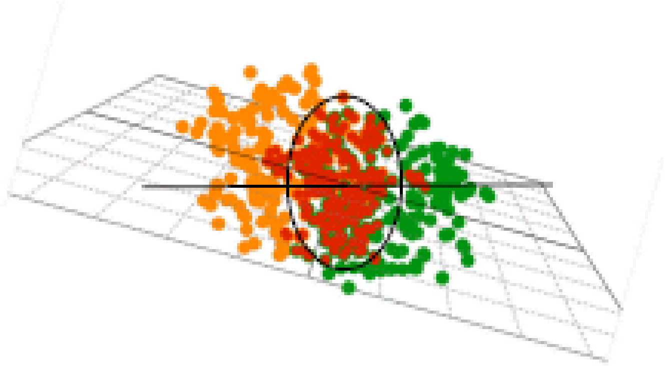
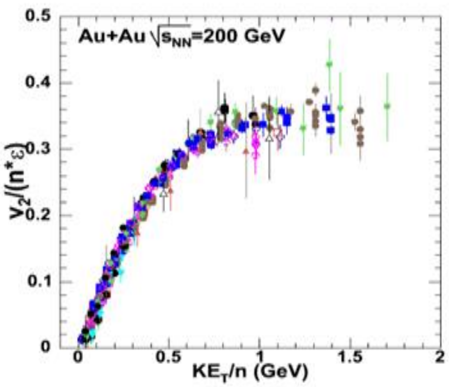
Collective Flow in Small and Large Colliding Systems





Arkadiy Taranenko

National Research Nuclear University MEPhI
(Moscow Engineering Physics Institute)

Modern problems in nuclear and elementary particle physics
11th APCTP-BLTP JINR-PNIP NRC KI-SPbU Joint Workshop
24 - 28 July 2017, Peterhof, Russia

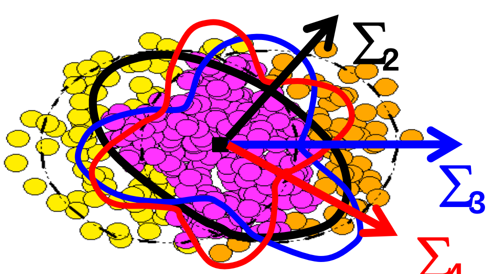
OUTLINE

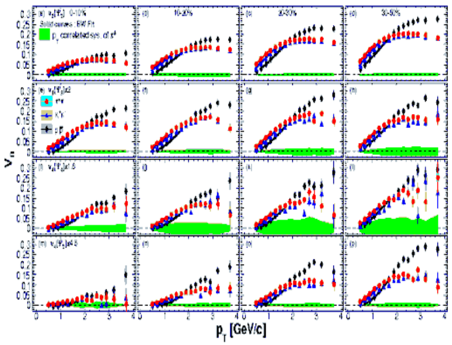
1) Introduction: anisotropic collective flow, methods

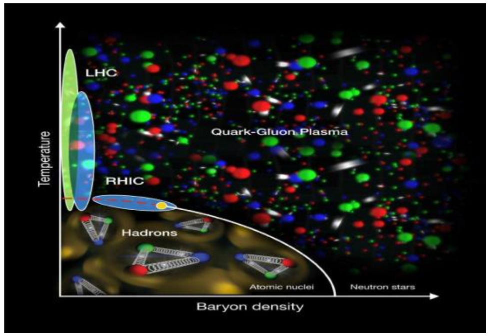
2) Results for Heavy-Ions at RHIC-LHC

3) Collective effects in small systems

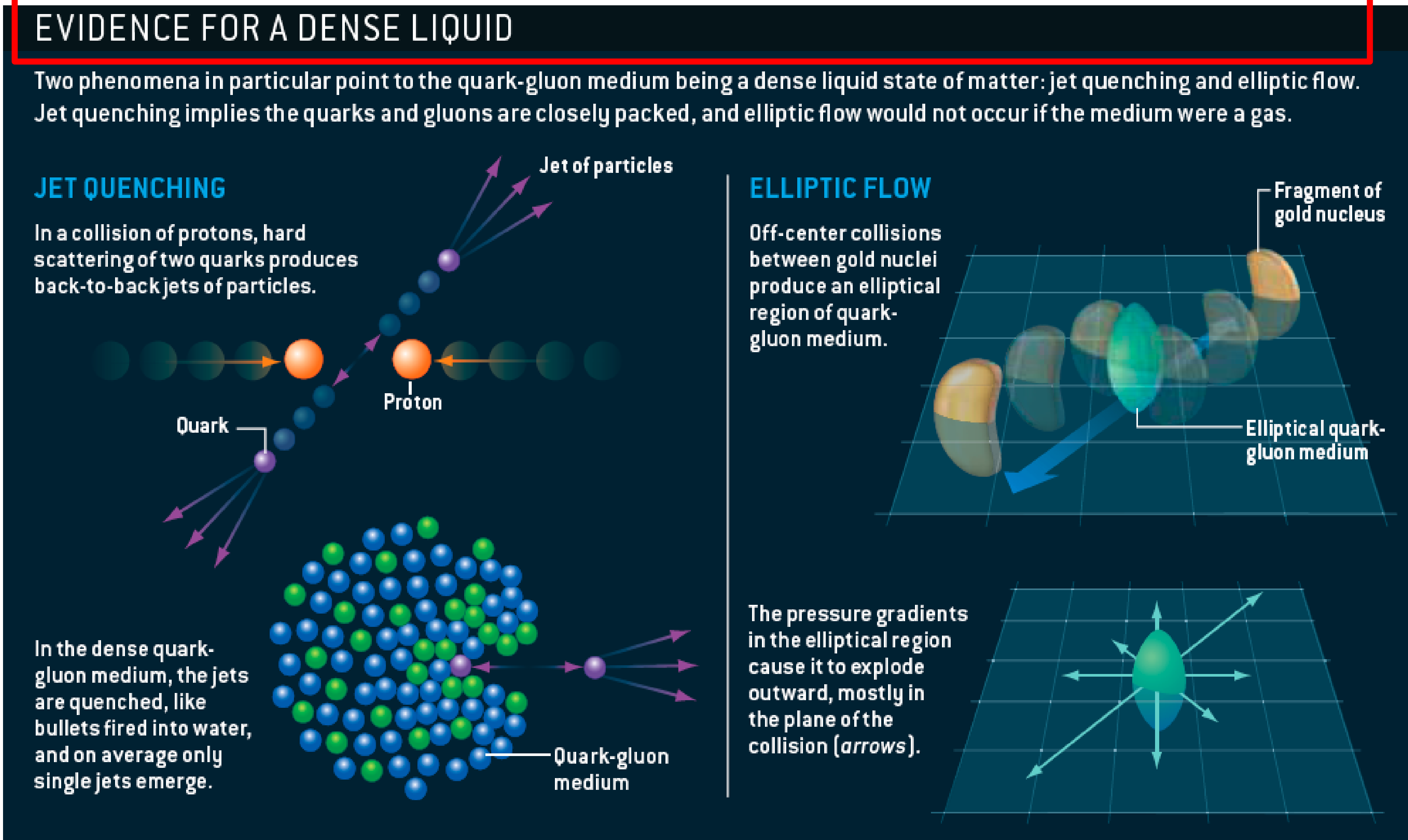
4) Summary





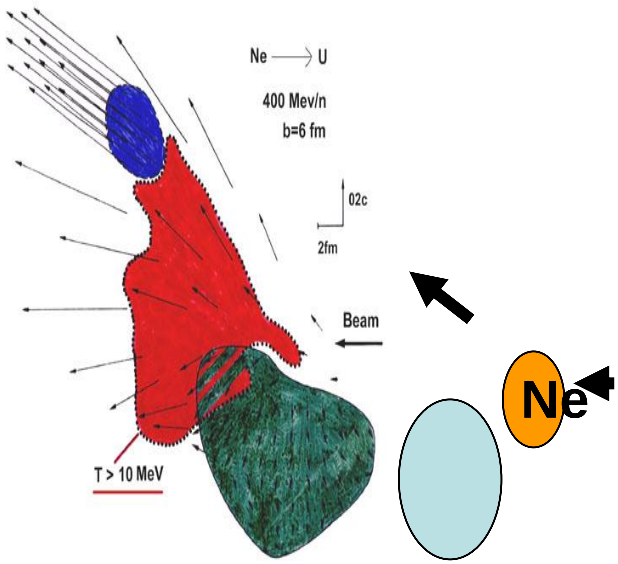


The sQGP Discovered at RHIC: 2005-2006

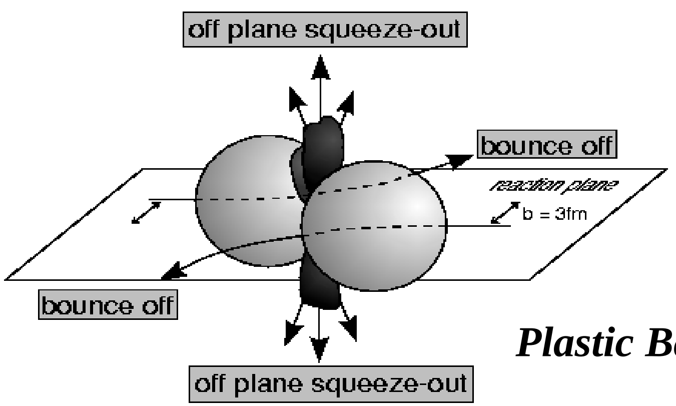


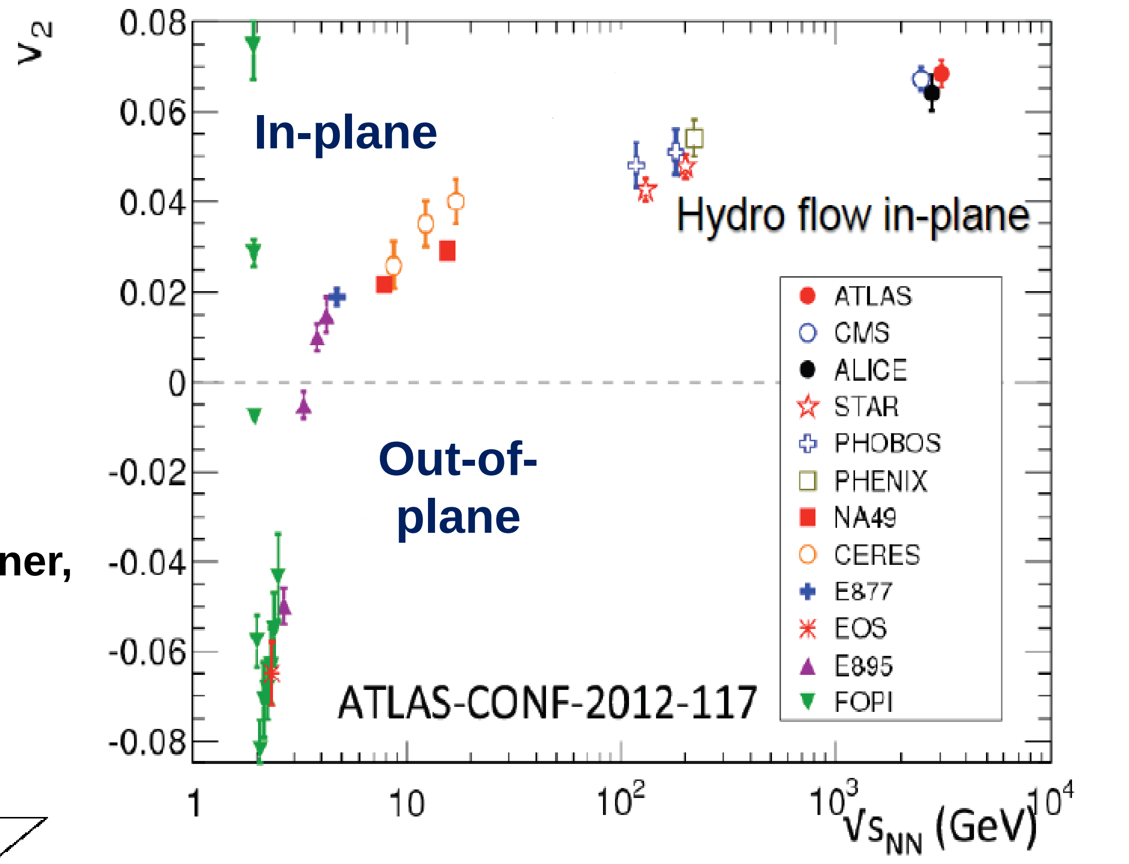
M. Roirdan and W. Zajc,
Scientific American, May 2006

Elliptic Flow at HIC: 1988-2001



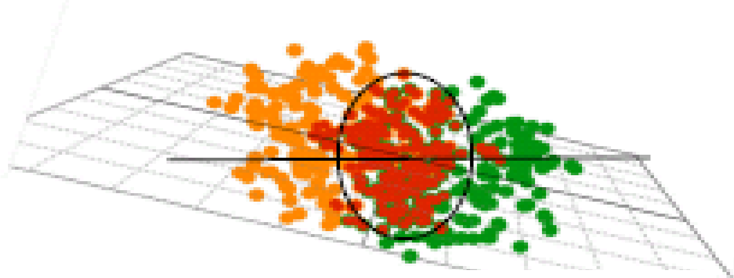
H. Stöcker, J.A. Maruhn, and W. Greiner, PRL 44, 725 (1980)

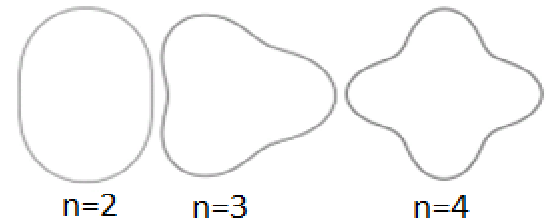




Plastic Ball, H.H. Gutbrod et al., Phys. Lett. B216, 267 (1989)

Anisotropic Flow at RHIC/LHC - methods





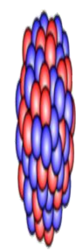
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

$$\frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

Initial eccentricity (and its attendant fluctuations) ε_n drive momentum anisotropy v_n with specific viscous modulation

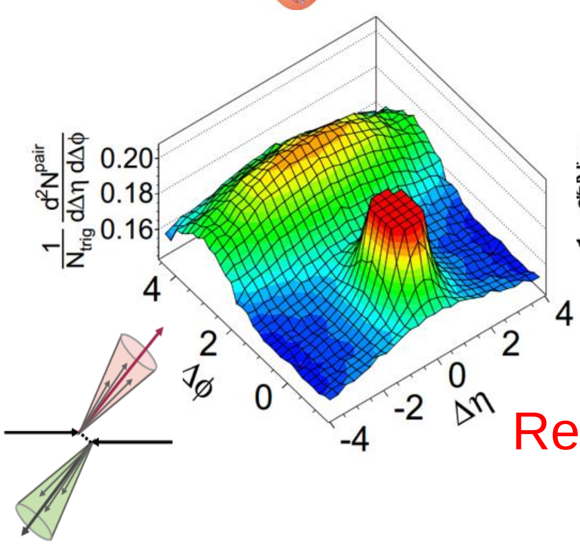
p+p

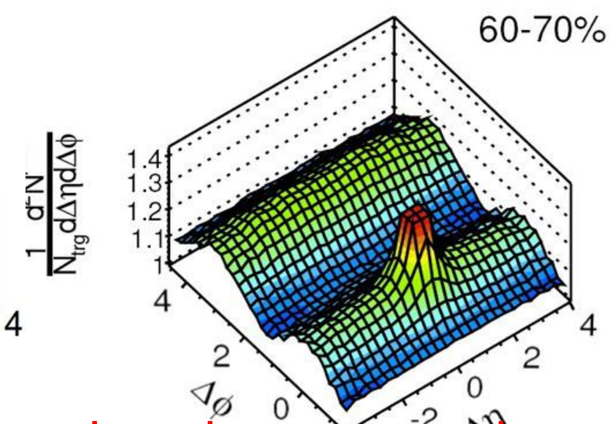
$$\frac{dN^{\text{pairs}}}{d\Delta\varphi} \propto \left(1 + \sum_{n=1} 2 v_n^a v_n^b \cos(n\Delta\varphi)\right)$$

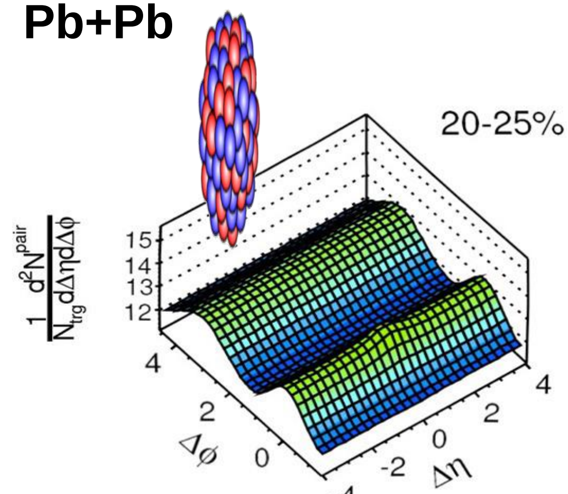


Pb+Pb

CMS 1201.3158







Requires the suppression of non-flow contributions

(**HBT, Jets & di-jets, Res. Decay, Mom. Consrv.**)

Different methods, non-flow, fluctuations

How fluctuations affect the measured values of v_n: $\sigma^2_{v_n} = \langle v_n^2 \rangle - \langle v_n \rangle^2$ - magnitude of flow flutuations

The effect of the fluctuations on v_n estimates can be obtained from

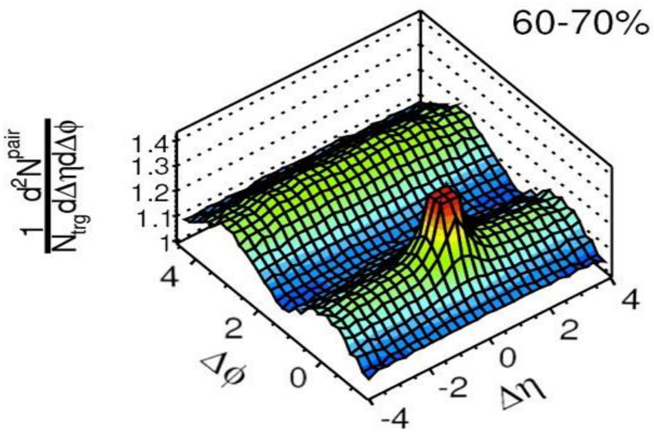
$$\begin{aligned} \langle v_n^2 \rangle &= \bar{v}_n^2 + \sigma^2_{v_n}, \\ \langle v_n^4 \rangle &= \bar{v}_n^4 + 6\sigma^2_{v_n}\bar{v}_n^2, \\ \langle v_n^6 \rangle &= \bar{v}_n^6 + 15\sigma^2_{v_n}\bar{v}_n^4, \end{aligned} \tag{1}$$

