FUTURE DIRECTION IN HIGH ENERGY QCD
Nishina Hall, RIKEN, Wako, 20-22 October 2011

THEORETICAL STATUS AND OUTLOOK OF HEAVY ION PHYSICS

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Many thanks to
Koichi Murase (the Univ. of Tokyo)
for numerical results

Outline

1. Introduction
2. Brief history after “perfect liquid”
3. Hydro-based event generator
4. Relativistic fluctuating hydro
5. Checklist for event generator in the next generation
6. Conclusion and outlook

Introduction

Physics of heavy ion collisions and the quark gluon plasma is getting matured:

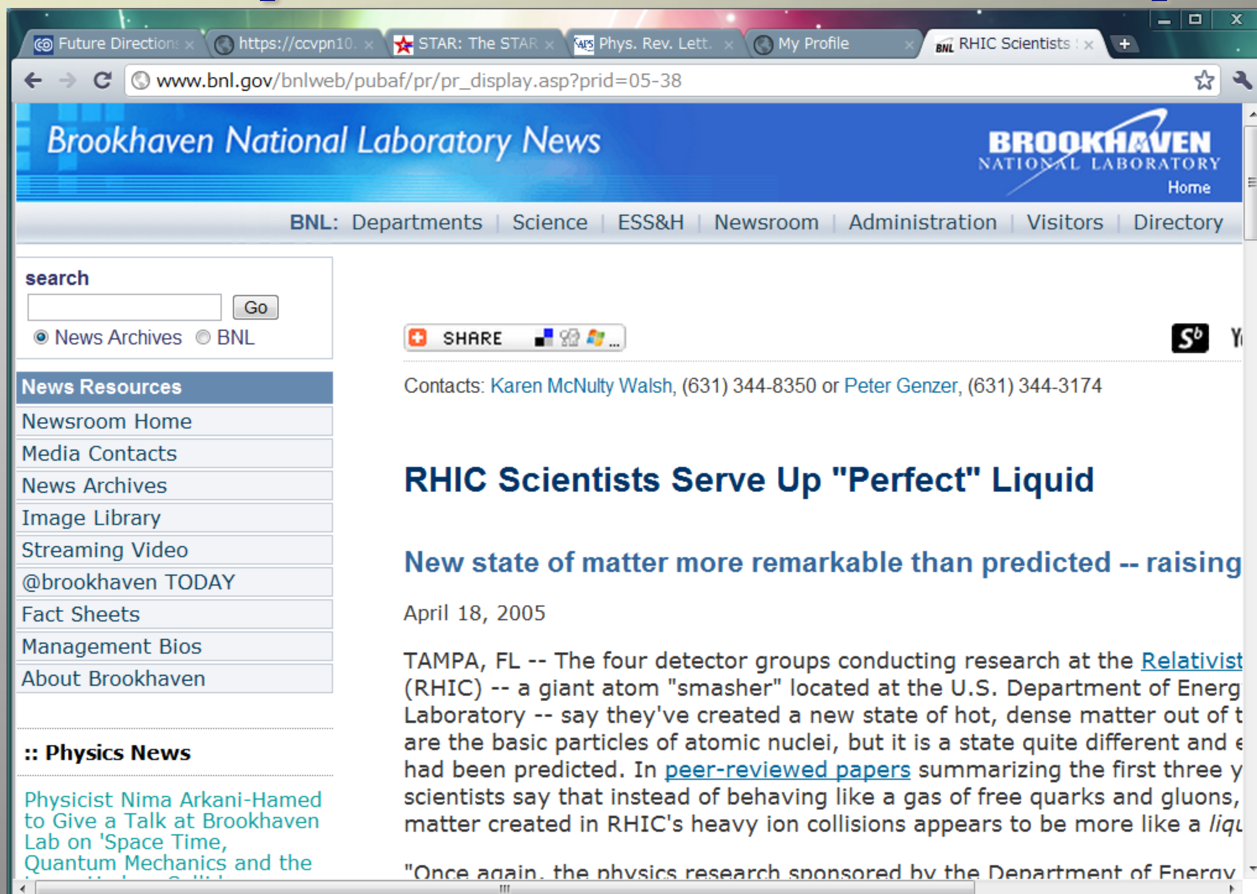
Discovery stage → Precision physics

Main focus in this talk:

Towards precise description of space-time evolution using hydrodynamics *after initial conditions*

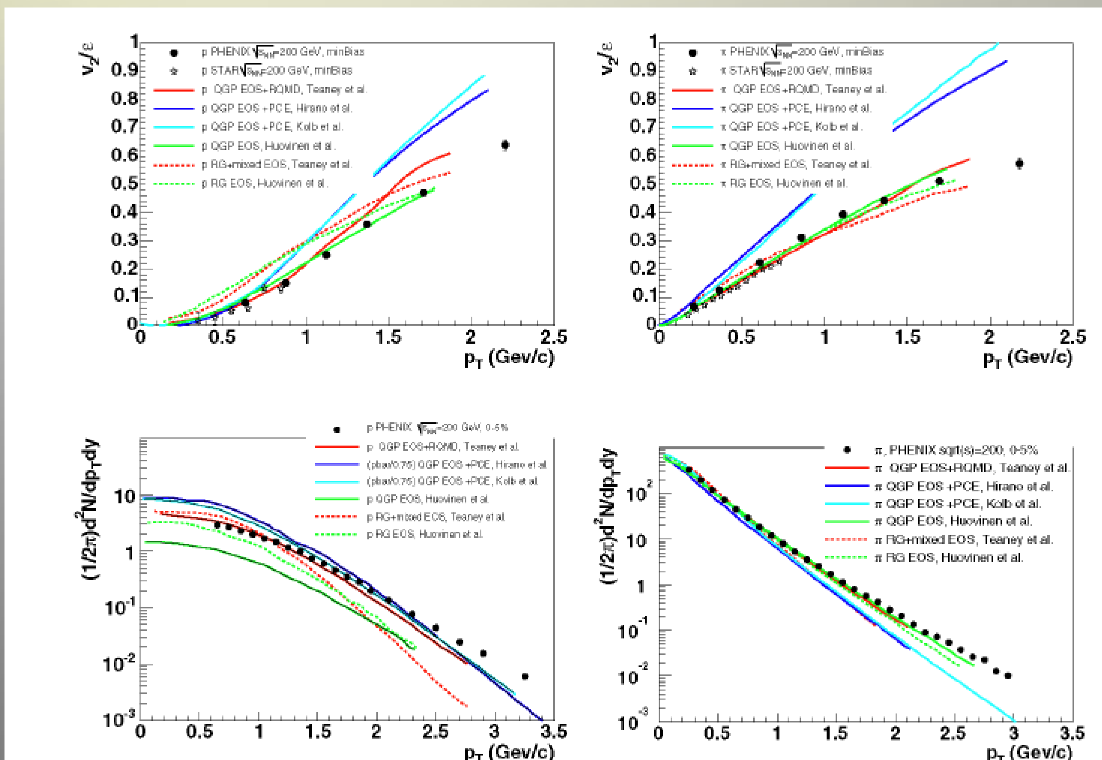
BRIEF HISTORY AFTER “PERFECT LIQUID”

Discovery for "Perfect Liquid"



http://www.bnl.gov/bnlweb/pubaf/pr/pr_display.asp?prid=05-38

Status as of Press Release



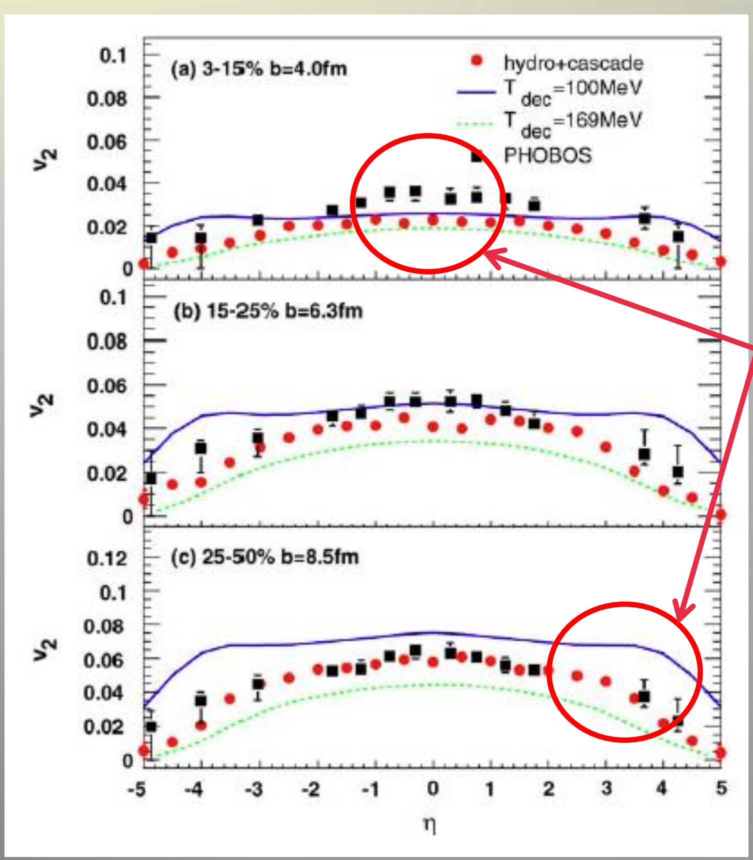
PHENIX, Nucl. Phys. A 757, 184 (2005)

Three pillars of modeling

- QGP ideal hydro
- hadronic cascade
- Glauber type initial conditions

Other sets of modeling?

