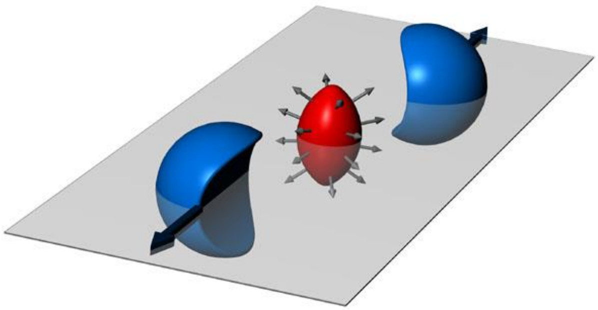
Anisotropic Flow in Heavy-Ion Collisions from LHC to NICA



Arkadiy Taranenko

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The XXIVth International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", September 17 - 22, 2018, JINR Dubna, Russia.

Many thanks for the invitation!

OUTLINE

1. Why measure anisotropic flow?
2. Flow (Vn) and sQGP at RHIC/LHC
3. Scaling properties of V_n
4. Collective effects in small systems
5. Flow results from Beam Energy Scan
6. Outlook for flow measurements at NICA

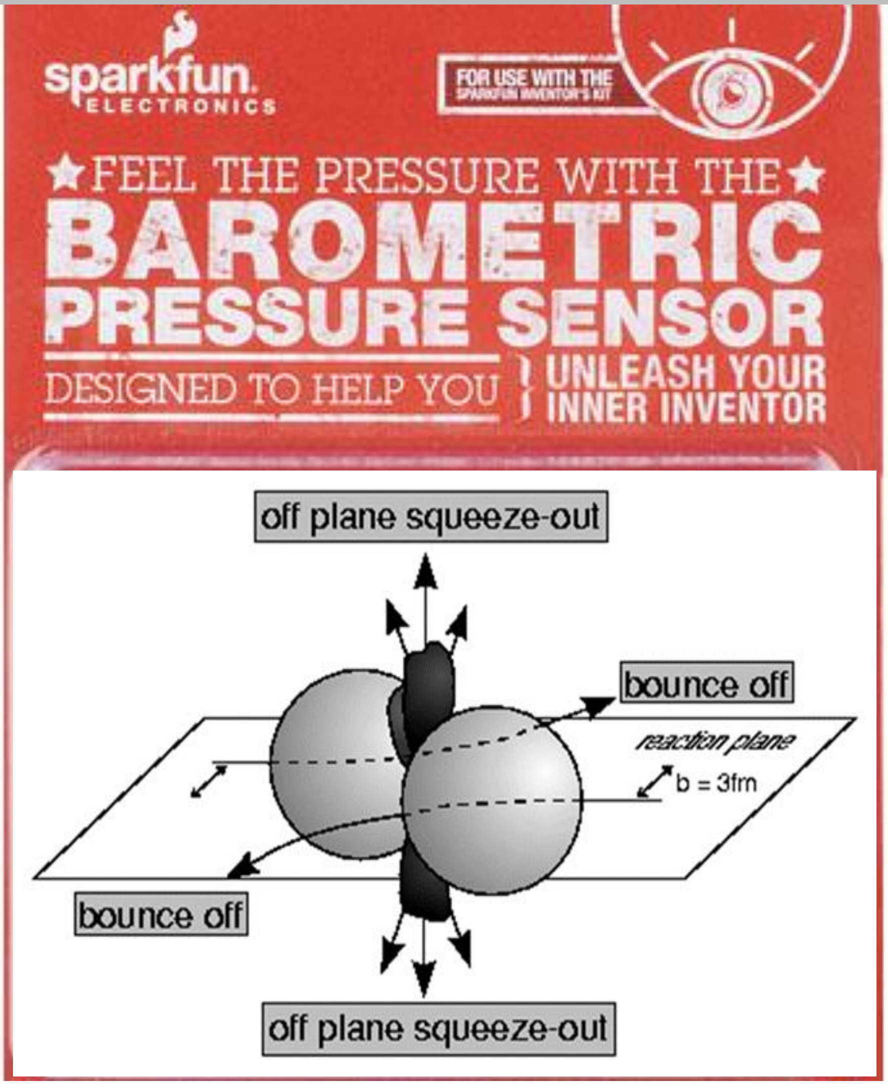
Anisotropic Flow in Heavy-Ion Collisions: 1988

Provides reliable estimates of pressure & pressure gradients

Can address questions related to thermalization

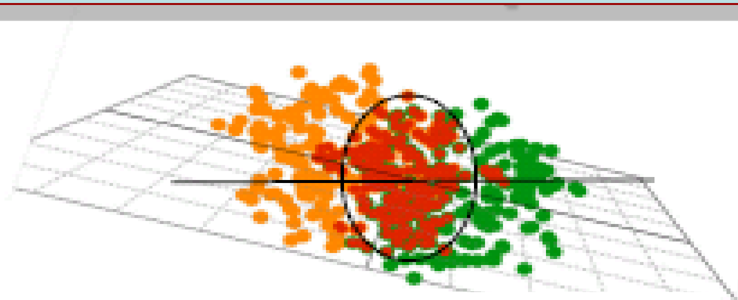
Gives insights on the transverse dynamics of the medium

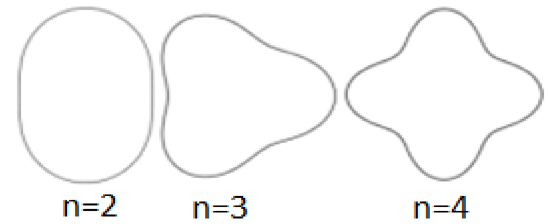
Provides access to the transport properties of the medium: EOS, sound speed (c_s), viscosity, etc



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

Anisotropic Flow at RHIC/LHC - methods



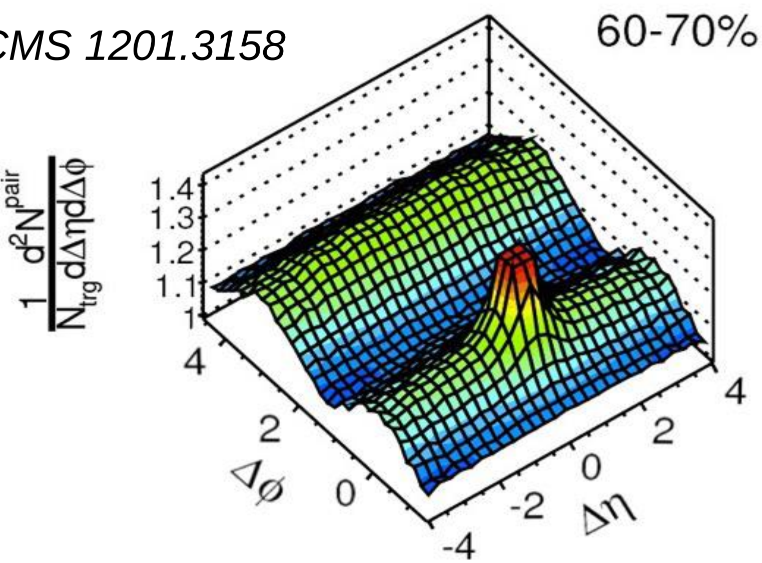


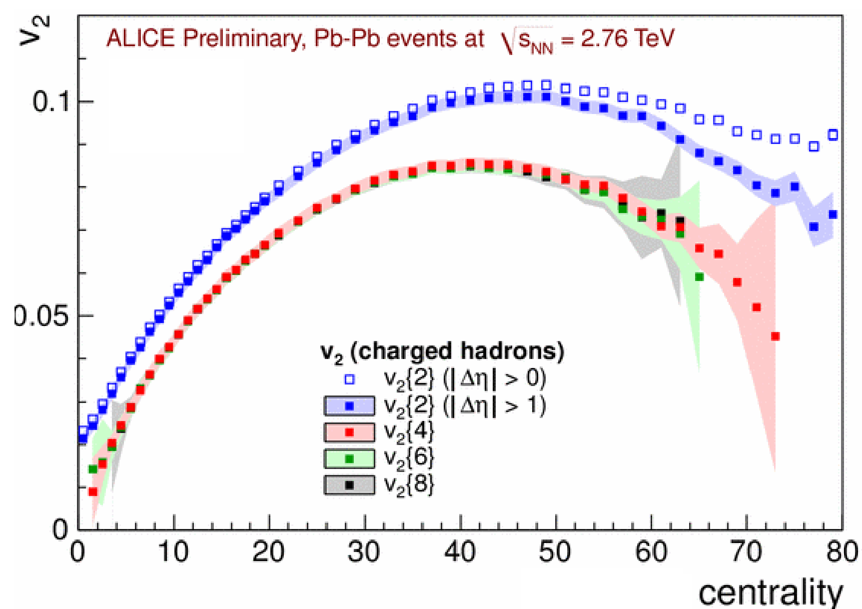
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

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

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

CMS 1201.3158

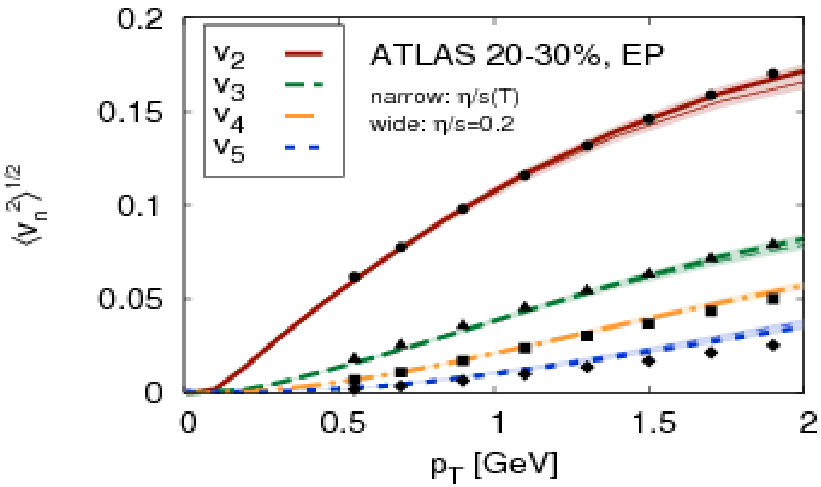


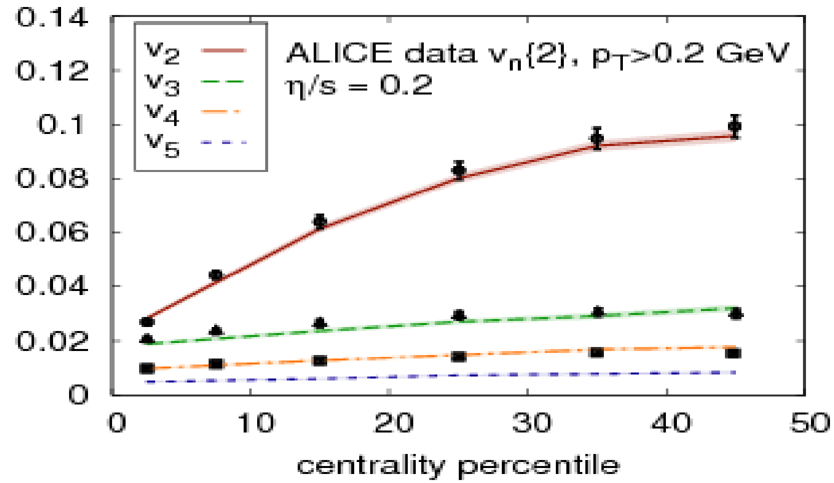


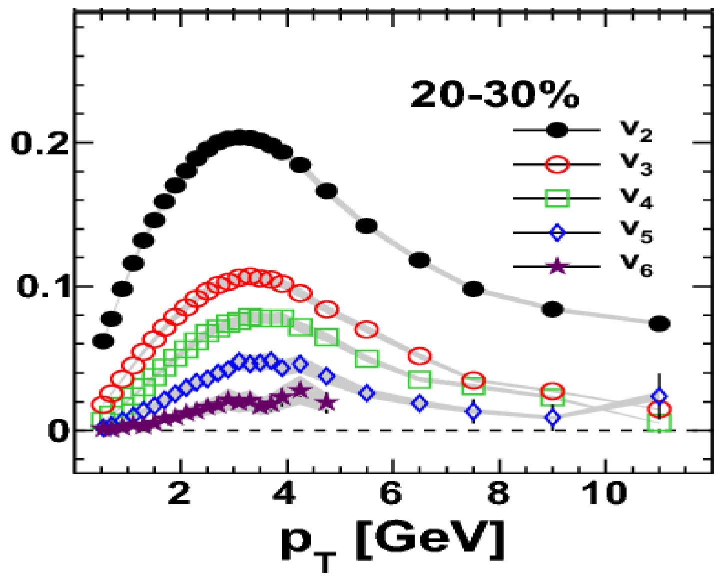
Different methods, non-flow, fluctuations

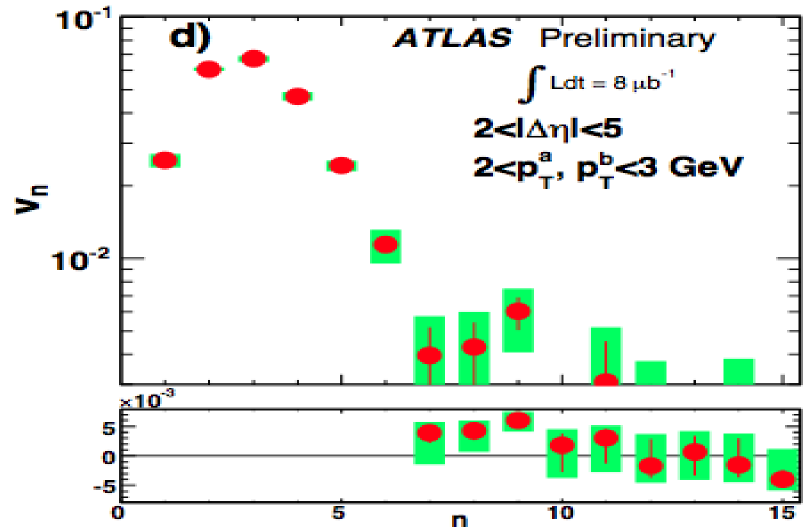
Anisotropic Flow at LHC – data vs models

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



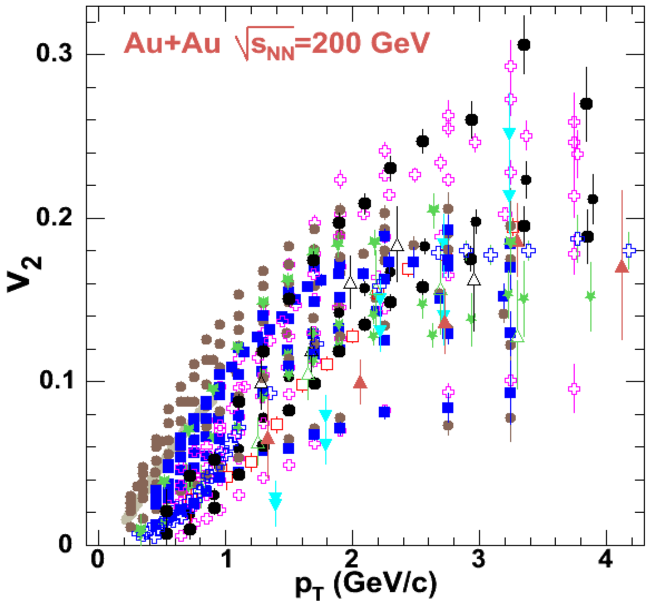


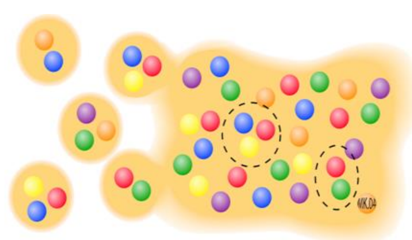




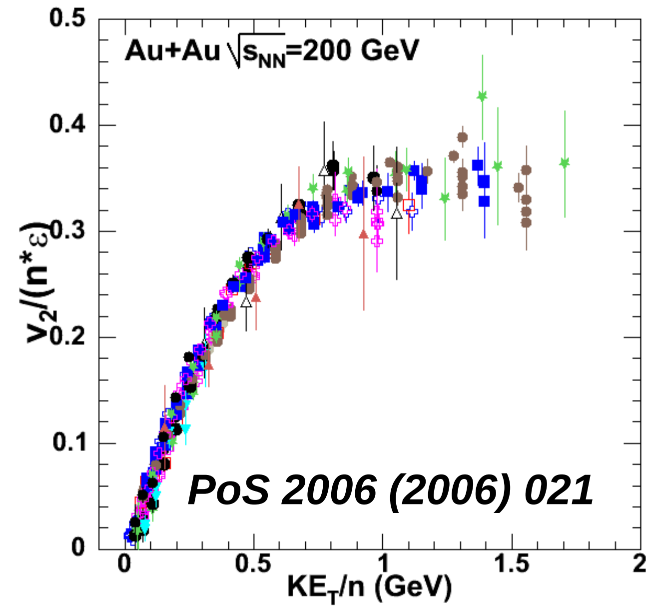
Shear viscosity suppresses higher flow harmonics more strongly

Anisotropic Flow at RHIC/LHC – scaling relations



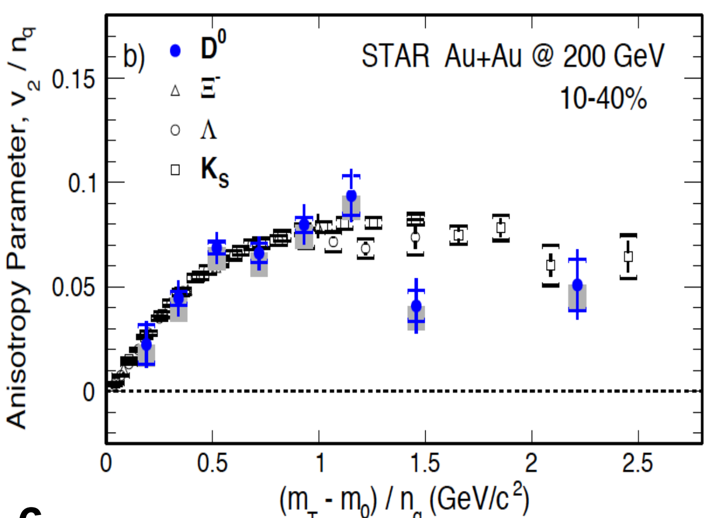


n=2 for mesons
and
n=3 for baryons

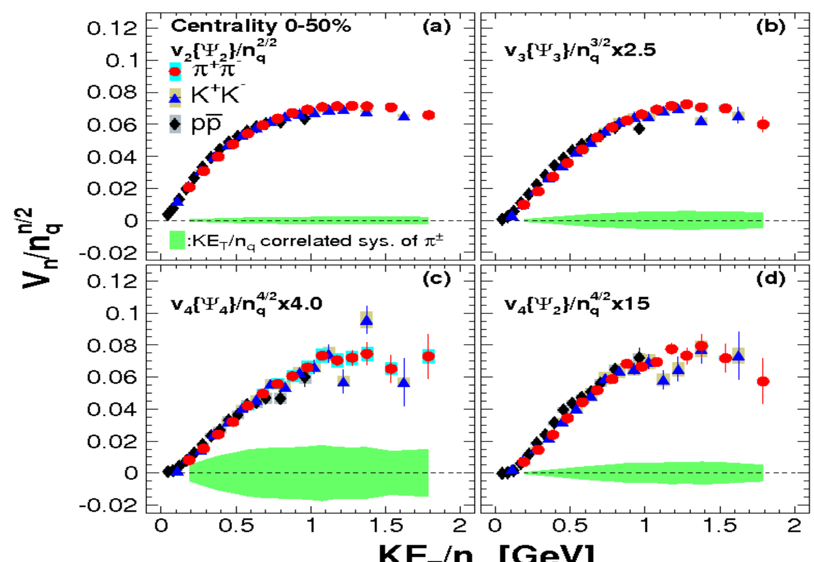


PoS 2006 (2006) 021

STAR: Phys. Rev. Lett. 118, 212301(2017)



PHENIX, Phys. Rev.C.93.051902(R)



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,

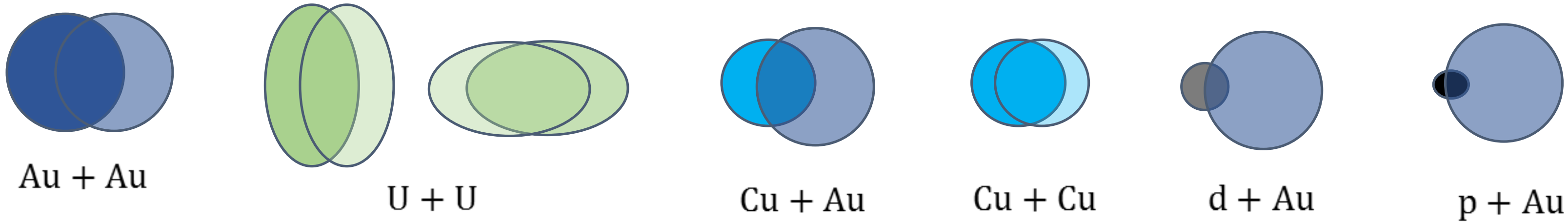
$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \quad \beta \propto \frac{\eta}{s}\frac{1}{RT}$$

arXiv:1601.06001
Roy A. Lacey, et al.

