Hydrodynamic Modeling: A Hybrid Approach

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Outline

- Introduction
  - Motivation
  - A short history of hybrid approaches
  - Importance of hadronic dissipation
- Hybrid approach
  - Initial condition
  - Hydrodynamic evolution
  - Hadronic afterburner
- Results
  - Default setting compared with data
  - Systematic studies on modeling
- Summary

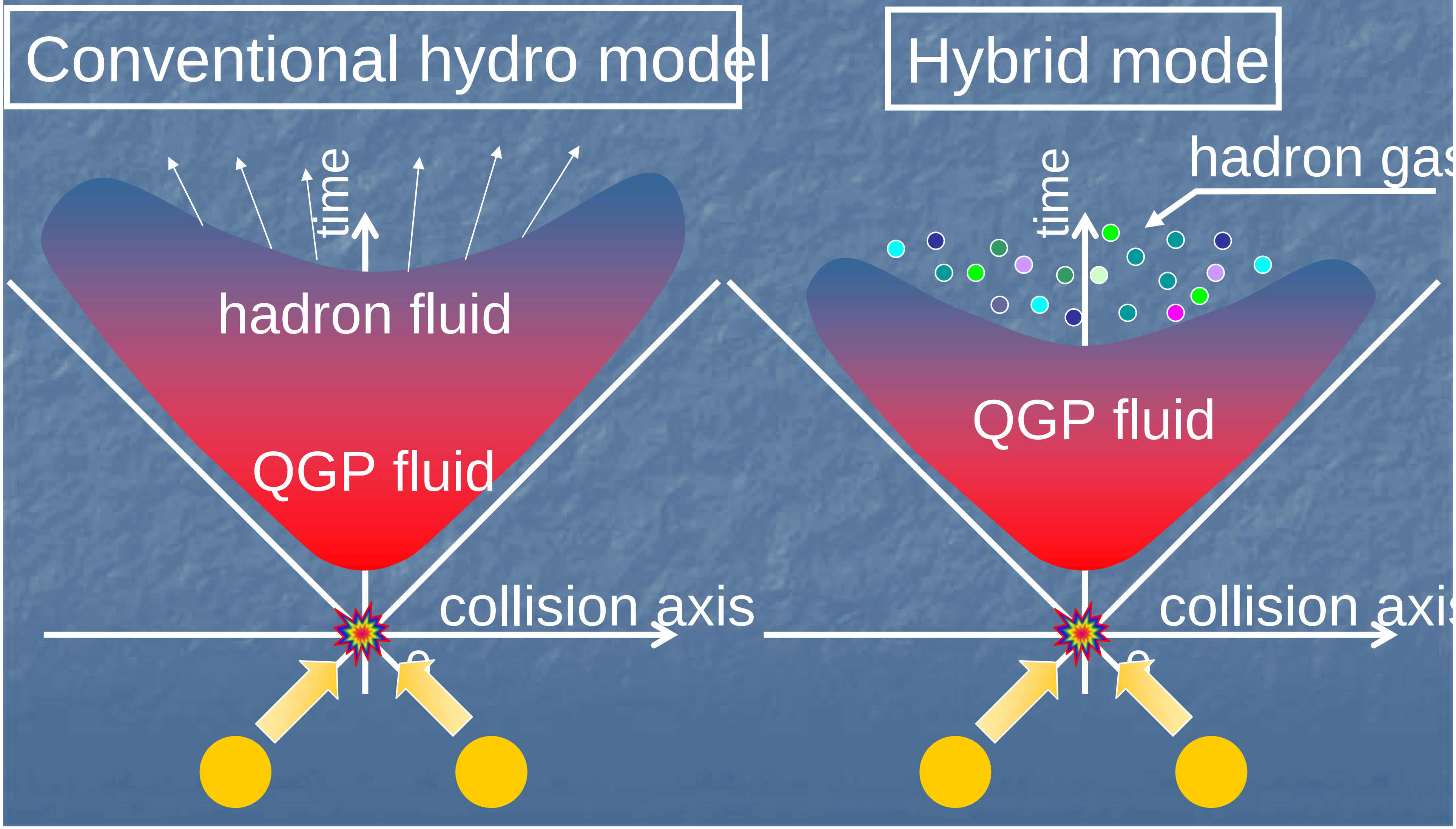
Introduction

- Main purpose: Understanding of QCD matter in equilibrium under extreme condition (QGP)
  - Equation of state
  - Transport coefficients
- Heavy ion collisions at relativistic energies
  - Unique opportunity, but complicated dynamics
- Analysis codes play important roles in various fields
  - Cosmic microwave background: CAMB, CMBFAST, etc.
  - Elementary particle reactions: PYTHIA, HERWIG, etc.
- Development of analysis code in relativistic

Introduction (contd.)

- Hydrodynamics describes dynamics of matter under local thermal equilibrium
  - Hydrodynamics can be applicable in the intermediate stage.
  - Need modeling before and after hydro regime
    - Initial conditions
    - Freezeout
- Detailed and systematic analysis based on ideal hydro towards quantifying viscous effects

Hybrid Approach



Short History of Hybrid Approach

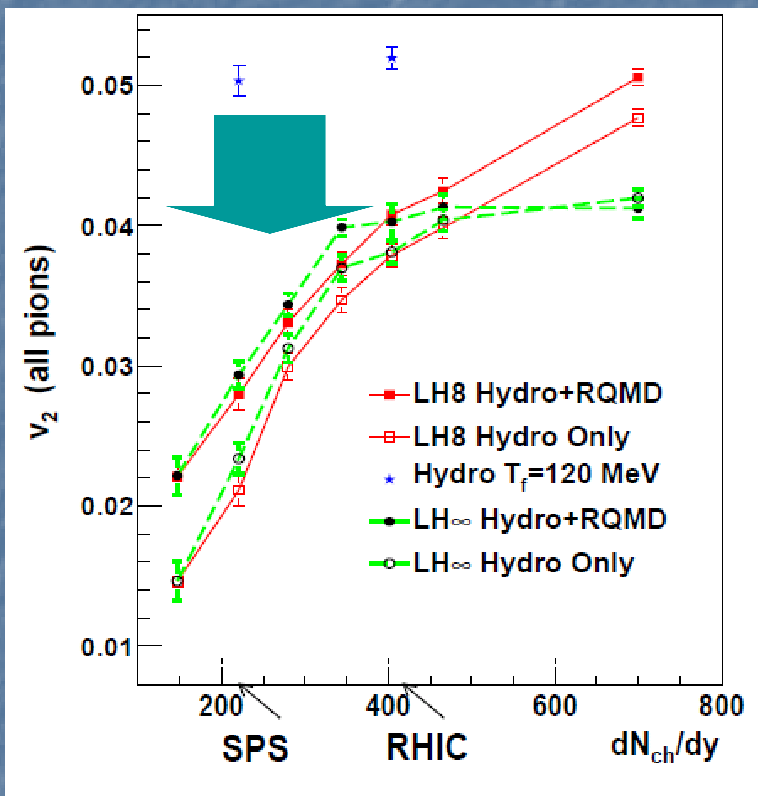
- (1+1)D ideal hydro + UrQMD: Dumitru et al. ('99)
  - mean p_T, HBT, …
- (2+1)D ideal hydro + RQMD: Teaney et al. ('01)
  - $v_2(p_T)$, v_2(cent), v_2(sqrt{s}), …
- Importance of hadronic viscosity: TH and Gyulassy ('05)
- (3+1)D ideal hydro + JAM: TH et al. ('06)

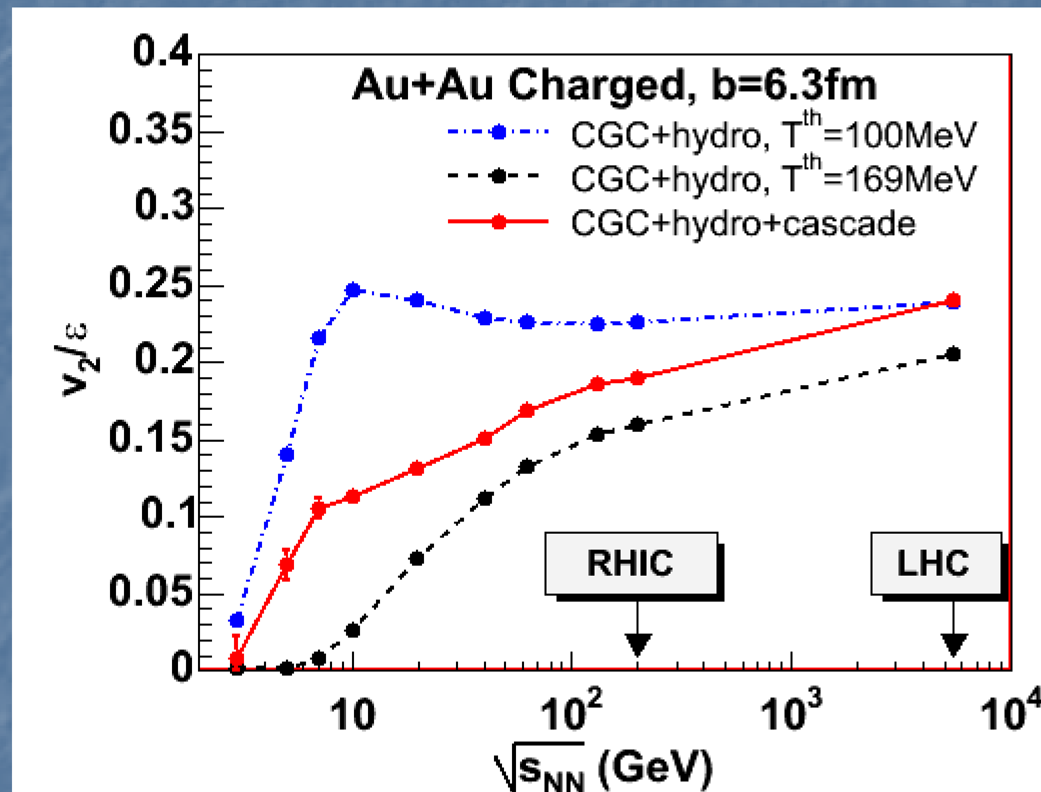
  (3+1)D ideal hydro + UrQMD: Nonaka et al. ('06)

  (3+1)D ideal hydro + UrQMD: Werner et al.('09)
  - v2(eta), …
- (2+1)D viscous hydro + UrQMD: Heinz-Song ('10)

  (2+1)D viscous hydro + UrQMD: Soltz et al.

Typical Results So Far

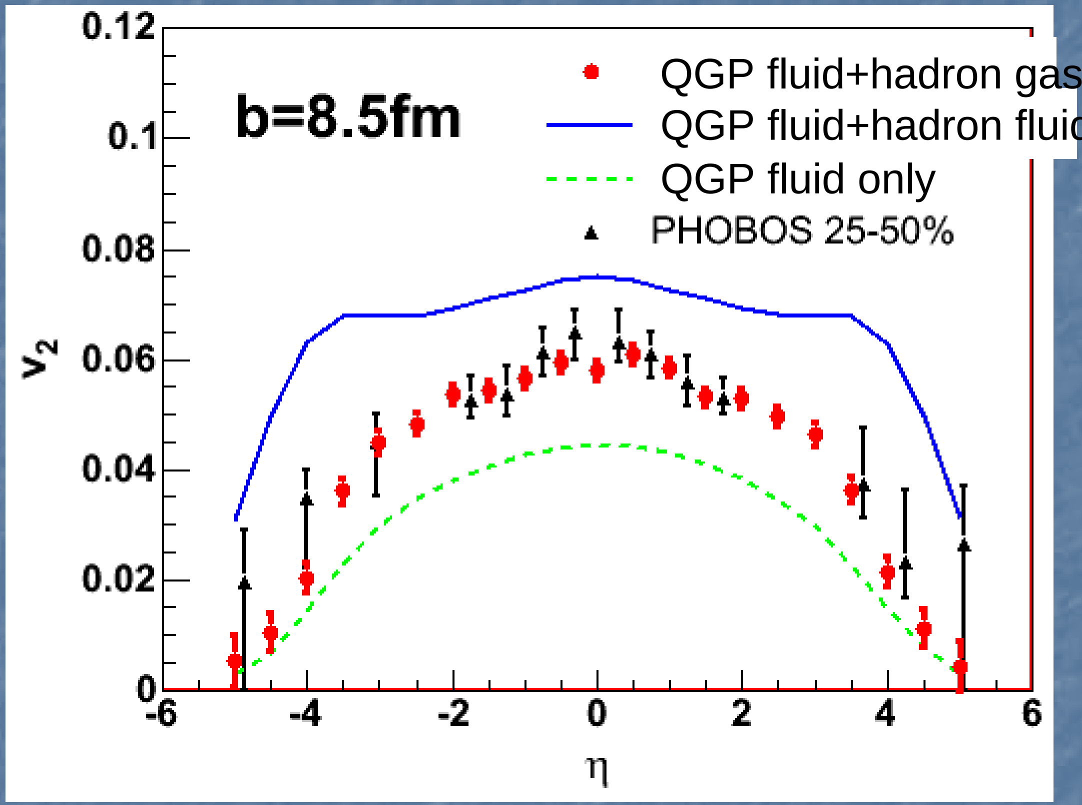




Large suppression in small multiplicity events

Teaney et al.('01) TH et al.('07)

Typical Results So Far (contd.)

