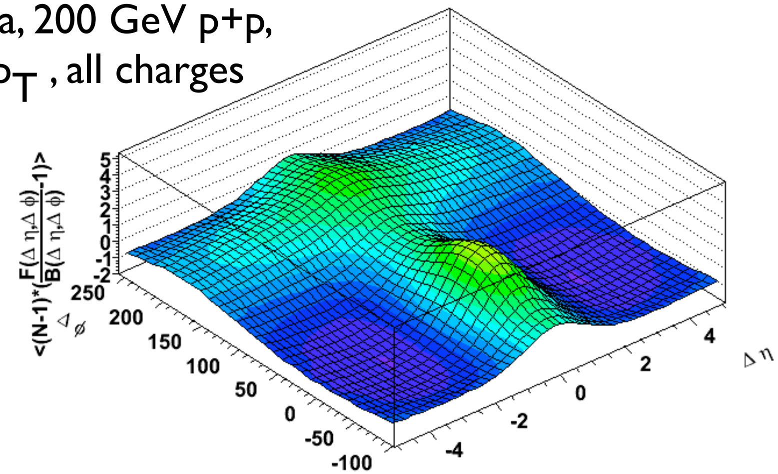
# Beyond global charge fluctuations

STAR
200 GeV p+p



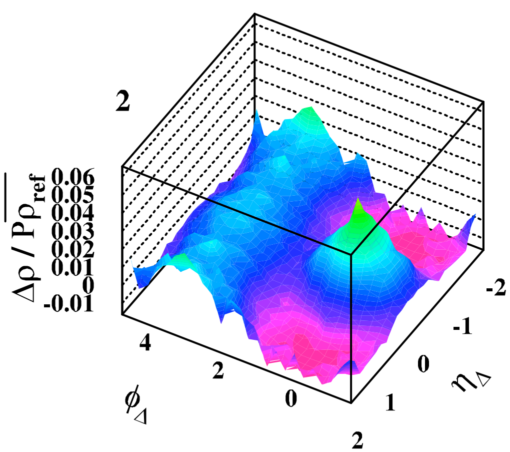

Low $p_T$

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




Split sample

2-D angular correlation function



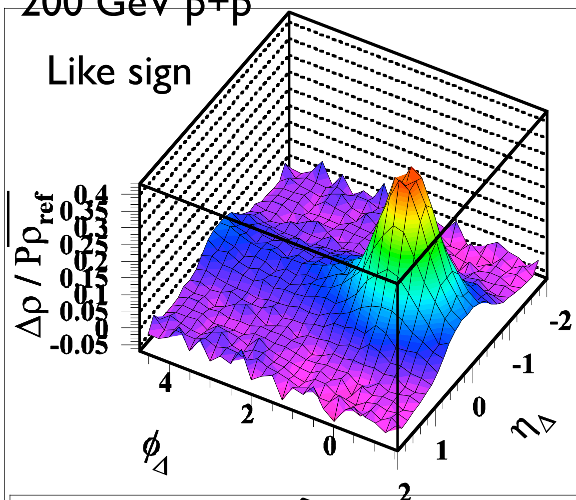

High $p_T$

Tom Trainor et al (STAR)

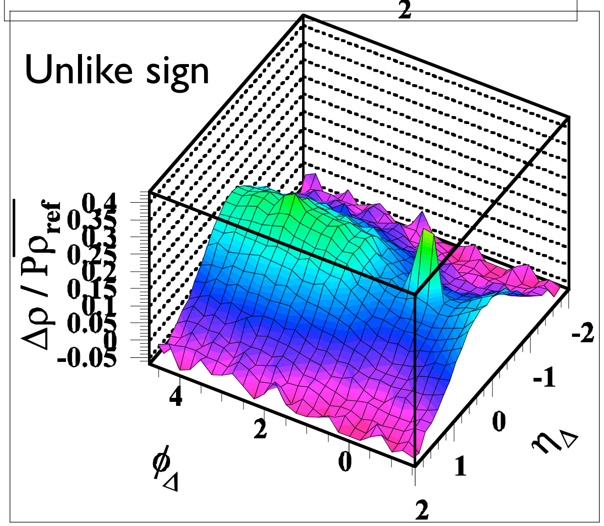
# Beyond global charge fluctuations

STAR
200 GeV p+p

Like sign

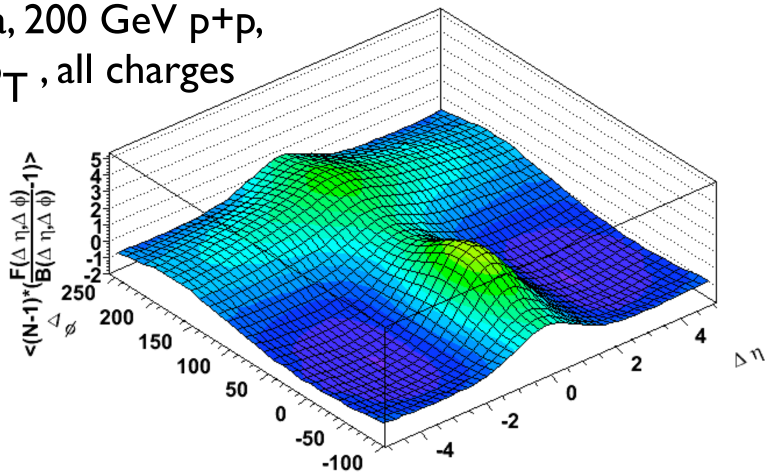



Unlike sign




Tom Trainor et al (STAR)