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

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

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

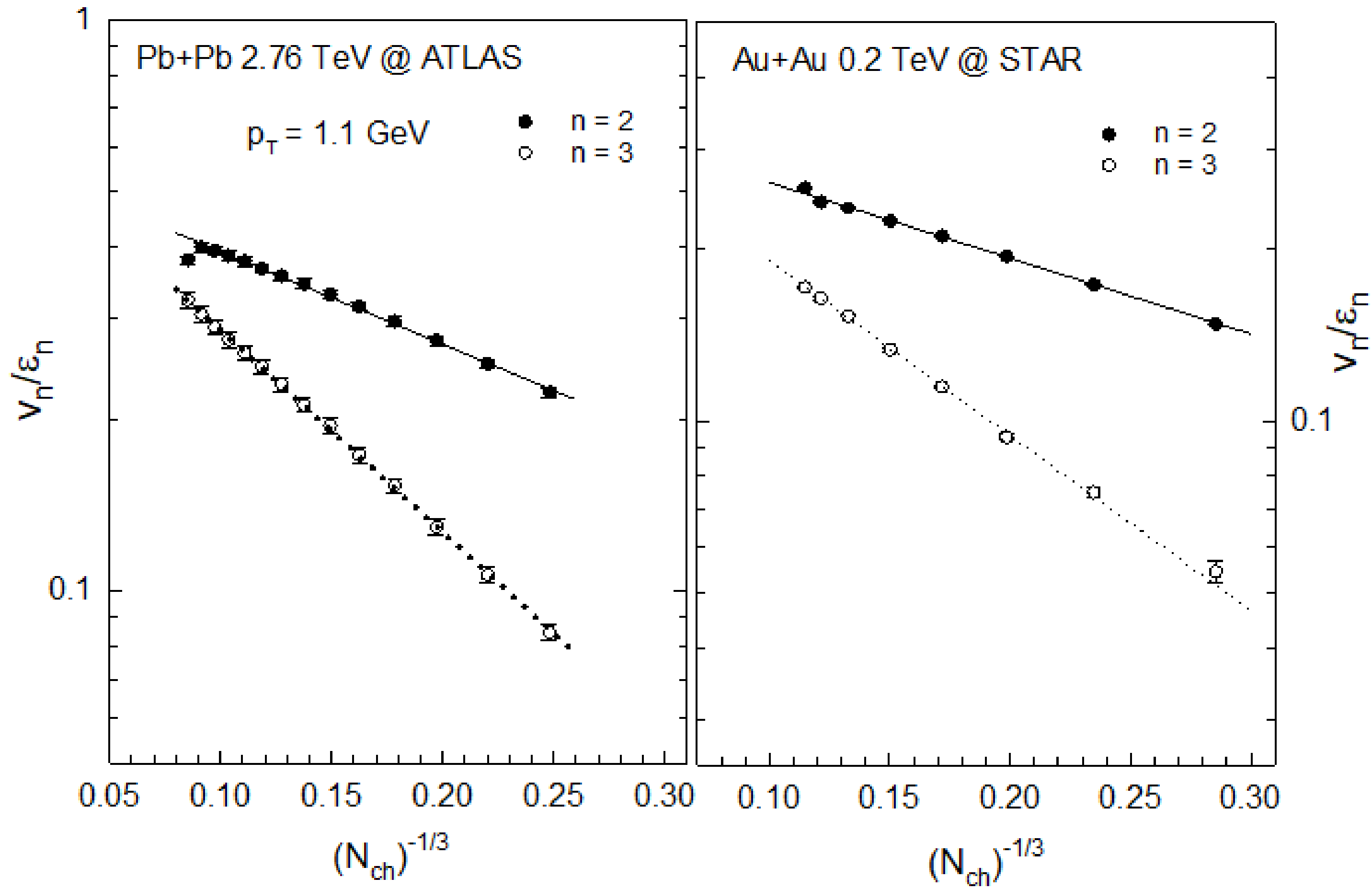


Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

Acoustic Scaling –

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

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

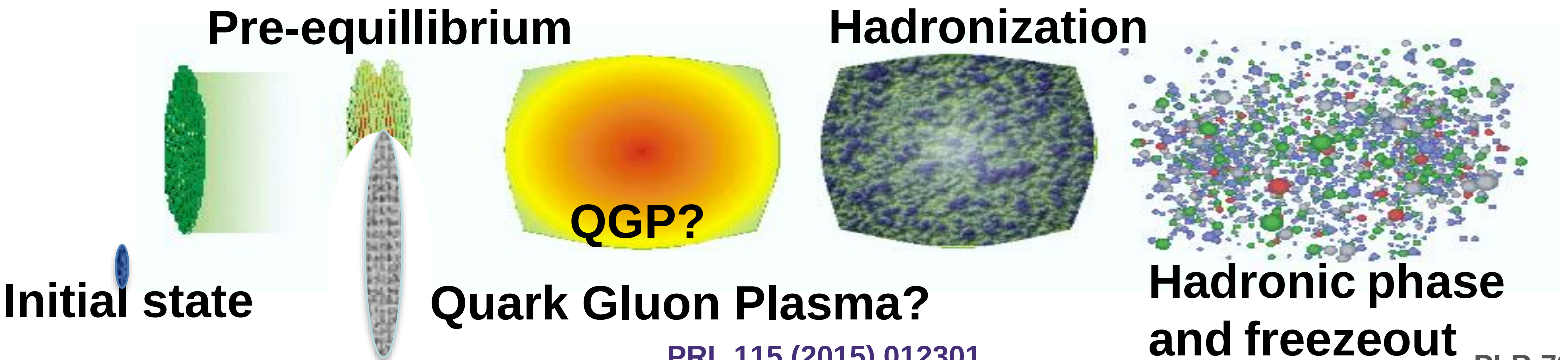


- ✓ **Characteristic 1/(RT) viscous damping validated**
  - ✓ ***Clear pattern for n^2 dependence of viscous attenuation***
  - ✓ ***Important constraint for η/s & ζ/s***

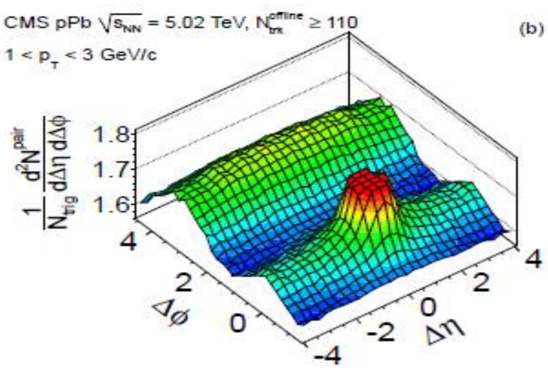
CAN WE TURN THE QGP OFF?

- ❑ **Small Systems**
- ❑ **Beam Energy Scan**

Collectivity in Small Colliding Systems

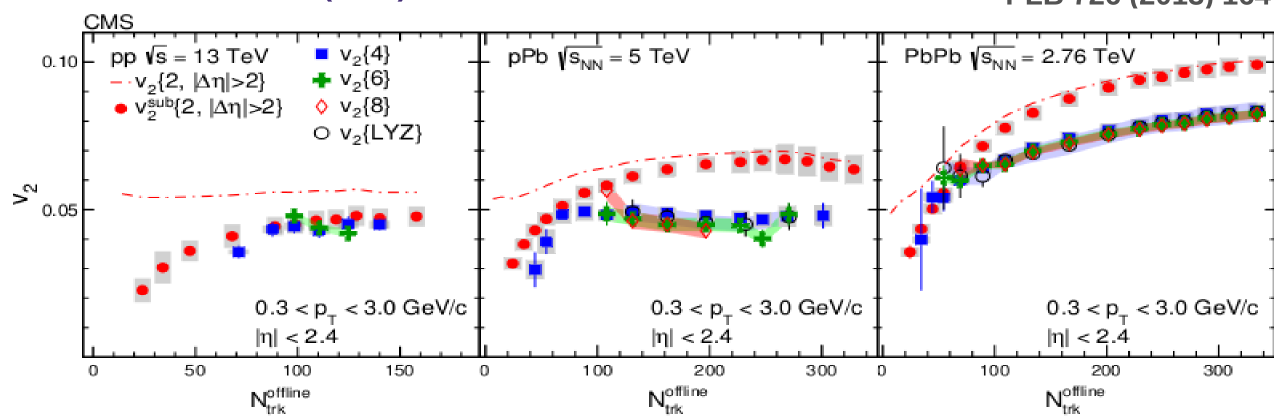


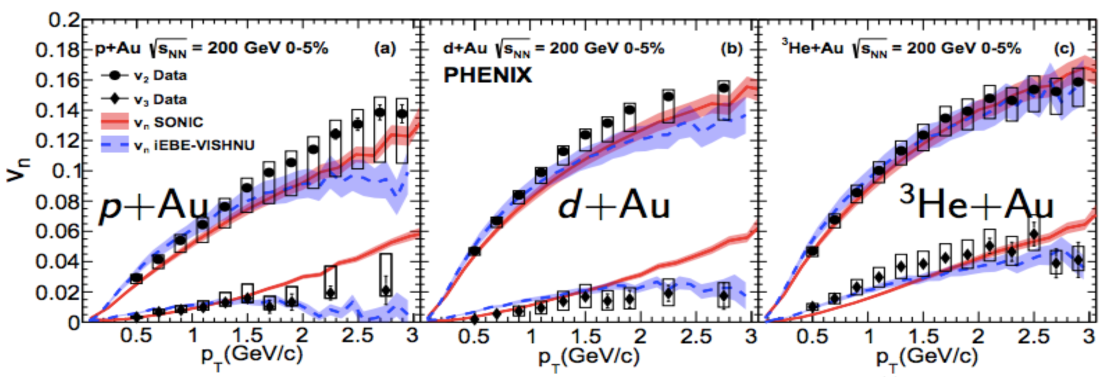
PLB 718 (2013) 795

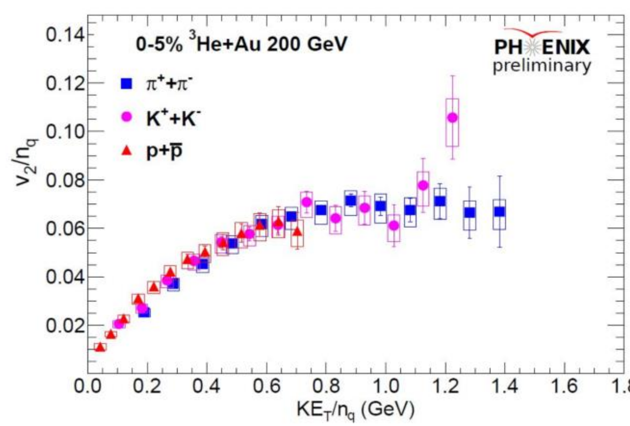


PRL 115 (2015) 012301

PLB 726 (2013) 164

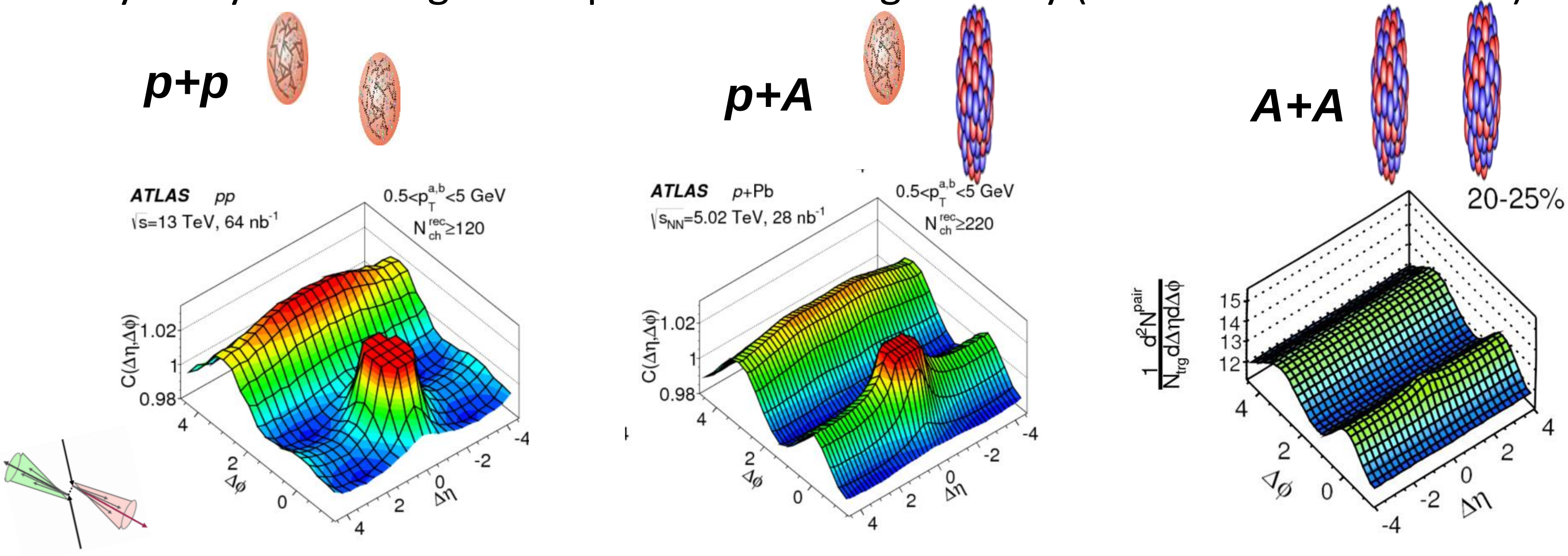






Definitions: Azimuthal anisotropy vs flow

- **Azimuthal anisotropy** = experimental observations without reference to a specific physical interpretation [`double hump' after non-flow subtraction which is long range in rapidity]
- **Collective flow** = azimuthal anisotropies established during the hydrodynamic stage in response to initial geometry (final state interactions).



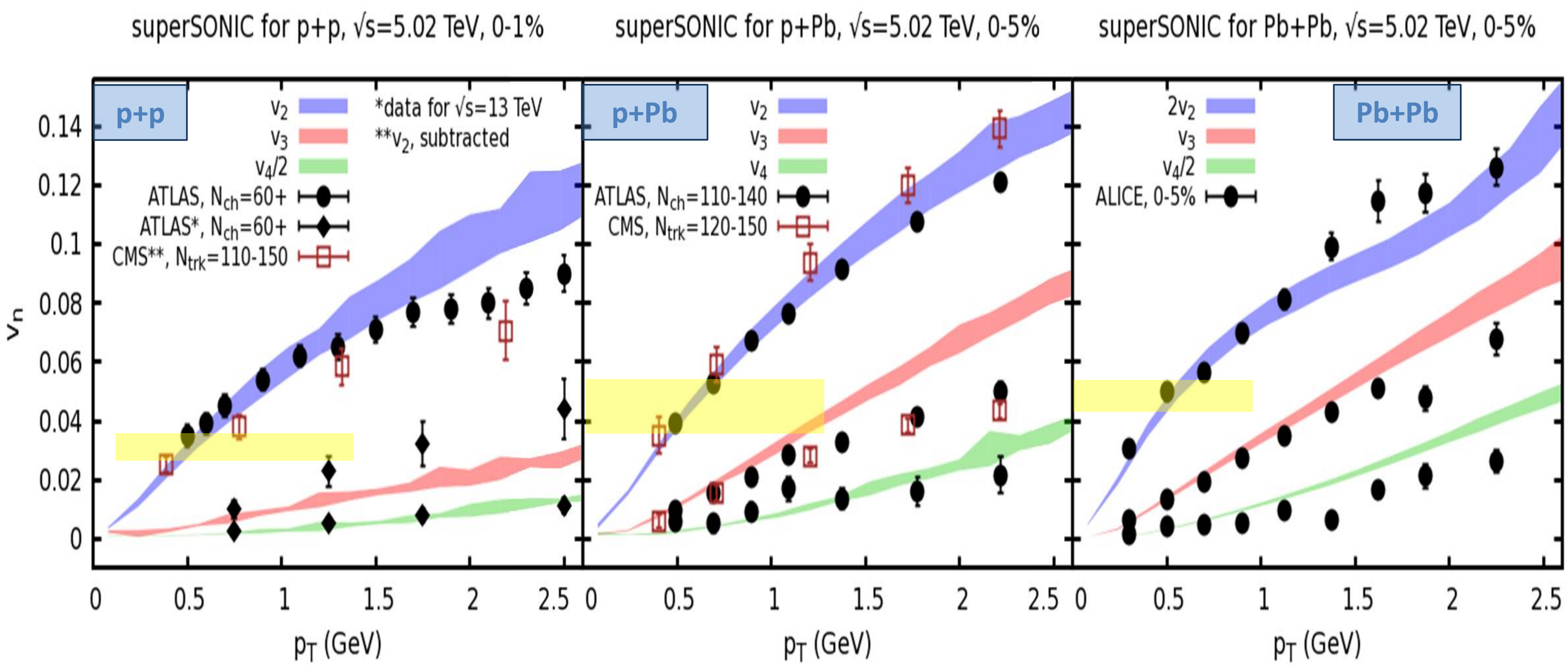
Final state interactions: Hydrodynamic Flow?

Initial momentum correlations: CGC?

How to distinguish initial vs final state effects ?

Azimuthal anisotropy from hydrodynamics

R. Weller and P. Romatschke, PLB 774, 351-356(2017).

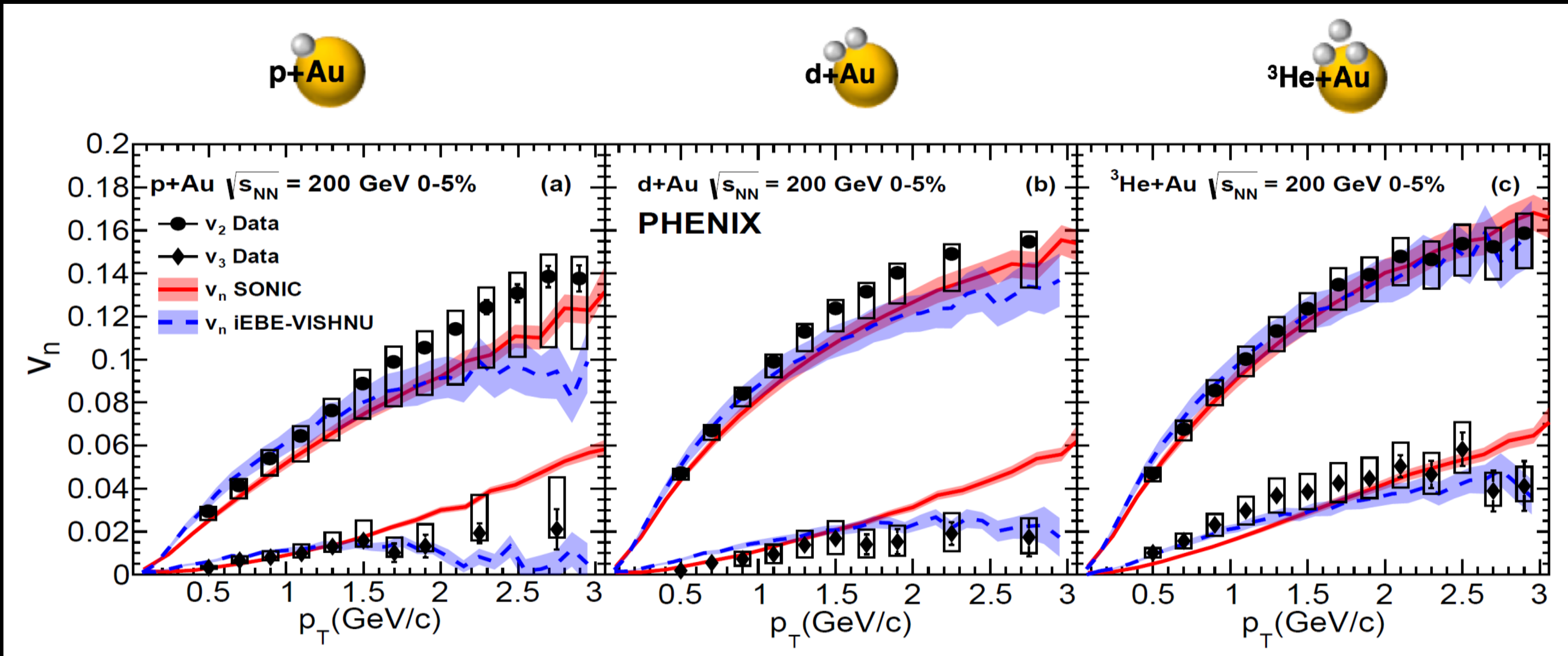


"ONE FLUID TO RULE THEM ALL"?

Viscous Hydrodynamics results strongly suggest that the **observed azimuthal anisotropies can be understood in terms of collective response to the initial geometry**, aka hydrodynamic flow.

