The Fluid Nature & Viscosity of the QGP

Huichao Song

Peking University

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08/05/2014

QGP-the most perfect fluid in the world?

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RHIC Scientists Serve Up "Perfect" Liquid

New state of matter more remarkable than predicted -- raising many new questions

April 18, 2005

TAMPA, FL -- The four detector groups conducting research at the Relativistic Heavy Ion Collider (RHIC) -- a giant atom "smasher" located at the U.S. Department of Energy's Brookhaven National Laboratory -- say they've created a new state of hot, dense matter out of the quarks and gluons that are the basic particles of atomic nuclei, but it is a state quite different and even more remarkable than had been predicted. In peer-reviewed papers summarizing the first three years of RHIC findings, the scientists say that instead of behaving like a gas of free quarks and gluons, as was expected, the matter created in RHIC's heavy ion collisions appears to be more like a *liquid*.

"Once again, the physics research sponsored by the Department of Energy is producing historic results," said Secretary of Energy Samuel Bodman, a trained chemical engineer. "The DOE is the principal federal funder of basic research in the physical sciences, including nuclear and high-energy physics. With today's announcement we see that investment paying off."

Secretary of Energy Samuel Bodman

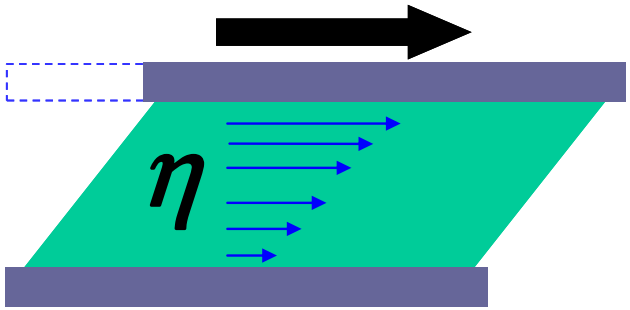
"The truly stunning finding at RHIC that the new state of matter created in the collisions of gold ions is more like a liquid than a gas gives us a profound insight into the earliest moments of the universe," said Dr. Raymond L. Orbach, Director of the DOE Office of Science.

Also of great interest to many following progress at RHIC is the emerging connection between the collider's results and calculations using the methods of string theory, an approach that attempts to explain

How perfect is the QGP fluid?

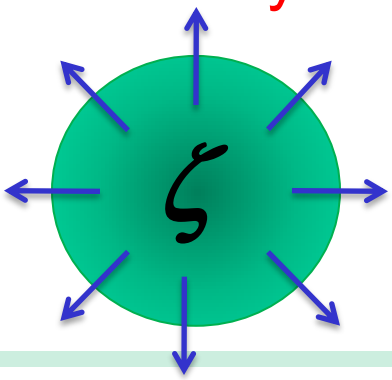
What is viscosity

Shear viscosity – measures the resistance to flow



act against the buildup of
flow anisotropy

Bulk viscosity – measures the resistance to expansion



act against the buildup of
radial flow

Heat conductivity – measures the ability of heat transfer

λ

Assume: $\lambda = 0, \quad n \approx 0$ (RHIC&LHC)

Hydrodynamics & its Hybrid Model

Viscous Hydrodynamics

$$\partial_\mu T^{\mu\nu}(x) = 0 \qquad T^{\mu\nu} = (e + p + \Pi)u^\mu u^\nu - (p + \Pi)g^{\mu\nu} + \pi^{\mu\nu}$$

Evolution equations for shear pressure tensor $\pi^{\mu\nu}$ and bulk pressure

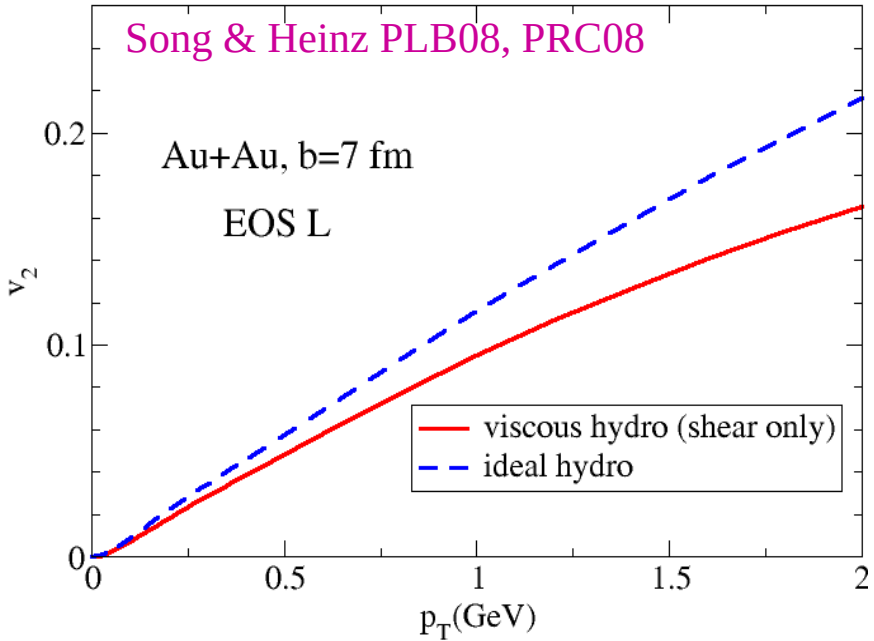
$$\tau_\pi \Delta^{\alpha\mu}\Delta^{\beta\nu}\dot{\pi}_{\alpha\beta} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \frac{1}{2}\pi^{\mu\nu}\frac{\eta T}{\tau_\pi}\partial_\lambda\left(\frac{\tau_\pi}{\eta T}u^\lambda\right)$$

$$\tau_\Pi \dot{\Pi} + \Pi = -\zeta(\partial\cdot u) - \frac{1}{2}\Pi\frac{\zeta T}{\tau_\Pi}\partial_\lambda\left(\frac{\tau_\Pi}{\zeta T}u^\lambda\right)$$

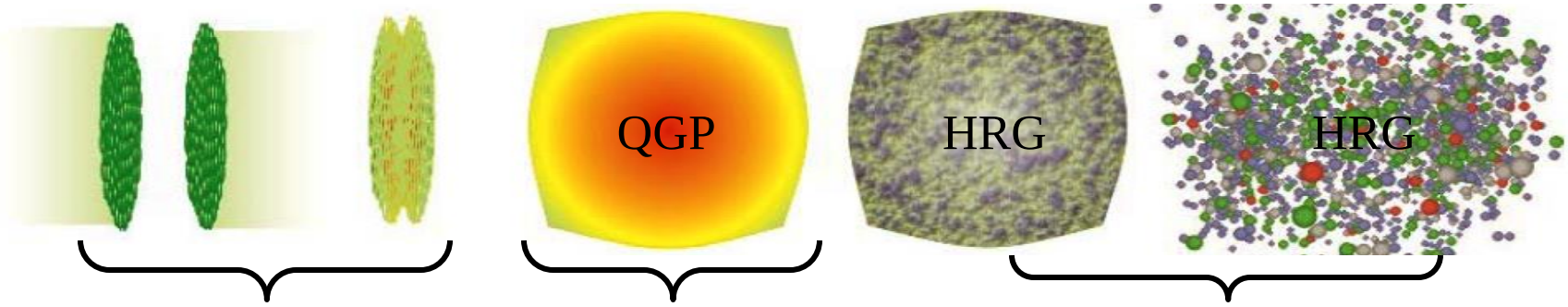
Assume **zero net baryon density & heat conductivity** at RHIC and the LHC

2+1-d: OSU, INT, Stony Brook, Pudue, Calcutta (2008), Crakow, Frankfurt(2010) … …

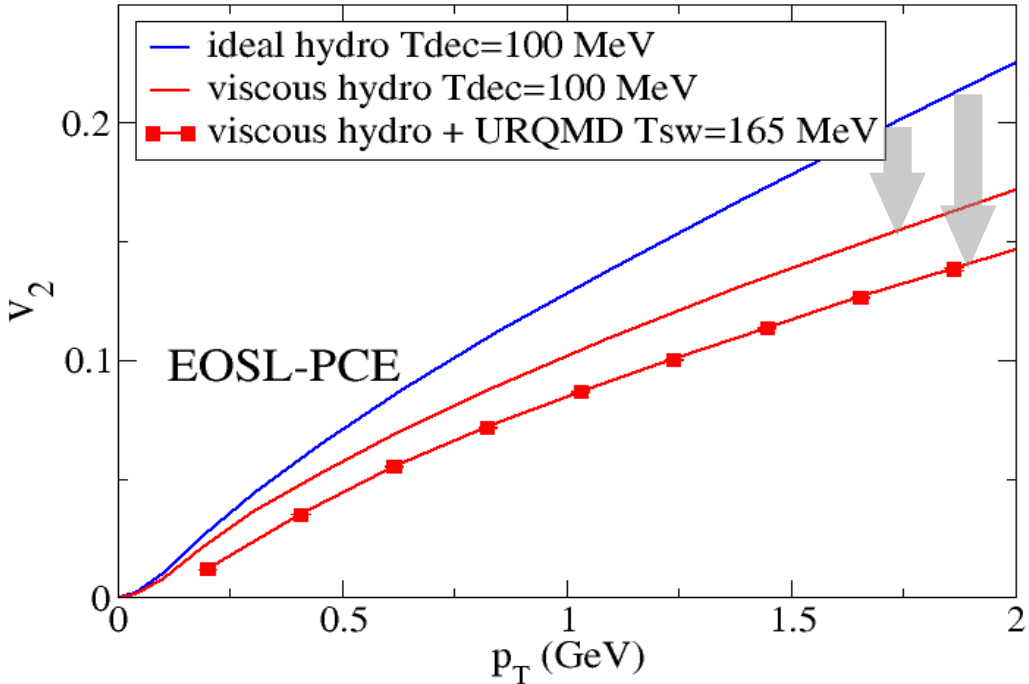
3+1-d: Mcgill(2011), MSU(2012), Crakow(2012), Nagoya(2013)… …



Viscous Hydro + Hadron Cascade Hybrid Model



Initial conditions **viscous hydro** **hadron cascade**



ideal hydro (QGP & HRG)

viscous hydro (QGP & HRG)

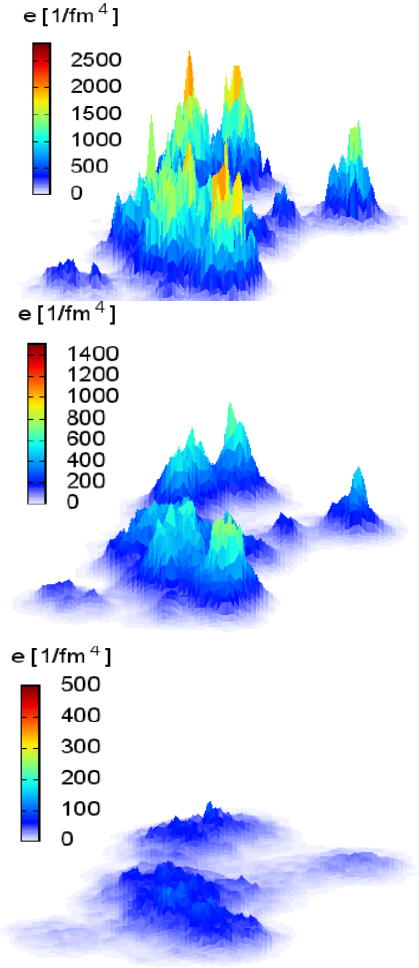
viscous hydro (QGP) + URQMD (HRG)

H. Song, S. Bass, U. Heinz, PRC2011

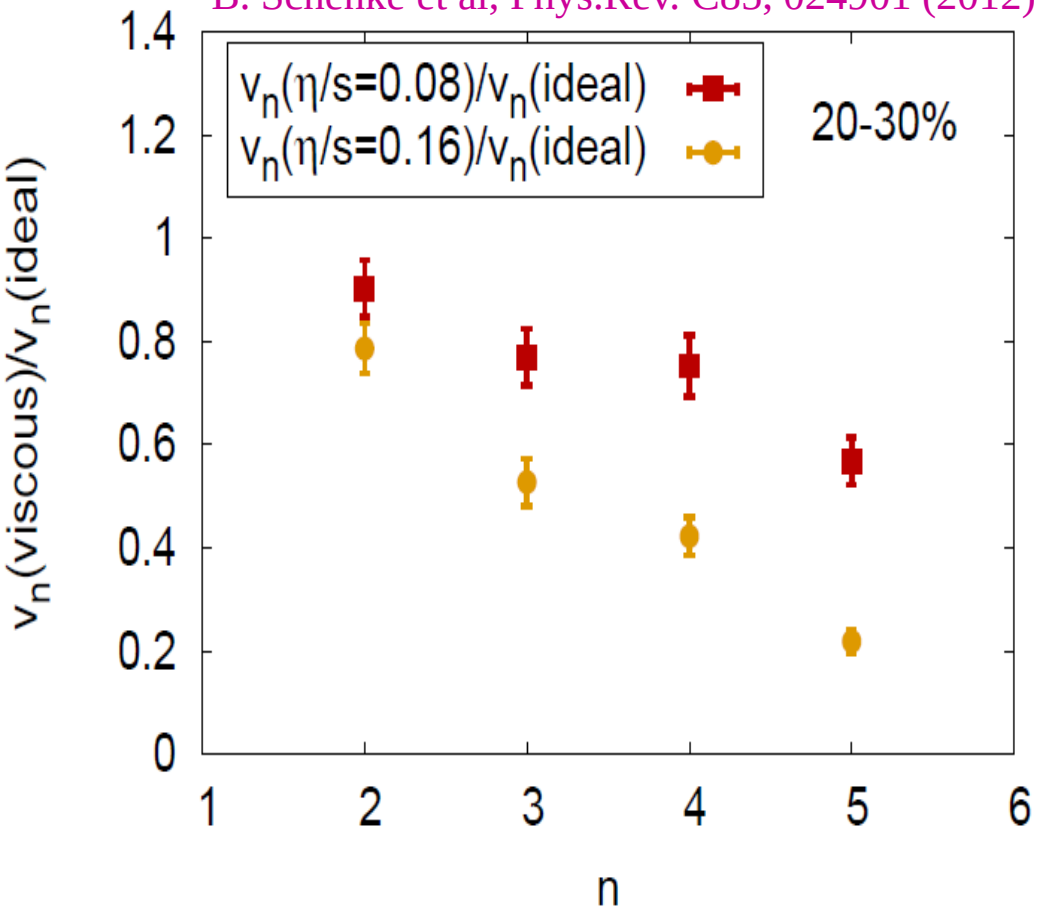
Event-by-event hydrodynamics

Single shot simulations: smoothed initial conditions (before 2010)

E-b-E **simulations**: fluctuating initial conditions (since 2010)



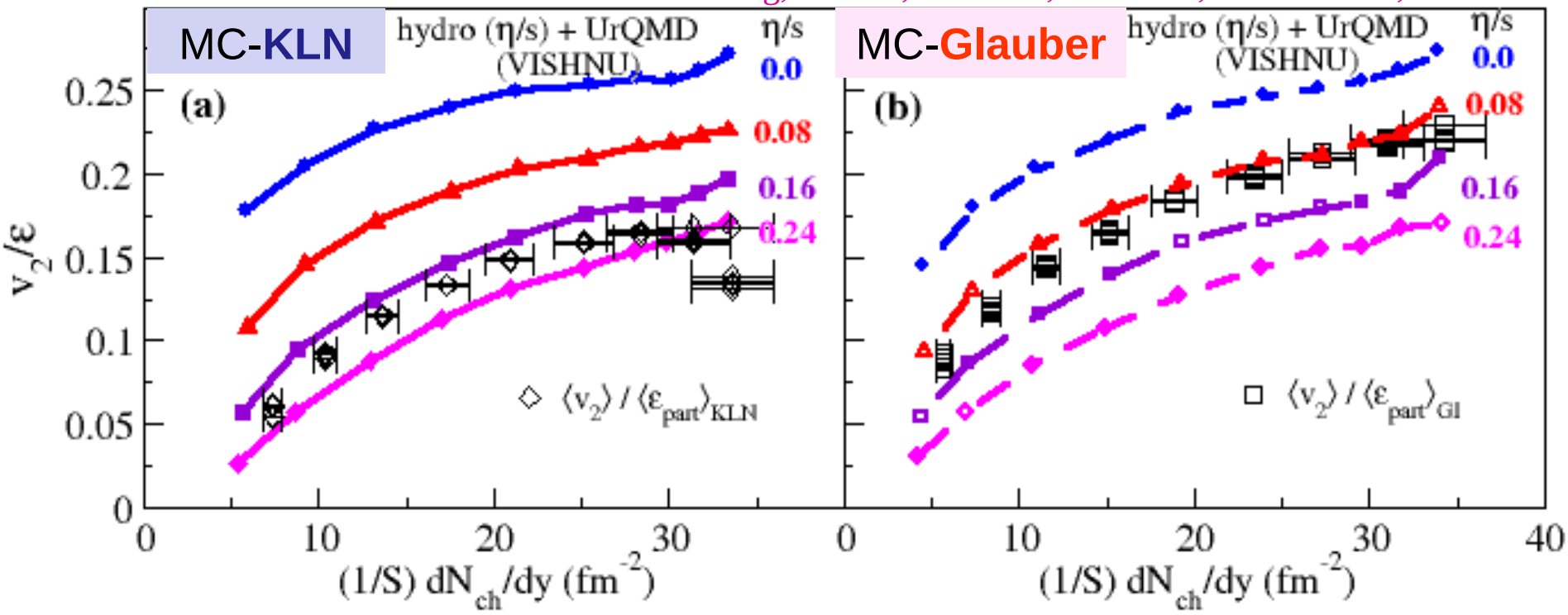
B. Schenke et al, Phys.Rev. C85, 024901 (2012)



Extracting QGP viscosity from elliptic flow data – VISHNU results

VISHNU hybrid model & QGP viscosity (2011)

H. Song, S. Bass, U. Heinz, T. Hirano, and C. Shen, PRL2011



$$1\times(1/4\pi) \le (\eta/s)_{QGP} \le 2.5\times(1/4\pi)$$

-Main uncertainties come from initial conditions

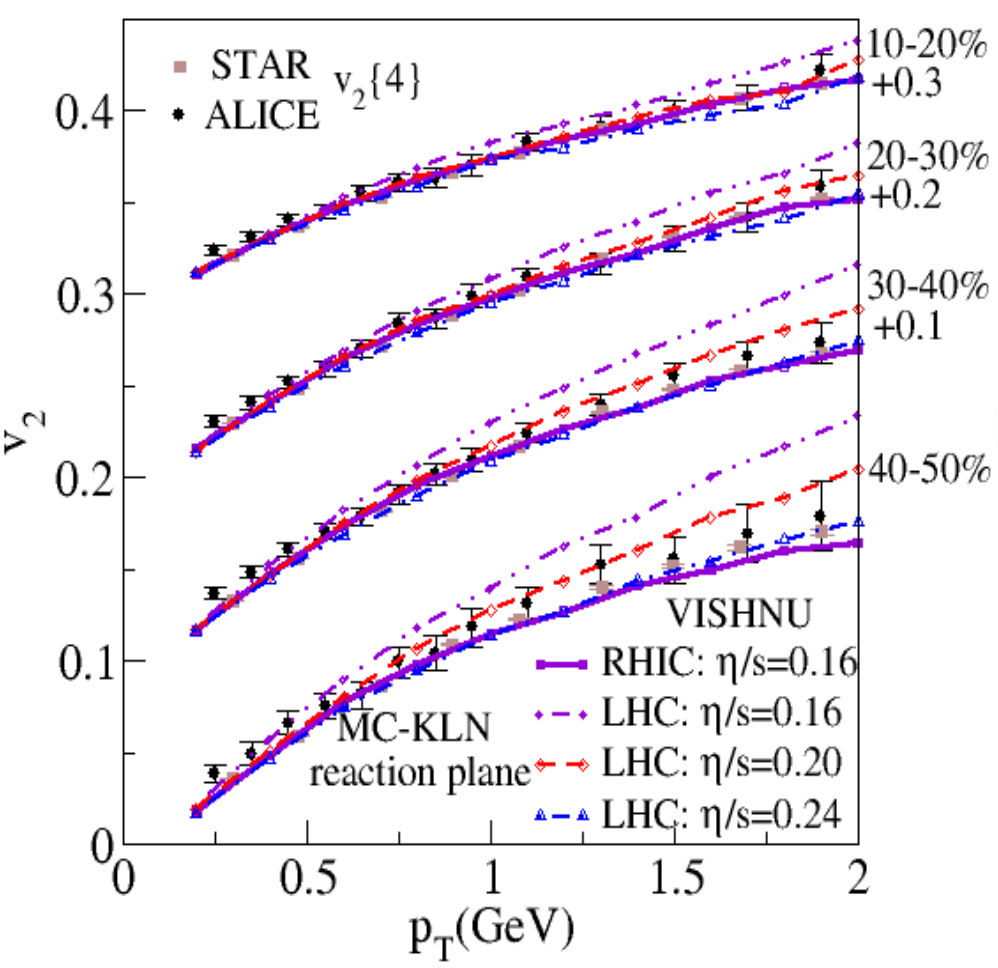
-Other uncertainties (much smaller)