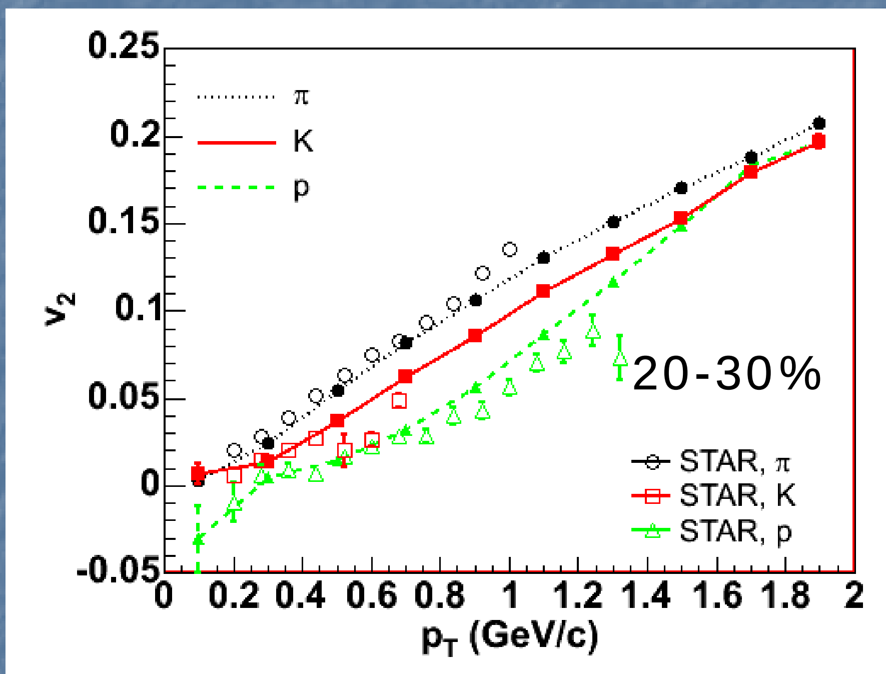


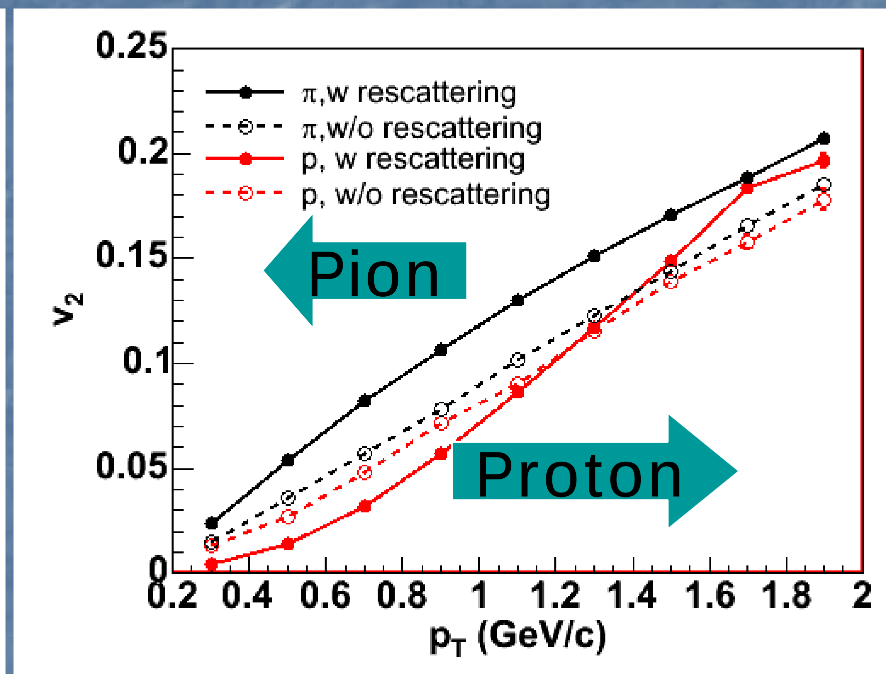
Suppression in forward and backward rapidity

Importance of hadronic viscosity

TH et al.('05)

Typical Results So Far (contd. 2)



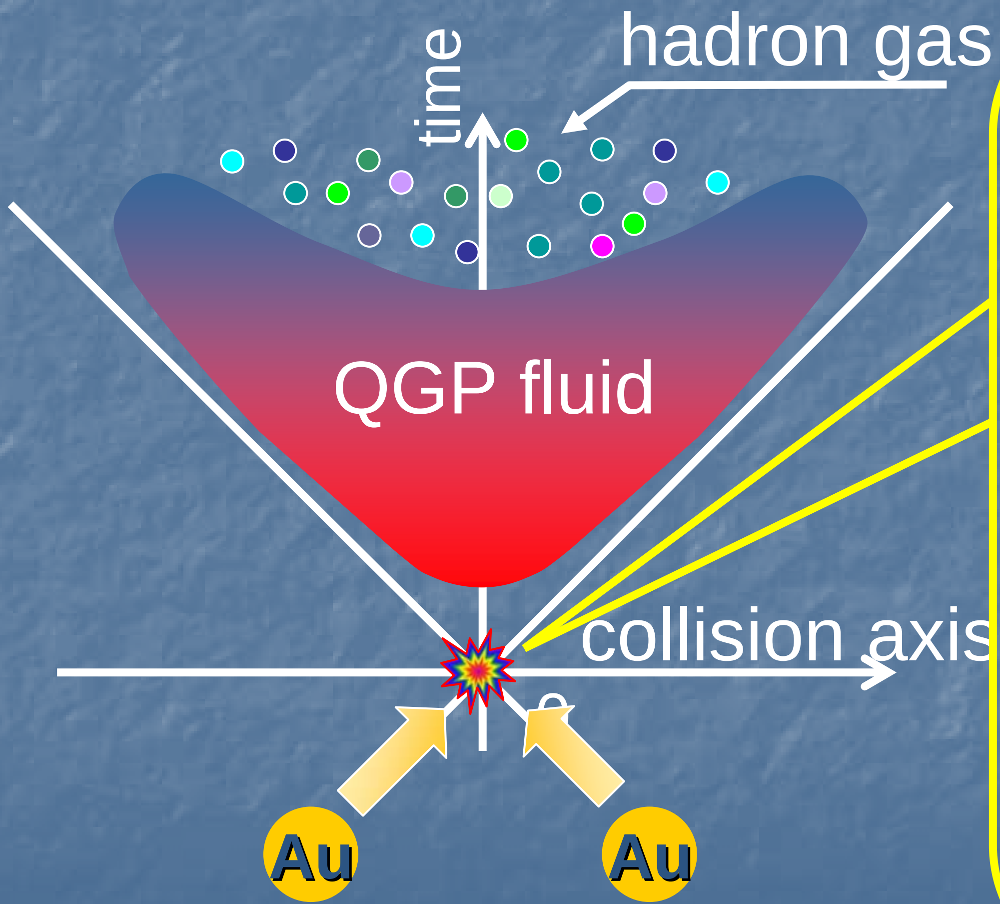


Mass dependence is o.k. from hydro+cascade.
When mass splitting appears?

Mass ordering comes from hadronic rescattering effect.
Interplay btw. radial and elliptic flows.

TH et al.('08)

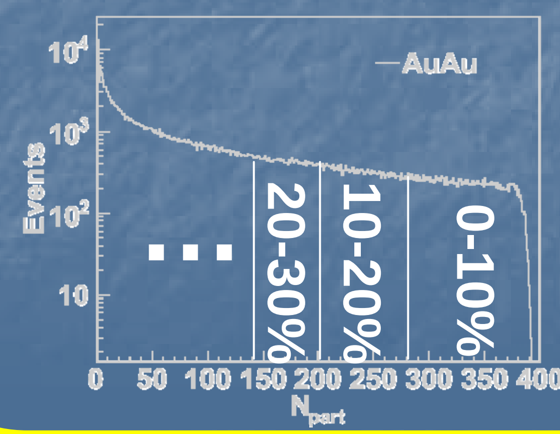
A Hybrid Approach: Initial Condition



Model*

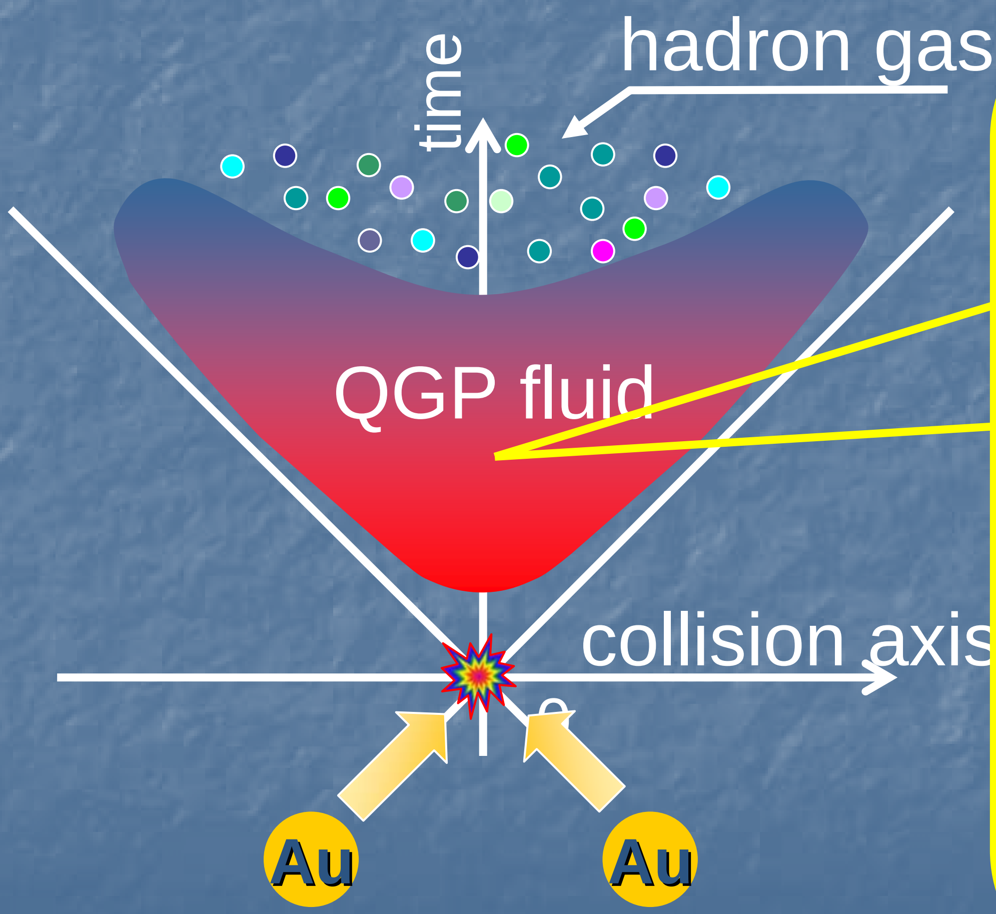
- MC-Glauber
- MC-KLN (CGC)