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

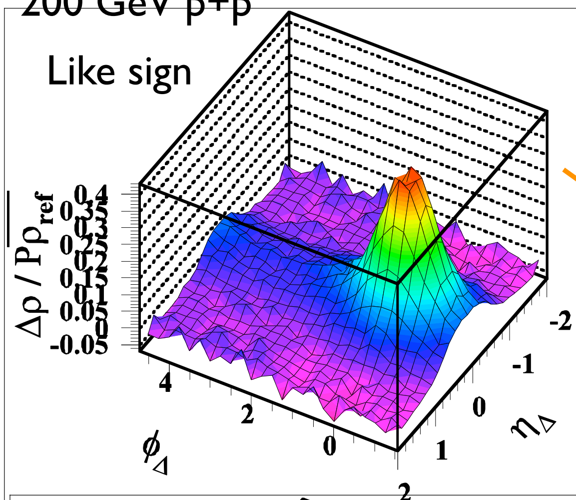


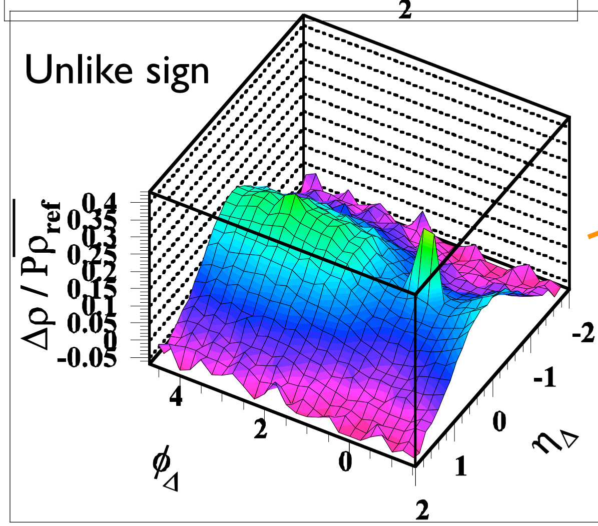

Split sample

2-D angular correlation function

# Charge Dependent Correlations

STAR
200 GeV p+p

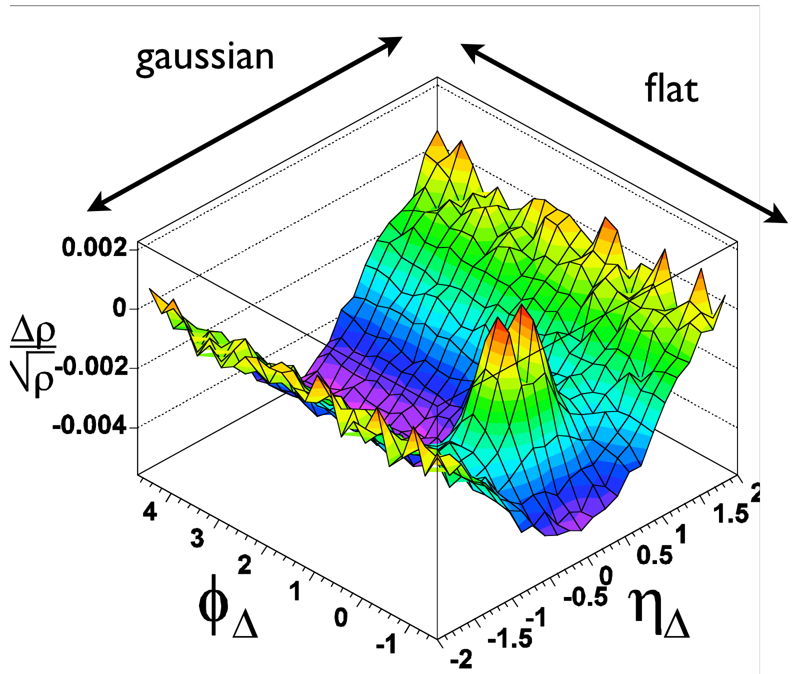



Tom Trainor et al (STAR)

