Fluctuations and Correlations in Nuclear Collisions - Results and Opportunities

Gunther Roland - MIT

STAR Collaboration Meeting
BNL
March 3 2006

What can we learn from fluctuations?

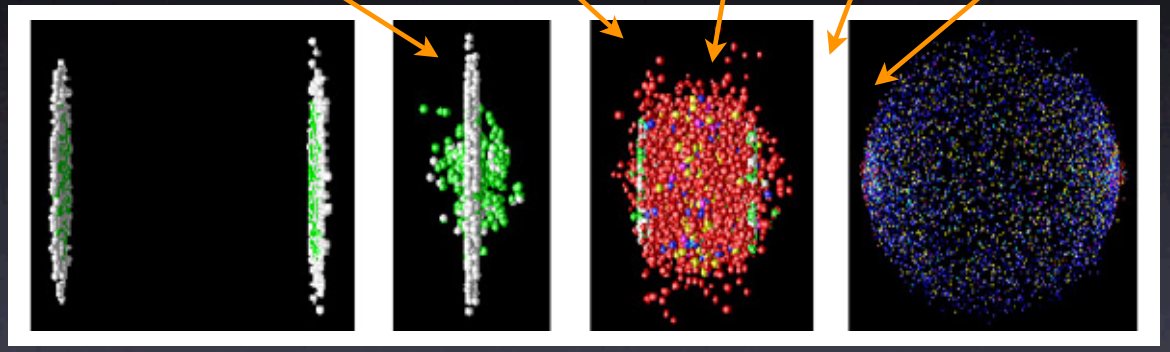
(How) Does matter thermalize?

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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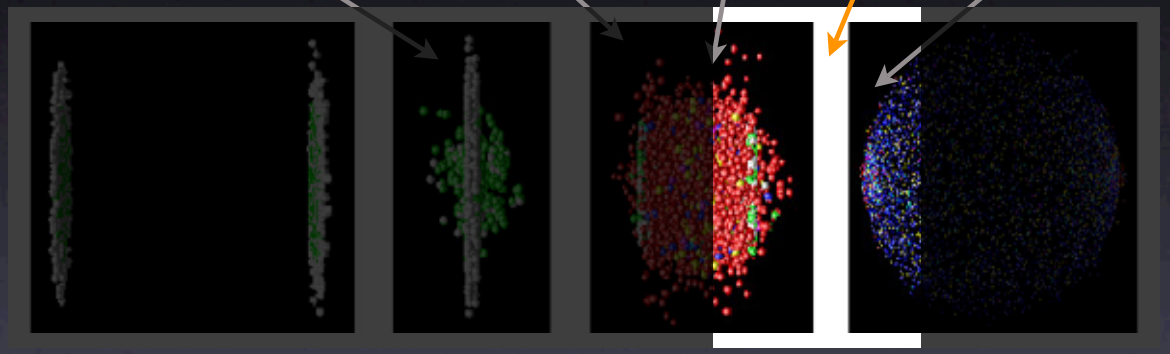
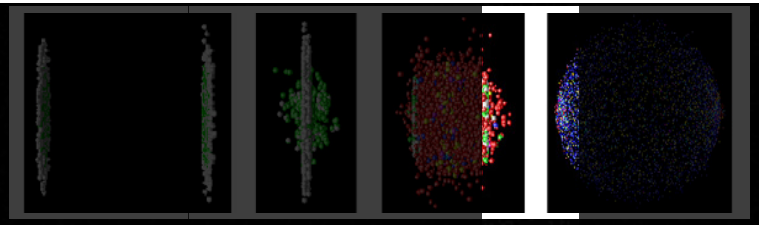
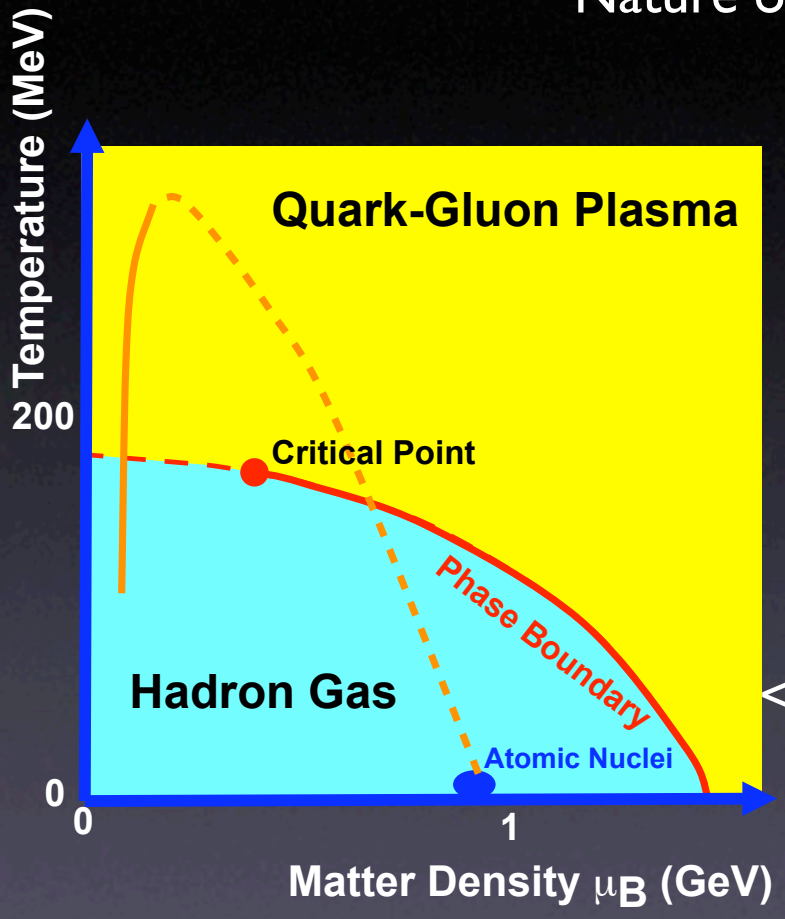


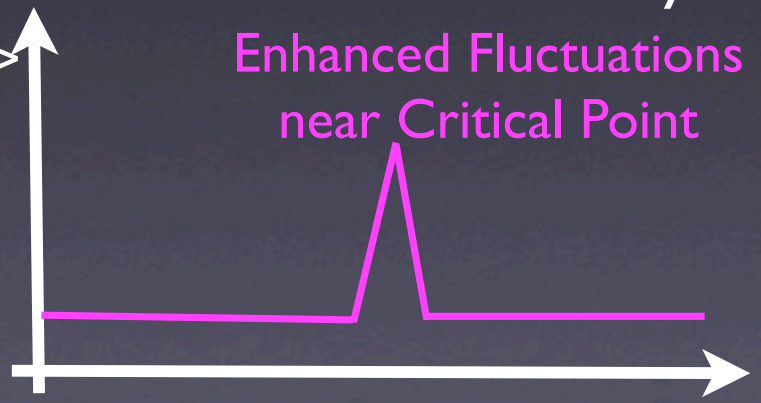
ca 1995



Nature of the Phase Transition

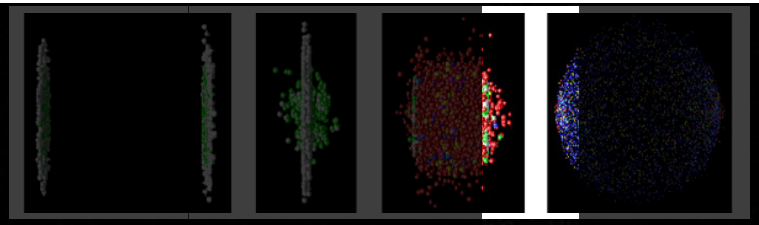


$\langle (X - \langle X \rangle)^2 \rangle$



Search for critical phenomena induced near phase transition/critical point

Rajagopal, Shuryak, Stephanov, Wilczek



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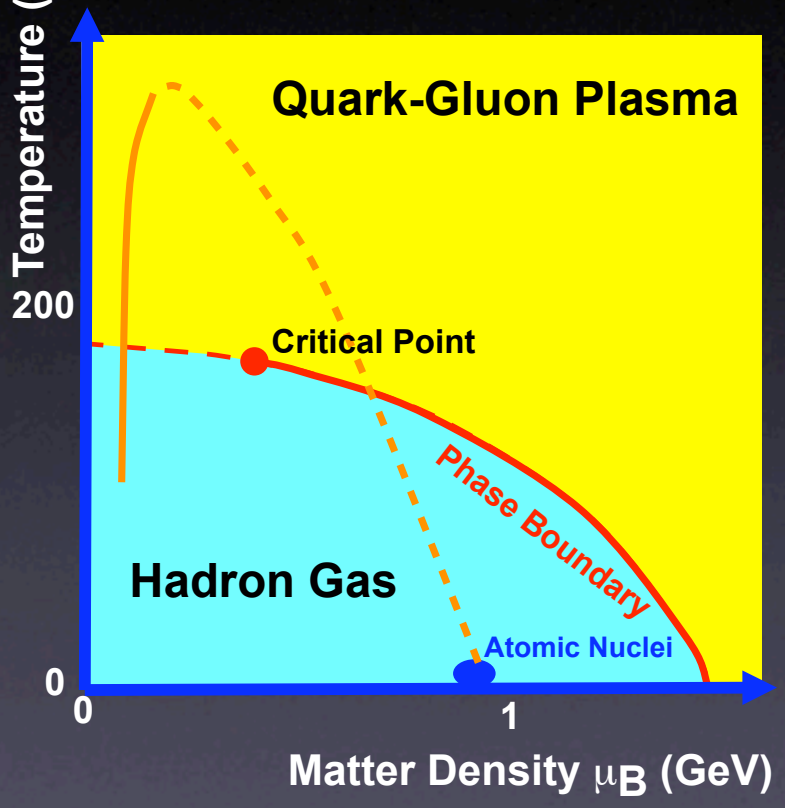
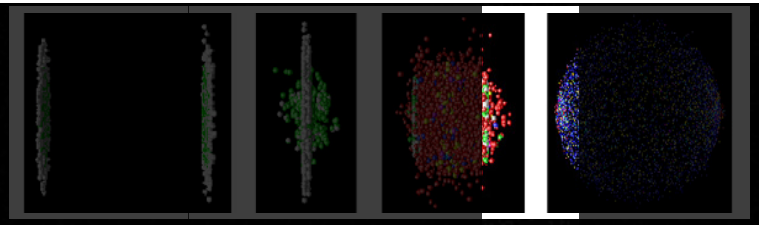


- Phase transition/Latent heat
  - Supercooling — Mishustin
  - Droplet Formation
  - <pT>, Multiplicity Fluctuations
- Location of critical point
  - <pT> Fluctuations — Rajagopal, Shuryak, Stephanov, Wilczek
- Chiral Symmetry Restoration
  - DCC formation — Rajagopal, Wilczek, Bjorken
  - Charge/neutral fluctuations

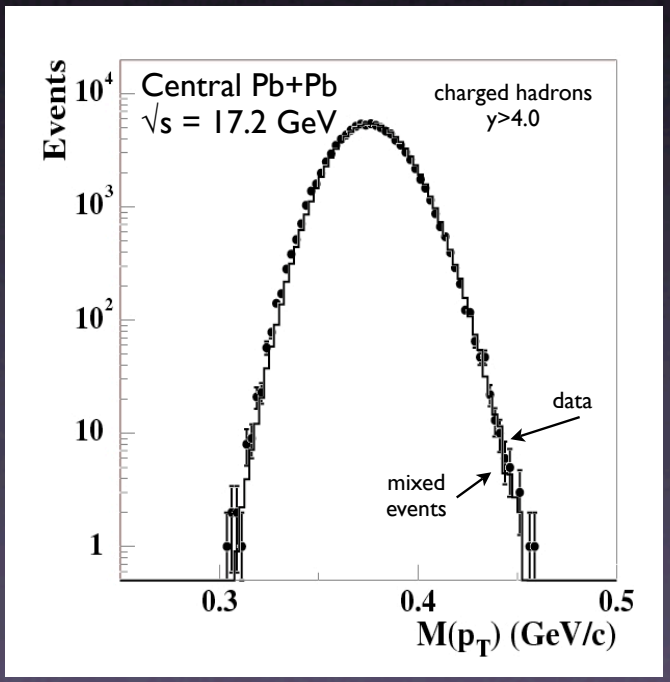


Nature of the Phase Transition

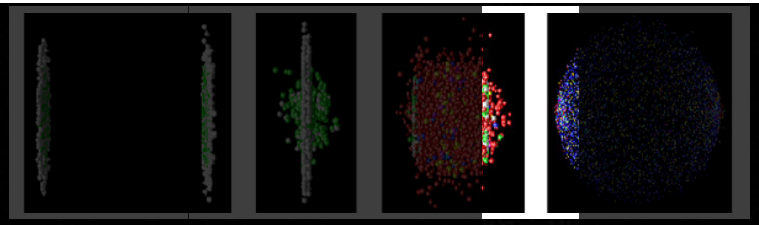
$\langle p_T \rangle$ Fluctuations

- 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

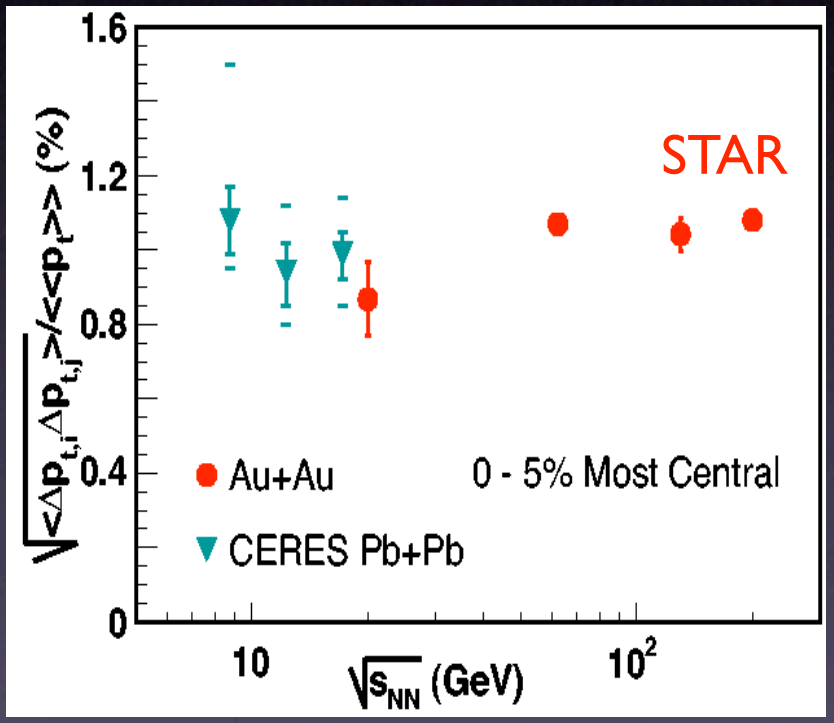


Event-by-event $\langle p_T \rangle$ compared to stochastic reference (mixed events)



