Heavy Ion Meeting, Yonsei University

Seoul, Dec. 10, 2011

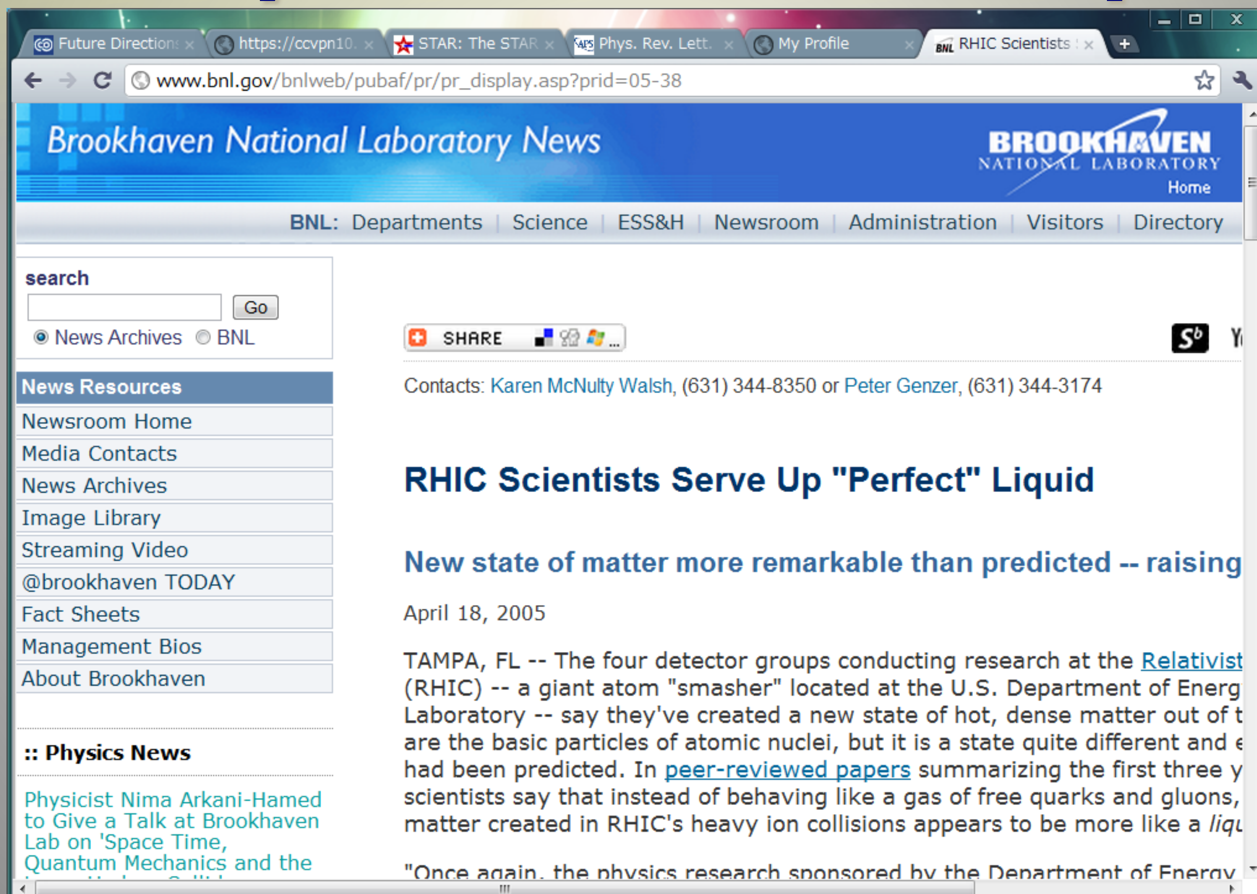
RECENT DEVELOPMENT OF HYDRO MODEL AFTER "PERFECT LIQUID"

T.H., P.Huovinen, K.Murase, Y.Nara (in preparation)

Outline

- Introduction
  - Discovery of Perfect fluid
  - Importance of initial fluctuation
- Hydro-based event generator
  - Initial state fluctuation
  - Flow analysis
  - Results
- Conclusion

Discovery of "Perfect Liquid"



Future Direction | https://ccvpn10. | STAR: The STAR | Phys. Rev. Lett. | My Profile | RHIC Scientists

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

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:: Physics News

Physicist Nima Arkani-Hamed to Give a Talk at Brookhaven Lab on 'Space Time, Quantum Mechanics and the

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Contacts: Karen McNulty Walsh, (631) 344-8350 or Peter Genzer, (631) 344-3174

RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising

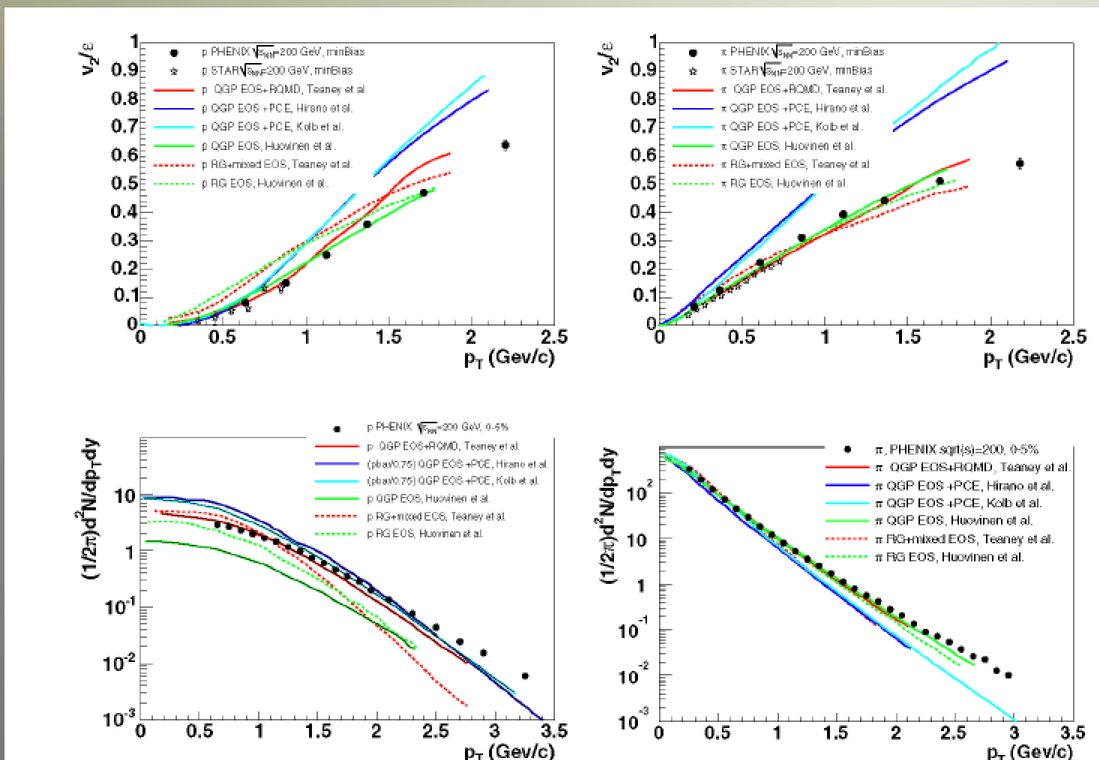
April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativist
(RHIC) -- a giant atom "smasher" located at the U.S. Department of Energ
Laboratory -- say they've created a new state of hot, dense matter out of t
are the basic particles of atomic nuclei, but it is a state quite different and e
had been predicted. In peer-reviewed papers summarizing the first three y
scientists say that instead of behaving like a gas of free quarks and gluons,
matter created in RHIC's heavy ion collisions appears to be more like a *liqu*

