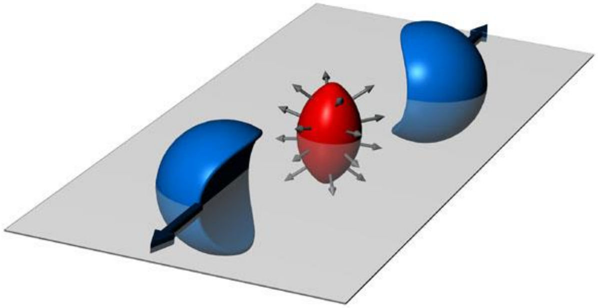
# Scaling properties of azimuthal anisotropy from RHIC to NICA



**Arkadiy Taranenko**

**Petr Parfenov, Anton Truttse**

**National Research Nuclear University MEPhI**

**The XXIV International Workshop**

**High Energy Physics and Quantum Field Theory**

**September 22-29, 2019, Sochi, Russia**

Project supported by RFBR № 18-02-40086

# 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**

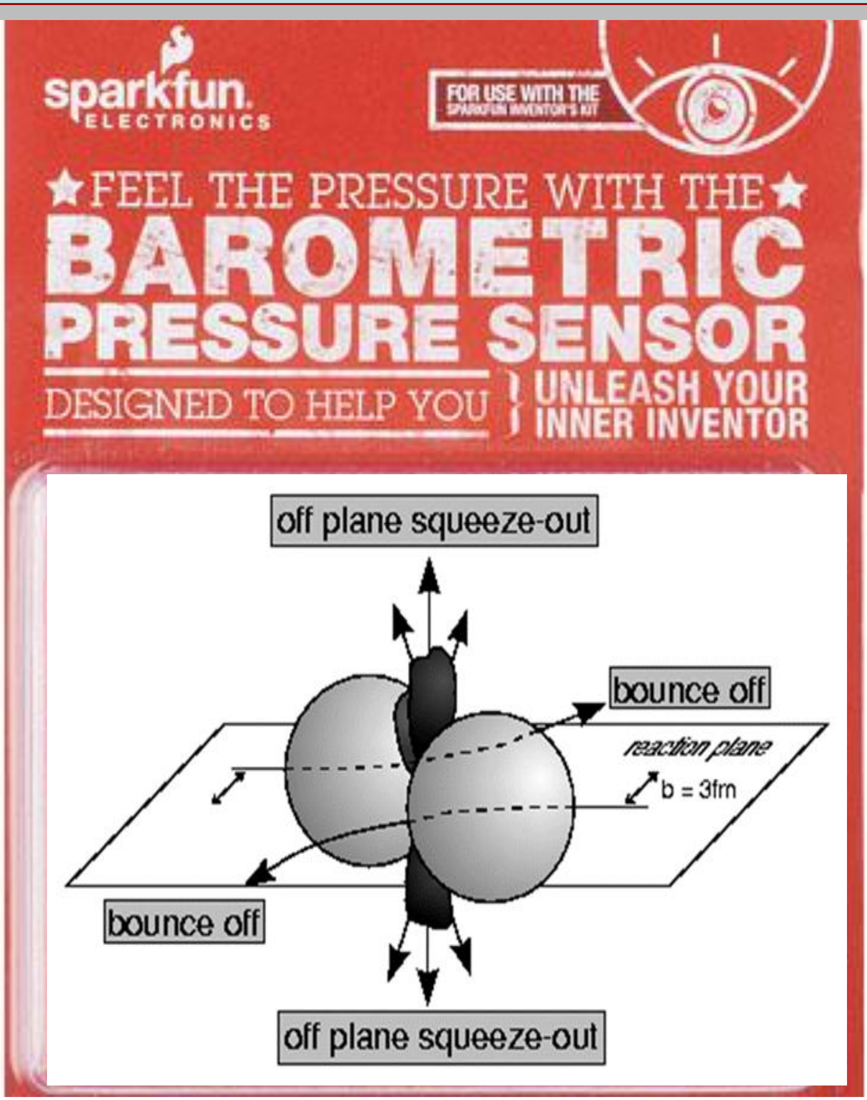
# *Anisotropic Flow in Heavy-Ion Collisions: 1988*