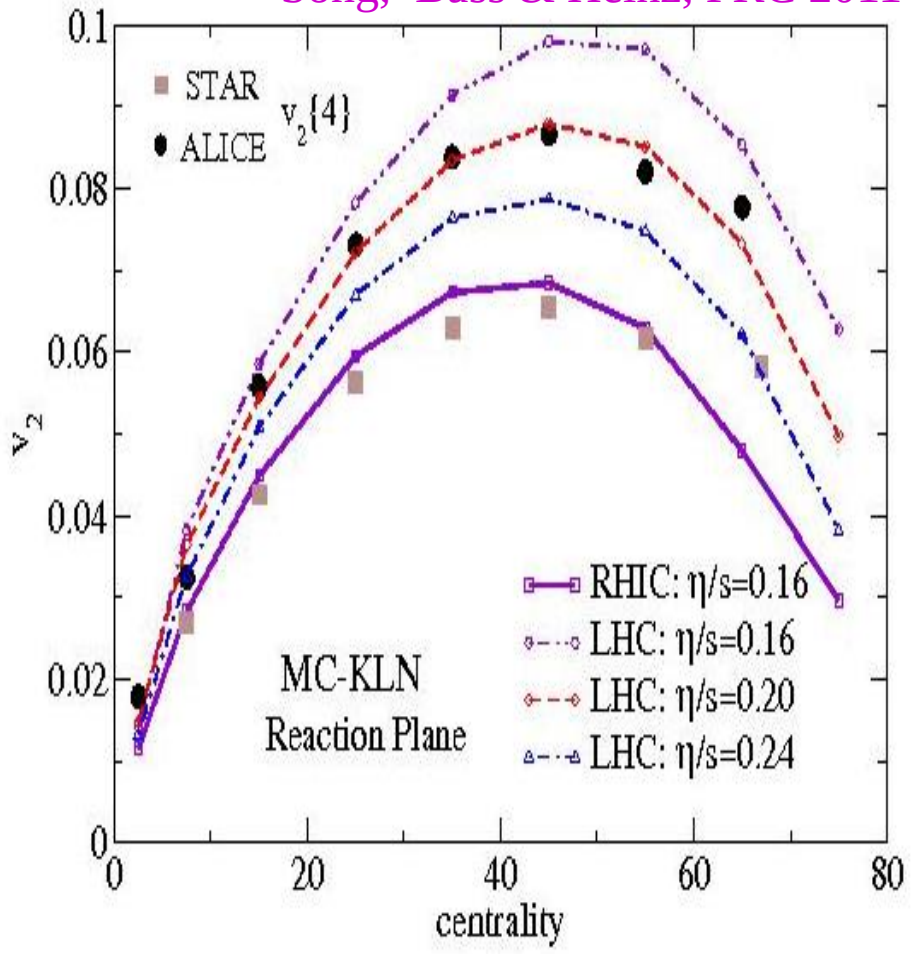
-Initial flow, bulk viscosity, single shot vs. e-b-e calculations

(each of them shift V_2 by a few percent, partial cancellation among them)

V_2 and QGP viscosity at the LHC

Song, Bass & Heinz, PRC 2011



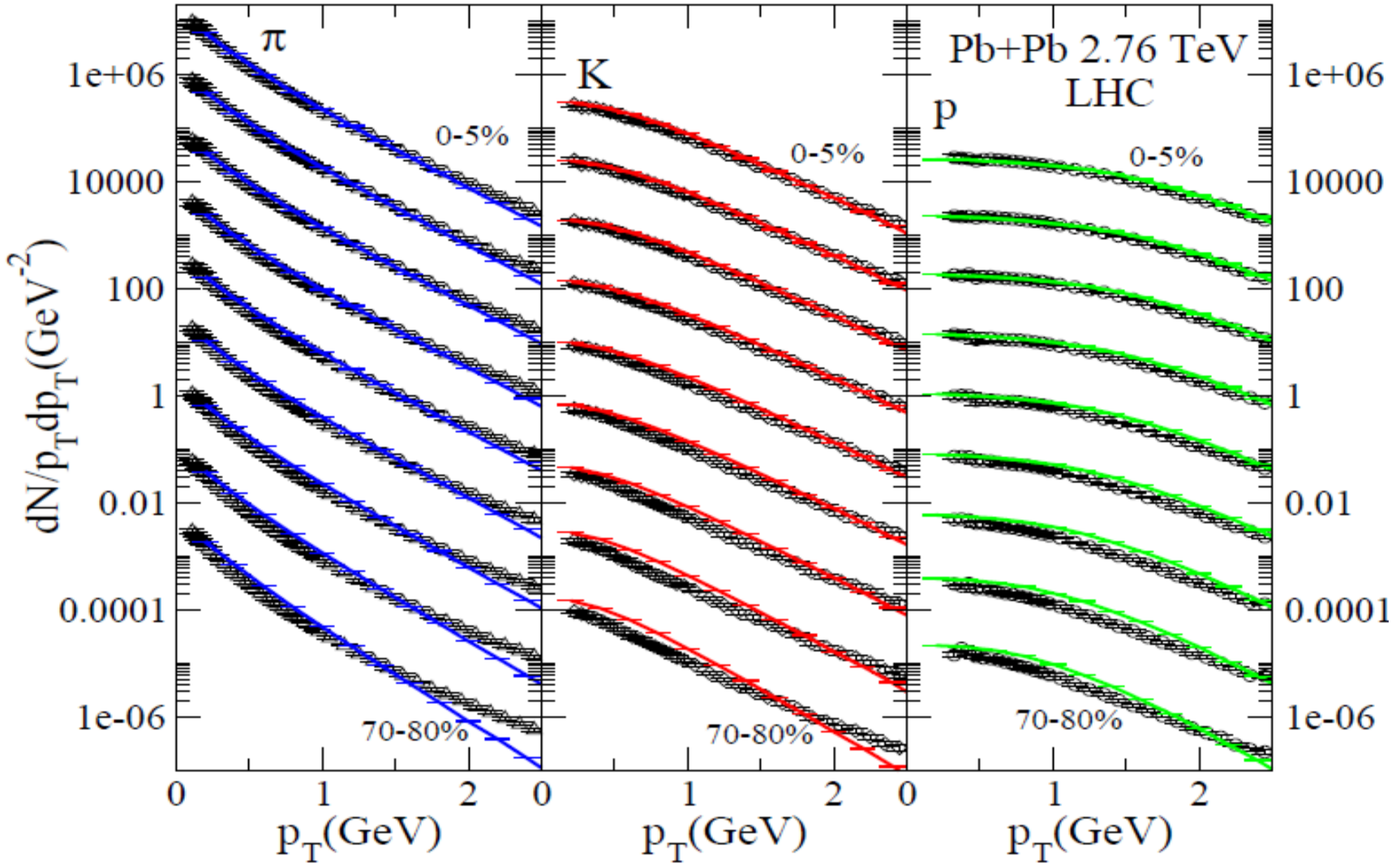


The average QGP viscosity is slightly larger at the LHC

Please also refer to Gale, Jeon ,Schenke, Tribedy &Venugopalan, PRL2013

LHC: spectra for identified hadrons

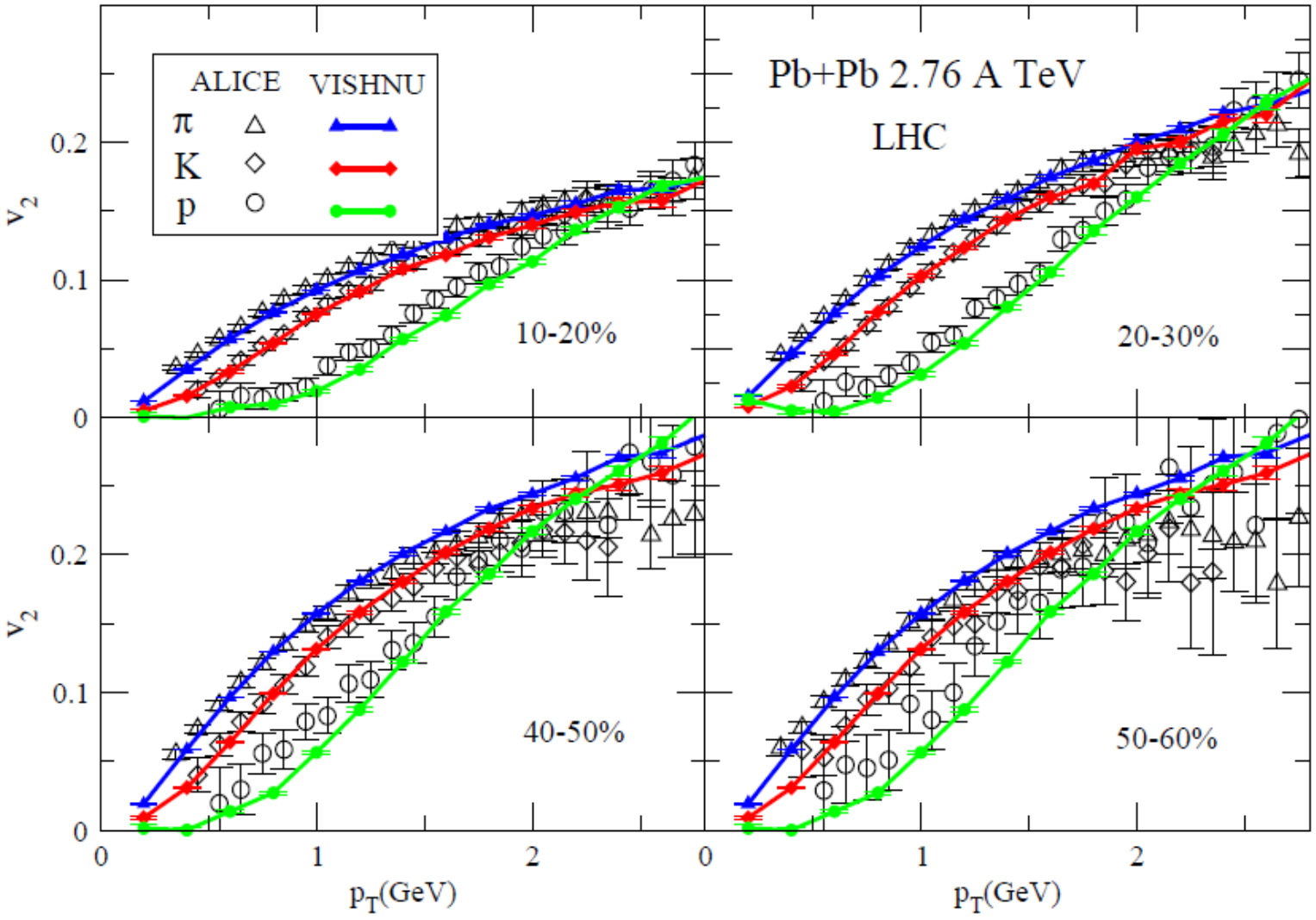
H. Song, S. Bass, U. Heinz, PRC2014



-a nice fit for pions, kaons and proton spectra

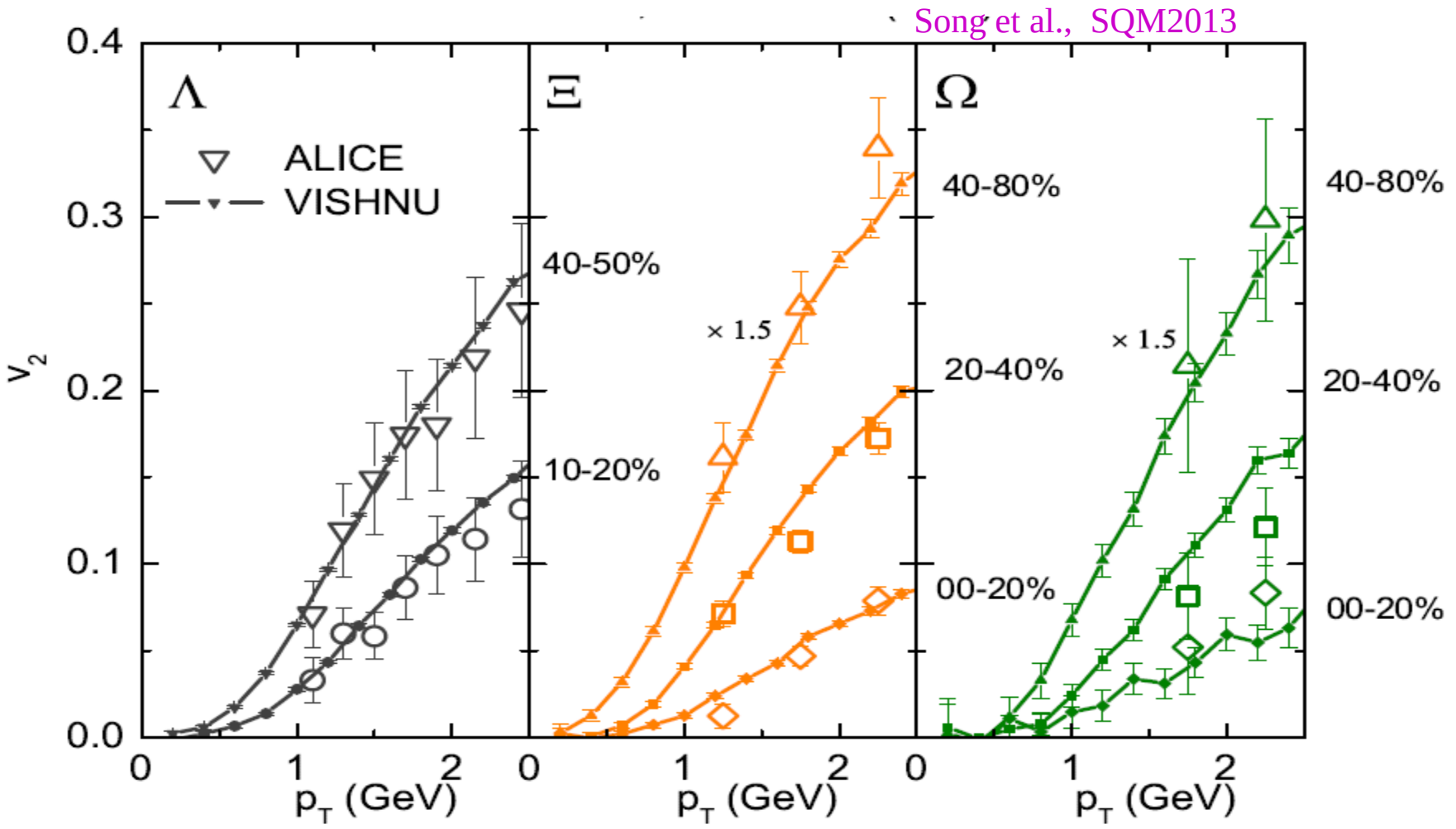
LHC: $V_2(p_T)$ for identified hadrons

H. Song, S. Bass, U. Heinz, PRC2014



A very nice fit of $V_2(P_T)$ for all centrality bins at LHC from VISHNU hybrid model

v_2 of Strange & Multi-strange Hadrons

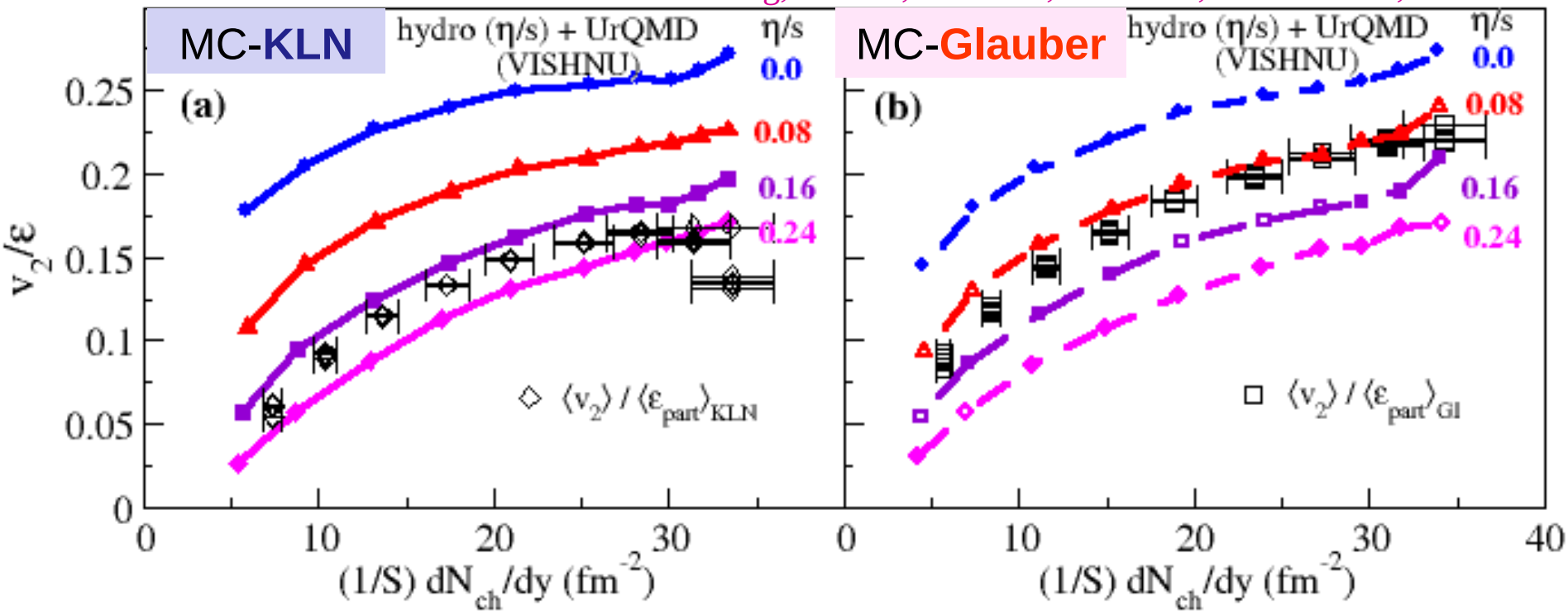


-Nice descriptions of Lambda, Xi and Omega v_2 at various centralities

Initial State Fluctuations, Final State Correlations & the QGP Viscosity

Uncertainties from Initial Conditions

H. Song, S. Bass, U. Heinz, T. Hirano, and C. Shen, PRL2011



$$1\times(1/4\pi) \le (\eta/s)_{QGP} \le 2.5\times(1/4\pi)$$

Main uncertainties come from initial conditions

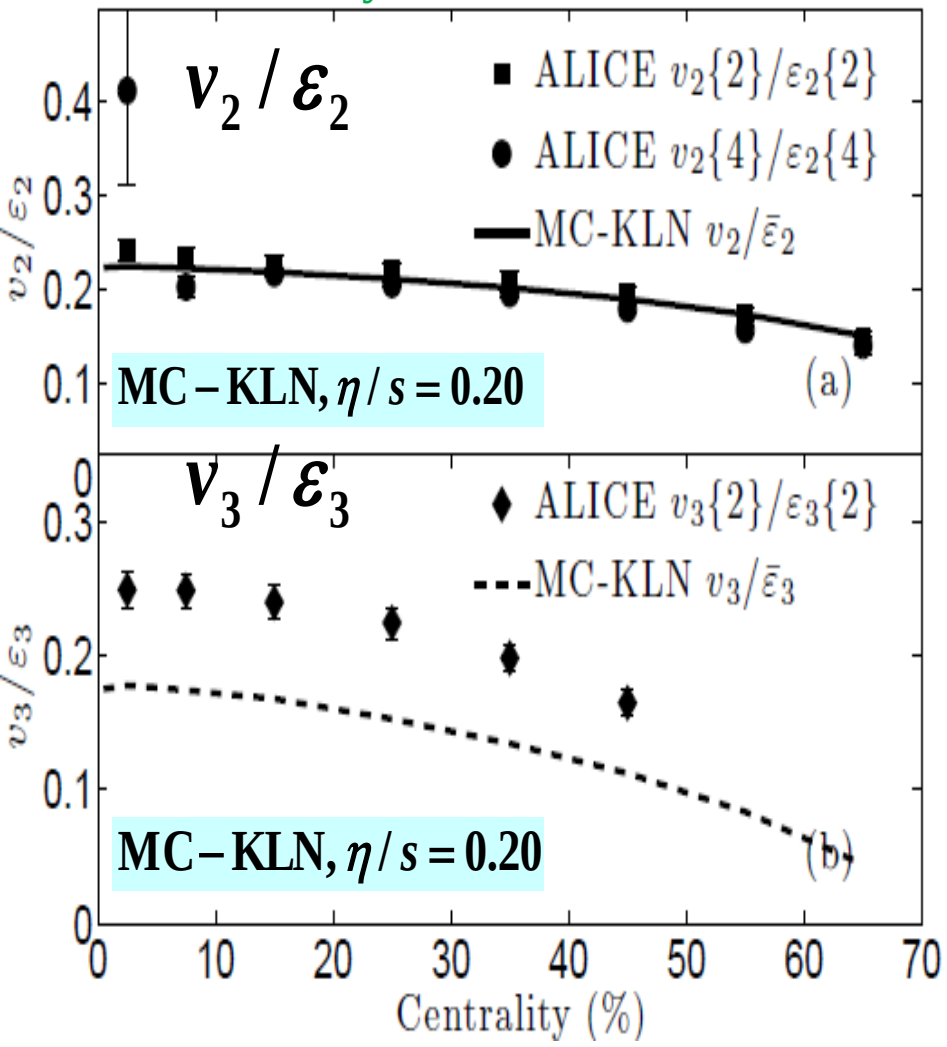
MC-KLN, larger ε_2 ⟶ HIGHER value of QGP viscosity

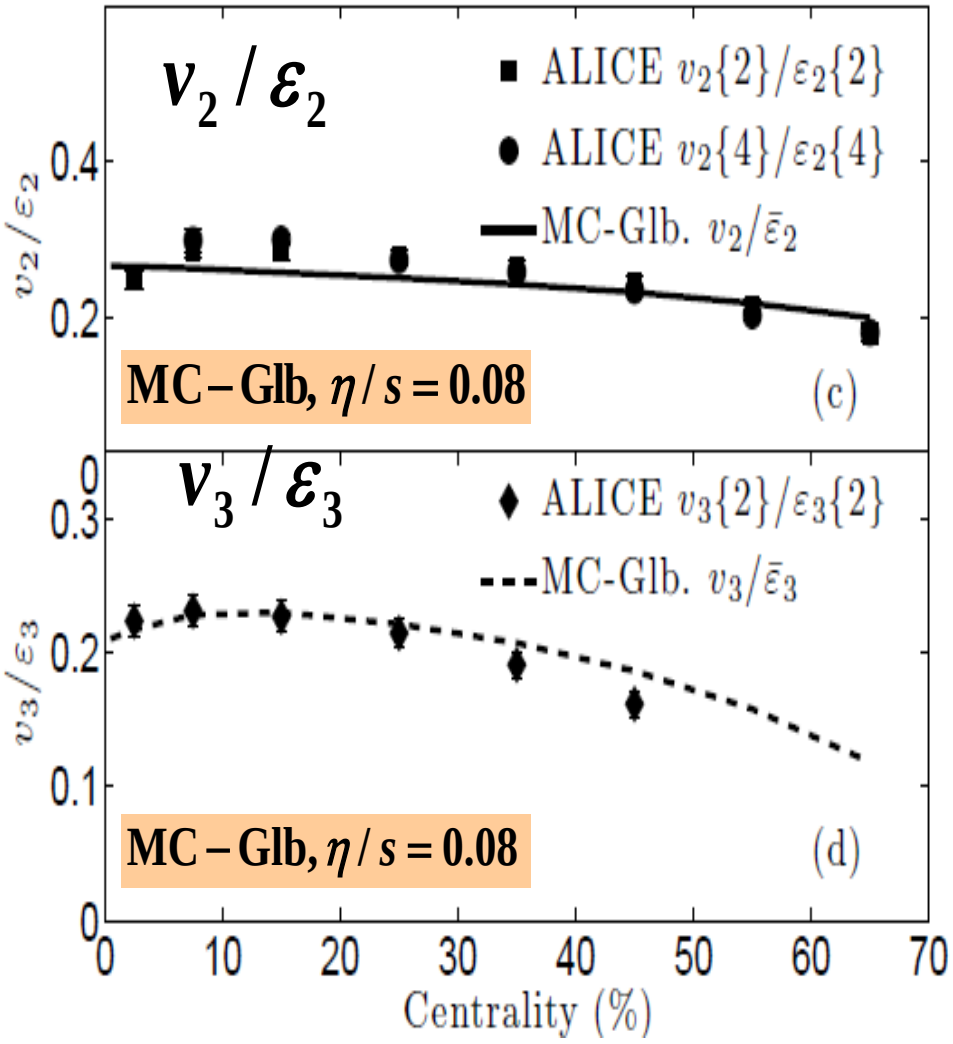
MC-Glauber, smaller ε_2 ⟶ LOWER value of QGP viscosity

MC-KLN & MC-Glauber initializations & V_3

Pure viscous hydro simulations :

Qiu, Shen & Heinz, PLB2012





V_3 prefer lower value of QGP viscosity

Initialization & Pre-equilibrium: Updates after 2011

-fluctuations of nucleon positions: **MC-Glauber, MC-KLN**

-fluctuations of color charges (in the framework of CGC):

IP-Glasma: B. Schenke et al., Phys.Rev. C85, 024901 (2012).

