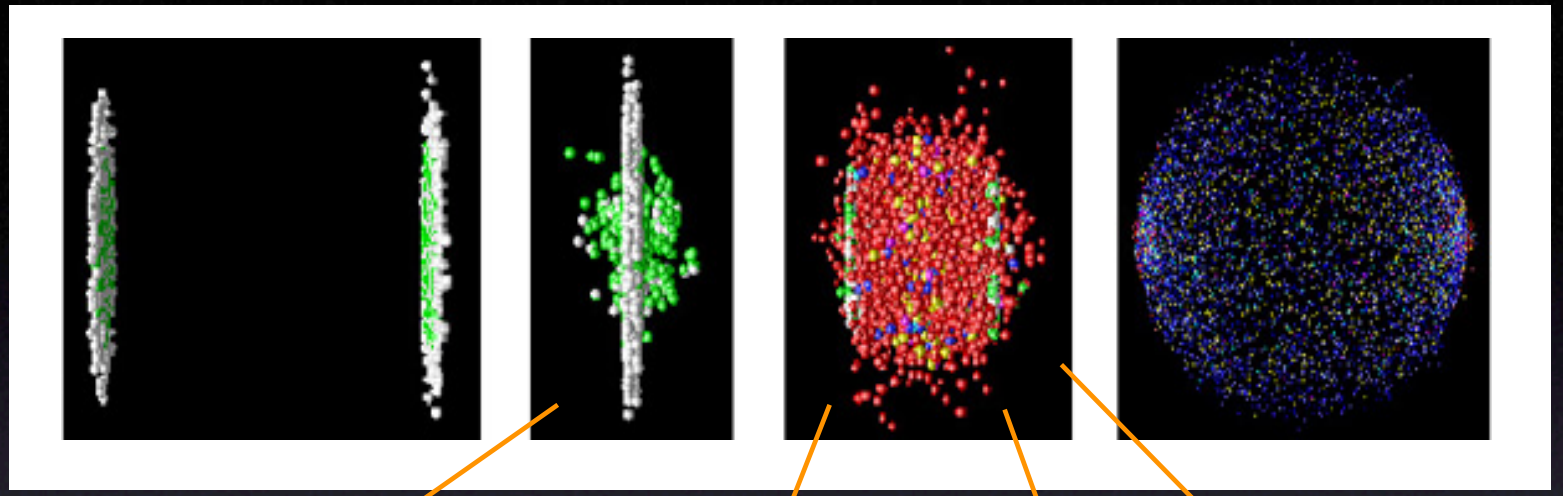
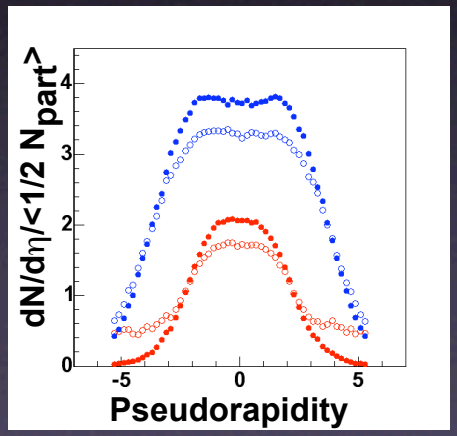
Correlations and Fluctuations in Nuclear Collisions - Experimental Overview

Gunther Roland - MIT

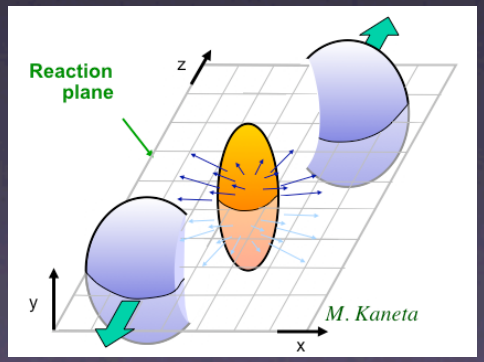
Supercomputing RHIC Physics
TIFR, Mumbai
Dec 5-9 2005

This talk

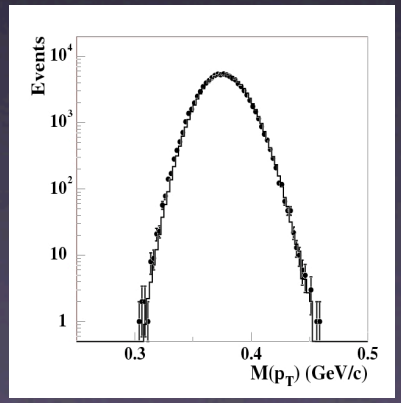




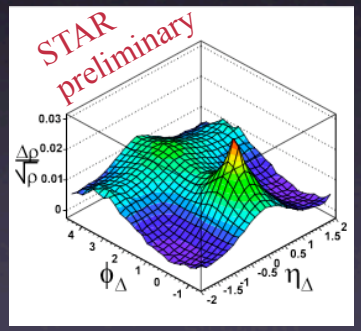
Hadron Multiplicities



Elliptic Flow

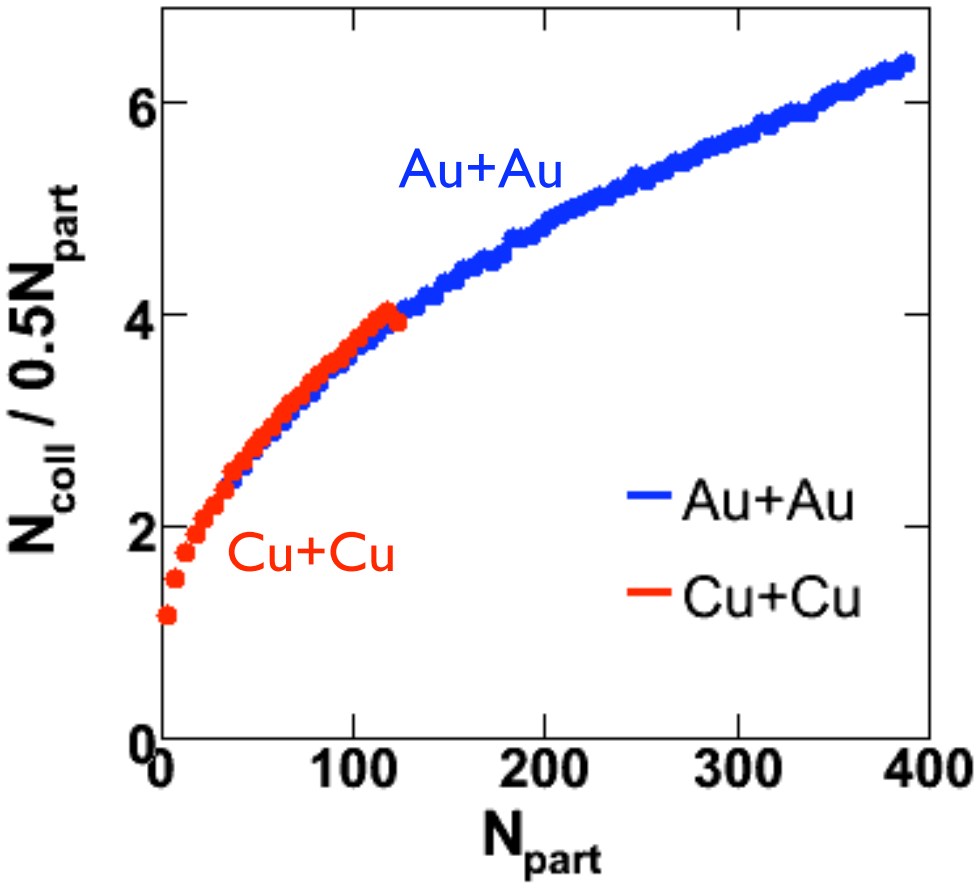


Event-by-event Fluctuations

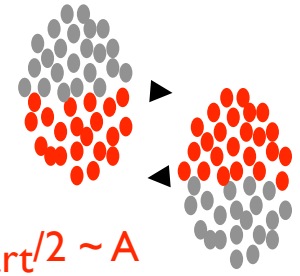


Two-particle Correlations

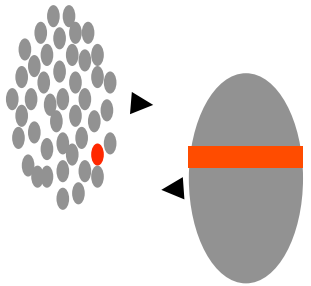
Pre-requisites: Centrality Characterization



"Participants"



$N_{part}/2 \sim A$



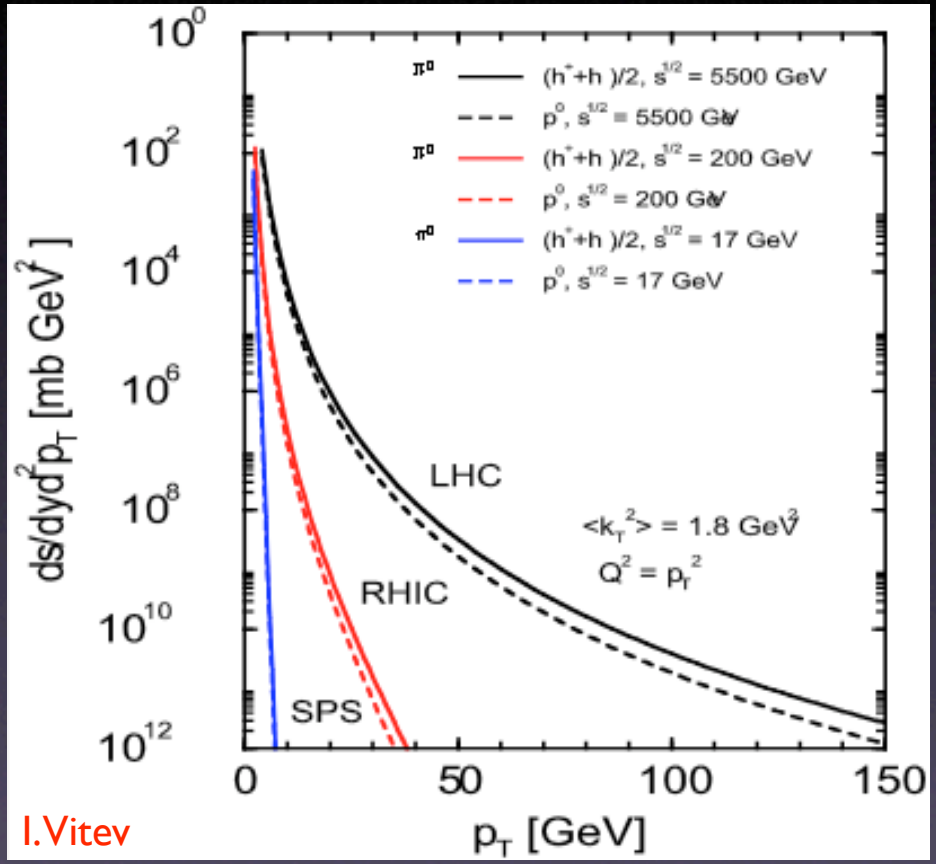
$L \sim A^{1/3}$

N_{coll}= # of NN collisions: $\sim A^{4/3}$

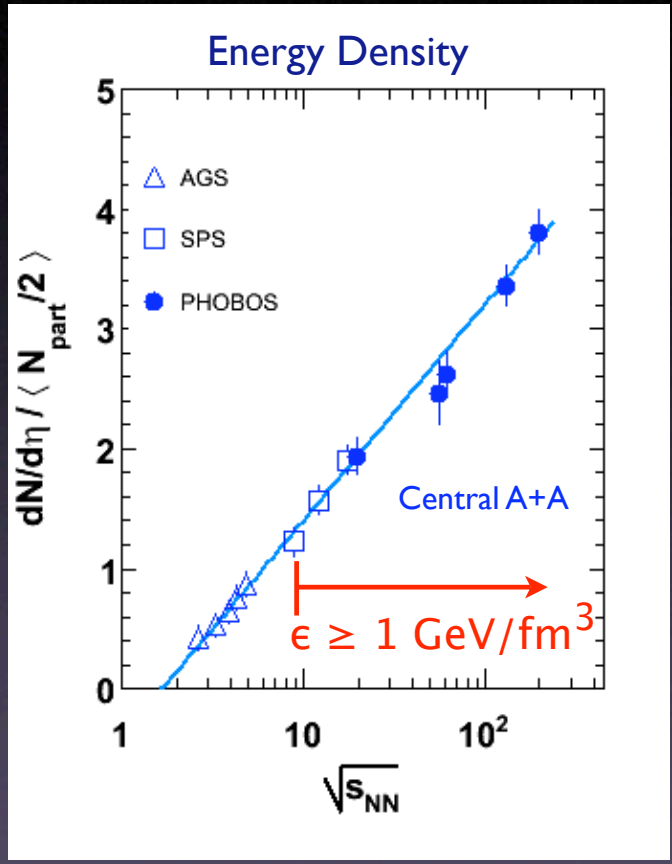
"Collisions"

Number of participating nucleons from Glauber MC

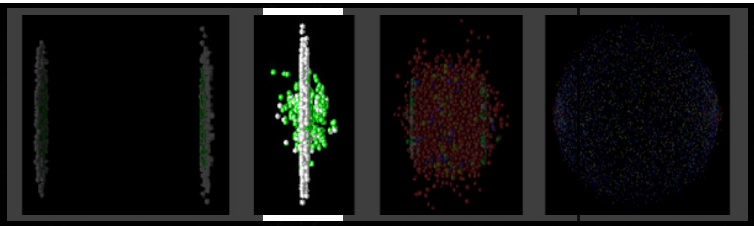
Pre-requisites: Hard vs Soft Hadron Production



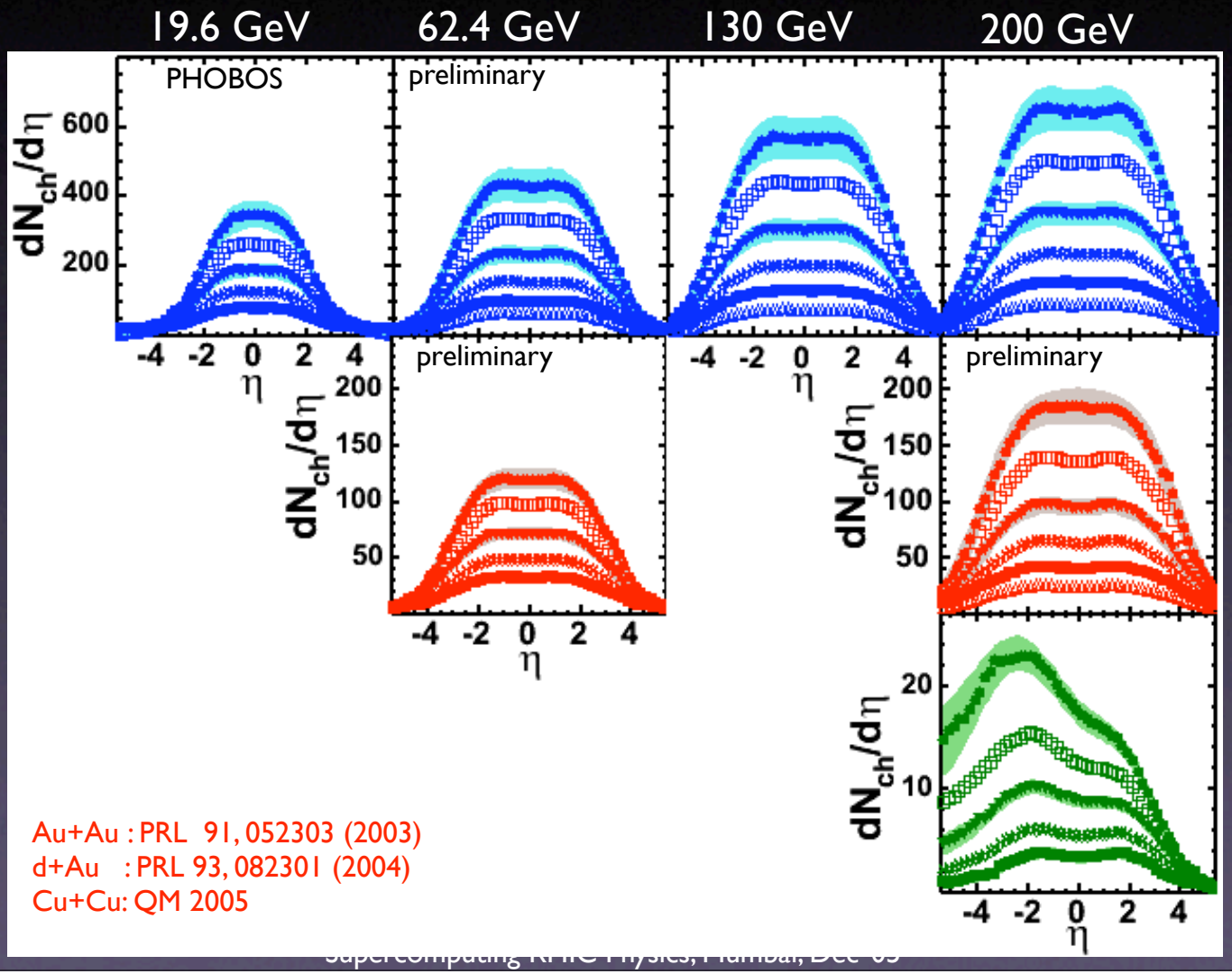
Fast rise of high p_T yields from hard collisions



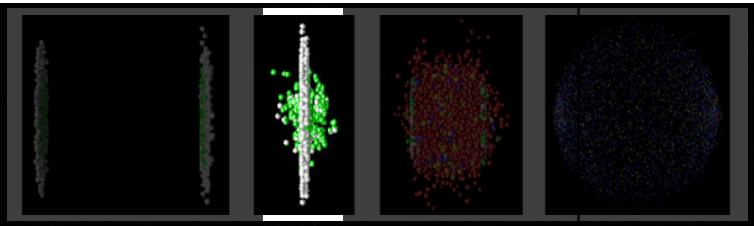
Logarithmic rise of particle (≈energy) density



Hadron Multiplicities

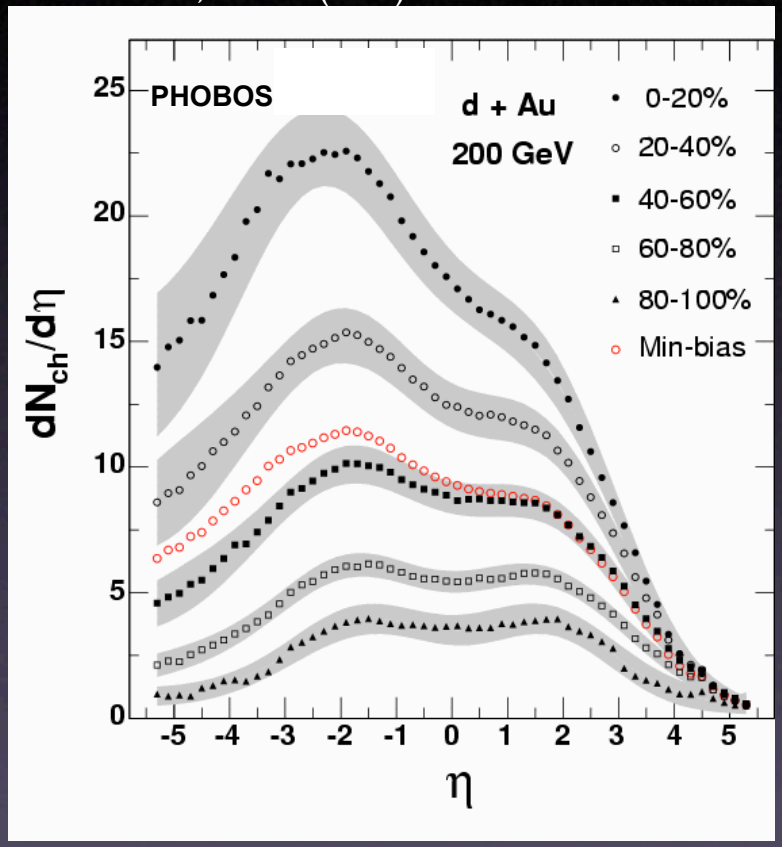


Au+Au : PRL 91, 052303 (2003)
d+Au : PRL 93, 082301 (2004)
Cu+Cu: QM 2005

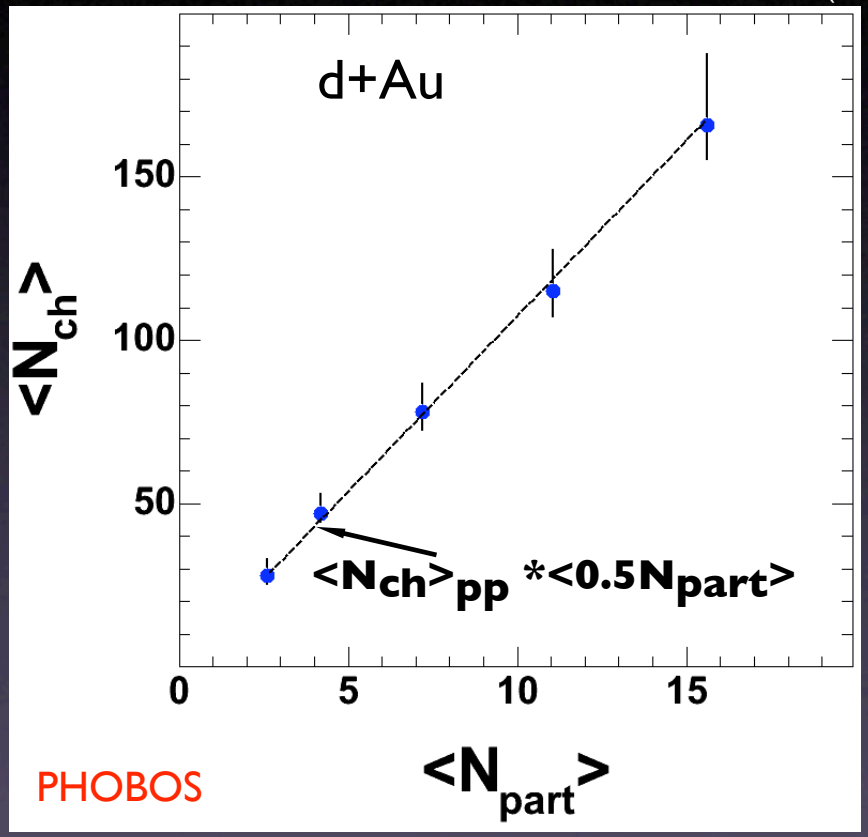


Hadron Multiplicities

PHOBOS PRL 93, 082301 (2004)

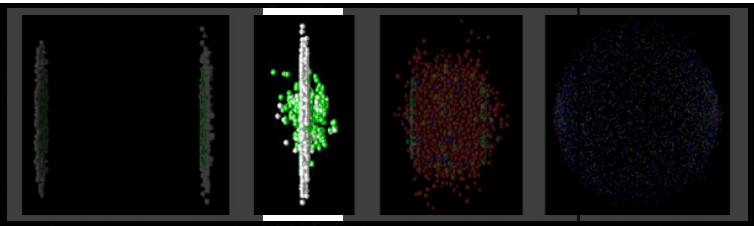


PHOBOS PRL 93, 082301 (2004)



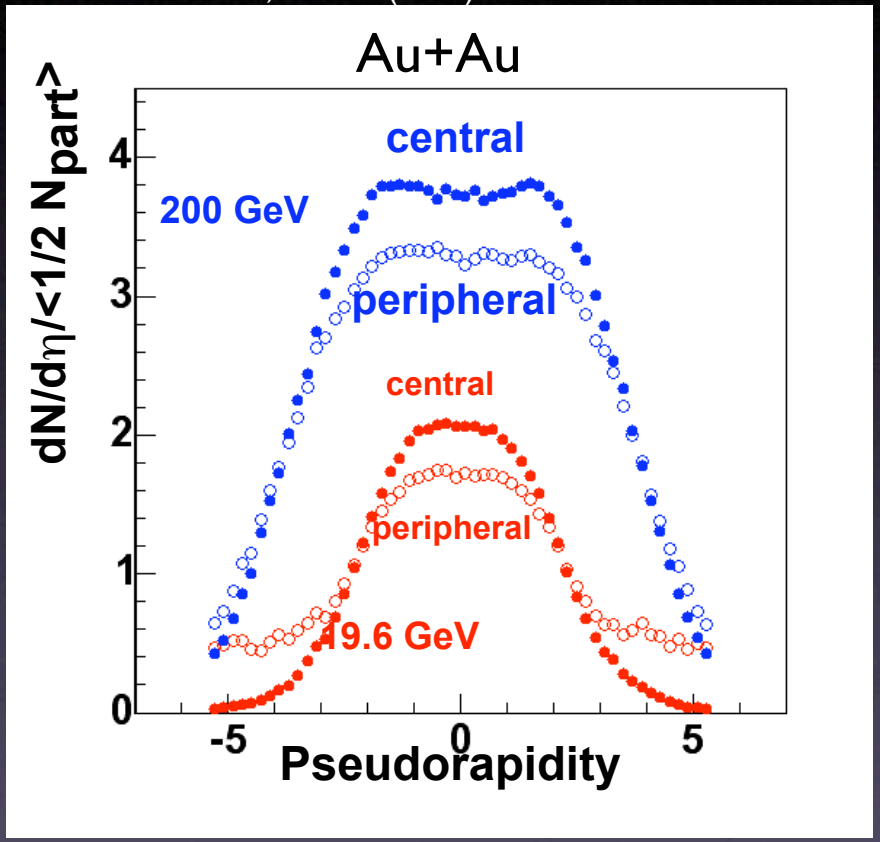
Shape changes dramatically versus centrality

Multiplicity per participant is constant

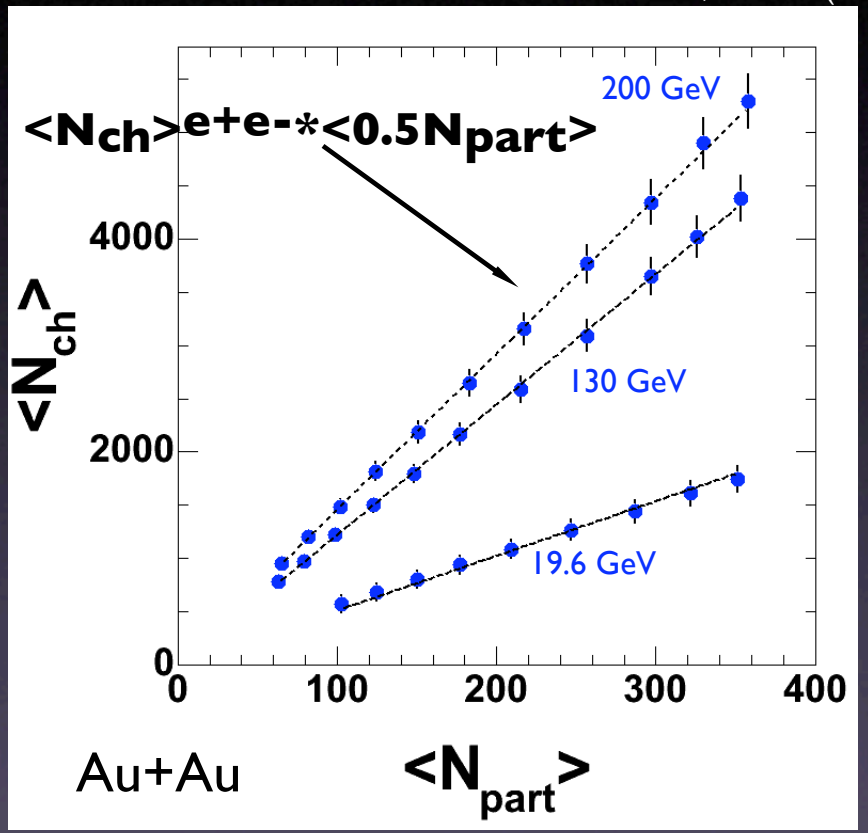


Hadron Multiplicities

PHOBOS PRL 91, 052303 (2003)