Viscous Hydrodynamic Comparison

PHENIX, arXiv:1805.02973



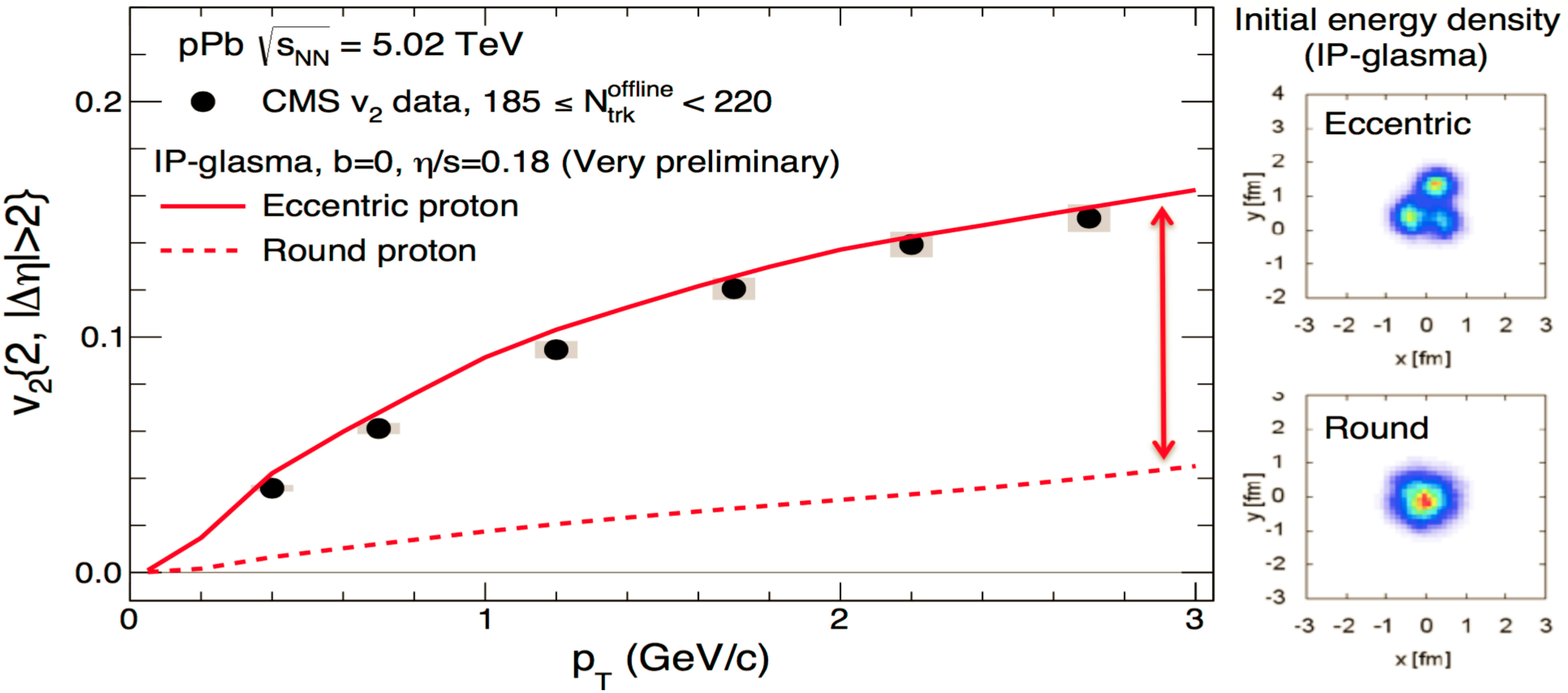
Following the ordering of eccentricities.

Good agreement with v_2, v_3 (p_T) for all three systems

No tuning of parameters or options for different systems

Indication of a strongly coupled QCD matter?

Sub-nucleonic fluctuations



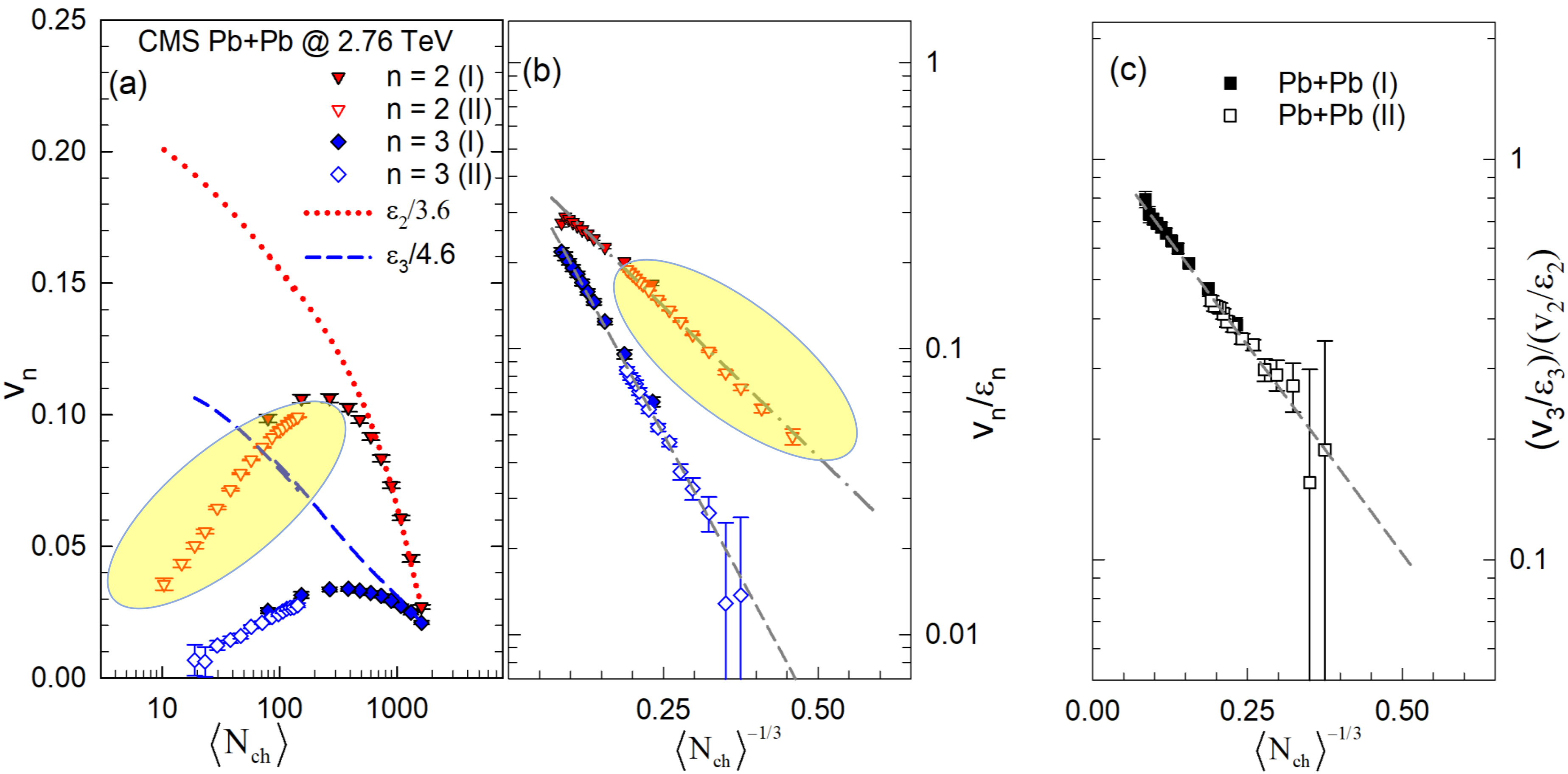
- A crucial ingredient in all successful hydrodynamical descriptions is the inclusion of **sub-nucleonic fluctuations**.
- Without them, initial eccentricities generated are too small to produce the observed azimuthal anisotropy.

R. Weller and P. Romatschke, PLB 774, 351-356 (2017)
H. Mäntysaari and B. Schenke, Nucl. Part. Phys. Proc. 289-290 457 (2017)
H. Mäntysaari, B. Schenke, C. Shen, P. Tribedy, PLB 772, 681 (2017)
J. Albacete, H. Petersen, and A. Soto-Ontoso, Phys.Lett. B778, 128 (2018)

Acoustic Scaling - RT

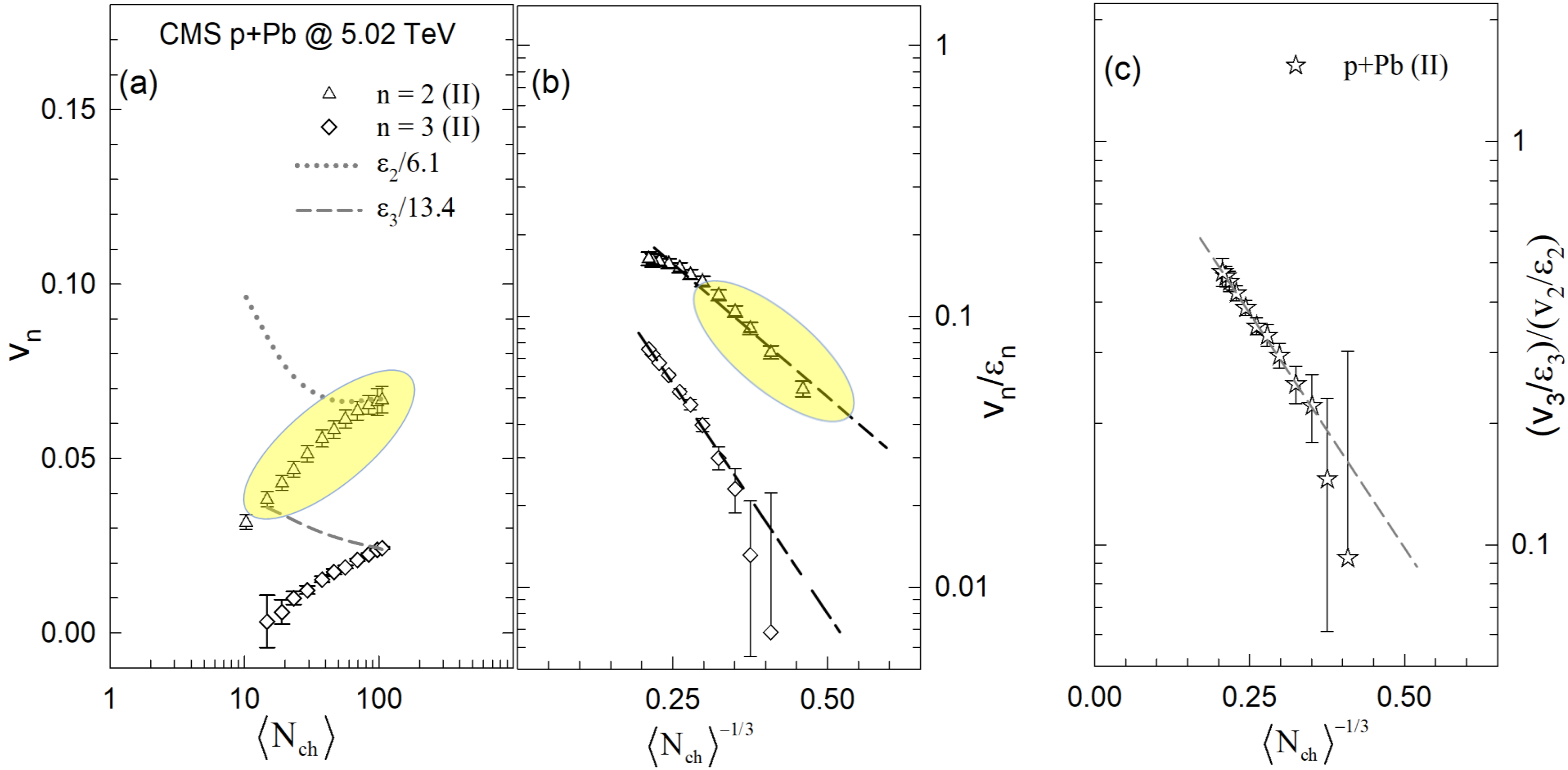
$$ln\left(\frac{v_n}{\epsilon_n}\right) \propto A\,\frac{\eta}{s}\left(\frac{dN}{d\eta}\right)^{\frac{-1}{3}}$$

R.A. Lacey Phys. Rev. C **98**, 031901(R), 2018



- ✓ Characteristic 1/(RT) viscous damping validated
- ✓ Clear pattern for n^2 dependence of viscous attenuation
- ✓ Viscous damping supersedes the influence of eccentricity for “small” systems

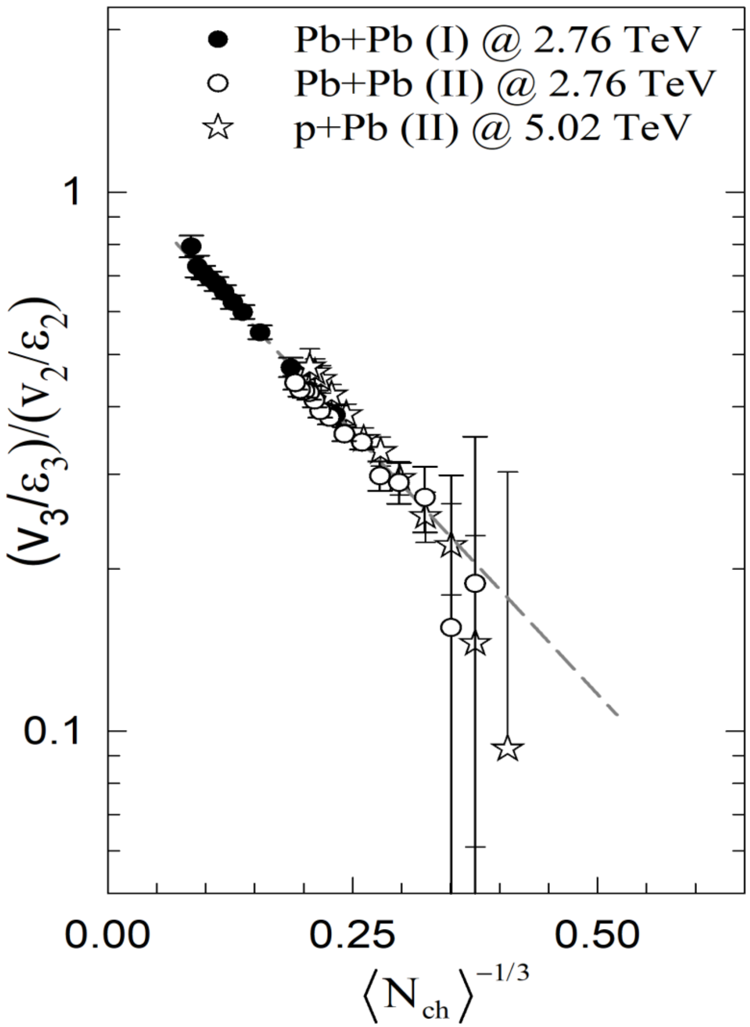
R.A. Lacey Phys. Rev. C **98**, 031901(R), 2018

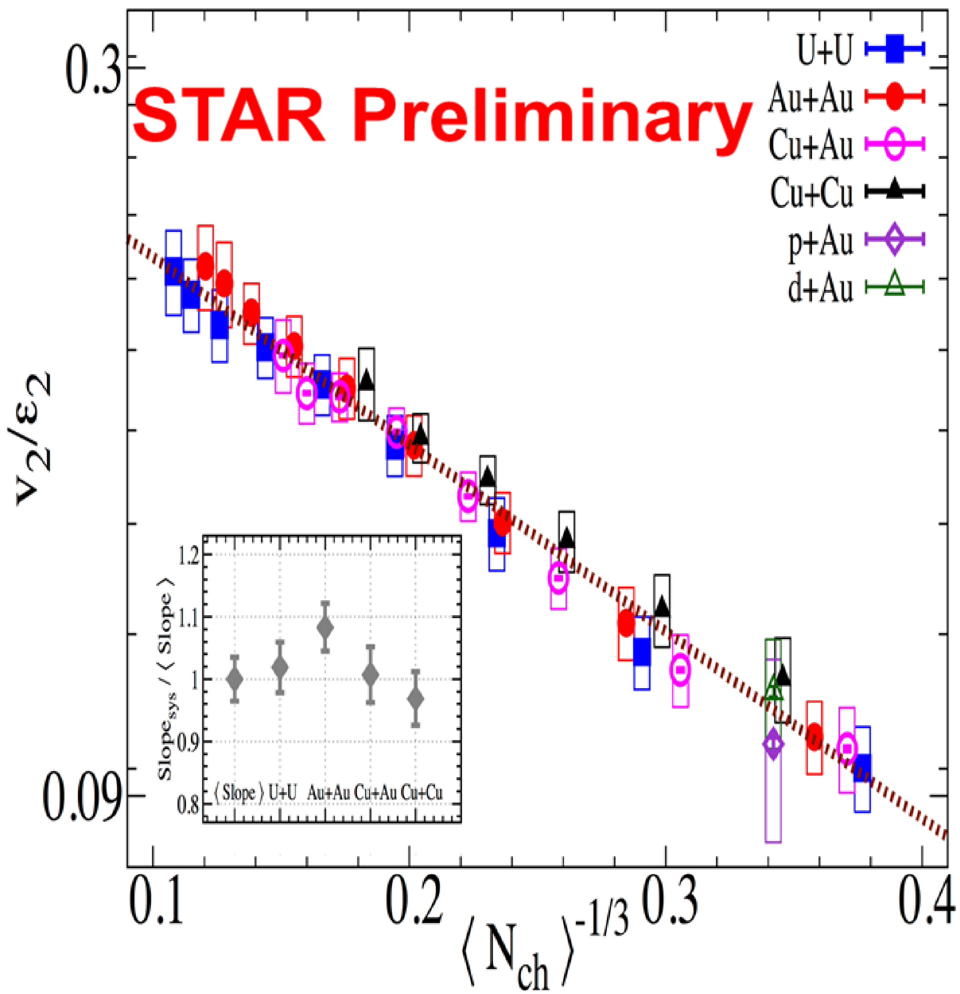


- ✓ Characteristic 1/(RT) viscous damping validated
- ✓ Clear pattern for n^2 dependence of viscous attenuation
- ✓ Viscous damping supersedes the influence of eccentricity for “small” systems

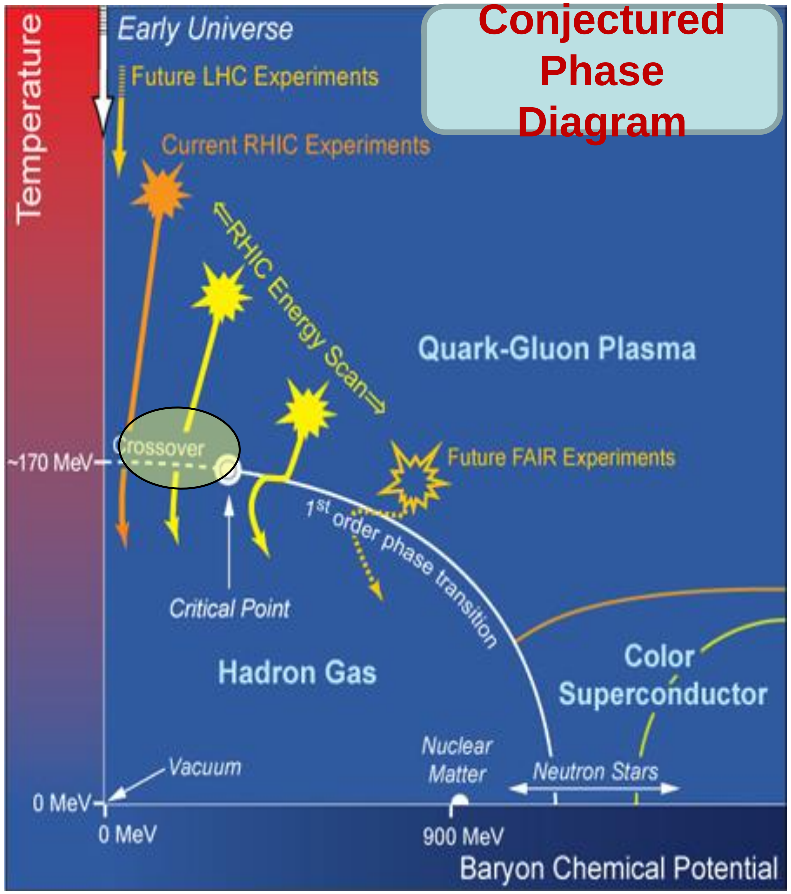
Acoustic Scaling – different systems

R.A. Lacey Phys. Rev. C **98**, 031901(R), 2018





Quantitative study of the QCD phase diagram



Validation of the crossover transition leading to the QGP

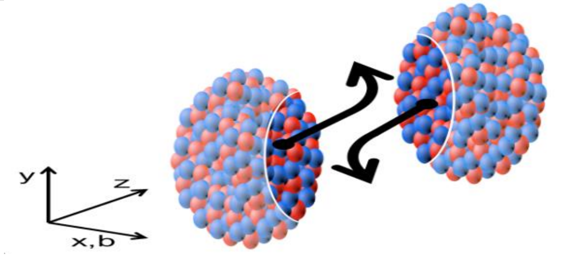
→ **Necessary requirement for CEP**

Strategy for RHIC BES

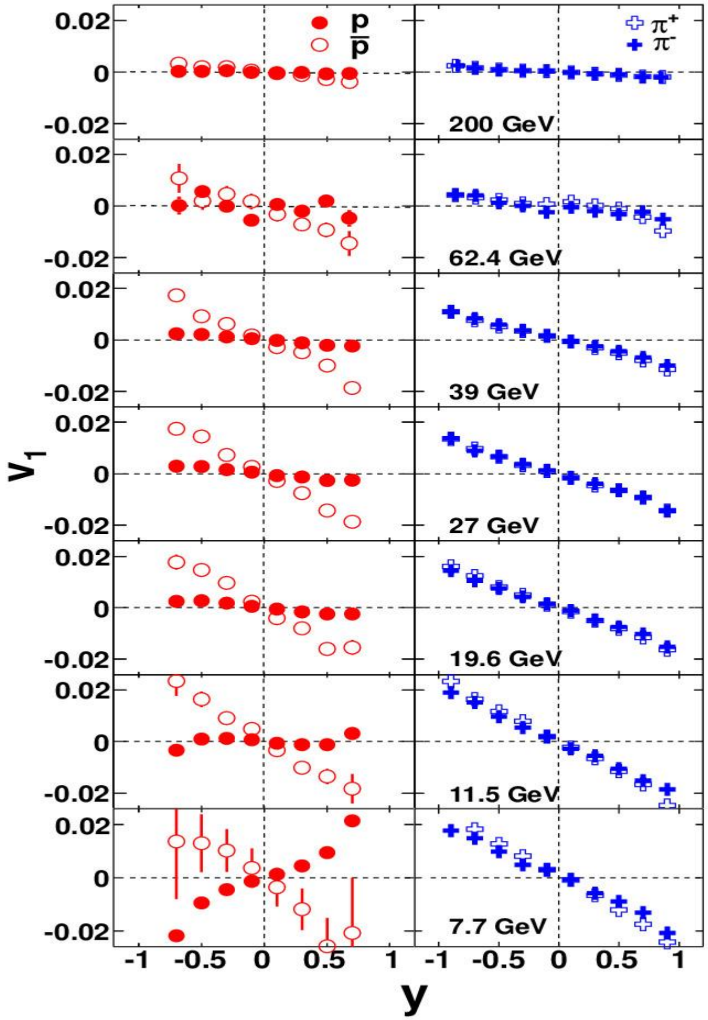
- **Map turn-off of QGP signatures**
- **Location of the Critical End Point (CEP)?**
- **Location of phase coexistence regions?**
- **1st order phase transition signs**
- **Detailed properties of each phase?**

