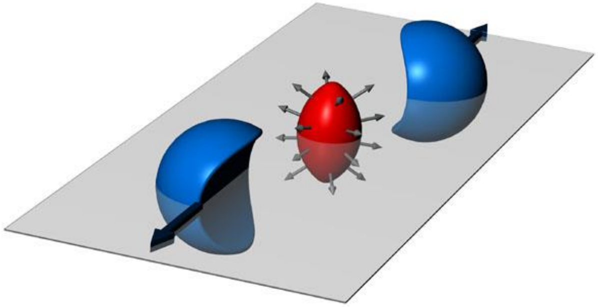
Anisotropic Flow Measurements at NICA Energies



Arkadiy Taranenko

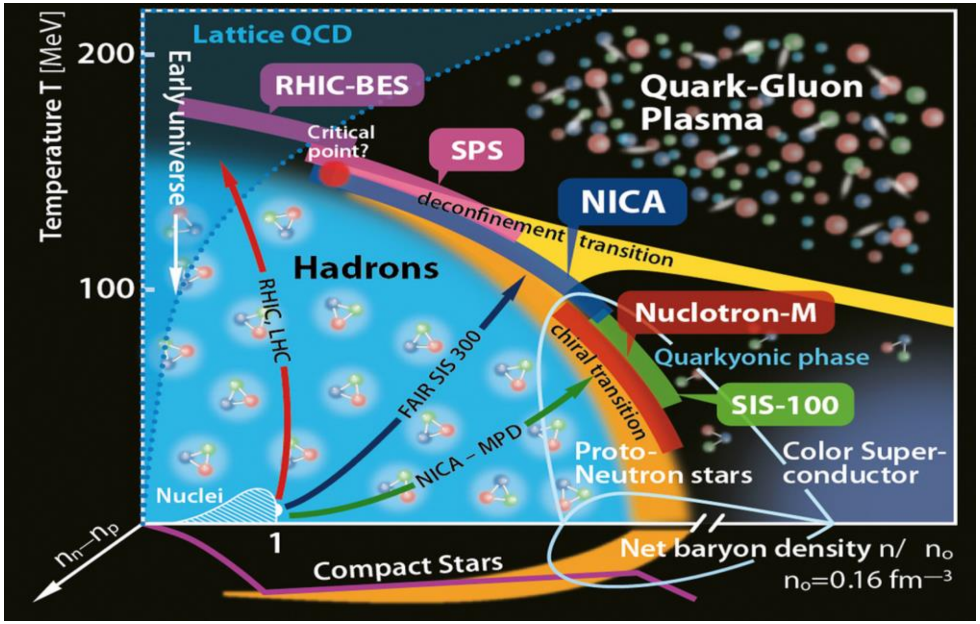
National Research Nuclear University MEPhI

The II International Workshop on
Theory of Hadronic Matter Under Extreme Conditions
JINR, Dubna (Russia), September 16-19, 2019

OUTLINE

1. Why measure anisotropic flow?
2. Flow (V_n) and sQGP at RHIC/LHC
3. Flow results from Beam Energy Scan (RHIC)
4. Outlook for flow measurements at NICA

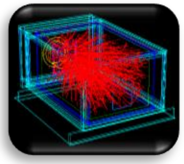
Phase diagram



Past measurements

Observation of the phase transition

BNL AGS



CERN SPS

BNL RHIC

CERN LHC

Current & future measurements

Facility	SPS	RHIC	LHC	NICA	SIS100	J-PARC-HI	HIAF
Laboratory	CERN	BNL	CERN	JINR	GSI FAIR	J-PARC	Huizhou
Experiment	NA61	STAR	ALICE, ATLAS, CMS, LHCb	BM@N MPD	HADES CBM	JHITS	CEE
Start data taking	2009	2010	2009	2018 2021	2025	2025	2024
CMS Energy [GeV/(N+N)]	5.1– 17.3	3.0 - 200	up to 5500 14000 (p+p)	2.7 - 11.0	2.3 – 4.7	1.9 – 6.2	1.8 - 2.7
Type of measurements	energy, size	energy	energy	energy	energy	energy	energy

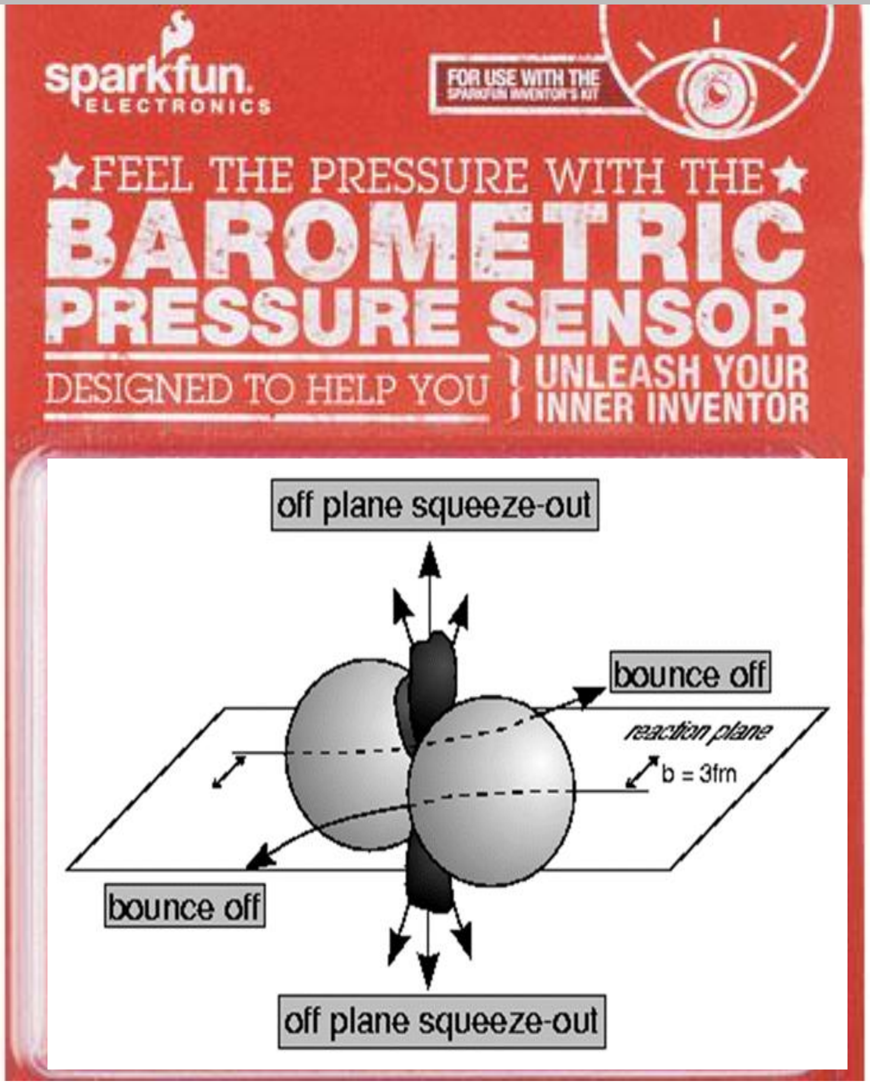
Anisotropic Flow in Heavy-Ion Collisions: 1988

Provides reliable estimates of pressure & pressure gradients

Can address questions related to thermalization

Gives insights on the transverse dynamics of the medium

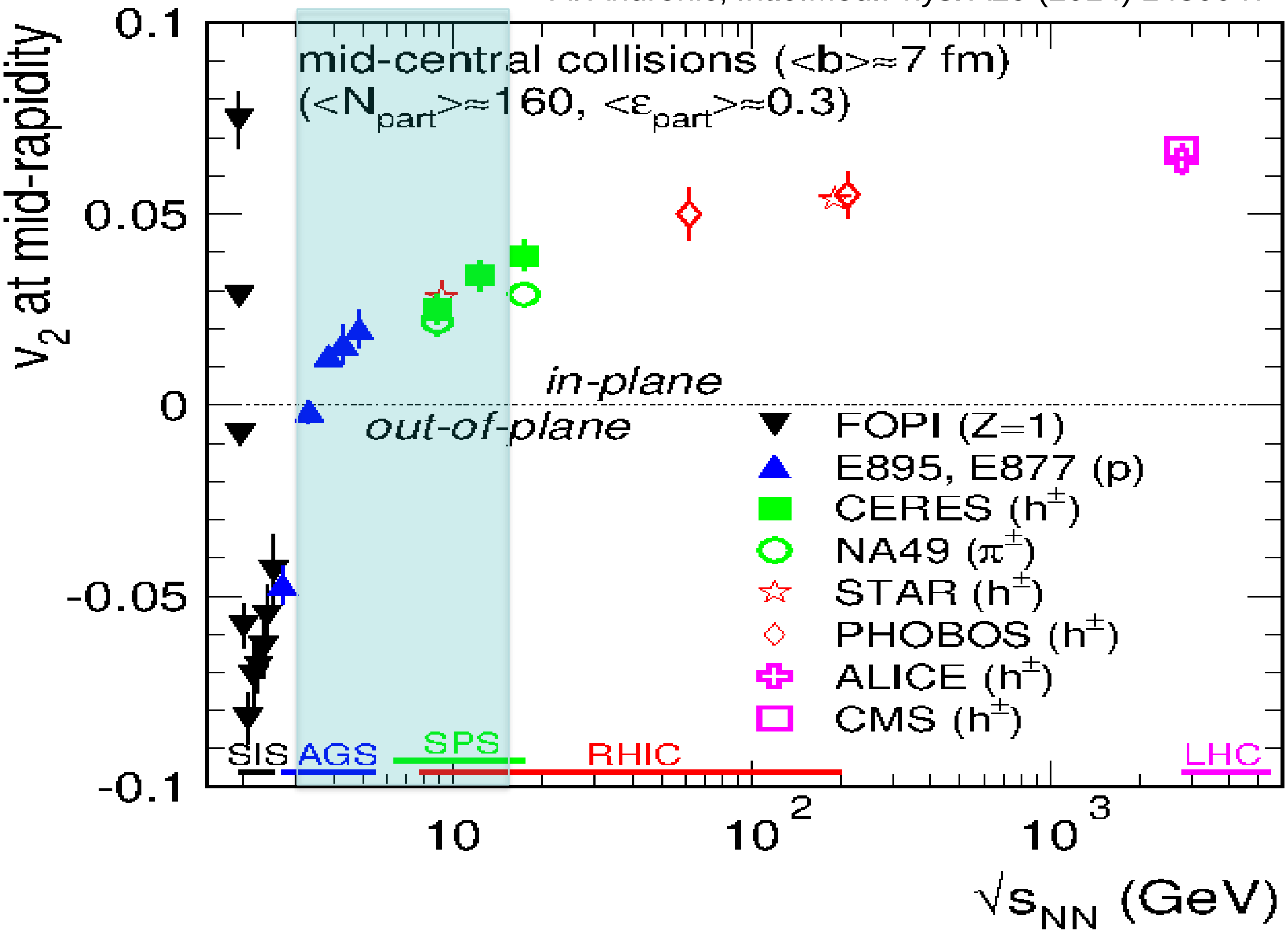
Provides access to the transport properties of the medium: EOS, sound speed (c_s), viscosity, etc



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

Excitation function of integral elliptic flow

A. Andronic, Int.J.Mod.Phys. A29 (2014) 1430047

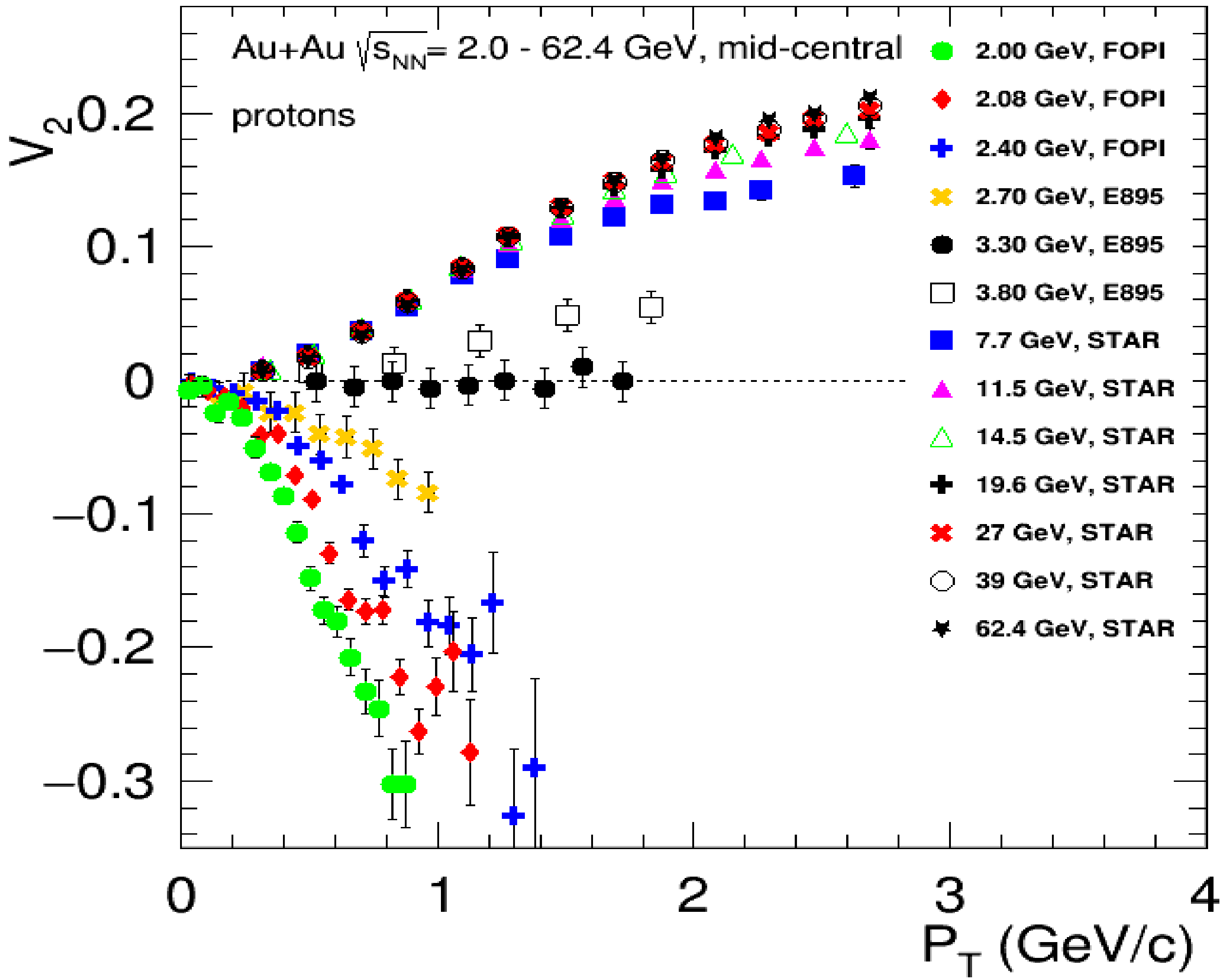


High precision differential measurements of anisotropic flow?

Excitation function of differential elliptic flow

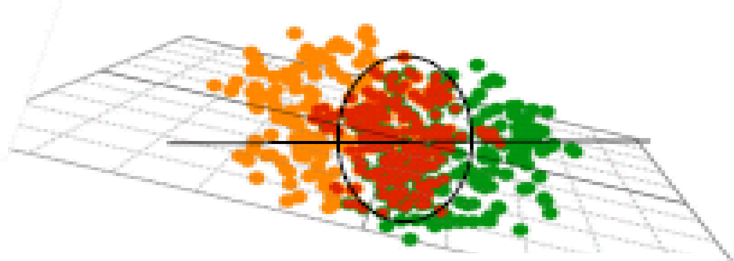
EPJ Web Conf. 204 (2019) 03009

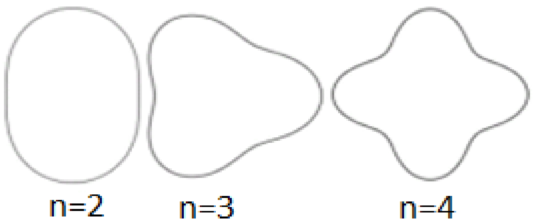
FOPI (15-29%)
E895 (12-25%)
STAR (10-40%)



High precision differential measurements of anisotropic flow?