subtract

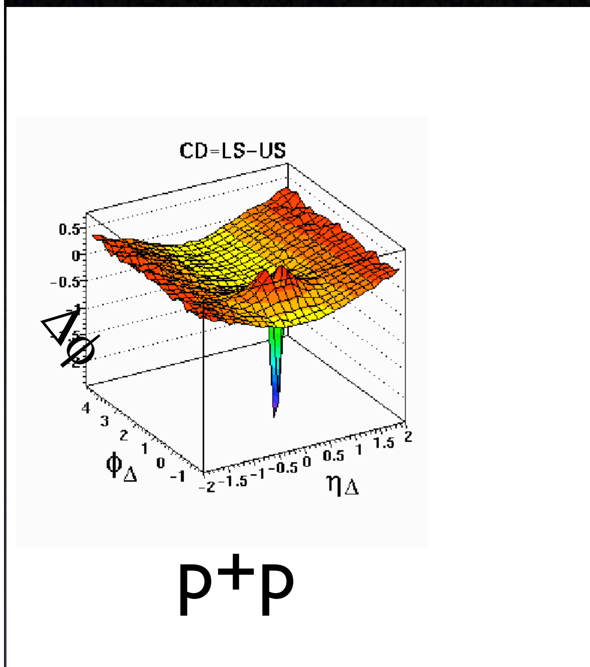
longitudinal charge ordering




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

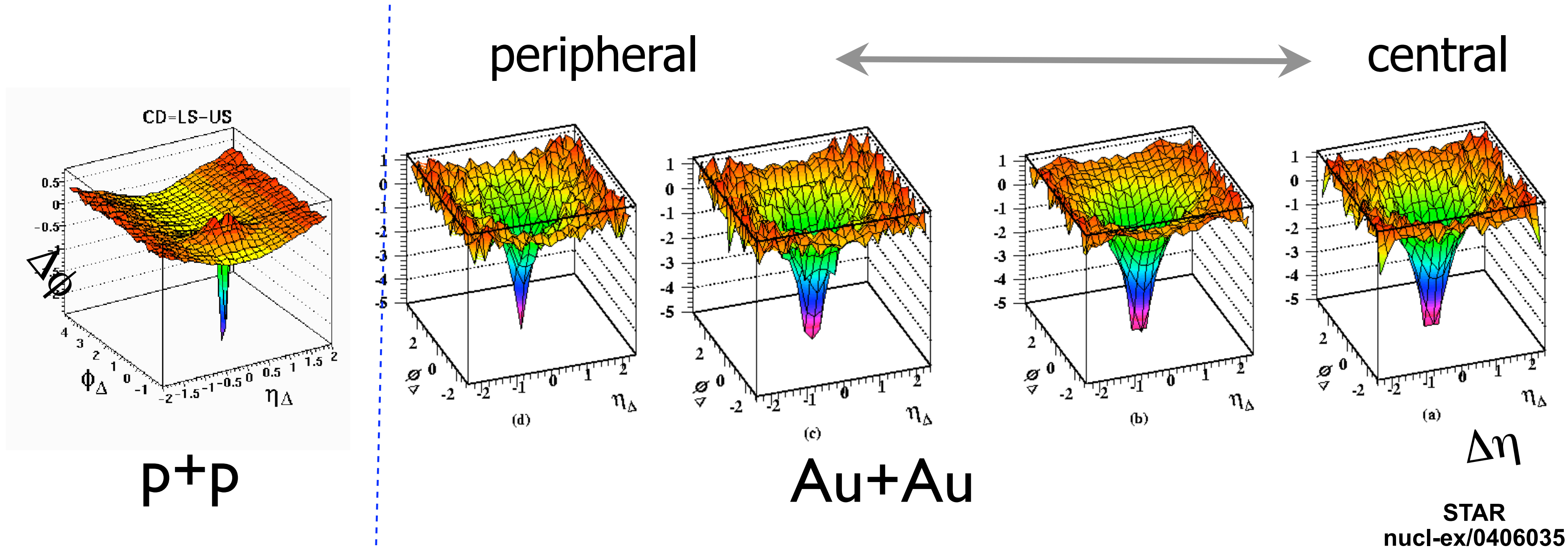
# Charge Dependent Correlations

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

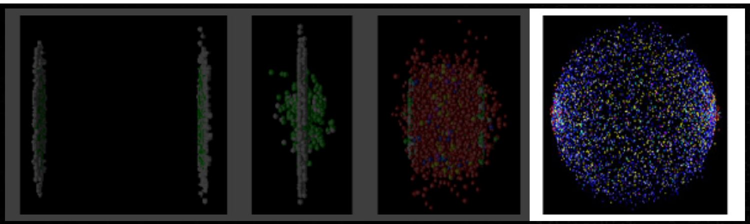


# Charge Dependent Correlations

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



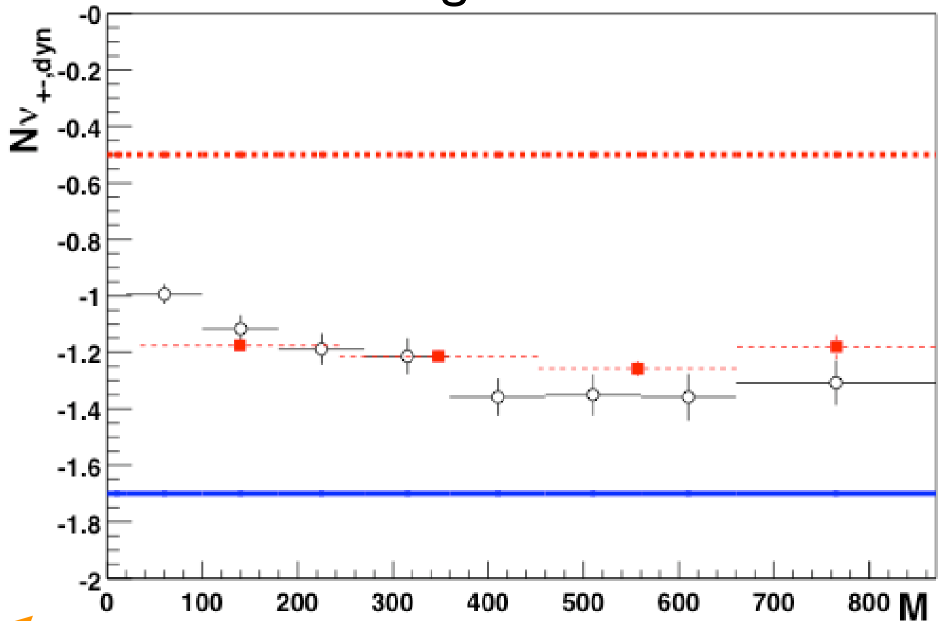

Evolution of "cluster" properties/charge correlations



Hadronization

# Correlations and Fluctuations, revisited

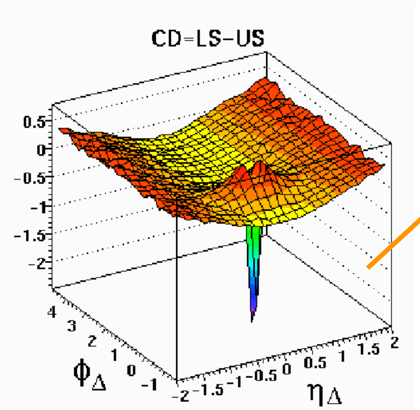
## Net-charge Fluctuations



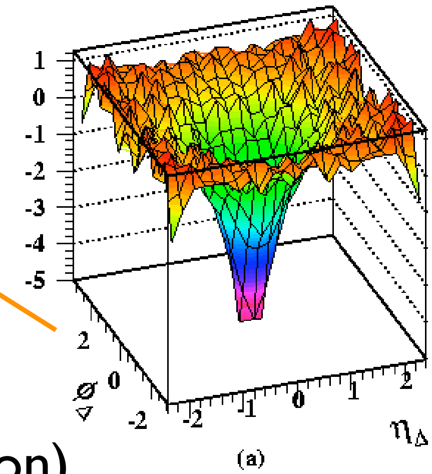

centrality →

Global scaling, even though underlying correlations change

p+p




Central A+A




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

# What can we learn from fluctuations?

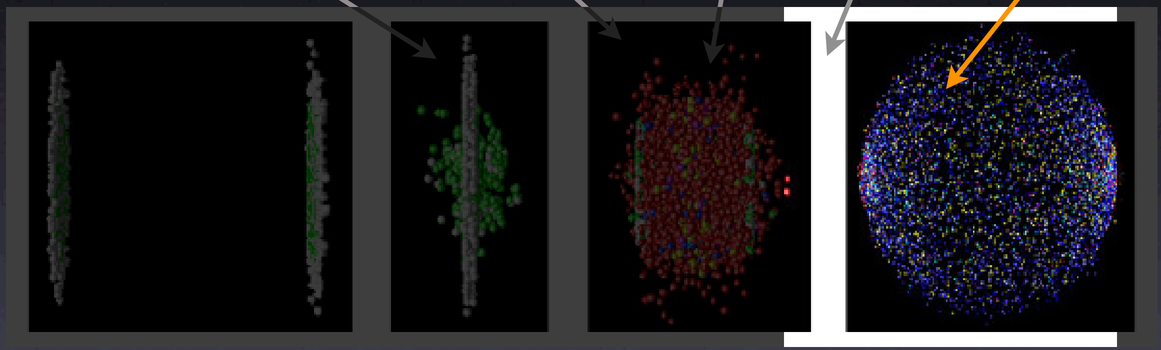
(How) Does matter thermalize?

Nature of the phase transition?

How is entropy produced?

Properties of the medium?

**How are hadrons made?**



Large multiplicity fluctuations

Strong change in underlying correlation structure

→

Particles produced in large 'clusters'

Understanding of hadronization essential

Collision dynamics reflected in correlation structure

# What can we learn from fluctuations?

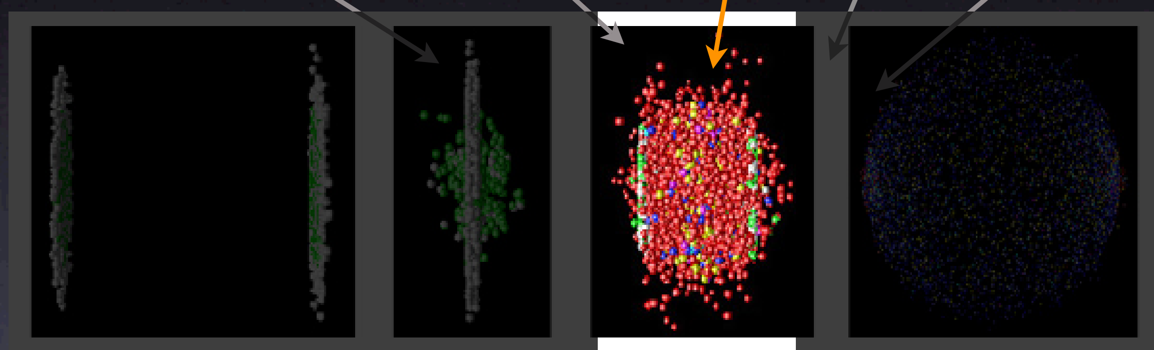
(How) Does matter thermalize?

Nature of the phase transition?

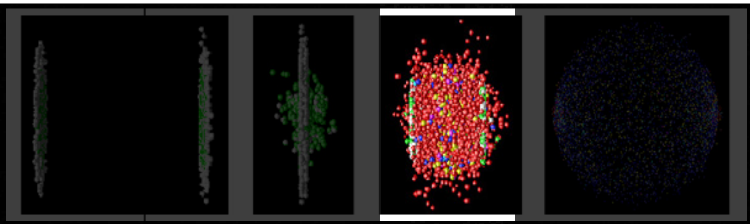
How is entropy produced?

**Properties of the medium?**

How are hadrons made?