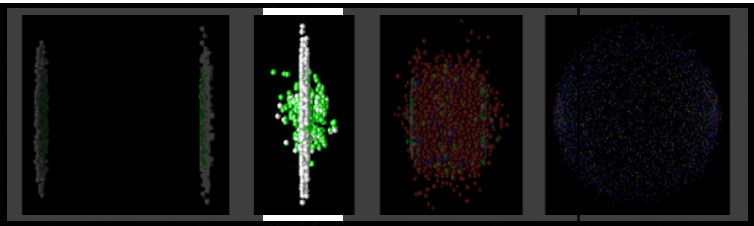


PHOBOS PRL 91, 052303 (2003)



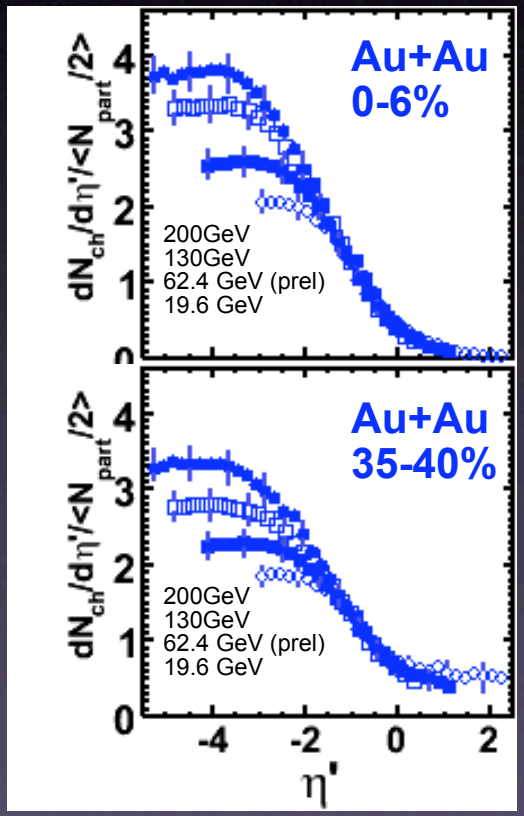
Shape changes dramatically versus centrality

Multiplicity per participant is constant

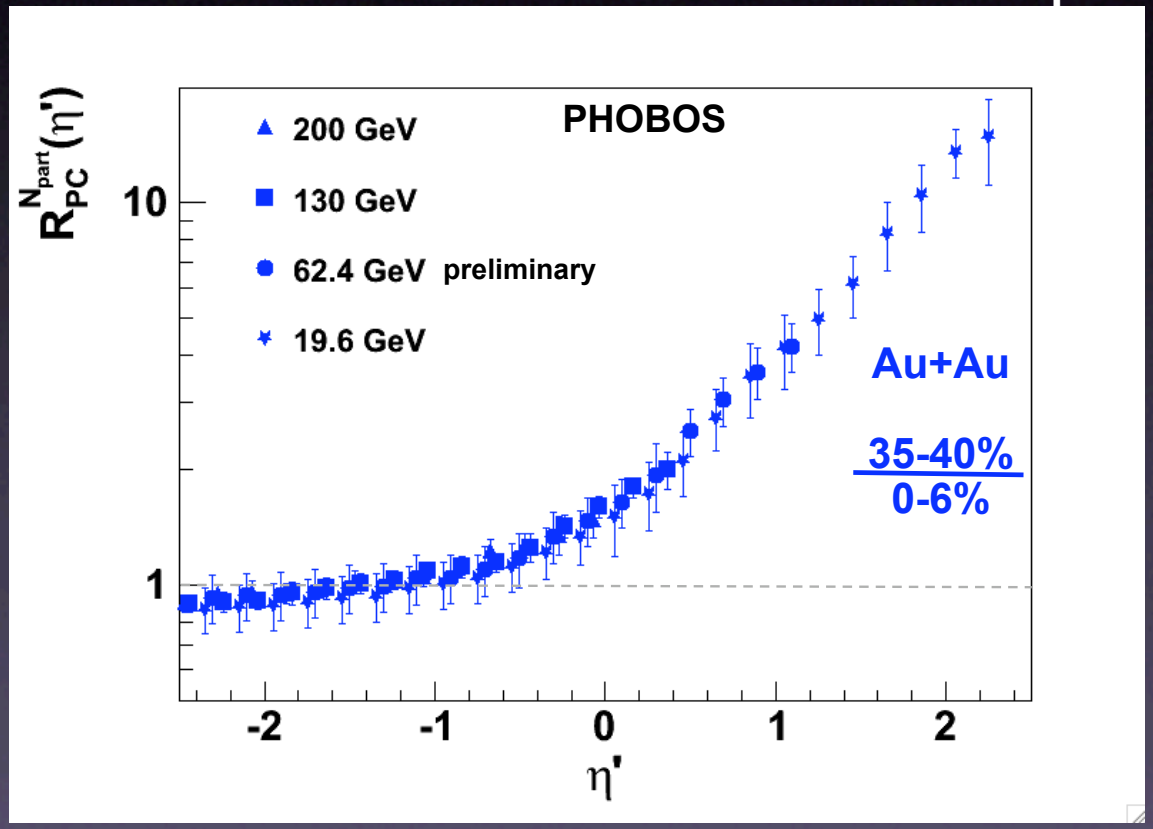


Hadron Multiplicities

Limiting Fragmentation



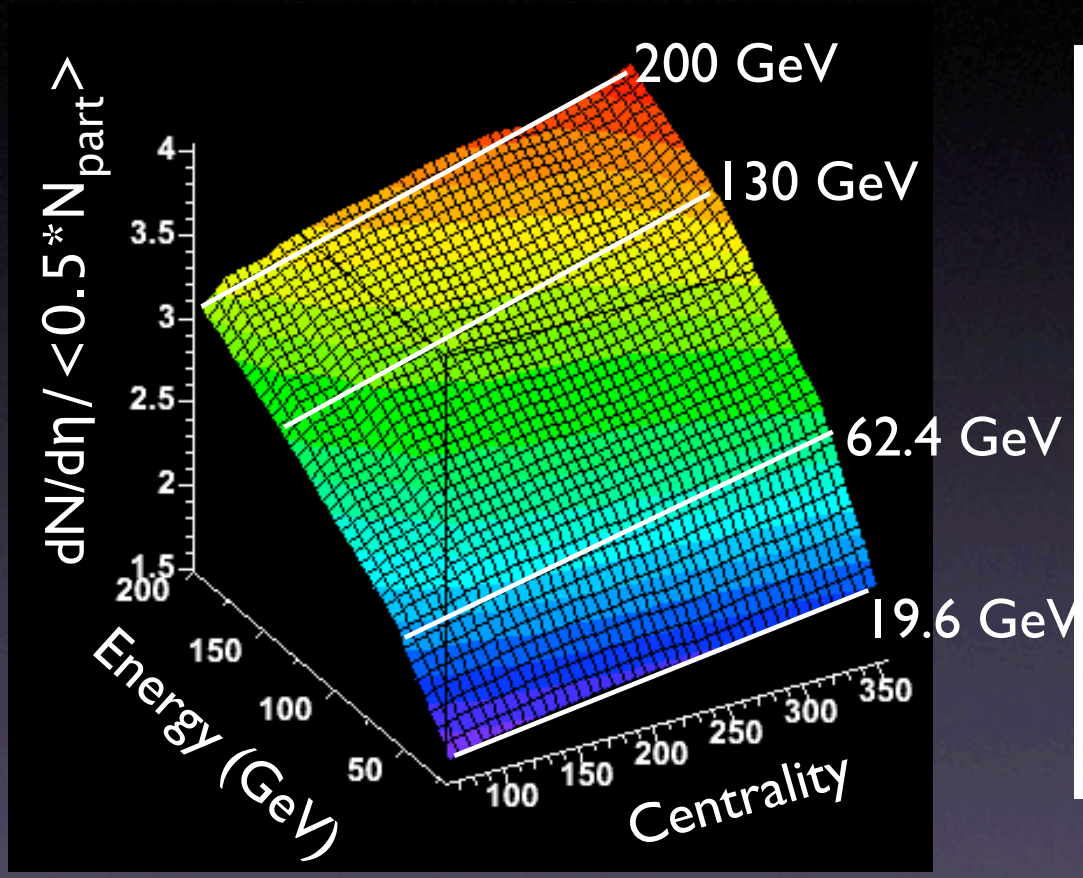
Ratio of 0-6% and 35-40% centrality bins, each normalized by N_{part}

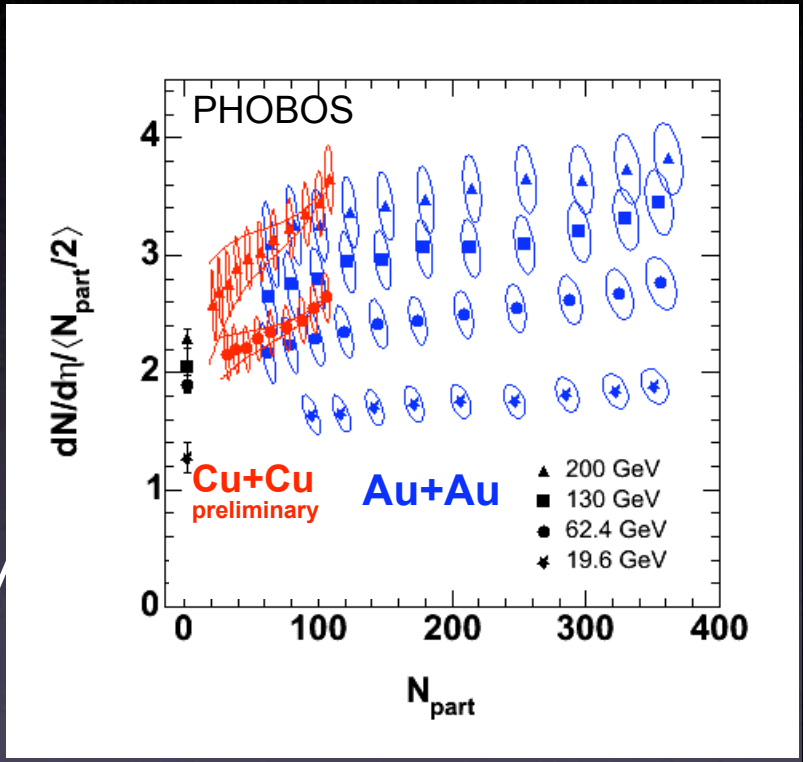


Shape change of longitudinal distributions is energy independent

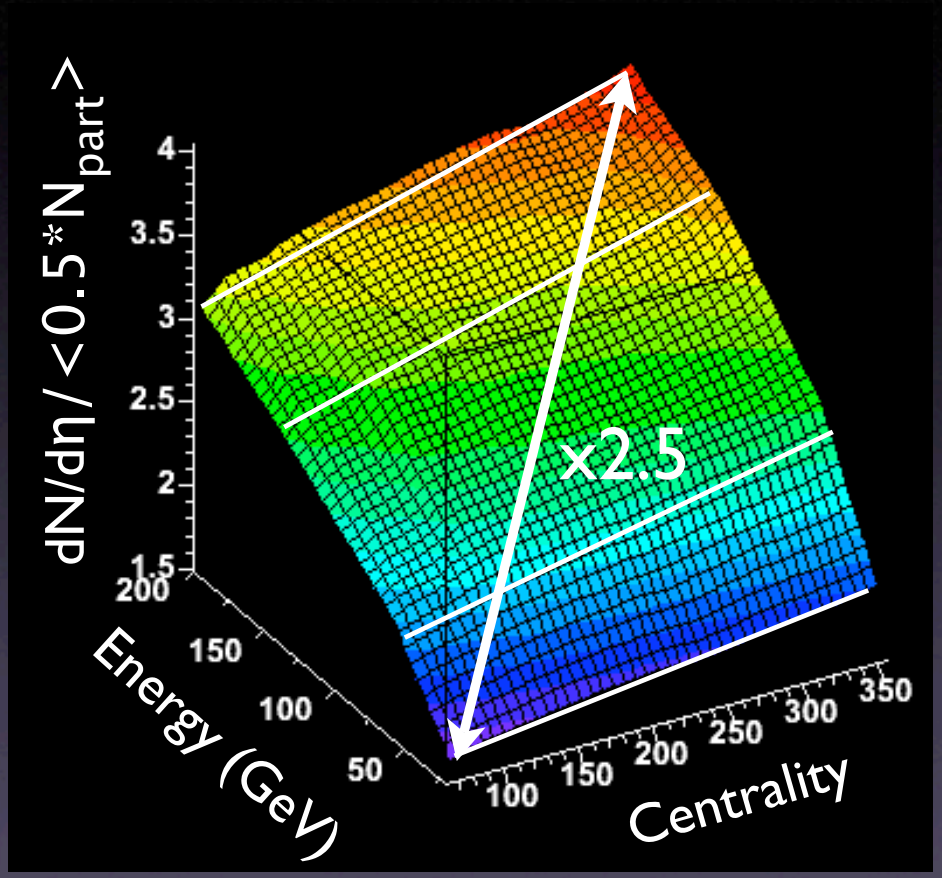
Mid-rapidity dN/dη vs √s and N_{part}

Au+Au : nucl-ex/0509034, submitted to PRC
Cu+Cu: QM 2005





dN/dη vs √s and N_{part}



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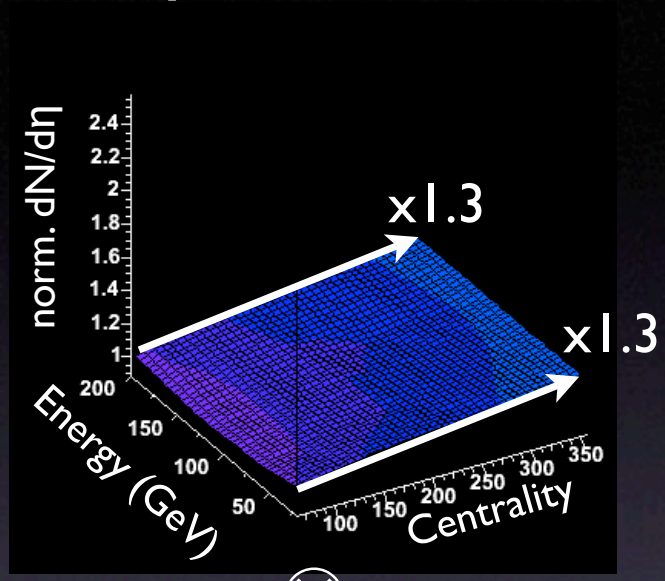

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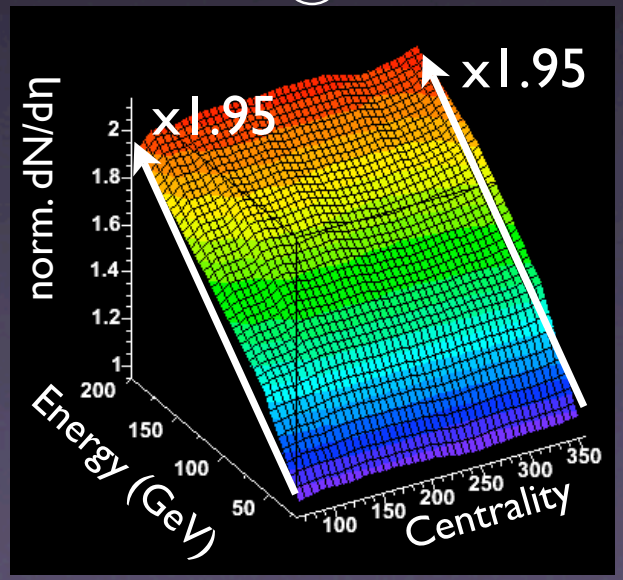
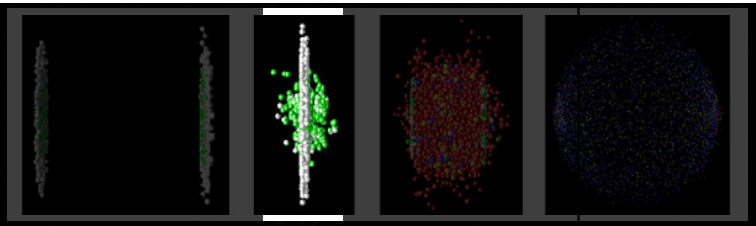
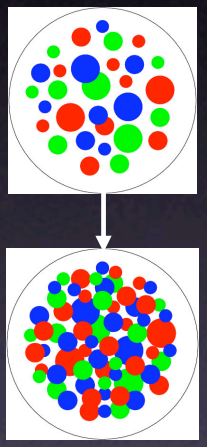




Hadron Multiplicities

Initial State
Parton Saturation

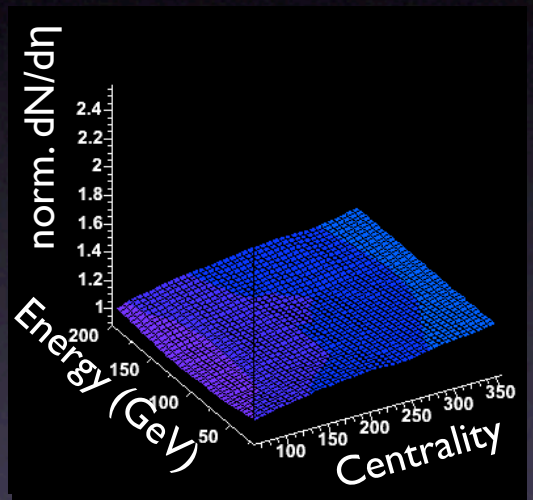


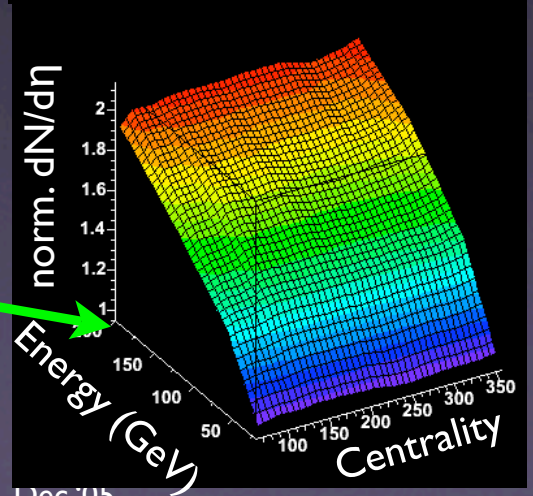
Low Energy

High Energy

$$\left.\frac{1}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\right|_{\eta\sim 0} = N_0\sqrt{s}^{\lambda}N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

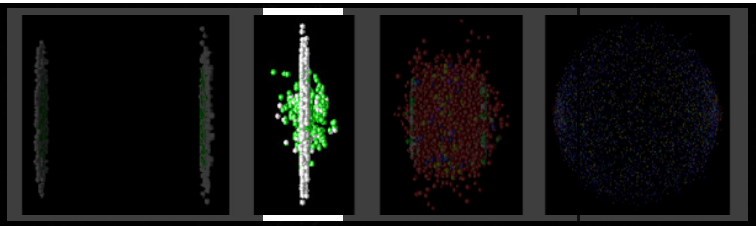
Armesto, Salgado, Wiedemann hep-ph/0407018





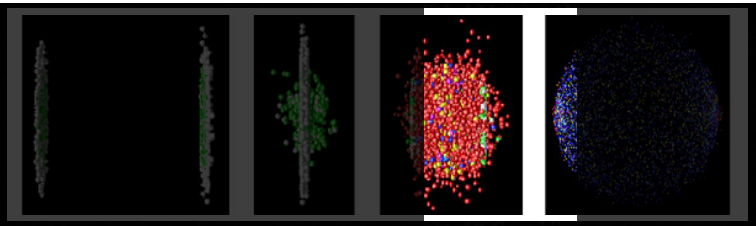
Also limiting fragmentation, N_{part} scaling

(c.f. Kharzeev, McLerran, Venugopalan, Jalilian-Marian, Nardi et al)



Hadron Multiplicities

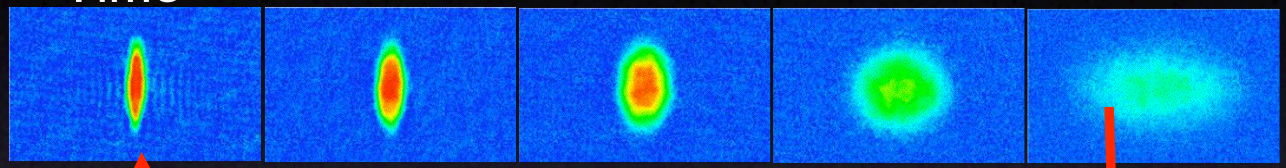
- Participant scaling of total multiplicities
  - Global constraints over full η range
- Slow growth of multiplicity with energy
  - Saturation + LPHD?
- Factorization of energy/centrality dependence
  - Saturation +LPHD?
- No modification during expansion/hadronization/recscattering?

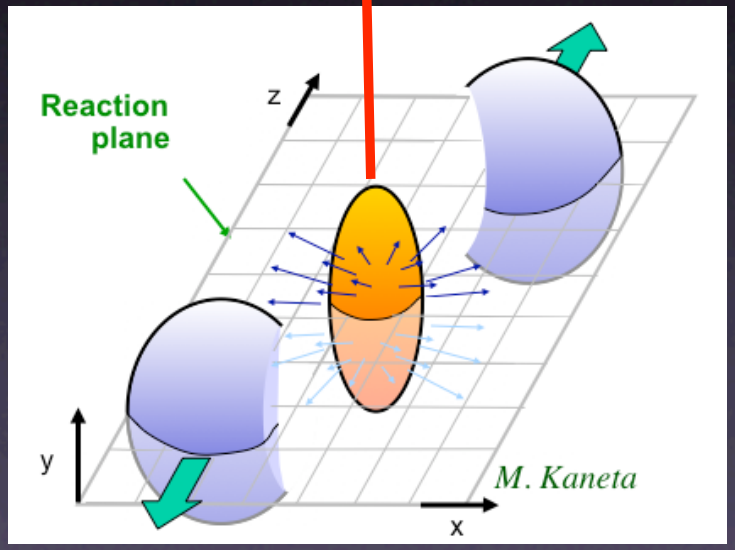


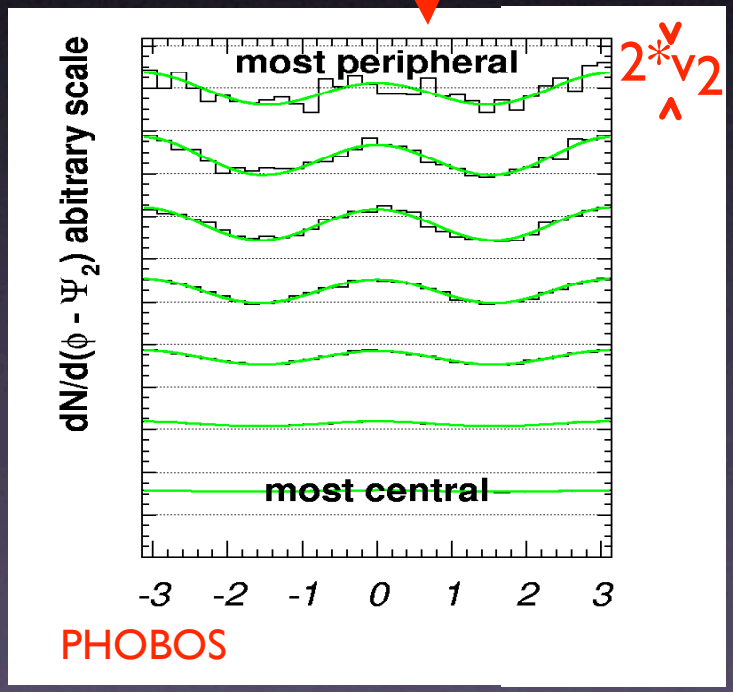
Hydrodynamic Evolution

Time ⟶

Transverse Plane



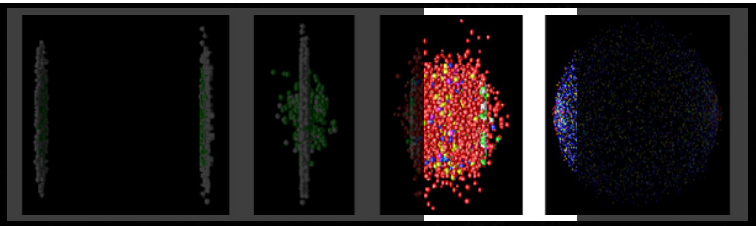




$2 * \hat{v}_2$

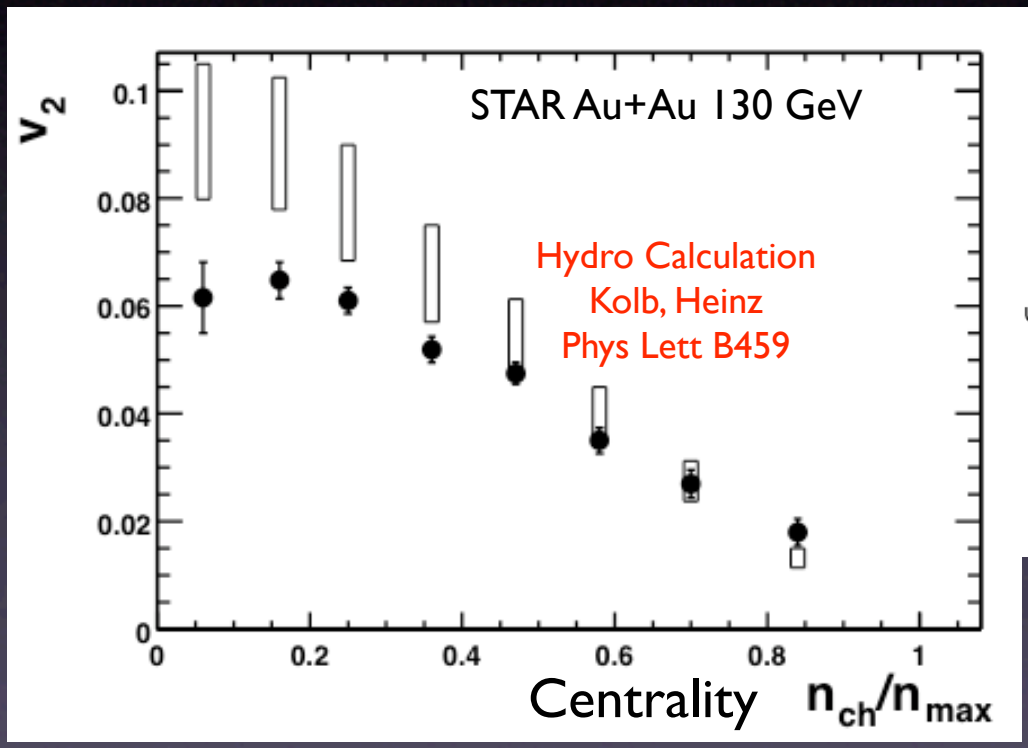
Non-central collision:
Initial state eccentricity