Anisotropic Flow at RHIC-LHC



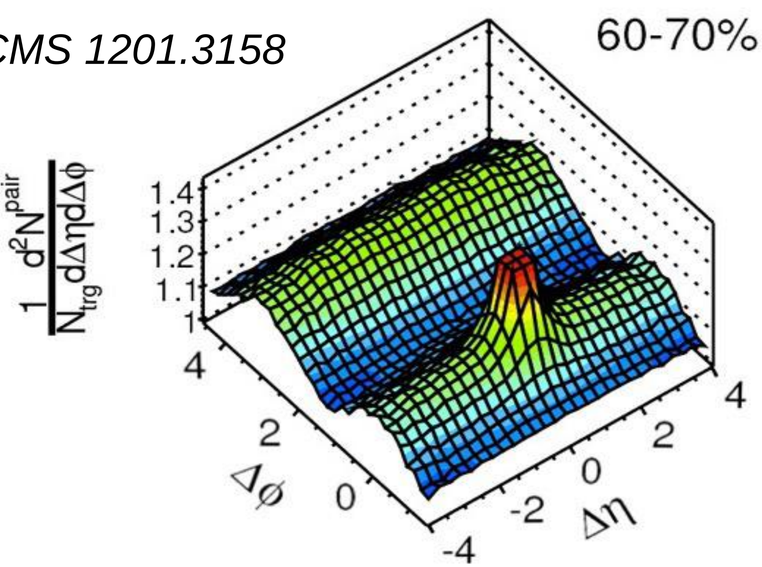


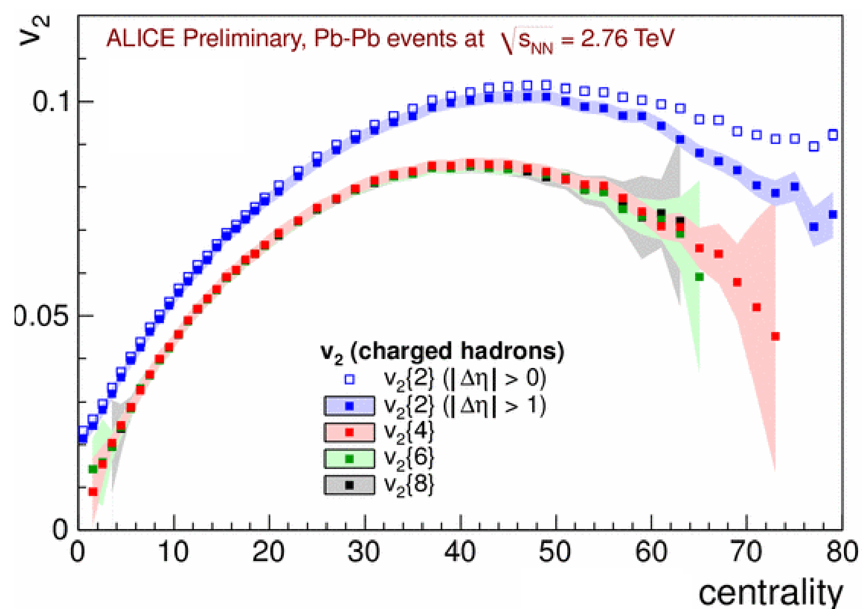
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

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

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

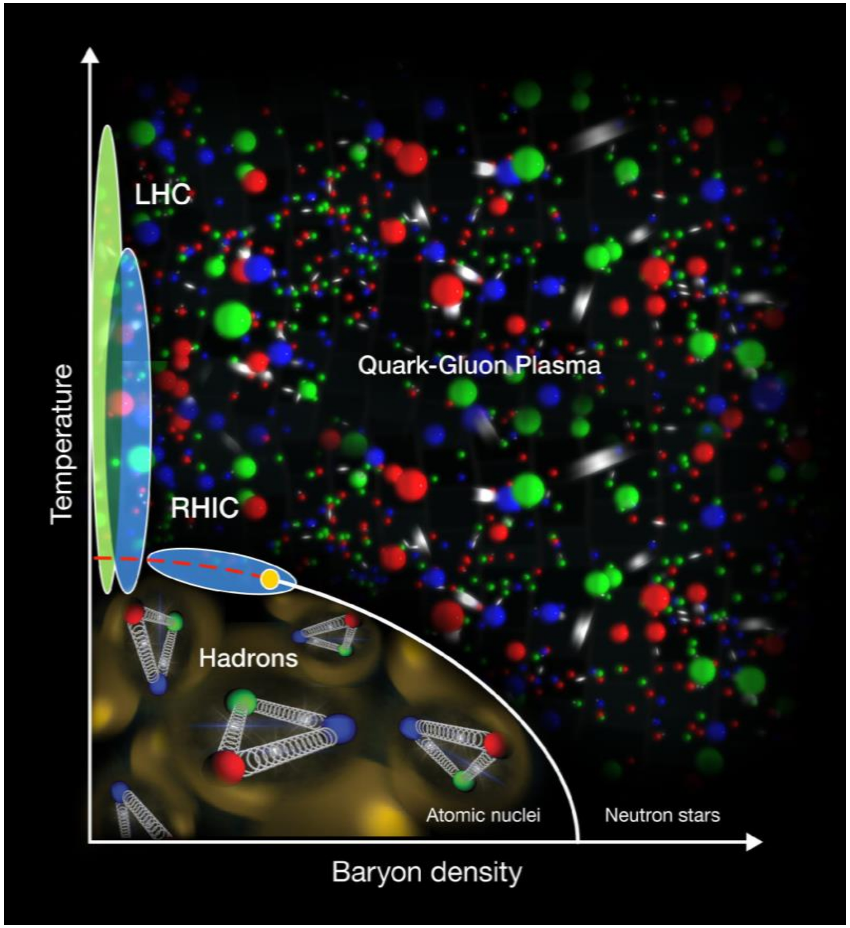
CMS 1201.3158

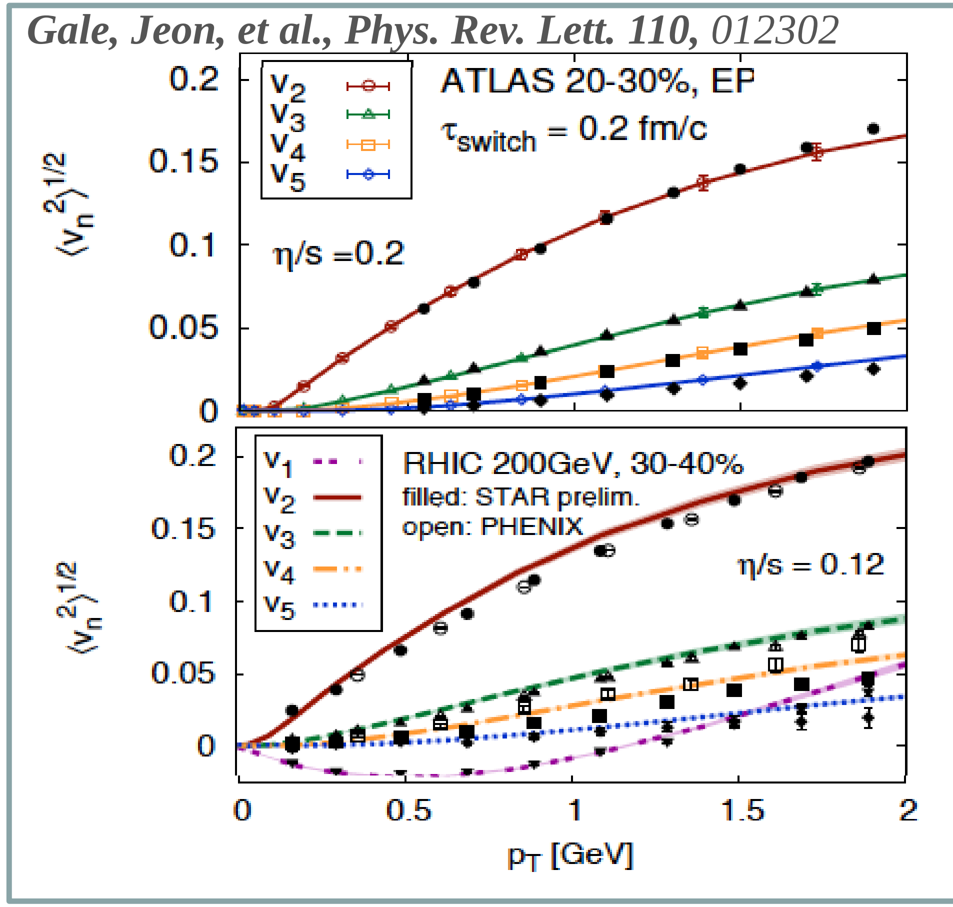




Different methods, non-flow, fluctuations

Perfect Liquid at RHIC and LHC

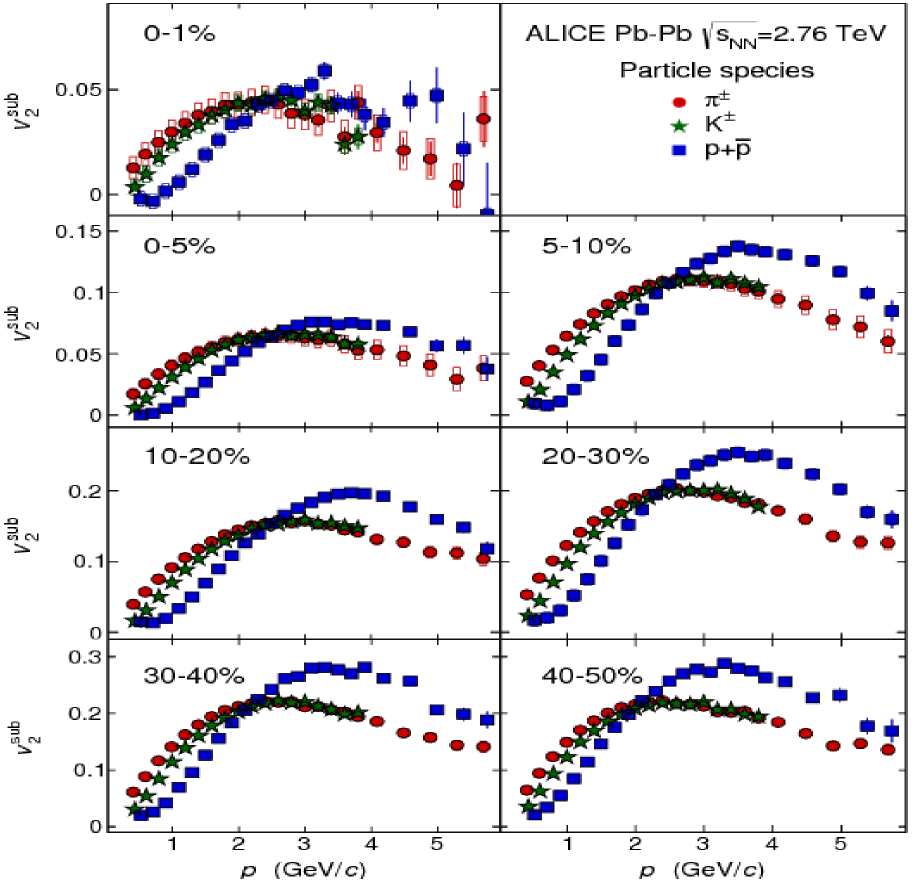




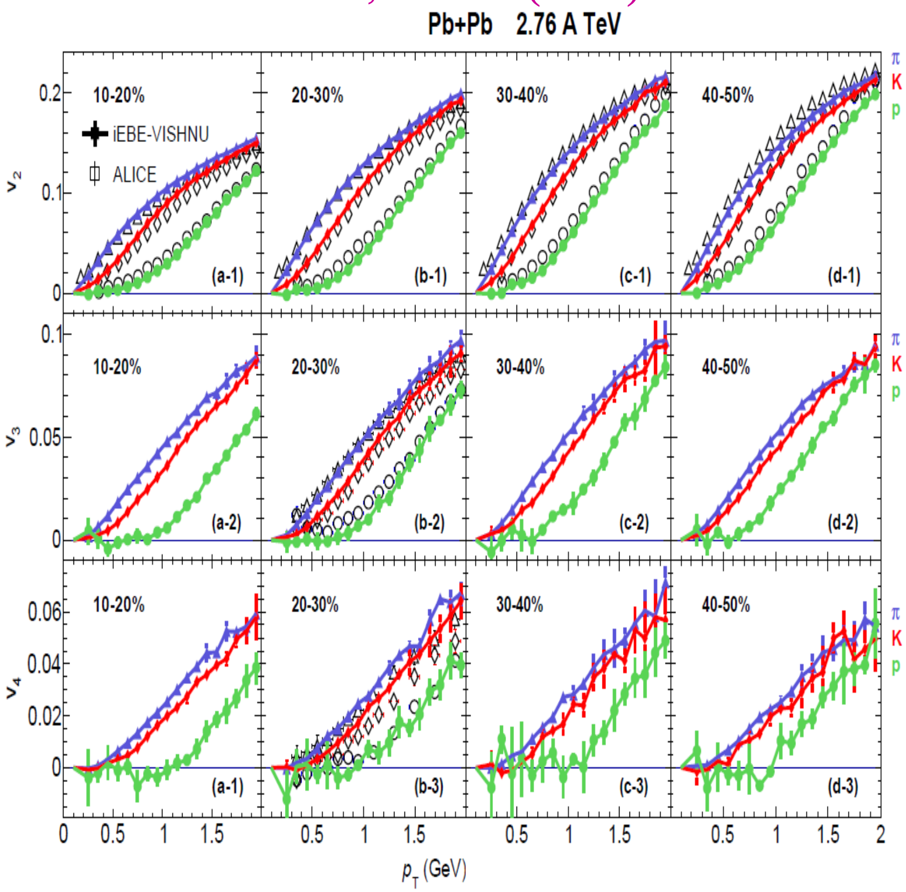
$$\frac{\eta}{s}(T,\mu),\ \frac{\zeta}{s}(T,\mu),\ c_s(T),\ \hat{q}(T),\ \alpha_s(T),\ \text{etc}$$

V_n of identified hadrons at RHIC/LHC

J. Adam et al., (ALICE) JHEP 1609, 164



Viscous Hydro + cascade, H.Xu, Z.Li, H. Song
PRC 93, 064905 (2016)



Mass ordering at p_T < 2 GeV/c (hydrodynamic flow, hadron re-scattering) : for heavy-particles the radial flow "blueshifts" the entire flow signal to higher p_T

Baryon/meson grouping at p_T > 2.5 GeV/c (recombination/coalescence),

Scaling properties of collective flow

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

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

"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. …The evolution in non-viscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances are rescaled in terms of a typical size parameter, such as the nuclear radius. Momenta and energies are rescaled in terms of the beam velocities, momenta or energies.

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,

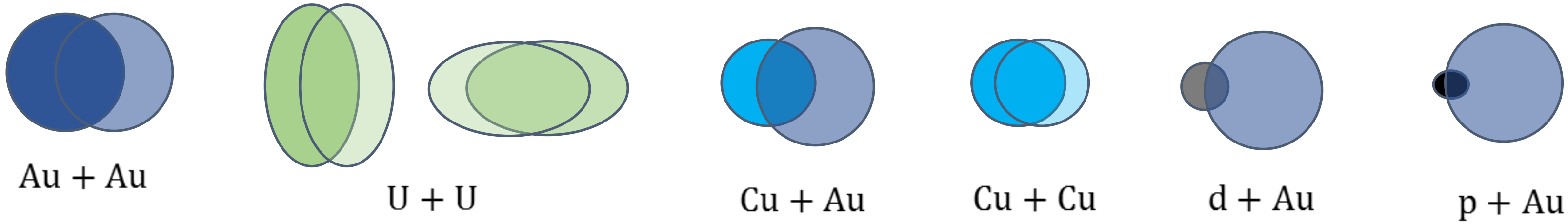
$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \quad \beta \propto \frac{\eta}{s}\frac{1}{RT}$$