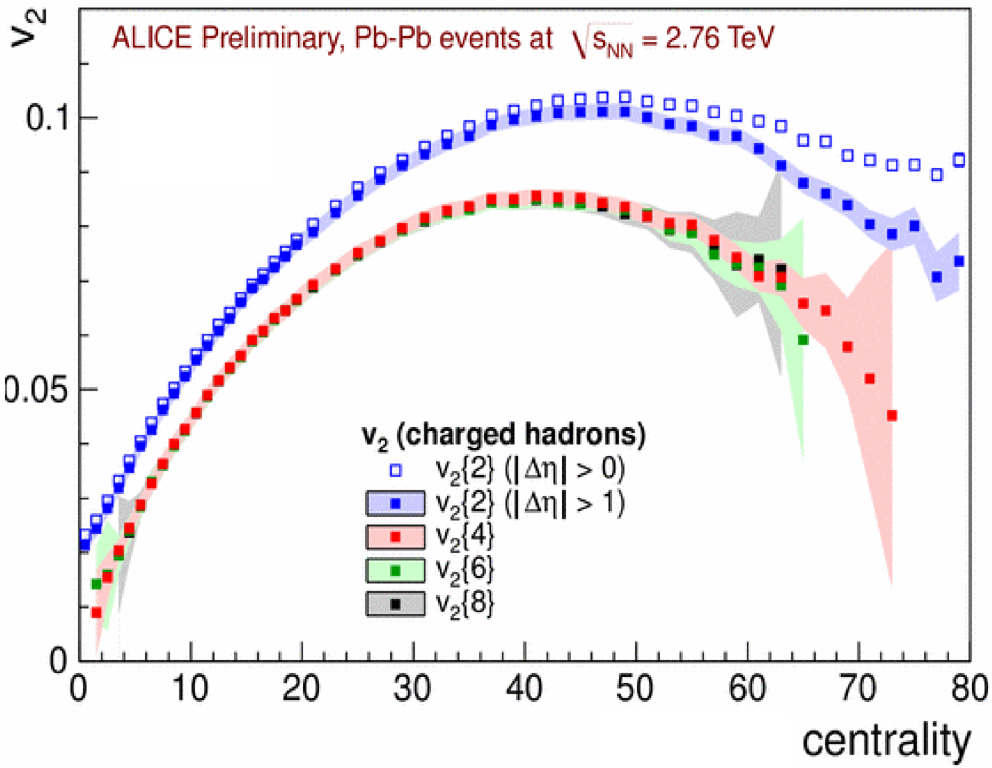
$$\begin{aligned} v_n\{2\} &= \sqrt{\langle v_n^2 \rangle}, \\ v_n\{4\} &= \sqrt[4]{2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle}, \\ v_n\{6\} &= \sqrt[6]{\frac{1}{4}(\langle v_n^6 \rangle - 9\langle v_n^2 \rangle\langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3)}. \end{aligned} \tag{2}$$

Here we have introduced the notation $v_n\{k\}$ as the flow estimate from the cumulant $c_n\{k\}$. In case that $\sigma_{v_n} \ll \bar{v}_n$ we obtain, up to order $\sigma^2_{v_n}$:

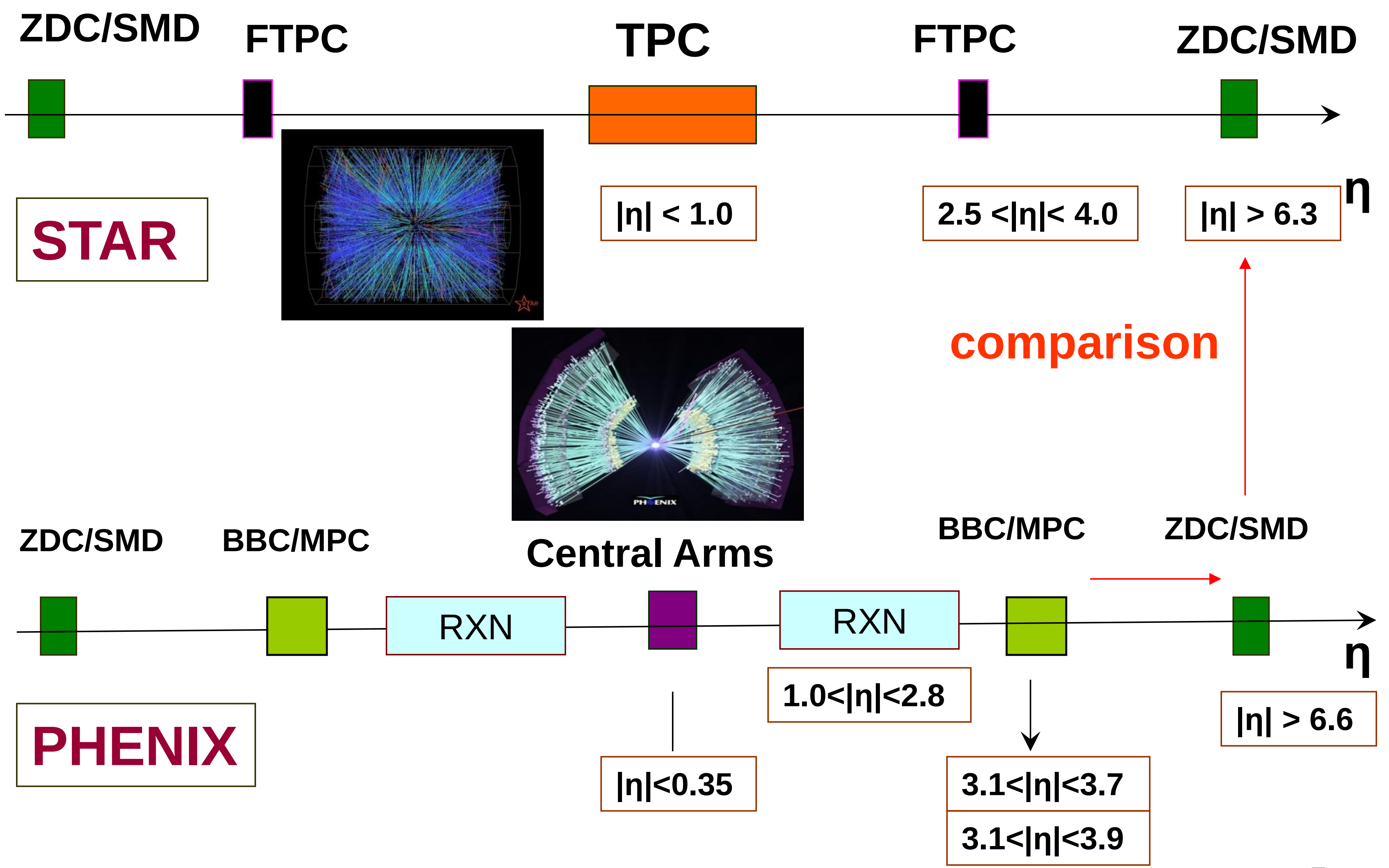
$$\begin{aligned} v_n\{2\} &= \bar{v}_n + \frac{1}{2}\frac{\sigma^2_{v_n}}{\bar{v}_n}, \\ v_n\{4\} &= \bar{v}_n - \frac{1}{2}\frac{\sigma^2_{v_n}}{\bar{v}_n}, \\ v_n\{6\} &= \bar{v}_n - \frac{1}{2}\frac{\sigma^2_{v_n}}{\bar{v}_n}. \end{aligned} \tag{3}$$

The difference between $v_n\{2\}$ and $v_n\{4\}$ is sensitive to not only nonflow but also to the event-by-event v_n fluctuations.



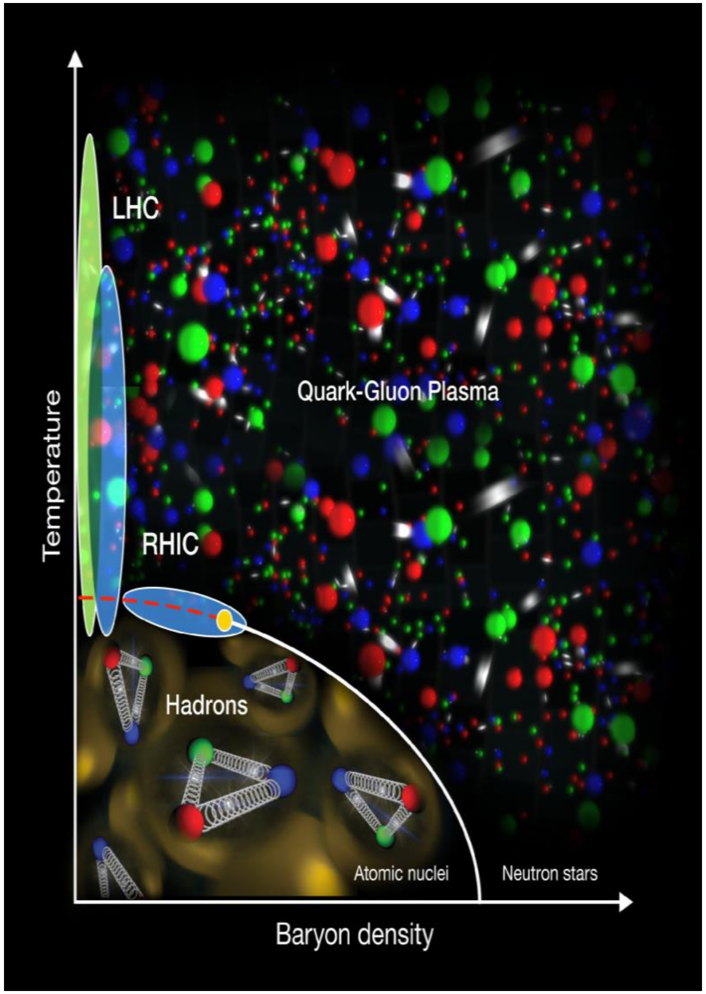


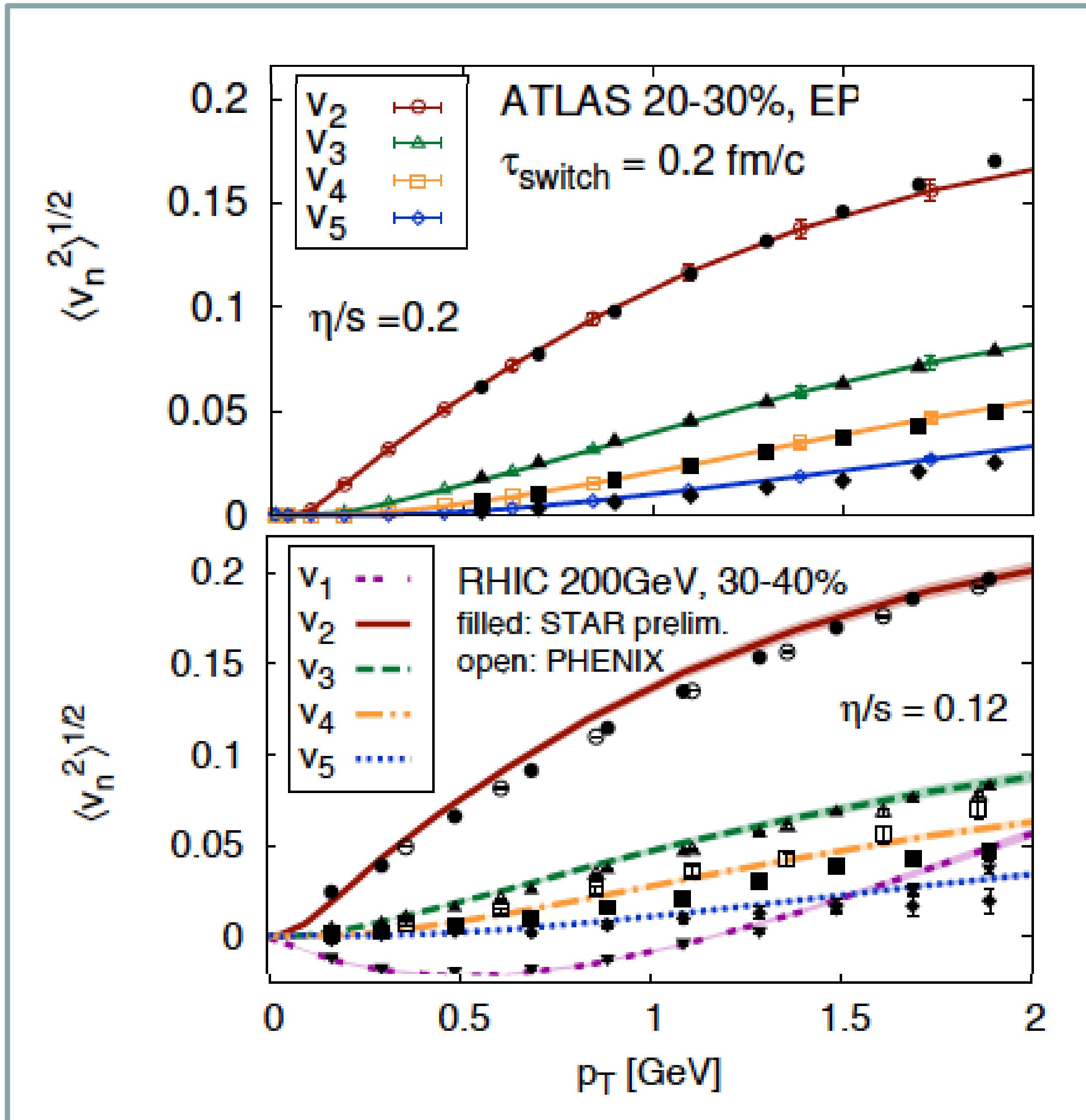
Flow Measurements at RHIC with STAR/PHENIX



2012- FVTX 1 < |η| < 3

Perfect Liquid at RHIC and LHC

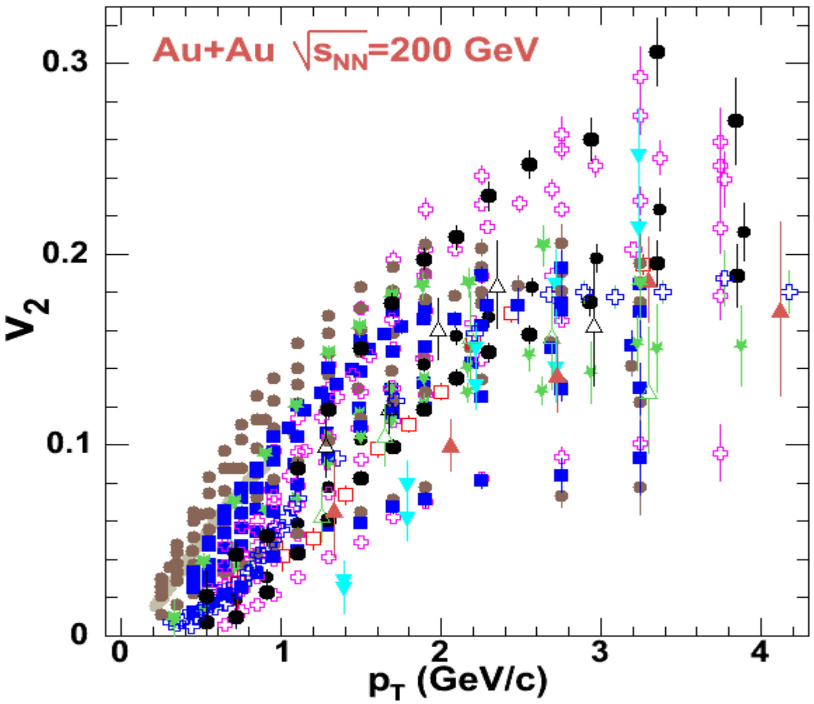




Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302

Calculation from Bjoern Schenke

Anisotropic Flow at RHIC – scaling relations

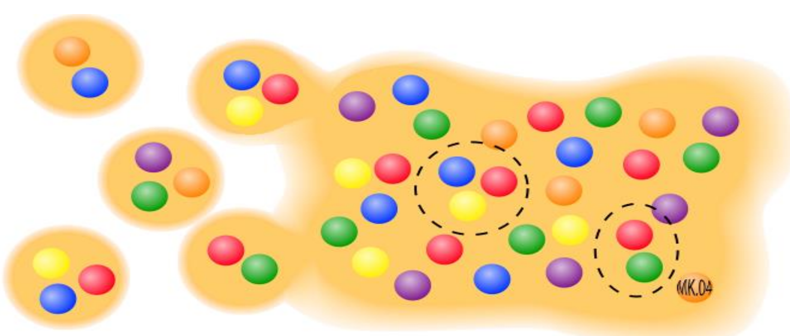


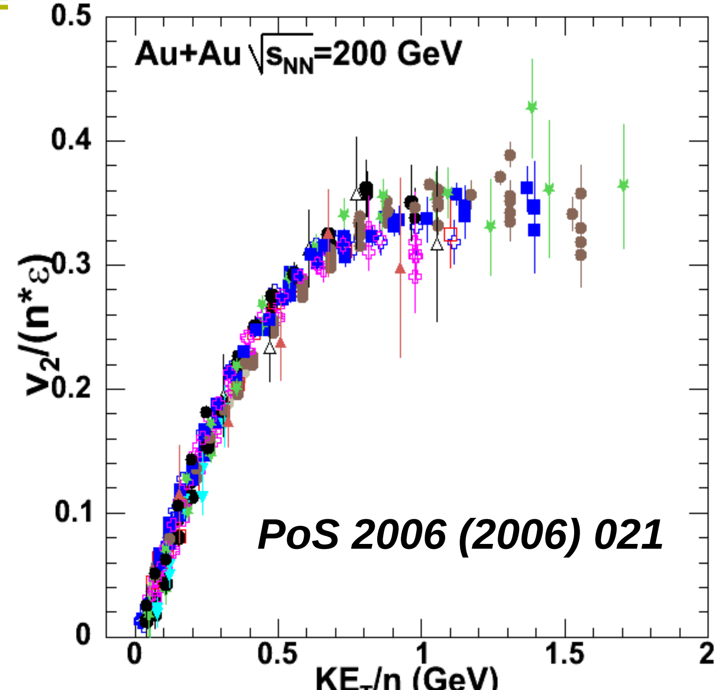
PHENIX (Phys.Rev.Lett.91, Preliminary: QM05, GRC 06)

- $\pi^+ + \pi^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $K^+ + K^-$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- $p+\bar{p}$: min.bias, 0-10%,10-20%,20-30%,30-40%,40-50%,20-60%
- d : min.bias, 10-50%
- ϕ : 20-60%

STAR (Phys. Rev. Lett. 92,Phys. Rev. C 72 (2005), Preliminary QM05, SQM06)

- $\pi^+ + \pi^-$: min.bias
- K^0_S : min.bias, 5-30%,30-70%
- $p+\bar{p}$: min.bias
- $\Lambda+\bar{\Lambda}$: min.bias, 5-30%,30-70%
- $\Xi+\bar{\Xi}$: min.bias
- $\Omega+\bar{\Omega}$: min.bias