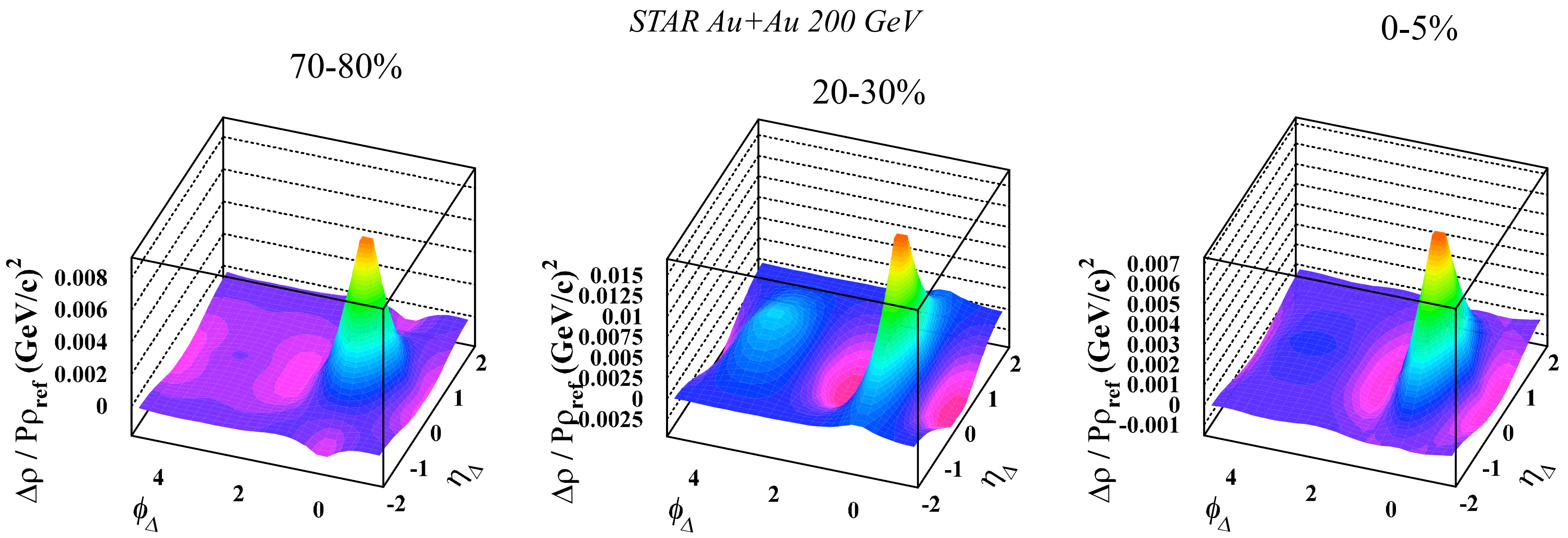


Look at the medium using 2-particle correlations (untriggered) at high(er) $p_T$

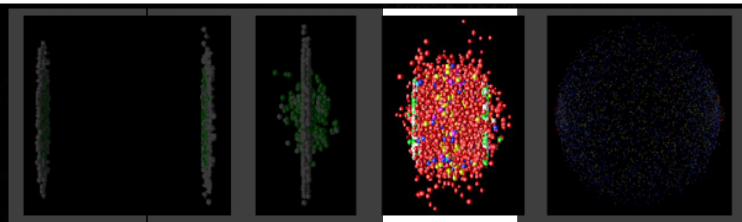


Properties of the Medium

# 2-particle momentum correlations

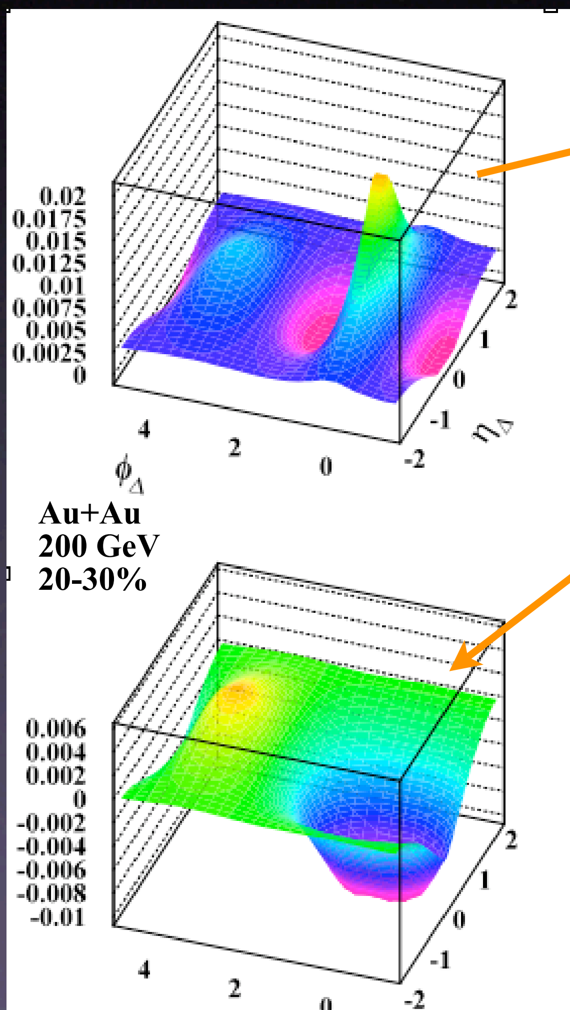



Shape of near-side "parton-fragmentation" peak evolves with centrality

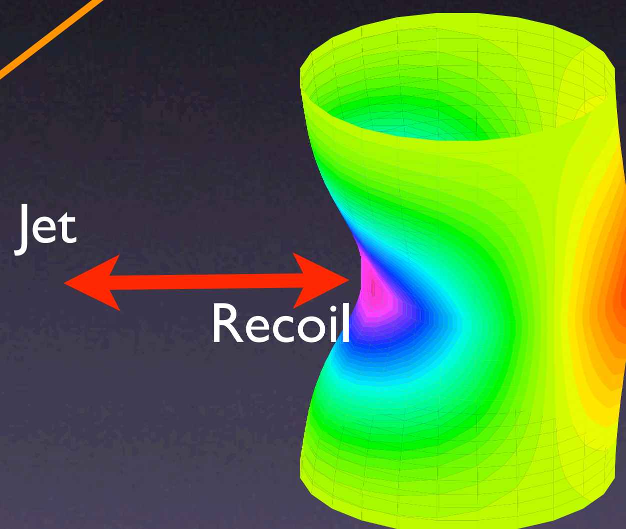


## Properties of the Medium

# 2-particle momentum correlations




Subtract fragmentation peak
to look at medium




*bulk medium*

# What can we learn from fluctuations?

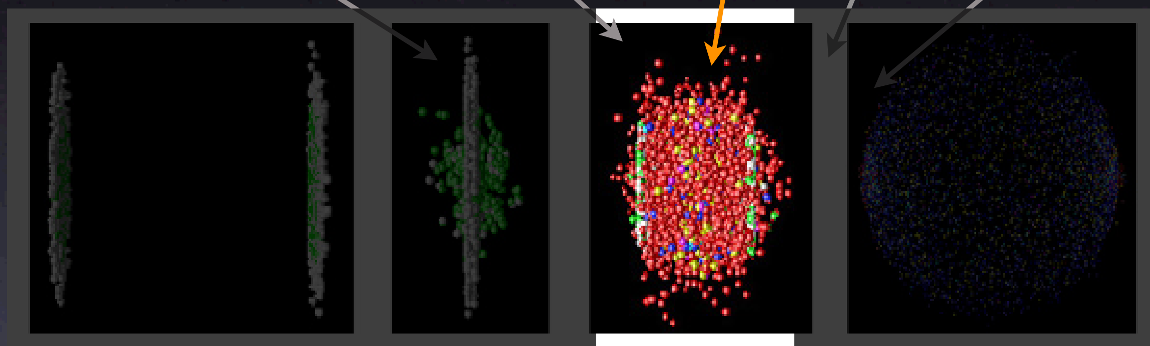
(How) Does matter thermalize?

Nature of the phase transition?

How is entropy produced?

**Properties of the medium?**

How are hadrons made?



Medium modification of pT correlation shape

Possible medium modification due to partonic recoil

→

Interaction of partons with bulk medium (flow field)

Extract bulk properties (e.g. viscosity)?

# What can we learn from fluctuations?

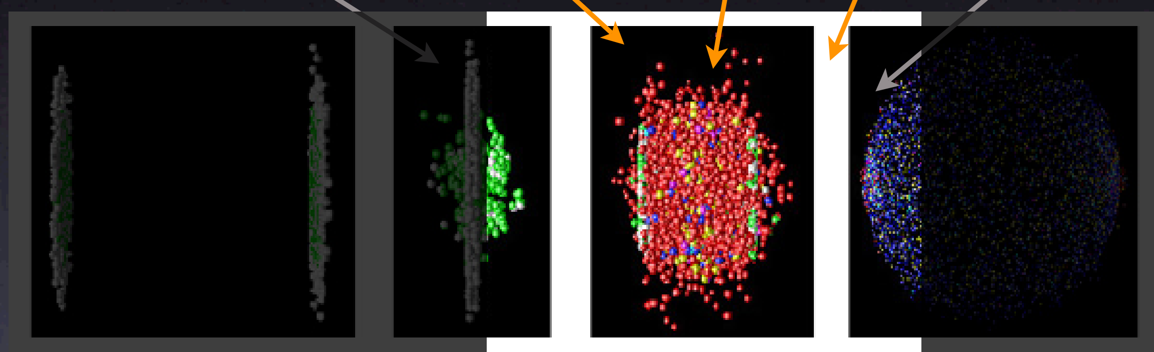
Nature of the phase transition?

(How) Does matter thermalize?

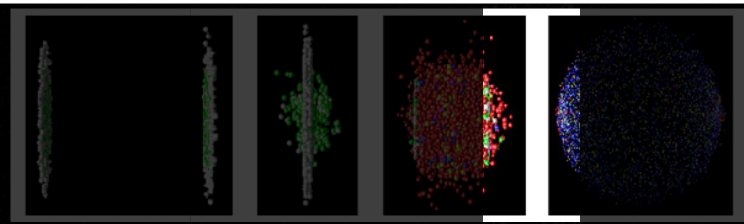
How is entropy produced?

Properties of the medium?