Correlated Fluctuation: B. Muller & A. Schafer, Phys.Rev. D85,114030 (2012).

-fluctuations of local gluon numbers (in the famework of MC-KLN):

Multiplicity fluctuations: A. Dumitru and Y. Nara, Phys. Rev. C 85, 034907 (2012).

-Pre-equilibriums:

URQMD initialization: H.Petersen & M. Bleicher, Phys. Rev. C81, 044906, (2010).

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EPOS/NEXUS initialization: K. Werner et al., Phys. Rev. C83:044915, (2011).

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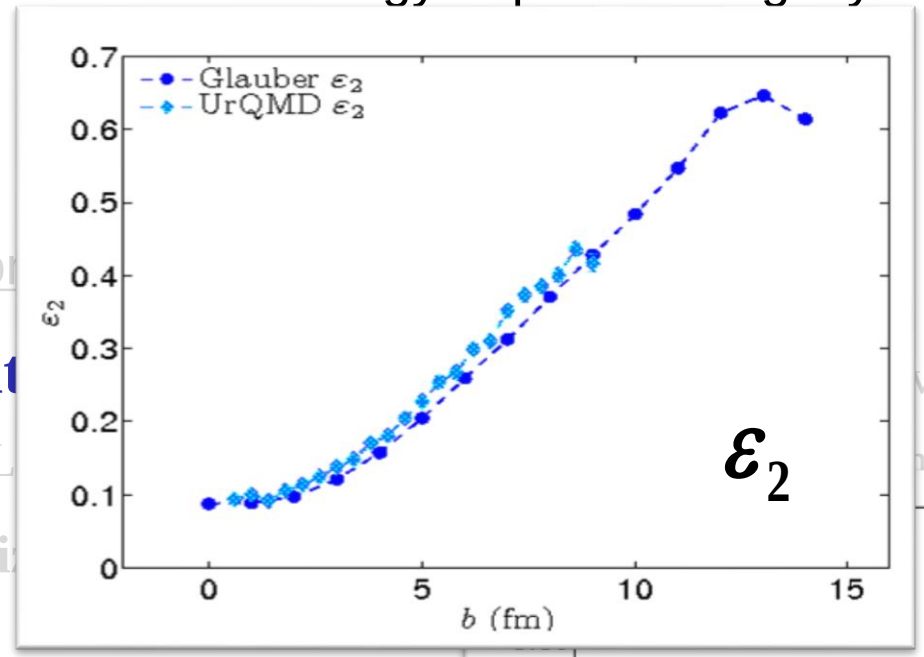
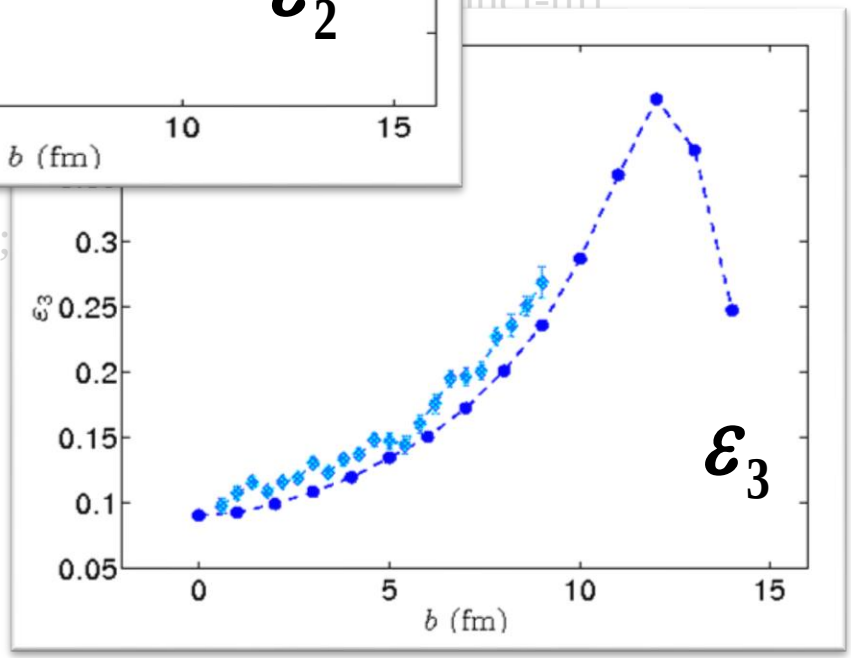
Fluctuations in energy deposition slightly increase $\varepsilon_2, \varepsilon_3$





Petersen & Qiu, unpublished notes; please also refer to Phys.Rev. C82 041901 (2010)

-early flow & fluctuation

URQMD initializat

v. C81,

044906 2010.

AMPT initialization: L

nucl-th]

EPOS/NEXUS initiali

IP-Glasma: B. Schenke, et.al, arXiv:1202.6646;

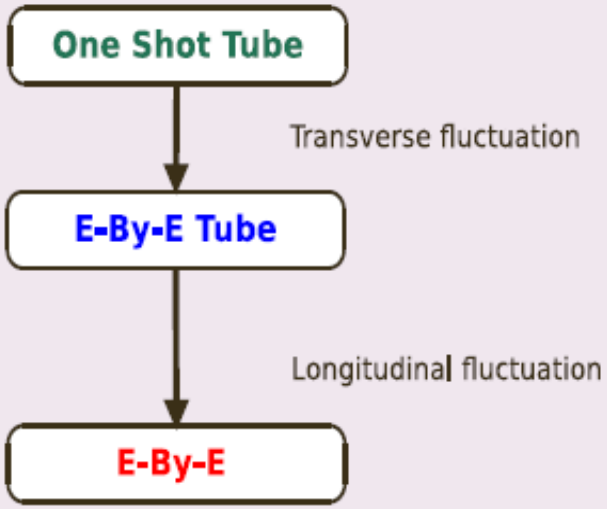
Early longitudinal flow fluctuations reduce v_2

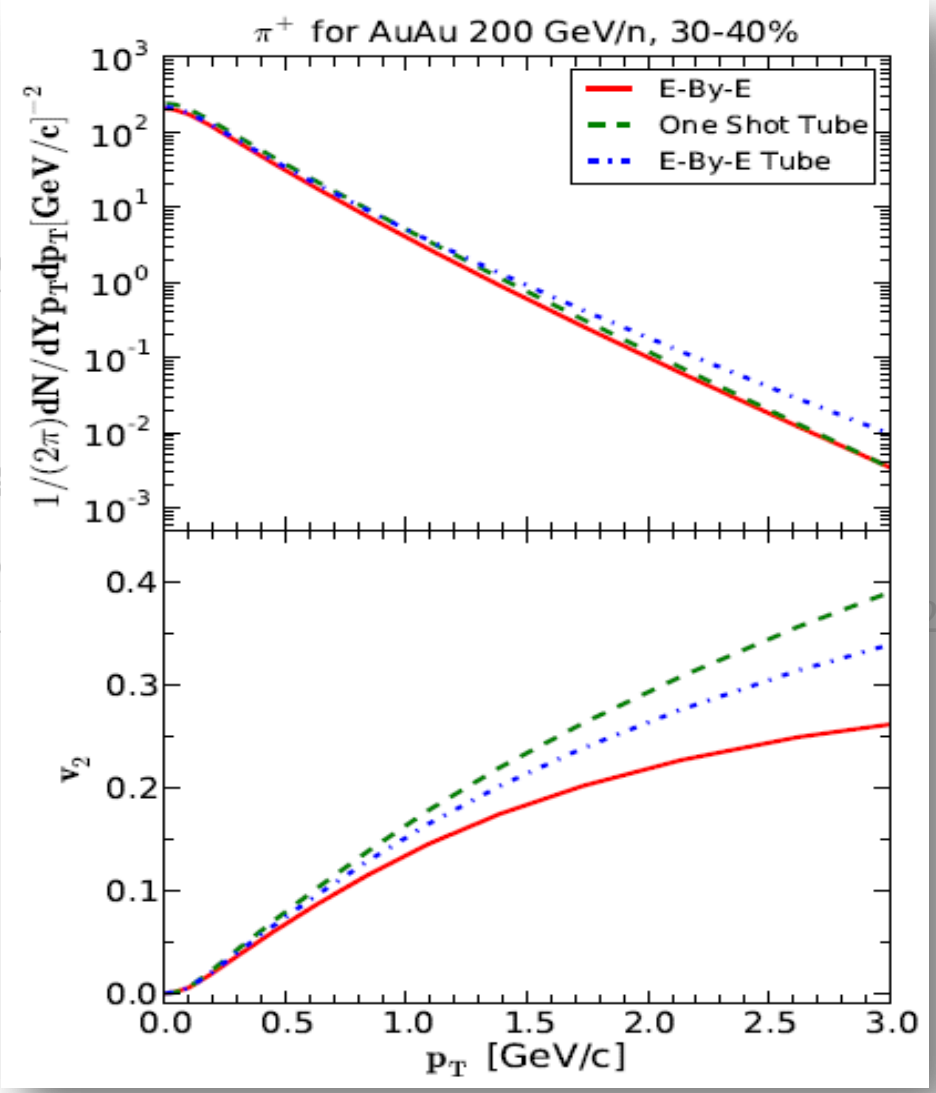
L. Pang, Q.Wang & X.Wang, PRC2012

-early flow & fluctuations from dy

URQMD initialization: H.Petersen

AMPT initialization: L. Pan





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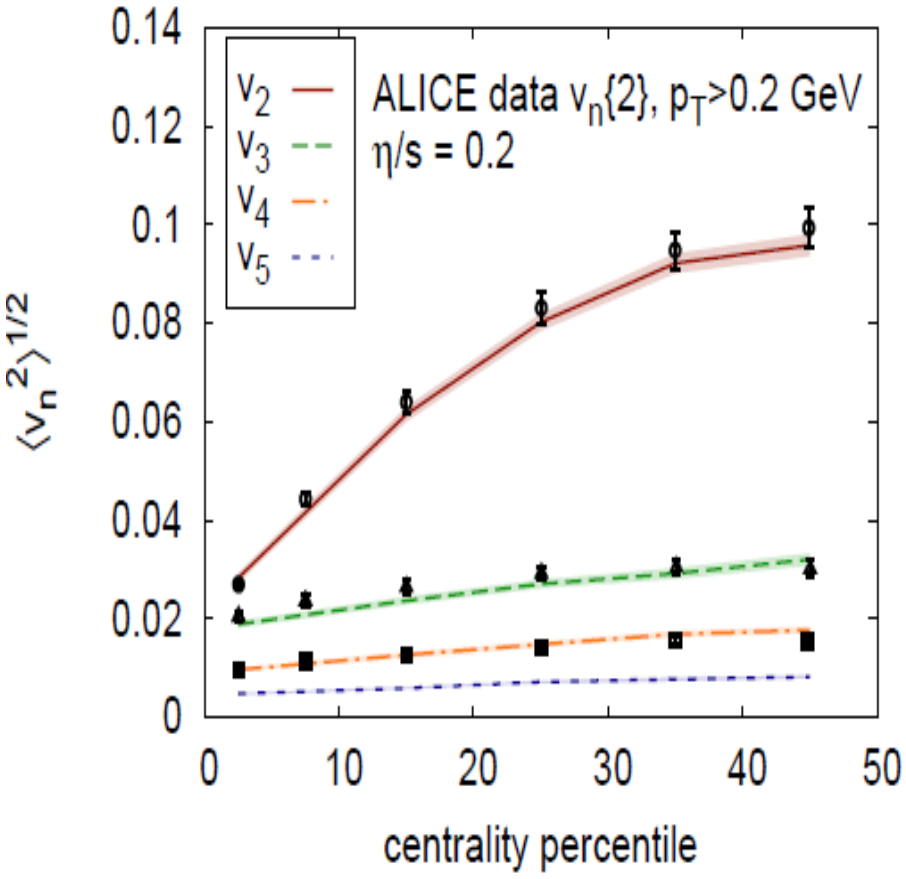
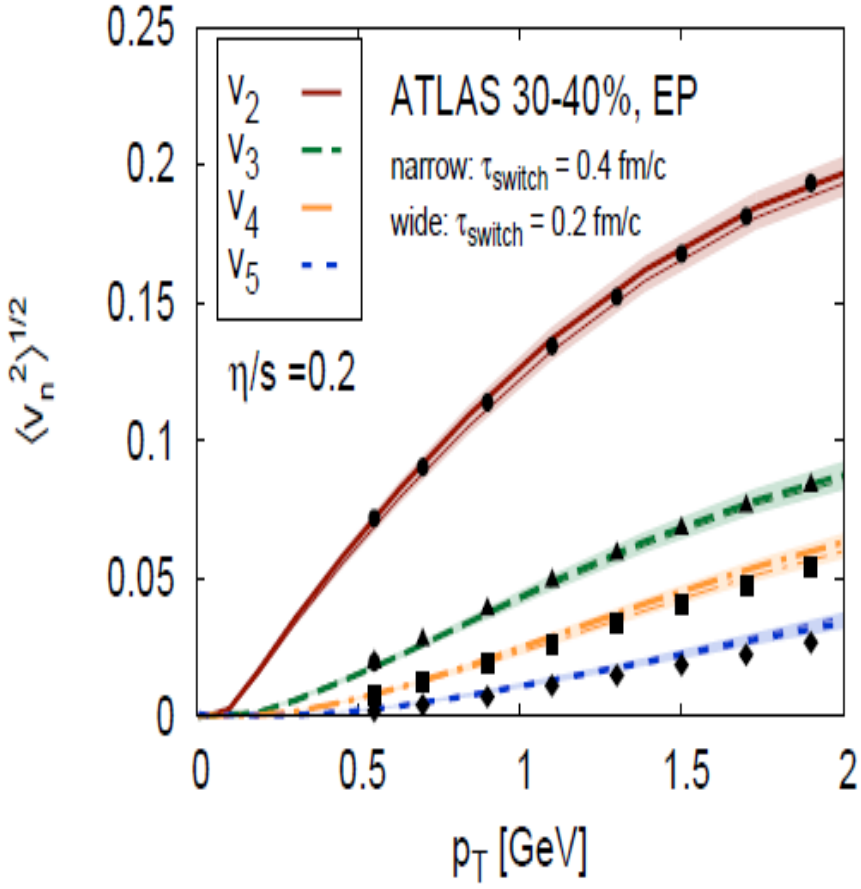
. . . .

Many of these initial conditions and pre-equilibrium dynamics have not been fully explored

The Success of IP-Glasma + MUSIC

Gale, Jeon ,Schenke, Tribedy &Venugopalan PRL2013

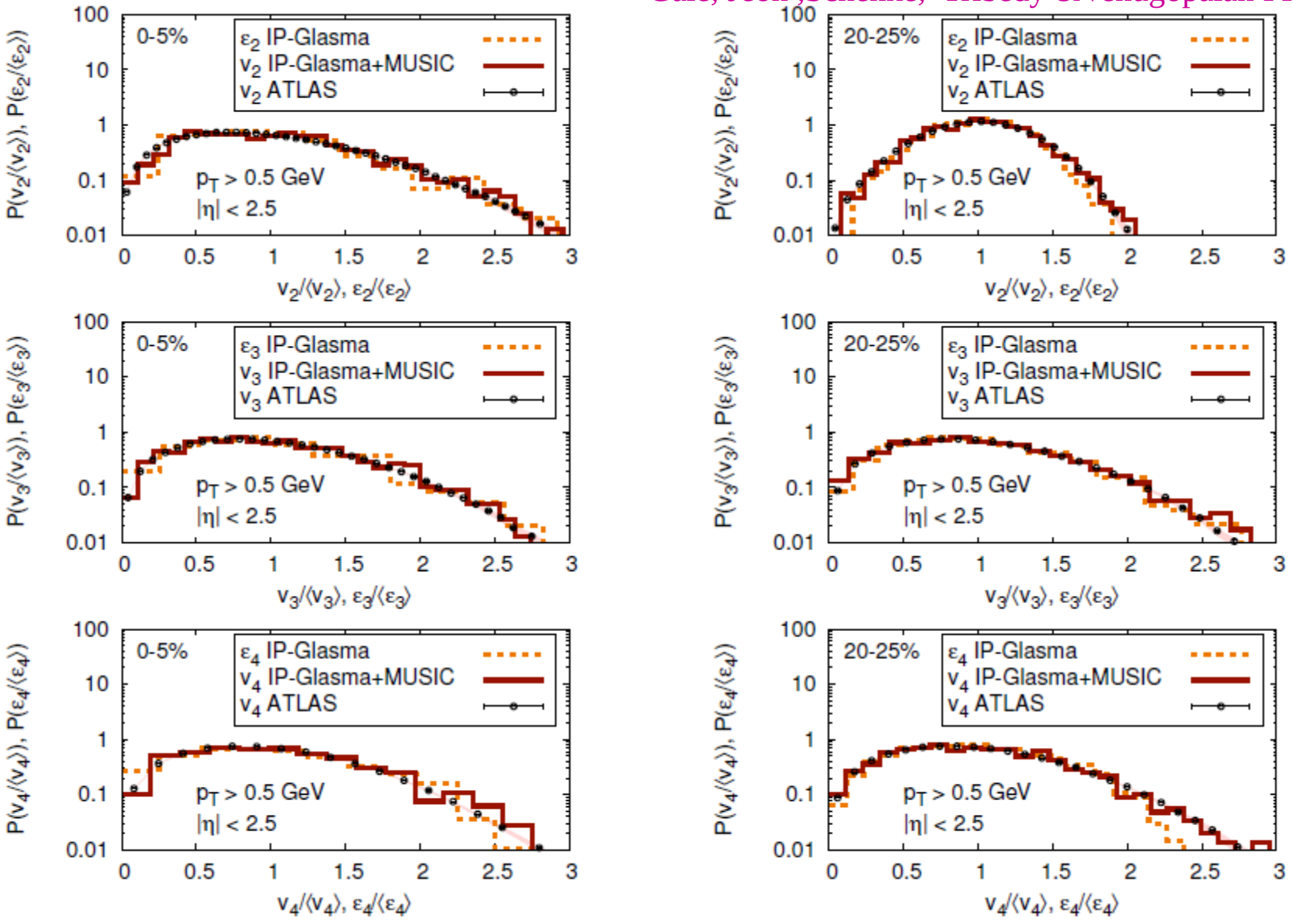




-IP–Glasma: sub-nucleonic color fluctuations + CYM dynamics

-nice descriptions of integrated and differential V_n

Gale, Jeon ,Schenke, Tribedy &Venugopalan PRL2013

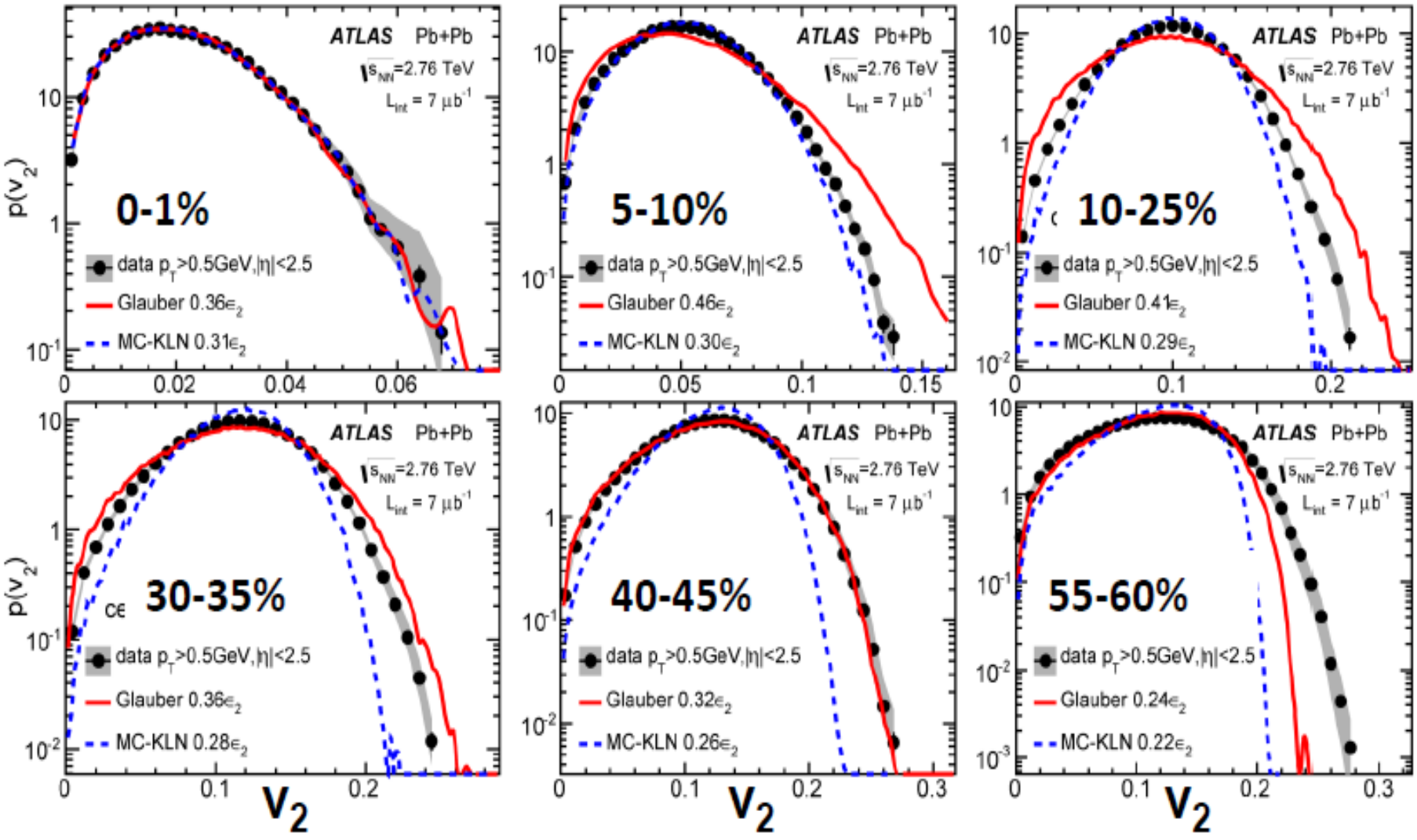


-In hydrodynamics, P(V_n) follows P($\boldsymbol{\varepsilon_n}$)

