Zakopane School, June 13, 2011

Hydrodynamic Approach to Relativistic Heavy Ion Collisions

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T.H., P.Huovinen, Y.Nara, arXiv:1012.3955; arXiv:1010.6222 (Phys.Rev.C83:021902,2011); Invited review article in Progress of Particle and Nuclear Physics (in preparation)

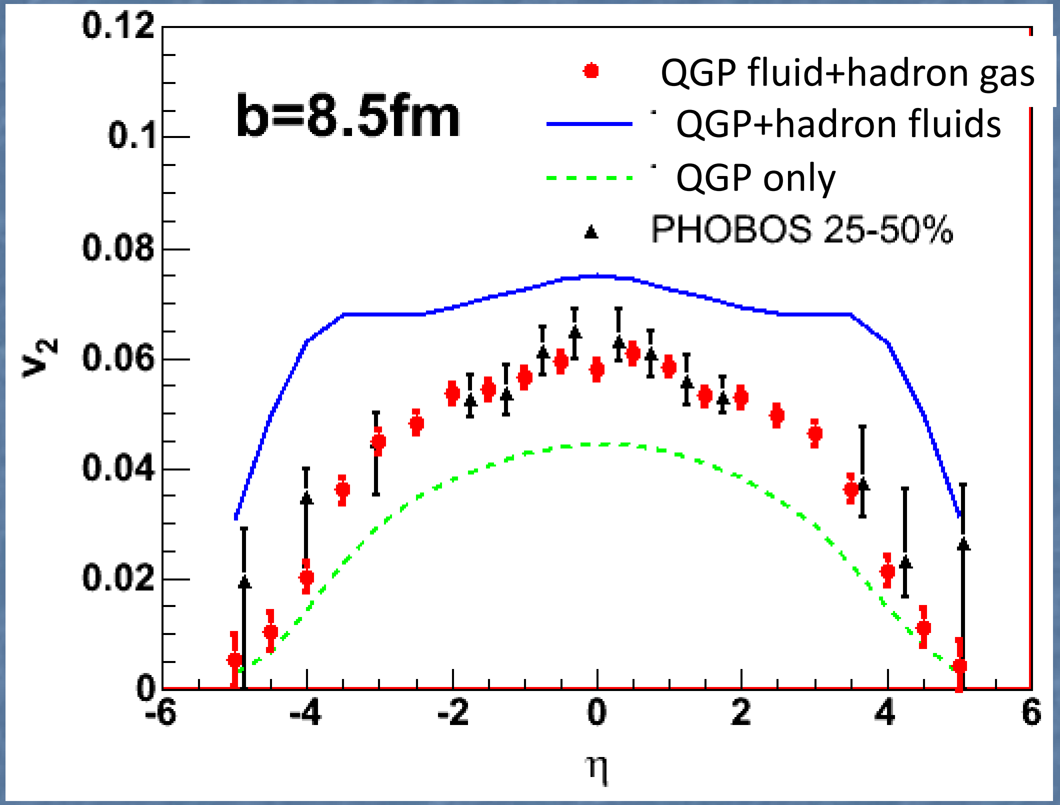
Outline

- Introduction
- Some highlights from the hydro+cascade model so far
- Model: QGP fluid + hadronic cascade picture
- Results at RHIC:
  - v_2
- Prediction and Postdiction at RHIC and LHC:
  - v_2 in U+U collisions
  - v_2 in Pb+Pb collisions
- Summary

Introduction

- Main aim: Understanding RHIC data based on a systematic analysis with QGP perfect fluid picture
- After press release of perfect fluid discovery in 2005 → Much progress: hadronic dissipation, eccentricity fluctuation, lattice EoS, CGC initial condition…
- Set a baseline for viscous hydro calculations
- Prediction and “post”diction for U+U at RHIC and Pb+Pb at LHC

Importance of Hadronic Dissipation

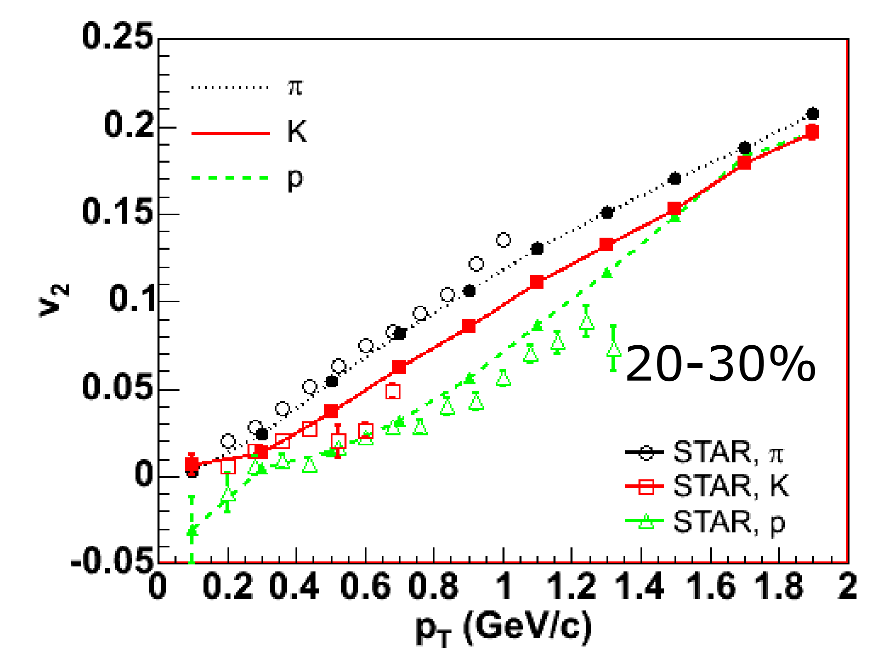


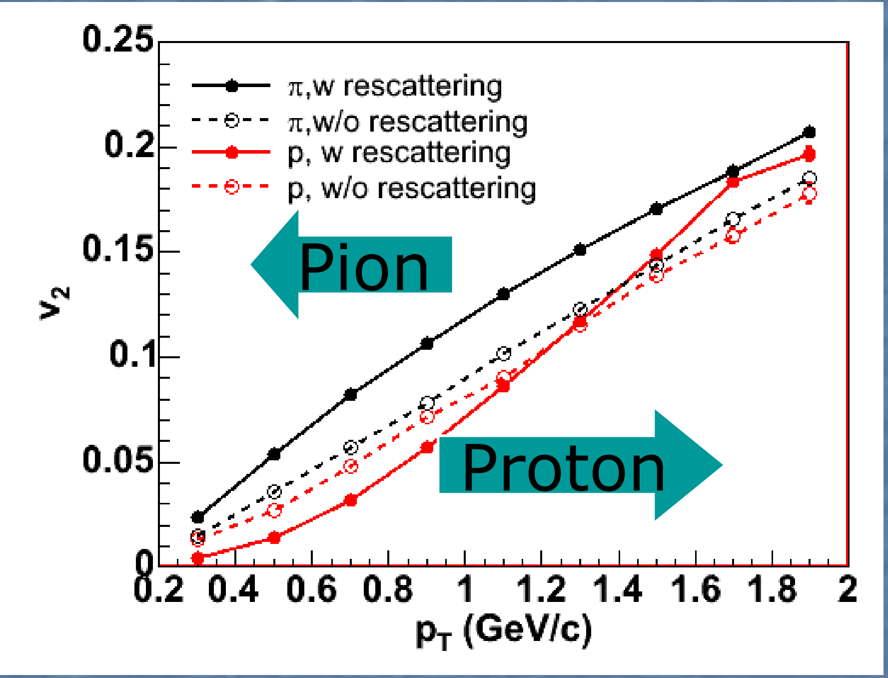
Suppression in forward and backward rapidity

Importance of hadronic viscosity

TH et al.,('05)

Mass Splitting = Hadronic effects



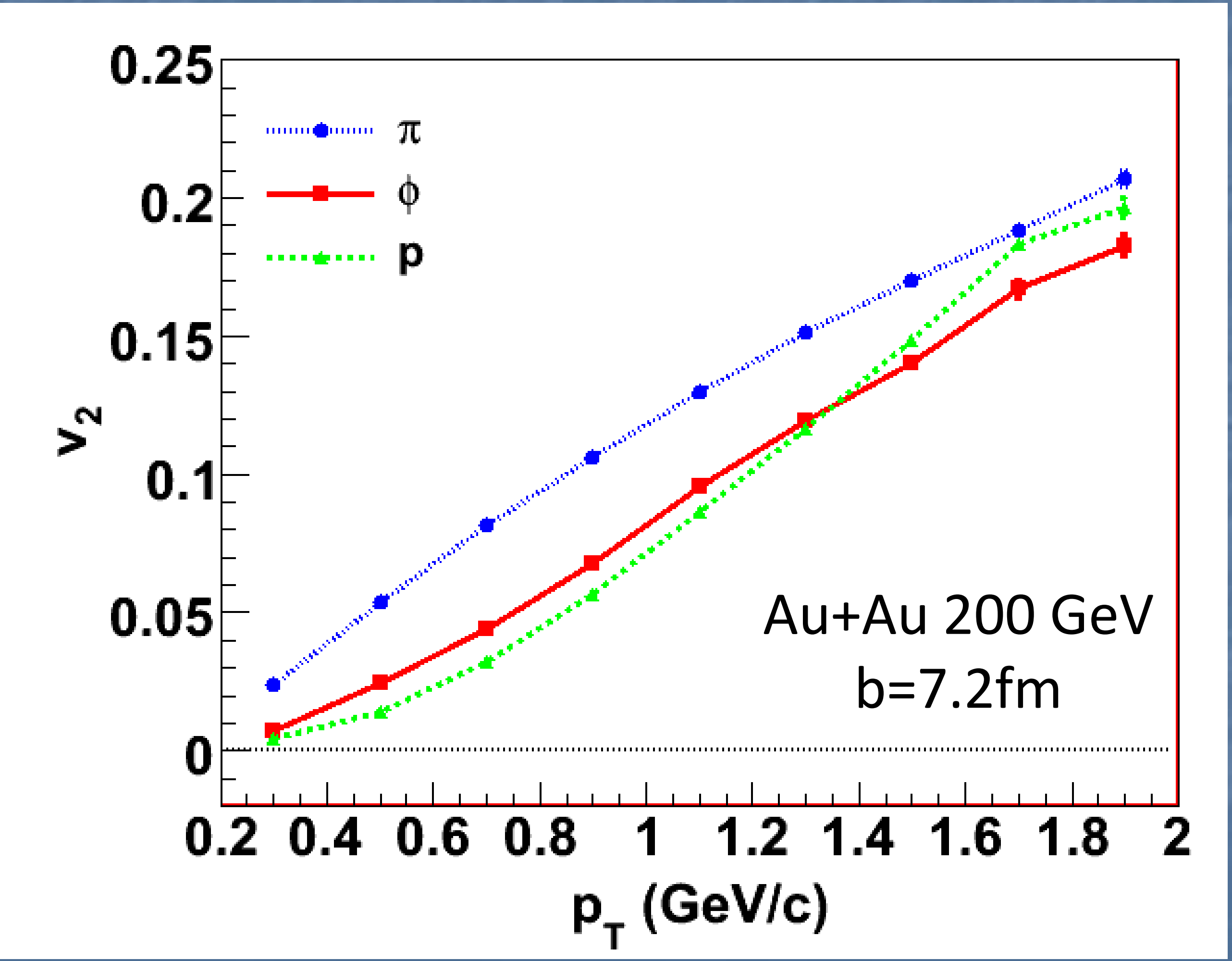


Mass dependence is o.k. from hydro+cascade.
When mass splitting appears?

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

TH et al.,('08)

Violation of Mass Splitting

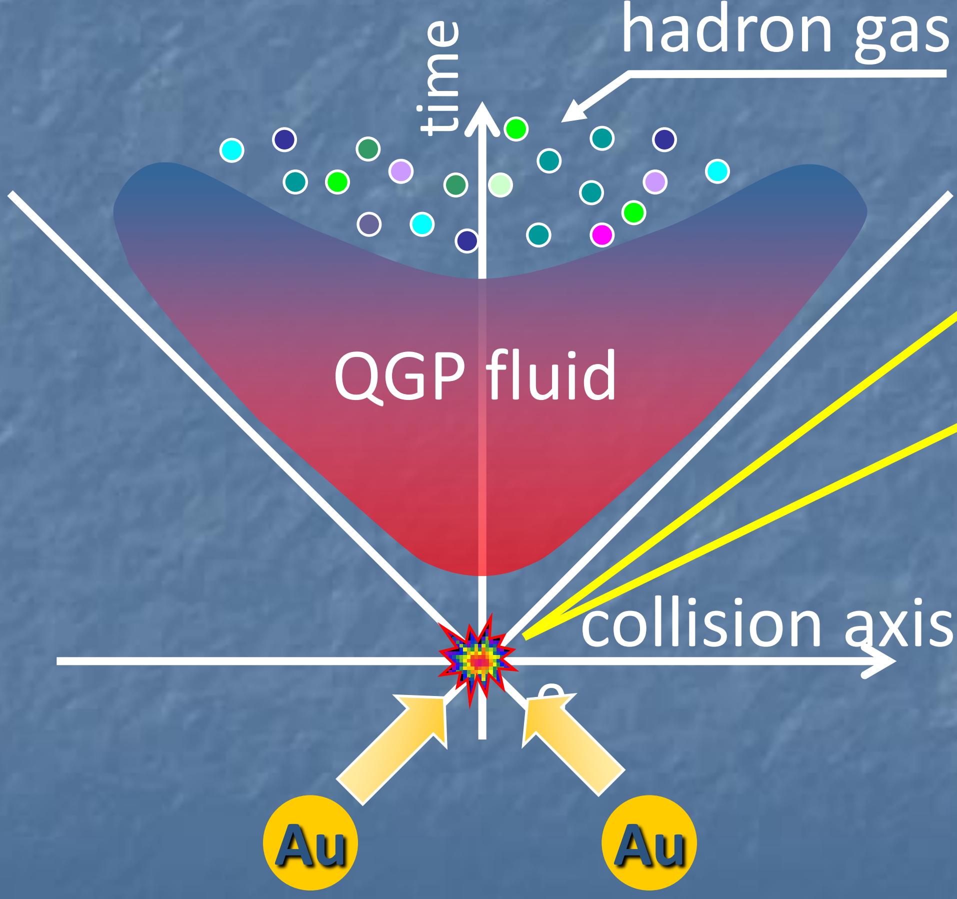


TH et al.,('08)

Model

- No single model to understand heavy ion collision as a whole.
- Idea: Employ "cutting edge" modules as far as possible
  - 3D ideal hydro
  - Hadronic transport model, JAM
  - Lattice EoS + resonance gas in JAM NEW
  - Monte Carlo Glauber/KLN for initial condition NEW