Consistency of Three Pillars in Broad Rapidity Region

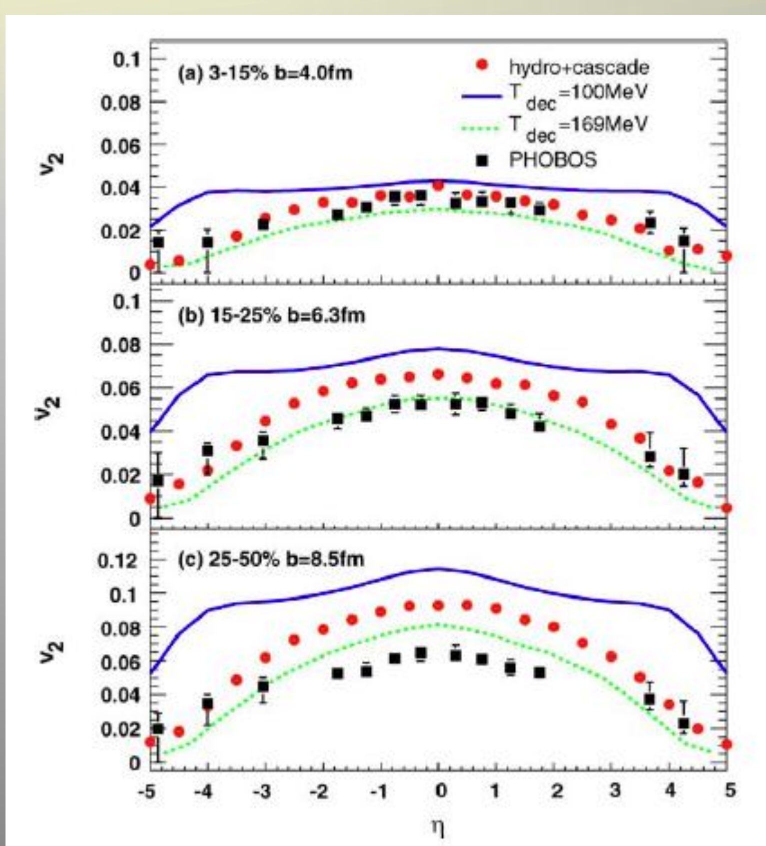


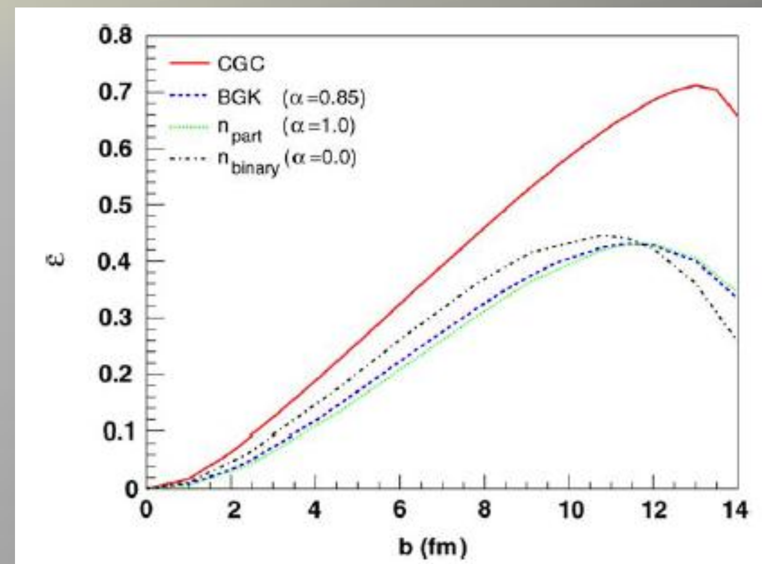
Triangular shape of $v_2(\eta)$ after all!

Undershoot the data at midrapidity in central collisions

T.Hirano *et al.*, Phys. Lett. B 636, 299 (2006)

CGC Initial Conditions

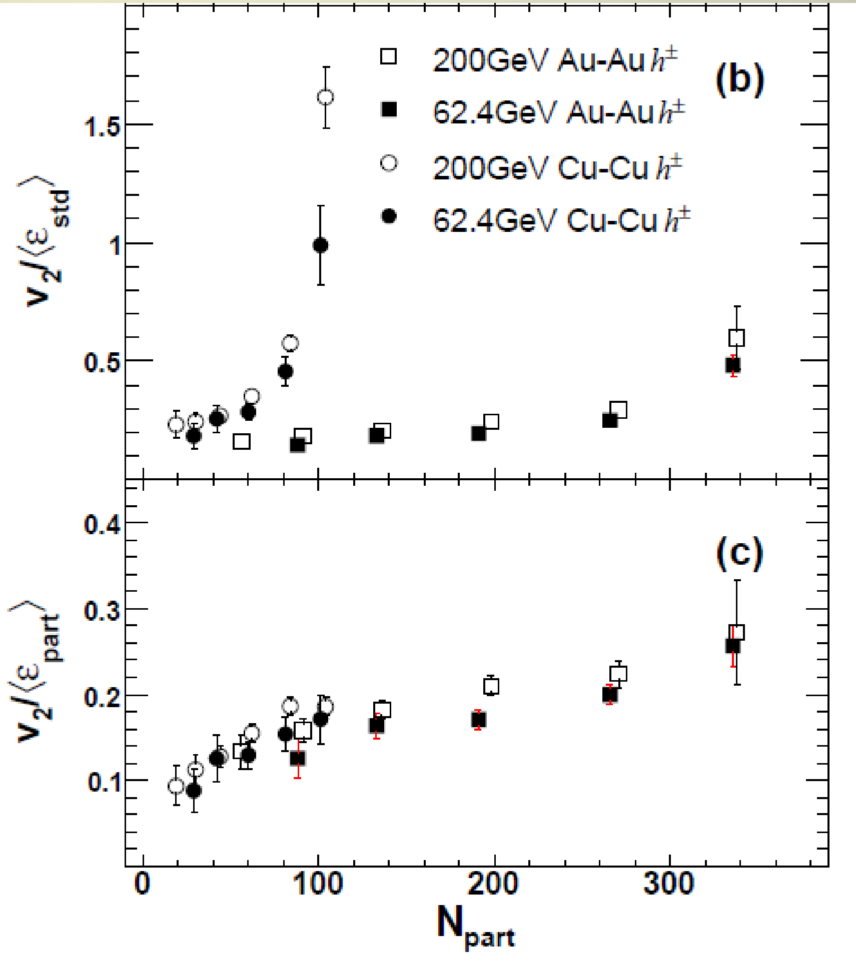


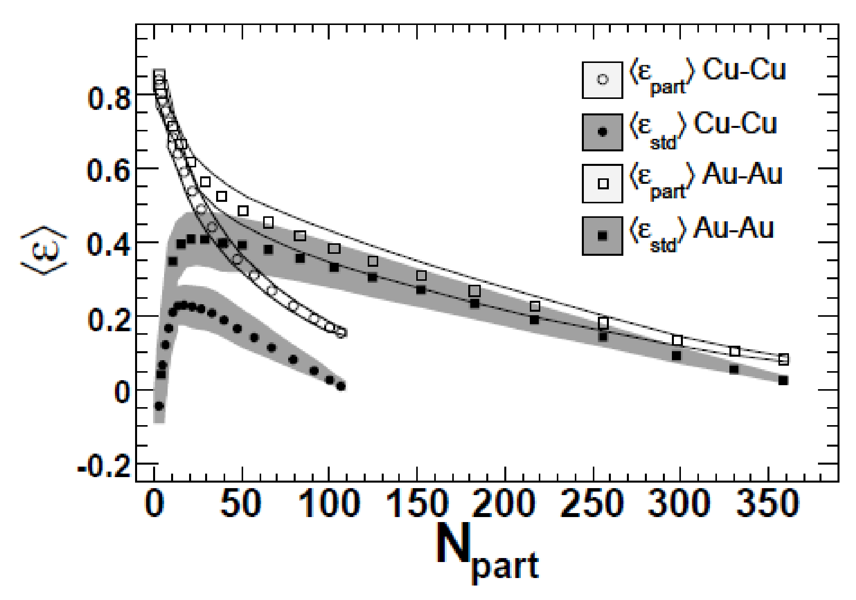


CGC and perfect fluid, are they compatible?