-A nice description of P(V_n) with IP-Glasma initialization

ε_n & V_n distributions (MC-Glauber vs. MC-KLN)

G. Aad et al. [ATLAS Collaboration], JHEP 1311, 183 (2013)

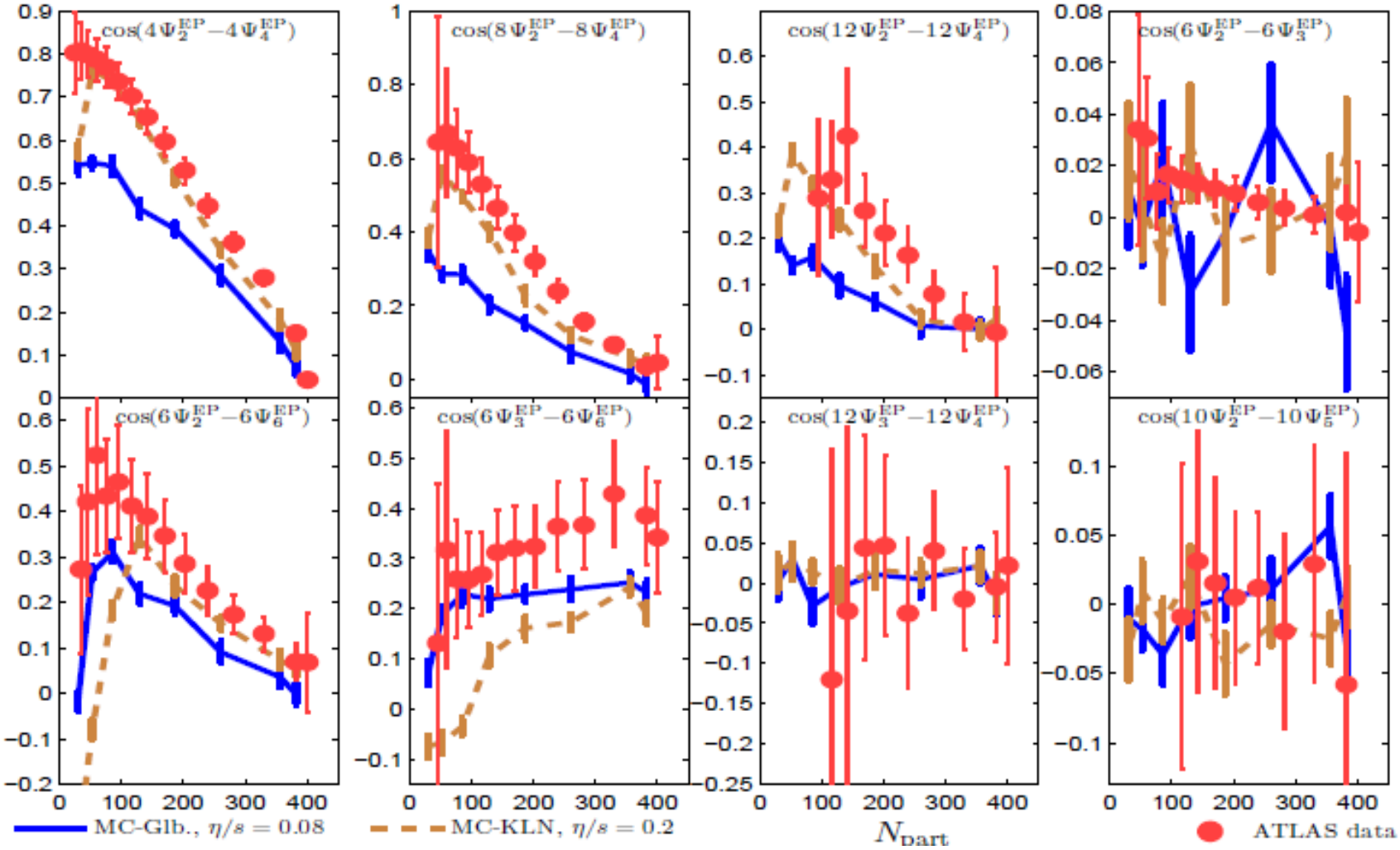


-Neither MC-Glauber nor MC-KLN works for all centralities

More flow observables

Higher Order Event Plane Correlations

Qiu & Heinz, PLB(2012)



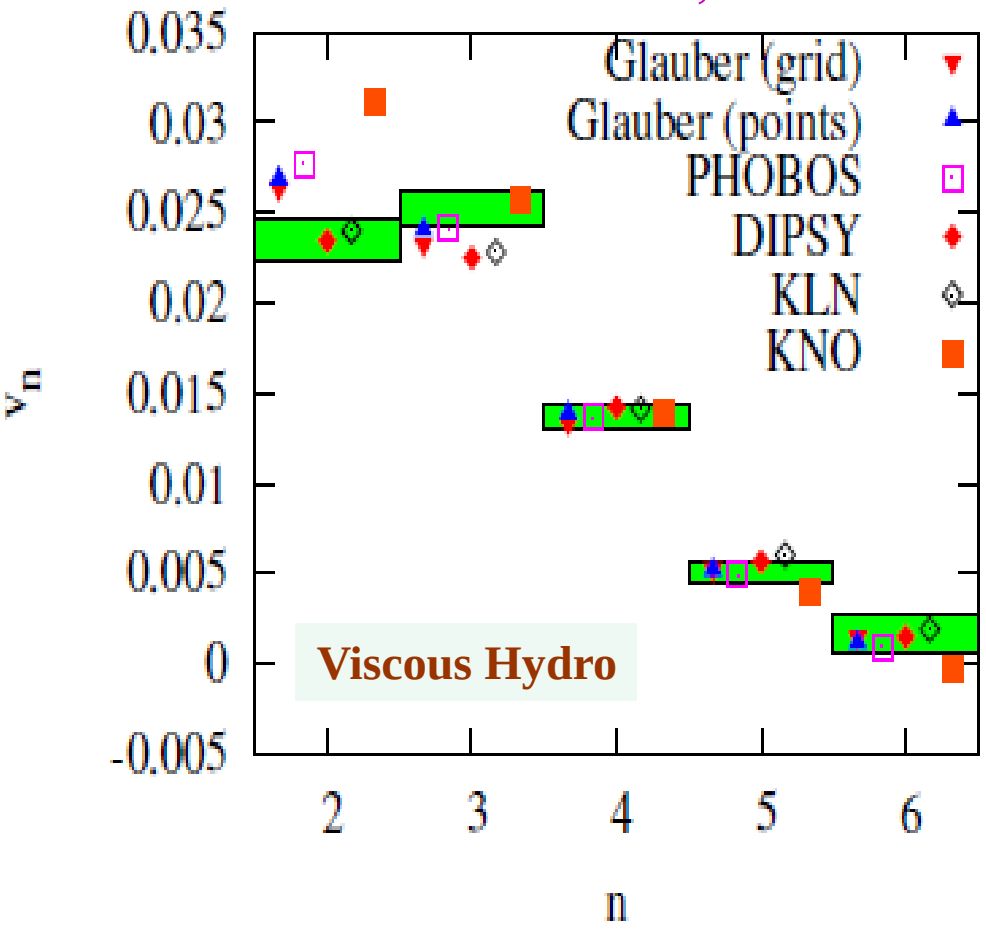
EXP. data:[ATLAS Collaboration], CERN preprint ATLAS-CONF-2012-049

Pure e-b-e viscous hydro simulations :

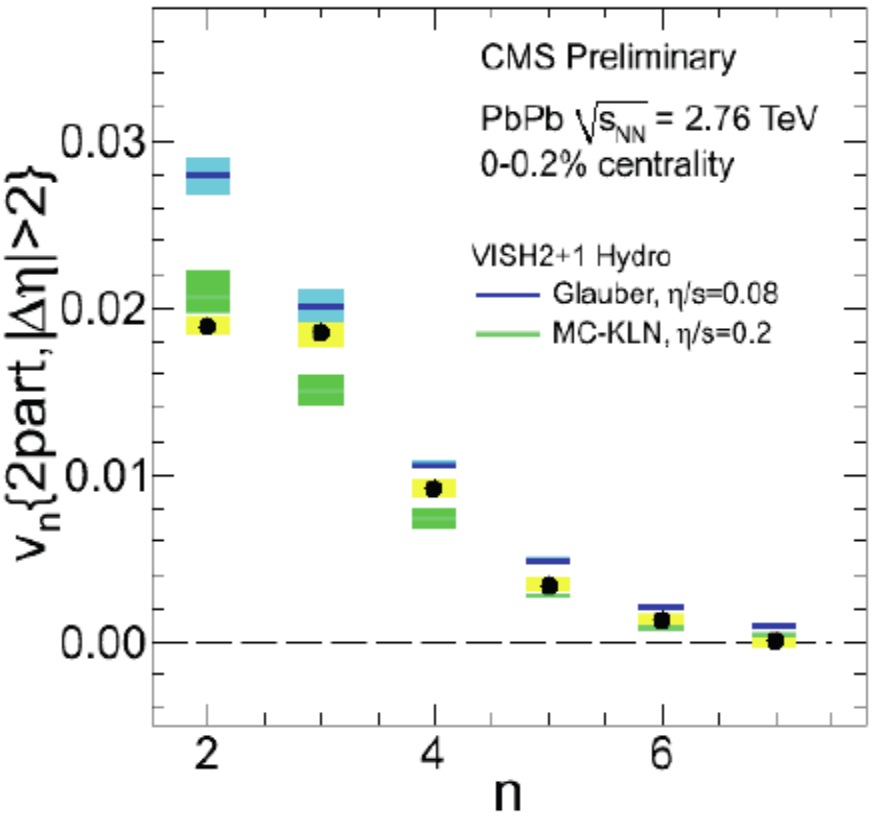
-qualitatively reproduce the measured event plane correlations

Extracting η/s from V_n in ultra-central collisions

Luzum & Ollitrault, NPA 2013



Shen, Qiu and Heinz 2013



-In most central collisions, fluctuation effects are dominant (Geometry effects are suppressed)

-can not simultaneously fit V_2 and V_3 with single η/s (MC-Glauber & MC-KLN)

Massive Data evaluation

Exp Observables

- particle yields
- spectra
- elliptic flow
- triangular flow & higher order flow harmonics
- event by event V_n distributions
- higher-order event plane correlations

… ... … …

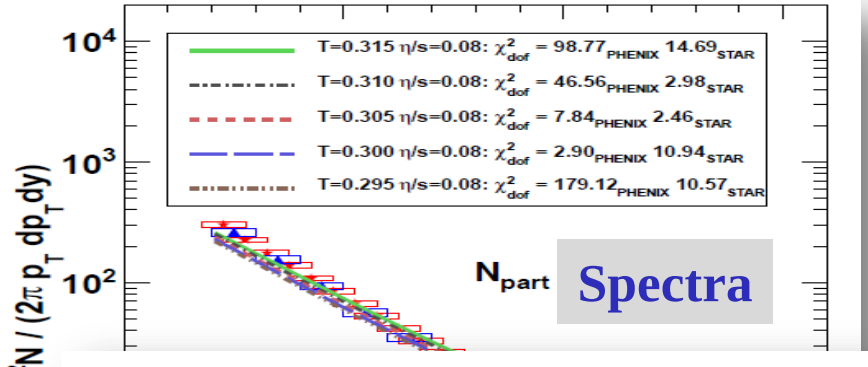
Theoretical Inputs:

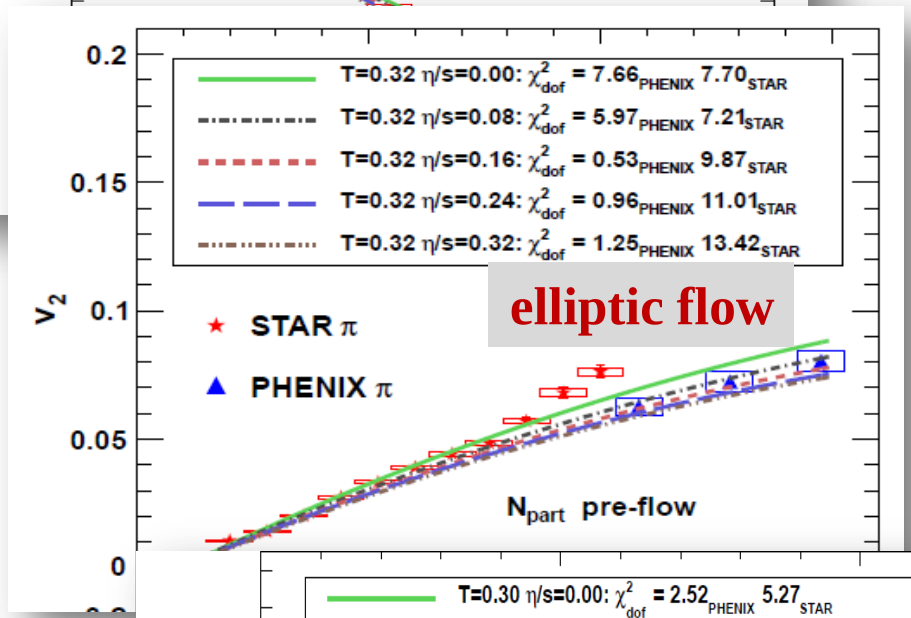
- type of initial conditions
- initial flow
- starting time
- EoS
- shear viscosity
- bulk viscosity
- relaxation times
- freeze-out/switching cond.

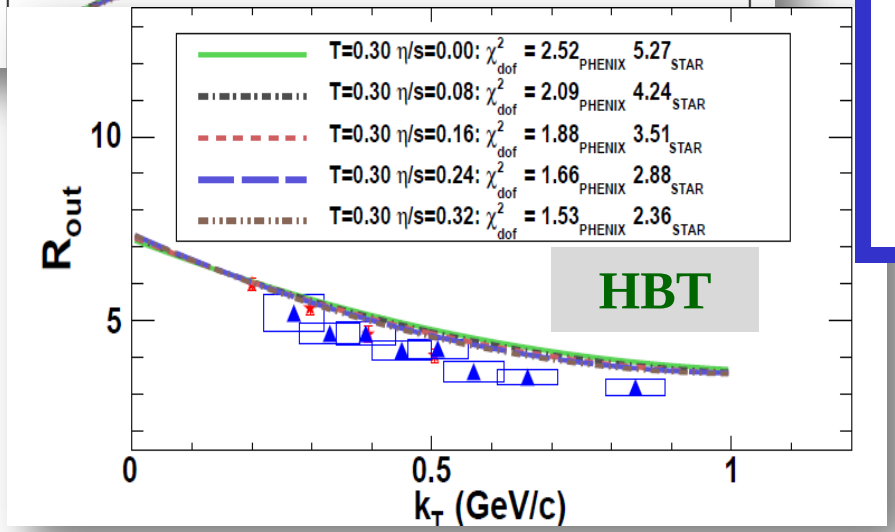
… … … …

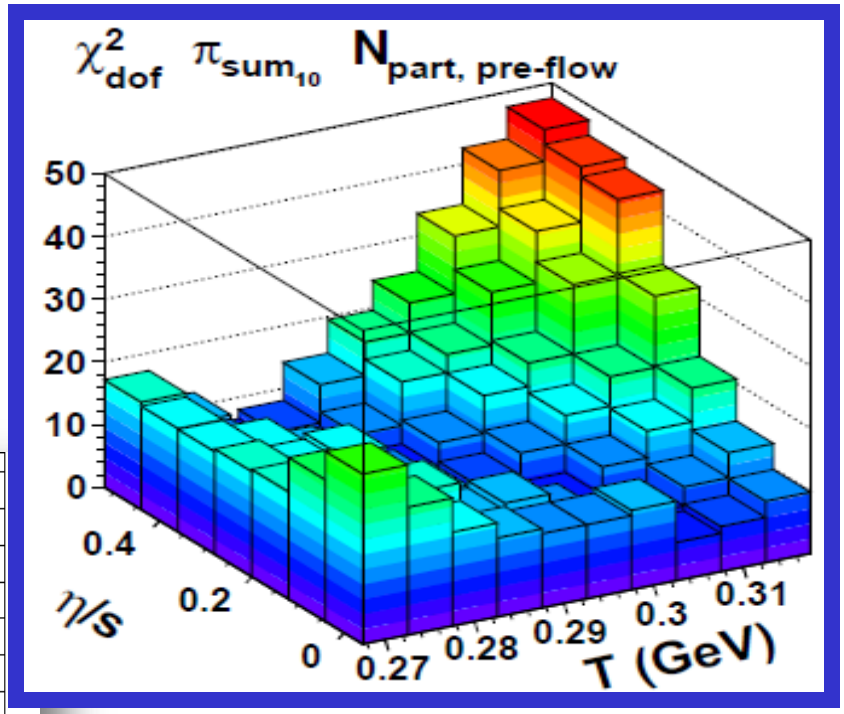
Massive data evaluation

Early CHIMERA Results
(Comprehensive Heavy Ion Model Evaluation and Reporting Algorithm)