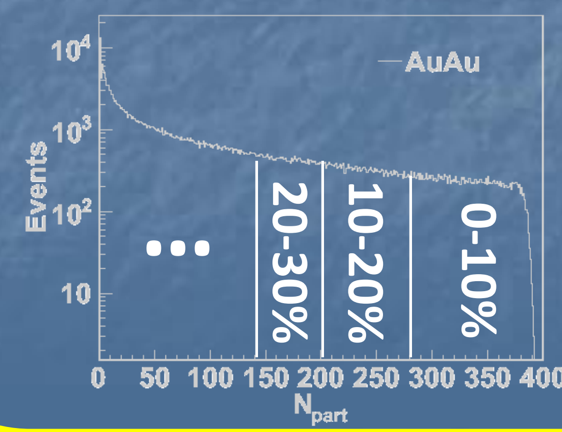
A Hybrid Approach: Initial Condition



Model*

- MC-Glauber
- MC-KLN (CGC)

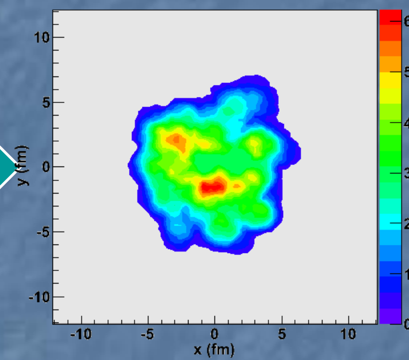
- ε_{part}, $\varepsilon_{R.P.}$
- Centrality cut



*H.J.Drescher and Y.Nara (2007)

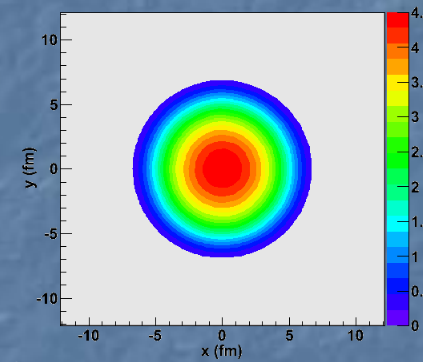
Initial Condition w.r.t. Participant Plane

Throw a dice to choose *b* and calculate N_{part}



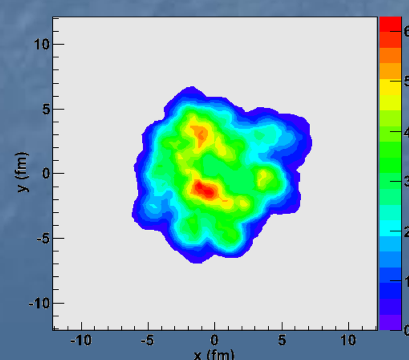
average over events

Reaction plane



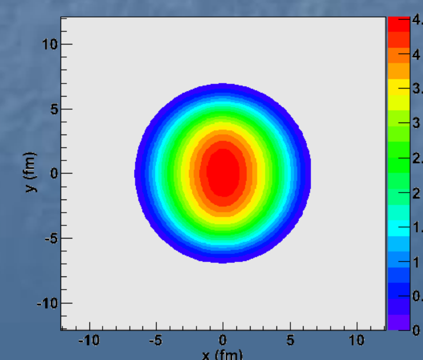
Shift: (<x>,<y>)
Rotation: Ψ

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

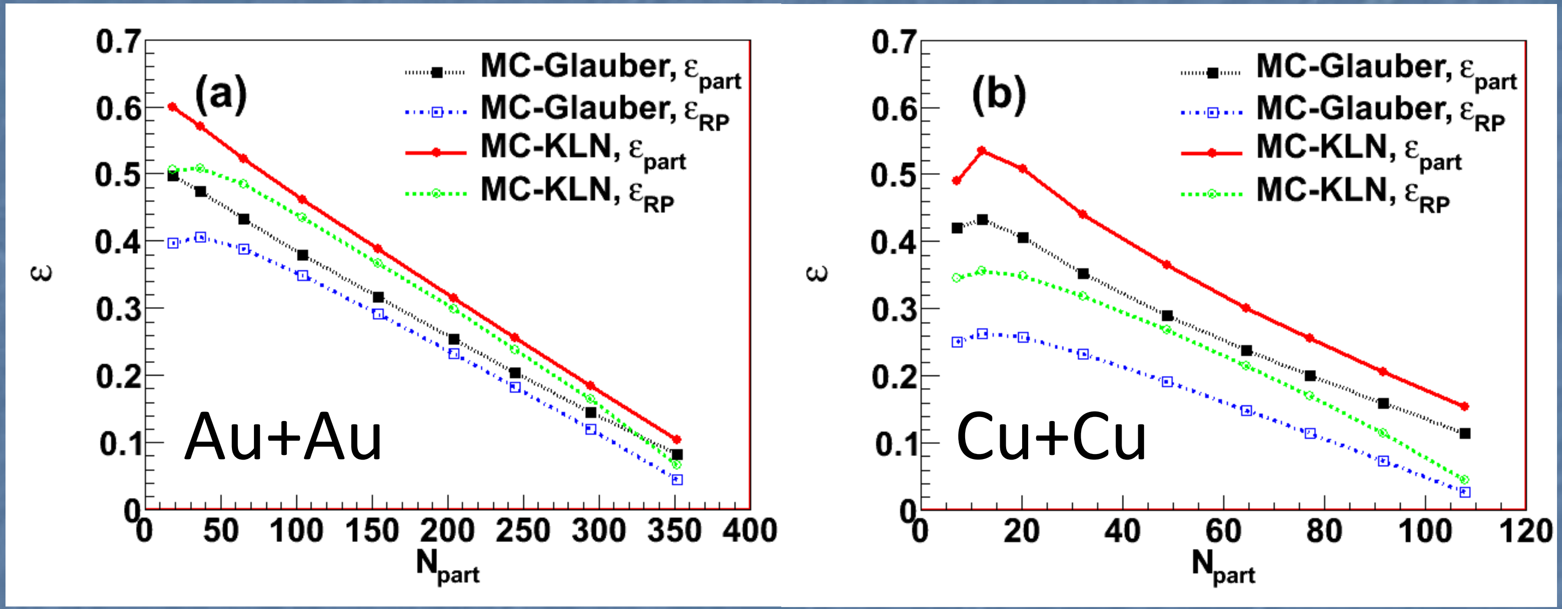


average over events

Participant plane



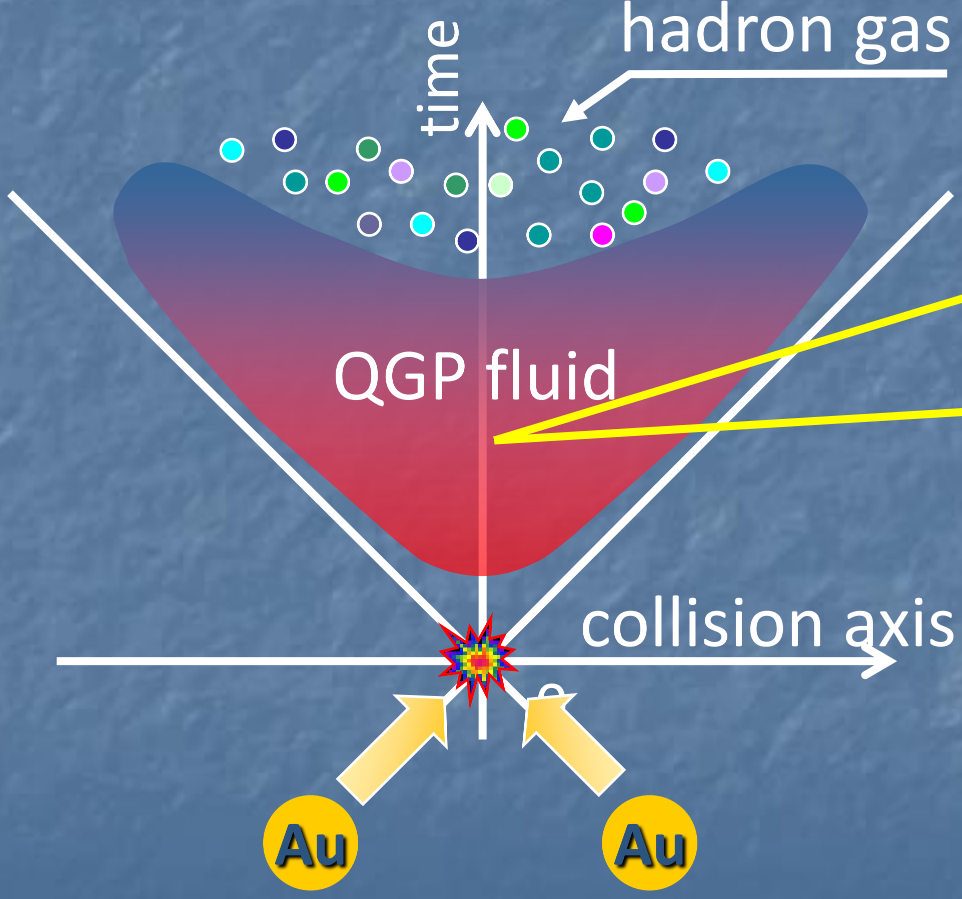
ε_{part} and $\varepsilon_{R.P.}$



- Eccentricity enhanced due to fluctuation
- Significant in small system, e.g., Cu+Cu, perpheal Au+Au
- MC-KLN > MC-Glauber *

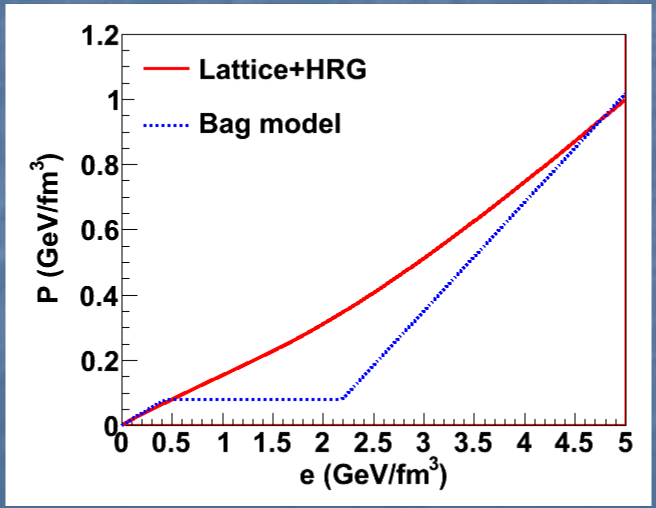
*See, Drescher and Nara, PRC 75, 034905 (2007).

A Hybrid Approach: Hydrodynamics



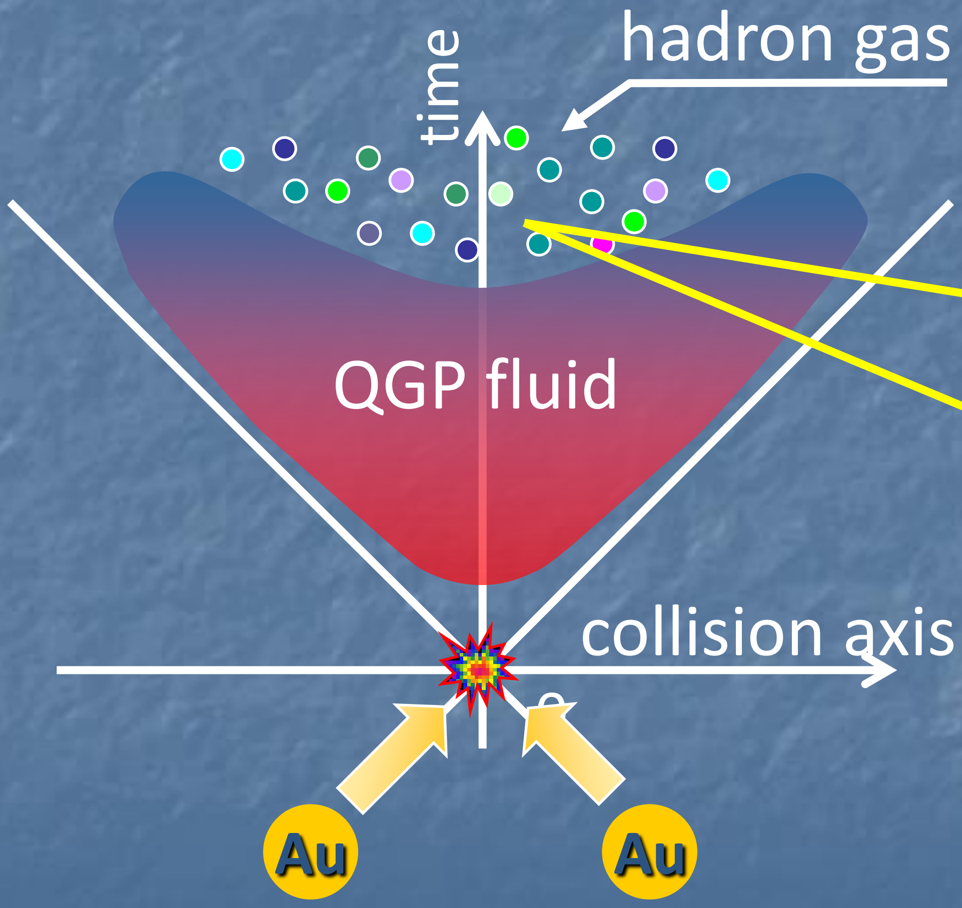
Ideal Hydrodynamics[#]