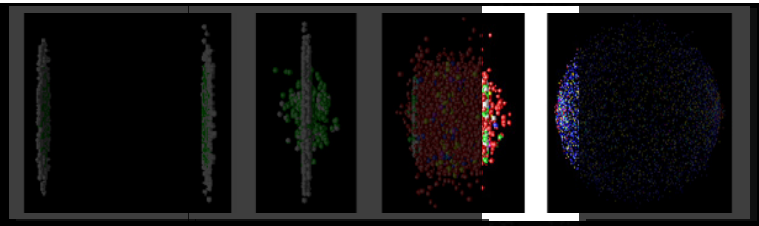
Nature of the Phase Transition

$\langle p_T \rangle$ Fluctuations



No evidence for non-monotonic energy dependence

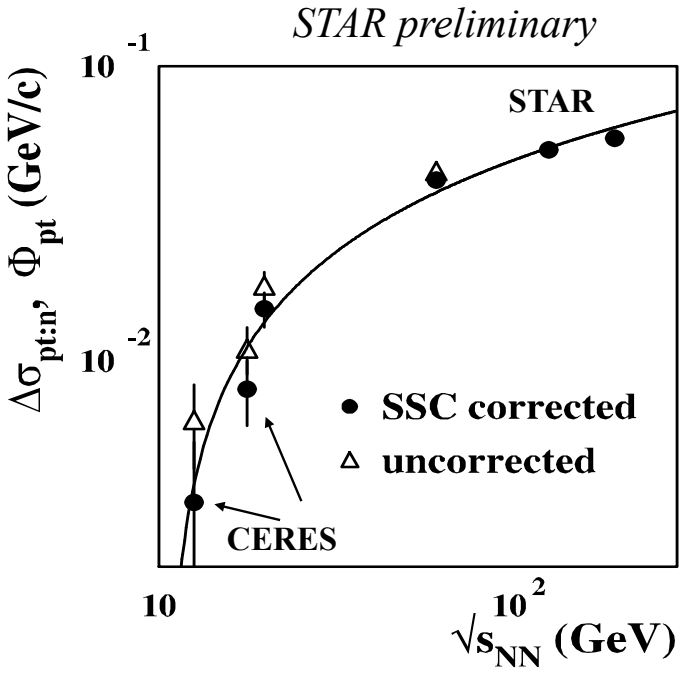
But: Interpretation ⇔ choice of variables



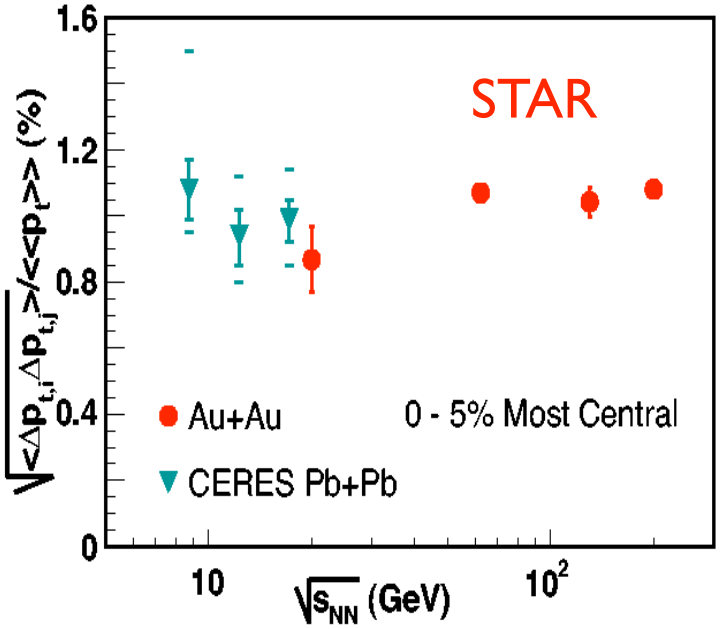
Nature of the Phase Transition

$\langle p_T \rangle$ Fluctuations

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



$\Sigma_{pT} \approx$



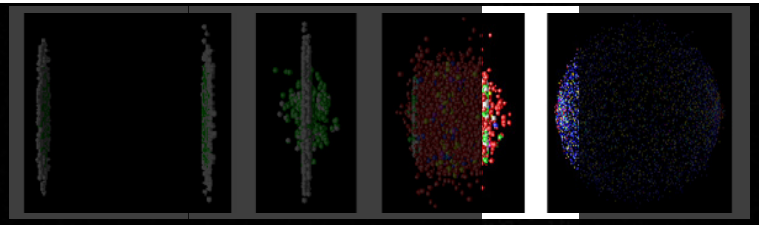
Connection to 2-particle correlations

Normalization to $\langle p_T \rangle$

Normalization per particle

Linear or quadratic measures

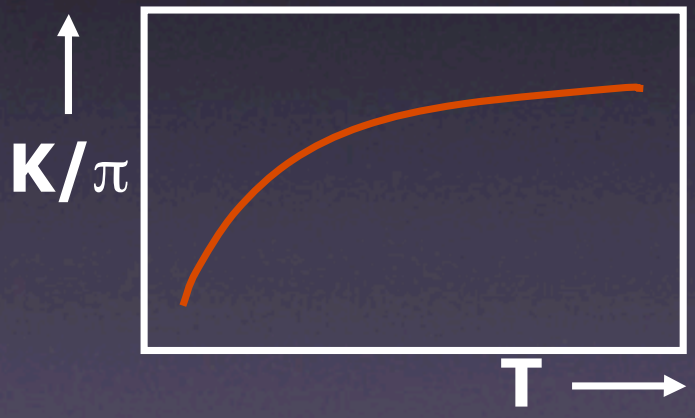
$$\Sigma_{p_T} \simeq \sqrt{\frac{2\Phi_{p_T}\sqrt{\sigma^2_{\hat{p}_T}}}{\overline{N}\overline{p}^2_T}}$$



Nature of the Phase Transition

K/π Fluctuations

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

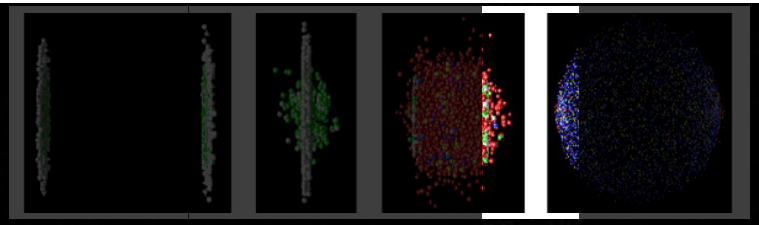


NA49 Measurement

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

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

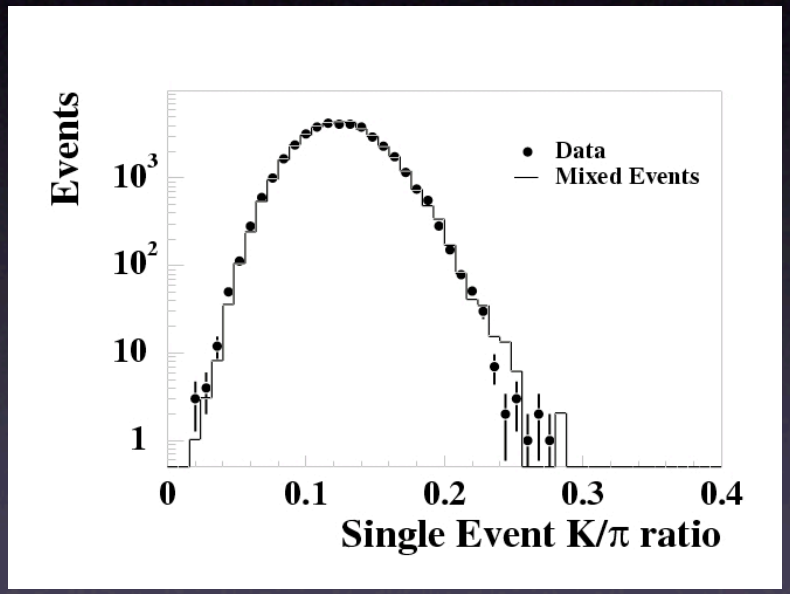
- Required 2 years of detector calibation to eliminate dE/dx – multiplicity correlation

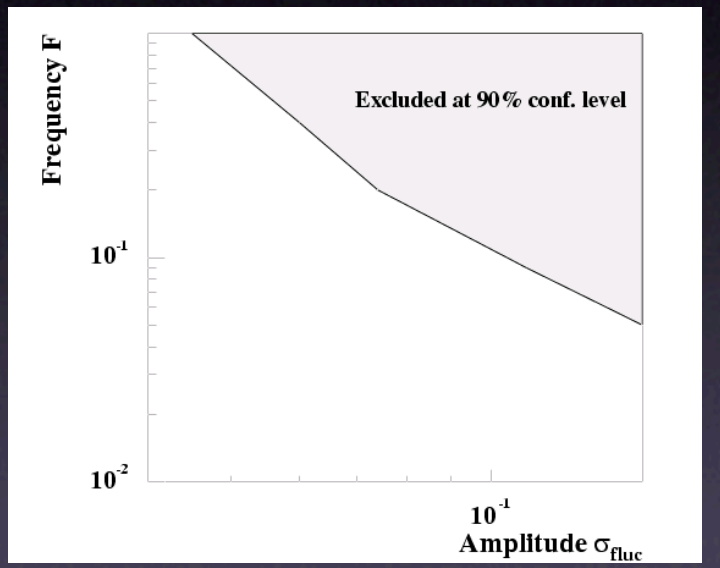


Nature of the Phase Transition

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

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Properties of the medium?

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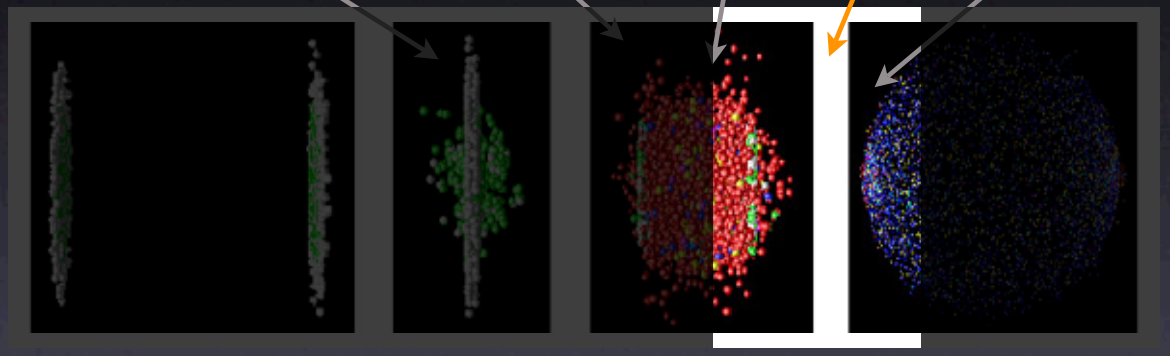

Monotonic √s evolution of global fluctuations

Magnitude of fluctuations moderate

Scaling of relative fluctuations

→

Small latent heat?

Equilibrium evolution?

Freeze-out far from critical point?

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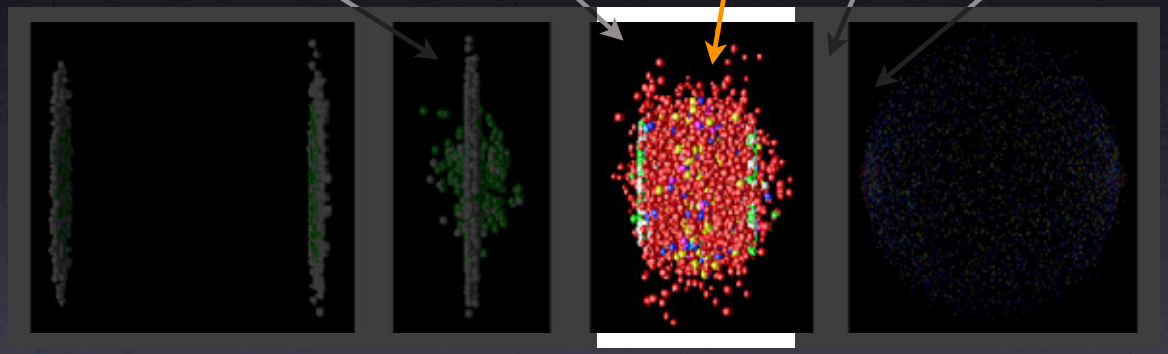
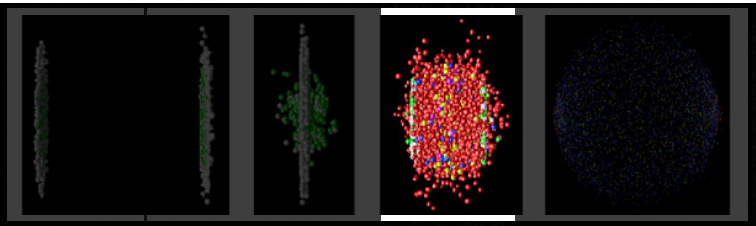
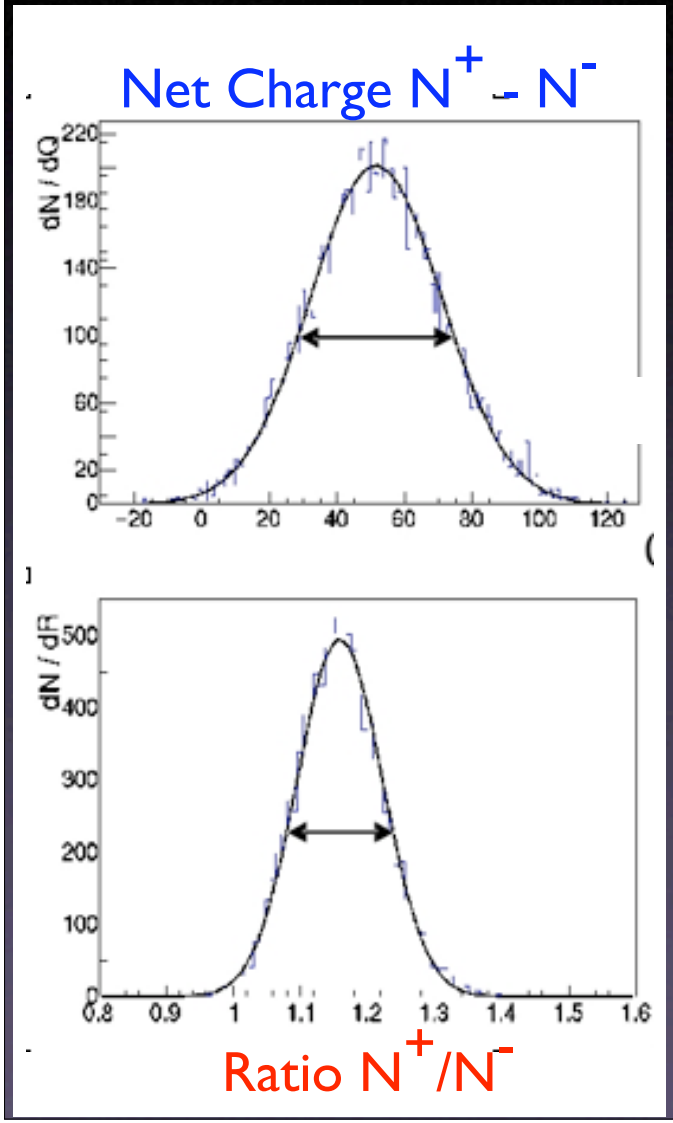