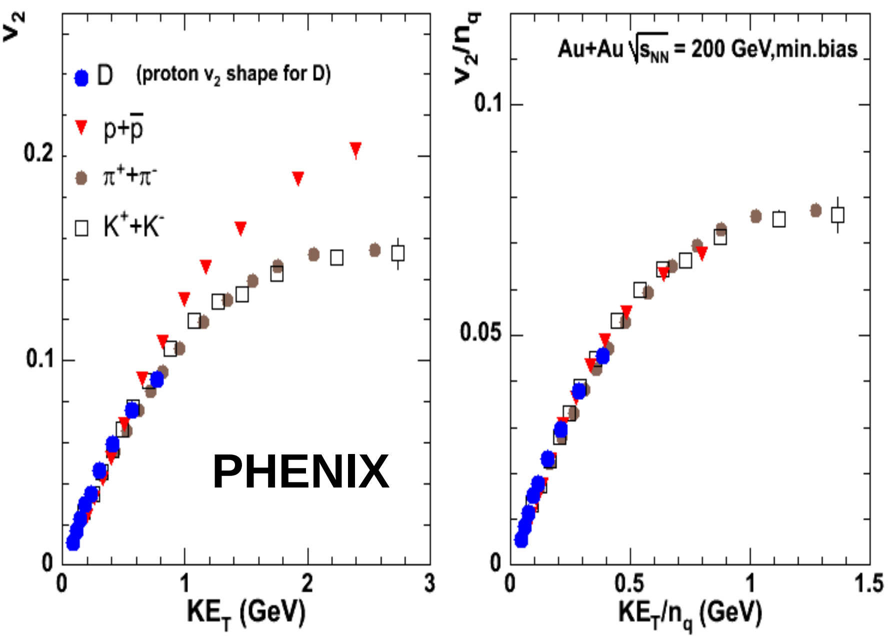




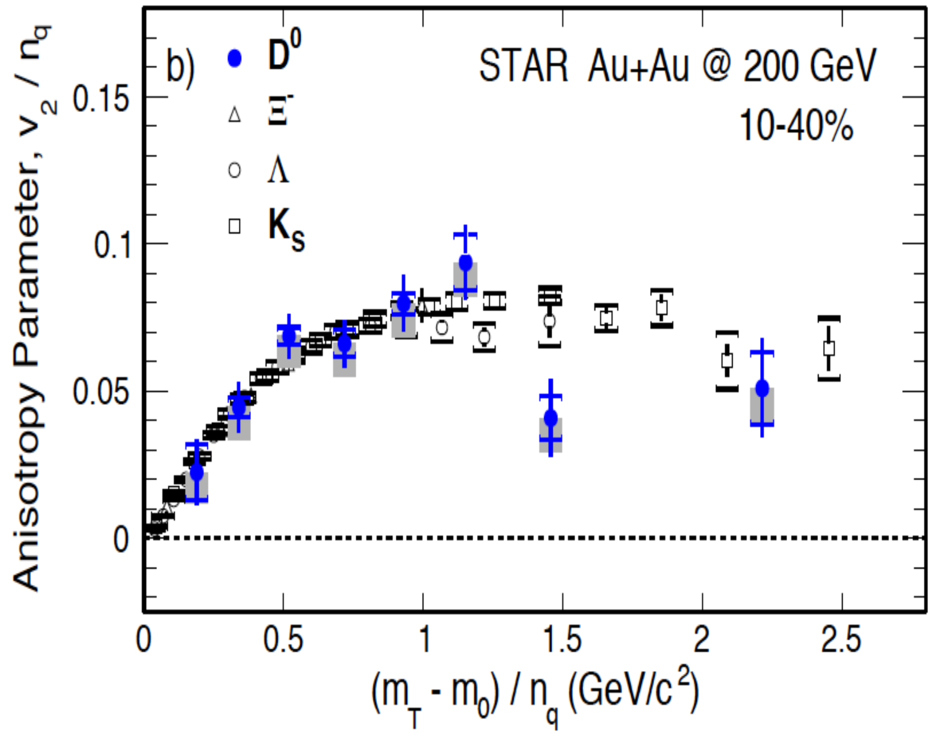
n=2 for mesons and n=3 for baryons

Elliptic flow of D meson in 2006-2017

PoS 2006 (2006) 021



PRL118 (2017) 212301

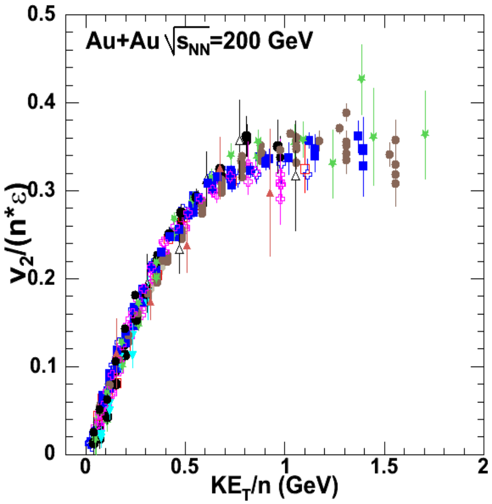


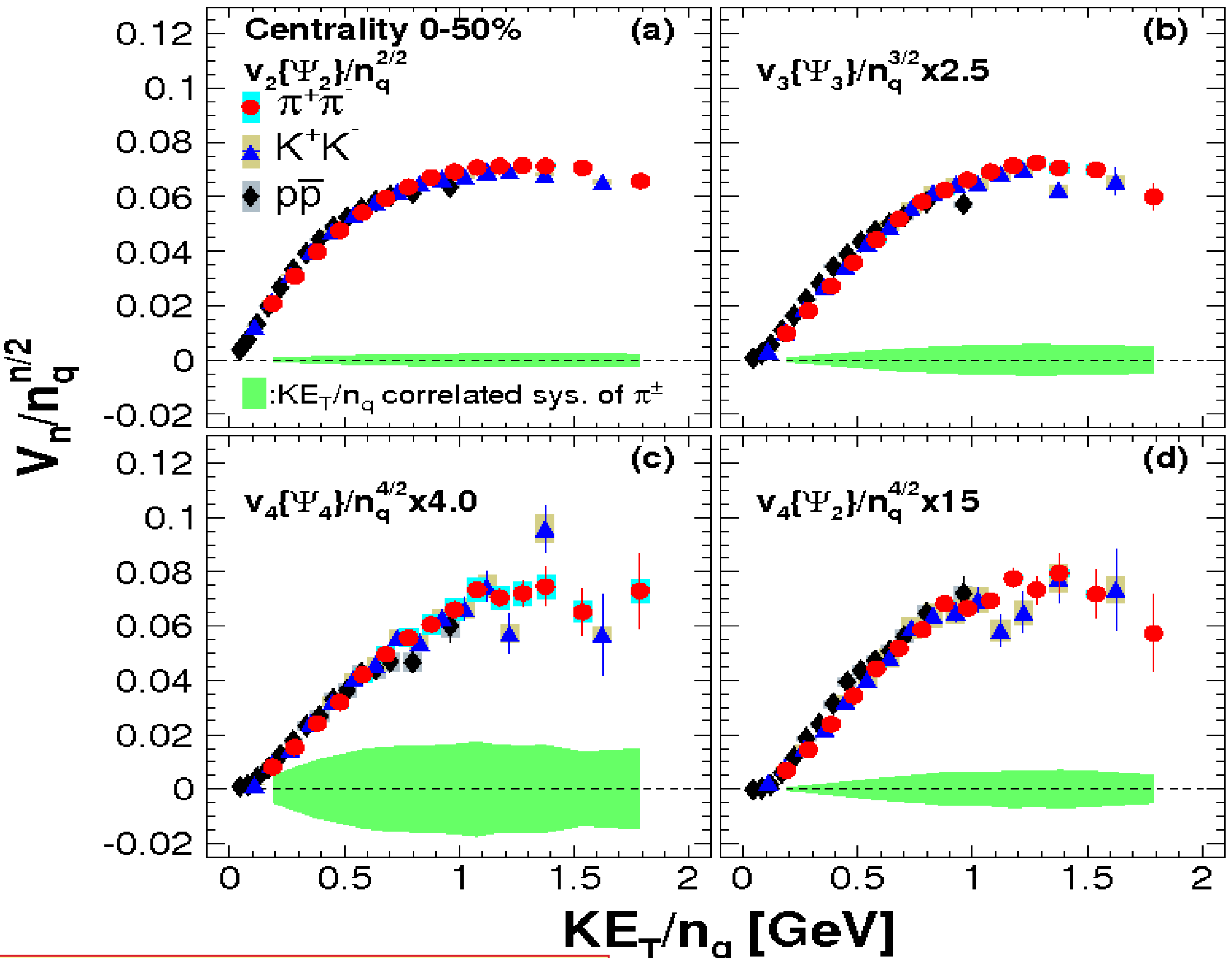
The D meson not only flows, it scales over the measured range

Flow at RHIC – scaling relations for $\mathbf{v_n}$

PHENIX 2015

Phys. Rev.C.93.051902(R)



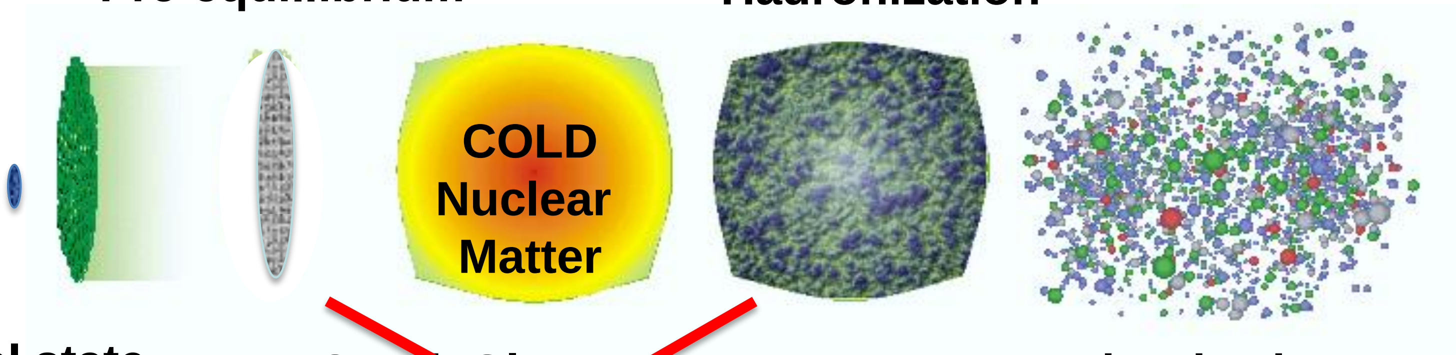


KE$_T$ & $(n_q)^{n/2}$ scaling validated for v_n
→ **Partonic flow**

Small colliding systems paradigm

Pre-equillibrium

Hadronization



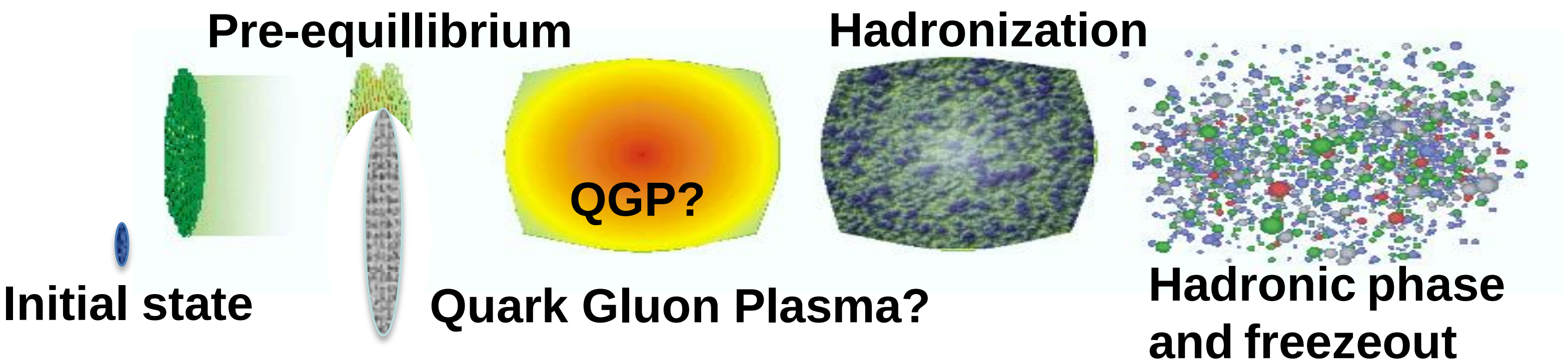
Initial state

~~Quark Gluon Plasma~~
~~thermally equilibrated~~
~~Hydrodynamic collective flow~~

Hadronic phase
and freezeout

- Not enough particles to achieve equilibration
- The formed medium is expected to be short-lived.
- No QGP
- pp collisions serve as a reference baseline
- pA or dA: reference for cold nuclear matter effects

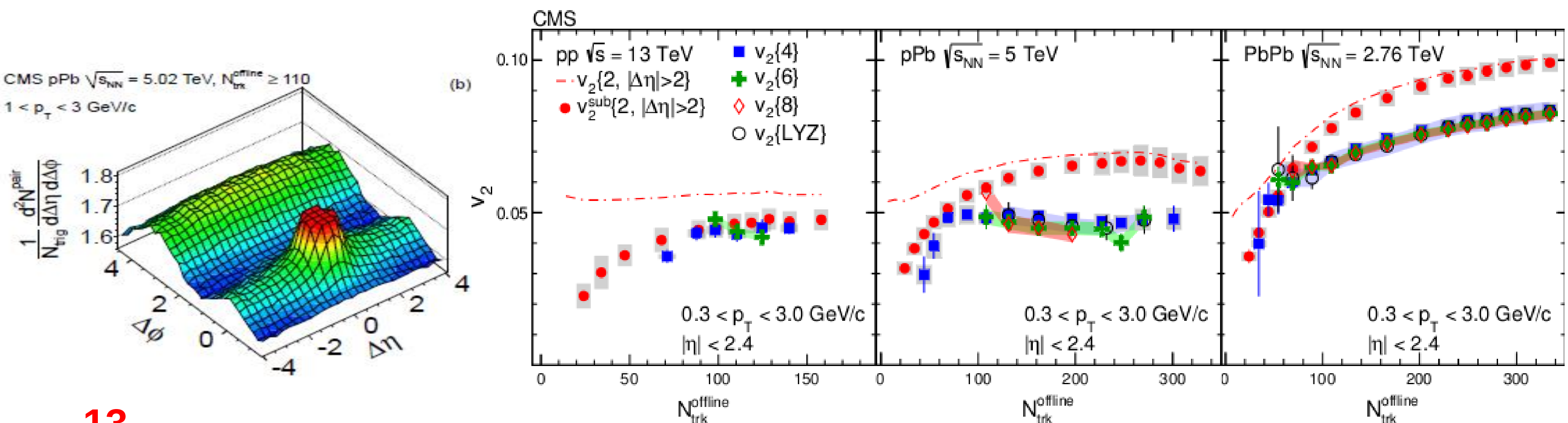
Collectivity in Small Colliding Systems



Final state interactions: Hydrodynamic Flow?

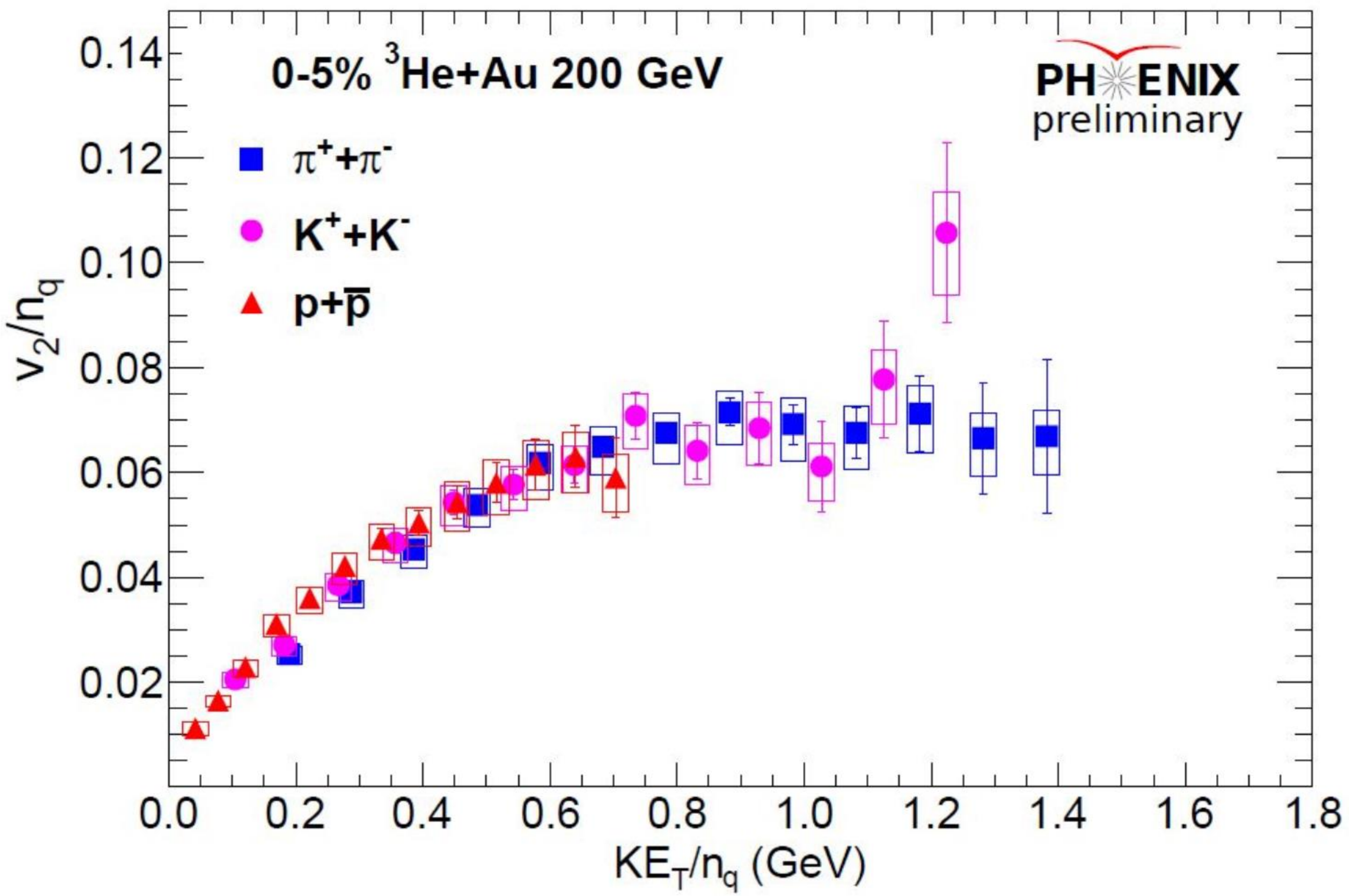
Initial momentum correlations: CGC?

How to distinguish initial vs final state effects ?