- Initial time 0.6 fm/*c*
- Lattice + HRG EoS*



[#]Hirano (2002), *Huovinen and Petreczky (2010) + JAM HRG

A Hybrid Approach: Hadronic Cascade



<u>Interface</u>

- Cooper-Frye formula at switching temperature T_{sw} = 155 MeV

<u>Hadronic afterburner</u>

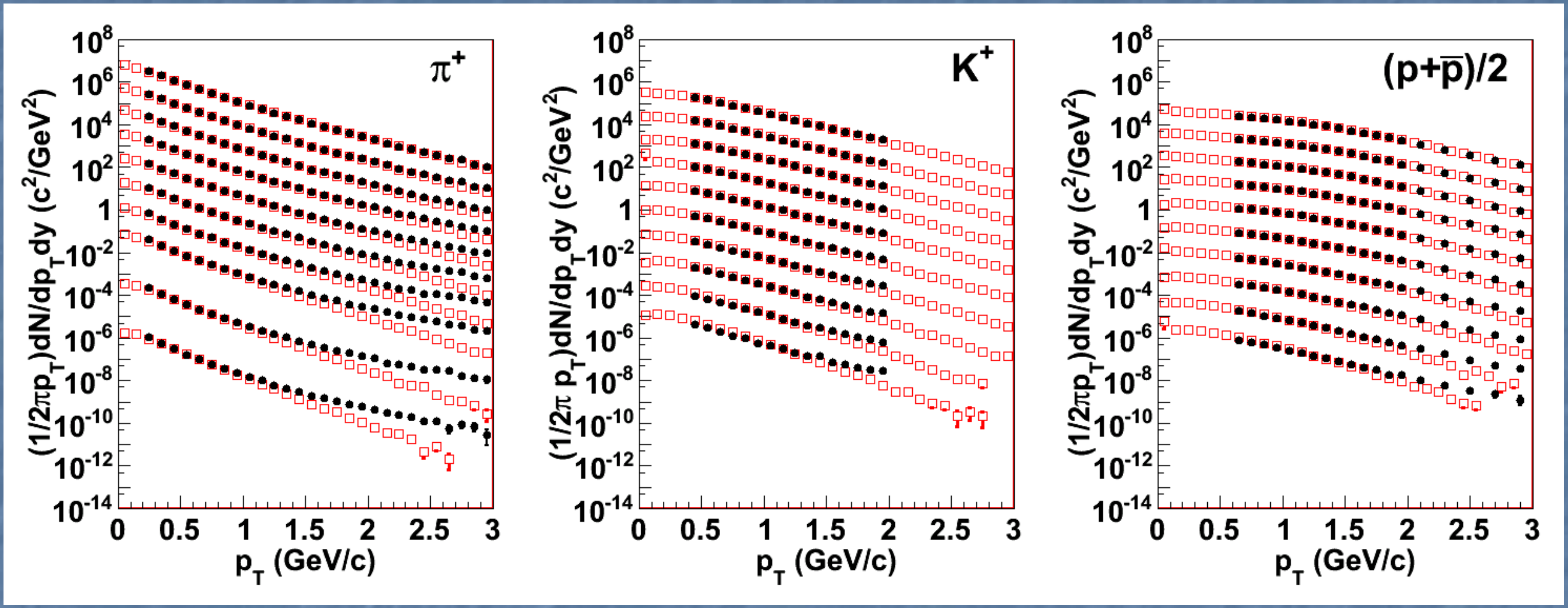
- Hadronic transport model based on kinetic theory → JAM*

*Y.Nara et al., (2000)

Comparison of Hydro+Cascade Results with Available Data

Filled: PHENIX, PRC69, 034909 (2004), Open: Hydro+cascade
From top to bottom, 0-5, 5-10, 10-15, …, 70-80% centrality

p_T Spectra: MC-Glauber

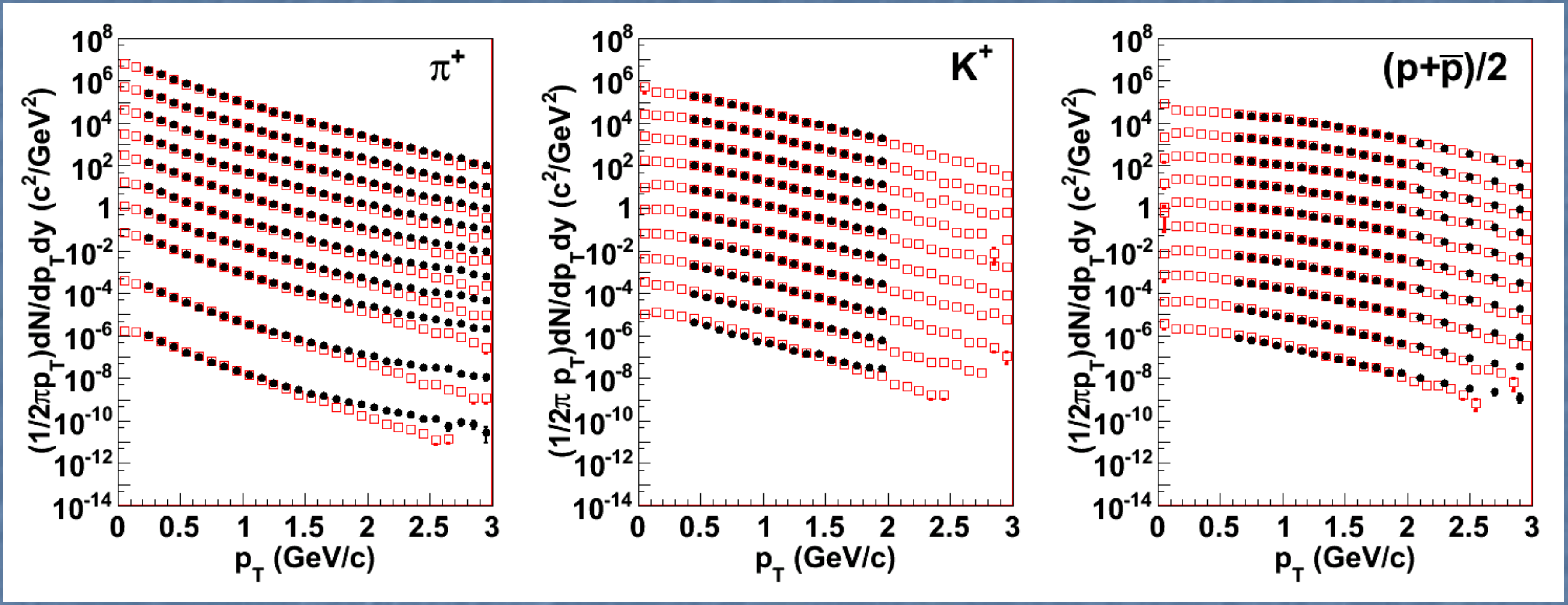


(1) Absolute value of entropy, (2) soft/hard fraction α = 0.18, and (3) switching temperature T_{sw} = 155 MeV.

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

Filled: PHENIX, PRC69, 034909 (2004), Open: Hydro+cascade
From top to bottom, 0-5, 5-10, 10-15, …, 70-80% centrality

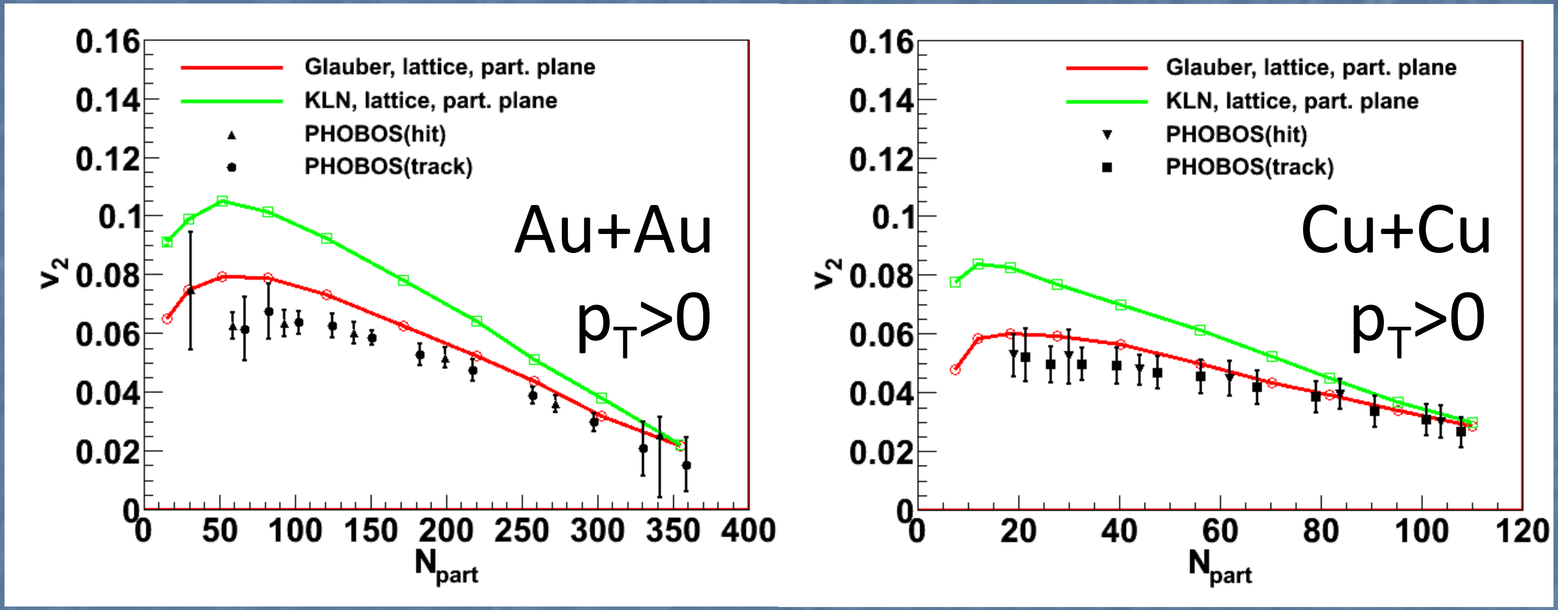
p_T Spectra: MC-KLN



(1) Absolute value of saturation scale and (2) scaling parameters λ=0.28 and (3) switching temperature T_{sw} = 155 MeV

$$Q^2_{s,A}(x_\perp) \quad \propto \quad t_A(x_\perp)x^{-\lambda}$$

$v_2(N_{part})$



<u>MC-Glauber</u>:

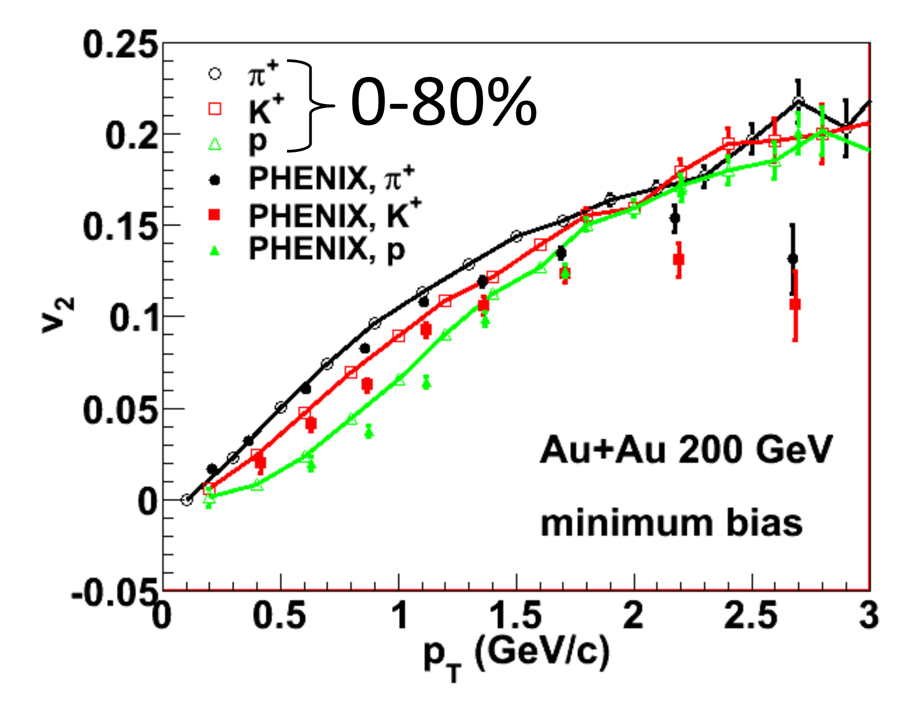
Apparent reproduction. No room for QGP viscosity?

<u>MC-KLN</u>:

Overshoot due to larger eccentricity. How small QGP viscosity?

PHOBOS, PRC72, 051901 (2005); PRL98, 242302 (2007).

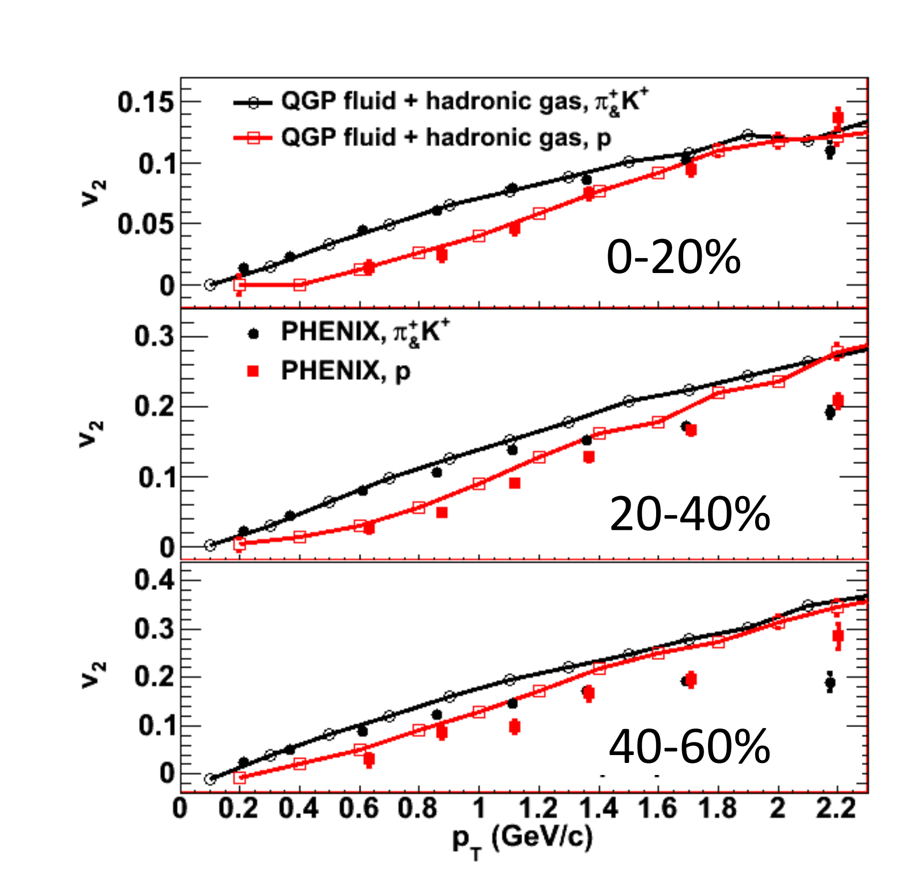
$v_2(p_T)$ for PID Particles



- Results based on MC-Glauber initialization
- Mass splitting pattern OK
- A little bit overshoot even in low p_T region
→ Centrality dependence (next slide)?