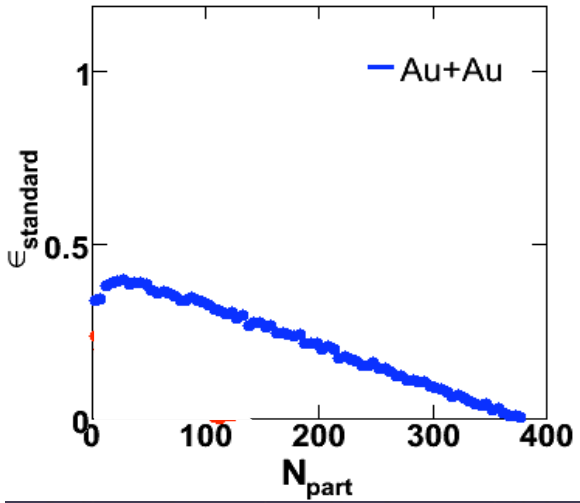
Momentum space anisotropy



Hydrodynamic Evolution

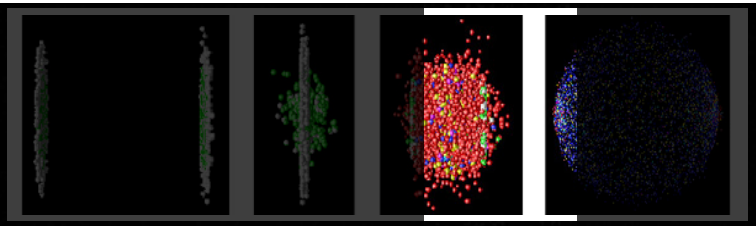
Phys. Rev. Lett. **86** (2001) 402





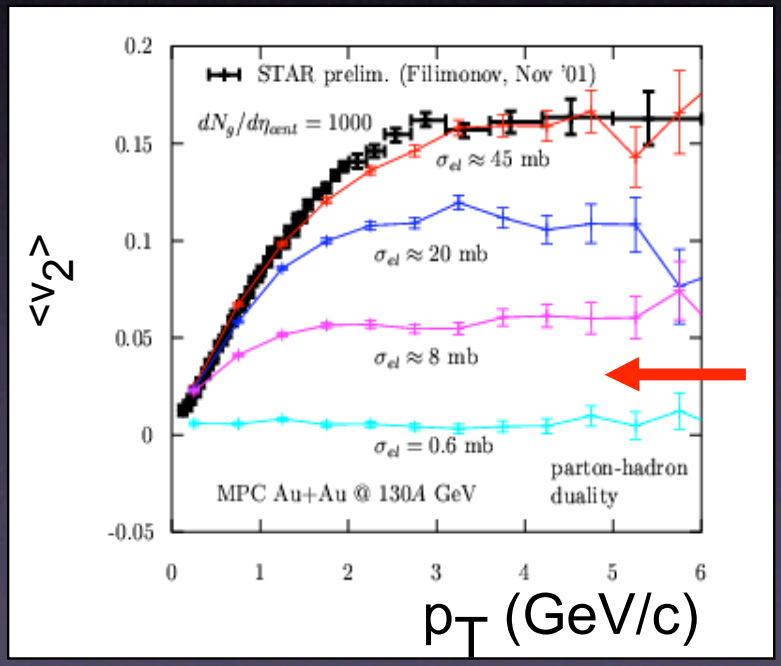
Geometrical initial state eccentricity from Glauber model

Elliptic Flow signal exhausts "hydro limit" for mid-central to central collisions



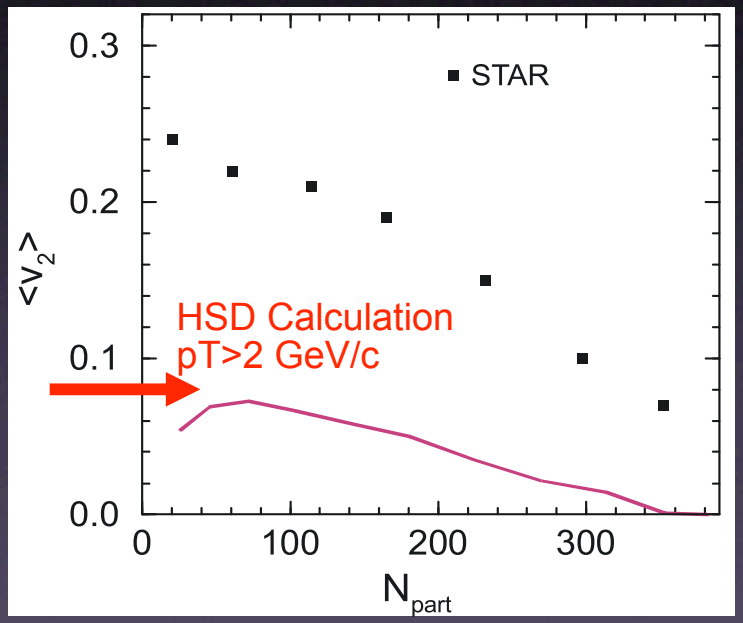
Hydrodynamic Evolution

Parton Cascade



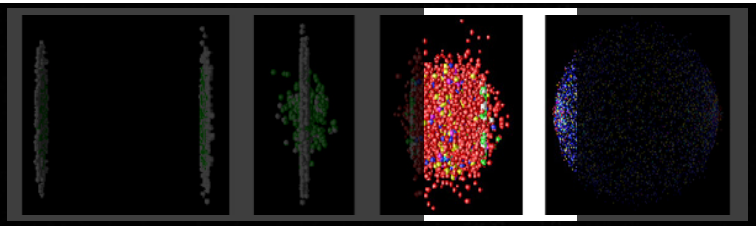
Molnar et al

Hadron Cascade

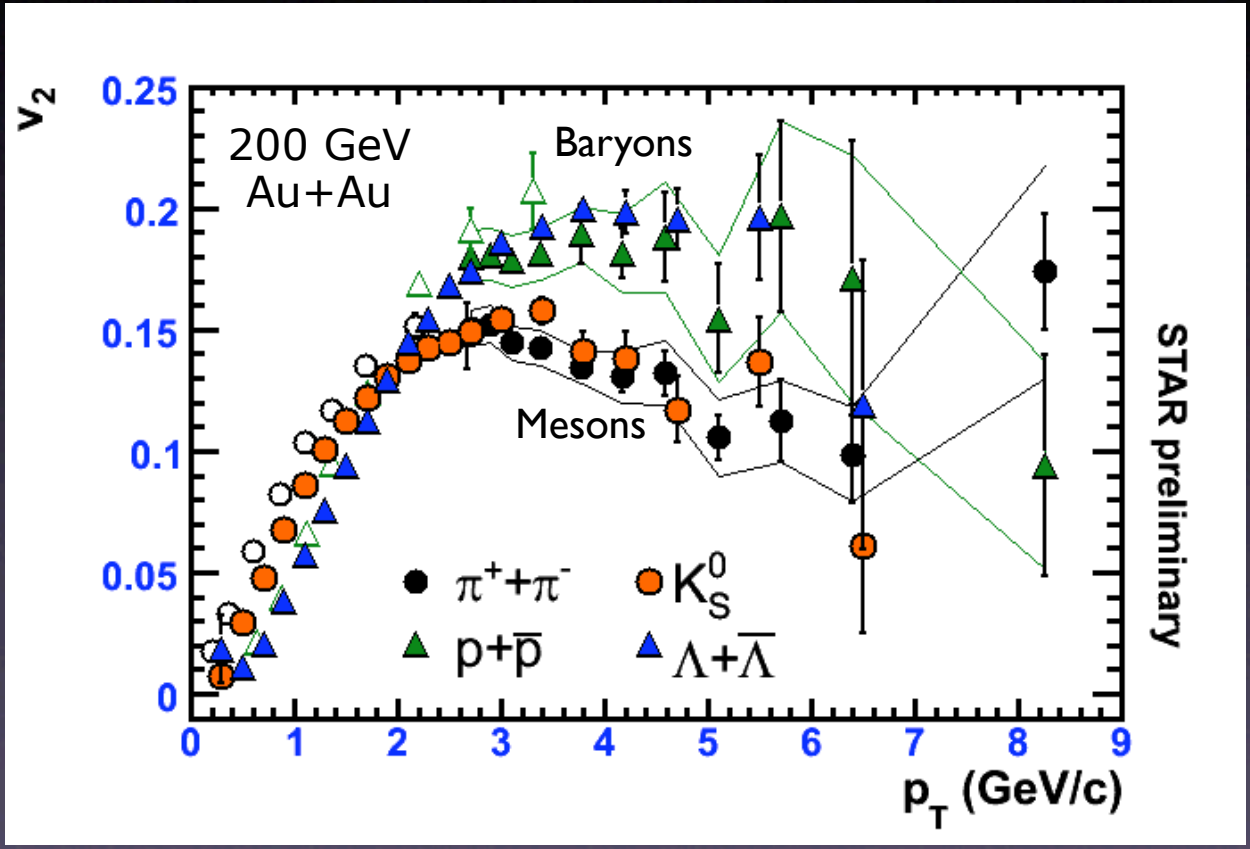


Cassing et al

Neither partonic nor hadronic cascades reproduce flow



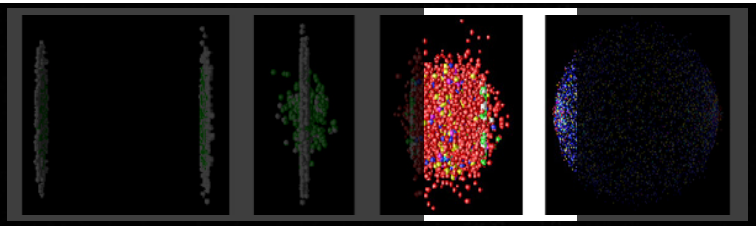
Hydrodynamic Evolution



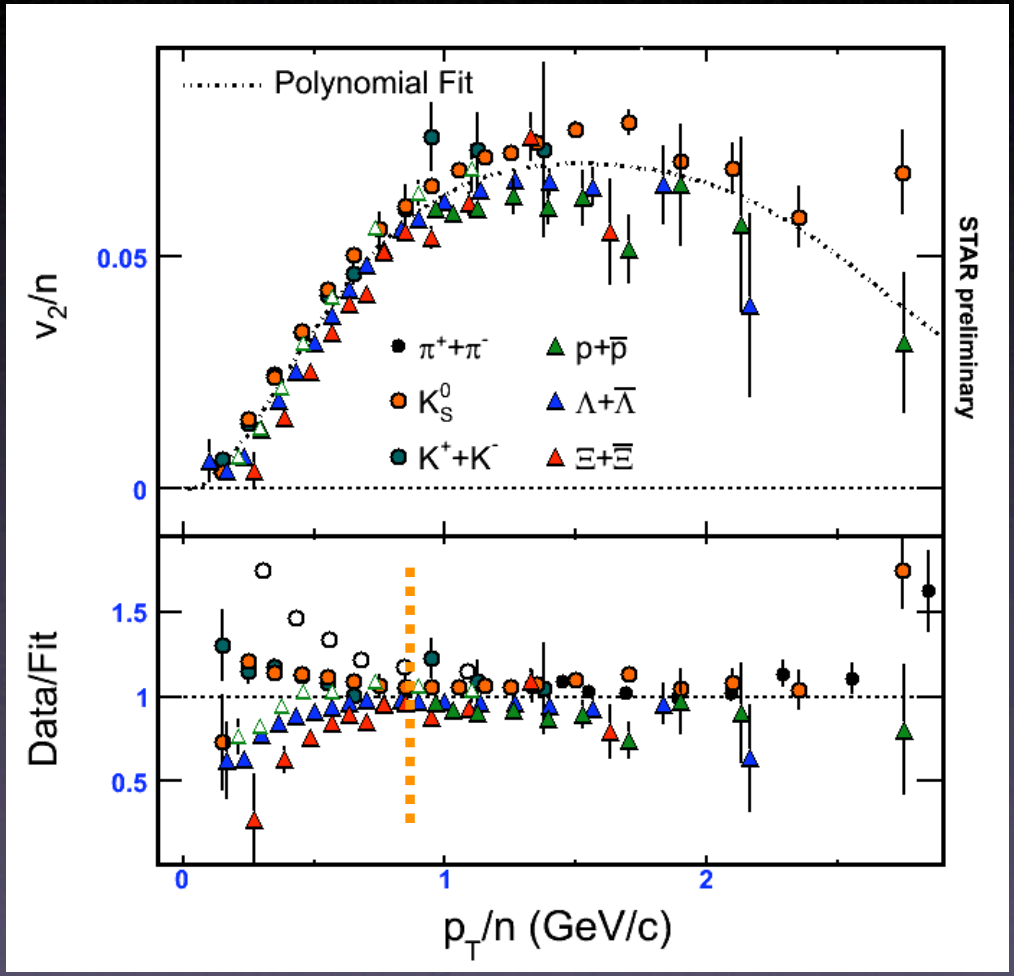
PHENIX
(open symbols):
Phys. Rev. Lett. ***91***,
182301 (2003)

Rich structure vs mass (?) and pT

M. Oldenburg, STAR, QM2005



Hydrodynamic Evolution

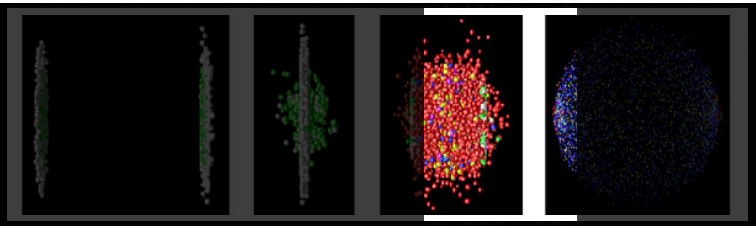


PHENIX
(open symbols):
Phys. Rev. Lett. ***91***,
182301 (2003)

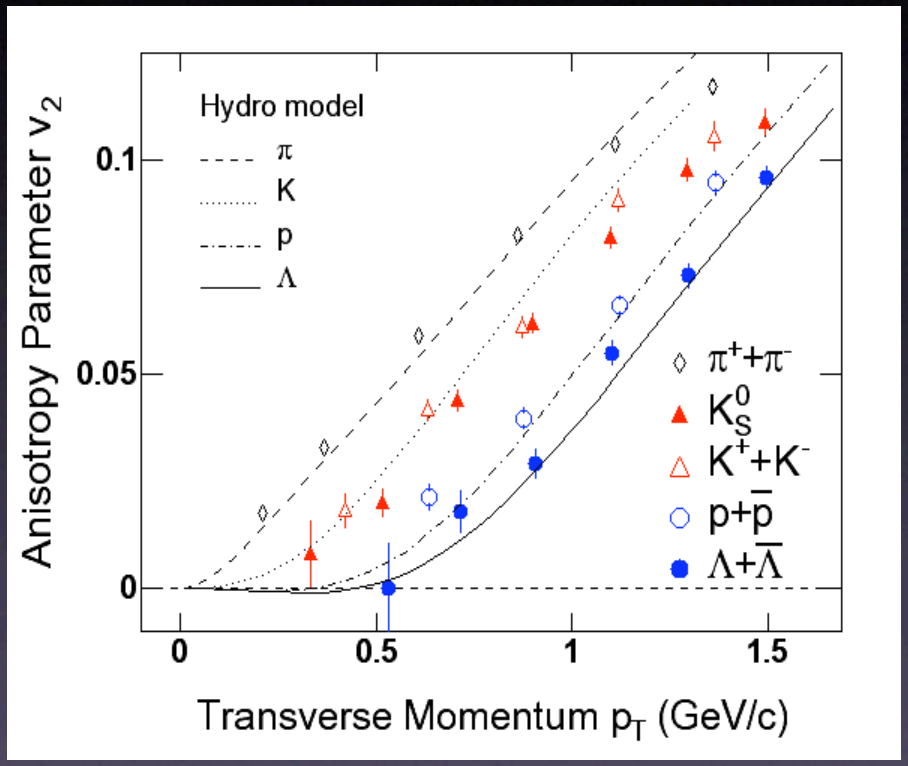
Mass scaling

Quark-number scaling

M. Oldenburg, STAR, QM2005



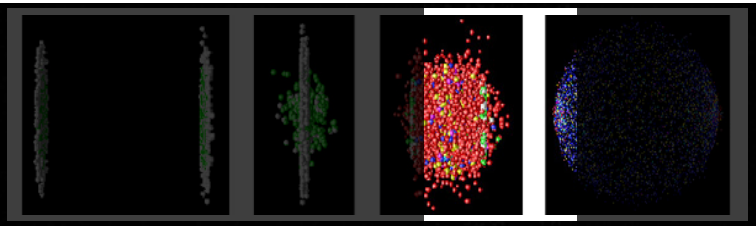
Hydrodynamic Evolution



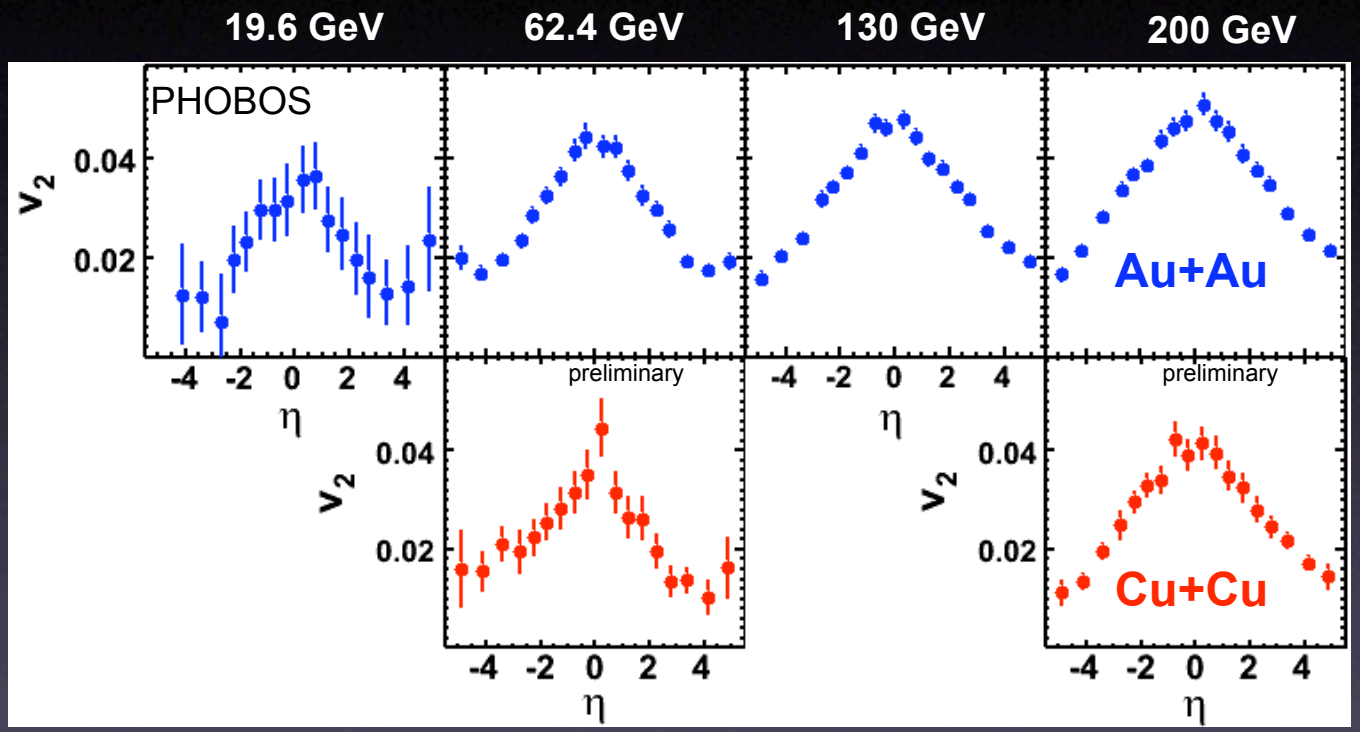
200 GeV Au+Au
Data: STAR, PHENIX

Hydro: P. Huovinen et al.,
Phys. Lett. B503, 58 (2001)

Mass splitting at low p_T understood in hydro calculations

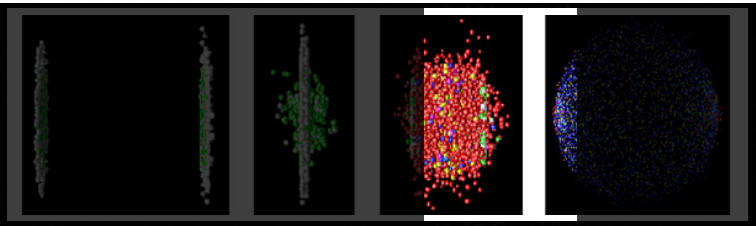


Hydrodynamic Evolution



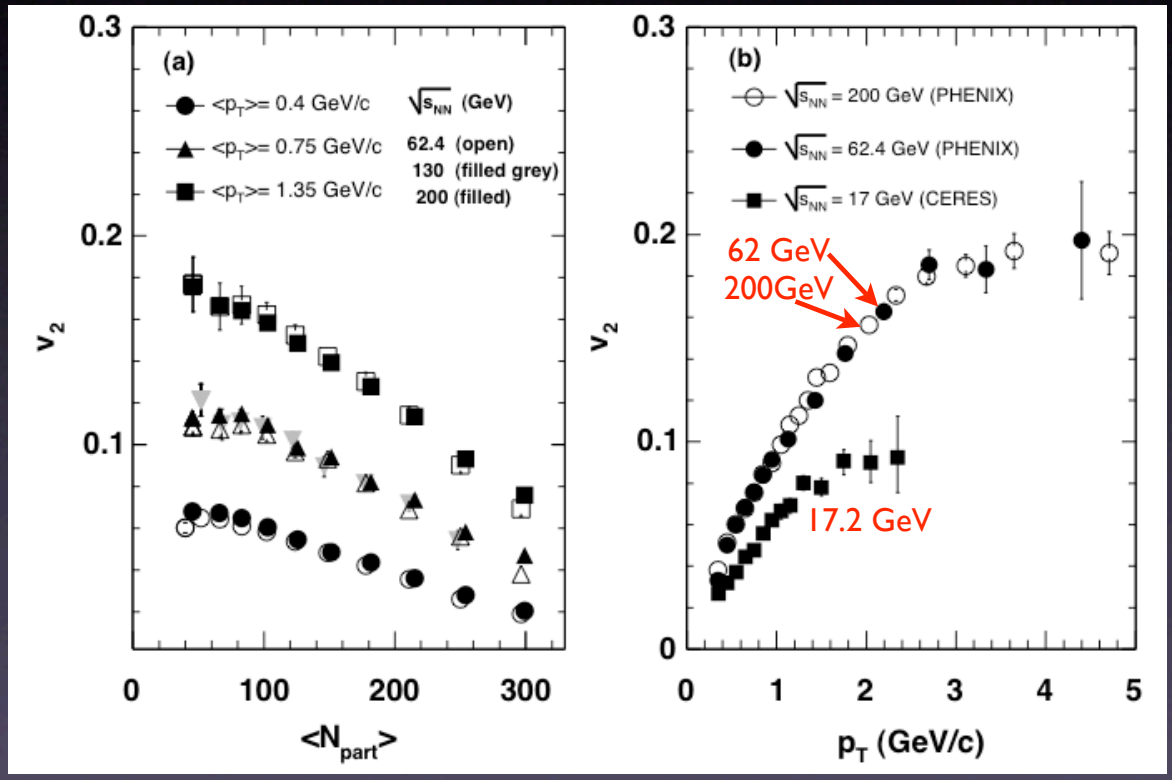
Strong rapidity dependence of elliptic flow
Challenge to hydrodynamic calculations
Connection between flow and dN/dη

Au+Au: PHOBOS PRL 94 122303 (2005)
Cu+Cu: PHOBOS QM 2005

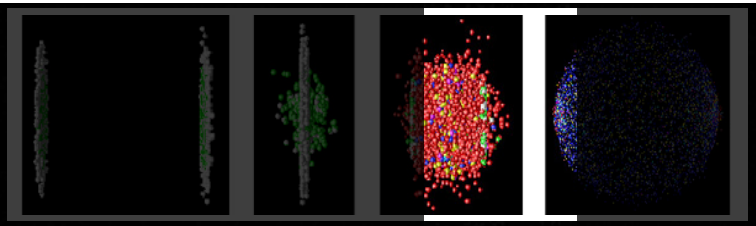


Hydrodynamic Evolution

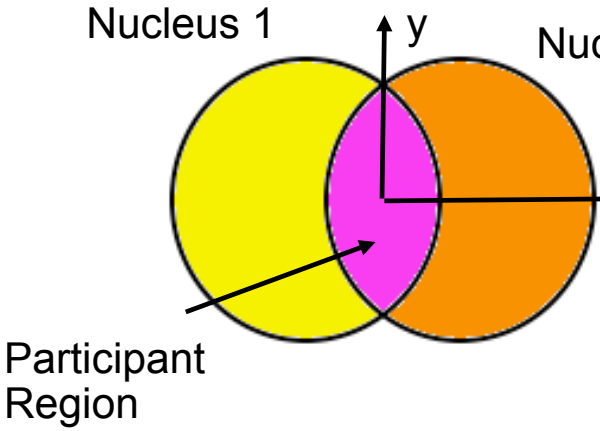
PHENIX nucl-ex/0411040



Saturation of $v_2(p_T)$ above $\sqrt{s} \approx 62$ GeV

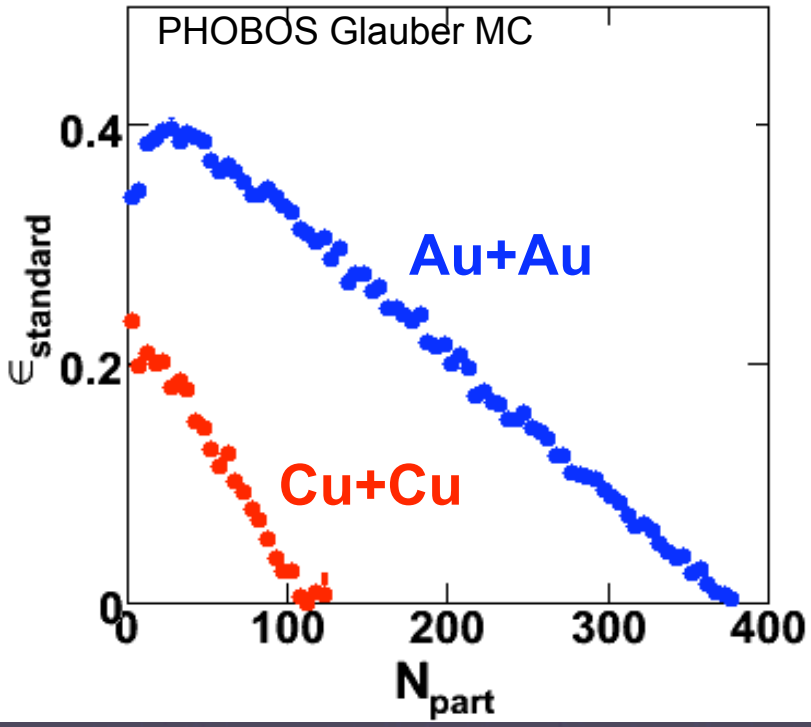


Hydrodynamic Evolution



$$\varepsilon = \frac{\sigma_y^{\,2} - \sigma_x^{\,2}}{\sigma_y^{\,2} + \sigma_x^{\,2}}$$