- ε_{part}, $\varepsilon_{R.P.}$
- Centrality cut



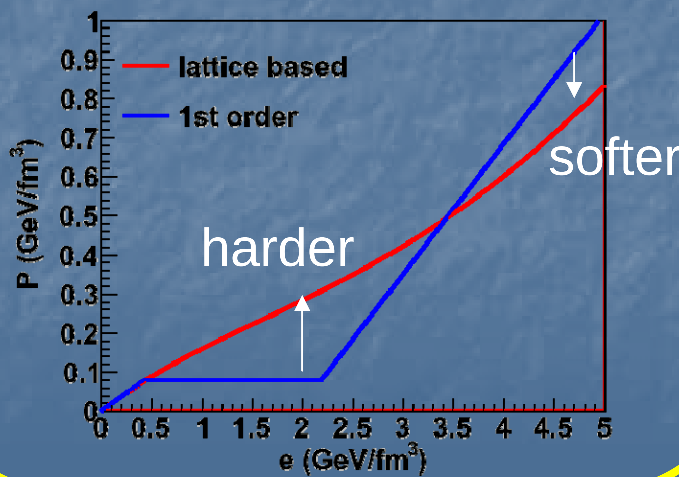
*H.J.Drescher and Y.Nara (200

A Hybrid Approach: Hydrodynamics



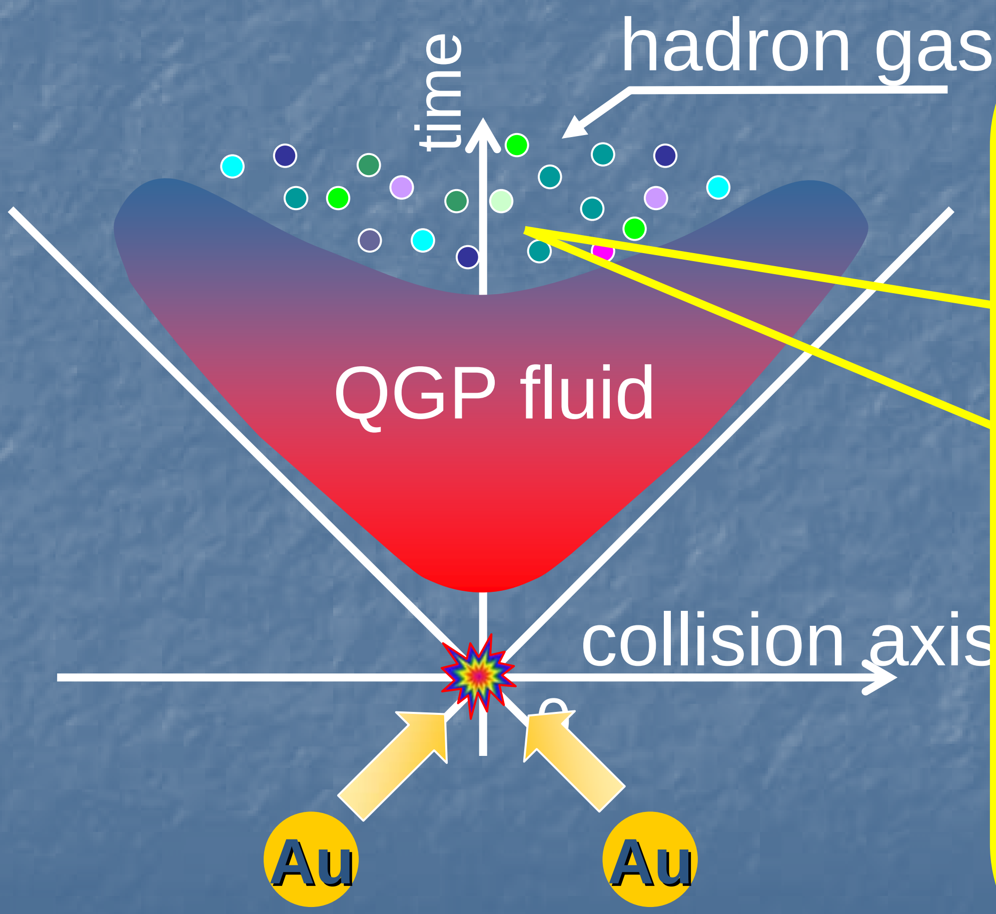
Ideal Hydrodynamics*

- Initial time 0.6 fm/*c*
- Model EoS
  - lattice-based#
  - 1st order



#Lattice part : M.Cheng *et al*. (2008) + resonance gas (Mor

A Hybrid Approach: Hadronic Cascade



<u>Interface</u>

- Cooper-Frye formula at switching temperature T_{sw} = 160 MeV
- Resonance gas model at T=160 MeV

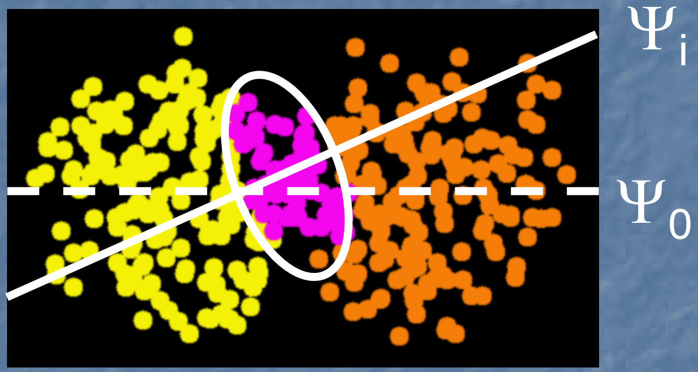
<u>Hadronic afterburner</u>

- Hadronic transport model based on kinetic theory → JAM*

*Y.Nara et al., (2000)

Eccentricity Fluctuation

Adopted from D.Hofman(PHOBOS) talk at QM2006



A sample event from Monte Carlo Glauber model

Interaction points of participants vary event by event.

→ Apparent reaction plane also varies.

→ The effect is significant for smaller system such as Cu+Cu collisions

See also talks by Poskanzer and R...

Event-by-Event Eccentricity

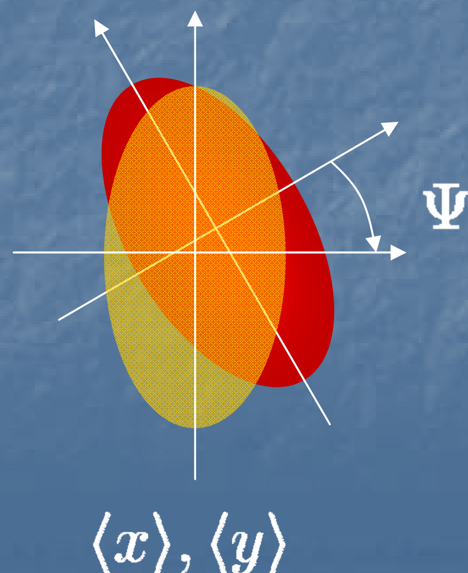
$$\begin{aligned}\sigma_x^2 &= \langle x^2\rangle - \langle x\rangle^2,\\ \sigma_y^2 &= \langle y^2\rangle - \langle y\rangle^2,\\ \sigma_{xy} &= \langle xy\rangle - \langle x\rangle\langle y\rangle.\end{aligned}$$

$$\langle\cdots\rangle = \frac{\int d^2x_\perp \cdots s_0(\boldsymbol{x}_\perp)}{\int d^2x_\perp s_0(\boldsymbol{x}_\perp)},$$

$$\varepsilon_{\mathrm{RP}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

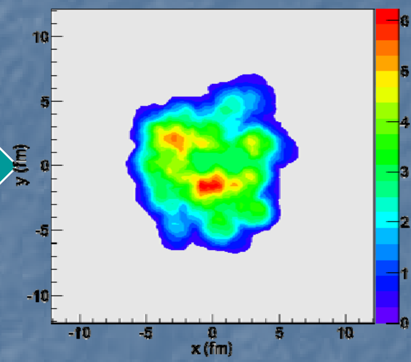
$$\varepsilon_{\mathrm{part}} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

$$\tan 2\Psi = \frac{\sigma_y^2 - \sigma_x^2}{2\sigma_{xy}}.$$



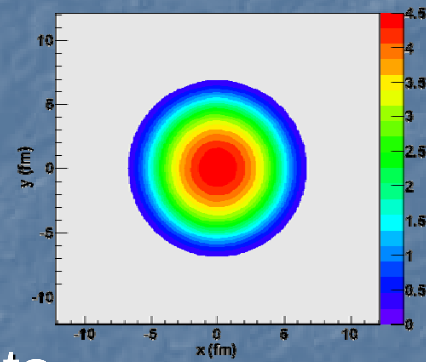
Initial Condition with an Effect of Eccentricity Fluctuation

Throw a dice to choose *b*



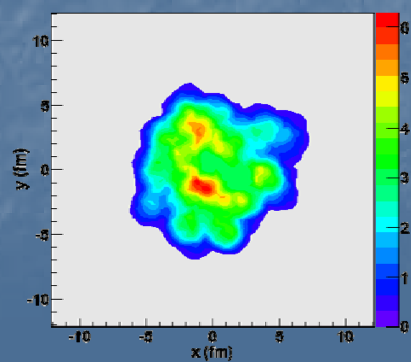
average over events

Reaction plane



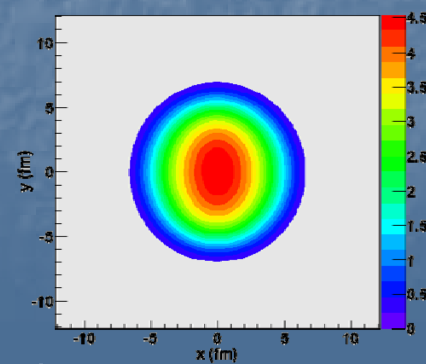
Shift: (<x>,<y>)
Rotation: Ψ

E.g.)
N_{part}^{min}= 279
N_{part}^{max}= 394
in Au+Au collisions at 0-10% centrality

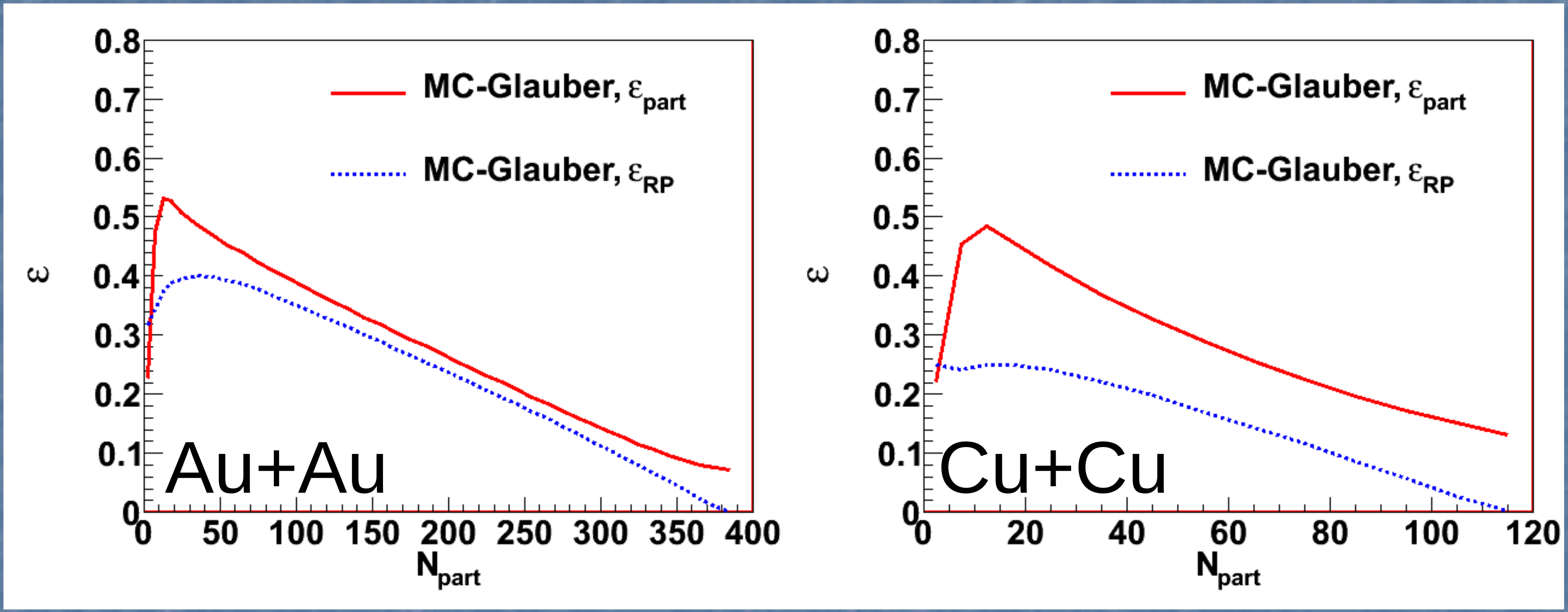


average over events

Participant plane



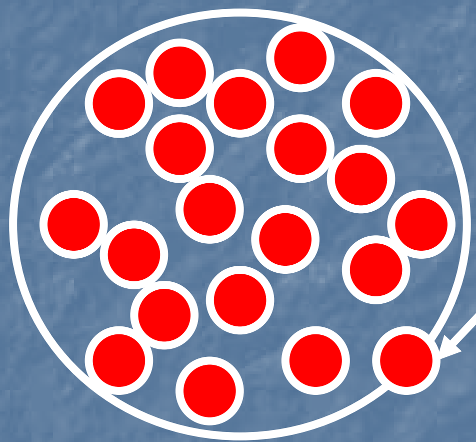
Eccentricity w.r.t. Participant Plane



Large fluctuation in small system such as Cu+Cu and peripheral Au+Au

Need these effects for apple-to-apple comparison

Caveat in Monte Carlo Approach



How do we consider this?