PHENIX, PRL91, 182301 (2003)

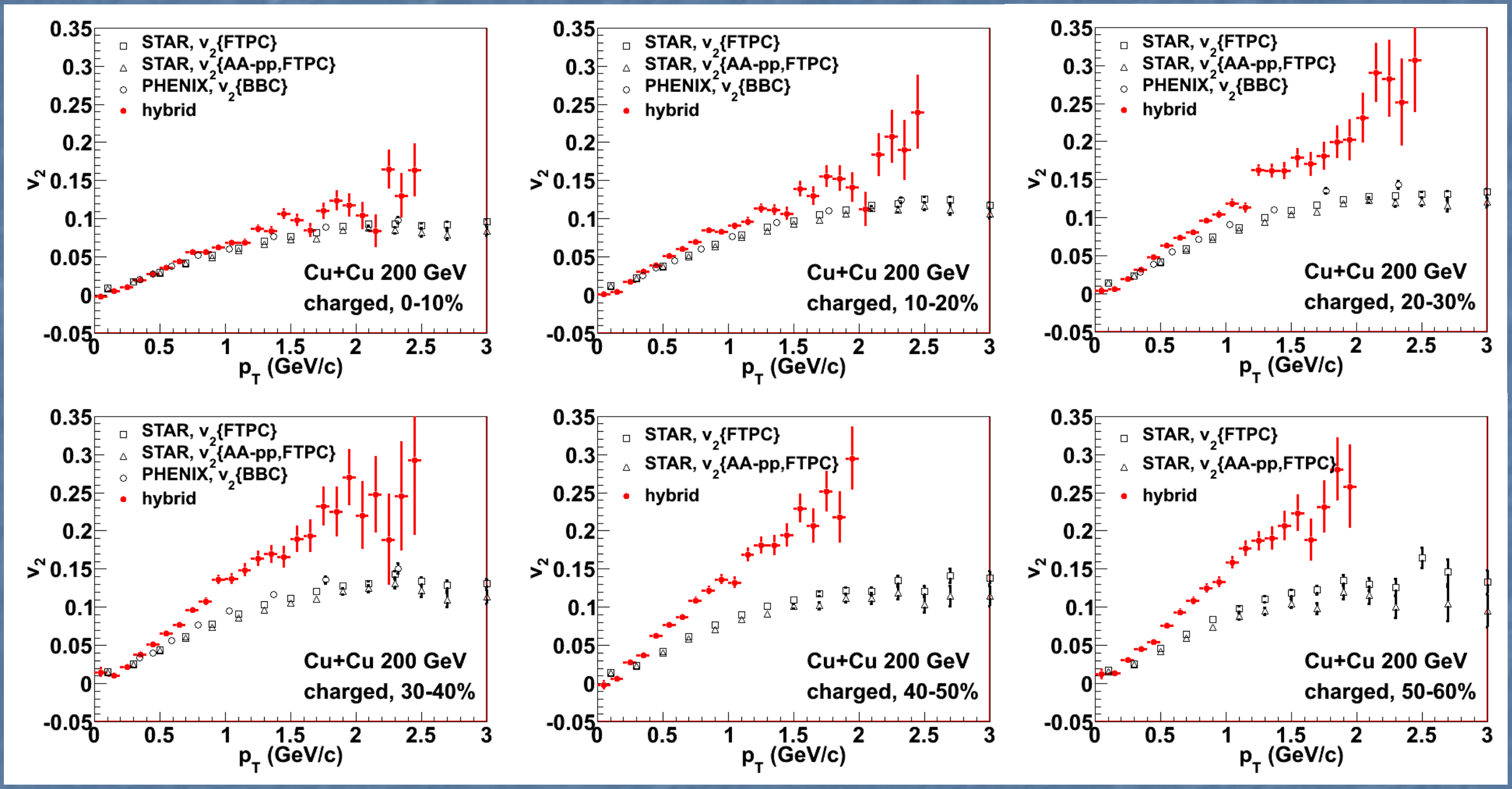
$v_2(p_T)$ for PID Particles: Centrality Dependence



- Hydro+cascade with MC-Glauber at work in 0-20% centrality
- Need QGP viscosity
- Or, need jet or recombination/coalescence components?
- MC-KLN results not available yet due to less statistics

PHENIX, PRL91, 182301 (2003)

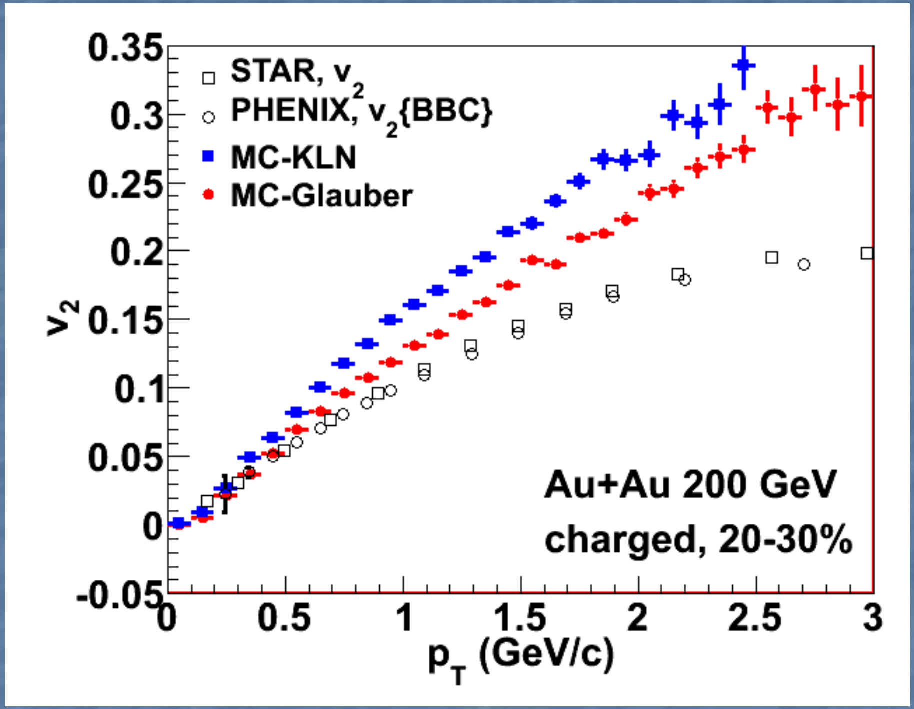
$v_2(p_T)$ for Charged Particles: Cu+Cu



- Tendency is the same as that in Au+Au collisions

PHENIX, PRL98, 162301 (2007).
STAR, PRC81, 044902 (2010).

MC-KLN vs. MC-Glauber



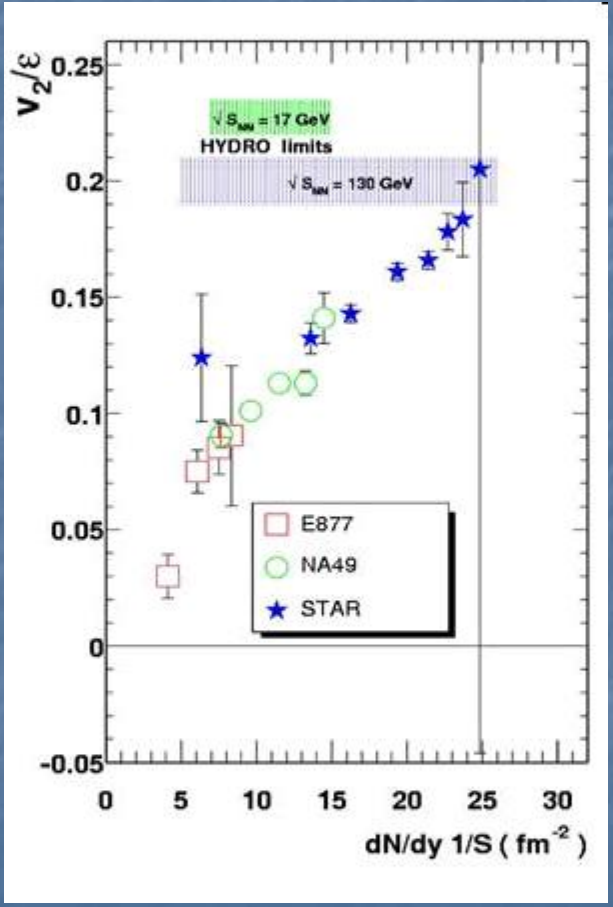
Slope of $v_2(p_T)$ steeper in MC-KLN than in MC-Glauber

← $v_{2,\mathrm{MC\text{-}KLN}} > v_{2,\mathrm{MC\text{-}Glauber}}$

- p_T dependent viscous correction at $T=T_{sw}$ might interpret the data
- Extracted transport coefficients depend on initial condition

Predictions and Postdiction from Hydro+Cascade Model

Collisions of Deformed Nuclei at RHIC



STAR, PRC66, 034904 (2002)

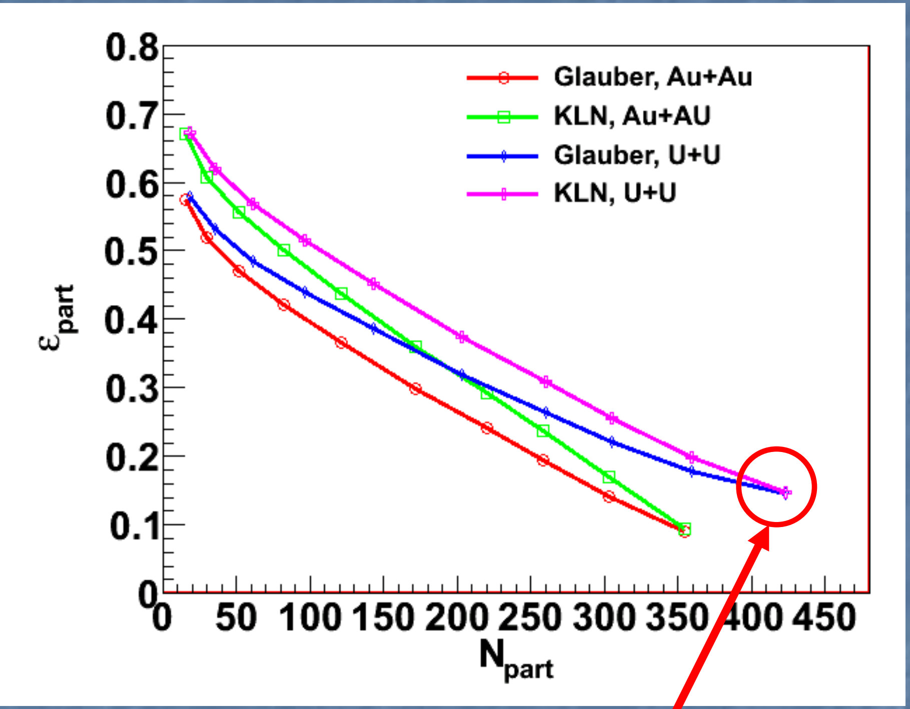
- How v_2/ε behaves as increasing multiplicity?*
    - Saturate?
    - Still enhance?

U+U collision in run12 at RHIC(?)

- More multiplicity
- Larger eccentricity

*U.Heinz and A. Kuhlman, PRL94, 132301 (2005).

Eccentricity in U+U Collisions at RHIC

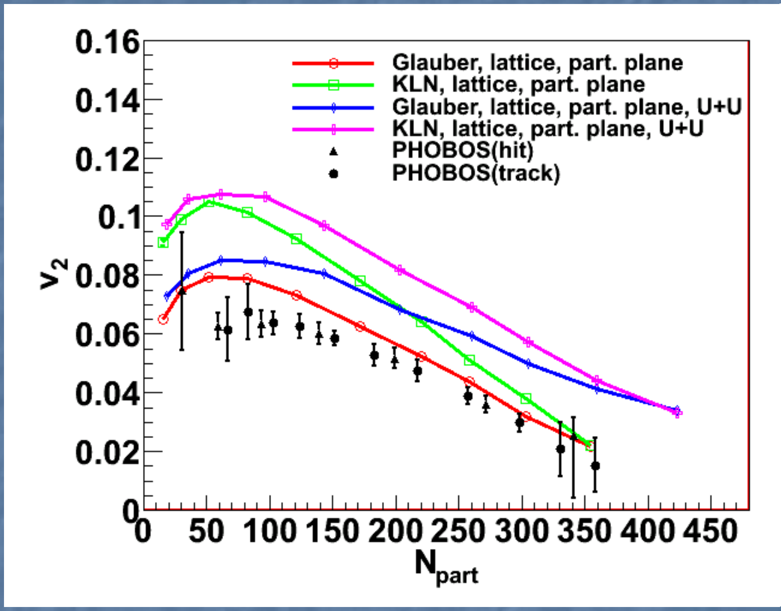


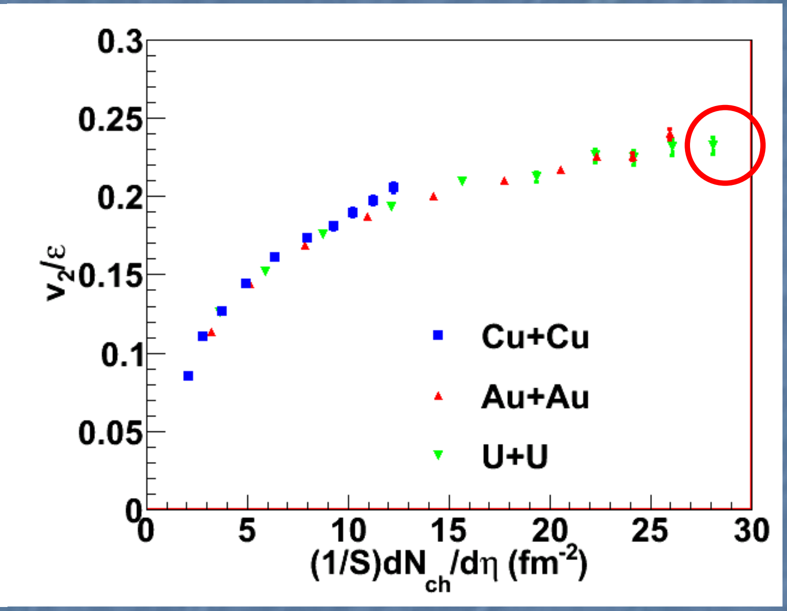
- Larger eccentricity
- Finite eccentricity at zero impact parameter body-body collision
- Unable to control configuration → Need Monte-Carlo study and event selection*

0-5%→ 0.146 (MC-Glauber), 0.148 (MC-KLN)

*See, e.g., P.Filip et al. PRC80, 054903 (2009).