***Provides reliable estimates of pressure & pressure gradients***

***Can address questions related to thermalization***

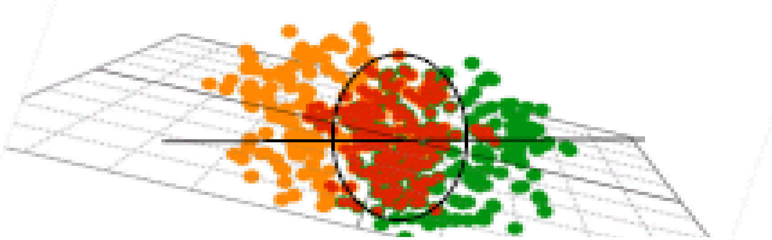
***Gives insights on the transverse dynamics of the medium***

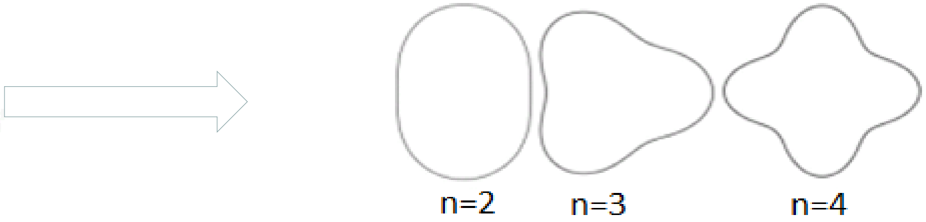
***Provides access to the transport properties of the medium: EOS, sound speed ($c_s$), viscosity, etc***