Naïve Glauber calculation:

$$\rho_{\mathrm{WS}}(\vec{x}) = \int \delta^{(3)}(\vec{x}-\vec{x}_0)\rho_{\mathrm{WS}}(\vec{x}_0)d^3\vec{x}_0$$

MC-Glauber calculation:

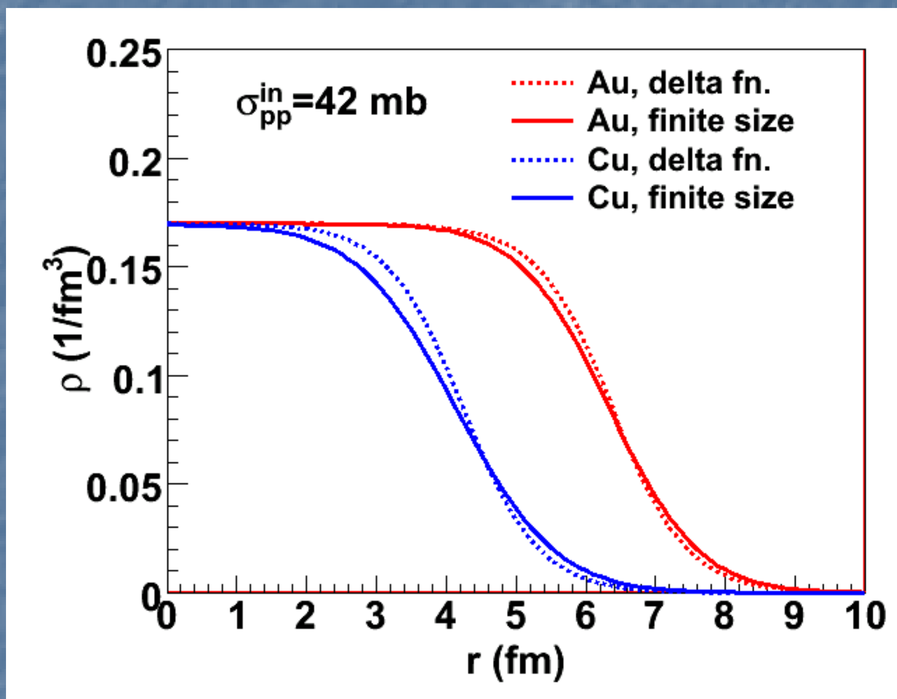
$$\rho_{\mathrm{WS}}(\vec{x}) \neq \rho(\vec{x}) \quad = \quad \int \Delta(\vec{x}-\vec{x}_0)\rho_{\mathrm{WS}}(\vec{x}_0)d^3x_0$$

Finite nucleon profile

$$\Delta(\vec{x}-\vec{x}_0) \quad = \quad \frac{\theta(r - \mid \vec{x}-\vec{x}_0 \mid)}{V}$$

$$V \quad = \quad \frac{4\pi r^3}{3}, \quad r = \sqrt{\frac{\sigma_{pp}^{\mathrm{in}}}{\pi}}$$

More diffused!



→ Reduction of eccentricity by ~5-10%
→ Necessity of re-tuning parameters in Woods-Saxon density
→ We have retuned parameters.

R = 6.38 fm → 6.42 fm (Au)

δr = 0.535 fm → 0.44 fm (Au)

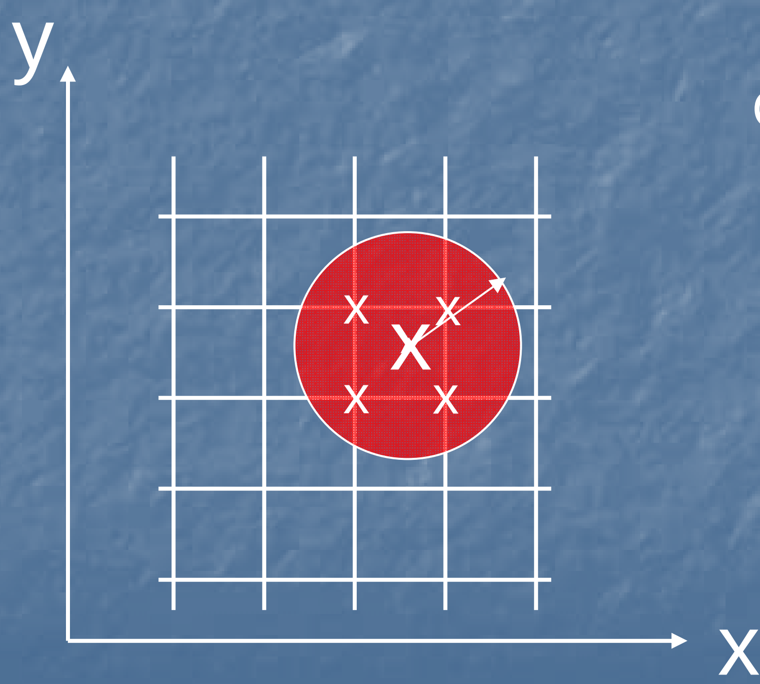
TH and Y.Nara, PRC79, 064904 (20

Caveat in Monte Carlo Approach 2

2-component model:

$$\frac{dS}{d^2x_\perp} = C\left[\frac{1-\delta}{2}\frac{dN_{\rm part}}{d^2x_\perp} + \delta\frac{dN_{\rm coll}}{d^2x_\perp}\right]$$

Given from Monte Carlo



Interaction point (part./coll.)

Coarse grained

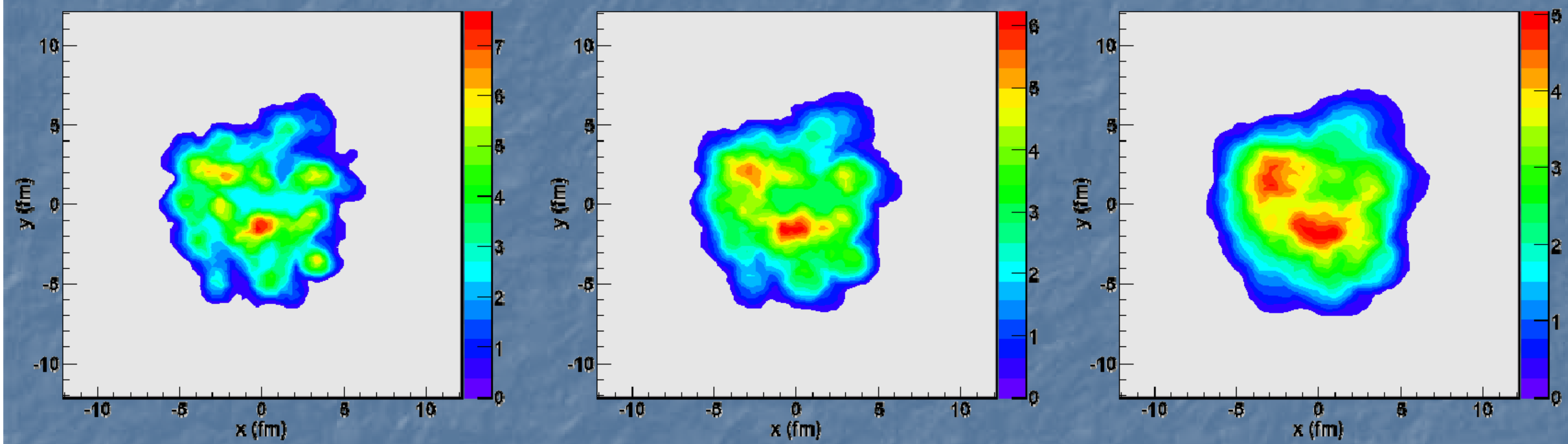
Interaction region

$$r = \sqrt{\frac{\sigma_{\rm in}}{\pi}} \sim 1.15 \ \rm fm$$

See also, Appendix in
H.-J. Drescher and Y. Nara, PRC75, 034905 (

Matter Profile after Coarse-Graining

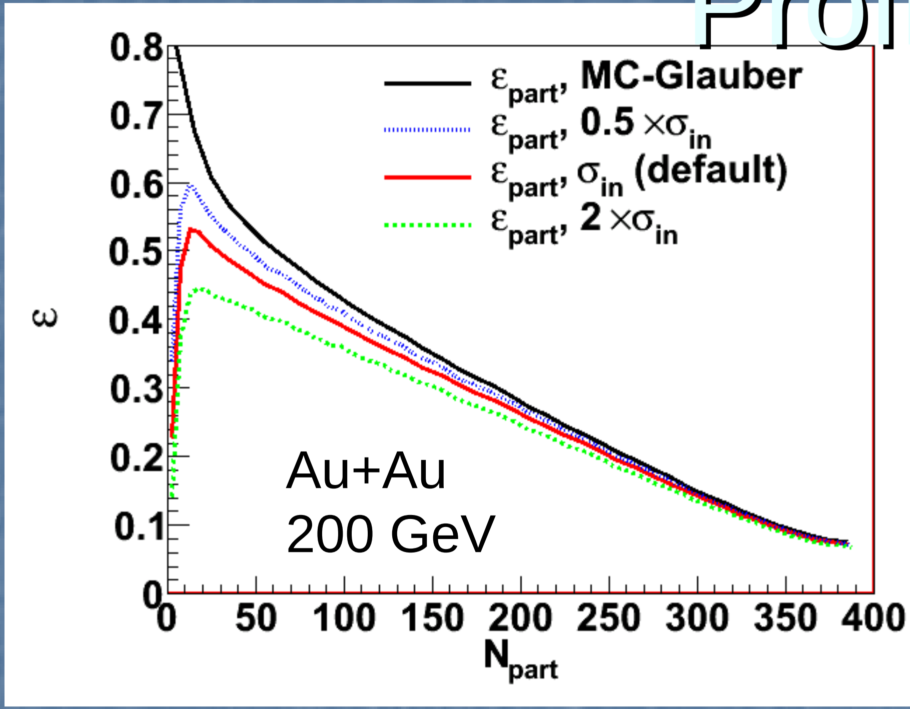
One typical central event



$0.5 \times \sigma_{in}$ σ_{in} $2 \times \sigma_{in}$

Coarse-grained

Eccentricity with Smeared Profile



~10 % reduction around N_{part}~ 50-100 in the default model (smearing area = σ_{in})

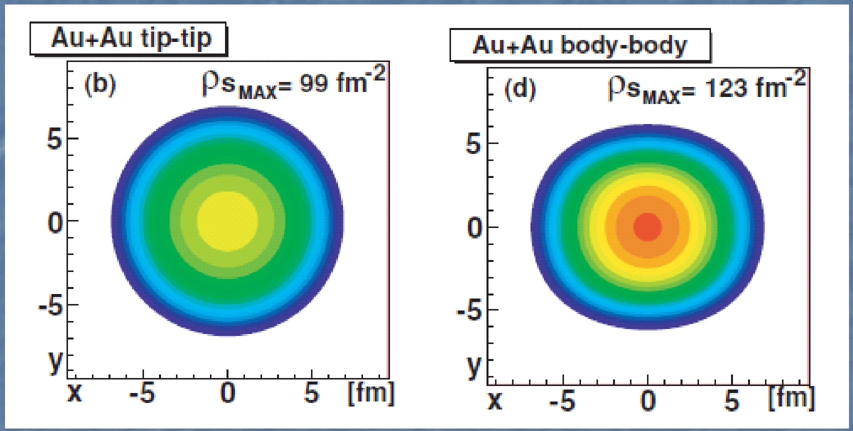
How to quantify smearing area?
→ Modeling of entropy production and thermalization process: CGC + Glasma?
→ Open problem: Importance of understanding hydrodynamic initial conditions

Gold and Copper, Deformed?