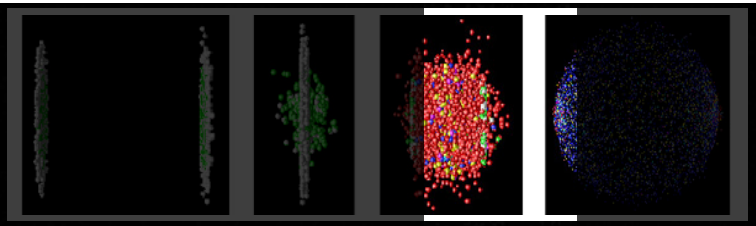
wrt reaction plane



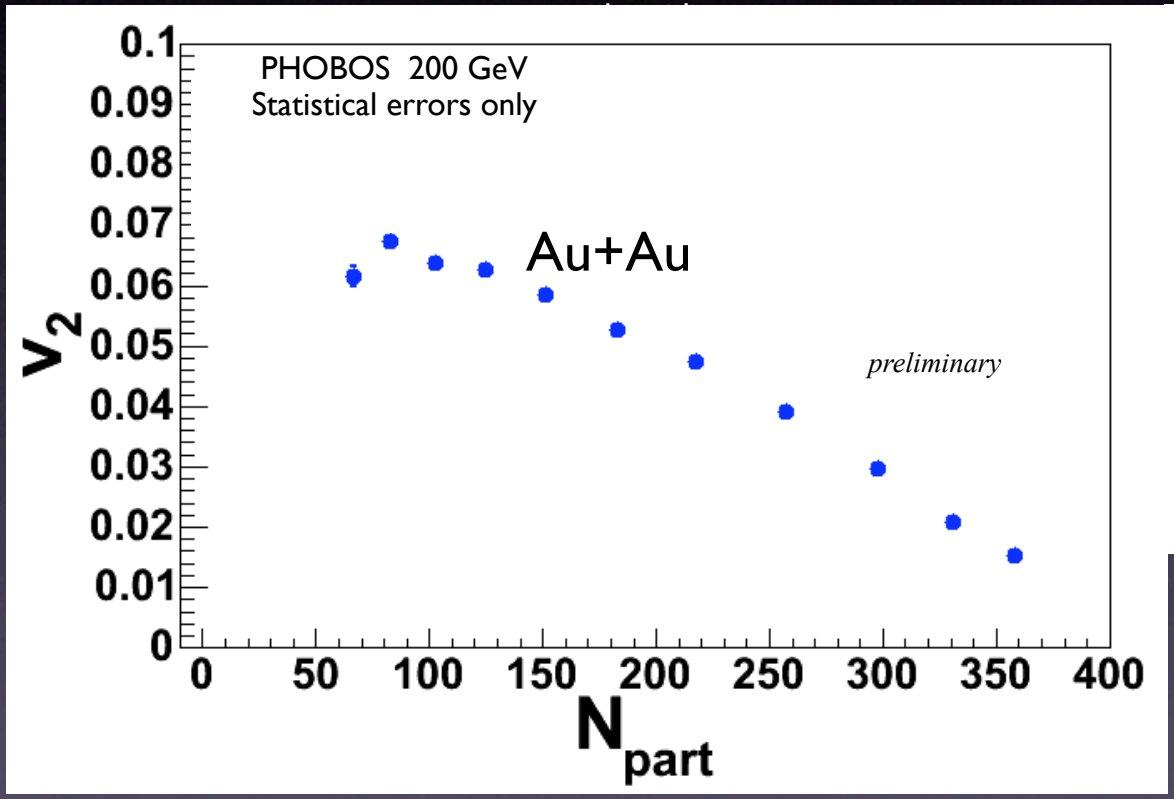
Au+Au vs Cu+Cu

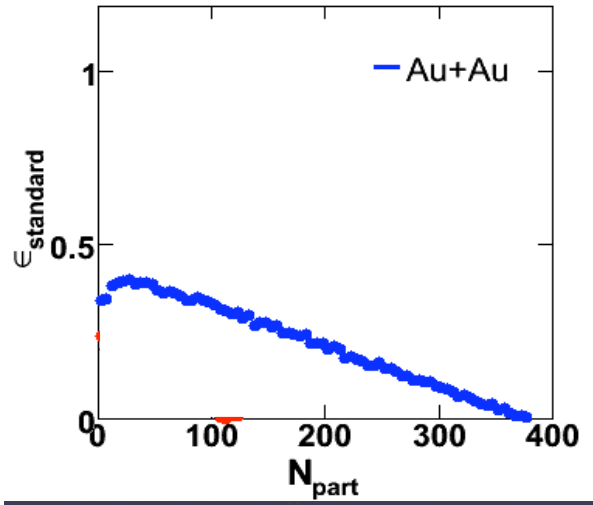
Interplay of initial geometry and initial density

Test ideas of early thermalization and collectivity

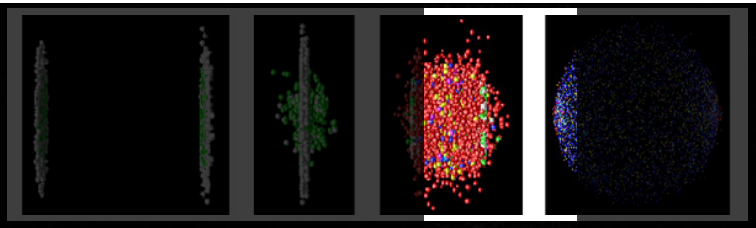


Hydrodynamic Evolution

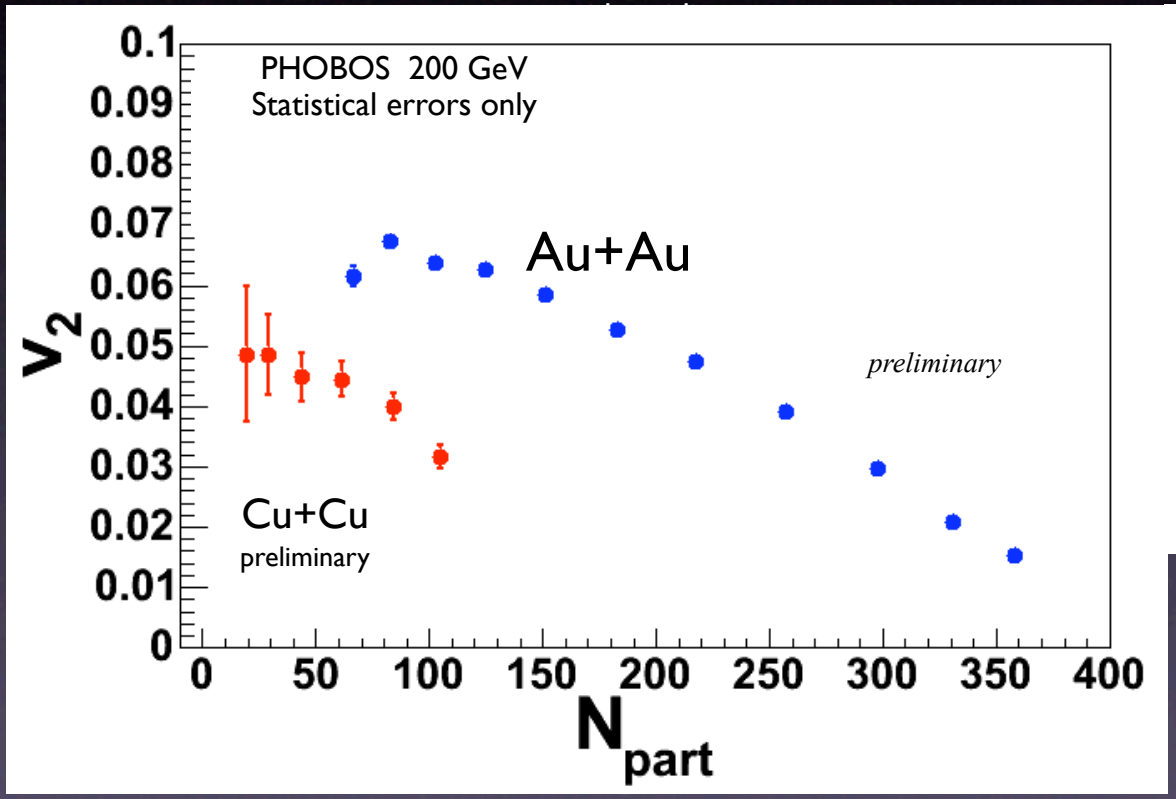


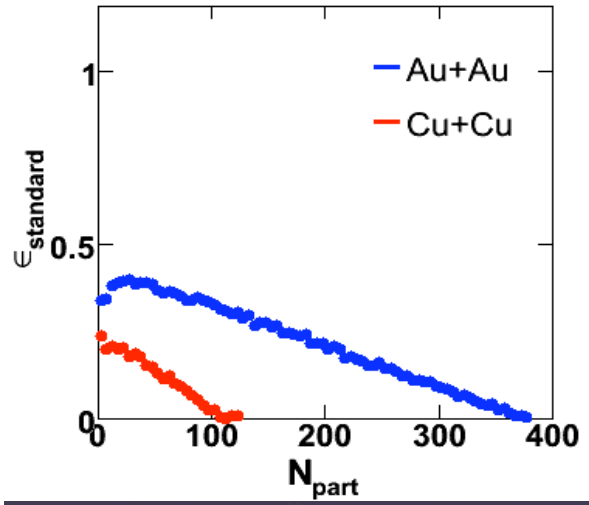


Geometrical initial state eccentricity from Glauber model



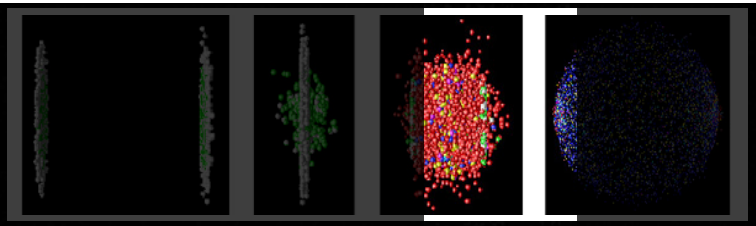
Hydrodynamic Evolution



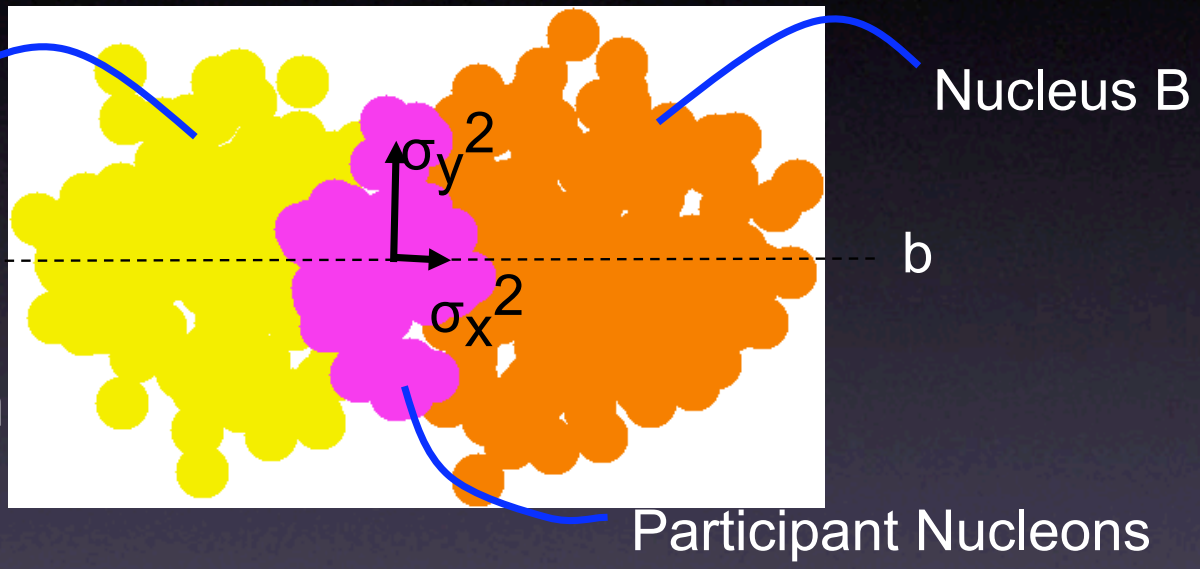


Geometrical initial state eccentricity from Glauber model

Surprisingly large flow signal in Cu+Cu!



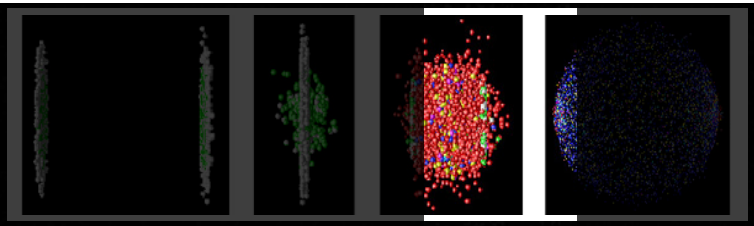
Hydrodynamic Evolution



Glauber model of AuAu collision

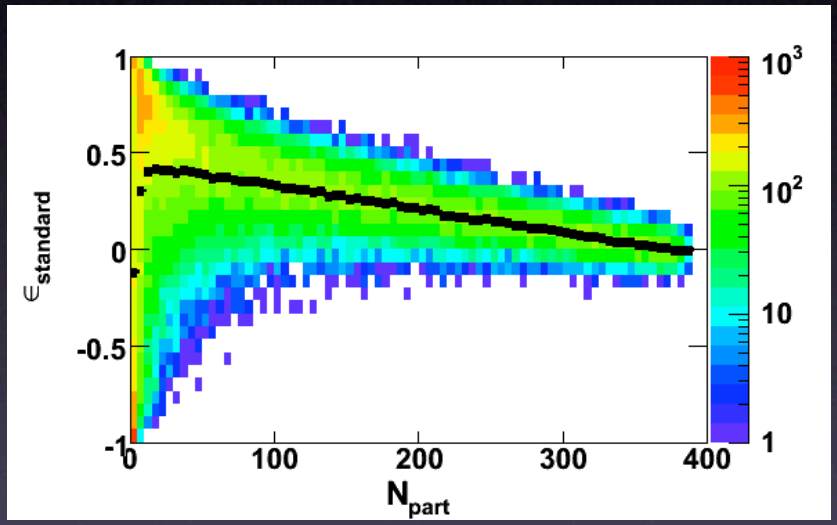
Using the impact parameter as the x-axis, we define the standard eccentricity using the widths of the distribution in x and y

$$\varepsilon = \frac{\sigma_y^{\,2} - \sigma_x^{\,2}}{\sigma_y^{\,2} + \sigma_x^{\,2}}$$



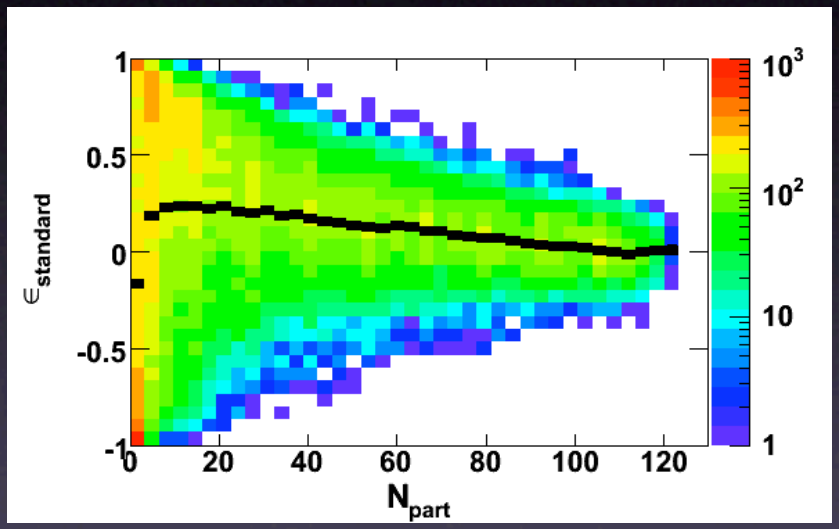
Hydrodynamic Evolution

Au+Au



Large fluctuations in eccentricity

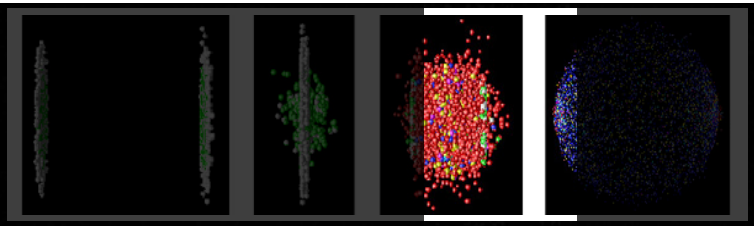
Cu+Cu



Even bigger fluctuations in Cu+Cu

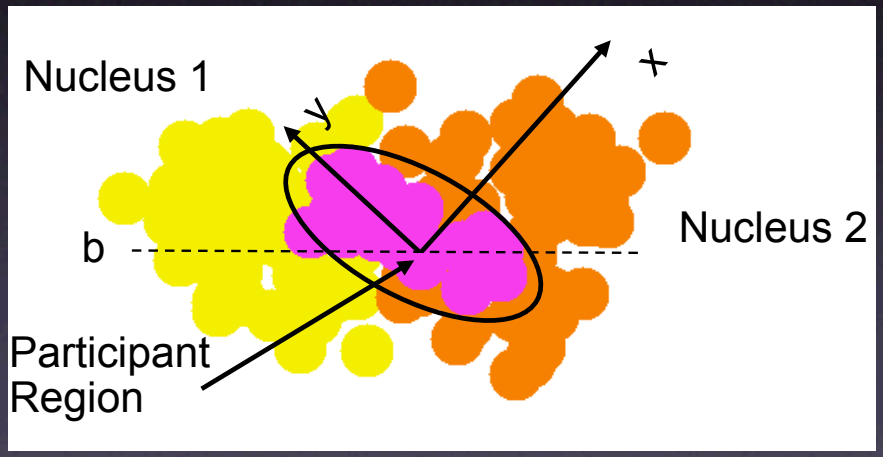
Many peripheral events with negative eccentricity

Glauber MC Calculations



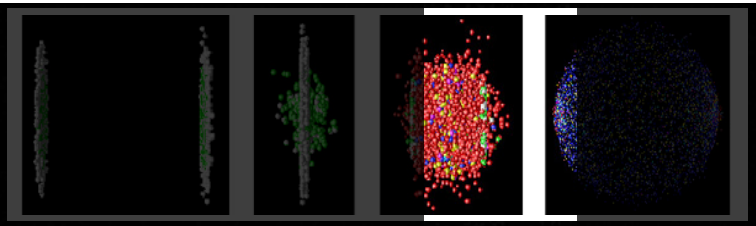
Hydrodynamic Evolution

Possibly reasonable method is to realign the coordinate system to maximize the ellipsoidal shape (a principal axis transformation)



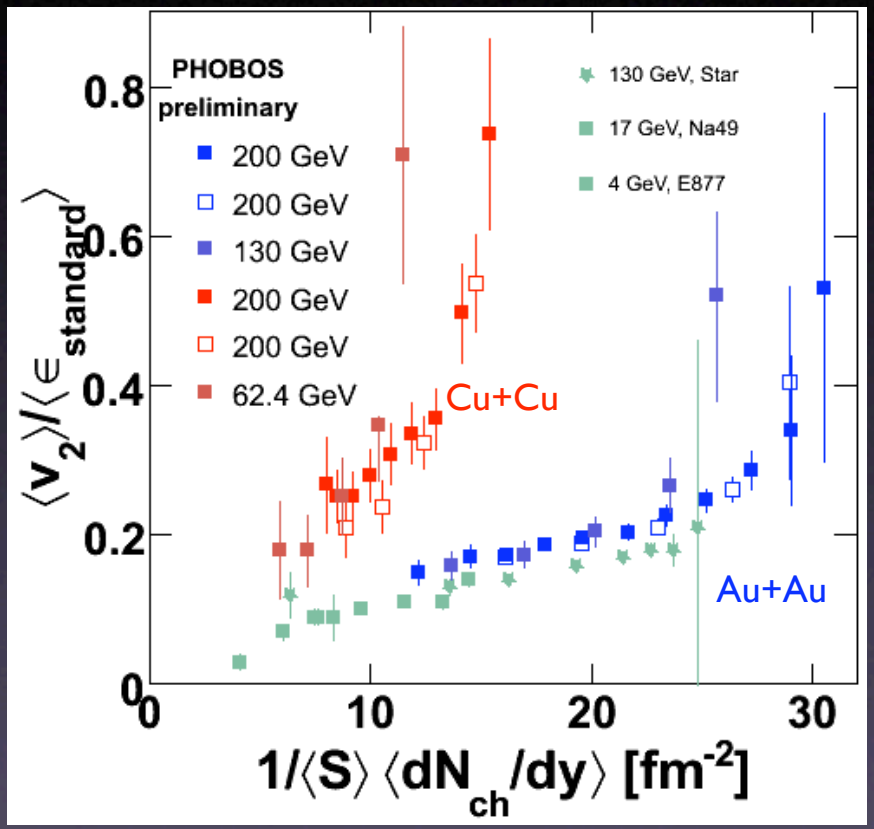
"Participant" eccentricity

(versus "standard" eccentricity)



Hydrodynamic Evolution

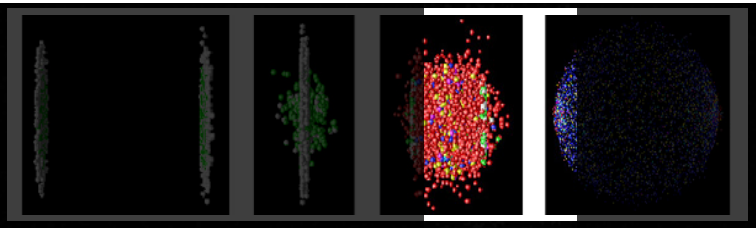
using "Standard" Eccentricity



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

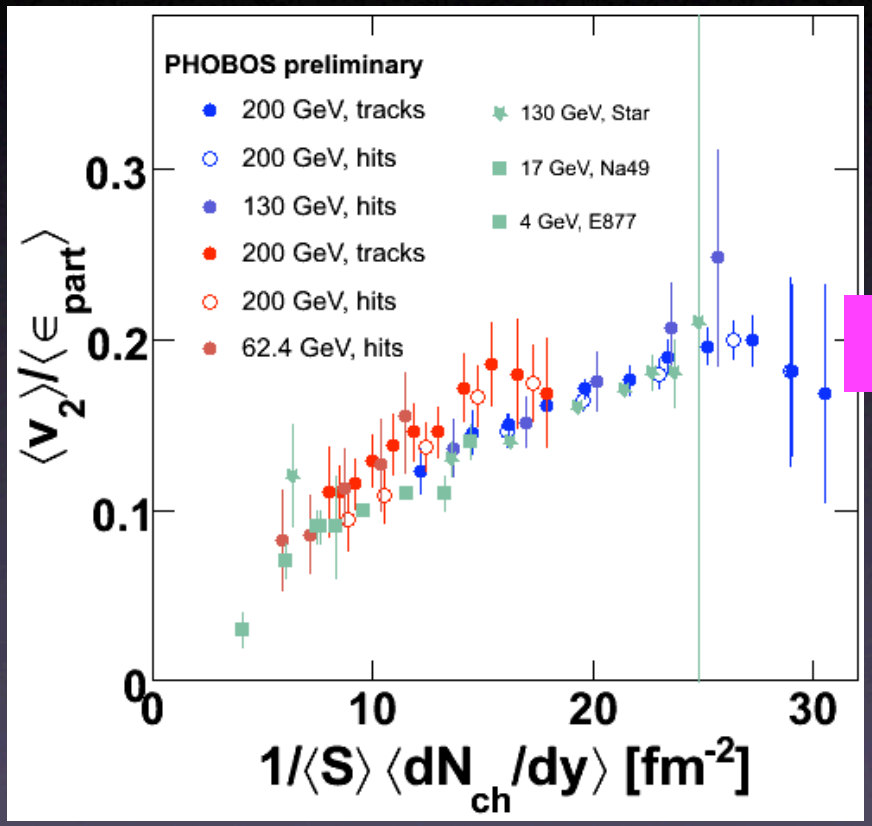
Surprisingly strong elliptic flow in Cu+Cu
Challenge to hydrodynamic picture??

Cu+Cu: PHOBOS QM 2005



Hydrodynamic Evolution

using "Participant" Eccentricity

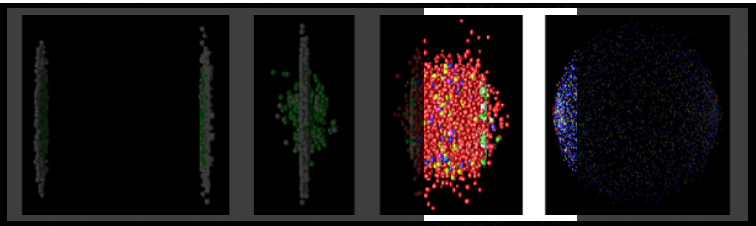


"Hydro-Limit"

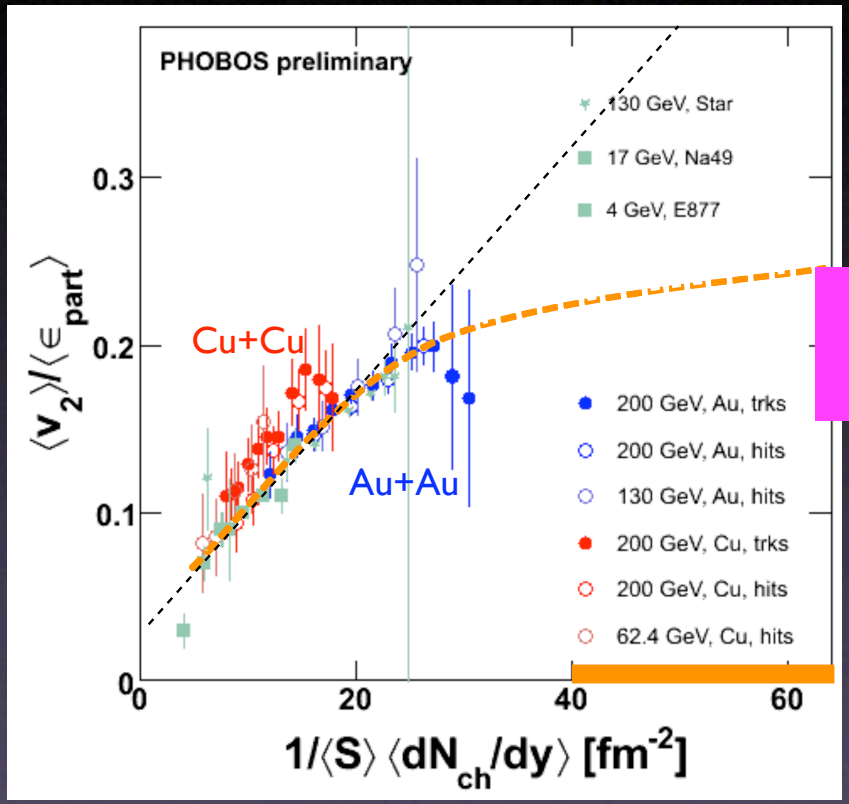
Low Density Limit:
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

"Participant Eccentricity" provides universal scaling
Approach to equilibrium?

Cu+Cu: PHOBOS QM 2005



Hydrodynamic Evolution

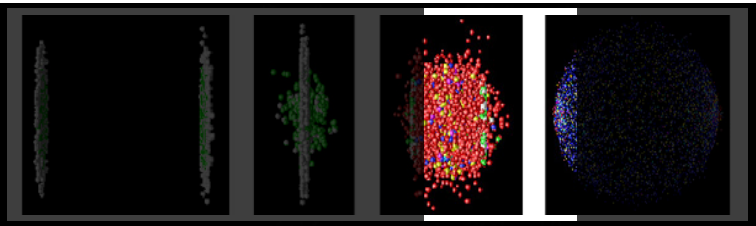


Low Density Limit:
STAR, PRC 66 034904 (2002)
Voloshin, Poskanzer, PLB 474 27 (2000)
Heiselberg, Levy, PRC 59 2716, (1999)

LHC

Will flow saturate at LHC as thermalization is achieved?

