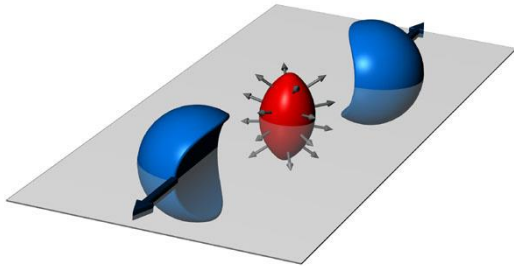


Scaling relations for anisotropic flow based on the data from beam energy scan experiments

Arkadiy Taranenko, Petr Parfenov, Alexander Demanov, Dim Idrisov,
Vinh Luong, Anton Truttse (NRNU MEPhI)



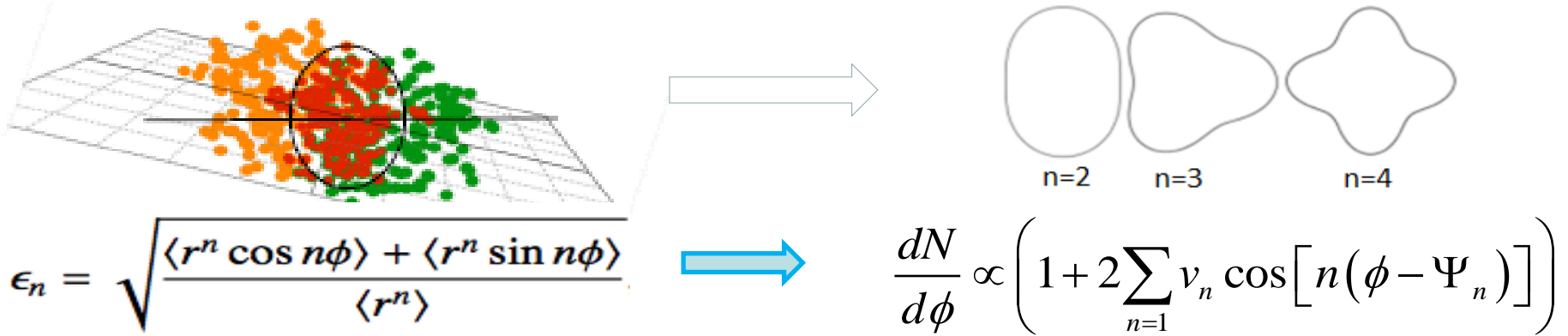
9th International Conference on New Frontiers in Physics (ICNFP 2020),
September 4-12, 2020, Kolumbari, Crete, Greece

This work is supported by: the RFBR according to the research project No. 18-02-40086 and by Ministry of Science and Higher Education of the Russian Federation, No 0723-2020-0041.

OUTLINE

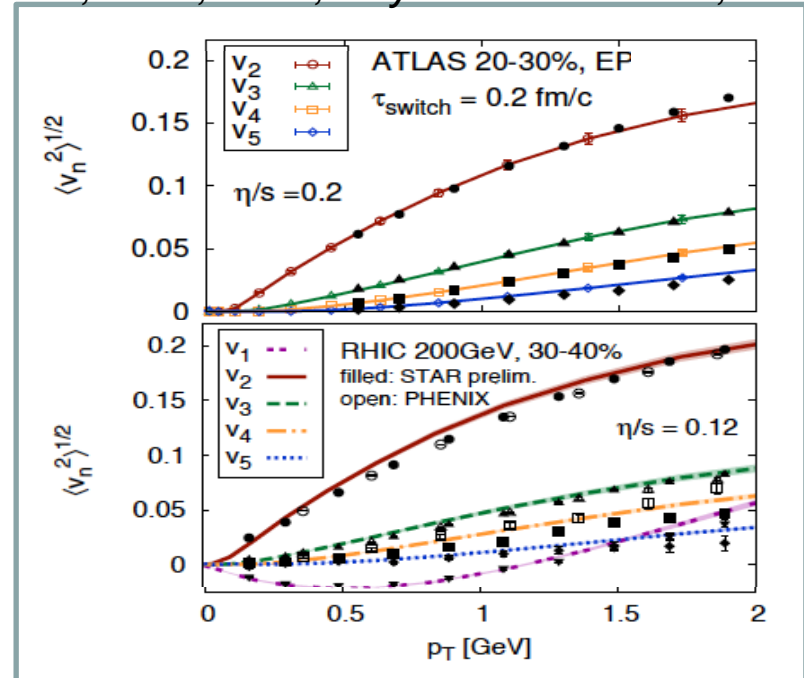
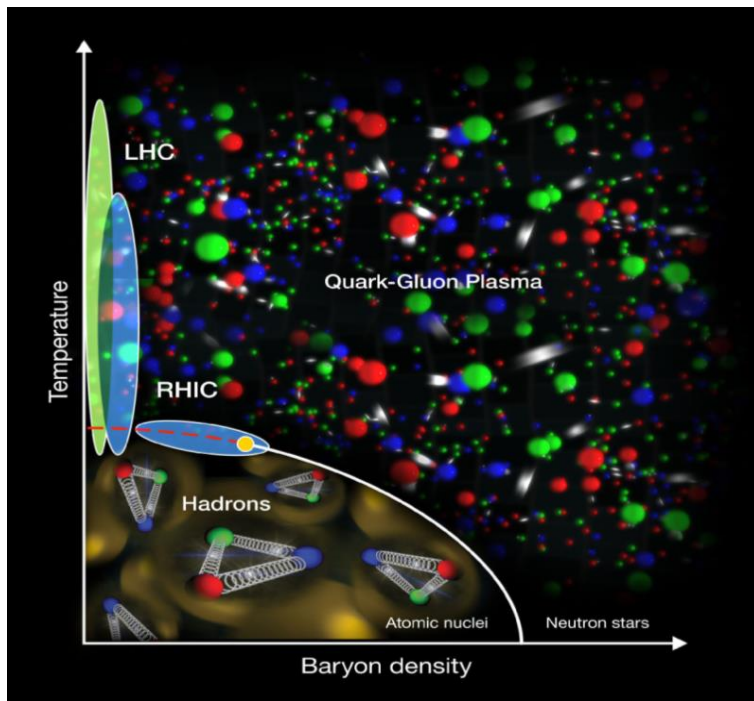
- 1. Why measure anisotropic flow?**
- 2. Scaling relation for flow (V_n) and sQGP at RHIC/LHC**
- 3. Flow results from Beam Energy Scan (RHIC)**
- 4. Outlook for flow measurements at NICA**

Anisotropic Flow at RHIC-LHC



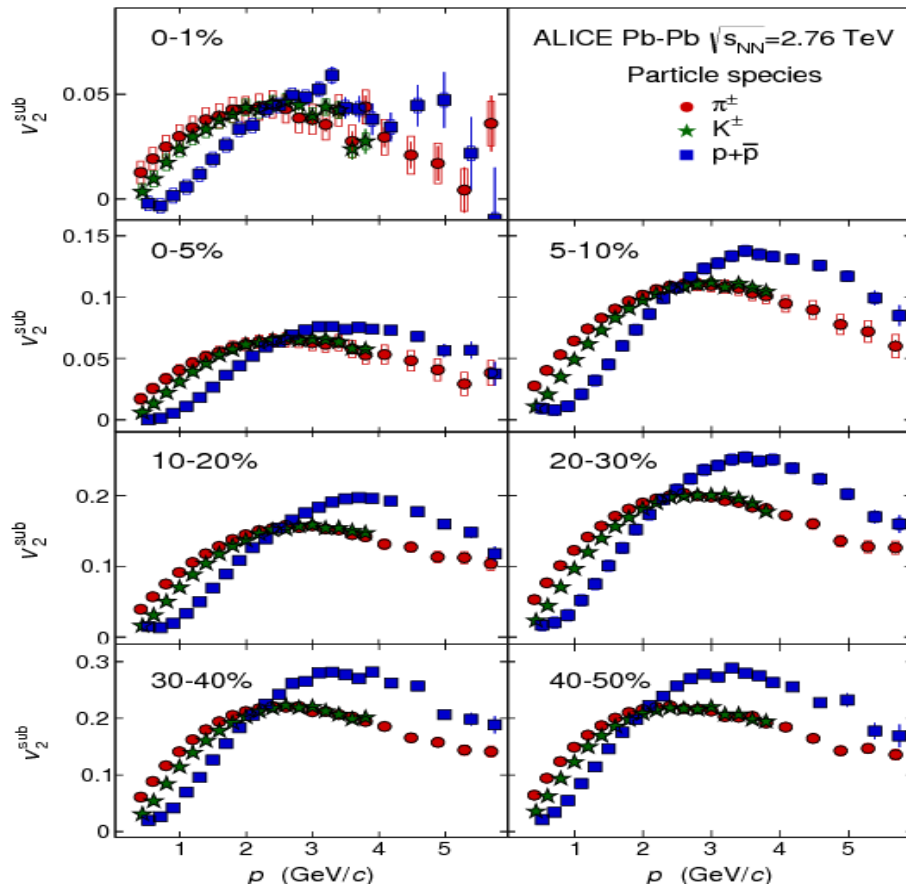
Initial eccentricity (and its attendant fluctuations) ϵ_n drive momentum anisotropy v_n with specific viscous modulation

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



V_n of identified hadrons at RHIC/LHC

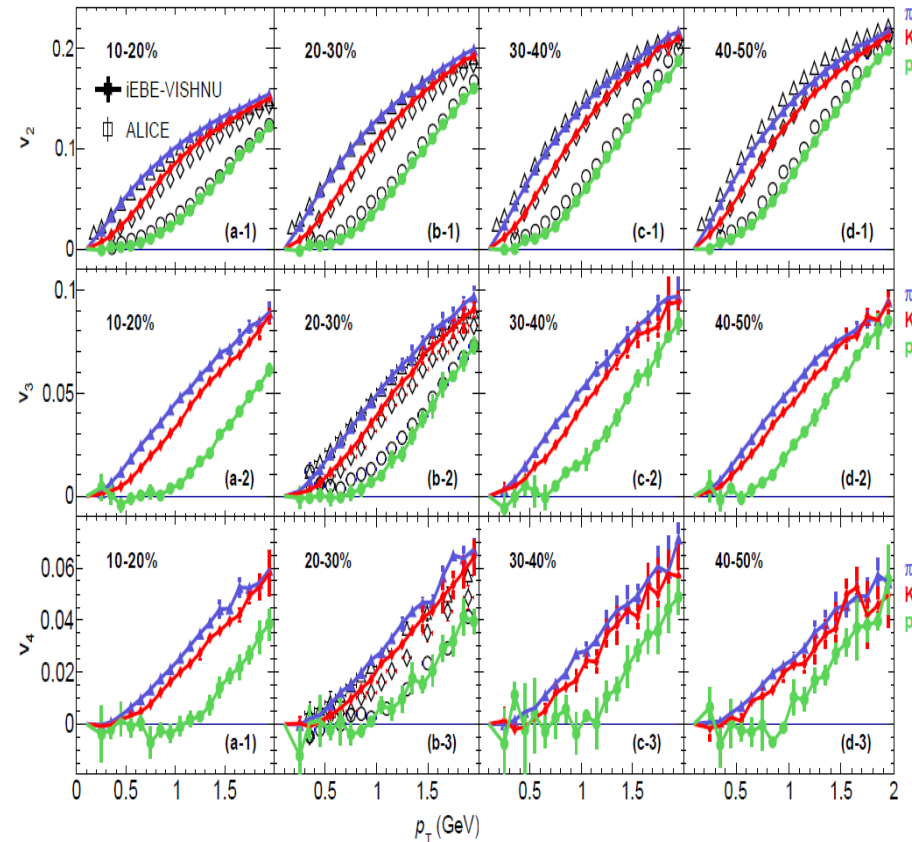
J. Adam et al., (ALICE) JHEP 1609, 164



Viscous Hydro + cascade, H.Xu, Z.Li, H. Song

PRC 93, 064905 (2016)

Pb+Pb 2.76 A TeV



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 $\left(\frac{\eta}{s}, \frac{\zeta}{s}, \dots\right)$.

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,

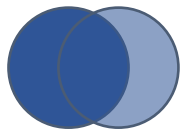
$$\frac{v_n}{\epsilon_n} \propto e^{-\beta n^2}, \quad \beta \propto \frac{\eta}{s} \frac{1}{RT}$$

arXiv:1601.06001
Roy A. Lacey, et al.

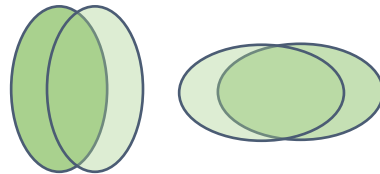
- From macroscopic entropy considerations $S \sim (RT)^3 \propto \frac{dN}{d\eta}$

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

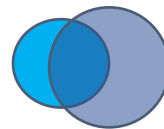
PRC 88, 044915 (2013)
E. Shuryak and I. Zahed