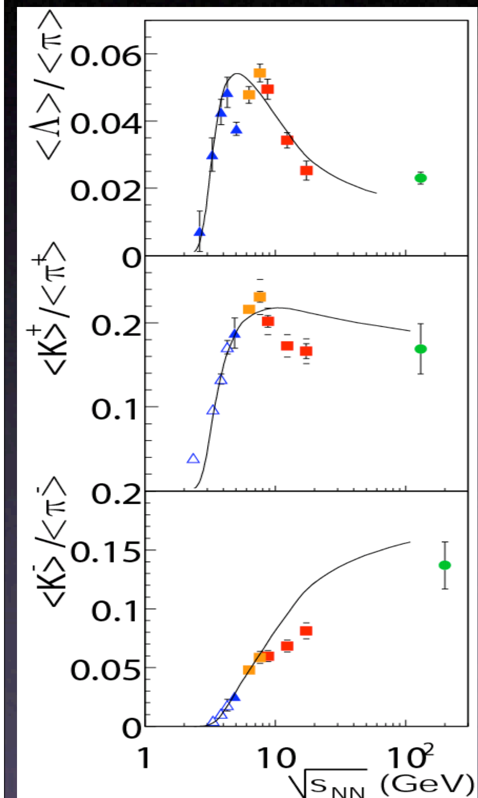
How are hadrons made?



## Some remarks on future measurements

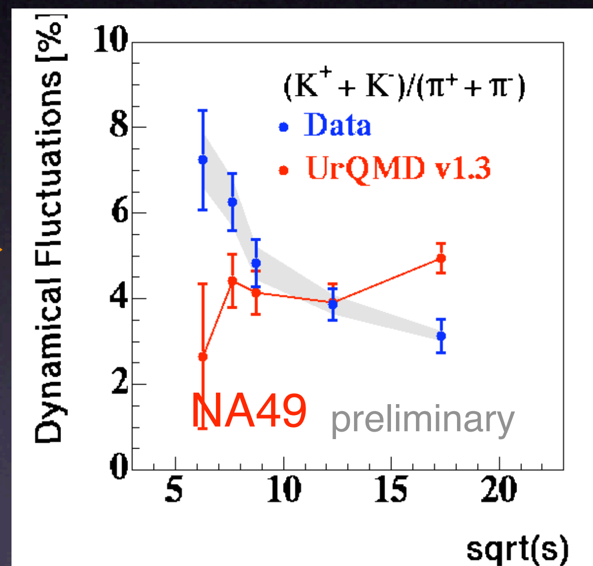


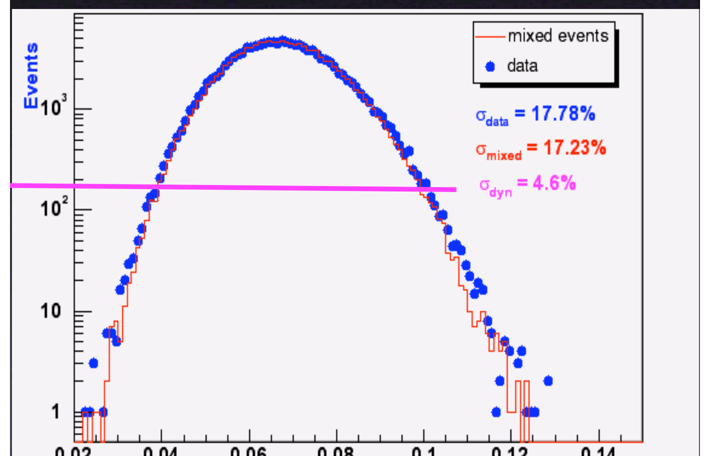
# NA49 'Horn'




## Strangeness Fluctuations vs √s

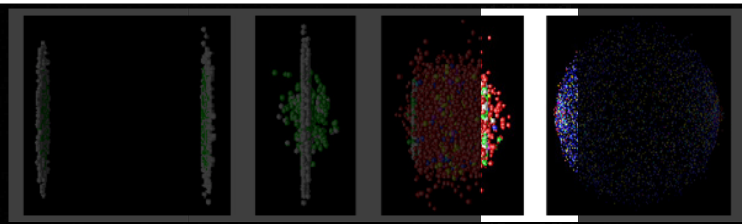
NA49 (Christof Roland QM'04)



