Experimentalist's view on

Fluctuations

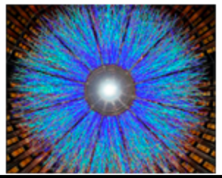
(and correlations)

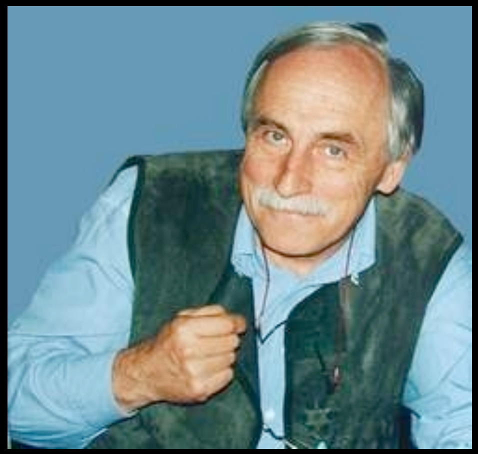
Gunther Roland

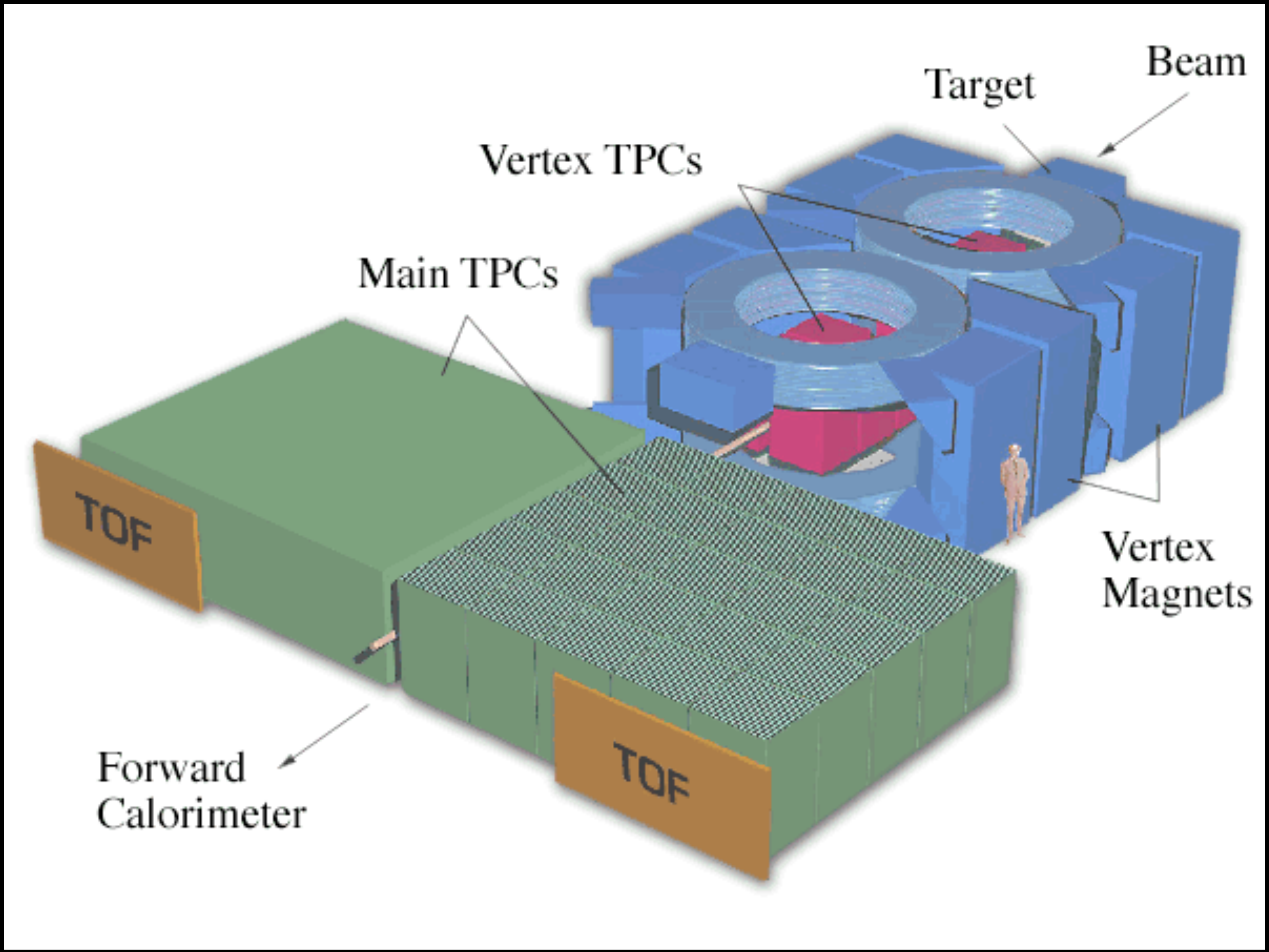
BERKELEY LAB

School of Collective Dynamics in High Energy Collisions

June 7 - 11, 2010

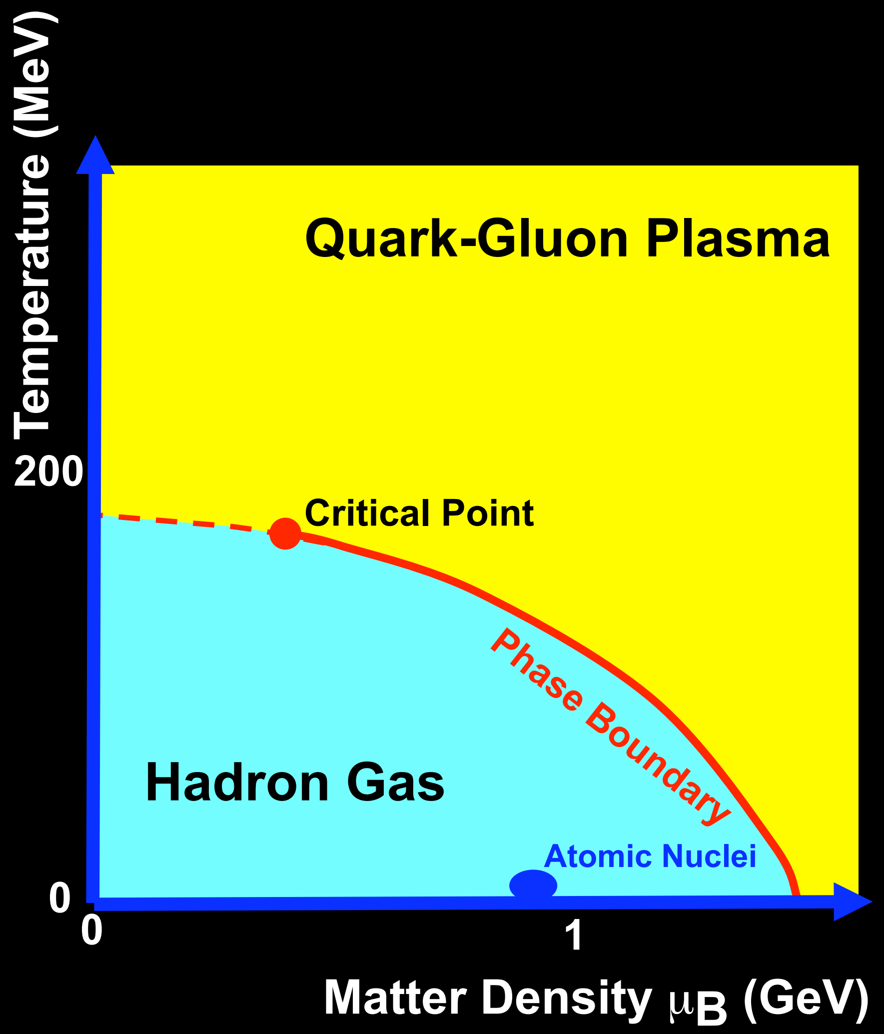






1994: Start of event-by-event fluctuation program

Exploring the QCD Phase Diagram

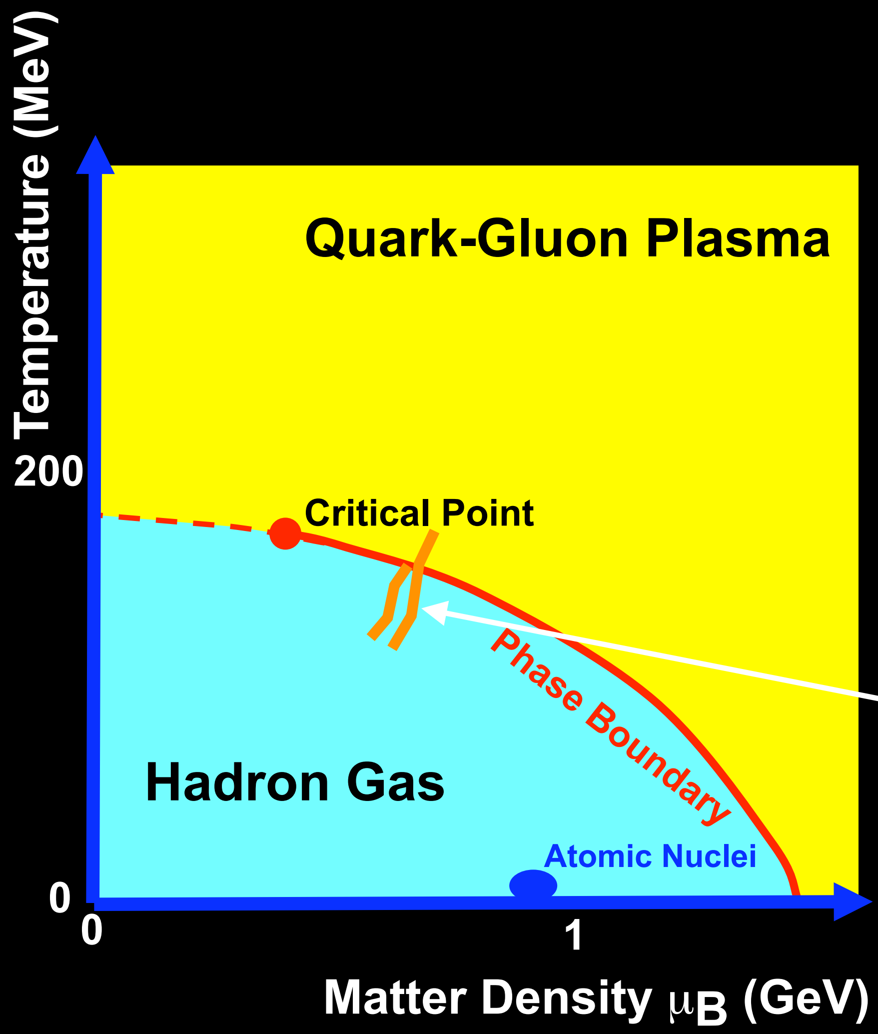


What is the nature of the phase transition?

Is there a critical point (and where is it)?

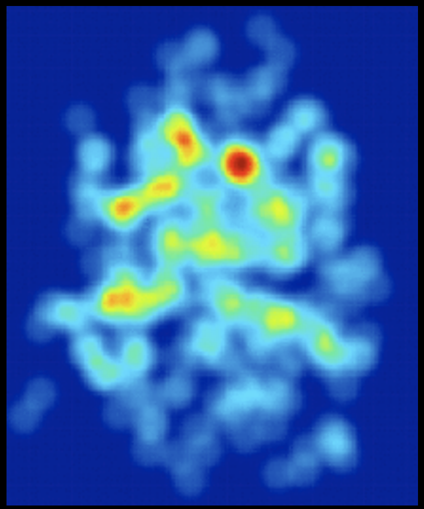
What are the properties of matter at high T?

Event-by-event physics



R. Stock: Even at fixed ($\sqrt{s}$,b) not all collisions created equal: Study collisions event-by-event

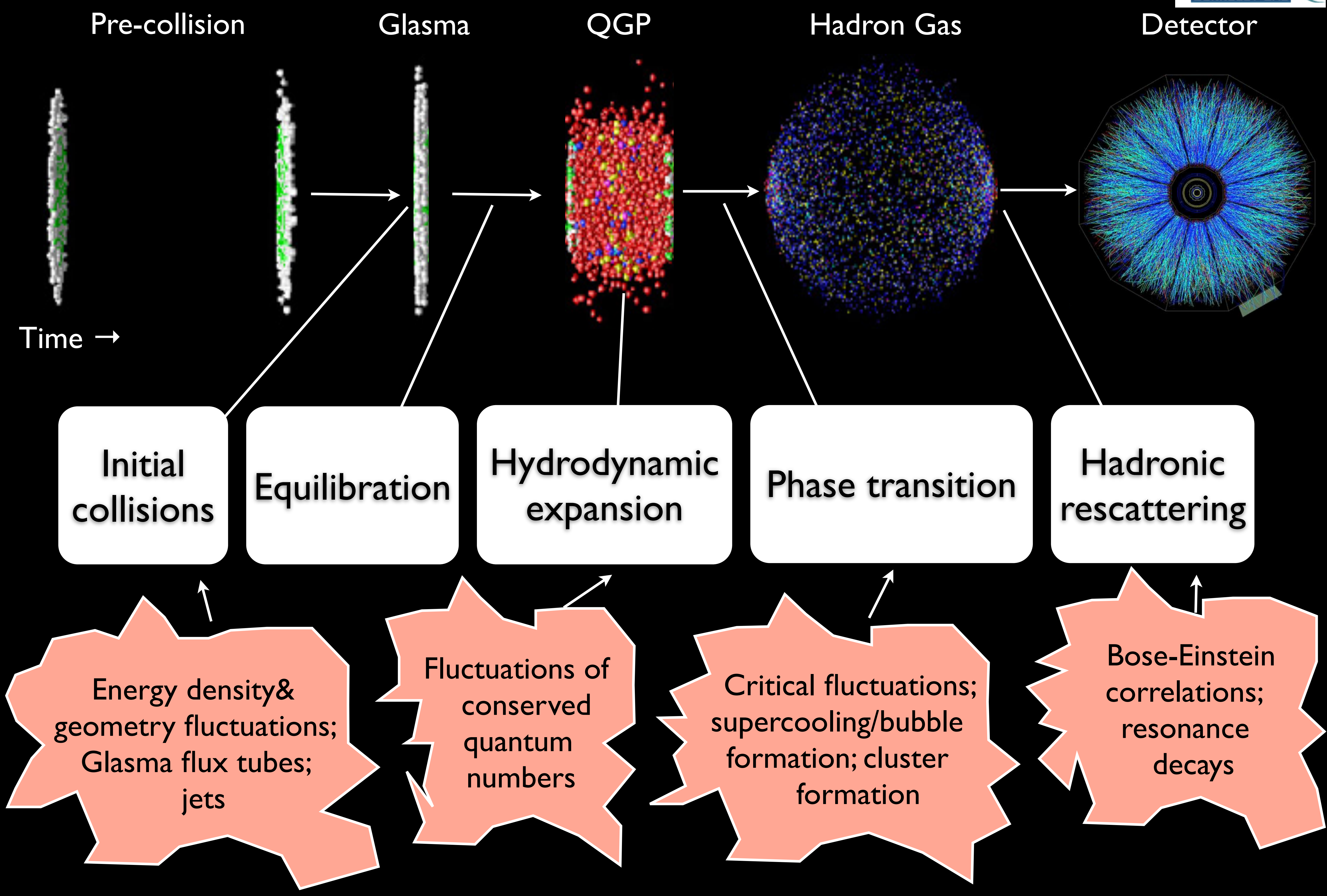
Density of collision points in a single AuAu event (Glauber MC/Mike McCumber)



Collision of two finite systems:

Energy density variation from event to event

Energy density variation within the event



Pre-collision
Glasma
QGP
Hadron Gas
Detector
Time →
Initial collisions
Equilibration
Hydrodynamic expansion
Phase transition
Hadronic rescattering
Energy density& geometry fluctuations; Glasma flux tubes; jets
Fluctuations of conserved quantum numbers
Critical fluctuations; supercooling/bubble formation; cluster formation
Bose-Einstein correlations; resonance decays

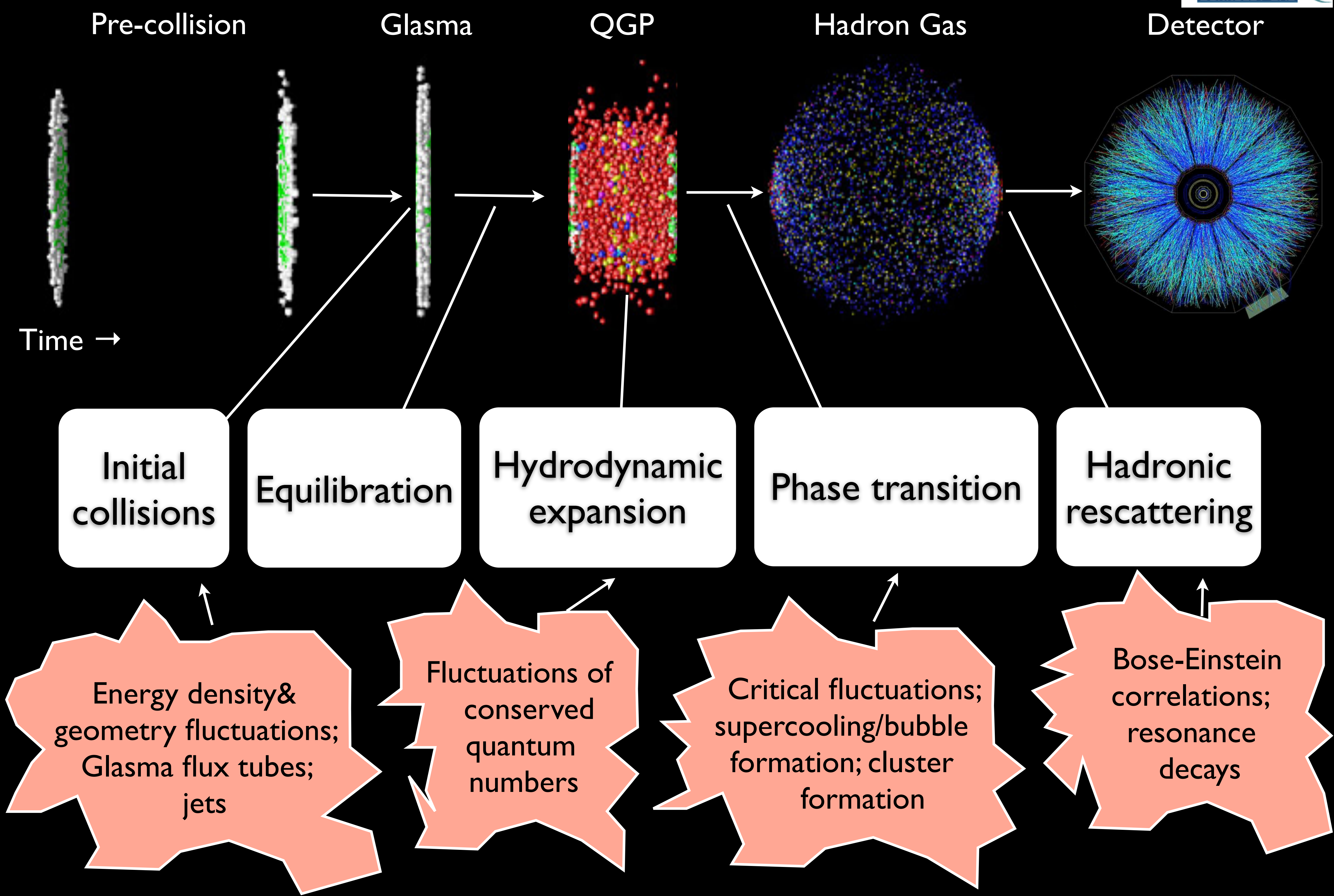
Many potential sources of fluctuations

How are fluctuations modified during system evolution?

Can they be seen/distinguished experimentally?