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

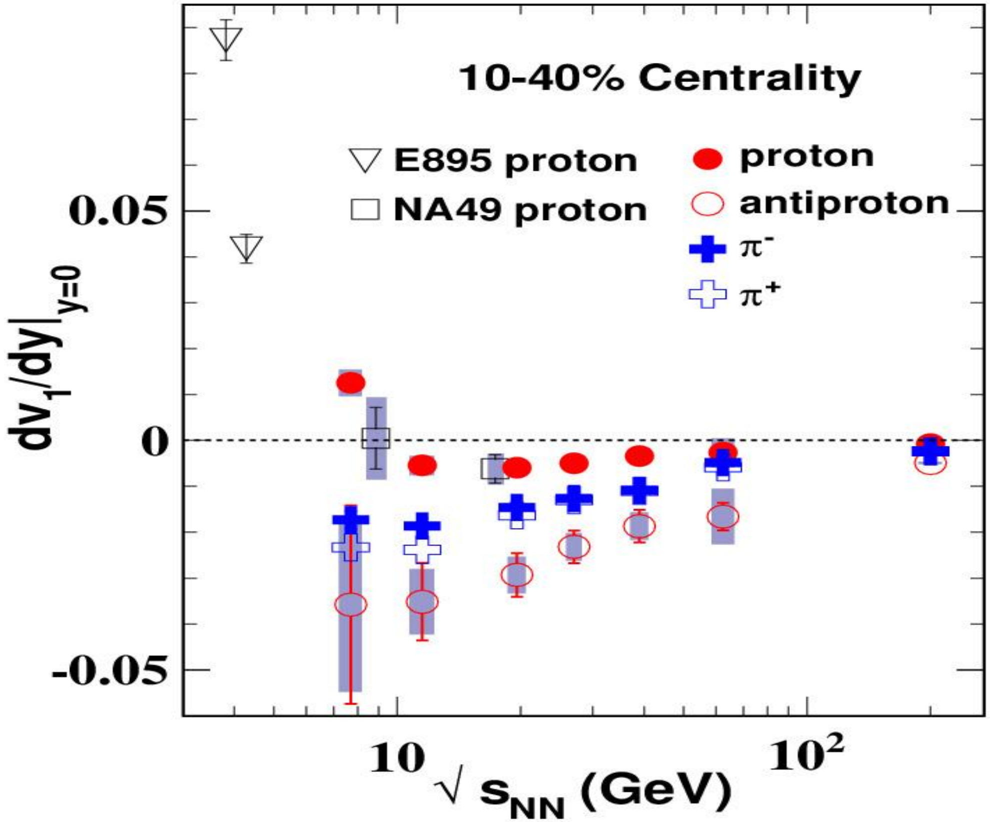
Beam Energy Dependence of Directed Flow (v_1)



- *Generated during the nuclear passage time (2R/γ) – sensitive to EOS*
- *RHIC 200 GeV (2R/γ) ~ 0.1 fm/c*
- *AGS: 3-4.5 GeV (2R/γ) ~ 9-5 fm/c*

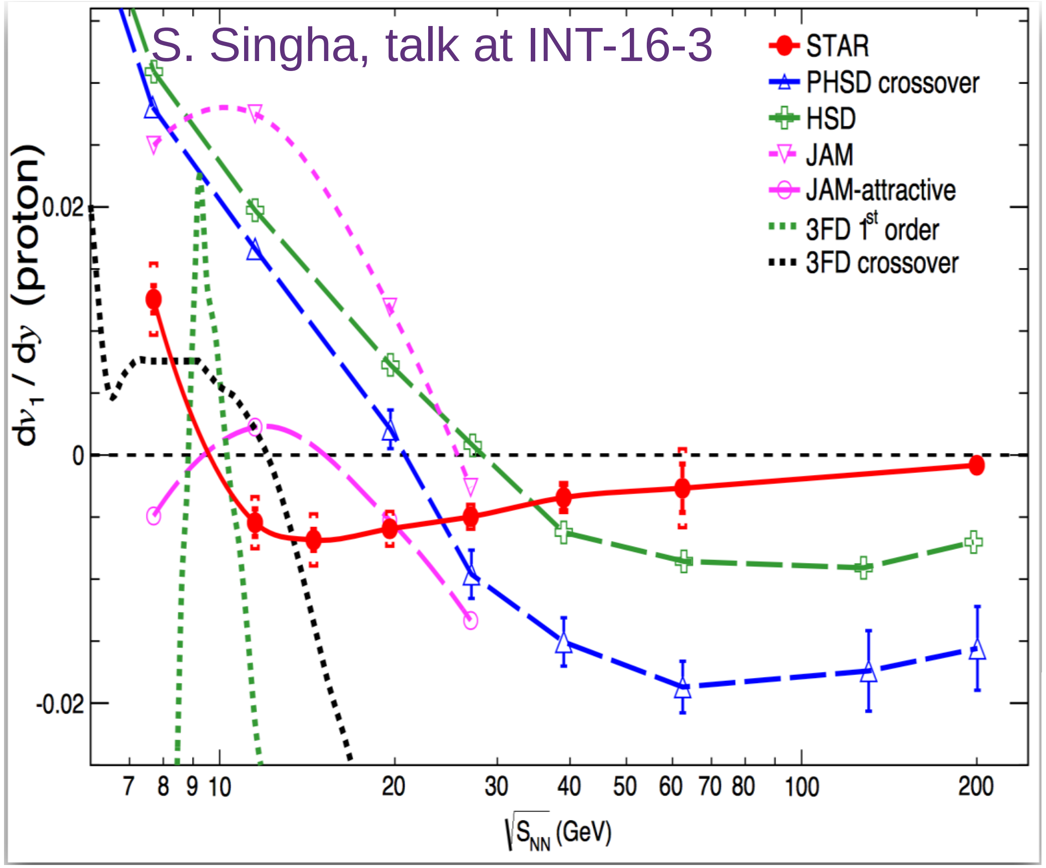


STAR: Phys.Rev.Lett. 112 (2014)



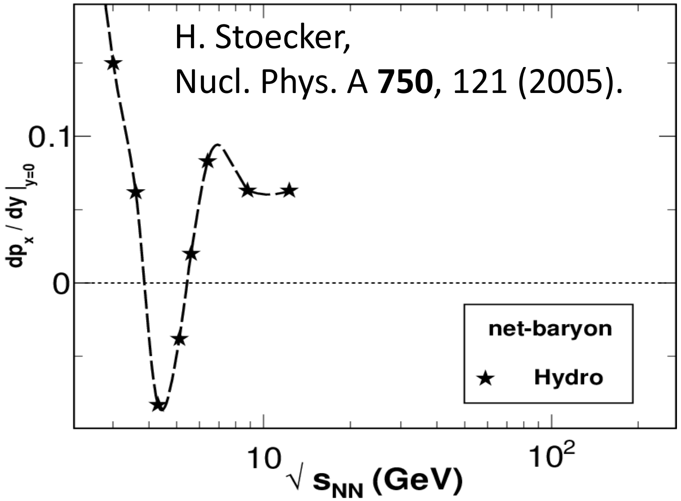
Trend observed by STAR inline with NA49 and E895 data

Beam Energy Dependence of Directed Flow (v_1)



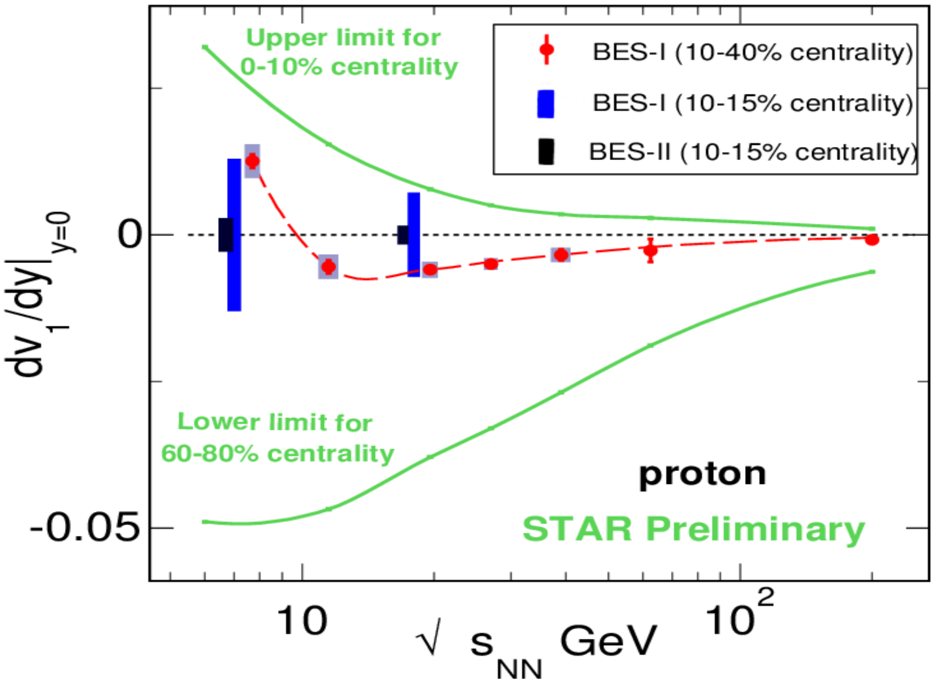
Minimum in slope of directed flow (dv_1/dy) as a function of beam energy for baryons may suggest sudden softening of EOS - sign of the 1st order phase transition

Proton v_1 probes interplay of baryon transport and hydro behavior



None of the models explains the data
• Systematics associated with the models is quite large

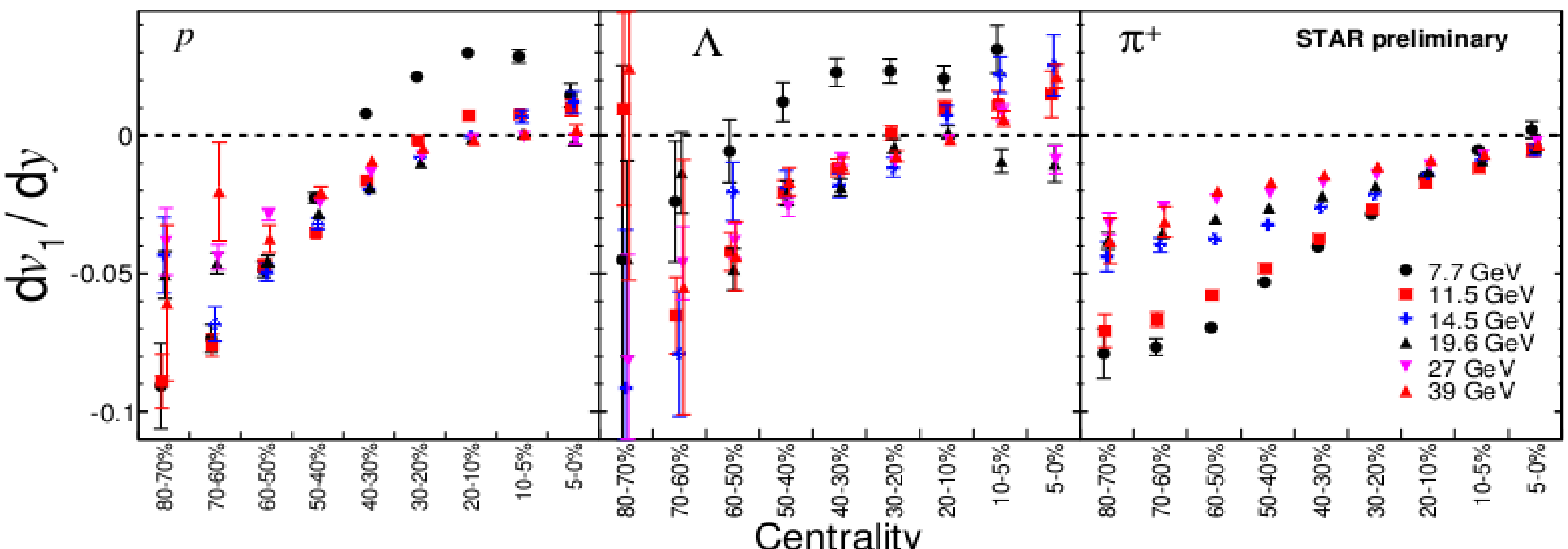
Centrality Dependence of Directed Flow (v_1)



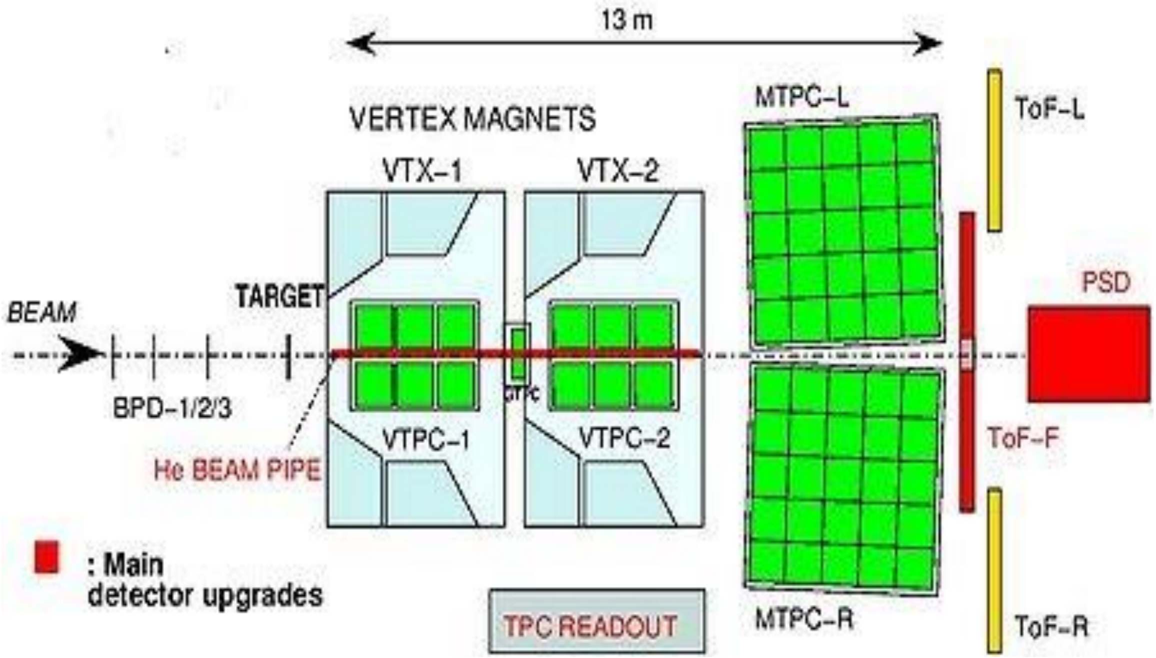
1. Strong centrality dependence
2. Complicated Pt dependence
3. Non-linear terms are important for non-central collisions

STAR Preliminary, QM2015

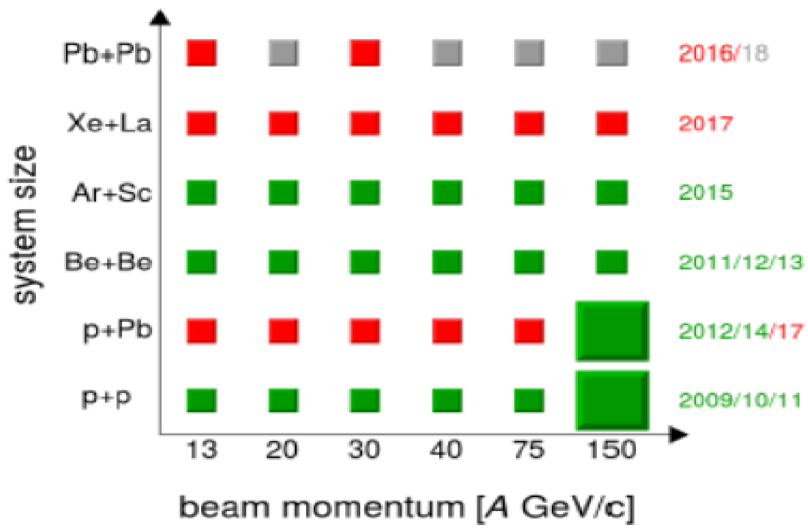
Nucl.Phys. A956 (2016) 260-263



Prospects for directed flow measurements: NA61/SHINE



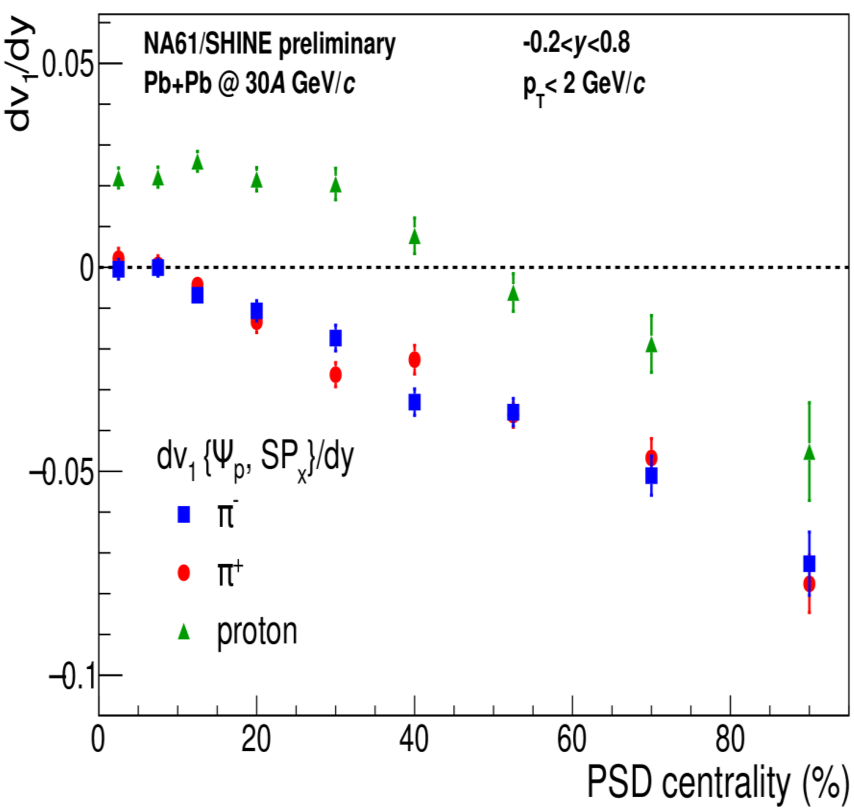
INR RAS + MEPhI

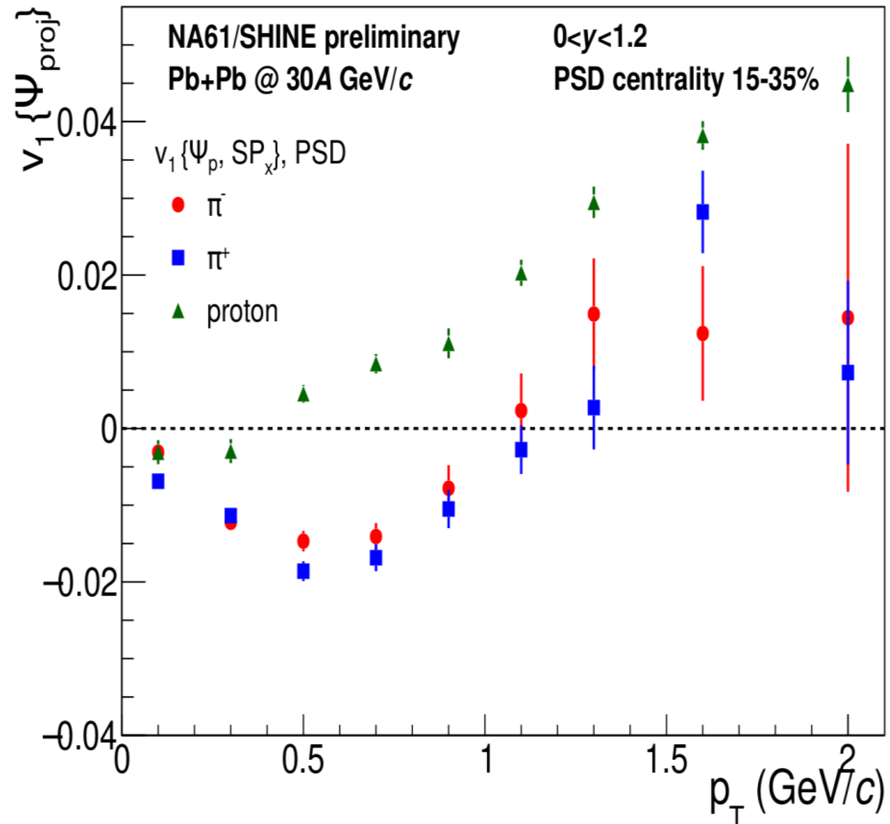


- Results will be important for flow measurements at BM@N, MPD (NICA) and CBM(FAIR)
- Different colliding systems – study the effect of spectator matter