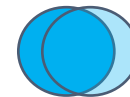
Au + Au



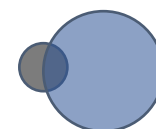
U + U



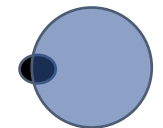
Cu + Au



Cu + Cu



d + Au



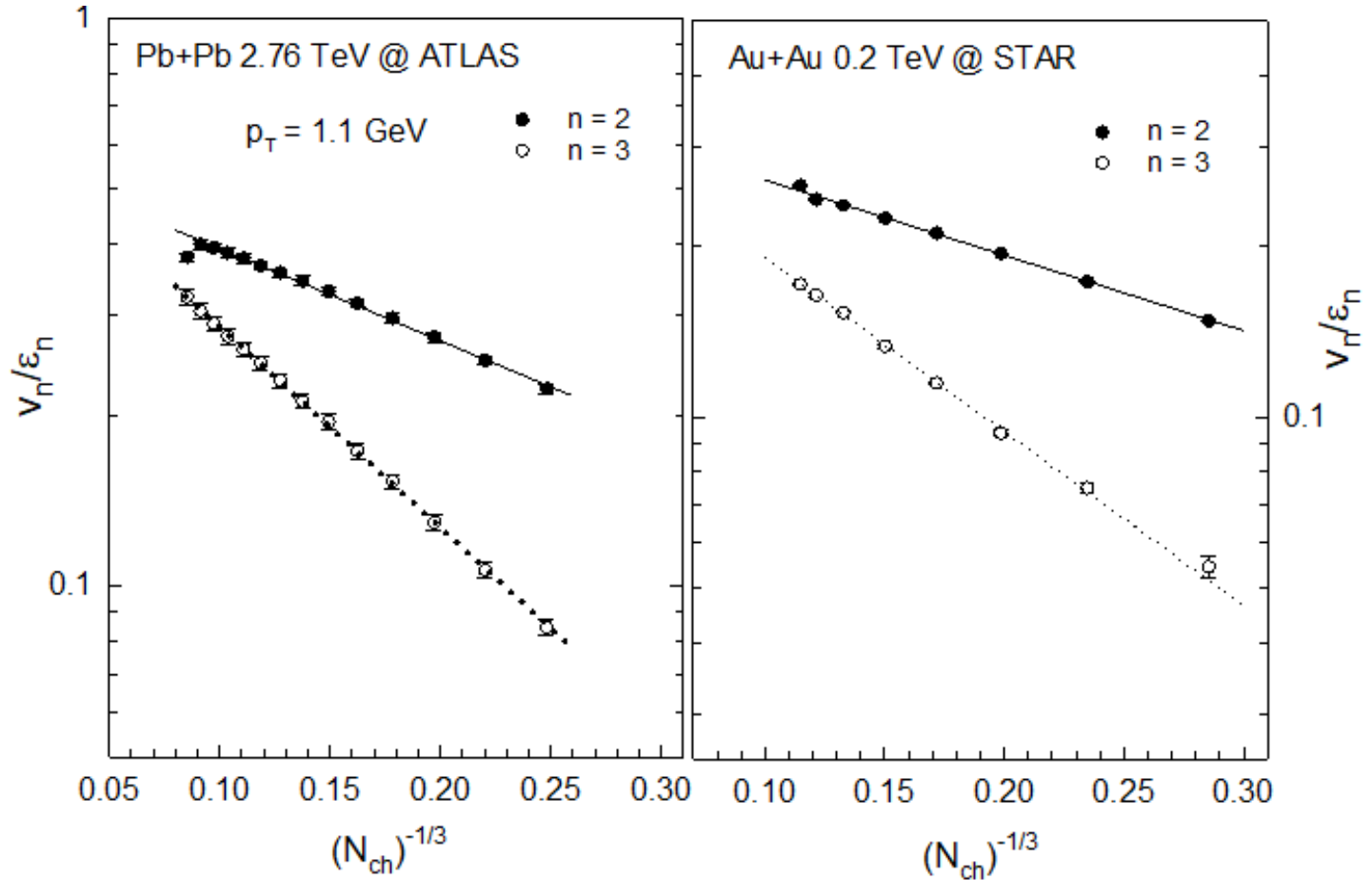
p + Au

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

Acoustic Scaling -

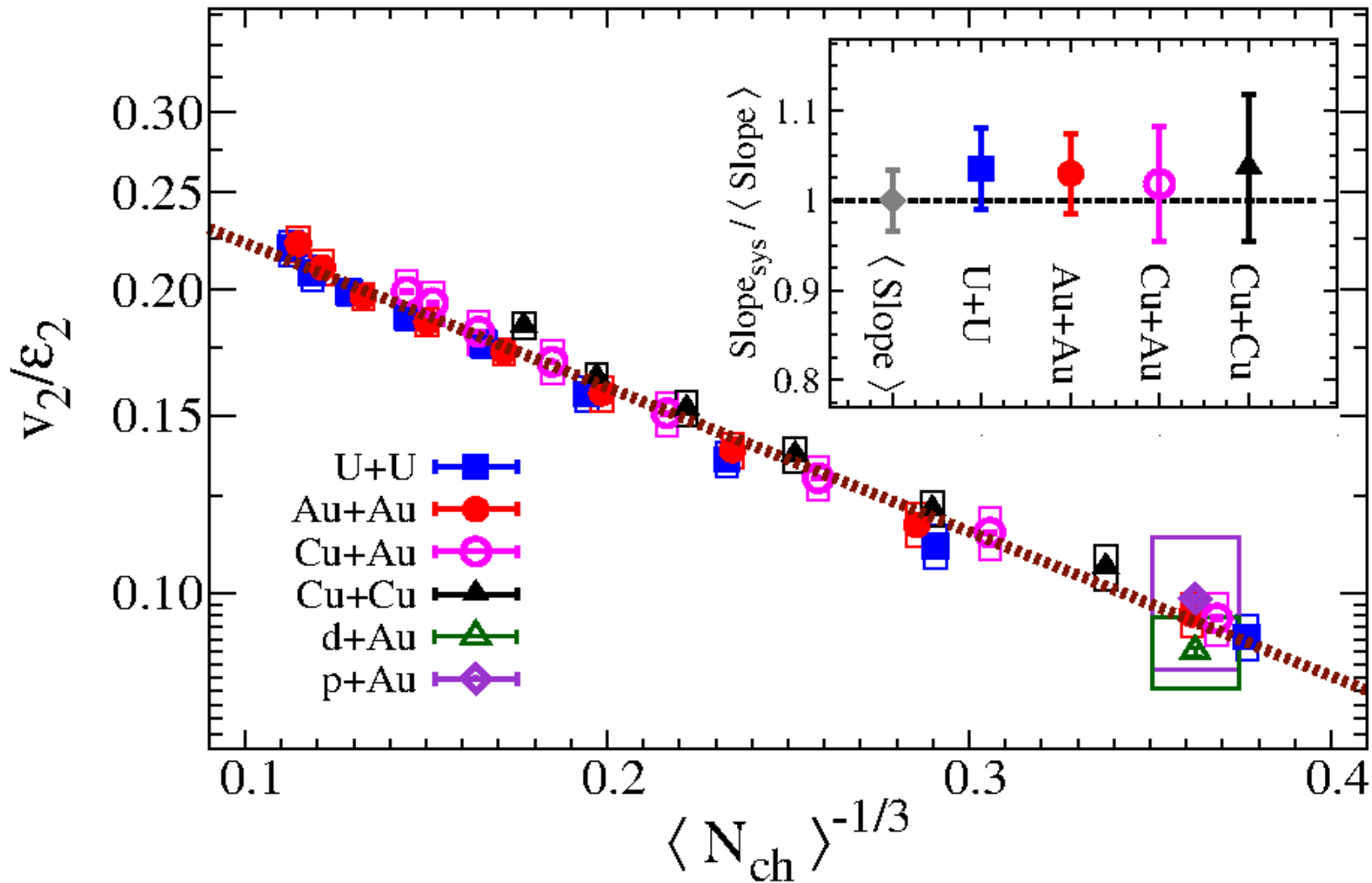
$$\ln\left(\frac{v_n}{\varepsilon_n}\right) \propto \frac{-\beta''}{RT}$$

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

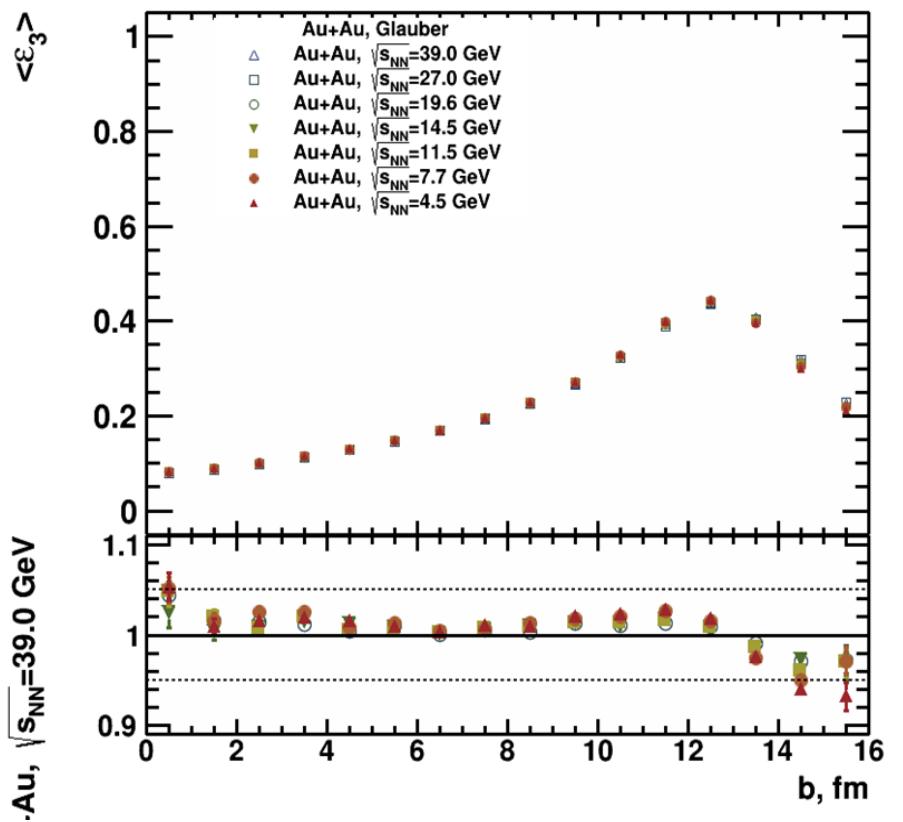
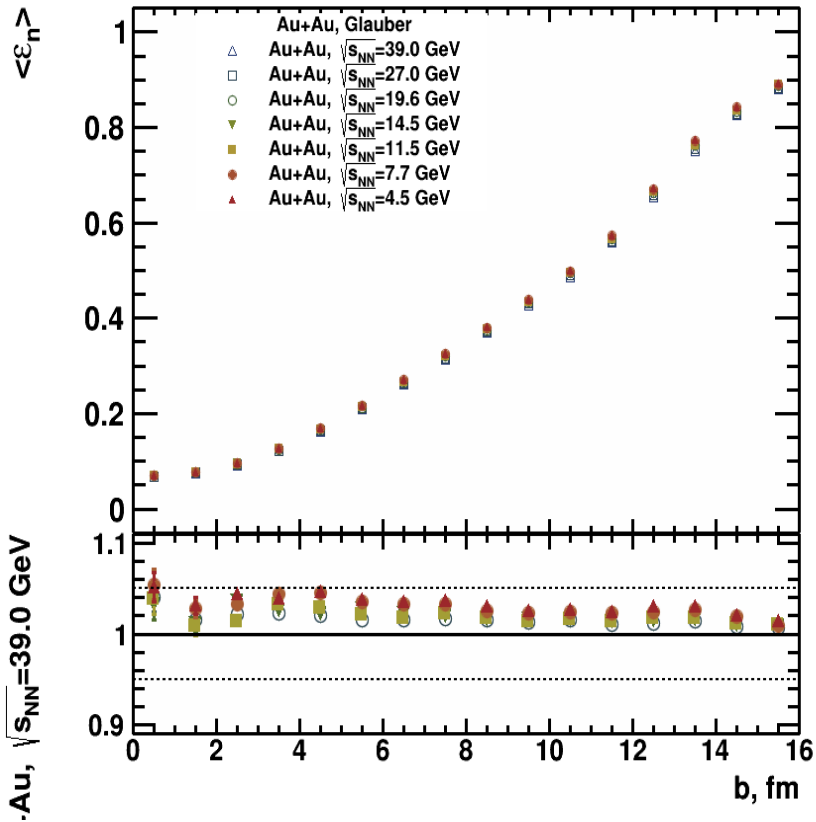


- ✓ **Characteristic $1/(RT)$ viscous damping validated**
 - ✓ **Clear pattern for n^2 dependence of viscous attenuation**
 - ✓ **Important constraint for η/s & ζ/s**