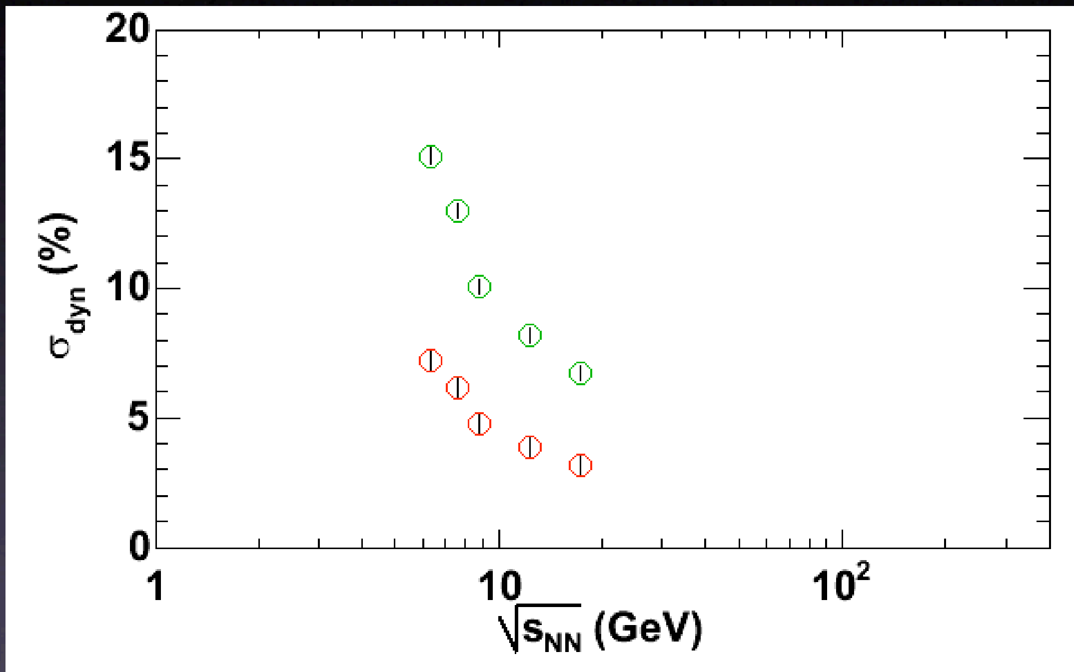




STAR 200 GeV Au+Au
preliminary

Fluctuations in
K/pi ratio

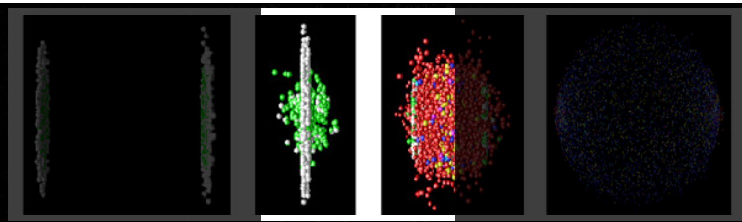


# Strangeness Fluctuations vs √s

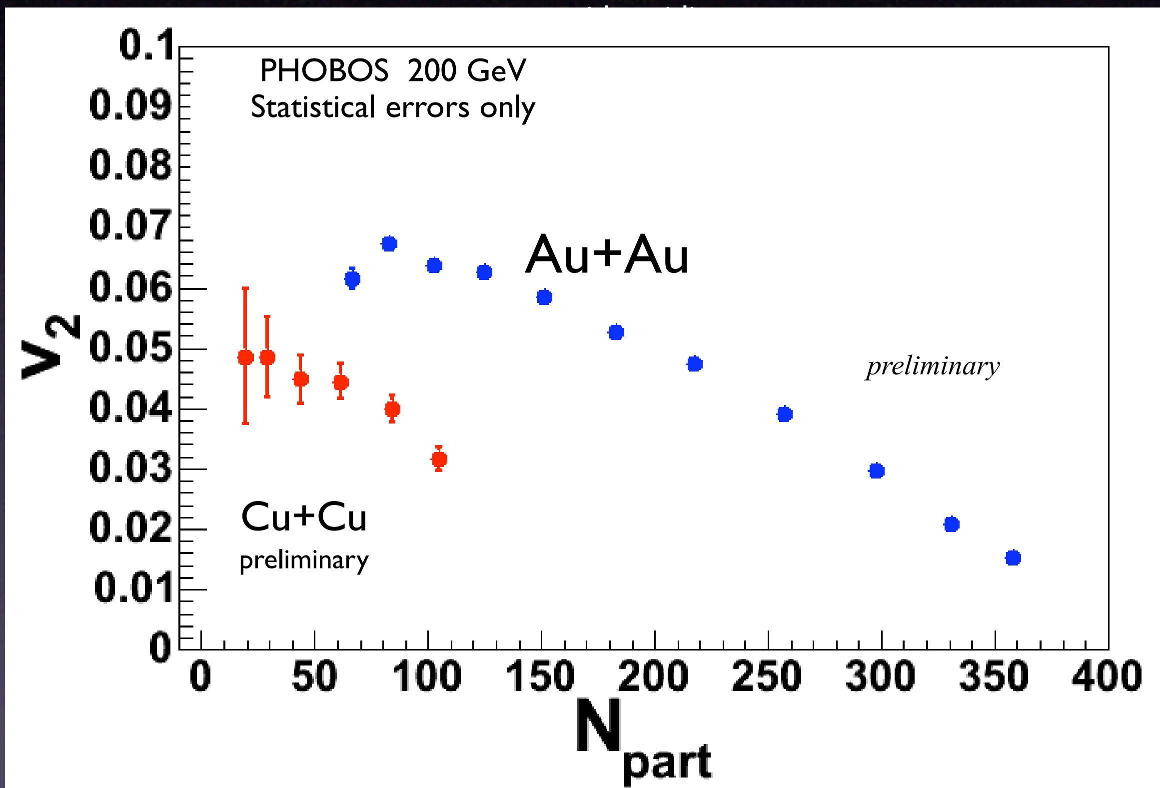


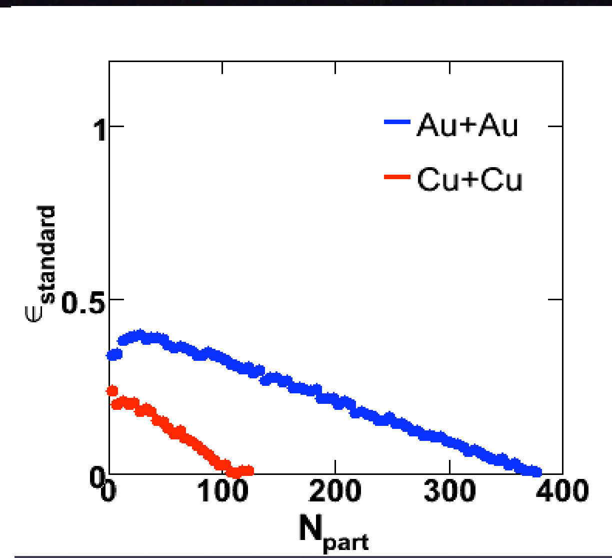

Opportunity with possible low-E run at RHIC

STAR with ToF/Si-VTX upgrade is ideal place



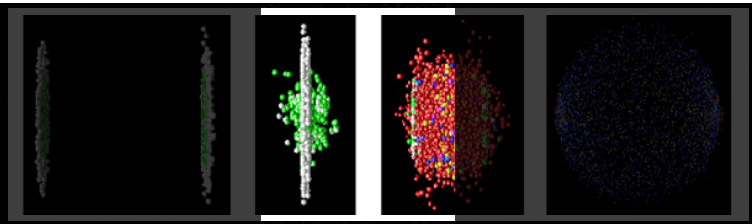
# Geometry and Thermalization



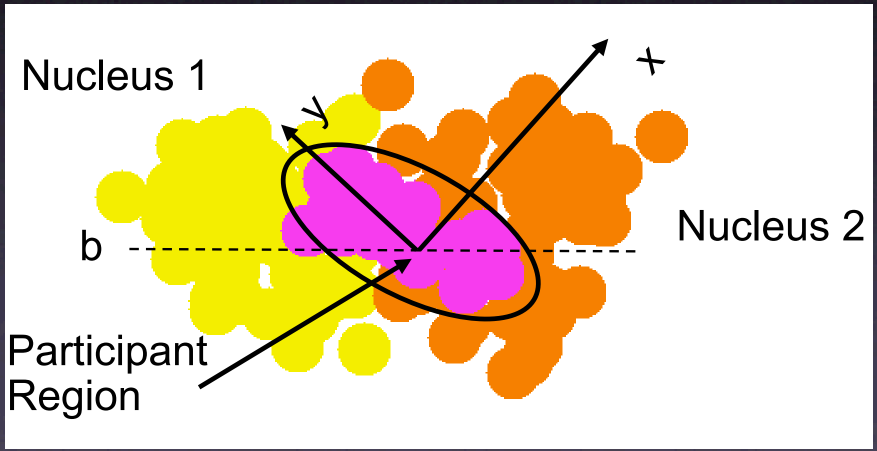

Geometrical initial state eccentricity from Glauber model

Surprisingly large flow signal in Cu+Cu!

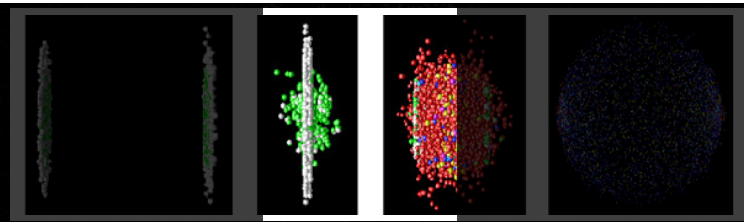


# Geometry and Thermalization

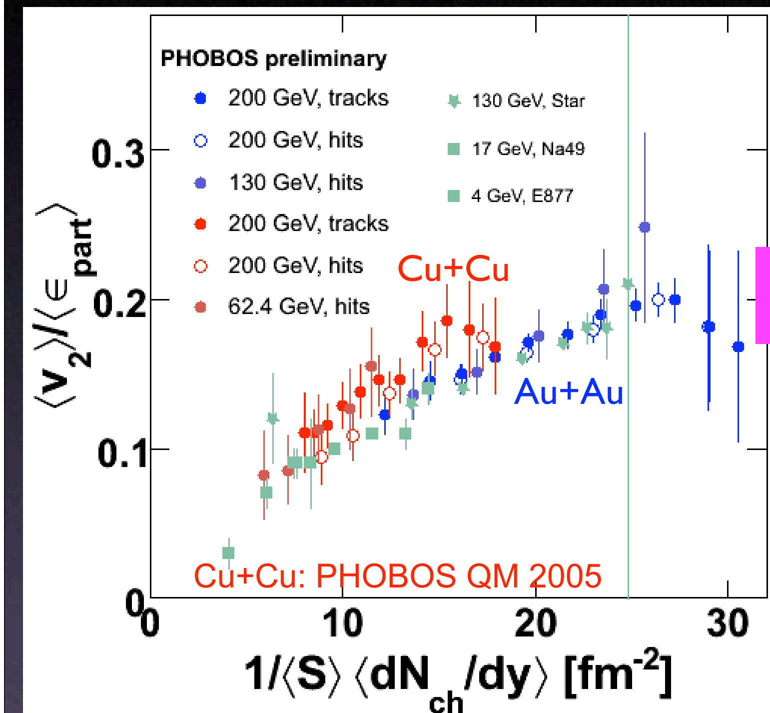
Realign the coordinate system to maximize ellipsoidal shape
(a principal axis transformation)




## "Participant" eccentricity
(versus "standard" eccentricity)



# Geometry and Thermalization




"Hydro-Limit"

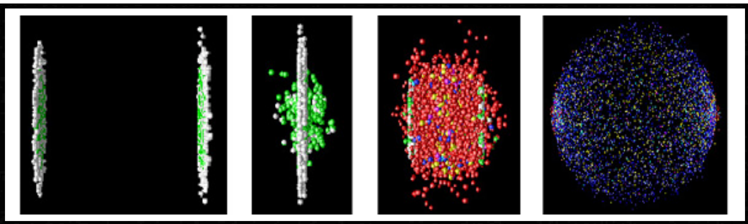
"Participant Eccentricity" provides universal scaling
Approach to equilibrium?