T.Hirano *et al.*, Phys. Lett. B 636, 299 (2006)

Importance of Fluctuation in Initial Conditions

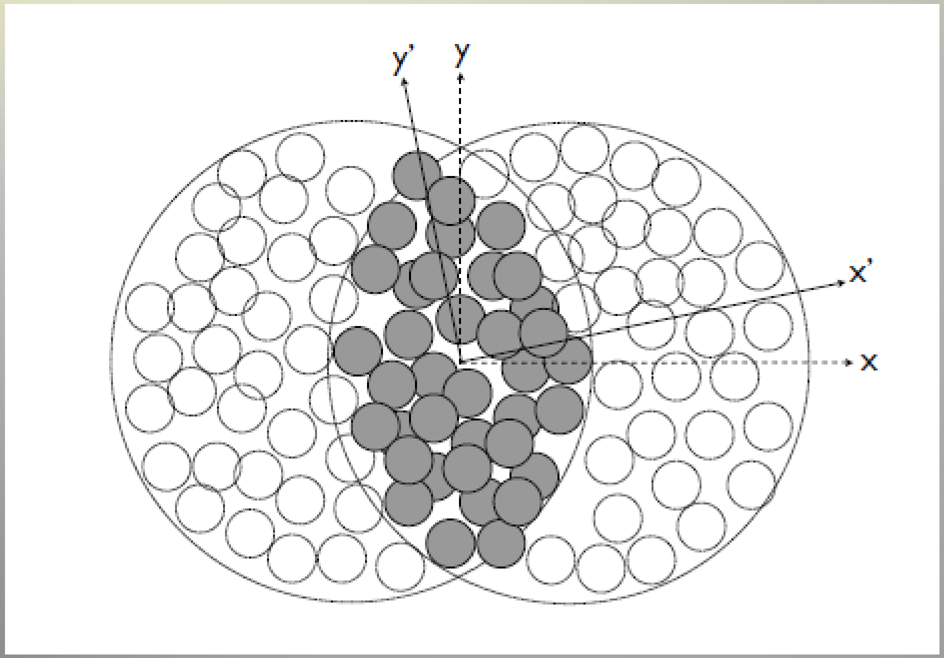




$$\varepsilon_{\mathrm{part}} > \varepsilon_{\mathrm{std}}$$

PHOBOS,
Phys. Rev. Lett. 98, 242302 (2007)

Fluctuation in Initial Conditions



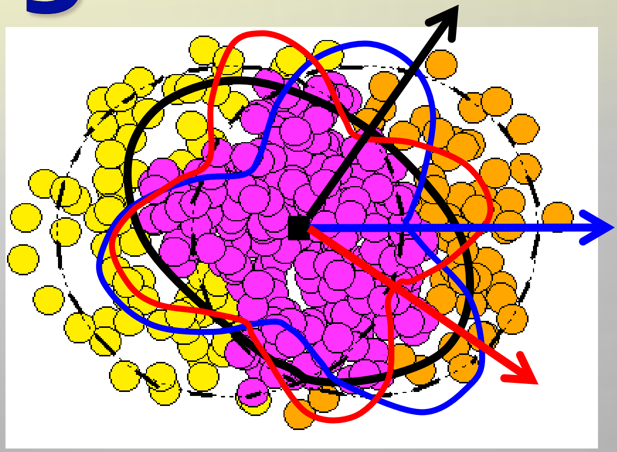
Elliptic flow is generated with respect to *participant plane (x'-y')* rather than *reaction plane (x-y).*

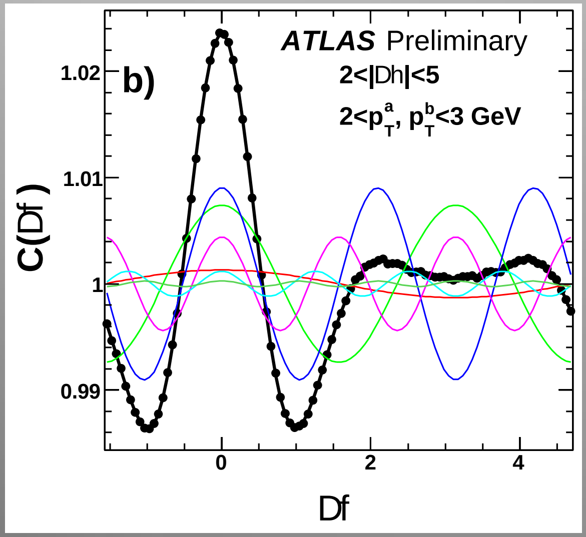
B.Alver *et al.*,
Phys. Rev. C 77, 014906 (2008)

Impact of PHOBOS finding

- System could (hydrodynamically?) respond to such a fine structure.
  - Is local thermalization achieved in such a short length scale (~1 fm)?
  - Number of particles is quite small in such a small system.
  - Concept of hydrodynamics? Is ensemble average taken? Event-by-event hydro
  - Higher harmonics?

Higher Harmonics is Finite!