"Once again, the physics research sponsored by the Department of Energy

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

Status as of Press Release

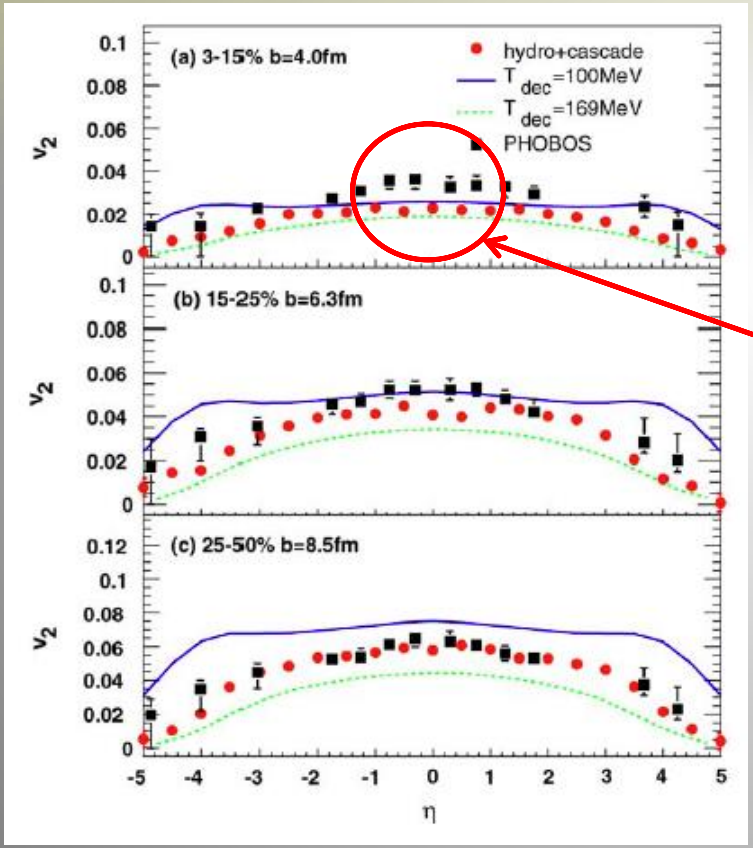


<u>Three pillars of modeling</u>

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

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

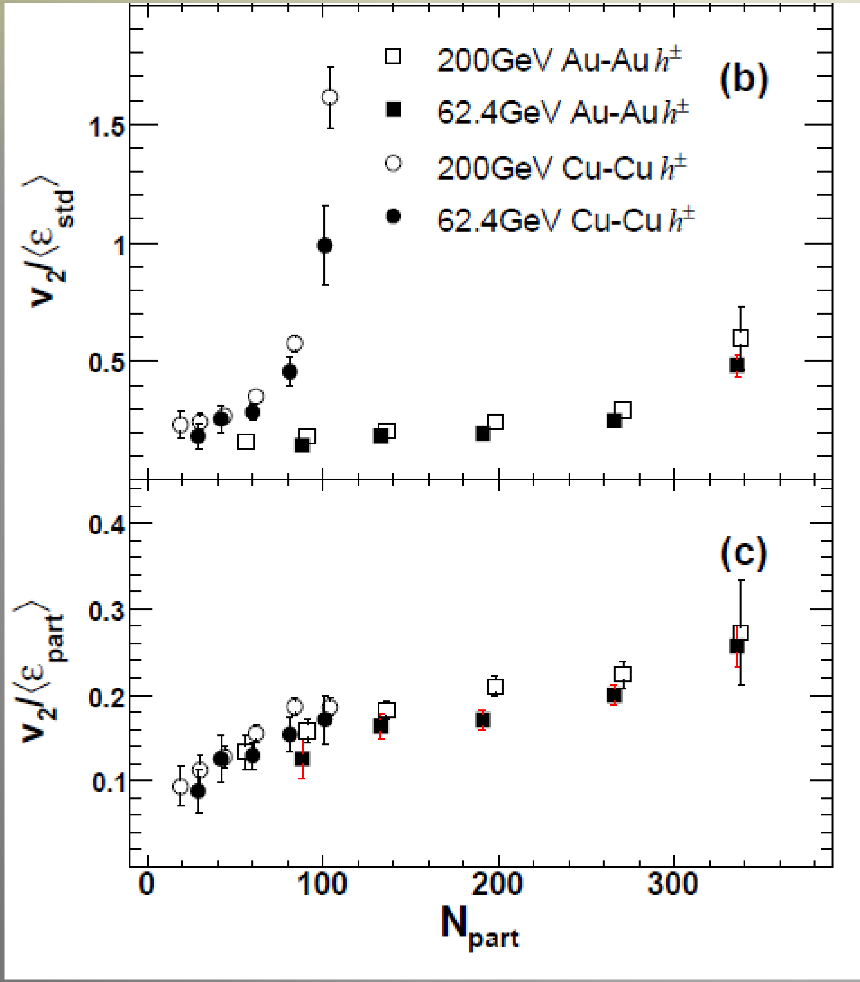
What is missing in central collisions?