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

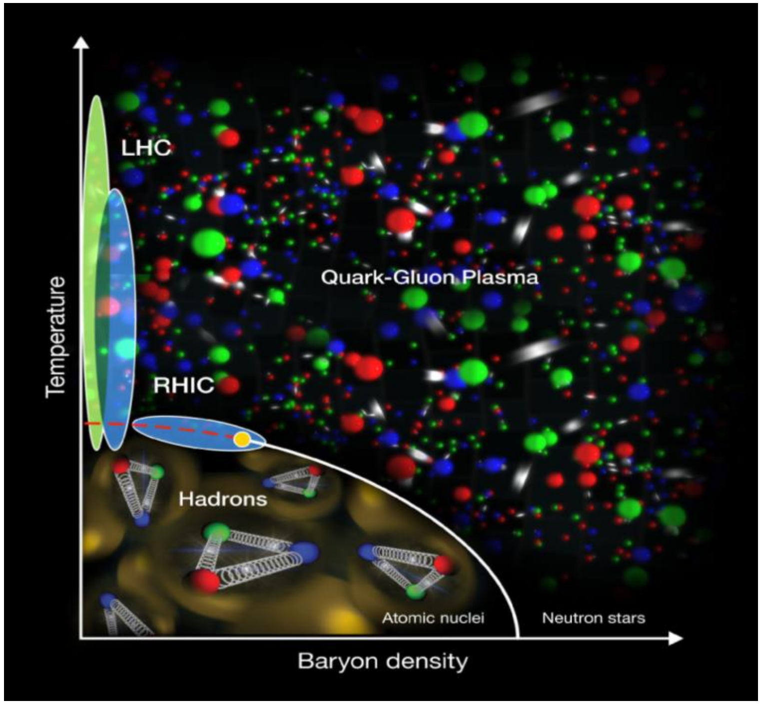
# Anisotropic Flow at RHIC-LHC



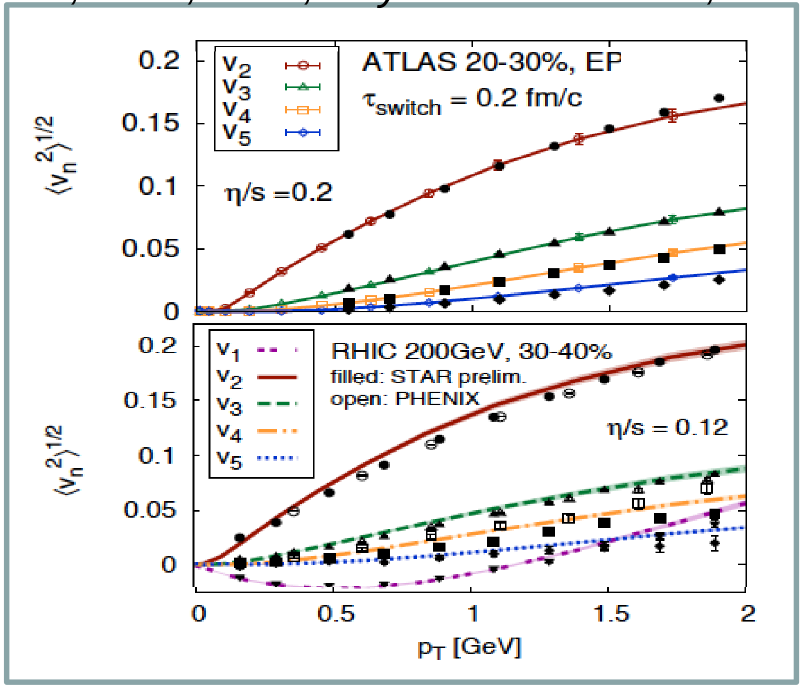


$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi \rangle + \langle r^n \sin n\phi \rangle}{\langle r^n \rangle}} \quad \Rightarrow \quad \frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]\right)$$

**Initial eccentricity (and its attendant fluctuations) $\varepsilon_n$ drive momentum anisotropy $v_n$ with specific viscous modulation**