ca 2000



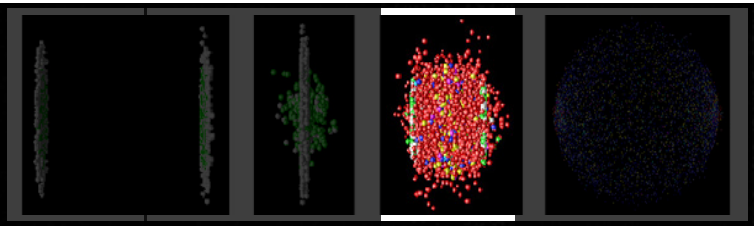
Properties of the Medium



- Net Charge/Δy Fluctuations <-> Charge/DoF
  - Jeon, Koch hep-ph/0003168
  - Asakawa, Heinz, Mueller hep/ph/0003169
  - Change from 1-2 (QGP) to 4 (Pion Gas)

- Fluctuations frozen b/c charge conservation
  - Diffusion vs Expansion timescale

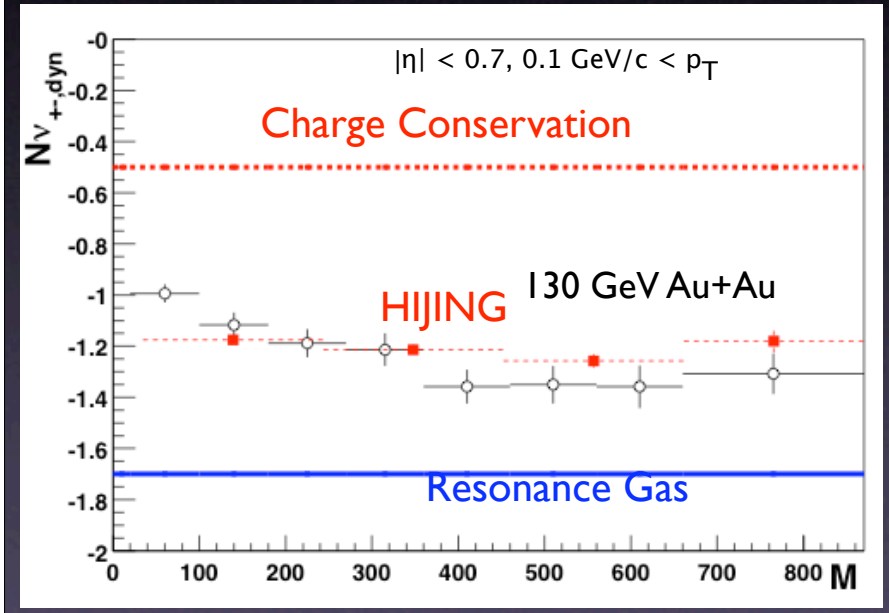
- Fluctuations of $N^+ - N^-$ or N^+/N^- vs statistical reference



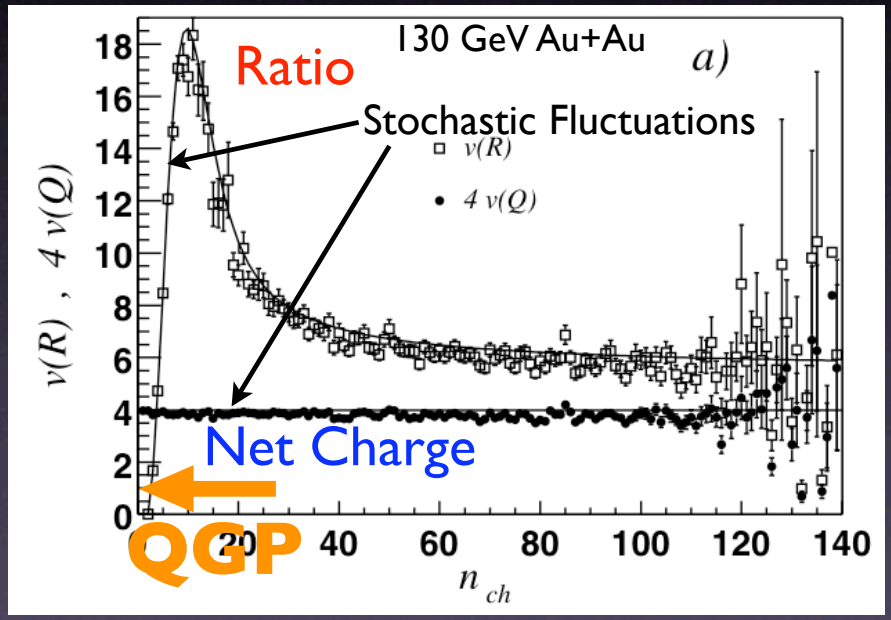
Properties of the Medium

Net Charge Fluctuations

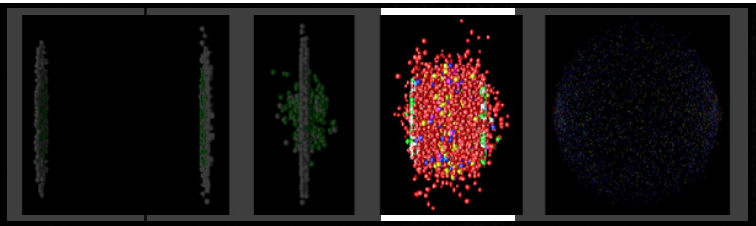
STAR PRC 68 (2003)



PHENIX PRL 89 (2002)



Fluctuations agree with stochastic distributions of *Hadrons*



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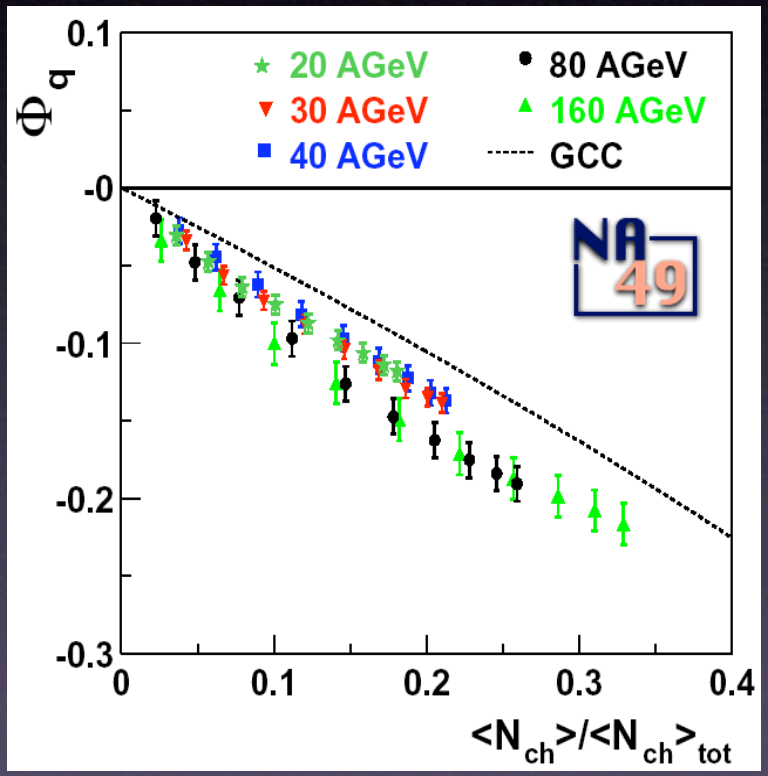

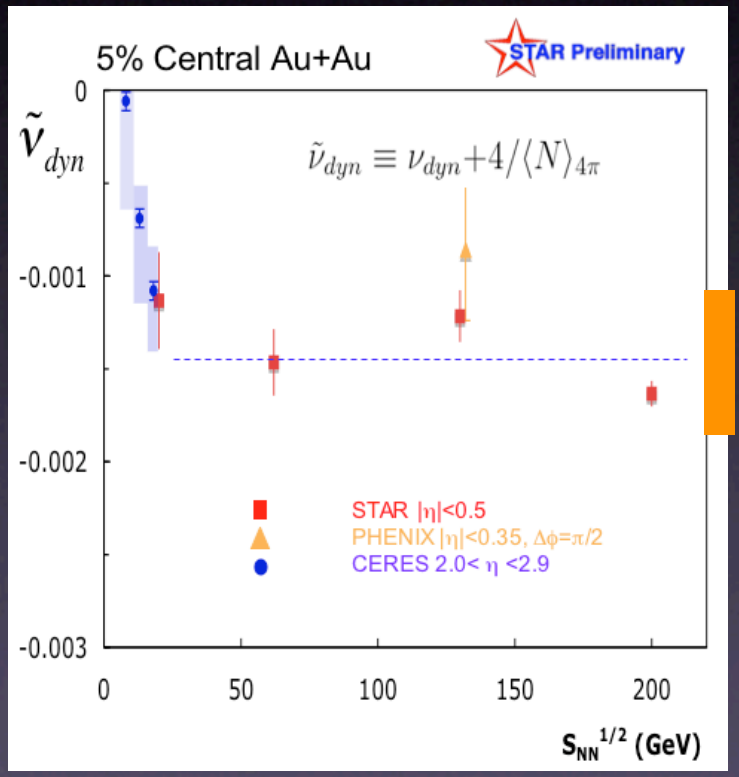

Quark-Coalescence

Bialas, 2003

QGP

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

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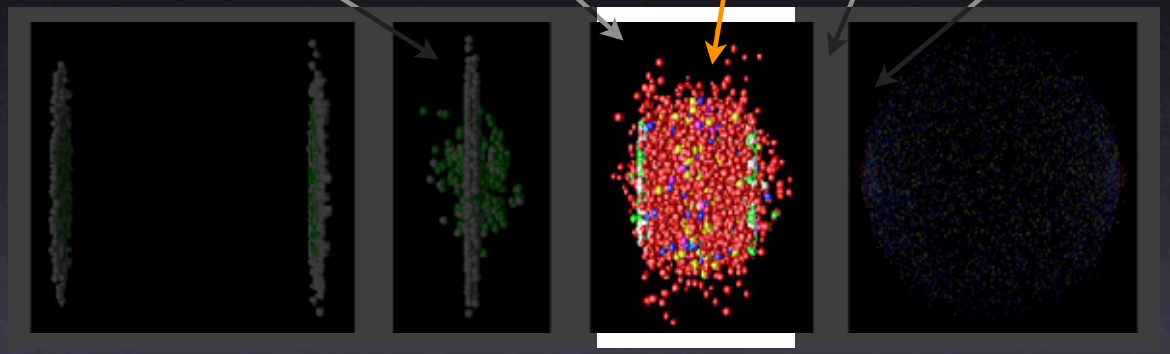

Net charge fluctuations large (~ hadron gas)

Small/no √s dependence

→

Quark coalescence?

Property of Hadronization?

Diffusion?

Bound states?