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

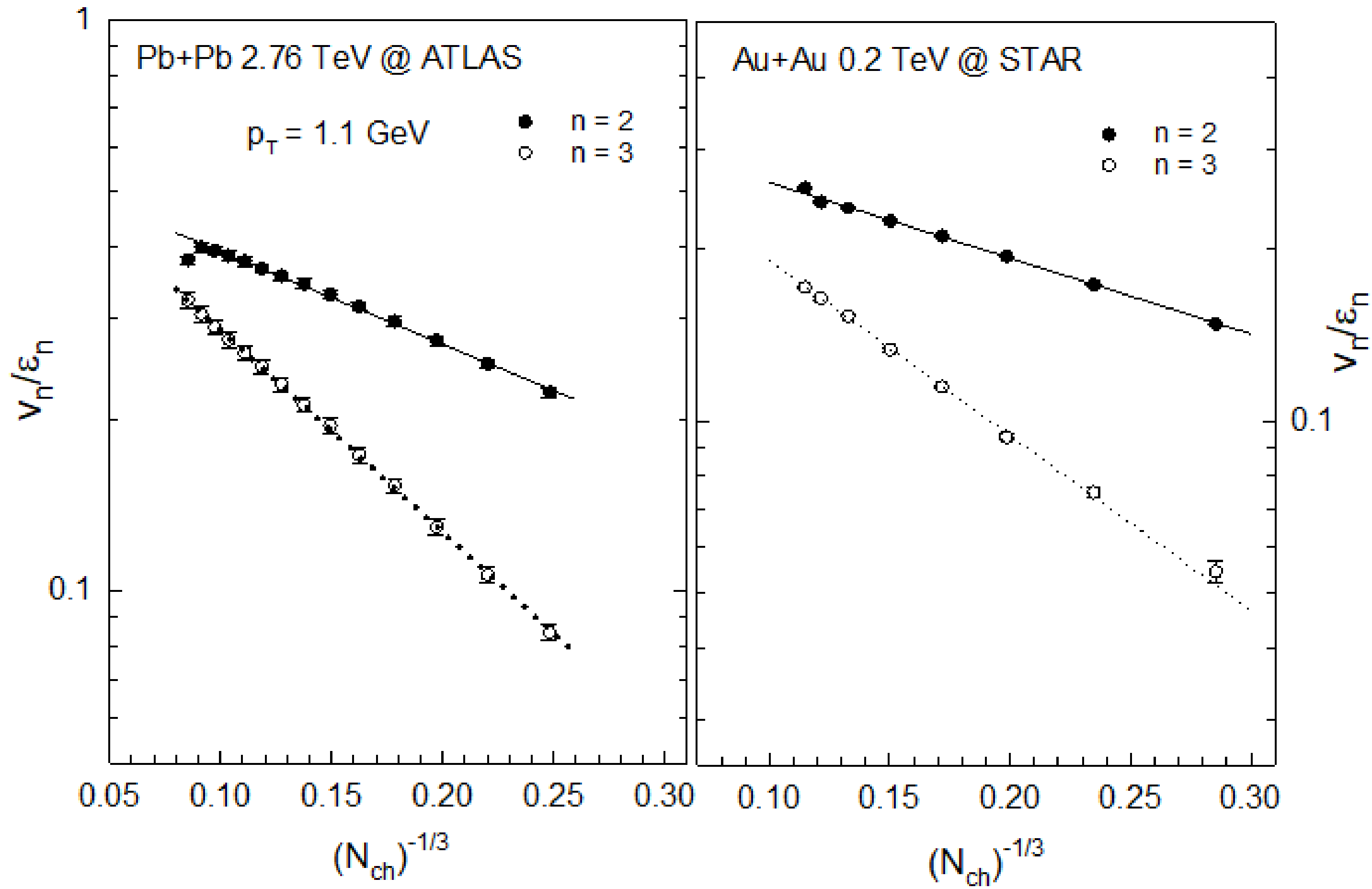


Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

Acoustic Scaling –

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

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

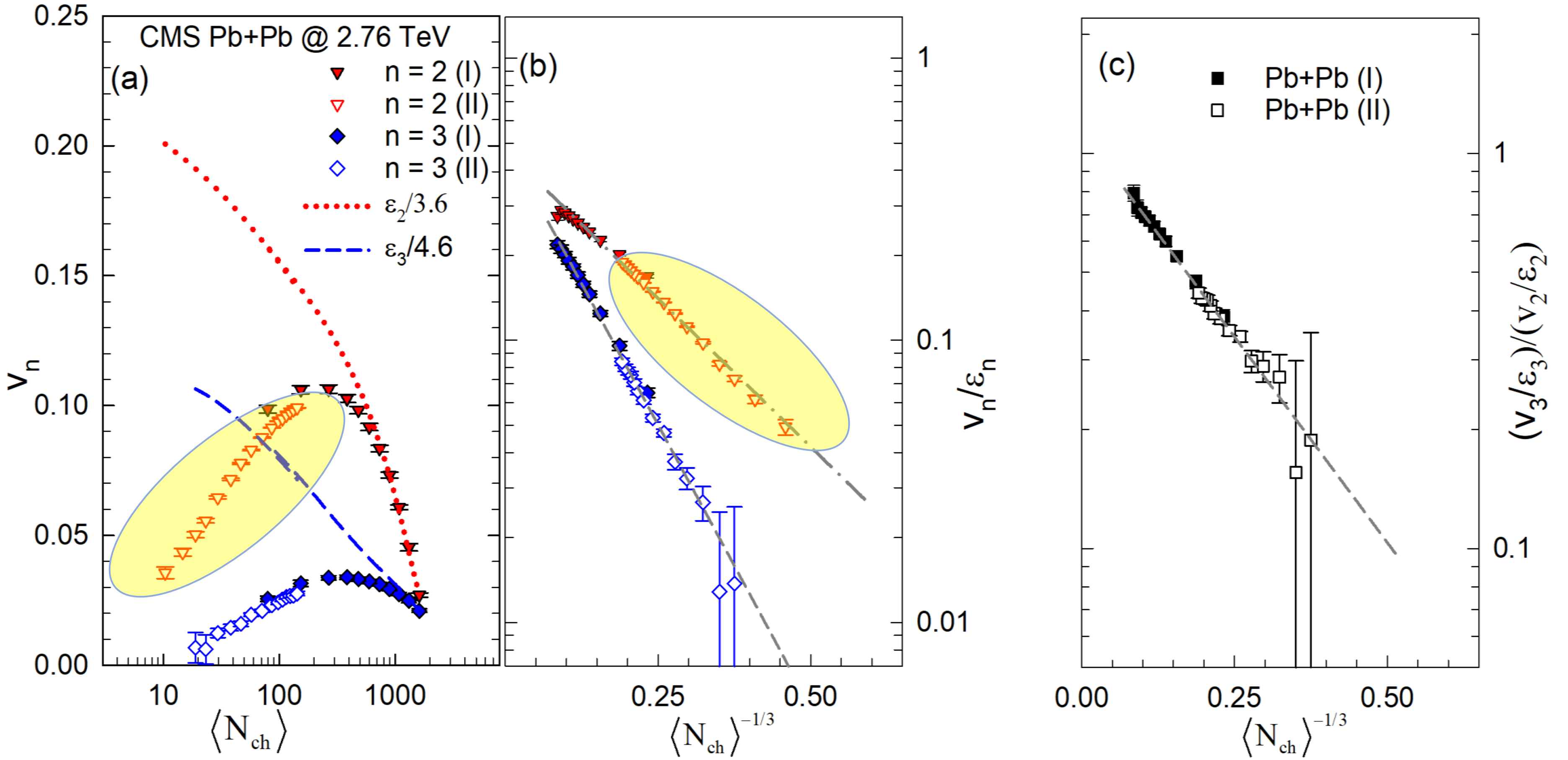


- ✓ **Characteristic 1/(RT) viscous damping validated**
  - ✓ ***Clear pattern for n^2 dependence of viscous attenuation***
  - ✓ ***Important constraint for η/s & ζ/s***

Acoustic Scaling - RT

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

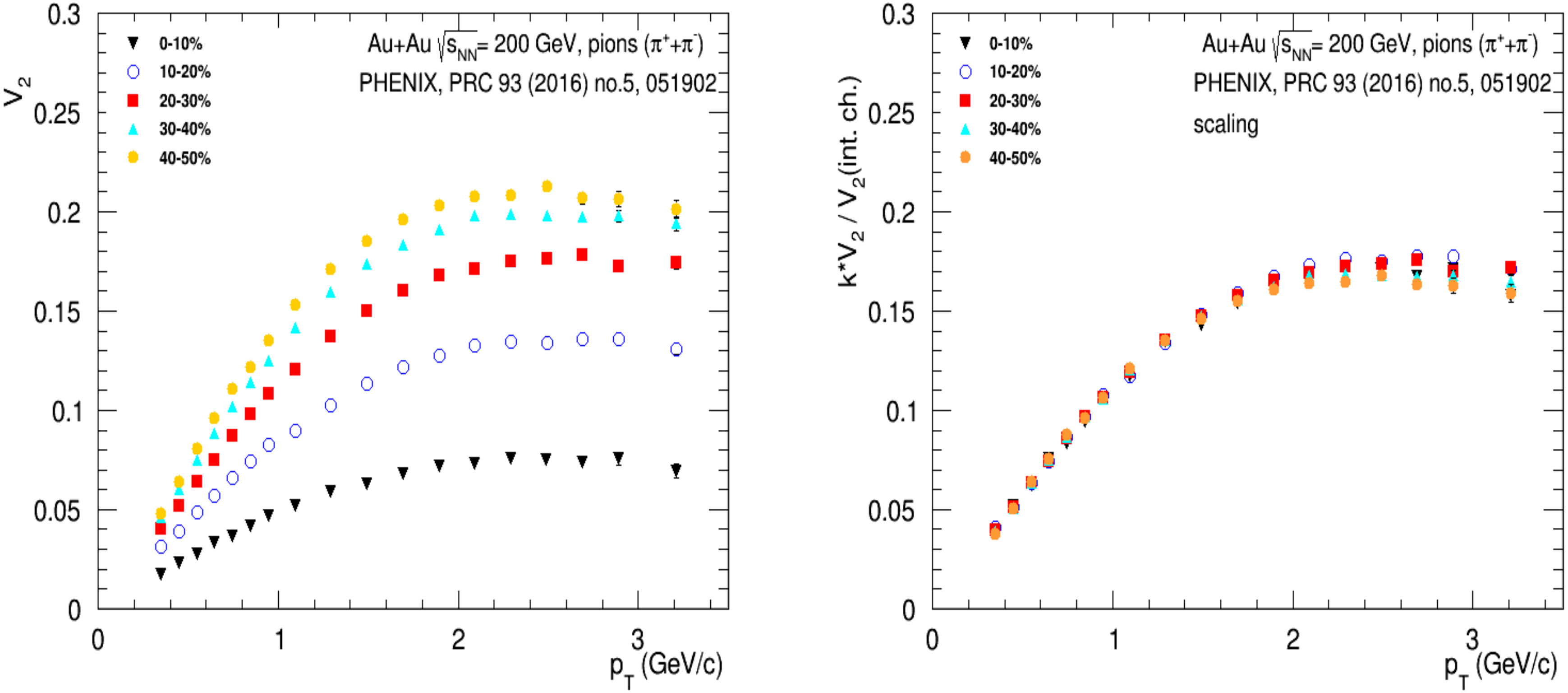
R.A. Lacey et al Phys. Rev. C **98**, 031901(R), 2018



- ✓ 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

V_2 of identified hadrons at top RHIC energy: pions

Scaling with integral flow of charged hadrons

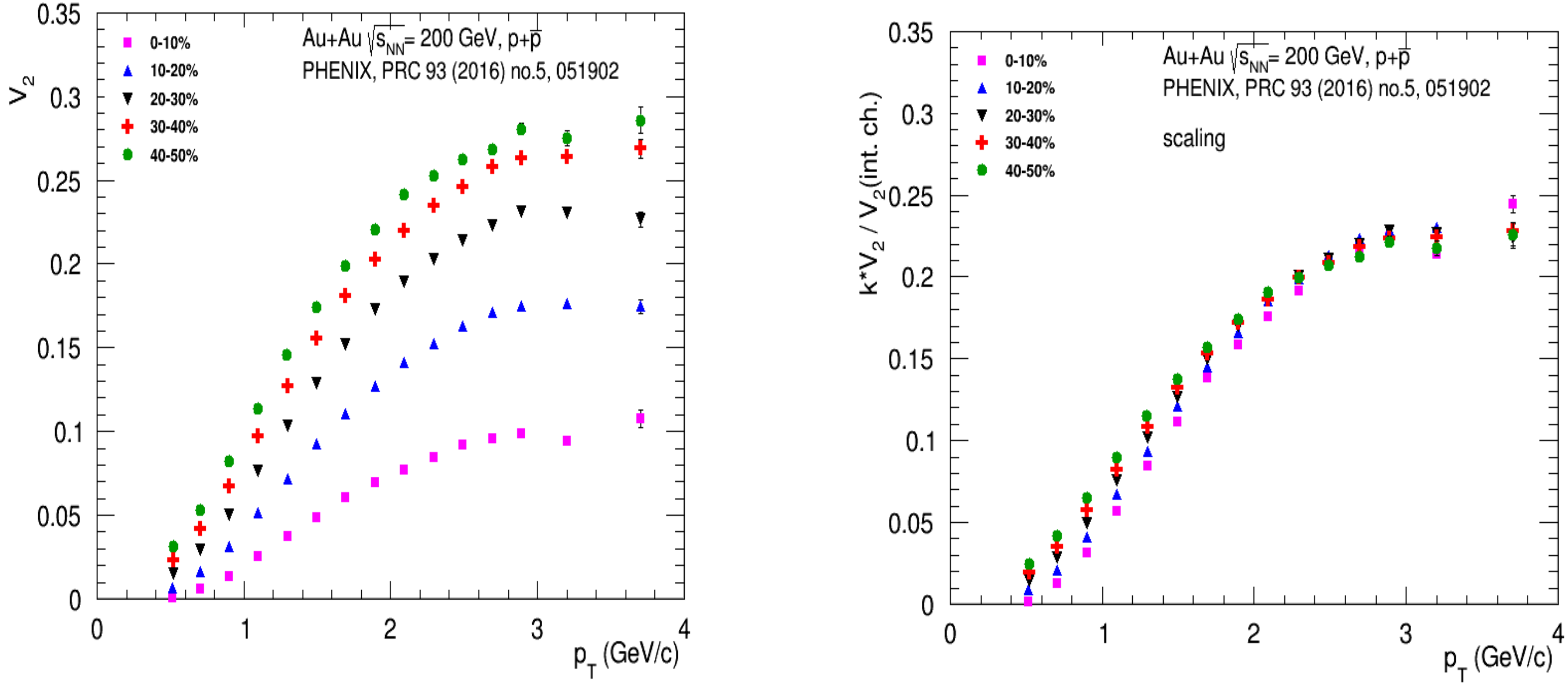


A.T., Acta Phys.Hung. A25 (2006) 371-379

$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* \, V_2(PID, p_T)???$$

V_2 of identified hadrons at top RHIC energy: protons

Scaling with integral flow of charged hadrons

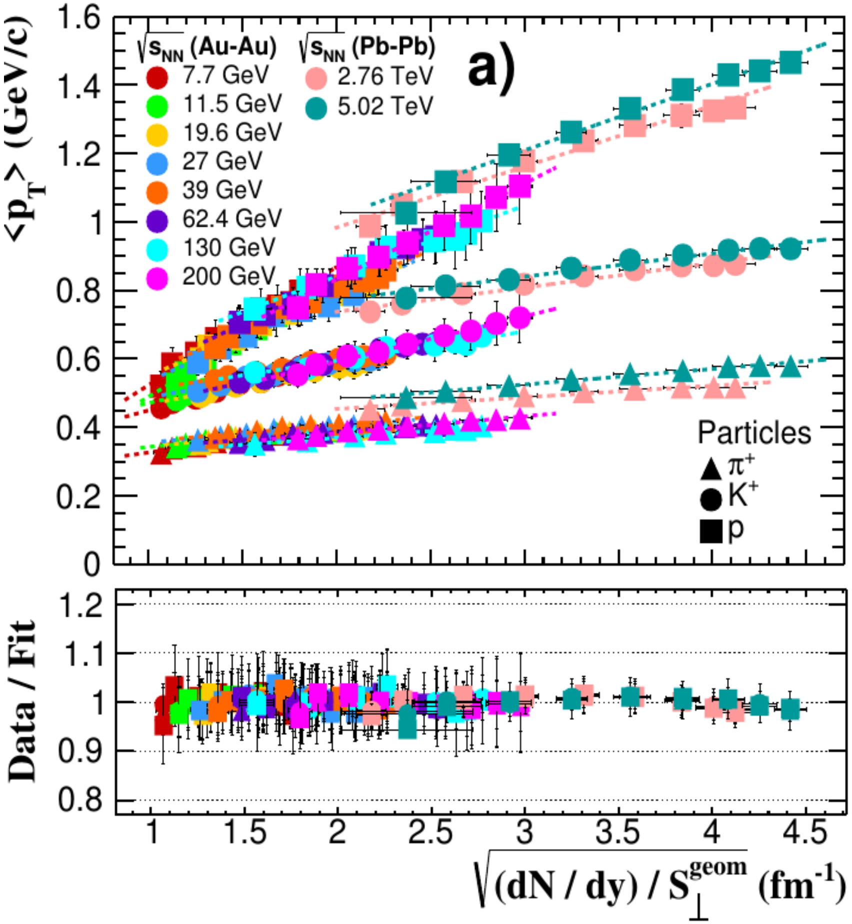


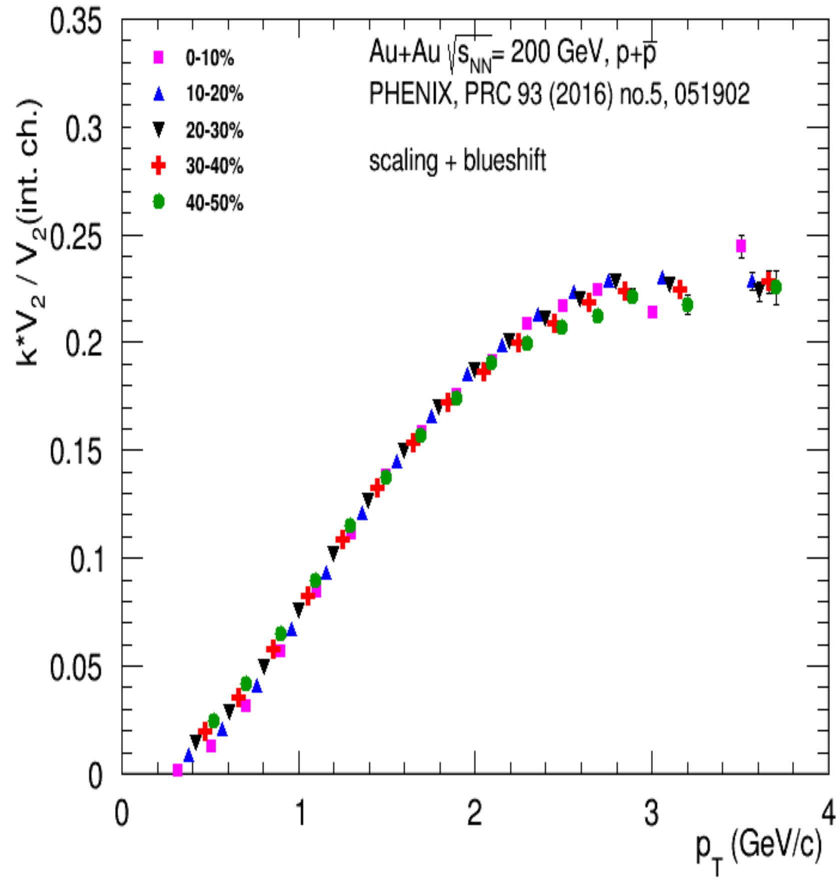
for protons the strong radial flow "blueshifts" the entire flow signal to higher p_T : $p_T \sim p_T^{th} + mc\beta$

V_2 of identified hadrons at top RHIC energy: protons

Use the geometrical scaling to estimate "blue shift" for protons

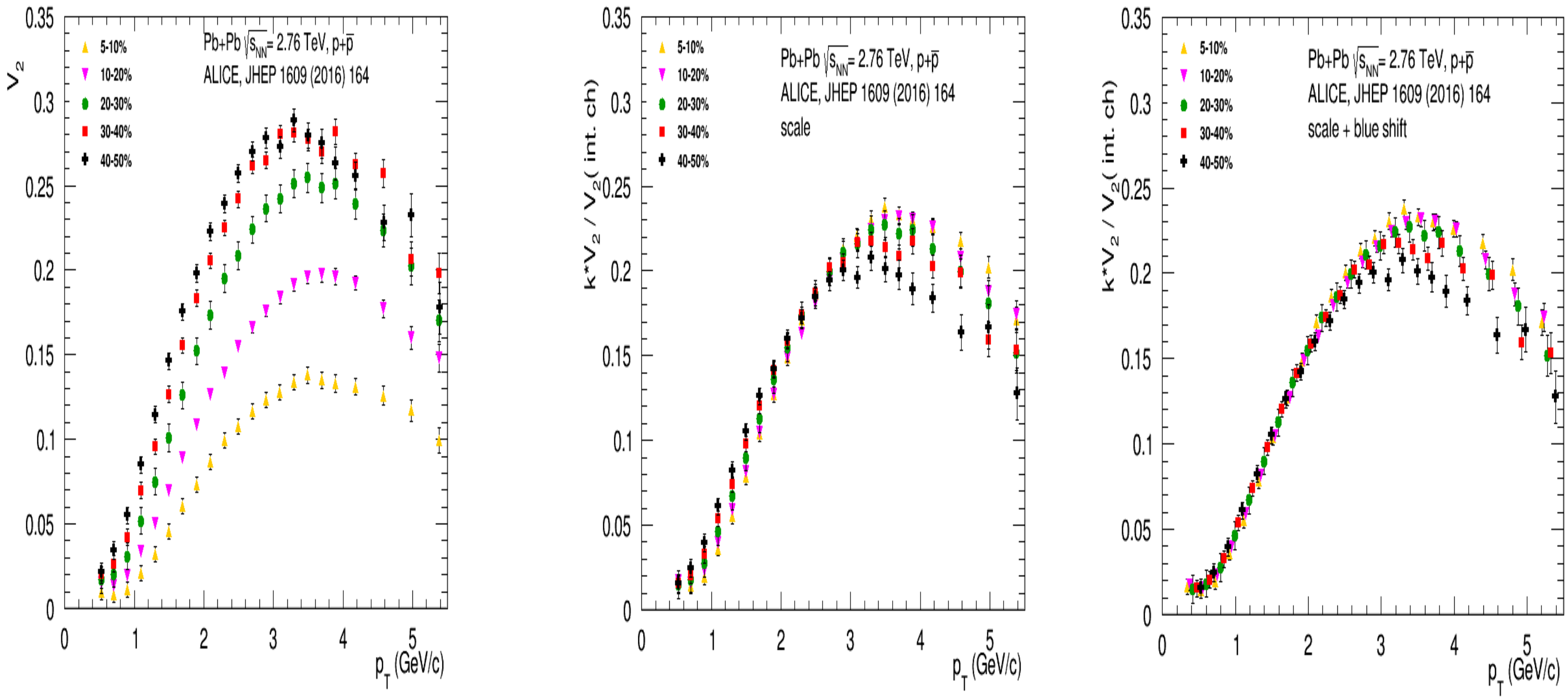
M. Petrovici at el, Phys Rev C 98 (2018)