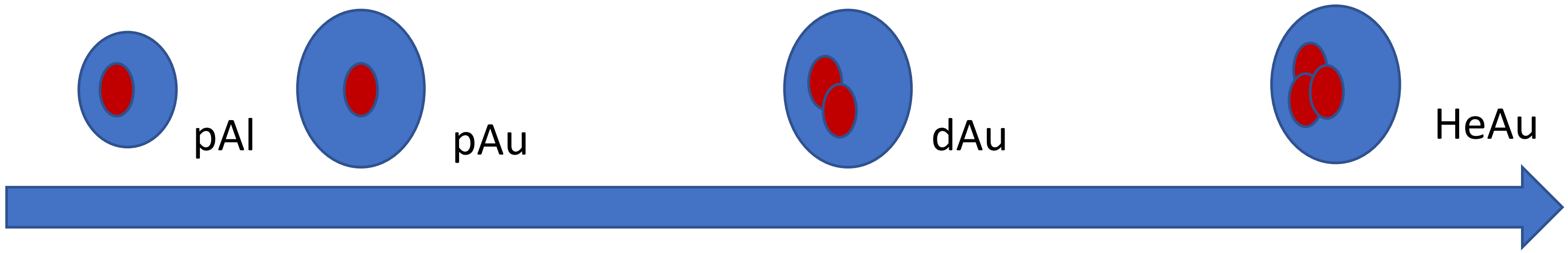


PLB 718 (2013) 795 PRL 115 (2015) 012301 PLB 726 (2013) 164

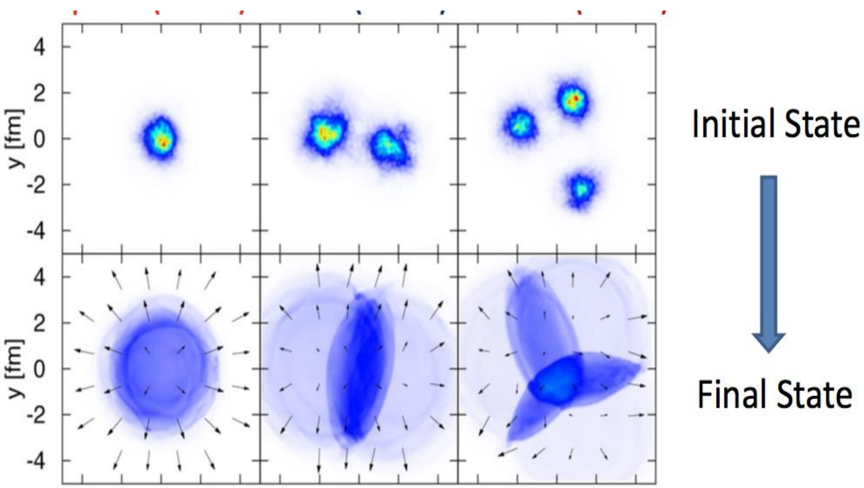
Collectivity in Small Colliding Systems (PID)



Small system program at RHIC



Geometry Scan

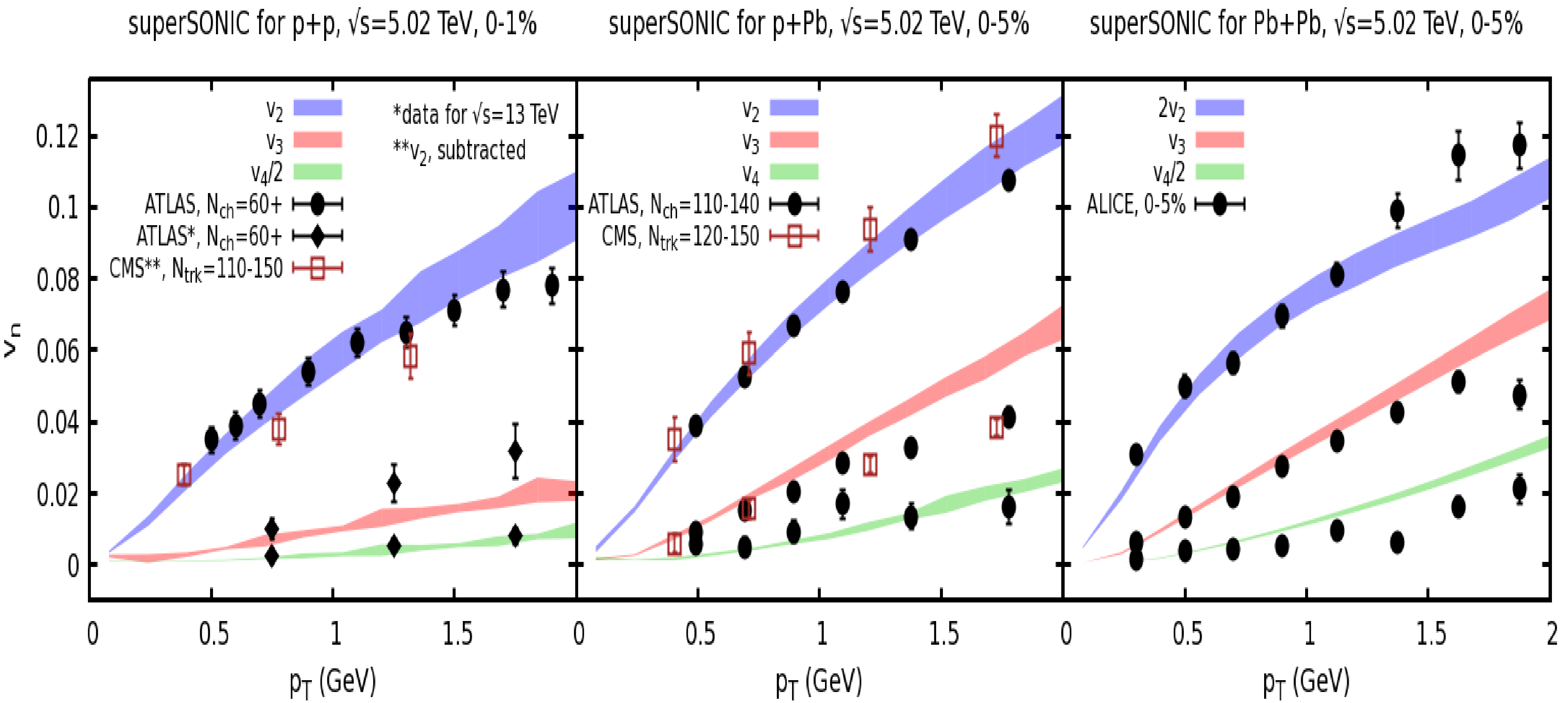


graphic from Bjoern Schenke

	0-5% p+Au	0-5% d+Au	0-5% He+Au
ε_2	0.23	0.54	0.50
ε_3	0.16	0.19	0.28

Different initial geometry → different final state particle emission for p+Au, d+Au and ^{3}He+Au collisions at 200 GeV

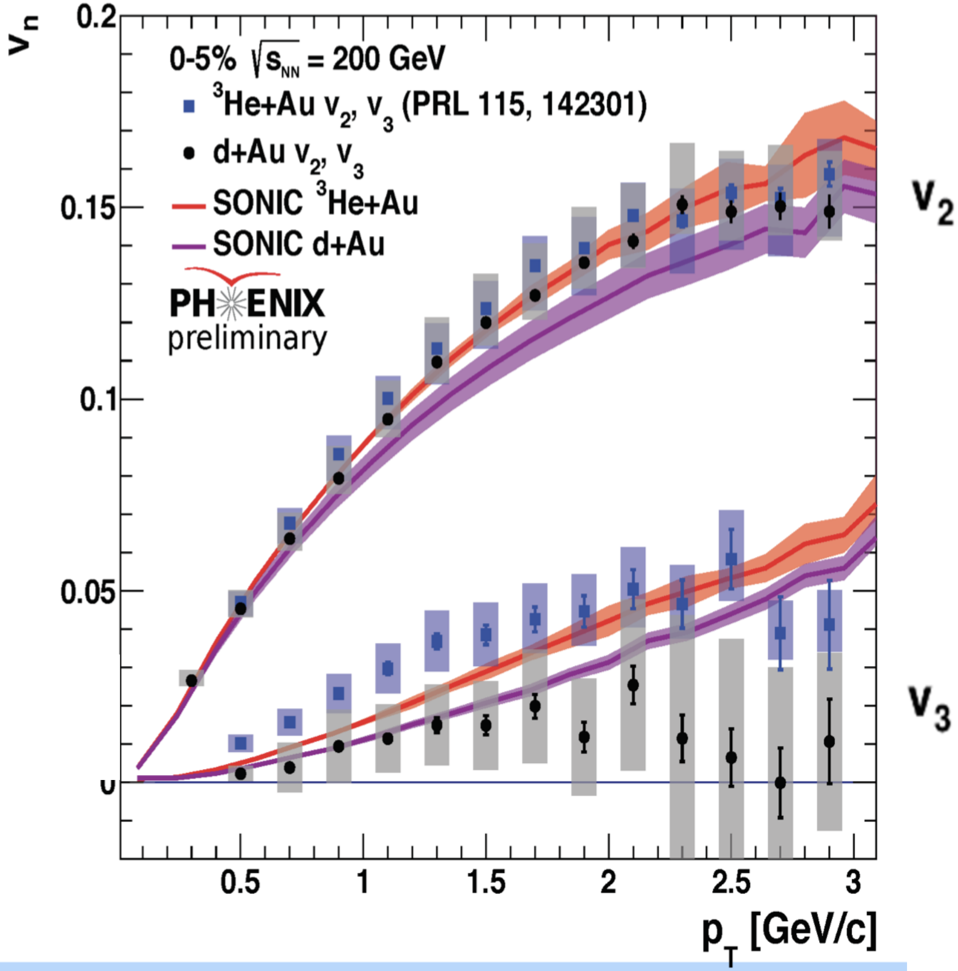
“ONE FLUID TO RULE THEM ALL”?

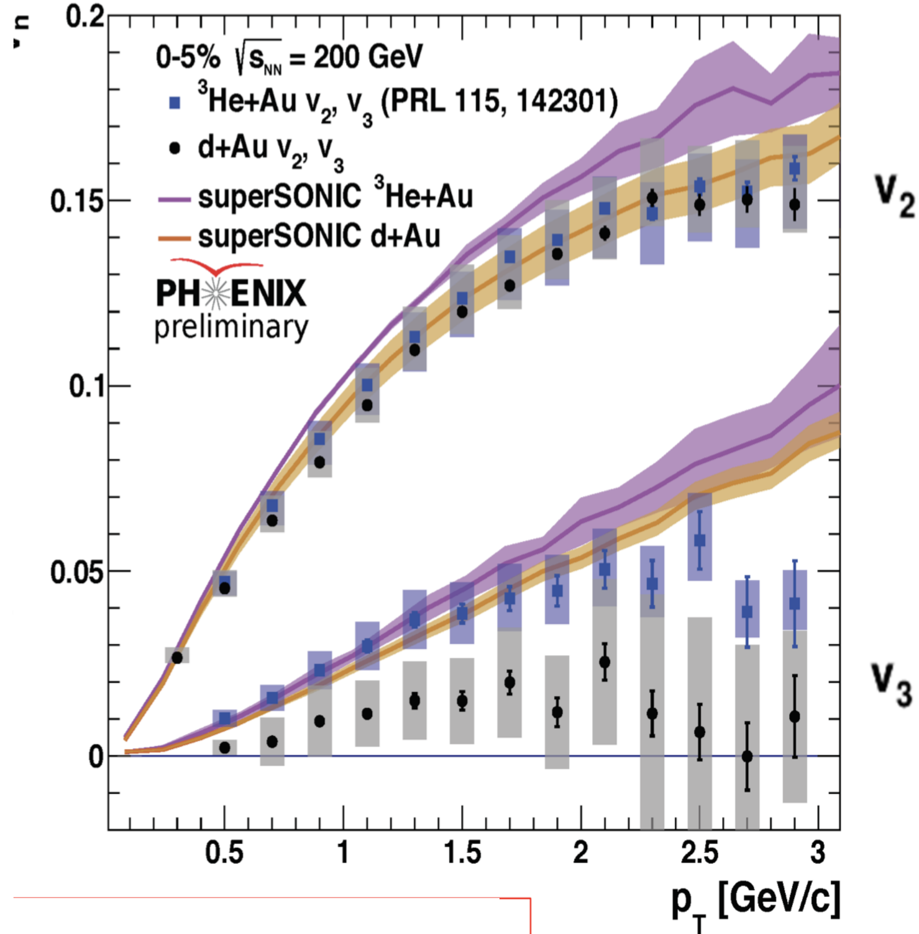


Ryan D. Weller, Paul Romatschke

[arXiv:1701.07145]

Comparison with viscous hydro calculations

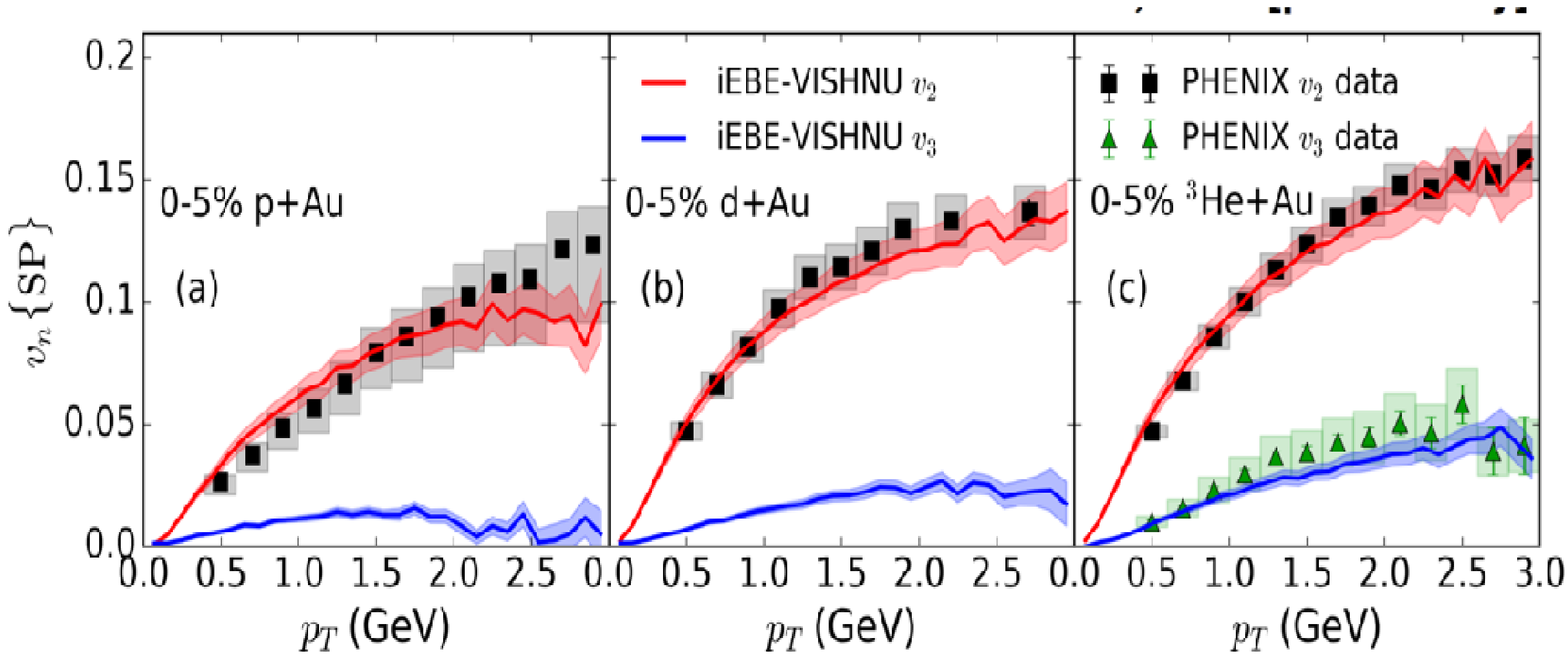




Hydro without preflow (SONIC) Better describes the data

Hydro with preflow (super SONIC) over estimates v_3 and v_2

Comparison with viscous hydro calculations



Hydrodynamic response converts spatial gradients into measured momentum anisotropy

C. Shen, *et al.*,

Phys. Rev. C **95**, 014906 (2017)

Indication of a strongly coupled QCD matter?

Flow is acoustic

PRC 84, 034908 (2011)
P. Staig and E. Shuryak.

- v_n measurements are sensitive to system shape (ε_n), system size (RT) and transport coefficients $\left(\frac{\eta}{s}, \frac{\zeta}{s}, \ldots\right)$.

arXiv:1305.3341
Roy A. Lacey, et al.

- Acoustic ansatz
  - ✓ Sound attenuation in the viscous matter reduces the magnitude of v_n.
- Anisotropic flow attenuation,

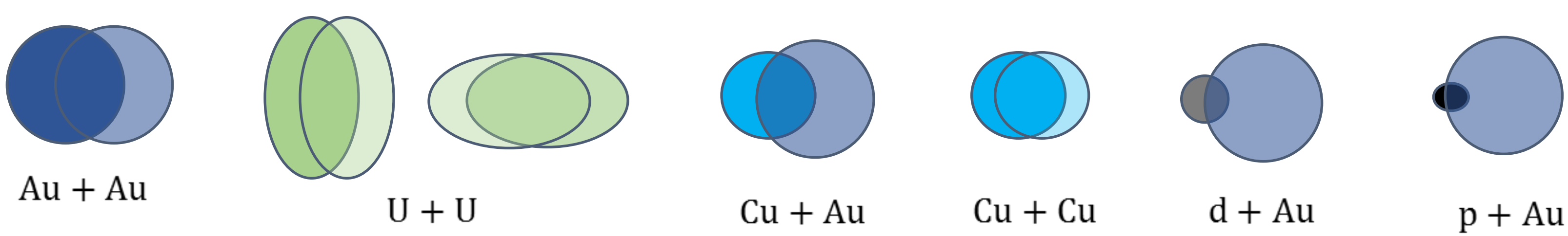
$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \quad \beta \propto \frac{\eta}{s}\frac{1}{RT}$$

arXiv:1601.06001
Roy A. Lacey, et al.

- From macroscopic entropy considerations $S \sim (RT)^3 \propto \frac{dN}{d\eta}$

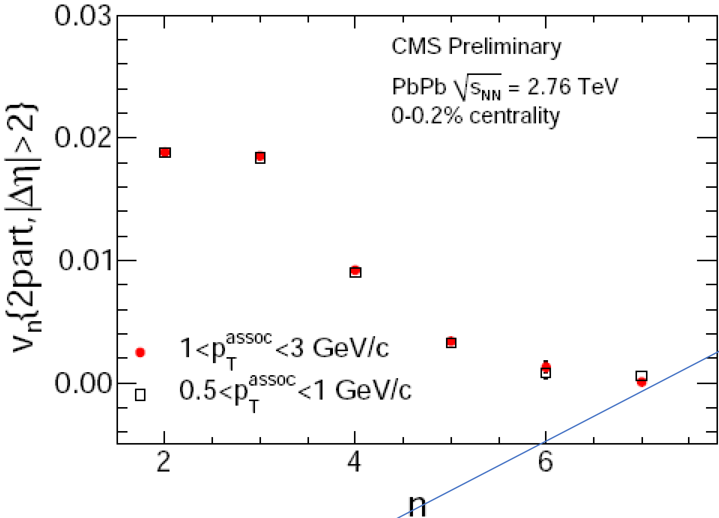
PRC 88, 044915 (2013)
E. Shuryak and I. Zahed

$$ln\left(\frac{v_n}{\epsilon_n}\right) \propto A\,\frac{\eta}{s}\left(\frac{dN}{d\eta}\right)^{\frac{-1}{3}}$$

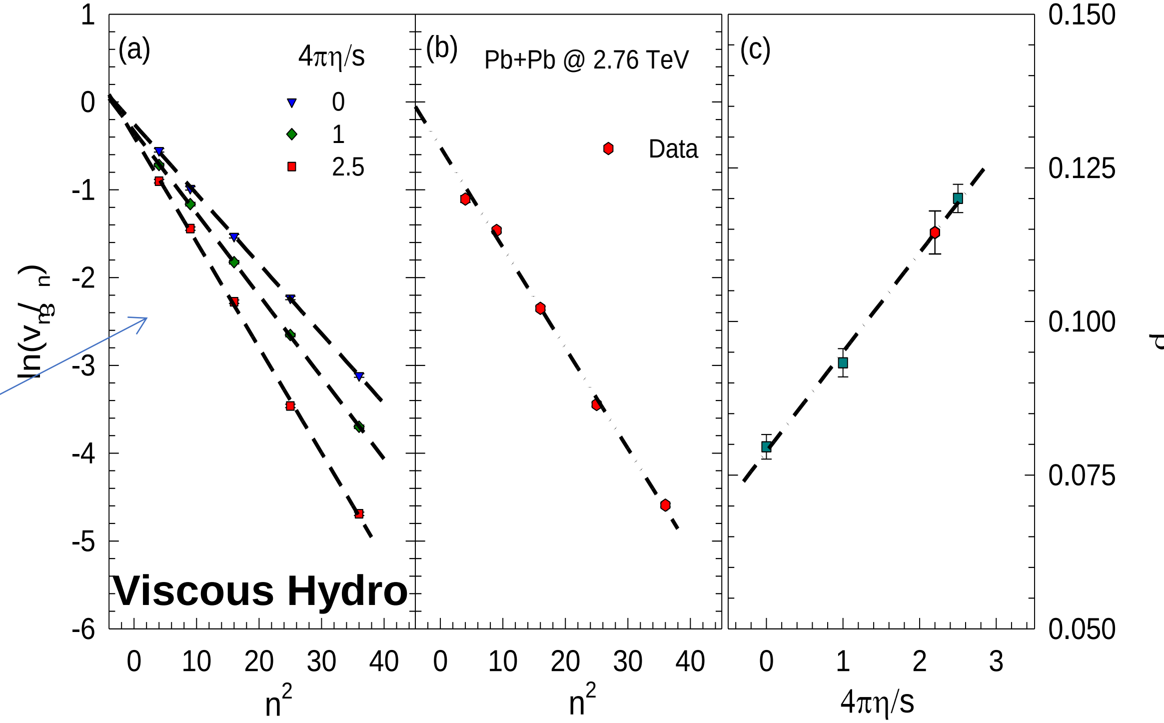


Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

$$\boxed{\frac{v_n(p_T)}{\varepsilon_n} \propto \cdot \exp\left(-\beta' n^2\right)}$$



arXiv:1301.0165 & CMS PAS HIN-12-011



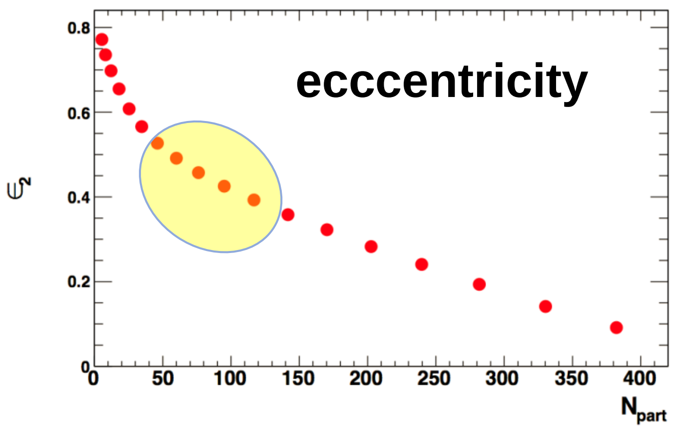
Slope sensitive to η/s

Characteristic n^2 viscous damping validated in viscous hydrodynamics;