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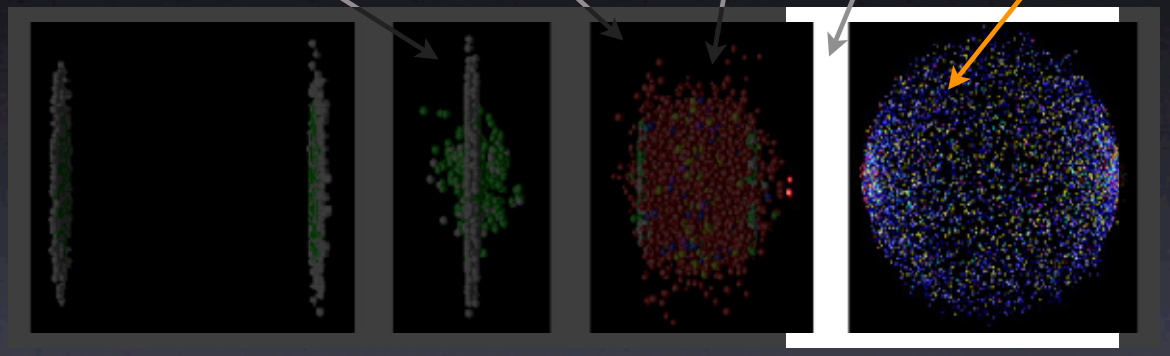

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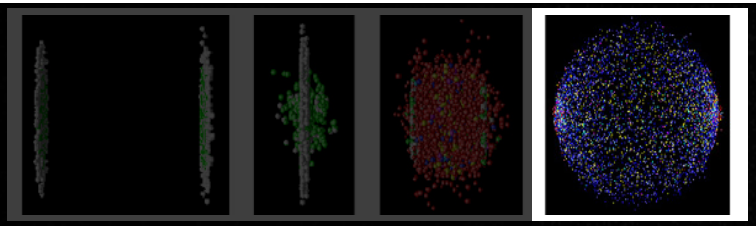
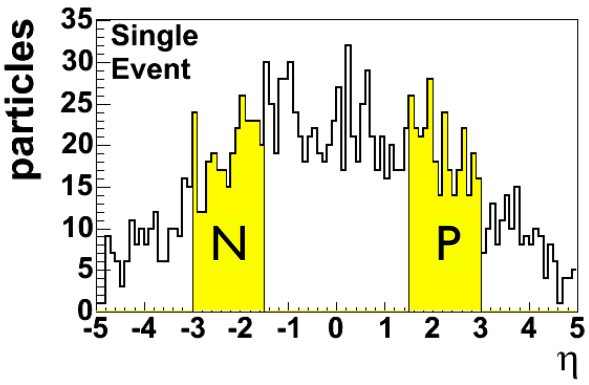


Hadronization

Forward/backward multiplicity correlations



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

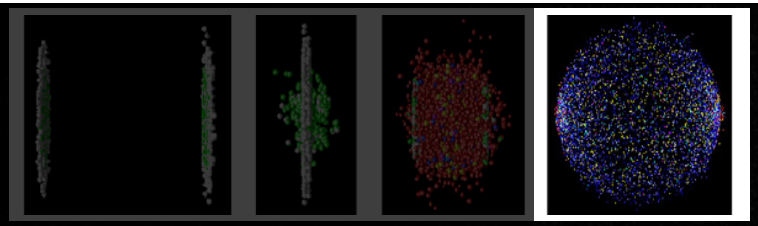
Use variance σ^2_C

Particles produced independently:

$\sigma^2_C = 1$

Particles produced in clusters of size *K*:

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



Hadronization

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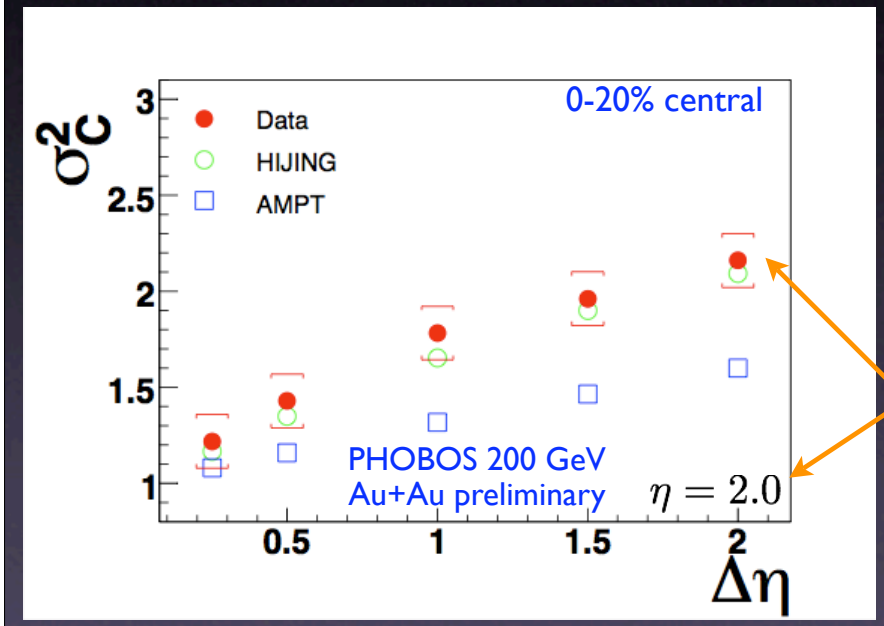

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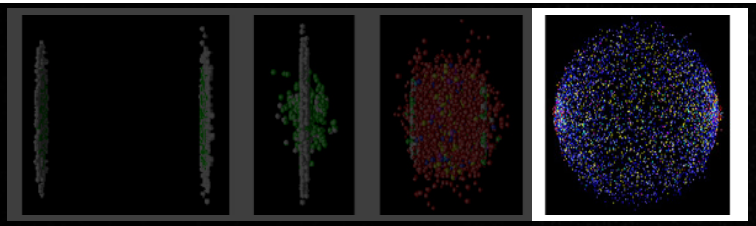
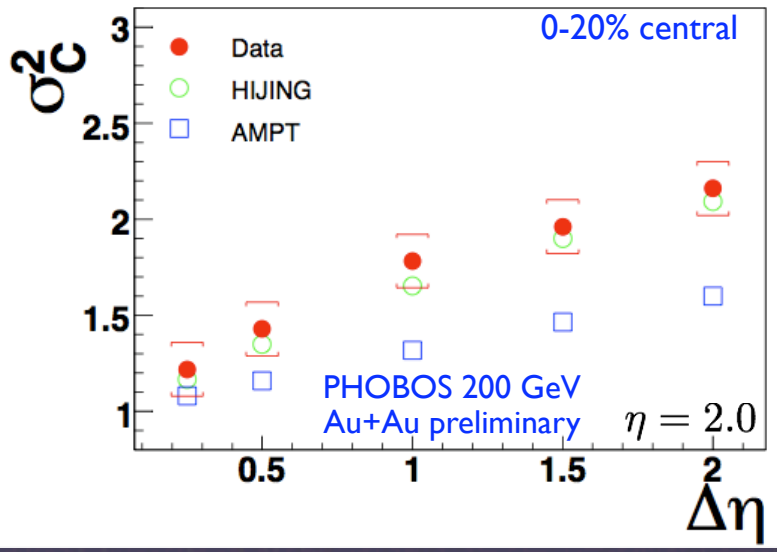
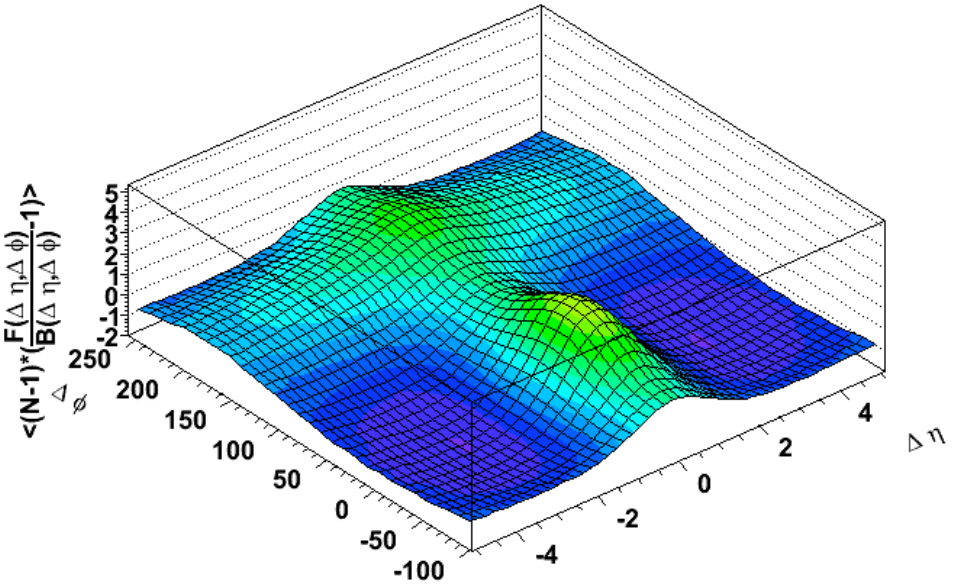
effective cluster size ≈ 2-2.5 for 200 GeV Au+Au



Hadronization

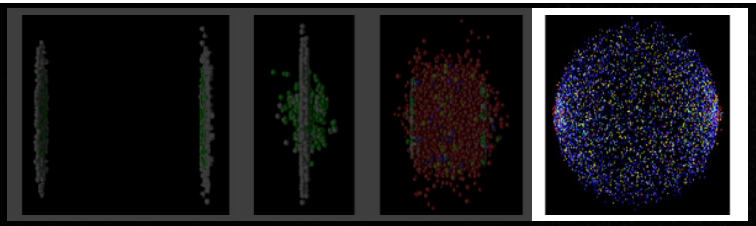
Clusters in A+A (and p+p) collisions





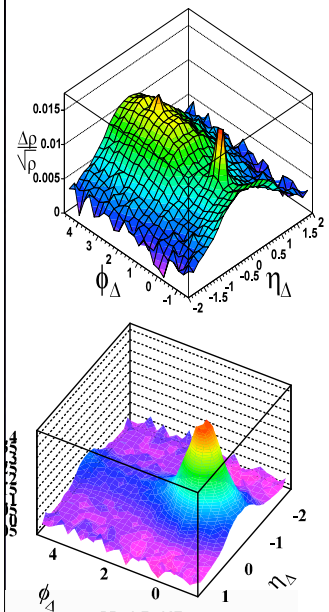
effective cluster size ≈ 2-2.5
for 200 GeV Au+Au

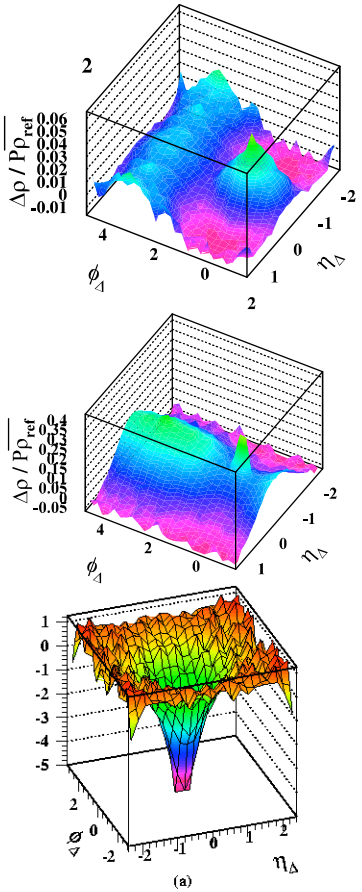
"Cluster" in Δη,Δφ space via
2-particle correlations
(pythia p+p @200 GeV, η<3)