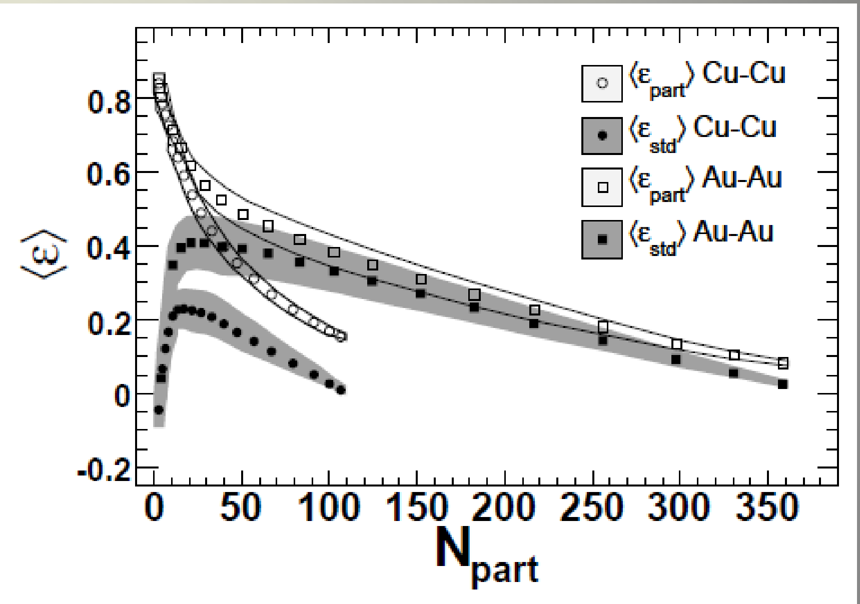


Undershoot the data at midrapidity in central collisions
→ Open question

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

Importance of Fluctuation in Initial Conditions

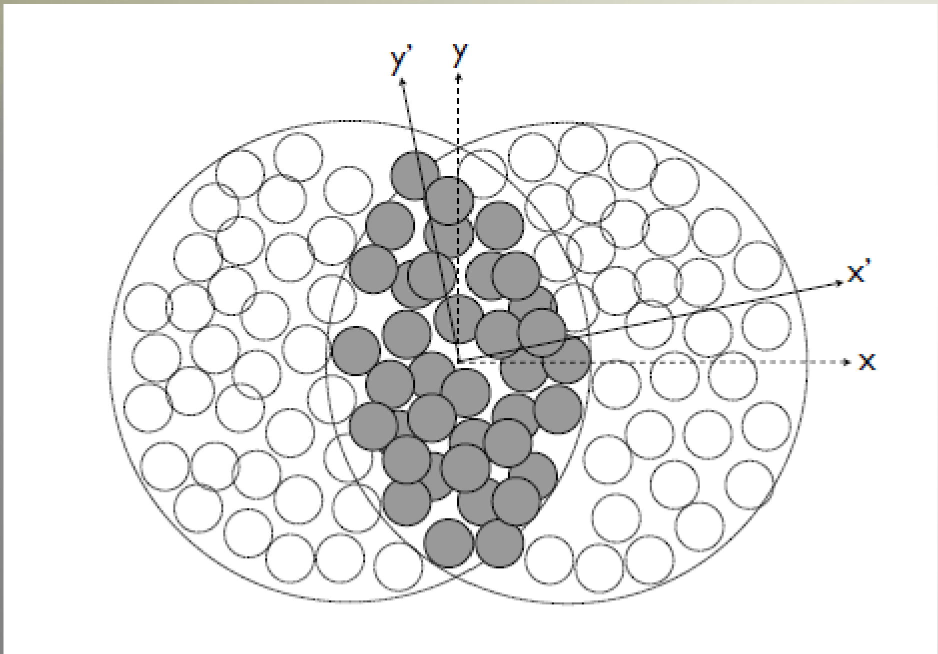




$$\varepsilon_{part} > \varepsilon_{std}$$

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

Fluctuation in Initial Conditions



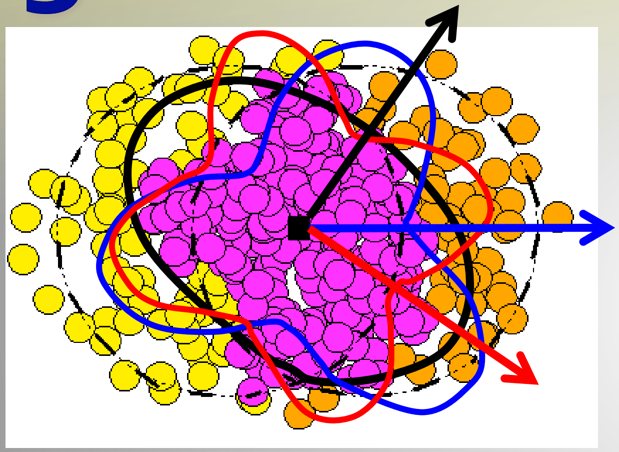
Elliptic flow is generated with respect to *participant plane* (x'-y' frame) rather than *reaction plane* (x-y frame).

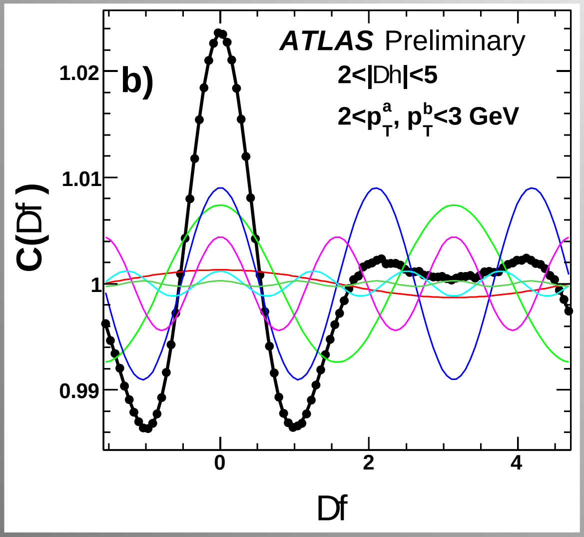
B.Alver *et al.*,
Phys. Rev. C 77, 014906 (2008)

Importance of PHOBOS finding

- System could (hydrodynamically?) respond to such a fine structure.
  - Is local thermalization achieved in such a short length scale (~1 fm)?
  - Need event-by-event hydro simulations?
  - Higher harmonics?

Higher Harmonics is Finite!

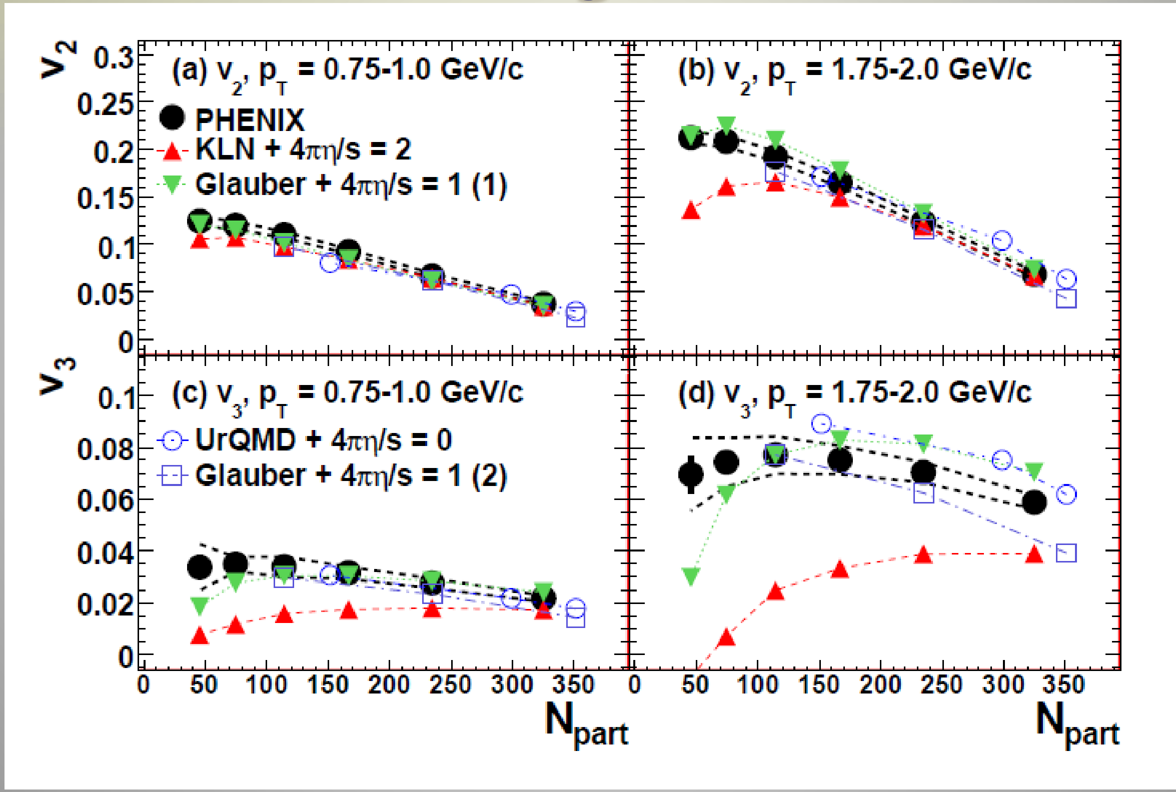




- Two particle correlation function is composed solely of higher harmonics
- Away-side two bumps just from hydrodynamic responses?

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

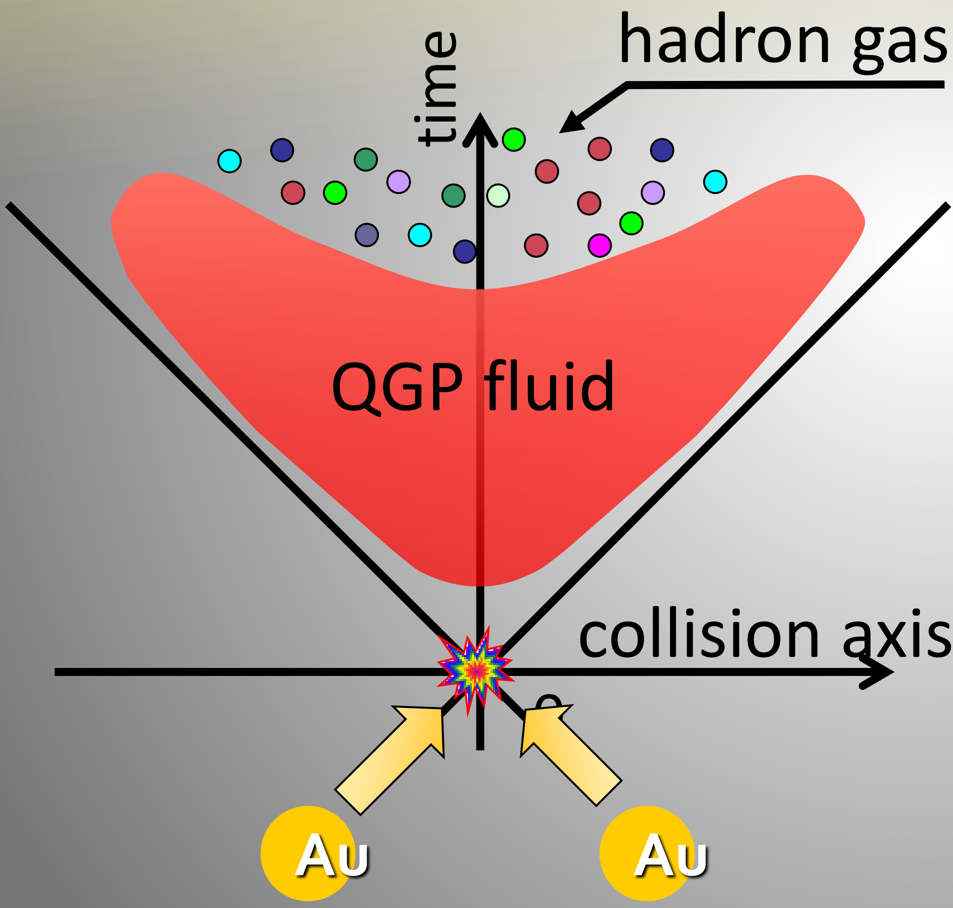
PHENIX v_2 vs. v_3 Argument



Analysis of v_2 and v_3 at once constrains the model
New challenge to hydrodynamic models