Initial collisions | Equilibration | Hydrodynamic expansion | Phase transition | Hadronic rescattering

- Energy density& geometry fluctuations; Glasma flux tubes; jets
- Fluctuations of conserved quantum numbers
- Critical fluctuations; supercooling/bubble formation; cluster formation
- Bose-Einstein correlations; resonance decays

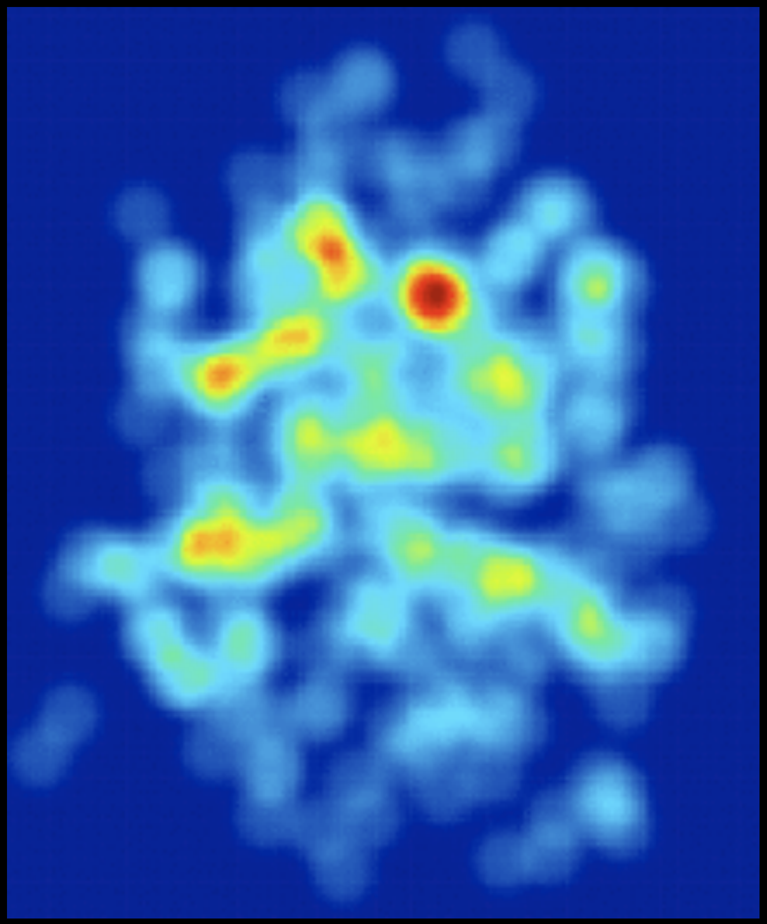

Pre-collision
Glasma
QGP
Hadron Gas
Detector
Time →
Initial collisions
Equilibration
Hydrodynamic expansion
Phase transition
Hadronic rescattering
Energy density& geometry fluctuations; Glasma flux tubes; jets
Fluctuations of conserved quantum numbers
Critical fluctuations; supercooling/bubble formation; cluster formation
Bose-Einstein correlations; resonance decays

Fluctuations in the intial stage

Glasma

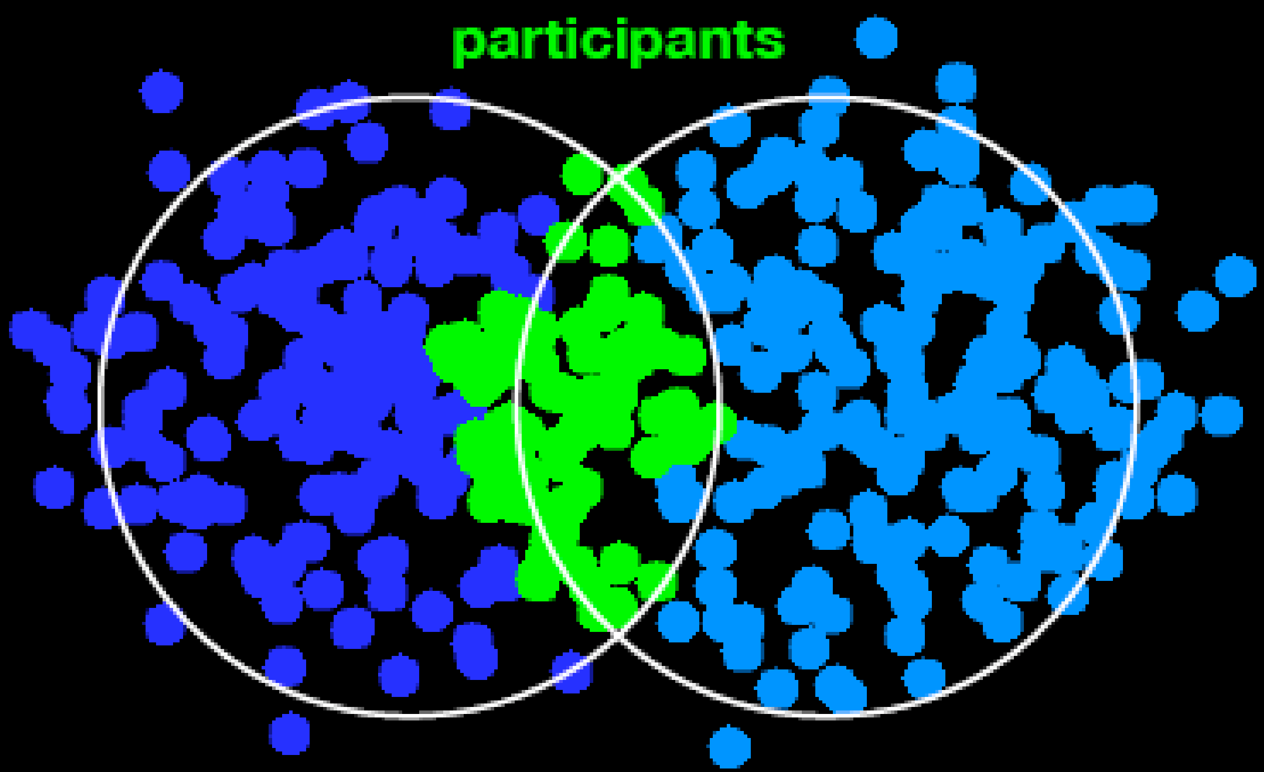
Initial collisions

Energy density&
geometry fluctuations;
Glasma flux tubes;
jets



Fluctuations in the intial stage

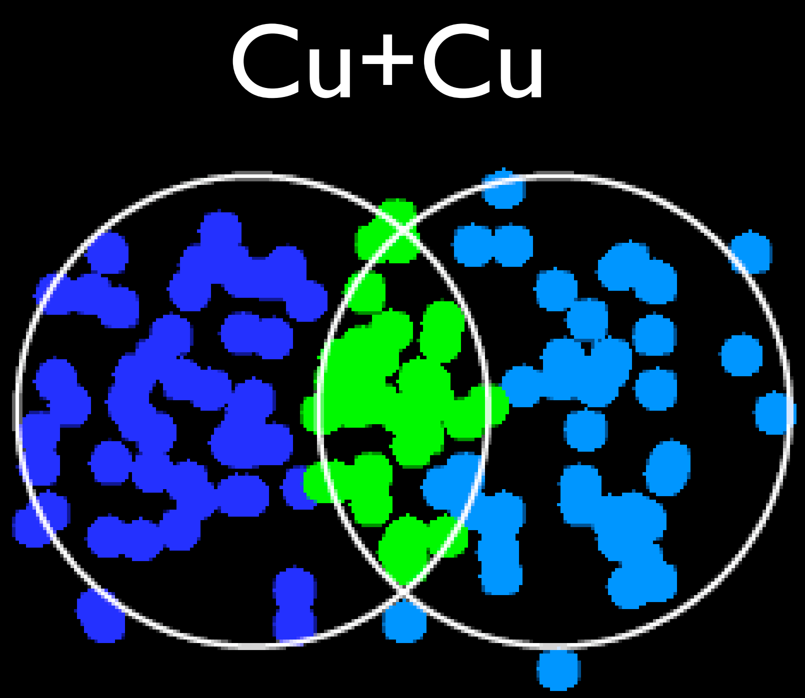
At fixed *b*



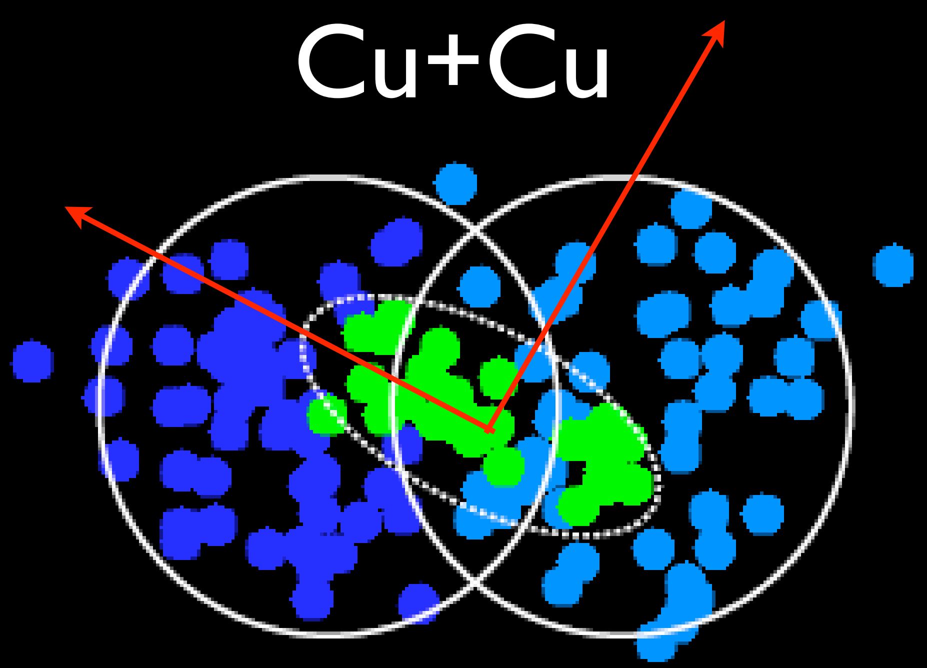
In Glauber MC model, geometry is sampled by finite number of nucleons → Geometry varies from event-to-event, even at fixed *b*

Aguiar, Hama, Kodama, Osada, hep-ph/0106266 (QM 2001)
Miller, Snellings, nucl-ex/0312008

Fluctuations in the intial stage



Plots from Richard Bindel, Maryland,
using PHOBOS Glauber MC



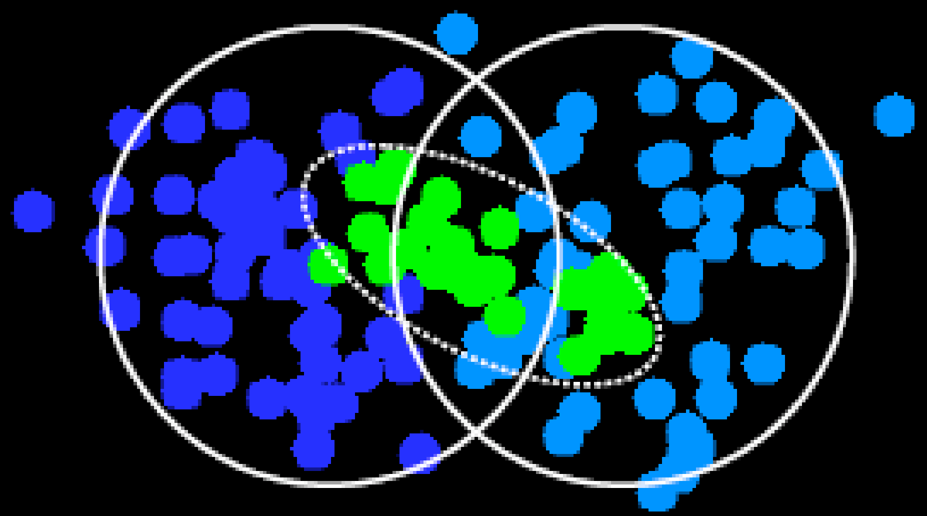
$$\epsilon_{part} = \frac{\sigma_y'^2 - \sigma_x'^2}{\sigma_y'^2 + \sigma_x'^2} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4(\sigma_{xy}^2)^2}}{\sigma_y^2 + \sigma_x^2}$$

"Participant Eccentricity"

PHOBOS 2005, see also
Broniowski et al, arXiv:0706.4266

If flow is driven by initial matter distribution,
the orientation (and shape) of that distribution
should determine direction and magnitude of flow

Cu+Cu



How do we know the Glauber shapes and shape fluctuations are real?

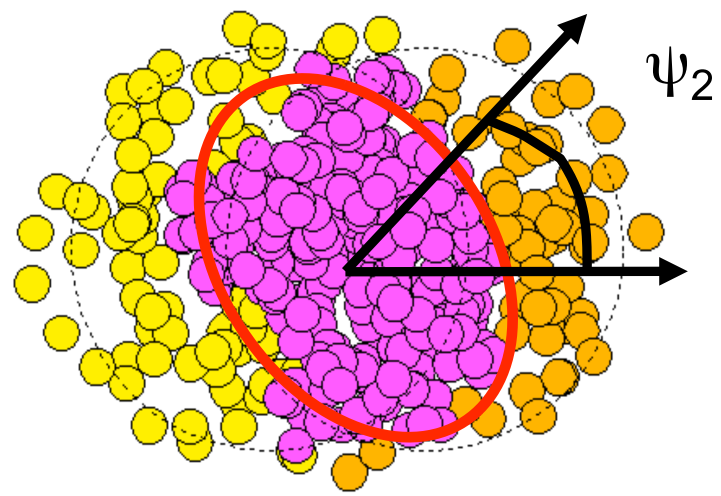
Measure them directly!
If $v_2 \propto \varepsilon$, then:

$$\frac{\sigma(v_2)}{\langle v_2 \rangle} = \frac{\sigma(\varepsilon)}{\langle \varepsilon \rangle}$$

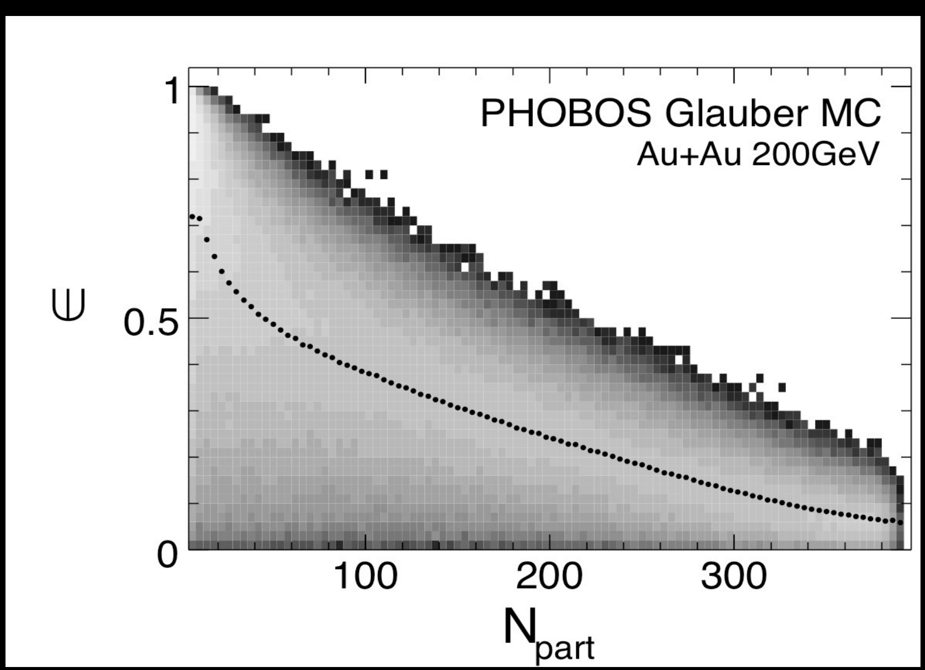
i.e. relative fluctuations in v_2 should be determined by relative fluctuations in ε

Shape Fluctuations

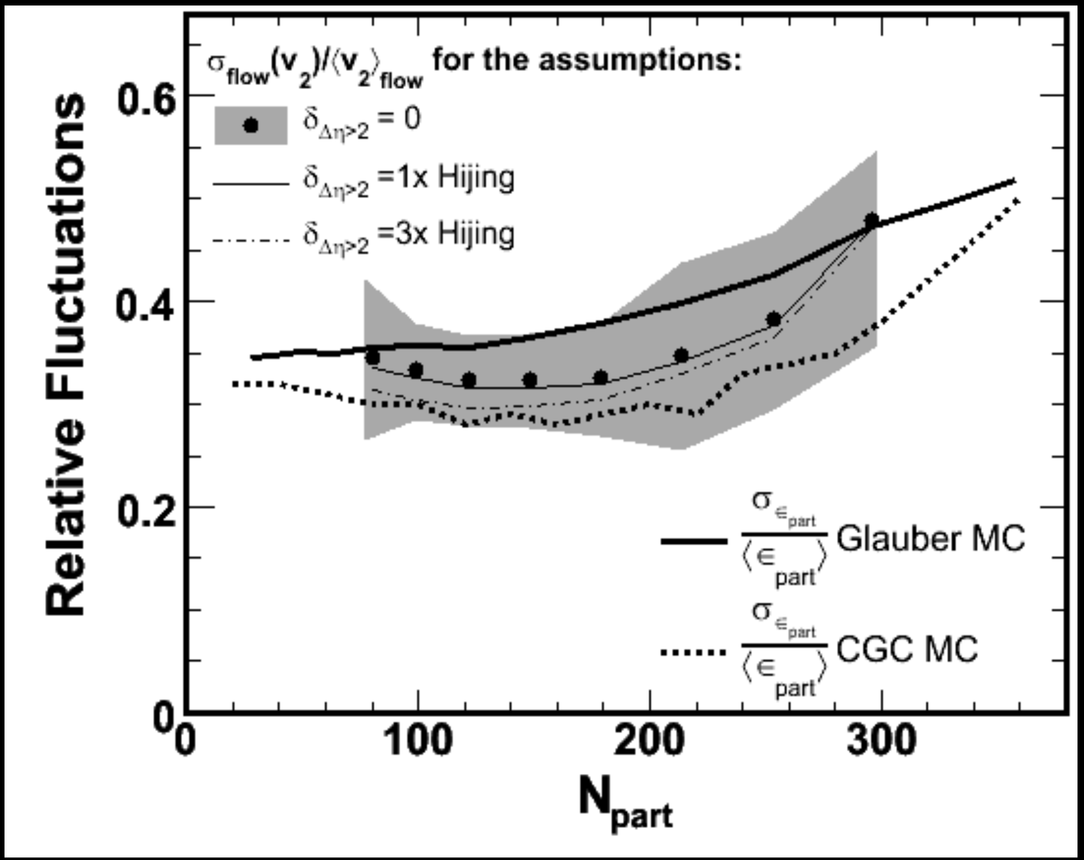
Participant Eccentricity



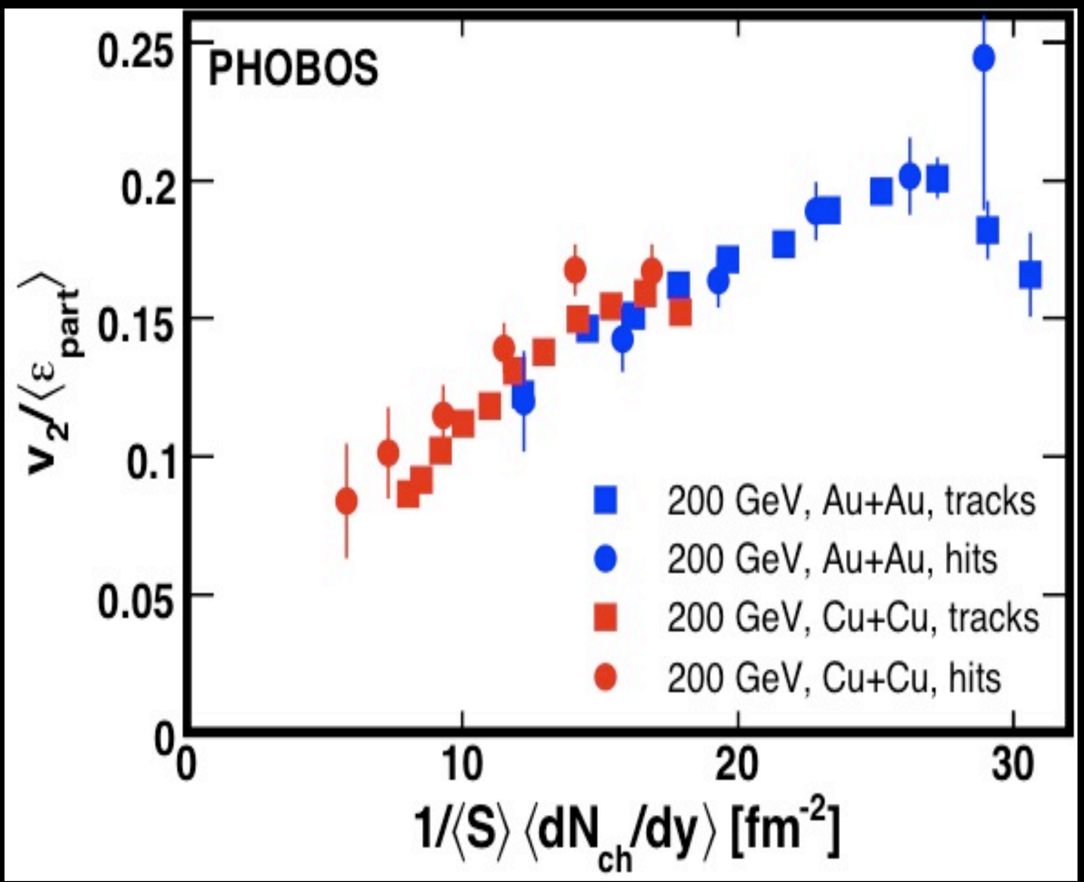
$$\varepsilon = \frac{\sqrt{\left\langle \left(r^2 \cos(2\phi) \right) \right\rangle^2 + \left\langle \left(r^2 \sin(2\phi) \right) \right\rangle^2}}{\left\langle r^2 \right\rangle}$$



PHOBOS PRL 104, 142301 (2010)
PHOBOS PRC81, 034915 (2010)

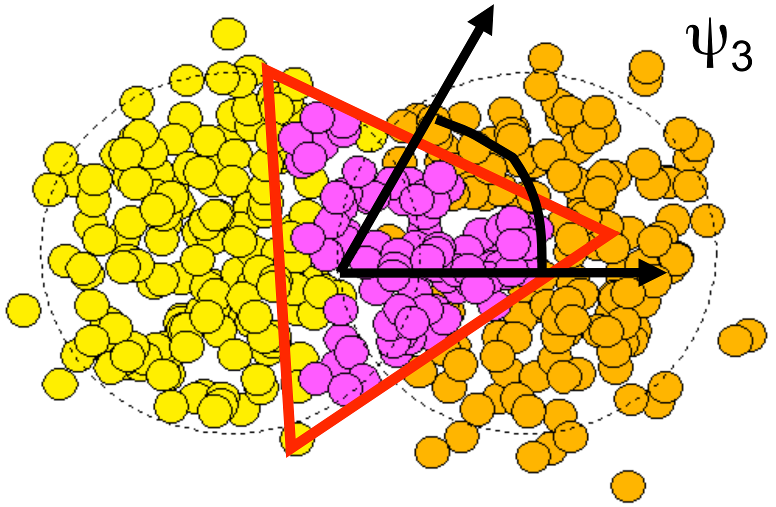


PHOBOS PRL 98, 242302 (2007)