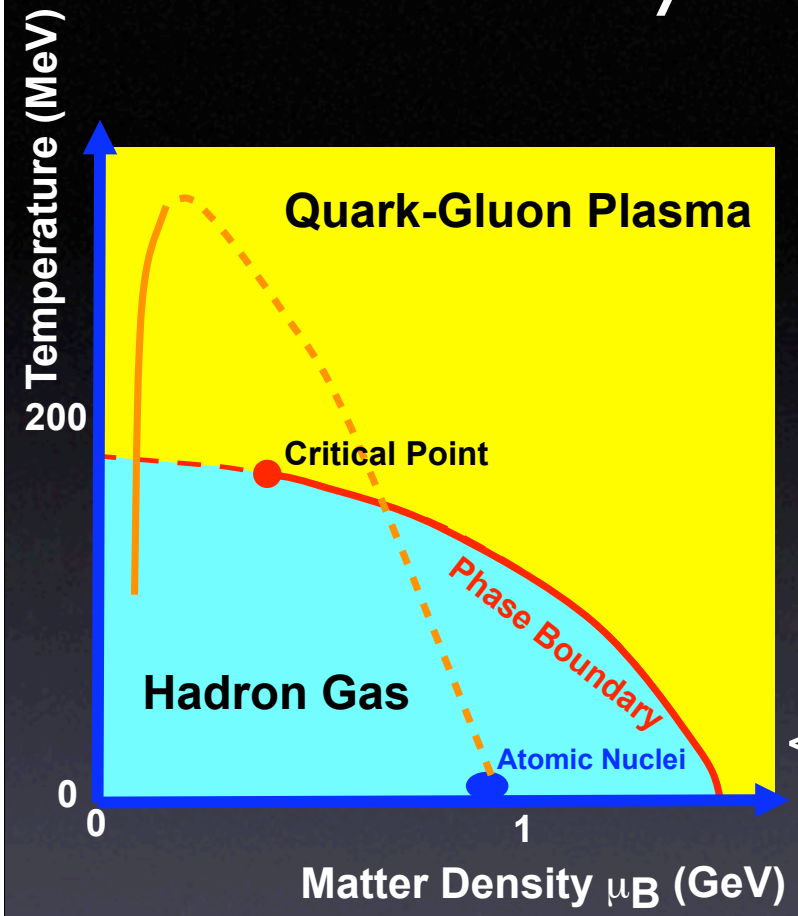
Cu+Cu: PHOBOS QM 2005



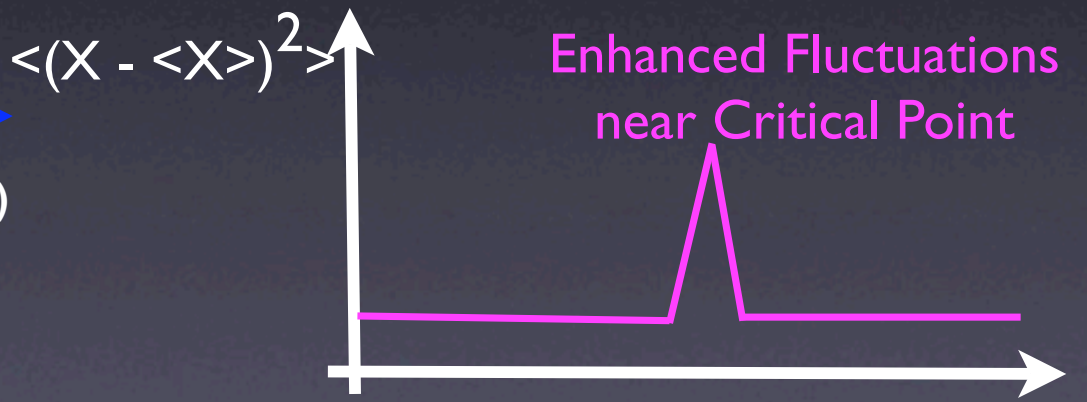
Hydrodynamic Evolution

- Large collective flow signal observed in Au+Au
- Overall magnitude + mass splitting ≈ hydro
- Additional (geometrical?) azimuthal correlations in Cu+Cu
- How is thermalization/pressure build-up achieved?
- What are the (early) degrees of freedom?

Event-by-Event Physics (last century)



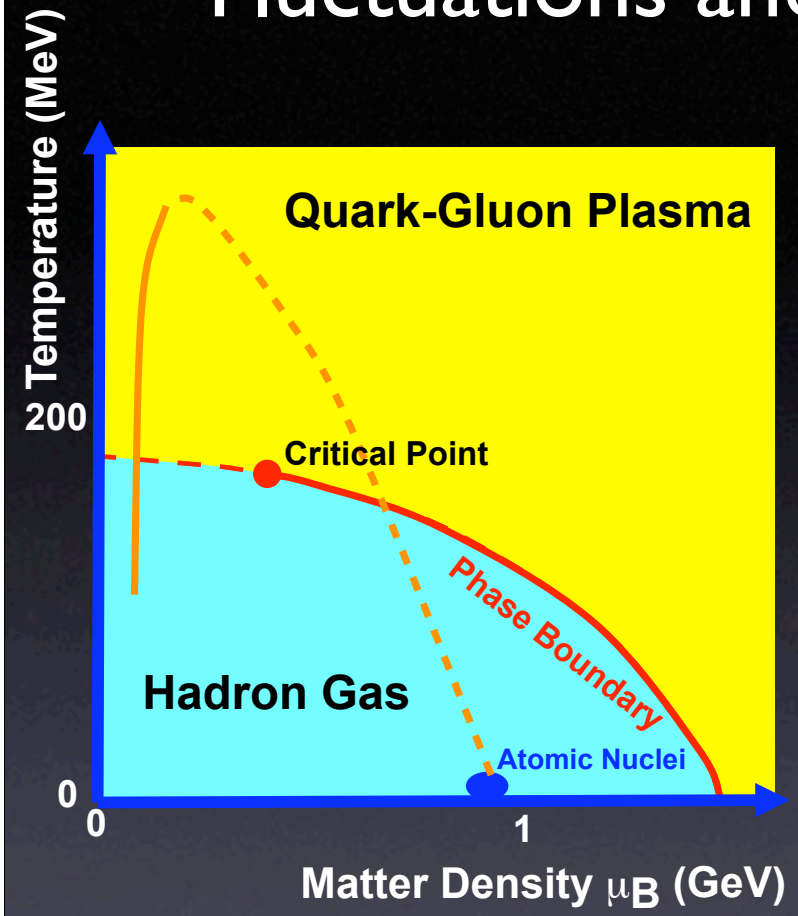
Stock



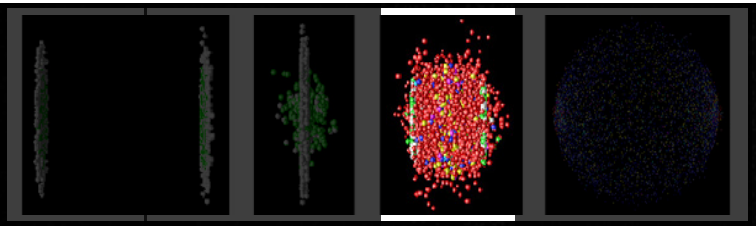
"Event-by-event Physics":
Search for critical phenomena
induced near phase transition/critical point

Rajagopal, Shuryak, Stephanov, Wilczek

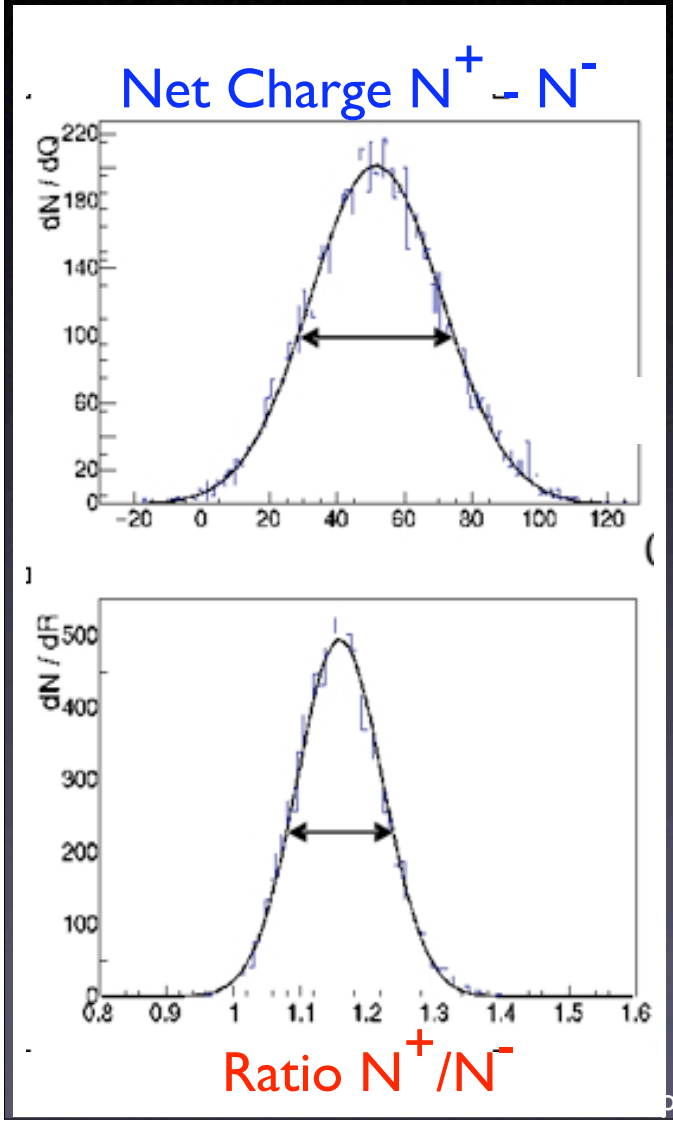
Fluctuations and the QCD Phase Diagram



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



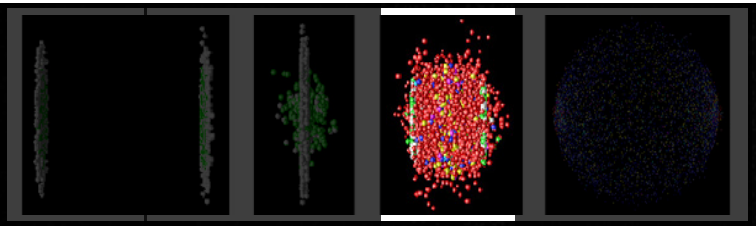
Net Charge Fluctuations



- 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)

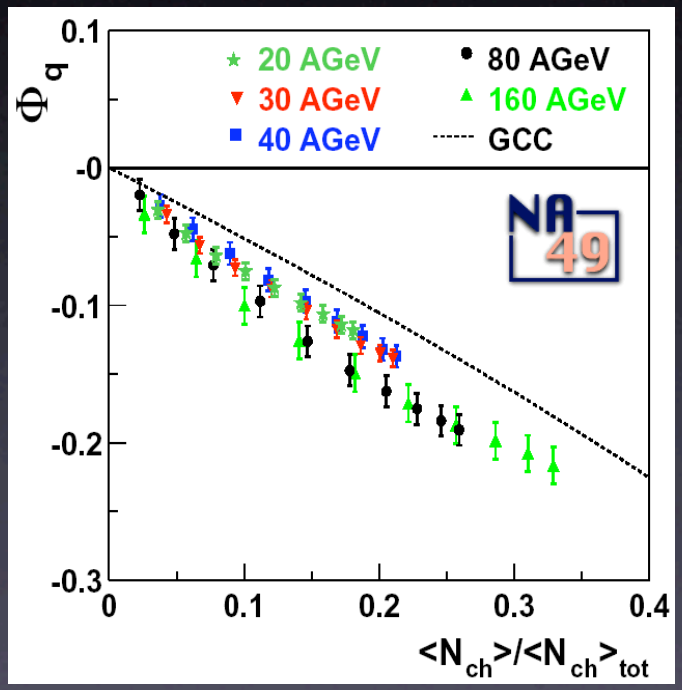
- Fluctuations frozen b/c charge conservation
  - Diffusion vs Expansion timescale

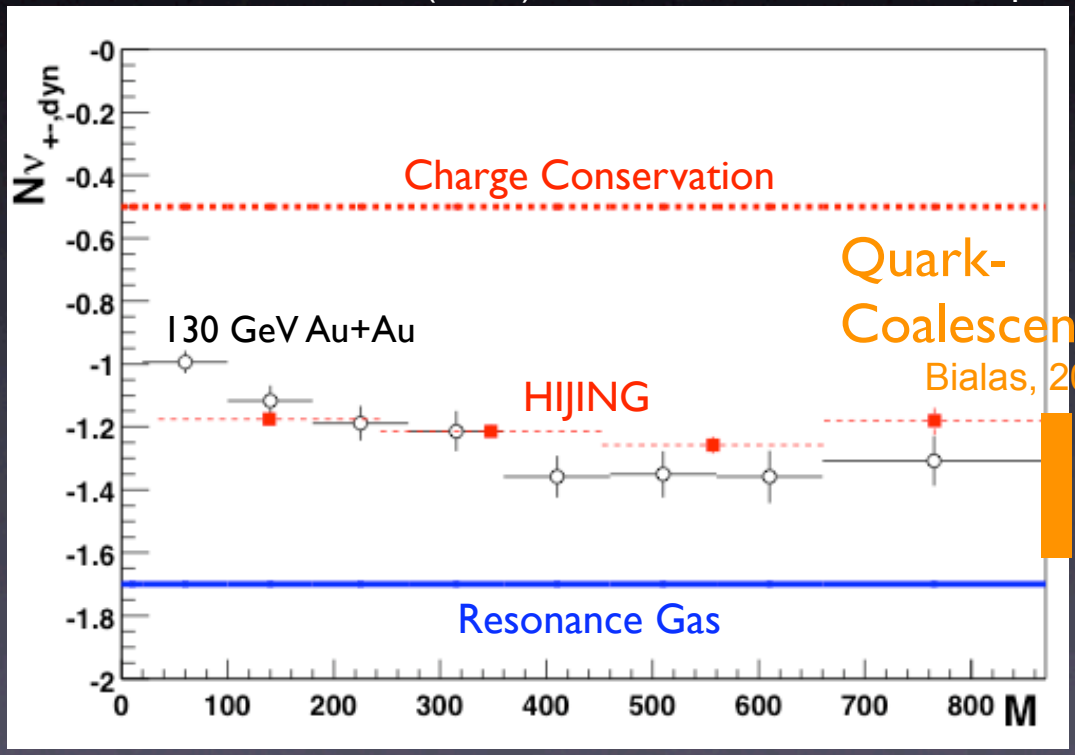
- Fluctuations of N^+/N^- or $N^+ - N^-$ vs statistical reference

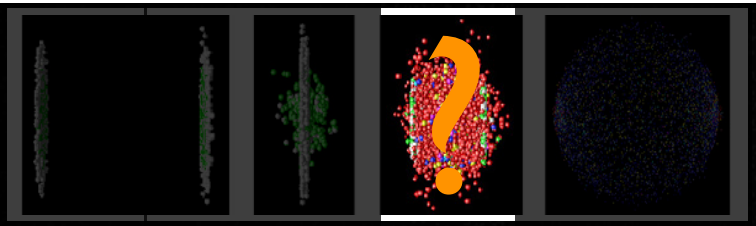


Net Charge Fluctuations

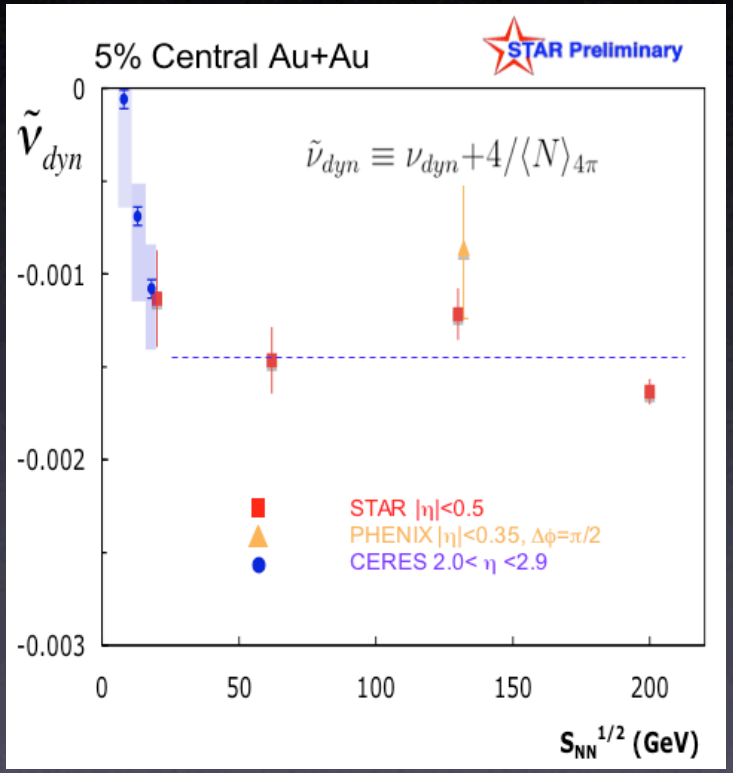
STAR PRC 68 (2003) $|\eta| < 0.7$, $0.1\ \text{GeV/c} < p_T$



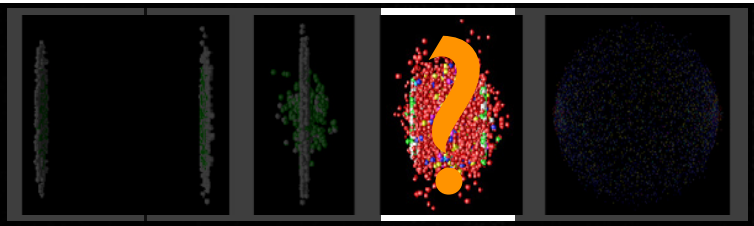




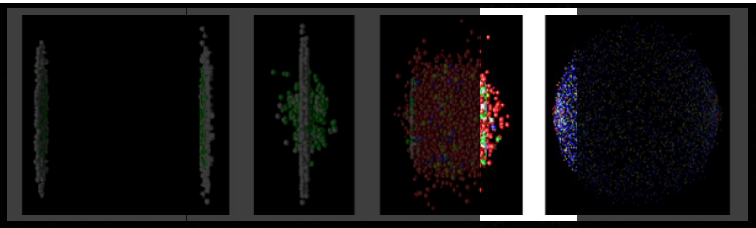
Net Charge Fluctuations vs √s



← QGP



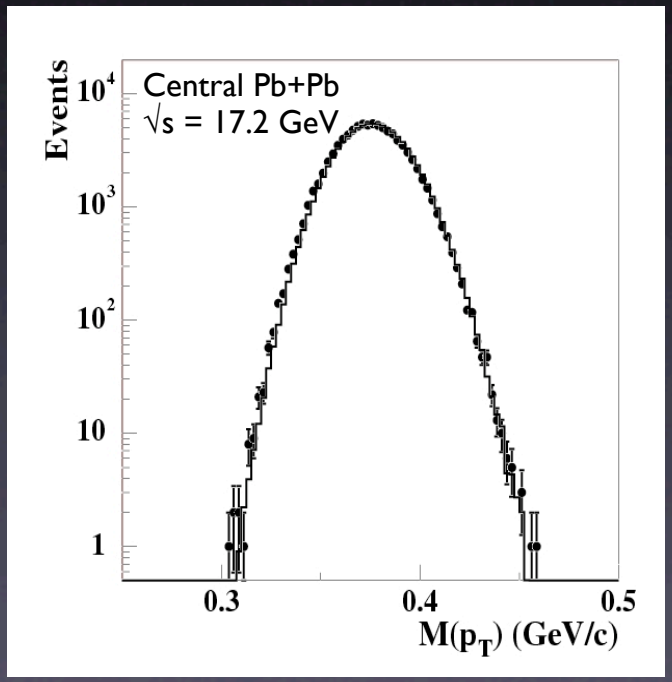
- Basic argument still appears valid
- Possible Explanations
  - Diffusion in long-lived hadronic phase?
  - Resonances?
  - A feature of hadronization?
  - Quark Coalescence?
  - Bound states?
- Need connection to other data and QCD



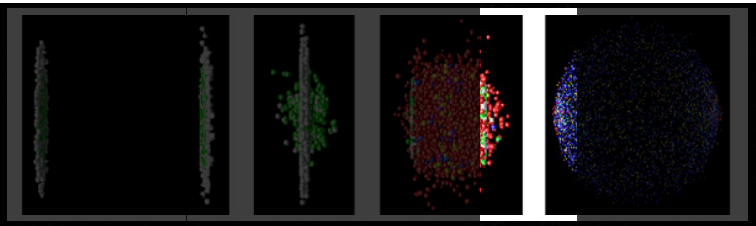
$\langle p_T \rangle$ Fluctuations

- 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)



$\langle p_T \rangle$ Fluctuations

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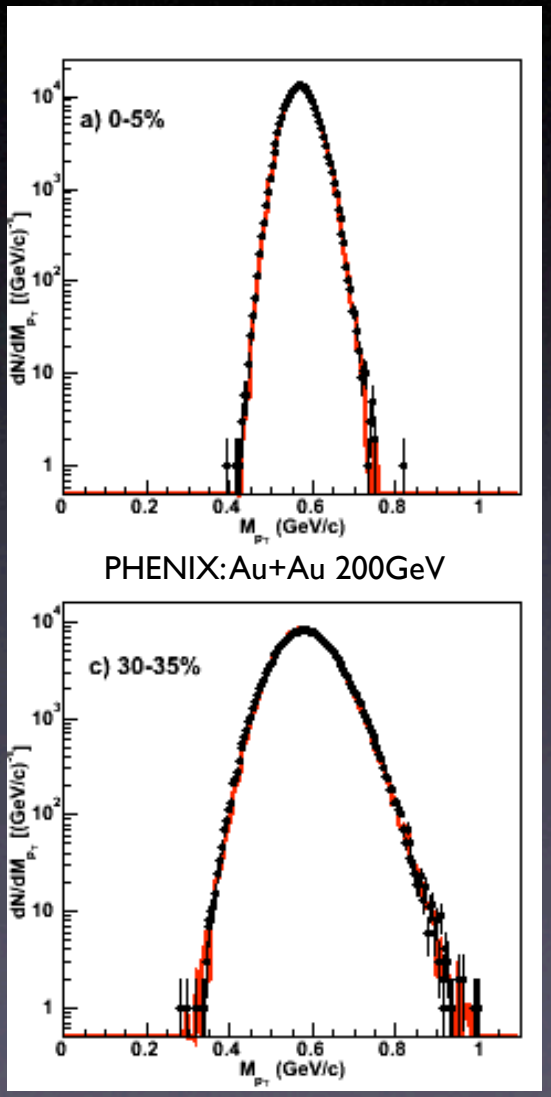
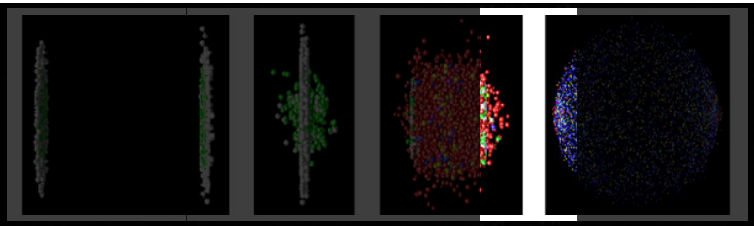
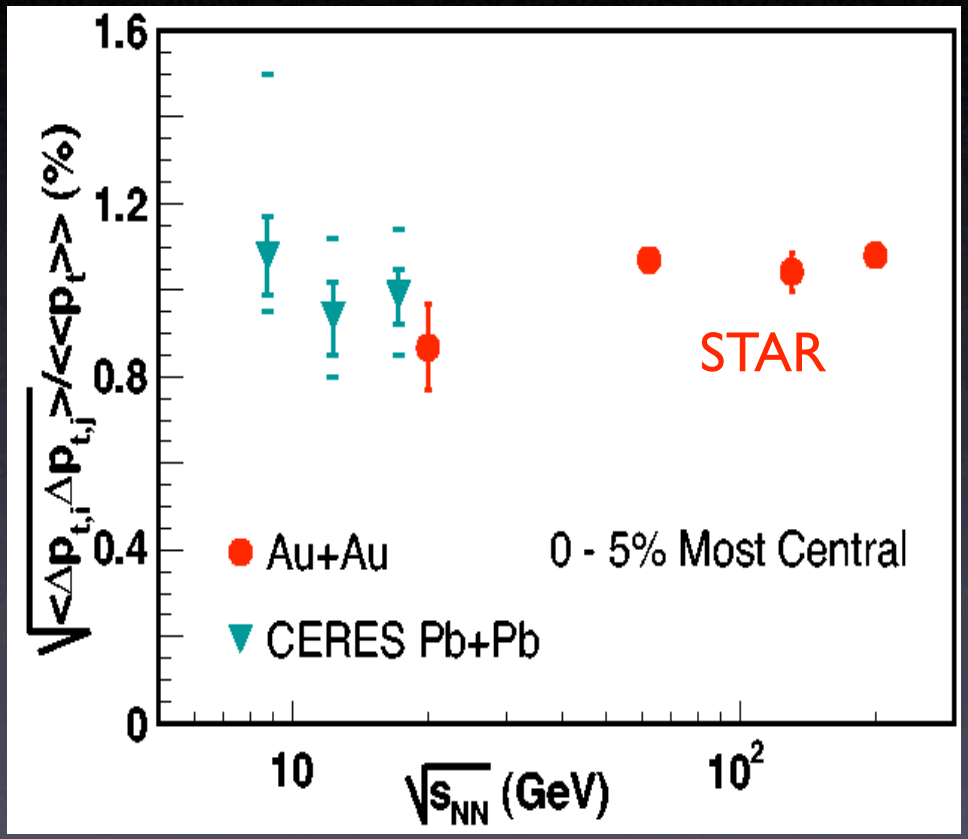


PHENIX: Au+Au 200GeV



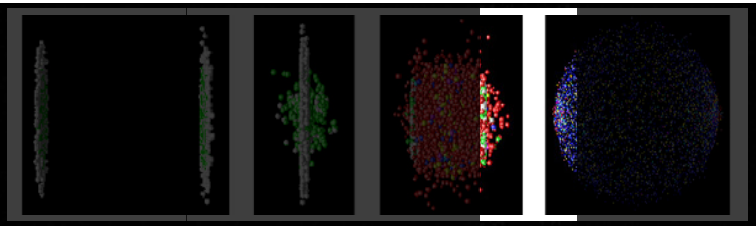
Energy Dependence?

