Study of the beam energy dependence of anisotropic flow in relativistic heavy ion collisions using scaling relations.

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LXXI International conference "NUCLEUS – 2021. Nuclear physics and elementary particle physics. Nuclear physics technologies", September 20-25, 2021, Saint Petersburg State University, Russia

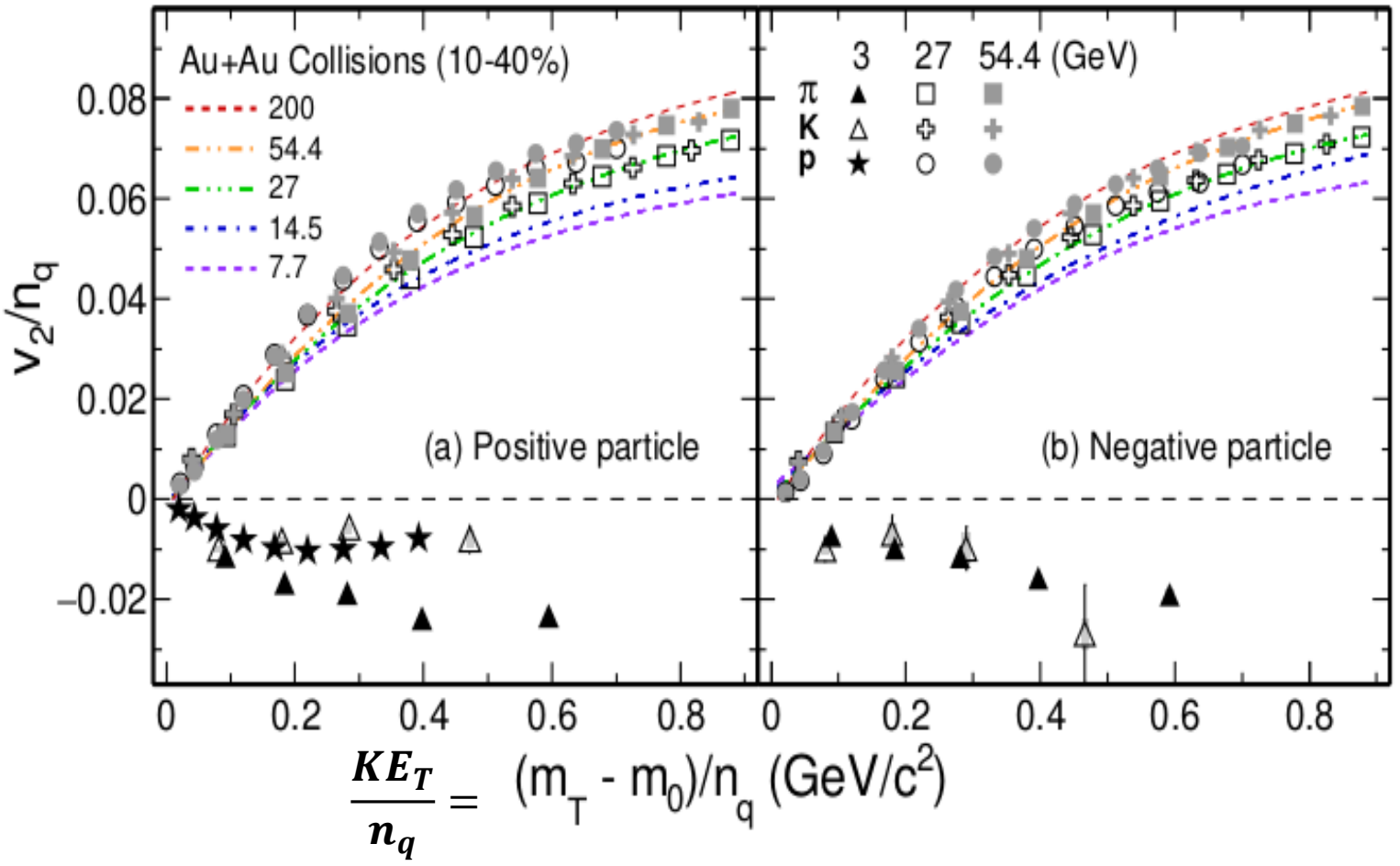
This work is supported by: the RFBR according to the research project No. 18-02-40086 and by Ministry of Science and Higher Education of the Russian Federation, No 0723-2020-0041.

OUTLINE

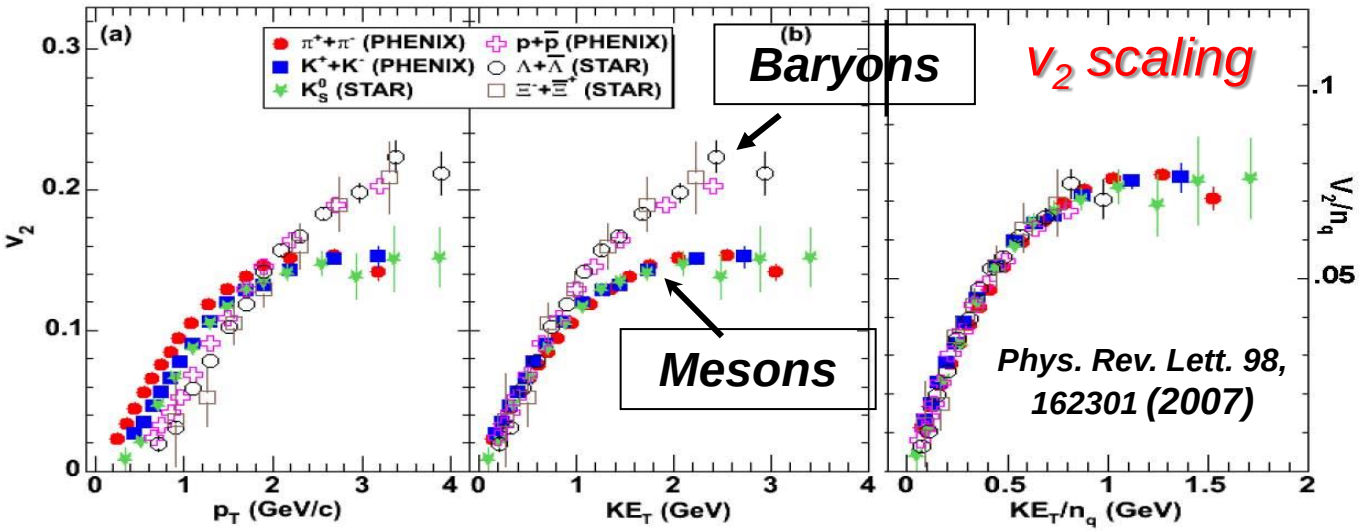
1. Scaling relations for flow (V_n) and partonic colectivity at RHIC?
2. Scaling tests for (V_n) from Beam Energy Scan Data: RHIC, AGS, SIS

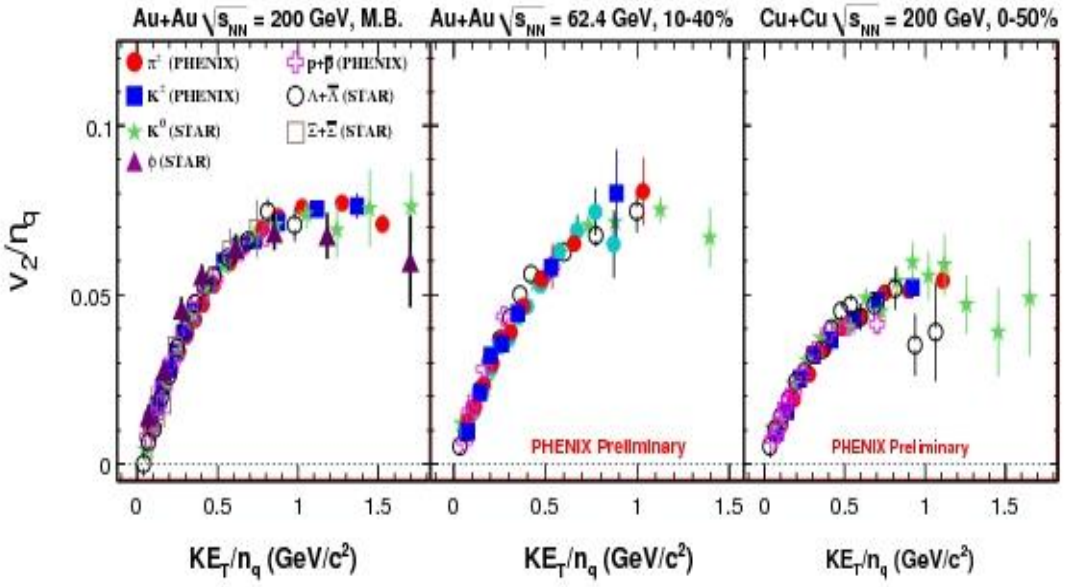
Disappearance of partonic collectivity in $\sqrt{s_{NN}}$= 3 GeV Au+Au collisions at RHIC

STAR: https://arxiv.org/abs/2108.00908



KE_T / n_q scaling and partonic collectivity at RHIC

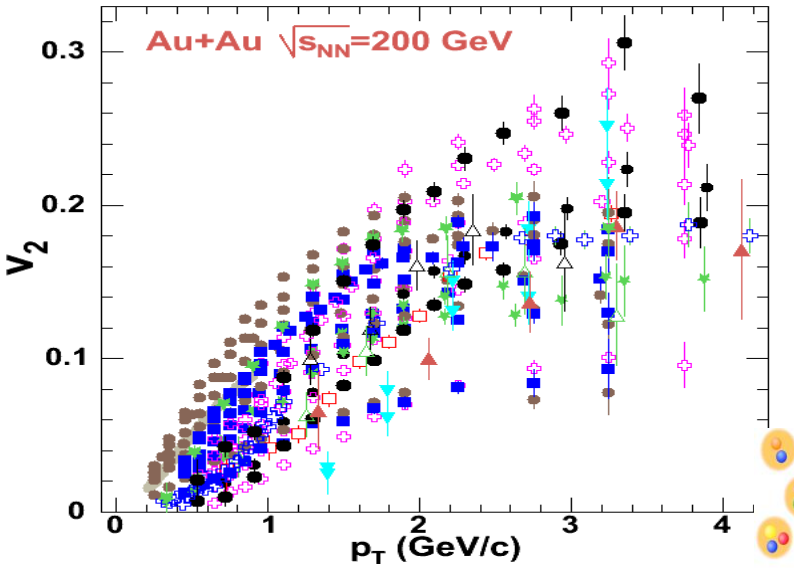


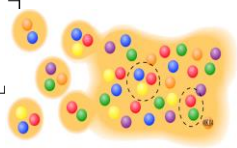


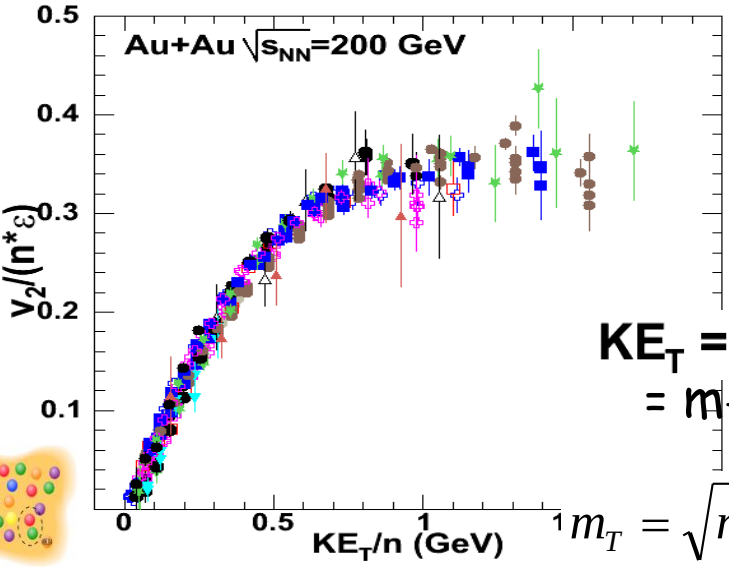
Significant part of flow at RHIC developed at partonic level.