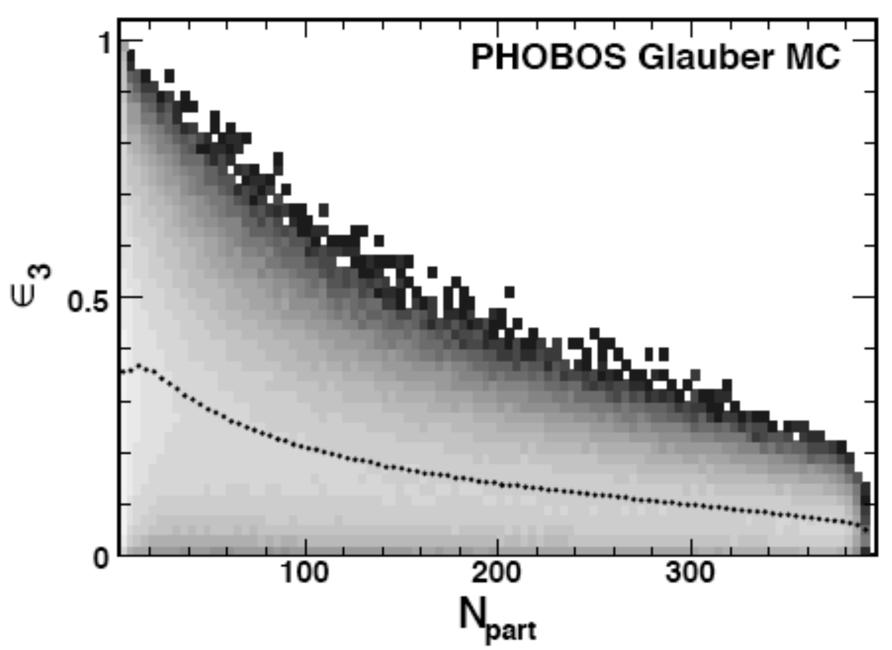


Shape Fluctuations

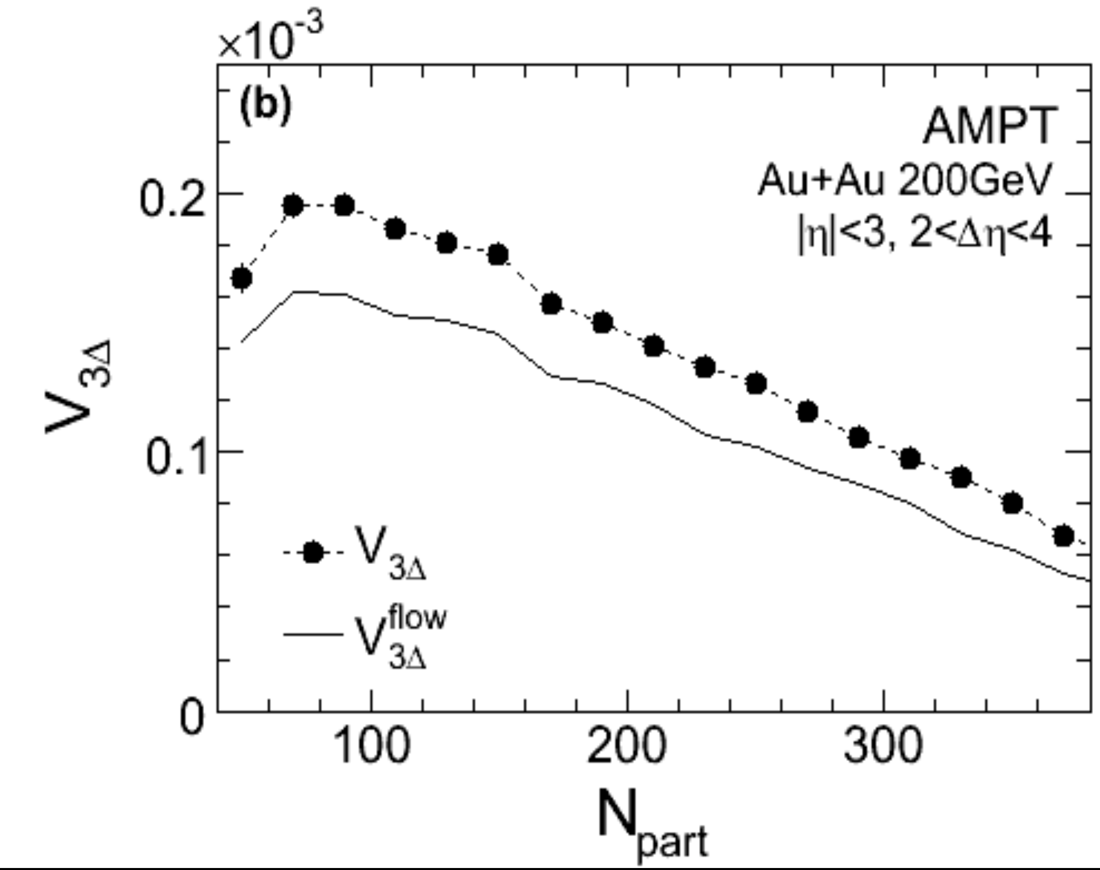
Participant Triangularity



$$\varepsilon_3 = \frac{\sqrt{\left\langle \left(r^2 \cos(3\phi)\right)\right\rangle^2 + \left\langle \left(r^2 \sin(3\phi)\right)\right\rangle^2}}{\left\langle r^2 \right\rangle}$$

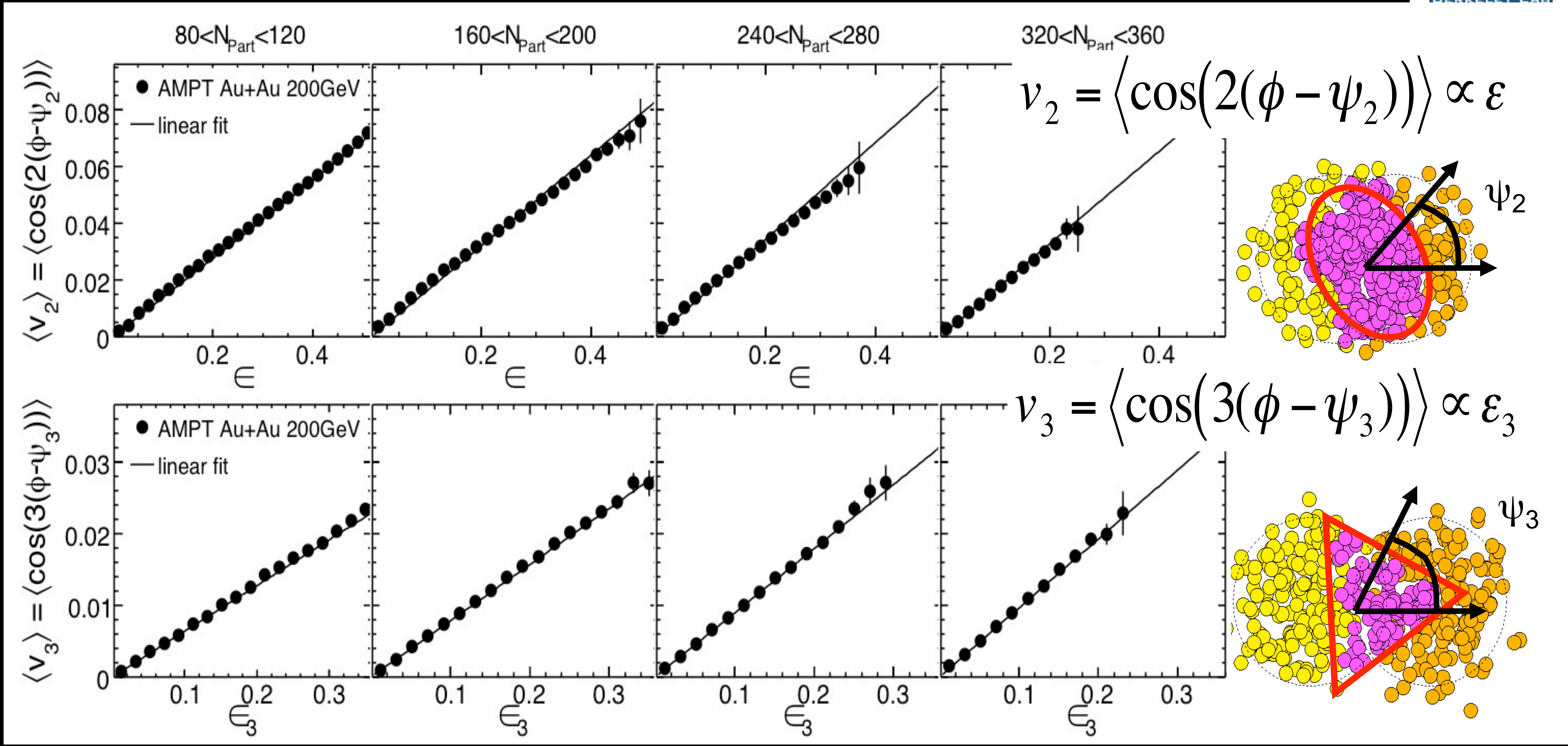


Burak Alver, GR, arXiv:1003.0194
(PRC in press)



Just like elliptic flow reflects event-by-event eccentricity, "triangular flow" (v_3) reflects event-by-event "triangularity" (ε_3)

Elliptic and triangular flow

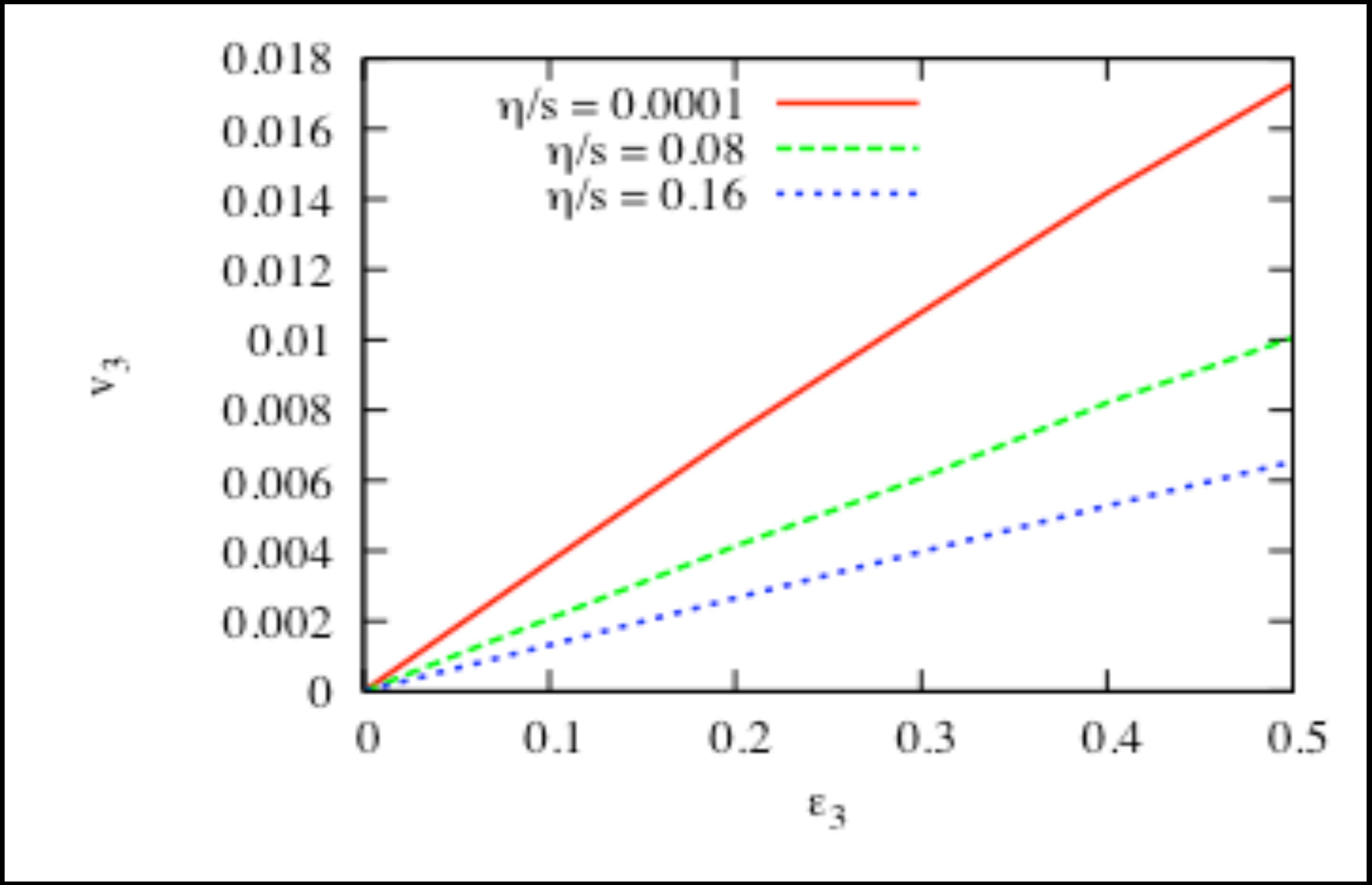


$$v_2 = \left\langle \cos\left(2(\phi - \psi_2)\right)\right\rangle \propto \varepsilon$$

$$v_3 = \left\langle \cos\left(3(\phi - \psi_3)\right)\right\rangle \propto \varepsilon_3$$

Burak Alver, GR, arXiv:1003.0194 (PRC in press)

Triangular Flow

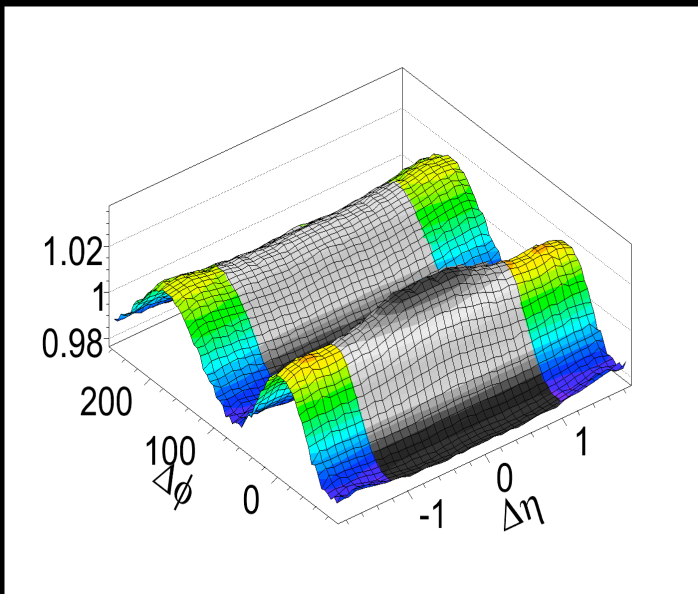


Triangular flow in hydro calculations, not just AMPT
Luzum, Ollitrault, private communication

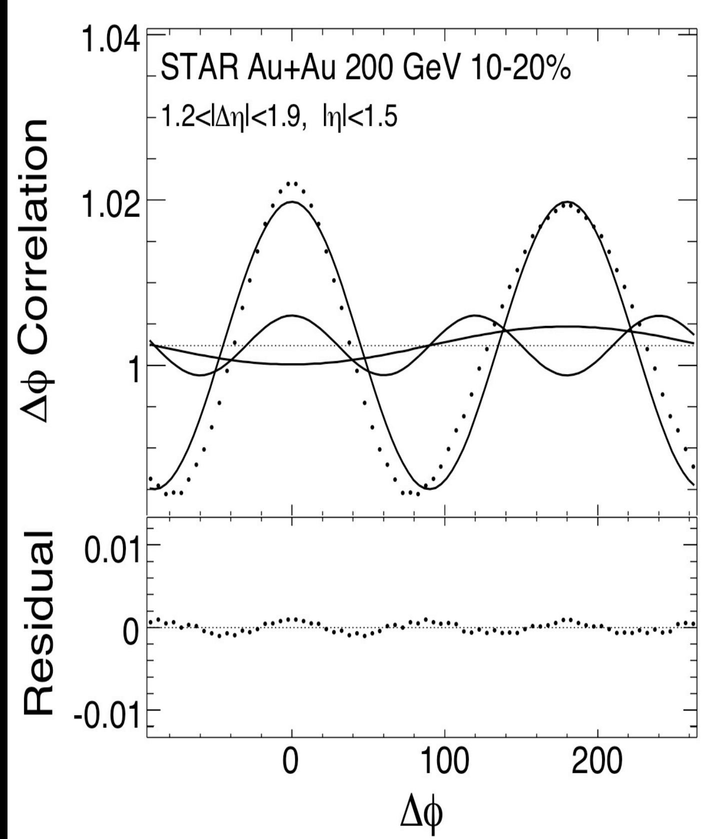
Comparison to published data

Burak Alver, GR, arXiv:1003.0194 (PRC in press)

Inclusive correlations

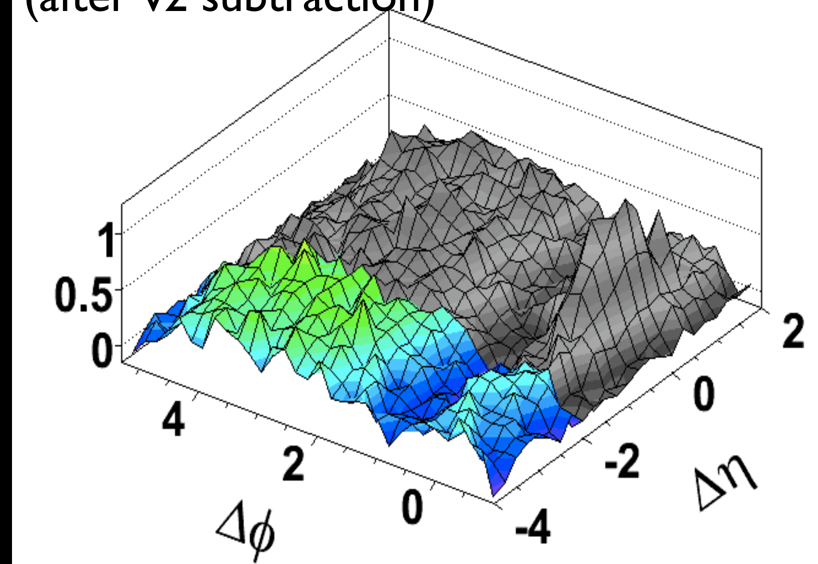


arXiv:0806.0513

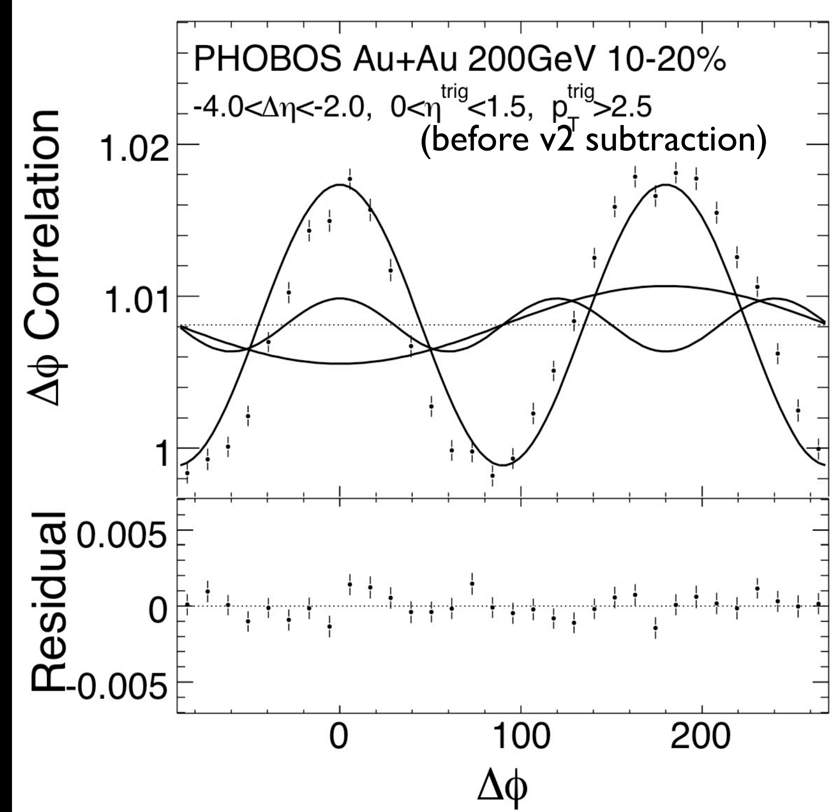


Triggered correlations

(after v2 subtraction)



PRL 104, 06230 (2010)



n.b. Ψ2 and Ψ3 are uncorrelated - triangular flow is not visible in v_2 event plane analysis

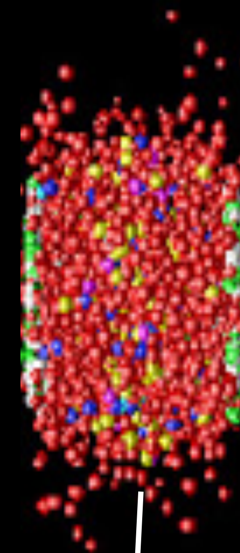
Published correlation data (STAR, PHOBOS) show v_3 component!