Radius in Woods-Saxon

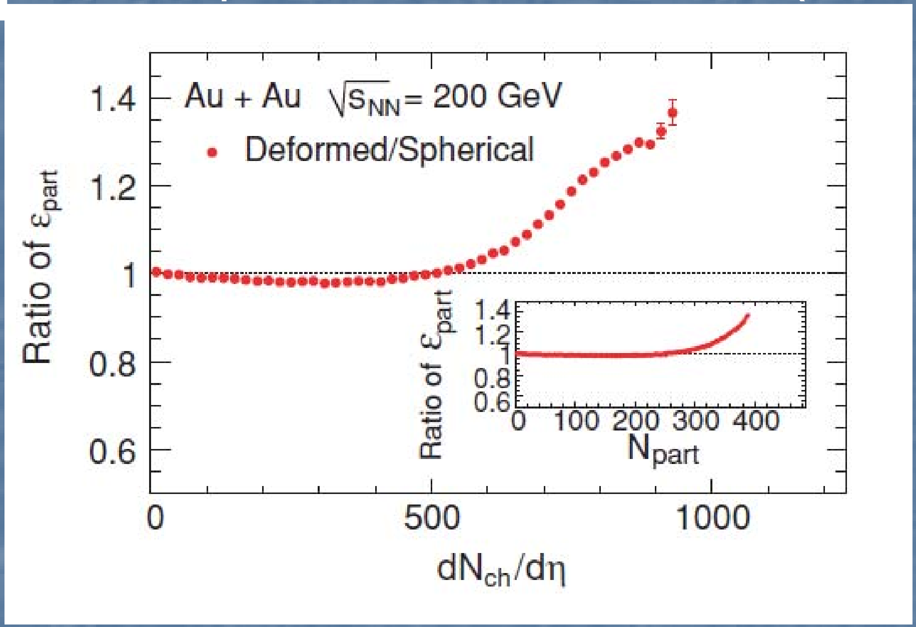
$$R_0 \rightarrow R_0(1 + \beta_2 Y_{20} + \beta_4 Y_{40})$$

$$\beta_2 = -0.13, \beta_4 = -0.03^*$$



Oblate Au+Au Collision

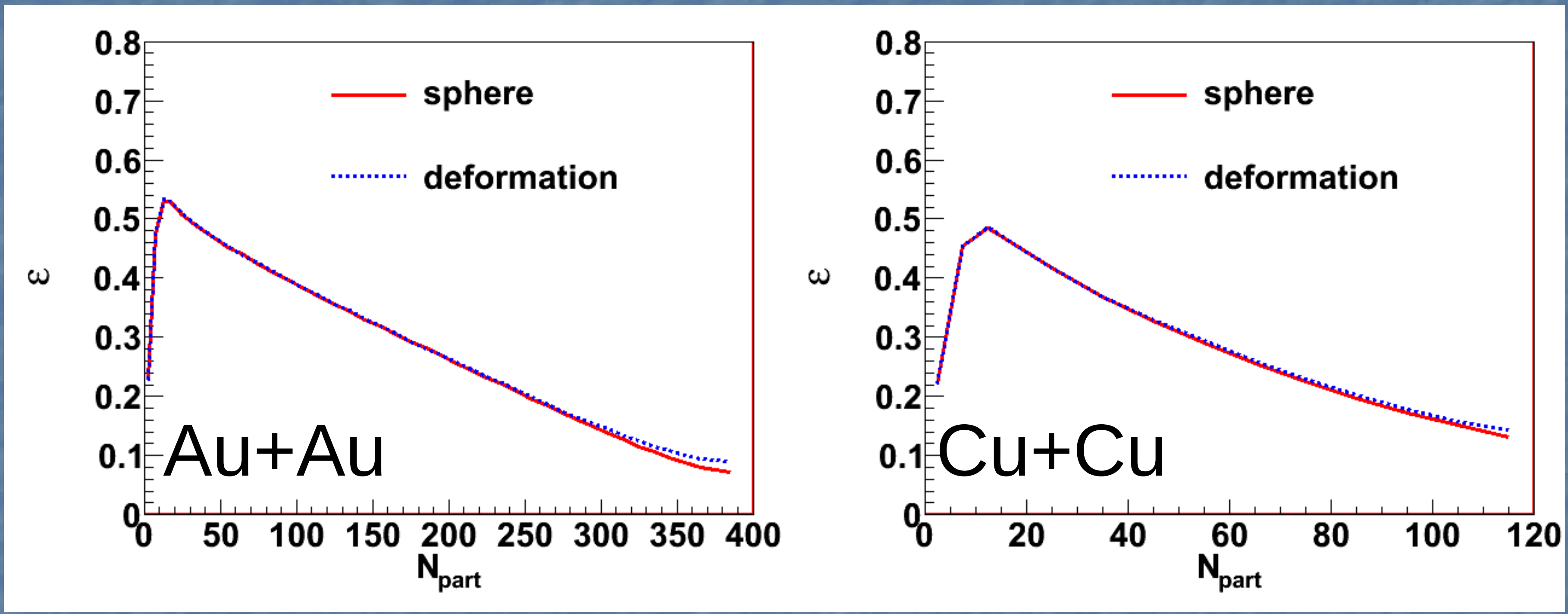
P.Filip et al., PRC**80**, 054903(2009).



Important in very central collision(?)

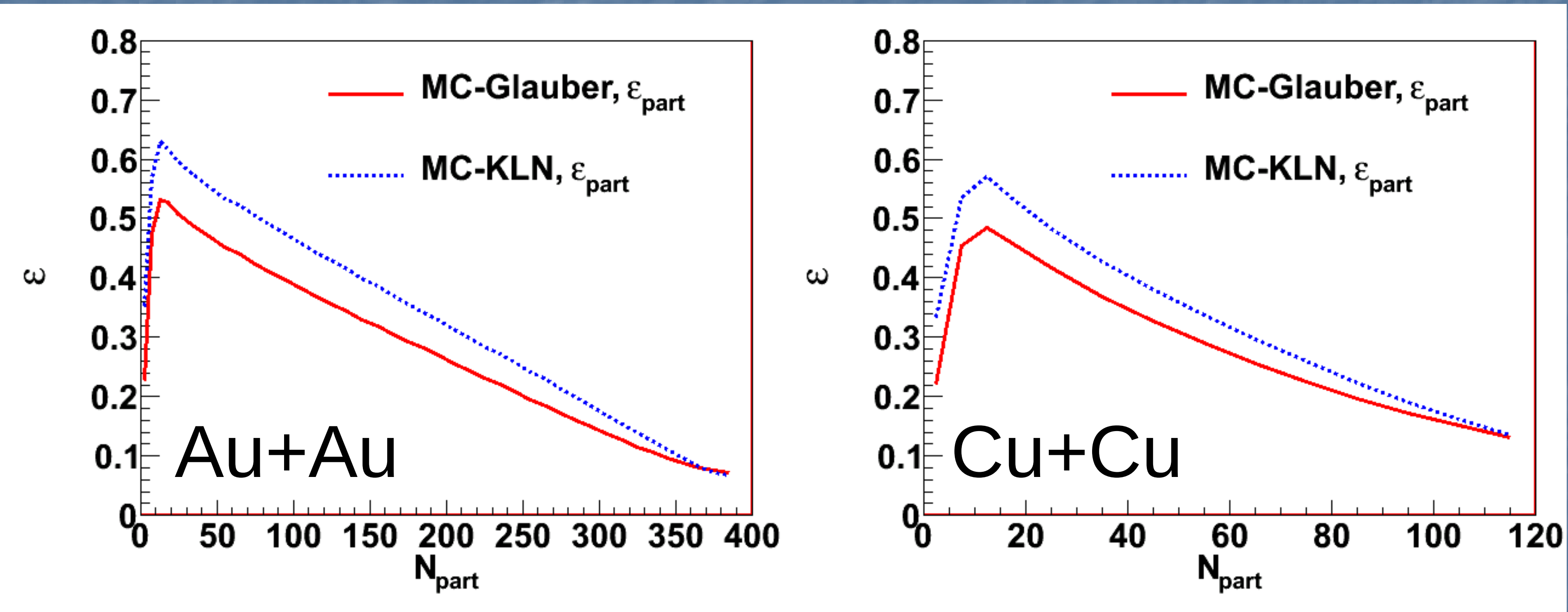
*P.Möller et al, At. Data Nucl. Data Table 59, 185 (1995)

Deformed Gold and Copper



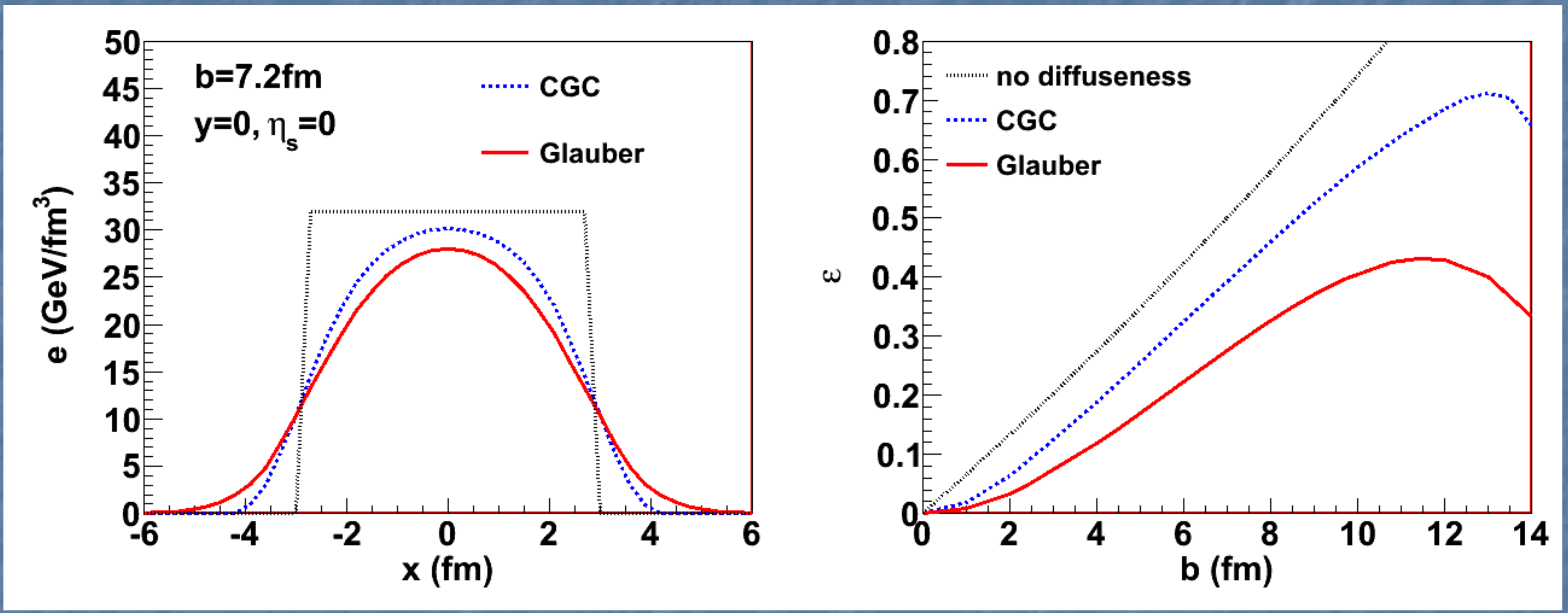
Effect of deformation is seen only in very central events

Initial Condition Dependence



$$\varepsilon_{\mathrm{MC-KLN}} > \varepsilon_{\mathrm{MC-Glauber}}$$

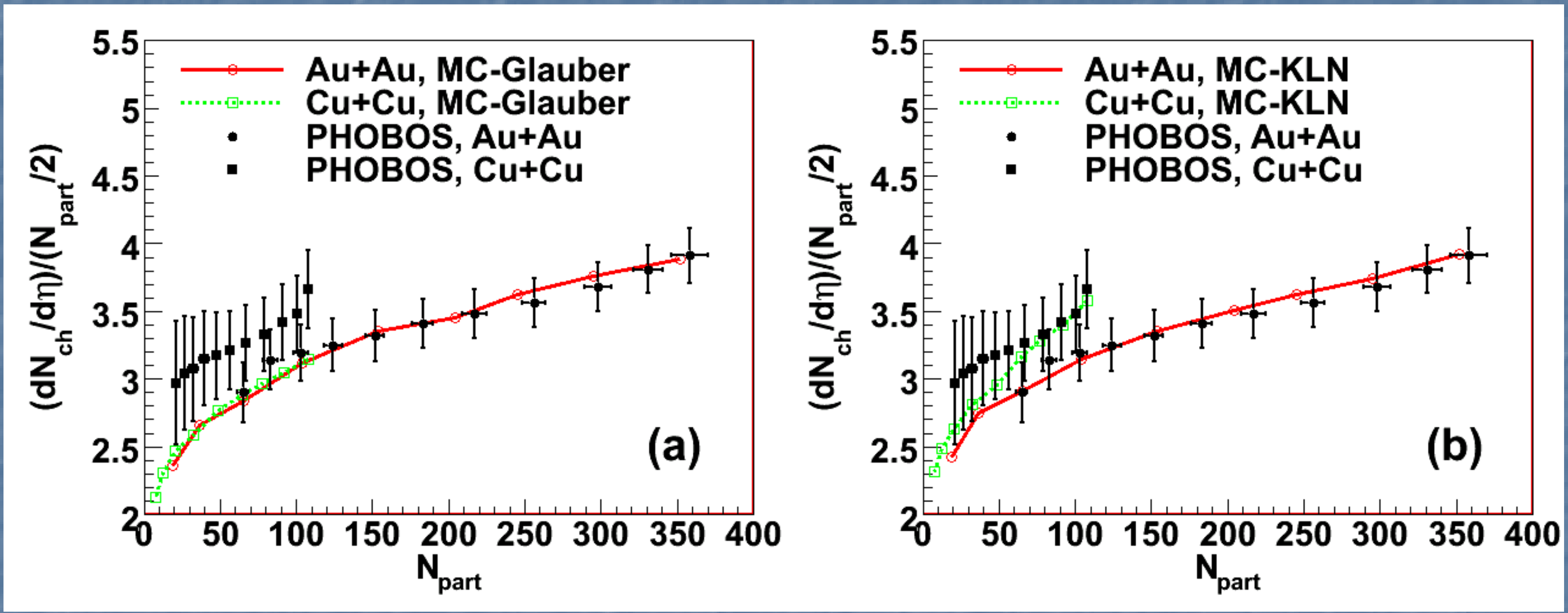
Steeper Transverse Profile in CGC



Closer to hard sphere than Glauber

Note: Original KLN model (not MC-KLN)