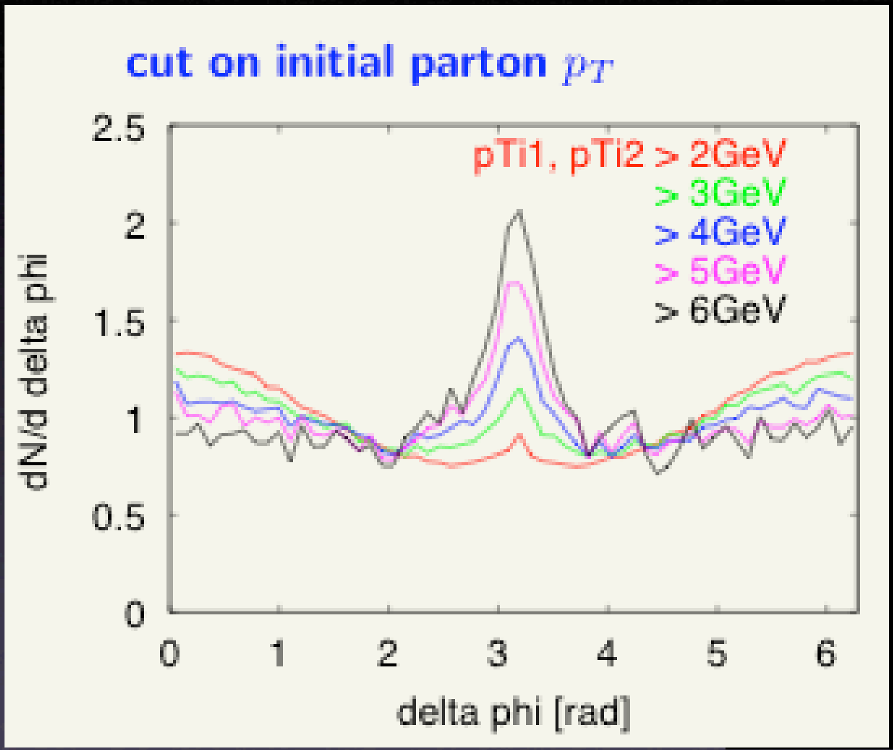
Low Density Limit:
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

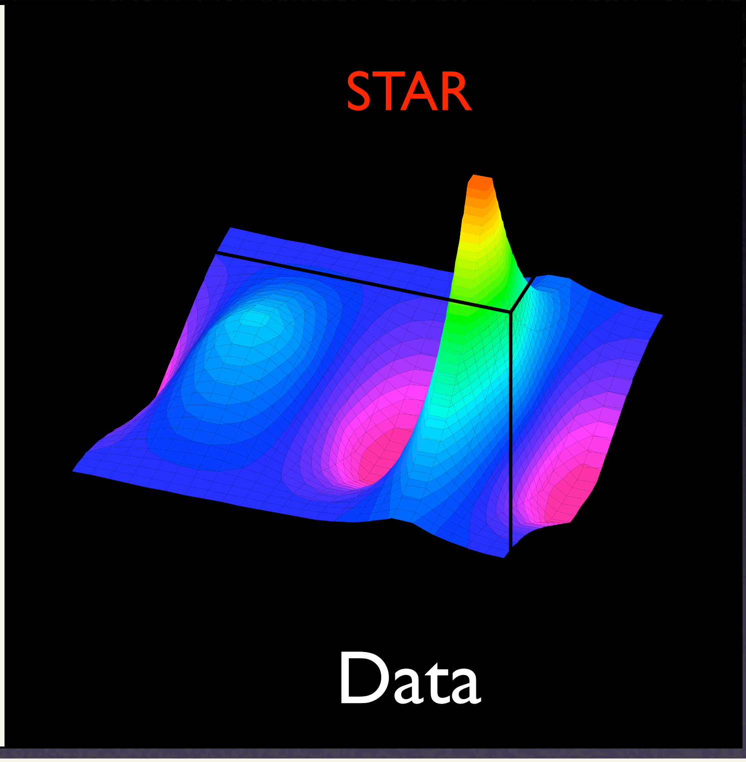
"Eccentricity Fluctuations" provide additional correlation strength

Nuclear Physics!?

➡ Measure $v_2$ fluctuations





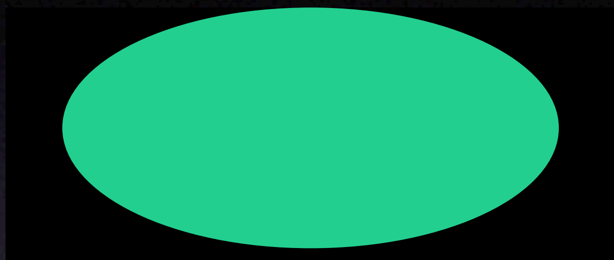



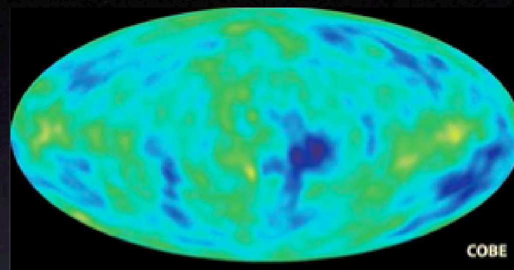

Denes Molnar, BNL workshop June '05

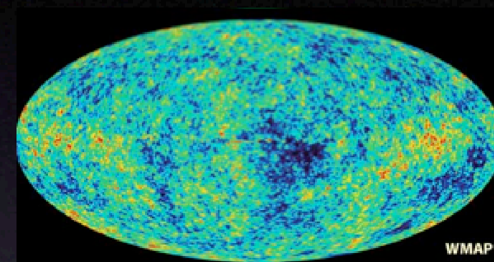
- This is the first study of jet correlations that treats the bulk sector and jets in the same framework. The results are encouraging but need several improvements:
  - add soft partons ("push" effect will contribute)
  - study centrality, particle type dependence (higher statistics)
  - include hadronization (coalescence, fragmentation)
  - extend to radiative processes, coherence
  - could also study other correlations, e.g., Mach cone ...

# Analogy: Cosmic Microwave Background

**Cosmic microwave background**





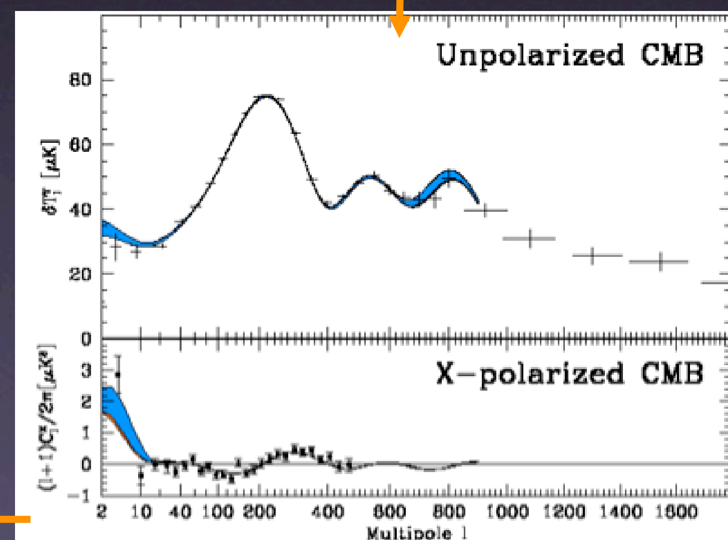

**Penzias, Wilson 1964**

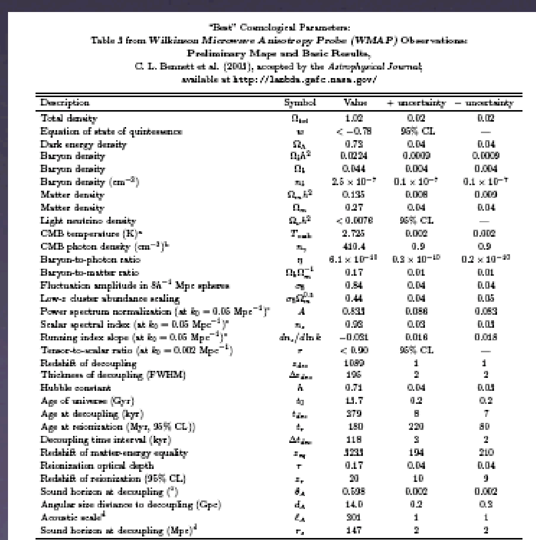
**COBE 1992**

**WMAP**

<T>=3K

$\Delta T/T \sim 10^{-5}$



"Best" Cosmological Parameters:
Table 3 from *Wilkinson Microwave Anisotropy Probe (WMAP) Observations: Preliminary Maps and Basic Results*,
C. L. Bennett et al. (2003), accepted by the *Astrophysical Journal*;
available at http://lambda.gsfc.nasa.gov/