Flow contribution to long-range "ridge" and "broad away-side"

This is purely a fluctuation effect - no fluctuations, no v_3!

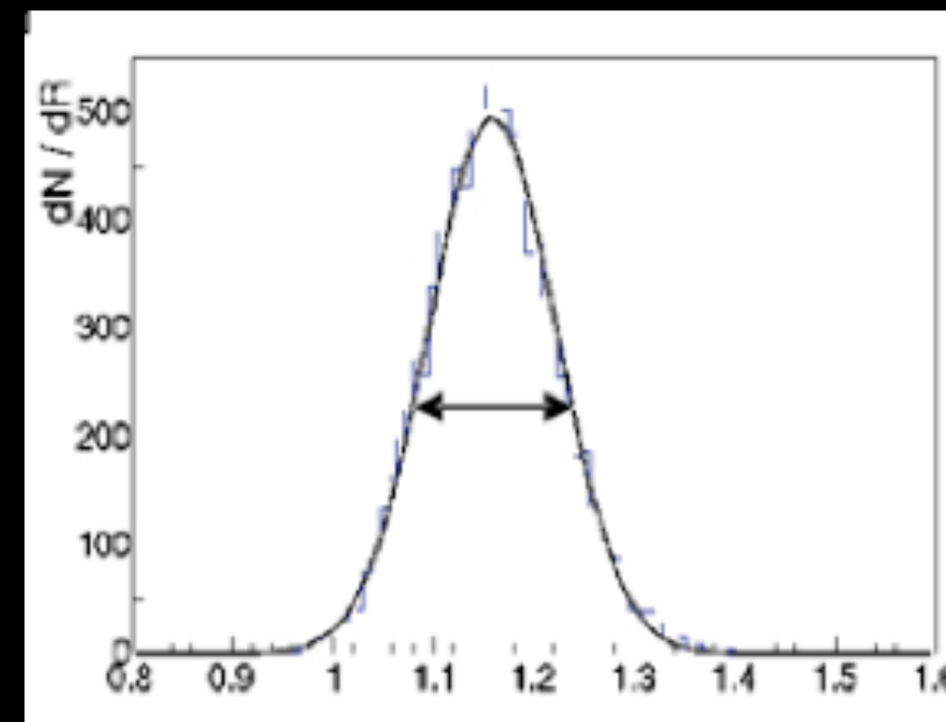
Fluctuations of Conserved Charges

QGP



Hydrodynamic expansion

Fluctuations of conserved quantum numbers



Event-by-event distribution of net charge ratio

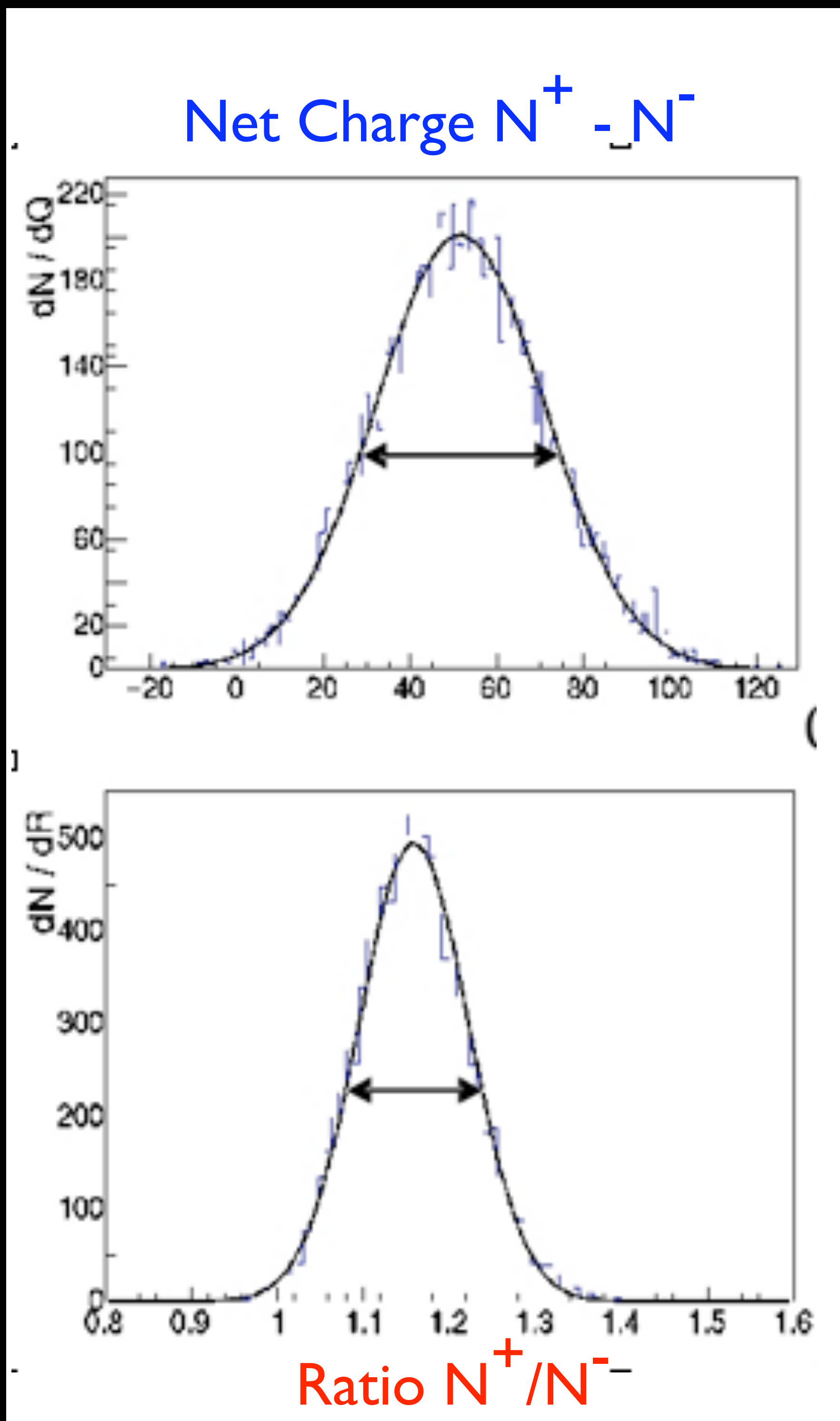
- Net Charge/Δy Fluctuations ⇔ Charge/DoF
  - Fluc's change from 1-2 (QGP) to 4 (Pion Gas)
- Fluctuations frozen b/c charge conservation
  - Diffusion vs Expansion timescale

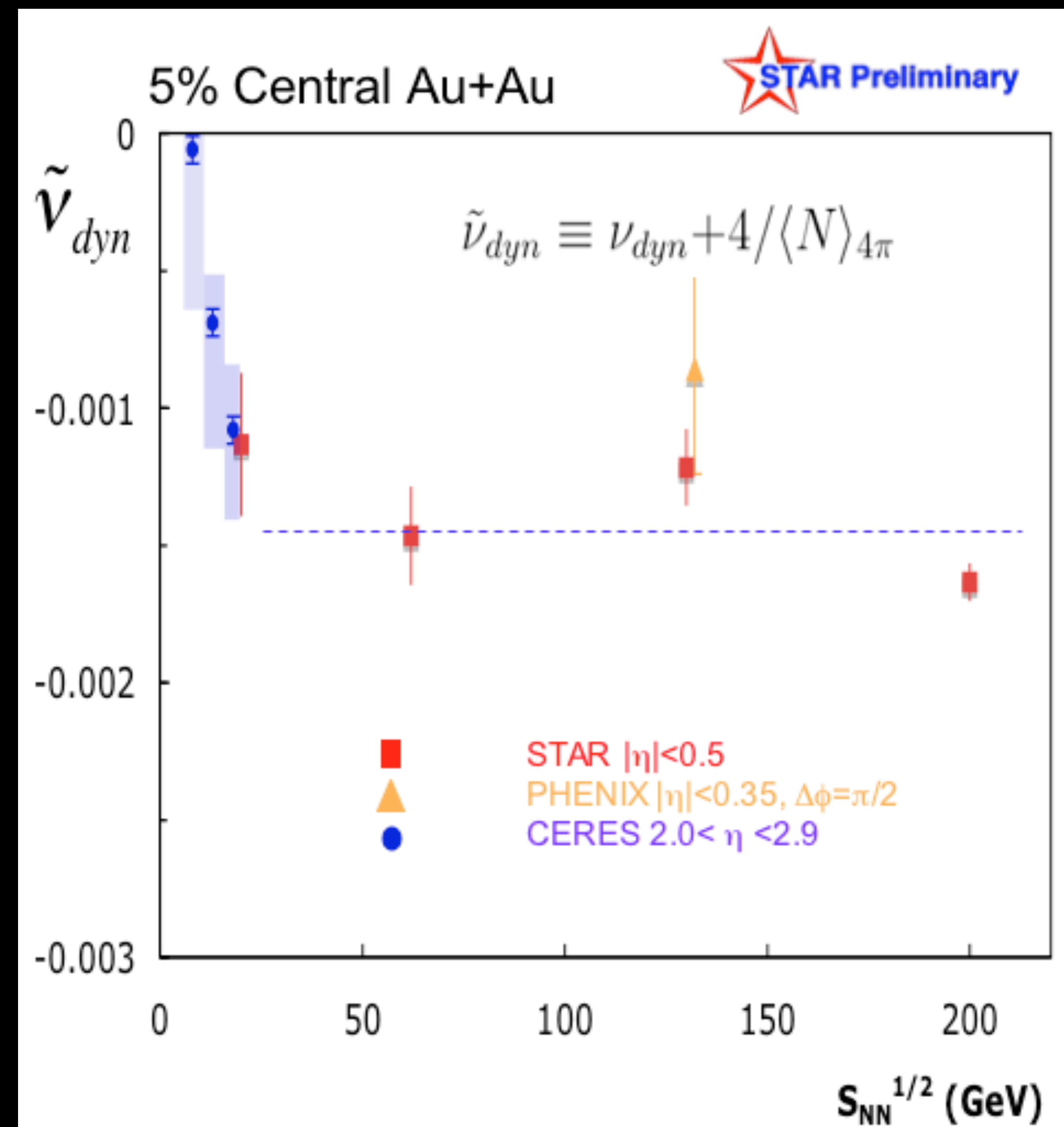
Jeon, Koch PRL (2000) hep-ph/0003168
Asakawa, Heinz, Mueller PRL (2000) hep-ph/0003169

Complete absence of signal in data

Plot from Claude Pruneau
RHIC Users meeting workshop '04

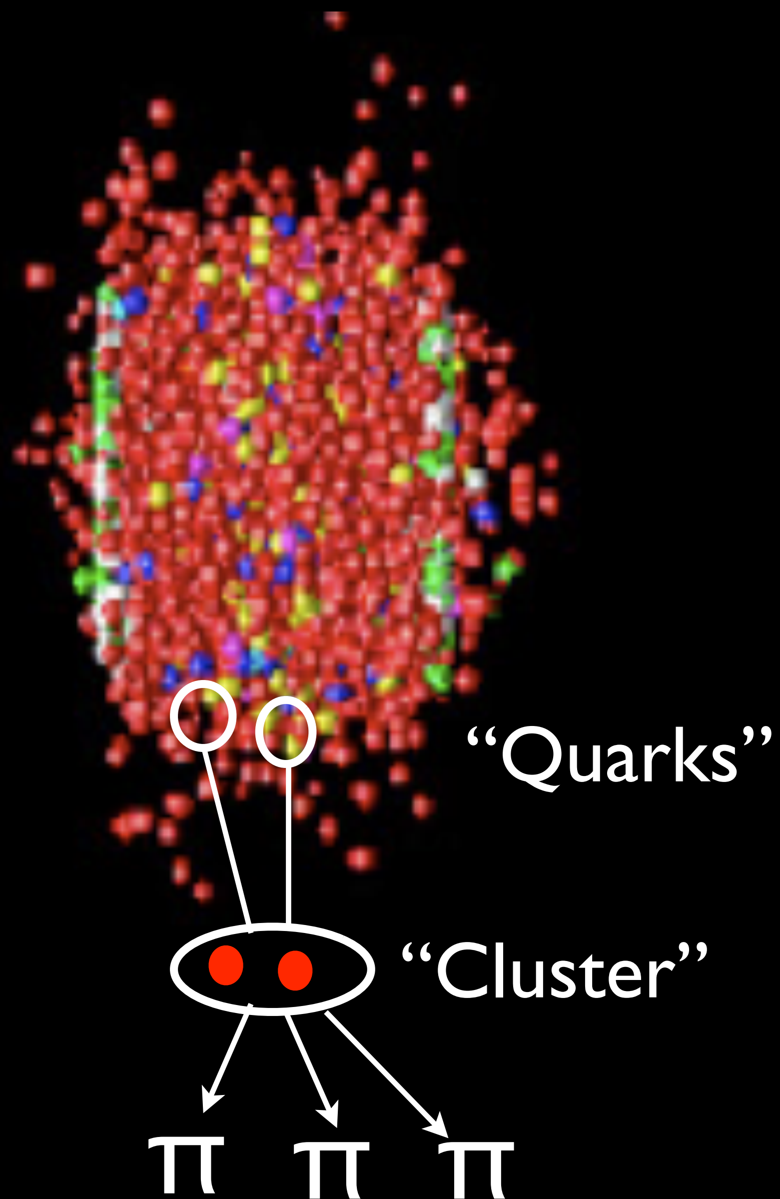
PHENIX: PRL 89 082301 (2002)



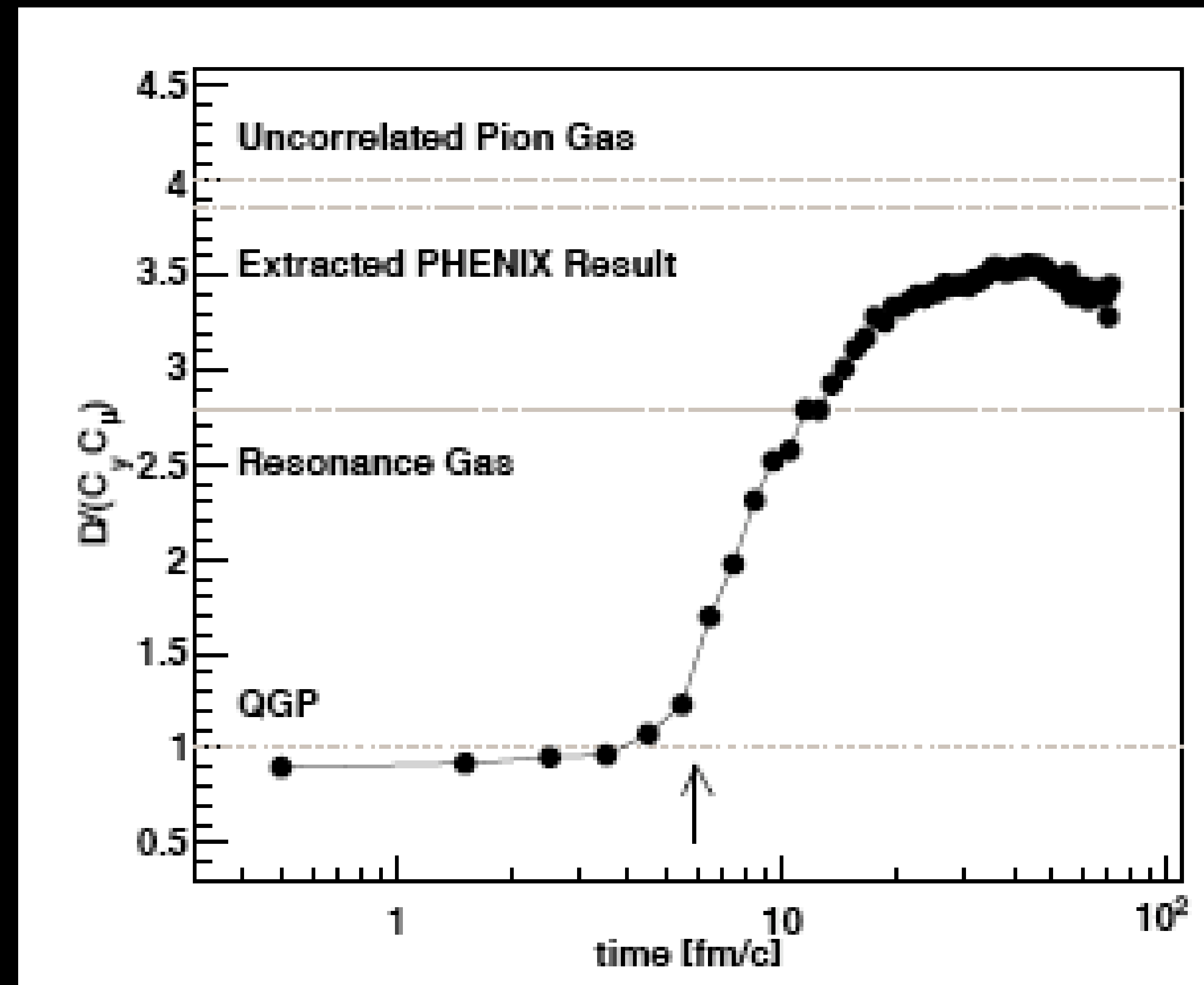


QGP

Hadronization via Recombination



Haussler, Scherer, Bleicher, hep-ph/0702188

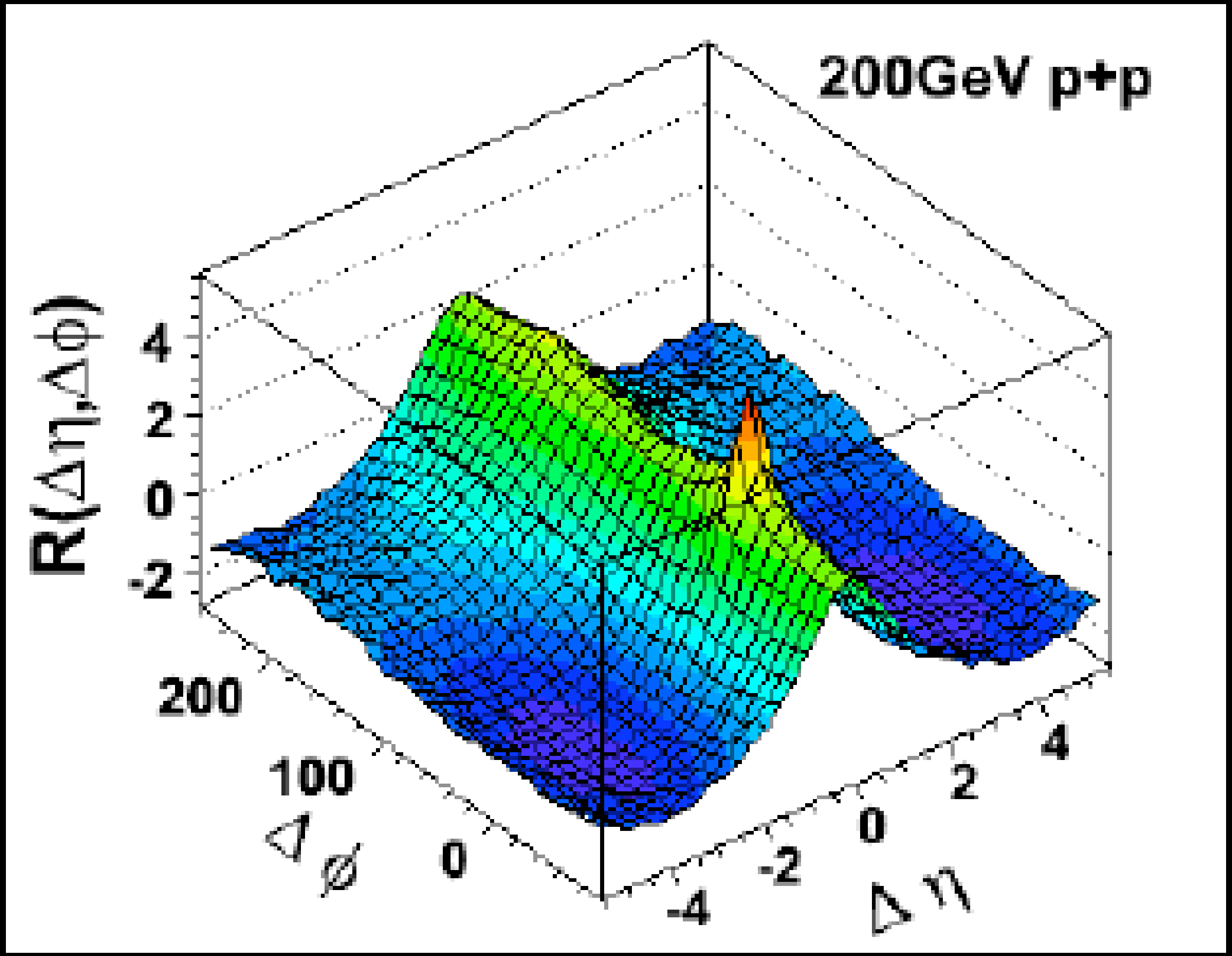


Recombination of "quarks" into "clusters" and subsequent decay of clusters provides redistribution of charges