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

Anisotropic Flow at RHIC – scaling relations: 2005





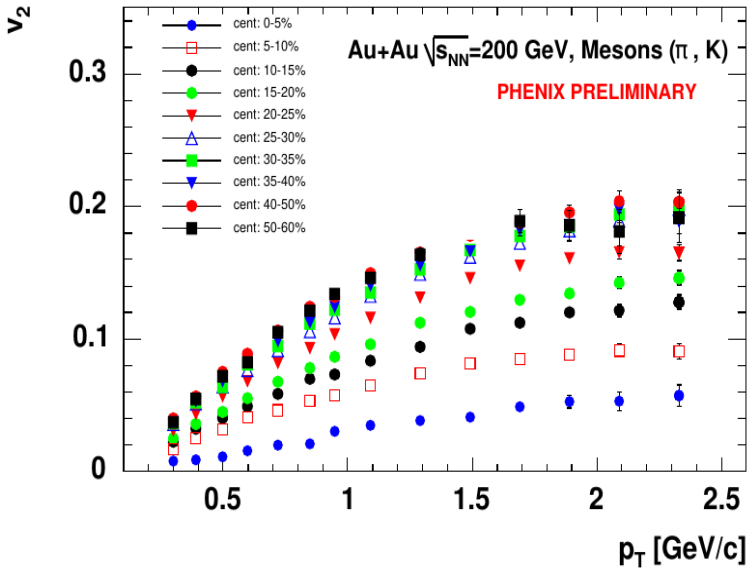


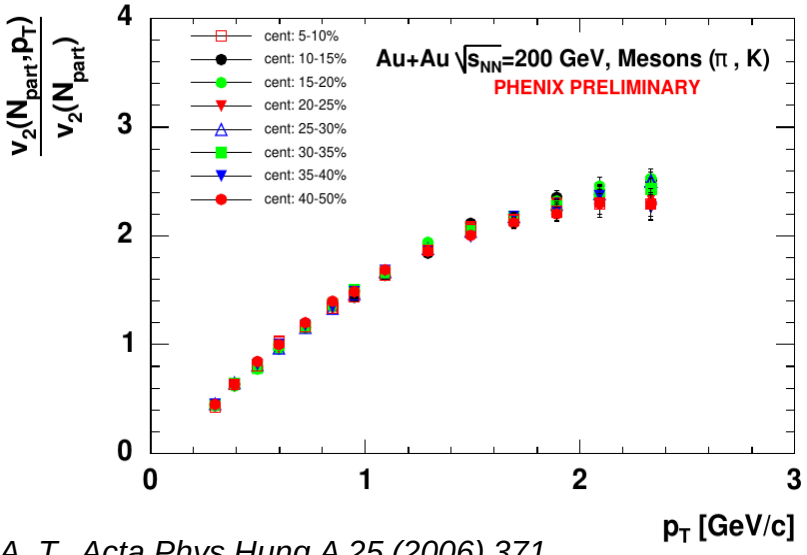
$KE_T = m(\gamma_T - 1) = m_T - m$

$m_T = \sqrt{m^2 + p_T^2}$

n=2 for mesons and n=3 for baryons

R.L, A.T, PoS 2006 (2006) 021



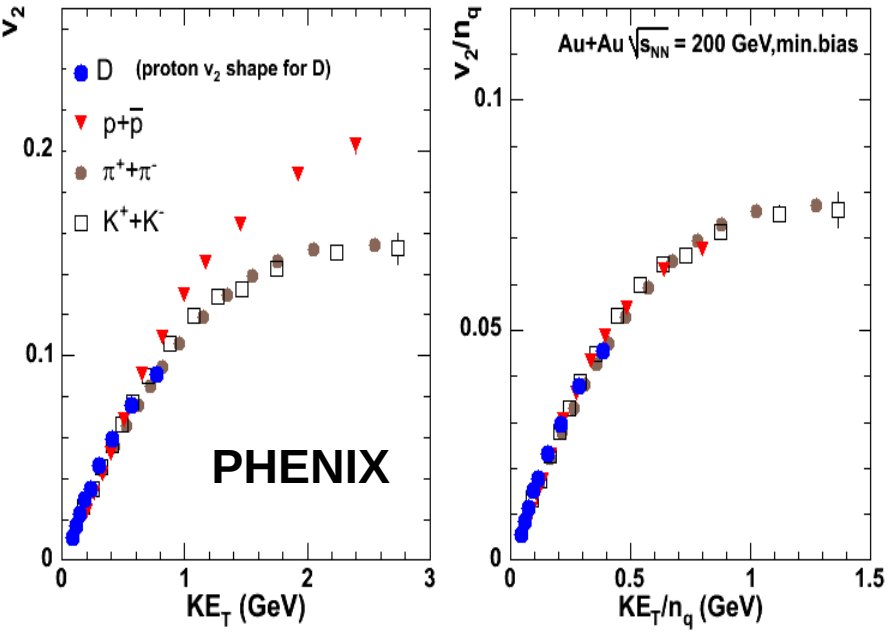


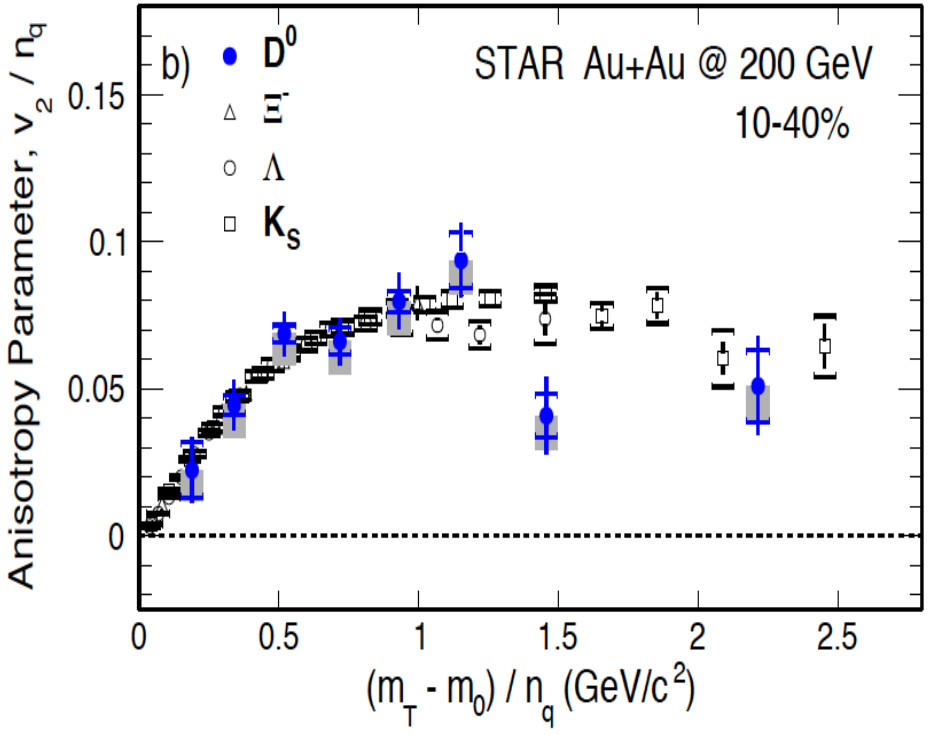
A. T., Acta Phys.Hung.A 25 (2006) 371

Elliptic flow of D meson in 2006-2017

PoS 2006 (2006) 021

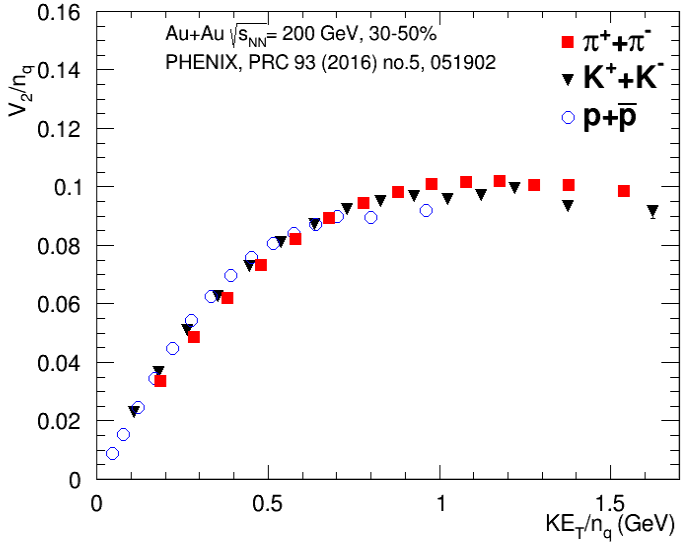
STAR, PRL118 (2017) 212301