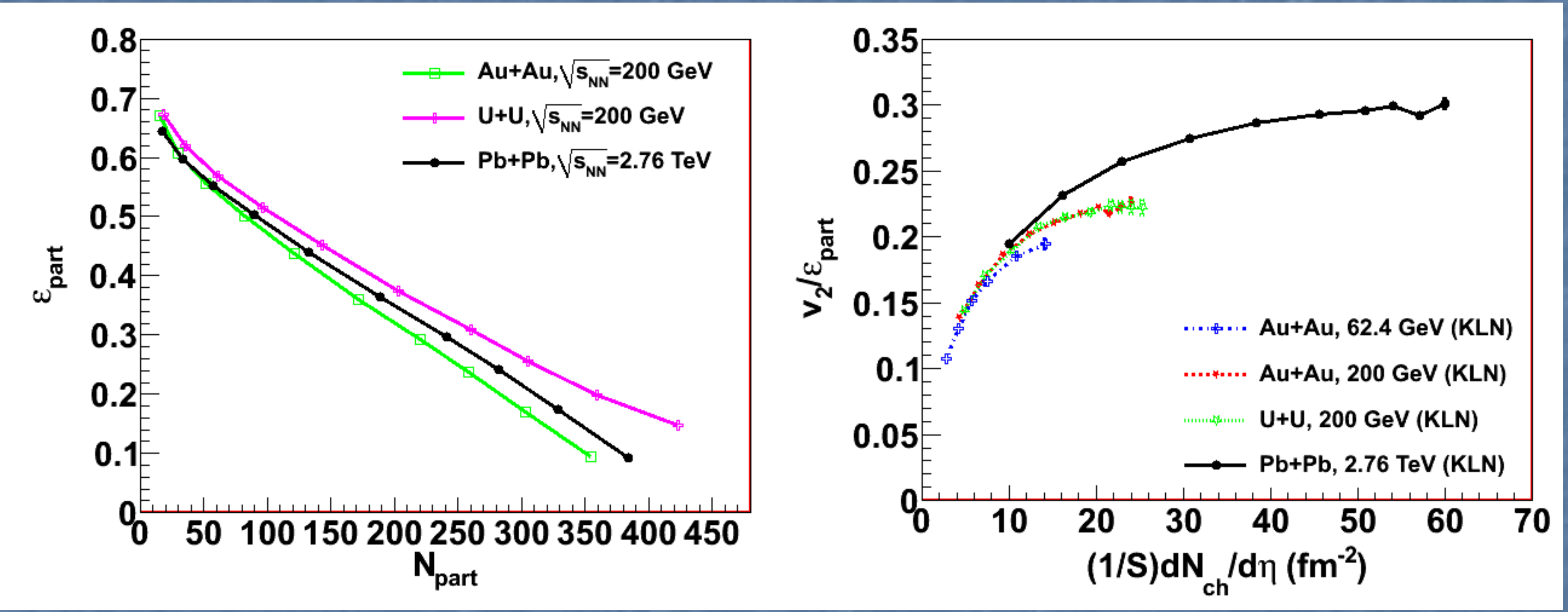
v_2 in U+U Collisions





- v_2 increases due to deformation of colliding nuclei.
- v_2/ε scales with transverse density.
- Maximum transverse density increases only by ~10% in central U+U collisions.

Prediction at LHC

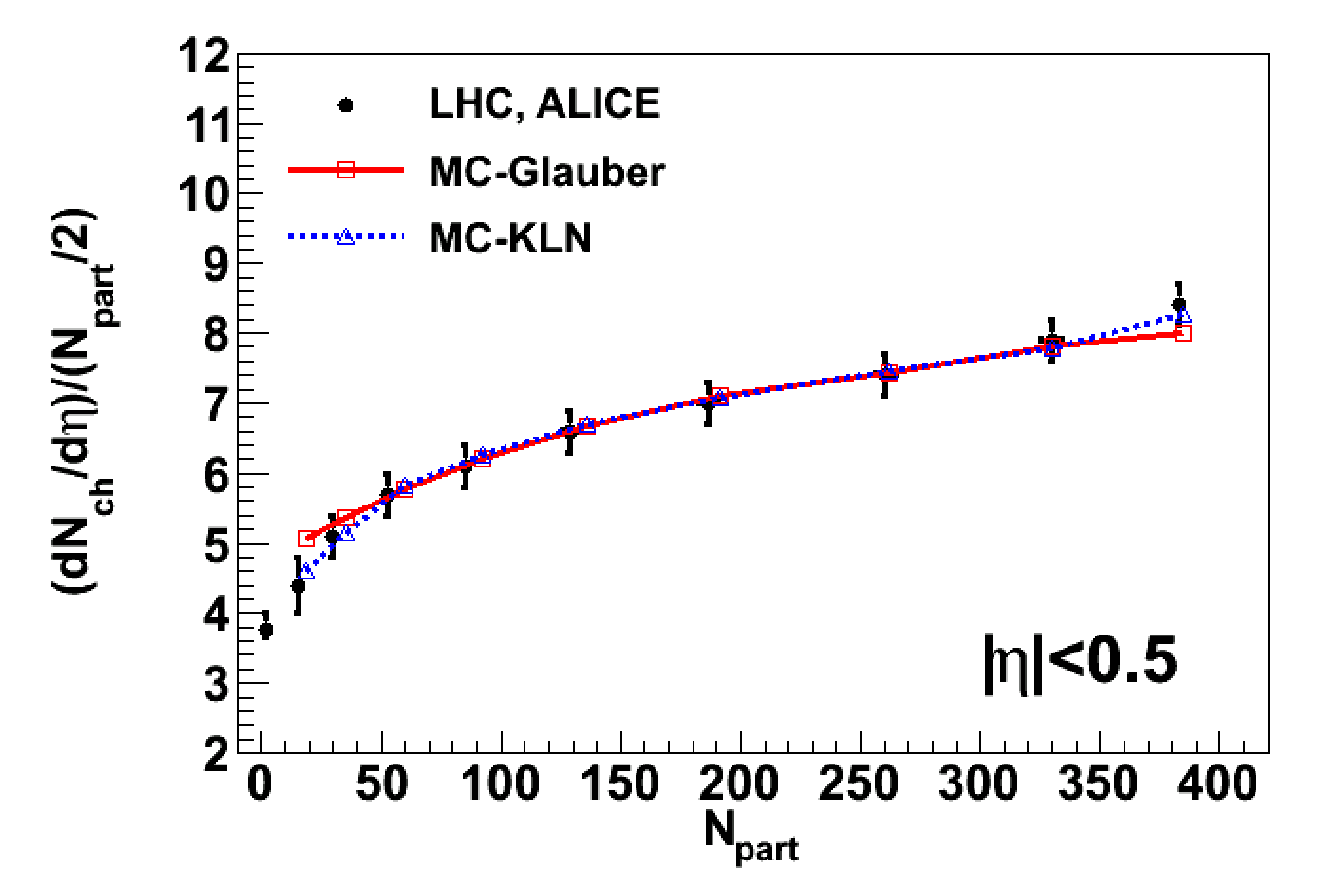


Eccentricity does not change from RHIC to LHC! Change due solely to size

v_2/ε does not follow RHIC scaling curve

“Post”diction at LHC

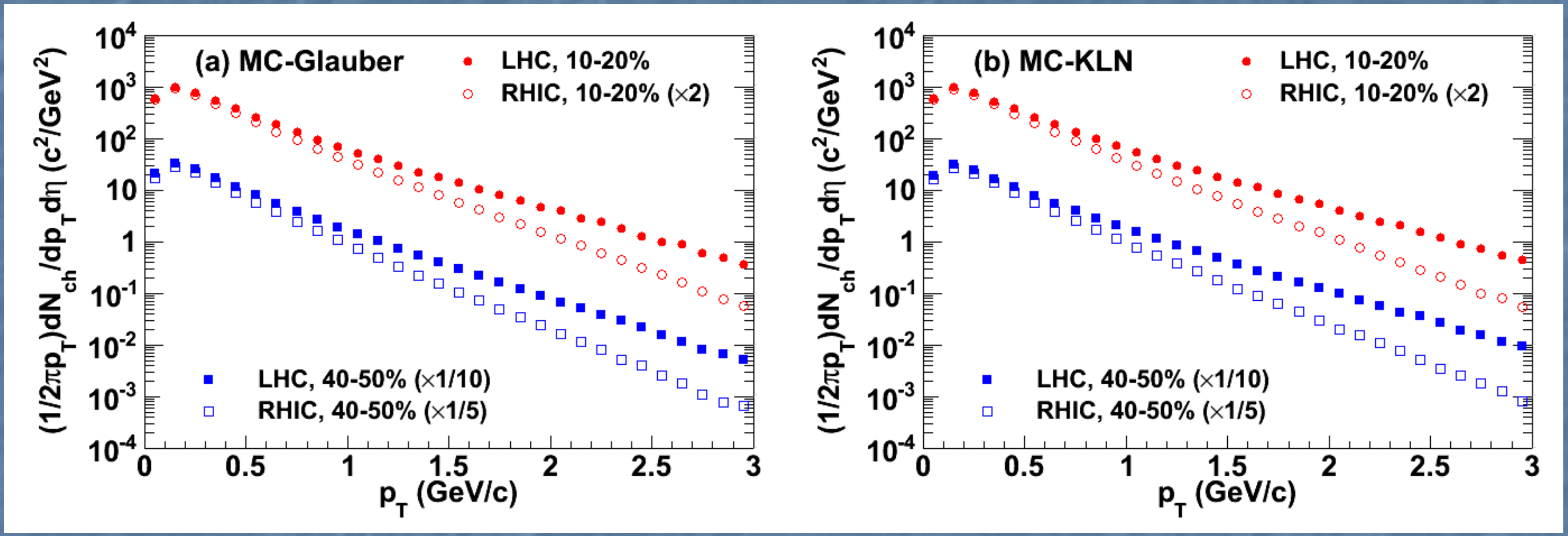
Centrality Dependence of Multiplicity



MC-KLN: Default, MC-Glauber: alpha = 0.08

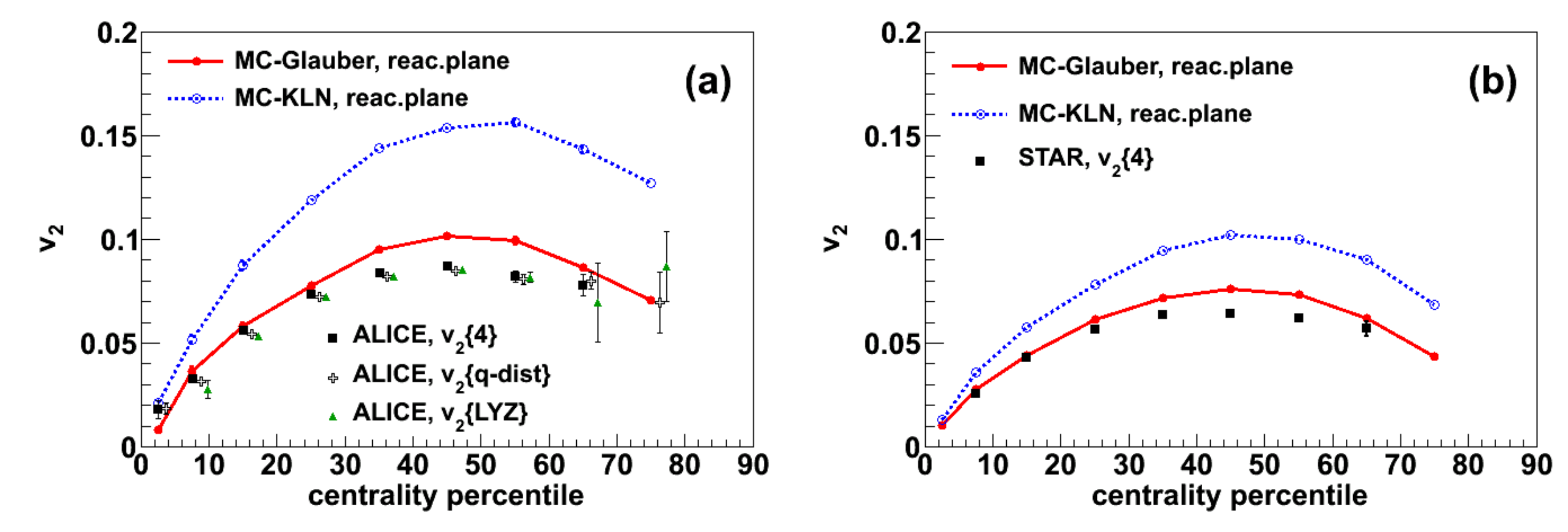
ALICE, arXiv:1012.1657

p_T Spectra of Charged Hadrons



Spectra at LHC get harder than at RHIC

Integrated v_2

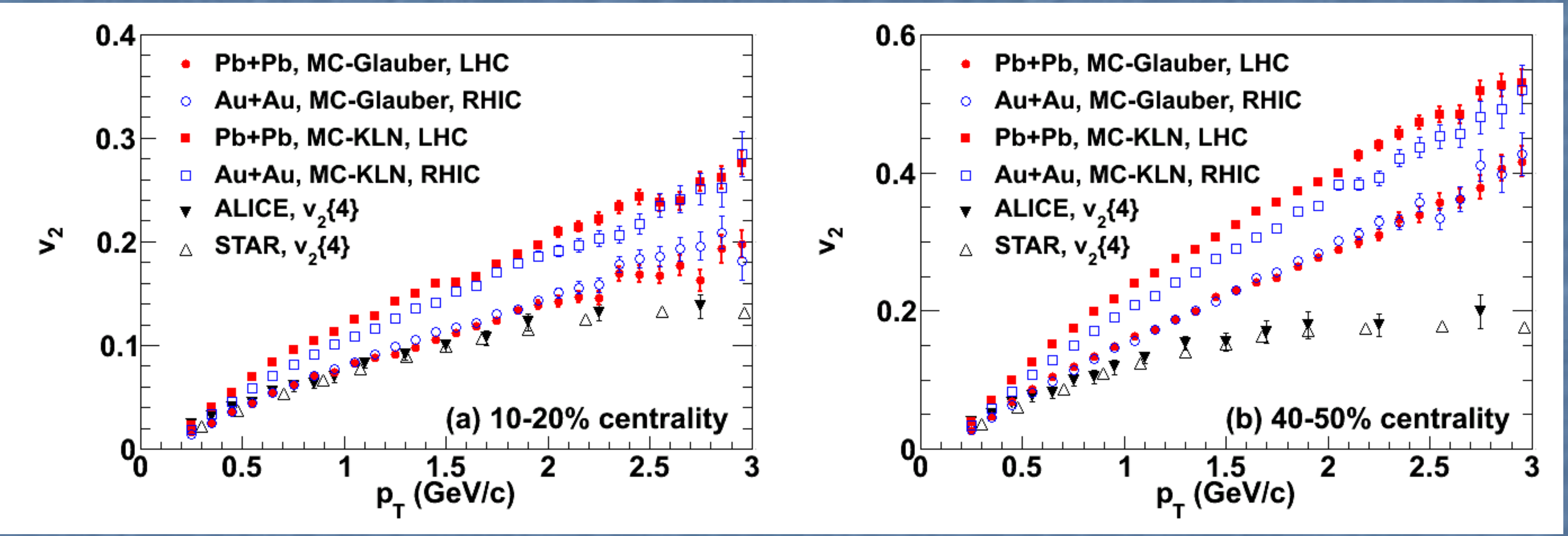


If the Nature chooses MC-KLN, viscous effects would be larger at LHC than at RHIC.

→ Importance of understanding initial conditions

ALICE, PRL105, 0252302(2010).