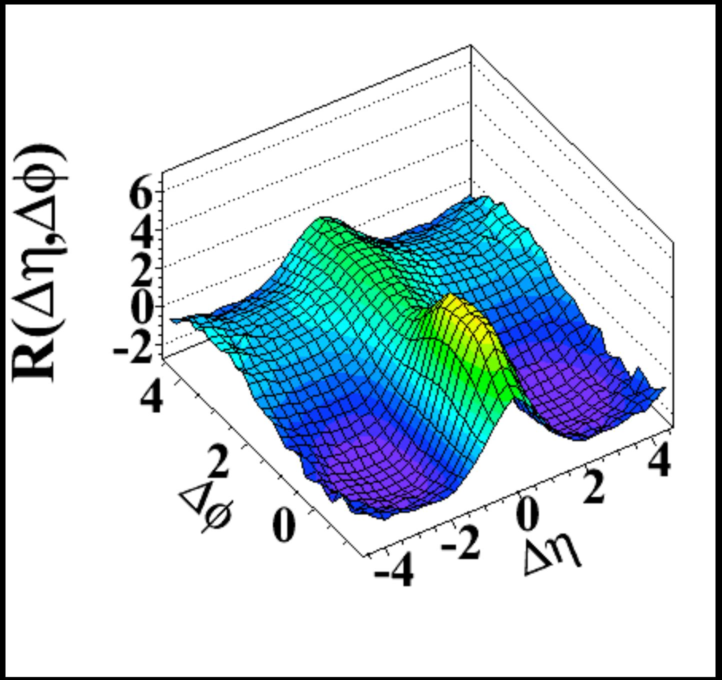
Clusters?

$$R(\Delta\eta) = \langle (n-1)\left(\frac{\rho(\eta_1 - \eta_2)}{\rho_{mix}} - 1\right)\rangle$$

PHOBOS (2008)



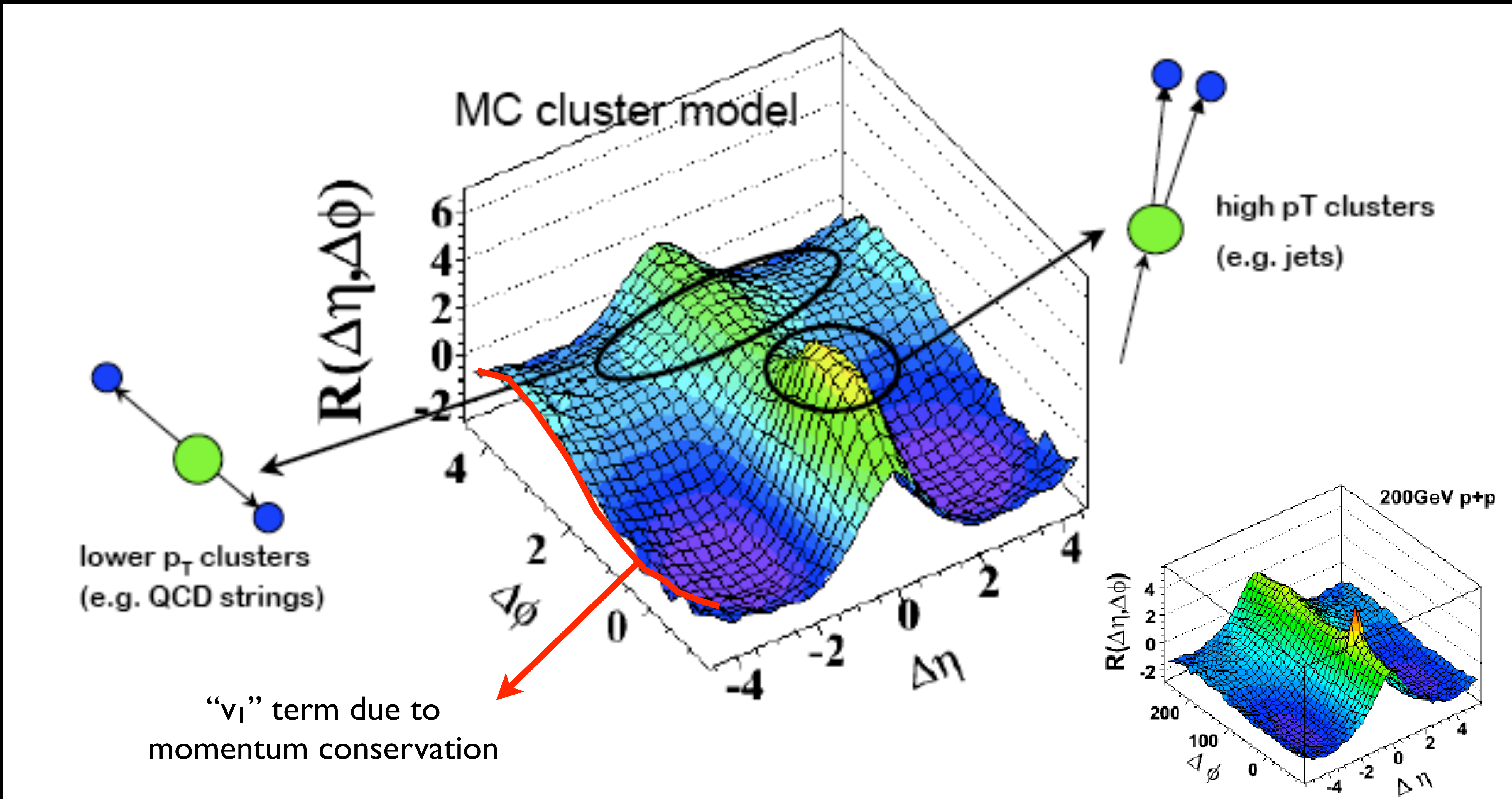
Cluster MC



Particles are not produced independently

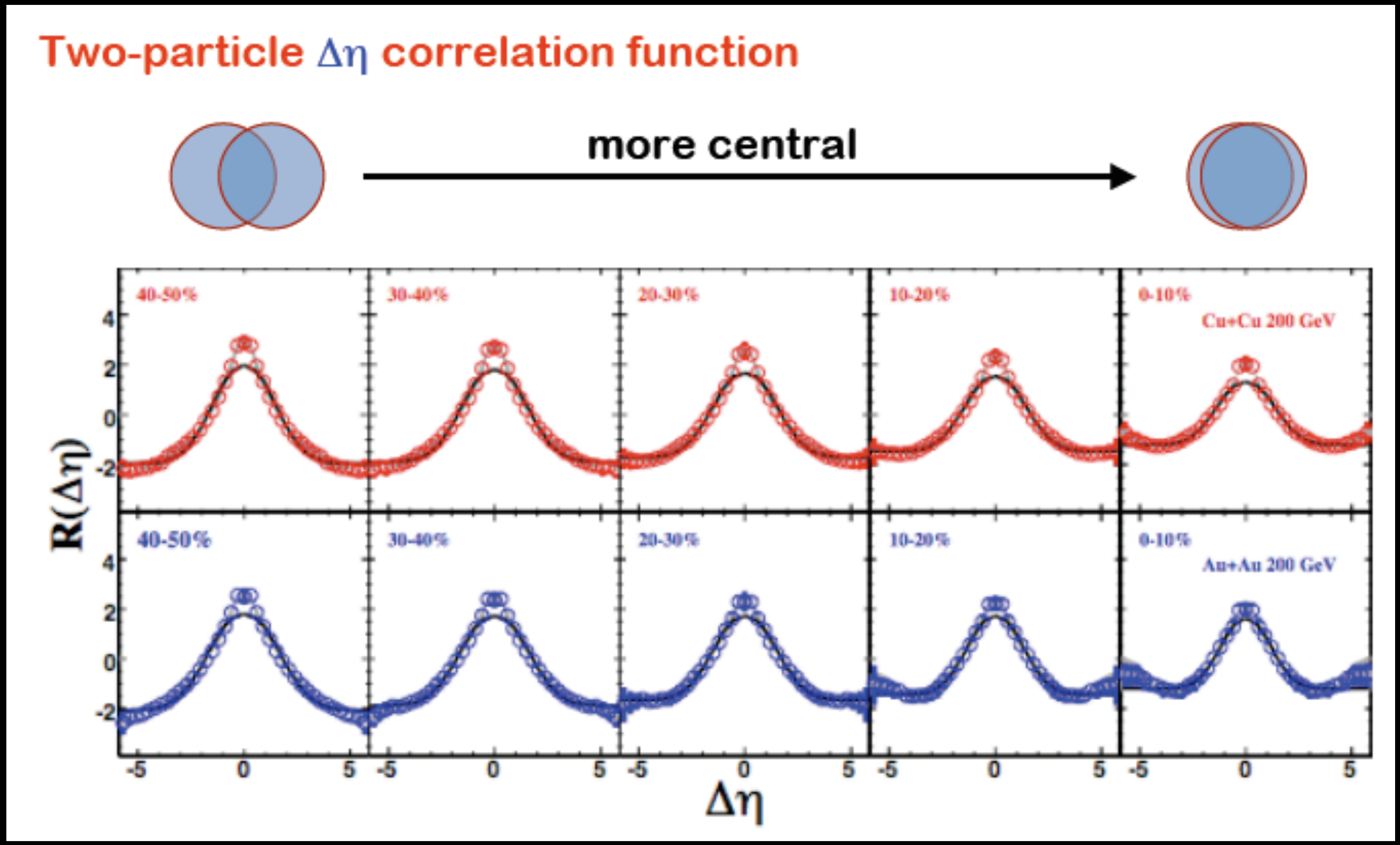
Anatomy of two-particle correlations

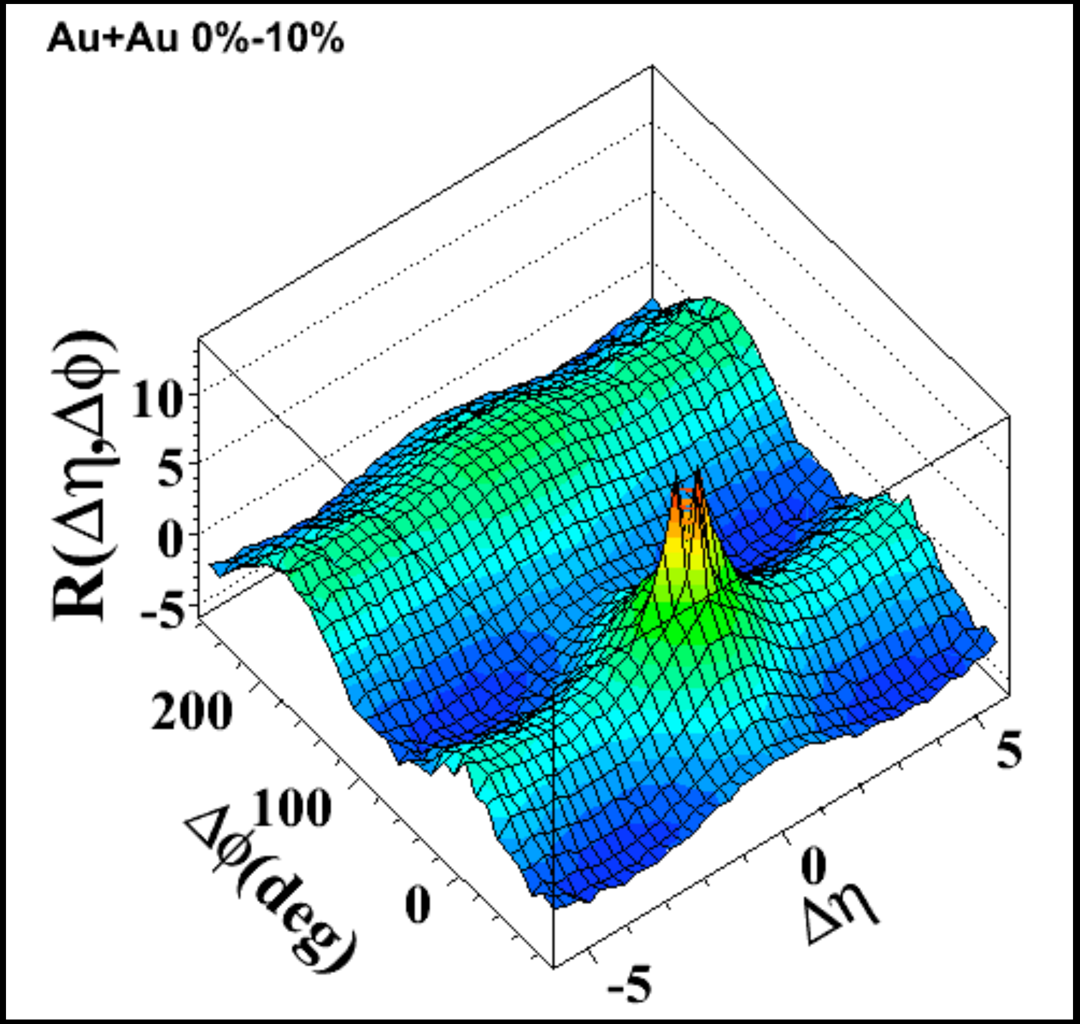
from Wei Li



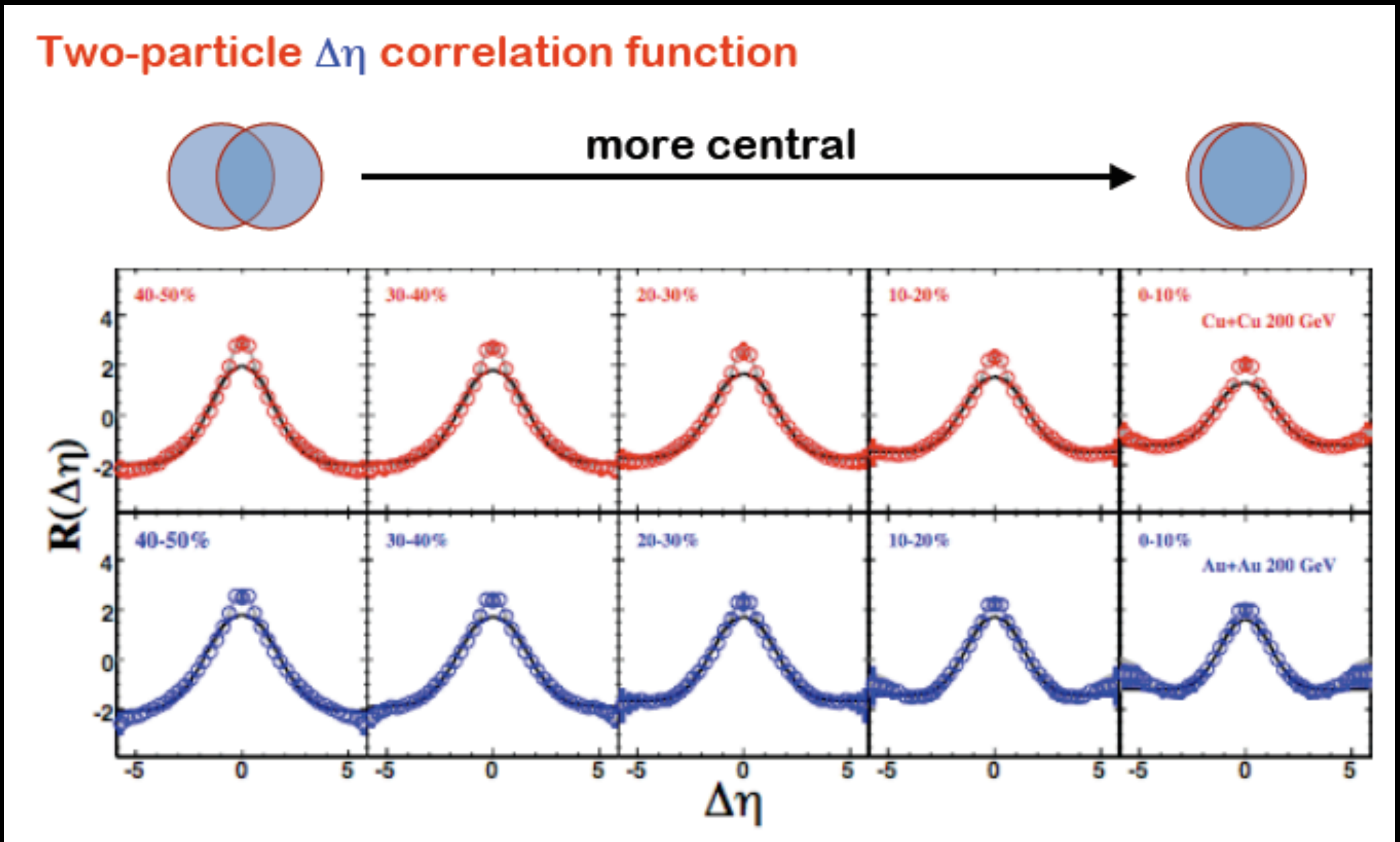
“Clusters” in AuAu collisions

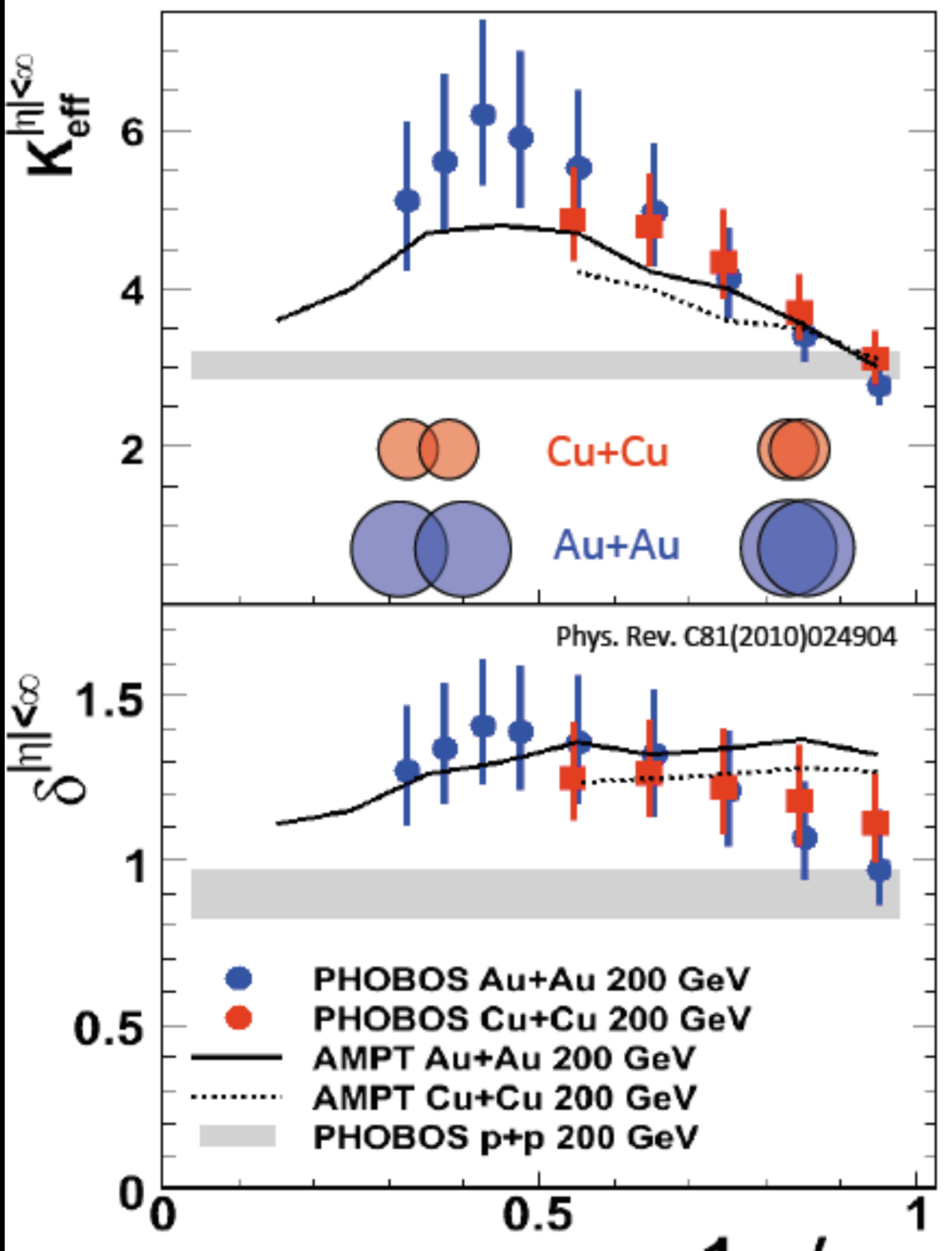
PHOBOS (2010)