HYDRO-BASED EVENT GENERATOR

Current Status: E-by-E H2C



Hadronic cascade

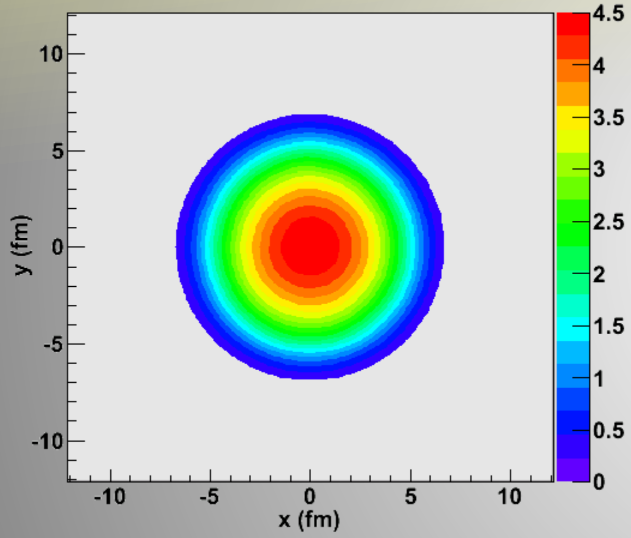
⇧

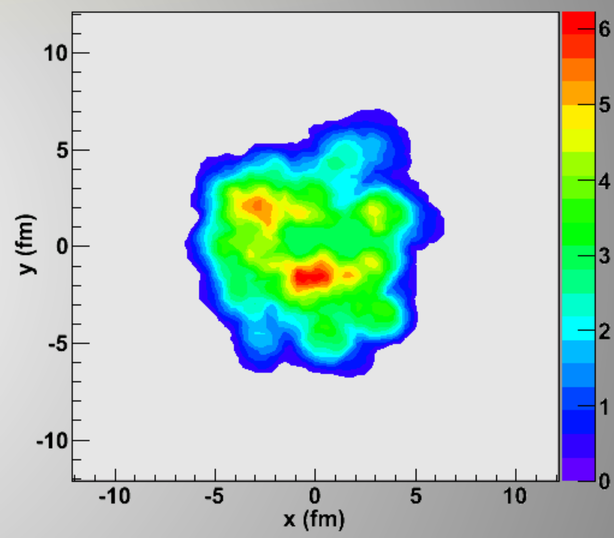
3D ideal hydro

⇧

Monte Carlo I.C. (MC-KLN)

Initial Density Fluctuation





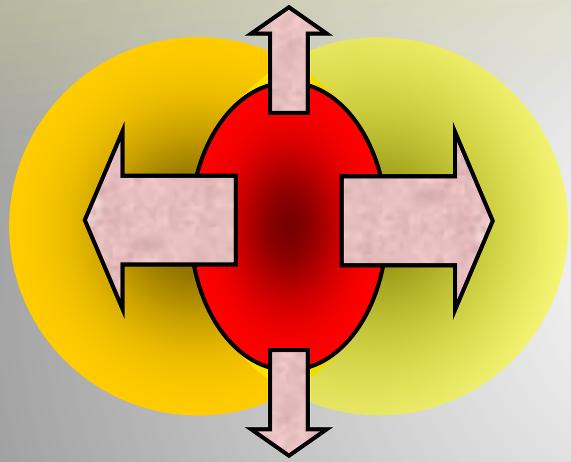
$$\frac{1}{N}\sum \text{initial condition}$$

single initial condition

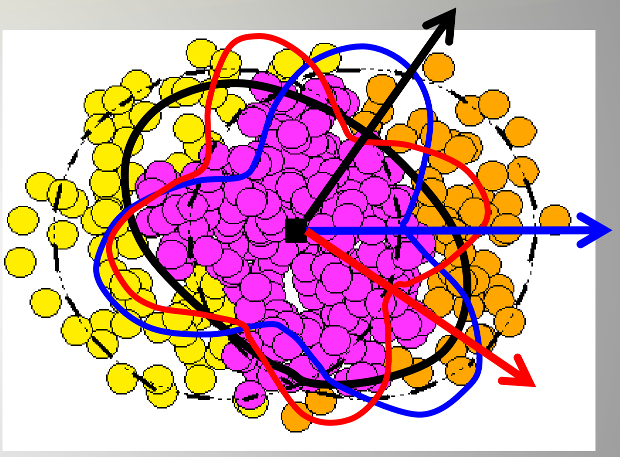
conventional hydro

event-by-event hydro

Event-by-event Fluctuation



Ideal, but unrealistic?
OK on average(?)



Actual collision?
→ Higher order deformation

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

Deformation at Higher Order

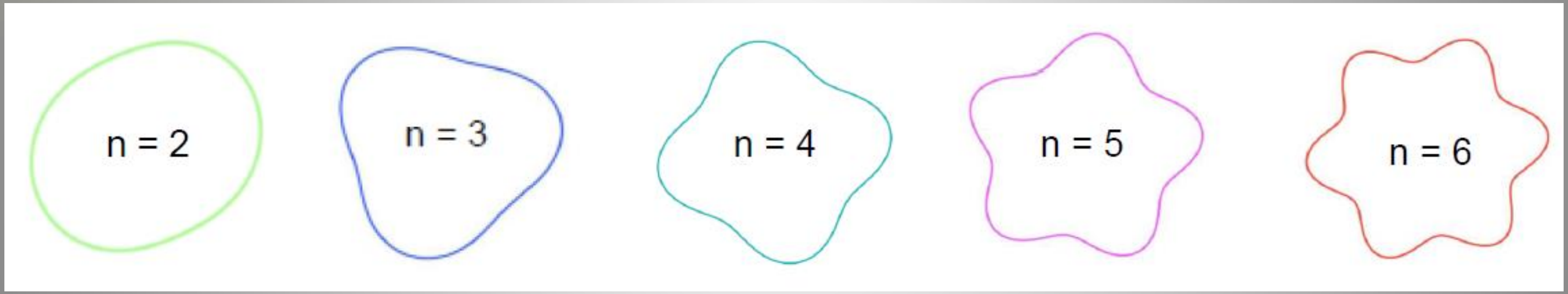
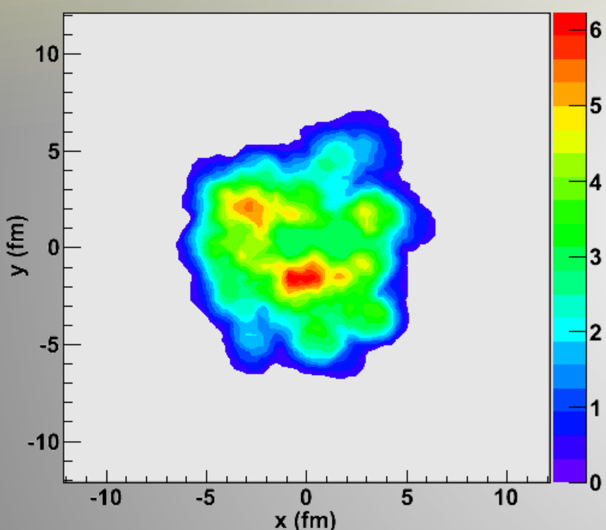
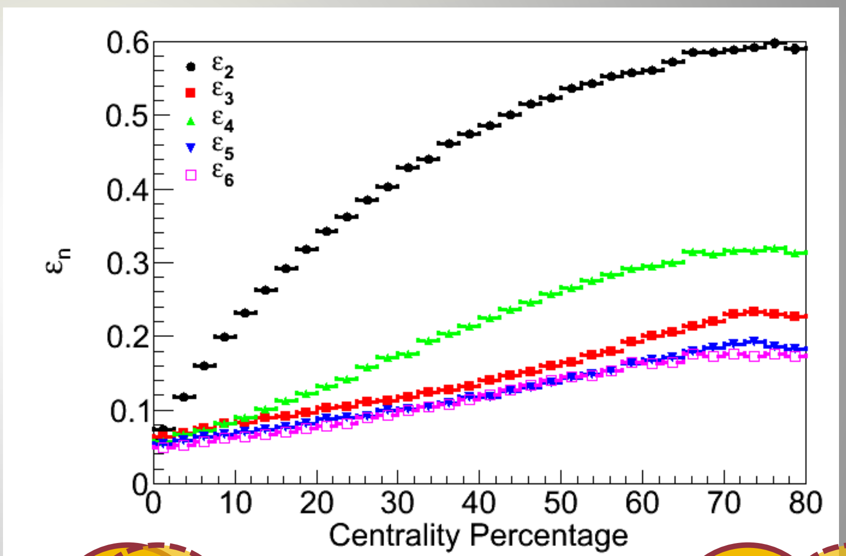