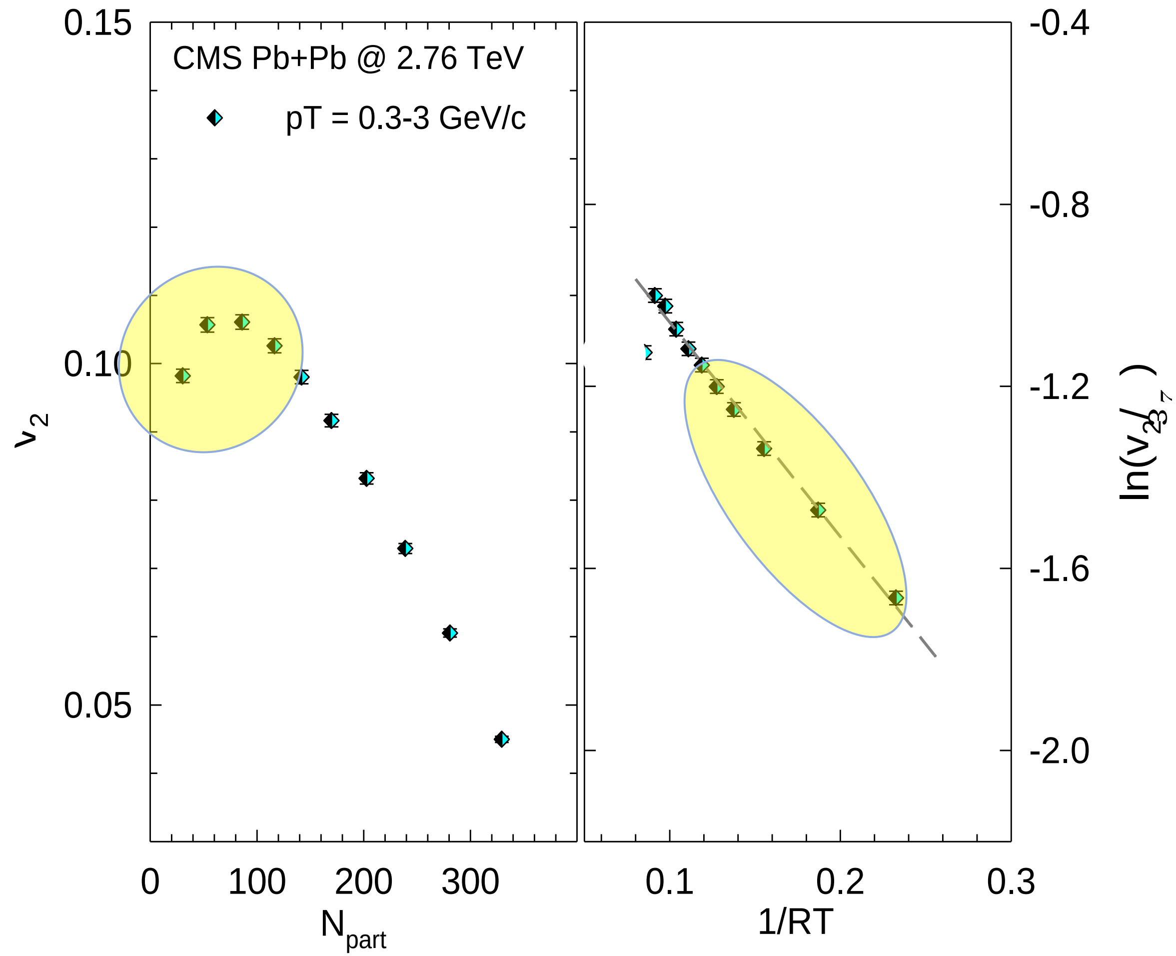
Acoustic Scaling - RT

$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{RT}$$

$$RT \propto \left(\frac{dN_{chg}}{d\eta}\right)^{1/3}$$



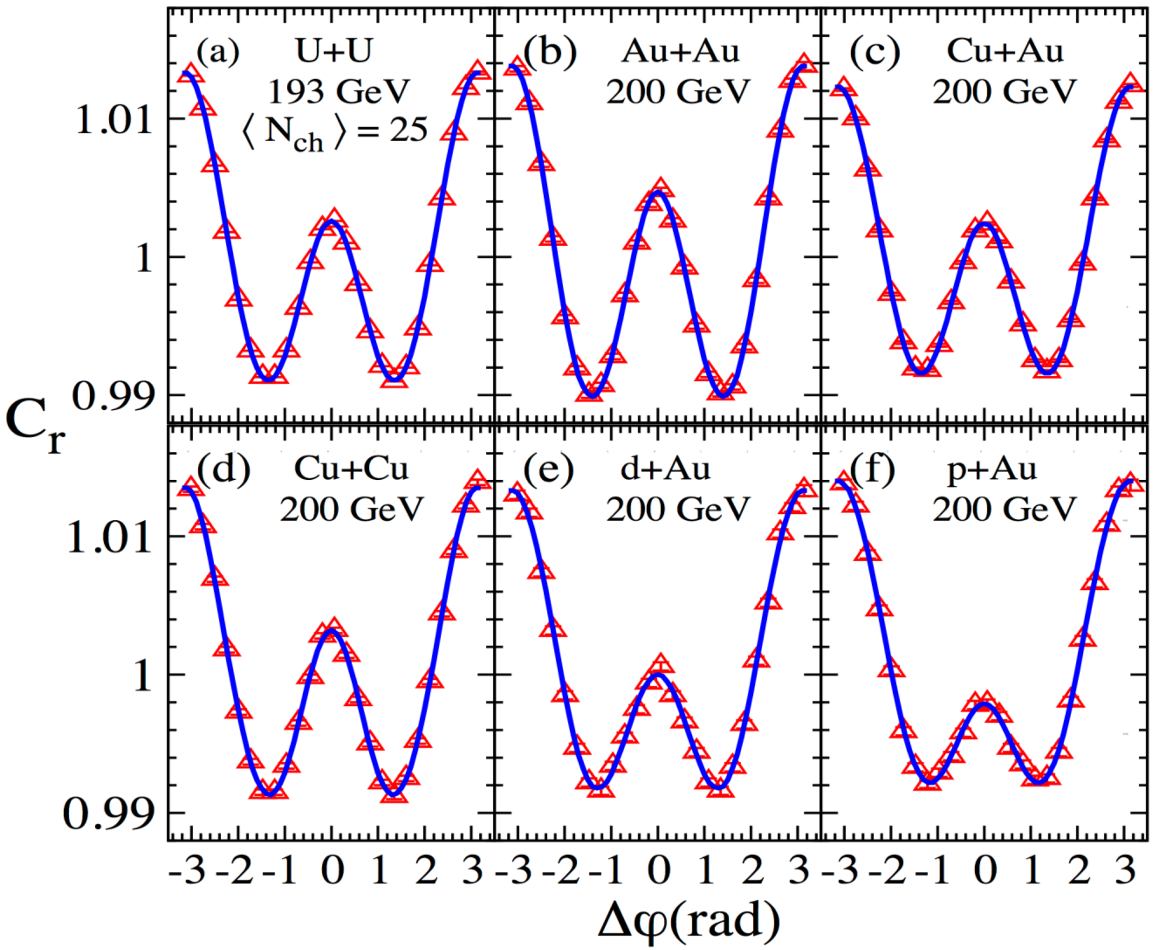
- Eccentricity change <u>alone</u> is not sufficient



✓ Characteristic 1/(RT) viscous damping validated
✓ Similar patterns for other p_T selections
✓ Important constraint for η/s & ζ/s

Ridge from large to small system (STAR)

STAR Preliminary, AUM2017

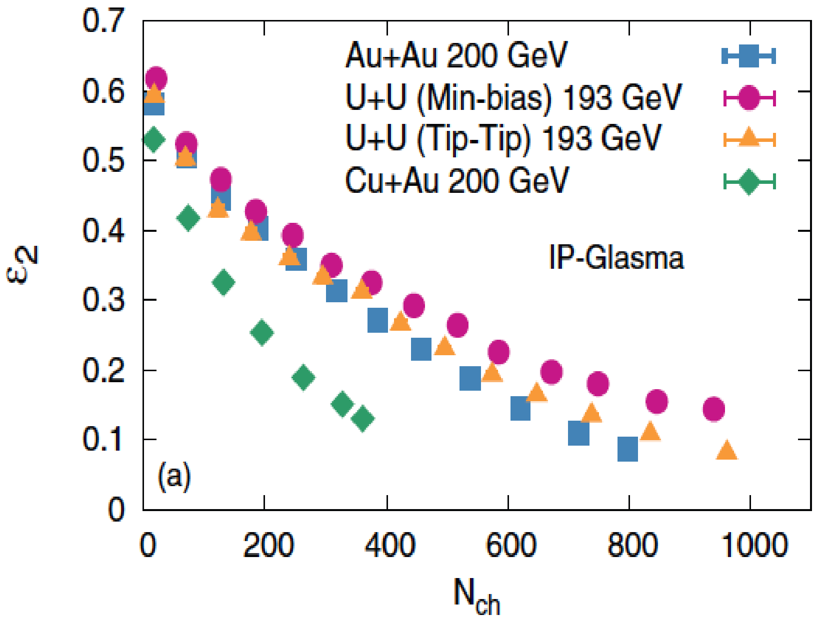


$|\Delta\eta|$>0.7, 0.2< p_T< 4.0 GeV

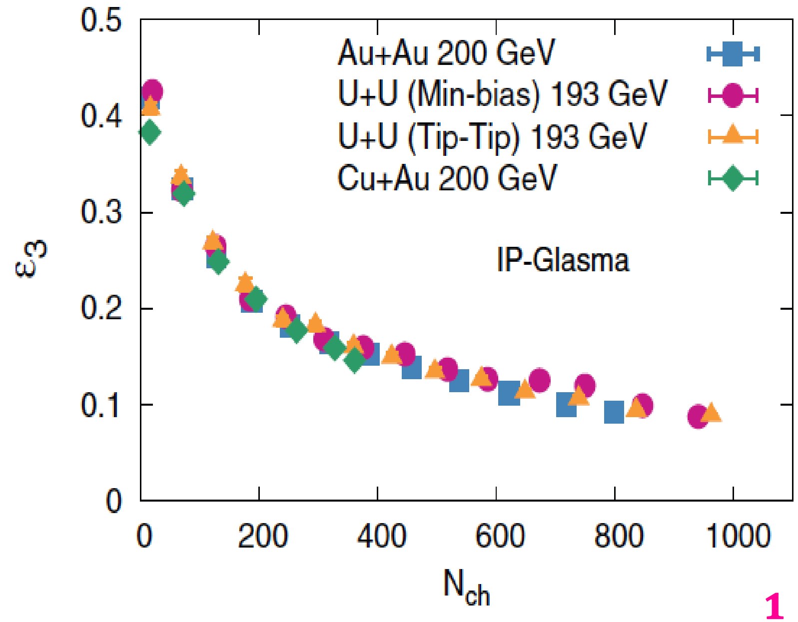
At a fixed <Nch>=25, the ridge is seen from large(UU, AuAu …) to small system(dAu, pAu)

Different systems, one unique picture?

v_n for a fixed <Nch>?



PRC 89, 064908 (2014)



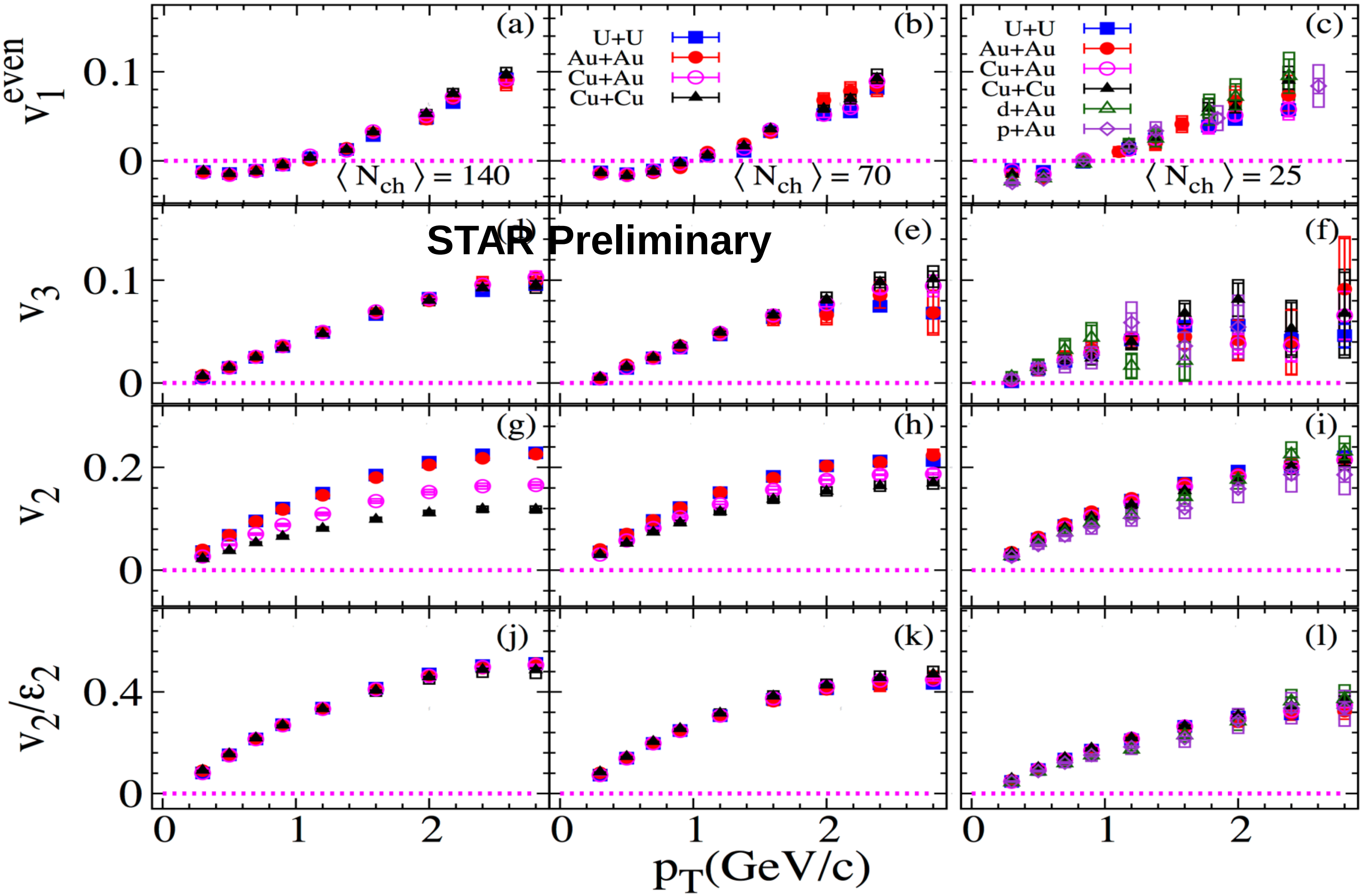
$$\varepsilon_3 \propto \frac{1}{\sqrt{N}}$$

Even harmonics are system dependent

Odd harmonics are system independent.

v_n for a fixed <Nch>

STAR Preliminary

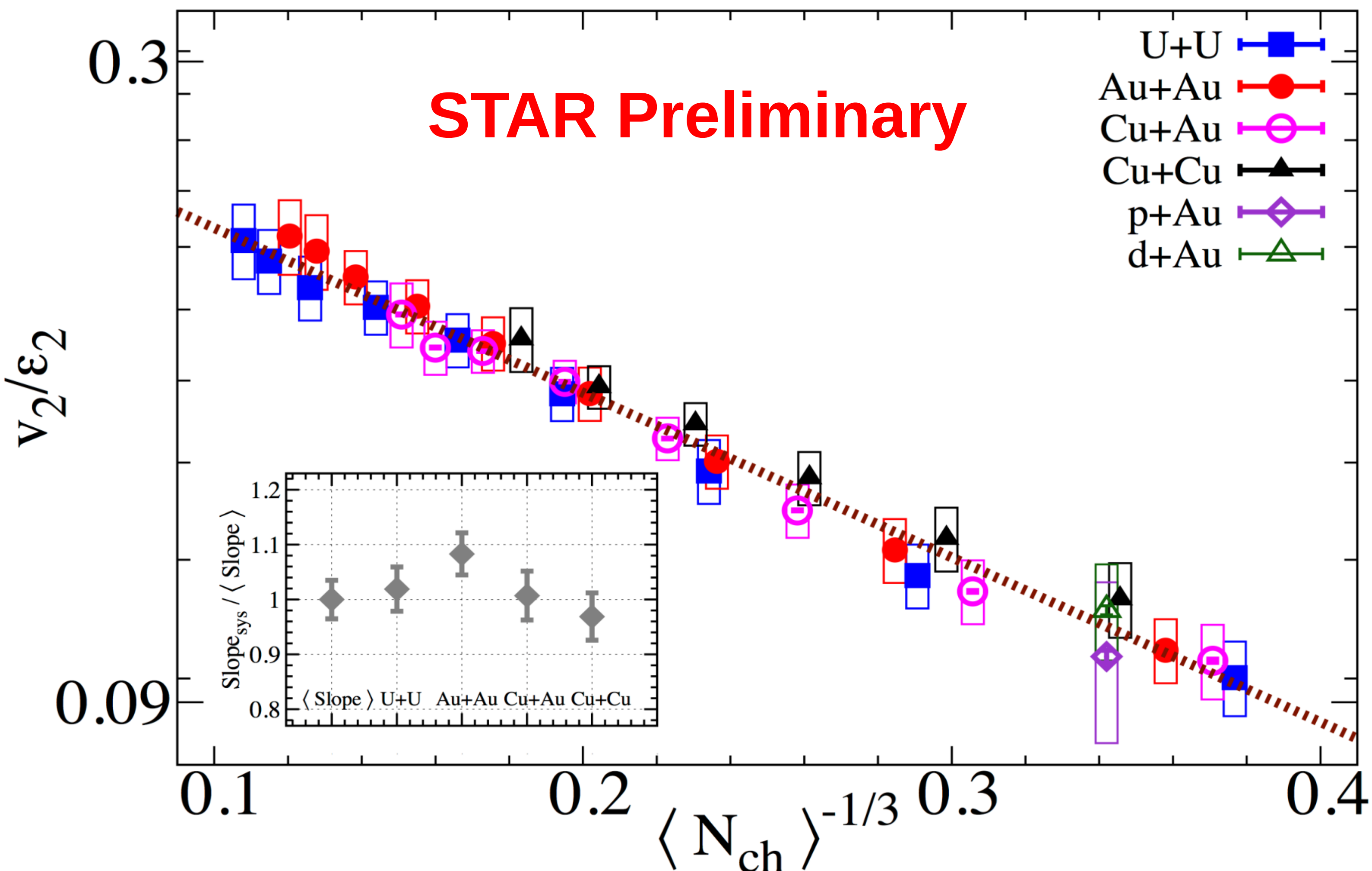


For a fixed <Nch>, the v_2/ε_2 are similar for different systems

Even harmonics are system dependent.**1**

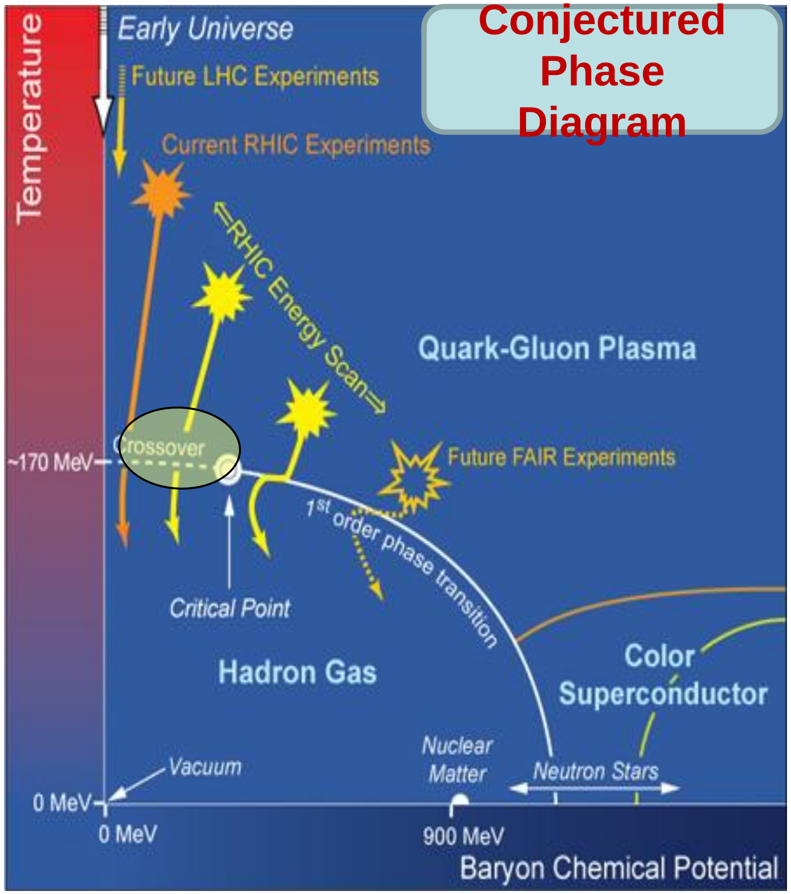
Odd harmonics are system independent.