Hadronization

Landscape of correlation analyses



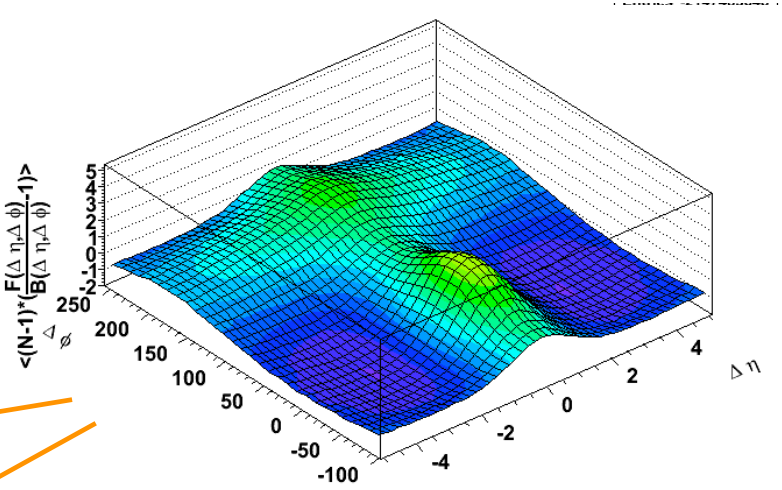


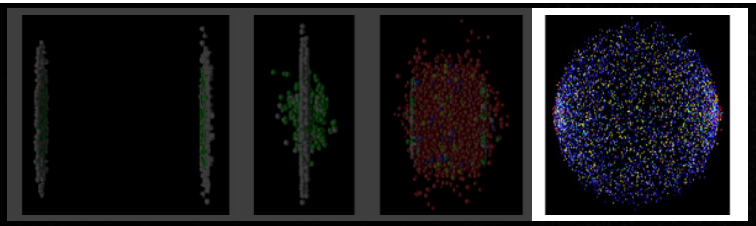
Low vs high p_T

Like vs unlike sign

p+p vs A+A

All p_T , all charges

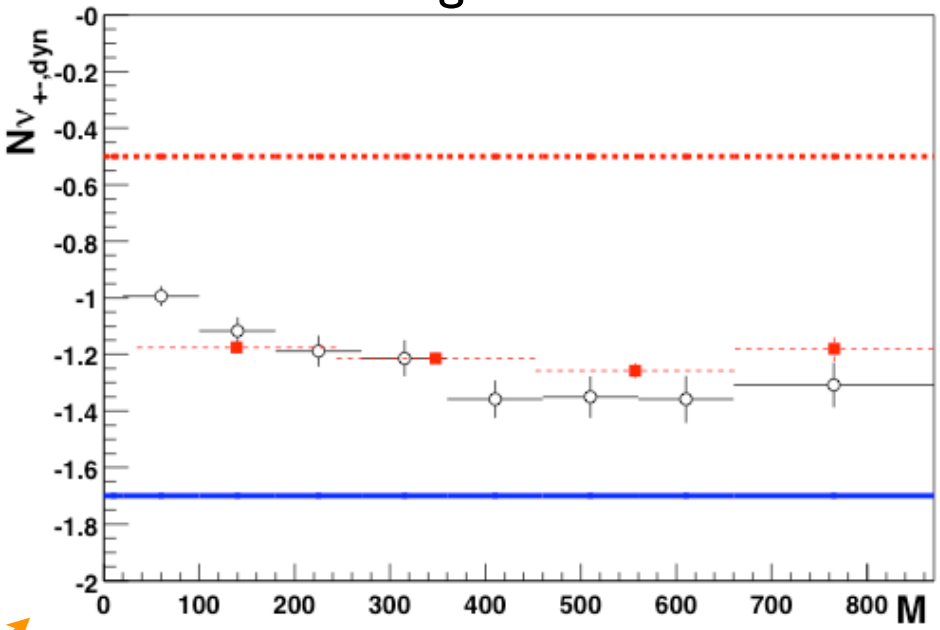




Hadronization

Correlations and Fluctuations, revisited

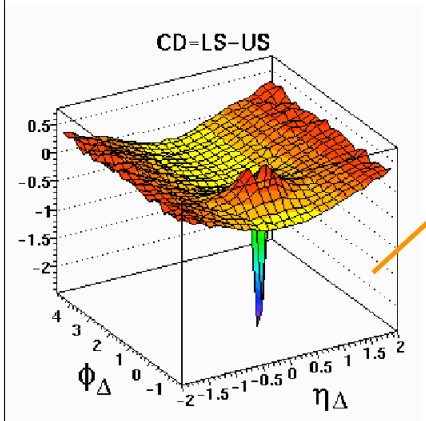
Net-charge Fluctuations



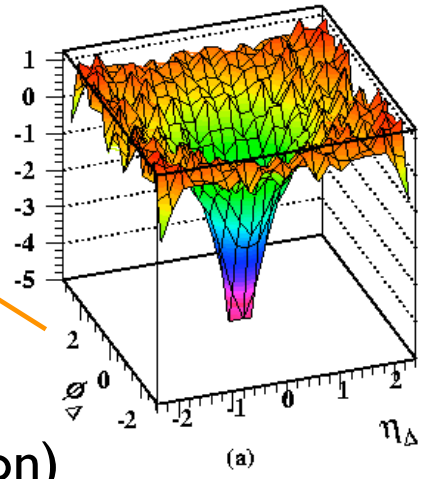
centrality →

Global scaling, even though underlying correlations change

p+p



Central A+A



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

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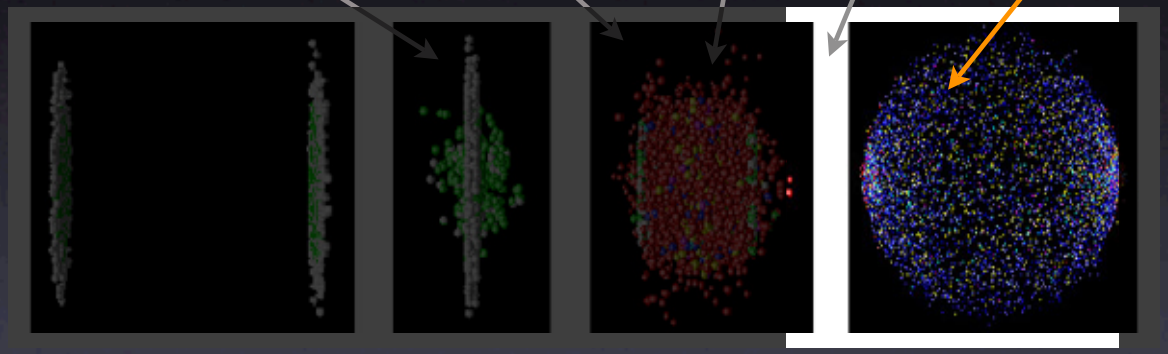


Large multiplicity fluctuations

Strong change in underlying correlation structure

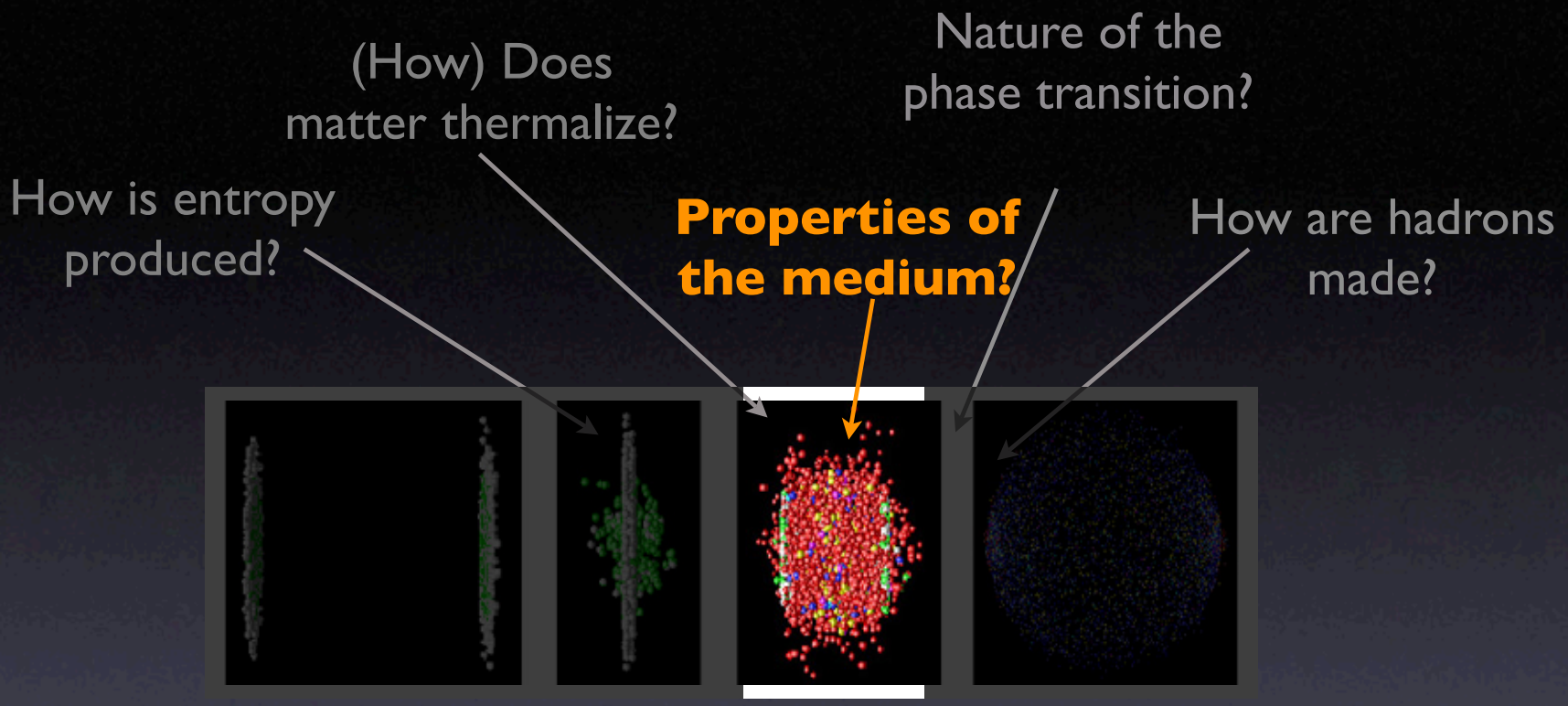
→

Particles produced in large 'clusters'

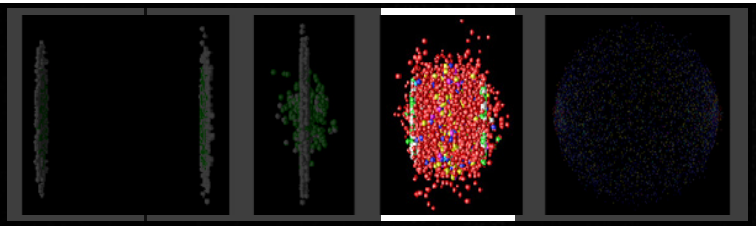
Understanding of hadronization essential

Collision dynamics reflected in correlation structure

What can we learn from fluctuations?

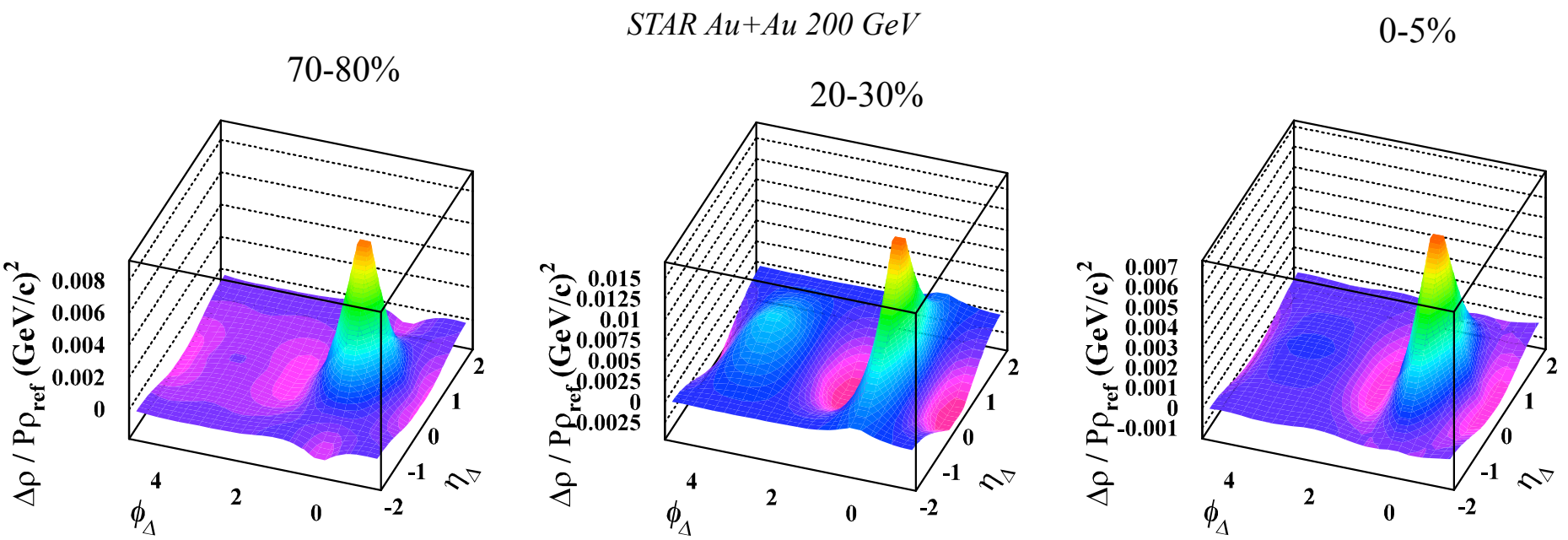


Look at the medium using 2-particle correlations (untriggered) at high(er) p_T

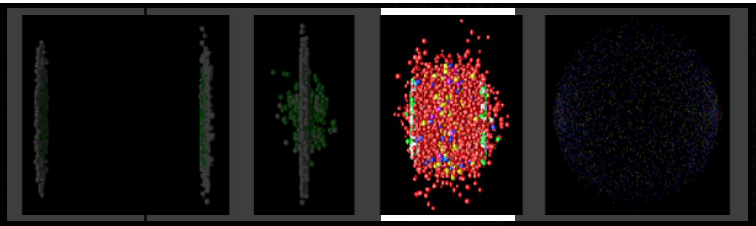


Properties of the Medium

2-particle momentum correlations

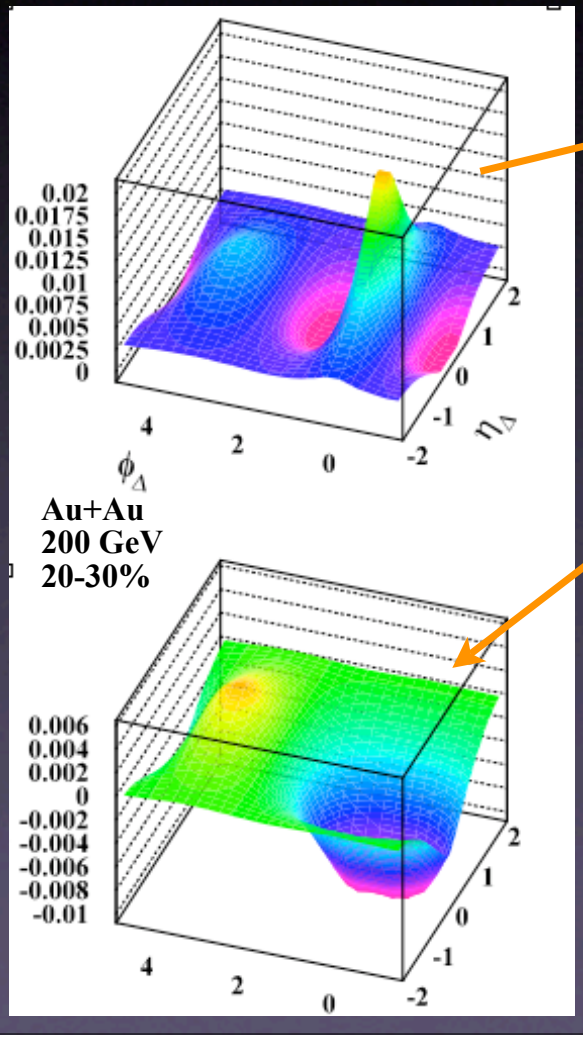


Shape of near-side "parton-fragmentation" peak evolves with centrality

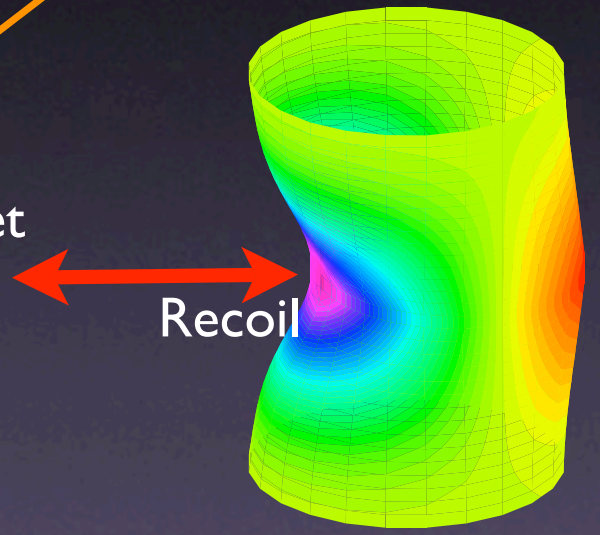


Properties of the Medium

2-particle momentum correlations



Subtract fragmentation peak to look at medium



bulk medium

What can we learn from fluctuations?

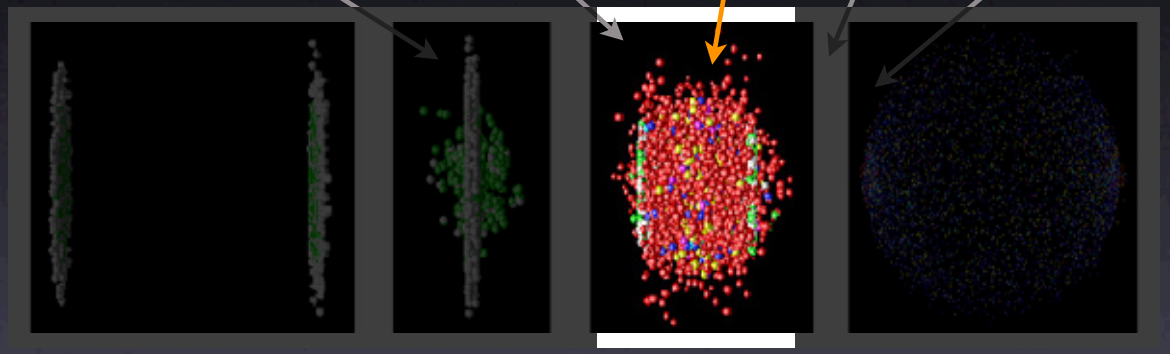
(How) Does matter thermalize?