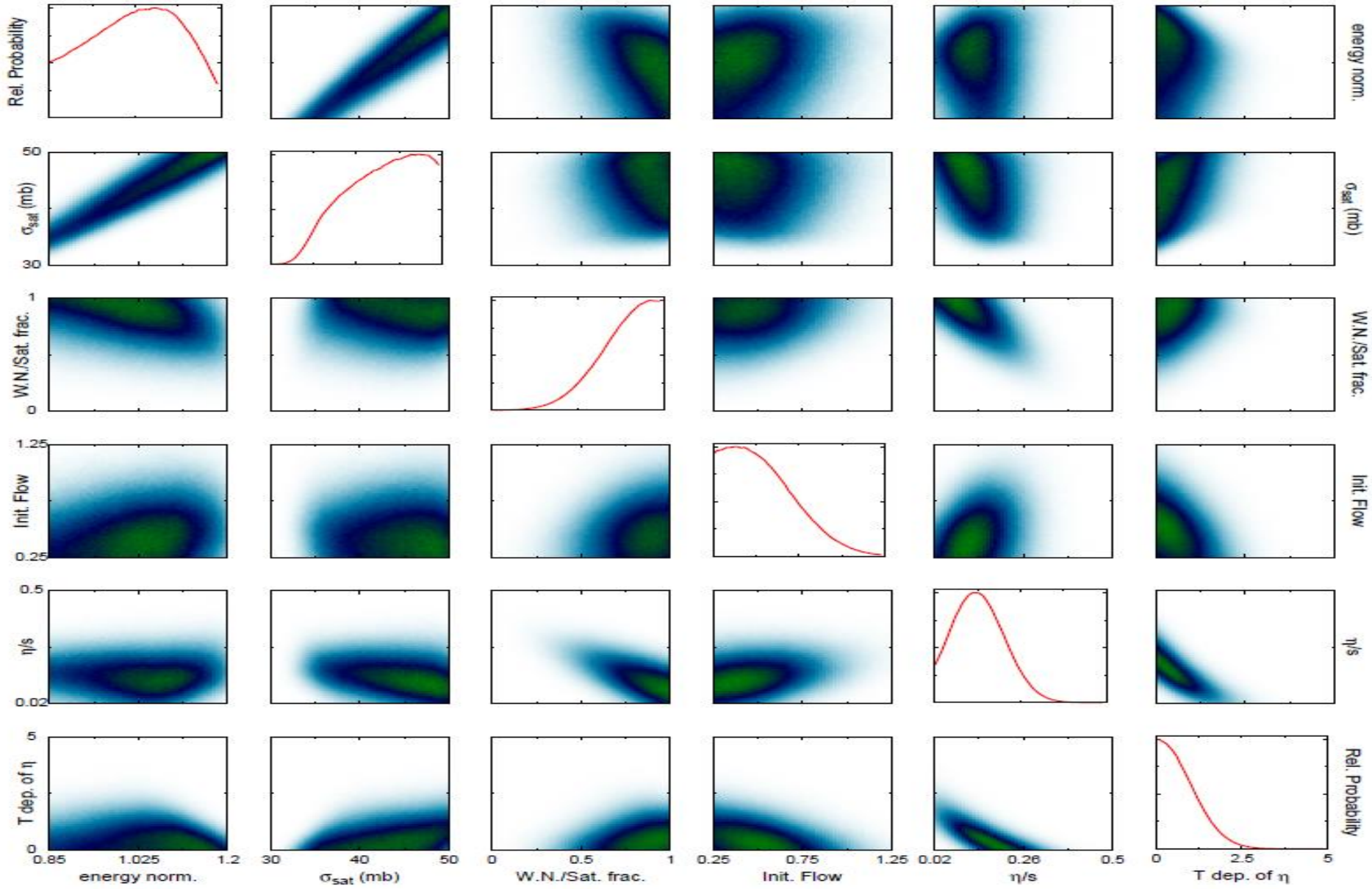


R. Soltz, et al., PRC2013

-- Massive data evaluating algorithm becoming available

MSU-DUKE collaboration,
arXiv: 1303.5769

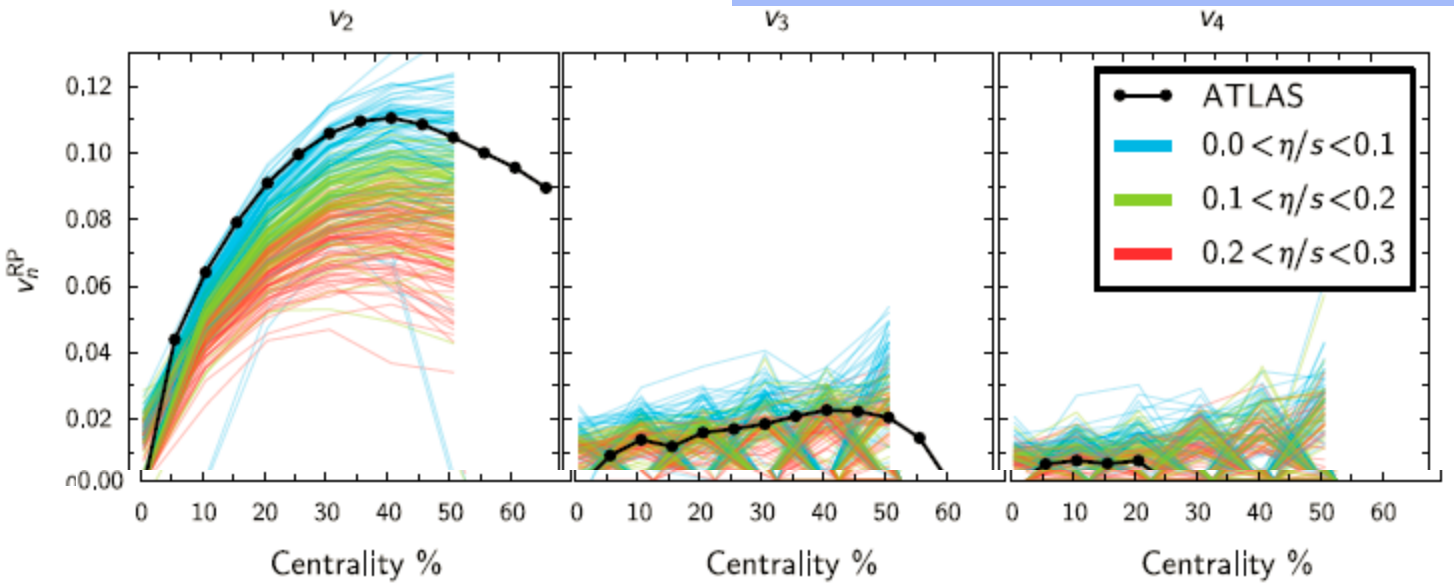
Massive data evaluation

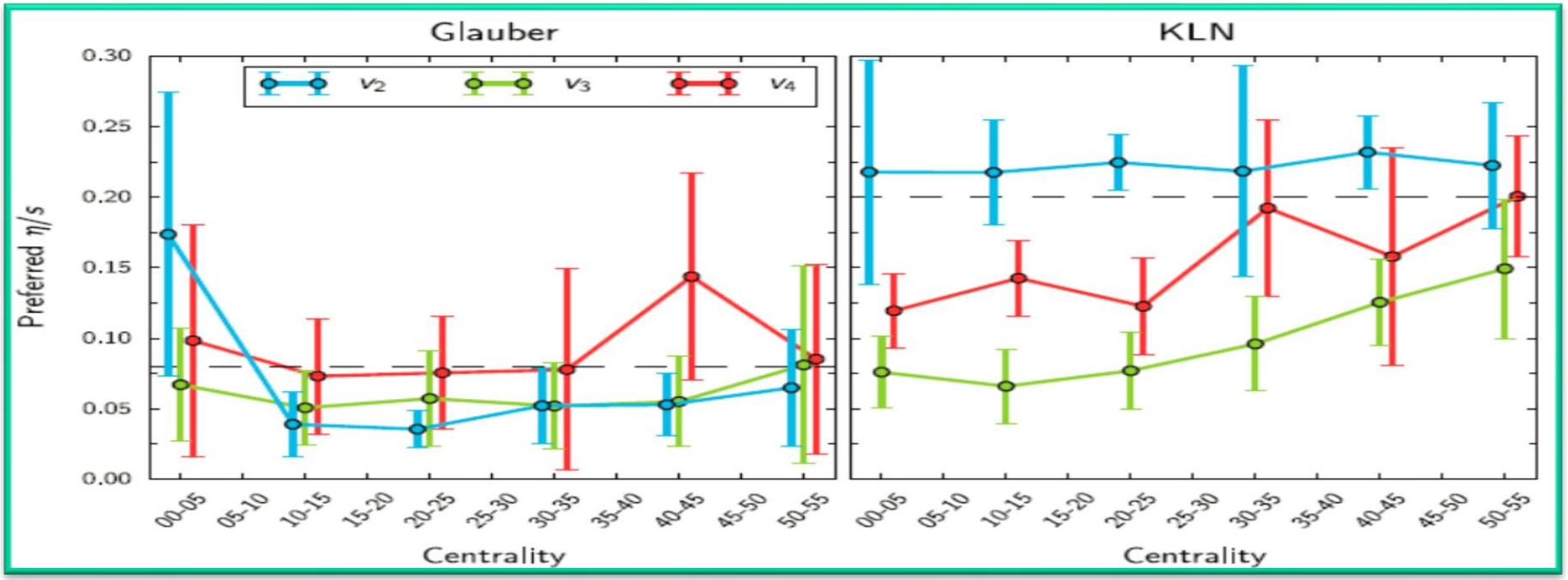


-An extension to 6-dimentional parameter space

Bernhard & Bass, JET collaboration

Massive data evaluation

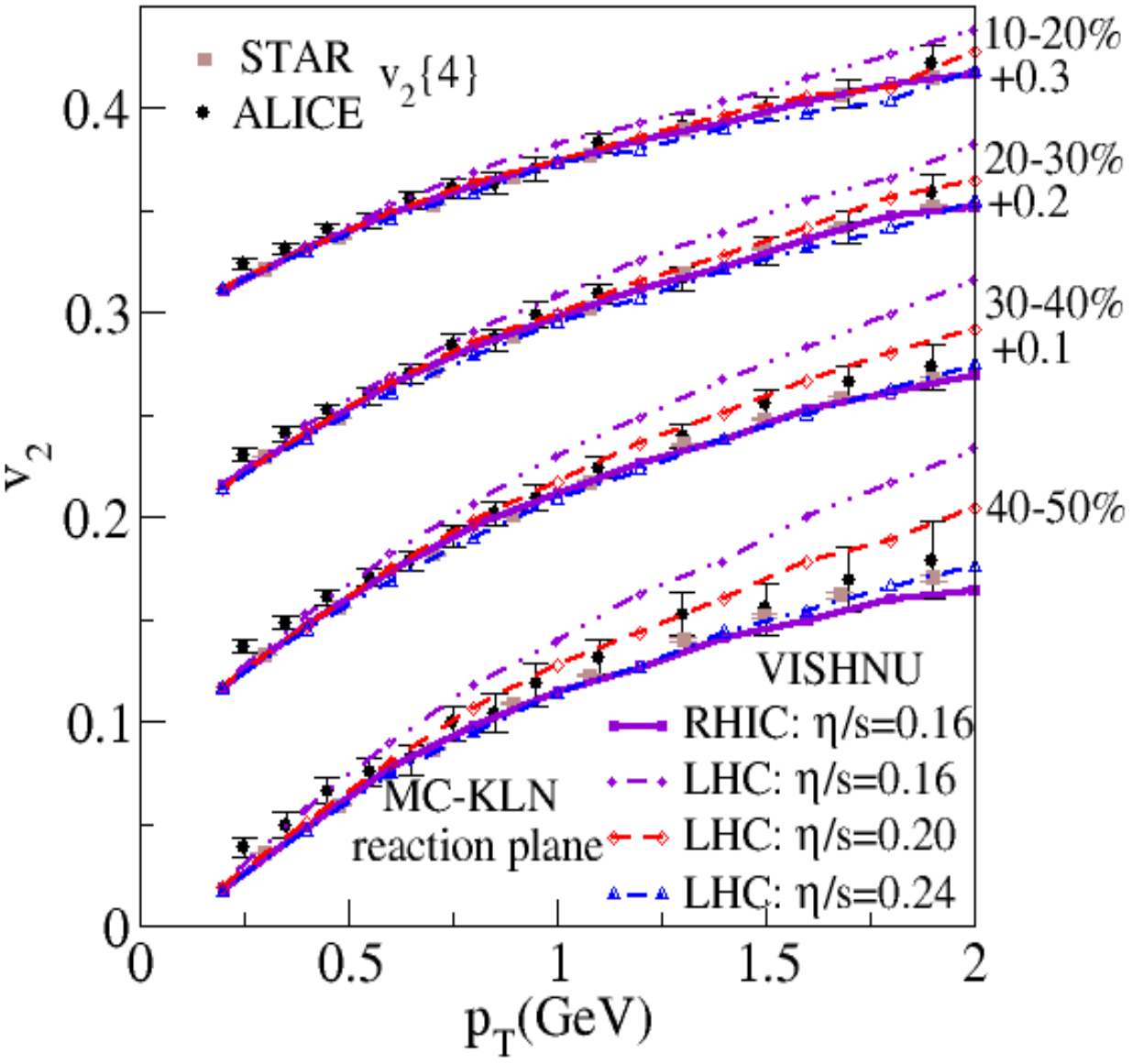




Temperature dependent $(\eta / s)(T)$

$V_2(P_T)$ at RHIC and LHC

Song, Bass & Heinz, PRC2011



Assuming const. η/s

RHIC: $\eta/s \approx 0.16$

LHC: $\eta/s \approx 0.20 - 0.24$

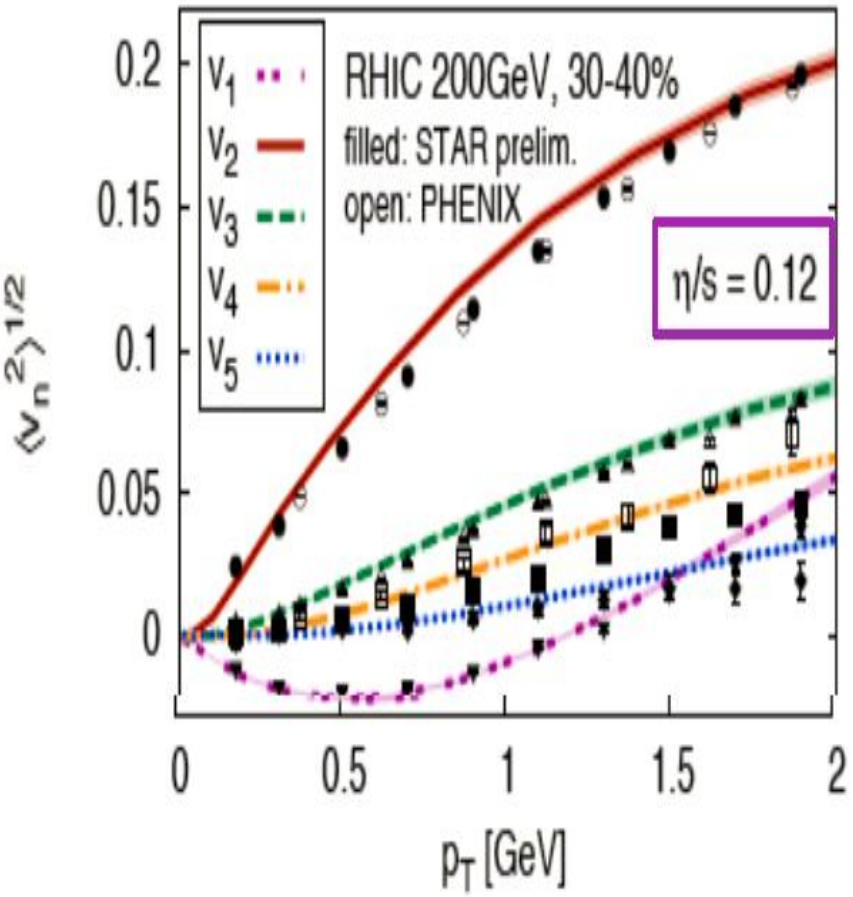
Is QGP fluid more viscous for the temperature region covered by LHC?

One needs to investigate the temperature dependence of $(\eta/s)(T)$

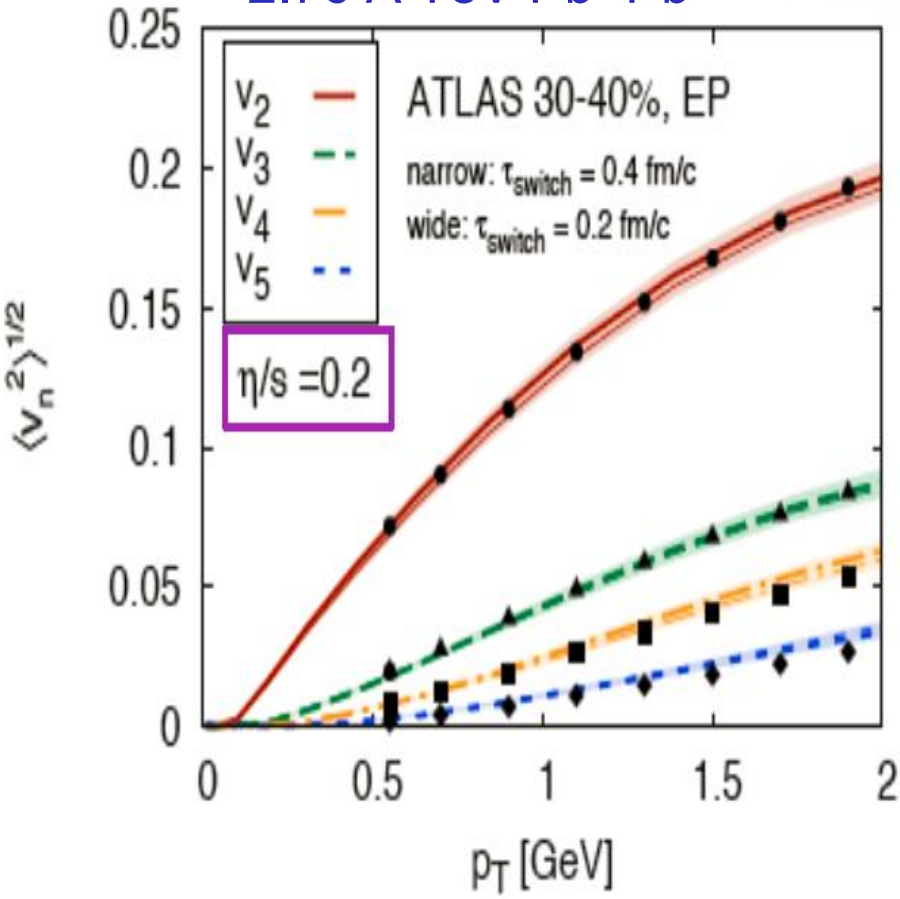
V_n at RHIC and LHC & η/s

C. Gale, et al., PRL2013

200 A GeV Au+Au



2.76 A TeV Pb+Pb



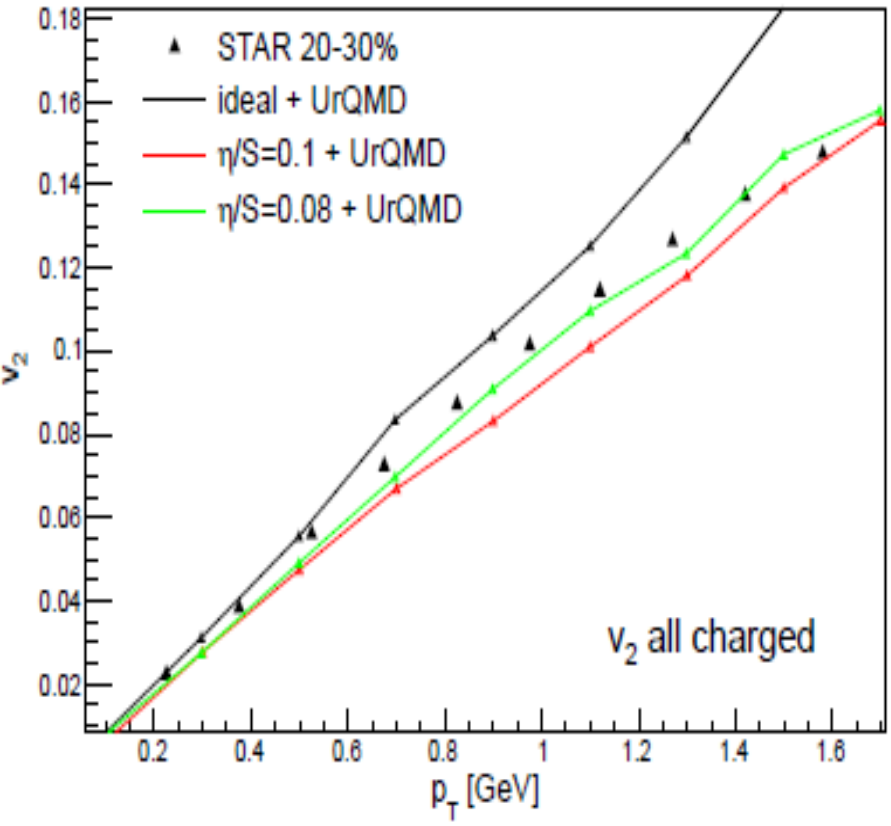
IP-Glasma + MUSIC:

The average QGP viscosity is slightly larger at the LHC

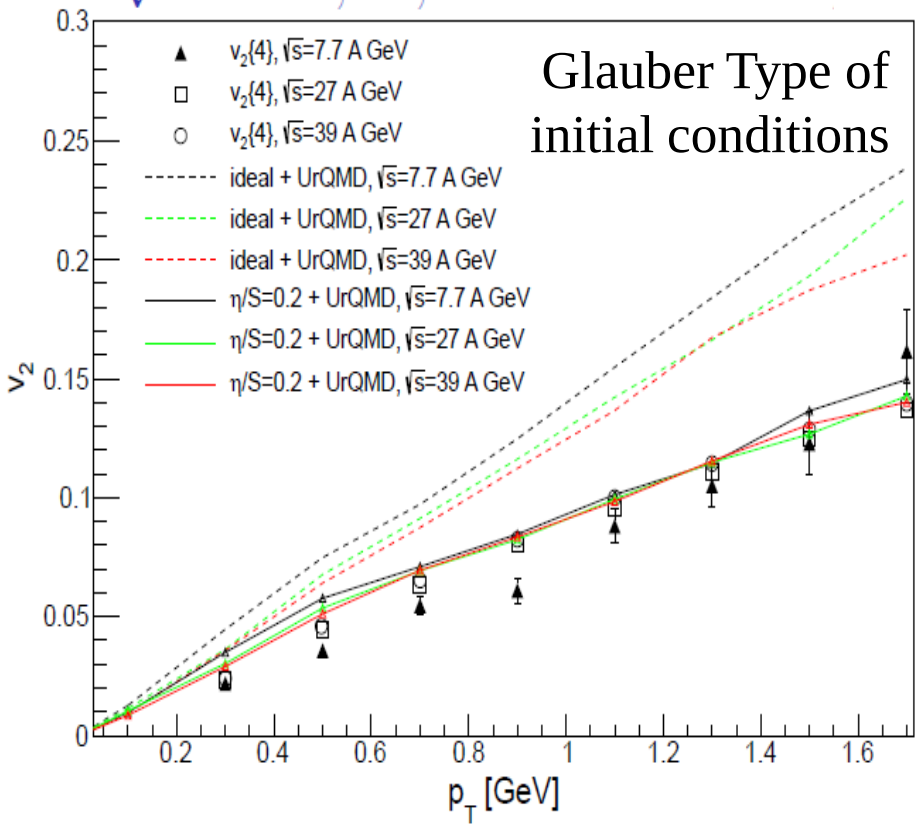
$V_2(P_T)$ at RHIC BES & η/s

Y. Karpenko, SQM2013

200 A GeV Au+Au



$\sqrt{s} = 7.7, 27, 39$ A GeV Au-Au



UrQMD (Glauber type) initializations:

$\eta/s \sim 0.1$ describes $v_2(p_T)$ at top RHIC energies

$\eta/s \geq 0.2$ is required to fit $v_2(p_T)$ at RHIC BES

Song, Bass & Heinz, PRC2011; C. Gale, et al., PRL2013; Y. Karpenko, SQM2013

The average QGP viscosity is changing with collision energies

- A systematic extraction of the averaged QGP viscosity from the BES flow data requires:

  -3+1 hydrodynamics

  -proper description of the non-equilibrium hadronic evolution

  - An EoS with finite T and μ

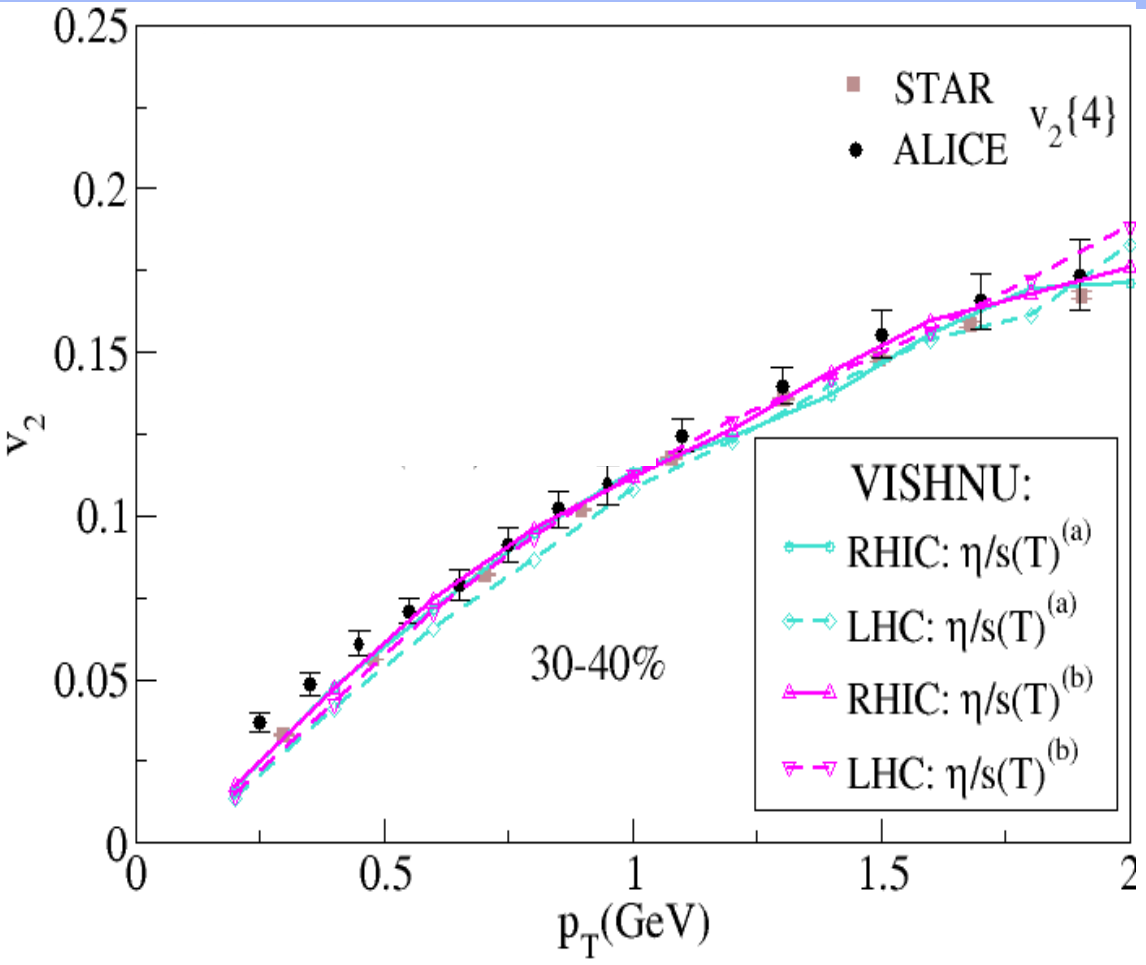
  -The conservation equation for net baryon density