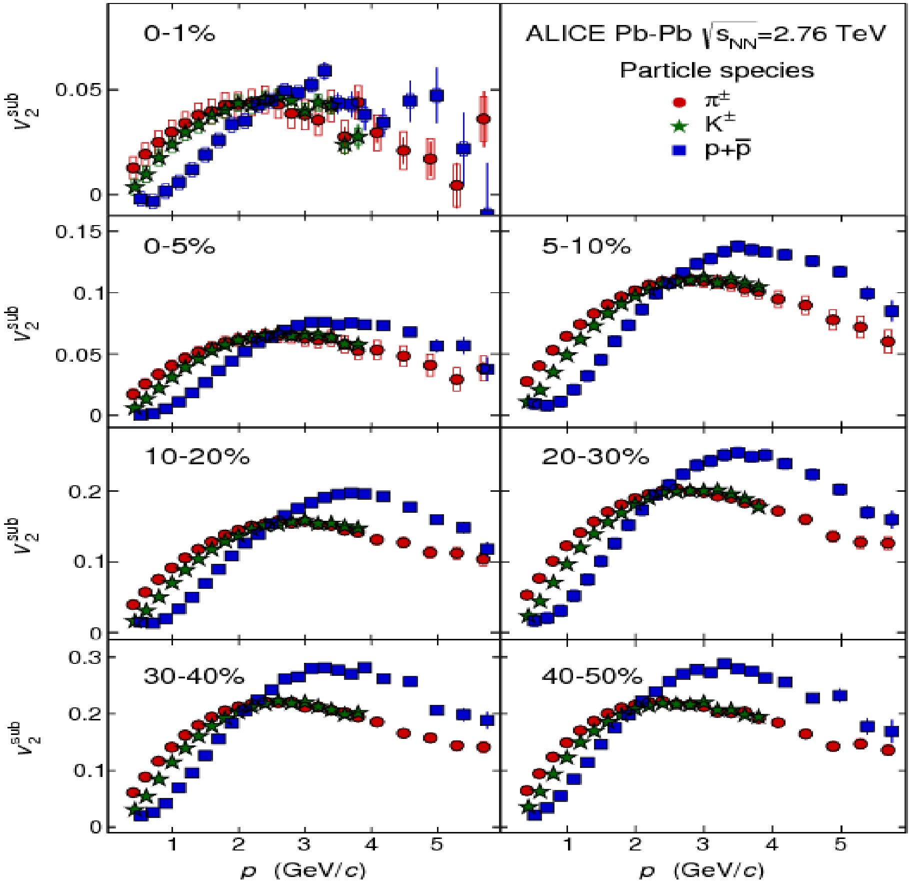


*Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302*

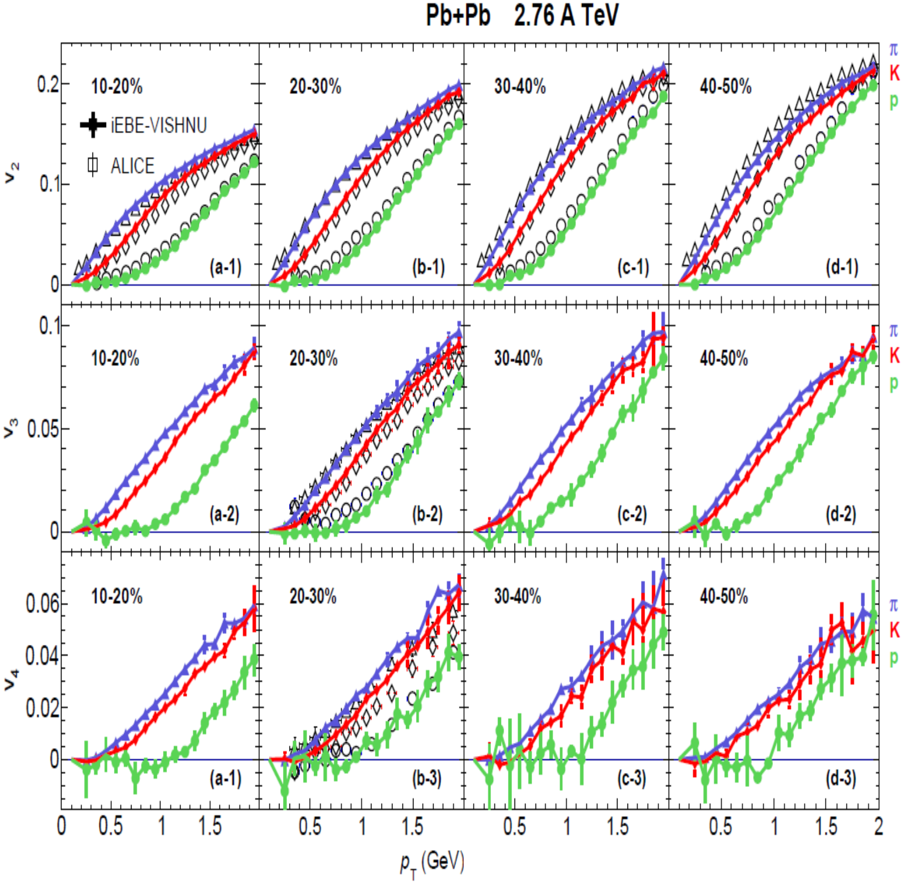


# $V_n$ of identified hadrons at RHIC/LHC

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



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



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.

6

# Flow is acoustic

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

- $v_n$ measurements are sensitive to system shape ($\varepsilon_n$), 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,

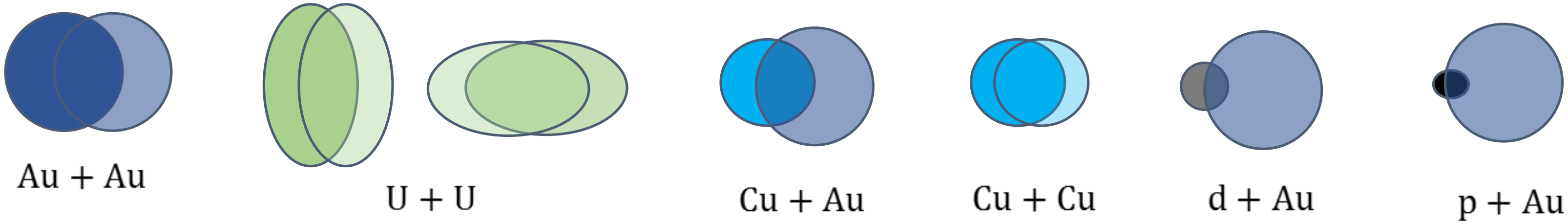
$$\frac{v_n}{\varepsilon_n} \propto e^{-\beta n^2}, \quad \beta \propto \frac{\eta}{s}\frac{1}{RT}$$