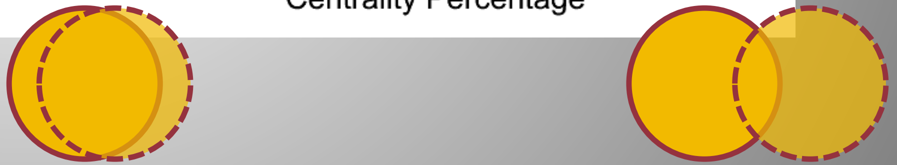
Figure adapted from
talk by J.Velkovska at QM11

Deformation in Model Calculations



Sample of entropy density profile in a plane perpendicular to collision axis





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

$v_2\{***\}$

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

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

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

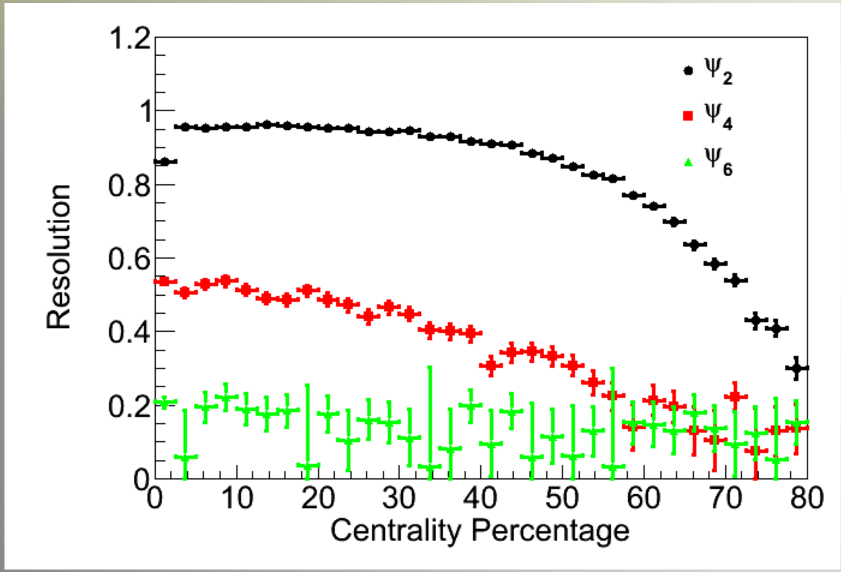
$$R_n = \sqrt{\left\langle \cos\left[n\left(\Psi_n{}^1 - \Psi_n{}^2\right)\right]\right\rangle}$$

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

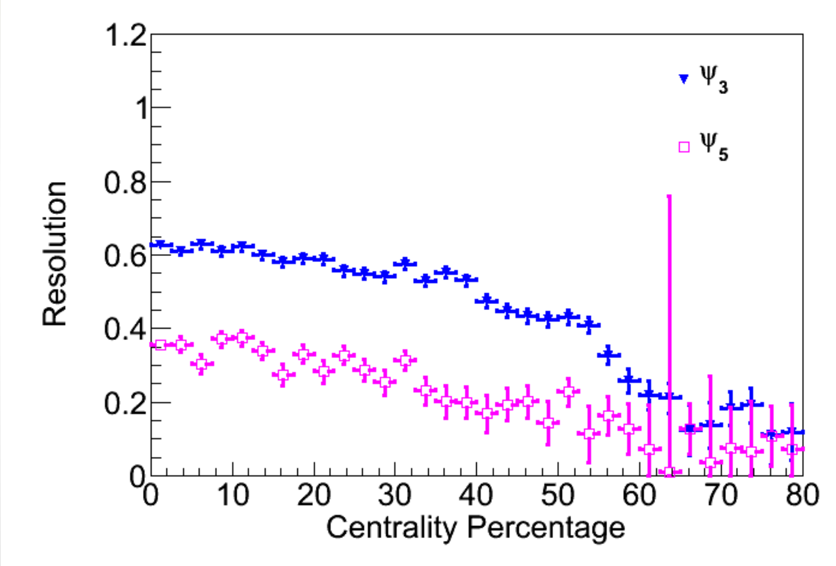
c.f.) A.M.Poskanzer and S.Voloshin, Phys. Rev. C 58, 1671 (1998)

Resolution of Event Plane from E-by-E H2C

Even Harmonics



Odd Harmonics



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

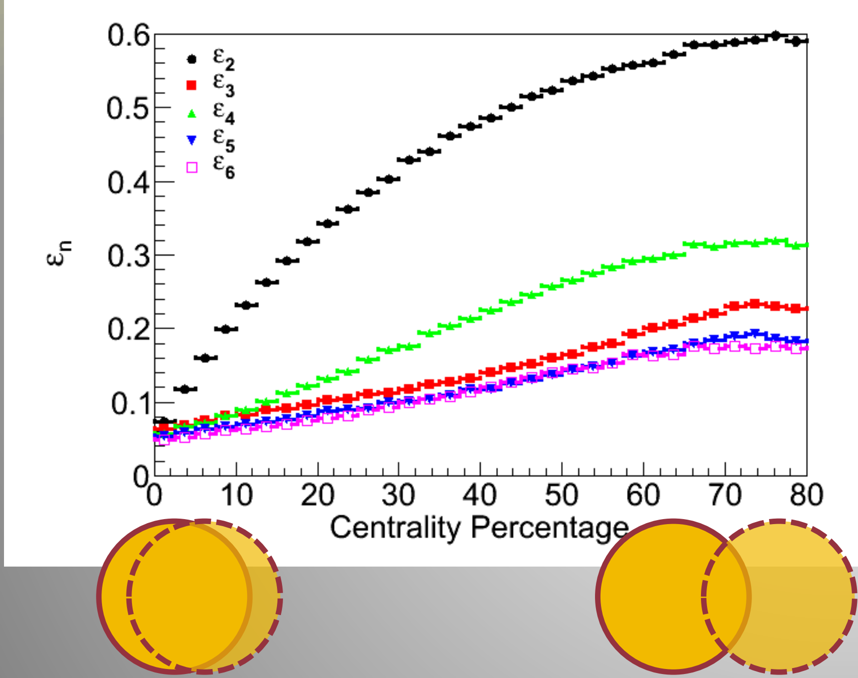
Subevent "N": charged, $-4.8 < \eta < -3.2$ (FCal in ATLAS)