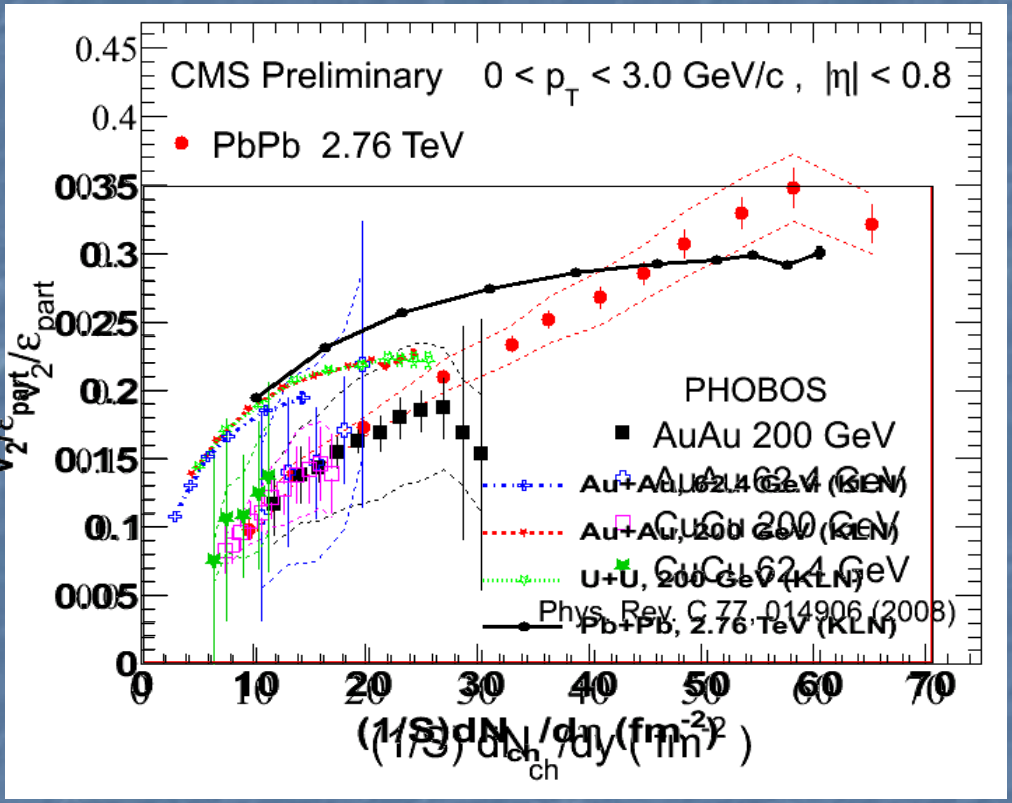
Differential v_2



- $v_2(p_T)$ at LHC is almost identical to $v_2(p_T)$ at RHIC, in particular, in MC-Glauber.
- Steeper slope in MC-CGC leads to larger v_2 even if increase of mean p_T in MC-CGC is identical to that in MC-Glauber.

ALICE, PRL105, 0252302(2010).

Comparison with Latest Results



Caveats: dN/dy ≠ dN/deta

$v_2(y) \neq v_2(\text{eta})$

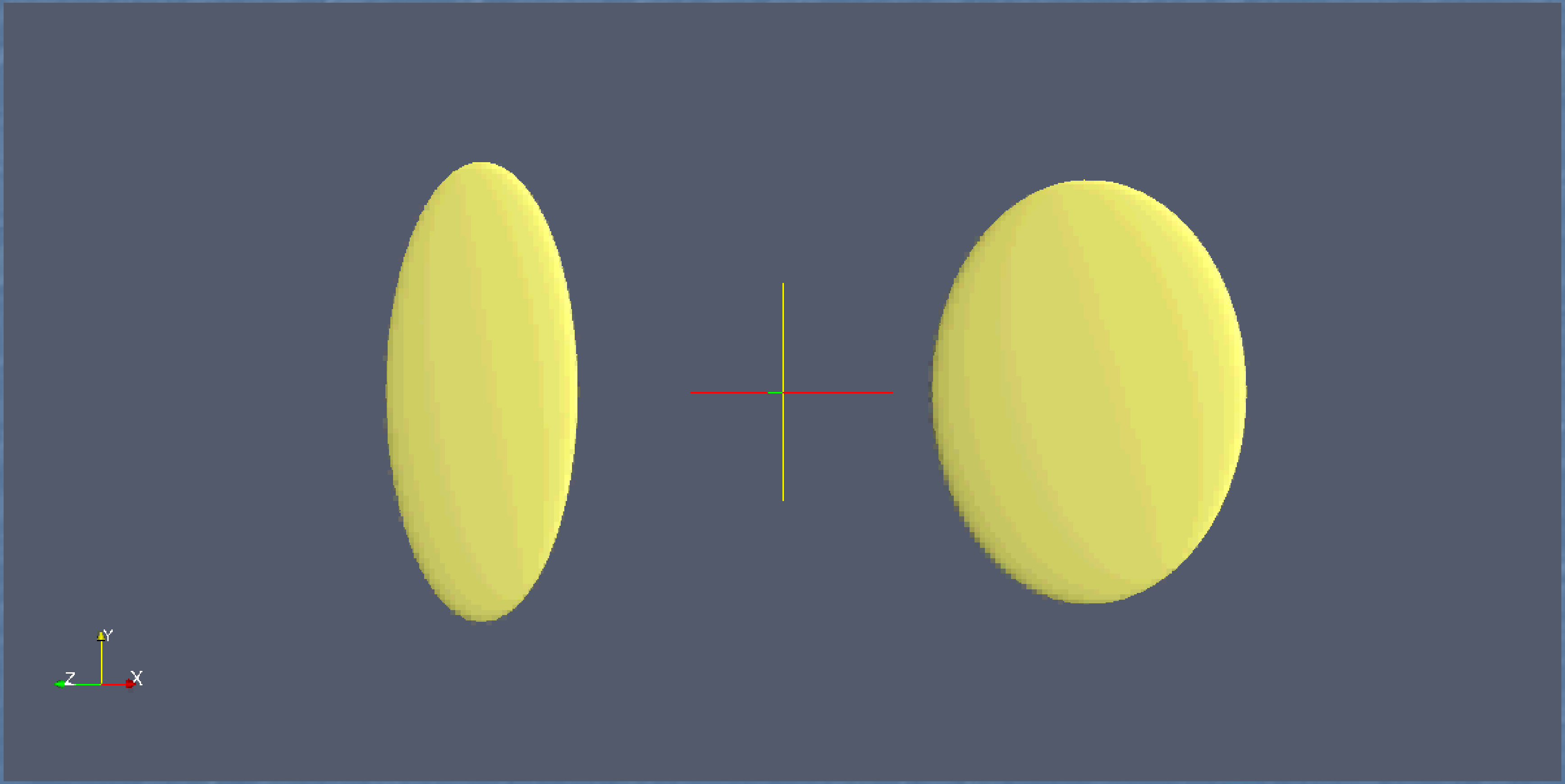
Summary

- Current status of the hybrid approach
  - Elliptic flow
    - MC-Glauber initialization gives a reasonable agreement with data in very central collisions.
    - Results deviate from data as moving away from central collisions.
    - QGP viscosity
  - Prediction
    - Results in U+U collisions follow scaling behavior, extend $(1/S)dN_{ch}/d\eta$ by ~10%
    - v_2/ε at LHC does not follow scaling seen at RHIC

Summary (contd.)

- Postdiction
  - QGP viscosity at LHC (higher T) is larger than at RHIC (lower T) in MC-KLN?
  - Understanding of transverse dynamics and initial state is important.

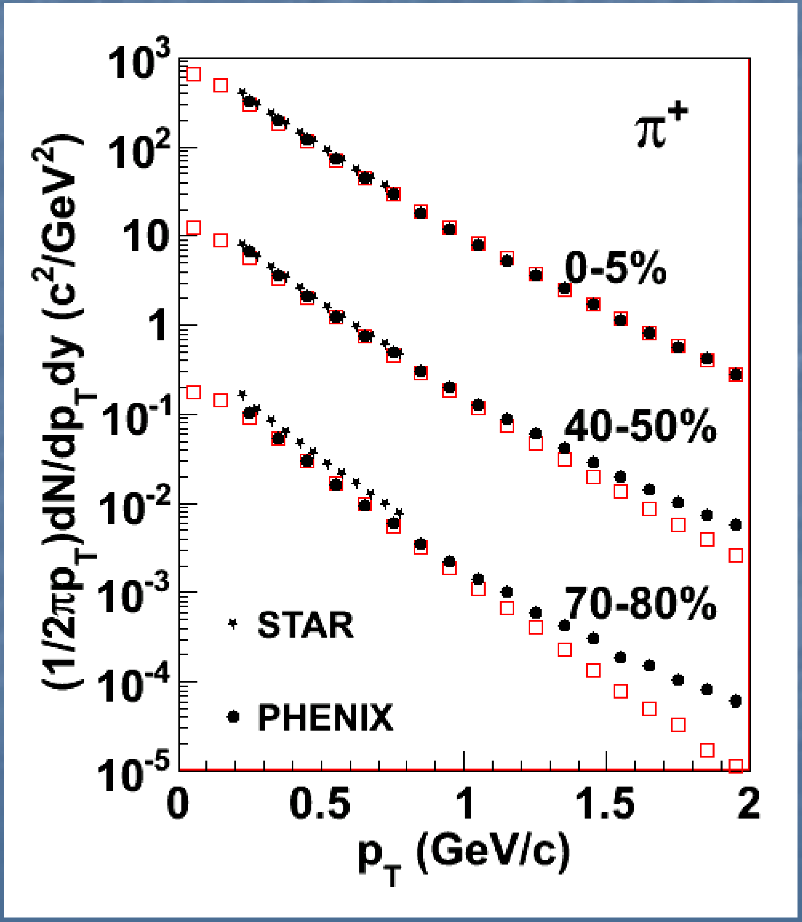
Thank You!



Available at YouTube

BACKUP SLIDES

p_T Spectra in STAR and PHENIX

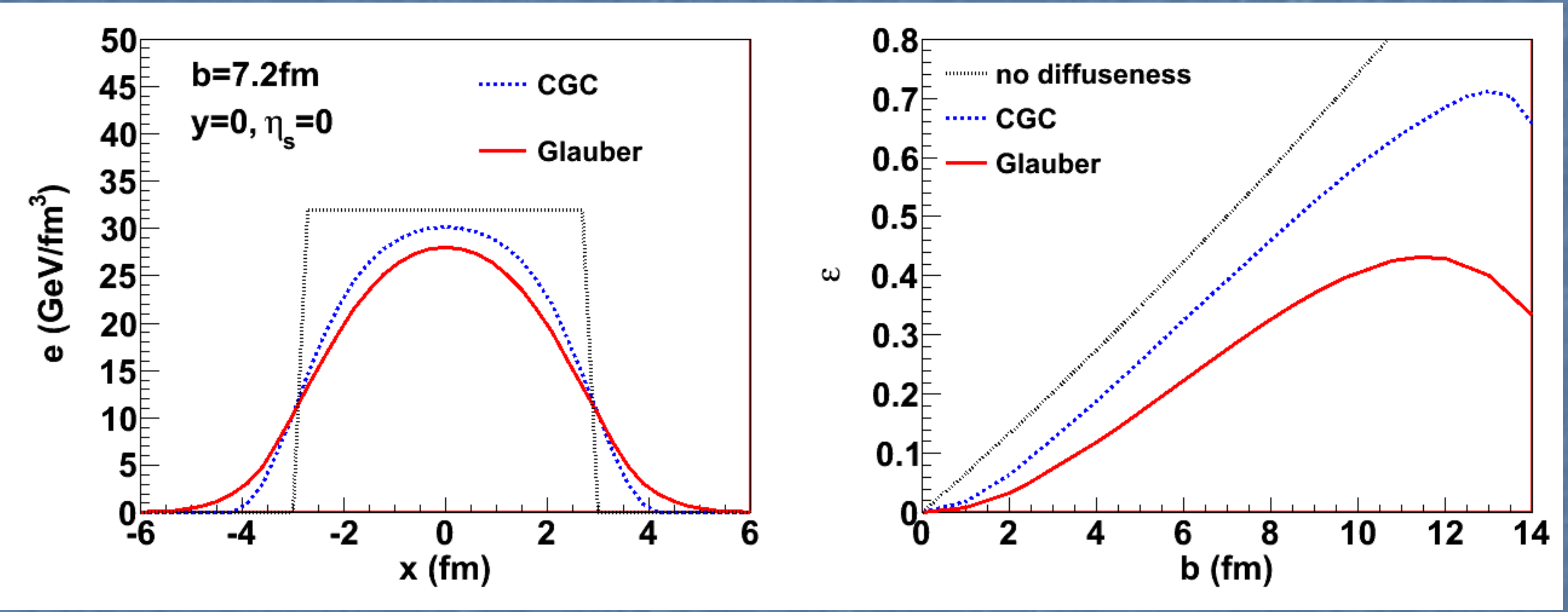


Central:
Consistent btw.
STAR and PHENIX

Peripheral:
(STAR) > (PHENIX)
STAR data are 50 %
larger than PHENIX data

STAR, PRC 79, 034909 (2009)
PHENIX, PRC69, 034909 (2004)

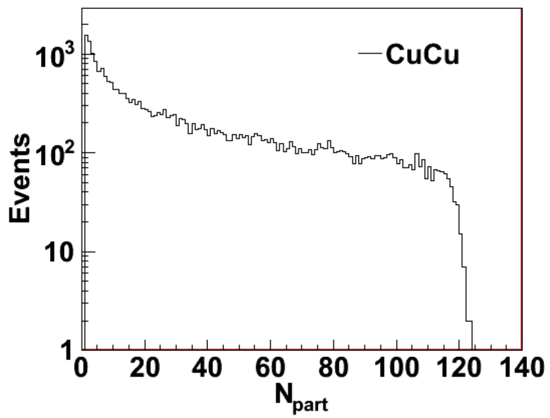
Steeper Transverse Profile in CGC

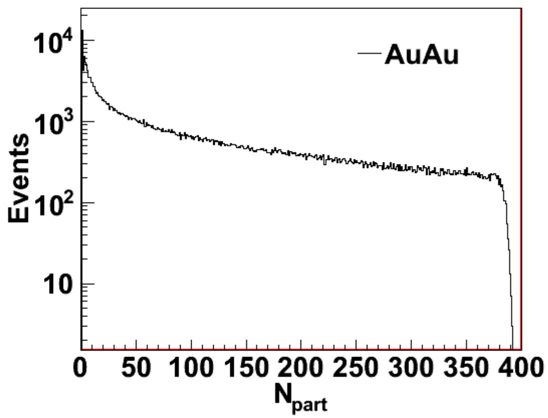


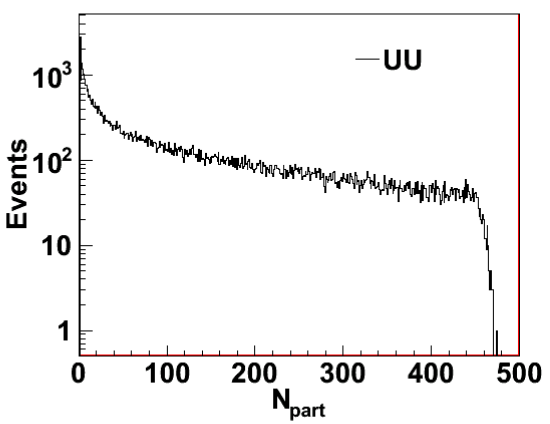
Closer to hard sphere than Glauber

Note: Original KLN model (not fKLN)