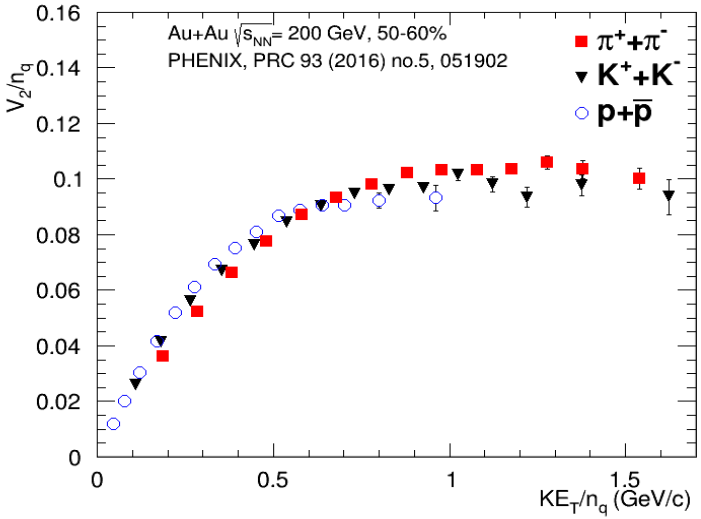


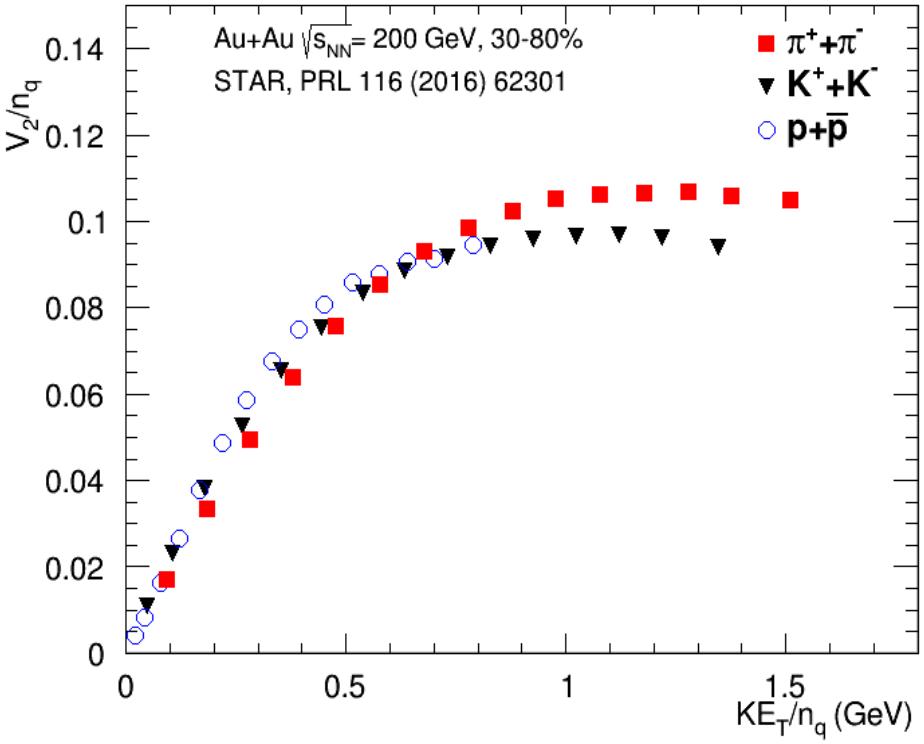


The D meson not only flows, it scales over the measured range

Quality of KE_T / n_q scaling at top RHIC energy



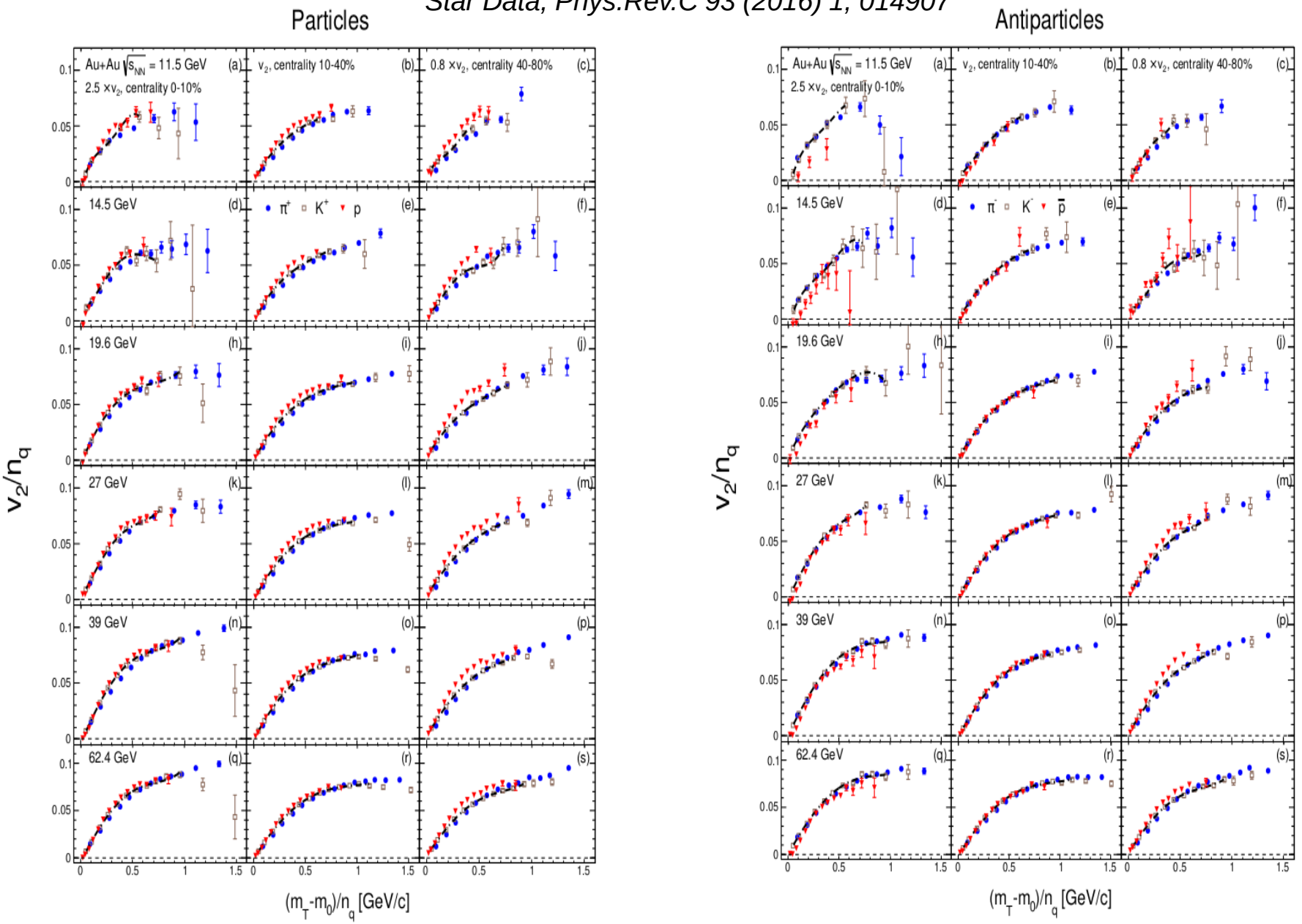




Different results in peripheral collisions: non-flow?

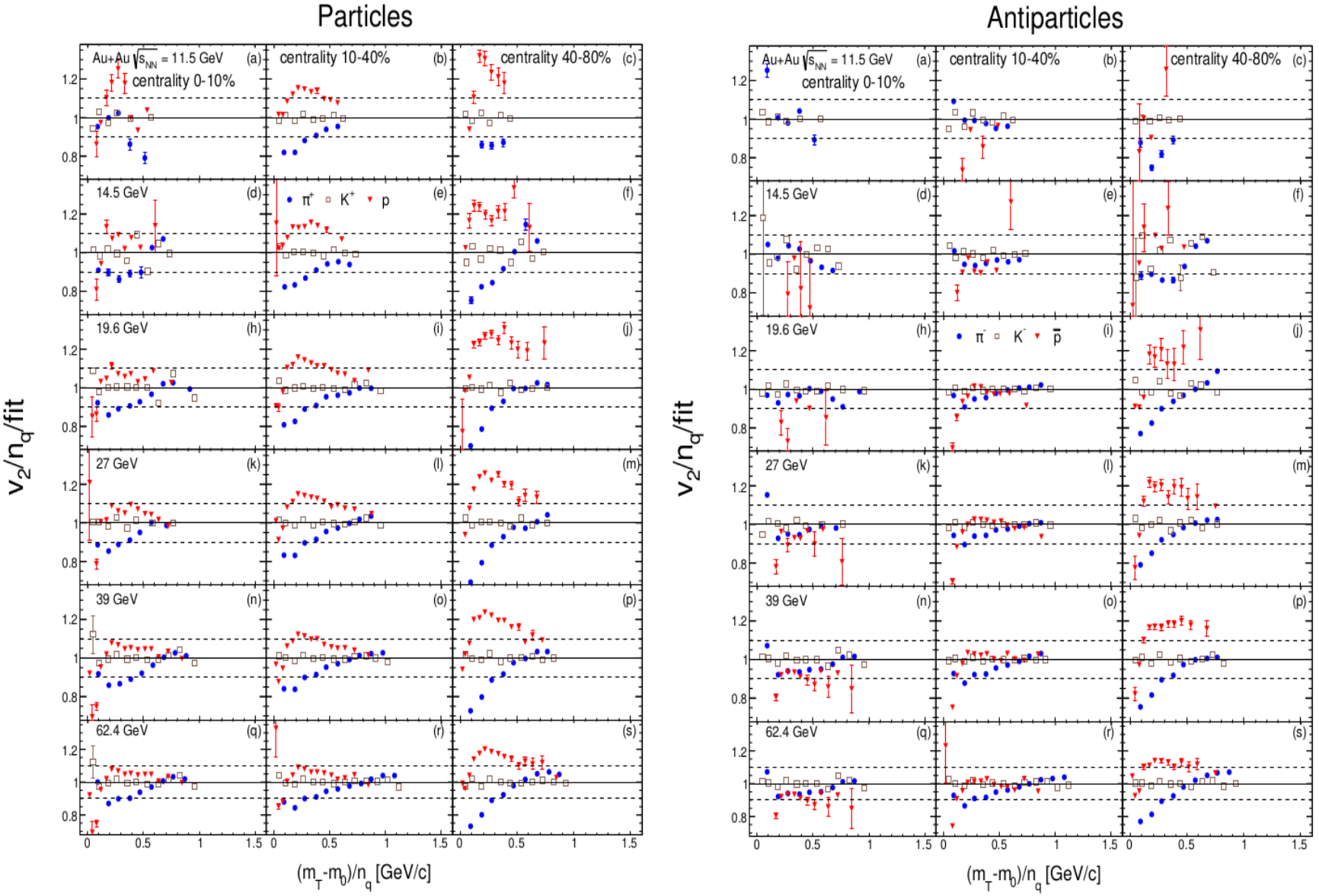
Quality of KE_T / n_q scaling : BES data

Star Data, Phys.Rev.C 93 (2016) 1, 014907

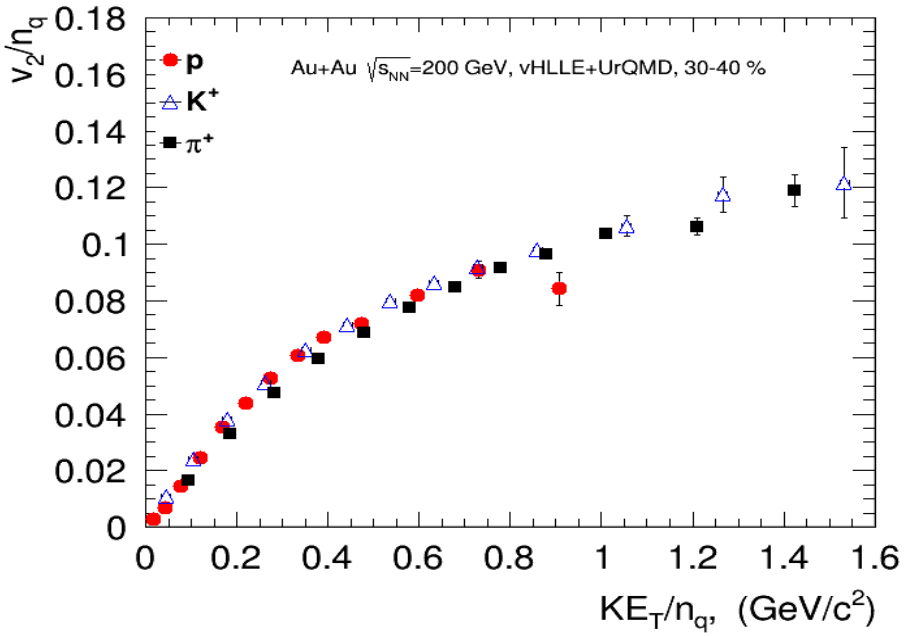


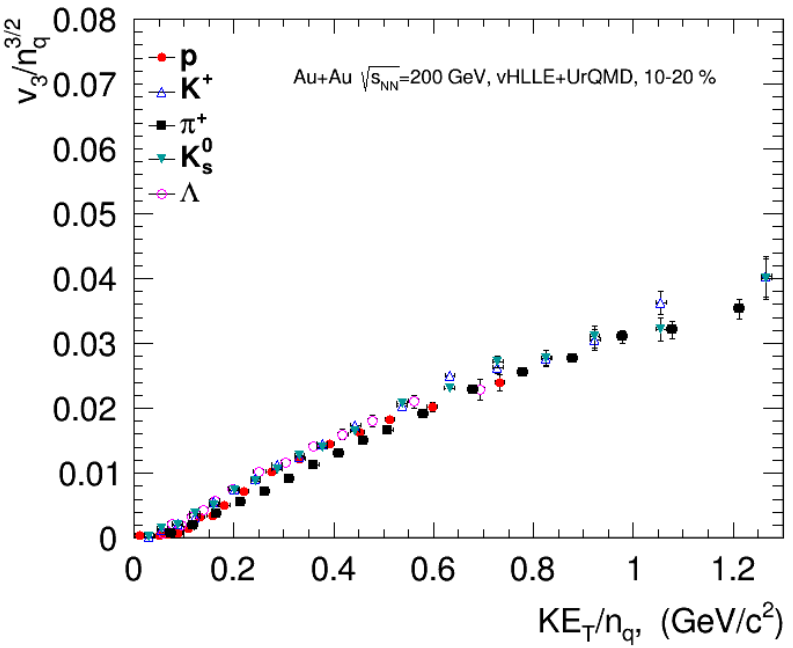
Quality of KE_T / n_q scaling : BES data