**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**

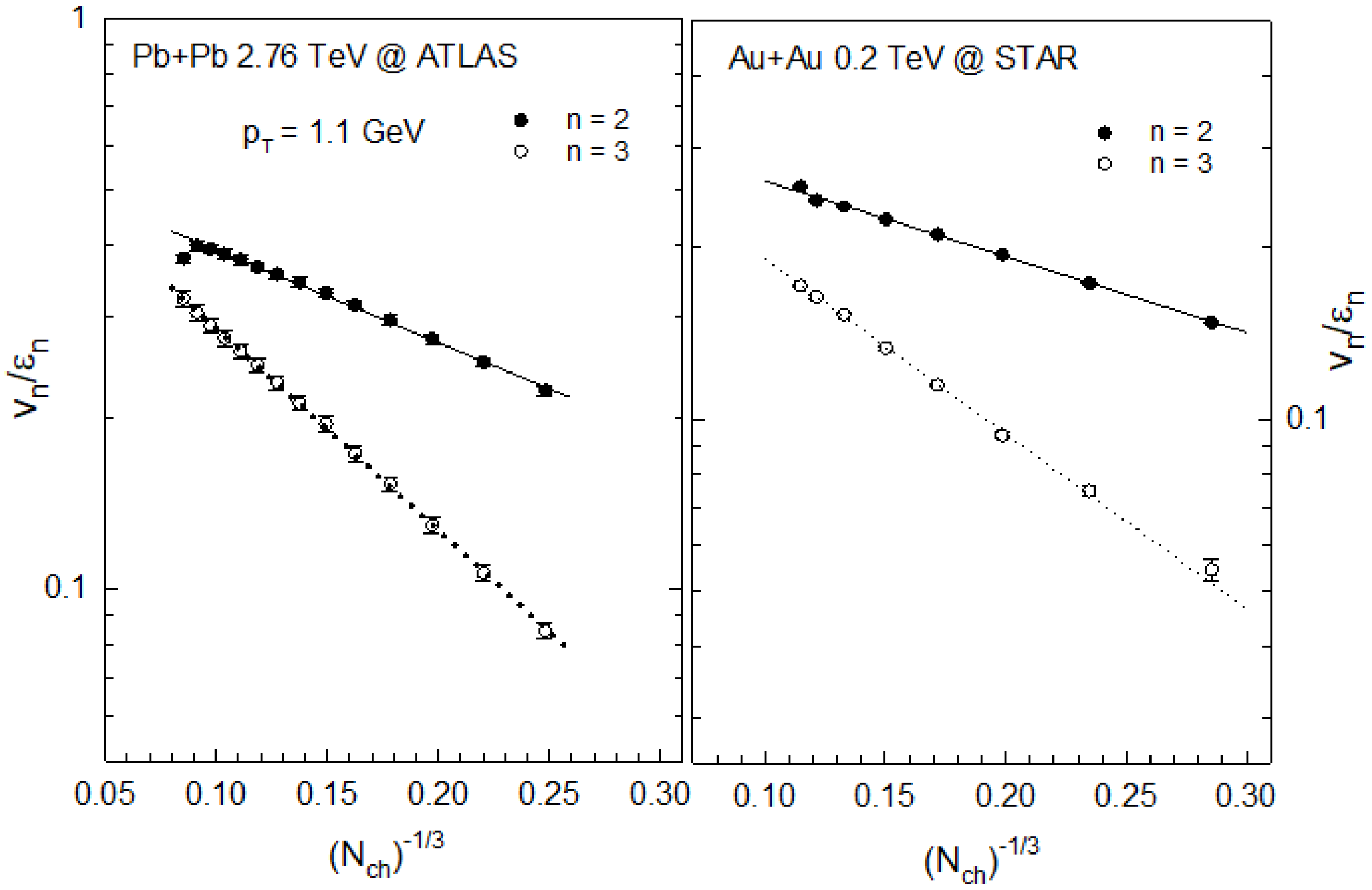


Scaling expected For *similar* $\frac{\eta}{s}$ *and* $\frac{dN}{d\eta}$

# Acoustic Scaling –

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

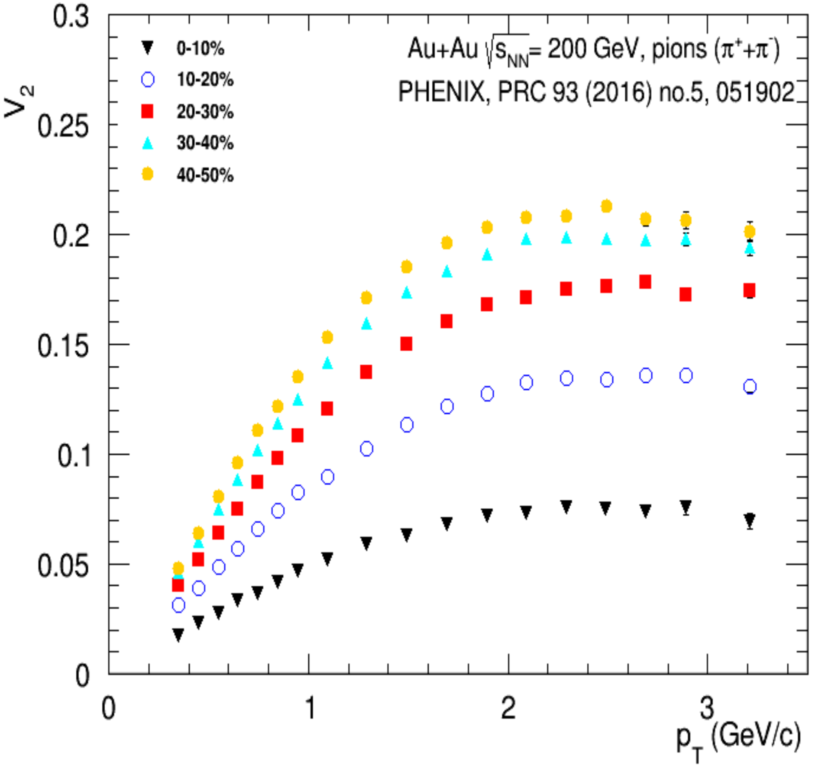
$$RT \propto \left(\frac{dN_{chg}}{d\eta}\right)^{1/3}$$