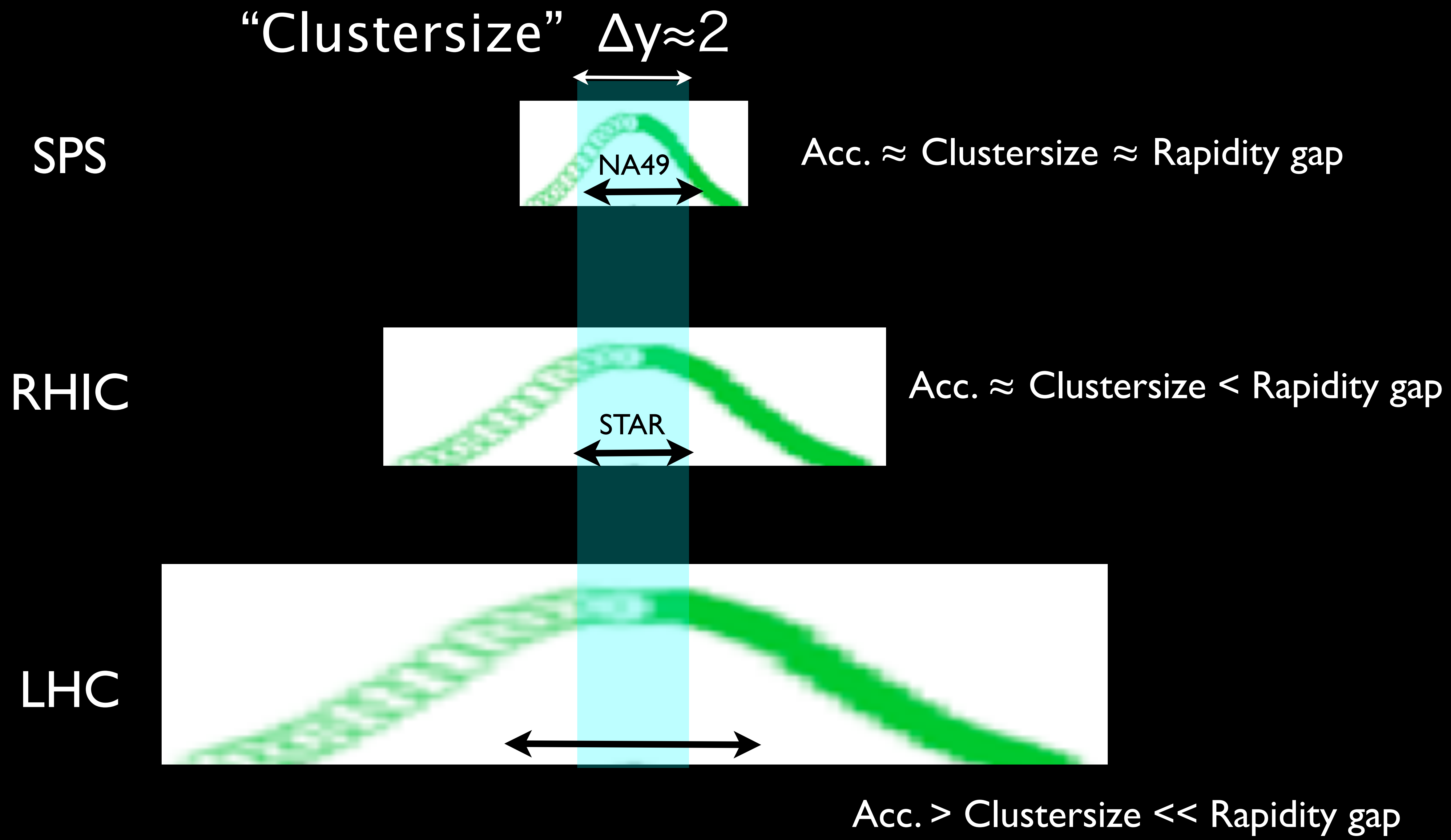
"Clusters" in AuAu collisions



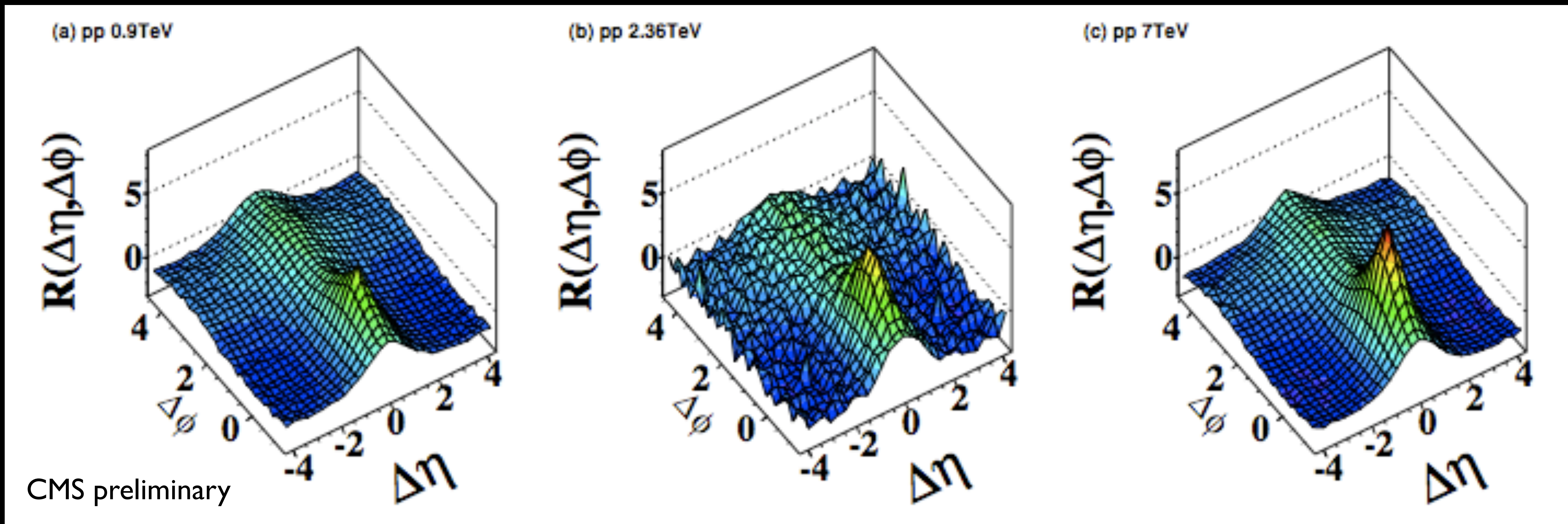


Note: extrapolated to full phase space

Try again at LHC?



Two-particle correlations at LHC

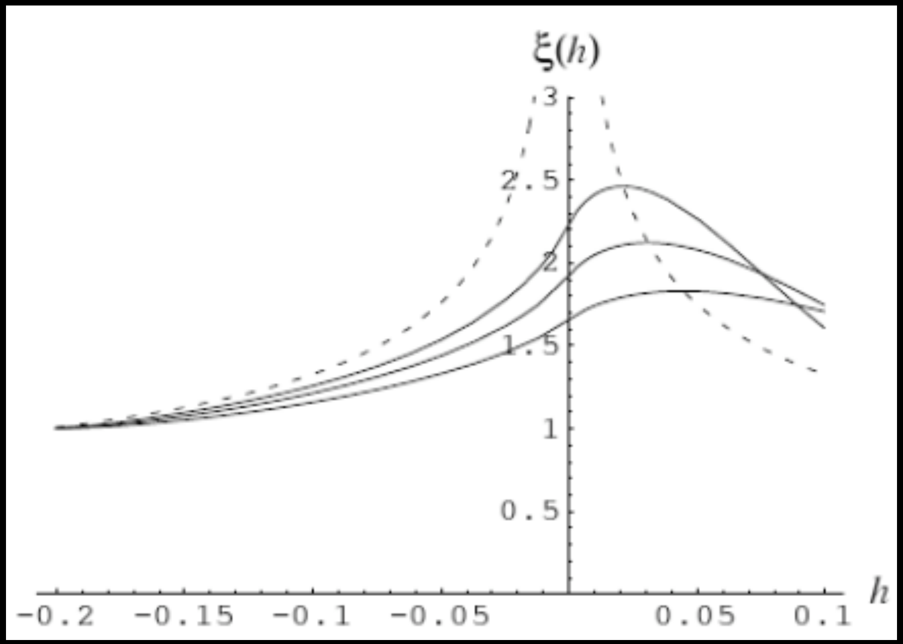


pp correlation functions from CMS

Correlation functions show increasing contribution from hard scattering

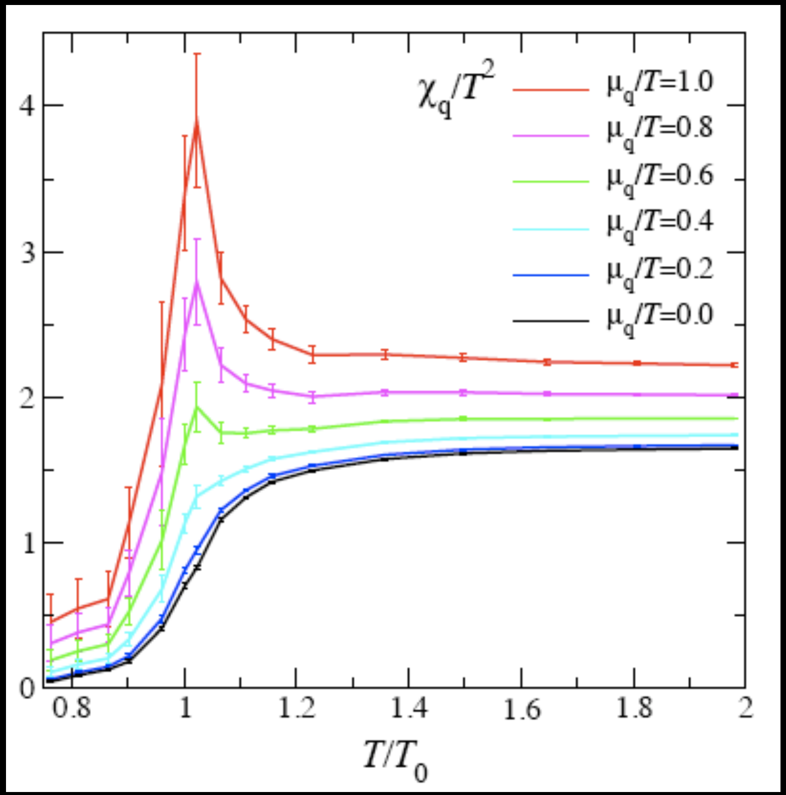
Critical Fluctuations

Correlation length near CP



Stephanov, Rajagopal Shuryak (1998)+...

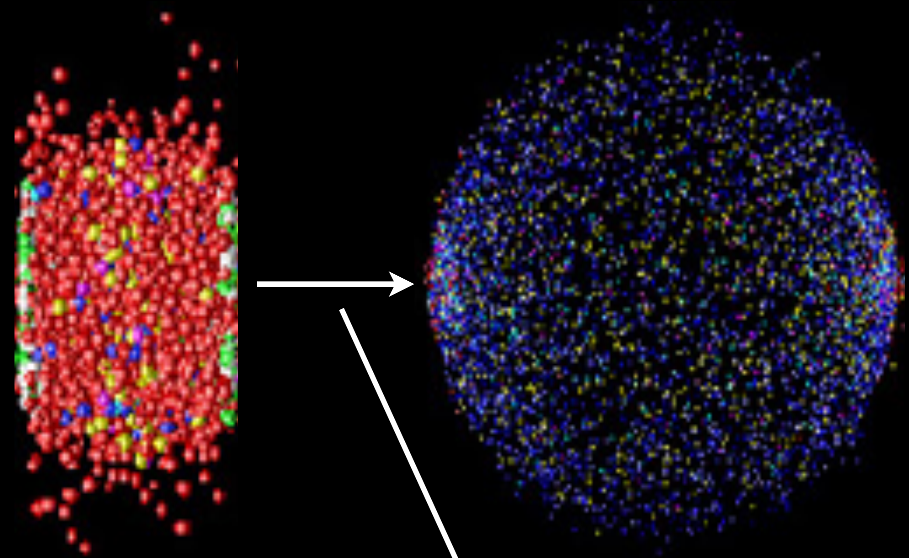
Quark-number susceptibility near CP



Karsch et al (2003)