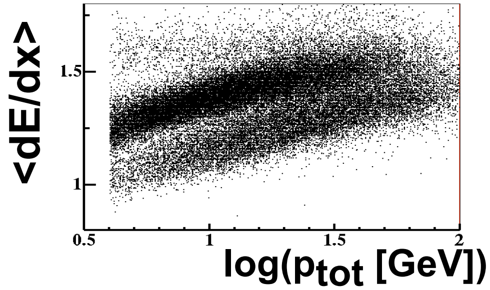
| Description | Symbol | Value | + uncertainty | − uncertainty |
|---|---|---|---|---|
| Total density | $\Omega_{tot}$ | 1.02 | 0.02 | 0.02 |
| Equation of state of quintessence | $w$ | $< -0.78$ | 95% CL | — |
| Dark energy density | $\Omega_\Lambda$ | 0.73 | 0.04 | 0.04 |
| Baryon density | $\Omega_b h^2$ | 0.0224 | 0.0009 | 0.0009 |
| Baryon density | $\Omega_b$ | 0.044 | 0.004 | 0.004 |
| Baryon density ($cm^{-3}$) | $n_b$ | $2.5 \times 10^{-7}$ | $0.1 \times 10^{-7}$ | $0.1 \times 10^{-7}$ |
| Matter density | $\Omega_m h^2$ | 0.135 | 0.008 | 0.009 |
| Matter density | $\Omega_m$ | 0.27 | 0.04 | 0.04 |
| Light neutrino density | $\Omega_\nu h^2$ | $< 0.0076$ | 95% CL | — |
| CMB temperature (K)[a] | $T_{cmb}$ | 2.725 | 0.002 | 0.002 |
| CMB photon density ($cm^{-3}$)[b] | $n_\gamma$ | 410.4 | 0.9 | 0.9 |
| Baryon-to-photon ratio | $\eta$ | $6.1 \times 10^{-10}$ | $0.3 \times 10^{-10}$ | $0.2 \times 10^{-10}$ |
| Baryon-to-matter ratio | $\Omega_b \Omega_m^{-1}$ | 0.17 | 0.01 | 0.01 |
| Fluctuation amplitude in $8h^{-1}$ Mpc spheres | $\sigma_8$ | 0.84 | 0.04 | 0.04 |
| Low-z cluster abundance scaling | $\sigma_8 \Omega_m^{0.5}$ | 0.44 | 0.04 | 0.05 |
| Power spectrum normalization (at $k_0 = 0.05$ $Mpc^{-1}$)[c] | $A$ | 0.833 | 0.086 | 0.083 |
| Scalar spectral index (at $k_0 = 0.05$ $Mpc^{-1}$)[c] | $n_s$ | 0.93 | 0.03 | 0.03 |
| Running index slope (at $k_0 = 0.05$ $Mpc^{-1}$)[c] | $dn_s/d\ln k$ | $-0.031$ | 0.016 | 0.018 |
| Tensor-to-scalar ratio (at $k_0 = 0.002$ $Mpc^{-1}$) | $r$ | $< 0.90$ | 95% CL | — |
| Redshift of decoupling | $z_{dec}$ | 1089 | 1 | 1 |
| Thickness of decoupling (FWHM) | $\Delta z_{dec}$ | 195 | 2 | 2 |
| Hubble constant | $h$ | 0.71 | 0.04 | 0.03 |
| Age of universe (Gyr) | $t_0$ | 13.7 | 0.2 | 0.2 |
| Age at decoupling (kyr) | $t_{dec}$ | 379 | 8 | 7 |
| Age at reionization (Myr, 95% CL)) | $t_r$ | 180 | 220 | 80 |
| Decoupling time interval (kyr) | $\Delta t_{dec}$ | 118 | 3 | 2 |
| Redshift of matter-energy equality | $z_{eq}$ | 3233 | 194 | 210 |
| Reionization optical depth | $\tau$ | 0.17 | 0.04 | 0.04 |
| Redshift of reionization (95% CL) | $z_r$ | 20 | 10 | 9 |
| Sound horizon at decoupling (°) | $\theta_A$ | 0.598 | 0.002 | 0.002 |
| Angular size distance to decoupling (Gpc) | $d_A$ | 14.0 | 0.2 | 0.3 |
| Acoustic scale[d] | $\ell_A$ | 301 | 1 | 1 |
| Sound horizon at decoupling (Mpc)[d] | $r_s$ | 147 | 2 | 2 |

# Summary

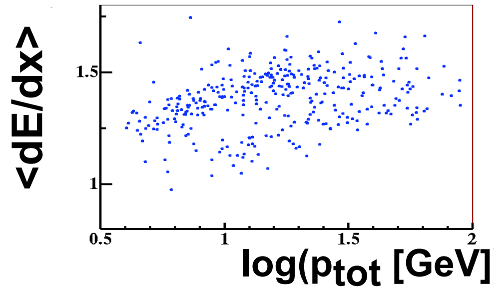
- Rich existing data set on fluctuations
  - Energy independence of global pT, charge fluctuations
  - Energy dependence in K/π, p/π fluctuations
    - limited statistical significance
  - Non-trivial structure/change in charge correlations
- Low-$\sqrt{s}$ scan at RHIC could confirm and improve experimental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

# Event-by-event fit of K/π (NA49)

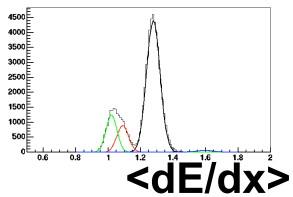
Event Ensemble:



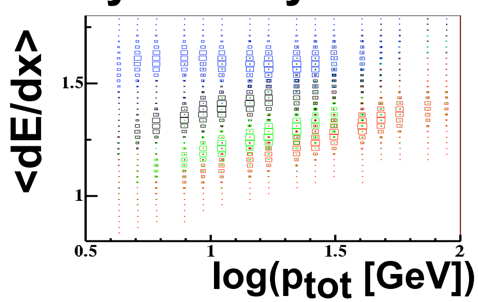

One Event:



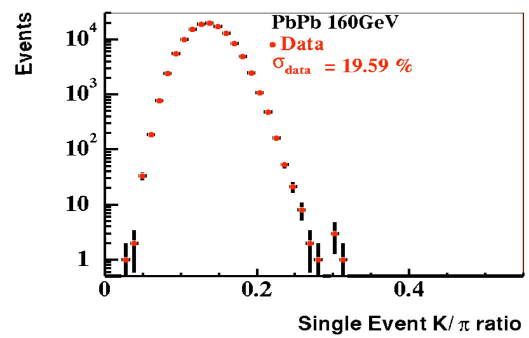

**Fit dE/dx spectra in 4D binning**




**Probability density function:**




- **Vary relative normalization of the particle species (K/π,p/π) in the PDF**
- **Extract ratios with maximum likelihood fit**




Slide from Christof Roland,
Correlations '05, MIT

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

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

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

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

The relationshipe between $\Phi_{p_T}$ and $\Sigma_{p_T}$ when $\Phi_{p_T}$ 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: $D \equiv \langle n_1 + n_2 \rangle \langle (\Delta r_{12})^2 \rangle$ $\quad \frac{D}{4} \approx 1 + \frac{(\tilde{R}_{++} + \tilde{R}_{--} - 2\tilde{R}_{+-})\langle n_+ + n_- \rangle}{4}$

# $\langle p_t \rangle$ 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

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

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

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