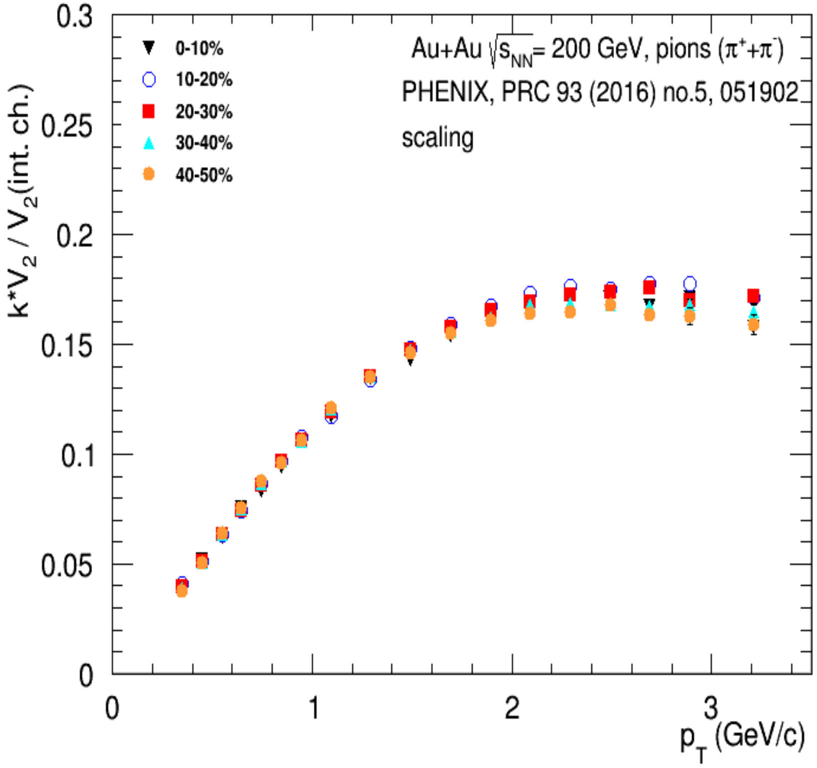


- ✓ **Characteristic 1/(RT) viscous damping validated**
  - ✓ ***Clear pattern for $n^2$ dependence of viscous attenuation***
  - ✓ ***Important constraint for η/s & ζ/s***