Event Distributions from Monte Carlo

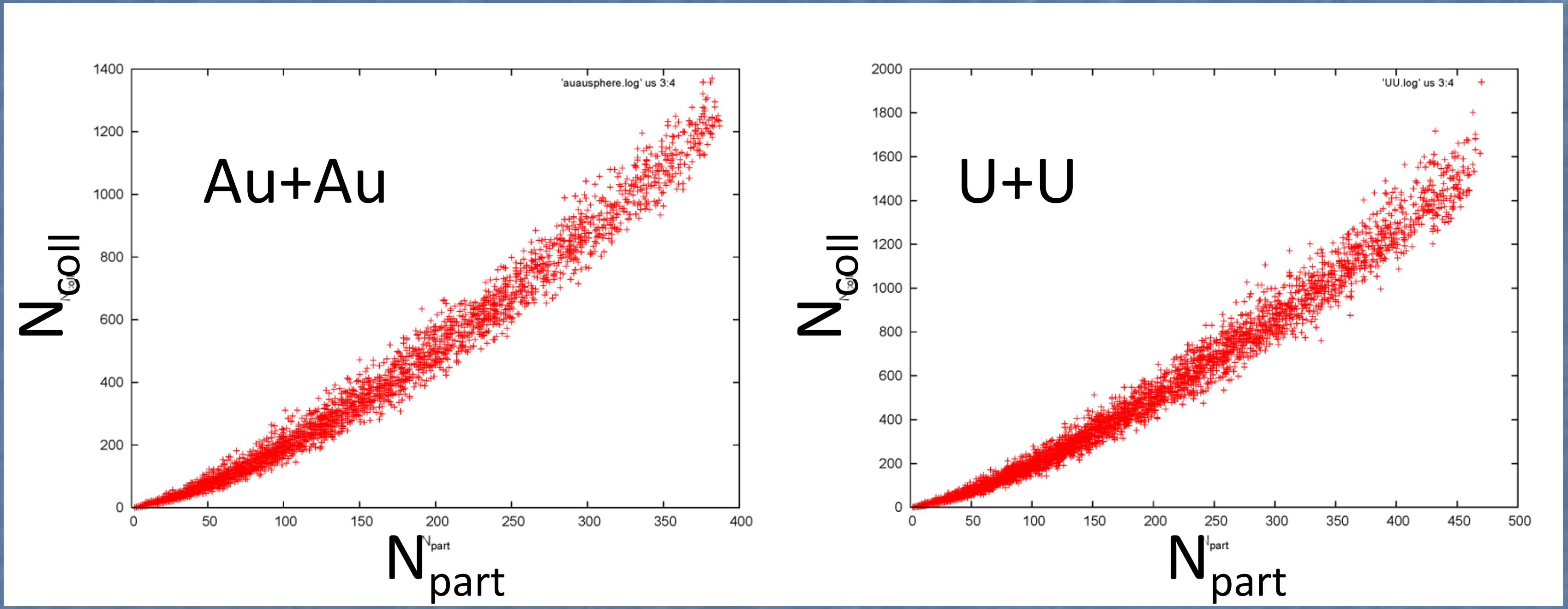






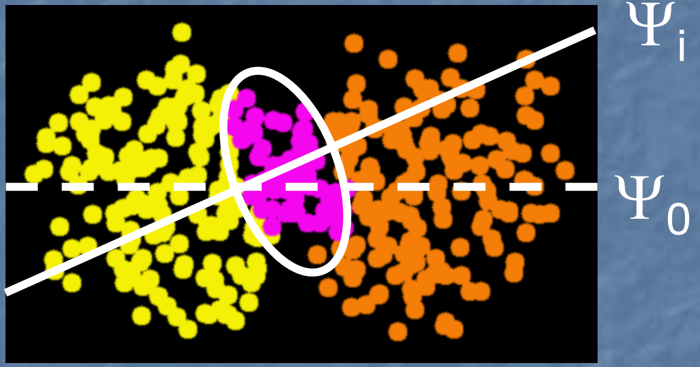
Centrality cut is done according to N_{part}

Correlation btw. N_{part} and N_{coll}



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

Event-by-Event Eccentricity

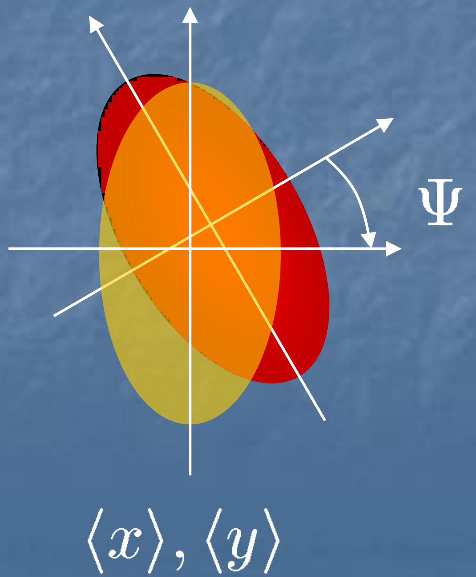
$$\begin{aligned}\sigma_x^2 &= \langle x^2\rangle - \langle x\rangle^2,\\ \sigma_y^2 &= \langle y^2\rangle - \langle y\rangle^2,\\ \sigma_{xy} &= \langle xy\rangle - \langle x\rangle\langle y\rangle.\end{aligned}$$

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

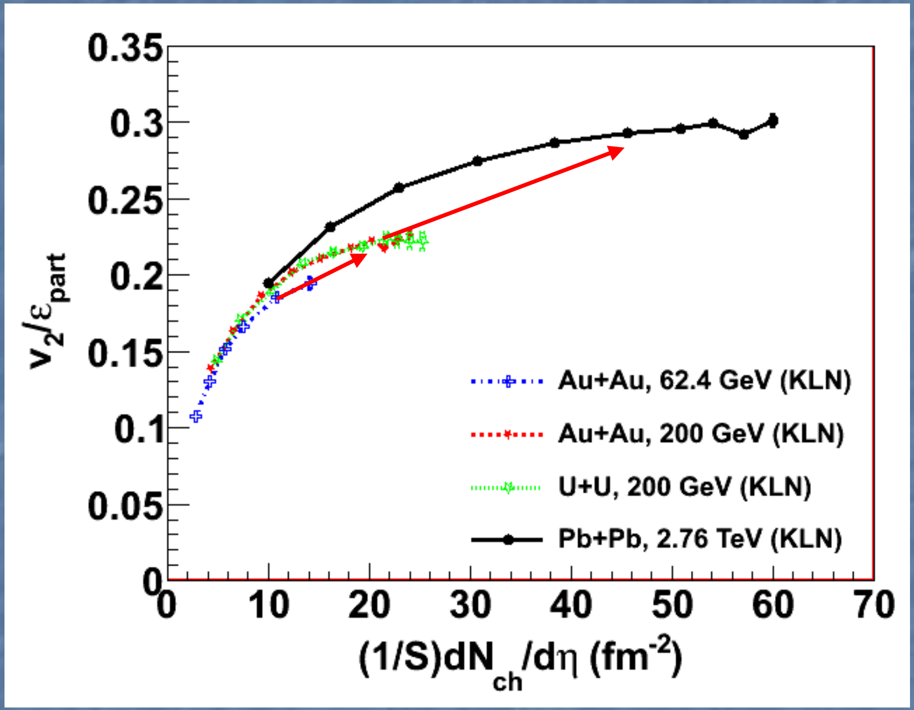
$$\varepsilon_{\mathrm{RP}} = \frac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$$

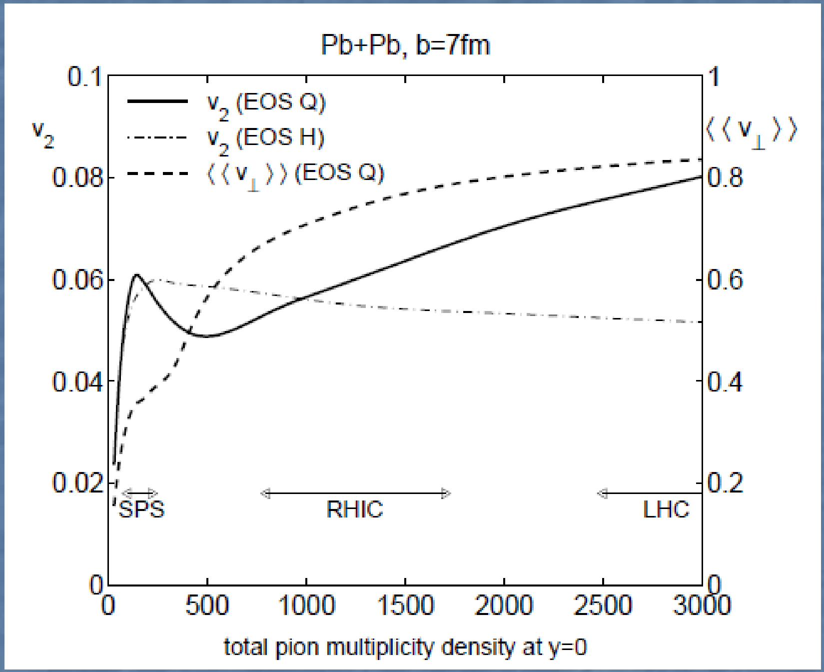
$$\varepsilon_{\mathrm{part}} = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$$

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



v_2/ε Scales at Fixed Collision Energy





Pick up points
with fixed centrality

consistent

Increase multiplicity
with fixed centrality.

P.F.Kolb et al., PRC62, 054909 (2000)

The First Heavy Ion Data at LHC

Selected for a Viewpoint in *Physics*

PRL **105,** 252302 (2010) PHYSICAL REVIEW LETTERS week ending 17 DECEMBER 2010

Elliptic Flow of Charged Particles in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

K. Aamodt *et al.**

(ALICE Collaboration)

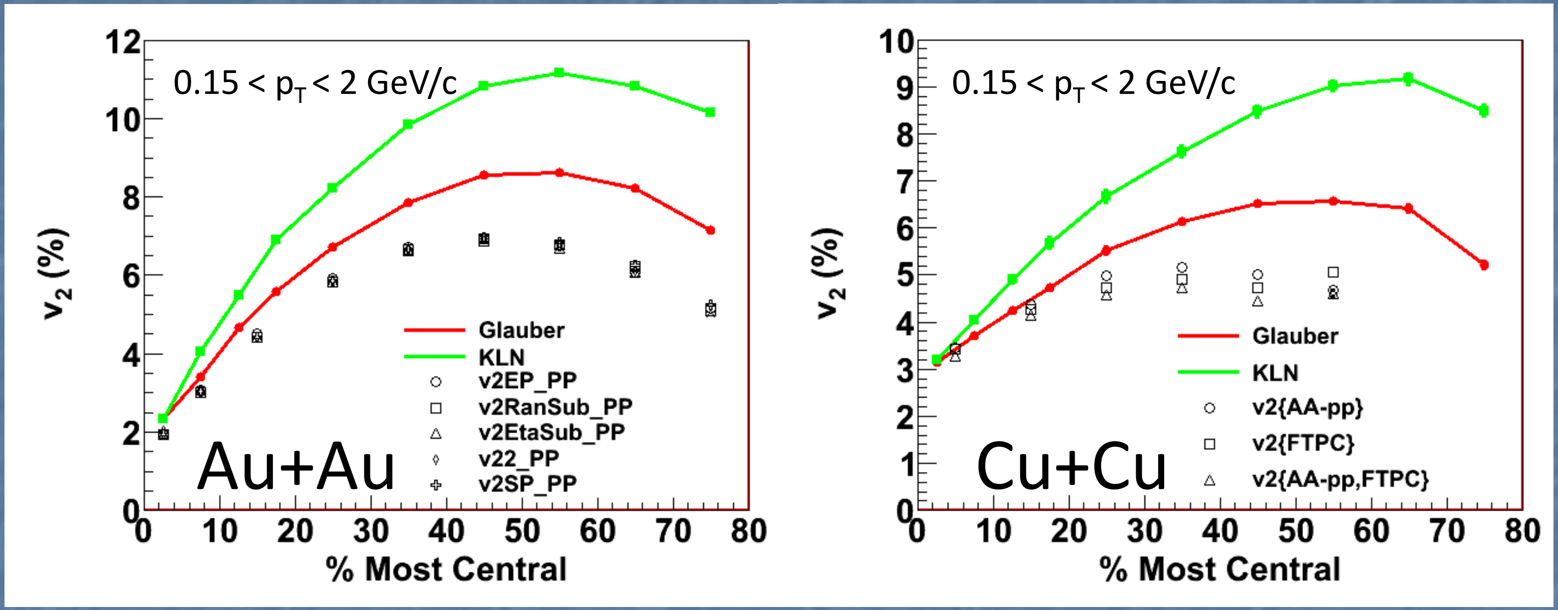
(Received 18 November 2010; published 13 December 2010)

We report the first measurement of charged particle elliptic flow in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.2 < p_t < 5.0$ GeV/c. The elliptic flow signal v_2, measured using the 4-particle correlation method, averaged over transverse momentum and pseudorapidity is $0.087 \pm 0.002(\text{stat}) \pm 0.003(\text{syst})$ in the 40%–50% centrality class. The differential elliptic flow $v_2(p_t)$ reaches a maximum of 0.2 near $p_t = 3$ GeV/c. Compared to RHIC Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the elliptic flow increases by about 30%. Some hydrodynamic model predictions which include viscous corrections are in agreement with the observed increase.

DOI: 10.1103/PhysRevLett.105.252302 PACS numbers: 25.75.Ld, 25.75.Gz, 25.75.Nq

Congrats!!!