Elliptic flow of identified hadrons at LHC : protons

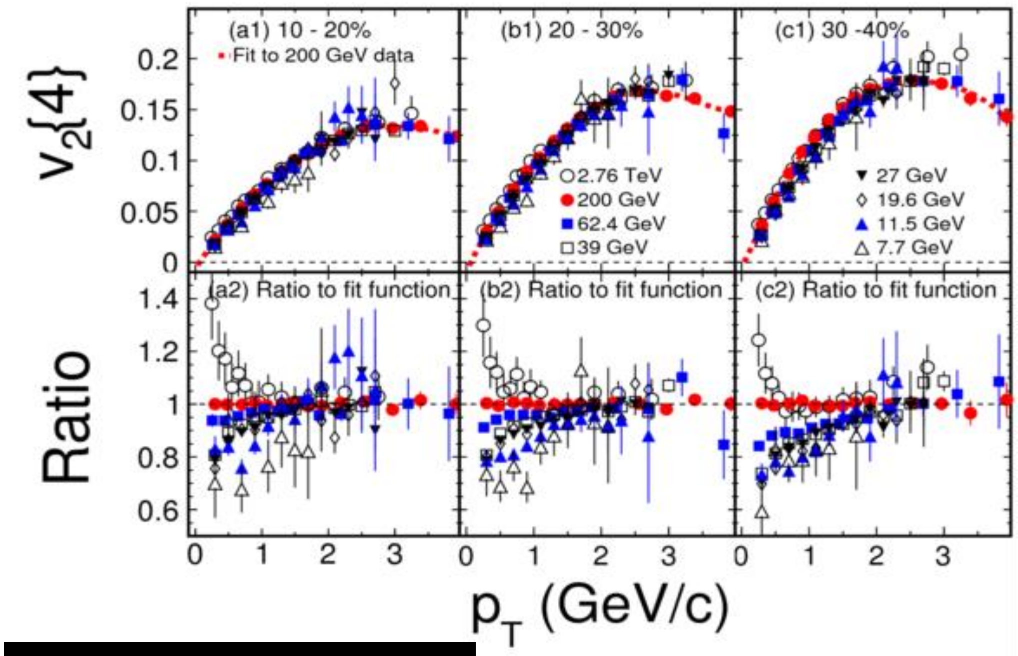
Scaling with integral flow of charged hadrons + correction for “blue shift”



$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}}) * V_2(PID, p_T)???$$

Beam Energy Dependence of Elliptic Flow (v_2)

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



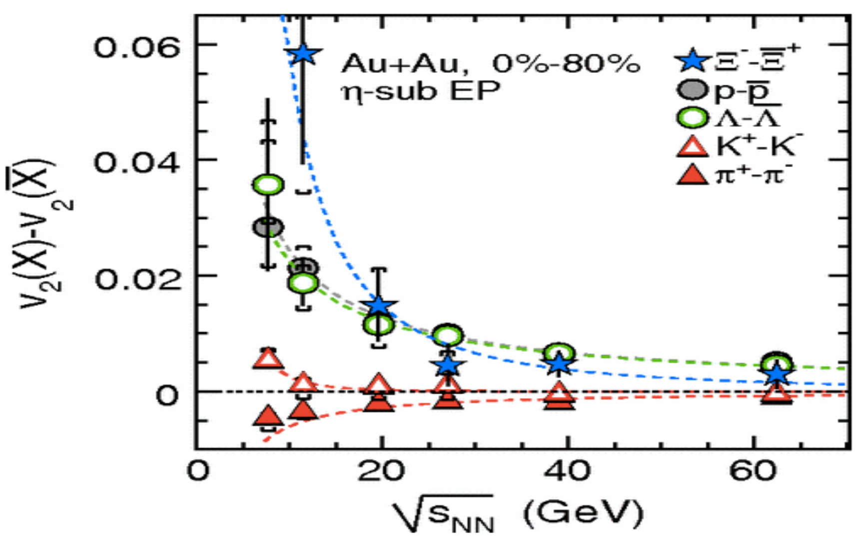
Surprisingly consistent as the energy changes by a factor ~400

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?

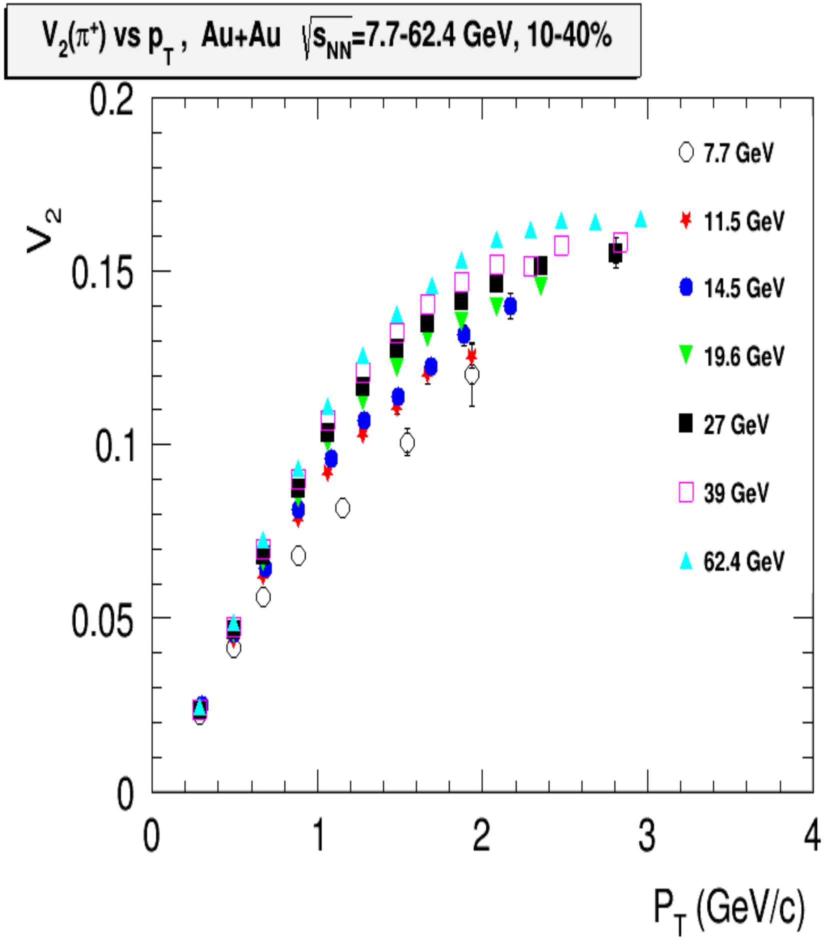
Phys. Rev. Lett. 110, 142301 (2013)

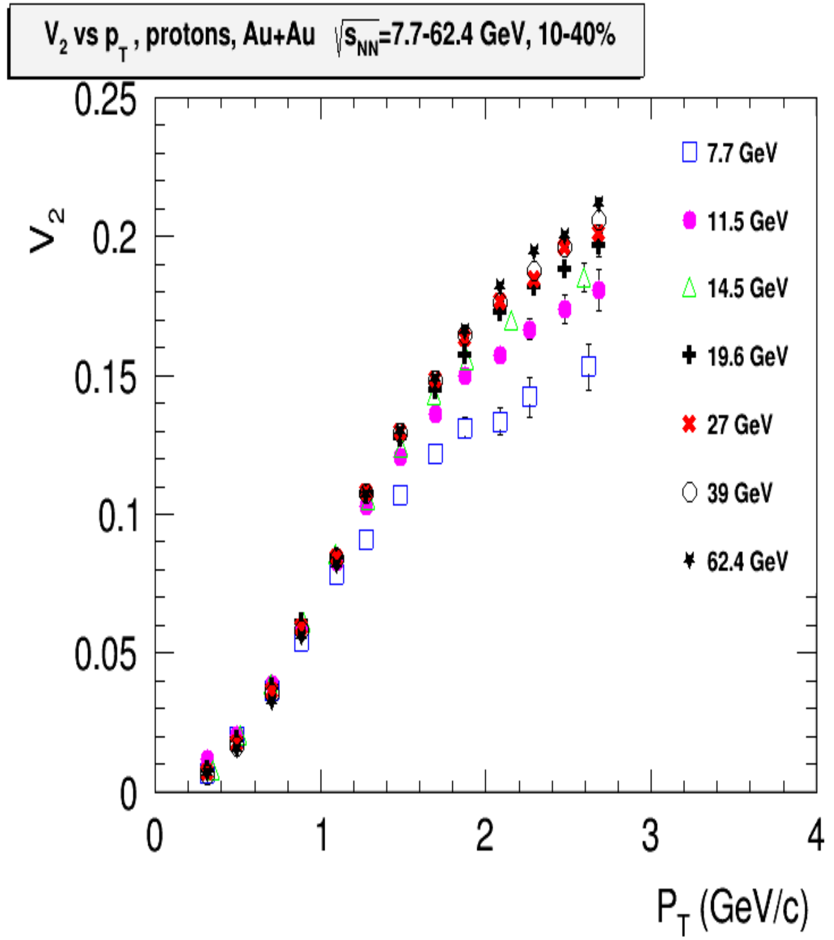


Substantial particle-antiparticle split at lower energies

Elliptic Flow at RHIC–BES: $\sqrt{s_{NN}}$ *= 7.7-62.4 GeV*

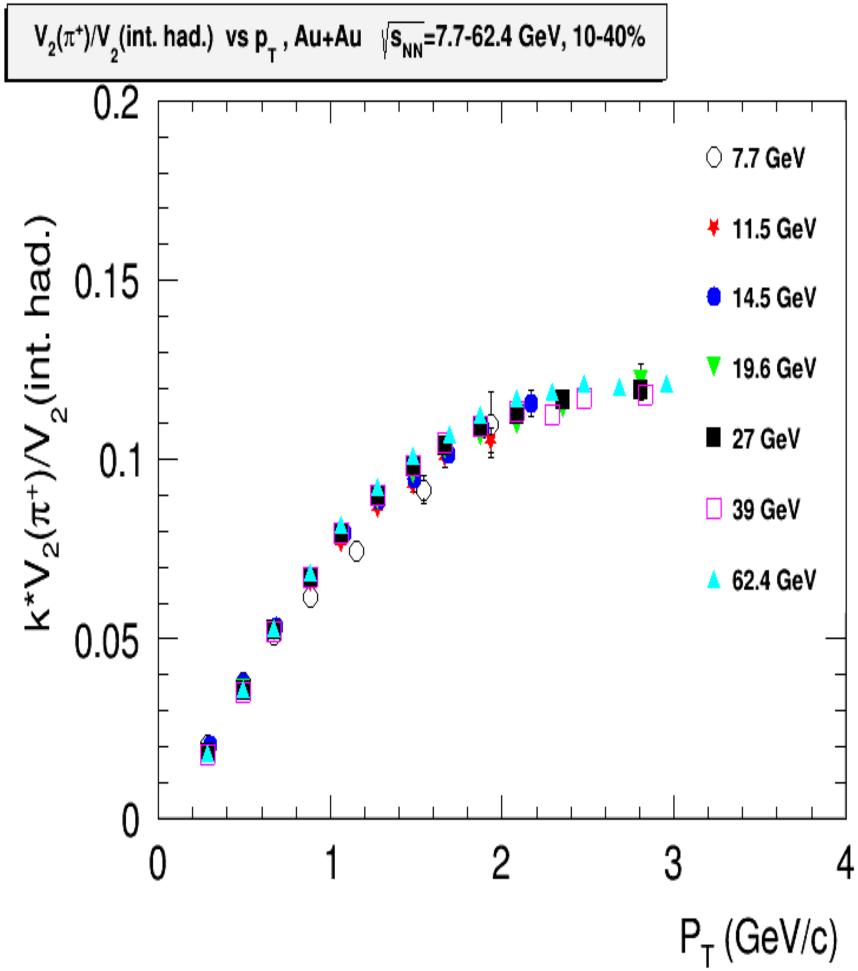
Phys. Rev. C **93** (2016) 14907

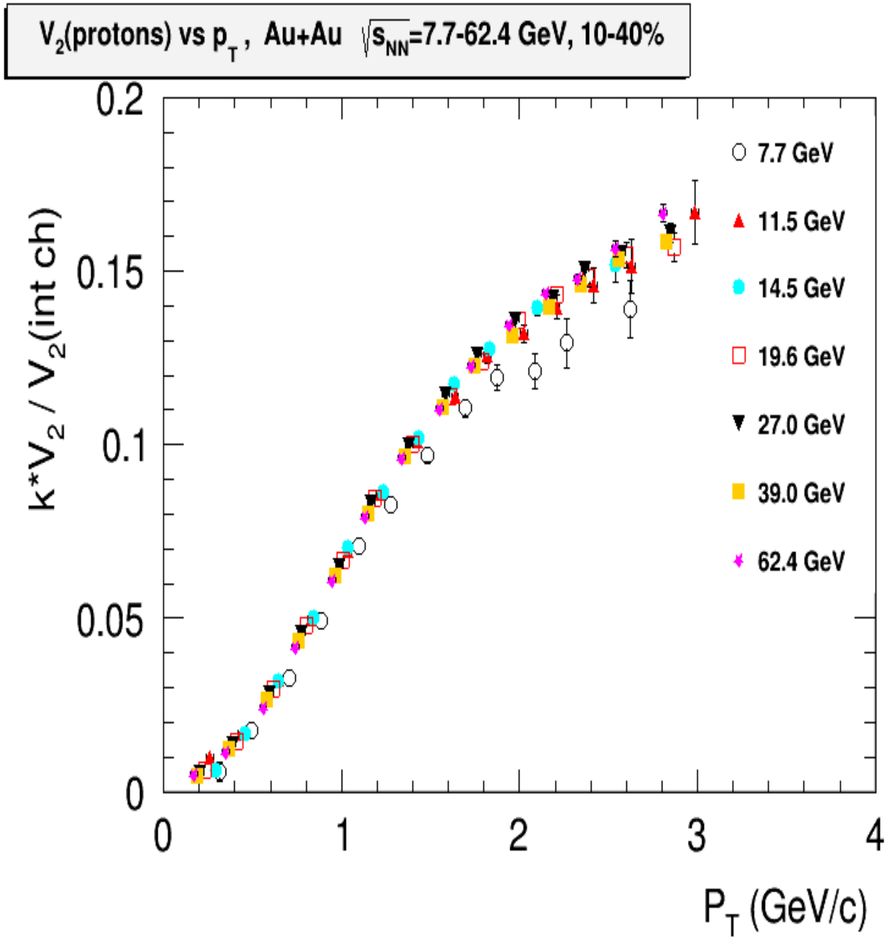




$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* \, V_2(PID, p_T)???$$

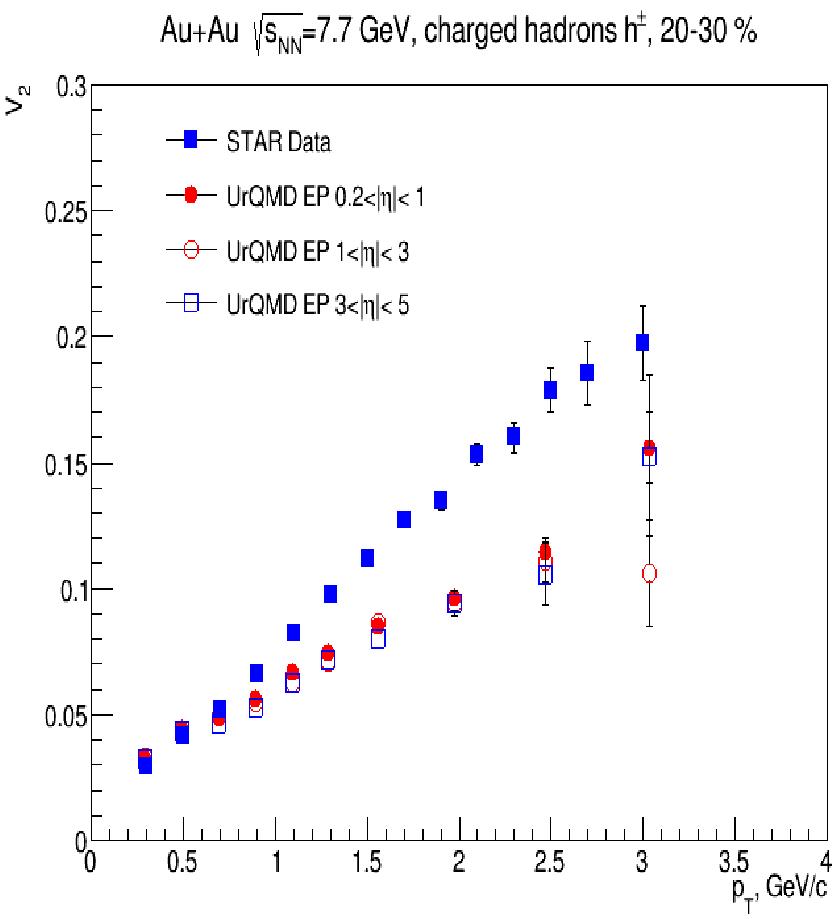
Elliptic Flow at RHIC–BES: $\sqrt{s_{NN}}$ = 7.7-62.4 GeV