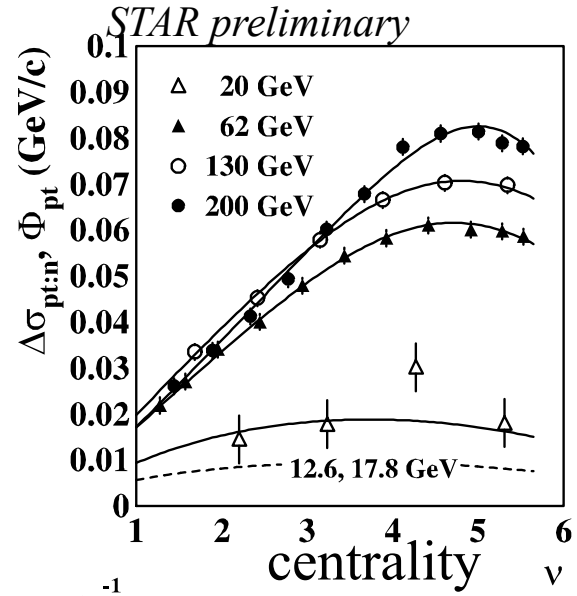


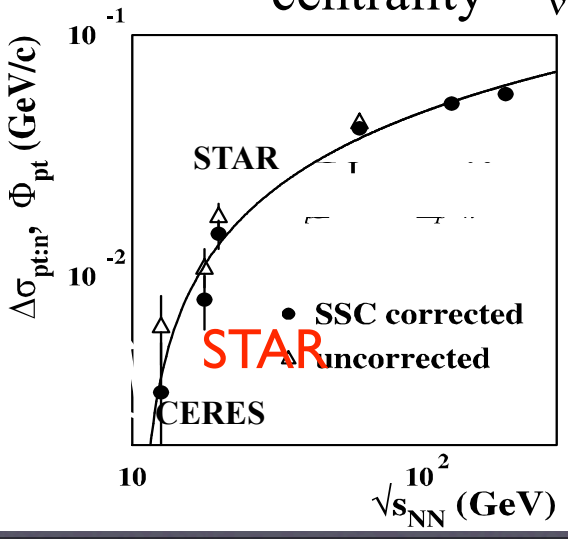
No evidence for non-monotonic energy dependence

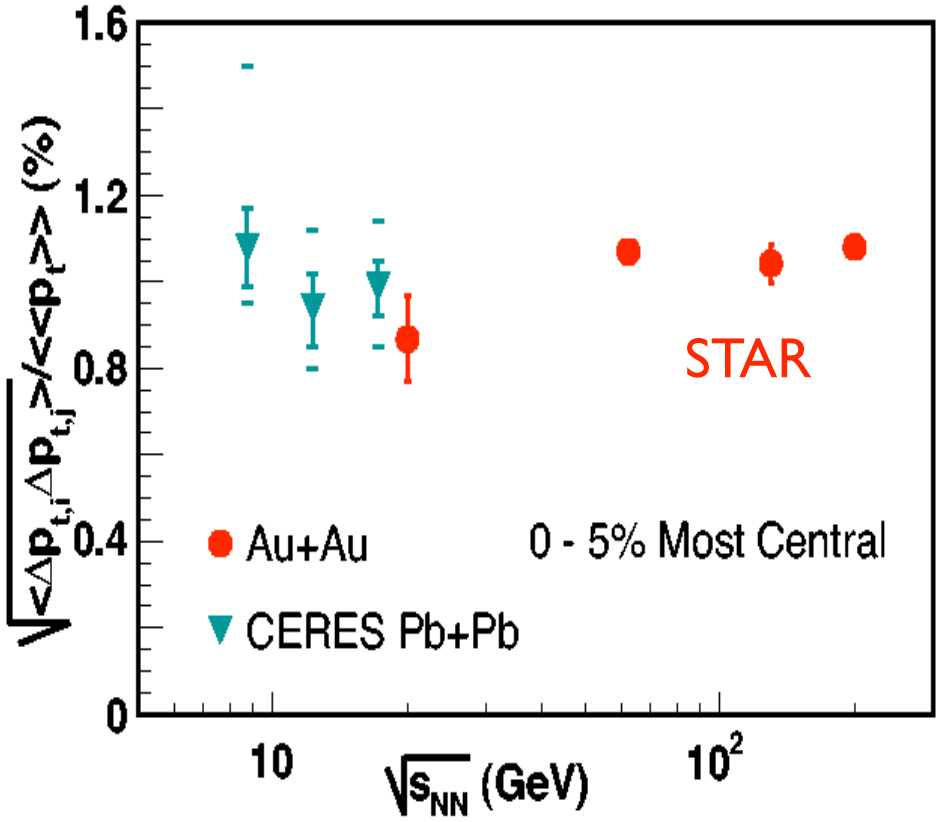
But: Interpretation ⇔ choice of variables

Non-monotonic system-size dependence

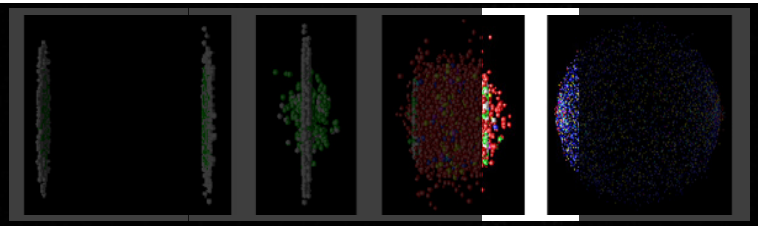








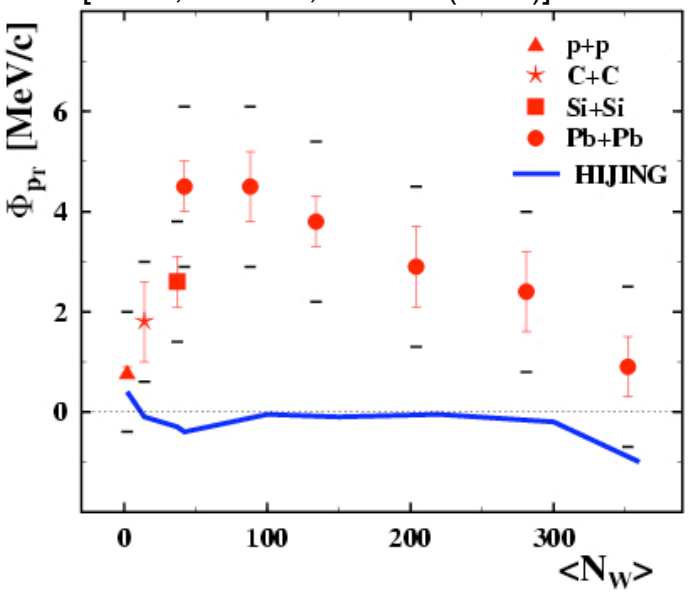
Normalization to <pT>
Normalization per particle
Linear or quadratic measures



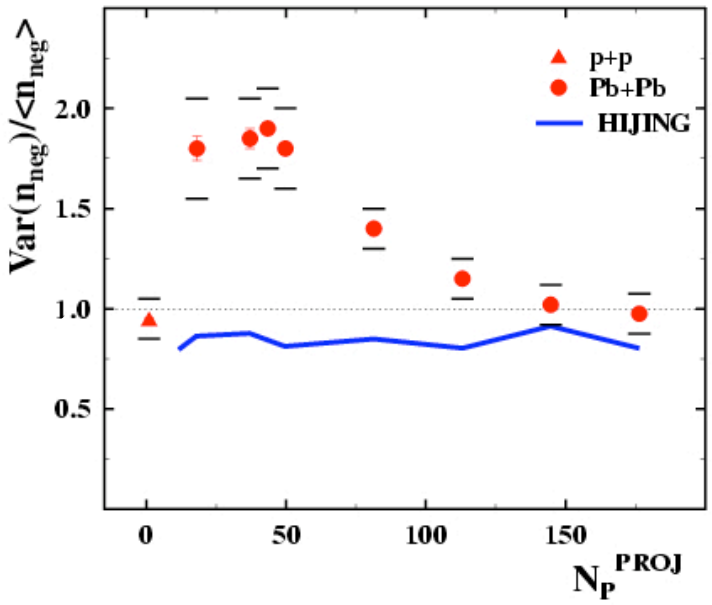
Fluctuations for small systems

all negatives, acceptance: $4 < y_\pi < 5.5$ and $0.005 < p_t < 1.5$ GeV/c

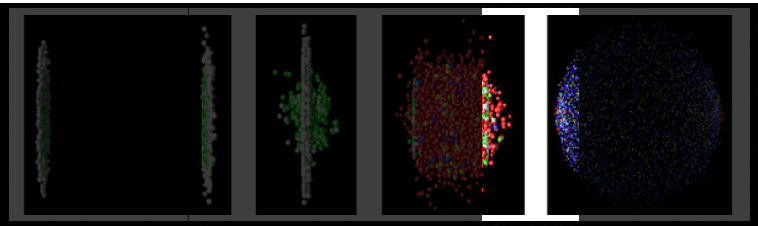
[NA49, PRC 70, 034902 (2004)]



NA49 preliminary

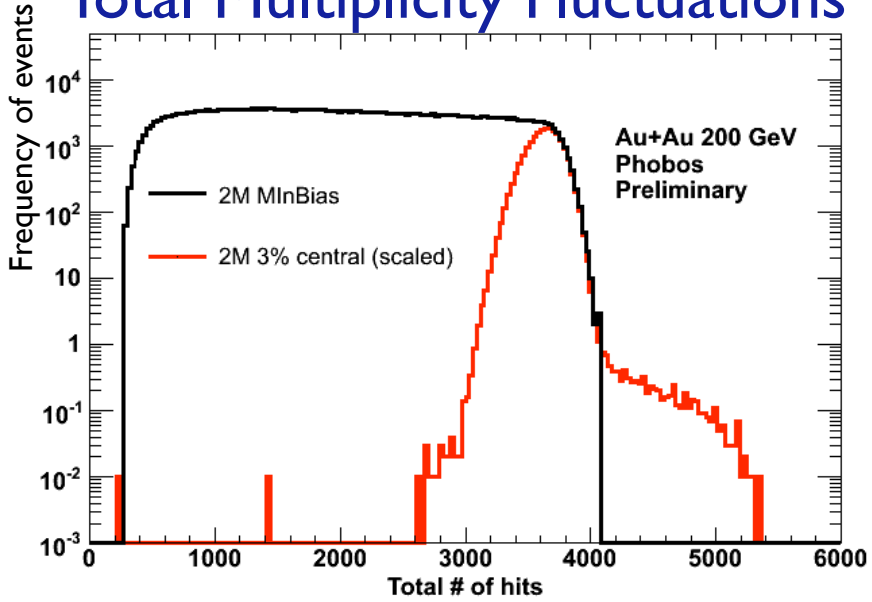


- Fluctuations and Percolation (Clustering) in small systems
- Connection to elliptic flow in Cu+Cu?
- Connection to strangeness enhancement vs N_{part}?

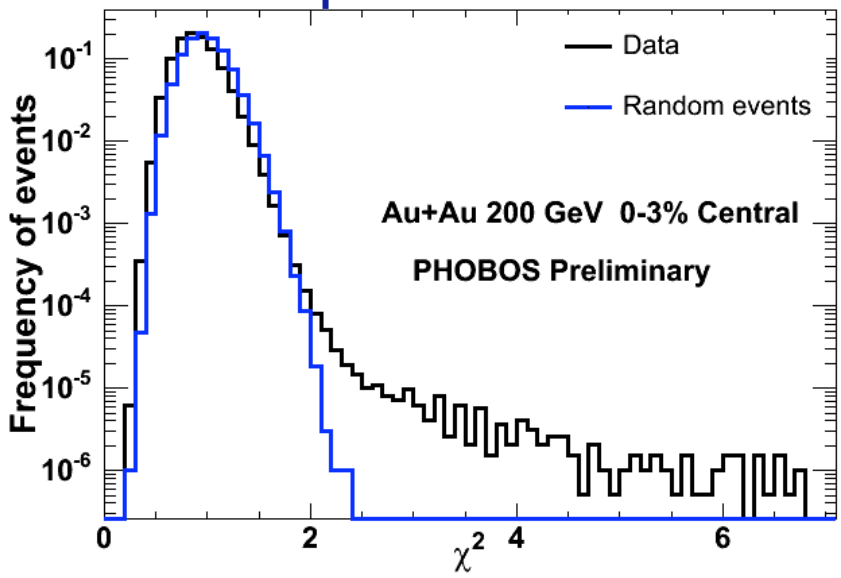


Search for "unusual" events in Au+Au

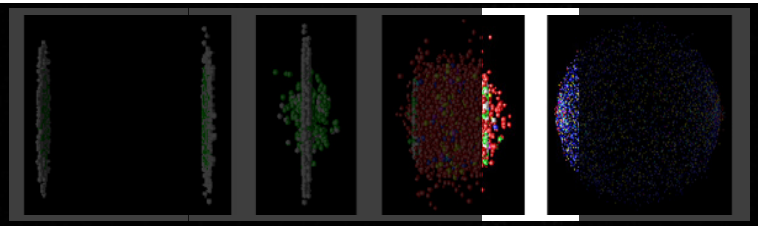
Total Multiplicity Fluctuations



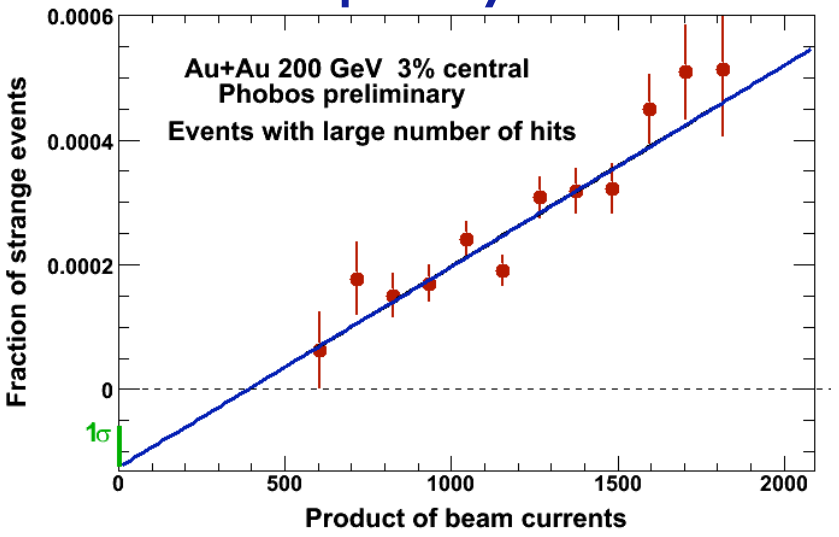
Shape Fluctuations



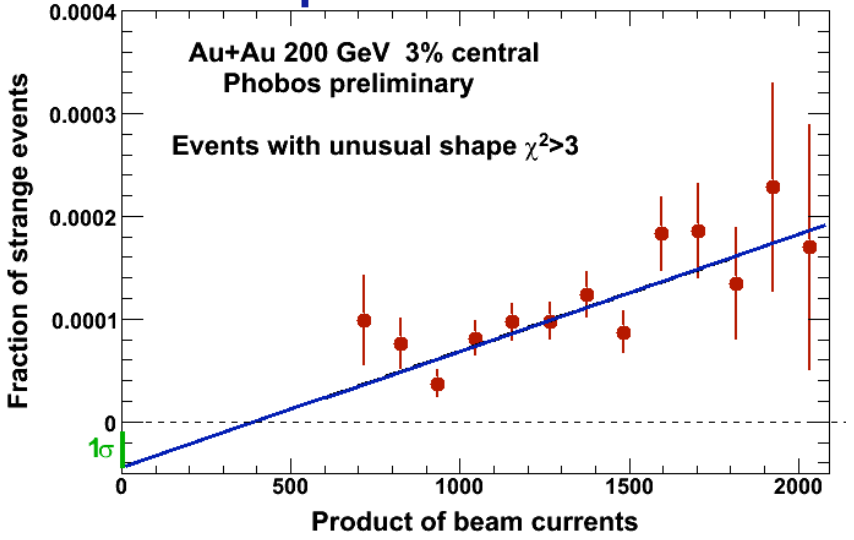
Multiplicity distribution and χ^2 (shape) distribution shows distinct tails - $O(10^{-4})$



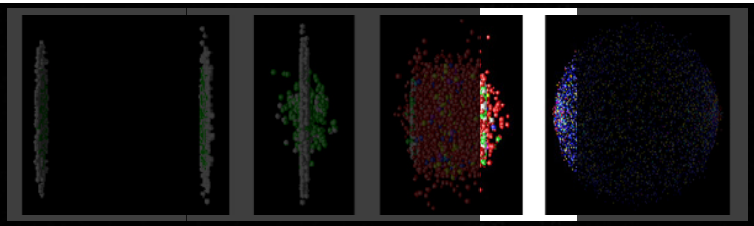
Total Multiplicity Fluctuations



Shape Fluctuations

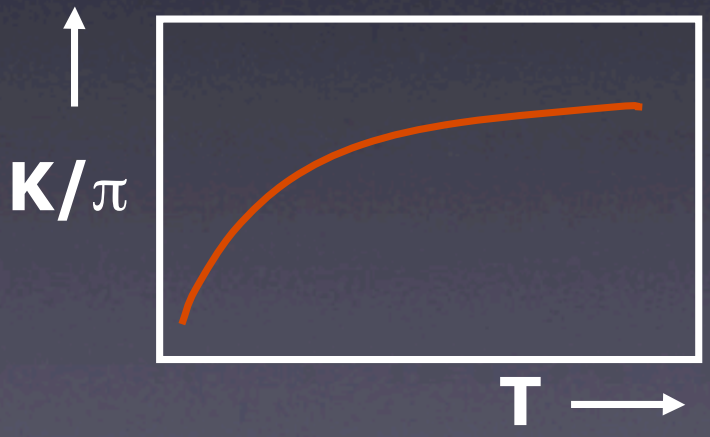


Rate of unusual events correlates with 'luminosity' -
Consistent with collision-pileup as source of rare events



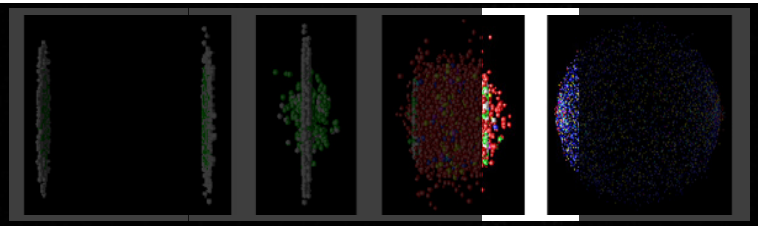
E-by-E fluctuations in the K/π ratio

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

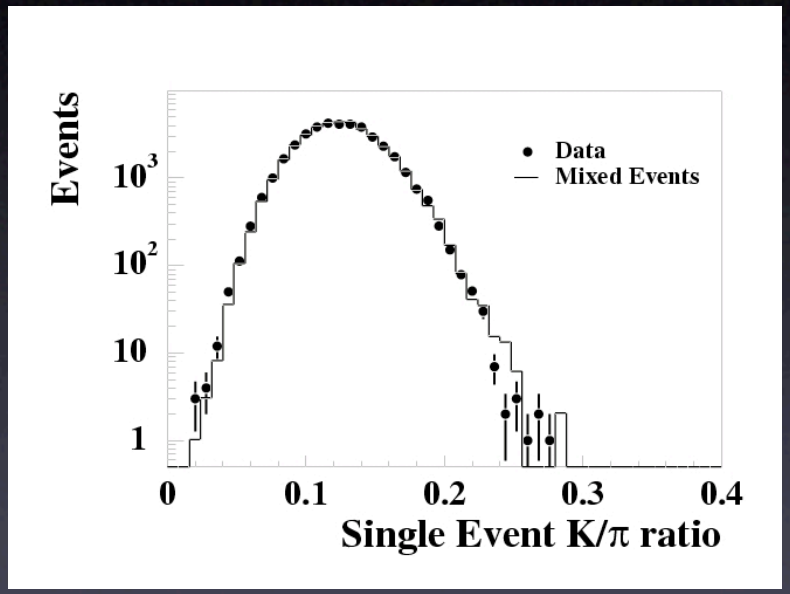


NA49 Measurement

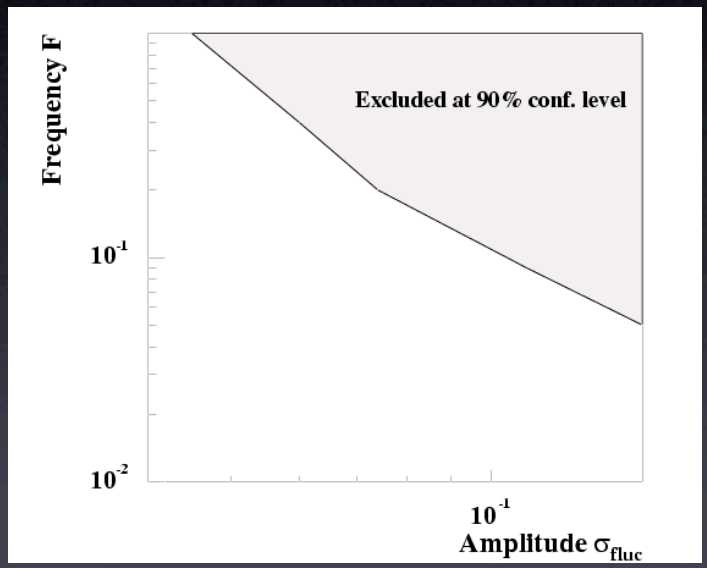
- Use dE/dx to identify π,K,p event-by-event
- Do Max Likelihood fit to extract K/π ratio event-by-event
- Required 2 years of detector calibation to eliminate dE/dx – multiplicity correlation



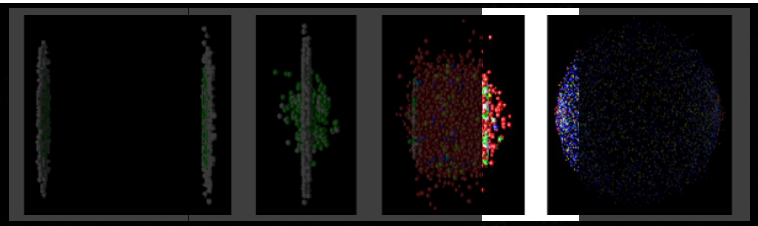
E-by-E fluctuations in the K/π ratio



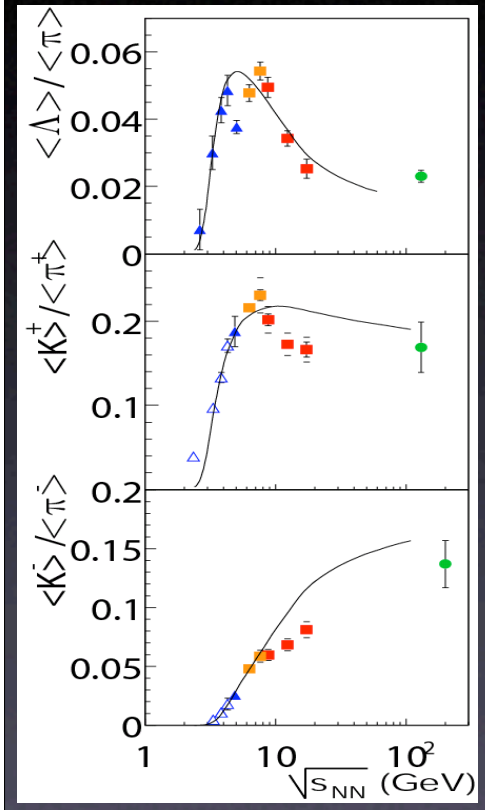
Pb+Pb, 17.2 GeV
NA49, PRL 86 (2001) 1965



- 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

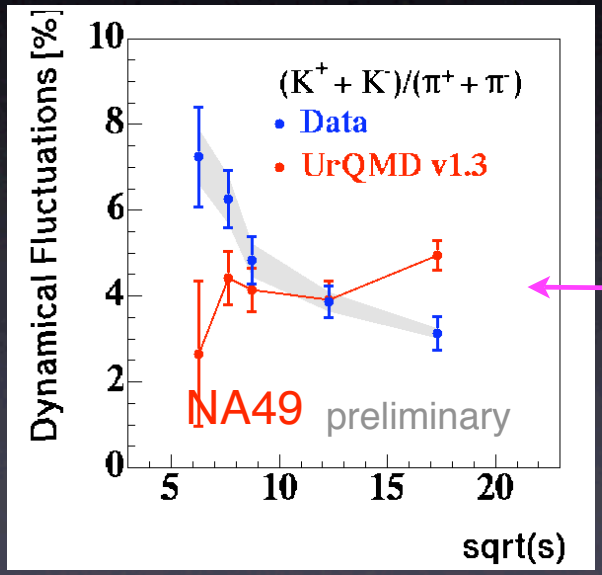


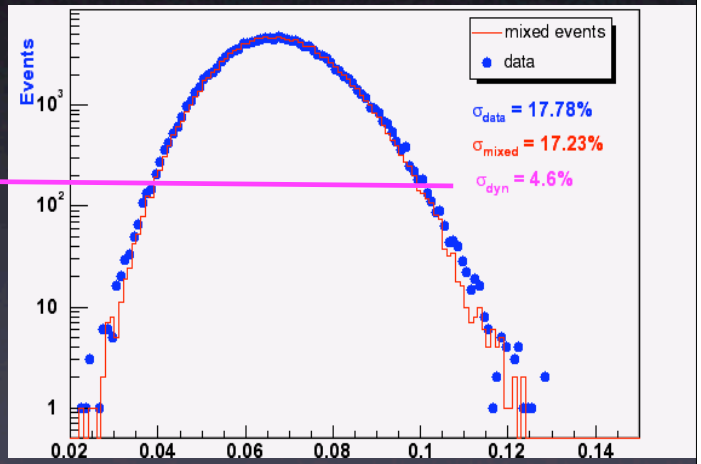
NA49 'Horn'



Strangeness Fluctuations vs √s

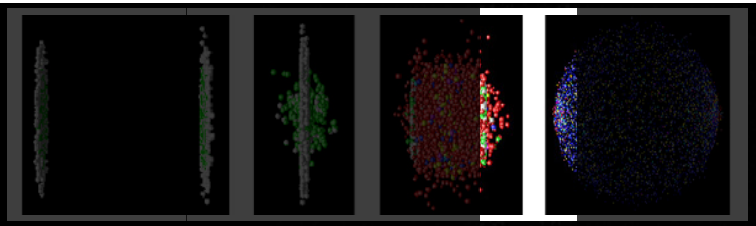
NA49 (QM'04)





Fluctuations in K/pi ratio

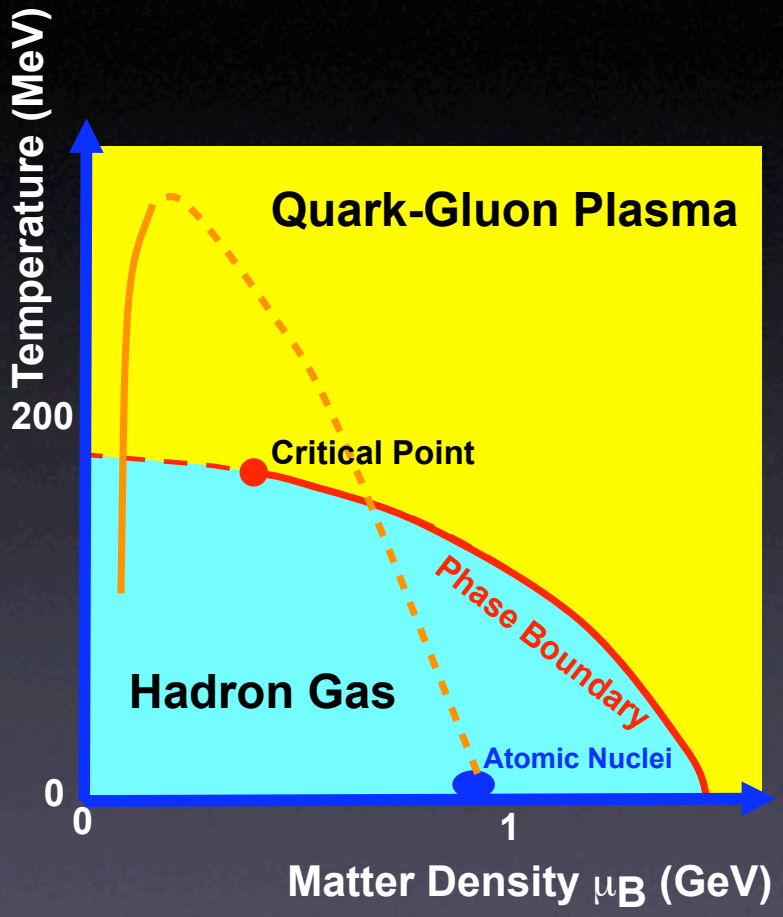
Rajagopal, Stephanov: Compatible with constant correlation strength



Event-by-Event fluctuations

- p_T fluctuations show 'smooth' $\sqrt{s}$ dependence
  - no 20, 30 GeV data yet
- Fluctuations small in central events at top SPS energy + above
- Energy dependence of k/pi fluctuations?
- Multiplicity + p_T fluctuations for peripheral events?