STAR: V_2 for different colliding systems



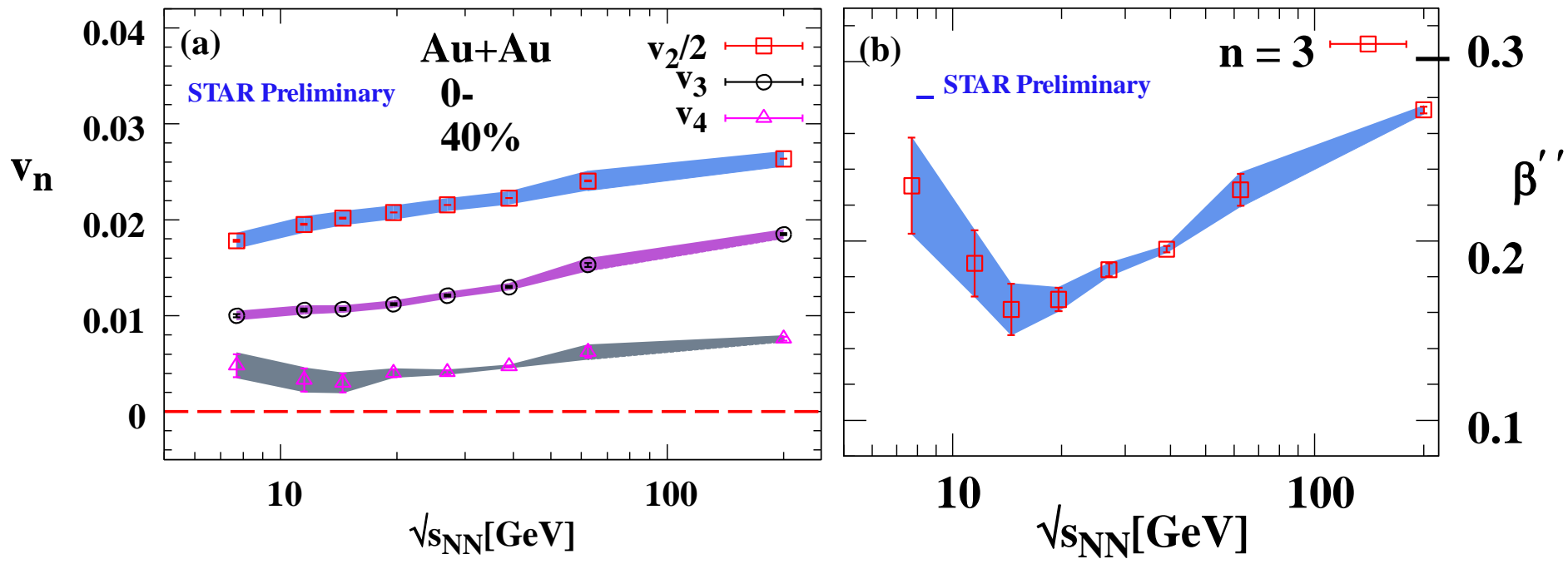
Collision energy dependence: ϵ_n



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

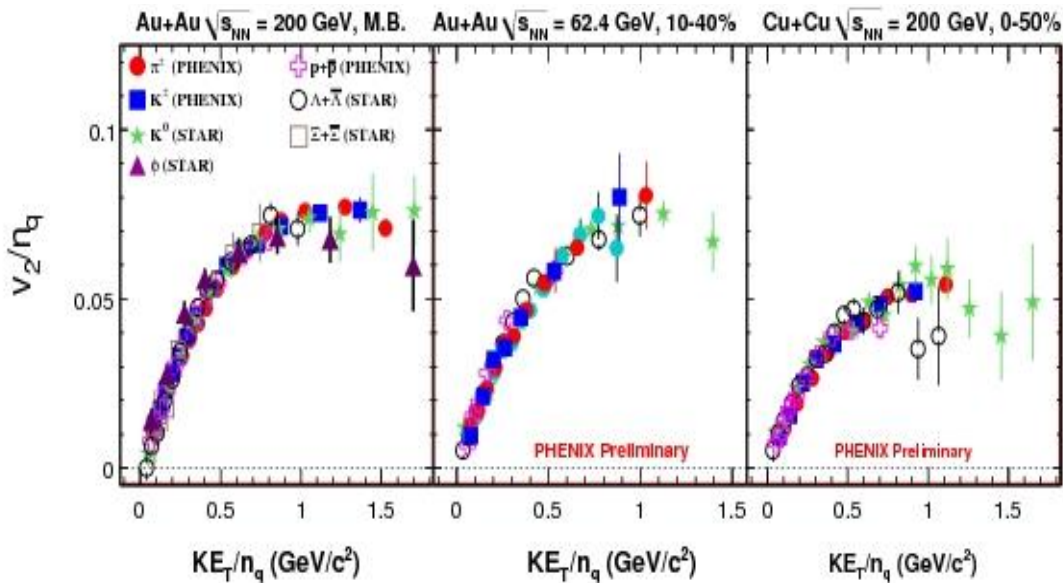
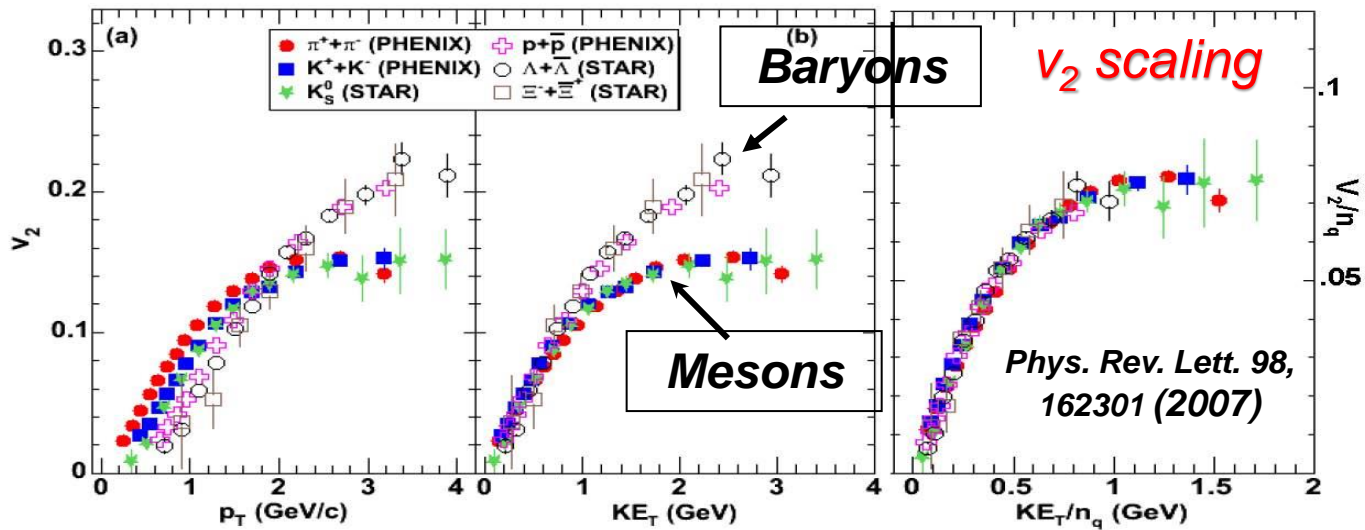
$$VC \propto \frac{\eta}{s}$$

Niseem Magdy, SQM 2016



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.

KE_T/n_q scaling and partonic collectivity at RHIC



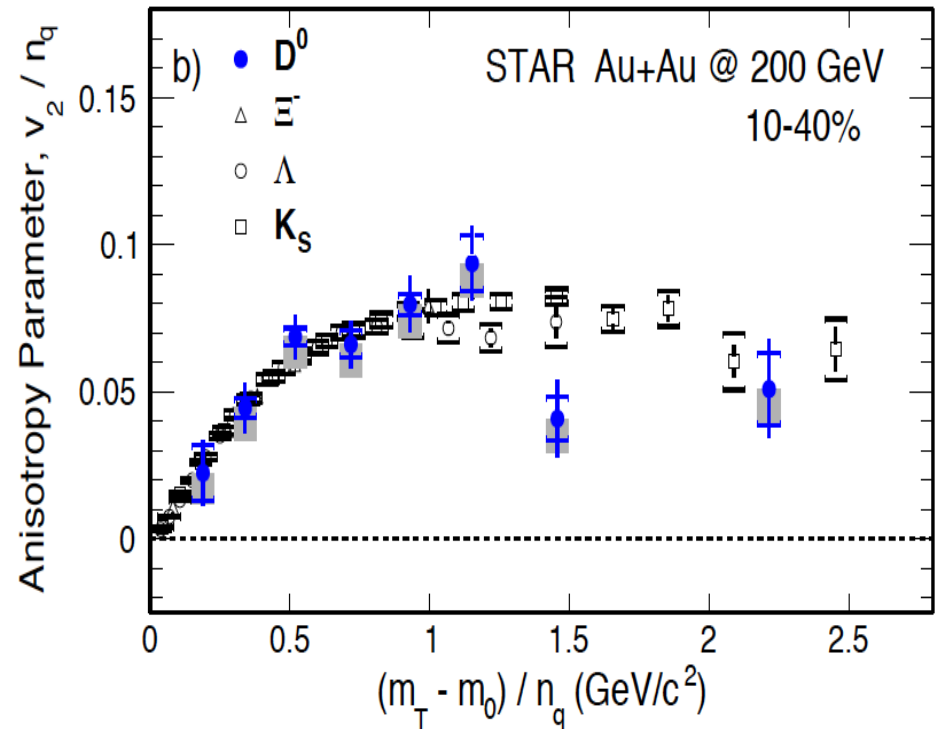
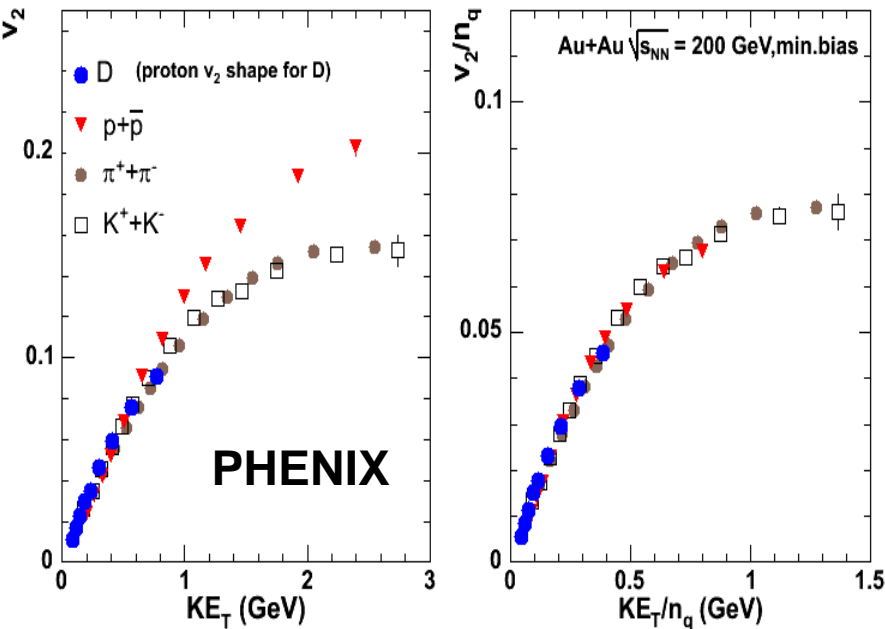
Significant part of flow at RHIC developed at partonic level.

Scaling provides an additional constraint for the mechanism for hadronization at RHIC

Elliptic flow of D meson in 2006-2017

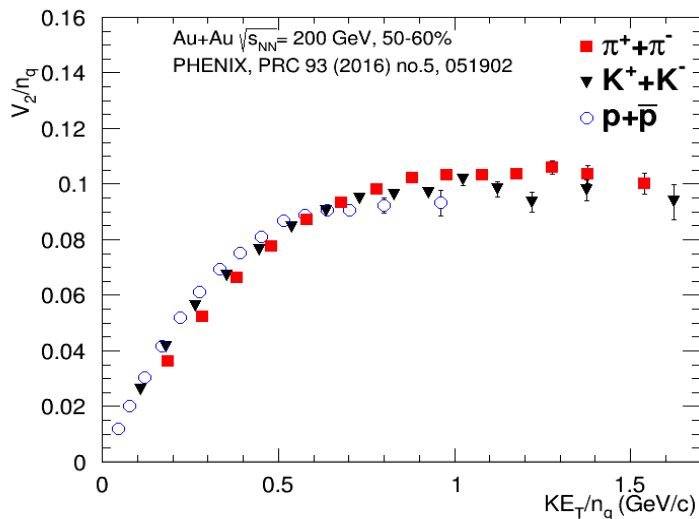
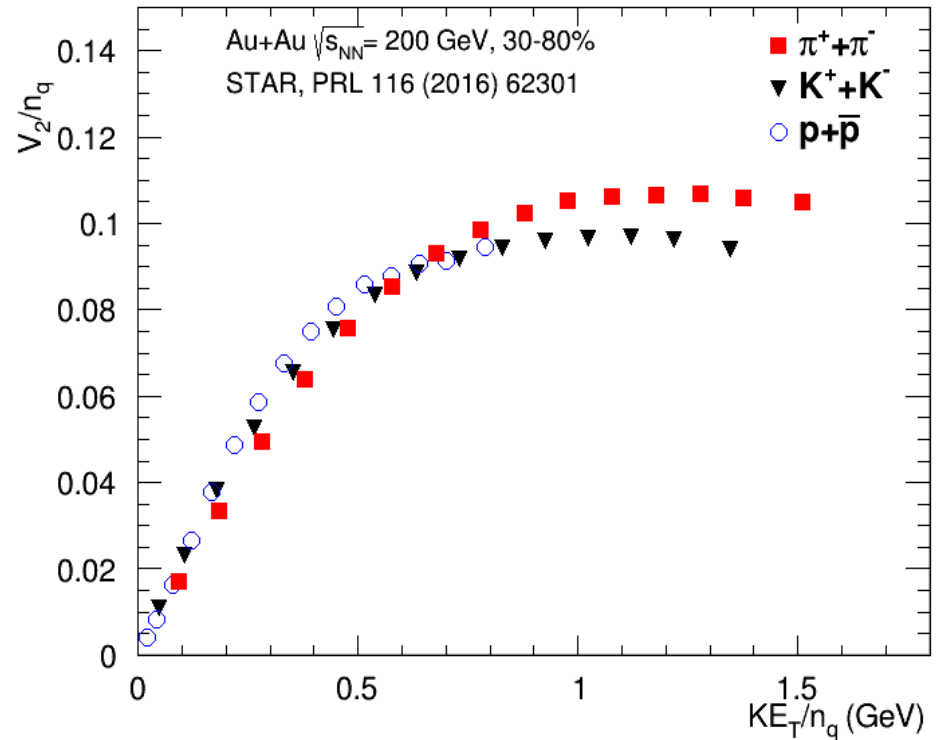
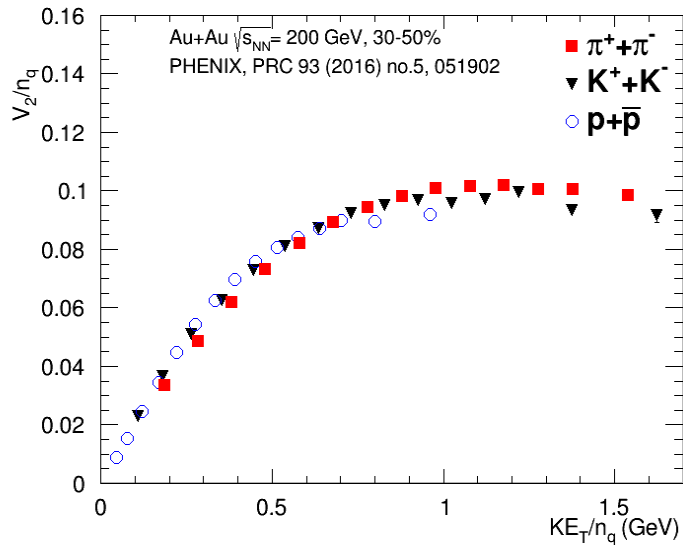
PoS 2006 (2006) 021