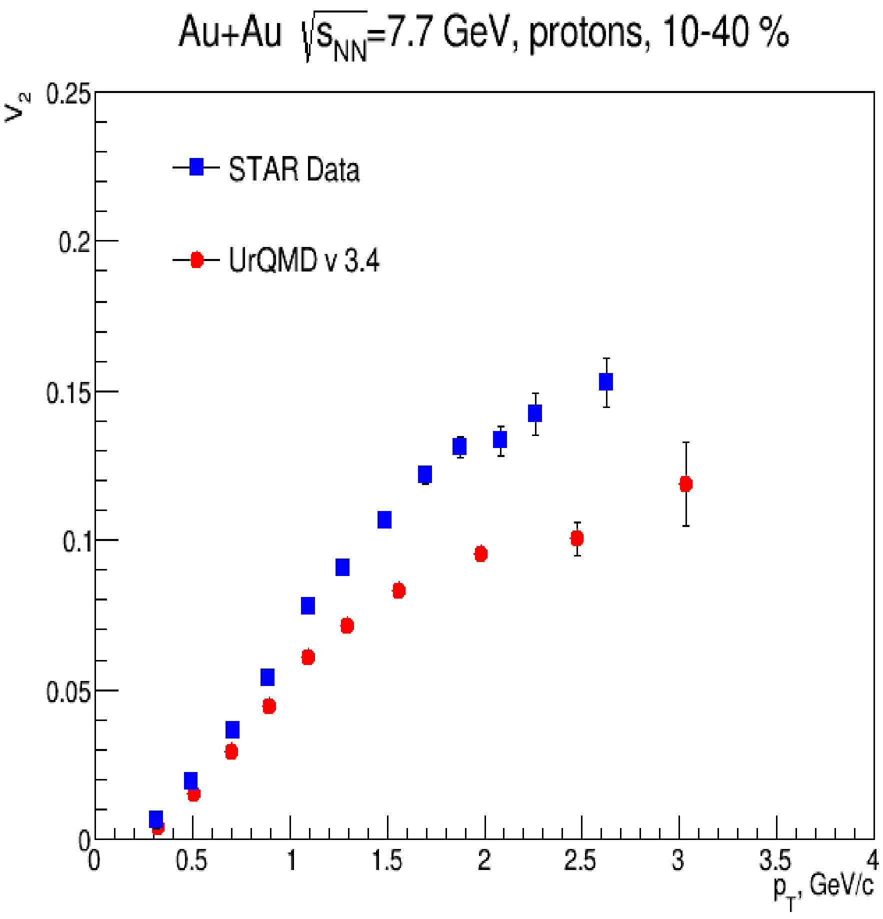




$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}}) * V_2(PID, p_T)???$$

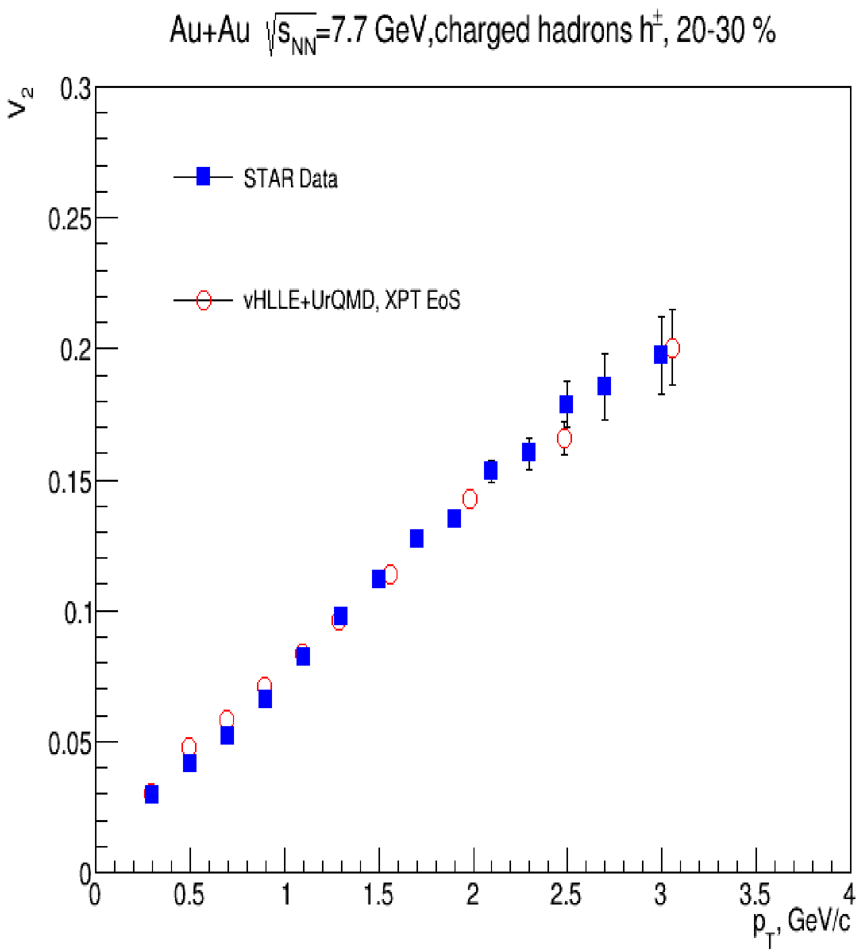
BES: differential elliptic flow: model comparison

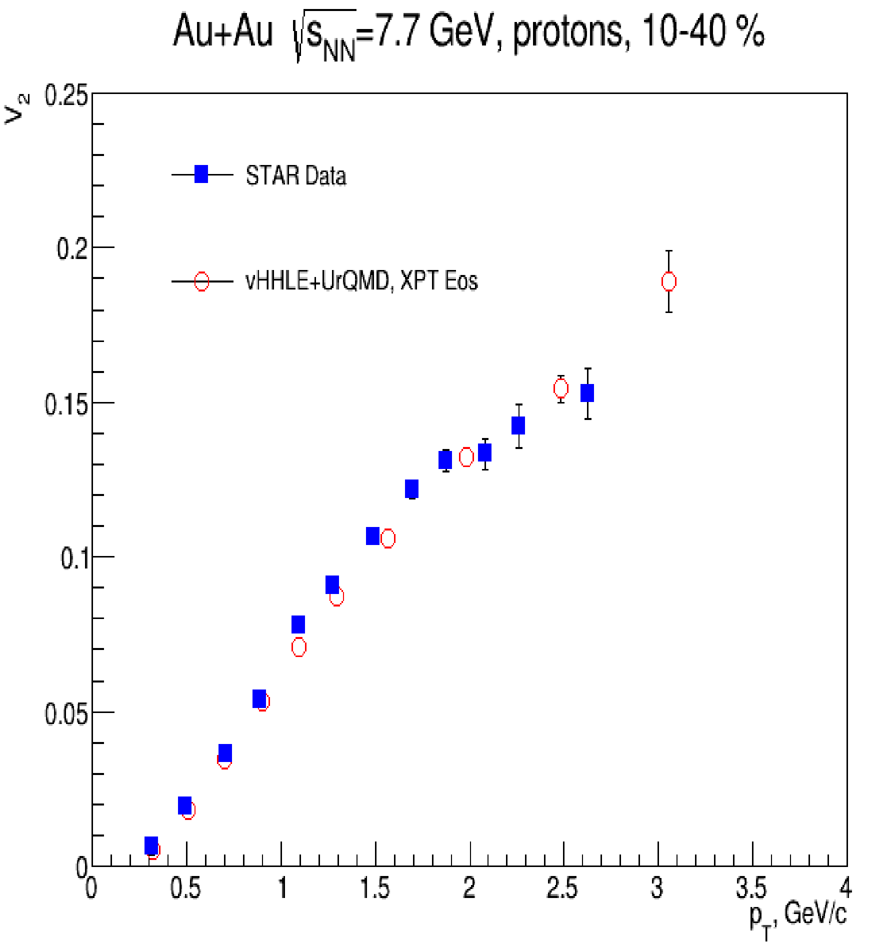




What about other "hadronic" models: SMASH, JAM, HSD?

BES: differential elliptic flow: model comparison

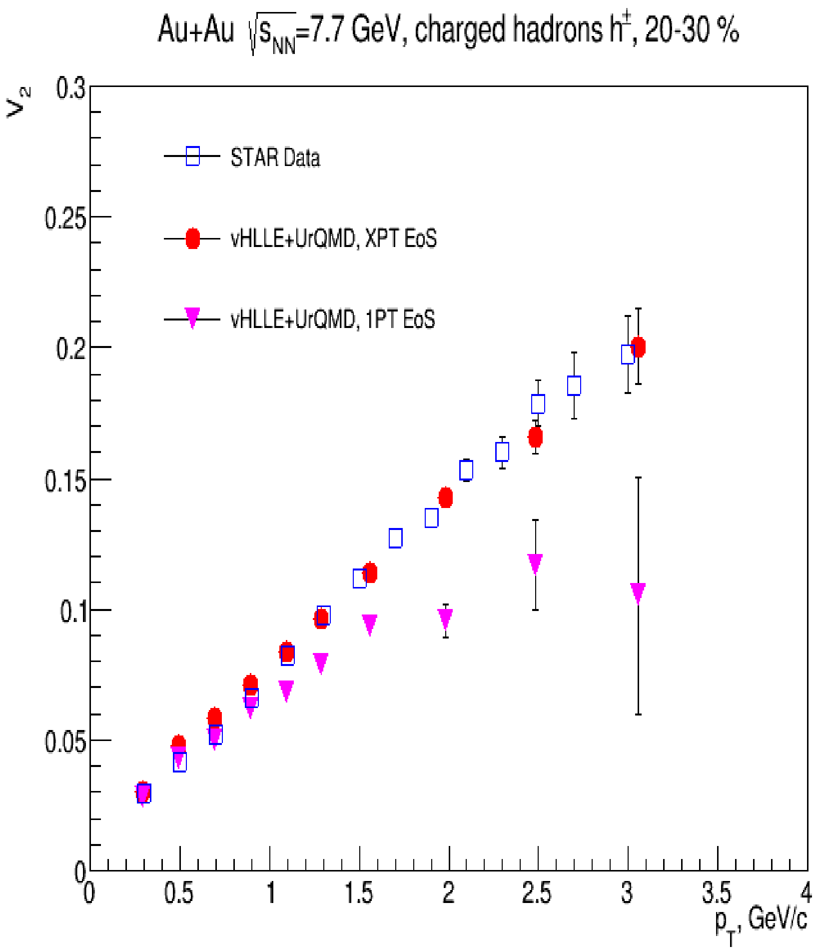


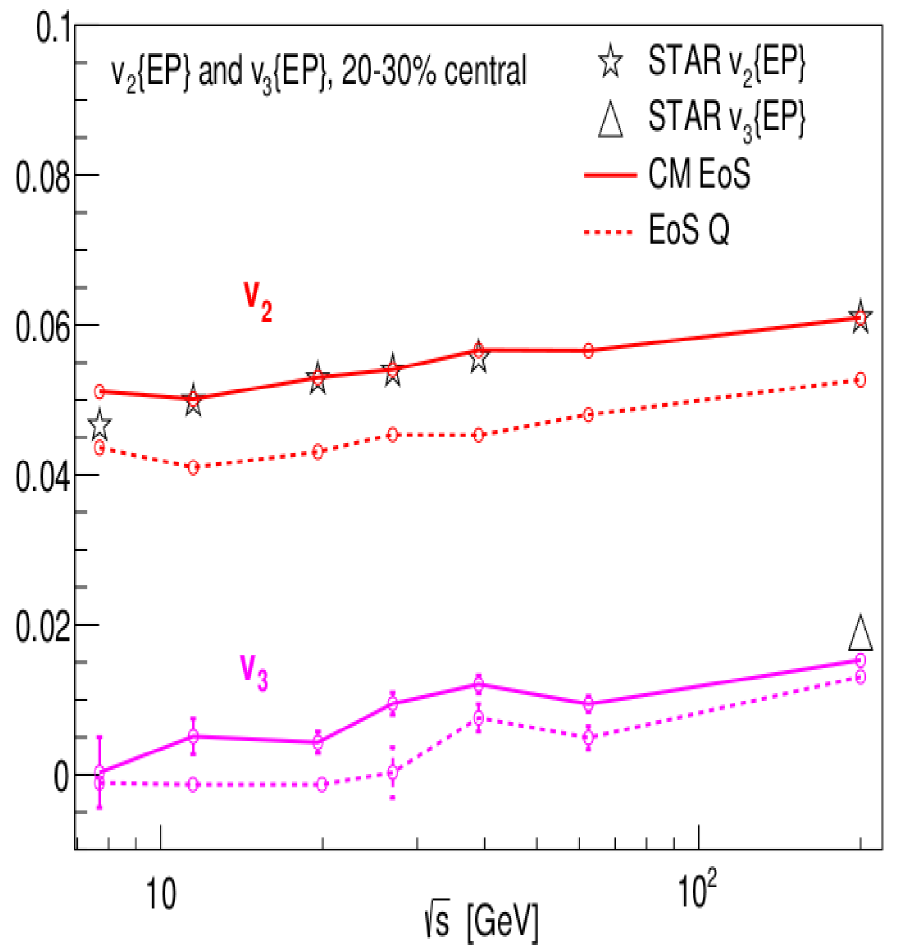


3D hydro model vHHLE + UrQMD (XPT EOS), $\eta/s = 0.2$ + param from

Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher , Phys.Rev. C91 (2015) no.6, 064901

BES: differential elliptic flow: model comparison



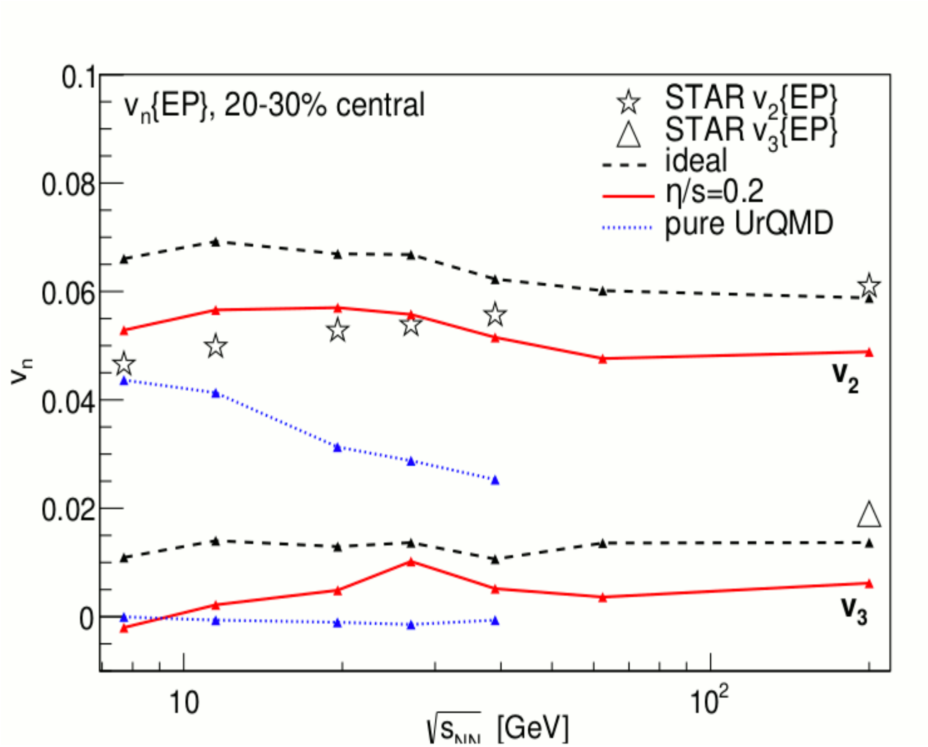


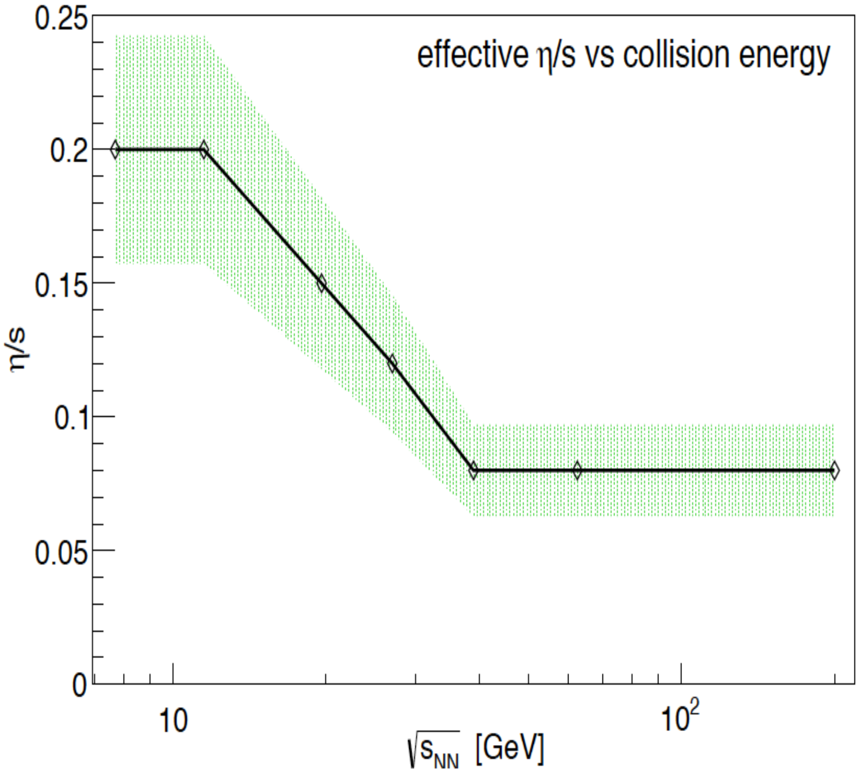
3D hydro model vHHLE + UrQMD (XPT EOS vs 1PT EOS)

Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher , Phys.Rev. C91 (2015) no.6, 064901

Elliptic and triangular flow at RHIC BES

Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher , Phys.Rev. C91 (2015) no.6, 064901