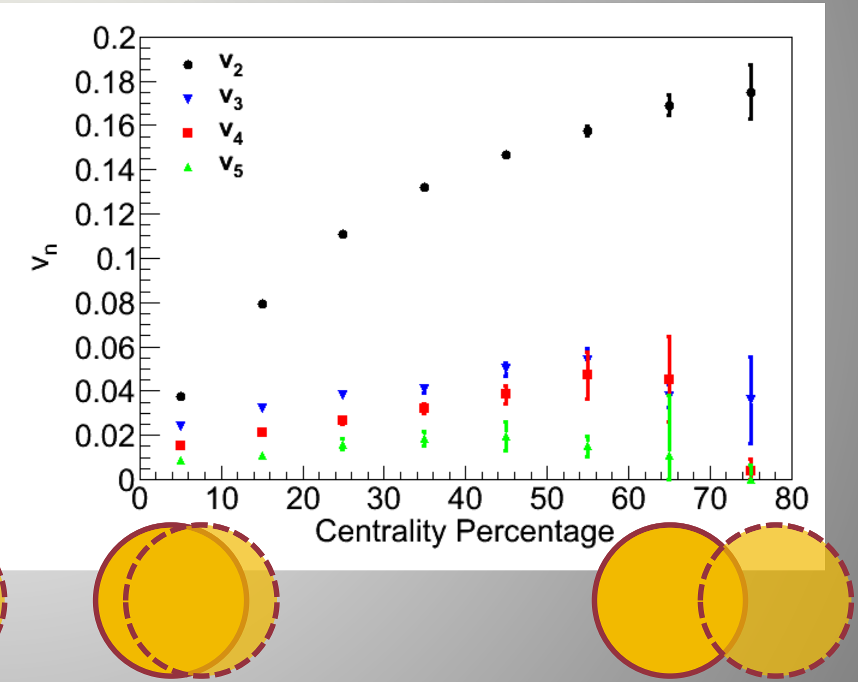
Subevent "P": charged, $3.2 < \eta < 4.8$ (FCal in ATLAS)

ATLAS, arXiv:1108.6018

v_n{EP}(centrality)

ε_n vs. centrality (input) v_n vs. centrality (output)





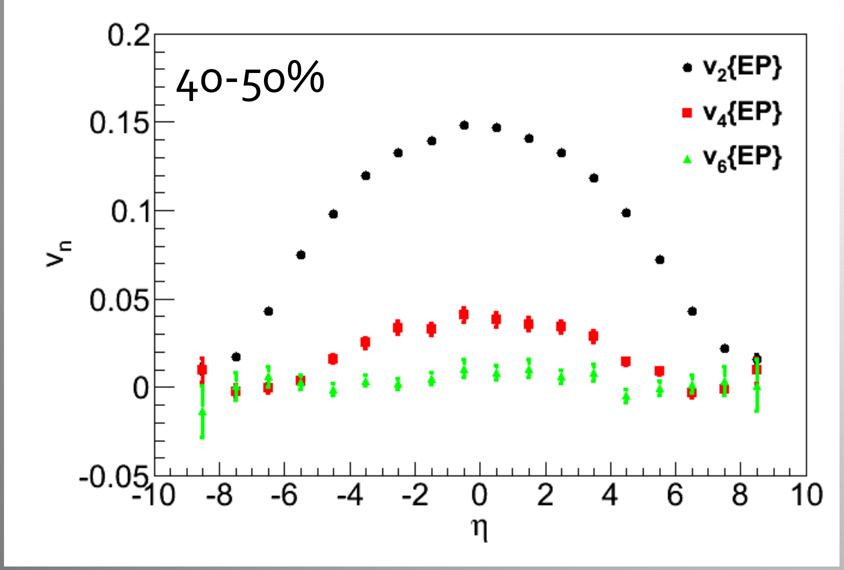
Response of the QGP to initial deformation