# $V_2$ of identified hadrons at top RHIC energy: pions

## Scaling with integral flow of charged hadrons

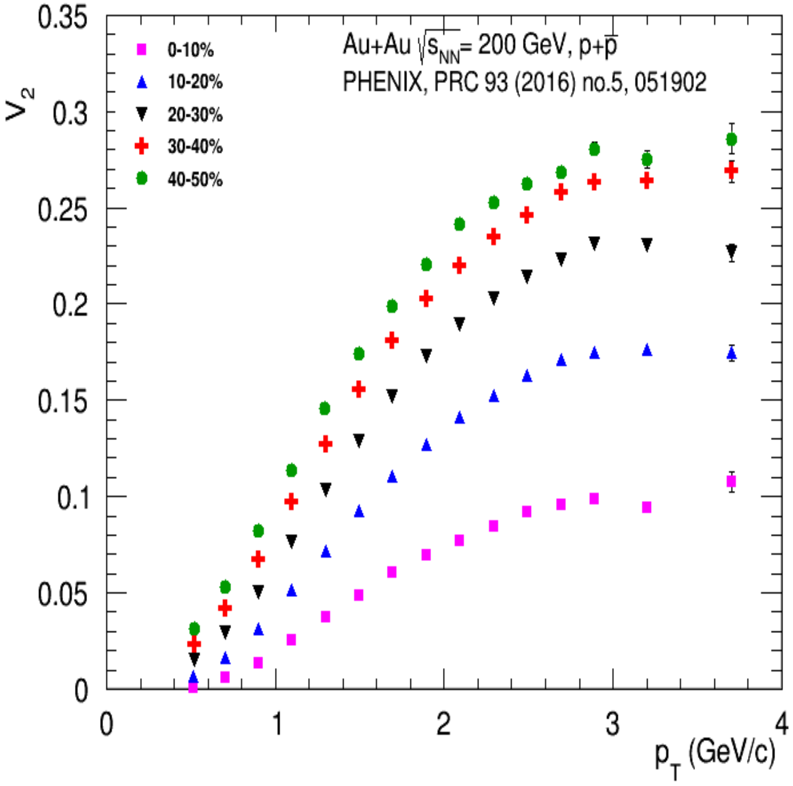


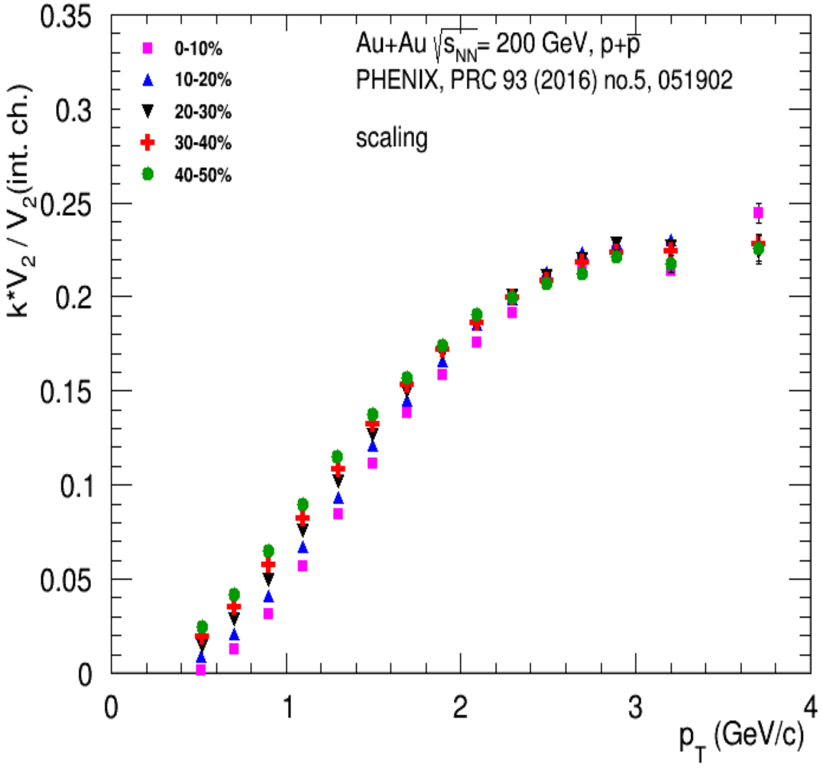