QGP

Hadron Gas



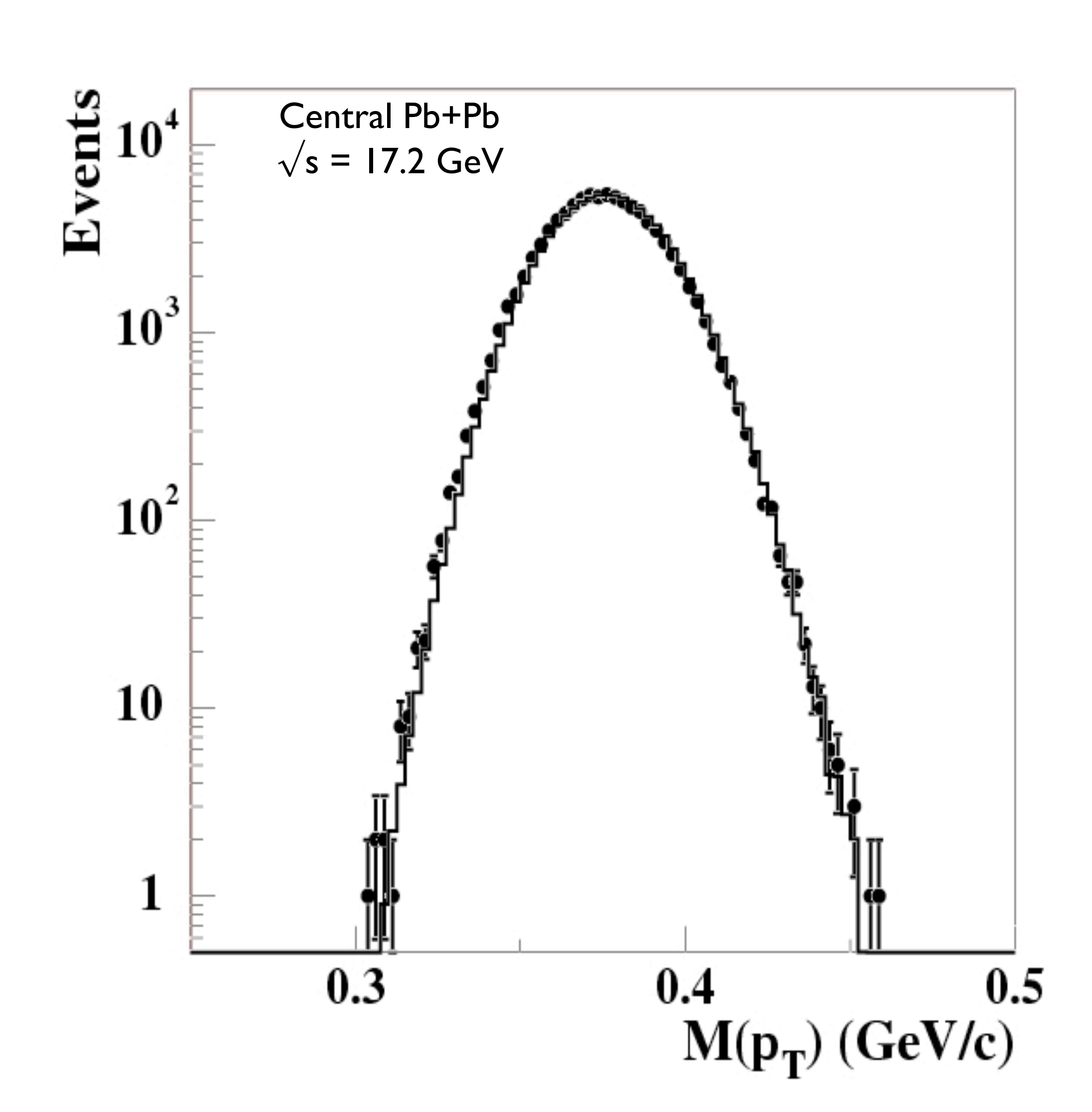
Phase transition

Critical fluctuations; supercooling/bubble formation; cluster formation

$<p_T>$ Fluctuations

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

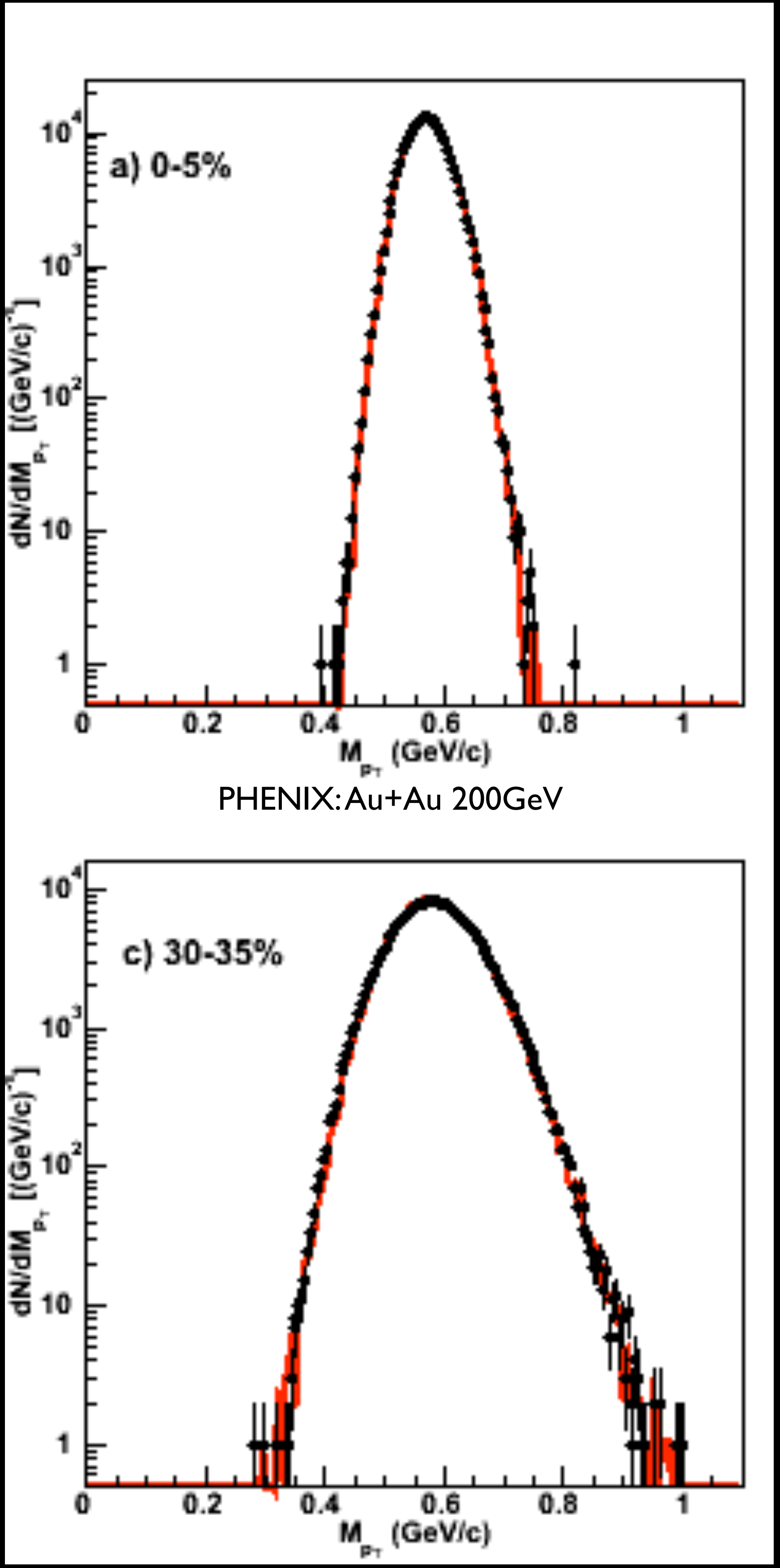
NA49, Phys Lett B459 (1999) 679



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

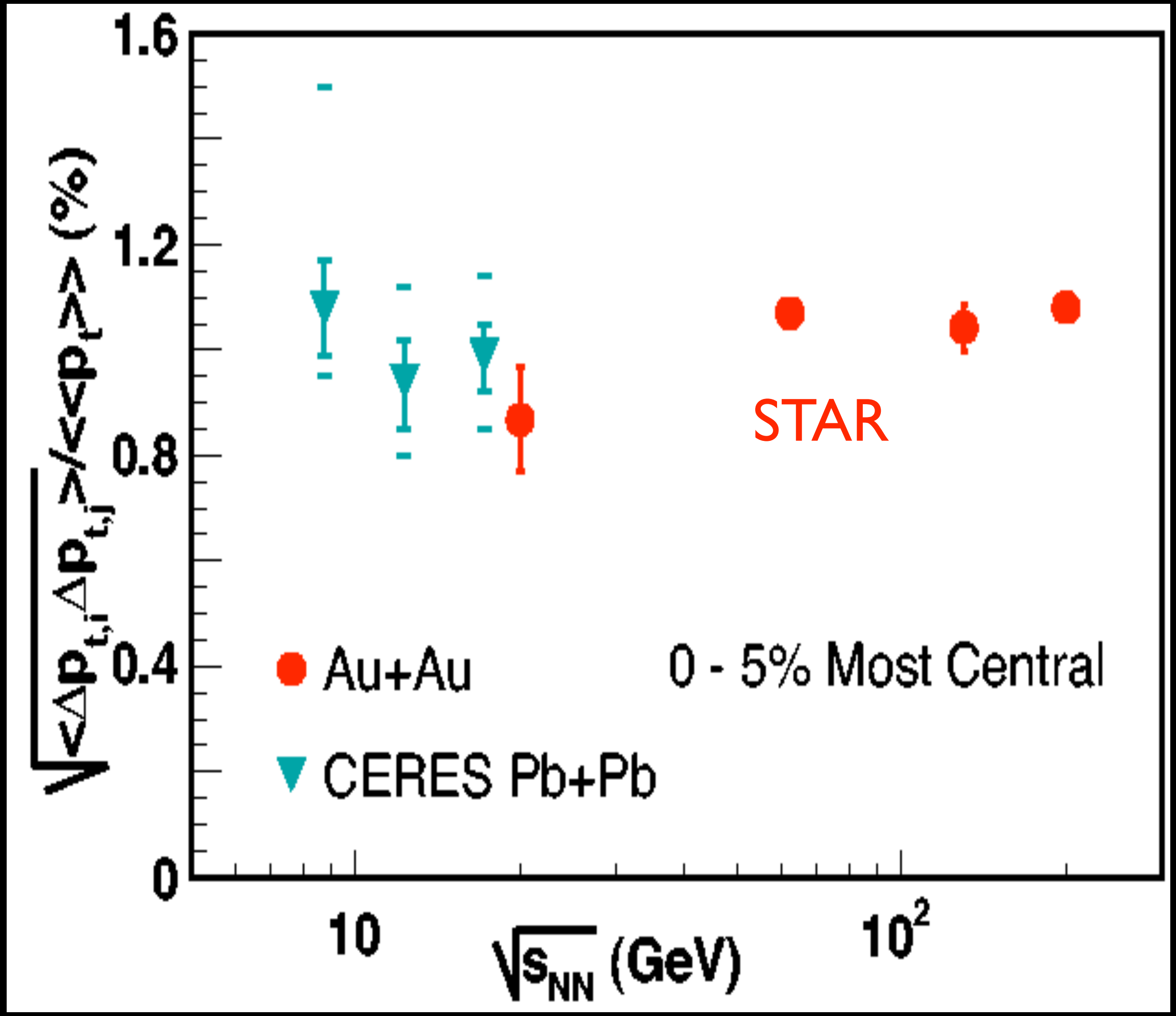
< p_T > Fluctuations

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

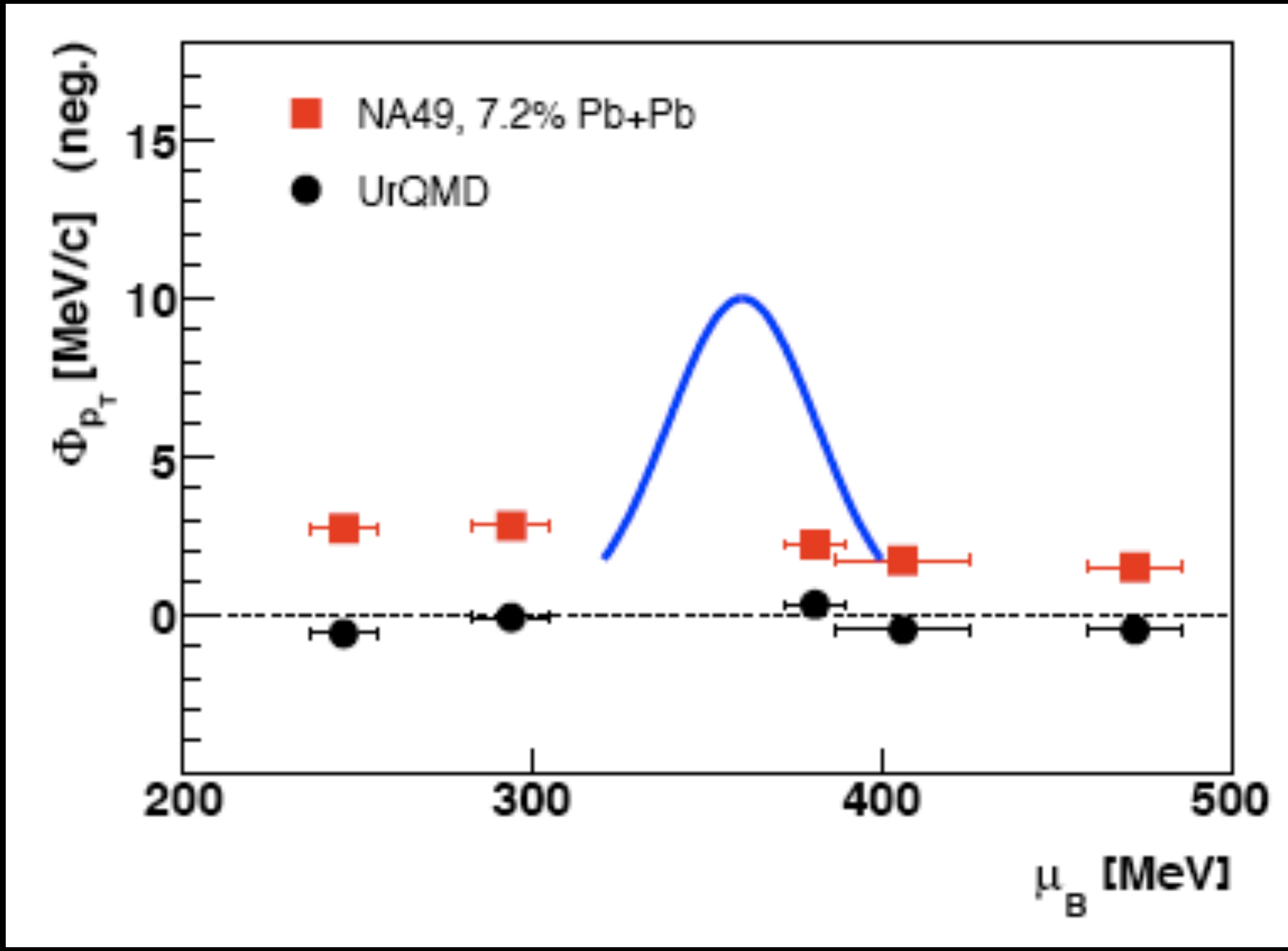


$\langle p_T \rangle$ Fluctuations vs $\sqrt{s}$

STAR PRC 72 044902 (2005)



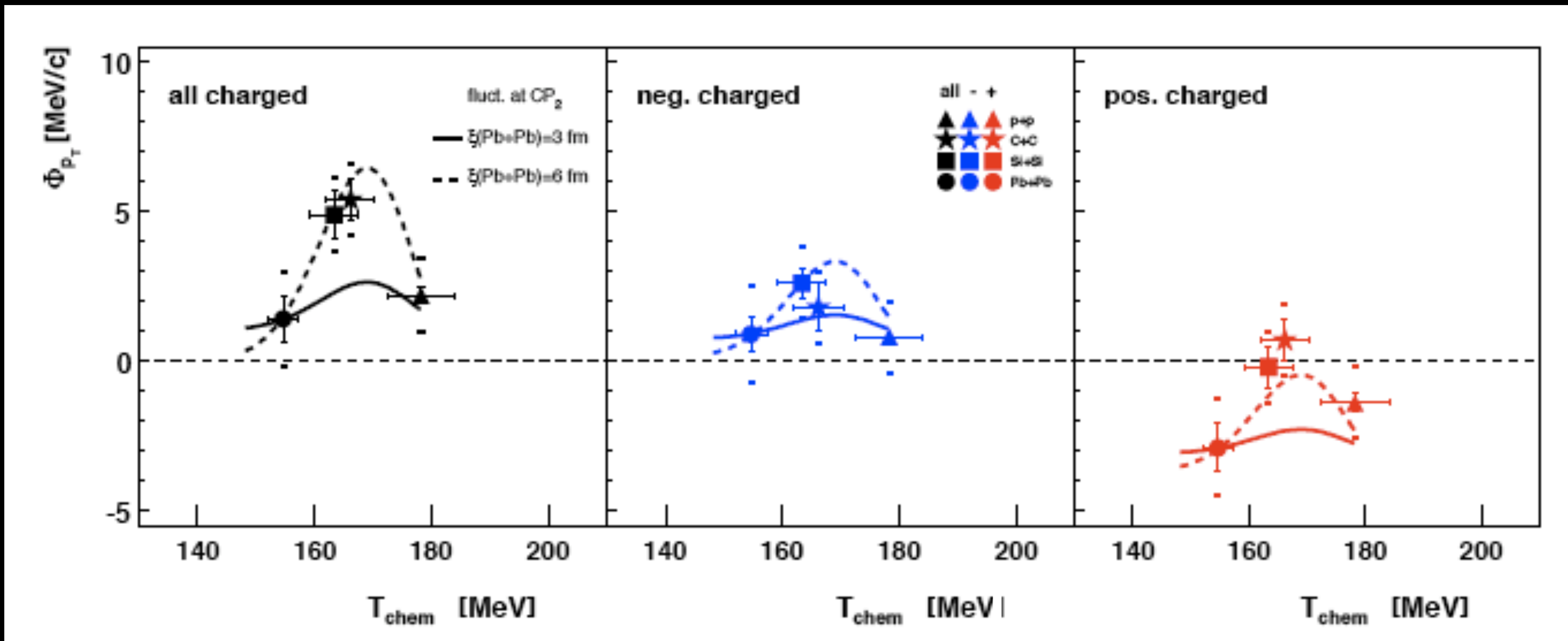
NA49 (2008)



$\langle p_T \rangle$ fluctuations(*) at 1% level, indpendent of $\sqrt{s}$

System Size Dependence

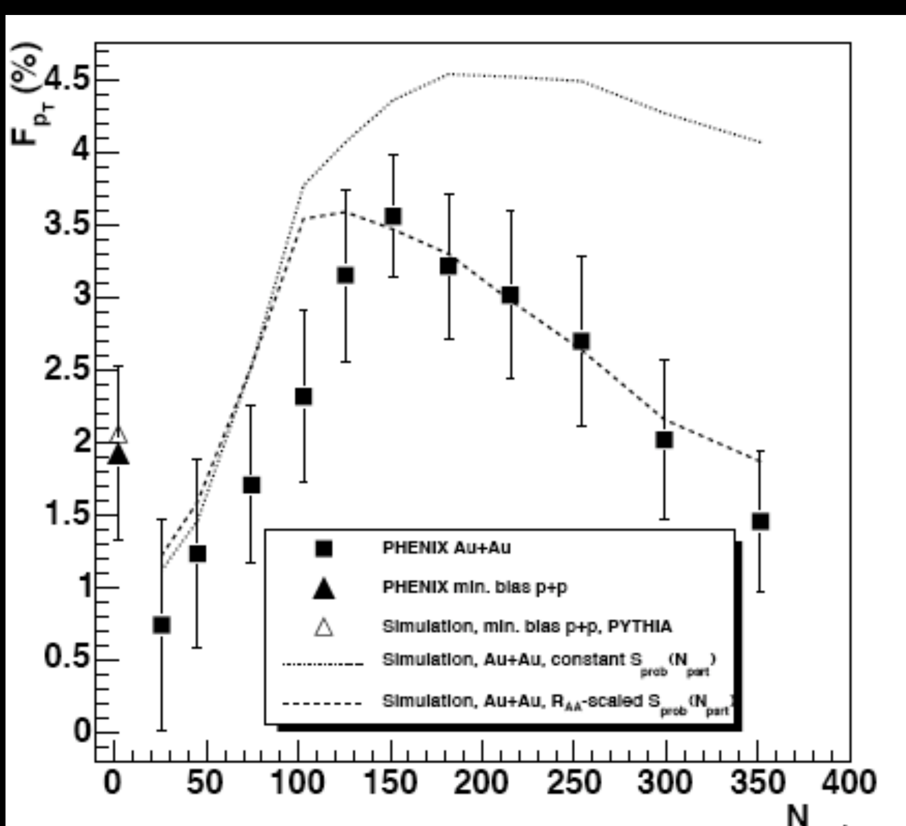
NA49/NA61 (2008)



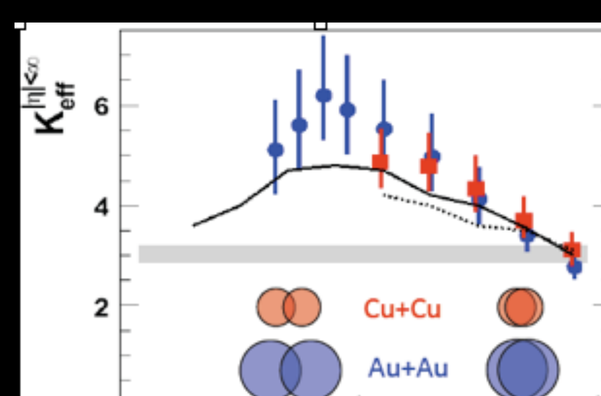
System size scan ($\sqrt{s}$ = 17.2 GeV)

Rise and Fall vs system size is a ubiquitous feature of fluctuation/correlation observables

Interplay of two opposing trends (e.g. initial state fluctuations vs thermalization)

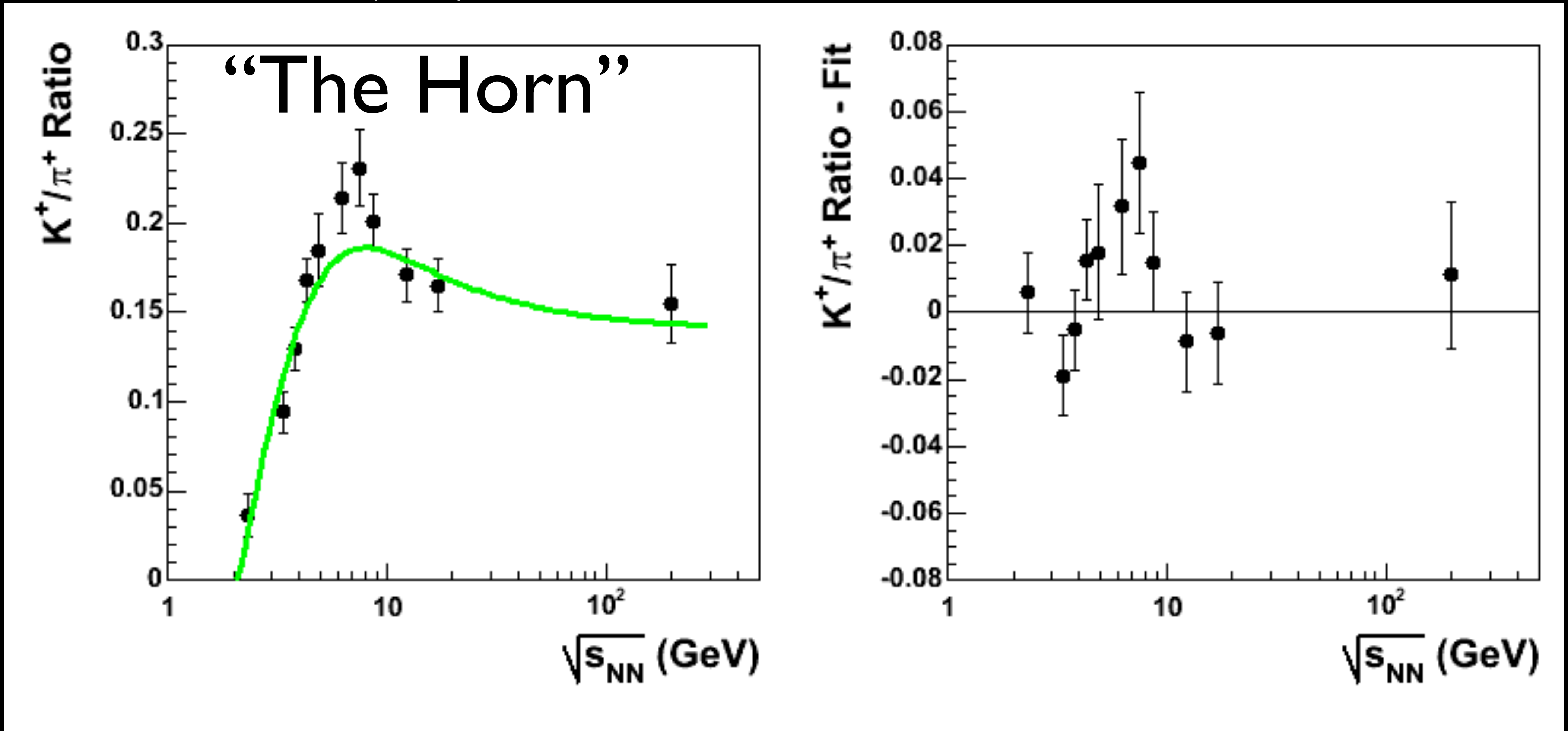


PHENIX (2003)

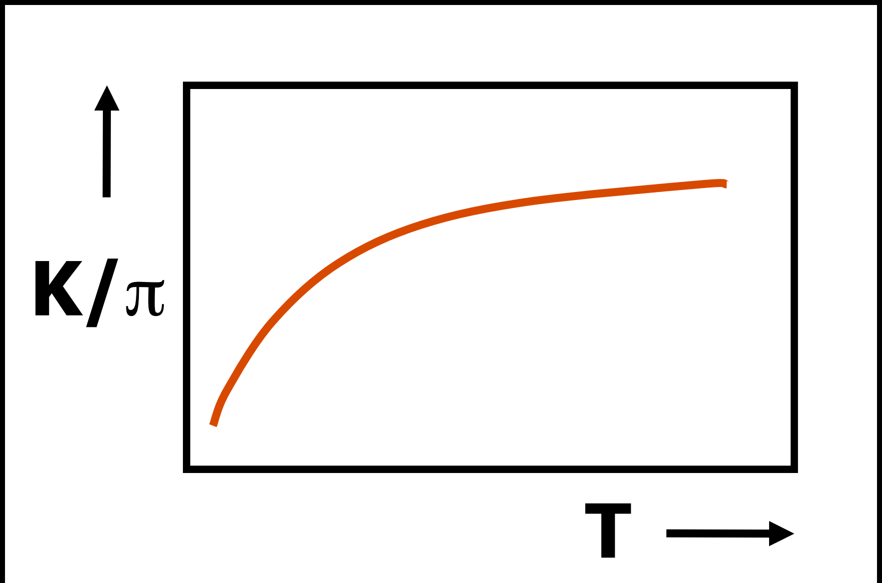


Strangeness production

NA49 (2002)



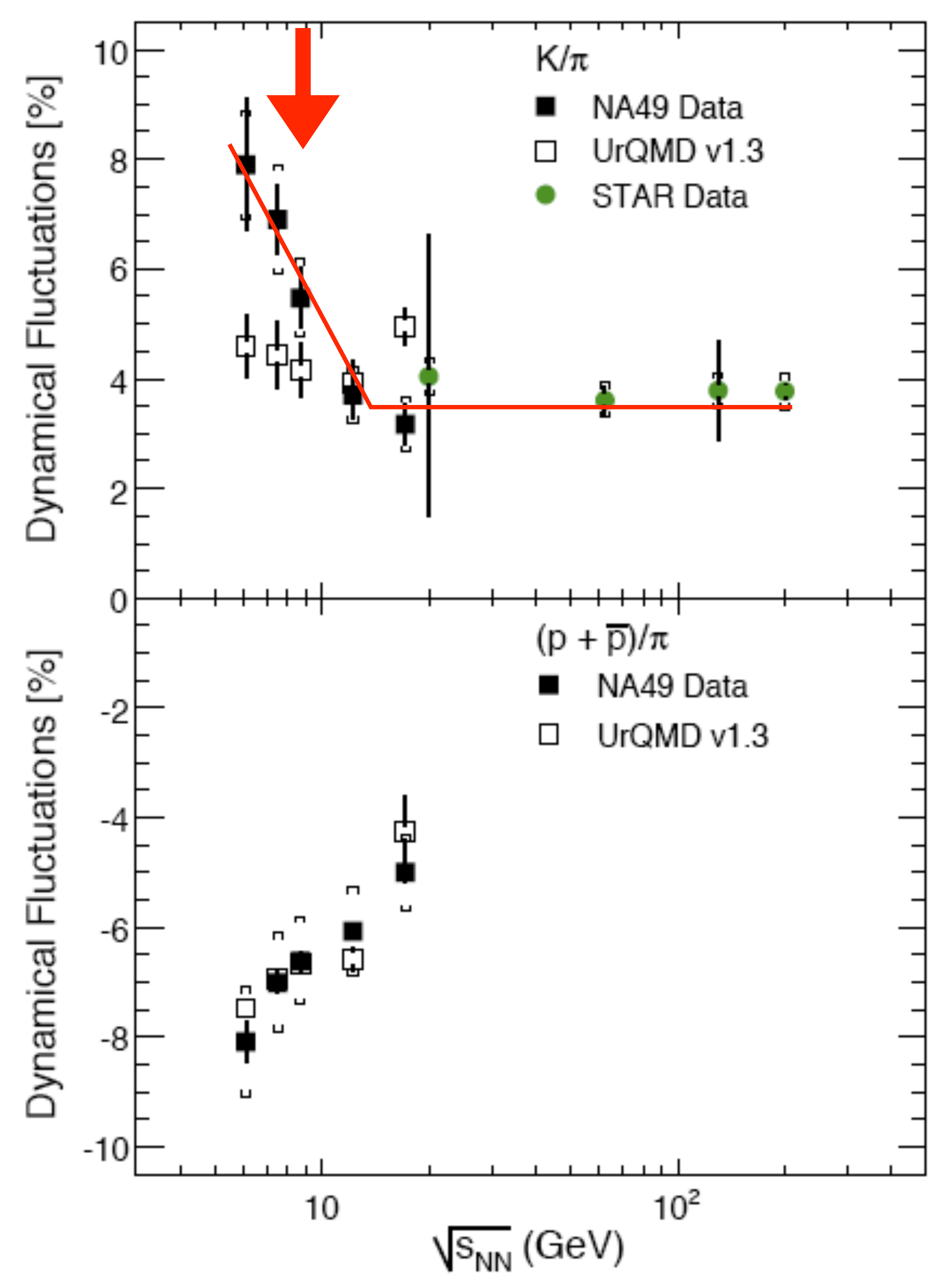
Rapid change of √s dependence for k/π ratio



Obvious question: What happens with k/π fluctuations at √s ~ 8 GeV?