Star Data, Phys.Rev.C 93 (2016) 1, 014907



vHLLE+UrQMD: Scaling of elliptic and triangular flow at top RHIC energy

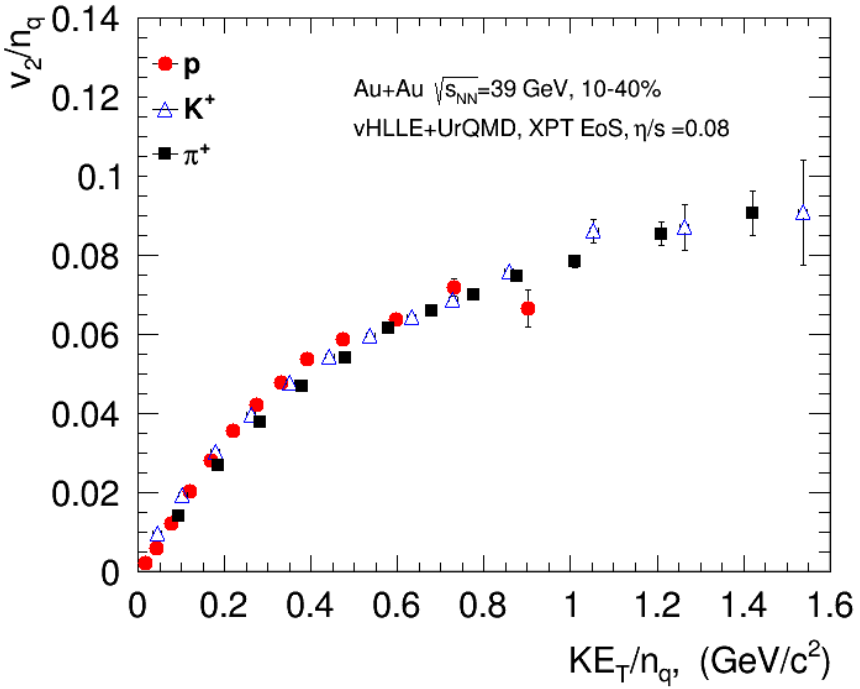


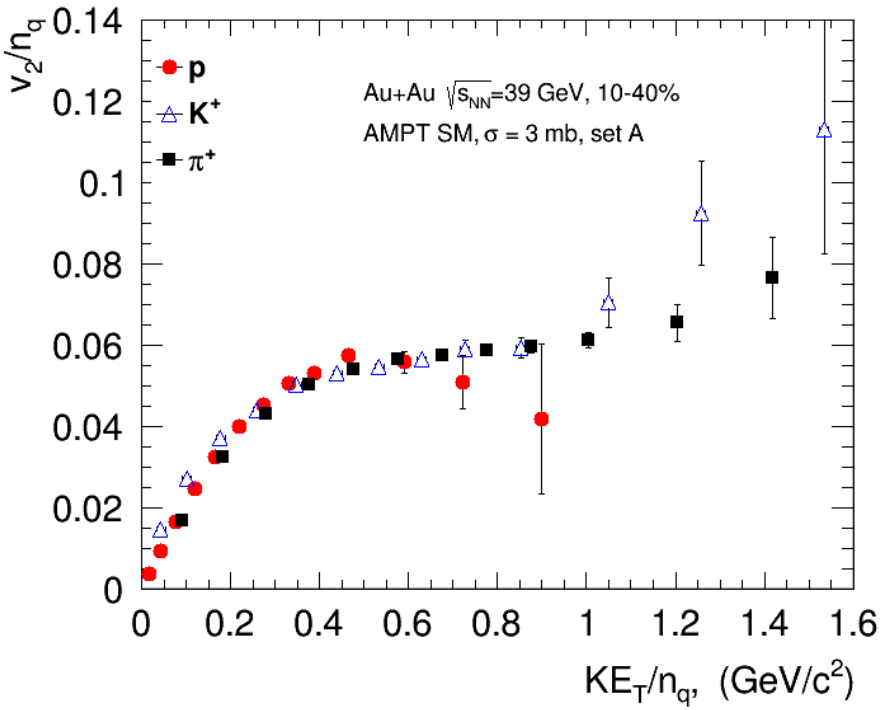


3D hydro model vHHLE + UrQMD (XPT EOS), $\eta/s = 0.08$ + param from
Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher , Phys.Rev. C91 (2015) no.6, 064901

Reasonable agreement between results of vHLLE+UrQMD model and published PHENIX data for 200 GeV including KET/nq scaling - see Peter Parfenov's talk for details

KE_T / n_q scaling : hybrid models





UrQMD + 3D viscous hydro model vHLLE + UrQMD

Iurii Karpenko, Comput. Phys. Commun. 185 (2014), 3016
https://github.com/yukarpenko/vhlle

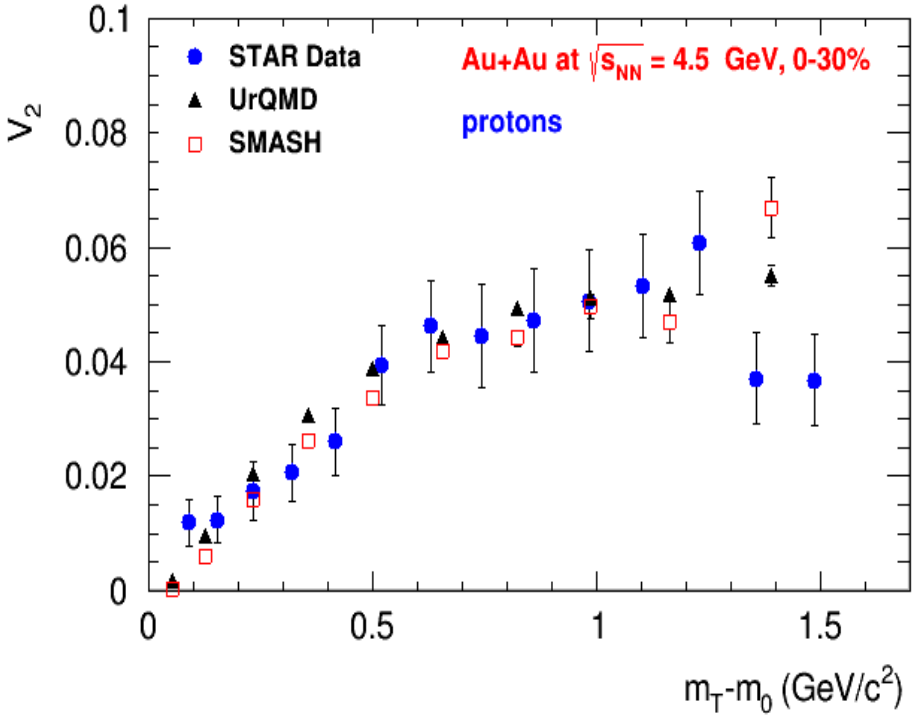
Initial conditions: model UrQMD
QGP phase: 3D viscous hydro (vHLLE) EOS (XPT)
Hadronic phase: model UrQMD

A Multi-Phase Transport model (AMPT) for high-energy nuclear collisions. (v1.26t9b/v2.26t9b)

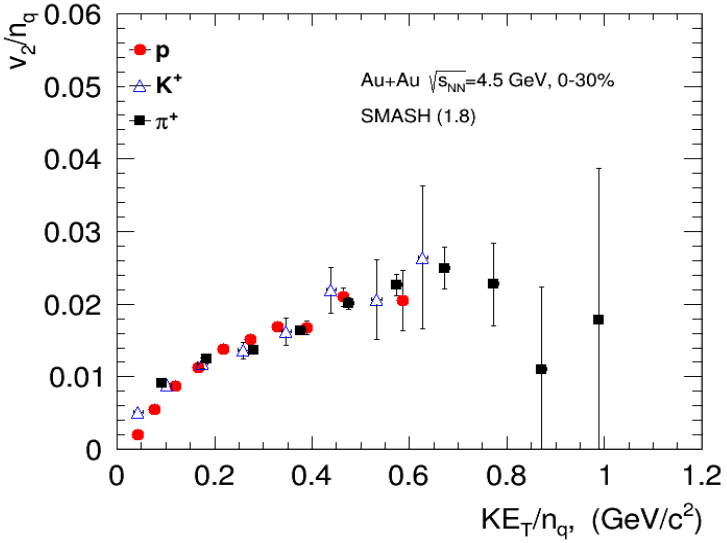
Initial conditions: model HIJING
QGP phase: Zhang's parton cascade for modeling partonic scatterings
Hadronic phase: model ART

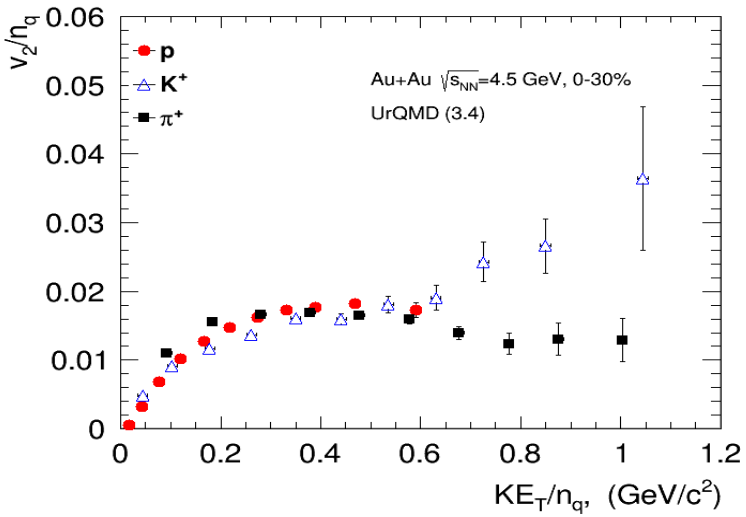
Z.W. Lin, C. M. Ko, B.A. Li, B. Zhang and S. Pal: Physical Review C 72, 064901 (2005).

KE_T / n_q scaling : String/Hadronic Cascade models



STAR Collaboration, arxiv.org/abs/2007.14005

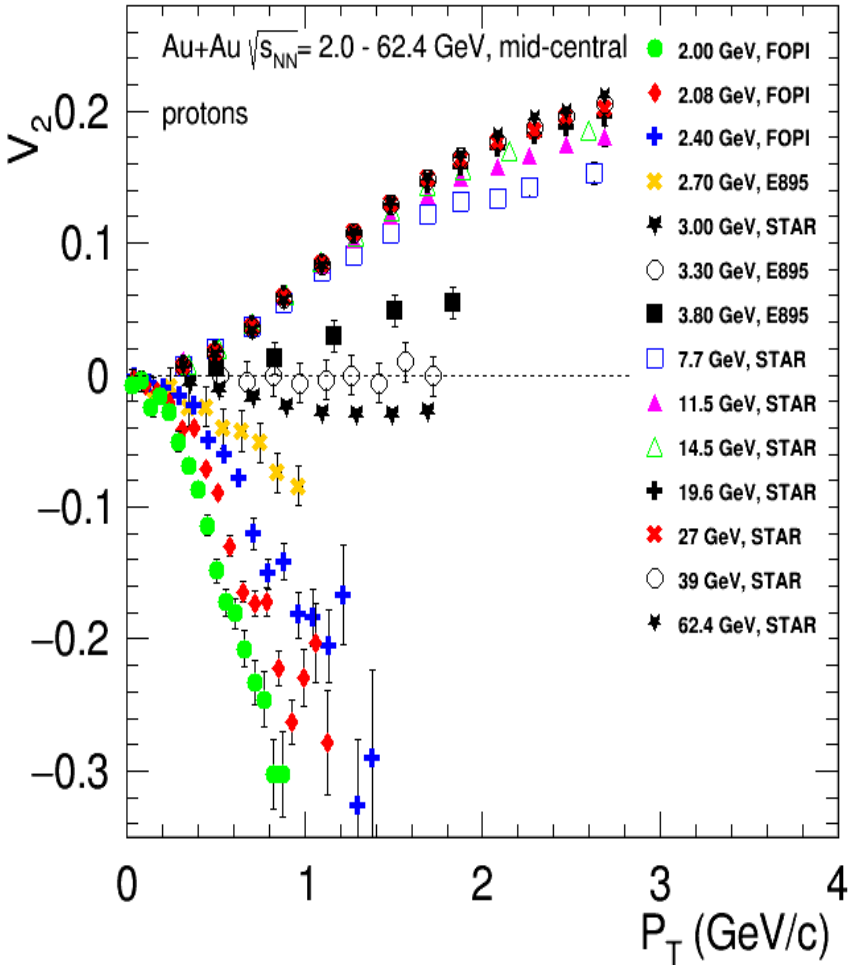


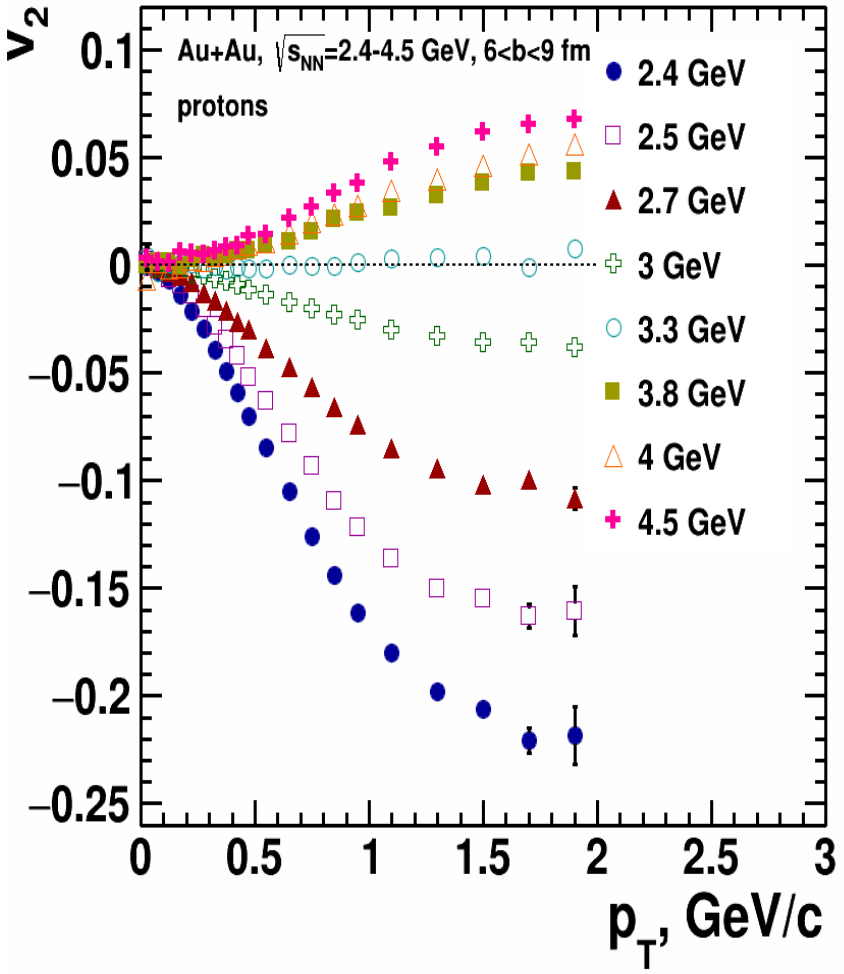


Pure String/Hadronic Cascade models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=4.5 GeV