STAR: V_2 for different colliding systems



STAR Preliminary

Quantitative study of the QCD phase diagram



Validation of the crossover transition leading to the QGP

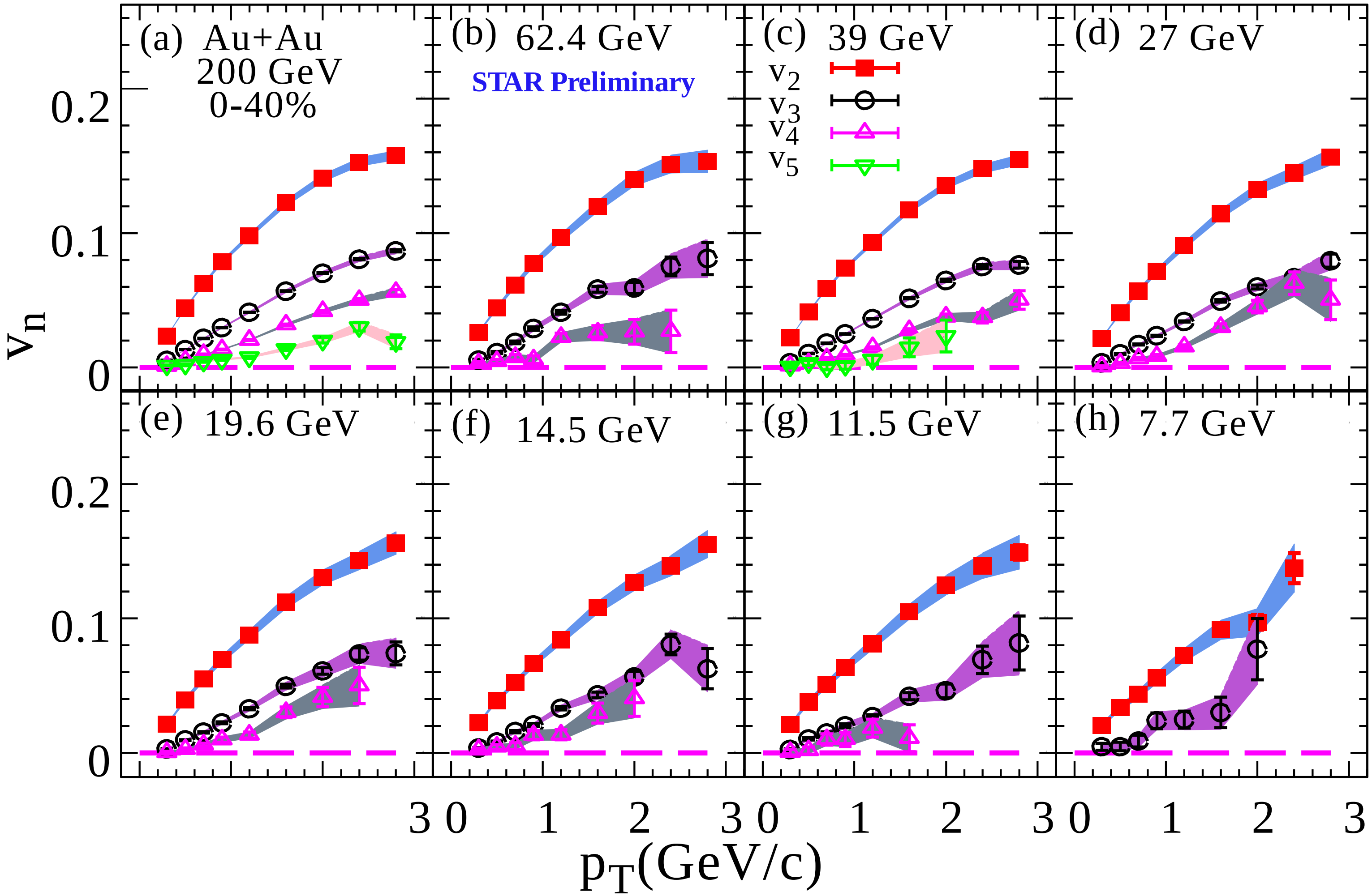
→ **Necessary requirement for CEP**

Strategy for RHIC BES

- **Map turn-off of QGP signatures**
- **Location of the Critical End Point (CEP)?**
- **Location of phase coexistence regions?**
- **1st order phase transition signs**
- **Detailed properties of each phase?**

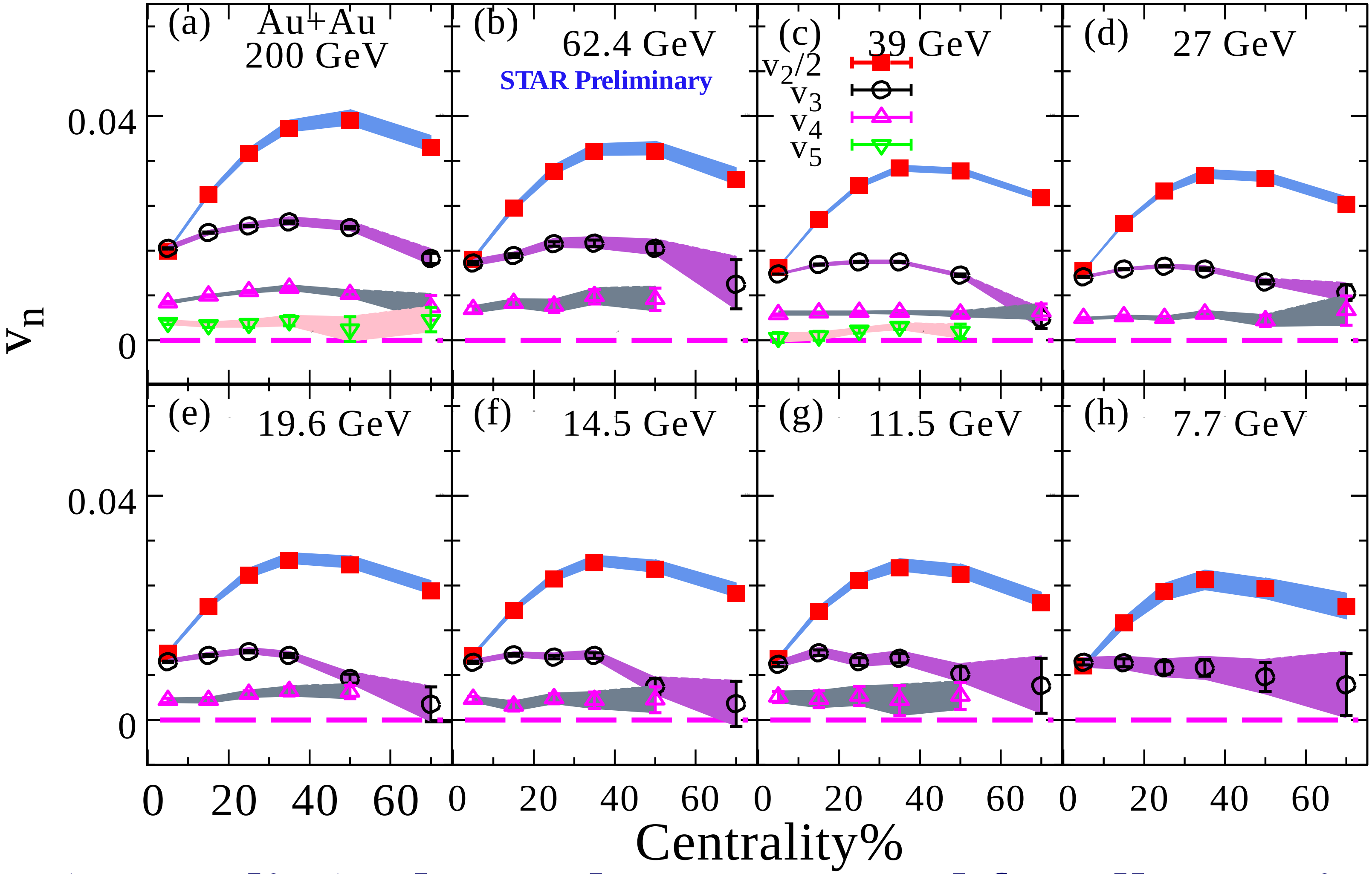
$$\frac{\eta}{s}(T,\mu),\ \frac{\zeta}{s}(T,\mu),\ c_s(T),\ \hat{q}(T),\ \alpha_s(T),\ \text{etc}$$

V_n (pT) as a function of beam energy



V_n (pT) shows the same trend for all energies from RHIC BES1: decreases with harmonic order n.

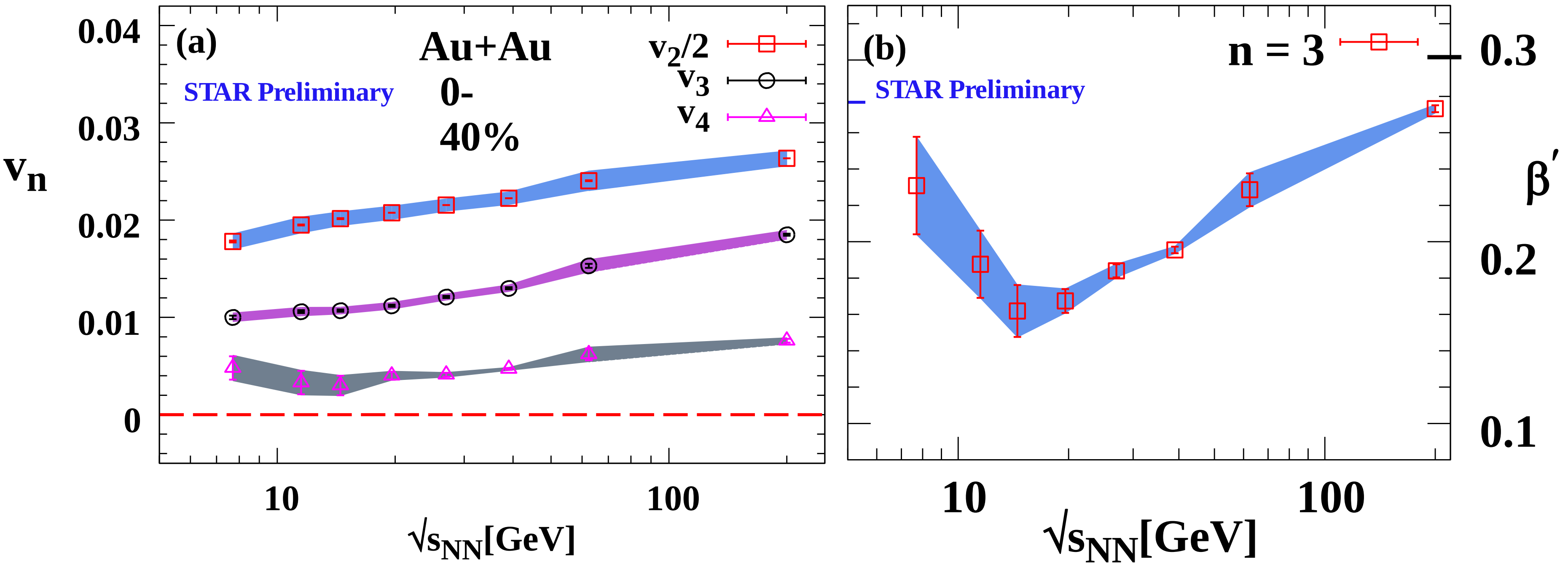
V_n (centrality) as a function of beam energy



V_n (centrality) shows the same trend for all energies from RHIC BES1: decreases with harmonic order n.

$$\mathrm{VC} = \ln\left(\frac{(v_n)^{\frac{1}{n}}}{(v_2)^{\frac{1}{2}}}\right)\left(\frac{dN}{d\eta}\right)^{\frac{1}{3}}$$

$$\mathrm{VC} \propto \frac{\eta}{s}$$



V_n shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient (*η*/*s*), indicates a non-monotonic behavior as a function of beam energy.

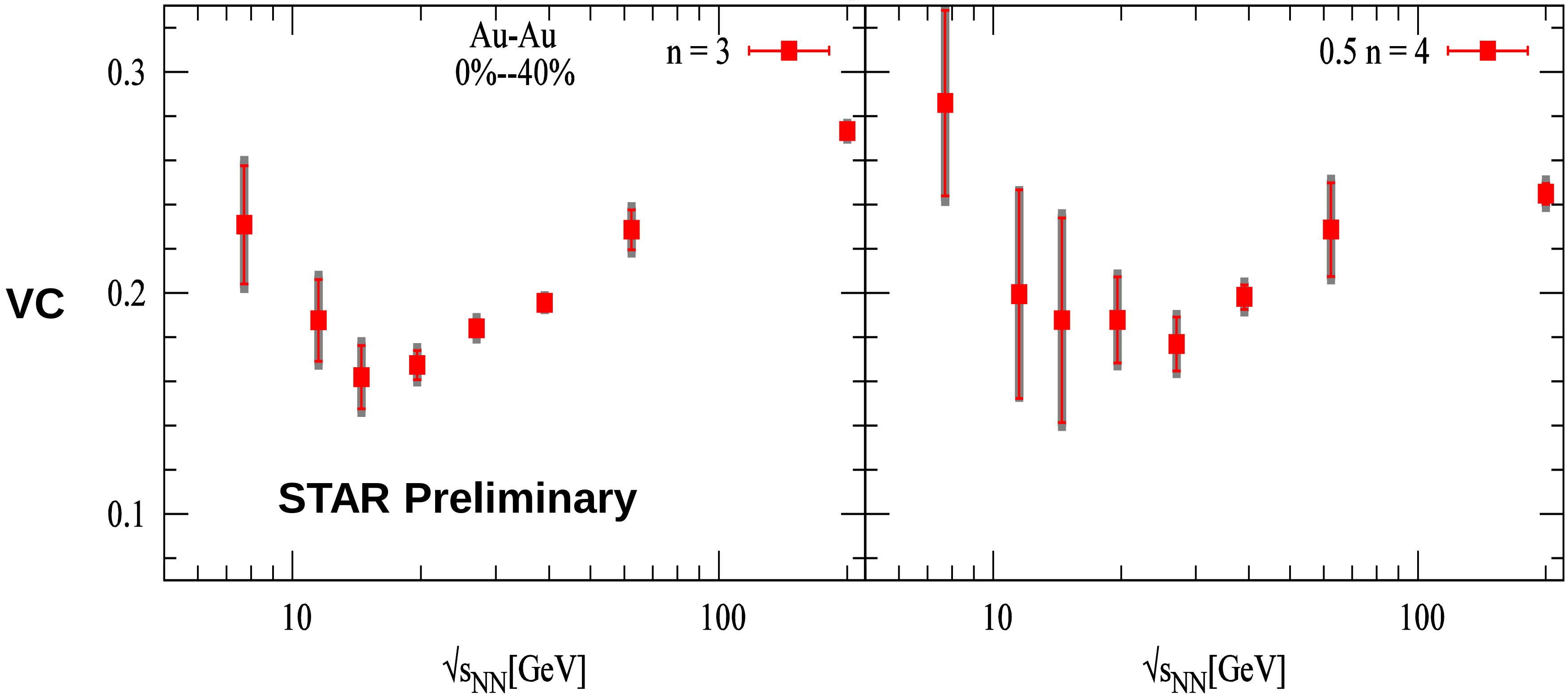
Viscous coefficient

$|\eta| < 1$ and $|\Delta\eta| > 0.7$

$0.2 < p_T < 4\mathrm{GeV/c}$

$$\mathrm{VC} = ln\left(\frac{(v_n)^{\frac{1}{n}}}{(v_2)^{\frac{1}{2}}}\right)\left(\frac{dN}{d\eta}\right)^{\frac{1}{3}}$$

$$\mathrm{VC} \propto \frac{\eta}{s}$$



➢ **The viscous coefficient vc shows a non-monotonic behavior with beam energy in both cases, n = 3 and n = 4.**

STAR Collaboration, Niseem Magdy, SQM 2016

Summary

- **By scanning different colliding systems RHIC/LHC experiments found that the initial geometry play an important roles for the ridge and v_n in small\large systems. And these results can be well described by the viscous hydro calculations. RHIC geometry scan suggest ordering of v_n follows that of ε_n.**

- **The mass ordering, NCQ scaling and four particles cumulant results indicate a collective behavior in small systems**

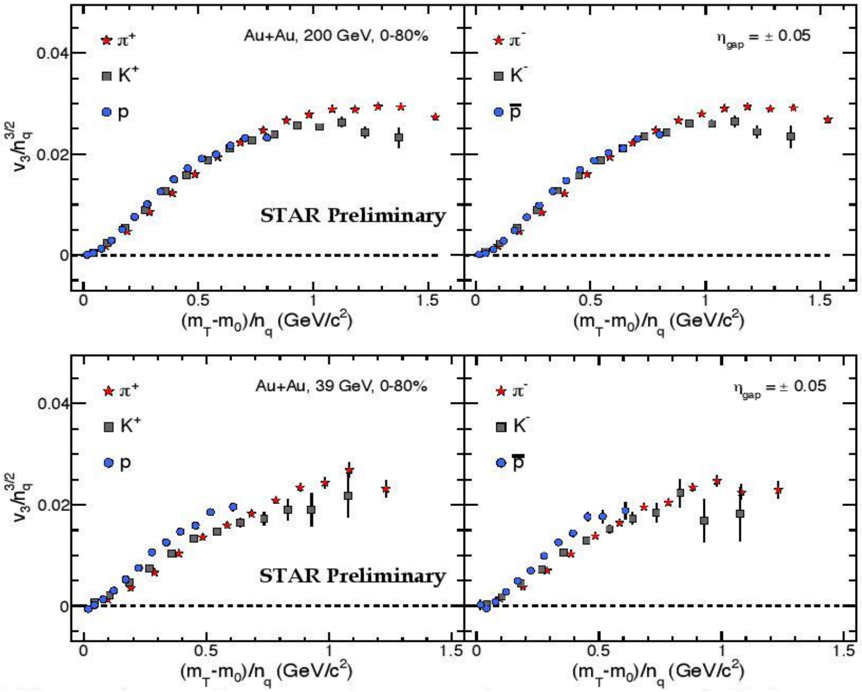
- **Vn shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient (η/s), indicates a non-monotonic behavior as a function of beam energy.**

Prospects for (v_3) PID measurements: STAR BES 1-2

v_3: NCQ ($n_q^{3/2}$) Scaling   Is broken?