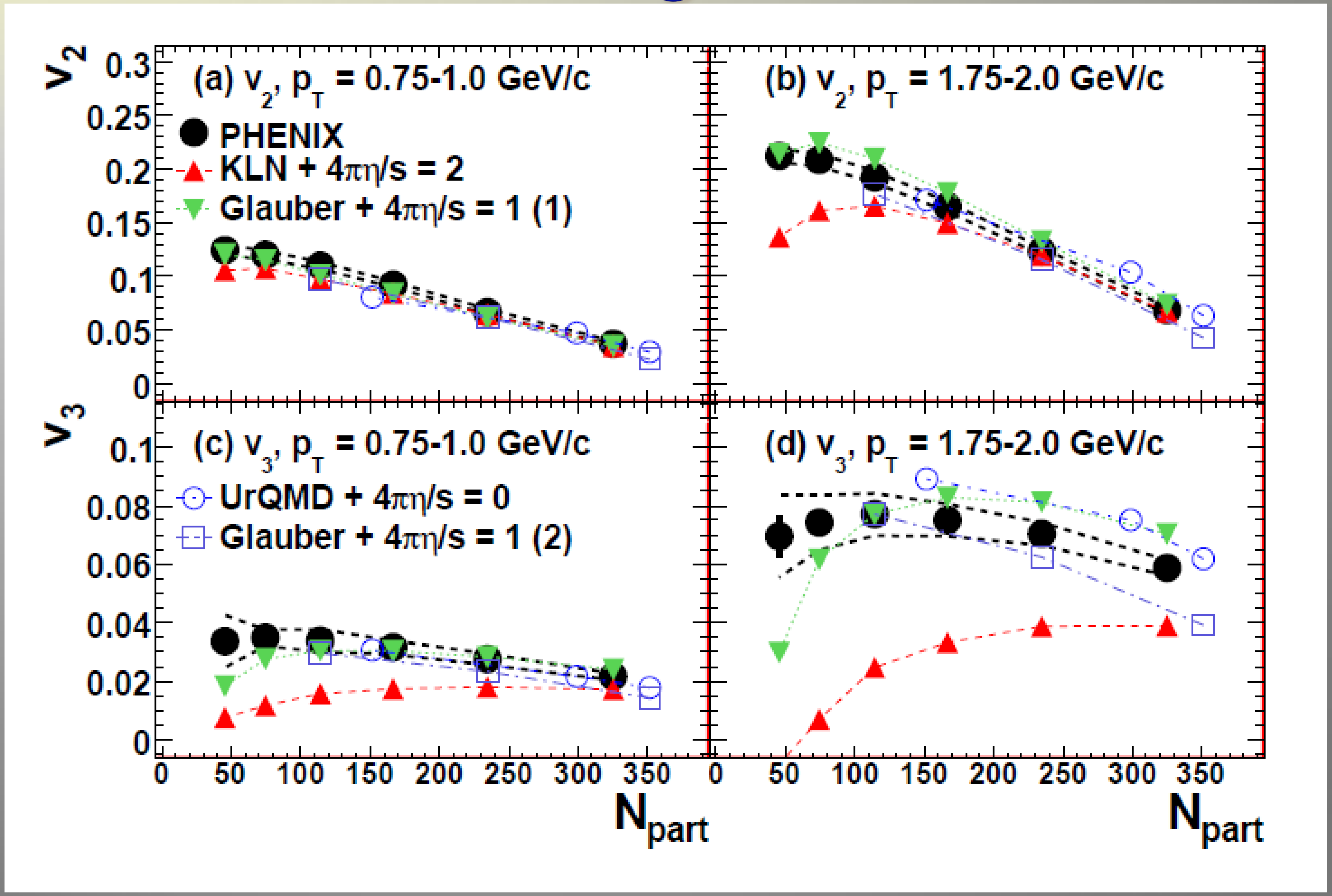




Two particle correlation function is composed solely of higher harmonics

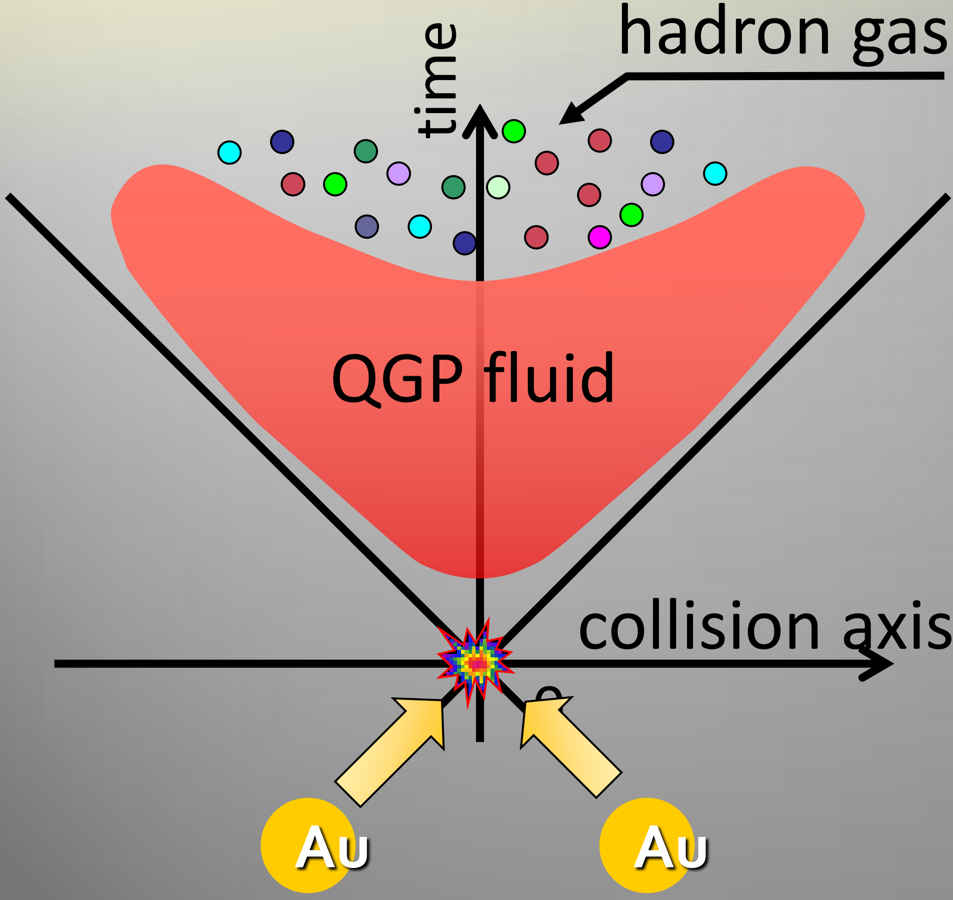
Figures adapted from talk by J.Jia (ATLAS) at QM2011

PHENIX v_2 vs. v_3 Argument



HYDRO-BASED EVENT GENERATOR

Current Status: E-by-E H2C



Hadronic cascade

↑

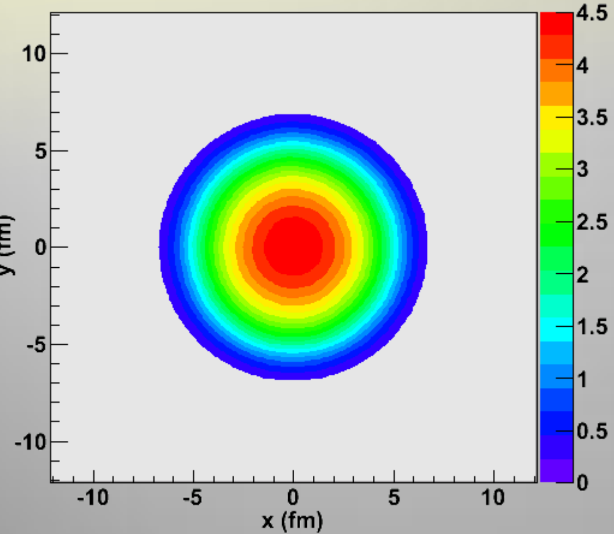
3D ideal hydro

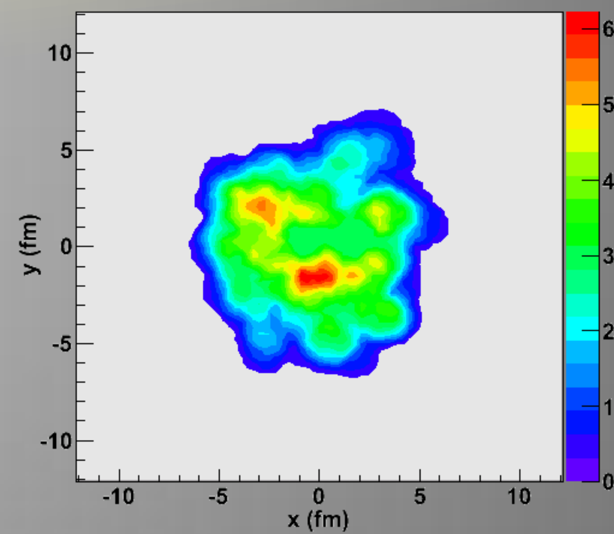
↑

Monte Carlo I.C.
(MC-KLN)

*Figure in PHENIX Decadal Plan (2010) adapted from MY figure…

Initial Density Fluctuation





$\frac{1}{N}\sum$ initial condition

conventional hydro

single initial condition

event-by-event hydro

$v_2\{***\}$

$v_2\{EP\}$, $v_2\{2\}$, $v_2\{4\}$, $v_2\{6\}$, $v_2\{LYZ\}$, …

Hydro-based event generator
→ Analysis of the outputs almost in the same way as experimental people do.

⇓

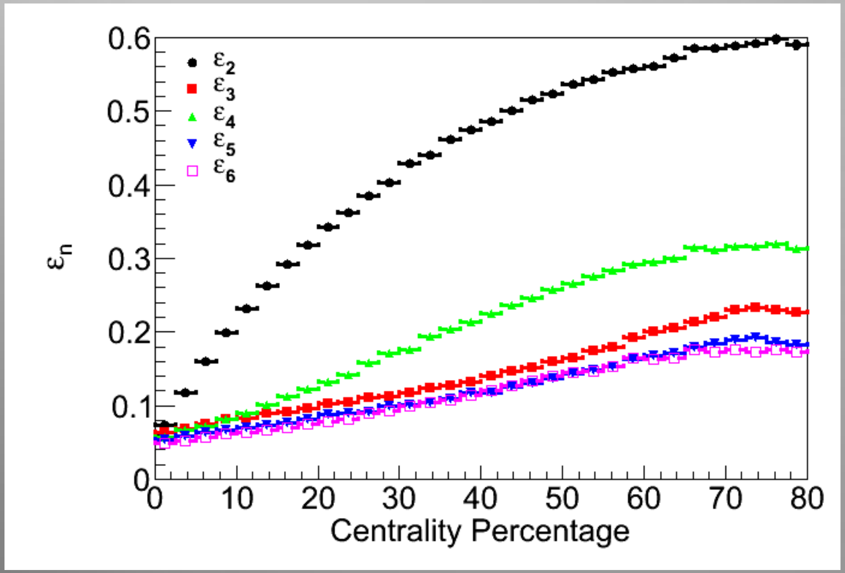
Demonstration of v_n analysis according to event plane method by ATLAS setup.
E.g.) Centrality cut using E_T in FCal region