v_n roughly scales with ε_n

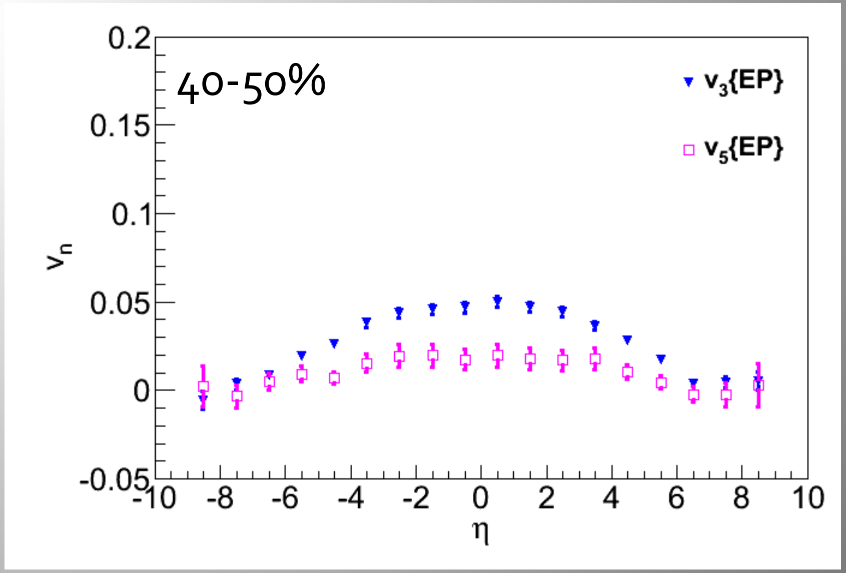
$V_n\{EP\}(\eta)$

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

Even Harmonics



Odd Harmonics

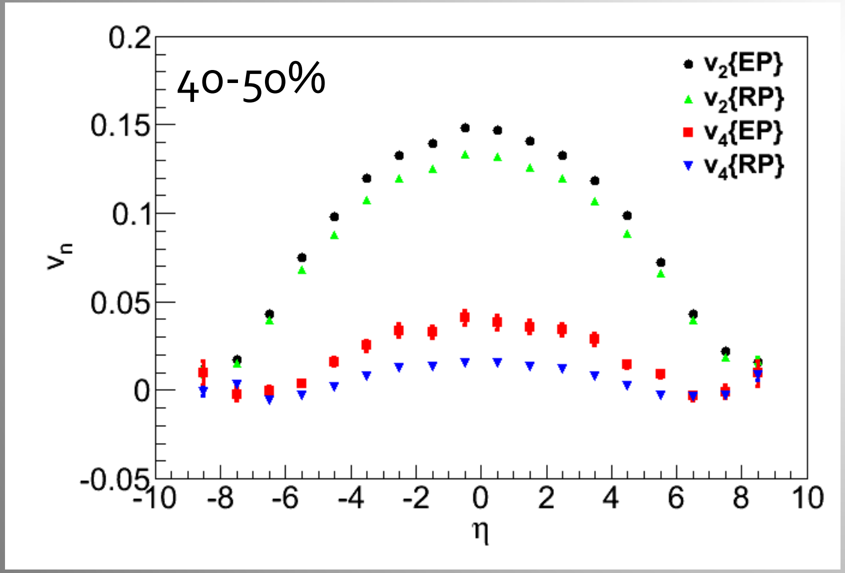


Not boost inv. ←→almost boost inv. for epsilon

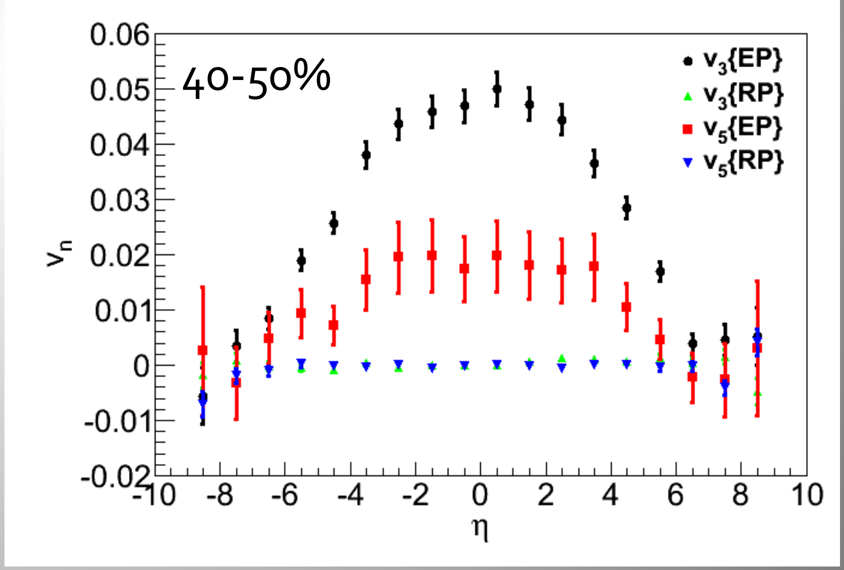
$v_n\{EP\}$ vs. $v_n\{RP\}$

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

Even Harmonics



Odd Harmonics

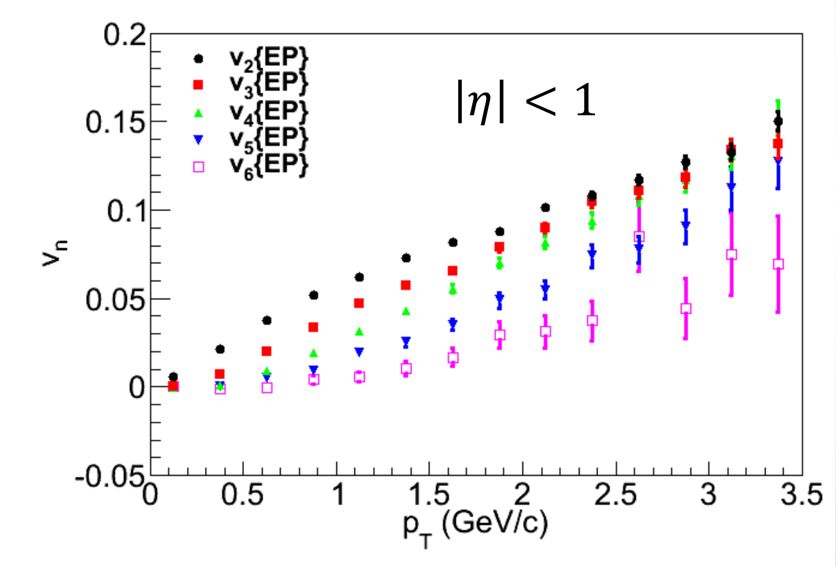


$v_{even}\{EP\}>v_{even}\{RP\}$ due to fluctuation

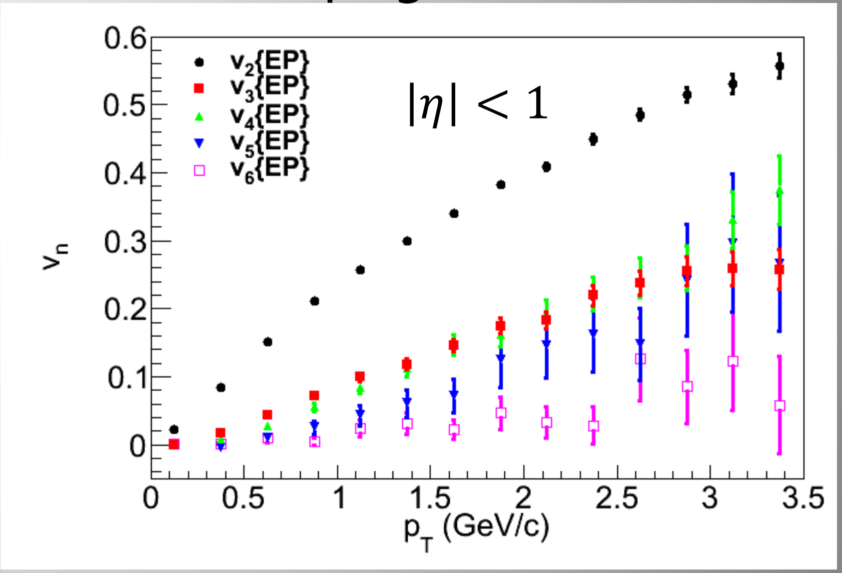
$v_{odd}\{RP\}$~0

$V_n\{EP\}(p_T)$

0-10%



40-50%



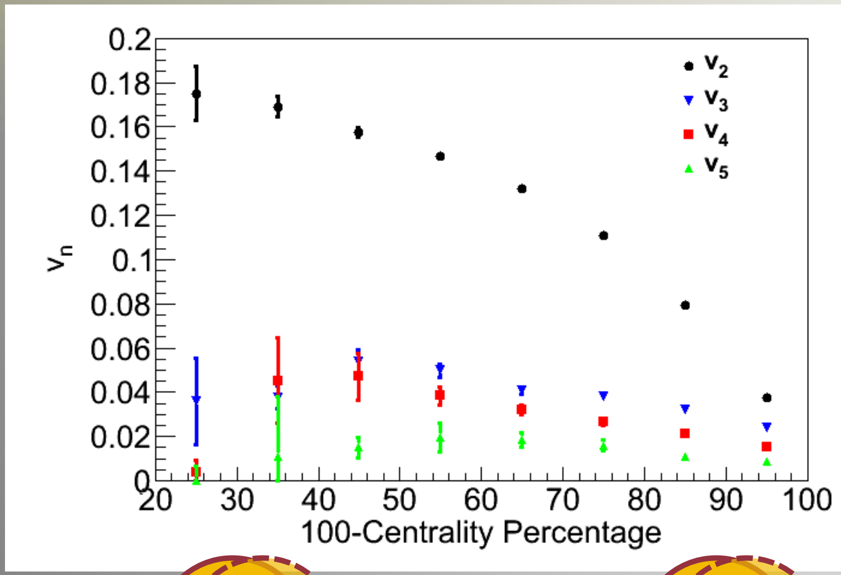
$v_2\{EP\} \approx v_3\{EP\}$

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

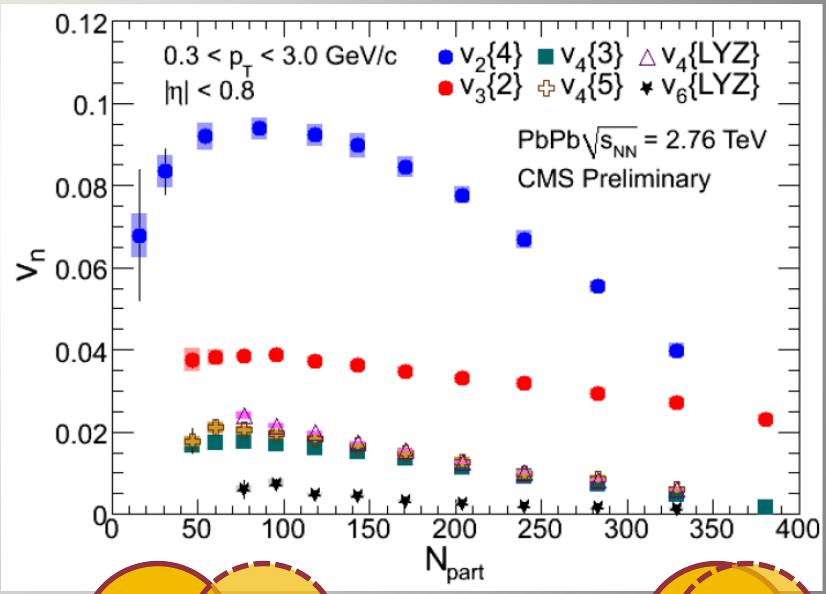
Note: $\varepsilon_2 > \varepsilon_3$

Comparison of v_n with Data

Theory



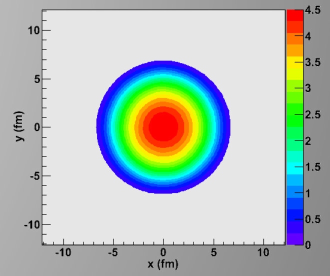
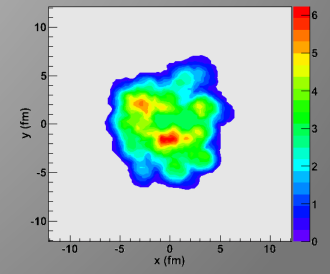
Experiment