200 GeV

39 GeV

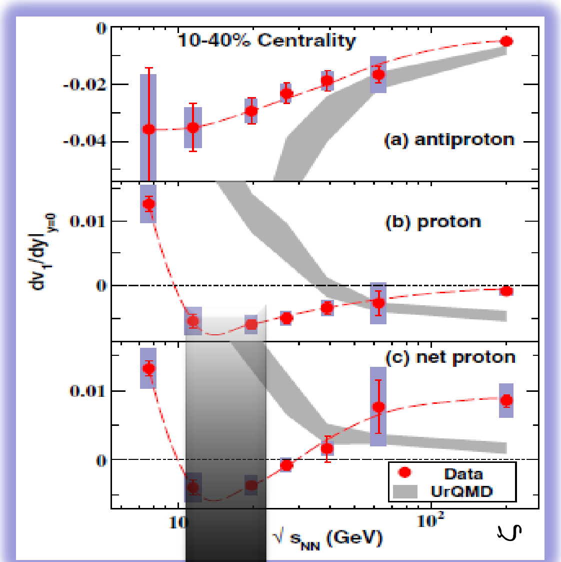


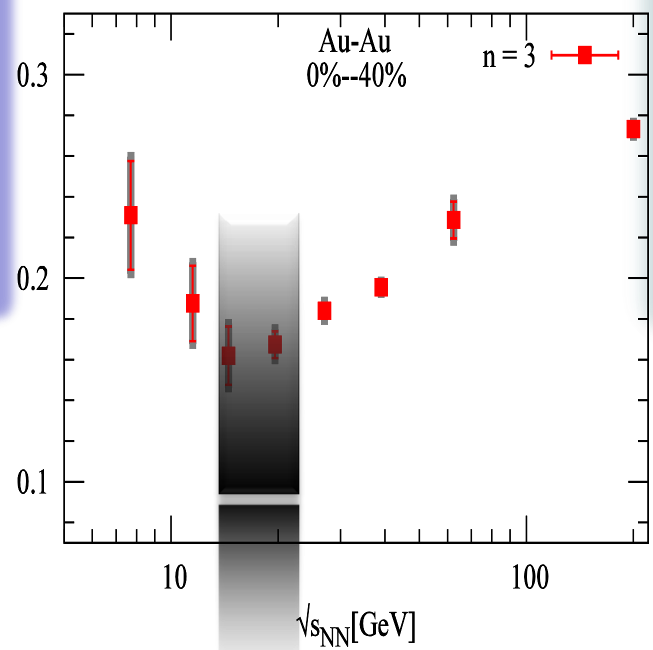
- $v_n \sim n_q^{n/2}$

J. Phys. G: Nucl. Part. Phys. 38 (2011) 124048

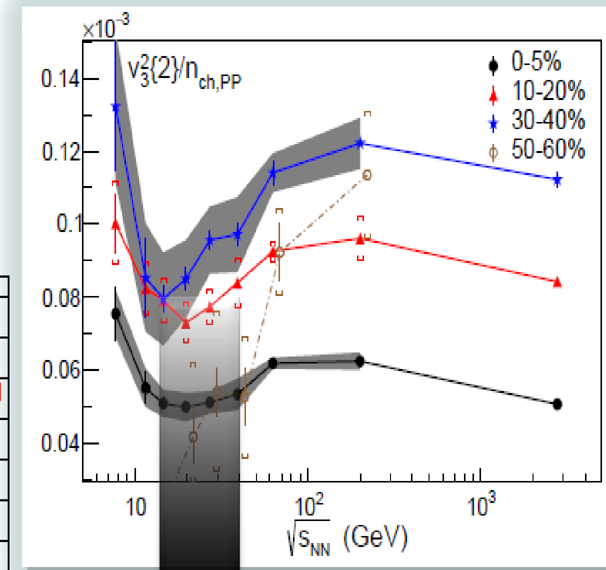
STAR data: Anomalies in the Pressure and η/s?

PRL 112,162301(2014)





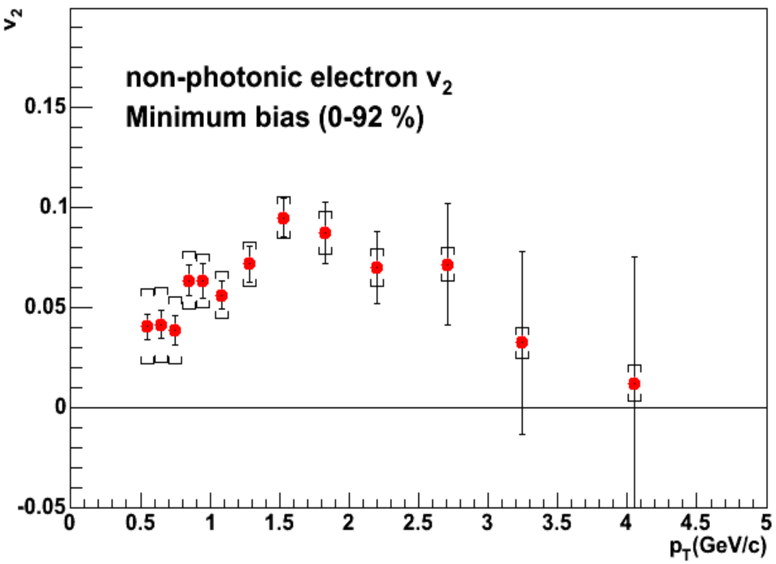
PRL 116, 112302 (2016)

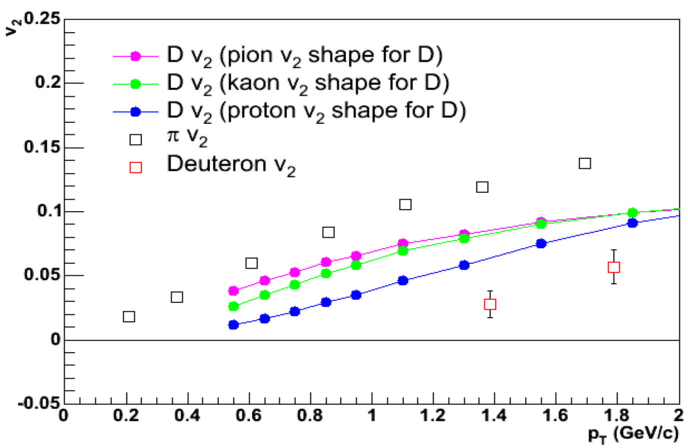


Region of interest $\sqrt{s_{NN}} \lesssim 20$ GeV, however, is complicated by a changing B/M ratio, baryon transport dynamics, longer nuclear passing times, etc. ***Requires concerted modeling effort.***

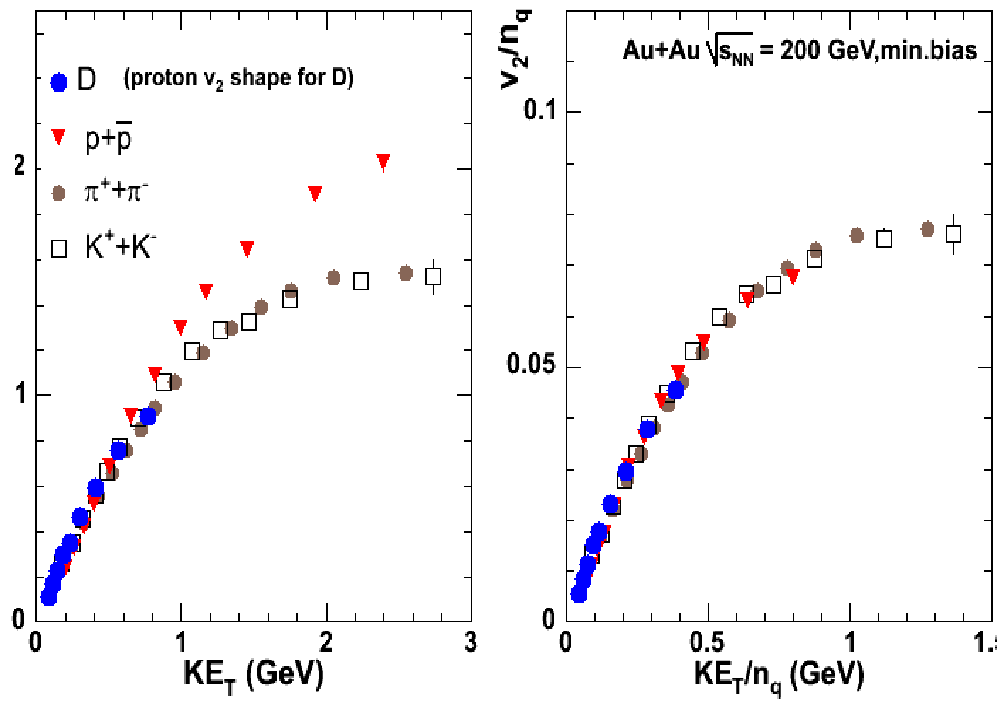
Elliptic flow of D meson in 2006 (PHENIX)

Au+Au at 200 GeV, QM2006





PoS 2006 (2006) 021



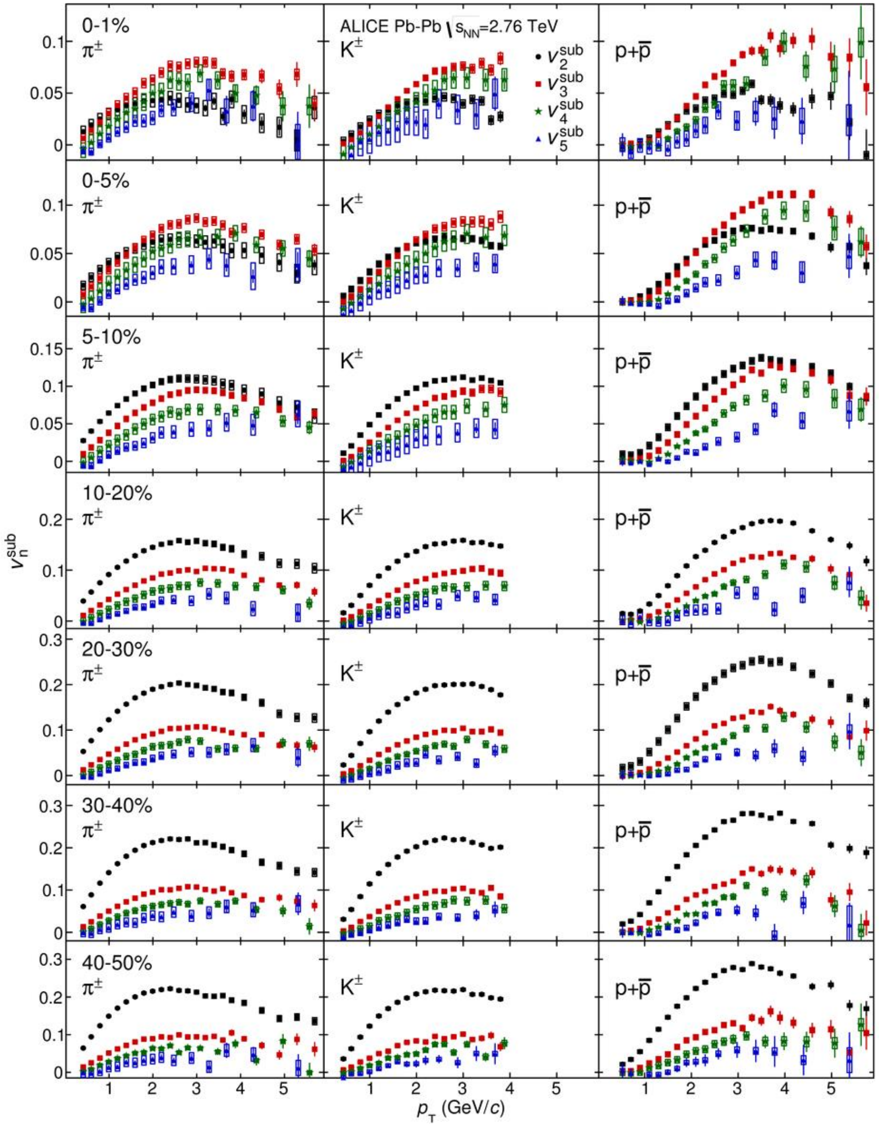
Simulations: Shingo Sakai (PHENIX)
(See SQM2006, HQ2006 Talks and proceedings for details)

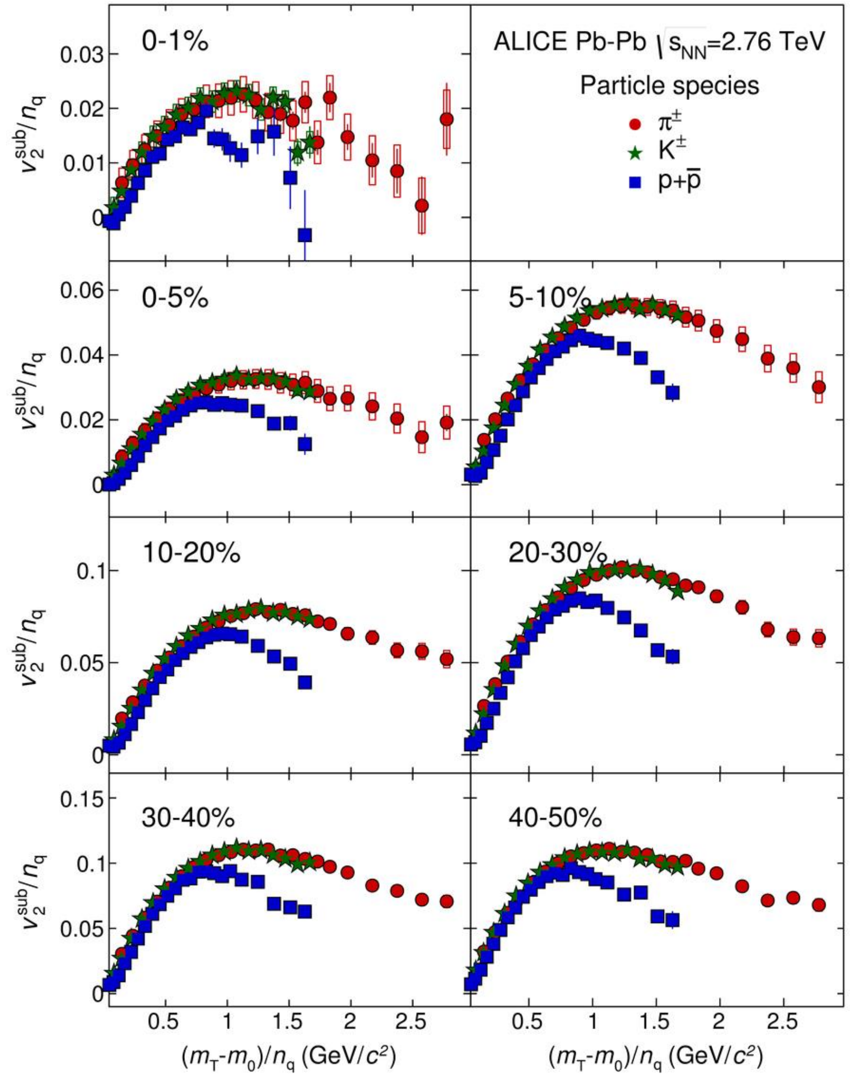
■expected D meson v2 from non-photonic electron v2 (pT < 2.0 GeV/c)

The D meson not only flows, it scales over the measured range

Flow is partonic @ LHC

Alice - arXiv:1606.06057



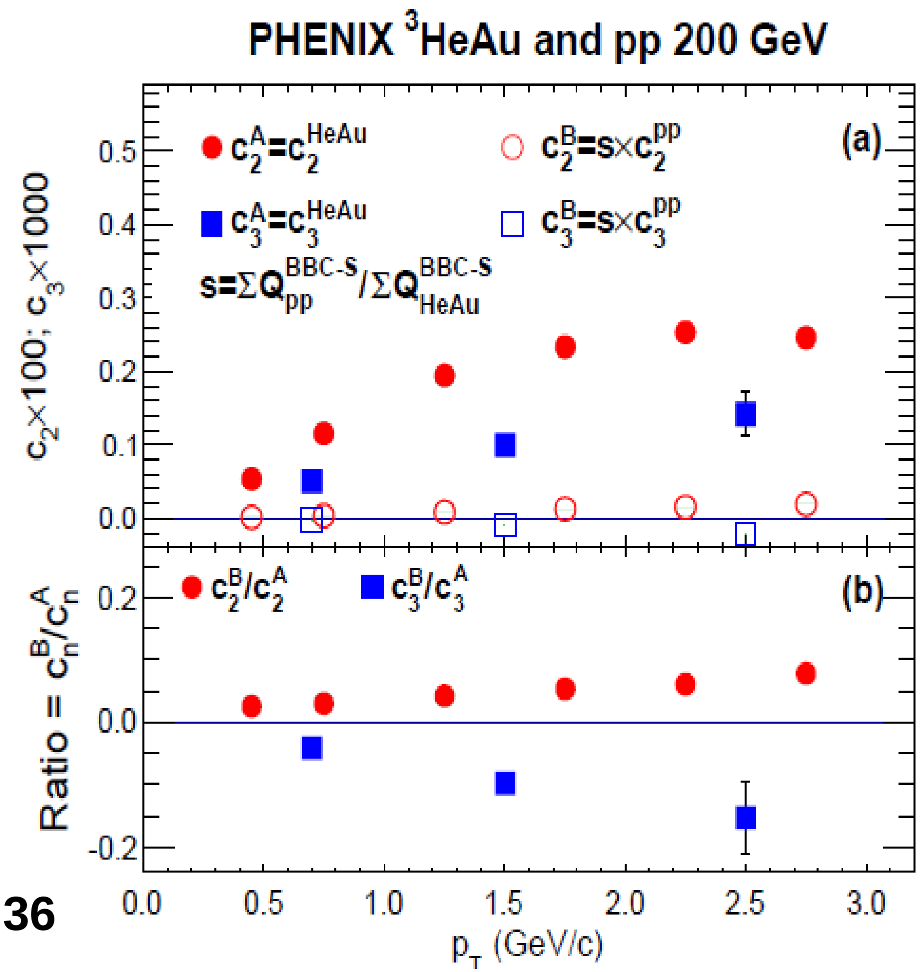


KE$_T$ & $(n_q)^{n/2}$ scaling validated for v_n → **Partonic flow**

PHENIX: Estimation of Non-Flow

$$c_2\,(p_T) = c_2^{\text{Non-Elementary}} + c_2^{\text{Elementary}}$$

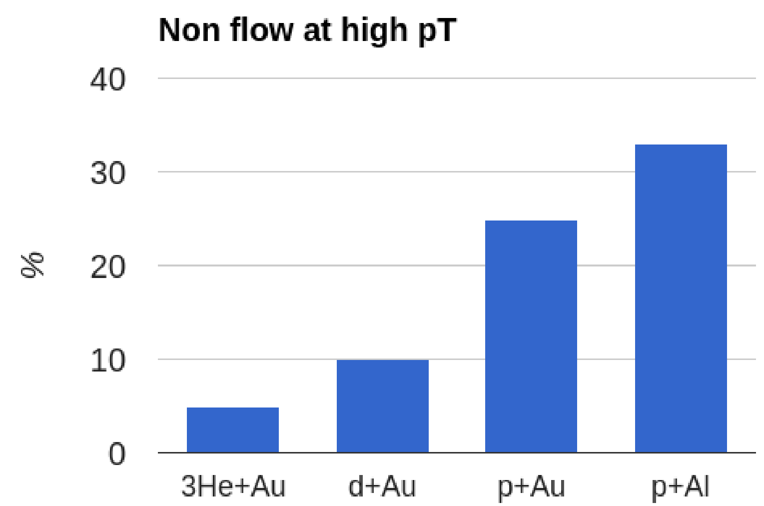
$$c_2\,(p_T) = c_2^{\text{Non-Elementary}} + c_2^{p+p} \times \frac{\text{Charge at Forward } \eta \text{ in p+p}}{\text{Charge at Forward } \eta \text{ in p+Au}}$$