Nature of the phase transition?

How is entropy produced?

Properties of the medium?

How are hadrons made?



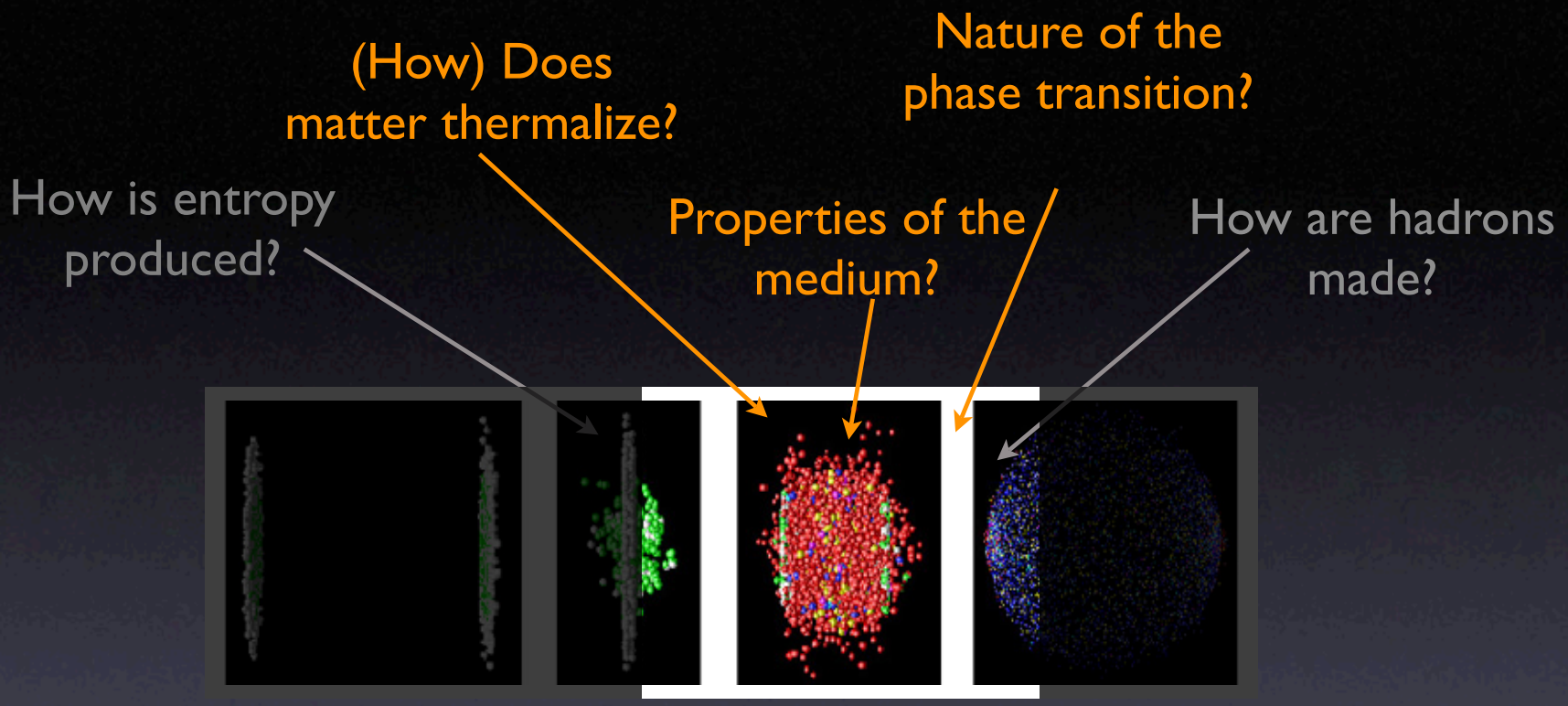
Medium modification of pT correlation shape

Possible medium modification due to partonic recoil

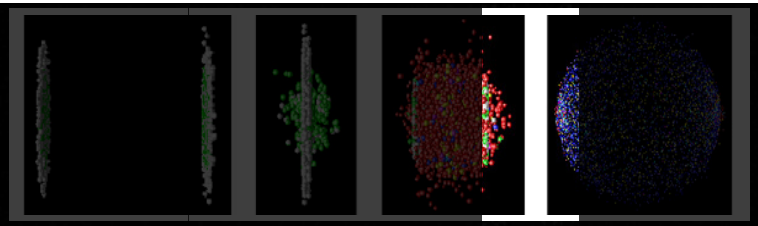
Interaction of partons with bulk medium (flow field)

Extract bulk properties (e.g. viscosity)?

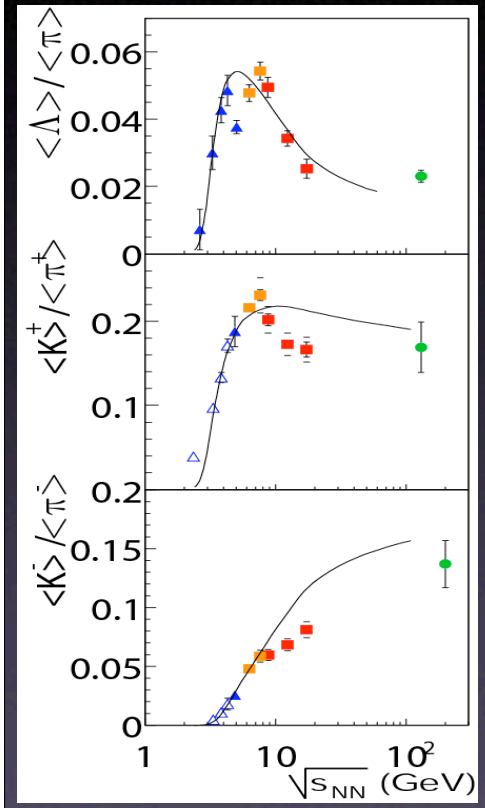
What can we learn from fluctuations?



Some remarks on future measurements

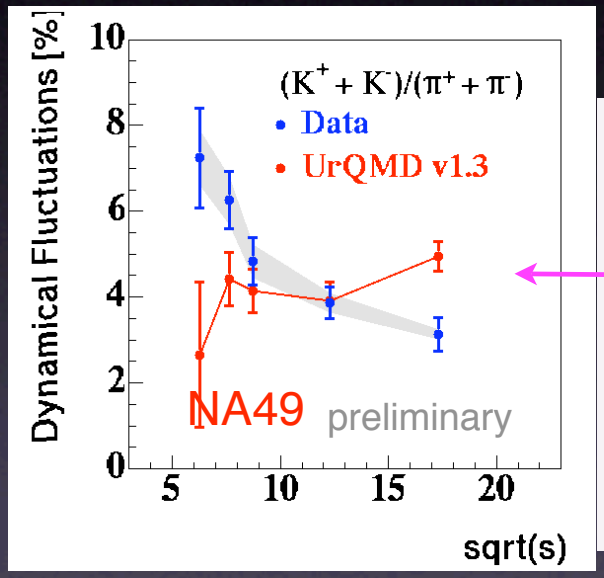


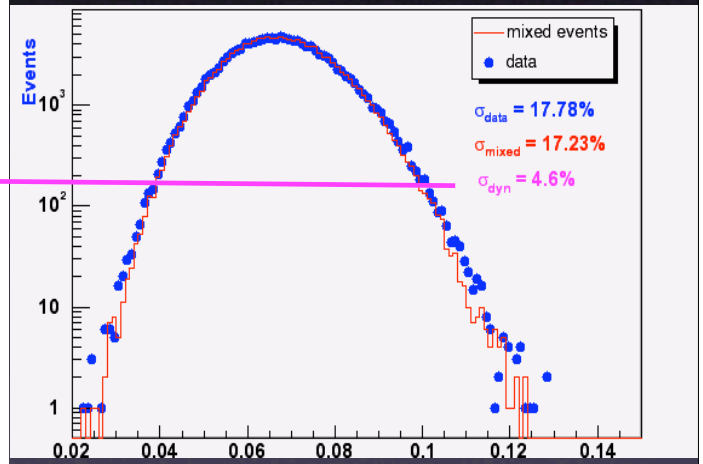
NA49 'Horn'



Strangeness Fluctuations vs √s

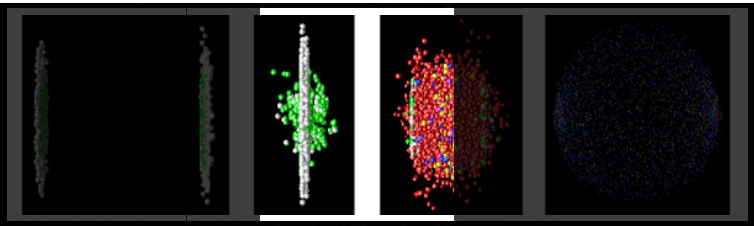
NA49 (Christof Roland QM'04)



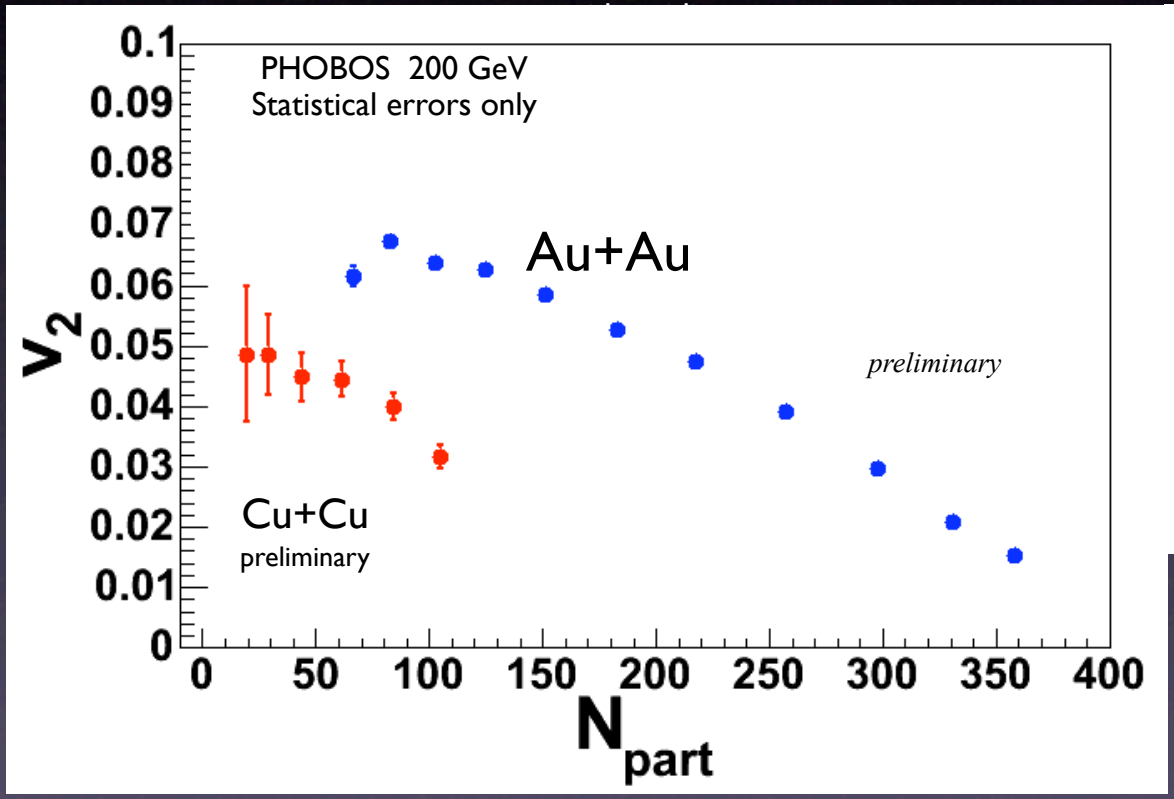


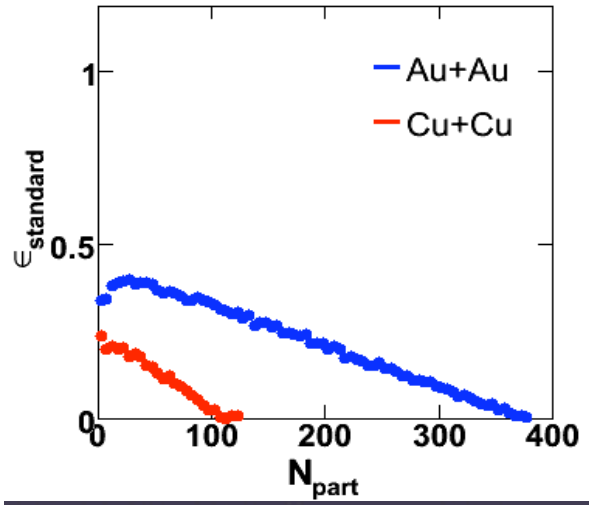
STAR 200 GeV Au+Au
preliminary

Fluctuations in K/pi ratio



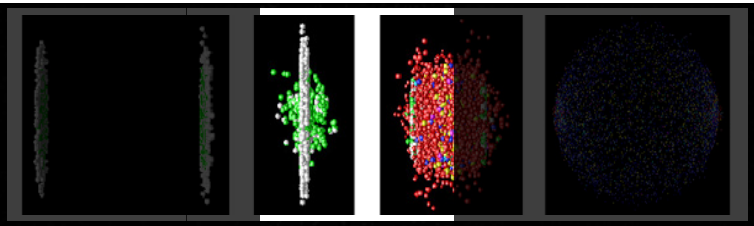
Geometry and Thermalization





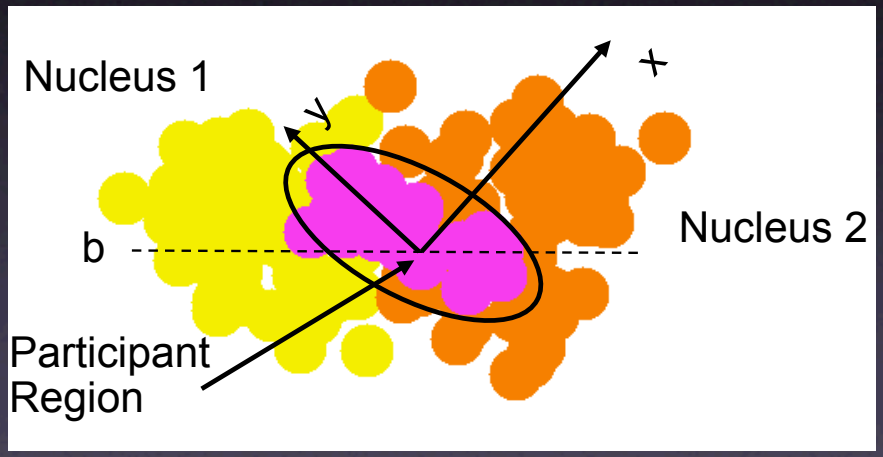
Geometrical initial state eccentricity from Glauber model

Surprisingly large flow signal in Cu+Cu!