Prospects for directed flow measurements: NA61/SHINE

V. Klochkov and I. Selyuzhenkov: Anisotropic flow with NA61/SHINE at CERN SPS (QM2018)

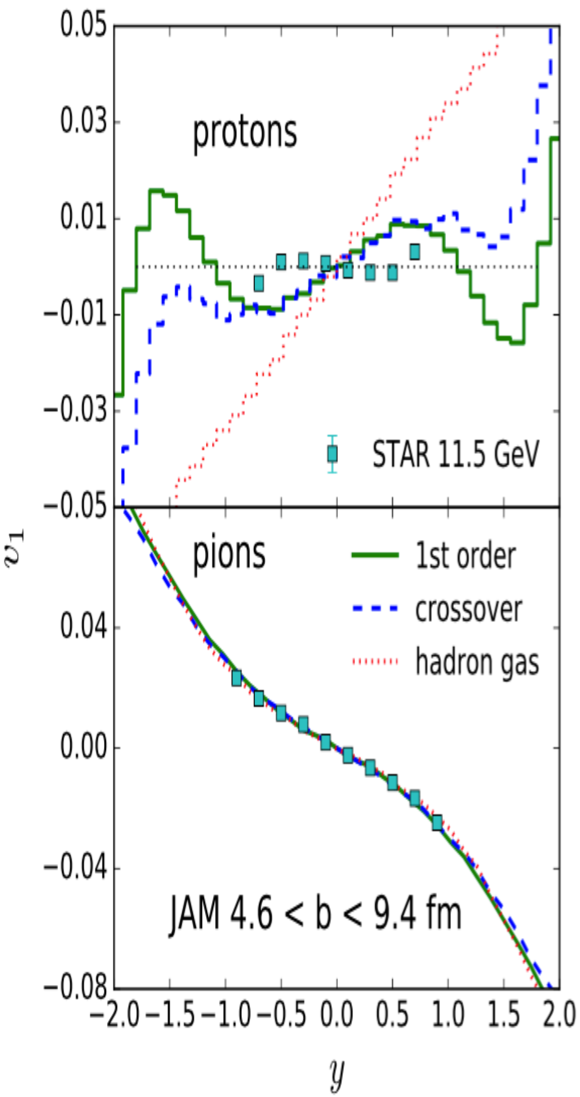




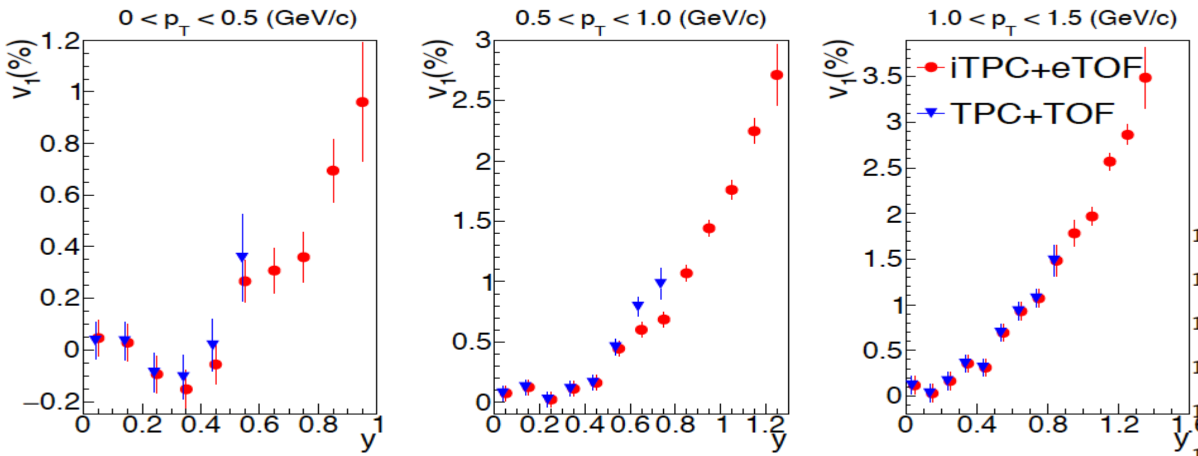
1) **Strong mass dependence of v1(pt)**
2) **Slope of proton v1 changes sign at about 50% centrality**
3) **Slope of pions v1 is always negative**

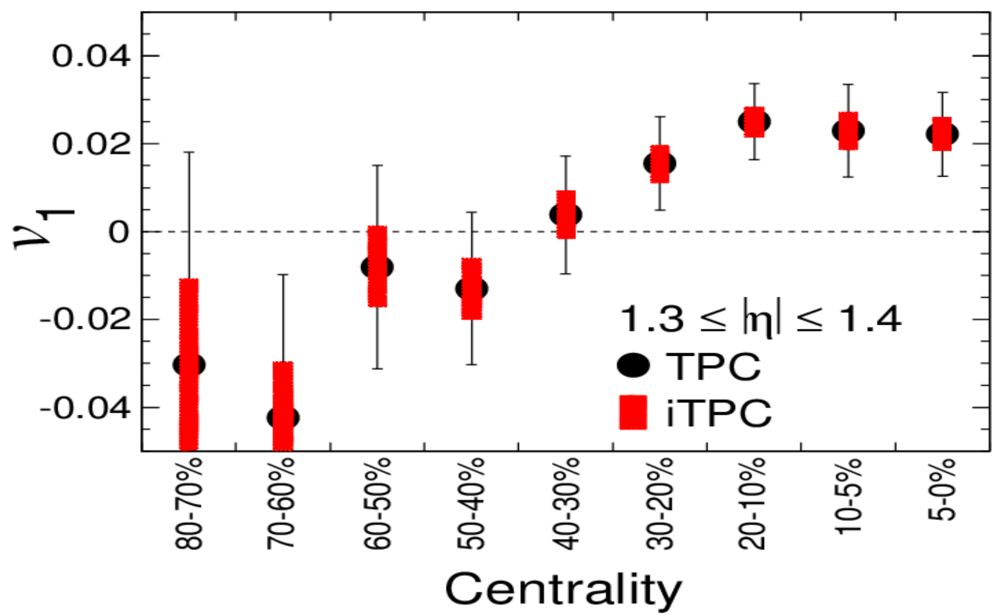
Prospects for directed flow measurements: STAR BES2

Phys.Rev. C94 (2016)



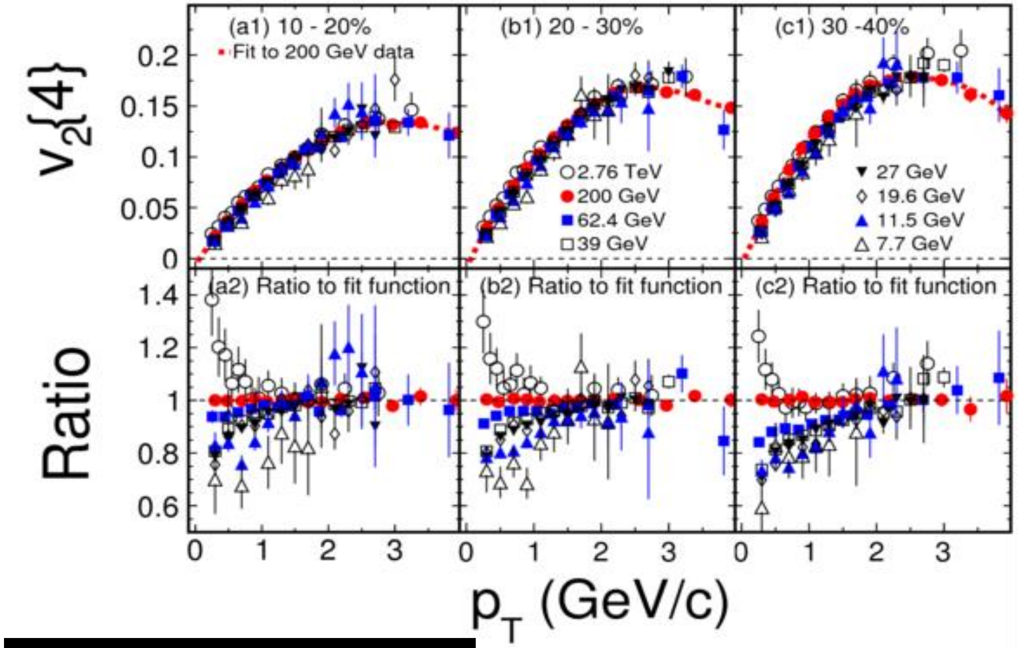
arXiv:1609.05100





Beam Energy Dependence of Elliptic Flow (v_2)

STAR: Phys. Rev. C 86 (2012) 54908



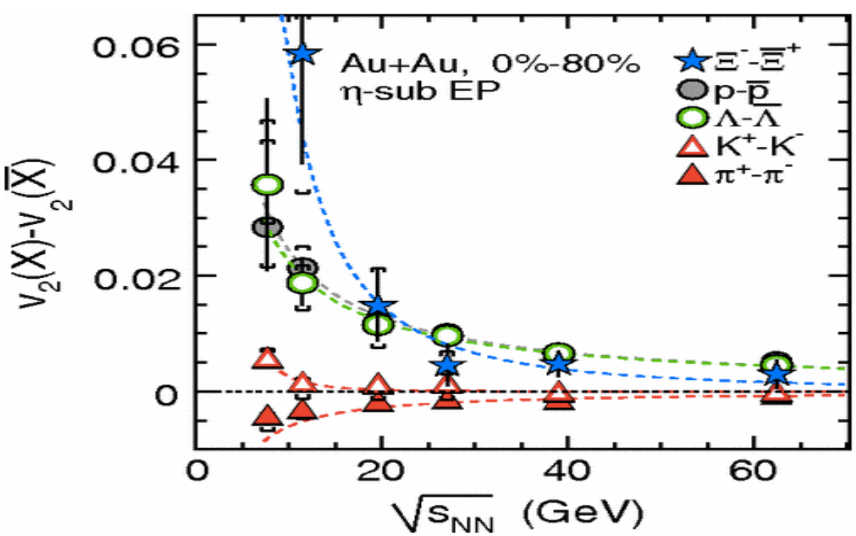
Surprisingly consistent as the energy changes by a factor ~400

Initial energy density changes by nearly a factor of 10

No evidence from v2 of charged hadrons for a turn off of the QGP

How sensitive is v_2 to QGP?

Phys. Rev. Lett. 110, 142301 (2013)

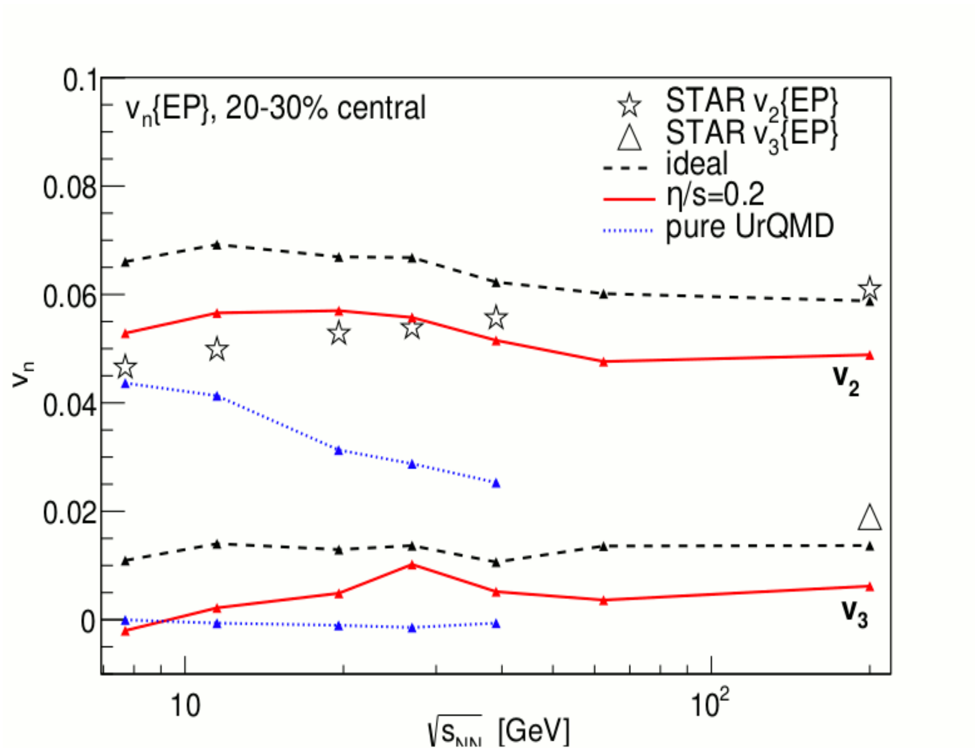


Substantial particle-antiparticle split at lower energies

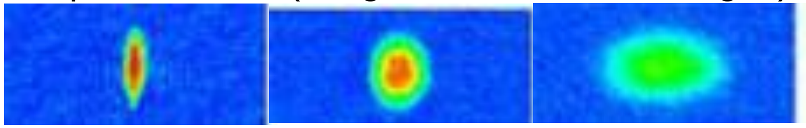
- The number of quark scaling in elliptic flow is broken at low energies
- Do ϕ-mesons or multi-strange particles deviate?

v_3 is more sensitive than v_2

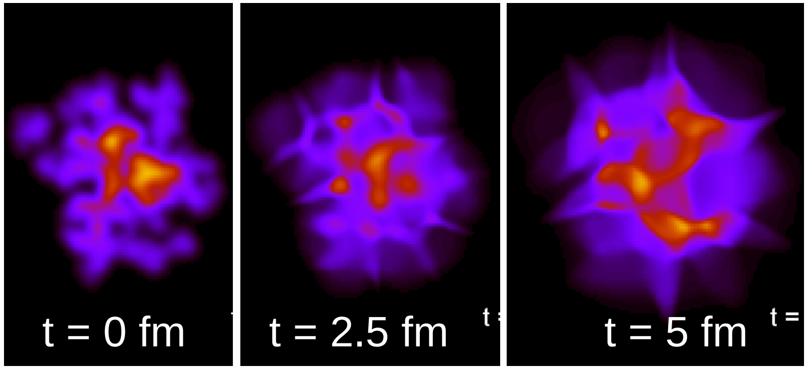
J. Auvinen, H. Petersen, Phys. Rev. C 88, 64908



Elliptic n=2 flow (image of an atomic fermi gas)



All harmonic flow (QGP simulation)



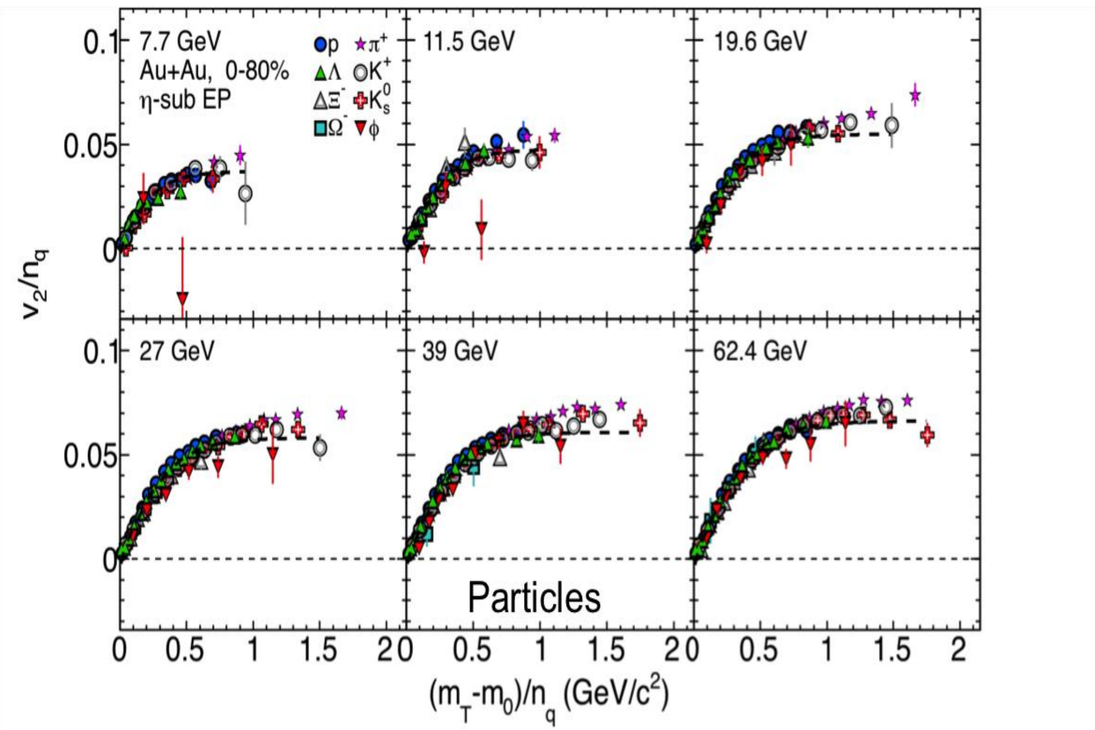
B. Schenke et.al., Phys. Rev. C 85, 024901

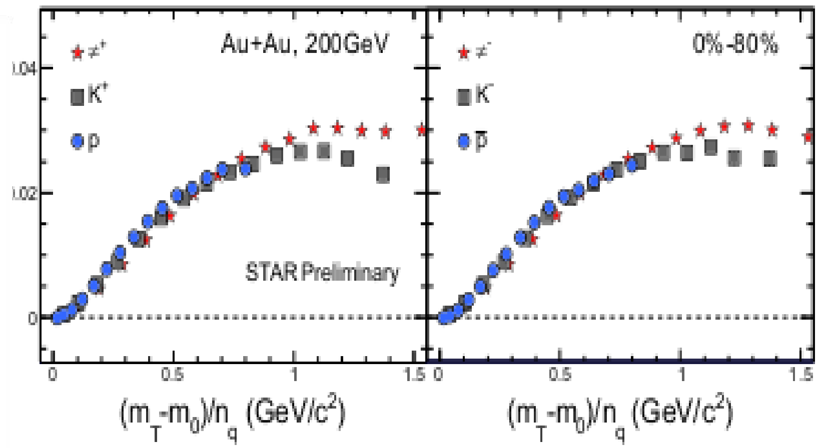
Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