PRL118 (2017) 212301



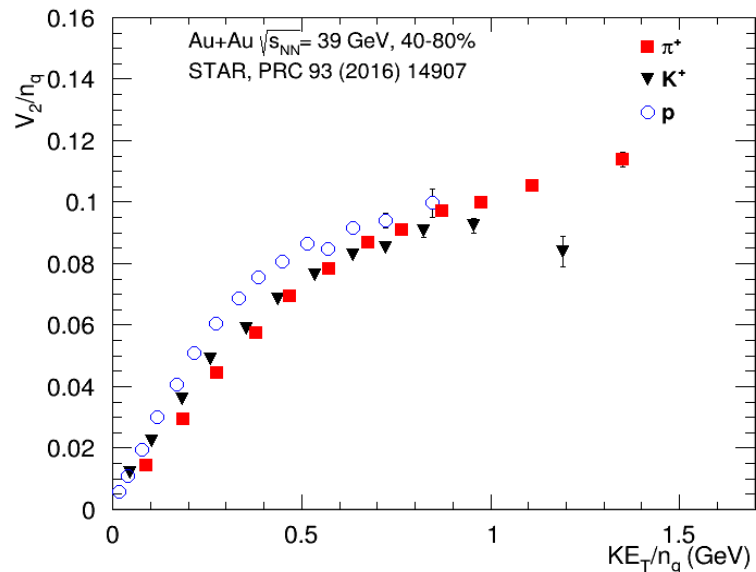
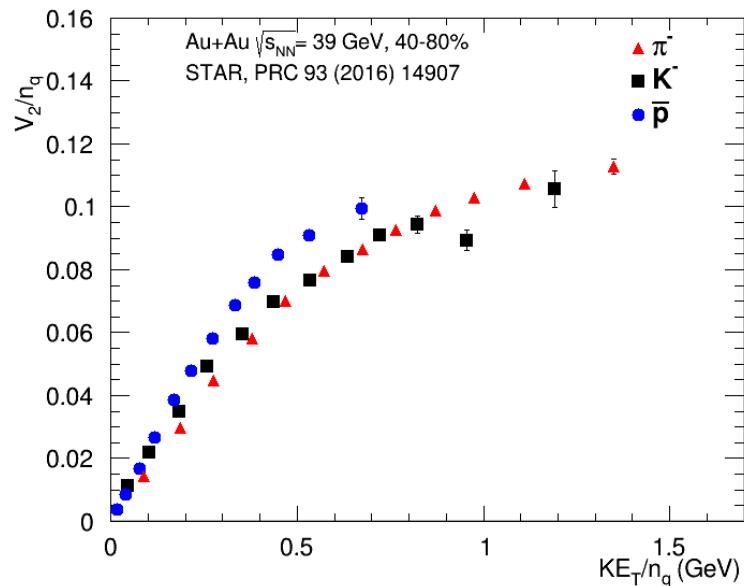
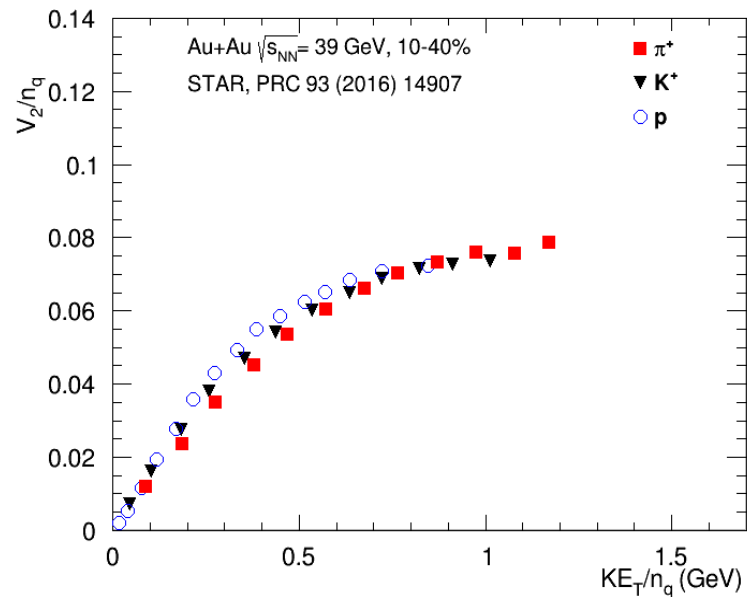
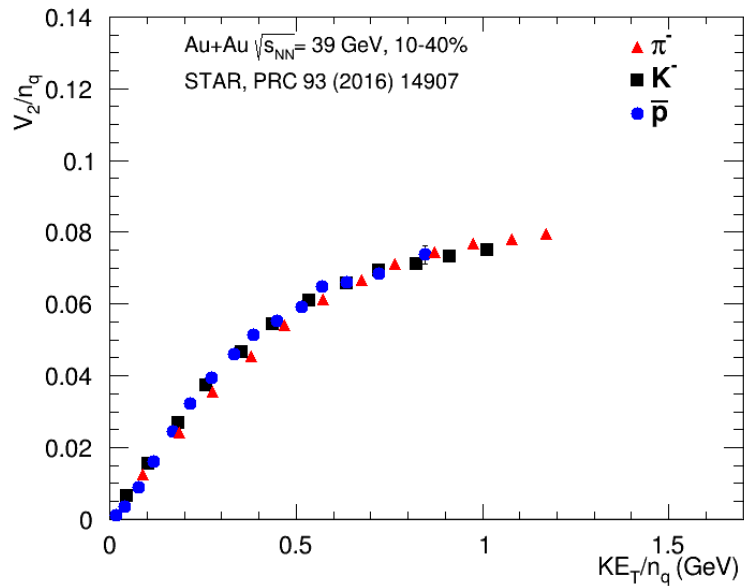
The D meson not only flows, it scales over the measured range

Quality of KE_T/n_q scaling at top RHIC energy

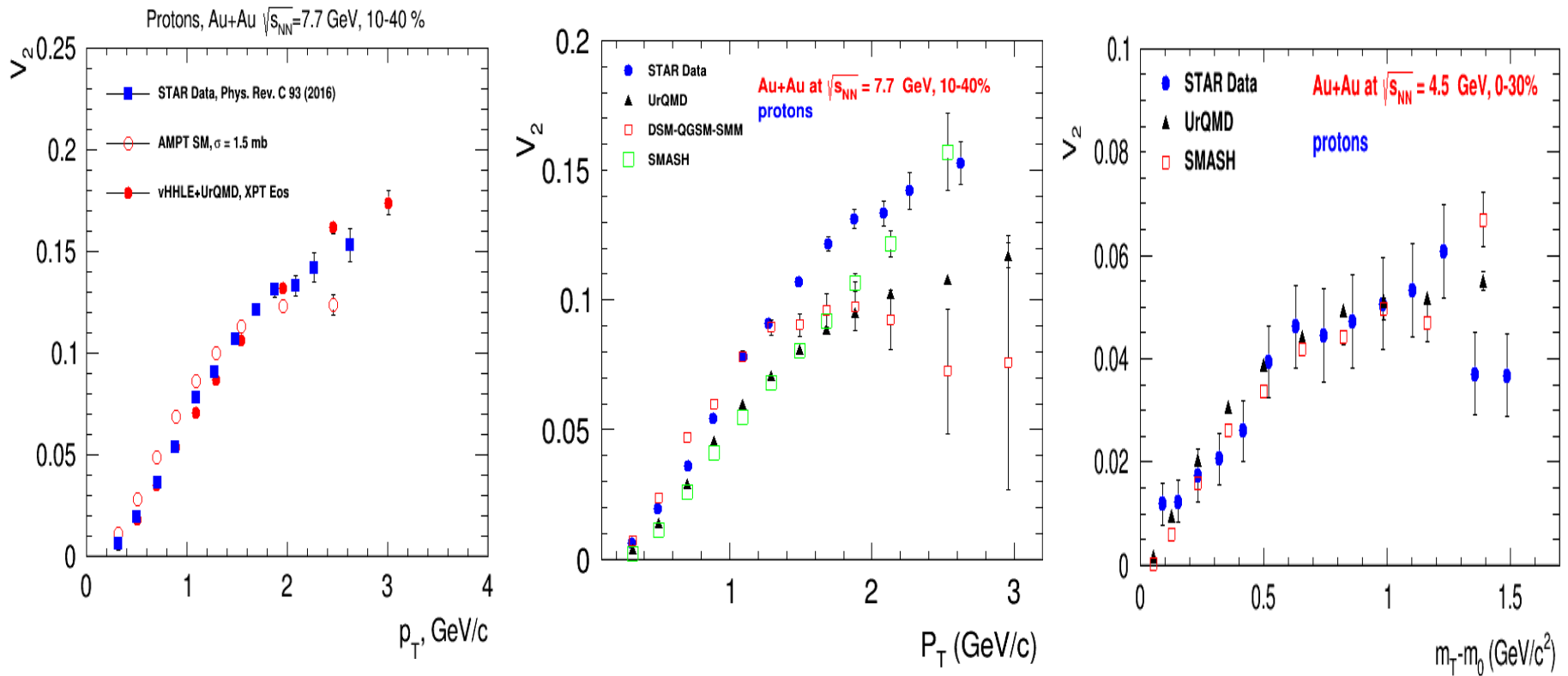


Different results in peripheral collisions: non-flow?

Quality of KE_T/n_q scaling : BES data



Elliptic flow: Models vs Data comparison

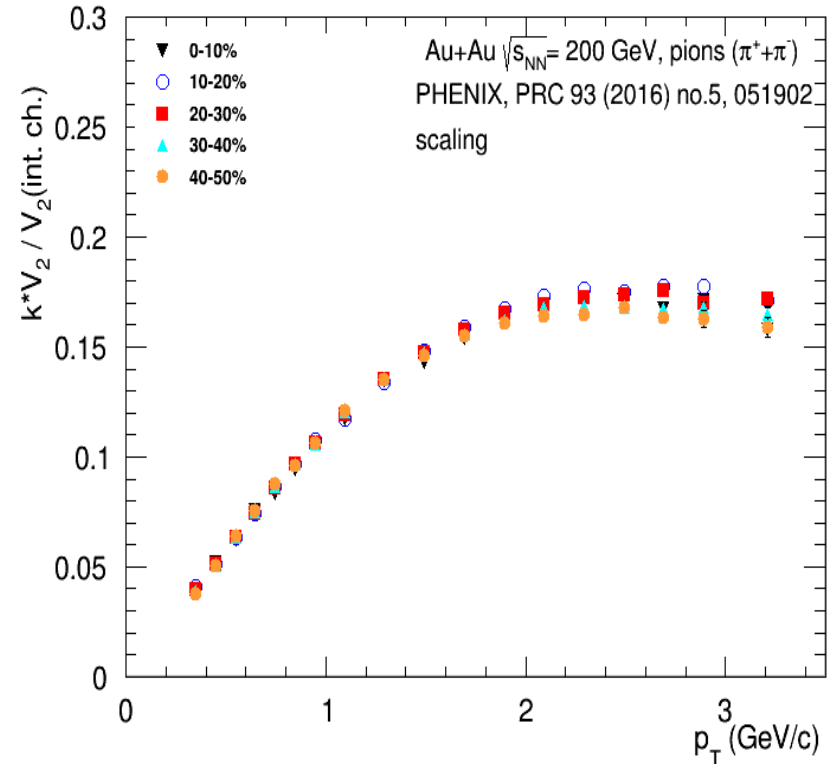
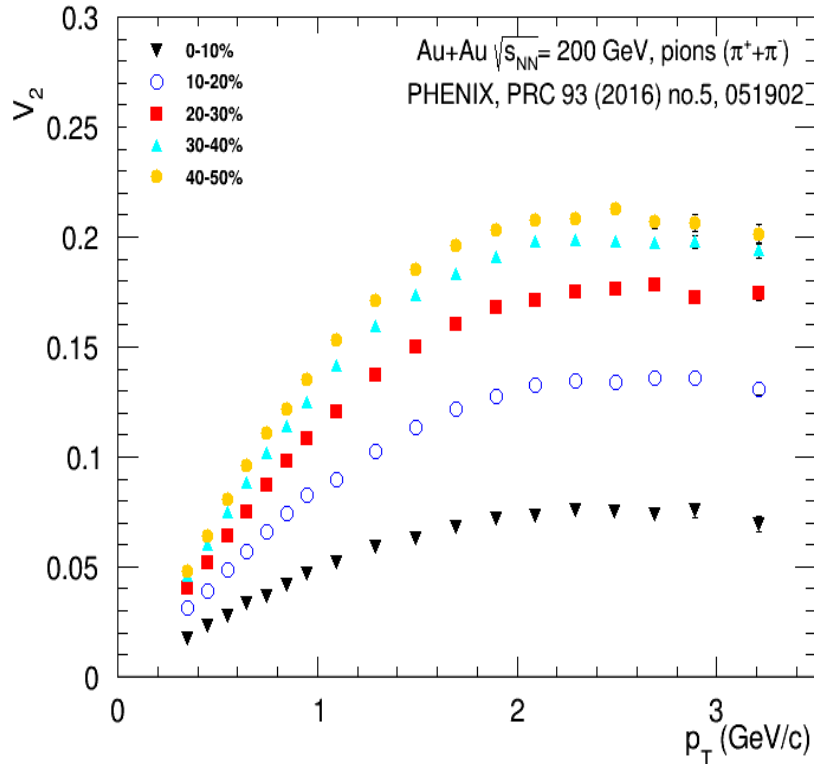


Pure String/Hadronic Cascade models give smaller v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}=7.7$ GeV and models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}=4.5$ GeV.

What should we expect for KET/nq scaling?

V_2 of identified hadrons at top RHIC energy: pions

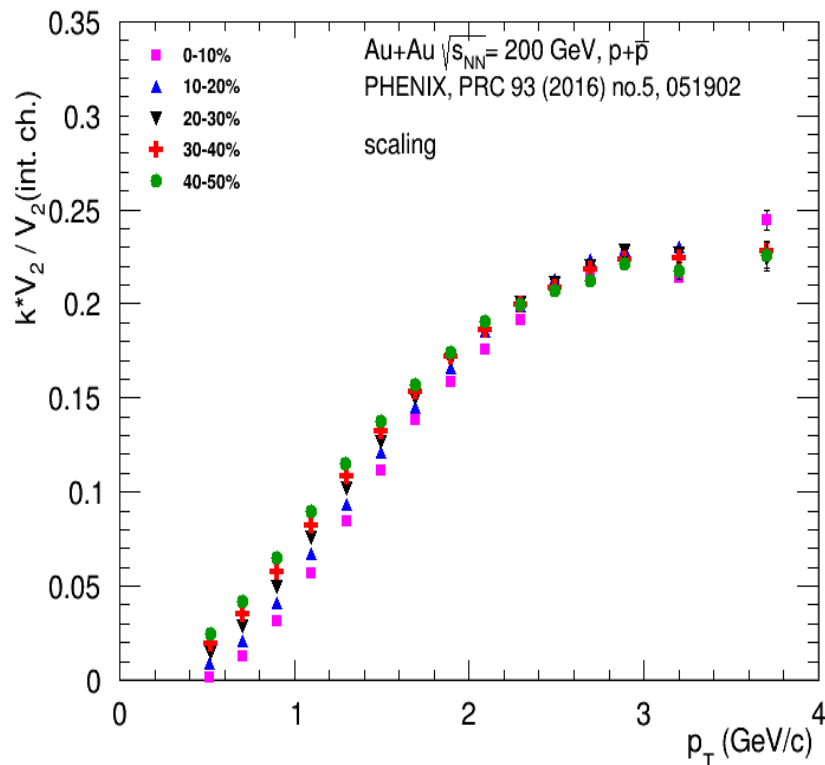
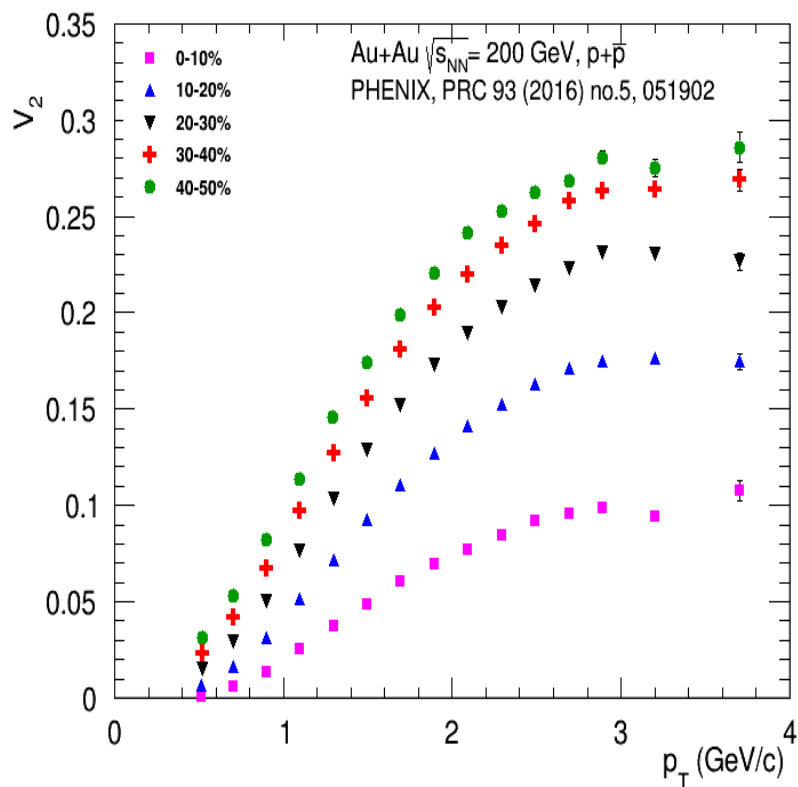
Scaling with integral flow of charged hadrons