Excitation function of differential elliptic flow

EPJ Web Conf. 204 (2019) 03009

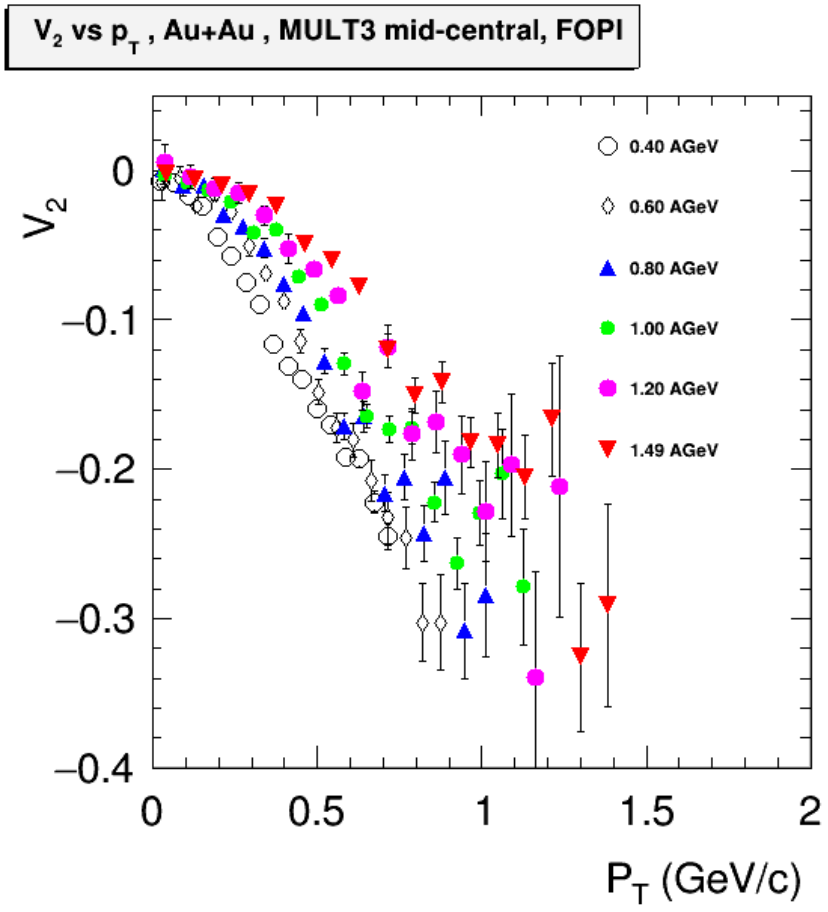




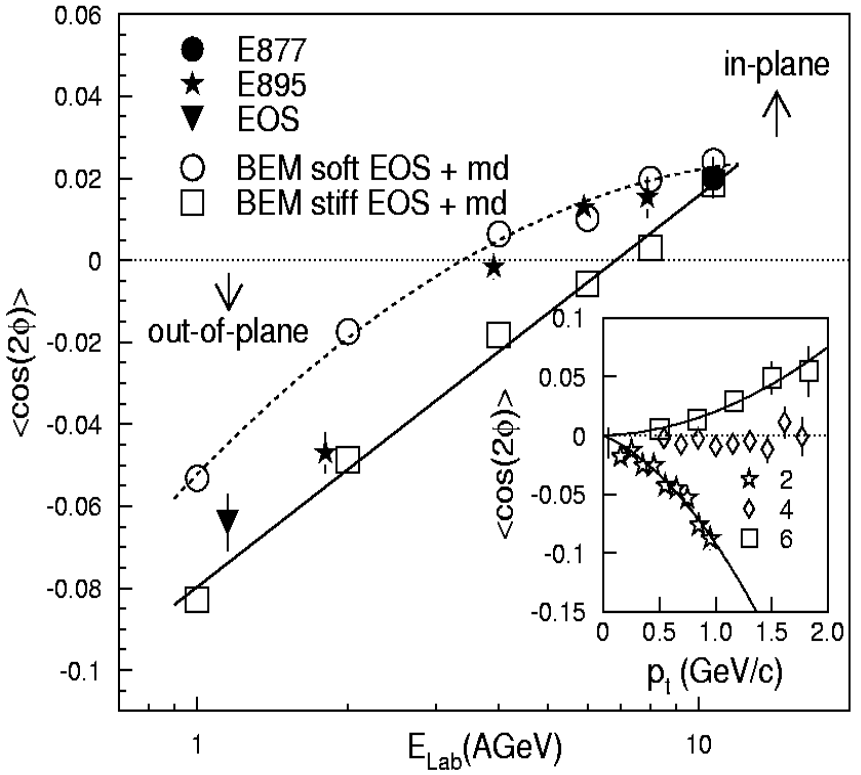
See Peter Parfenov's talk: JAM model calculations for Au+Au at $\sqrt{s_{NN}}$ = 2.4-4.5 GeV

Elliptic Flow at SIS-AGS: interactions with spectators

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



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



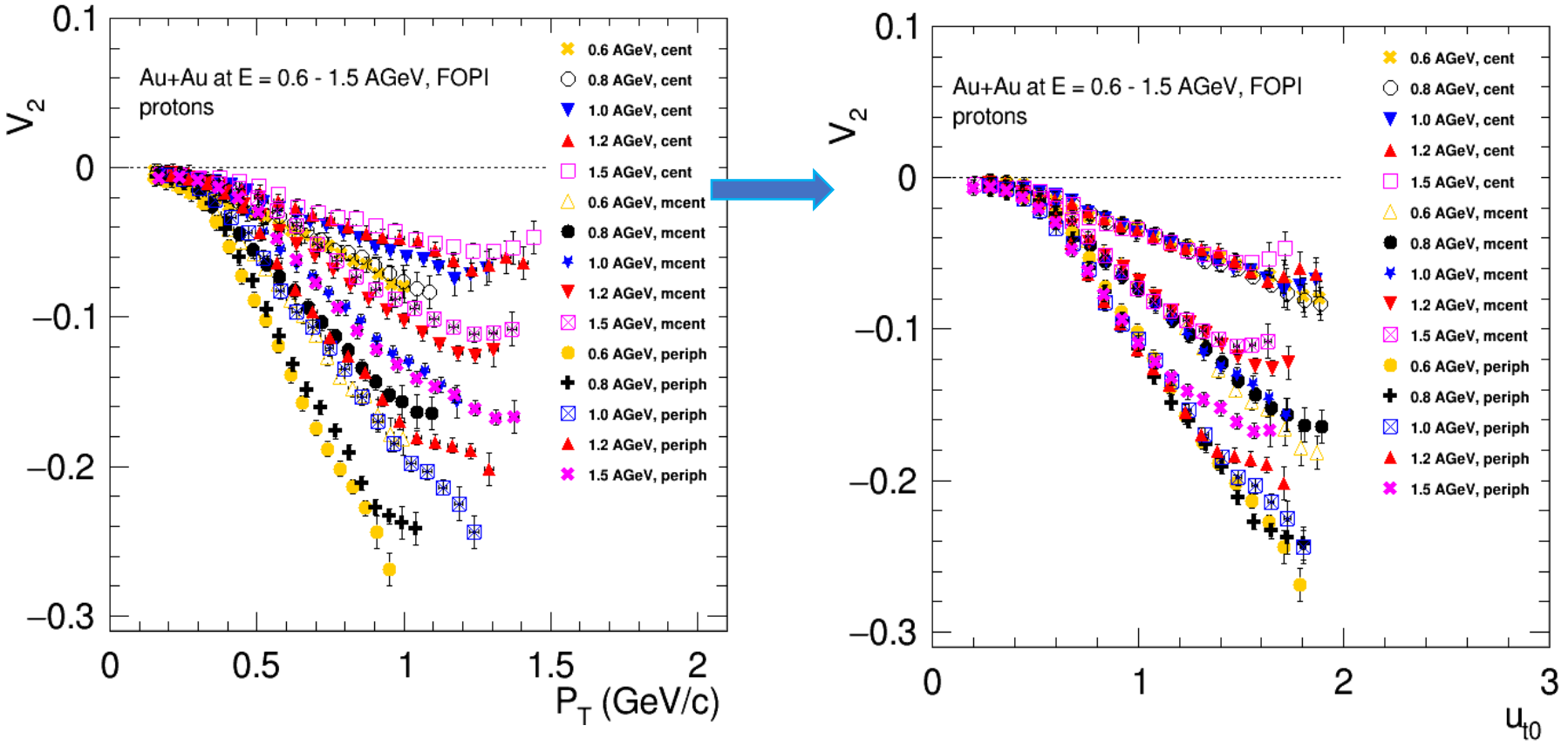
Passage time: $2R/(\beta_{cm}\gamma_{cm})$
Expansion time: R/c_s
$c_s=c\sqrt{dp/d\varepsilon}$ **- speed of sound**