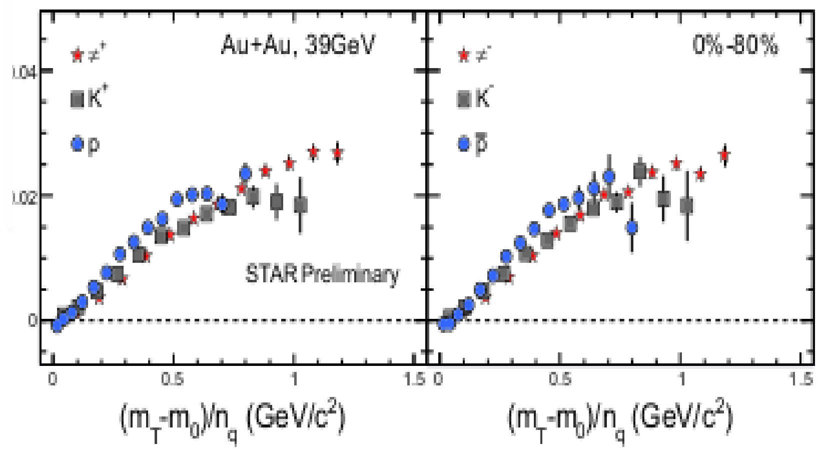
In models, v_3 goes away when the QGP phase disappears

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

Phys. Rev. C 88, 014902 (2013)

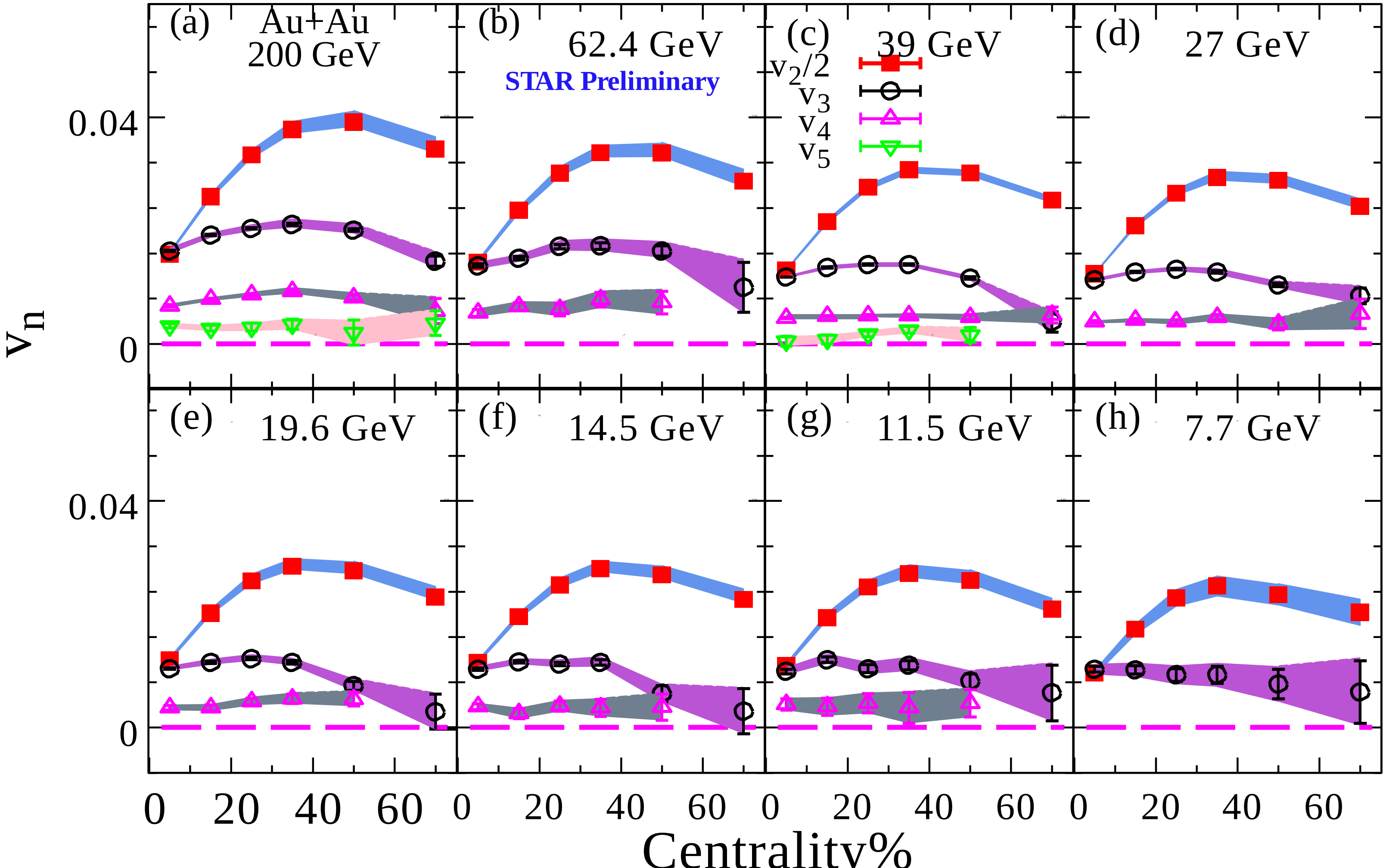






- NCQ-scaling holds for v2 of particles
- NCQ-scaling is broken for v3 of particles and anti-particles separately for < 39 GeV

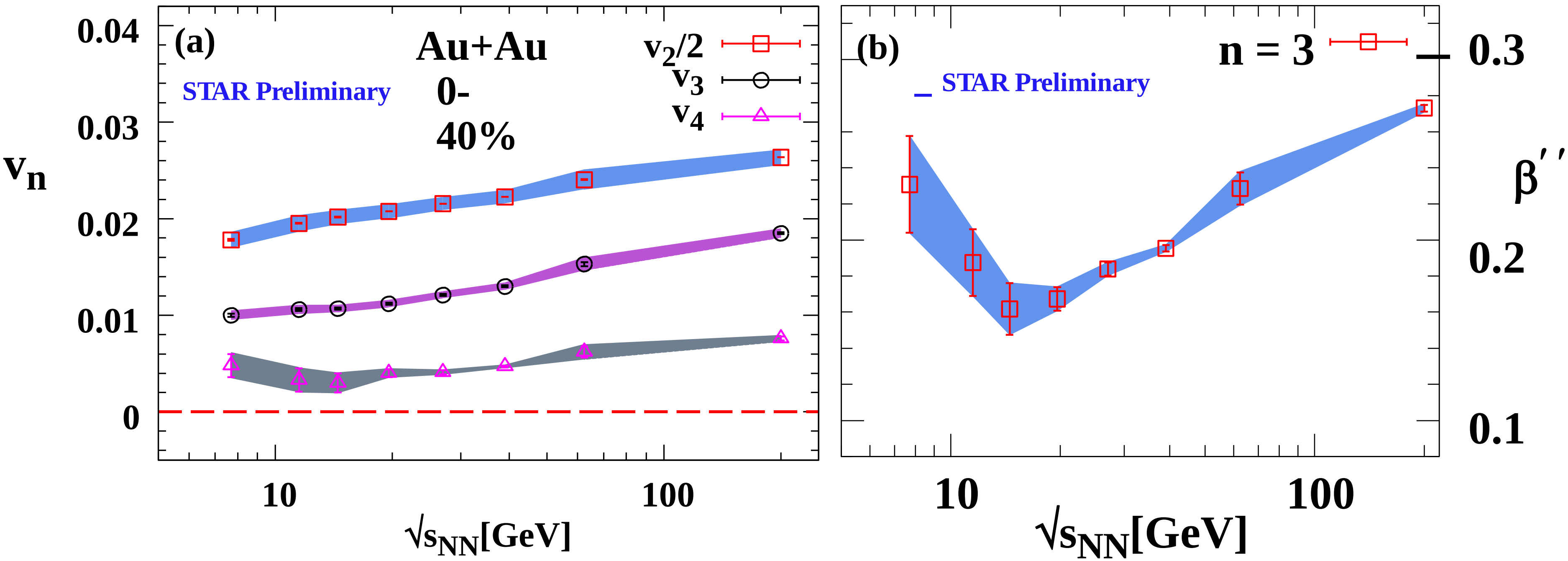
V_n (centrality) as a function of beam energy



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

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

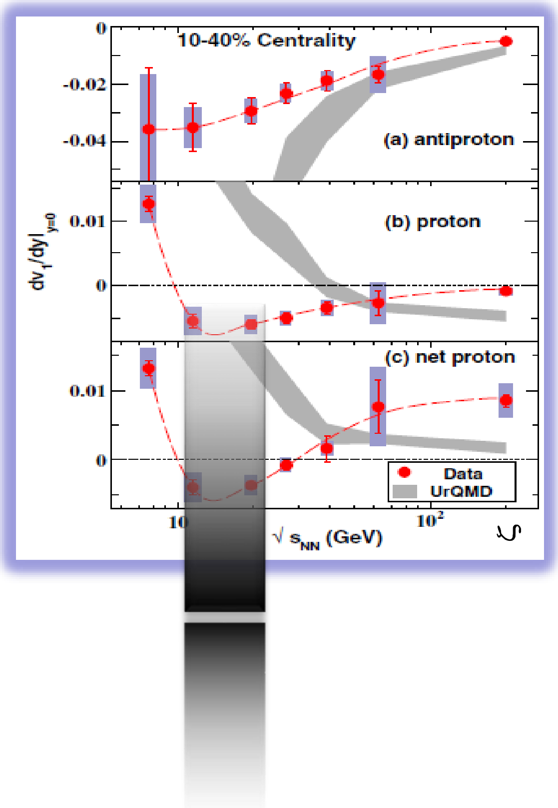
$$VC \propto \frac{\eta}{s}$$

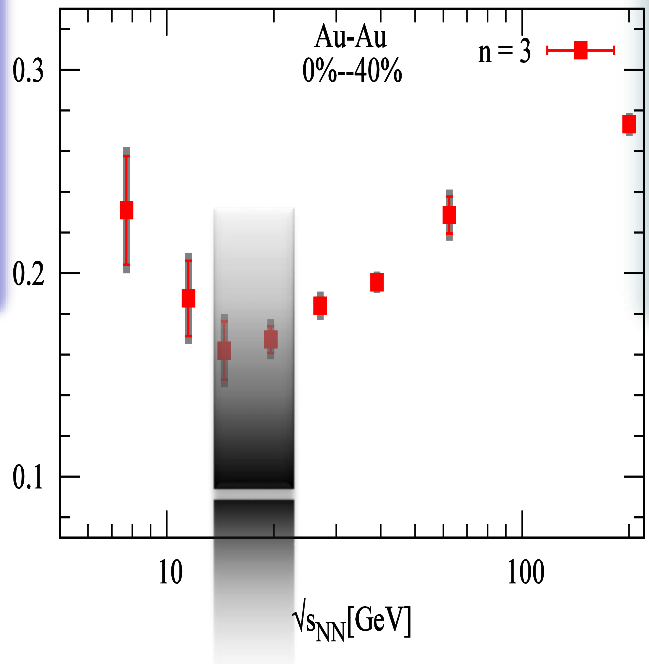


V_n shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient (η/s), indicates a non-monotonic behavior as a function of beam energy.

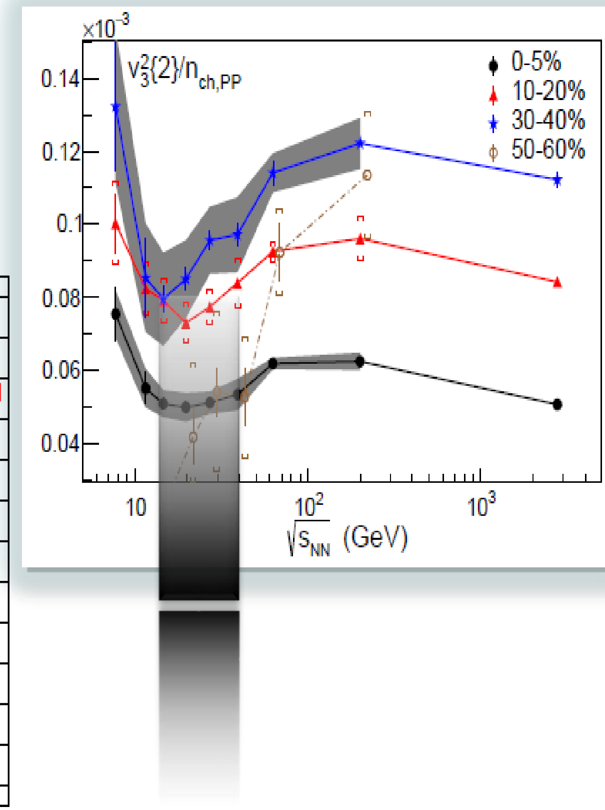
STAR data: Anomalies in the Pressure and η/s?

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 at AGS, SIS: from in-plane to out-of-plane (1)

VOLUME 83, NUMBER 7 PHYSICAL REVIEW LETTERS 16 AUGUST 1999

Elliptic Flow: Transition from Out-of-Plane to In-Plane Emission in Au + Au Collisions

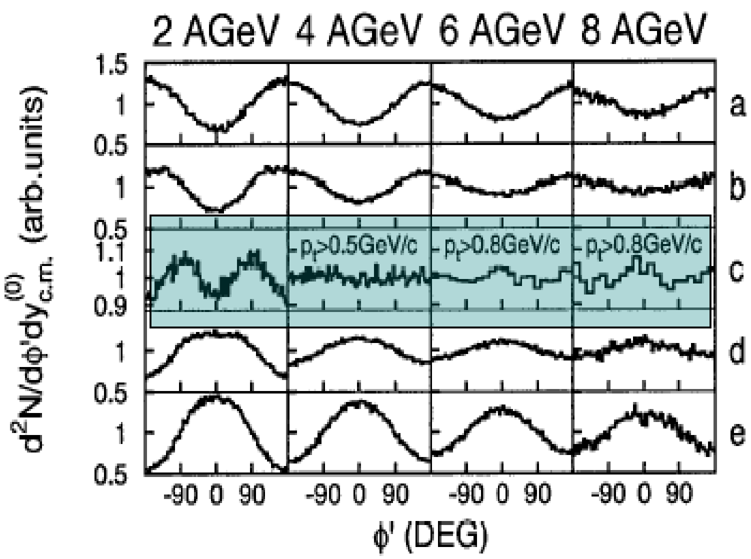
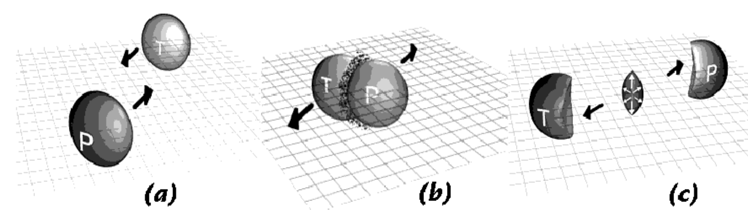
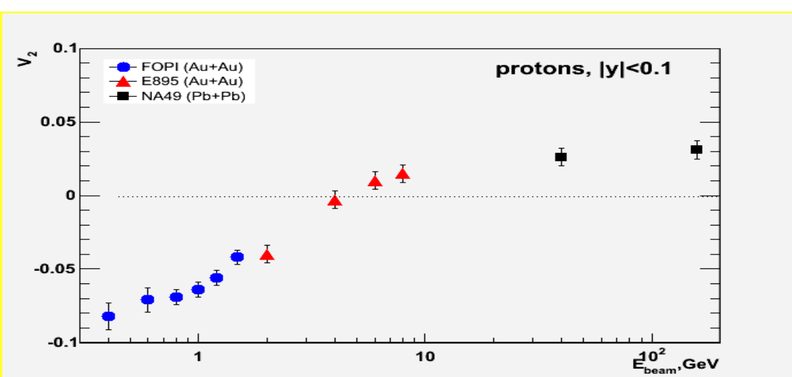
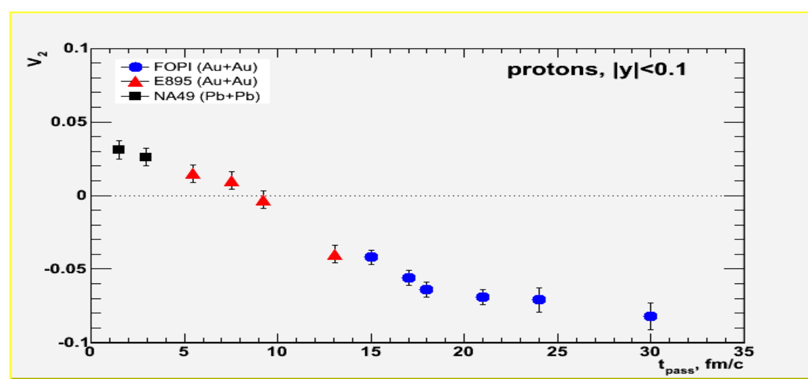


FIG. 2. Azimuthal distributions (with respect to the reconstructed reaction plane) for 2A, 4A, 6A, and 8A GeV Au + Au.

Passage time: $2R/(\beta_{cm}\gamma_{cm})$
Expansion time: R/c_s
$c_s = c\sqrt{dp/d\varepsilon}$ - speed of sound

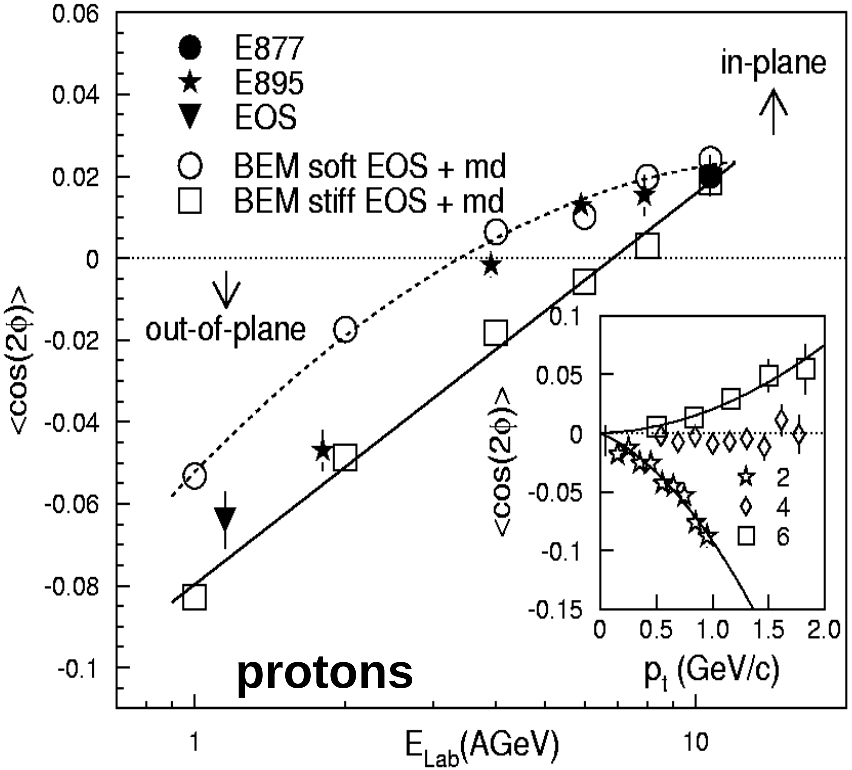




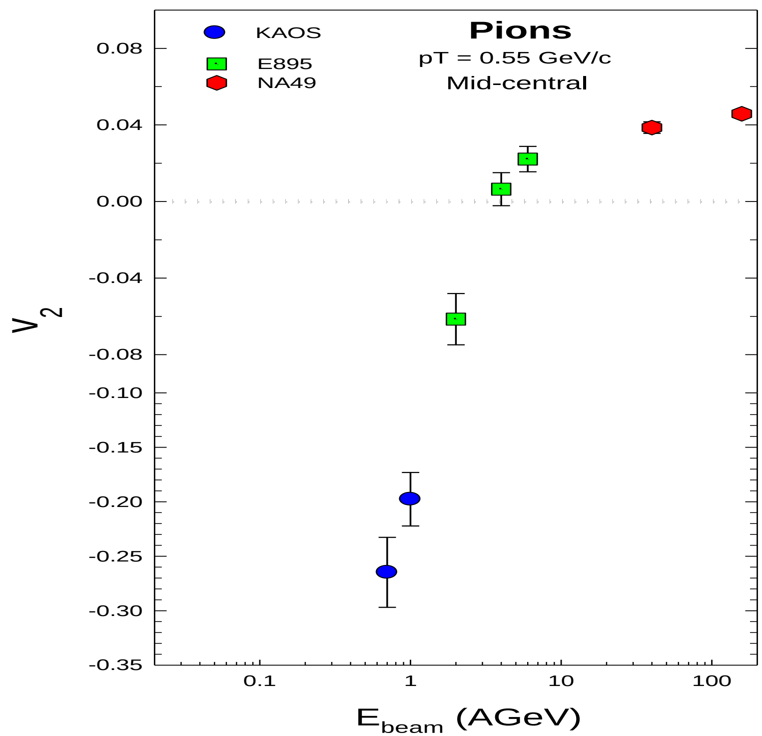


v_n Flow at AGS, SIS: from in-plane to out-of-plane (3)

Phys. Rev. Lett. **83**, 1295 (1999). E895



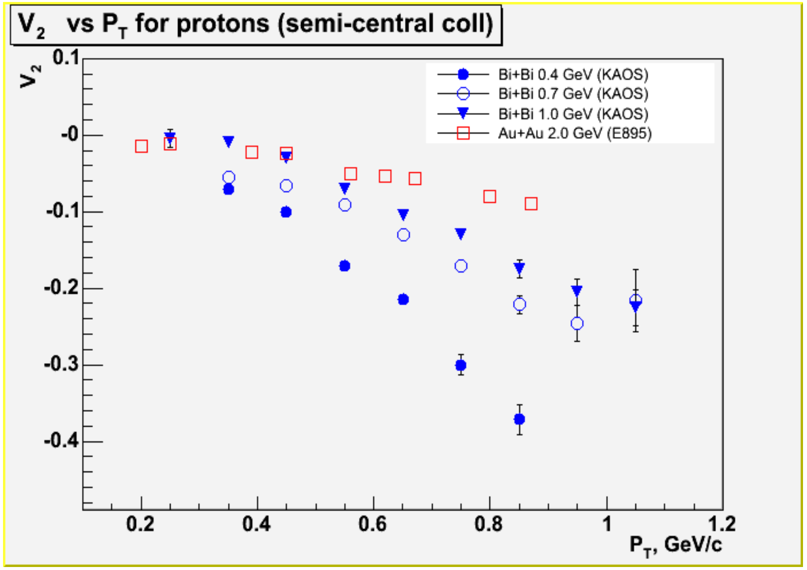
E895 preliminary ; SQM2004

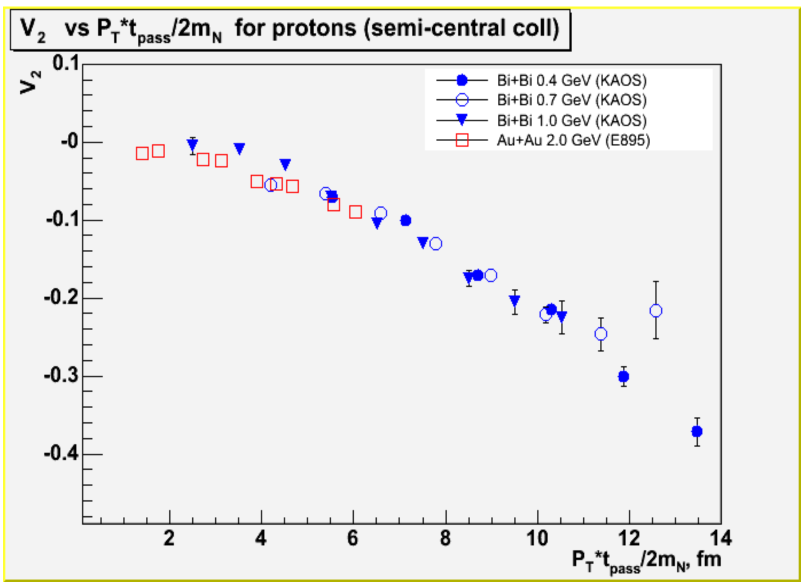


E895: for protons V2 changes sign at Elab=4 GeV. What about the other particle species? Other harmonics? Questions for STAR BES2, BM@N, CBM, NICA .