Fluctuations at RHIC



RHIC

Close to $\mu_B \sim 0$ axis

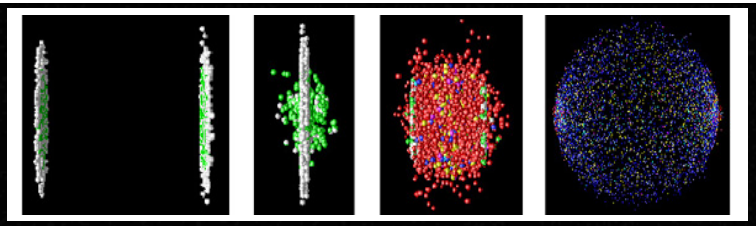
Cross-over?

Far from critical point?

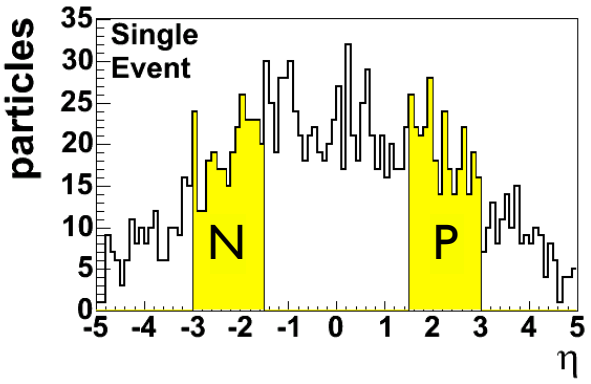
=>Fluctuations not induced by phase-change itself?

An Evolving Paradigm

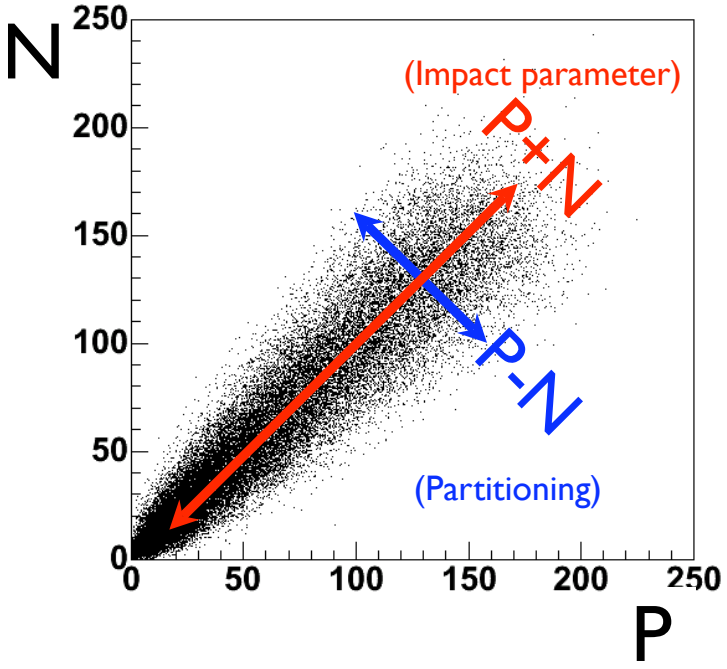
- Event-by-Event Physics
  - Critical phenomena (1990s)
  - Fluctuations of conserved quantities (2000)
- Fluctuations and Correlations
  - Connection between correlations and fluctuations (Koch, Bialas '98)
    - Study transport properties of the medium
    - Approach to thermalization
    - Properties of Hadronization



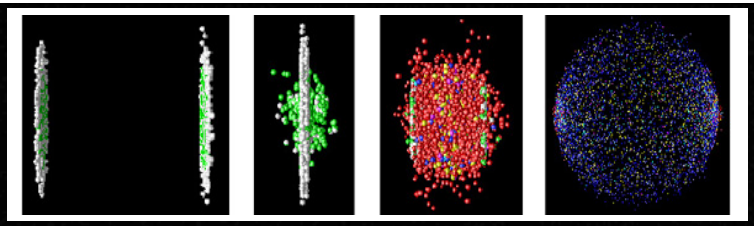
Forward/backward multiplicity correlations



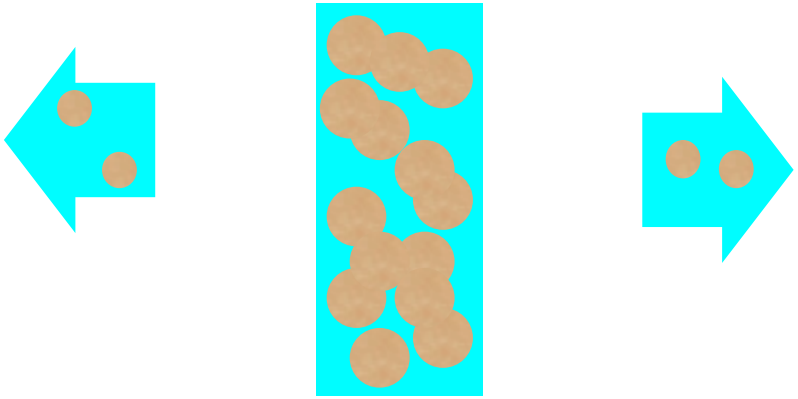
$$C = \frac{P - N}{\sqrt{P + N}}$$



Use variance σ^2_C



Clusters and σ^2_C

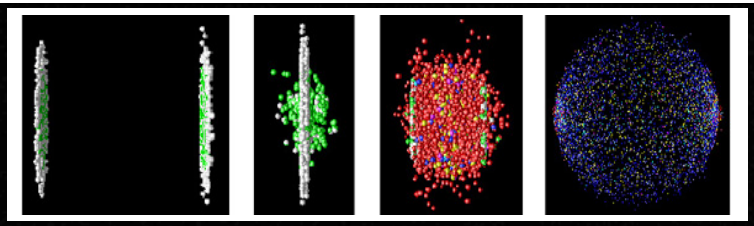


$$P \to KP \qquad N \to KN$$

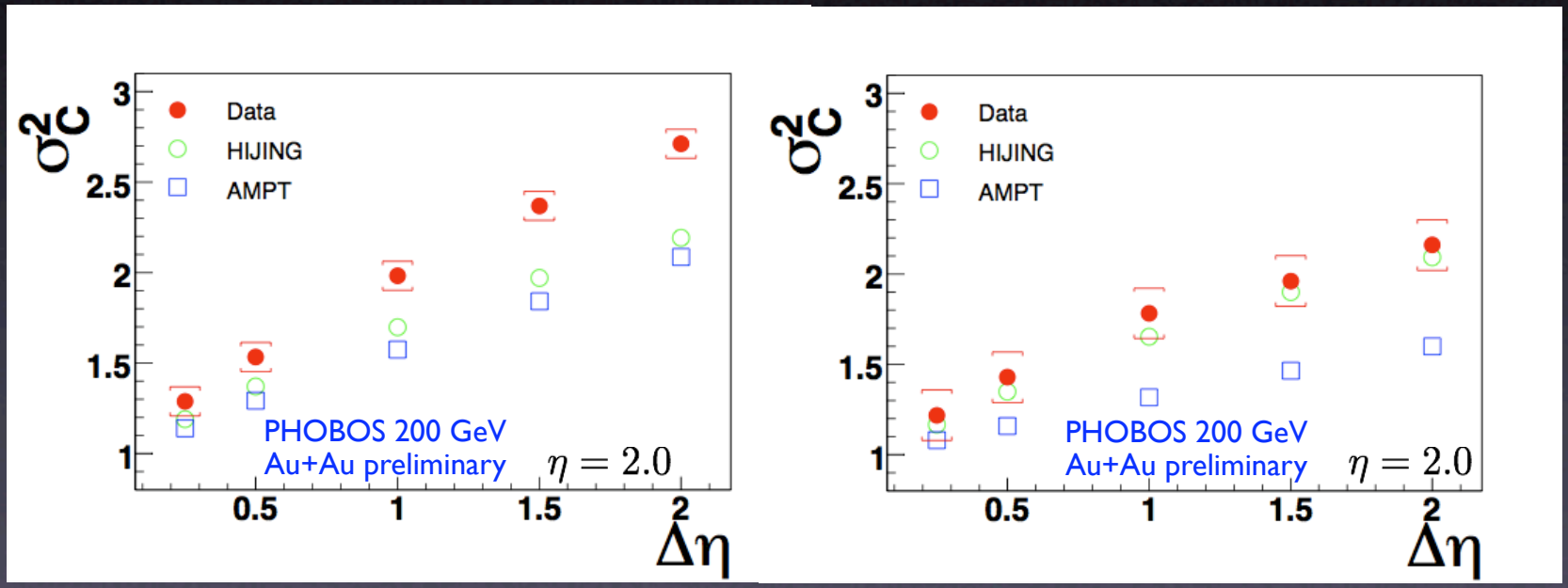
$$C(\eta, \Delta\eta) = \frac{P - N}{\sqrt{P + N}}$$

$$C \to \sqrt{K}C \qquad \sigma_C^2 \to K\sigma_C^2$$

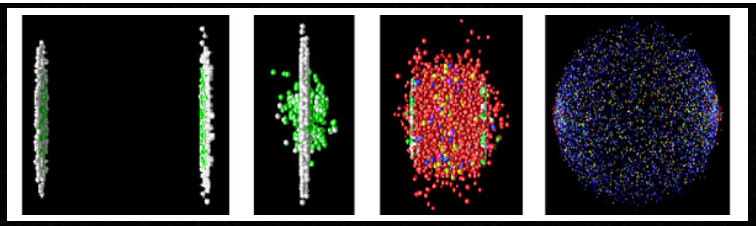
Forward/backward correlations give access to cluster structure of particle production



Cluster-size from F/B fluctuations

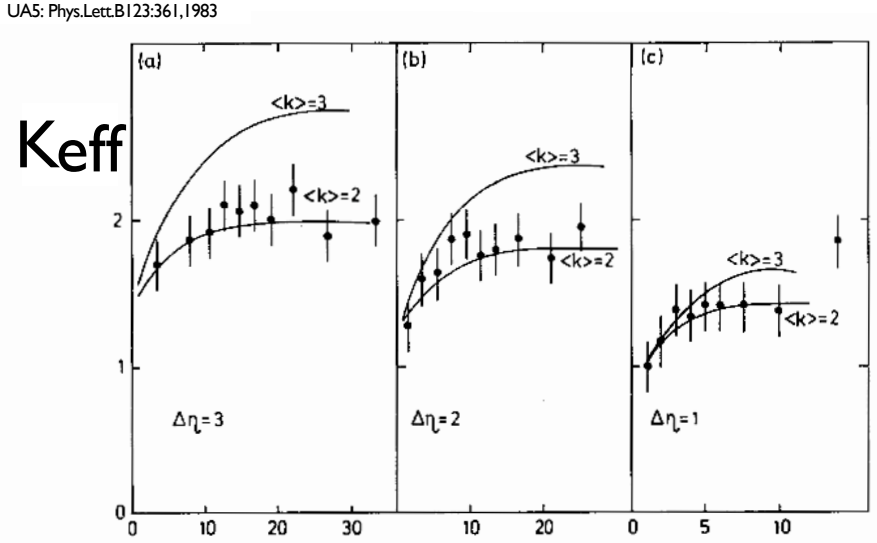


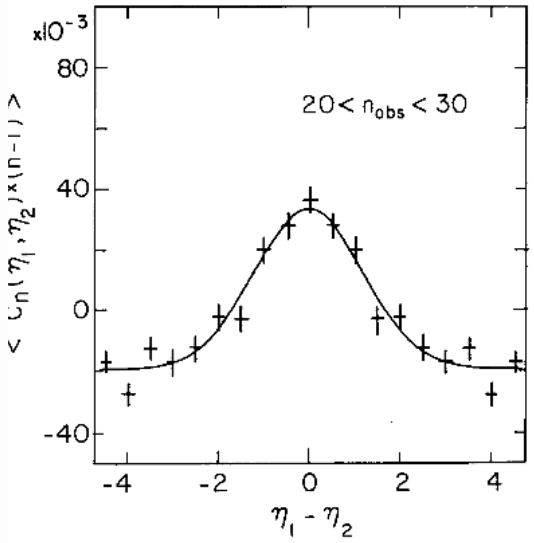
Forward/backward correlations suggest
effective cluster size ≈ 2-2.5 for 200 GeV Au+Au



Clusters in p+p

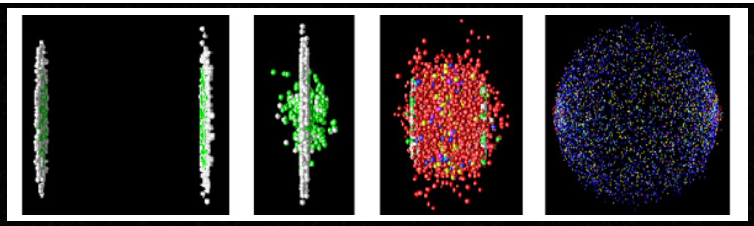
UA5: Phys.Lett.B123:361,1983



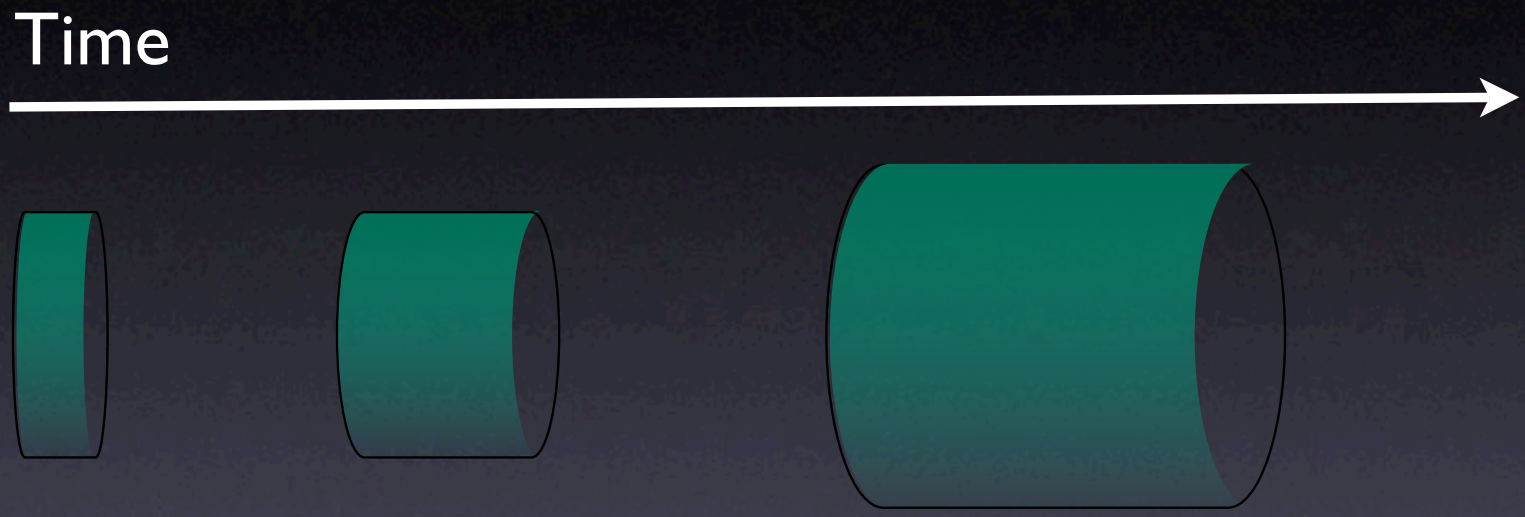


$\overline{p}+p$ 546 GeV

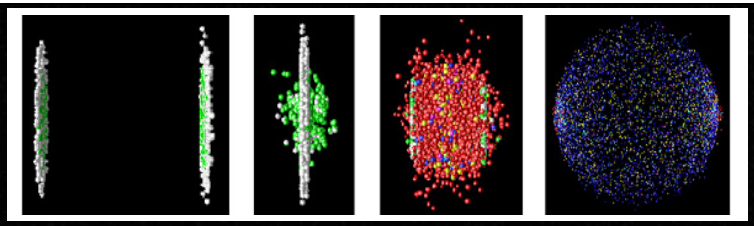
Clusters in Au+Au reminiscent of results from p+$\overline{p}$



Correlation Probes of the Medium

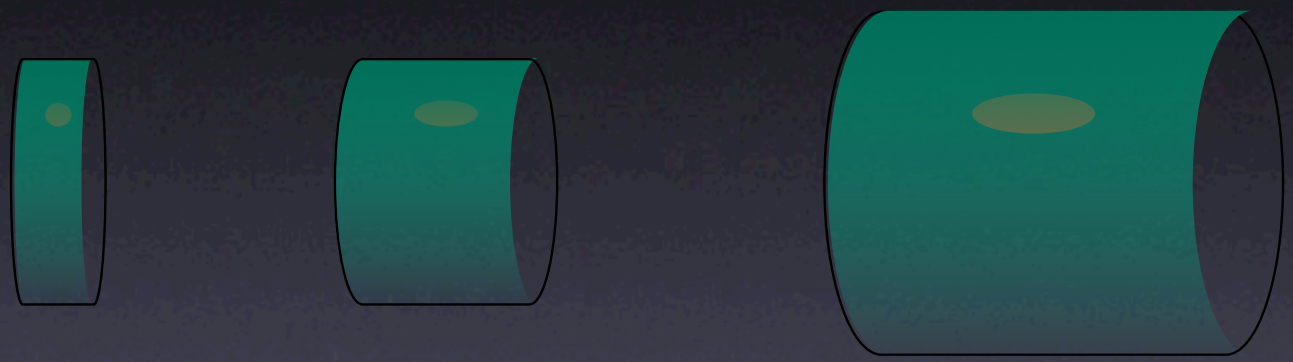


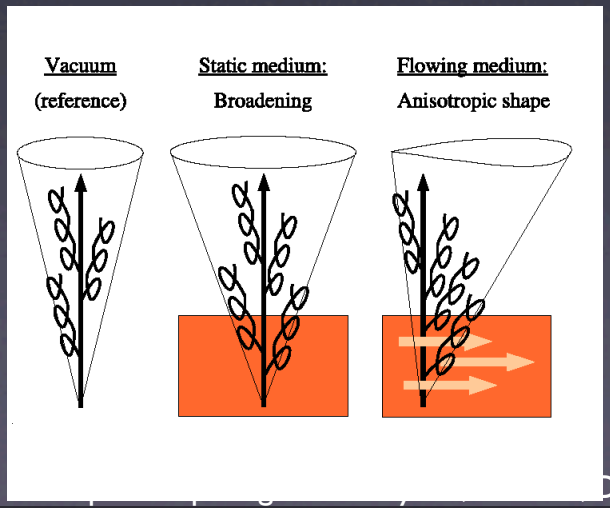
- Probe



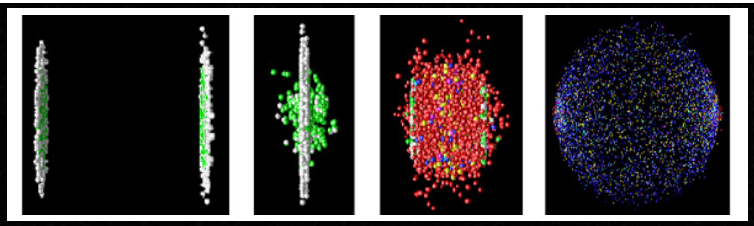
Correlation Probes of the Medium

Time

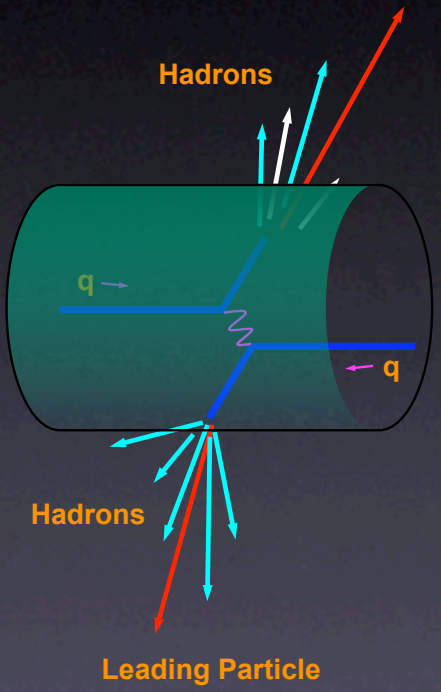




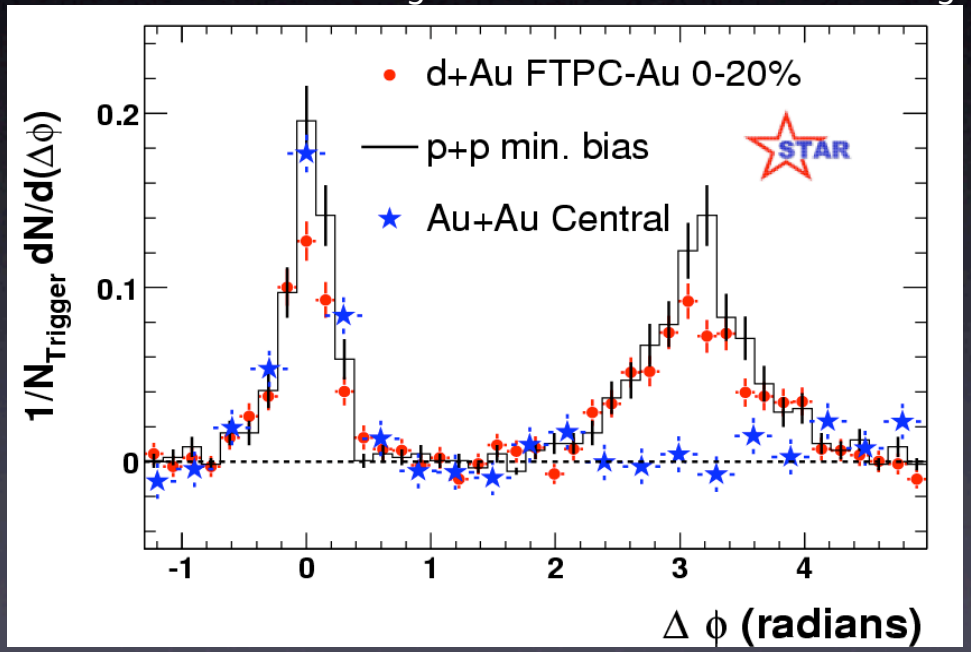
Armesto et al, nucl-ex/0405301



Correlations at 'high' p_T



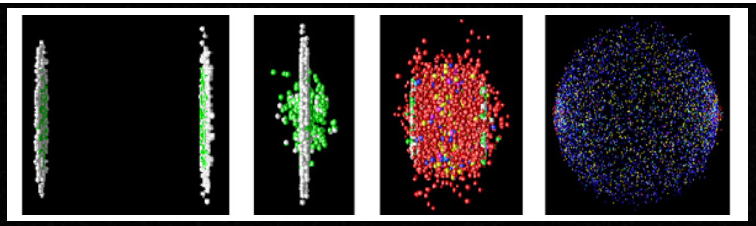
$|\eta| < 0.7$, $4\ \text{GeV/c} < p_{Ttrig} < 6\ \text{GeV/c}$, $2 < p_{TAsso} < p_{Ttrig}$



STAR PRL (2003)

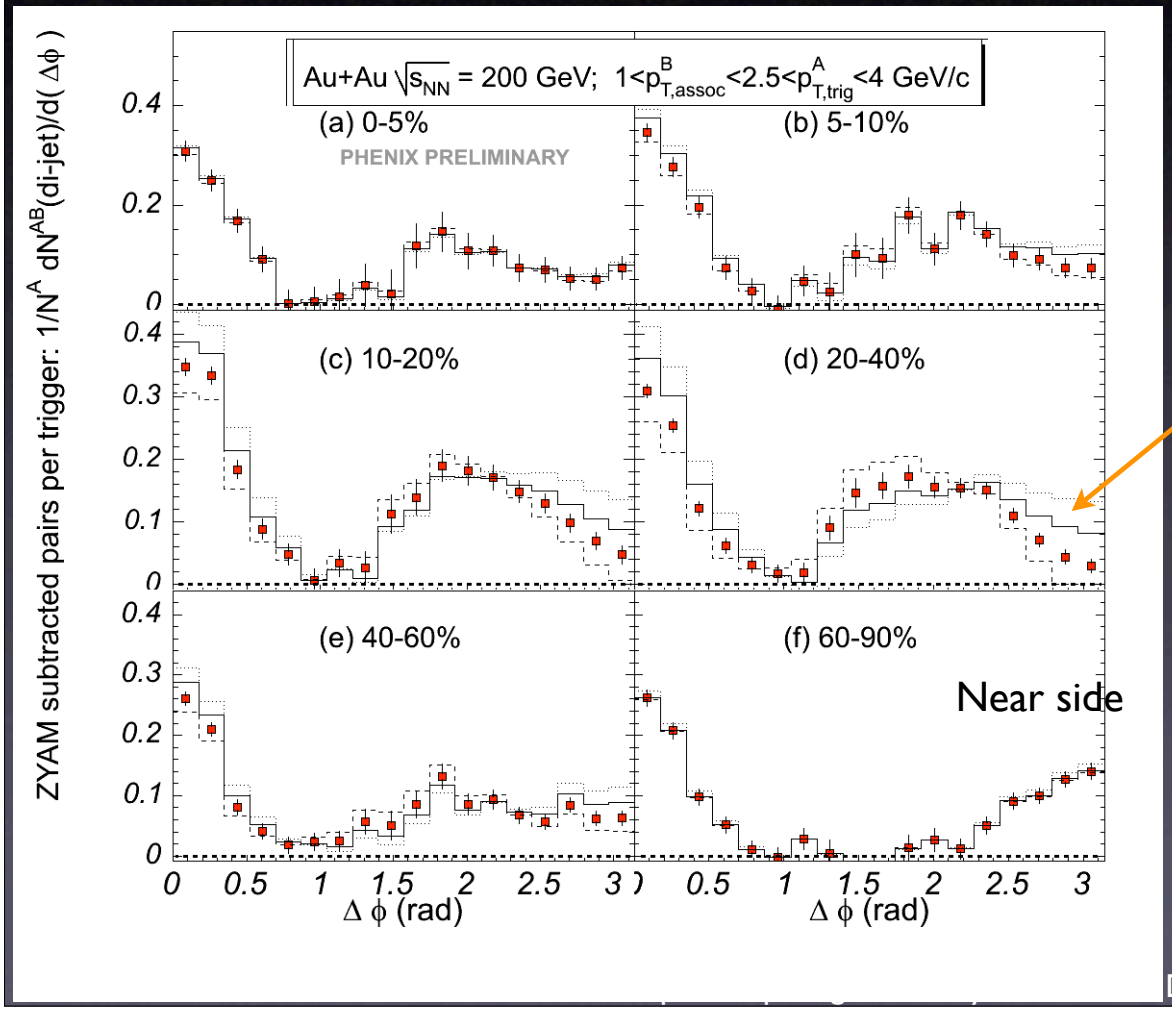
Relative to trigger particle:

- Jet-like near-side correlations visible in Au+Au
- Away-side correlations disappear for central Au+Au



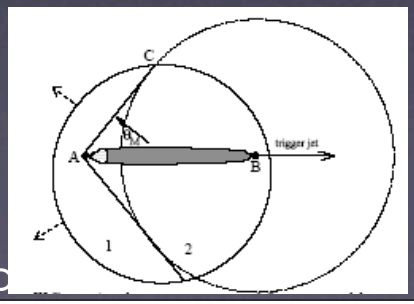
Correlations at not-so-high pT

PHENIX, ICPAQGP '05

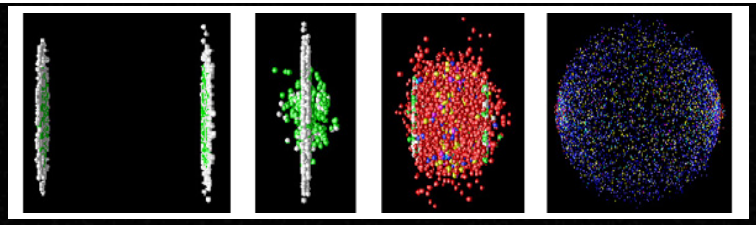


Cone-Structure?