16 $V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}}) * V_2(PID, p_T) ???$

V_2 of identified hadrons at top RHIC energy: protons

Scaling with integral flow of charged hadrons

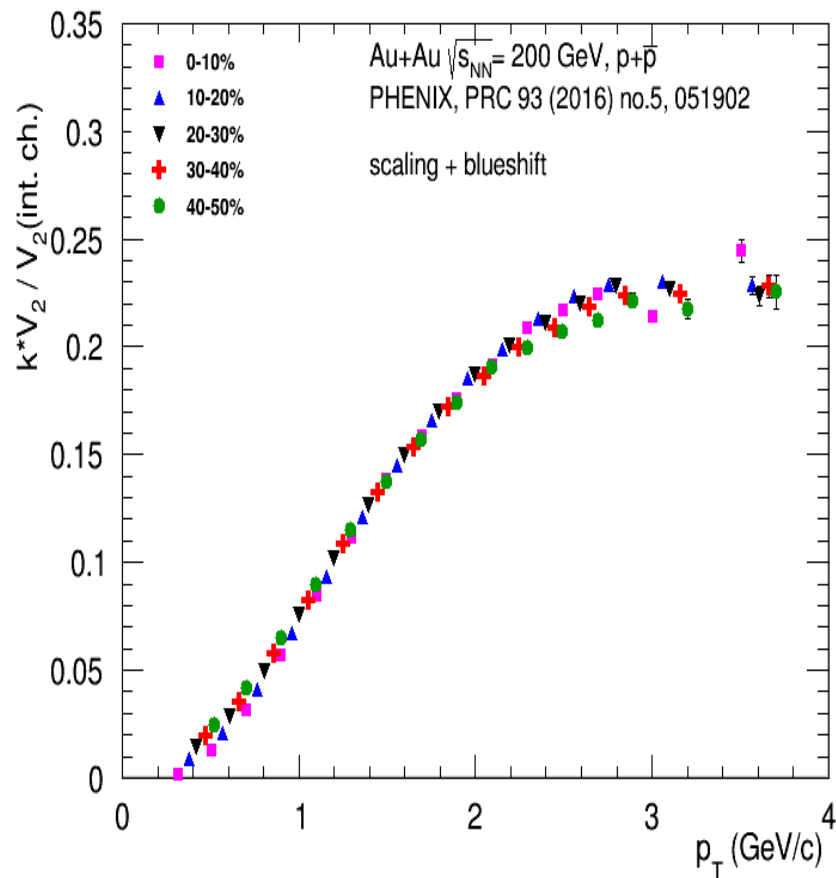
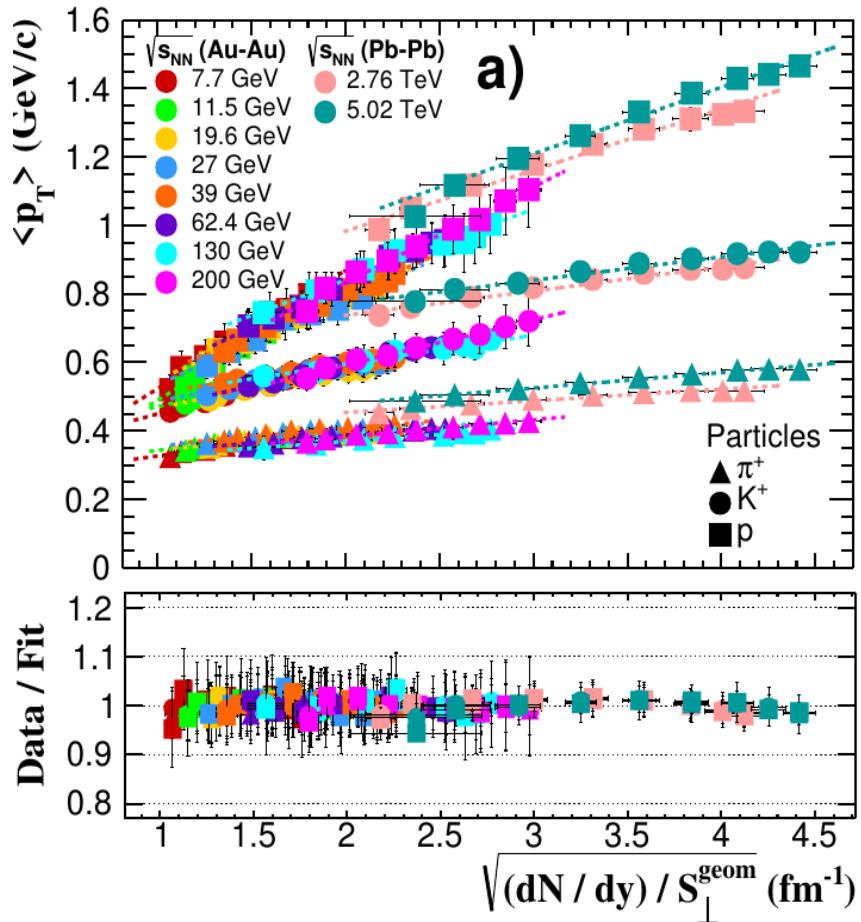


for protons the strong radial flow “blueshifts” the entire flow signal to higher p_T : $p_T \sim p_T^{th} + mc\beta$

V_2 of identified hadrons at top RHIC energy: protons

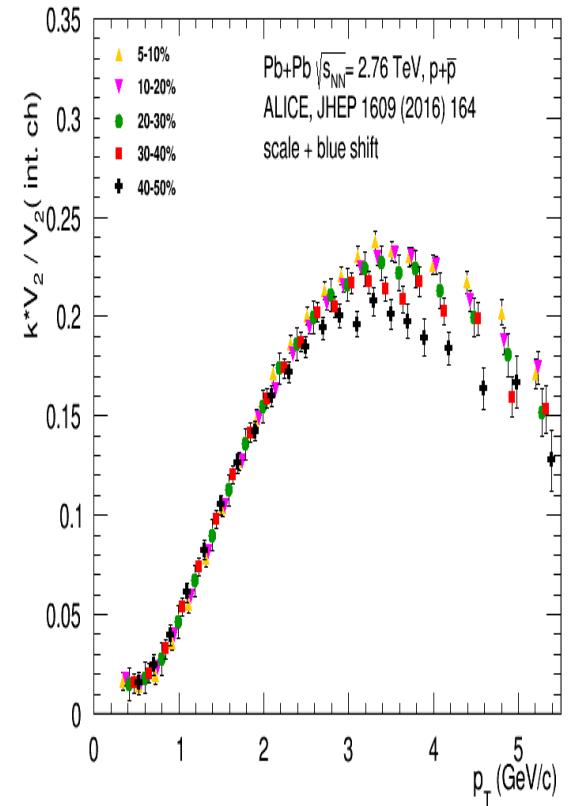
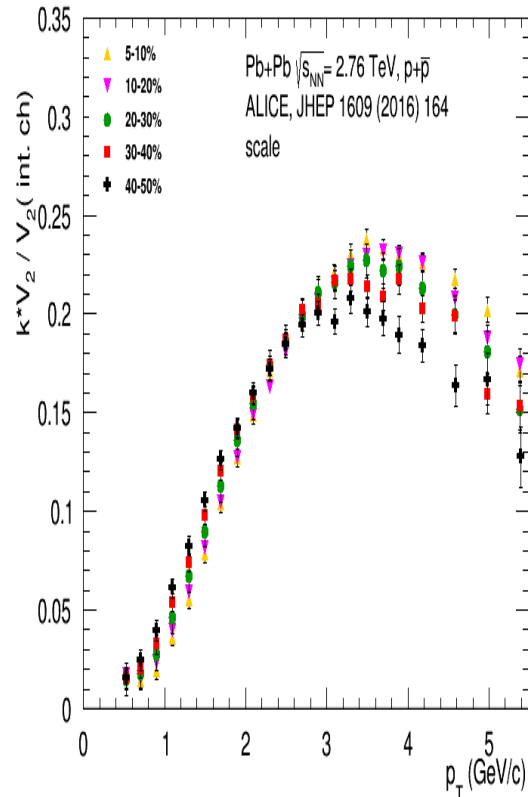
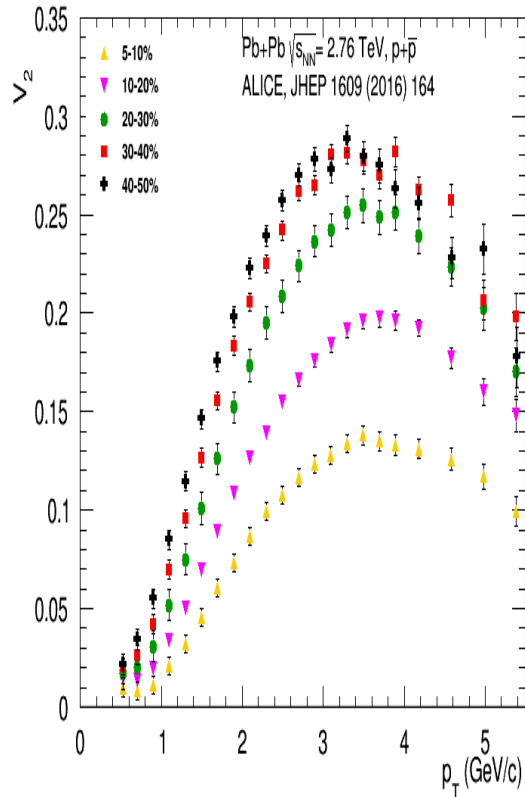
Use the geometrical scaling to estimate “blue shift” for protons

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”

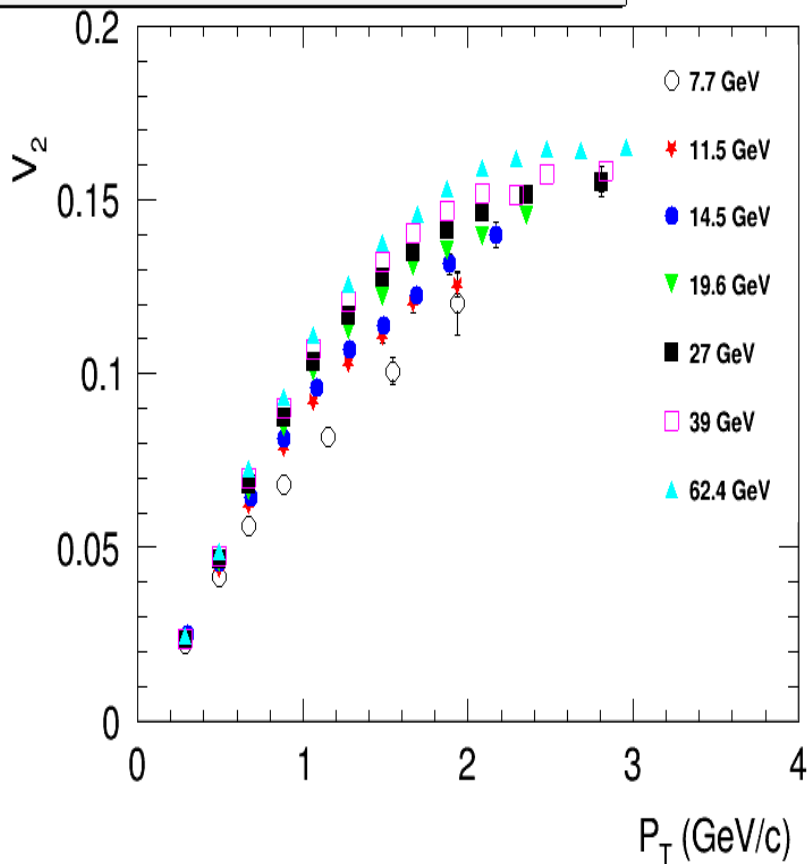


$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}}) * V_2(PID, p_T) ???$$

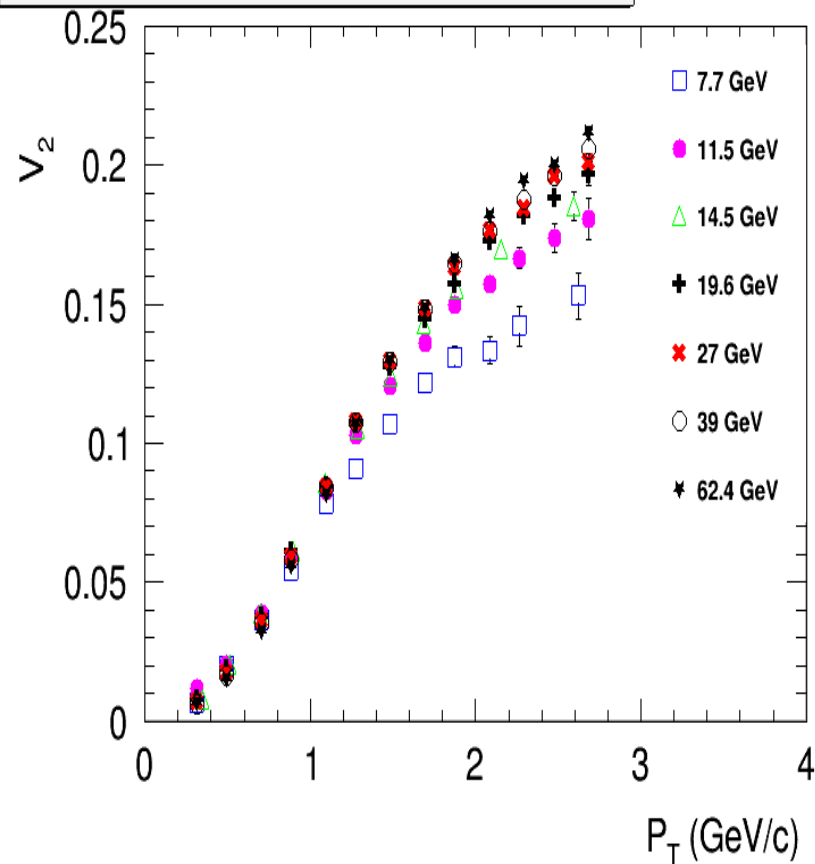
Elliptic Flow at RHIC-BES: $\sqrt{s_{NN}} = 7.7-62.4$ GeV