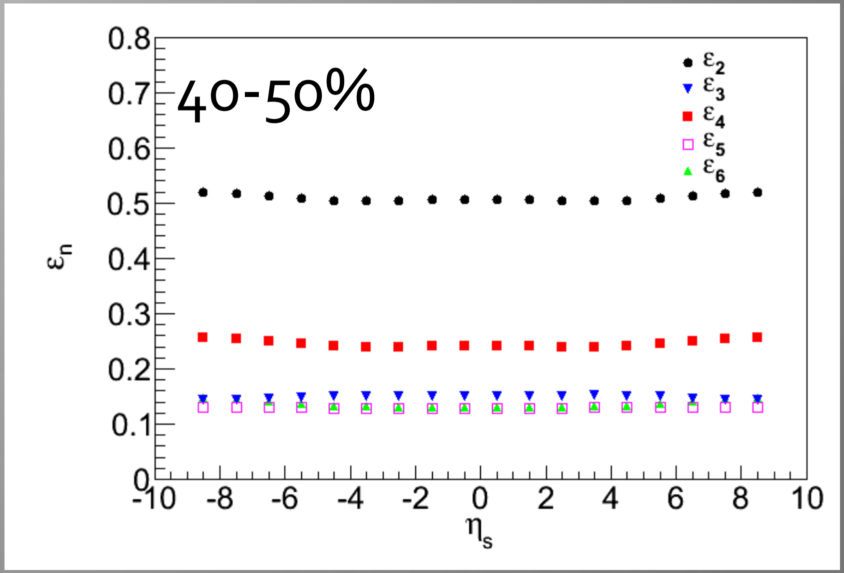
ATLAS, arXiv:1108.6018

*All calculations performed by K.Murase

Eccentricity, Triangularity, …

$$\varepsilon_n = \frac{\left|\langle r^2 e^{in\phi} \rangle\right|}{\langle r^2 \rangle} \qquad n\psi_n = \arg\langle r^2 e^{in\phi} \rangle$$





Almost boost invariant

Resolution of Event Plane

Reaction (Event) plane is not known experimentally nor in outputs from E-by-E H2C.

Event plane method

Event plane resolution using two subevents

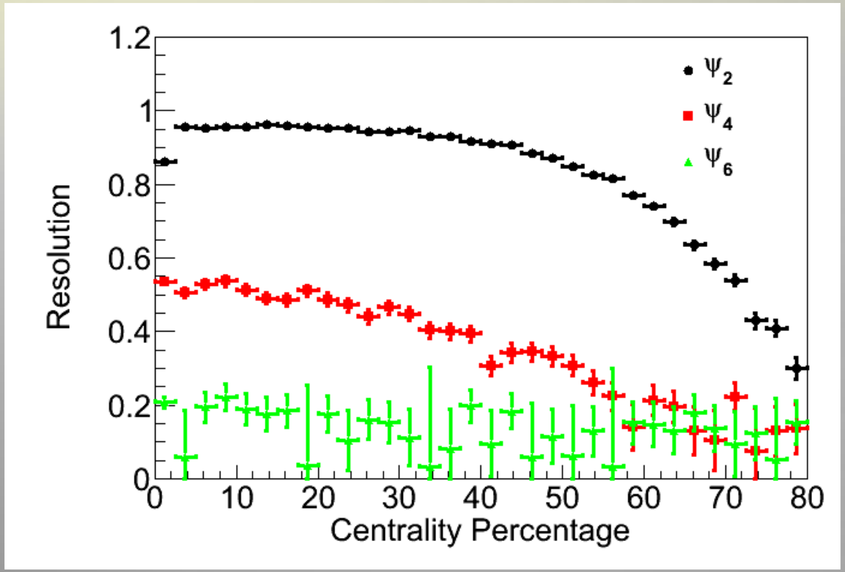
$$R_n = \sqrt{\langle \cos[n(\Psi_n{}^1 - \Psi_n{}^2)] \rangle}$$

$$n\Psi_n = \tan^{-1}\left(\frac{\sum E_{T,i} \sin n\phi_i}{\sum E_{T,i} \cos n\phi_i}\right)$$

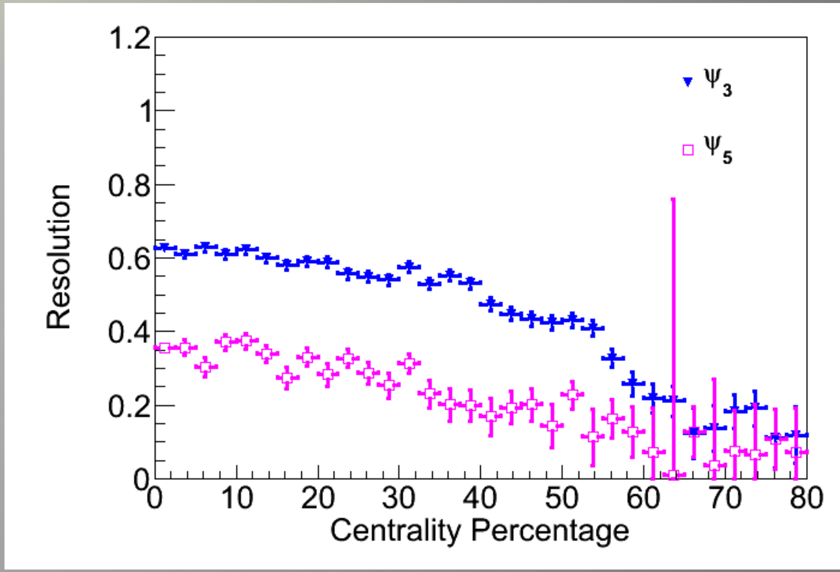
c.f.) A.M.Poskanzer and S.Voloshin, Phys. Rev. C 58, 1671 (1998)

Resolution of Event Plane from E-by-E H2C

Even Harmonics



Odd Harmonics



# of events: 80000 (Remember full 3D hydro+cascade!)

Subevent "N": charged, $-4.8 < \eta < -3.2$ (FCal in ATLAS)

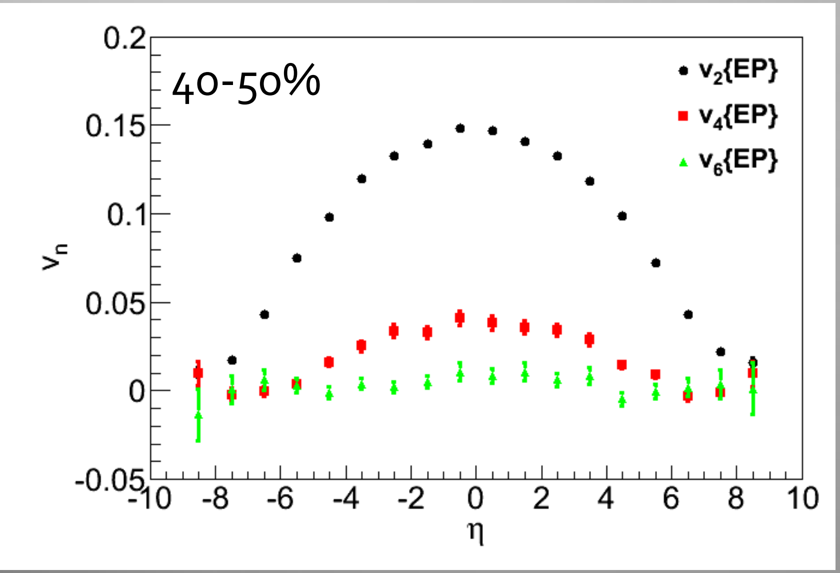
Subevent "P": charged, $3.2 < \eta < 4.8$ (FCal in ATLAS)

ATLAS, arXiv:1108.6018

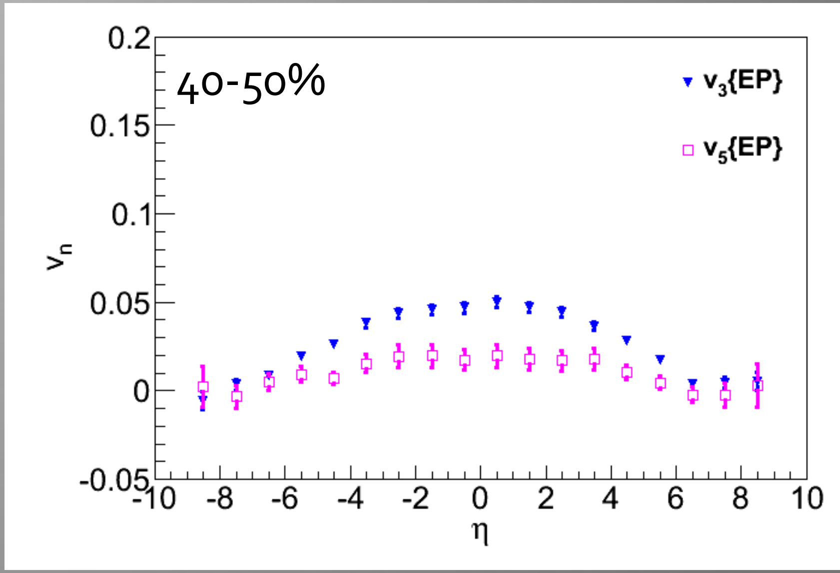
V_n\{EP\}(η)

$$v_n\{\mathrm{EP}\}(\eta, p_T) = \frac{1}{R}\left\langle \cos\left[n\left(\phi - \Psi_n{}^{P/N}\right)\right]\right\rangle$$