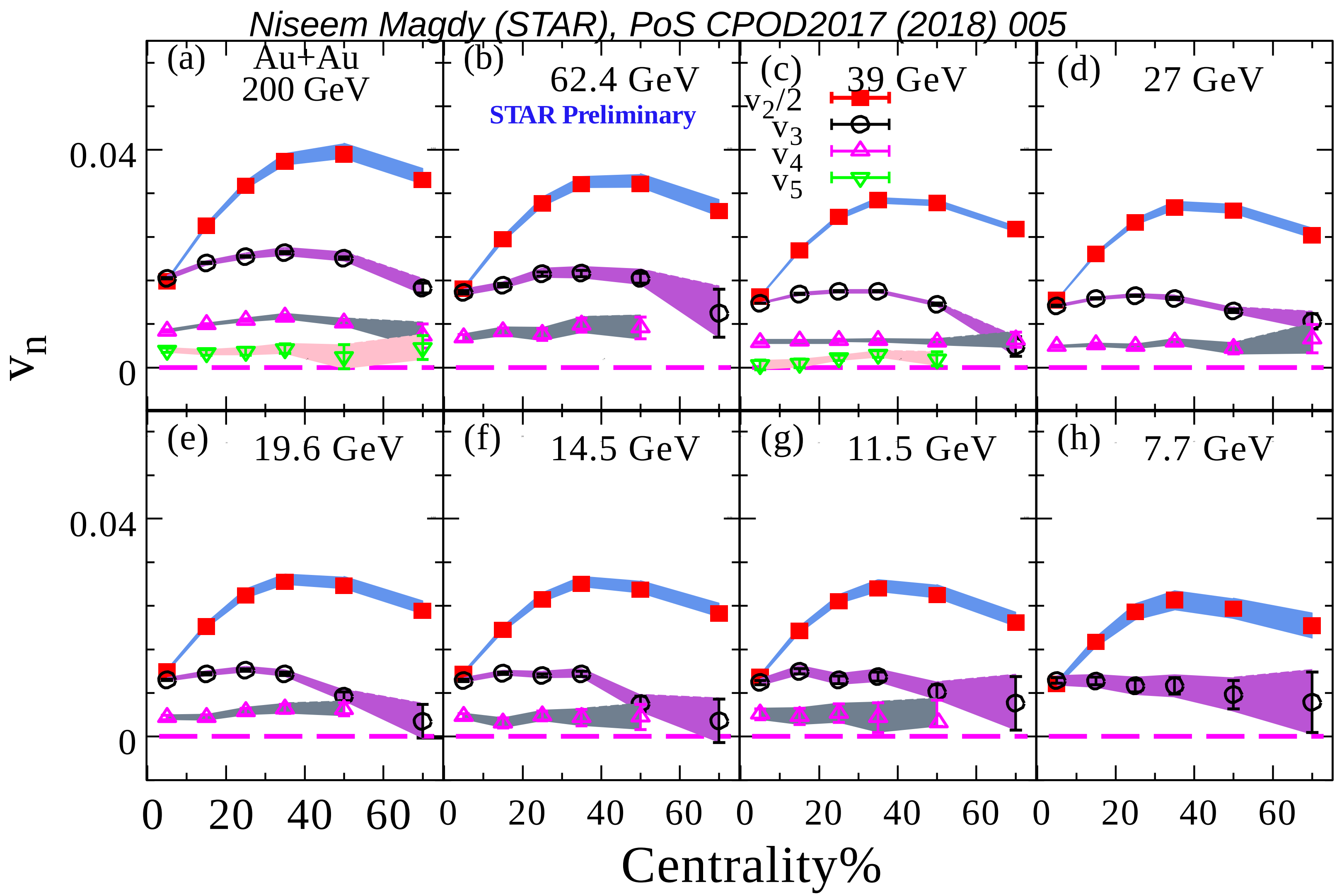


Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

In models, v_3 goes away when the QGP phase disappears????

V_n (centrality) as a function of beam energy

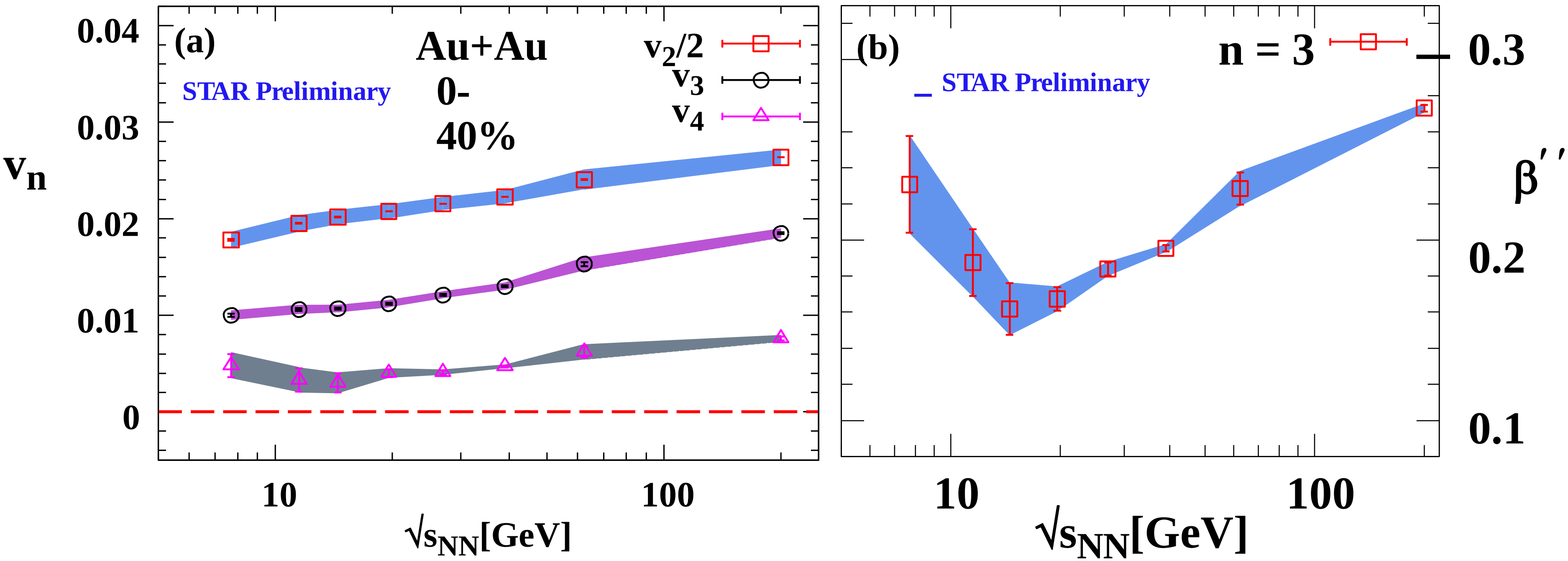
Niseem Magdy (STAR), PoS CPOD2017 (2018) 005



V_n data could serve as important constraints to test different initial-state models and to aid precision extraction of the η/s

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

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

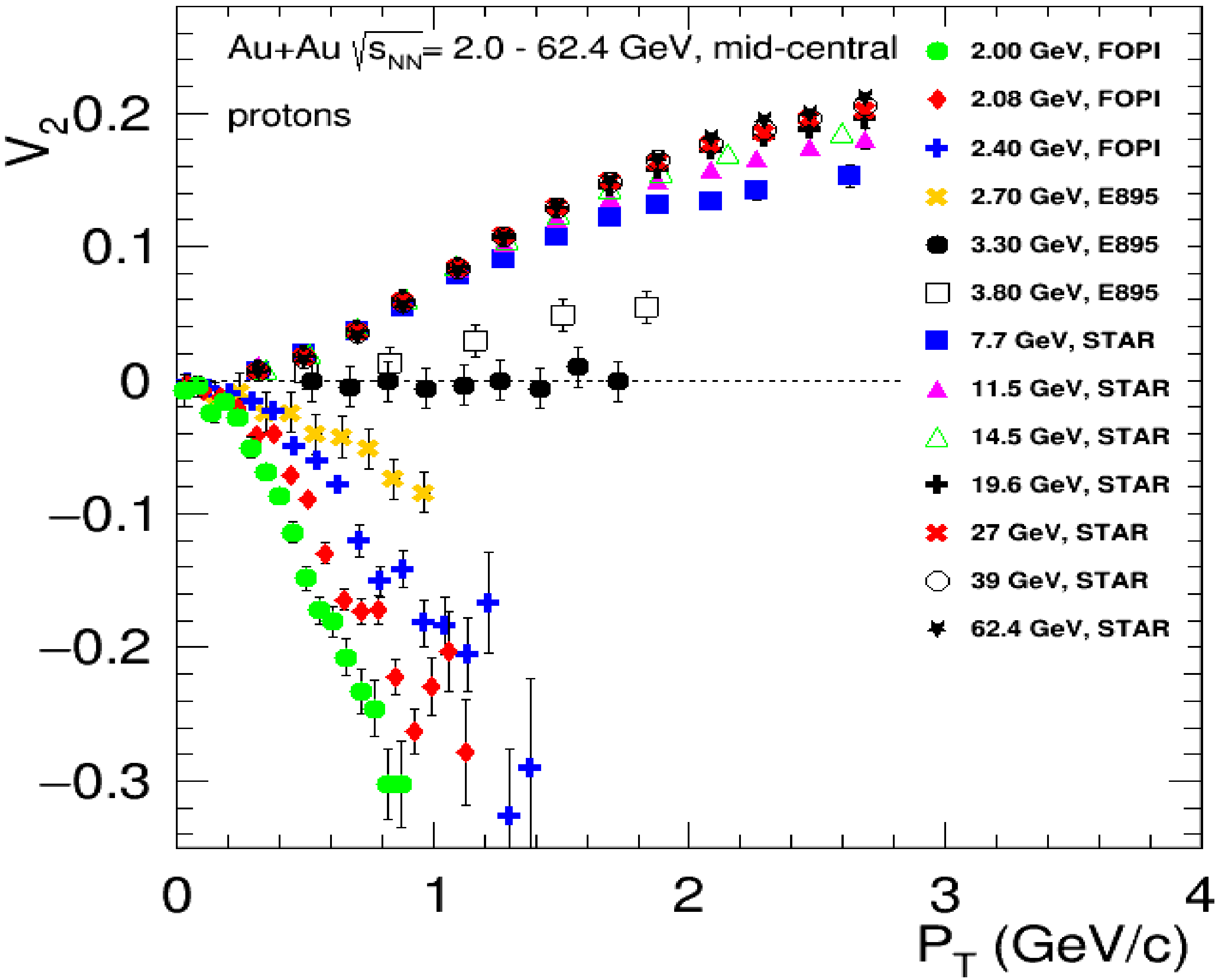


V_n shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient (*η*/*s*), indicates a non-monotonic behavior as a function of beam energy.

Excitation function of differential elliptic flow

EPJ Web Conf. 204 (2019) 03009

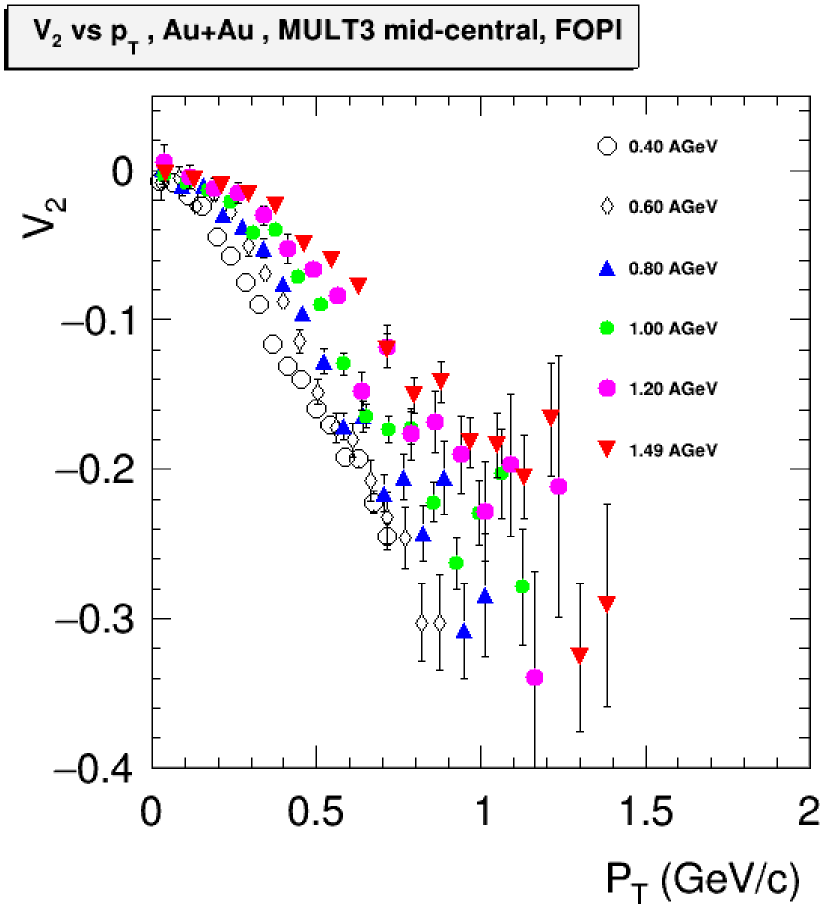
FOPI (15-29%)
E895 (12-25%)
STAR (10-40%)



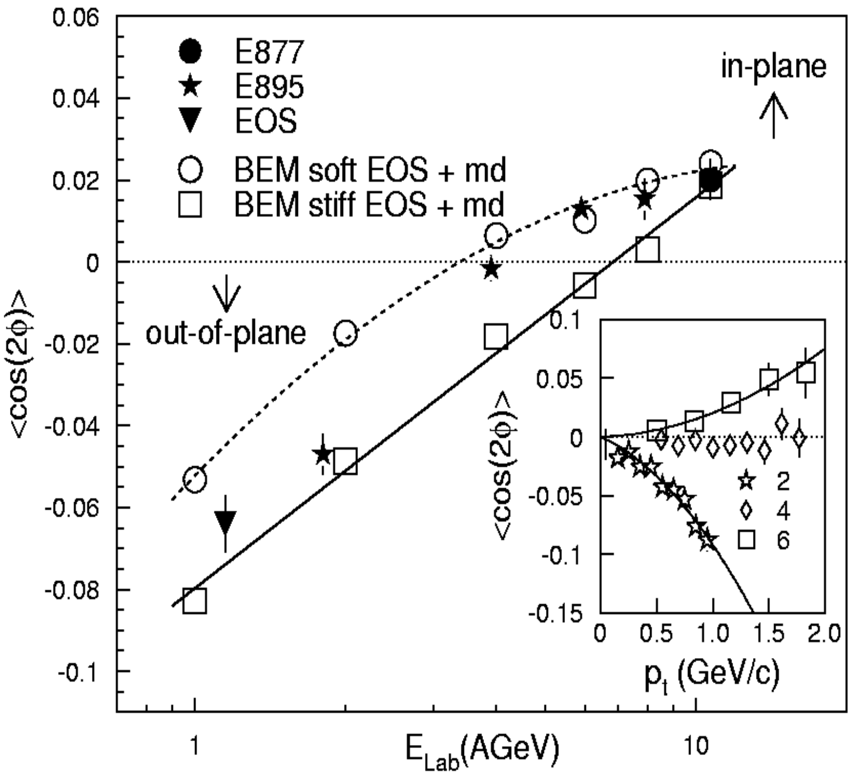
High precision differential measurements of anisotropic flow?

Elliptic Flow at SIS-AGS: interactions with spectators

Phys.Lett. B612 (2005) 173-180 , FOPI



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

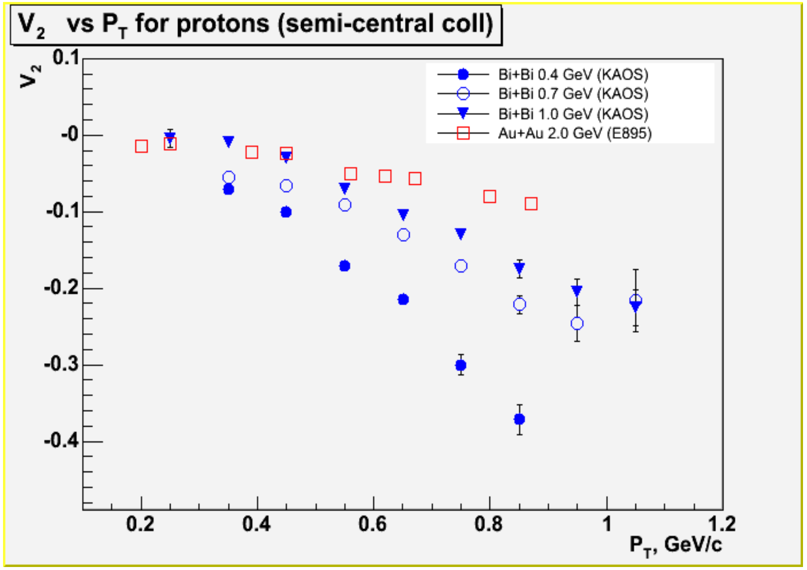


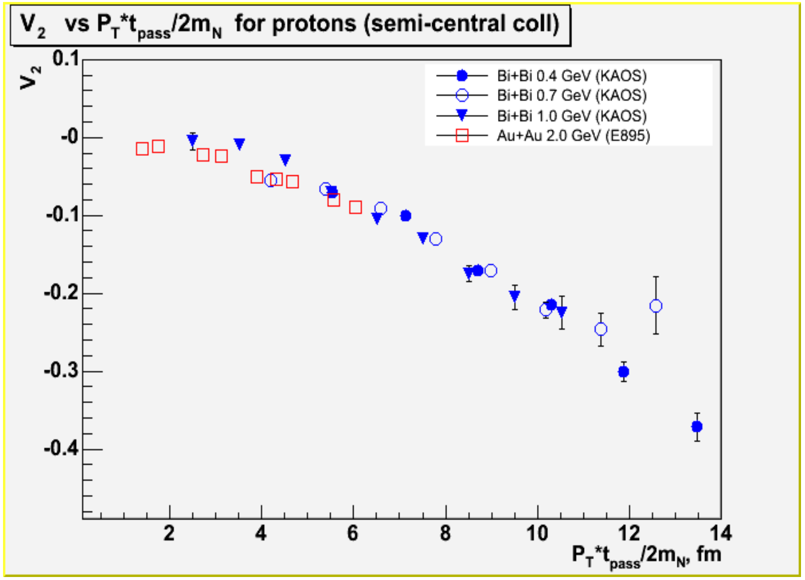
Passage time: $2R/(\beta_{cm}\gamma_{cm})$
Expansion time: R/c_s
$c_s = c\sqrt{dp/d\varepsilon}$ **- speed of sound**

a delicate balance between (i) the ability of pressure developed early in the reaction zone and (ii) the passage time for removal of the shadowing by spectators