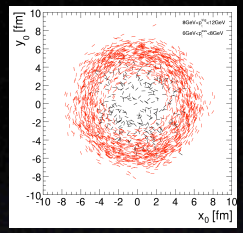
Sonic shock waves
Stoecker, nucl-th0406018
Casalderrey,Shuryak,Teaney, hep-ph/0411315

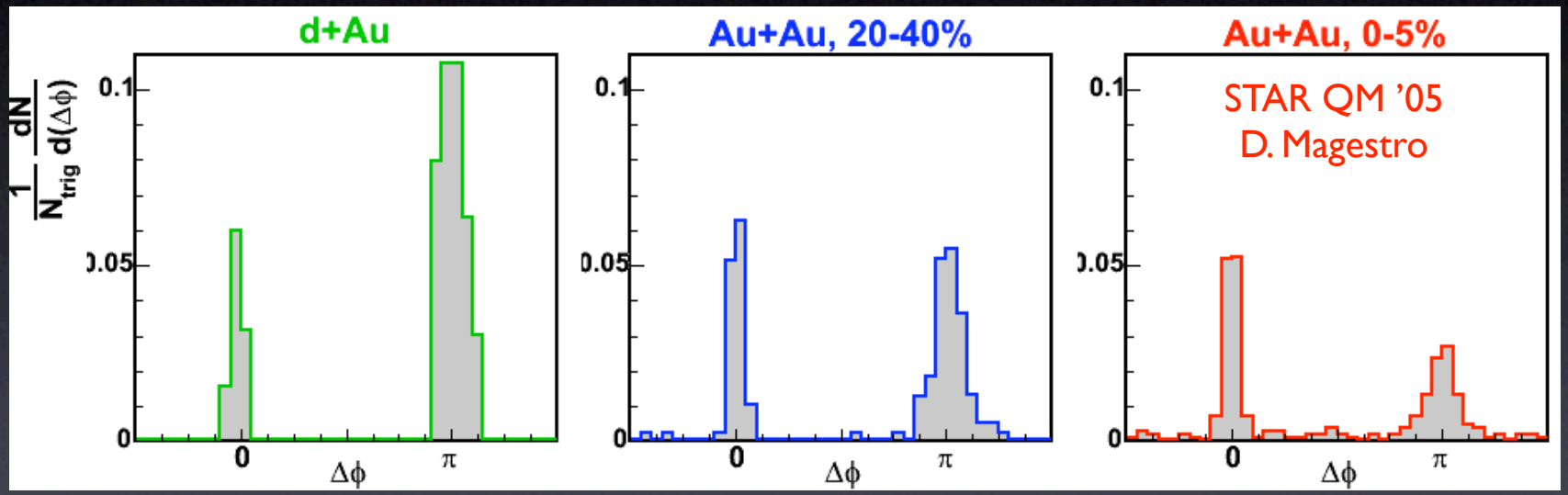


$\cos(\theta)=c_s$



Dainese, Loizides and Paic





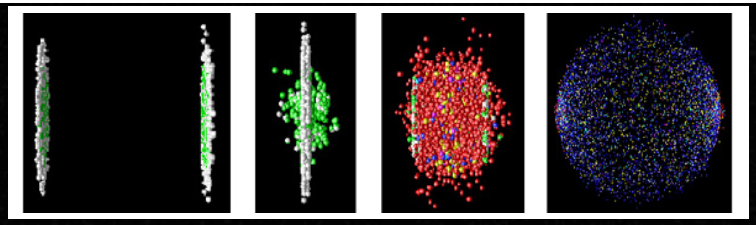
$8 < p_T(\text{trig}) < 15$ GeV/c

$p_T(\text{assoc}) > 8$ GeV/c

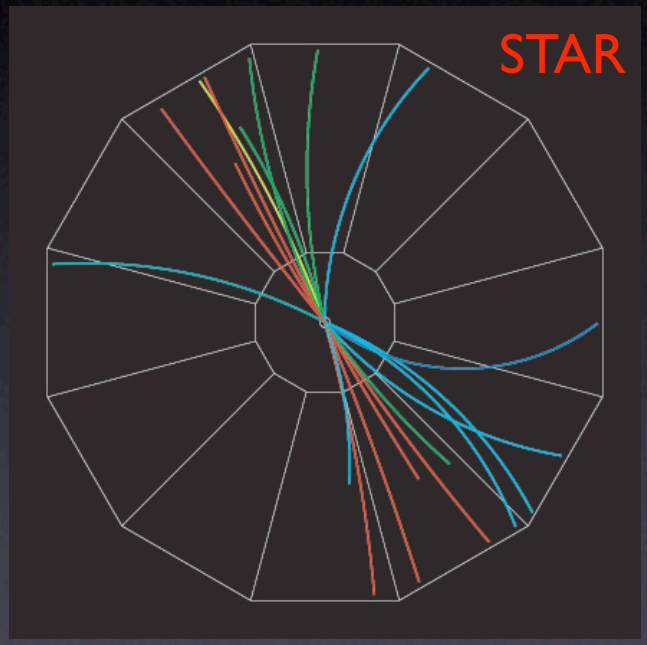
Back-to-back jets re-appear at sufficiently high pT

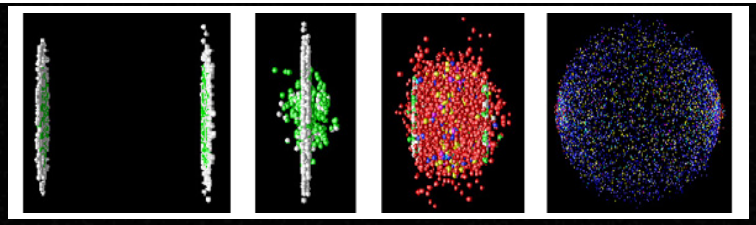
Fragmentation of *observed* jets similar in A+A, p+p

Surface emission?

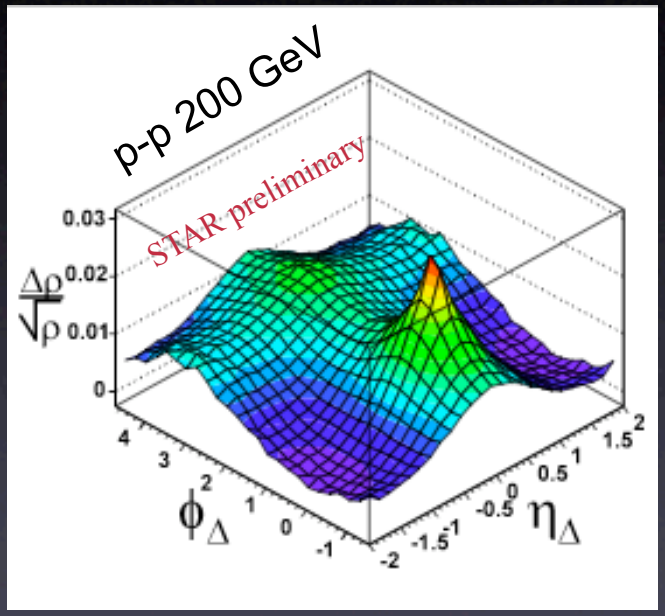


Seeing partons at high pT





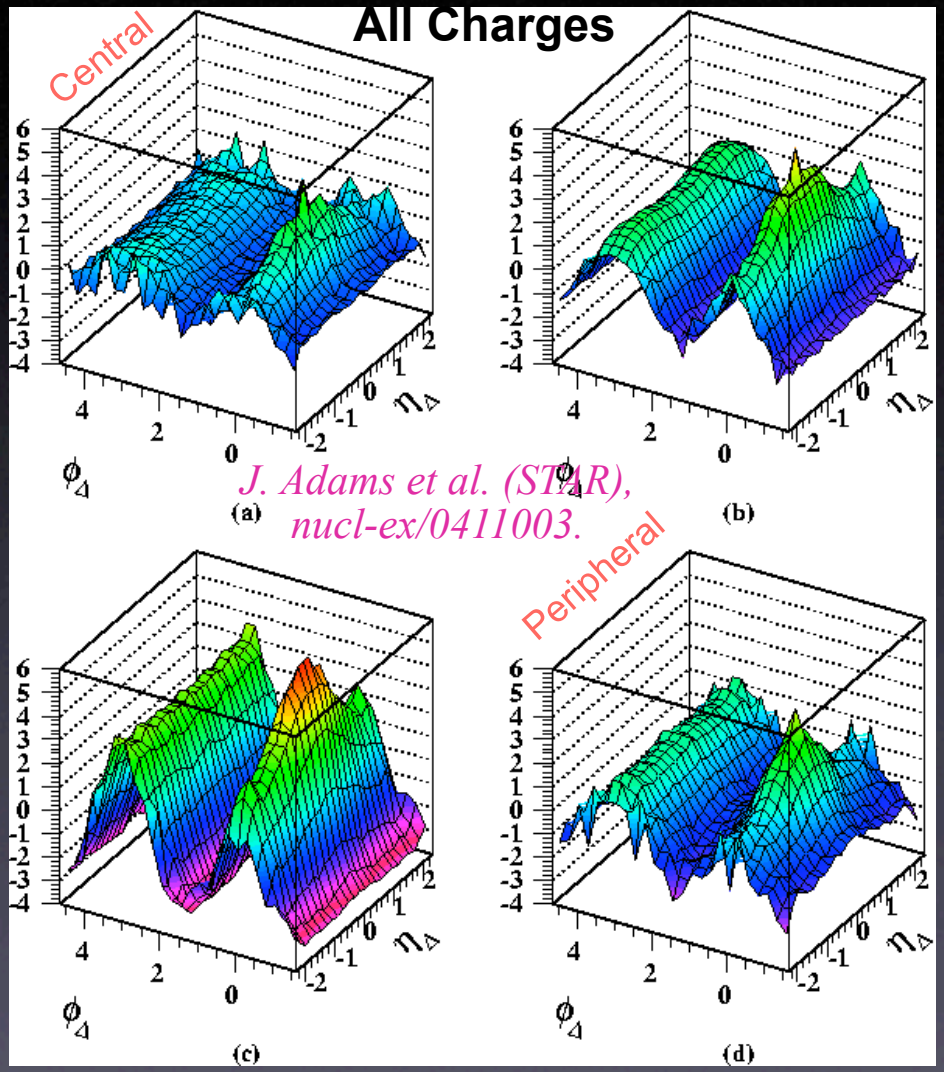
Soft Look at Partons



Tom Trainor, STAR

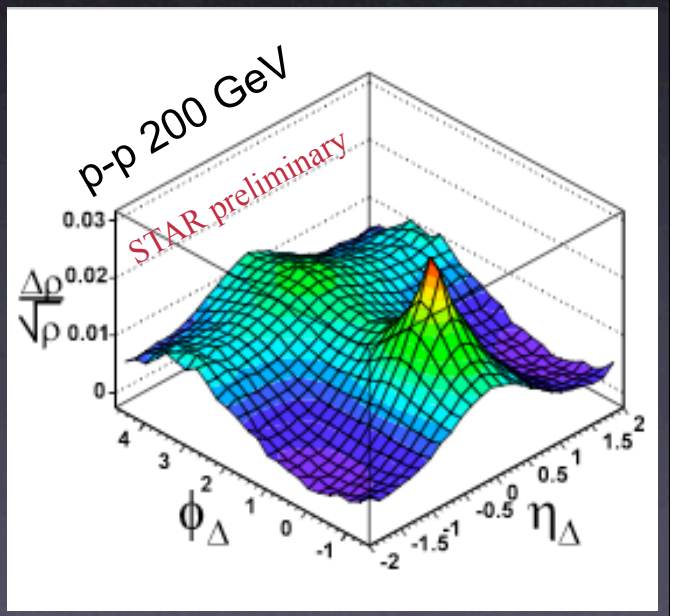
Two-particle angular correlations show rich structure at low to moderate p_T (~GeV/c)

From p+p to Au+Au

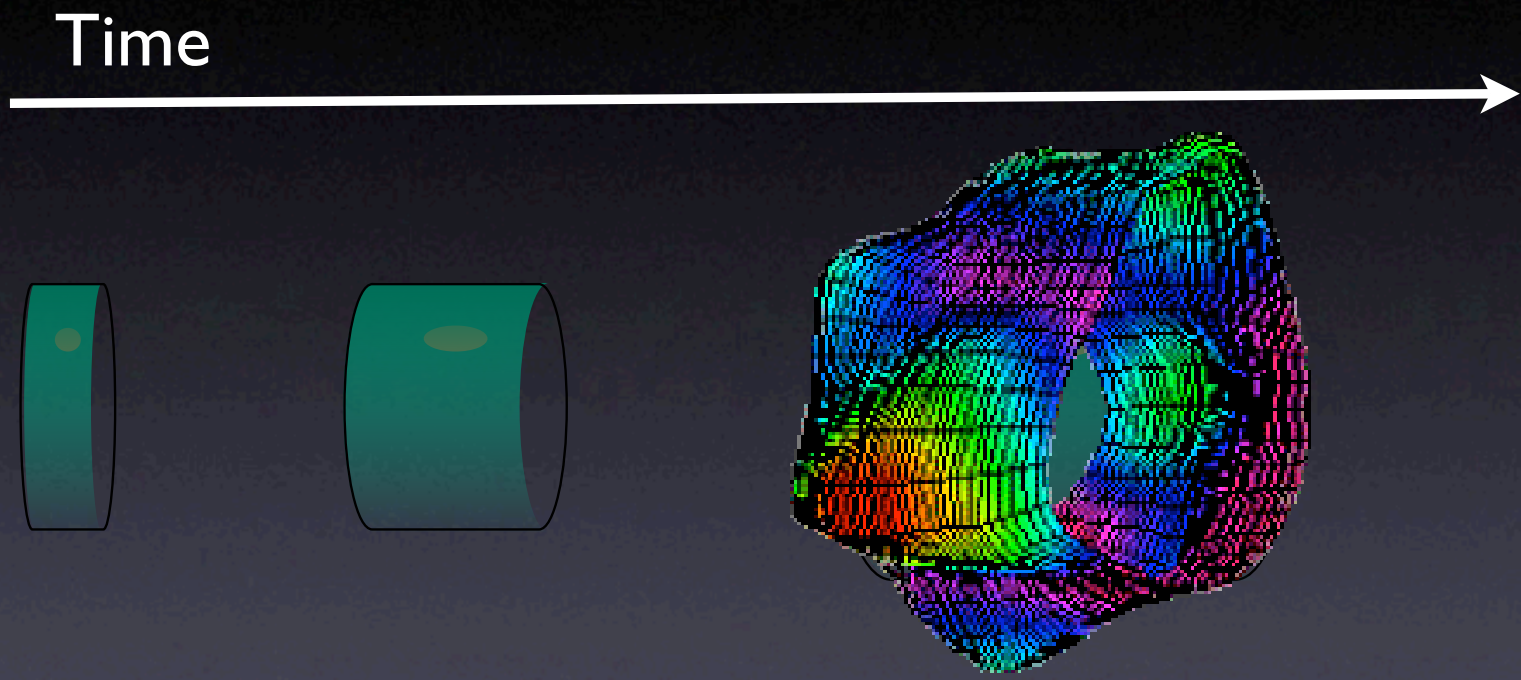


J. Adams et al. (STAR), nucl-ex/0411003.

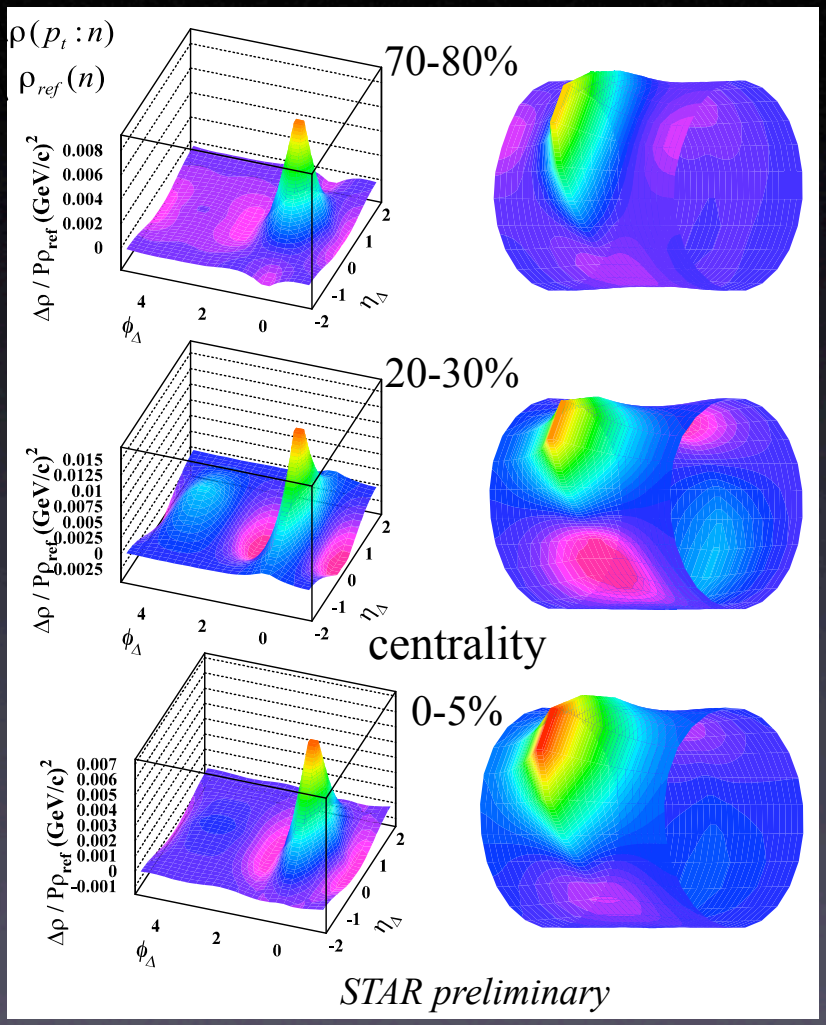
Evolution of Structure from p+p to central Au+Au



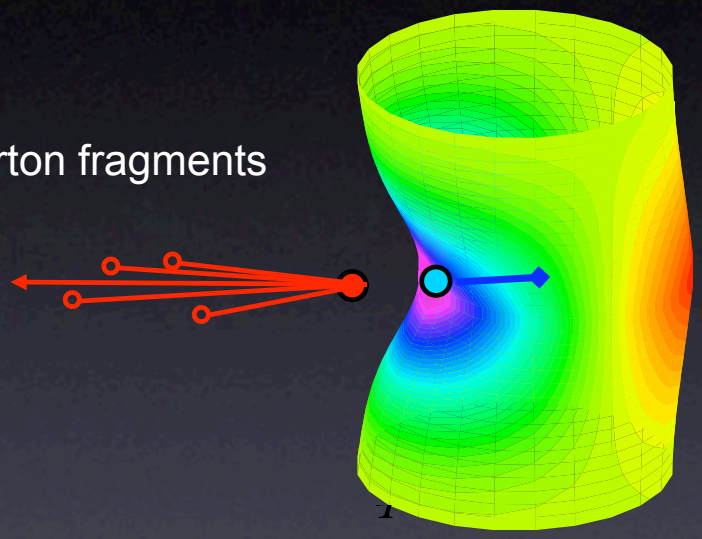
Correlation Probes of the Medium



Momentum Correlations at RHIC

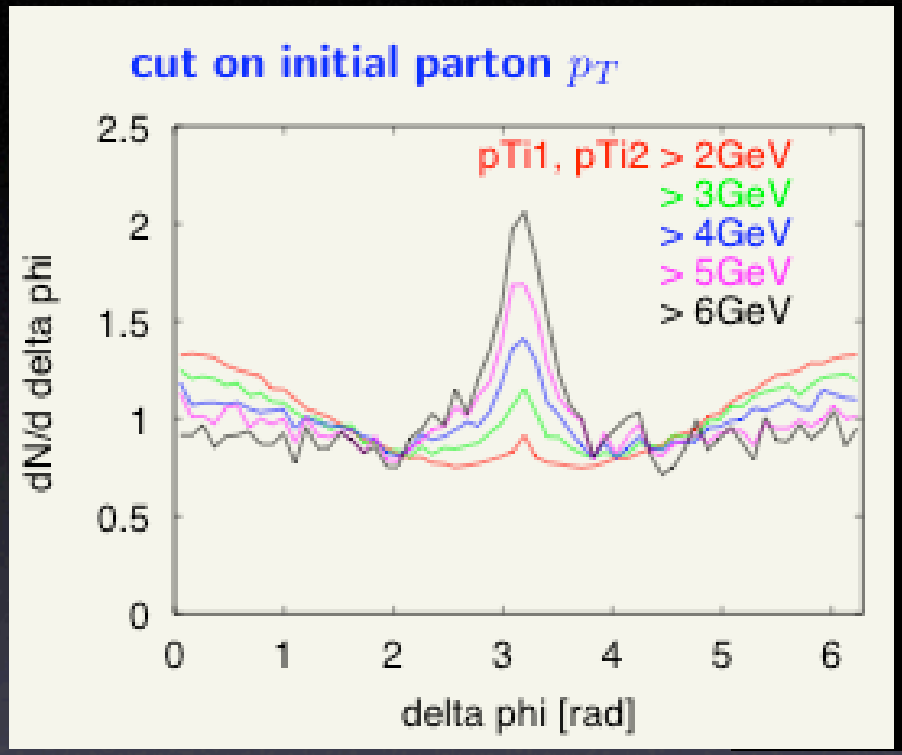


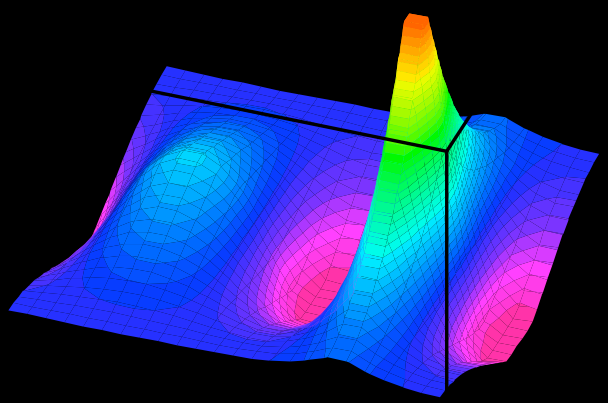
Subtract fragmentation peak to look at medium



"Minijets: *velocity/temperature* correlation structures on (η,ϕ)"

Correlations in Transport Models





Data

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 ...

Summary

- Evolving experimental + theoretical program
  - 'Global' scaling rules
  - Collective flow
  - Search for critical phenomena
  - Connection of correlations + fluctuations
  - Interaction of perturbations with medium
- Initial entropy production
- Fluctuations in small systems?
- Thermalization: How and what?
- What is the role of hadronization?

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

<p_t> Fluctuations

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

where

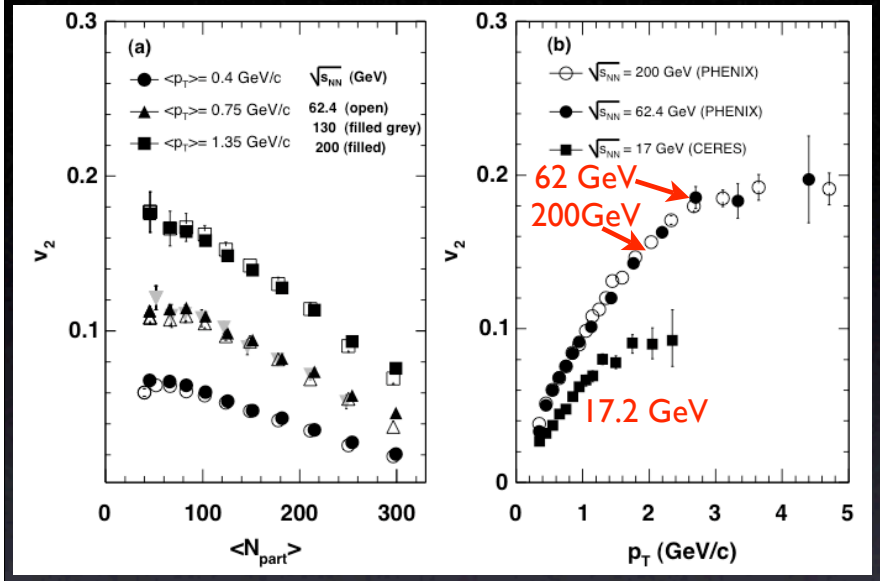
$$C_k = \sum_{i=1}^{N_k} \sum_{j=1, i \neq j}^{N_k} \left(p_{t,i} - \langle \langle p_t \rangle \rangle \right) \left(p_{t,j} - \langle \langle p_t \rangle \rangle \right)$$

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

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

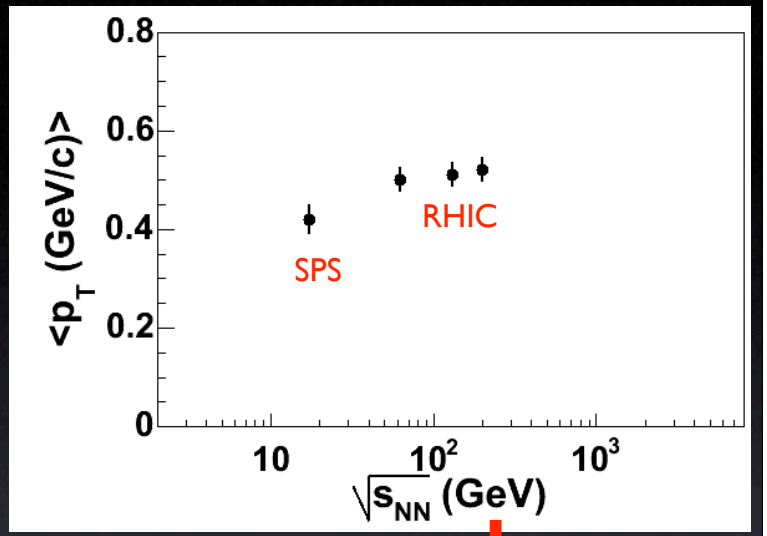
v_2 vs p_T

PHENIX nucl-ex/0411040

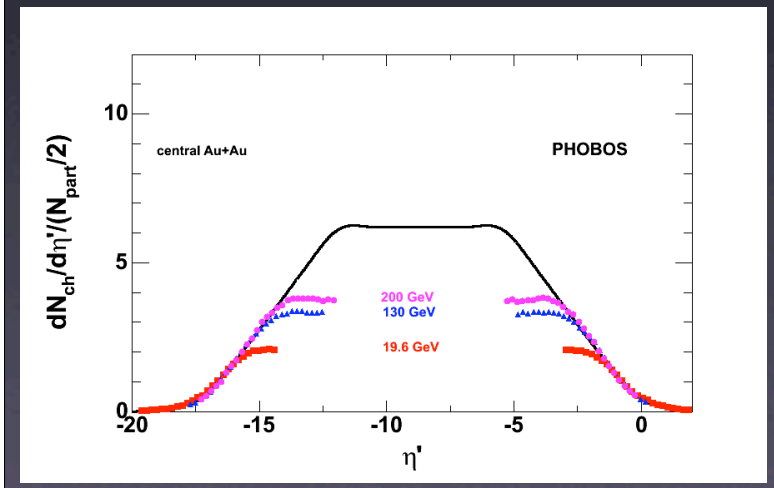


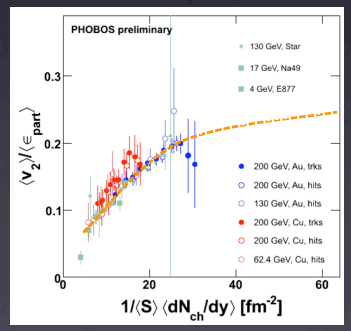
+

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



$dN/d\eta'$ vs $\sqrt{s}$





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