Inputs in Model Calculations



Parameters are fixed in Au+Au collisions

Glauber: $$\frac{dS}{d^2x_\perp} = C\left[\frac{1-\delta}{2}\frac{dN_{\rm part}}{d^2x_\perp} + \delta\frac{dN_{\rm coll}}{d^2x_\perp}\right]$$

KLN: standard parameters

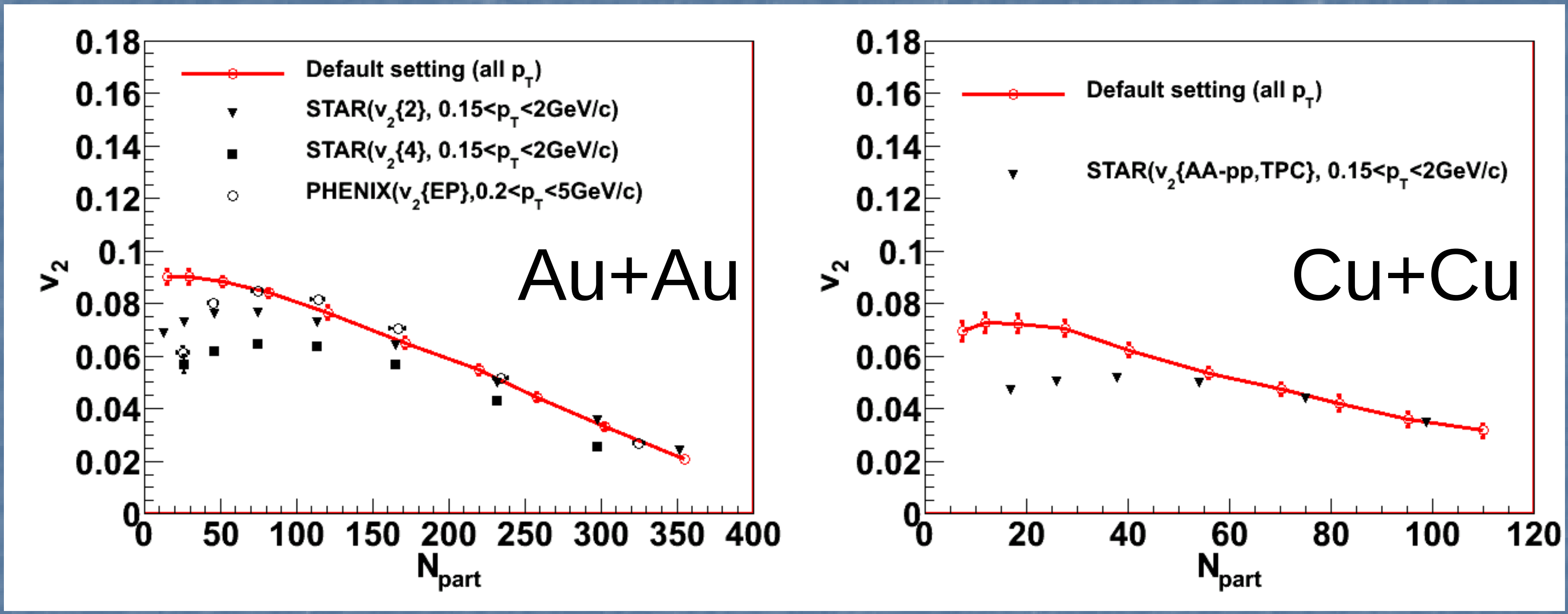
Systematic Studies on Elliptic Flow

Default setting as a reference result (Red Line)

- MC-Glauber, ε_{part}, spherical nuclei
- Lattice-based crossover EoS
- Hadronic rescattering

1. With rescattering vs. without rescattering
2. Lattice-based crossover vs. 1st order phase transition
3. ε_{part} vs. $\varepsilon_{R.P.}$
4. Glauber vs. CGC (factorized KLN)
5. Spherical vs. deformed nuclei

Comparison with Data



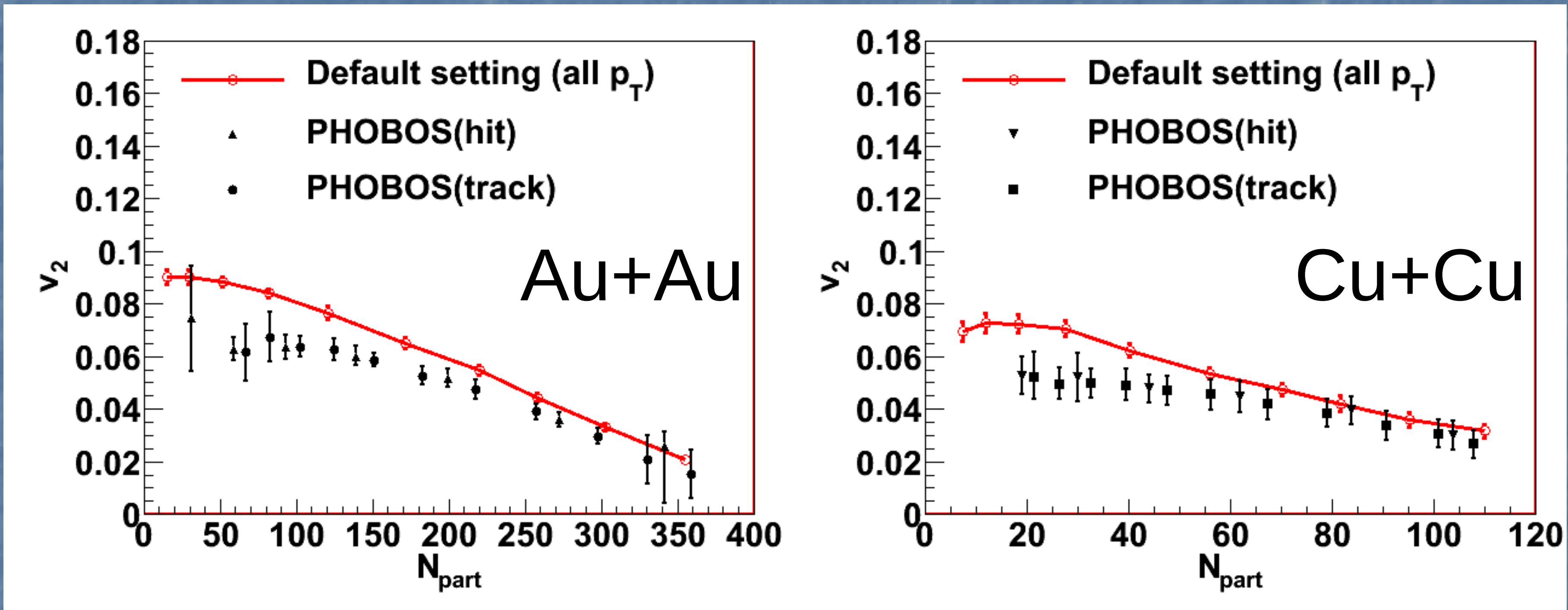
Note: $v_2\{2\}>v_2\{\text{“true”}\}>v_2\{4\}$

“True”: J.Y.Ollitrault,A.M.Poskanzer and S.A.Voloshin, Phys.Rev.C80, 014904 (2009).

Slight overshoot in peripheral region

STAR: PRC72, 014904 (2005) ; PRC 81, 44902 (2010), PHENIX: PRL91,18

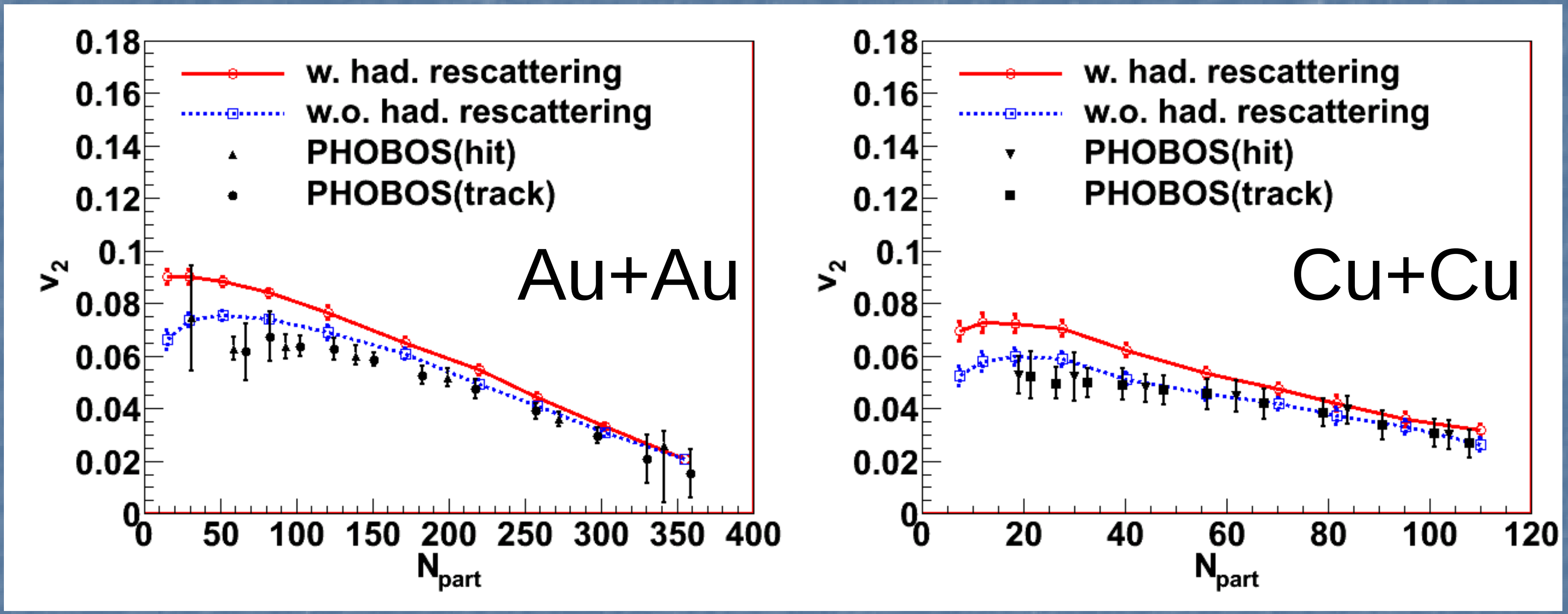
Comparison with Data (contd.)



System size dependence
→ Overshoot also in peripheral collisions
→ Room for (tiny) QGP viscosity

PHOBOS: PRC72, 051901(R) (2005);PRL98, 242302

Effect of Hadronic Rescattering

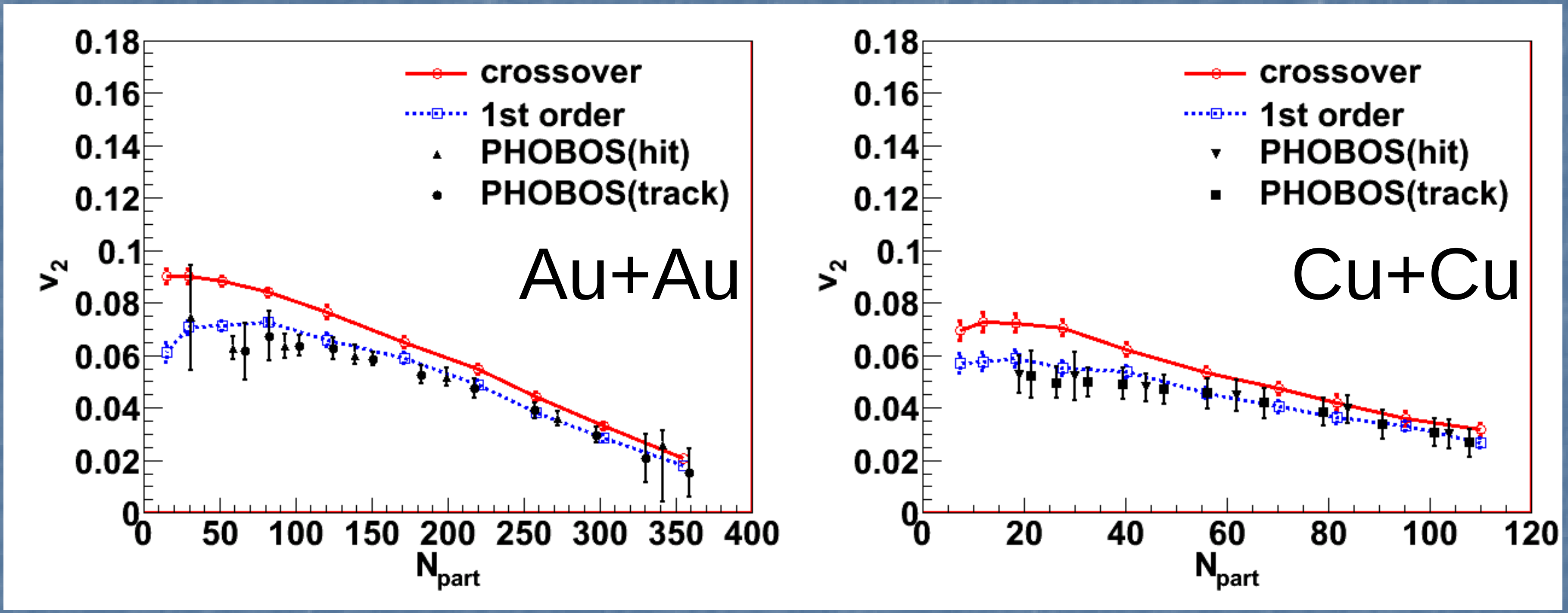


v_2 is slightly enhanced in peripheral collisions.