  -The effects from heat conductivity

-Only part of these factors have been implemented in different models

-Needs more systematic study in the near future

Extra complexities $(\eta/s)(T)$

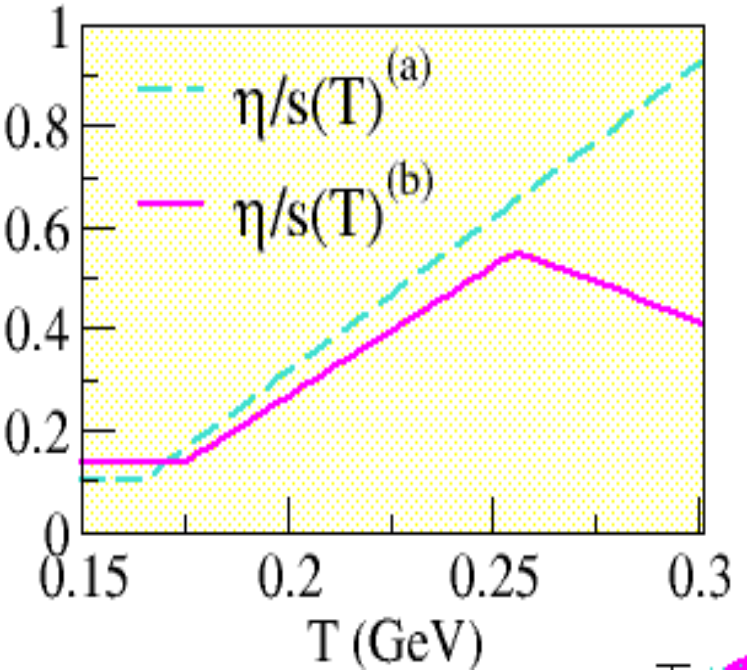


We can not constrain arbitrary $(\eta/s)_{QGP}(T)$ from the flow of two collision energies

Song, Bass & Heinz, PRC2011

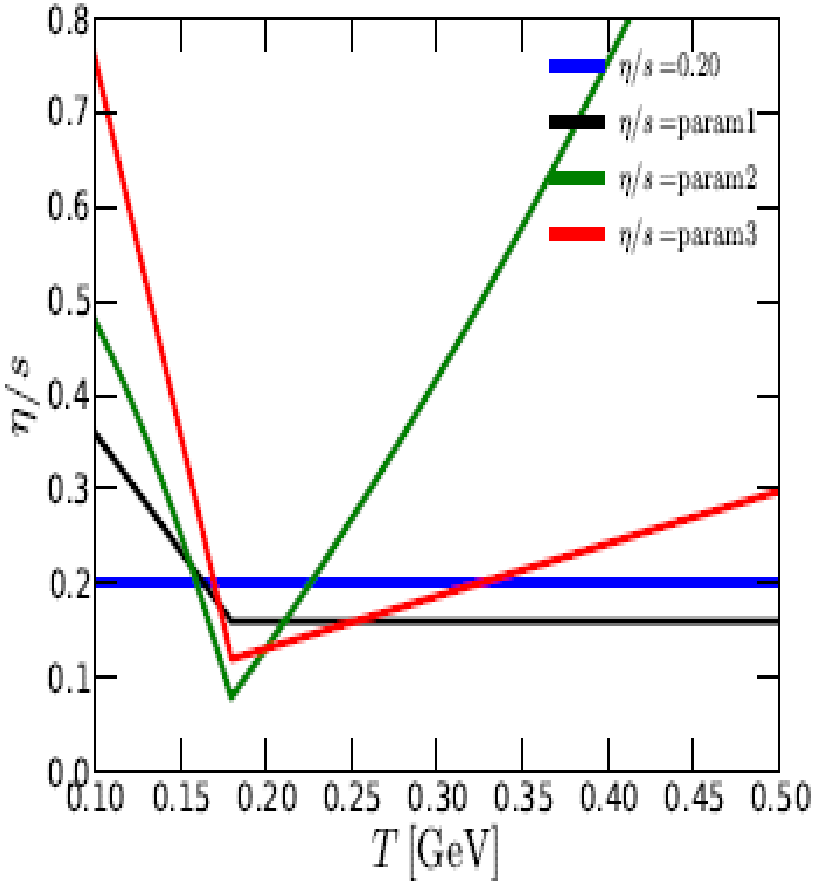
Constant η/s can not fully reveal QGP fluid is more viscous or more perfect

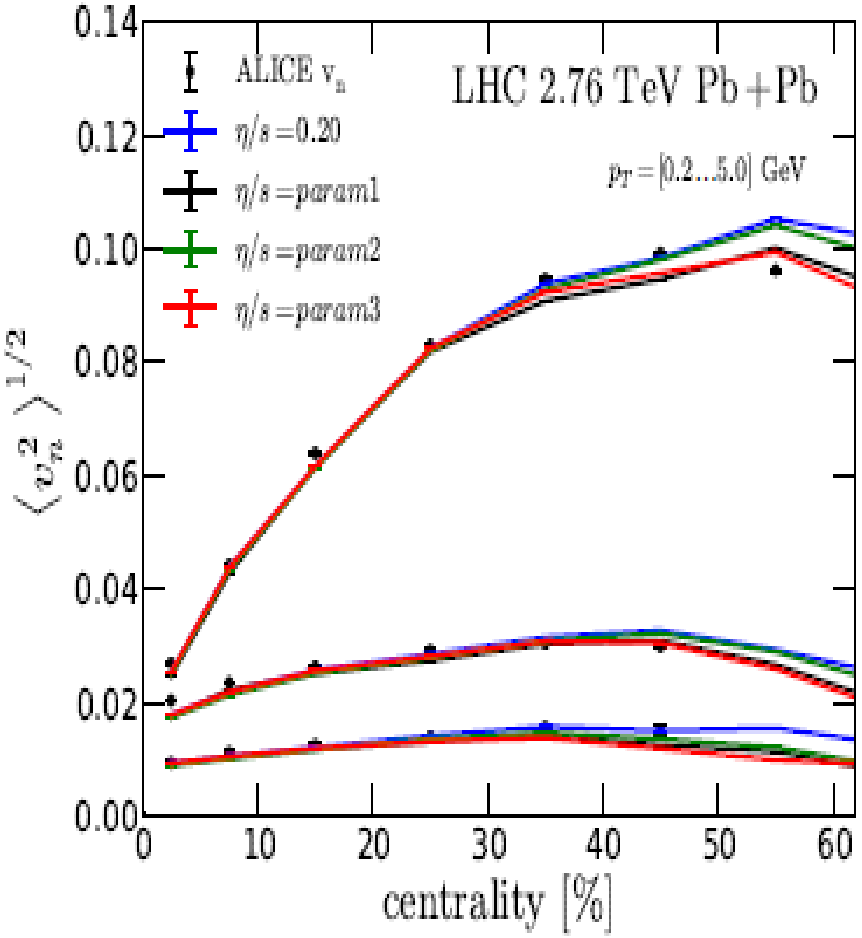
One needs to study the temperature dependence of $(\eta/s)(T)$



Extra complexities $(\eta/s)(T)$

Paatelainen, et. al., PLB 2014

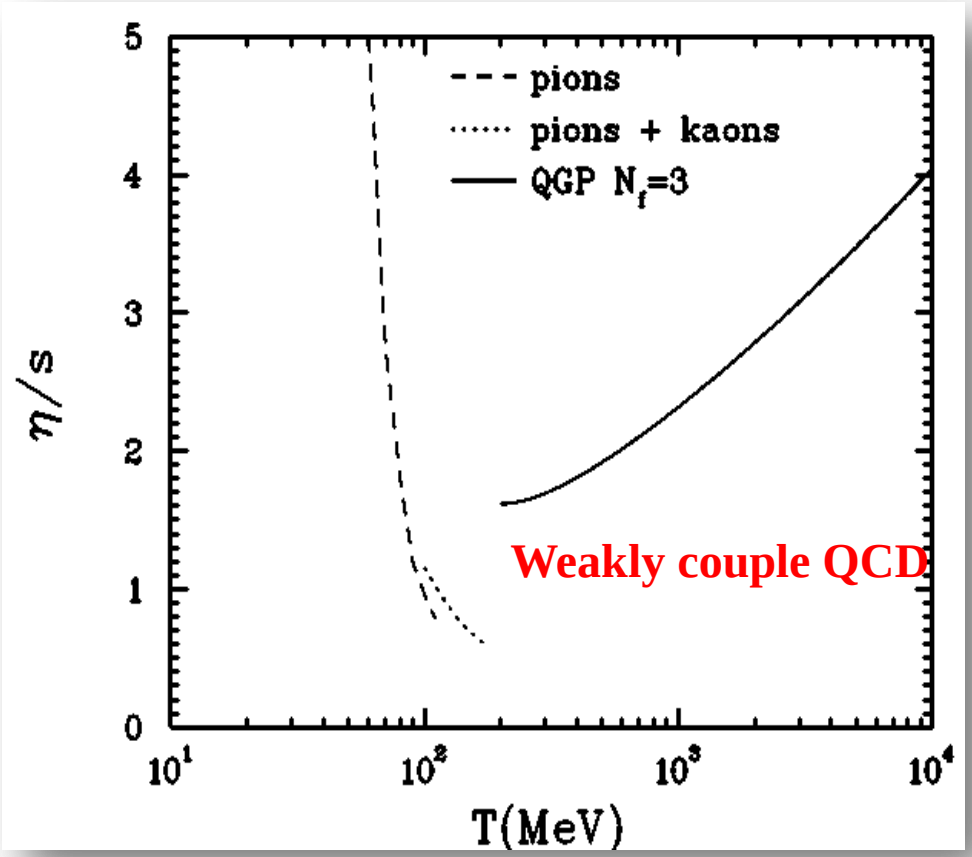




-V_n can not tightly constrain $(\eta/s)(T)$

Please also refer to C. Gale, et. al PRL (2013)

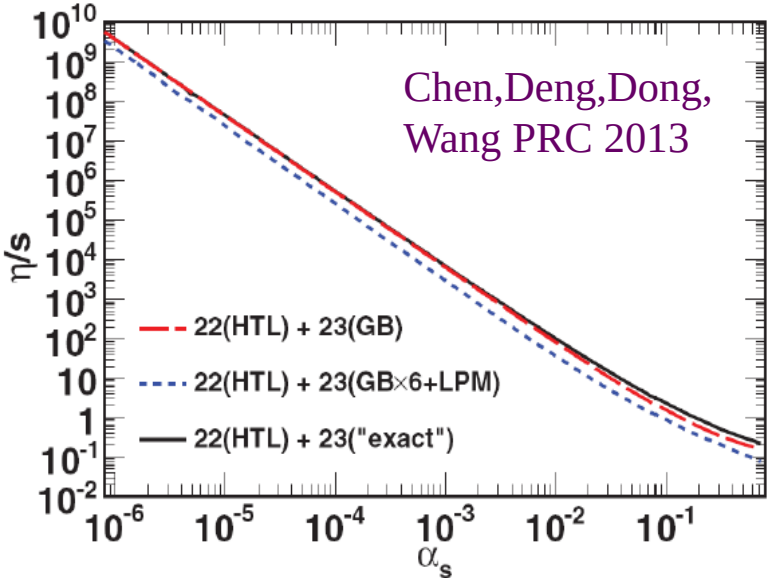
Theoretical Predictions for $\eta/s(T)$



Lattice results

$$\eta/s = \begin{cases} 0.134(33) & (T = 1.65T_c), \\ 0.102(56) & (T = 1.24T_c). \end{cases}$$

Meyer PRD 2007



$\eta/s(T)$ can be calculated from weakly coupled QCD; Lattice QCD ; effective field theory

Further prediction of $\eta/s(T)$ using other theories/models are needed … …

Future systematic study of flow data at the LHC, top RHIC and RHIC BEC will/may constrain $\eta/s(T)$ obtained from different theories / models.

Bulk Viscosity

Long , but not full lists of articles:

K. Rajagopal *et al.* JHEP 1003, 018(2008) .

R.Fries *et al.* Phys.Rev. C78 034913 (2008) .

G.Torrieri *et al.* Phys.Rev. C78, 021901(2008).

A. Monnai *et al.* Phys.Rev. C80 054906 (2009)

H.Song and U.WHeinz, Phys. Rev. C81, 024905 (2010)

P. Bozek, Phys. Rev. C81, 034909 (2010)

K.Dusling and T.Schäfer, Phys.Rev.C 85, 044909 (2012)

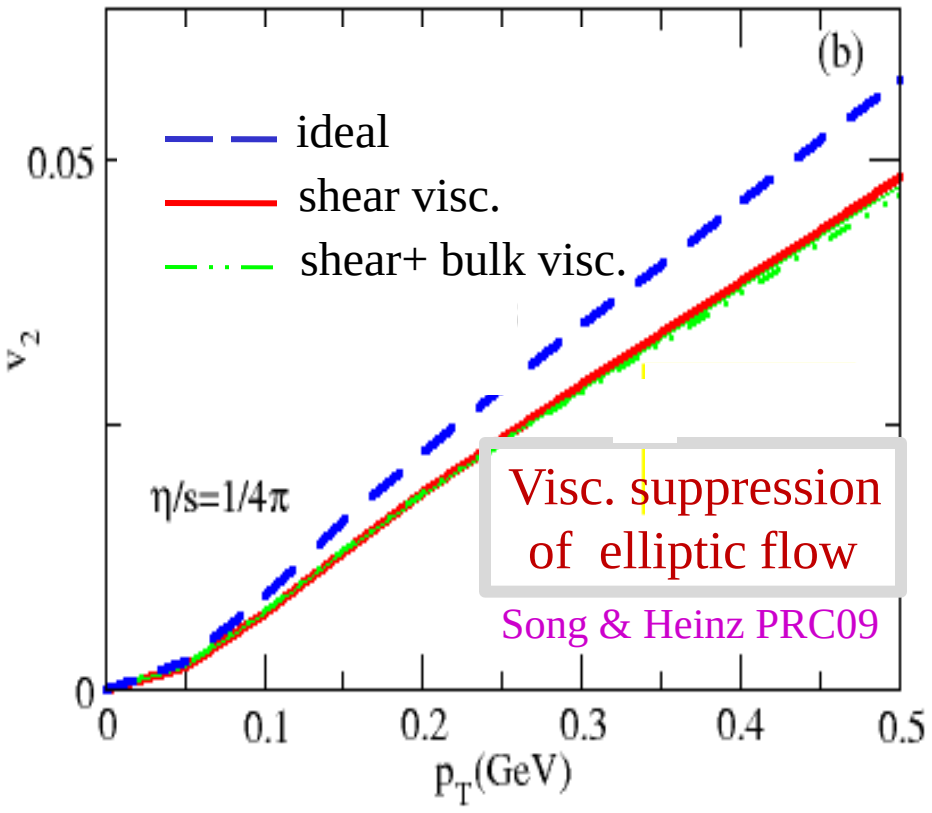
J.Noronha-Hostler, et.al., Phys.Rev. C 88, 044916 (2013)

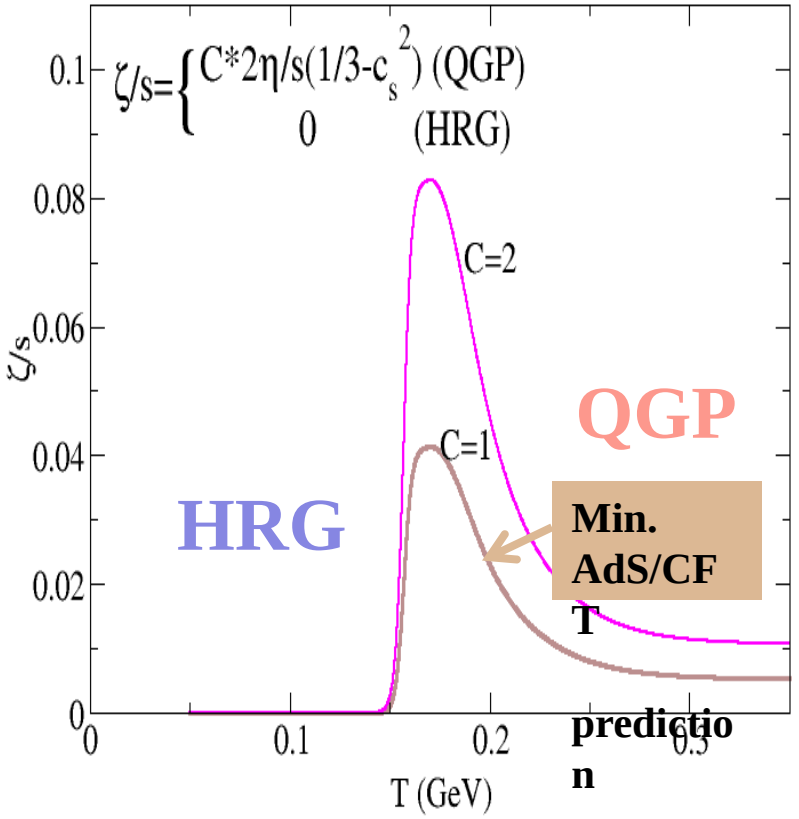
J.Noronha-Hostler, J.Noronha and F.Grassi, arXiv:1406.3333 [nucl-th]

M. Habich and P. Romatschke, arXiv:1405.1978 [hep-ph].

… … … … … …

The interplay between shear and bulk viscosity



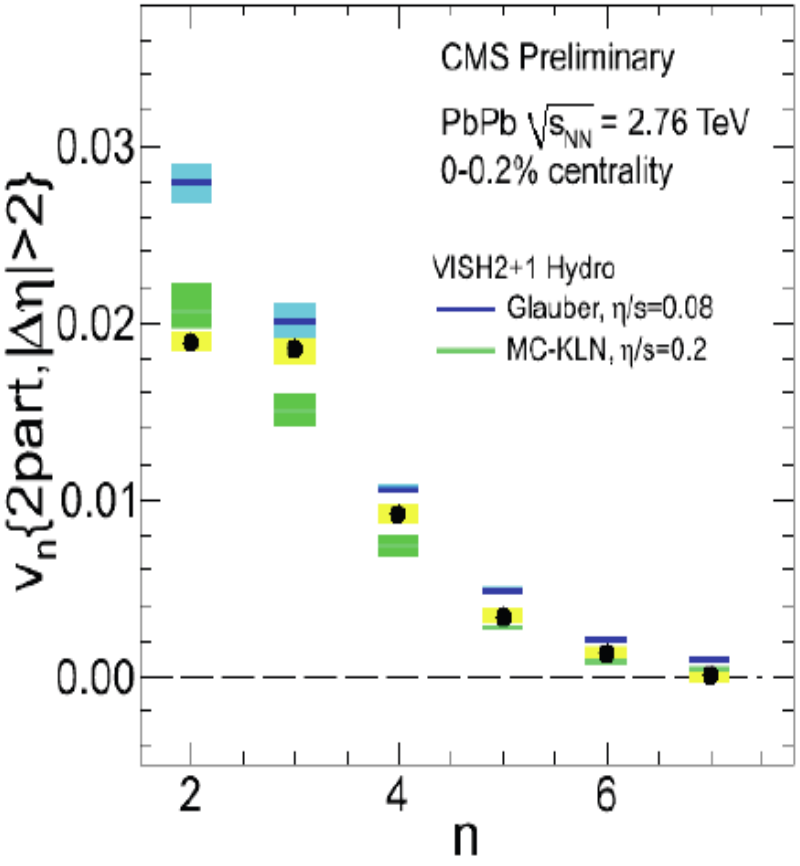


-Bulk viscous effects are much smaller than shear ones due to the critical slowing down near phase transition (Song & Heinz PRC09)