K/π fluctuations vs √s in central PbPb

Horn



NA49 (2009) STAR (2009)

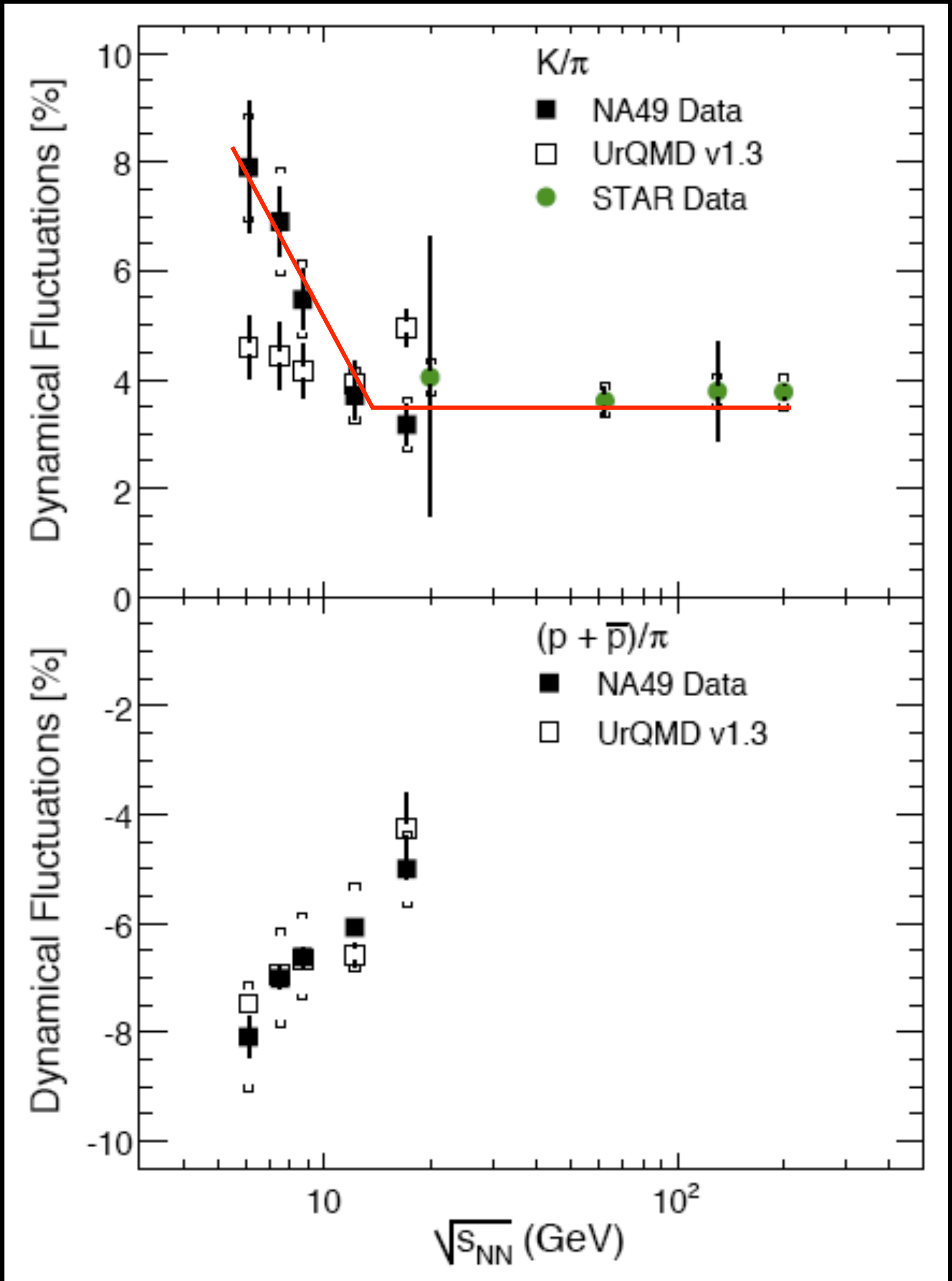
Timeline

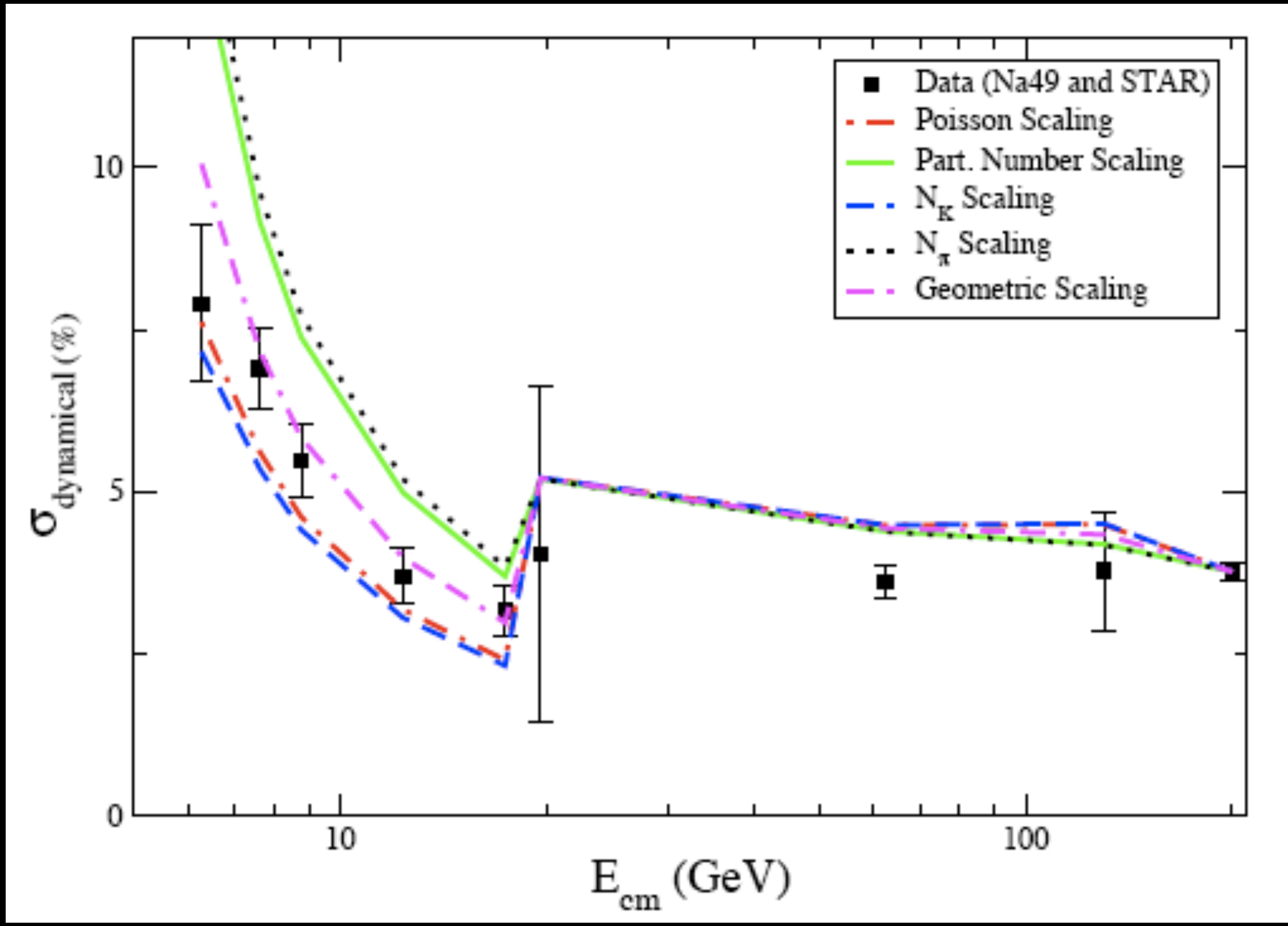
- 1994: NA49 first beam
- 1998: Preliminary result for √s =17.2 GeV
  - *Nucl.Phys.A638:91-102,1998*
- 2000: Final result for √s = 17.2 GeV
  - *Phys.Rev.Lett.86:1965-1969,2001*
- 2004: Preliminary result √s = 5.5 to 17.2GeV
  - *J.Phys.G30:S1381-S1384,2004*
- 2008: Final result for PbPb vs √s
  - *Phys.Rev.C79:044910,2009*

Strong, but monotonous, √s dependence of K/π fluctuations

K/π fluctuations vs √s

Koch, Schuster (2009)



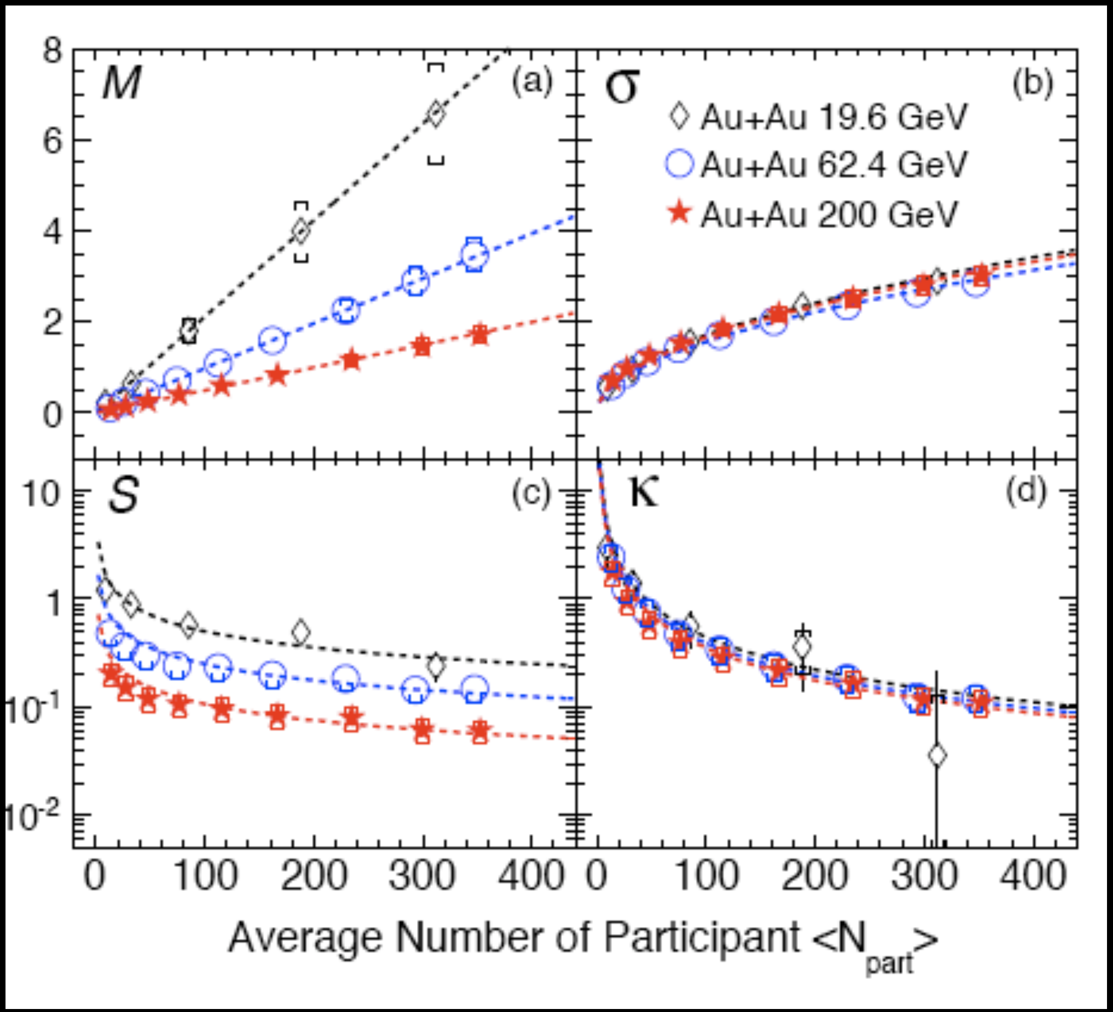


Data are compatible with constant correlation strength, once dilution with proper (i.e. in acceptance) multiplicity is taken into account

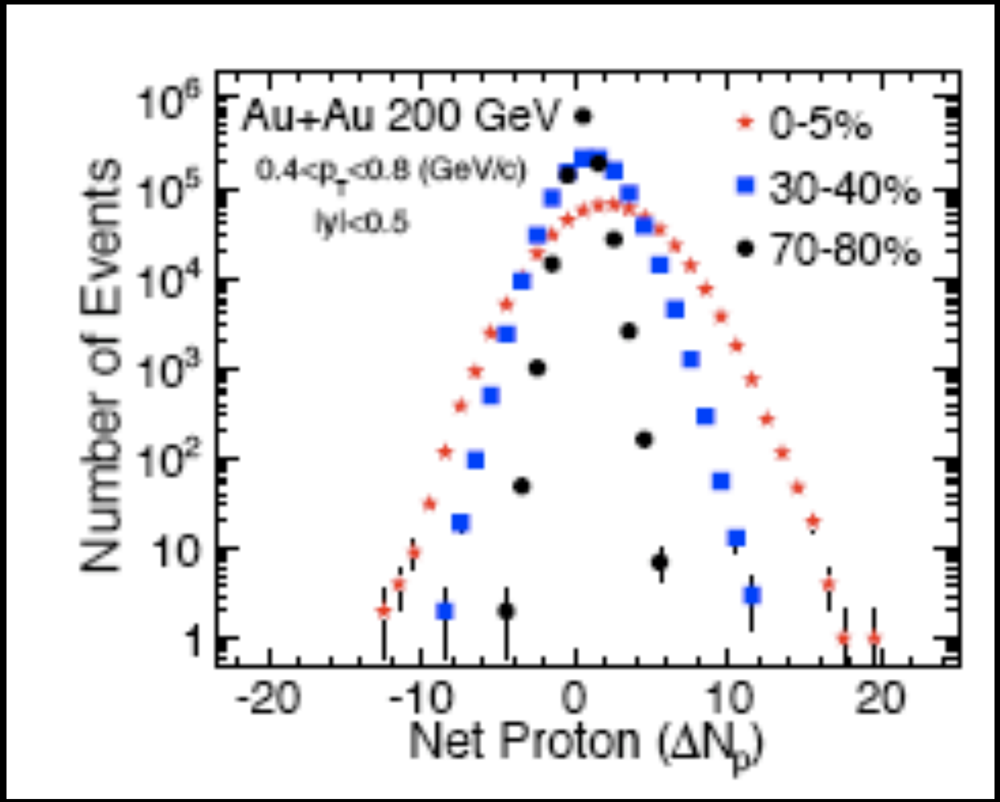
NA49 (2009) STAR (2009)

Net-"baryon" distributions

STAR (2010)



STAR (2010)

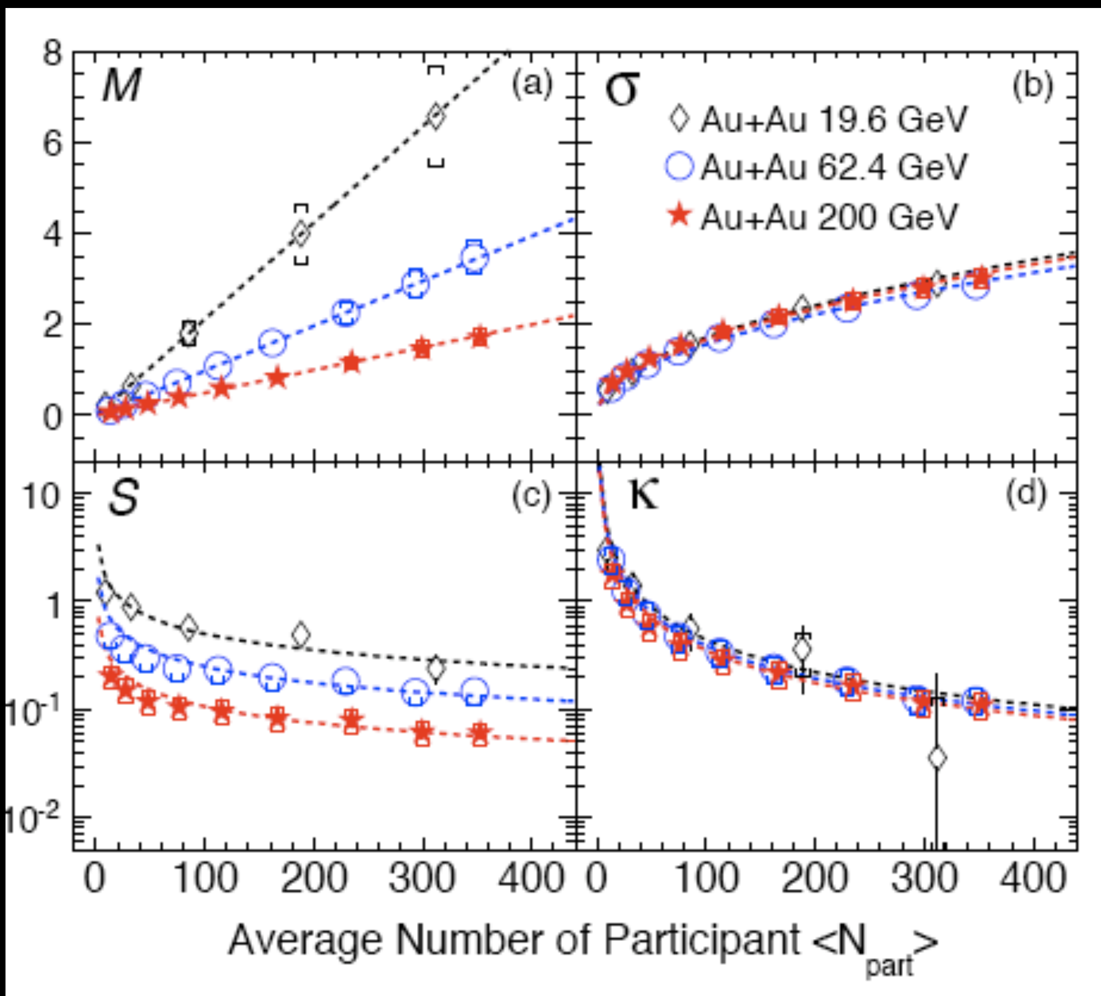


Moments of event-by-event net-baryon distributions are related to baryon number susceptibility

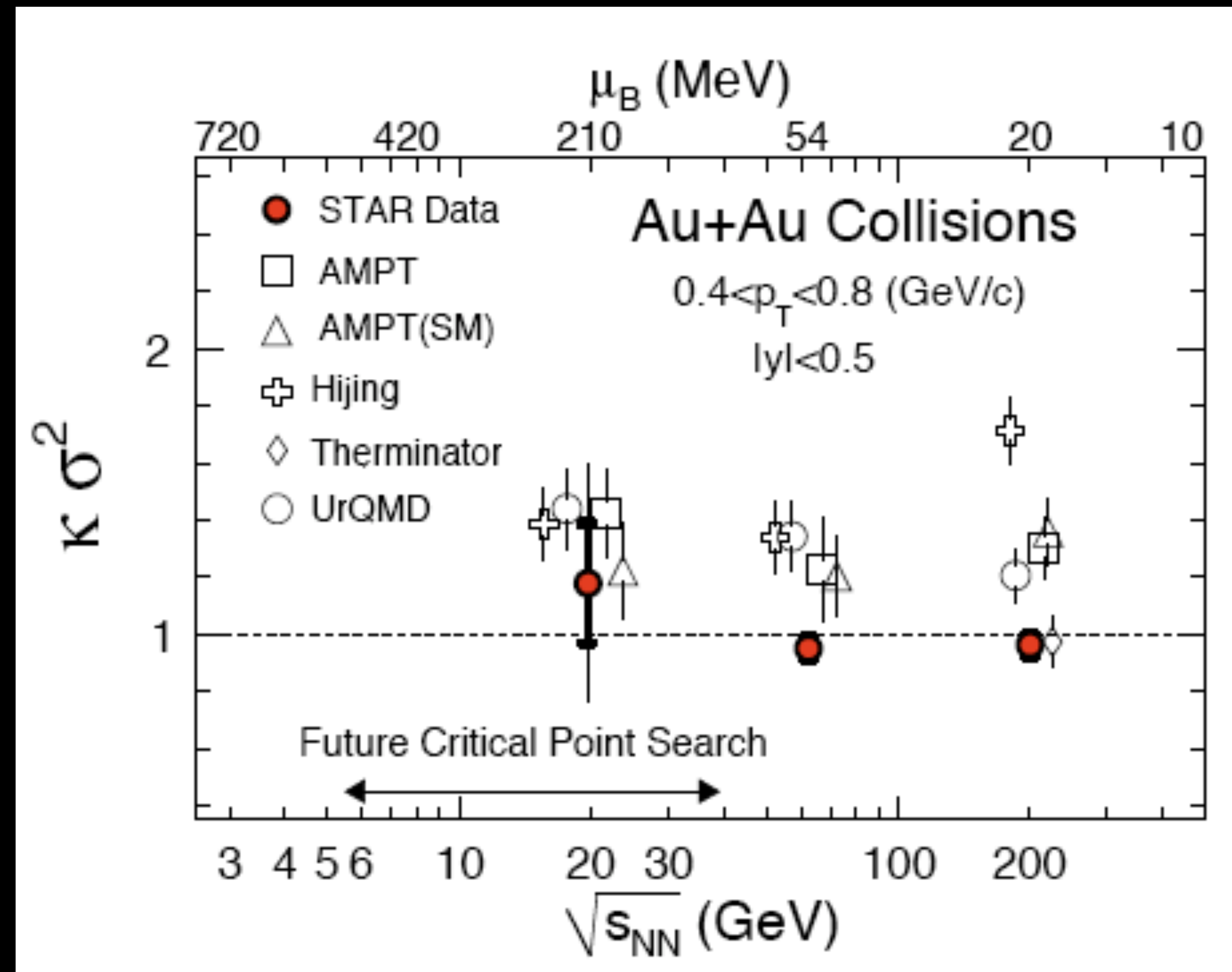
Experimentally, approximate net-baryons by net-protons

Net-"baryon" distributions

STAR (2010)



STAR (2010)



$$\kappa\sigma^2 = \frac{\chi_B^{(4)}}{\chi_B^{(2)}/T^2}$$

No sign of structure vs $\sqrt{s}$ (yet)

Even less fluctuations than in models!?

Summary

- Fluctuations carry information about stages of the collision process
- Shape fluctuations are preserved in collision evolution
- Hadronization needs to be considered
- Still chasing the grand prize