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

$V_2(\pi^+)$ vs p_T , Au+Au $\sqrt{s_{NN}}=7.7-62.4$ GeV, 10-40%



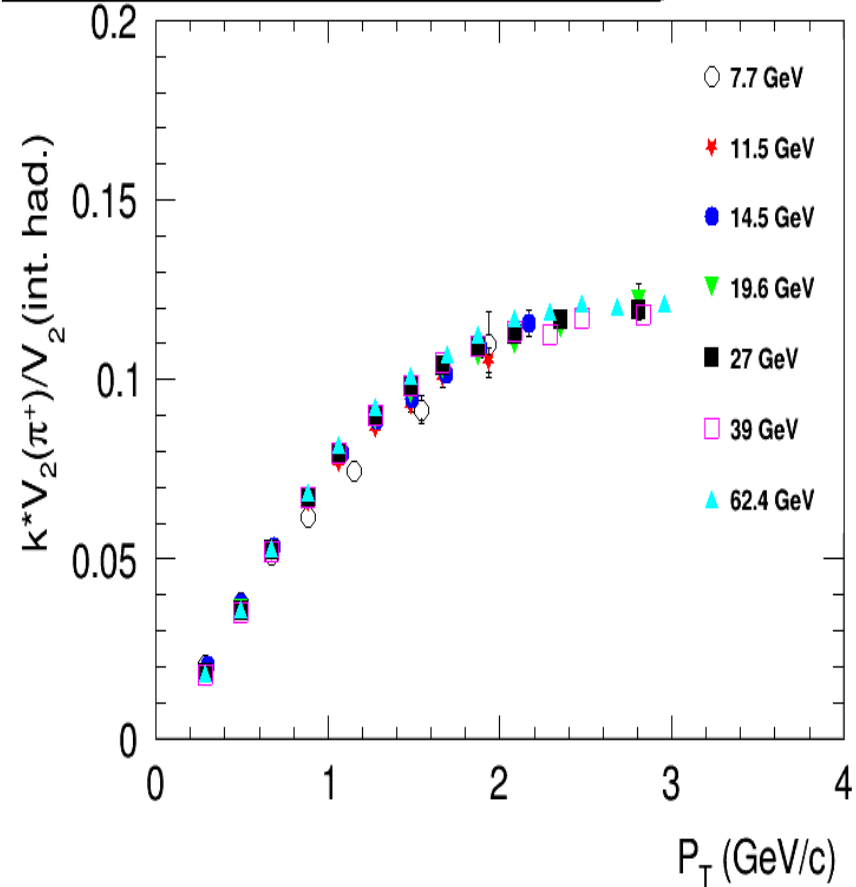
V_2 vs p_T , protons, Au+Au $\sqrt{s_{NN}}=7.7-62.4$ GeV, 10-40%



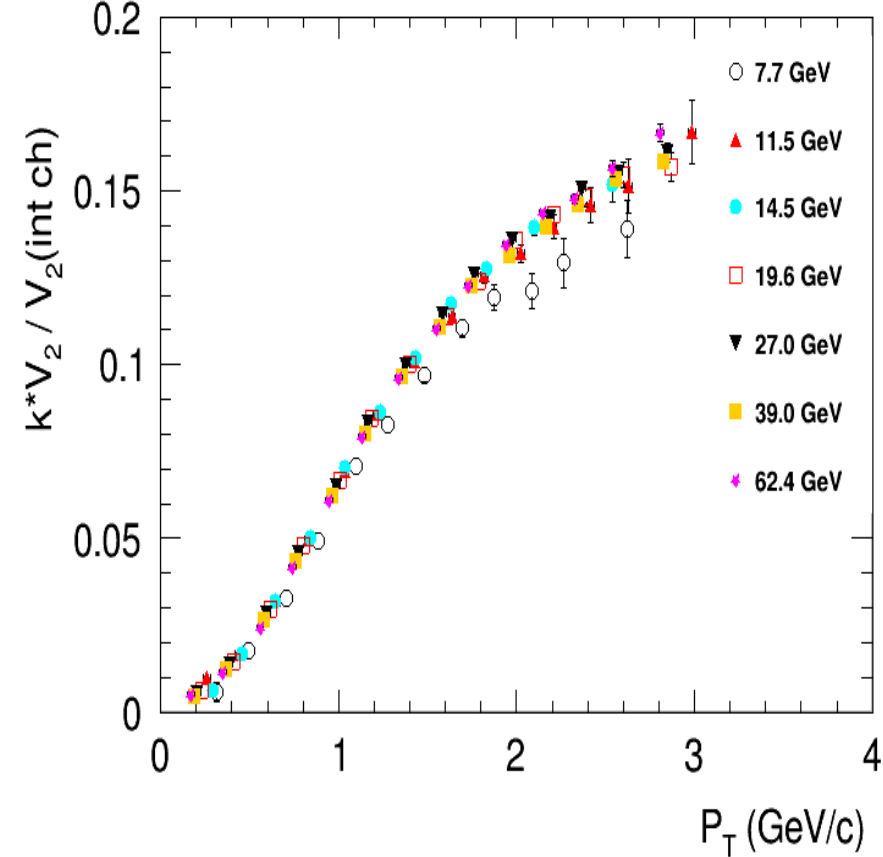
20 $V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}}) * V_2(PID, p_T) ???$

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

$V_2(\pi^+)/V_2(\text{int. had.})$ vs p_T , Au+Au $\sqrt{s_{NN}}=7.7-62.4$ GeV, 10-40%



$V_2(\text{protons})$ vs p_T , Au+Au $\sqrt{s_{NN}}=7.7-62.4$ GeV, 10-40%

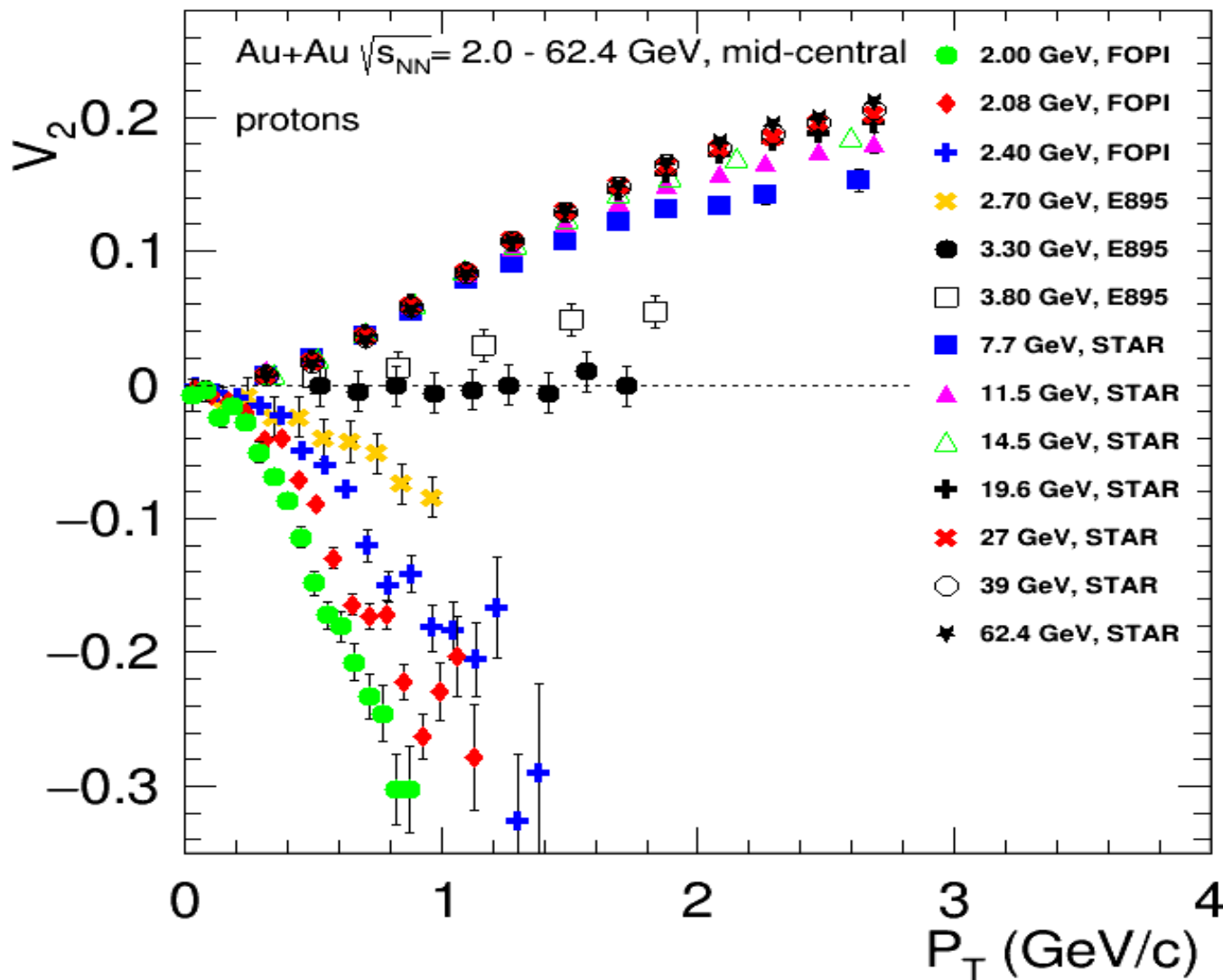


21 $V_2(\text{PID}, p_T, \text{centrality}, \sqrt{s_{NN}}) = V_2(\text{h, centrality}, \sqrt{s_{NN}}) * V_2(\text{PID}, p_T)???$

Excitation function of differential elliptic flow

EPJ Web Conf. 204 (2019) 03009

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

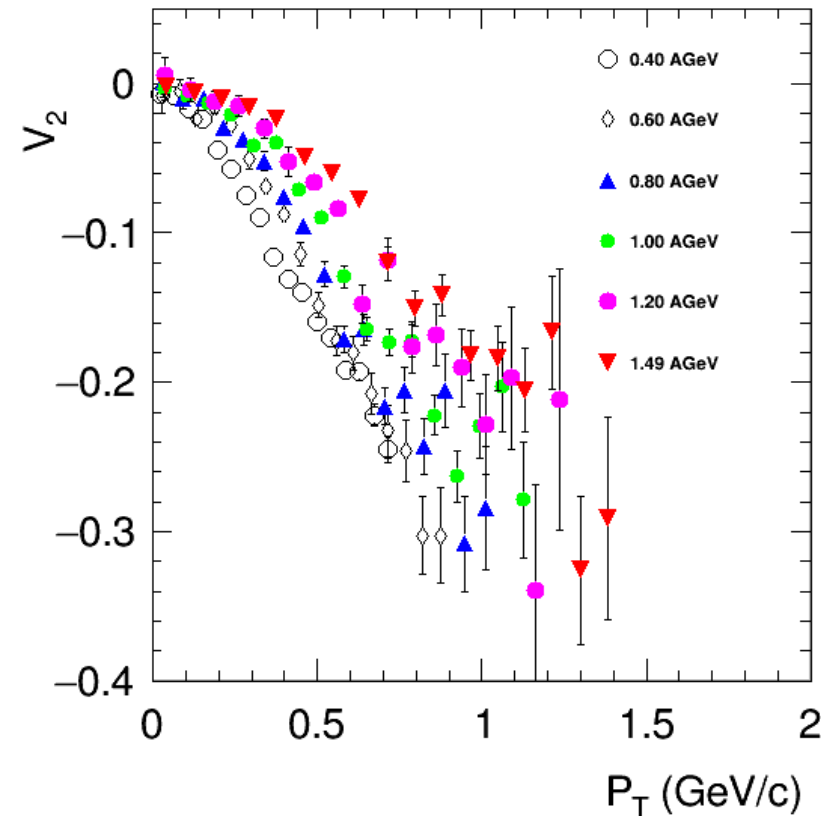


High precision differential measurements of anisotropic flow?