→ Not yet “quenched” at hadronization

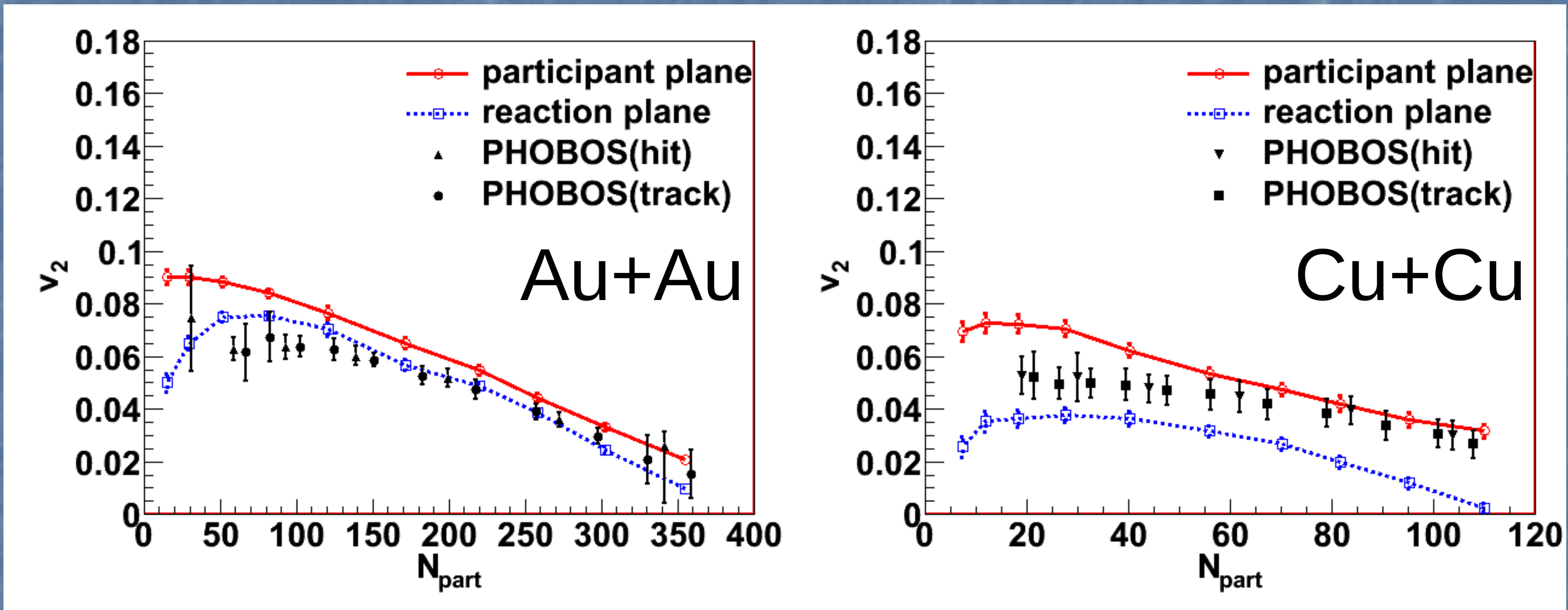
v_2 in central collisions is generated during the QC

EoS Dependence



1st order phase transition mimics viscous correctio
No room for QGP viscosity in the 1st order p.t. moc

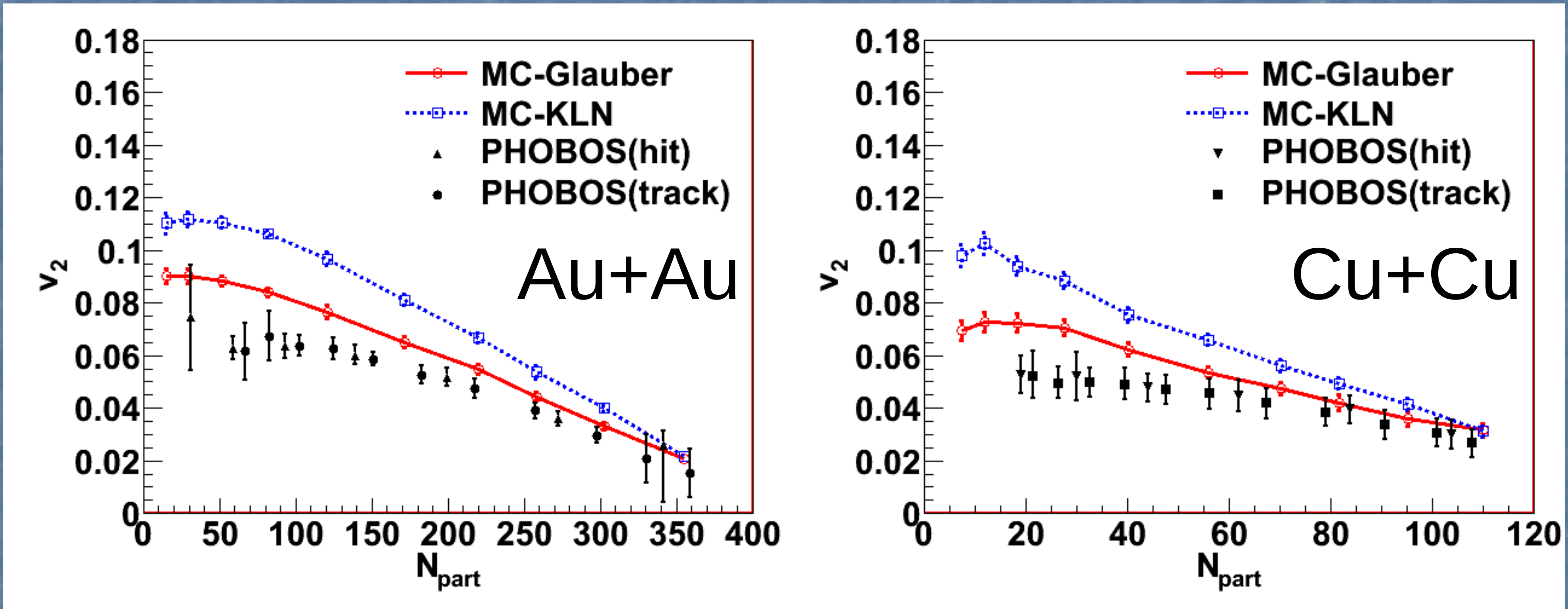
Effect of Eccentricity Fluctuation



Effect of fluctuation → Large in small system

Importance of eccentricity w.r.t. participant plane

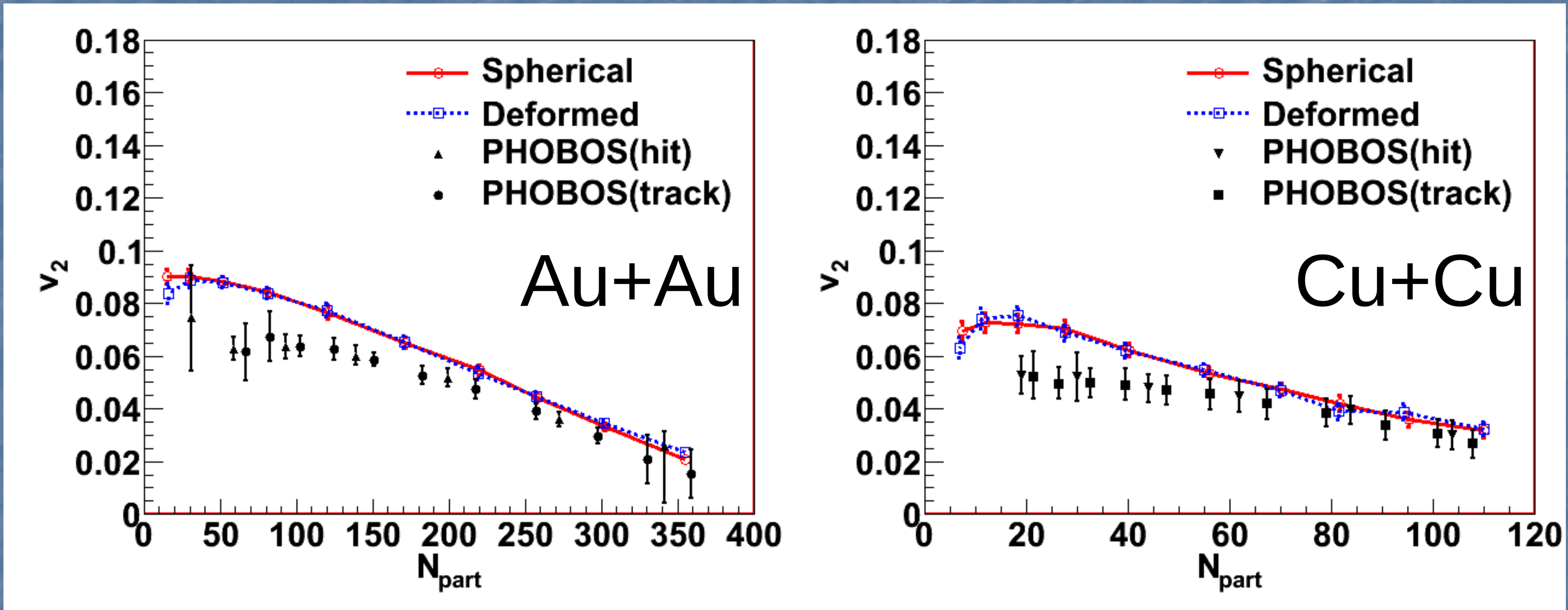
Initial Condition Dependence



- Sensitive to initial models.
- Perfect fluid and CGC, compatible?

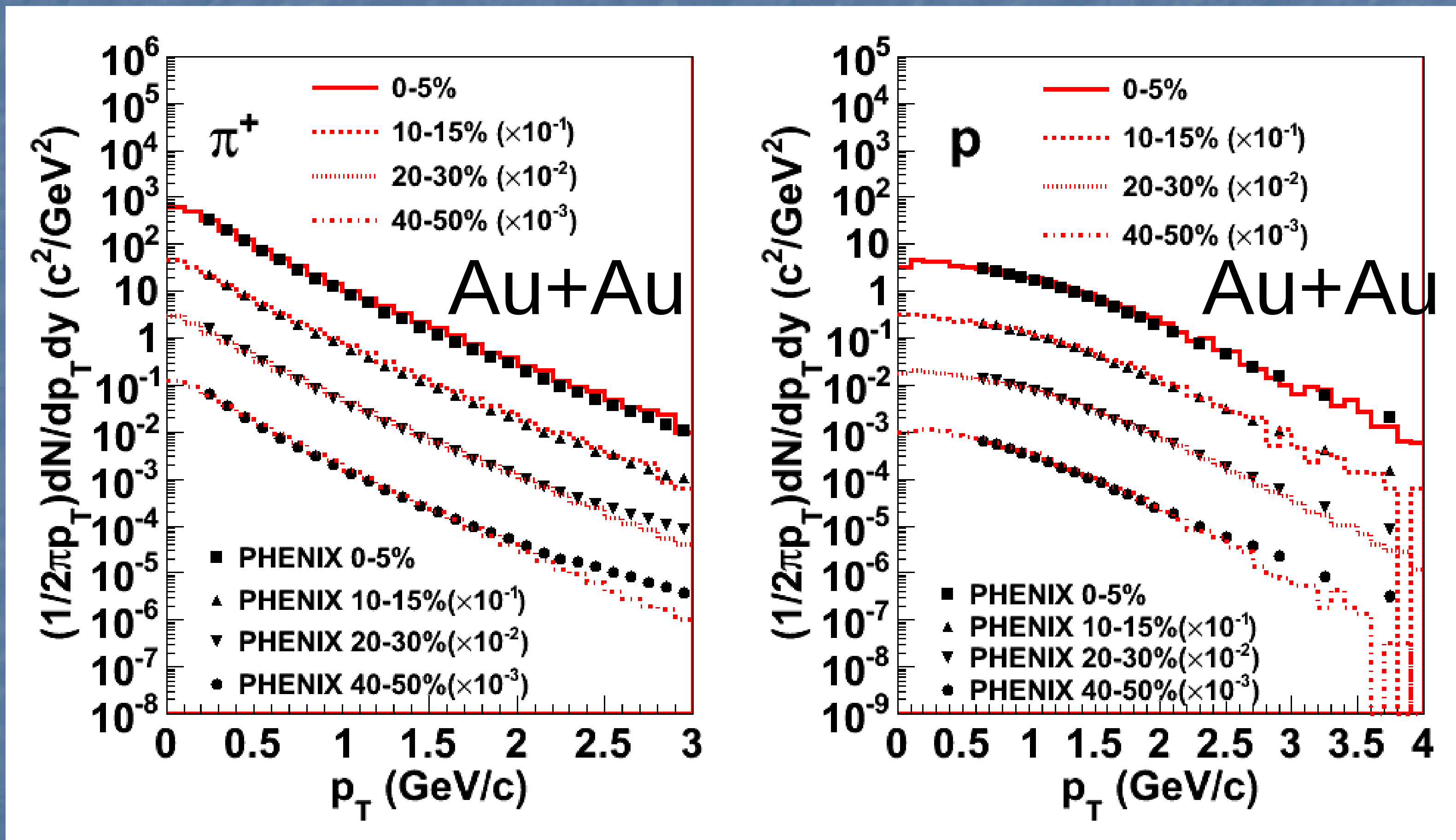
→ Need more studies on initial condition and viscosity

Effect of Deformation



Almost no effects in semi-central collisions
Small effect in central and peripheral event

Comparison with Data: p_T dist.