Tendency similar to experimental data

Absolute value ←→ Viscosity

Impact of Finite Higher Harmonics

	coarse graining size	initial profile
• Only few people believed hydro description of the QGP (~ 1995)		
• Hydro at work to describe elliptic flow (~ 2001)	$d \lesssim 5$ fm	
• Hydro at work (?) to describe higher harmonics (~ 2010)	$d \lesssim 1$ fm	

Conclusion

<u>Physics of the quark gluon plasma</u>

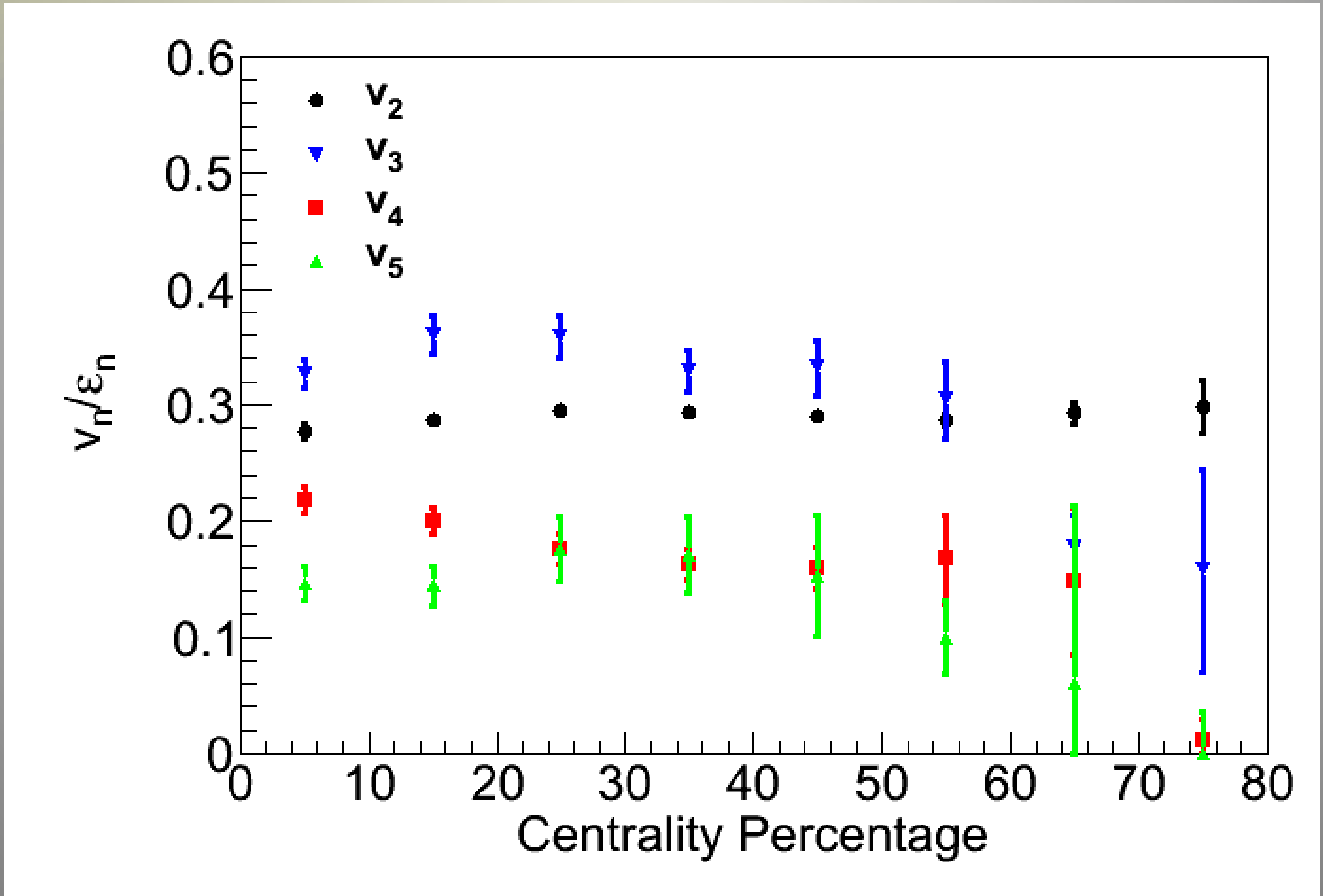
- Strong coupling nature
- Small viscosity

<u>Physics of relativistic heavy ion collisions</u>

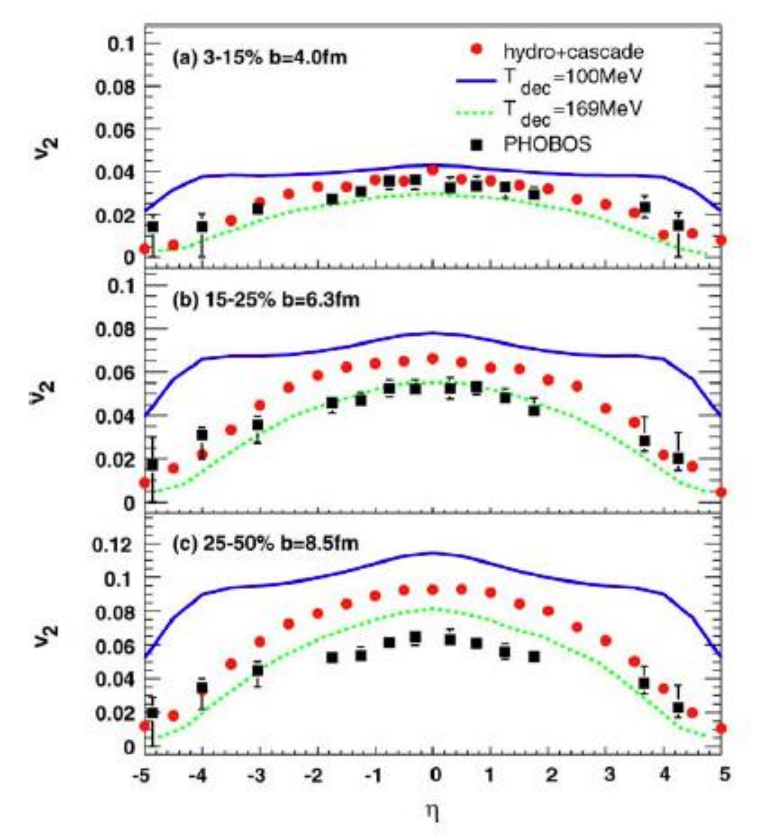
- Toward precision physics
  - 2^{nd} order harmonics → Higher order harmonics
  - Equilibration/coarse graining in a small system
  - Precise determination of transport coefficients

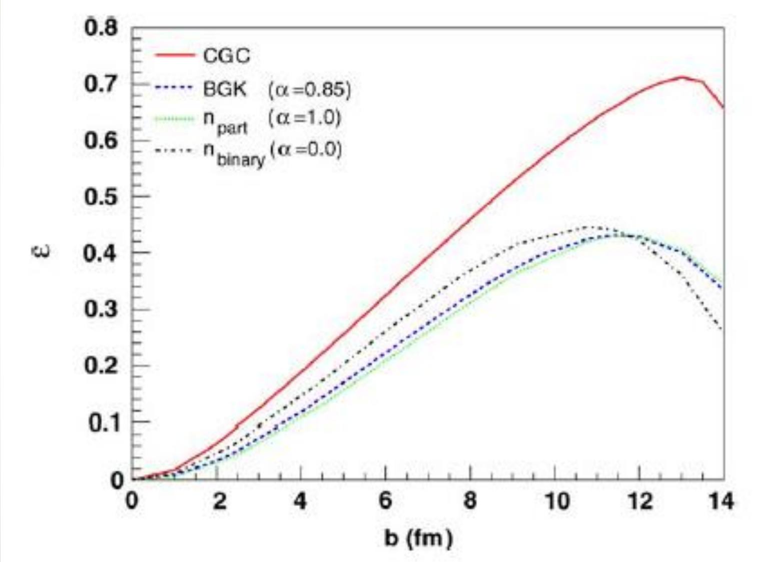
BACKUPS

Response to Deformation



CGC Initial Conditions





CGC and perfect fluid, are they compatible?

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