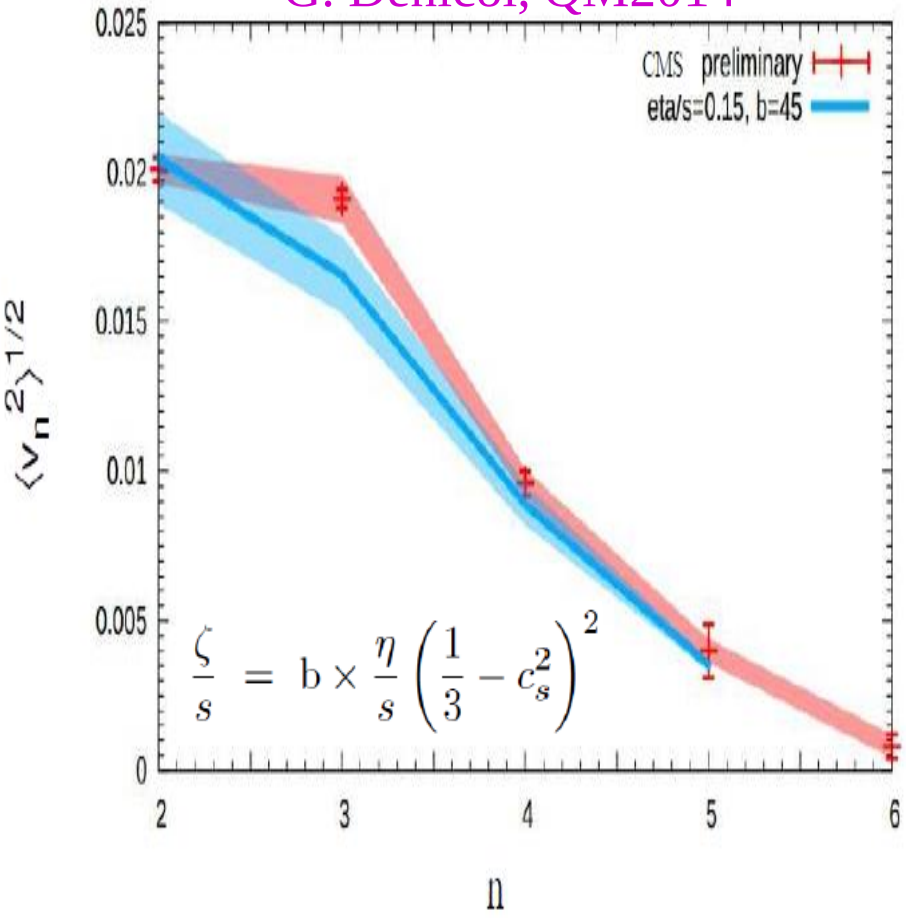
-One can extract the QGP shear viscosity from exp data without large contamination from bulk viscosity

Ultracentral Collisions: bulk visc. & NN correlations

Shen, Qiu and Heinz 2013



G. Denicol, QM2014

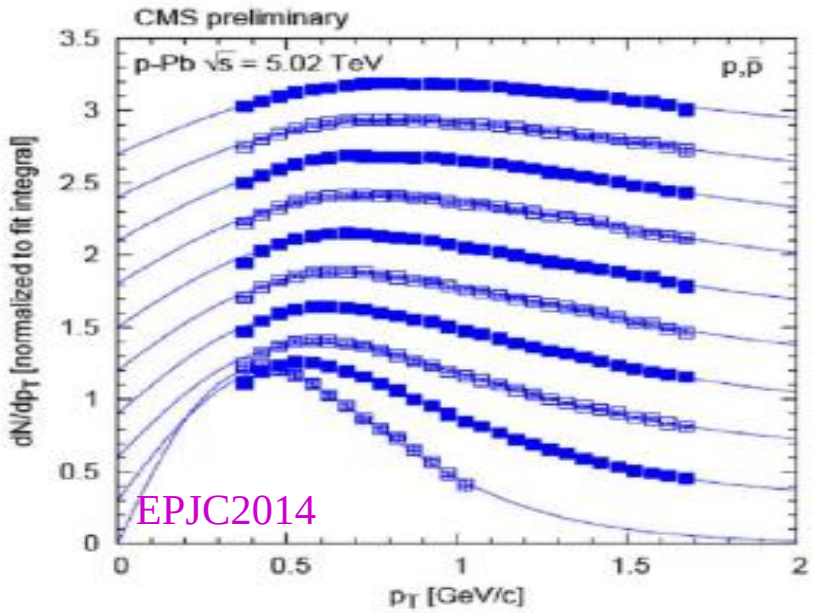


-MC-Glauber & MC-KLN: can not simultaneously fit V_2 and V_3

-IP+Glasma + NN correlations + bulk viscosity nicely reproduces V_n in ultra-central collisions

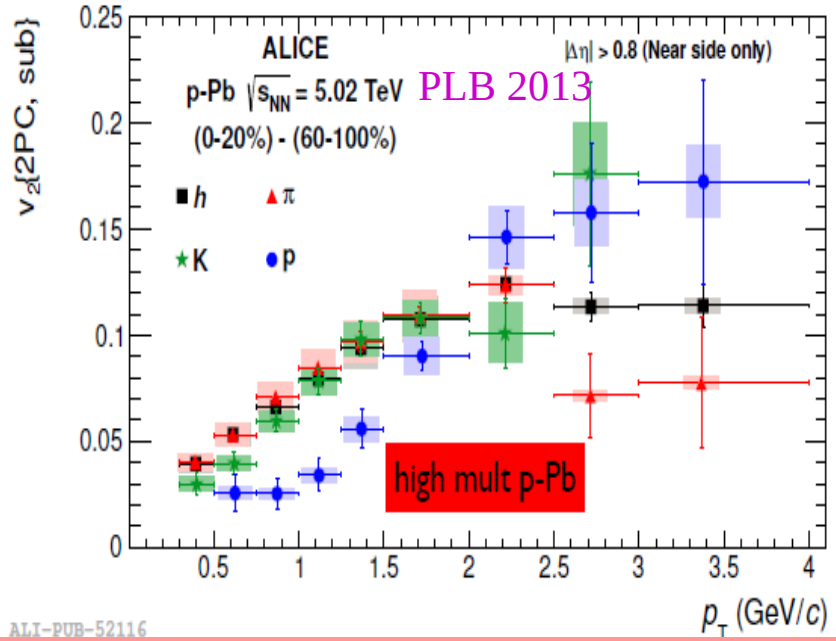
Flow & Hydrodynamics
in 5.02 TeV p+Pb collisions

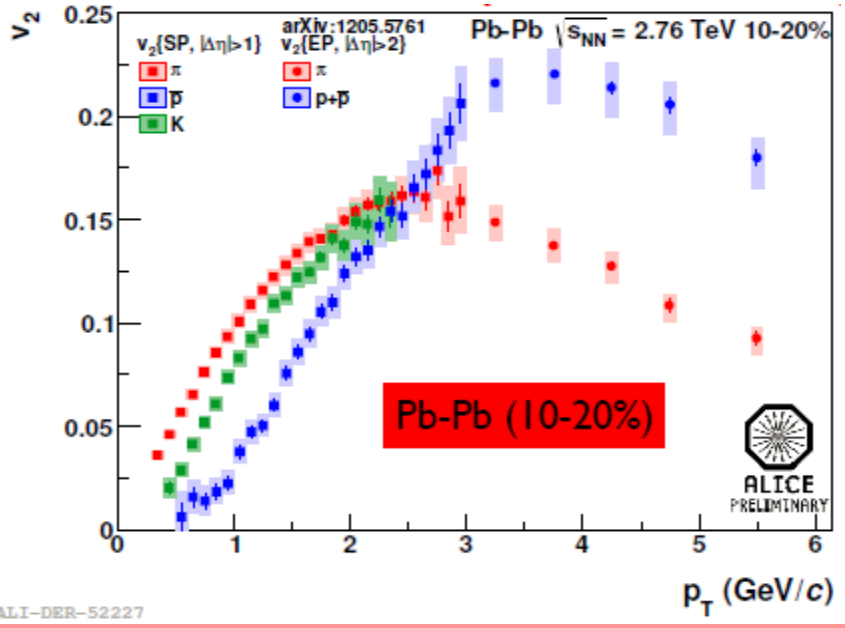
Radial & elliptic flow in 5.02 TeV p+Pd



Strong variation of the shape of the p_T spectra for pion kaon, and protons --large radial flow for higher multiplicity events

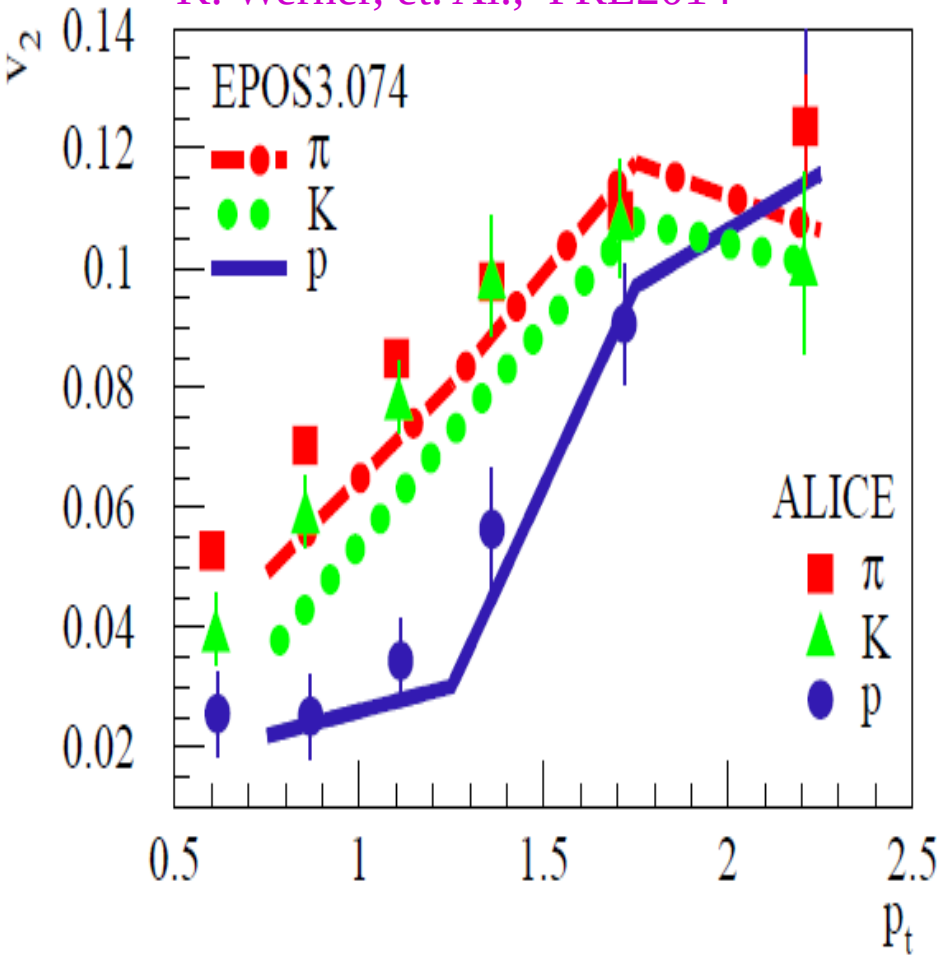
Elliptic flow: similar mass-ordering as 2.76 A TeV Pb+Pb Collisions



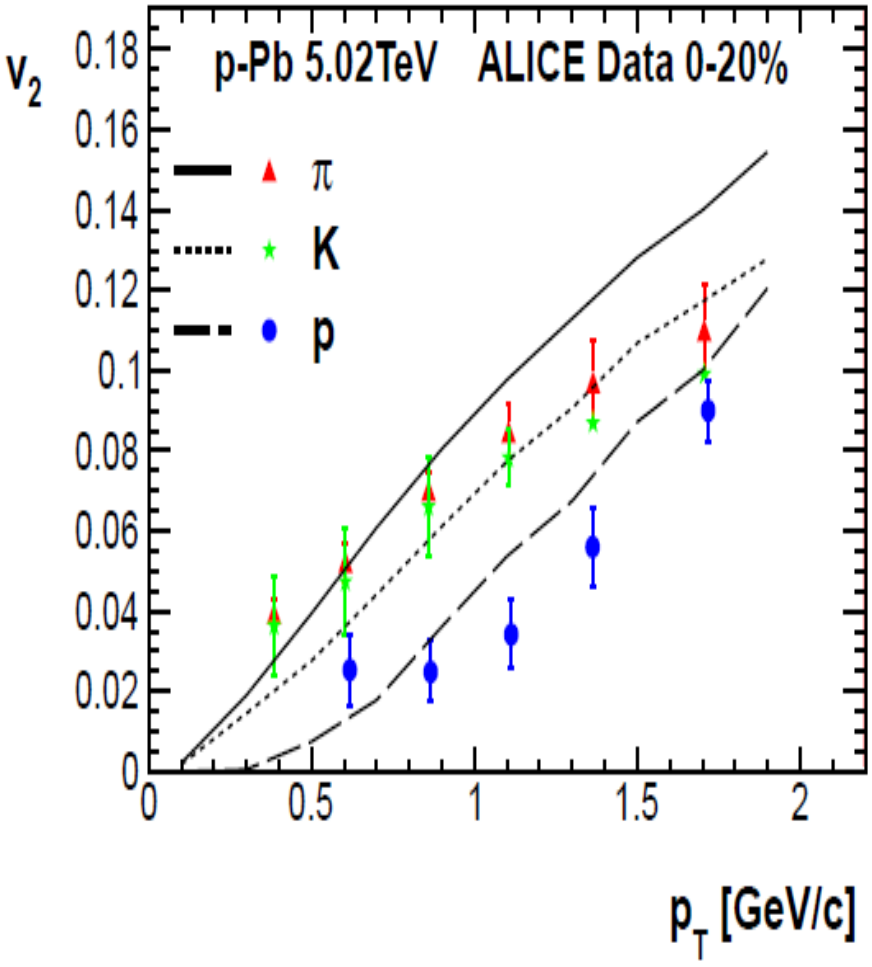


Mass Ordering of Elliptic flow in p+Pb

K. Werner, et. Al., PRL2014



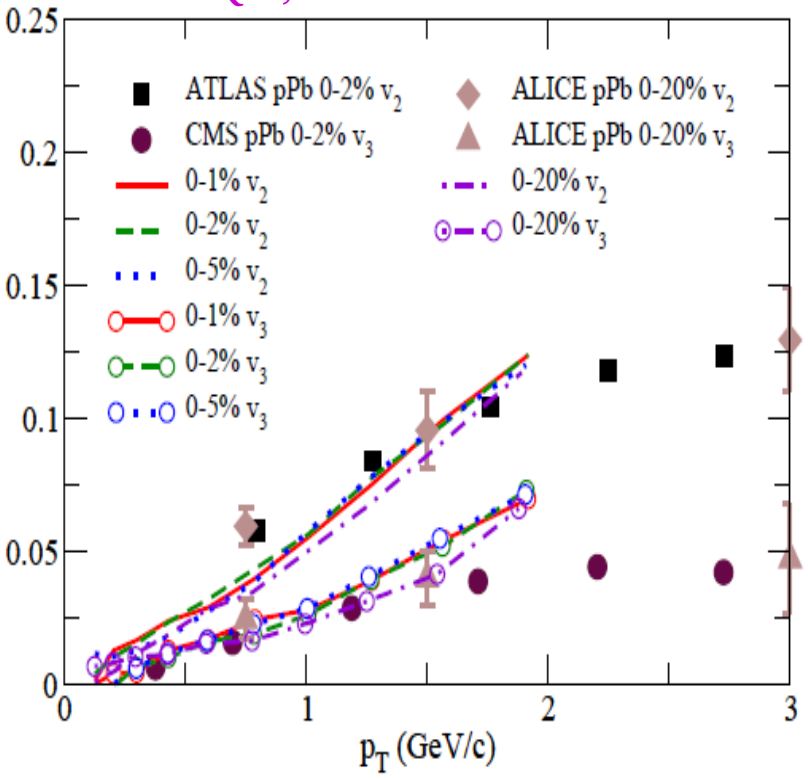
P. Bozek, W. Broniowski, G. Torrieri, PRL2013



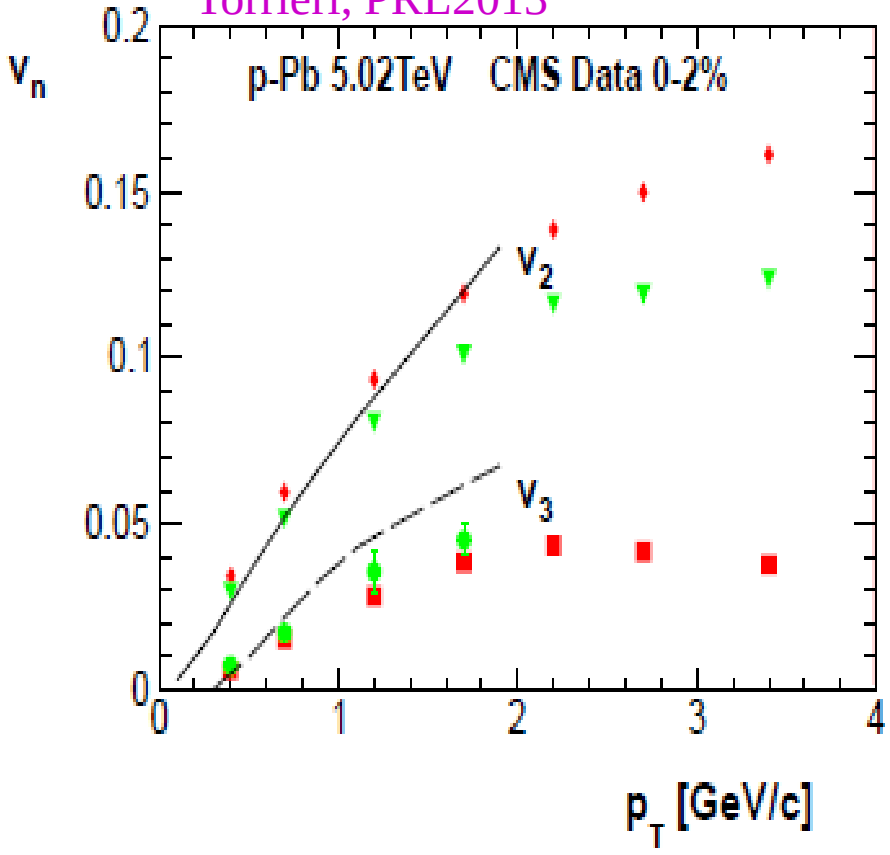
Hydrodynamic mass-ordering: interplay between radial & elliptic flow

Elliptic and Triangular flow in p+Pb

G.-Y. Qin, B. Muller. PRC2014



P. Bozek, W. Broniowski, G. Torrieri, PRL2013



Hydrodynamics nicely describes v_2 & v_3 in most central p+Pb collisions

-Perfect liquid or not? Please carefully extract the viscosity with realizable uncertainty estimates

Summary

-Extraction η/s from elliptic flow data using VISHNU indicates:

$1\times(1/4\pi)\le\eta/s\le 2.5\times(1/4\pi)$ (MC-Glauber; MC-KLN)

-Slightly larger averaged QGP viscosity at the LHC

-It is important to extract $(\eta/s)_{QGP}(T)$ from flow data at various collision energies (current on-going work are mostly assuming constant $(\eta/s)_{QGP}$)

-Recent developments on initialization models: **color charge fluctuations; multiplicity fluctuations; initial flow fluctuations** … …

-New flow data: triangular flow & higher order flow harmonics, higher-order event plane correlations e-b-e v_n … ...

-To implement e-b-e simulations to further study other flow will help us to constrain initialization models, tightening the limit on $(\eta/s)_{QGP}$