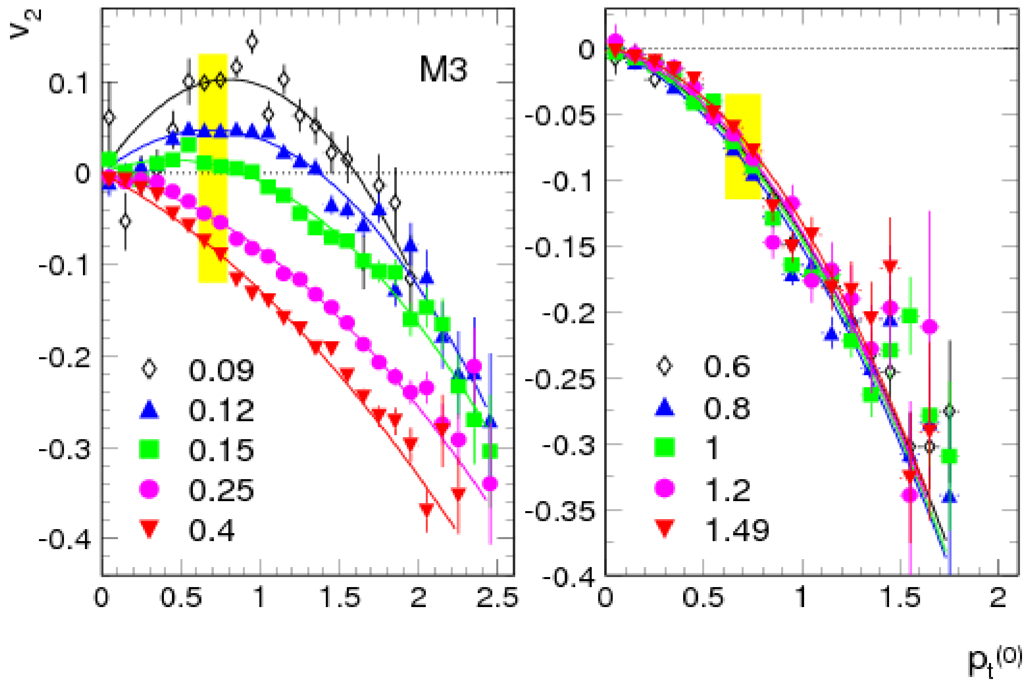
v_2 Flow at SIS-AGS: scaling relations

(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

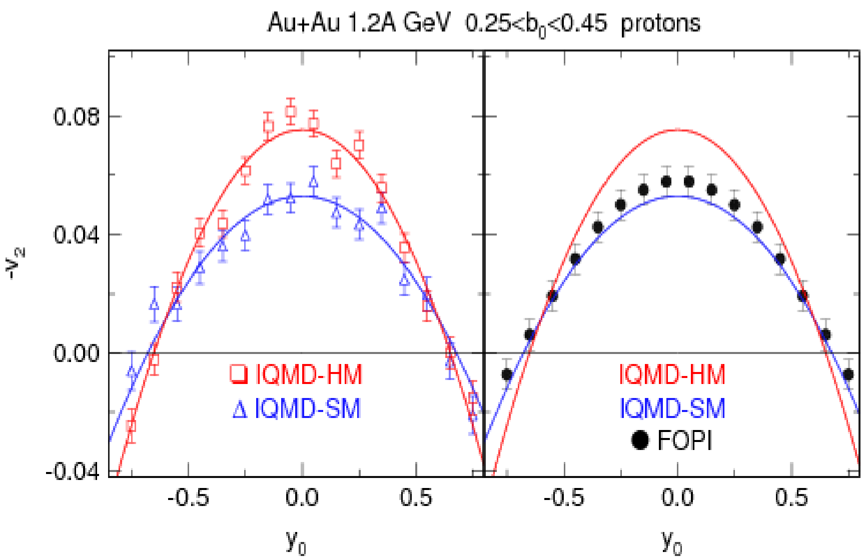


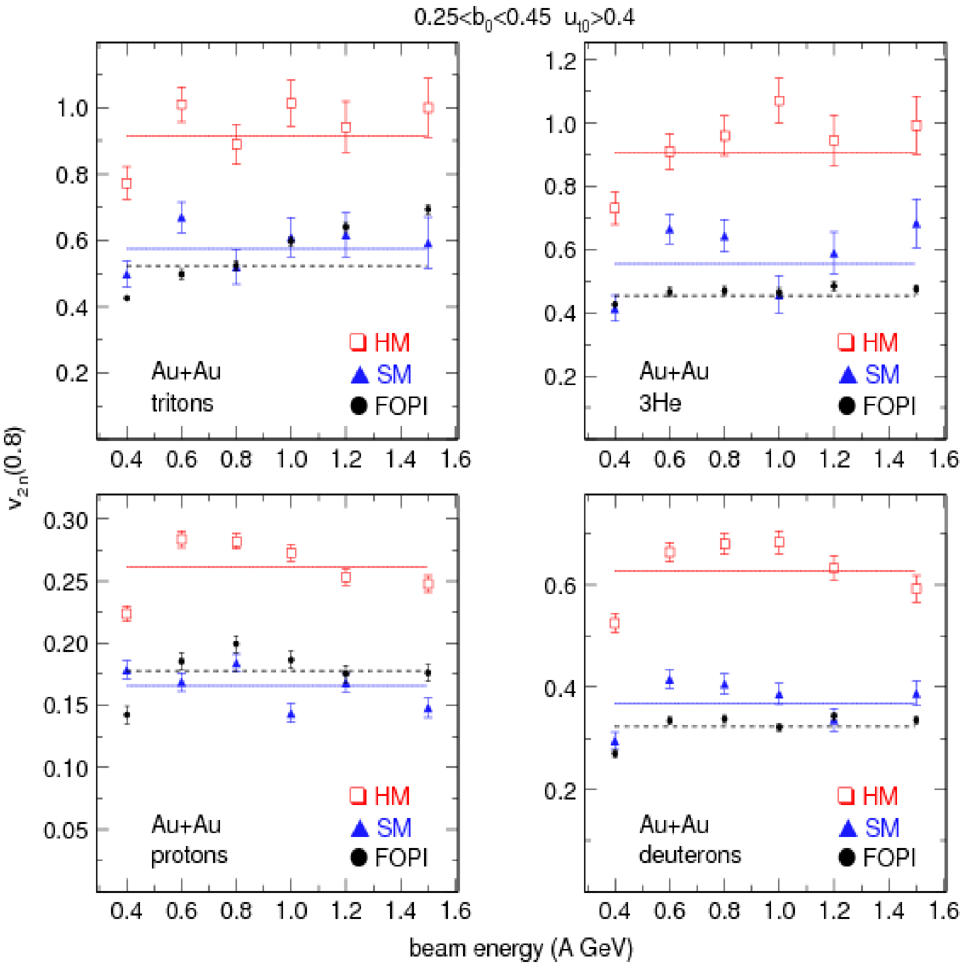
The rather good scaling observed suggest that c_s does not change significantly over beam energy range 0.4 – 2.0 AGeV. .

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

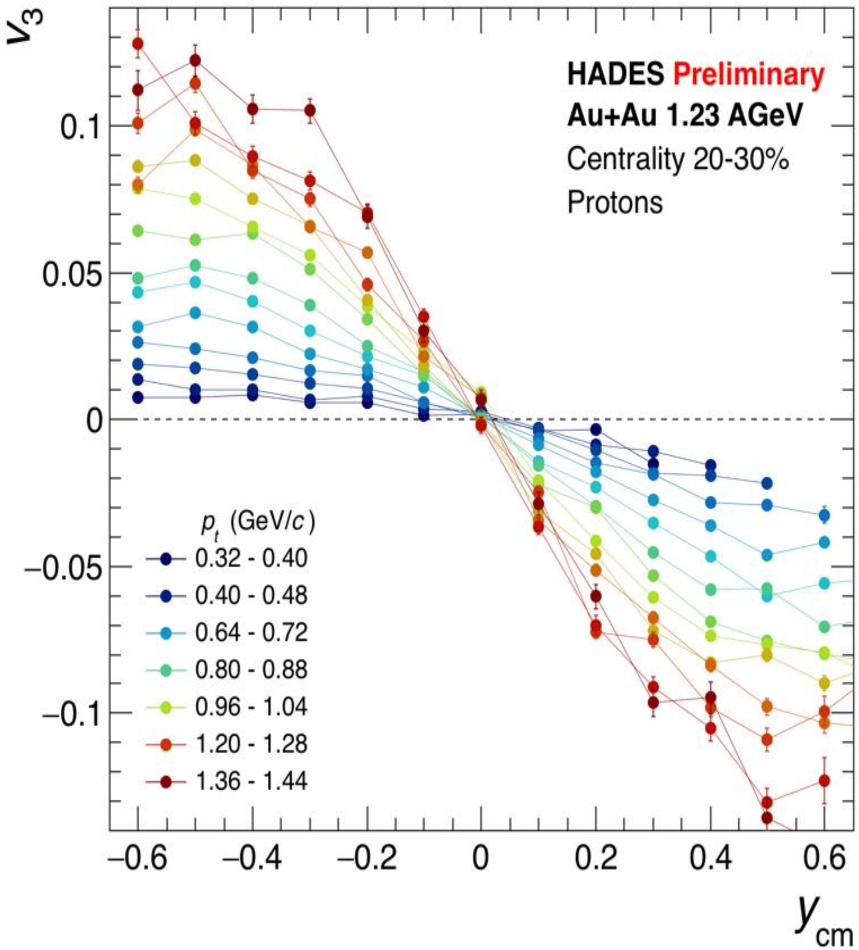
FOPI data : Nucl. Phys. A 876 (2012) 1
IQMD : Nucl Phys. A 945 (2016)

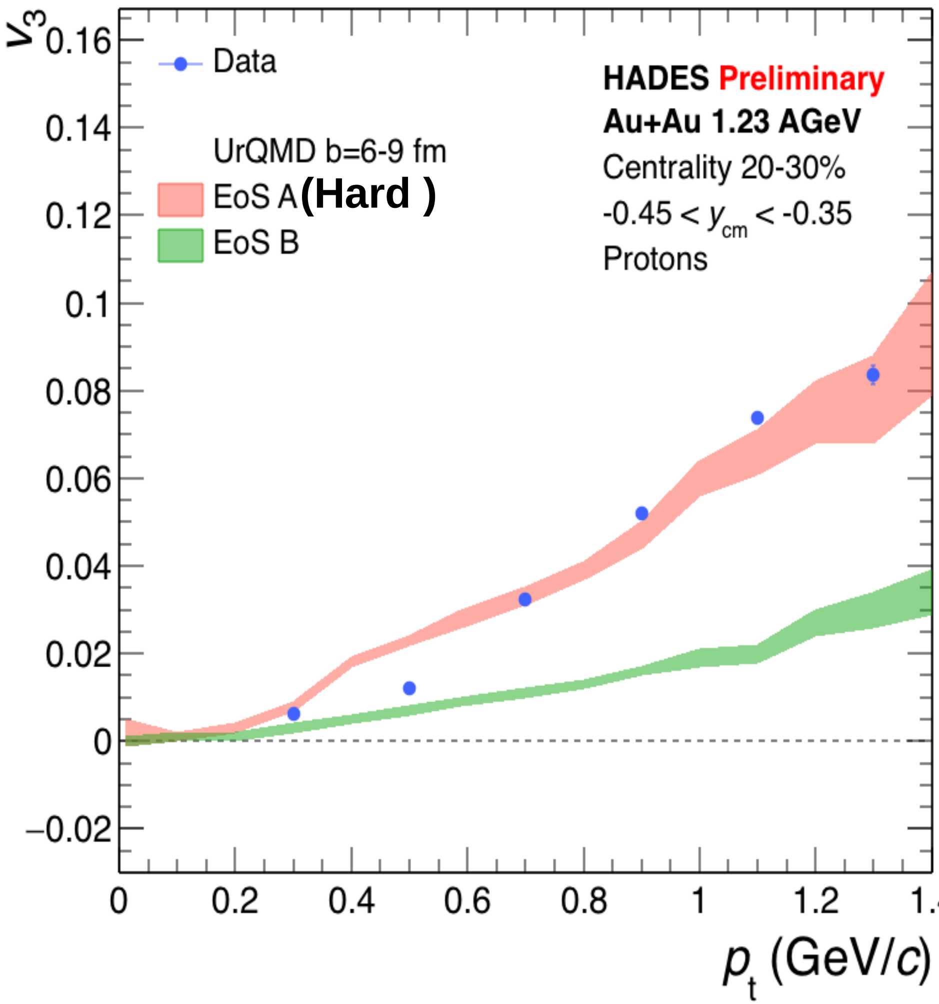




V2n=|V20|+|V22|
Fit: V2(y0)=V20+V22*Y0^2

HADES results at SIS: V_3 (odd)





Behruz Kardan (HADES Collaboration), Nucl.Phys. A982 (2019) 431-434

Paula Hillman et al, (UrQMD), J.Phys. G45 (2018) no.8, 085101

Anisotropic Flow at $\sqrt{s_{NN}}$ = 2-11 GeV : Lessons from SIS-AGS

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

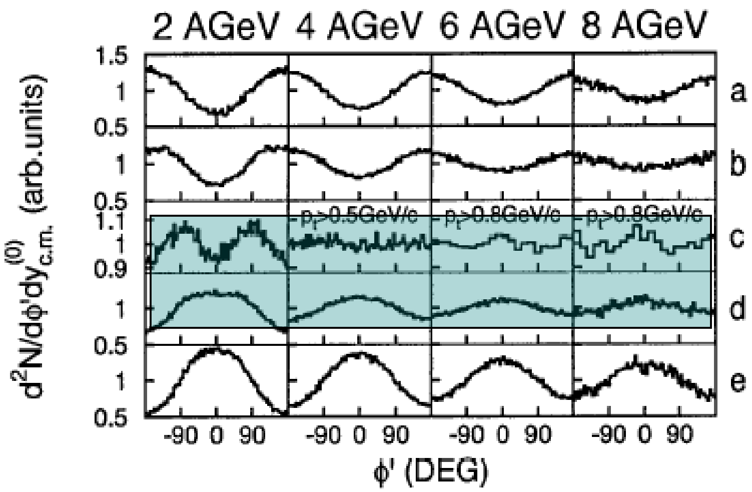
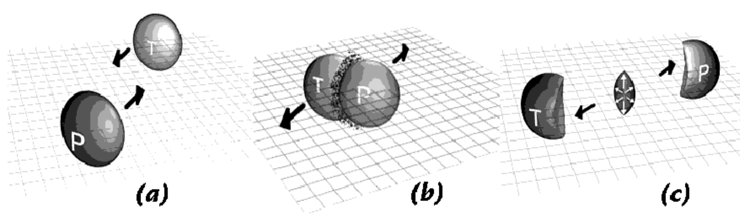


FIG. 2. Azimuthal distributions (with respect to the reconstructed reaction plane) for 2*A*, 4*A*, 6*A*, and 8*A* GeV Au + Au.

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



1) **Interations with spectators (need to be included in models), different colliding systems**
2) **Sensitive to EOS – rapidity dependence of elliptic flow**
3) **Importance of high harmonics.**

Conclusions and Perspectives

- **Anisotropic flow measurements provides access to the transport properties of the medium: EOS, sound speed (cs), viscosity, etc. Scaling relations help to understand the physics of the process.**

- **BM@N/NICA energies are very interesting: transition between hadronic and partonic matter.**
- **Robust experimental results and an intensive collaboration between theory and experimental groups is necessary to exploit this physics**

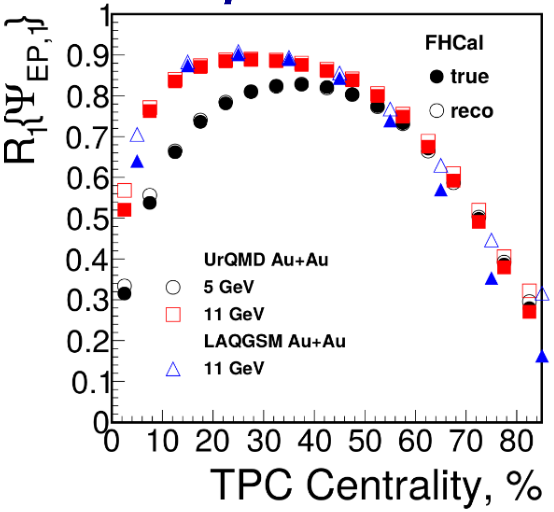
FXT in BES-II: Run 19

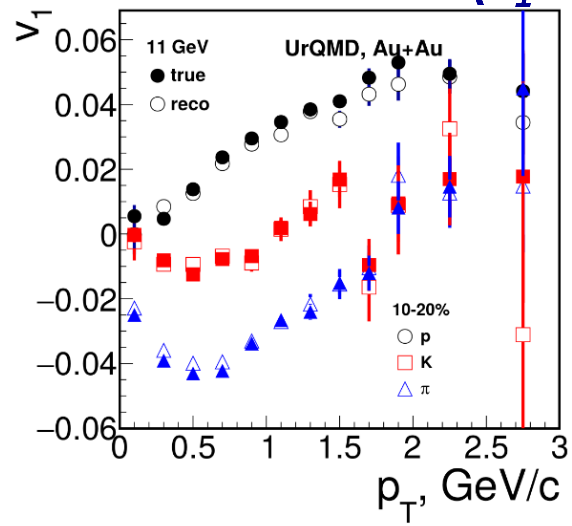
Beam Energy (GeV/nucleon)	$\sqrt{s_{NN}}$ (GeV)	Run Time	Species	Number Events
5.75	3.5	2 days	Au+Au	100M MB
7.3	3.9	2 days	Au+Au	100M MB
9.8	4.5	2 days	Au+Au	100M MB
13.5	5.2	2 days	Au+Au	100M MB
19.5	6.2	2 days	Au+Au	100M MB
31.2	7.7	2 days	Au+Au	100M MB