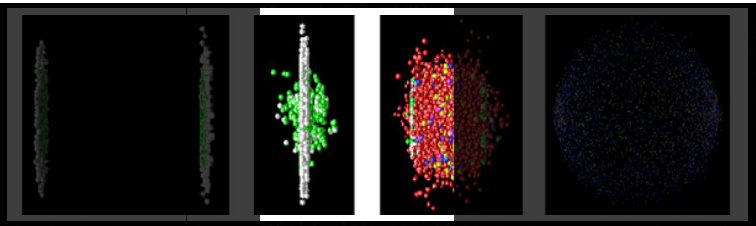
Geometry and Thermalization

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

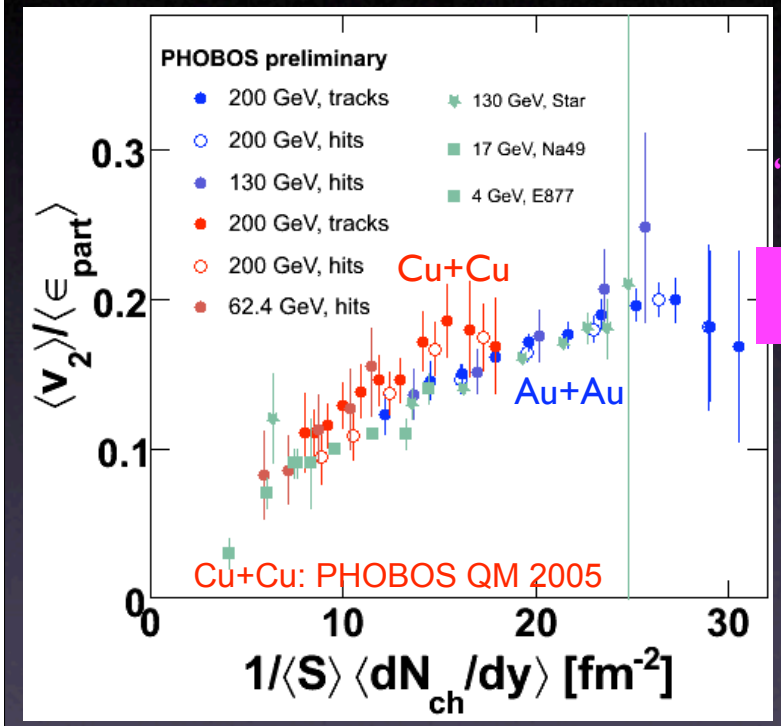


"Participant" eccentricity

(versus "standard" eccentricity)



Geometry and Thermalization



"Hydro-Limit"

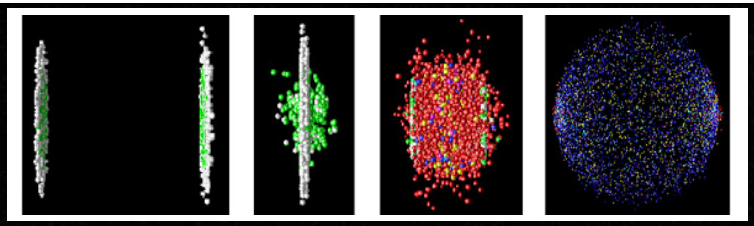
"Participant Eccentricity" provides universal scaling
Approach to equilibrium?

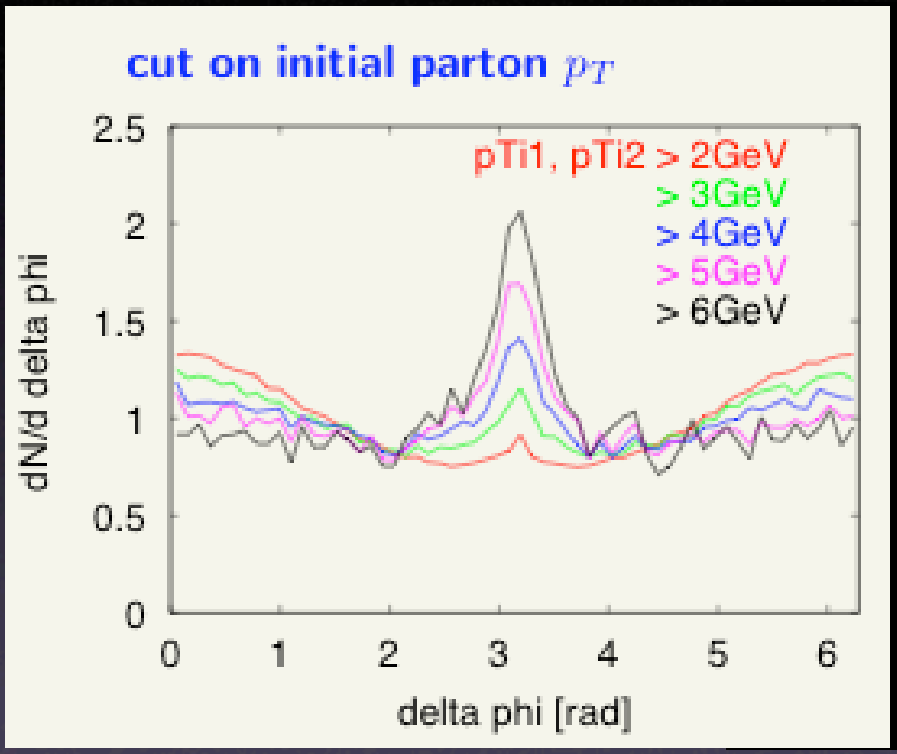
Low Density Limit:
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

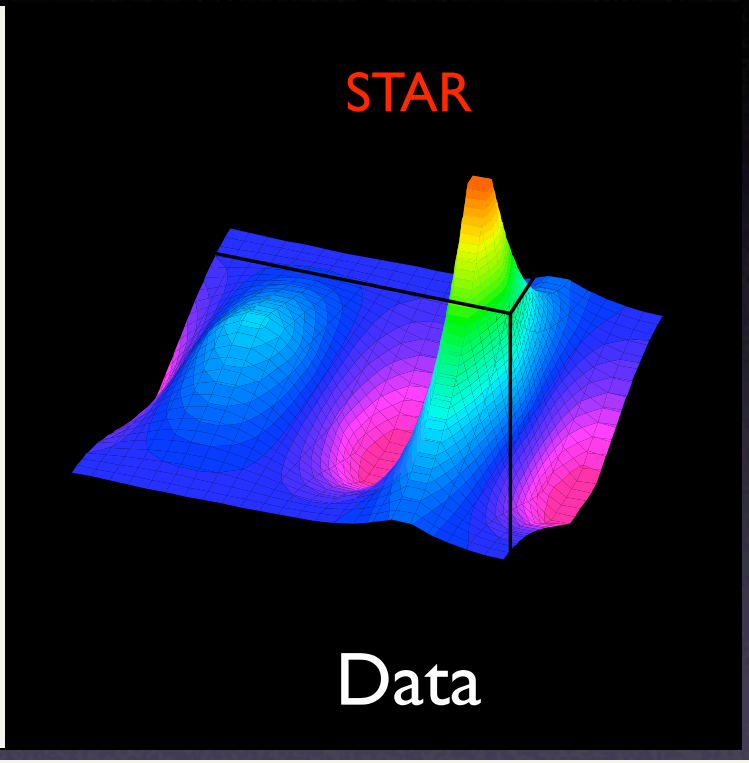
"Eccentricity Fluctuations" provide additional correlation strength

Nuclear Physics!?

➡ Measure v_2 fluctuations





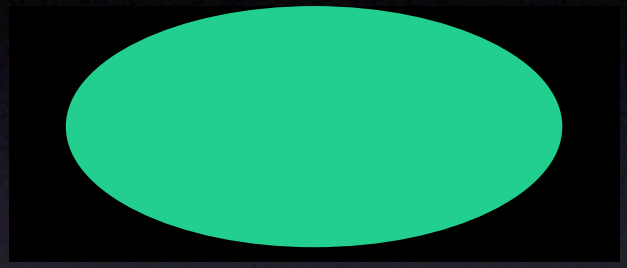


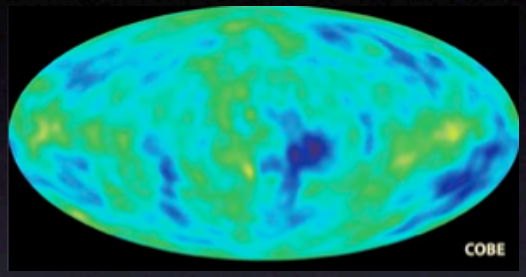
Denes Molnar, BNL workshop June '05

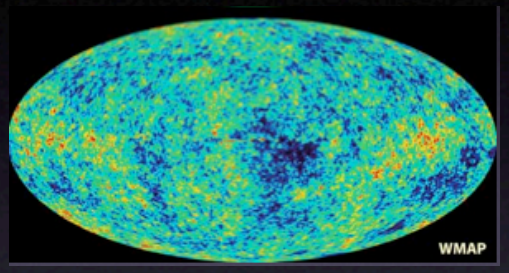
- This is the first study of jet correlations that treats the bulk sector and jets in the same framework. The results are encouraging but need several improvements:
  - add soft partons ("push" effect will contribute)
  - study centrality, particle type dependence (higher statistics)
  - include hadronization (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

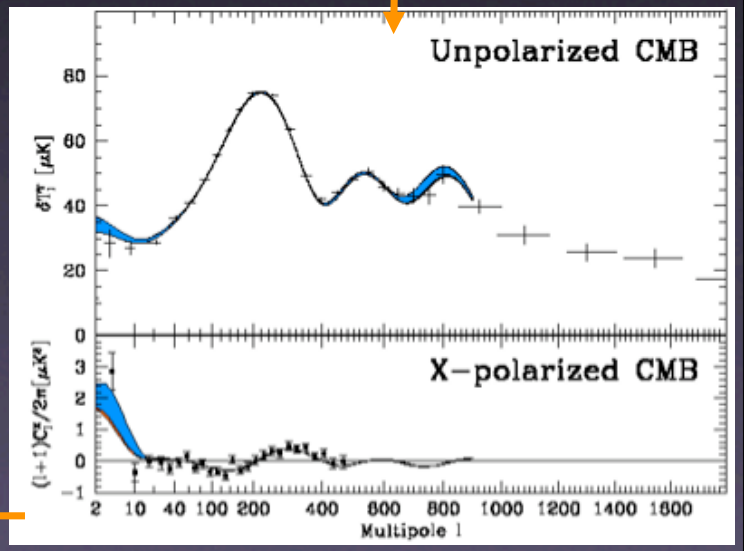
WMAP

<T>=3K

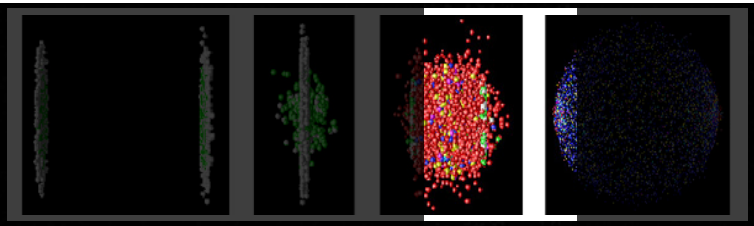
$\Delta T/T \sim 10^{-5}$

"Best" Cosmological Parameters:
Table 1 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	Ω_{tot}	1.02	0.02	0.02
Equation of state of quintessence	w	< -0.78	95% CL	—
Dark energy density	Ω_Λ	0.73	0.04	0.04
Baryon density	$\Omega_b h^2$	0.0224	0.0009	0.0009
Baryon density	Ω_b	0.044	0.004	0.004
Baryon density (cm^{-3})	n_b	2.5×10^{-7}	0.1×10^{-7}	0.1×10^{-7}
Matter density	$\Omega_m h^2$	0.135	0.008	0.009
Matter density	Ω_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_γ	410.4	0.9	0.9
Baryon-to-photon ratio	η	6.1×10^{-10}	0.3×10^{-10}	0.2×10^{-10}
Baryon-to-matter ratio	$\Omega_b \Omega_m^{-1}$	0.17	0.01	0.01
Fluctuation amplitude in $8h^{-1}$ Mpc spheres	σ_8	0.84	0.04	0.04
Low-z cluster abundance scaling	$\sigma_8 \Omega_m^{0.3}$	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)	Δz_{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)	Δt_{dec}	118	3	2
Redshift of matter-energy equality	z_{eq}	3233	194	210
Reionization optical depth	τ	0.17	0.04	0.04
Redshift of reionization (95% CL)	z_r	20	10	9
Sound horizon at decoupling (°)	θ_A	0.598	0.002	0.002
Angular size distance to decoupling (Gpc)	d_A	14.0	0.2	0.3
Acoustic scale[d]	ℓ_A	301	1	1
Sound horizon at decoupling (Mpc)[d]	r_s	147	2	2