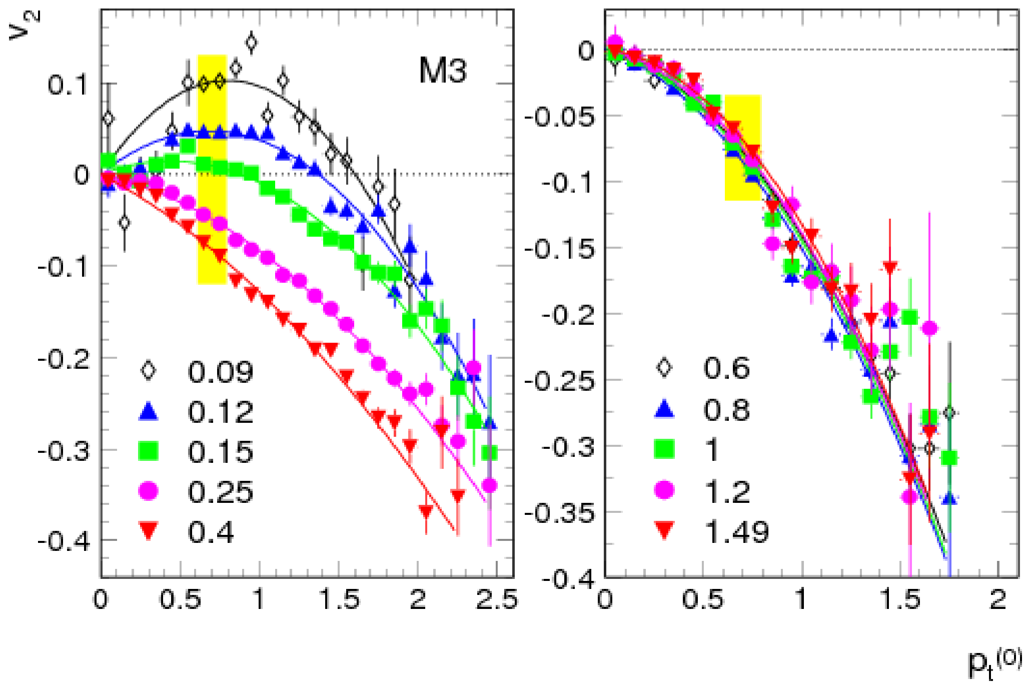
v_2 Flow at SIS-AGS: scaling relations

(KAOS – Z. Phys. A355 (1996);
(E895) - PRL 83 (1999) 1295





FOPI: v_2 of protons from
Elab=0.09 to 1.49 GeV
Phys.Lett. B612 (2005) 173-180



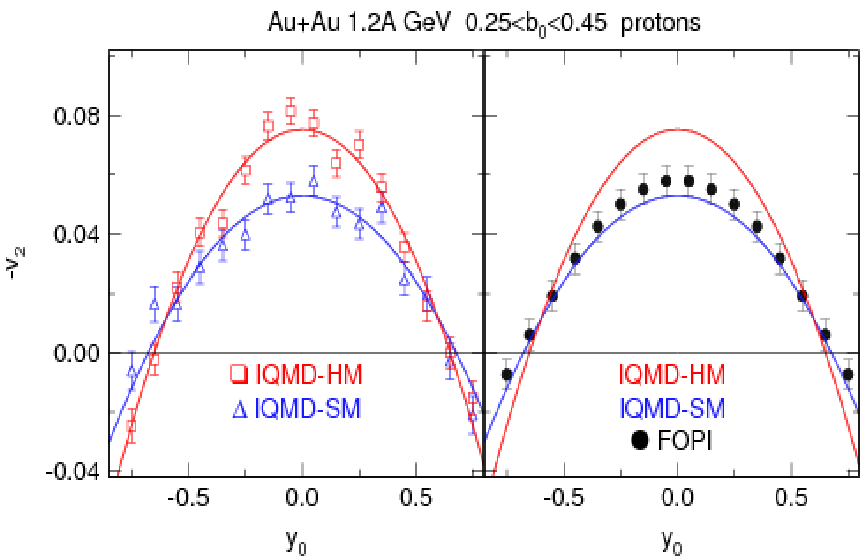
Pt dependence of v2 of protons revealing a rapid change with incident energy below 0.4 AGeV, followed by an almost perfect scaling at the higher energies: 0.4 -2AGeV

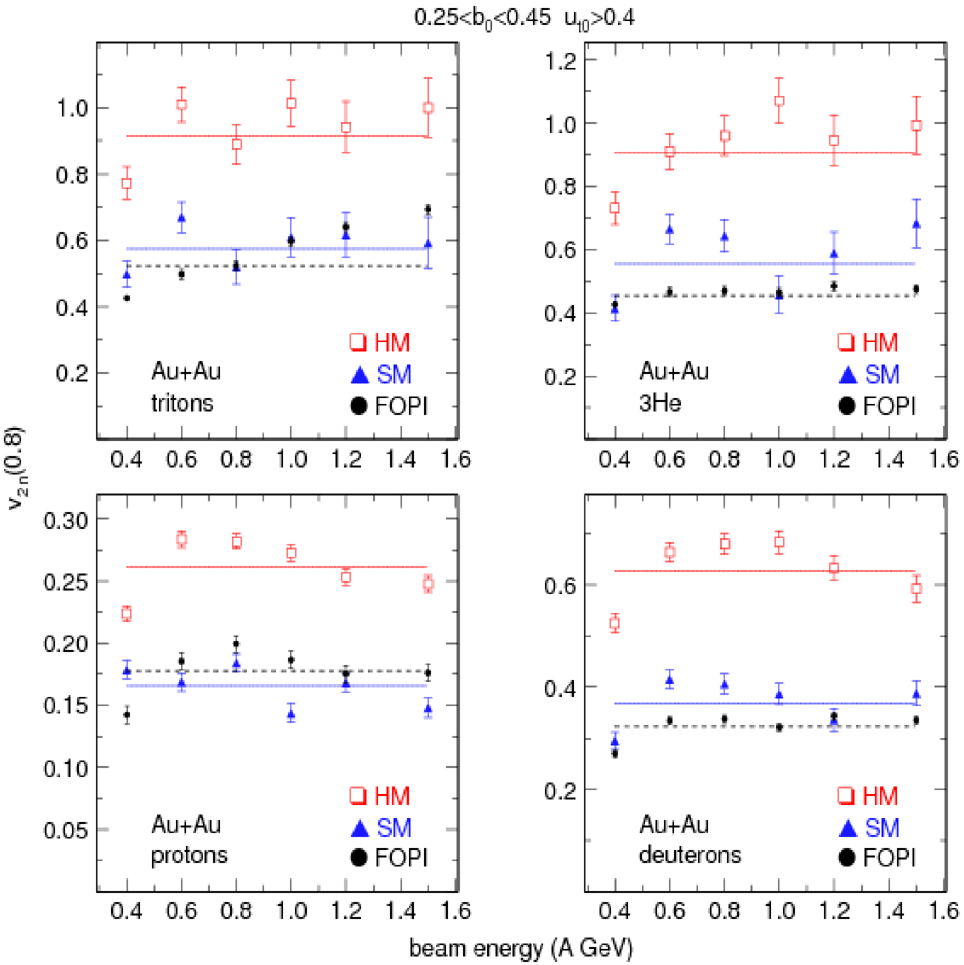
.

Flow at SIS: rapidity dependence of v2 and EOS

HM – stiff momentum dependent with K=376 MeV
SM – soft momentum dependent with K=200 MeV

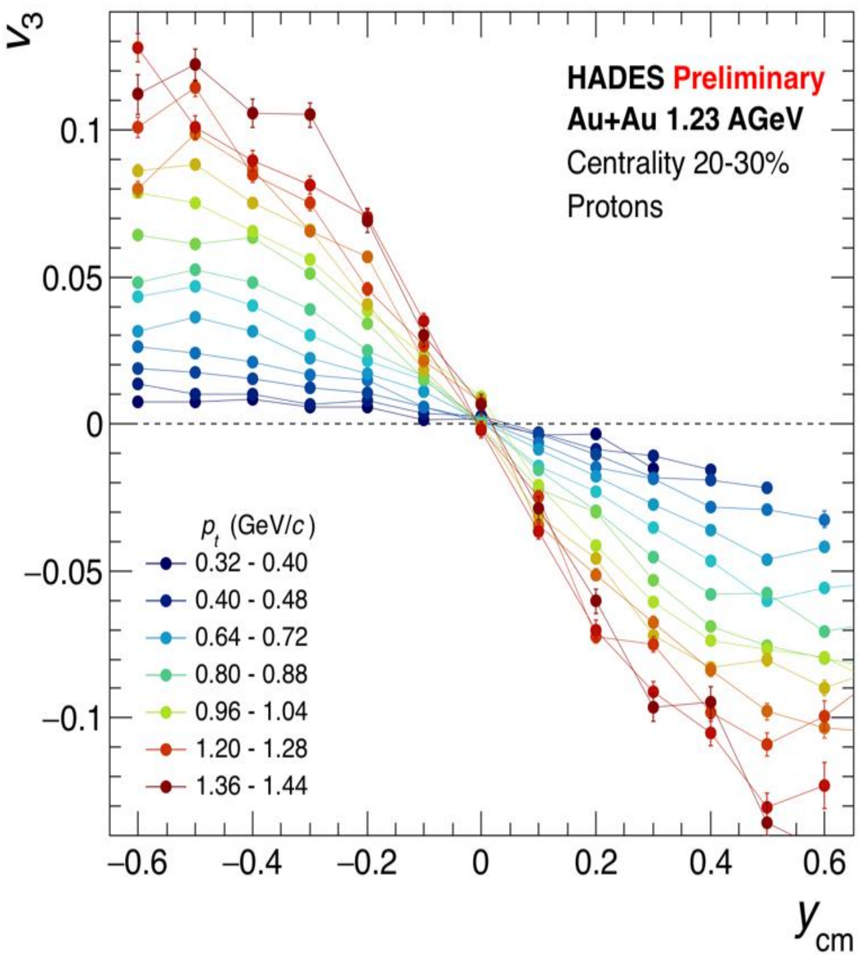
FOPI data : Nucl. Phys. A 876 (2012) 1
IQMD : Nucl Phys. A 945 (2016)



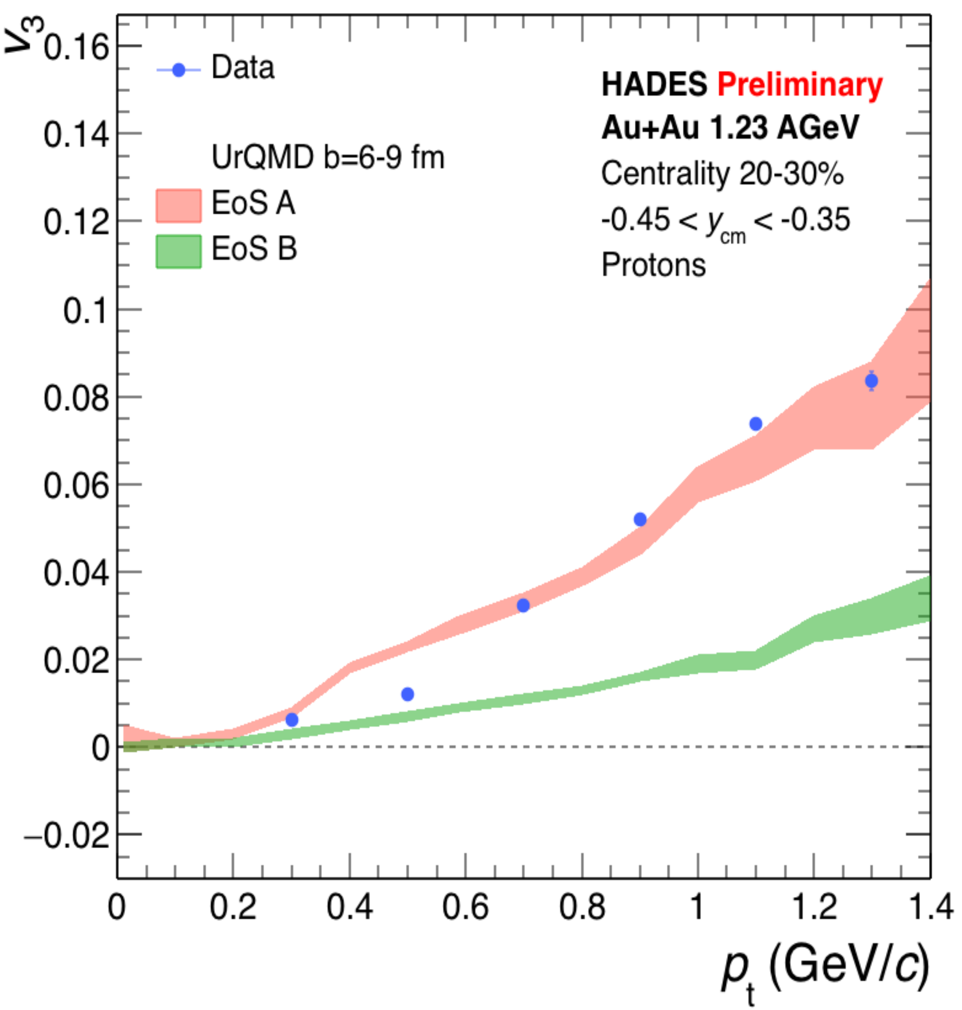


V2n=|V20|+|V22|
Fit: V2(y0)=V20+V22*Y0^2

HADES results at SIS: Vn harmonics n>2

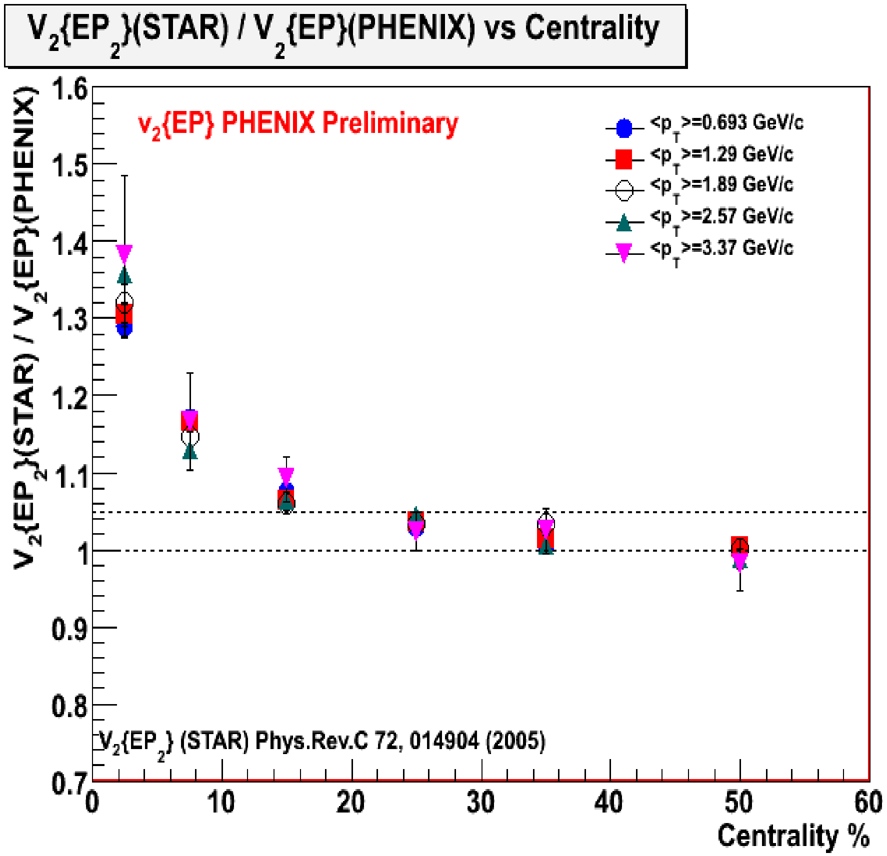


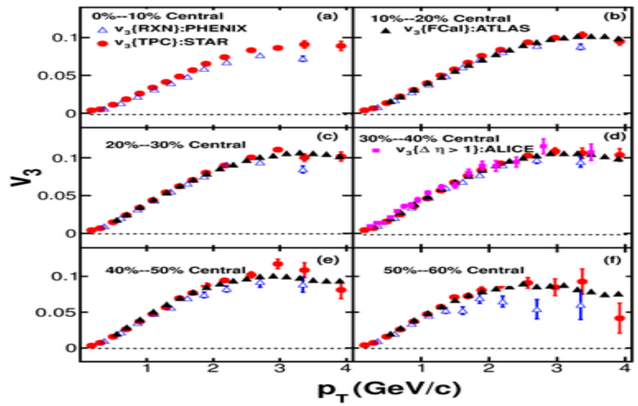
HADES preliminary QM2018

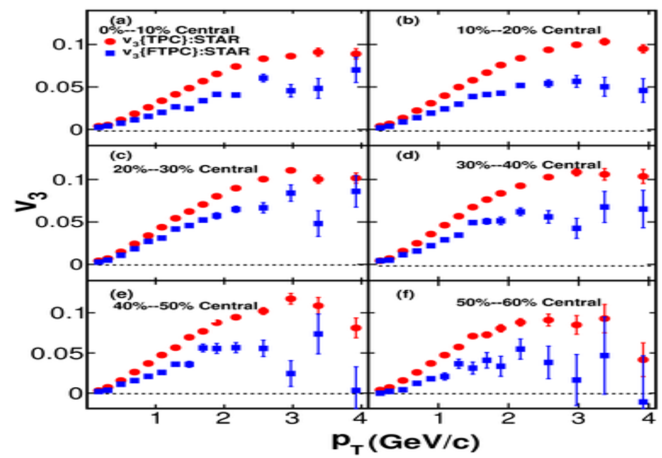


J.Phys. G45 (2018) no.8, 085101

Are flow measurements at RHIC reliable?