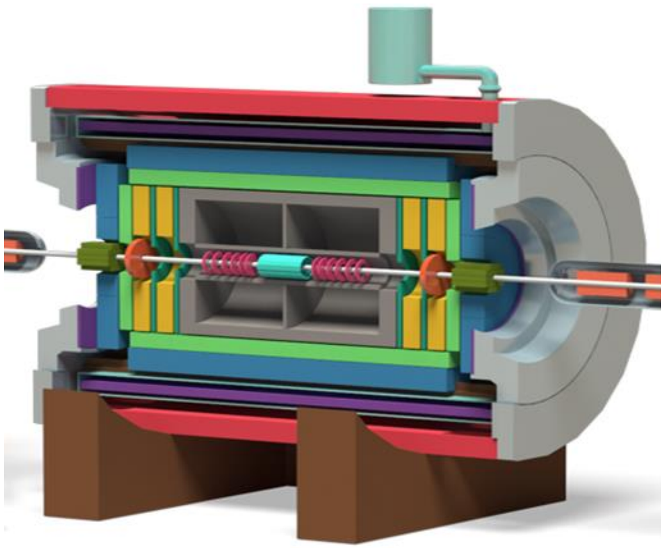
- iTPC and eTOF upgrades will be available
- Would need 100 Million Events at each energy to make the sensitivity of BES-II, 2 days per energy (3.5 GeV – 7.7 GeV)
- Data rate is DAQ limited
- Data at 7.7 GeV would provide an overlap energy with the collider mode

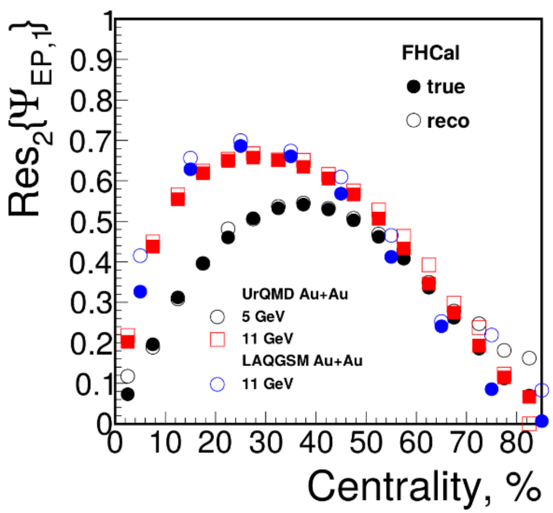
Flow performance: v_n of charged hadrons: MPD (NICA)

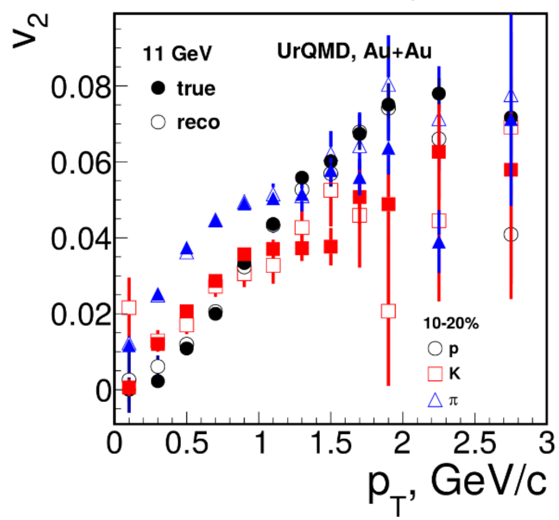
event plane resolution ***flow harmonics (v_1/v_2)***

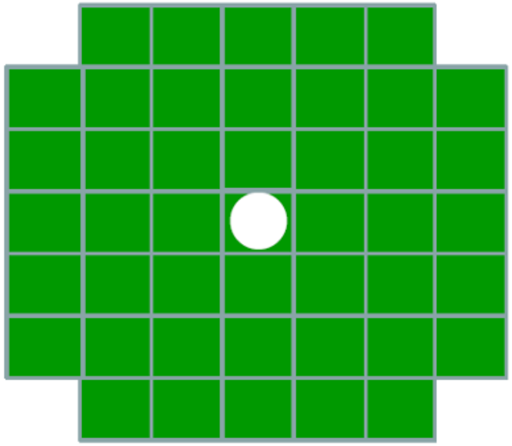












P. Parfenov, I. Selyuzhenkov, AT, (MEPhI), J.Phys.Conf.Ser. 798 (2017) no.1, 012067

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

Flow performance study for FHCAL TDR (2018)

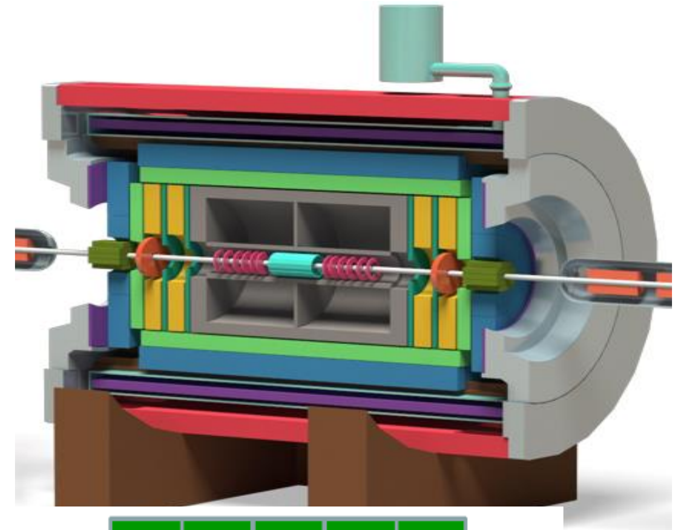

NICA

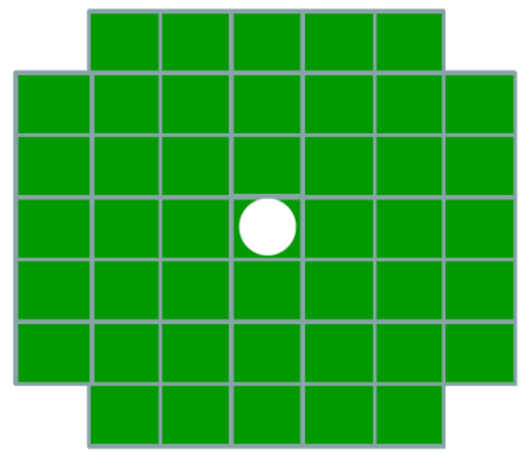
Technical Design Report for the MPD Experiment

Nuclotron Based Ion Collider Facility

Forward Hadron Calorimeter (FHCal)

December 2016

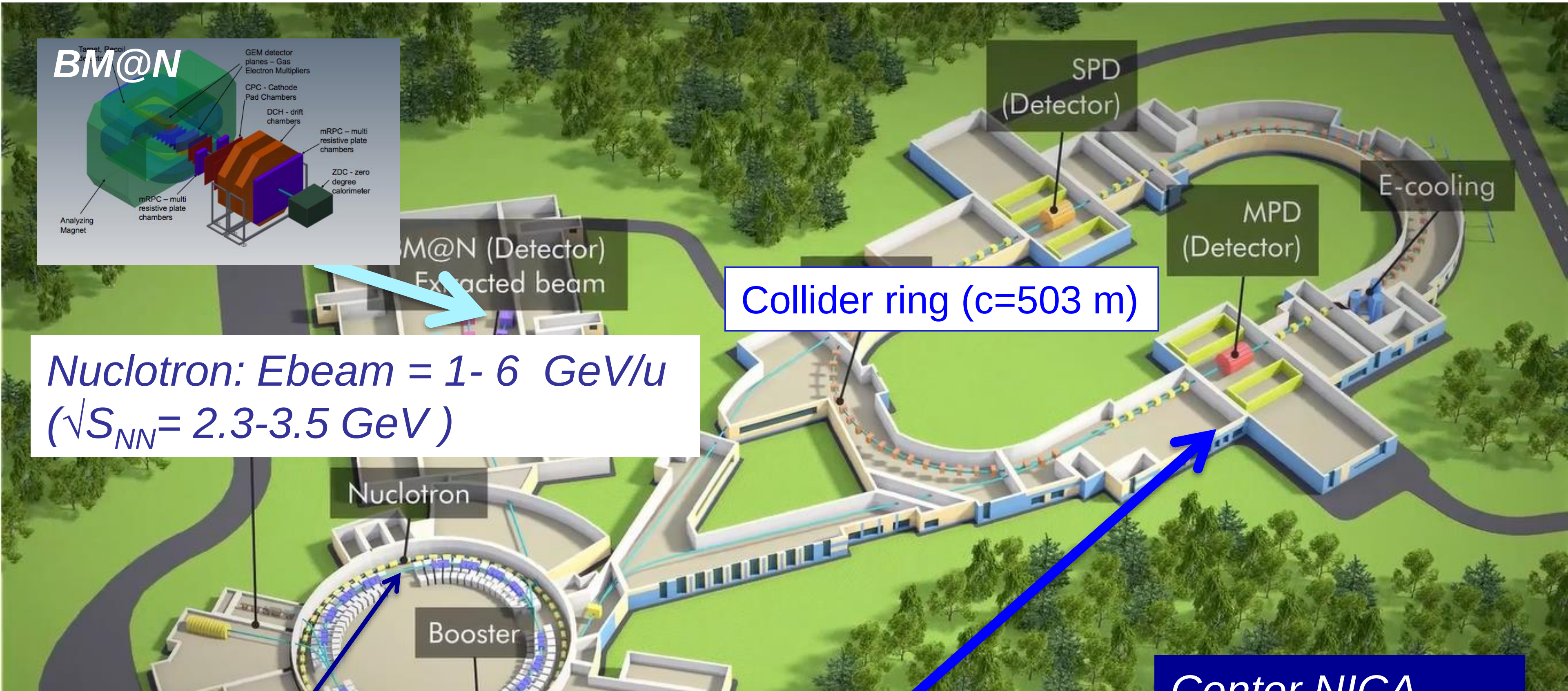




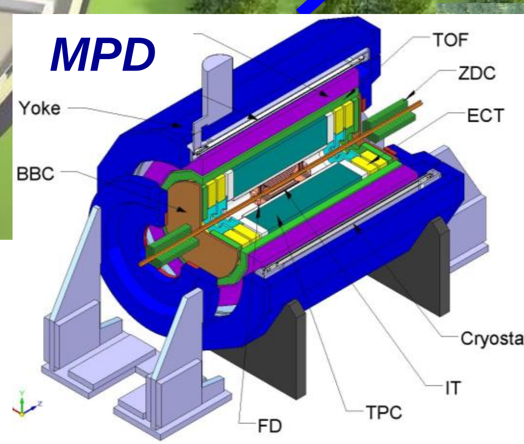
FHCal coverage:
$2.2<|\eta|< 4.8$

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

NICA(JINR), Dubna



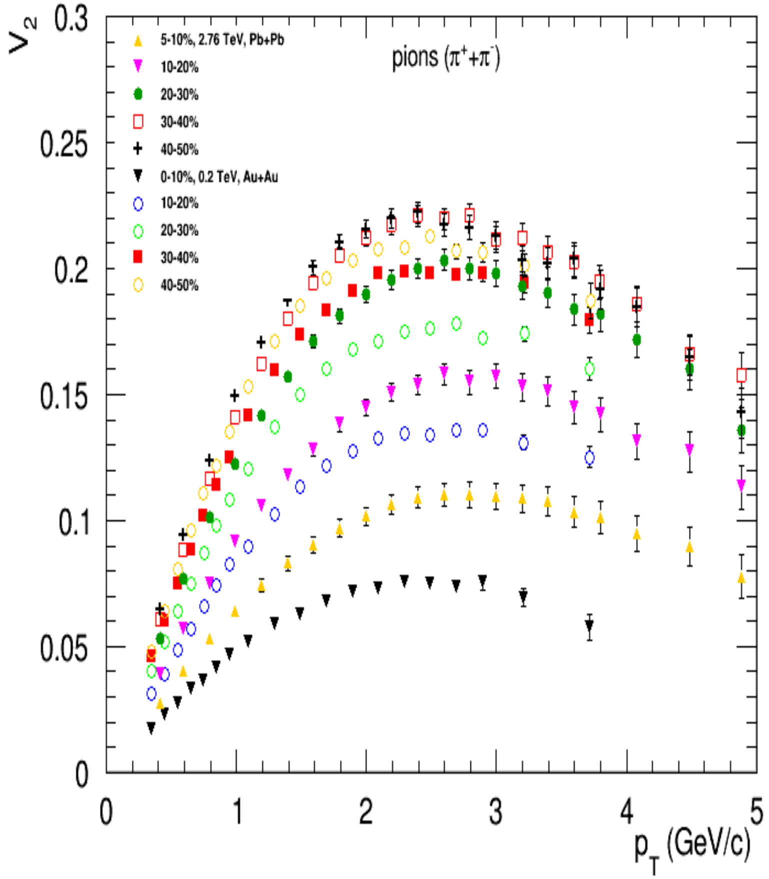
Nuclotron: Ebeam = 1- 6 GeV/u
($\sqrt{S_{NN}}$= 2.3-3.5 GeV)

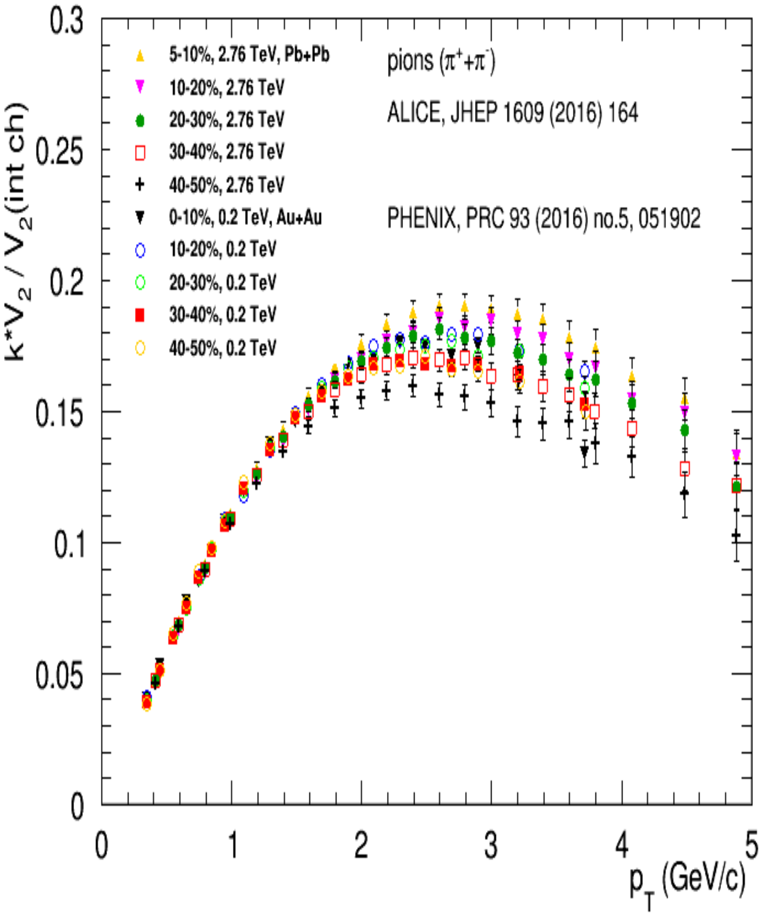


*NICA: $\sqrt{S_{NN}}$= 4-**11** GeV (Au^{79+})*

Elliptic flow of identified hadrons at RHIC/LHC : pions

Scaling with integral flow of charged hadrons

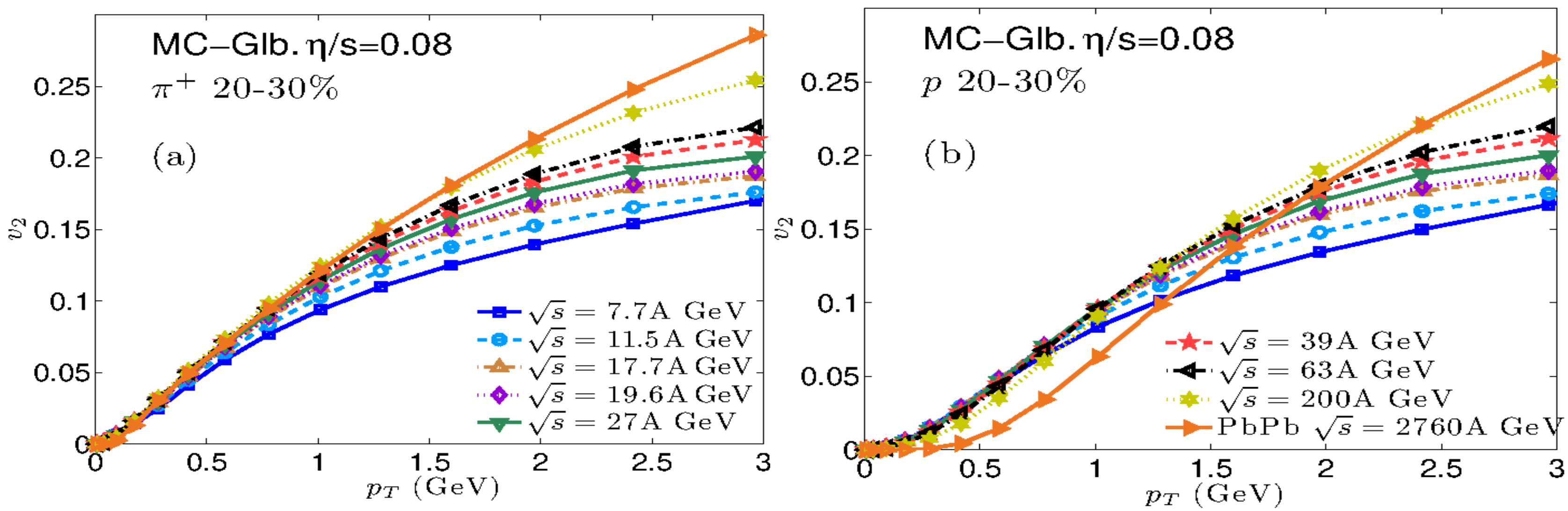




$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}}) * V_2(PID, p_T)???$$

v_2 of identified hadrons from RHIC to LHC (viscous hydrodynamics)

Chun Shen and Ulrich Heinz, Phys. Rev. C 85, 054902(2012), VISH2+1 model calculations



- ✓ **For pions $v_2(p_T)$ varies with $\sqrt{s_{NN}}$ very similarly to the total charged hadron $v_2(p_T)$.**
- ✓ For protons the strong radial flow "blueshifts" the entire flow signal to higher p_T .