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

Passing time scaling: FOPI data

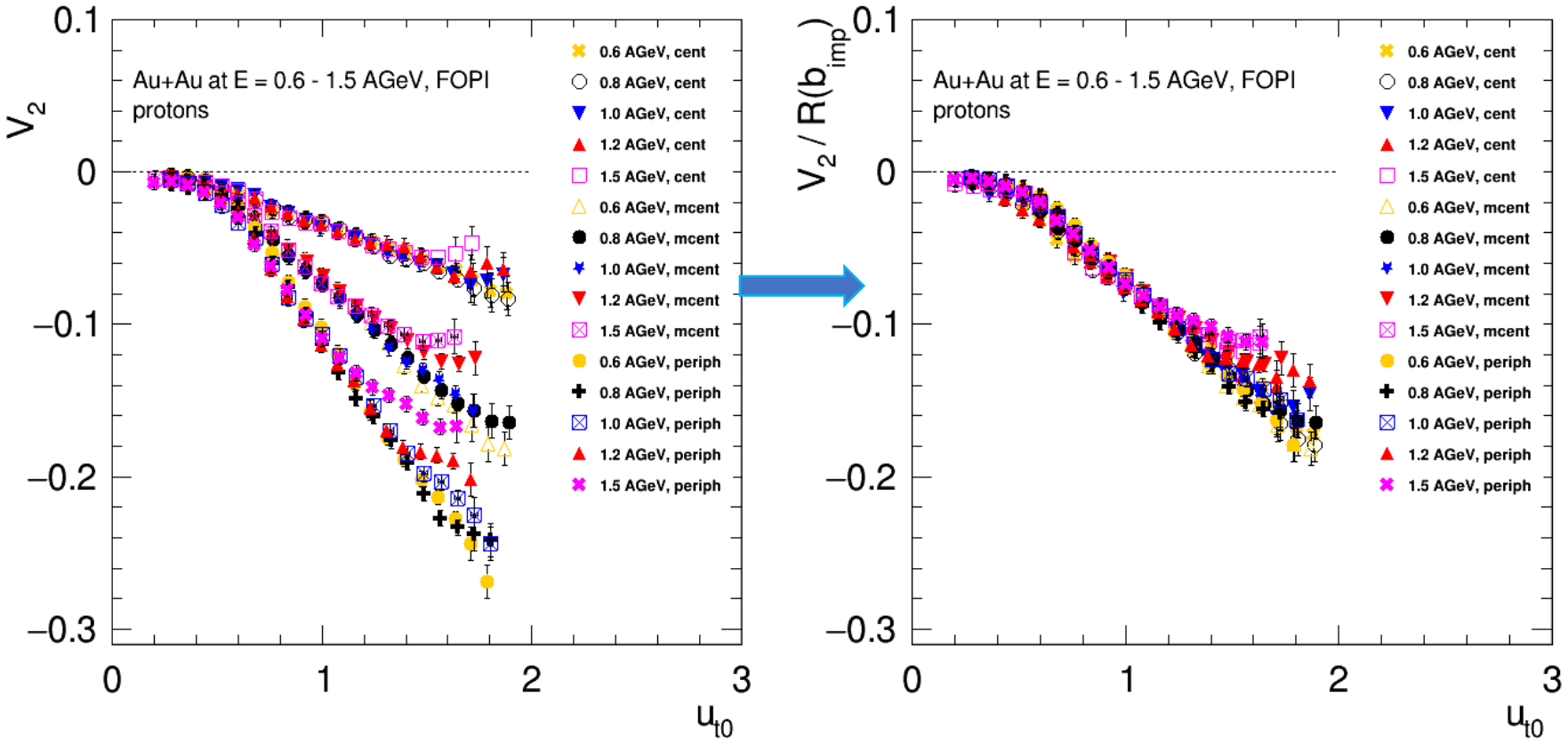
FOPI: Nucl. Phys A 876 (2012) 1-60

Protons: | y_0 | < 0.4



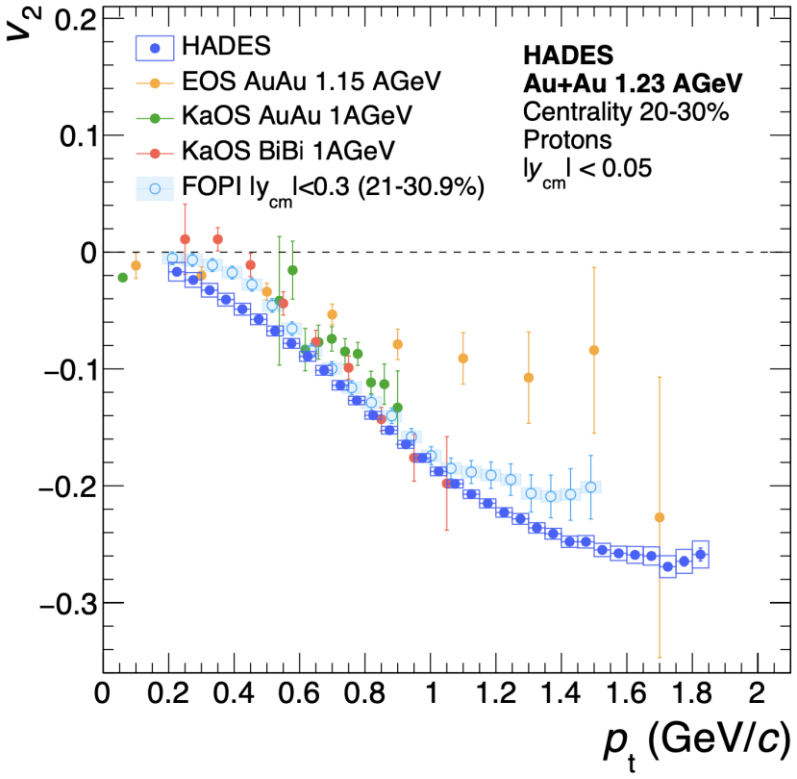
- Lets take ~300 $v_2(p_T)$ values from published data from FOPI experiment: 5 points in beam energy, 3 bins in centrality, 20 in p_T. Convert p_T to u_{t0}
- $u_{t0} = \frac{p_T}{\beta_{cm}\gamma_{cm}m_0}$ (passing time $t_{pass} = \frac{2R}{\beta_{cm}\gamma_{cm}}$ - scaling)

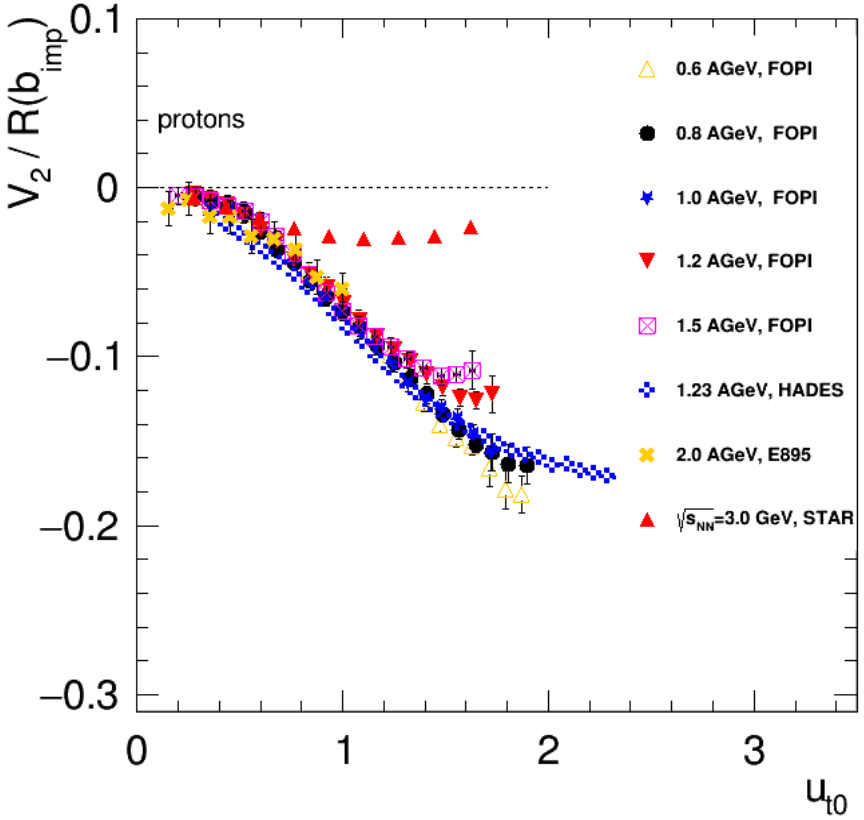
Passing time scaling: centrality dependence



- The passing time depends on centrality (impact parameter b) - v_n (b) – linear dependence?

Passing time scaling: FOPI, HADES, E895, STAR data

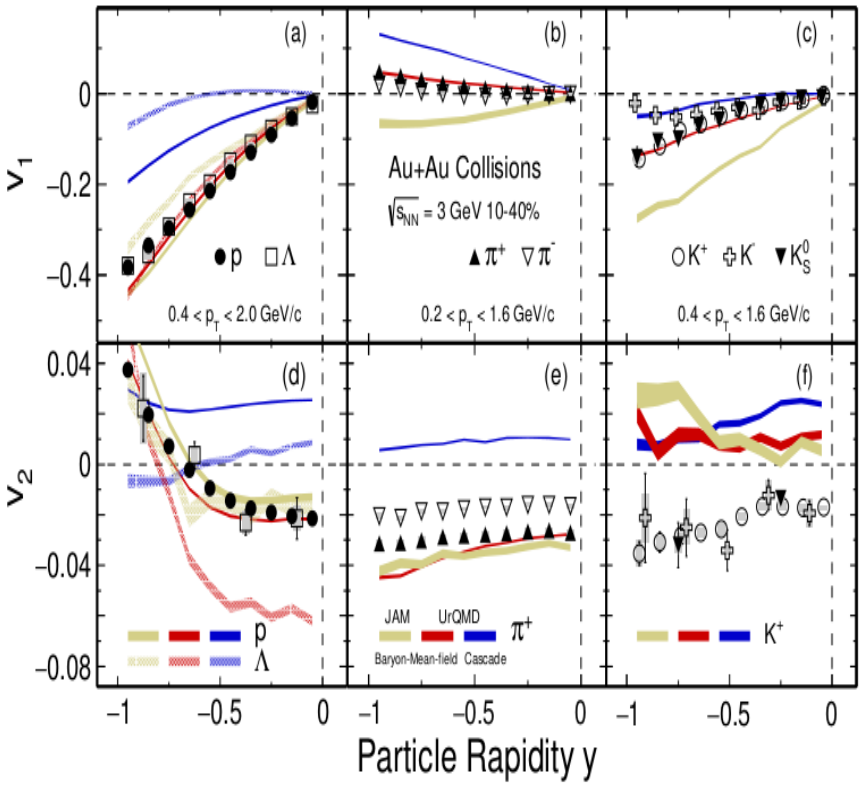


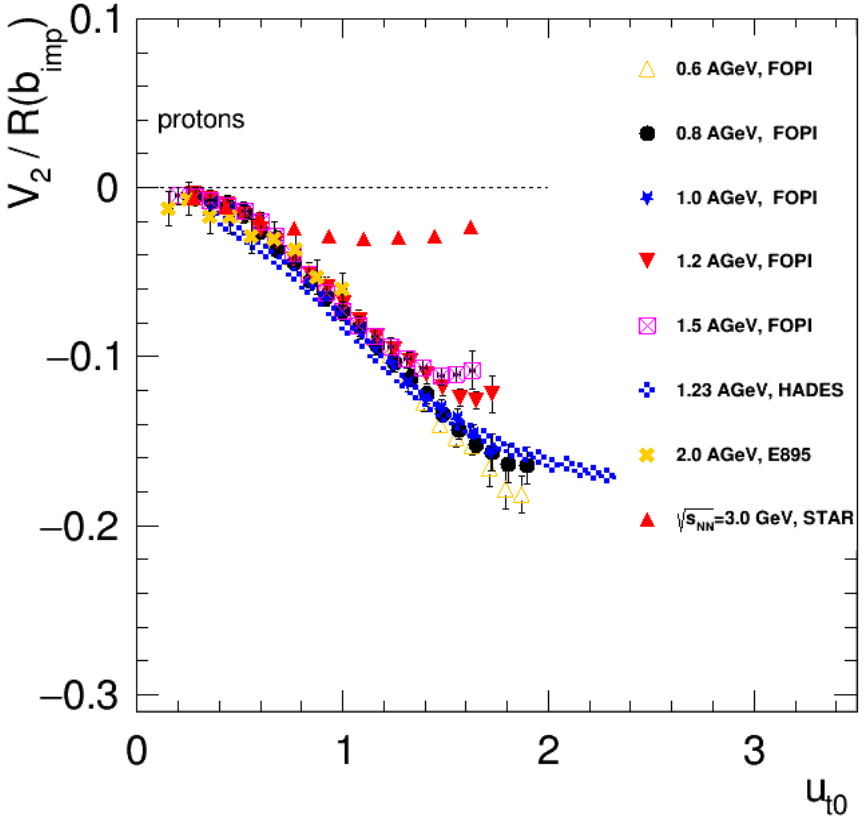


- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES). The passing time scaling is approximate
- New data from the future BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) experiments will provide more detailed and robust v_n measurements?

Passing time scaling: FOPI, HADES, E895, STAR data

STAR: https://arxiv.org/abs/2108.00908





- The main source of existing systematic errors in v_n measurements is the difference between results from different experiments (for example, FOPI and HADES). The passing time scaling is broken for STAR data – physics or different kinematics cuts – rapidity interval?
- New data from the future BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) experiments will provide more detailed and robust v_n measurements?

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 :

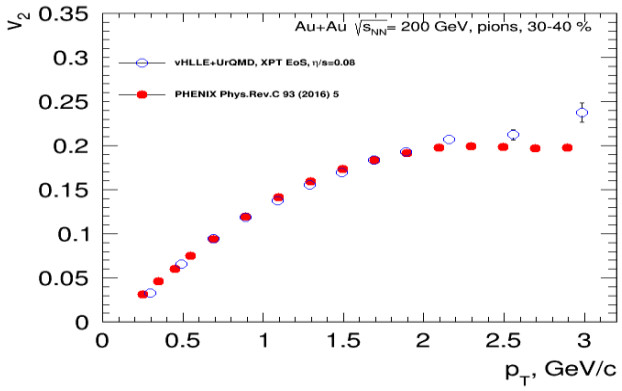
There is interest in using observables that are both coalescence and scale-invariant. …The evolution in non-viscous hydrodynamics does not depend on the size of the system nor on the incident energy, if distances are rescaled in terms of a typical size parameter, such as the nuclear radius. Momenta and energies are rescaled in terms of the beam velocities, momenta or energies.