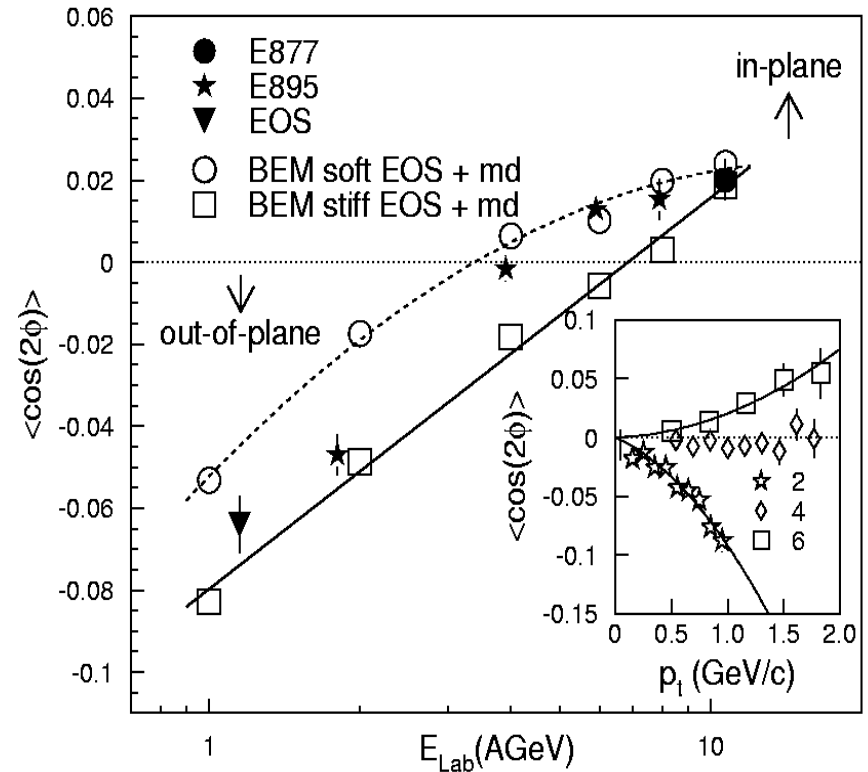
Elliptic Flow at SIS-AGS: interactions with spectators

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

V_2 vs p_T , Au+Au, MULT3 mid-central, FOPI



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



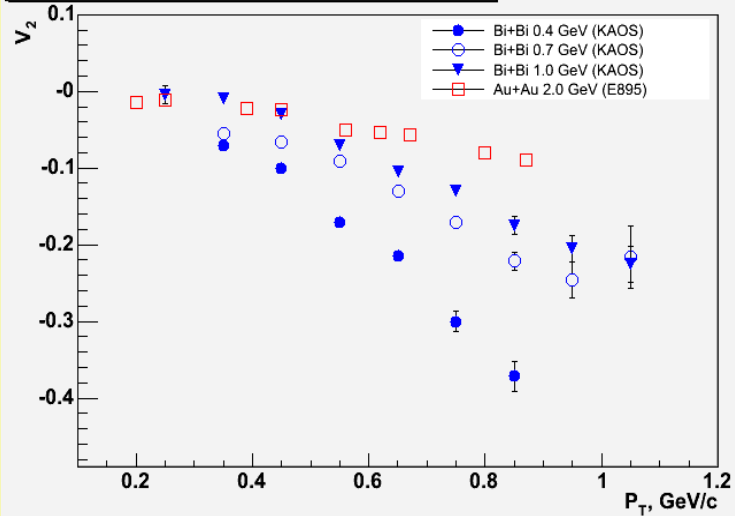
Passage time: $2R/(\beta_{cm}\gamma_{cm})$
 Expansion time: R/c_s
 $c_s = c\sqrt{dp/d\varepsilon}$ - speed of sound

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

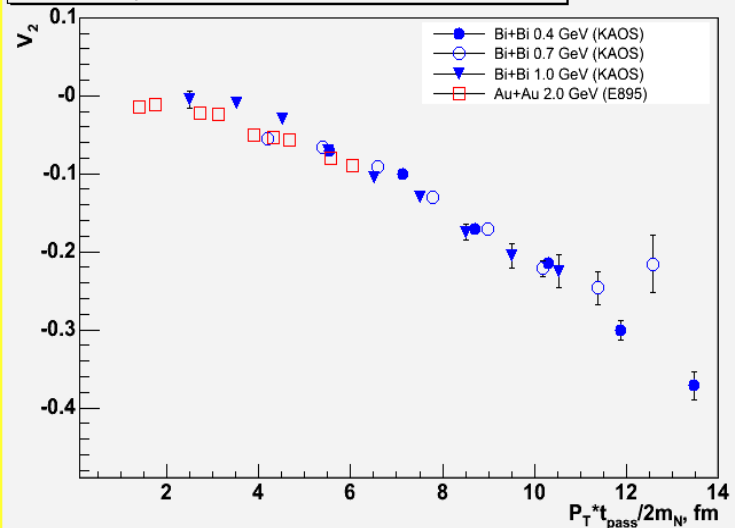
v_2 Flow at SIS-AGS: scaling relations

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

V_2 vs P_T for protons (semi-central coll)

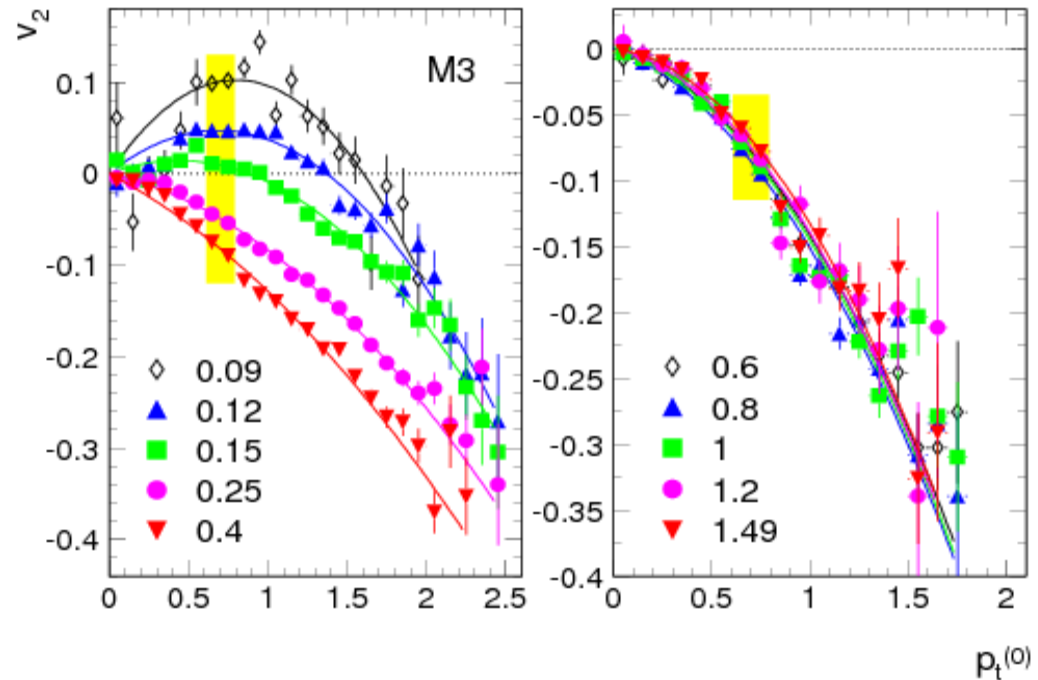


V_2 vs $P_T * t_{pass} / 2m_N$ for protons (semi-central coll)



**FOPI: v_2 of protons from
 $Elab=0.09$ to 1.49 GeV**

Phys.Lett. B612 (2005) 173-180

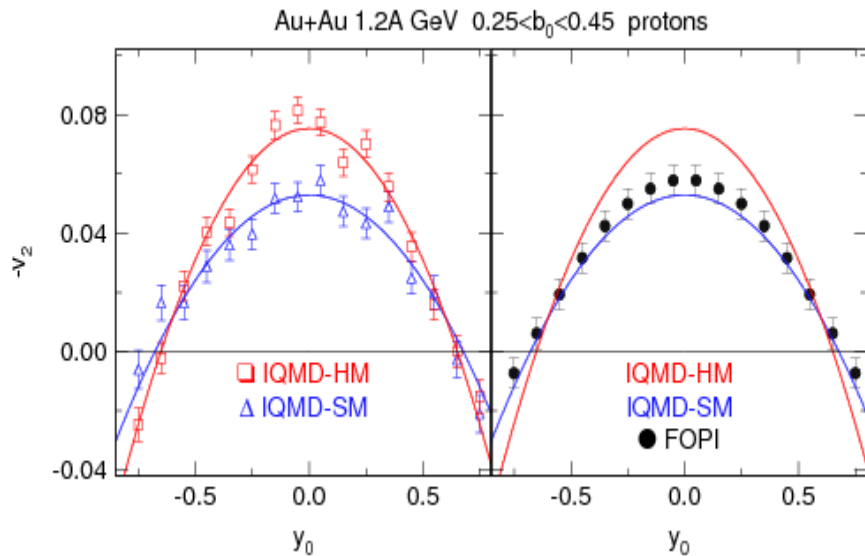


The rather good scaling observed suggest that c_s does not change significantly over beam energy range $0.4 - 2.0$ AGeV.

Flow at SIS: rapidity dependence of v_2 and EOS

HM – stiff momentum dependent
with $K=376$ MeV

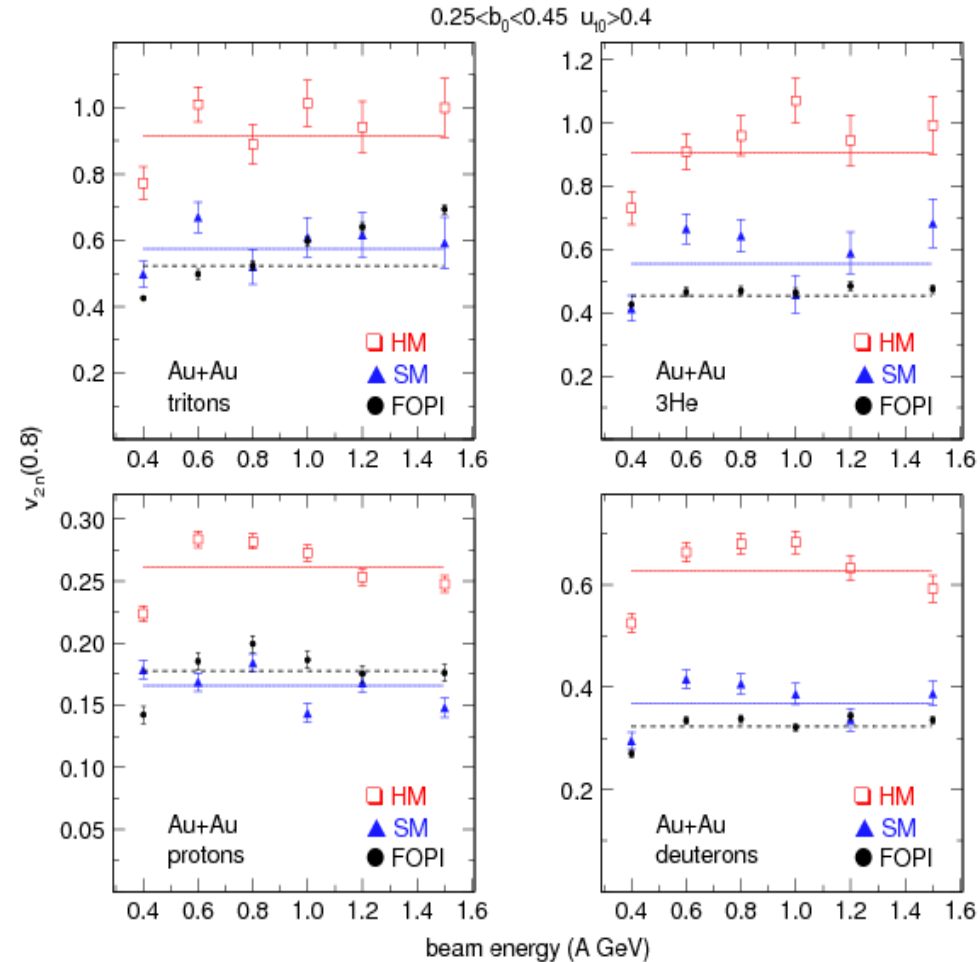
SM – soft momentum dependent
with $K=200$ MeV



$$V_{2n} = |V_{20}| + |V_{22}|$$

$$\text{Fit: } V_2(y_0) = V_{20} + V_{22} \cdot Y_0^2$$

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



Conclusions and Perspectives

- **Anisotropic flow measurements provides access to the transport properties of the medium: EOS, sound speed (c_s), viscosity, etc. Scaling relations help to understand the physics of the process.**
- **BM@N/NICA/FAIR energies are very interesting: transition between hadronic and partonic matter.**

Flow performance study for FHCAL TDR (2018)

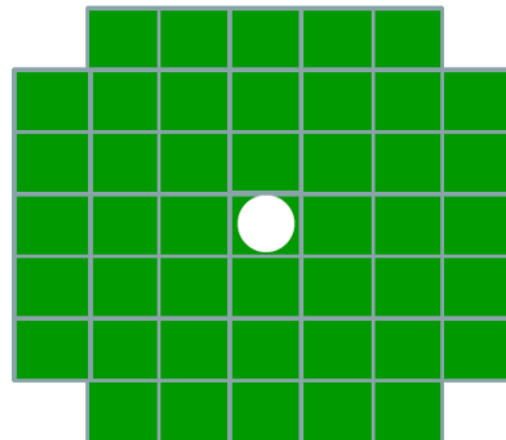
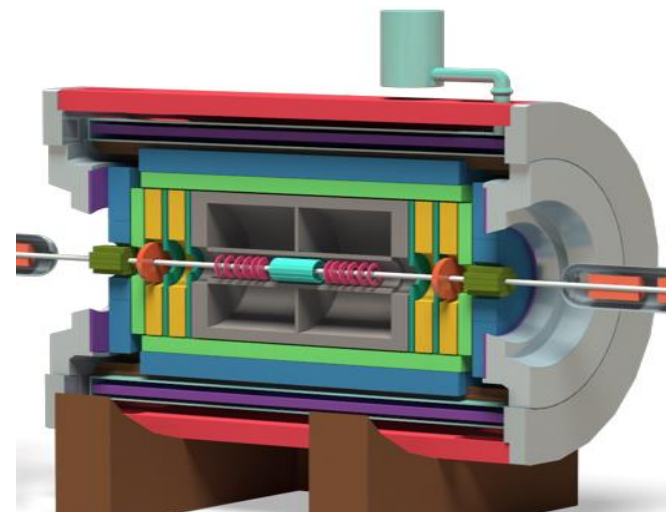
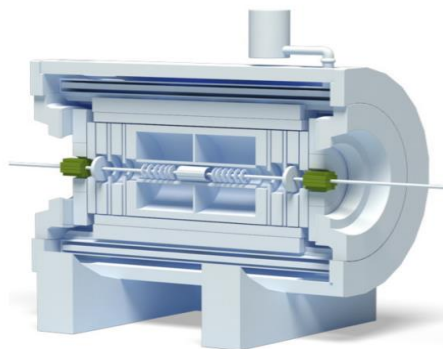


Technical Design Report for the MPD Experiment

Nuclotron Based Ion Collider Facility

Forward Hadron Calorimeter
(FHCAL)