Even Harmonics



Odd Harmonics

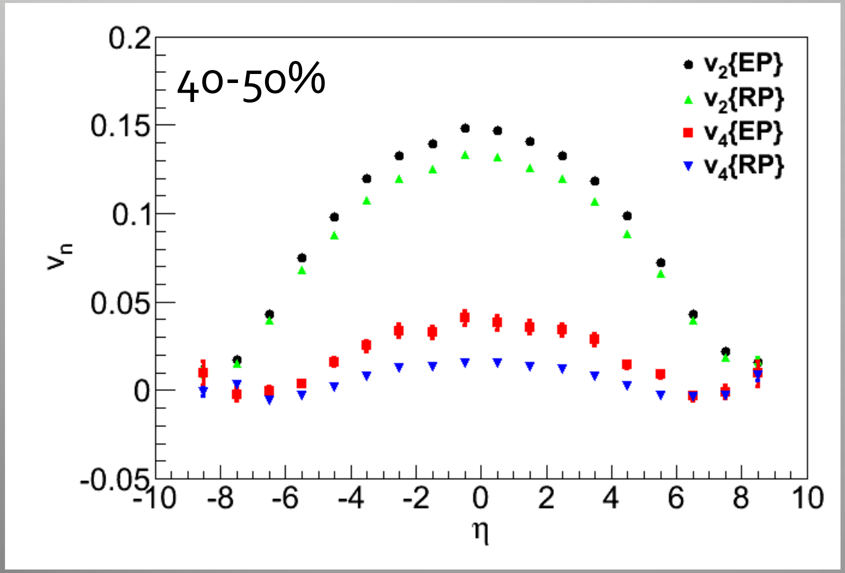


Not boost inv. ←→almost boost inv. for epsilon

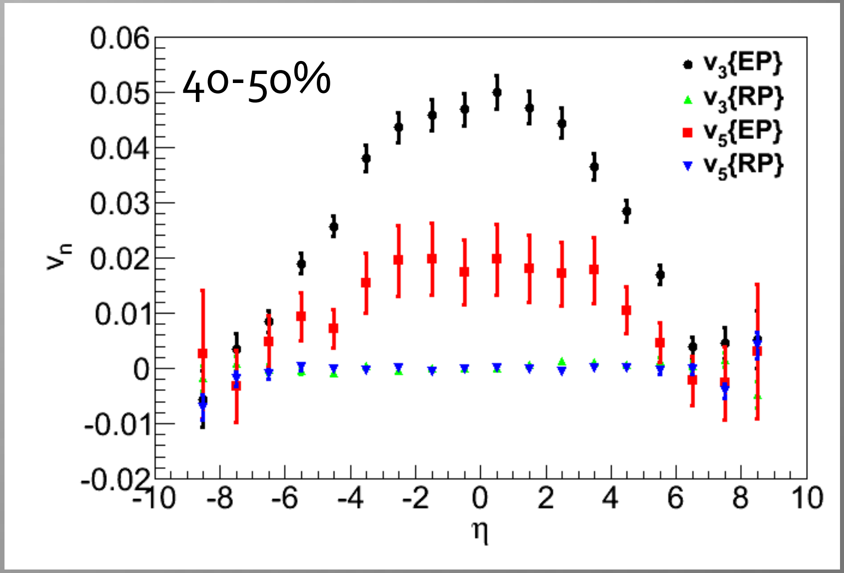
v_n\{EP\} vs. v_n\{RP\}

v_n\{RP\}: v_n w.r.t. reaction plane known in theory

Even Harmonics



Odd Harmonics

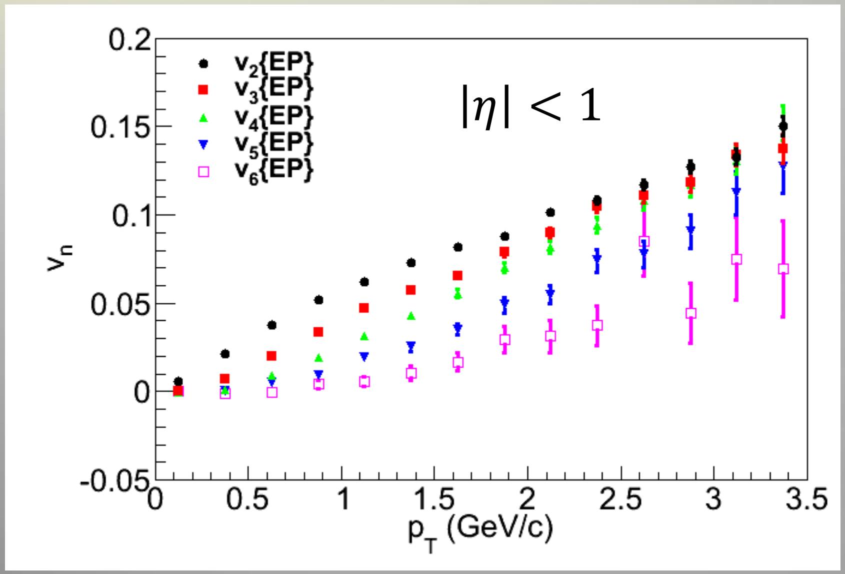


v_{even}\{EP\}>v_{even}\{RP\}
due to fluctuation

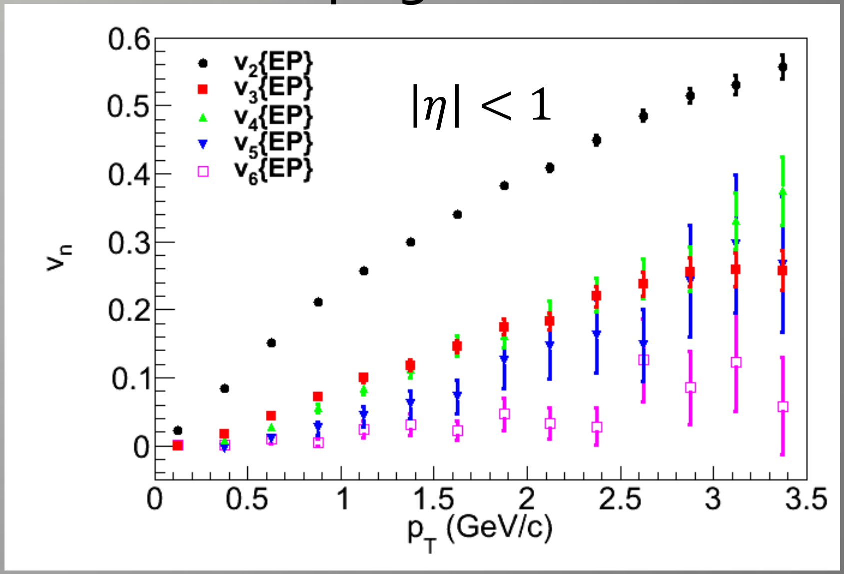
v_{odd}\{RP\}~0

$V_n\{EP\}(p_T)$

0-10%



40-50%



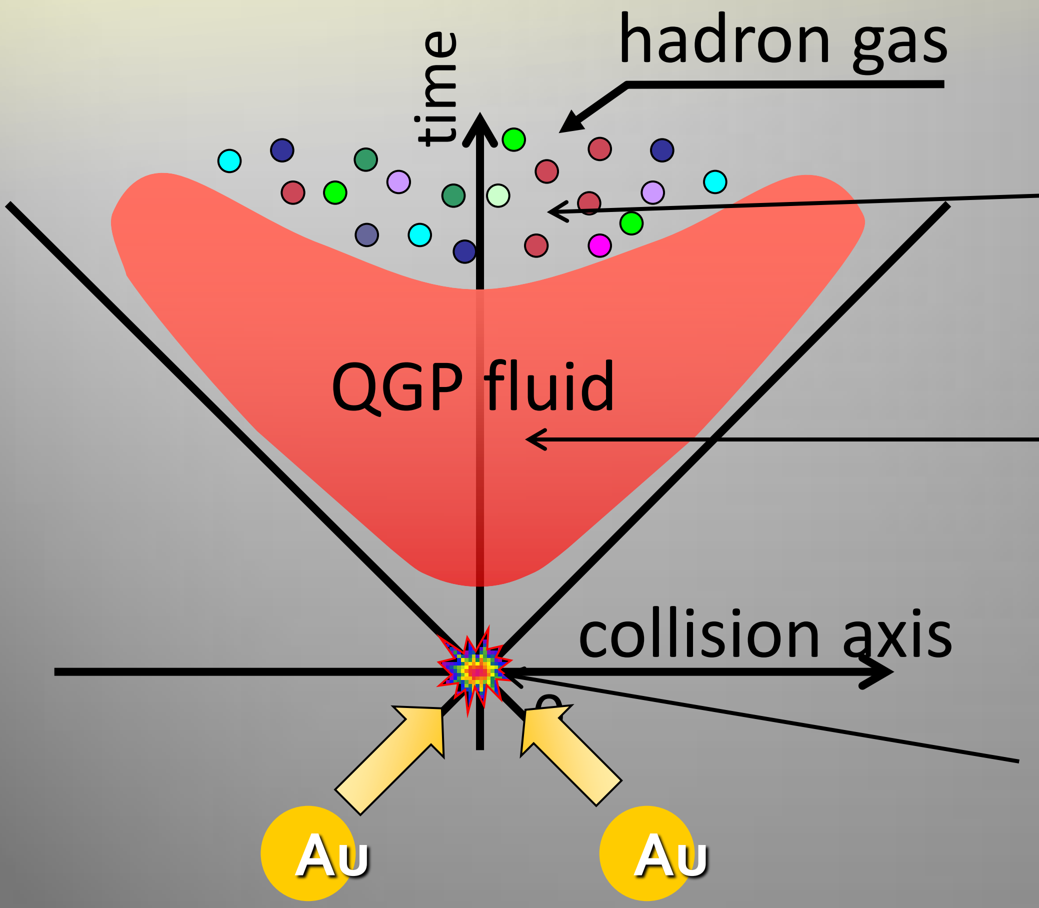
$v_2\{EP\} \approx v_3\{EP\}$

$v_2\{EP\} > v_3\{EP\}$

Note: $\varepsilon_2 > \varepsilon_3$

RELATIVISTIC FLUCTUATING HYDRODYNAMICS

Fluctuation Appears Everywhere



Finite number of hadrons

Thermal noise

Initial configuration of nucleons and particle production

Kubo Formula

$$\eta = \lim_{\omega \to 0} \lim_{q \to 0} \frac{1}{2\omega} \int dt dx\, e^{i(\omega t - qx)}$$

$$\times \left\langle \left[T_{xy}(t,x), T_{xy}(0,0) \right] \right\rangle$$

Slow dynamics is extracted. → How slow?
Finite relaxation time is crucial in relativistic dissipative hydrodynamics to be causal.

Causal Hydrodynamics

Within linear response

$$\Pi(t) = \int dt' G(t,t') F(t')$$

Suppose

$$G(t,t') = \frac{\kappa}{\tau} \exp\left(-\frac{t-t'}{\tau}\right) \theta(t-t')$$

one obtains differential form

$$\dot{\Pi}(t) = -\frac{\Pi(t) - \kappa F(t)}{\tau}$$

➡ Simplified Israel-Stewart Eq.

Relativistic Fluctuating Hydrodynamics (RFH)

Thermal fluctuation must be important in event-by-event simulations:

dissipative current

thermodynamic force

$$\Pi(x) = \int d^4x' G(x,x') F(x') + \xi(x)$$

thermal noise

$$\langle \xi(x)\xi(x') \rangle \approx G(x,x')$$

Fluctuation ←→ Dissipation

For non-relativistic case, see Landau-Lifshtiz, Fluid Mechanics

Finite Size Effect

In RFH, fluctuation depends naturally on local volume.

$$\xi(x) \propto \frac{1}{\sqrt{\Delta V}}$$