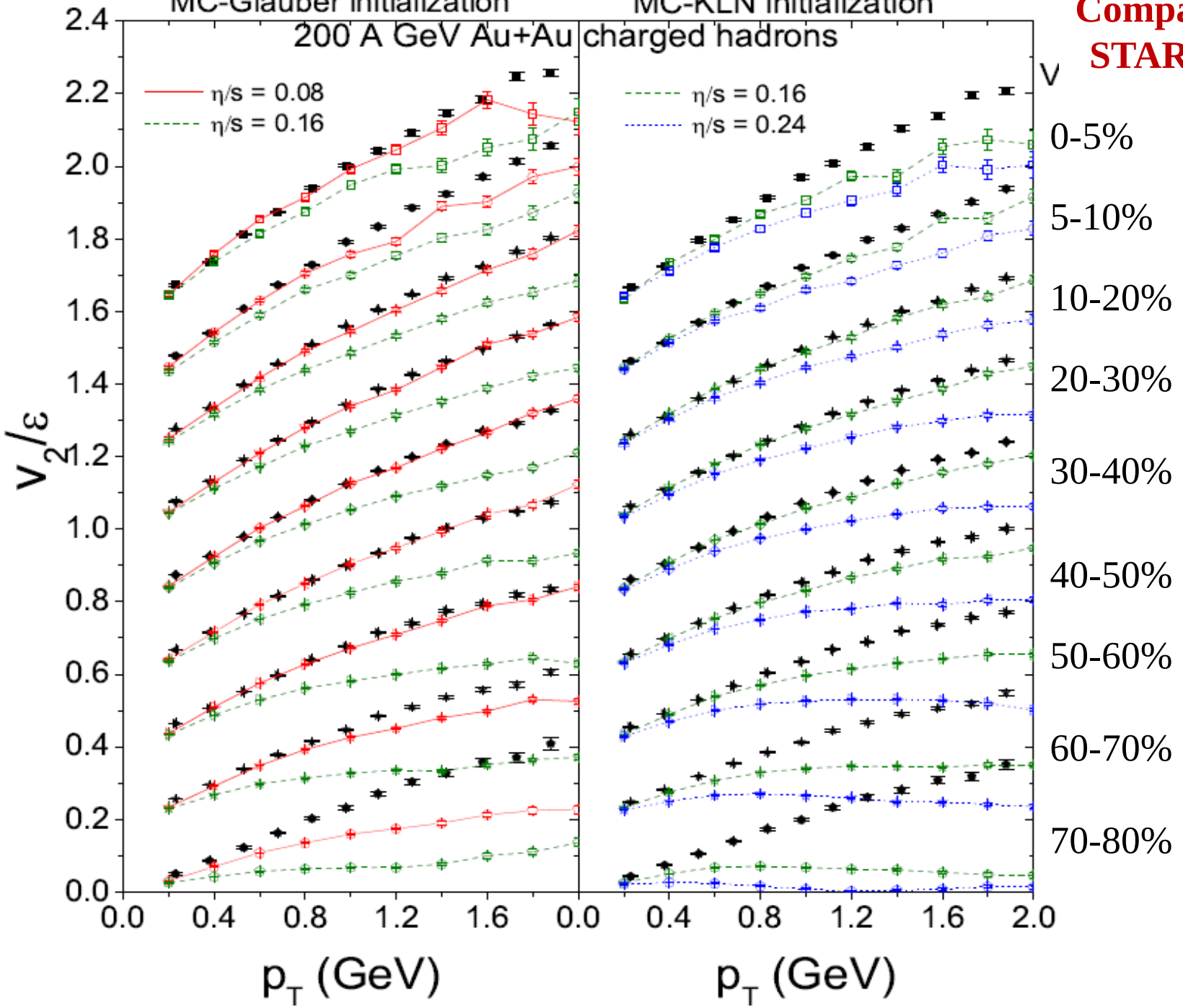
-massive data evaluation are needed

-Strong indication for collective flow in 5.02 TeV p+Pb collisions

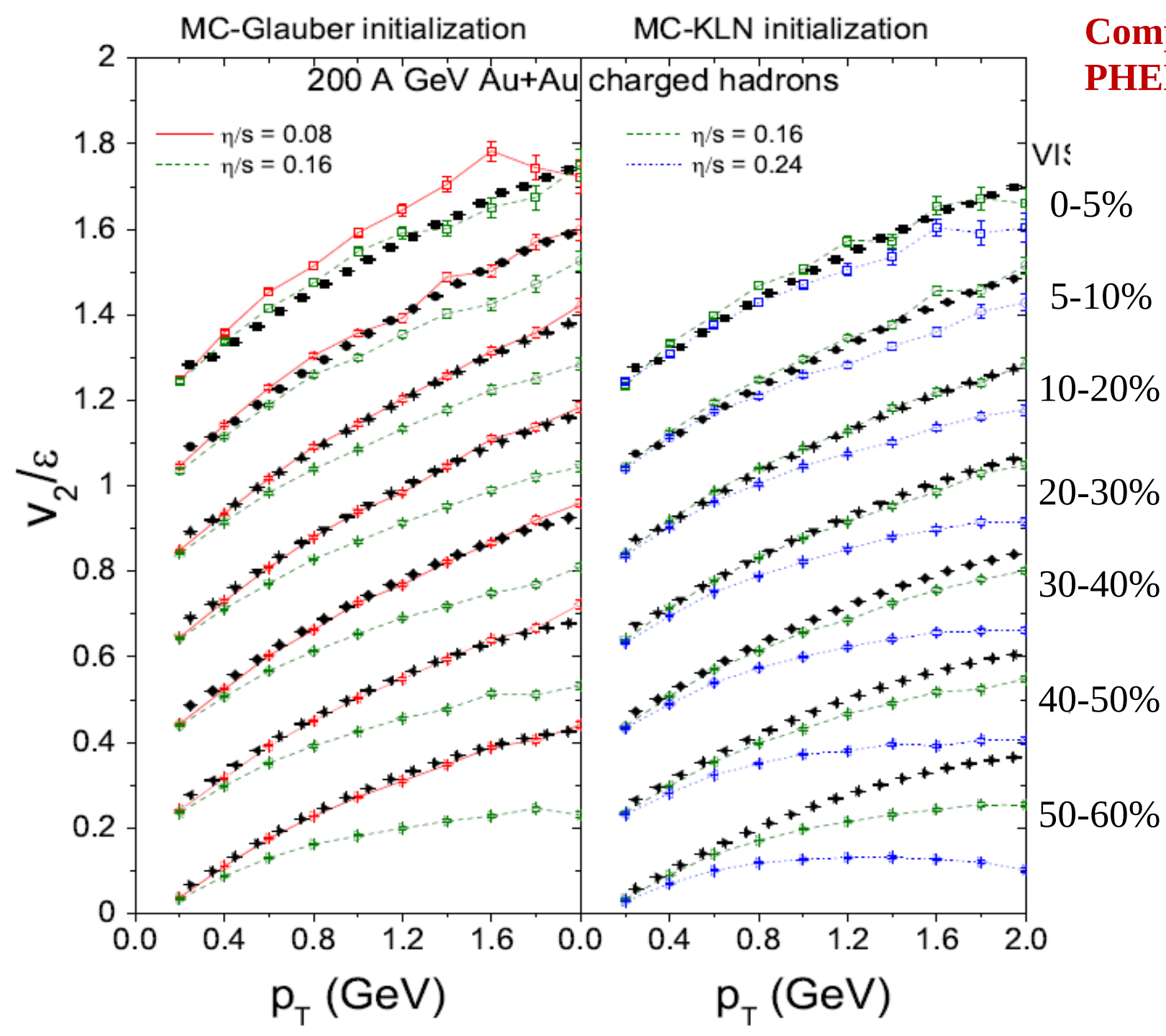
Thank you

Flow & Hydrodynamics

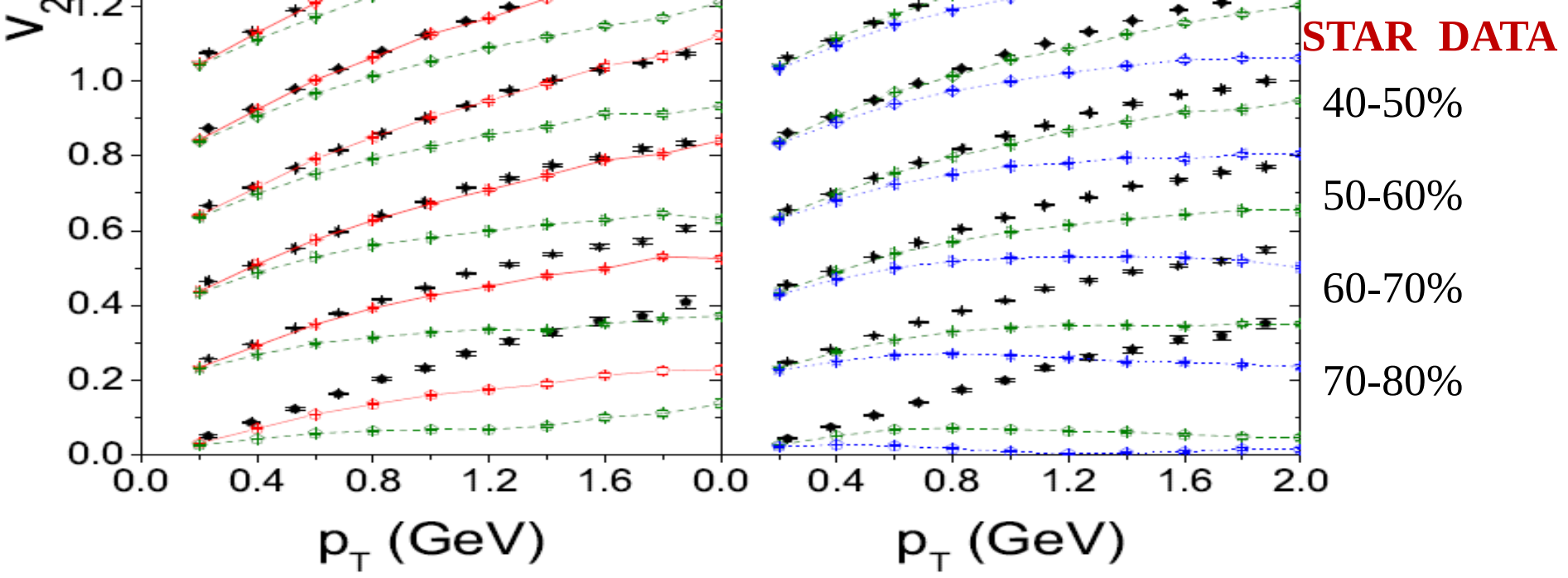
in peripheral Au+Au collisions

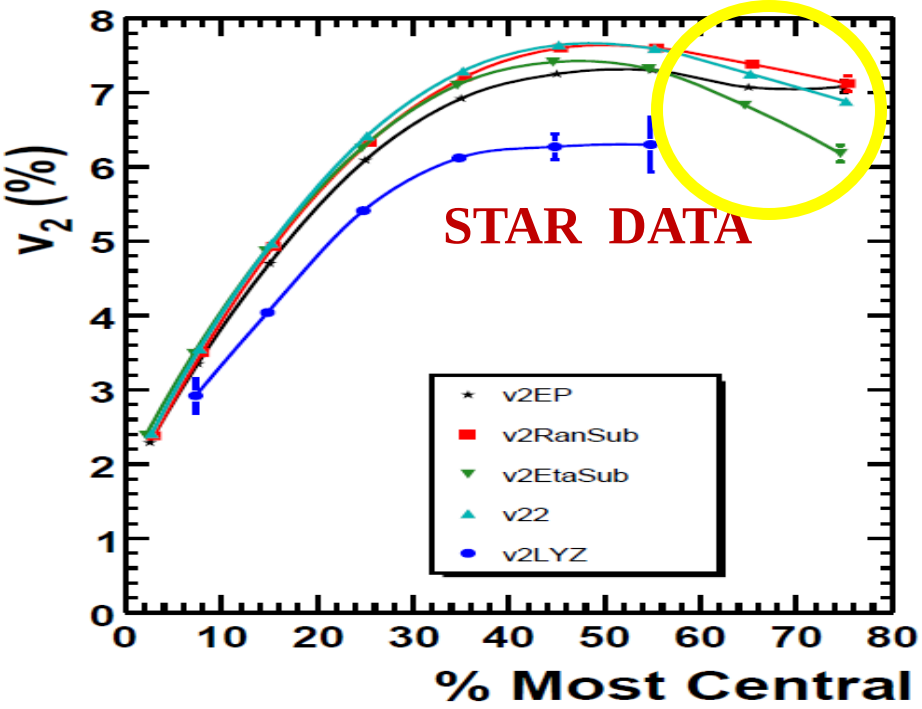


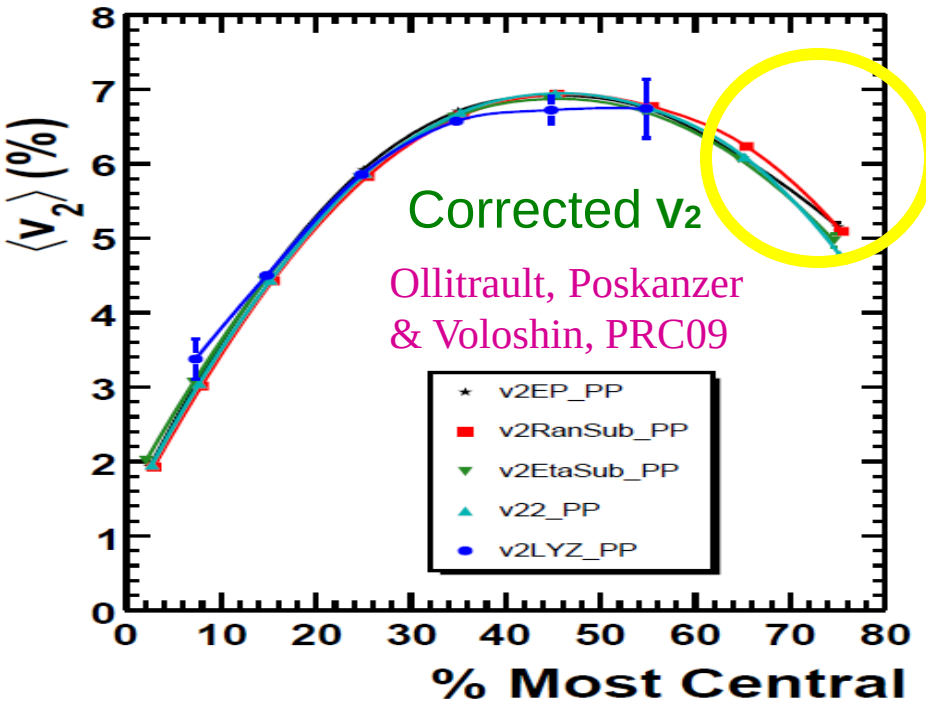
Compare with STAR DATA

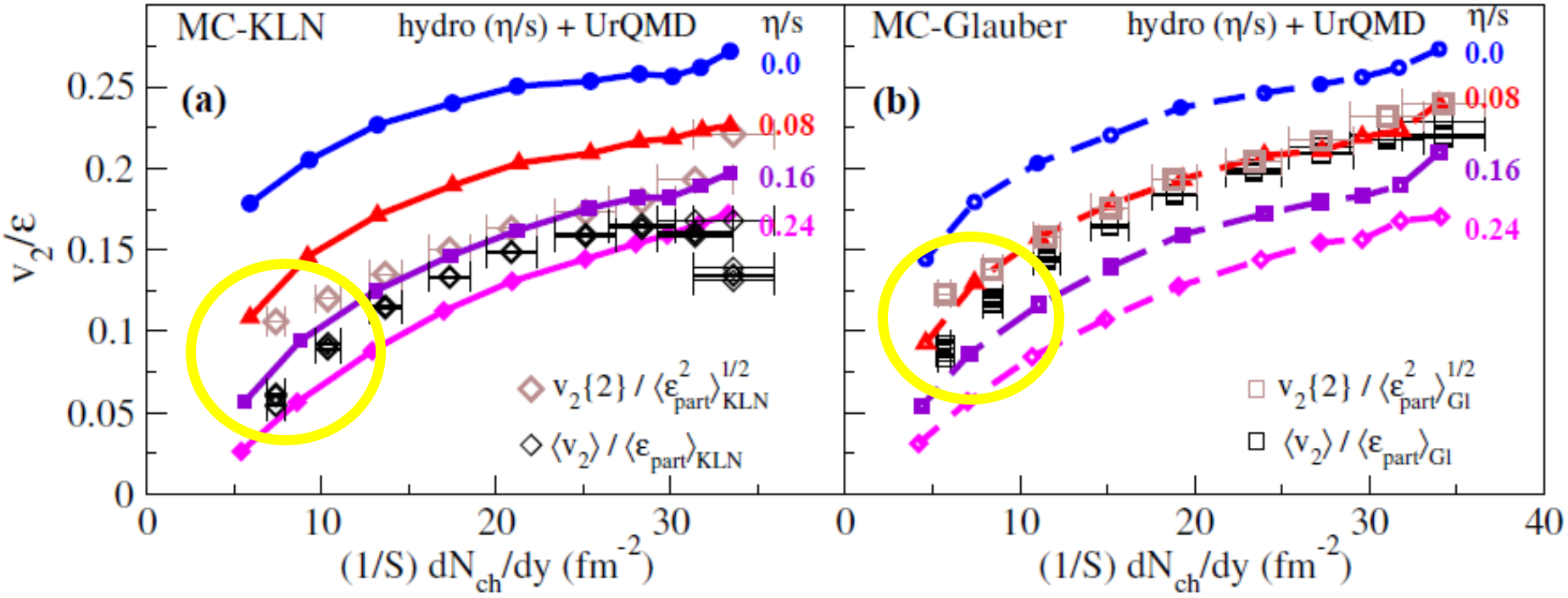


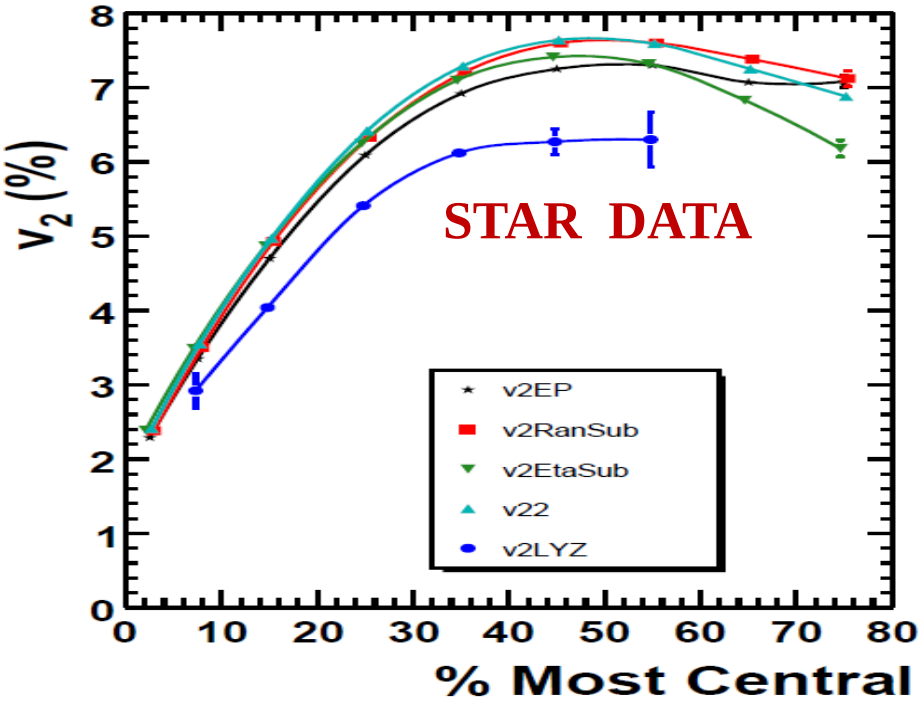
Compare with PHENIX DATA

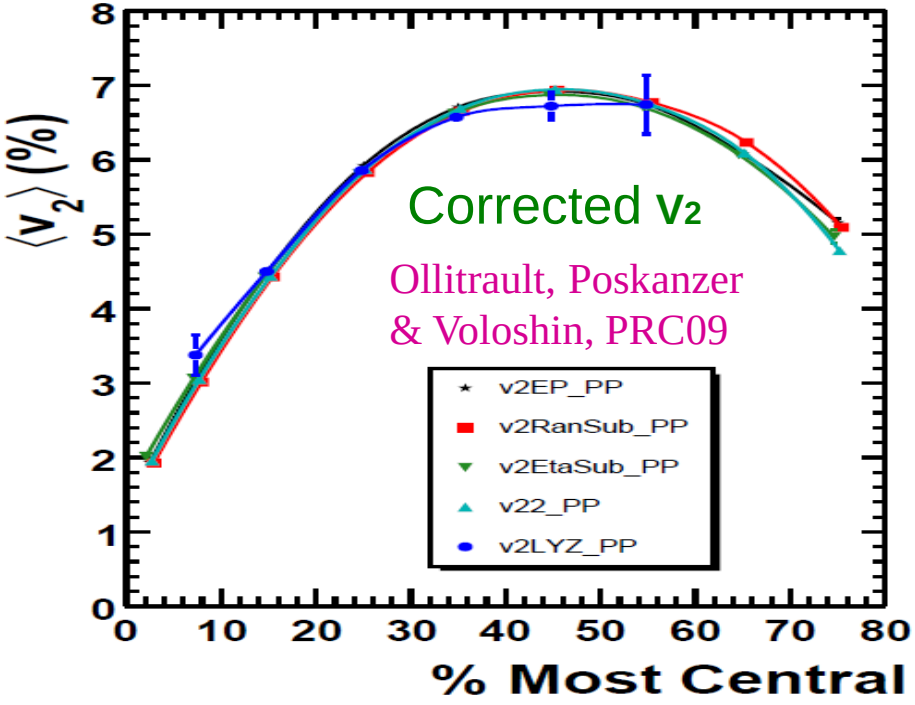

STAR DATA
40-50%
50-60%
60-70%
70-80%
p_T (GeV)
p_T (GeV)


v_2 (%)
STAR DATA
v2EP
v2RanSub
v2EtaSub
v22
v2LYZ
% Most Central

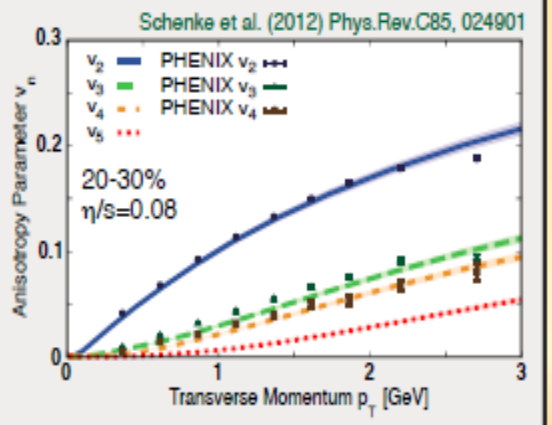

$\langle v_2 \rangle$ (%)
Corrected v_2
Ollitrault, Poskanzer
& Voloshin, PRC09
v2EP_PP
v2RanSub_PP
v2EtaSub_PP
v22_PP
v2LYZ_PP
% Most Central


MC-KLN
hydro (η/s) + UrQMD
η/s
0.0
0.08
0.16
0.24
(a)
v2/ε
0.25
0.2
0.15
0.1
0.05
0
v2{2} / ⟨ε²part⟩^1/2 KLN
⟨v2⟩ / ⟨εpart⟩KLN
0
10
20
30
(1/S) dNch/dy (fm-2)
MC-Glauber
hydro (η/s) + UrQMD
η/s
0.0
0.08
0.16
0.24
(b)
v2{2} / ⟨ε²part⟩^1/2 Gl
⟨v2⟩ / ⟨εpart⟩Gl
0
10
20
30
40
(1/S) dNch/dy (fm-2)

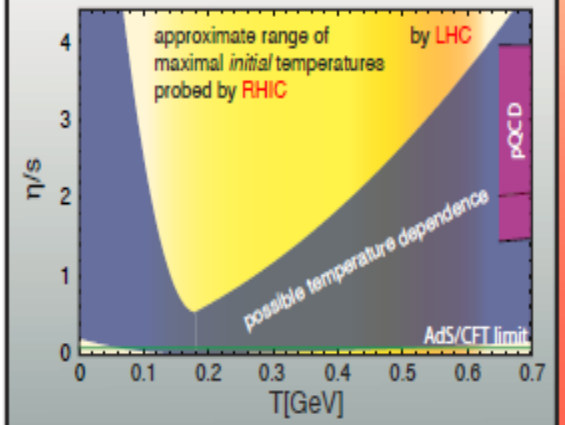

v2 (%)
STAR DATA
v2EP
v2RanSub
v2EtaSub
v22
v2LYZ
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
% Most Central


⟨v2⟩ (%)
Corrected v2
Ollitrault, Poskanzer
& Voloshin, PRC09
v2EP_PP
v2RanSub_PP
v2EtaSub_PP
v22_PP
v2LYZ_PP
0
1
2
3
4
5
6
7
8
0
10
20
30
40
50
60
70
80
% Most Central

Outlook



Higher moments constrain viscosity and fluctuating initial conditions better, but temperature dependence of η/s is not yet determined.



To determine (η/s)(T) different initial temperatures need to be accessible. Only possible with combined data from LHC and RHIC beam energy scan.

2012

2014

2022

- v_n
- v_n correlations
- $P(v_n)$

RHIC BES-II upgrade required to

- measure lower bound to ~10%
- determine (η/s)(T) dependence
- measure bulk viscosity and relaxation times
- constrain initial state and its fluctuations

- kinetic theory
- lattice QCD
- AdS/CFT limit
- viscous hydro + flow data

$$\frac{\eta}{s}(T),\ \frac{\zeta}{s}(T)$$

$$\tau_\eta,\ \tau_\zeta,\ \ldots$$

η/s near T_c

0 0.5 1 1.5 2

2012

2014

2022