December 2016

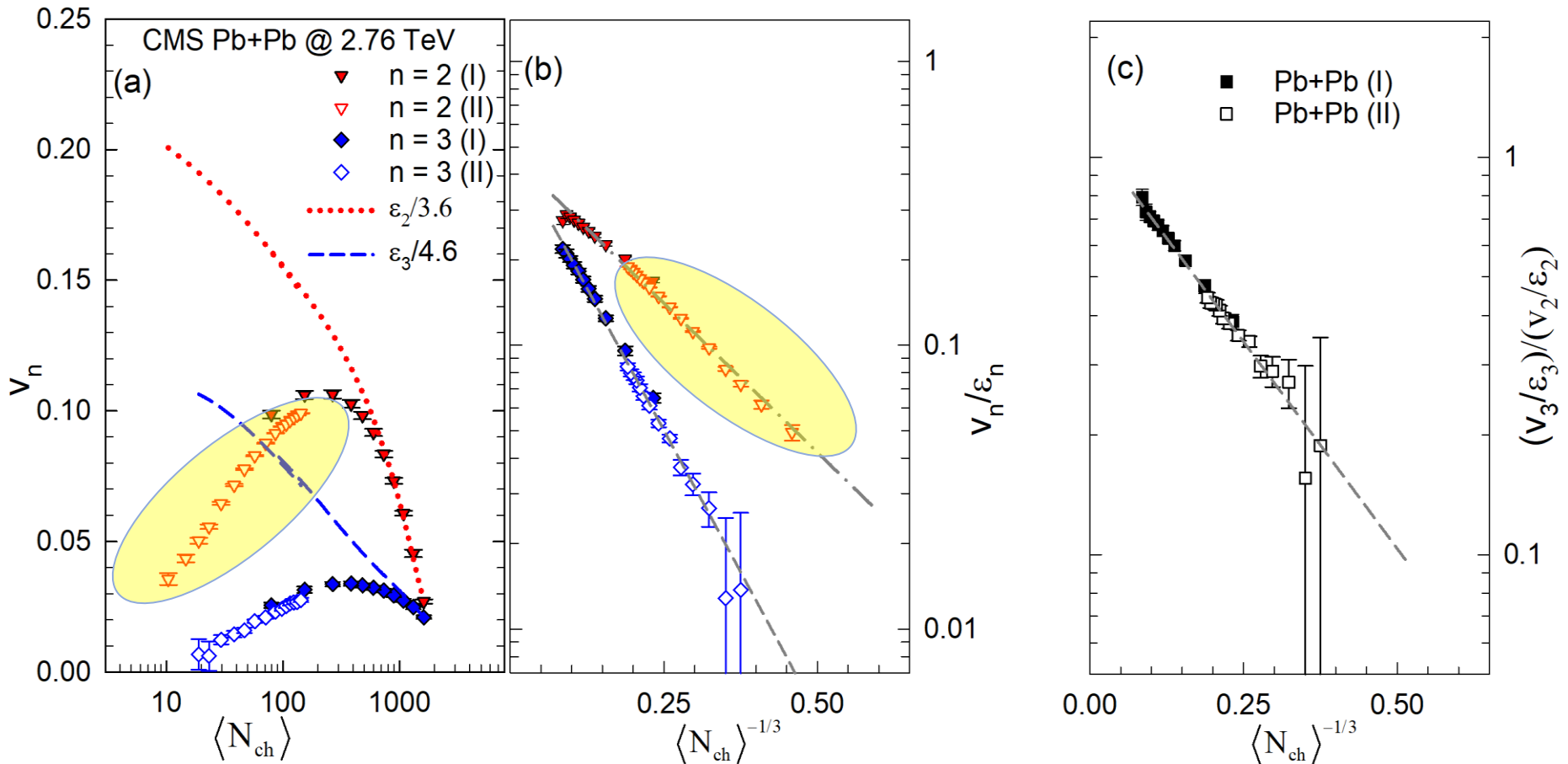


FHCAL coverage:
 $2.2 < |\eta| < 4.8$

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

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

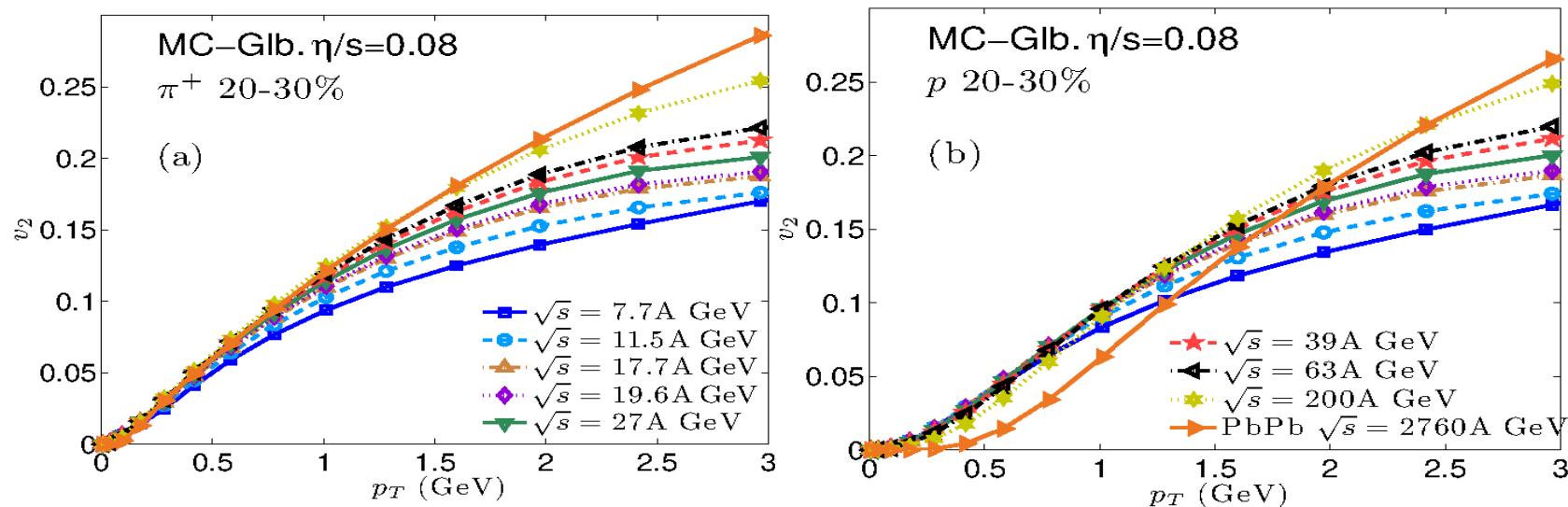
R.A. Lacey et al Phys. Rev. C **98**, 031901(R), 2018



- ✓ 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 from RHIC to LHC (viscous hydrodynamics)

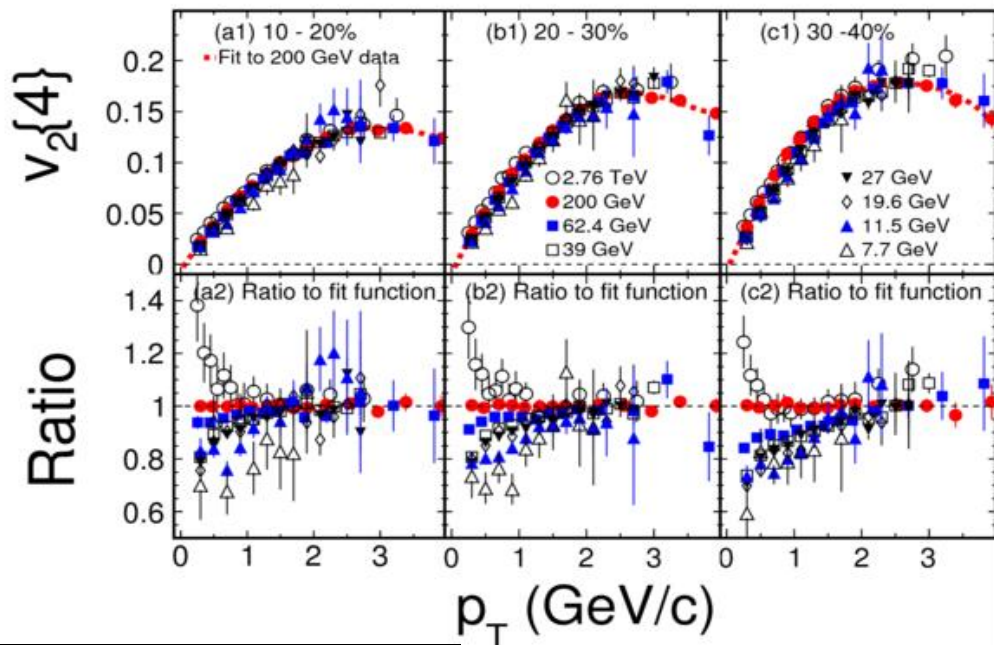
Chun Shen and Ulrich Heinz, Phys. Rev. C 85, 054902(2012), VISH2+1 model calculations



- ✓ 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 .

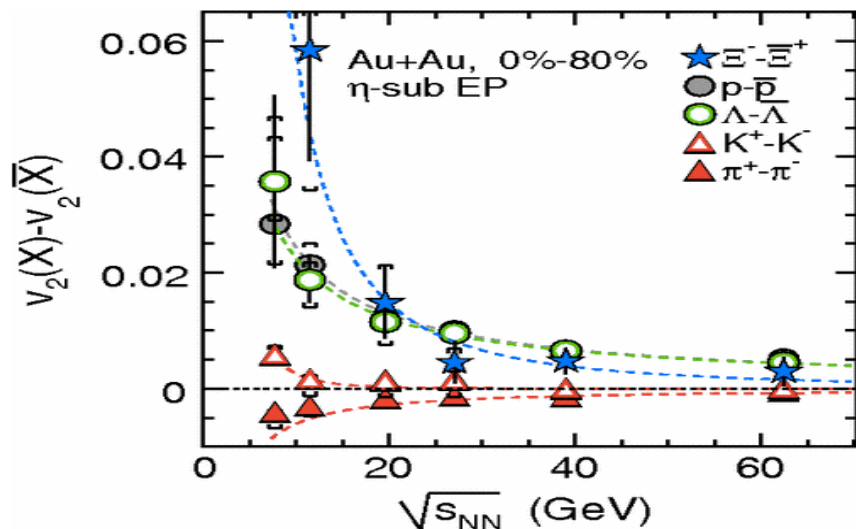
Beam Energy Dependence of Elliptic Flow (v_2)

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 v_2 of charged hadrons for a turn off of the QGP
How sensitive is v_2 to QGP?

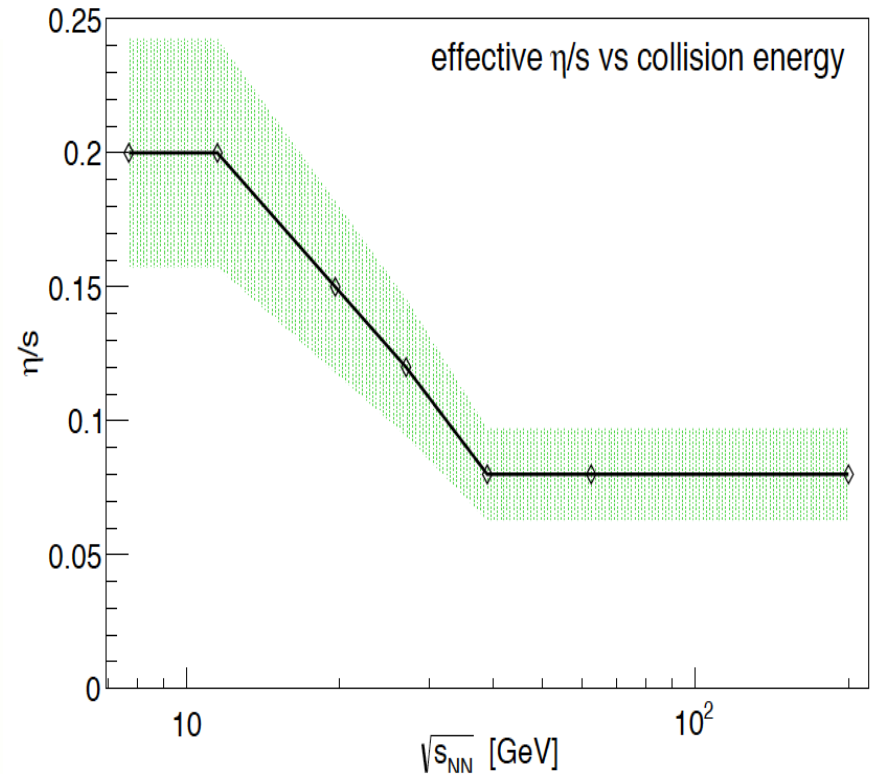
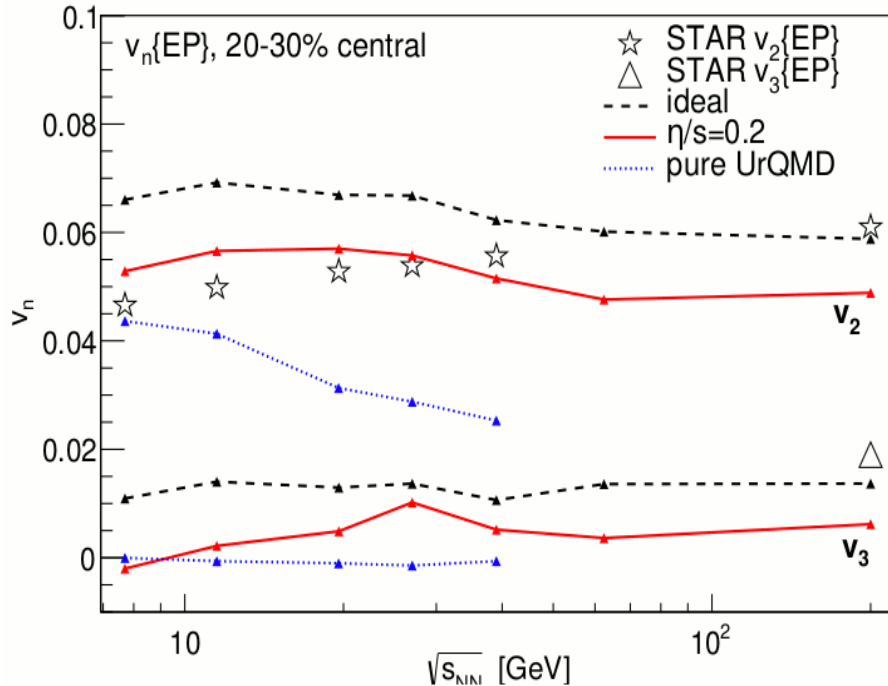
Phys. Rev. Lett. 110, 142301 (2013)



Substantial particle-antiparticle split at lower energies

Elliptic 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