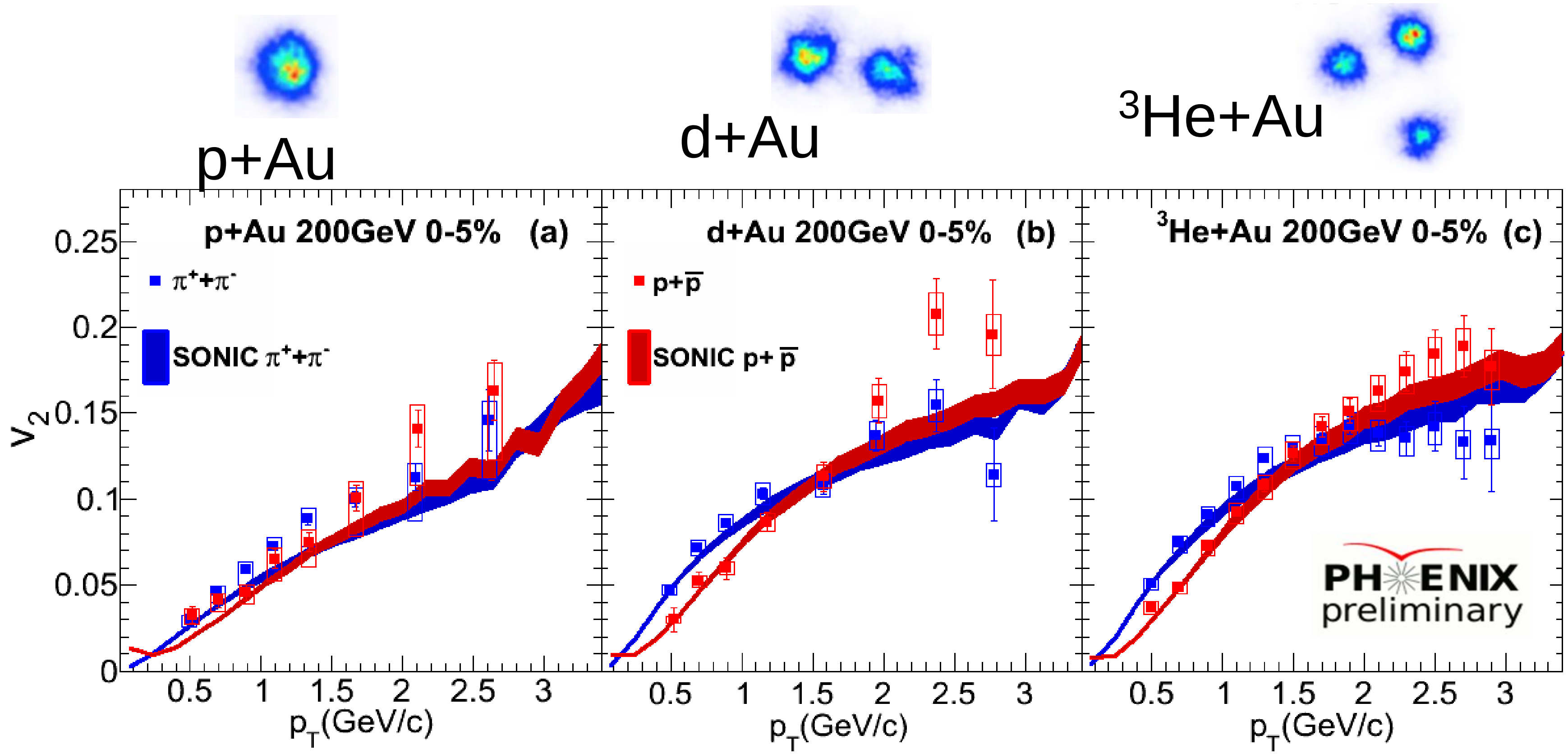
v_2: 7% in ^{3}He+Au,10% in d+Au; 25% in p+Au → increases in smaller systems

v_3 : 15% in ^{3}He+Au

cited as a systematic uncertainty



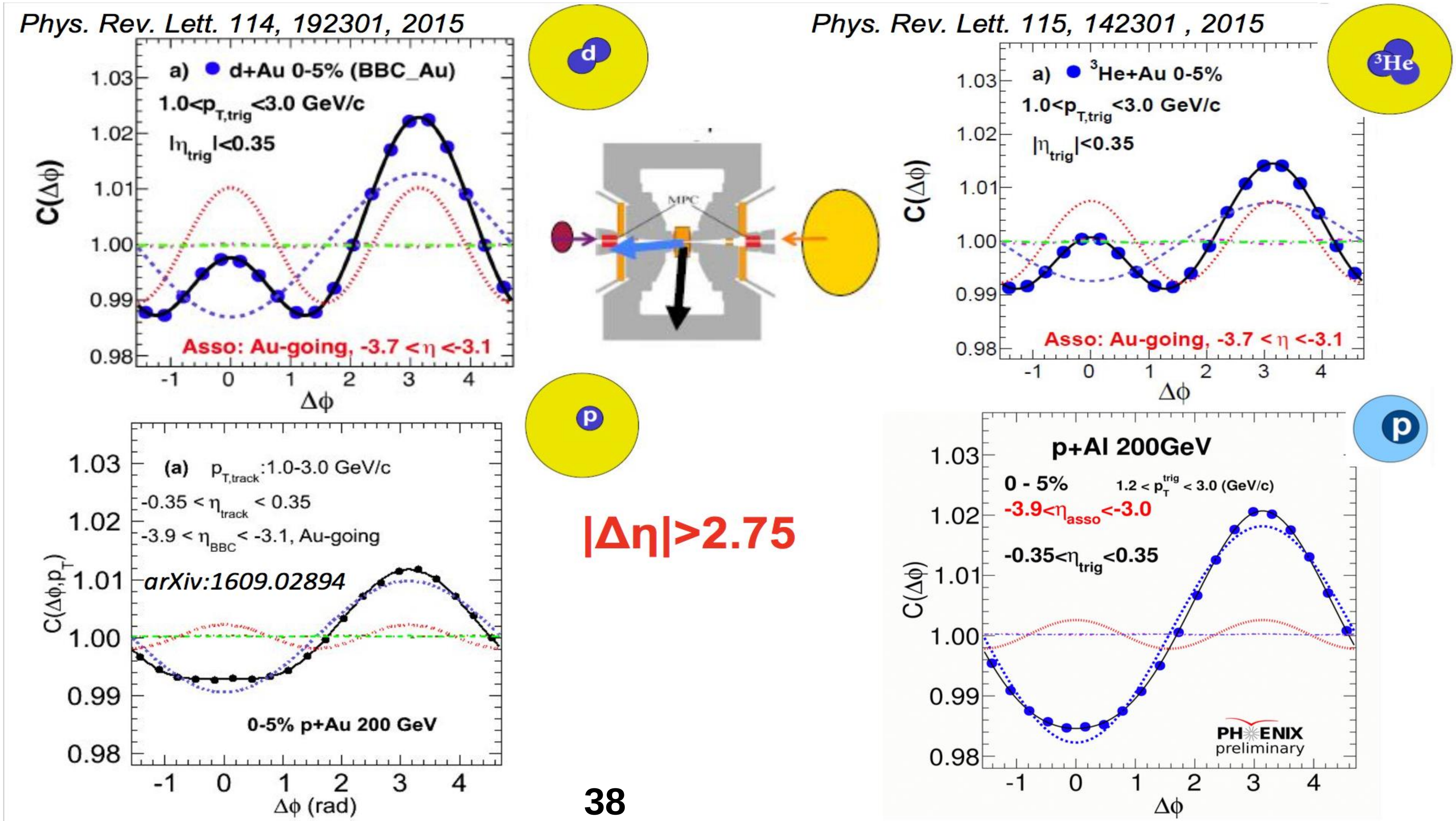
Identified particle v_2 comparison with hydro



- Well described p/d/^{3}He+Au results at low p_T
- Smaller mass split for v2 in p+Au is predicted
- High p_T data are not reproduced - recombination not included

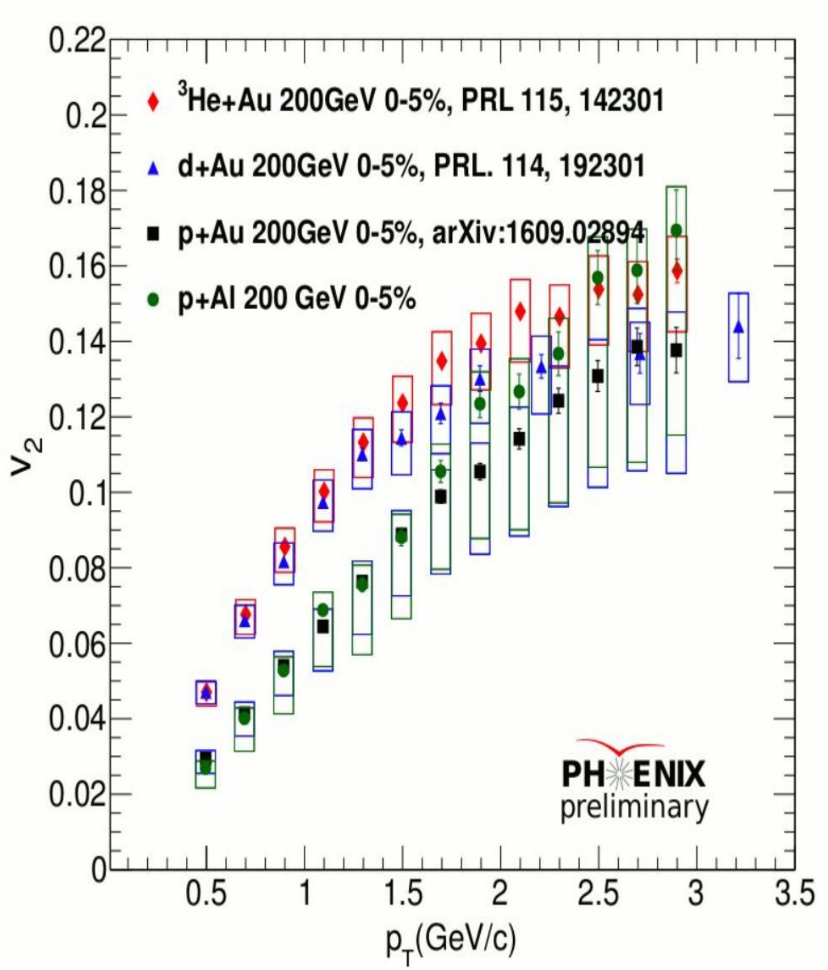
PHENIX

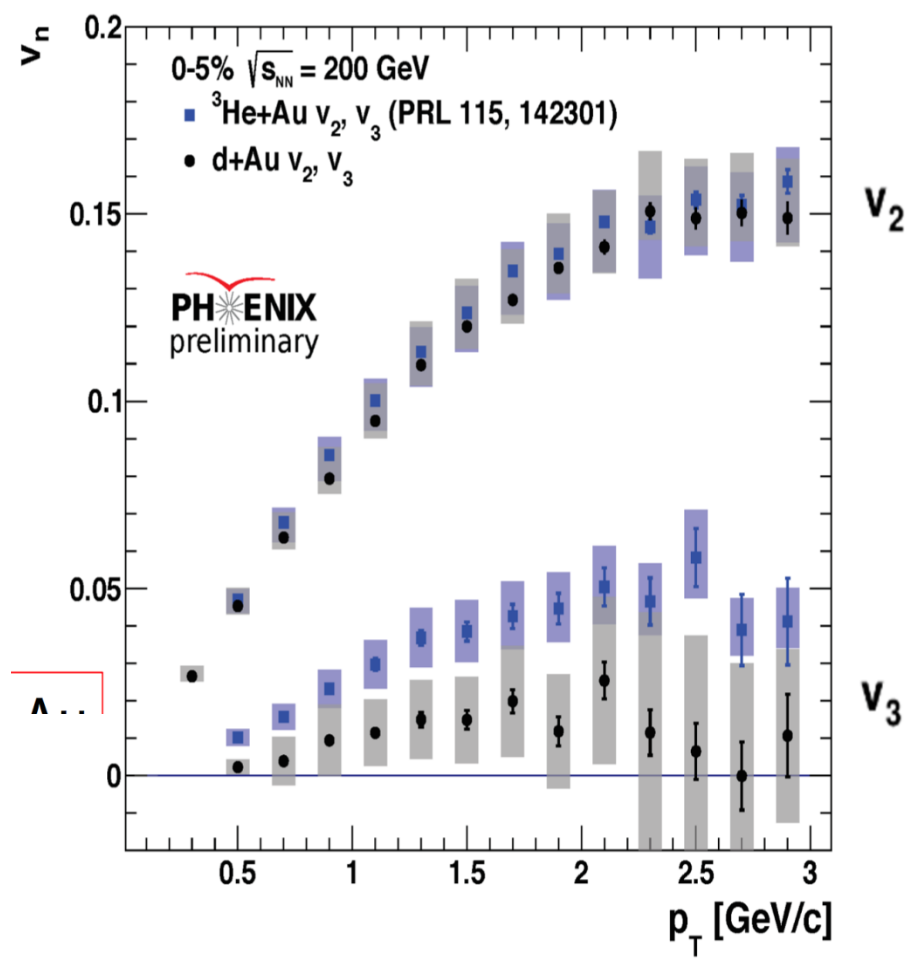
Ridge in small systems PHENIX (200 GeV)



The near side long-range angular correlation ("ridge") is observed in small systems for high multiplicity d+Au and ^{3}He+Au events

PHENIX: Vn in small systems (200 GeV)



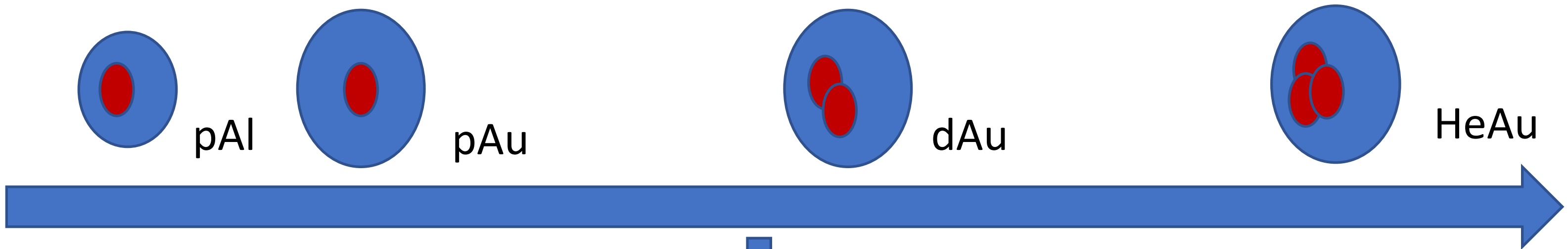


$v_2(^3\mathrm{HeAu}) \sim v_2(\mathrm{dAu}) > v_2(\mathrm{pAu}) \sim v_2(\mathrm{pAl})$

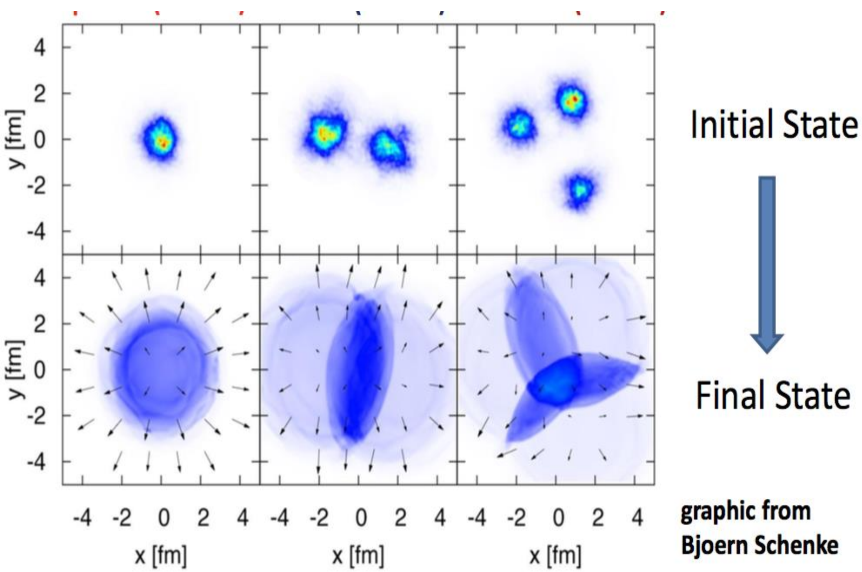
$v_3(^3\mathrm{HeAu}) > v_3(\mathrm{dAu})$

Hierarchy compatible with initial geometry + final state effects

Small system program at RHIC



Geometry Scan



	0-5% p+Au	0-5% d+Au	0-5% He+Au
ε_2	0.23	0.54	0.50
ε_3	0.16	0.19	0.28

Energy Scan

dAu 200GeV

dAu 39GeV

dAu 62.4GeV

dAu 19.6GeV

Beam Energy Scan (BES) will help us to search for the turning off the QGP signatures

Scaling properties of flow and correlations

"Change of collective-flow mechanism indicated by scaling analysis of transverse flow " A. Bonasera, L.P. Csernai , Phys.Rev.Lett. 59 (1987) 630-633

The general features of the collective flow could, in principle, be expressed in terms of scale-invariant quantities. *In this way the particular differences arising from the different initial conditions, masses, energies, etc. , can be separated from the general fluid-dynamical features. . …. Deviations from such an ideal scaling signal physical processes which lead to a not-scale-invariant flow, like special properties of the equation of state (EOS), potential energy, or phase transitions, dissipation, relativistic effects, etc.*

"Collective flow in heavy-ion collisions", W. Reisdorf, H.G. Ritter Ann.Rev.Nucl.Part.Sci. 47 (1997) 663-709 :

There is interest in using observables that are both coalescence and scale-invariant. *They allow comparison with theories that are limited to making predictions for single-particle observables. Under certain conditions the evolution in nonviscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances (such as impact parameters) are rescaled (reduced) in terms of a typical size parameter, such as the nuclear radius. Velocities, momenta and energies are rescaled in terms of the beam velocities, momenta or energies.*