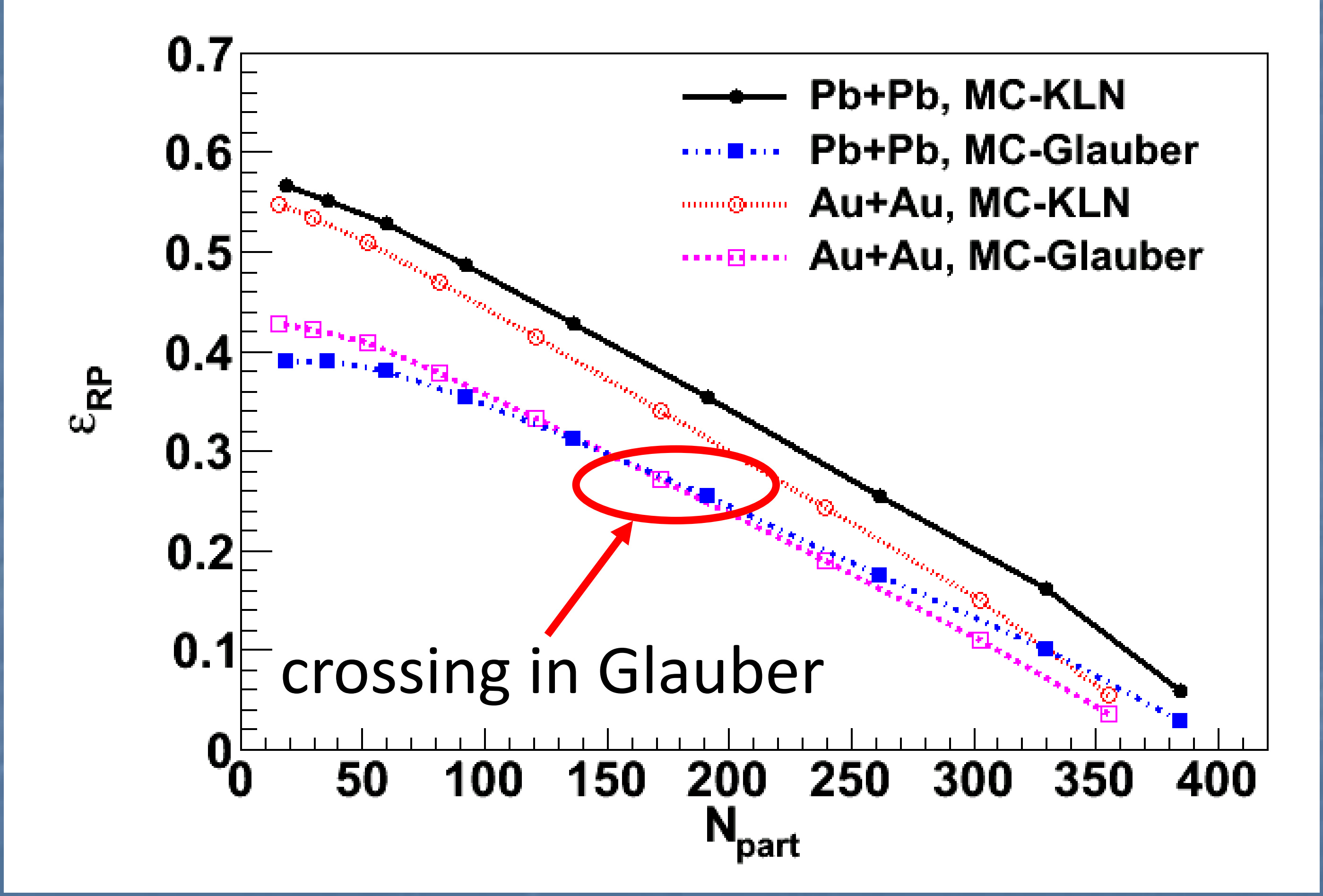
v_2(centrality)



- p_T cut enhances v_2 by ~10%
- STAR data in Au+Au corrected by Ollitrault et al.*
- v_2 w.r.t. participant plane

*J.Y.Ollitrault, A.M.Poskanzer and S.A.Voloshin, PRC80, 014904 (2009).

Eccentricity

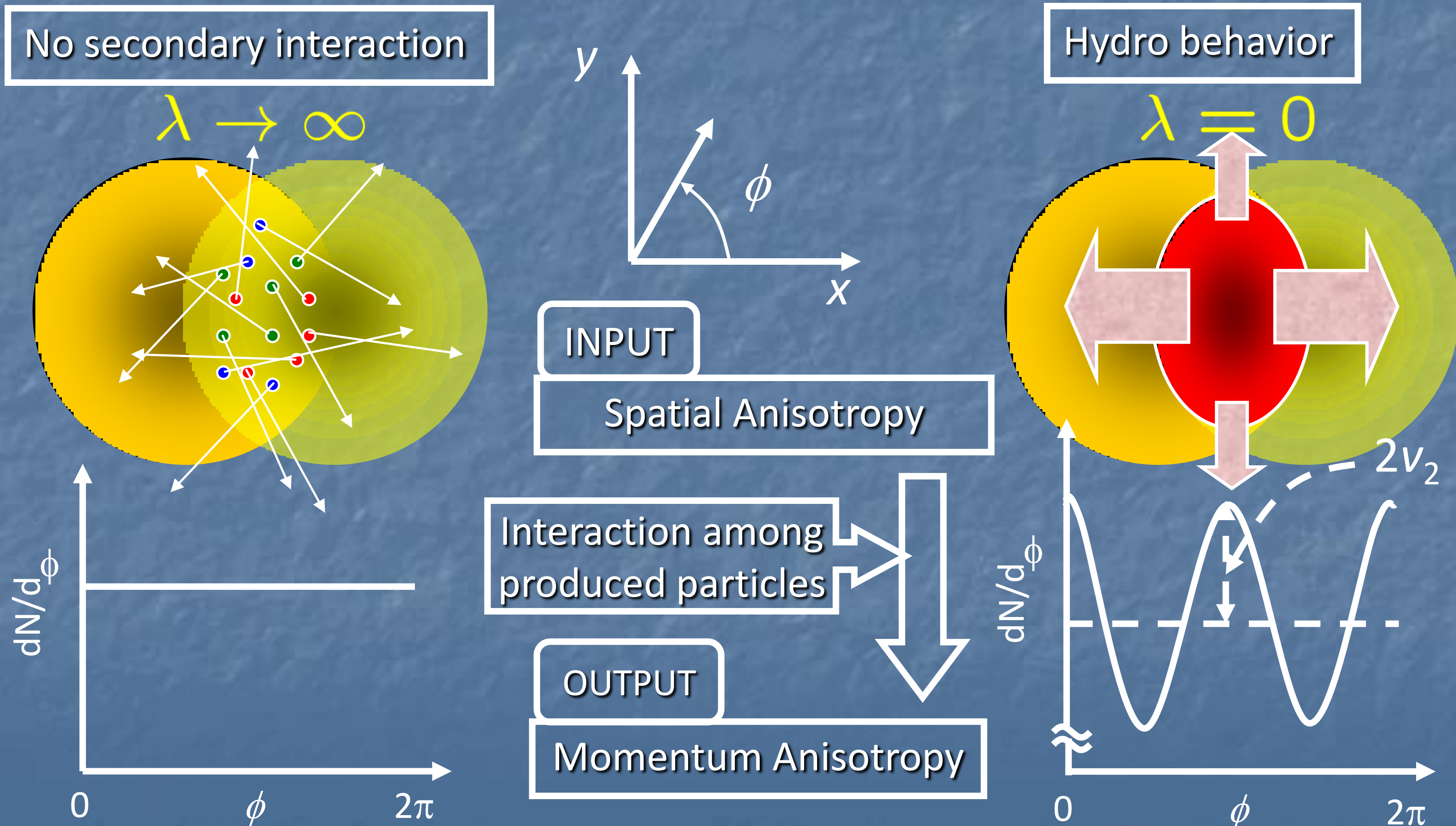


Crossing → Due to smearing effects

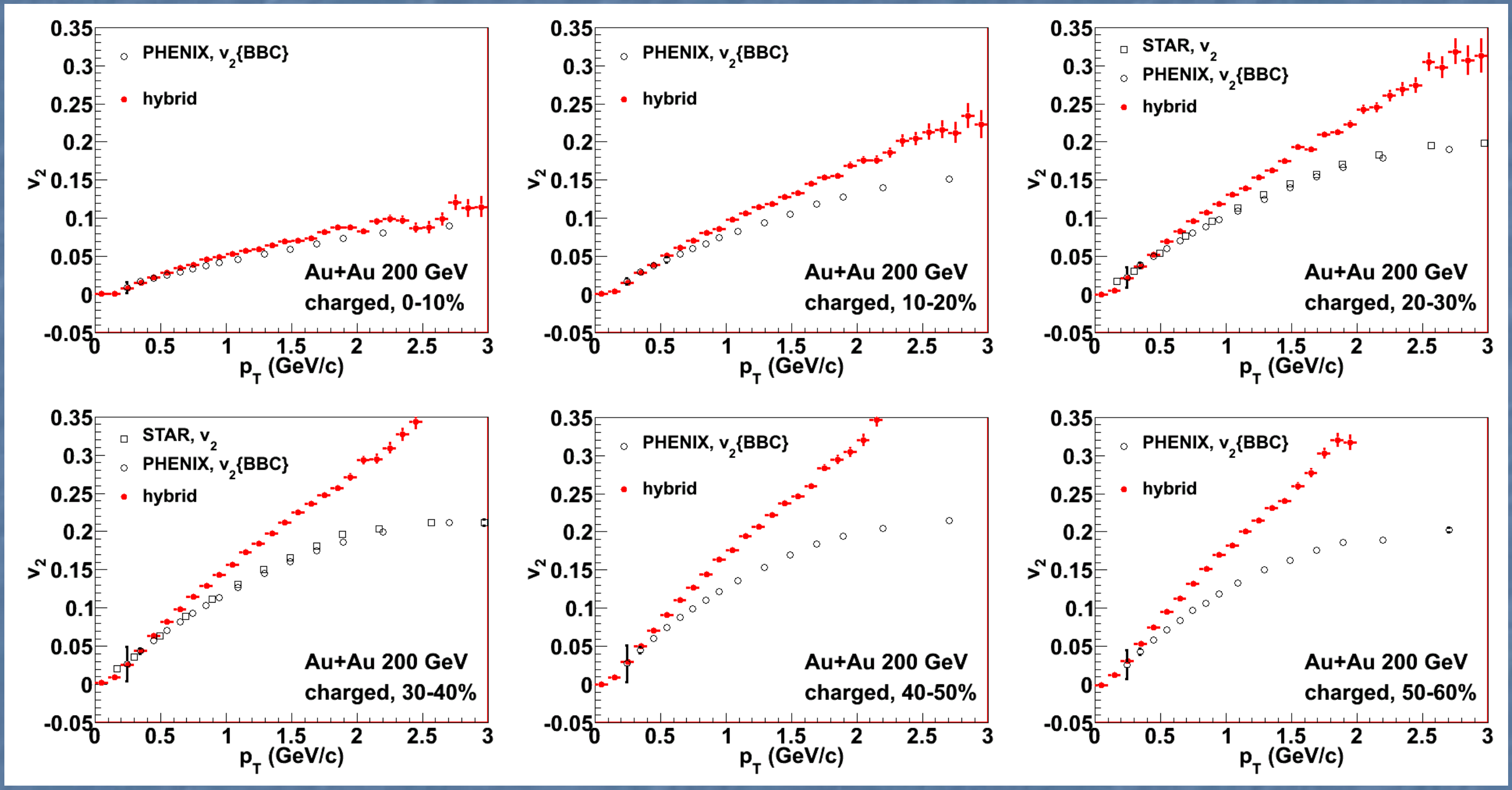
Ollitrault ('92)

Elliptic Flow

How does the system respond to spatial anisotropy?



$v_2(p_T)$ for Charged Particles: Au+Au

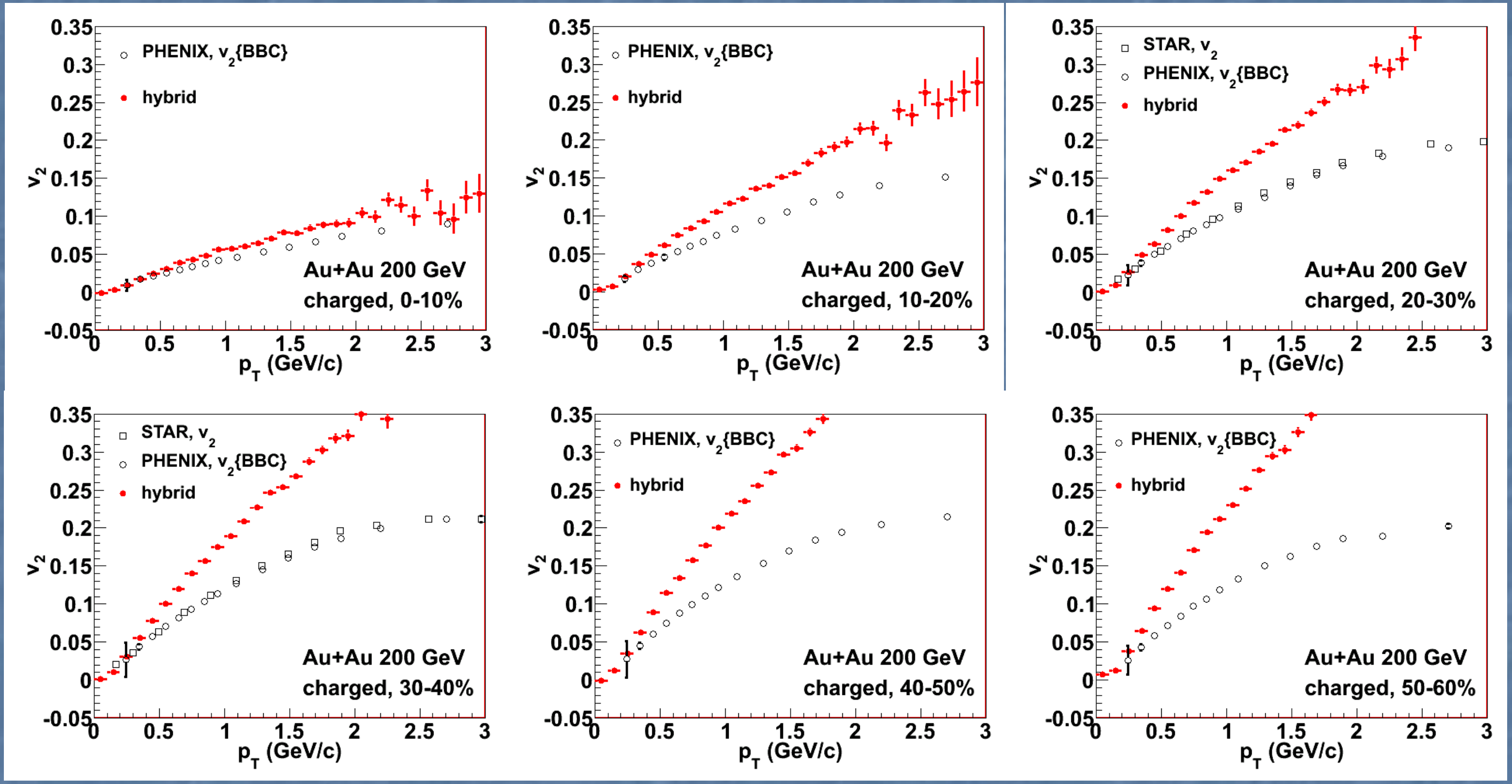


- Hydro+cascade with MC-Glauber at work in low p_T
- p_T region at work shrinks as moving to peripheral

→ Importance of viscosity

PHENIX, PRC80, 024909 (2009).
STAR, PRC72, 014904 (2005).

$v_2(p_T)$ for Charged Particles: Au+Au



- Hydro+cascade with **MC-KLN** at work in central collisions

PHENIX, PRC80, 024909 (2009).
STAR, PRC72, 014904 (2005).