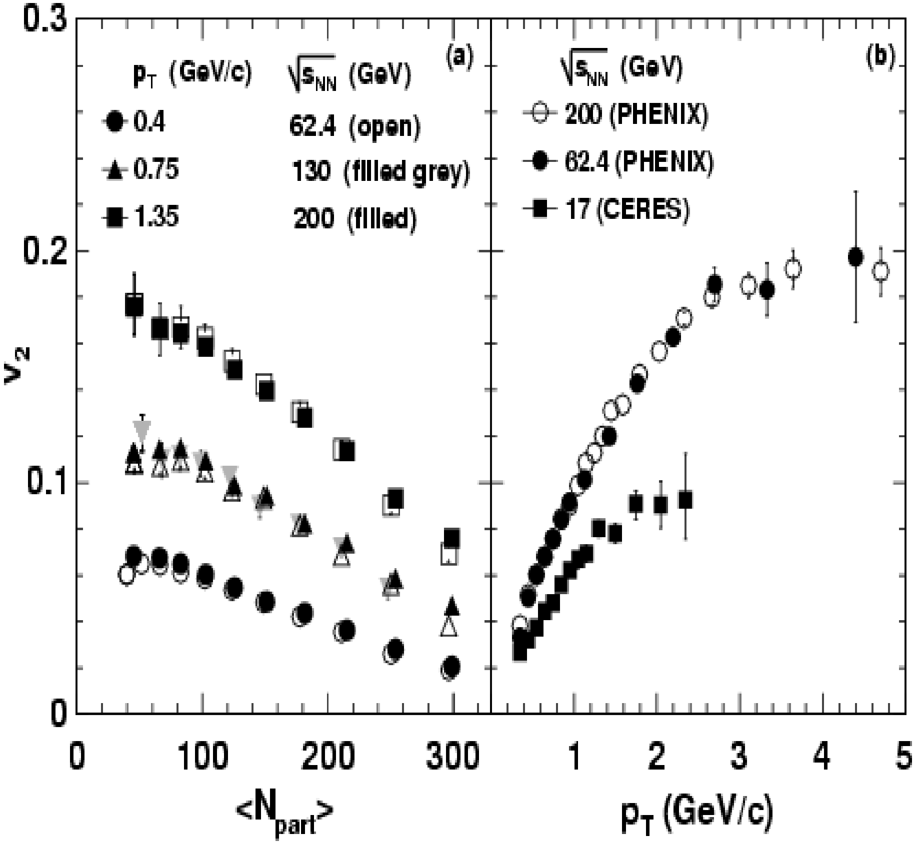


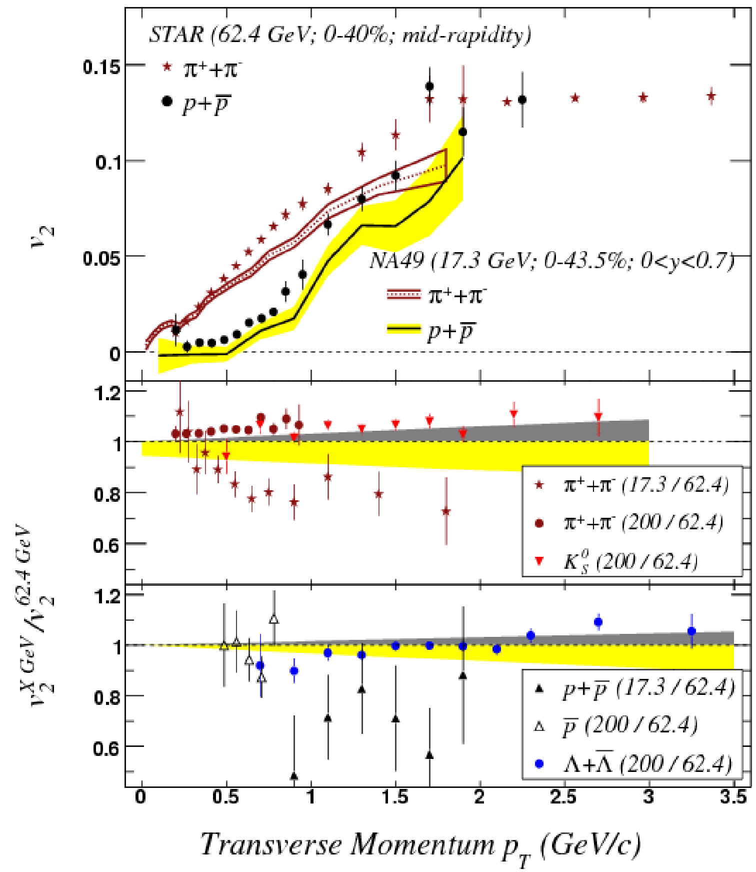
Do we understand the difference in v2 and v3 measurements between STAR and PHENIX ?

Are flow measurements at SPS reliable?

Phenix: Phys. Rev. Lett. 94, 232302 (2005)

STAR: Phys.Rev.C75:054906,2007

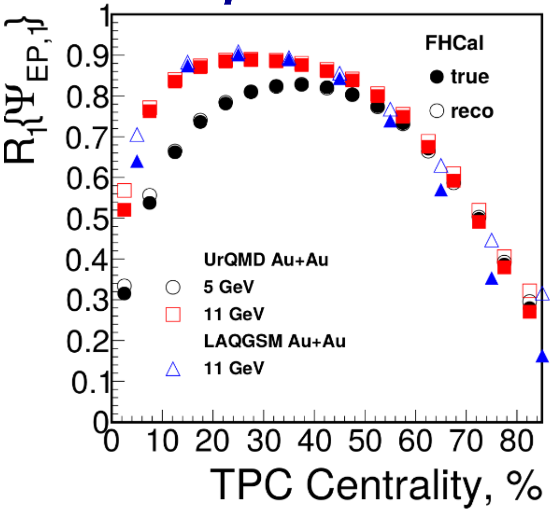


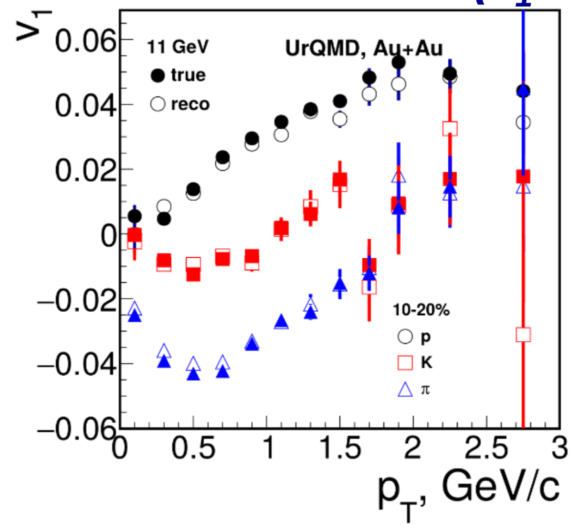


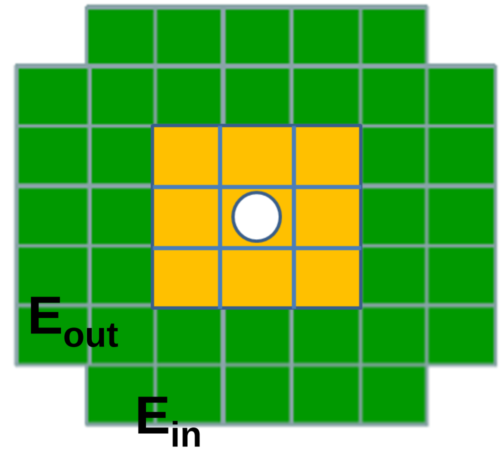
PHENIX: RHIC/SPS: ~ 50% difference . STAR: RHIC/SPS ~ 10-15% difference in the differential flow results !

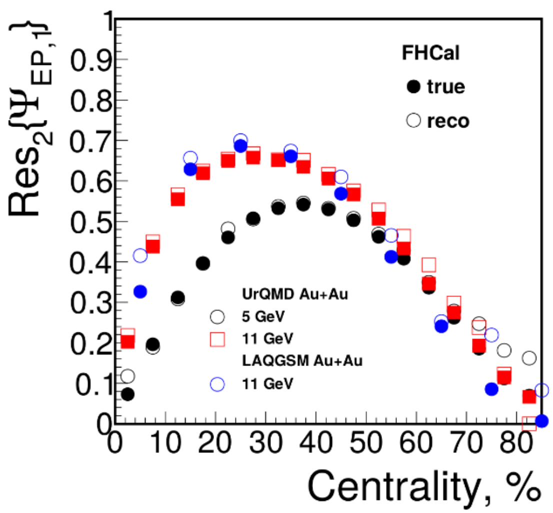
Flow performance: v_n of charged hadrons: MPD (NICA)

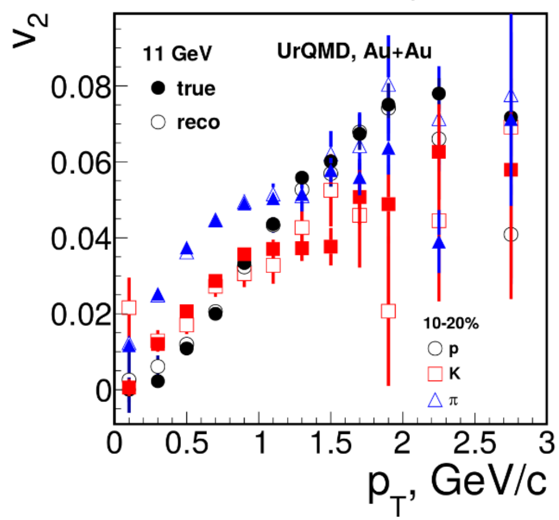
event plane resolution *flow harmonics (v_1/v_2)*











FHCal coverage: $2.2<|\eta|< 4.8$

19/09/2018 **Performance of Anisotropic Flow Studies at MPD (NICA) 20'**
15-50:16-10 Speaker Mr. Peter Parfenov (MEPhI, Moscow)

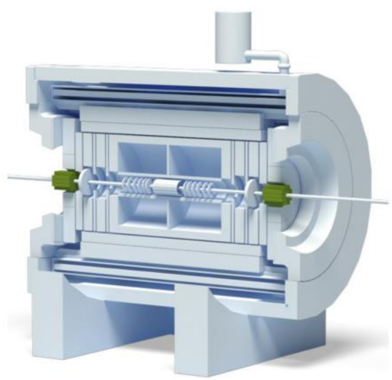
Flow performance study for FHCAL TDR (2016 -)

NICA

Technical Design Report for the MPD Experiment

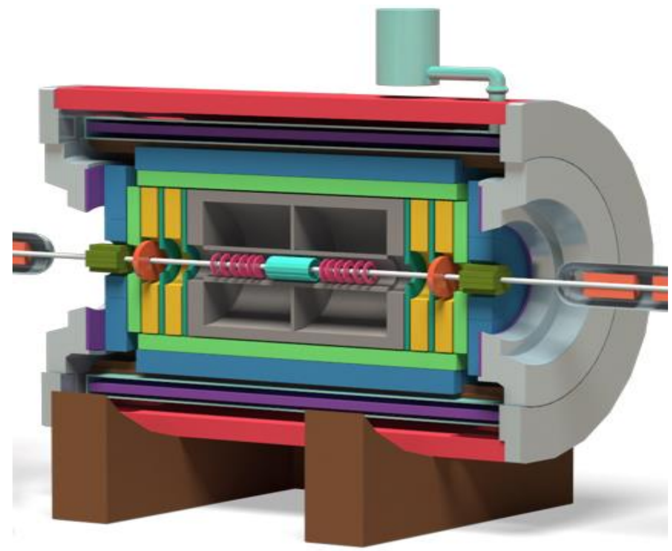
Nuclotron Based Ion Collider Facility

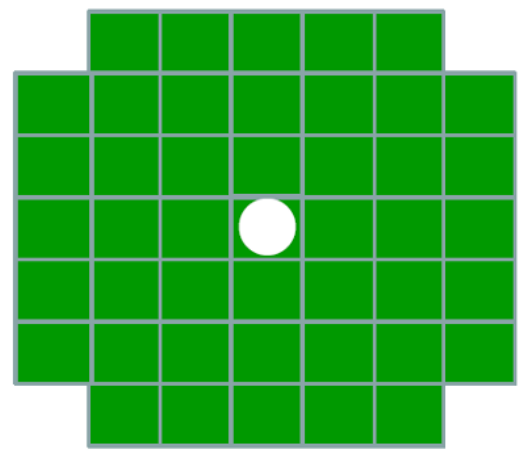
Forward Hadron Calorimeter (FHCal)



December 2016

http://mpd.jinr.ru/doc/mpd-tdr/





FHCal coverage: 2.2<|η|< 4.8

Thank you for your attention

MEPhI Relativistic Heavy-Ion Group

One of the youngest group in MEPhI. Est. in 2015

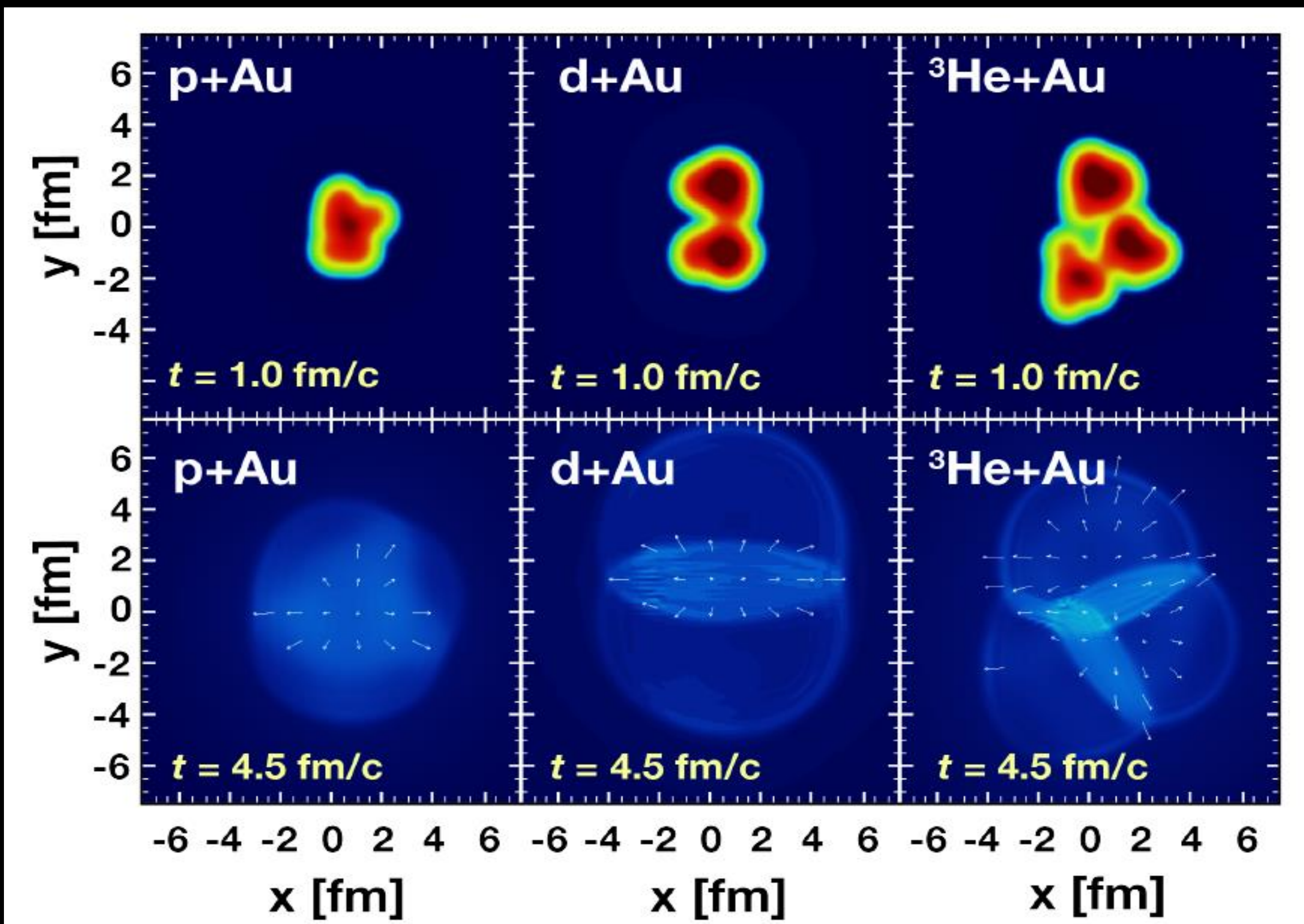
http://foswiki.oris.mephi.ru/

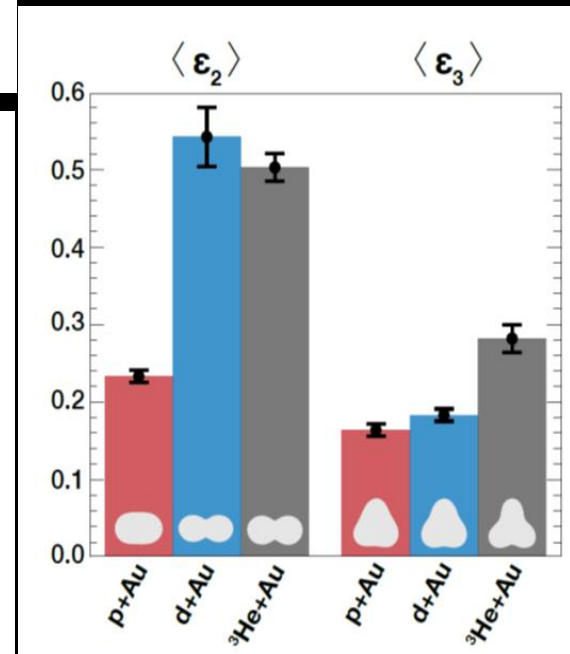
RHIC Geometry Scan

PRL 113, 112301 (2014) PHYSICAL REVIEW LETTERS week ending 12 SEPTEMBER 2014

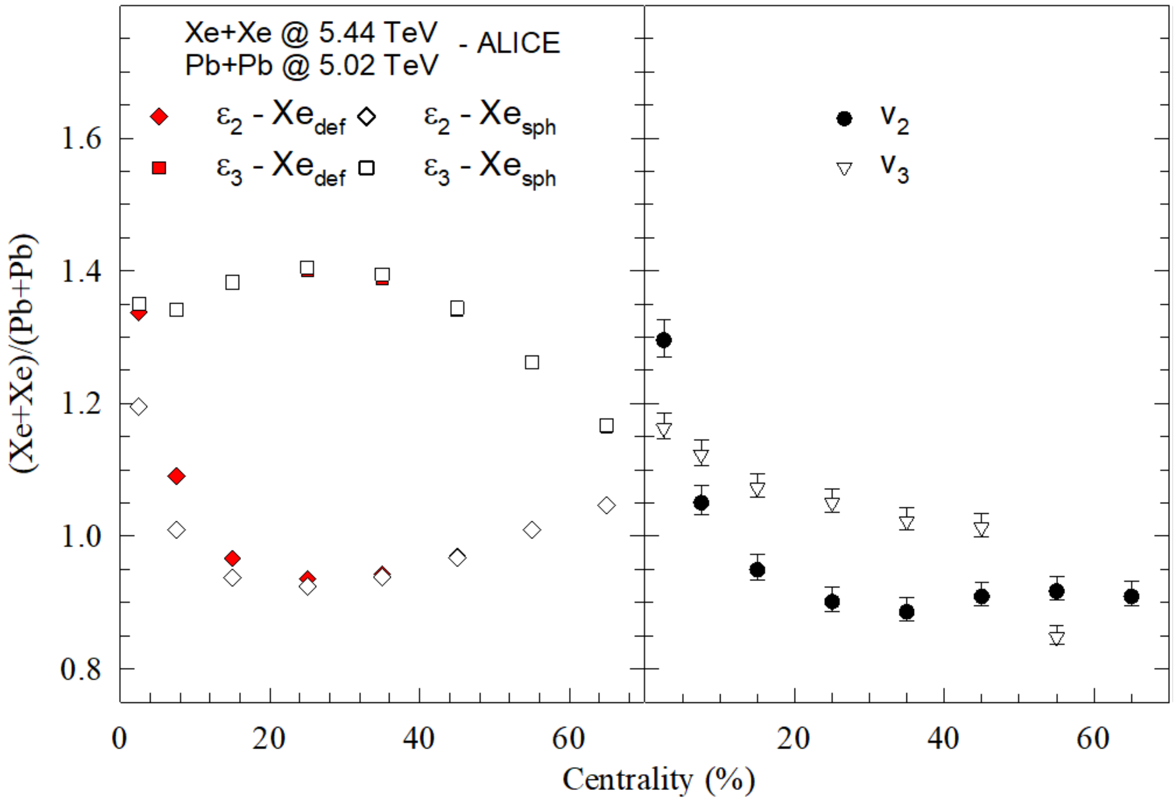
Exploiting Intrinsic Triangular Geometry in Relativistic ^{3}He + Au Collisions to Disentangle Medium Properties

J. L. Nagle,[1,*] A. Adare,[1] S. Beckman,[1] T. Koblesky,[1] J. Orjuela Koop,[1] D. McGlinchey,[1] P. Romatschke,[1] J. Carlson,[2] J. E. Lynn,[2] and M. McCumber[2]





Acoustic Scaling – System size



- **Eccentricity change alone is not sufficient**

- **Characteristic 1/(RT) viscous damping validated**
- *Similar slopes imply similar* $\frac{\eta}{s}$.
- ***Important constraint for η/s & ζ/s***