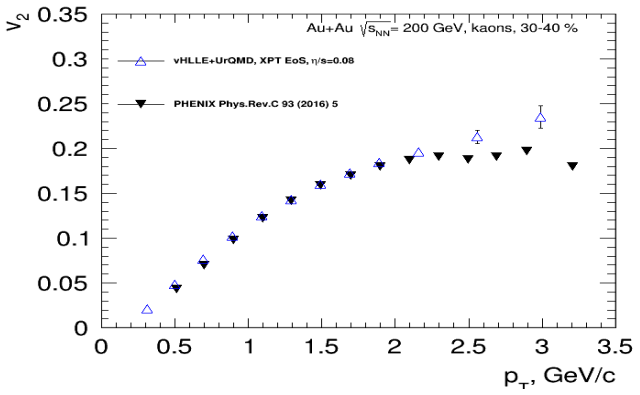
Conclusions and Perspectives

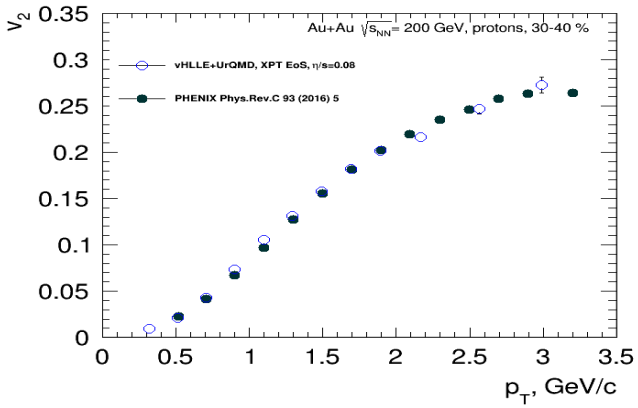
- **Anisotropic flow measurements provides access to the transport properties of the medium: EOS, sound speed (cs), viscosity, etc. Scaling relations may help to understand the physics of the process -**

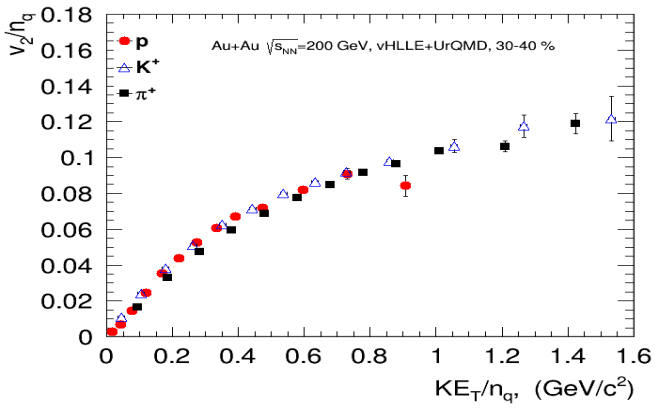
- **BM@N/NICA/FAIR energies are very interesting: transition between hadronic and partonic matter?**

vHLLE+UrQMD: Elliptic flow at top RHIC energy : $\sqrt{s_{NN}}$ = 200 GeV







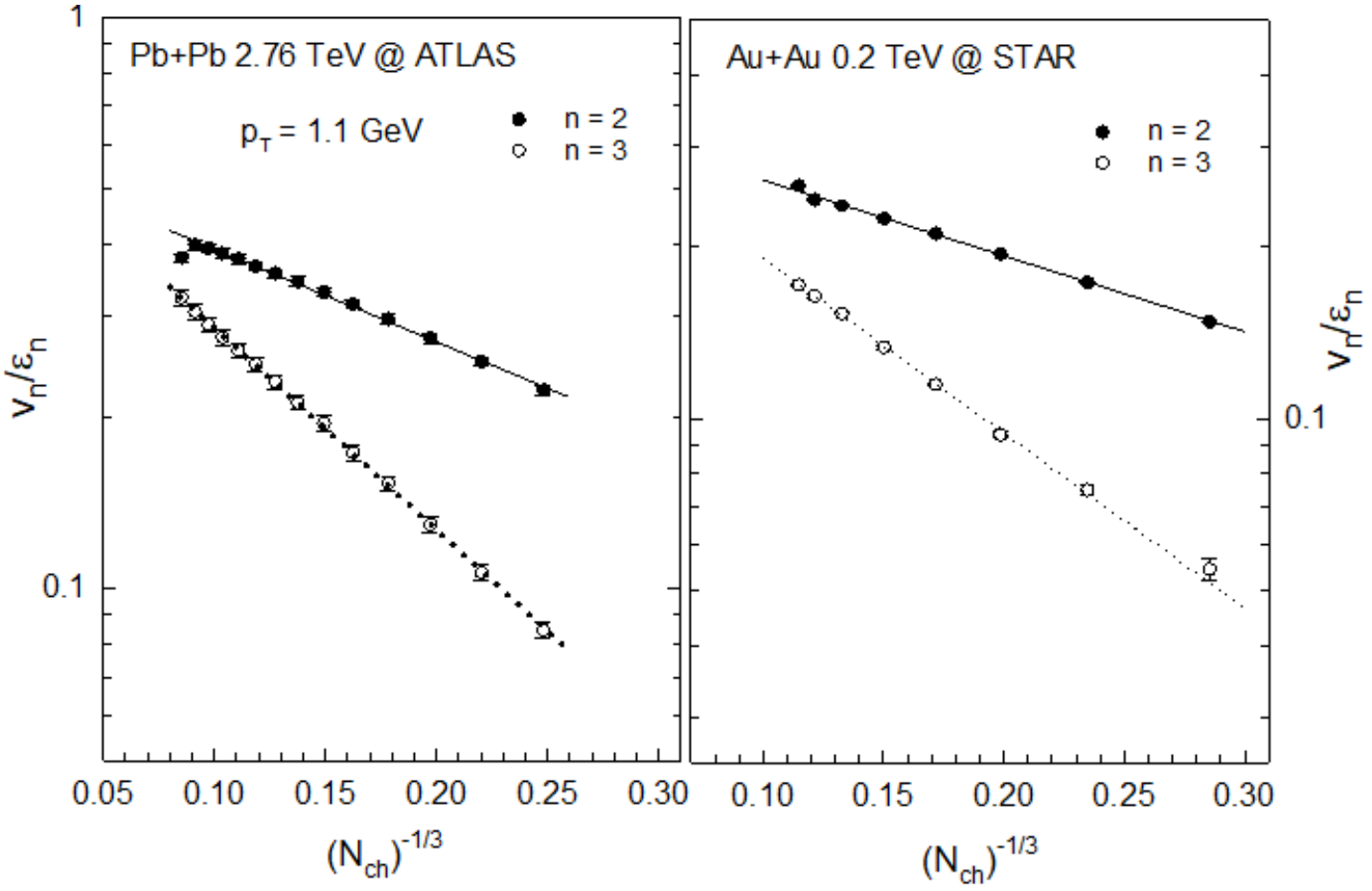


Reasonable agreement between results of vHLLE+UrQMD model and published PHENIX data for 200 GeV including KET/nq scaling

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***

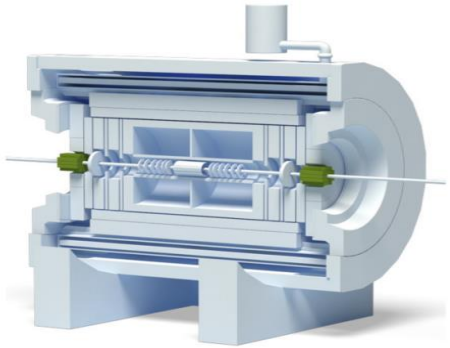
Flow performance study for FHCAL TDR (2018)

NICA

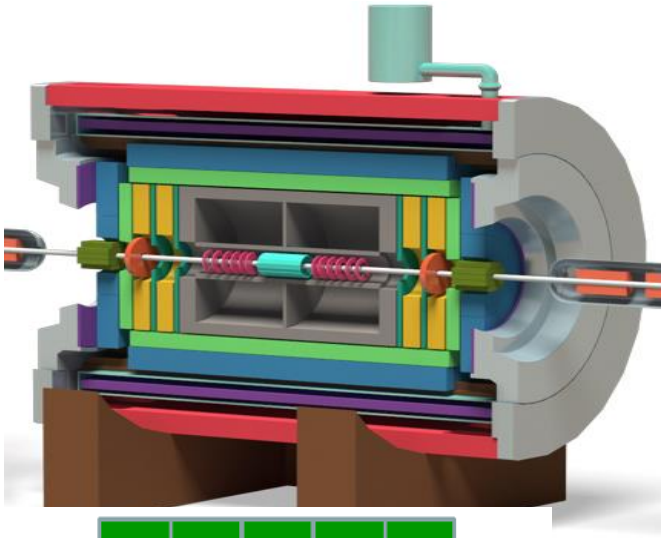
Technical Design Report for the MPD Experiment

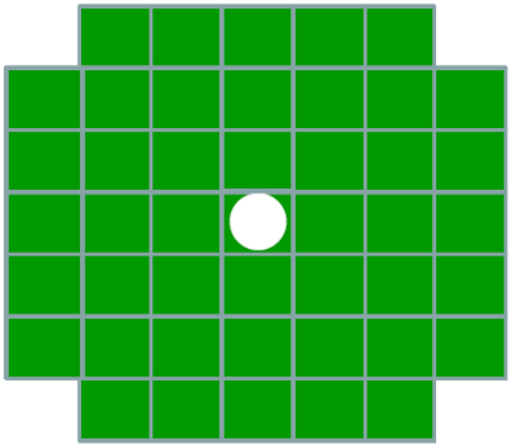
Nuclotron Based Ion Collider Facility

Forward Hadron Calorimeter (FHCal)