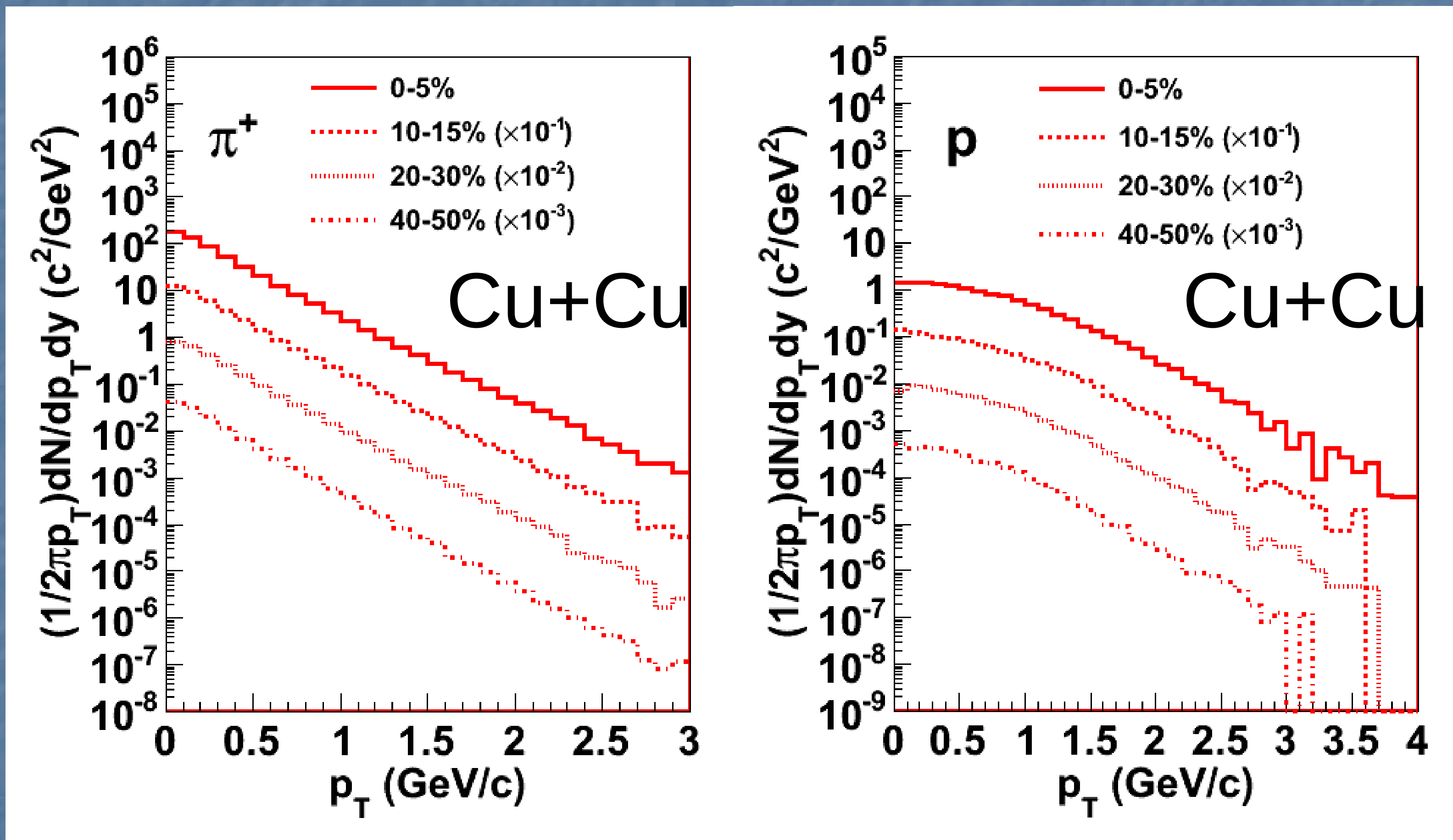


p_T distribution is *output* in hybrid models.

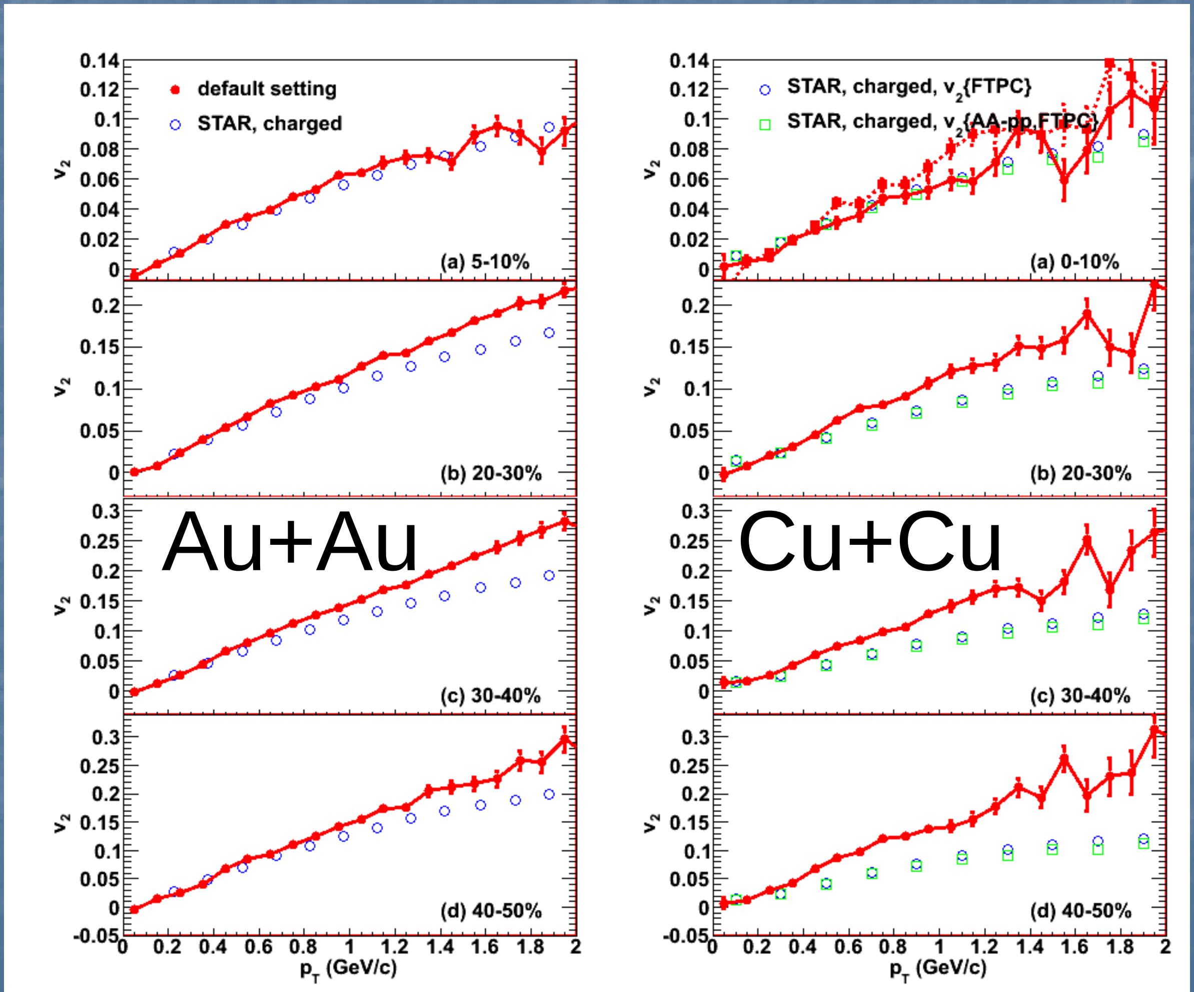
→ At work up to 2-3 GeV/*c*

PHENIX: PRC69,034909(20

p_T Dist. in Cu+Cu Collisions



Comparison with Data: $v_2(p_T)$



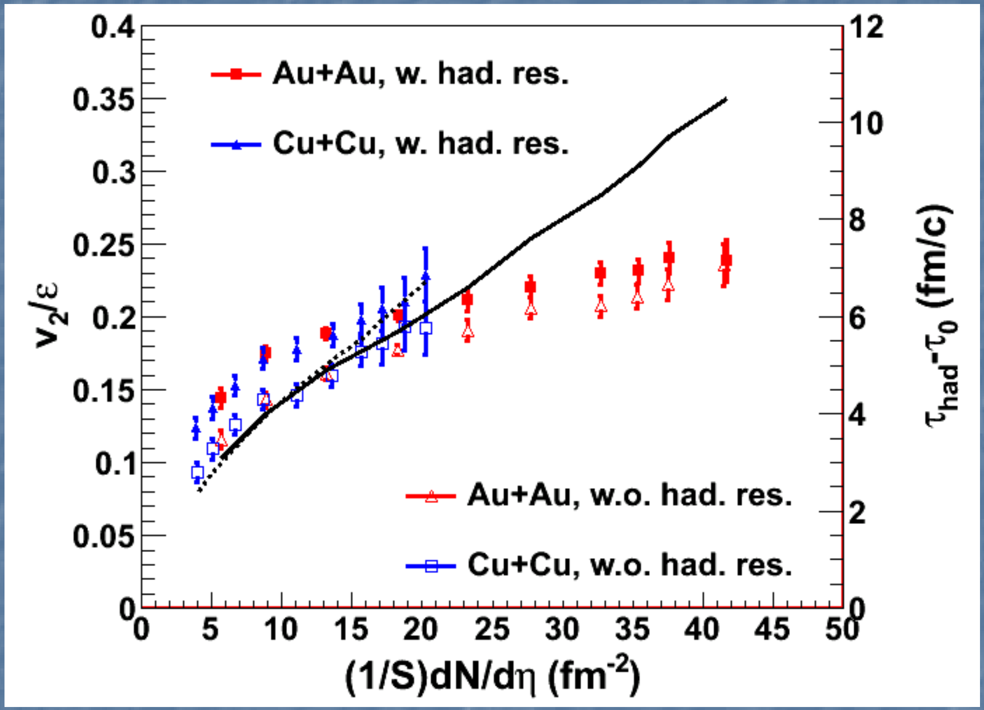
STAR: PRC72, 014904(2005)

Need (tiny?) viscosity in small system (such as Cu+Cu and peripheral Au+Au collision)

Not enough statistics

→ Stay tuned!

v_2 vs. Transverse Density



v_2/ε monotonically increases with transverse density *even within ideal hydro QGP*.

→ Finite lifetime effect

→ Mimics viscosity

→ This should be subtracted(?)

Summary

- Importance of hadronic dissipation
- Development of a hybrid model (Ideal hydro + hadronic afterburner) toward understanding of the QGP
- Systematic analyses of elliptic flow data using the hybrid model
  - Glauber vs. CGC, ε_{part} vs. $\varepsilon_{R.P.}$, spherical vs. deformed, 1st order vs. crossover, …
- Comment on v_2/ε
- Toward quantifying viscous corrections