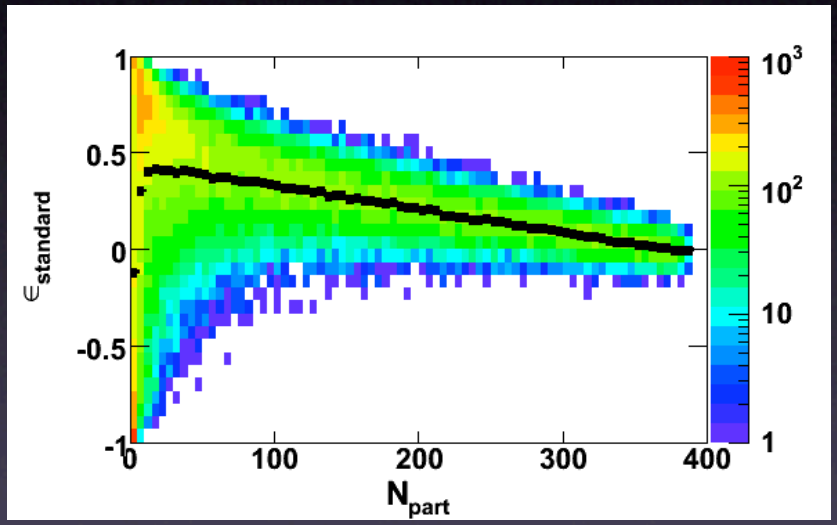


Meeting 3/3/2006



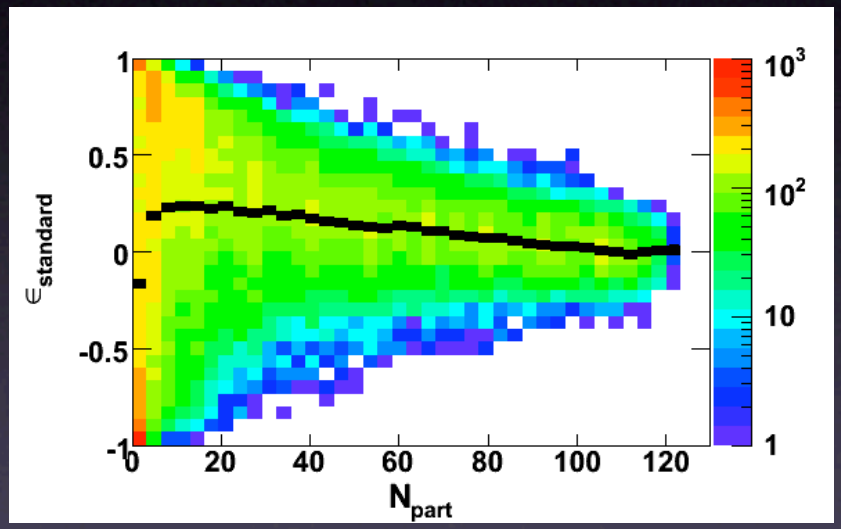
Hydrodynamic Evolution

Au+Au



Large fluctuations in eccentricity

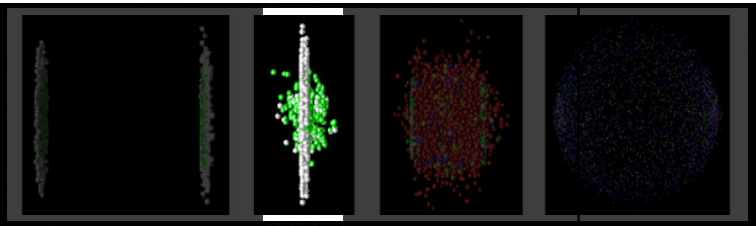
Cu+Cu



Even bigger fluctuations in Cu+Cu

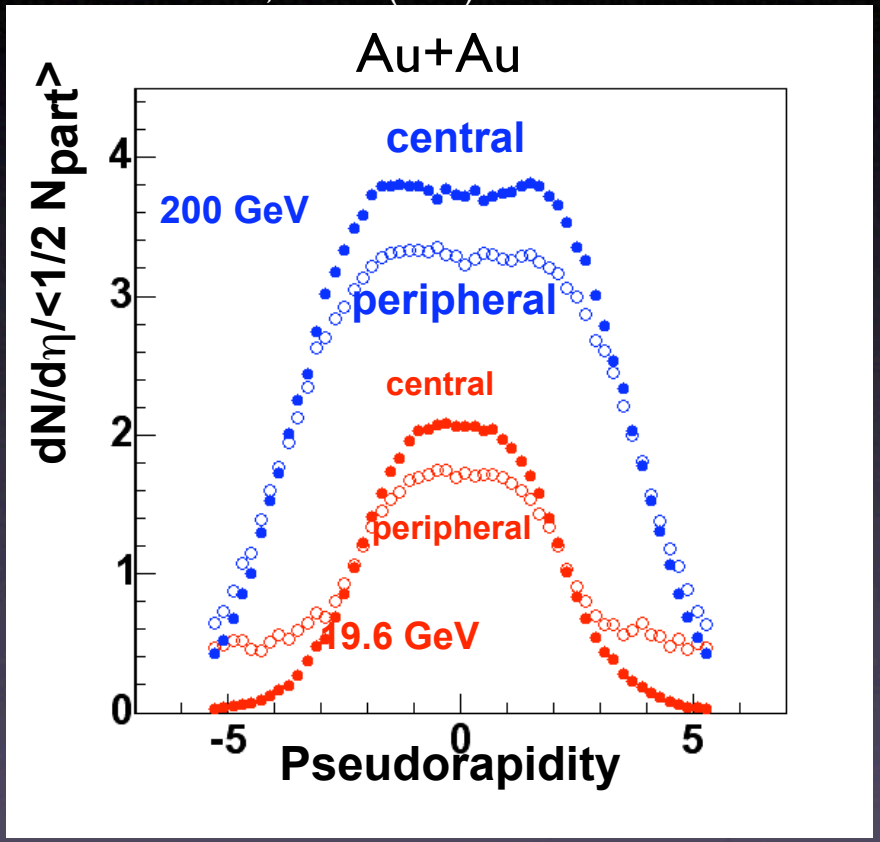
Many peripheral events with negative eccentricity

Glauber MC Calculations

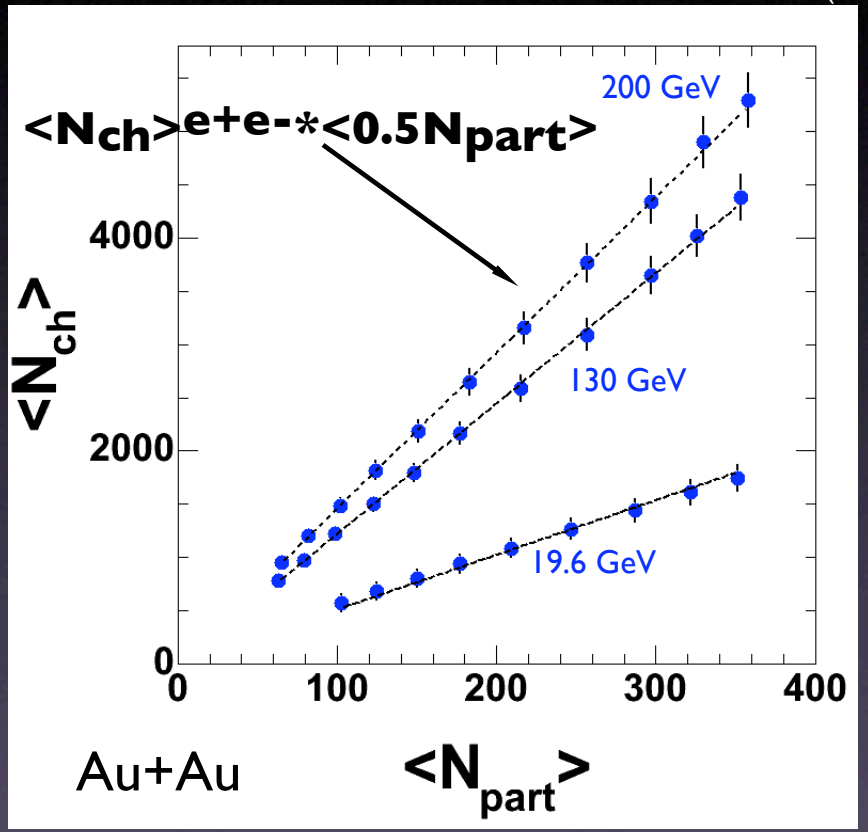


Hadron Multiplicities

PHOBOS PRL 91, 052303 (2003)



PHOBOS PRL 91, 052303 (2003)



Shape changes dramatically versus centrality

Multiplicity per participant is constant

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

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

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

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

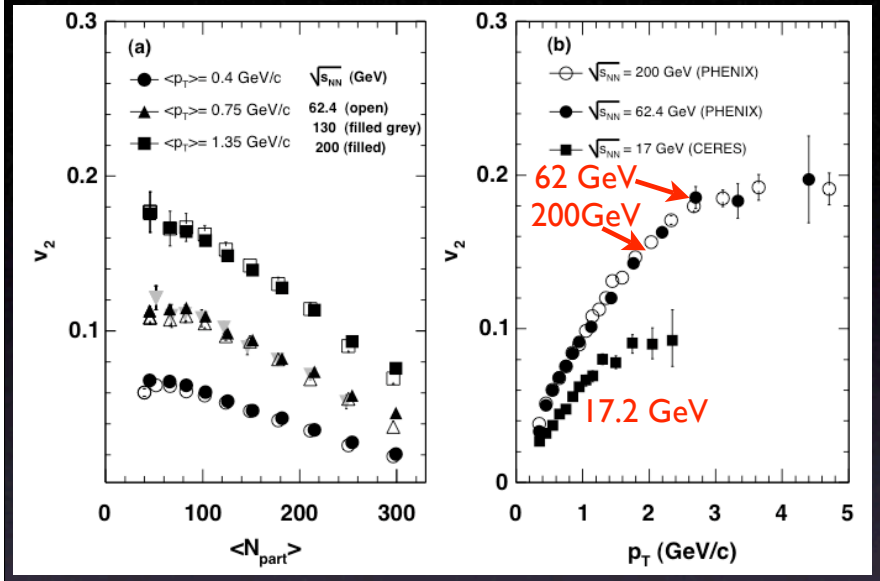
The relationshipe between Φ_{p_T} and Σ_{p_T} when Φ_{p_T} is small and $\Phi^2_{p_T}$ term is neglected:

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

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

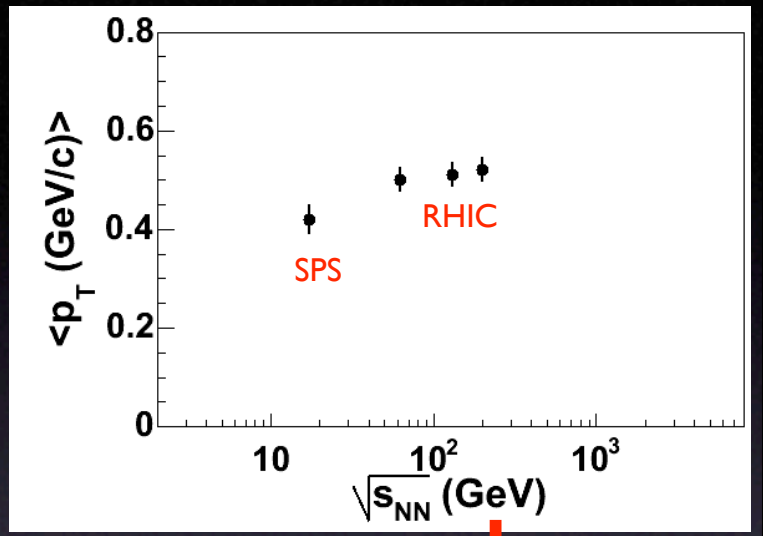
v_2 vs p_T

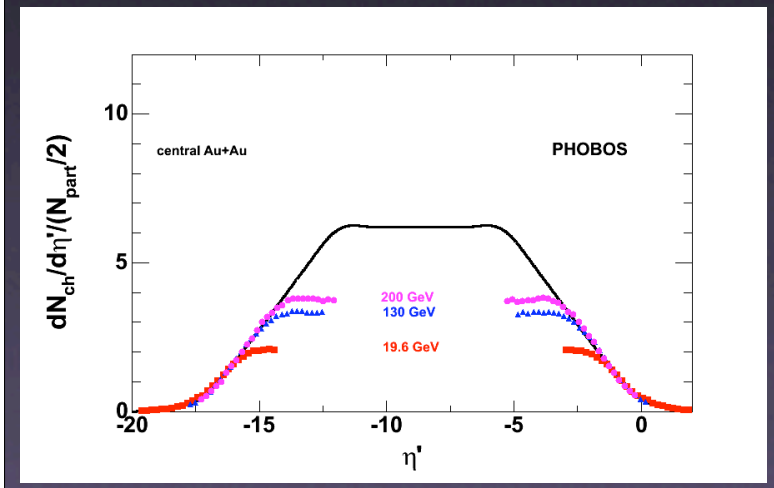
PHENIX nucl-ex/0411040

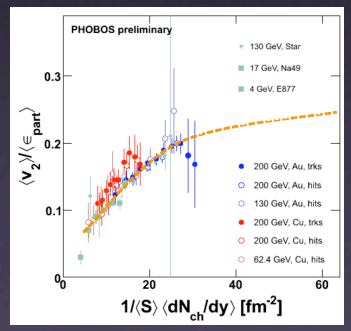


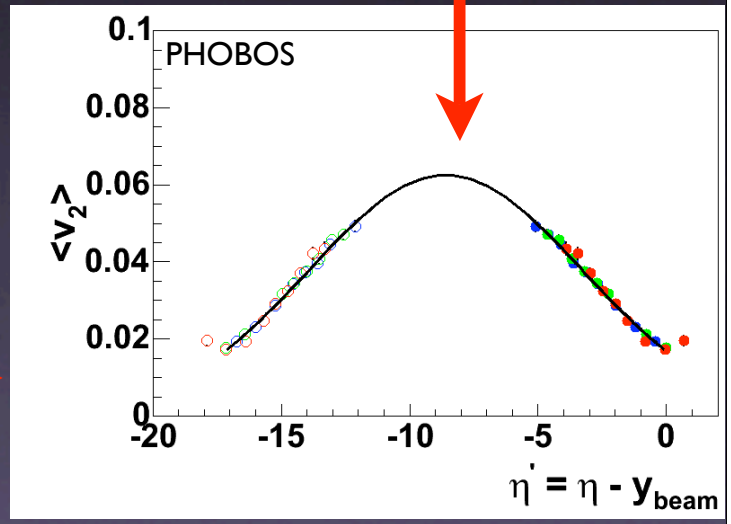
+

$\langle p_T \rangle$ vs $\sqrt{s}$









dN/dη' vs $\sqrt{s}$

$v_2(\eta')$ vs $\sqrt{s}$