- Information about coarse-grained size?
- Fluctuation term ~ average value?
- Need to consider (?) finite size effect in equation of state and transport coefficients

CHECKLIST FOR EVENT GENERATOR IN THE NEXT GENERATION

Checklist for Initial Conditions

- ☐ Glauber, Color Glass Condensate, or any other production mechanism
- ☐ Implement Monte-Carlo method
  - ☐ Fluctuation from nucleon configuration
  - ☐ Full 3D (even in Glauber)
  - ☐ Fluctuation of production mechanism itself
- ☐ Switchable among models of production mechanism
- ☐ Thermalization(?)

Checklist for Hydrodynamics

- ☐ Lattice equation of state (finite size effect?)
- ☐ Arbitrary temperature dependence of transport coefficients (finite size effect?)
- ☐ Full 3D causal dissipative hydro code
- ☐ Robust algorithm against shock wave
- ☐ Fluctuation terms in constitutive equation
- ☐ Interface with hadronic cascade
- ☐ Less numerical costs, in particular, at freezeout

Checklist for Hadronic Cascade

- ☐ Compatible with PDG hadron list
- ☐ Interface with hydro output (or, in general, arbitrary phase space distribution as an initial condition)
- ☐ Weak decays

Conclusion and Outlook

- Fluctuation would play an important role in dynamics of QGP
- More sophisticated dynamical model is required towards precision physics

- Finite baryon density for lower energy collisions
- Incorporate of hard/rare probes(?)

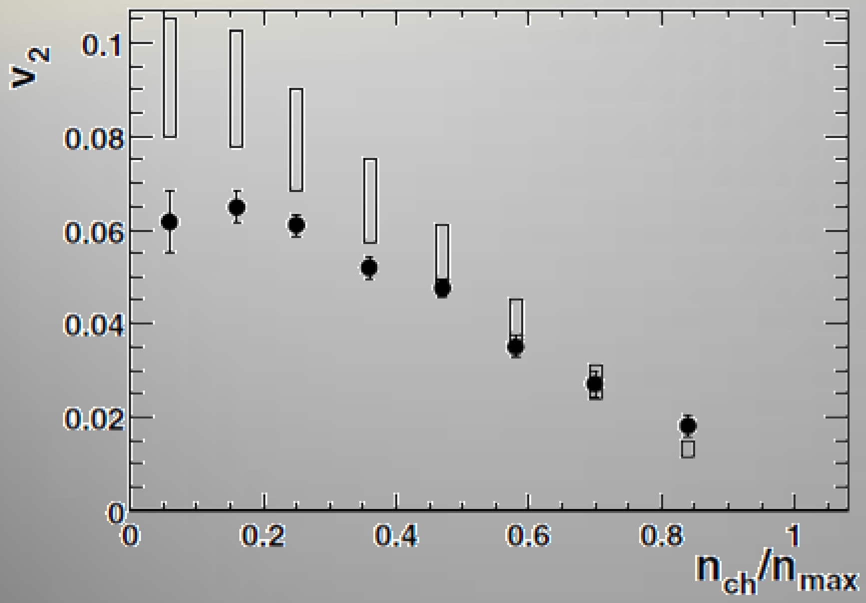
Energy-Momentum Flow from Jets

$$\partial_\mu T^{\mu\nu} = J^\nu$$

- Jet quenching might affect dynamics at LHC (and even at RHIC)
- Many jets could disturb fluid elements (or even heat them up?)
- Beyond linearized hydro → Full solution
- How to non-perturbatively formulate J^μ?

BACKUPS

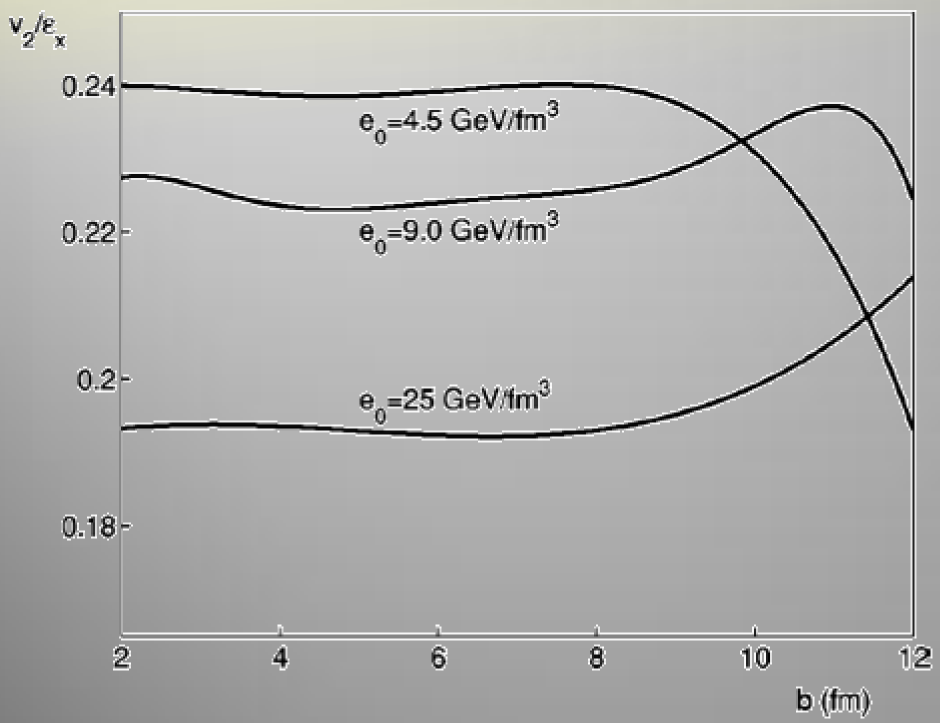
First Elliptic Flow Data at RHIC



p_T integrated v_2 for charged hadrons at midrapidity as a function of centrality for the first time at RHIC