December 2016





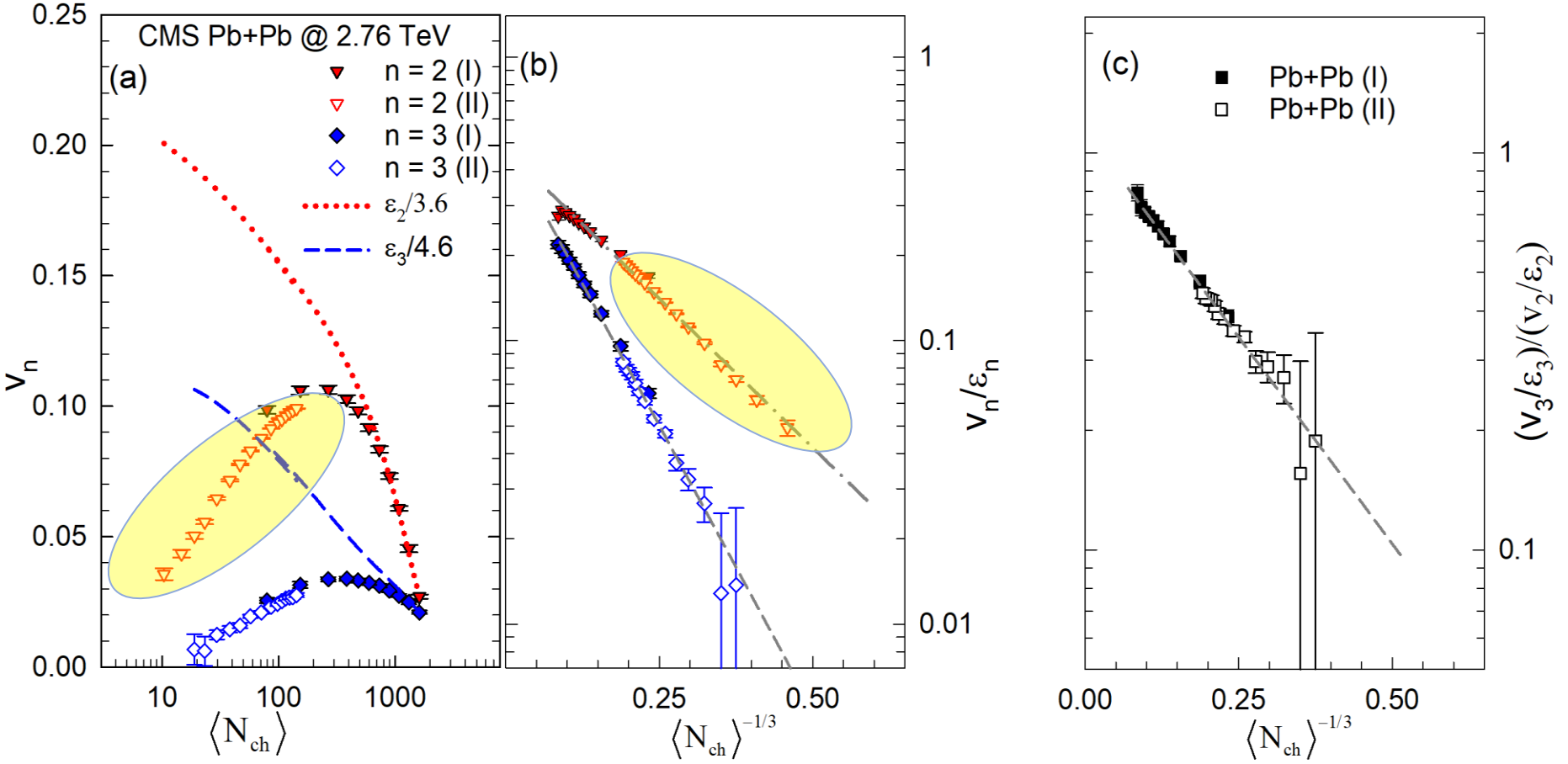
FHCal coverage: 2.2<|η|< 4.8

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

Acoustic Scaling - RT

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

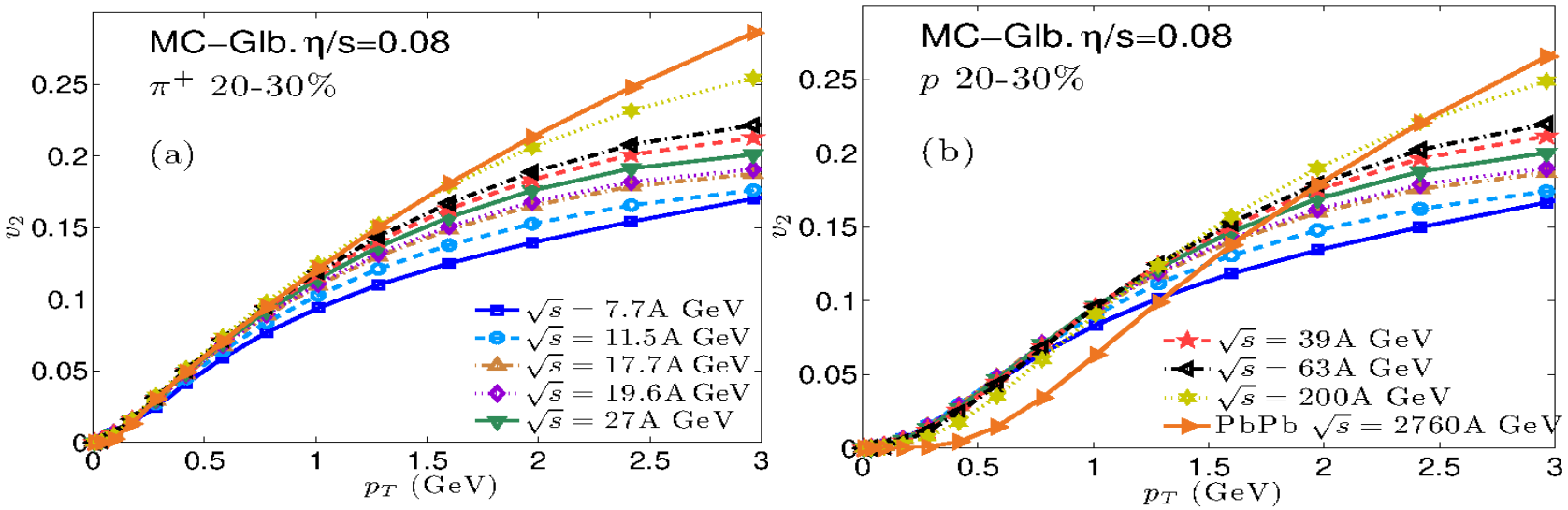
R.A. Lacey et al Phys. Rev. C **98**, 031901(R), 2018



- ✓ 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 from RHIC to LHC (viscous hydrodynamics)

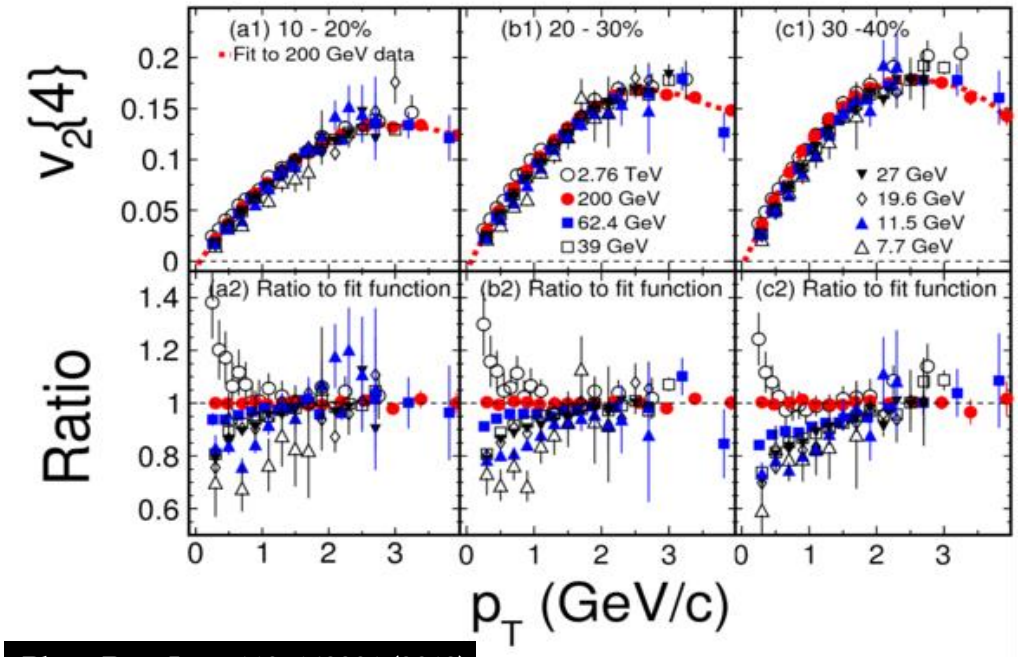
Chun Shen and Ulrich Heinz, Phys. Rev. C 85, 054902(2012), VISH2+1 model calculations



- ✓ **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 .

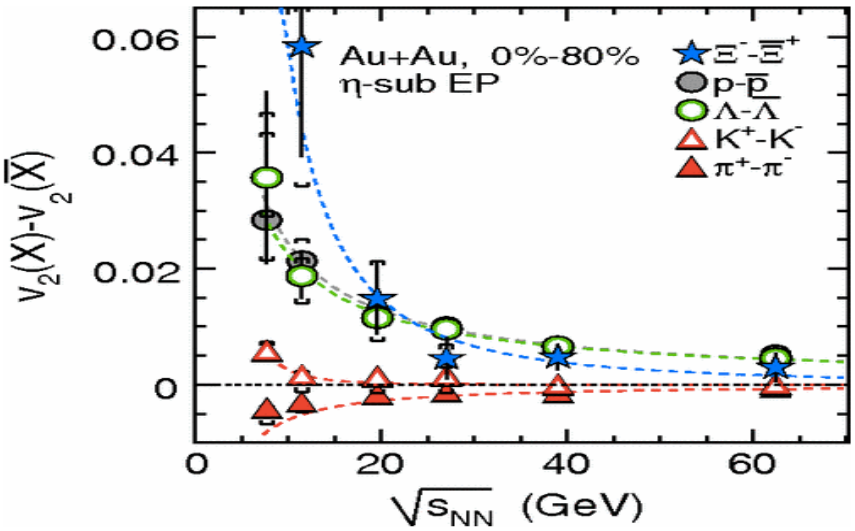
Beam Energy Dependence of Elliptic Flow (v_2)

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 v2 of charged hadrons for a turn off of the QGP
How sensitive is v_2 to QGP?

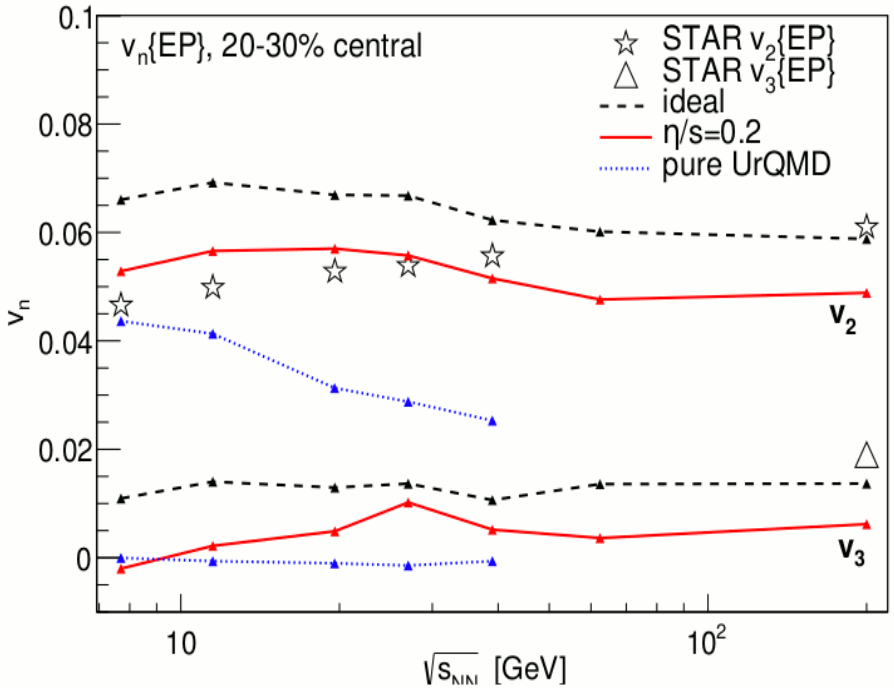
Phys. Rev. Lett. 110, 142301 (2013)

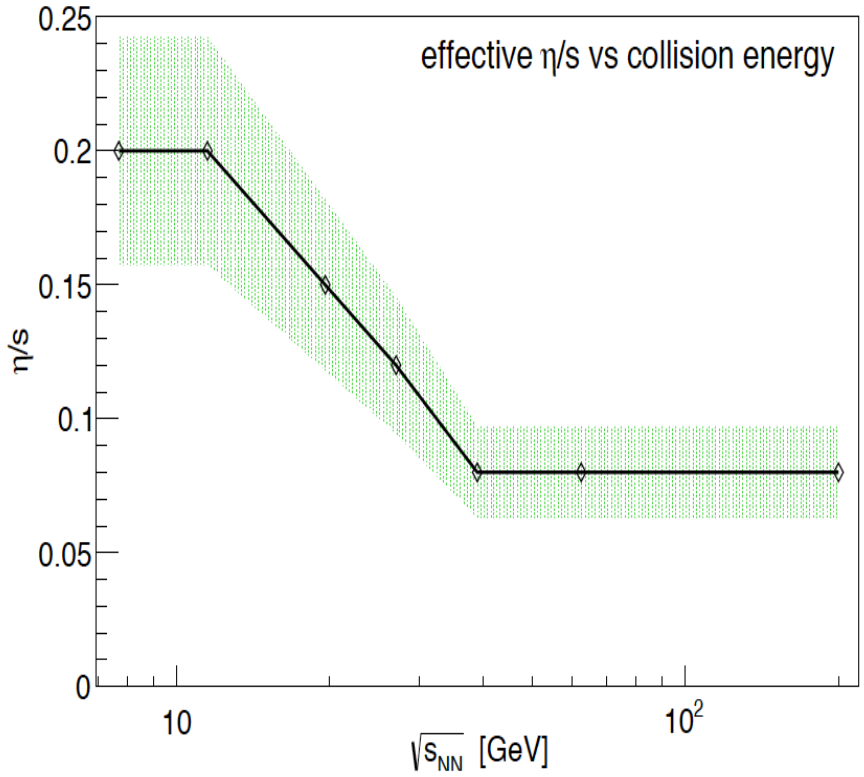


Substantial particle-antiparticle split at lower energies

Elliptic 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