STAR, Phys, Rev. Lett. 86, 402 (2001)

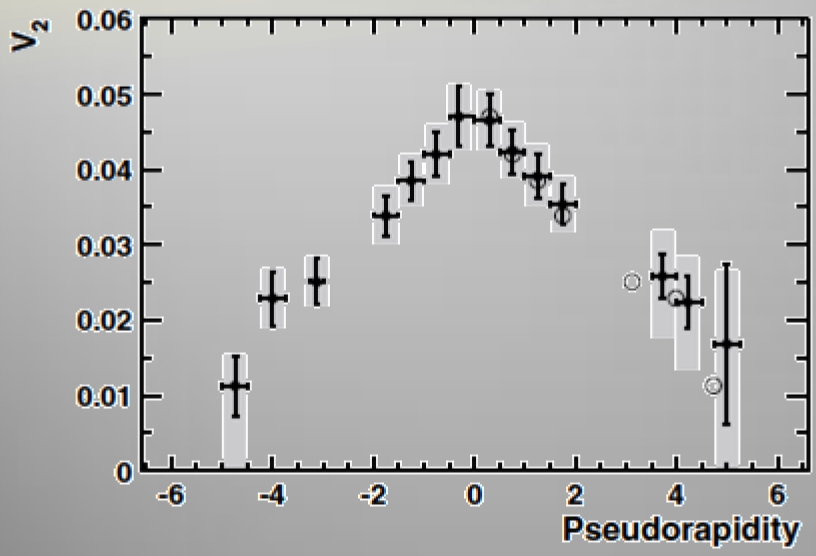
Theoretical Prediction of v_2 at RHIC



STAR v_2 data
→ comparable with ideal hydro prediction by Kolb et al. (v_2~0.2ε)

P.F.Kolb *et al.*, Phys, Rev. C 62, 054909 (2000)

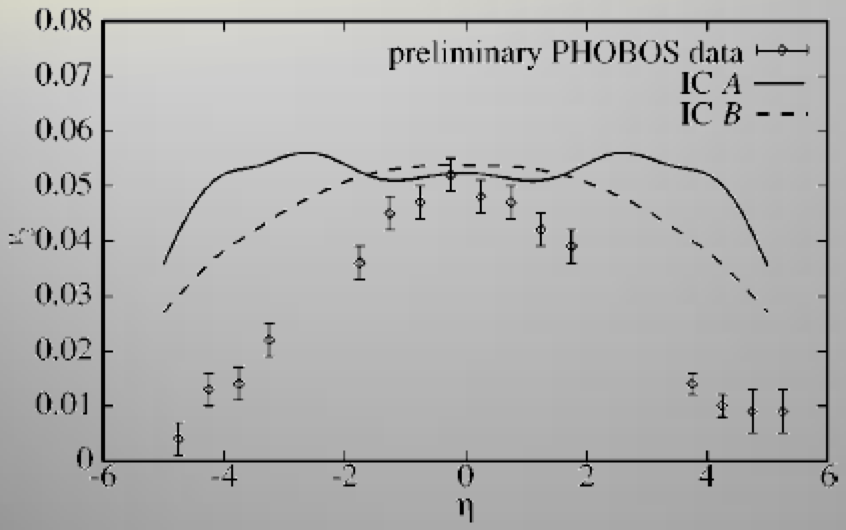
v_2 in Broad Pseudorapidty Region



PHOBOS,
Phys, Rev. Lett. 89, 222301 (2002)

Triangular shape in pseudorapidity
→ v_2 scales dN/dη rather than eccentricity.
← → Hydro prediction (v_2 ~0.2ε)?

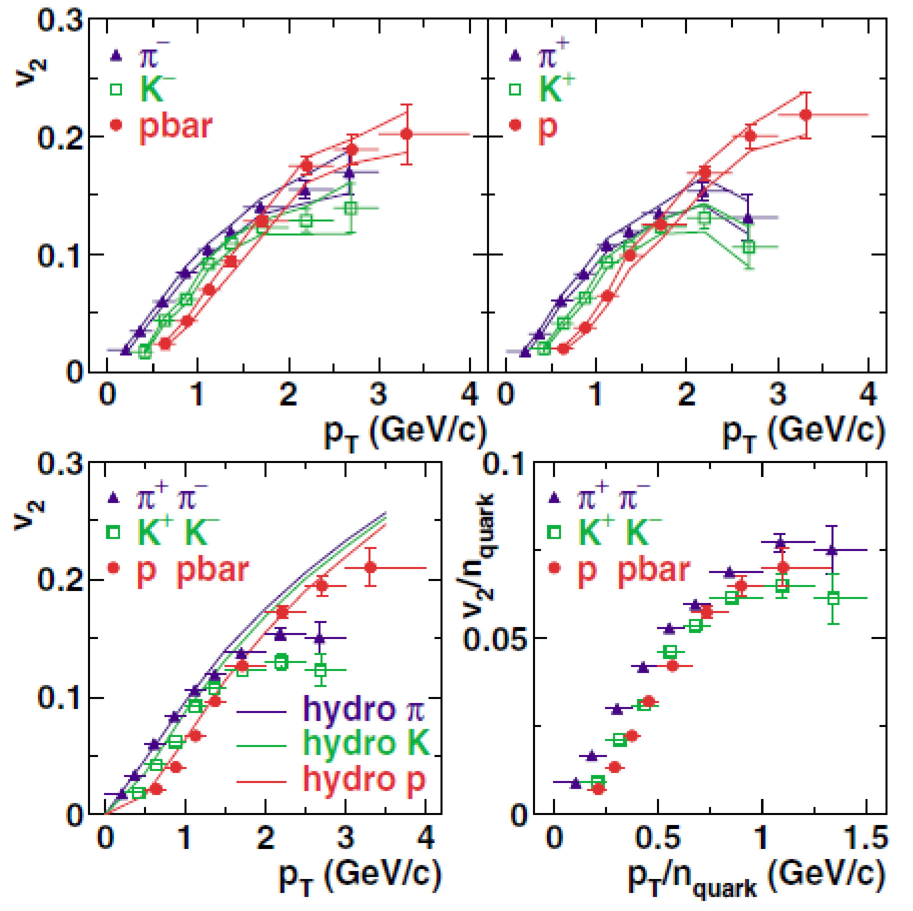
v_2 from Full 3D Hydro



T.Hirano,
Phys, Rev. C 65, 011901 (2001)

Result from ideal hydro ~ v_2 near midrapidity
→ This already indicates importance of viscosity in forward/backward region.

Particle Identified v_2 Data



PHENIX PID v_2 data

- Mass splitting pattern

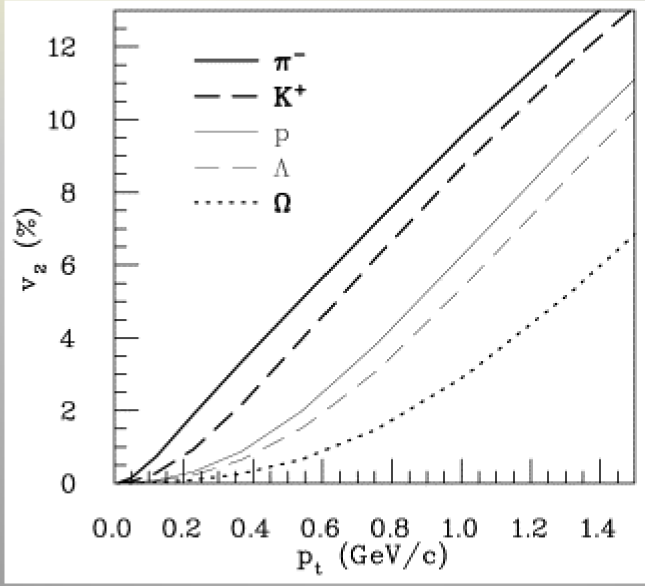
→ Consistent with ideal hydro results (caveat*)

- Quark number scaling

→ Collective flow of quark d.o.f.

PHENIX, Phys, Rev. Lett. 91, 182301 (2003)

Mass Splitting Pattern from Ideal Hydro



P.Huovinen *et al.*,
Phys, Lett. B 503, 58 (2001)

Mass splitting pattern from a radial flow effect

→ Developed in late stage, not early stage

→ Not necessary from hydro calculations

*Less rescattering particles need not follow the pattern.

*T. Hirano *et al.*, Phys. Rev. C77, 044909 (2007).