$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* \, V_2(PID, p_T)???$$

# $V_2$ of identified hadrons at top RHIC energy: protons

## Scaling with integral flow of charged hadrons



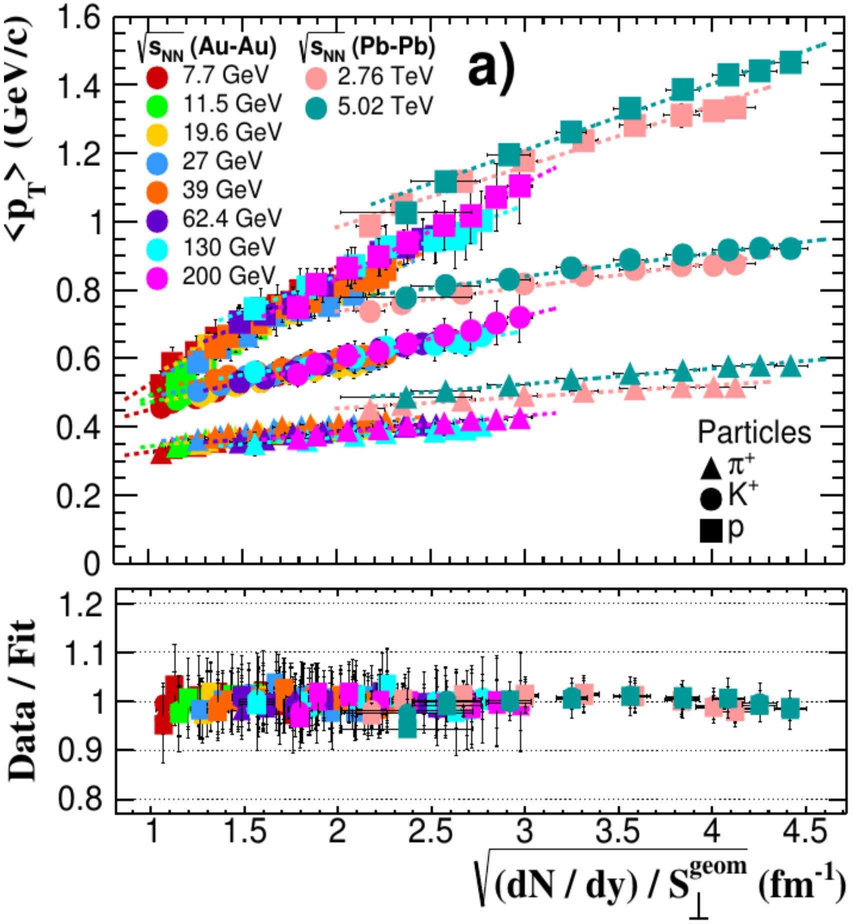


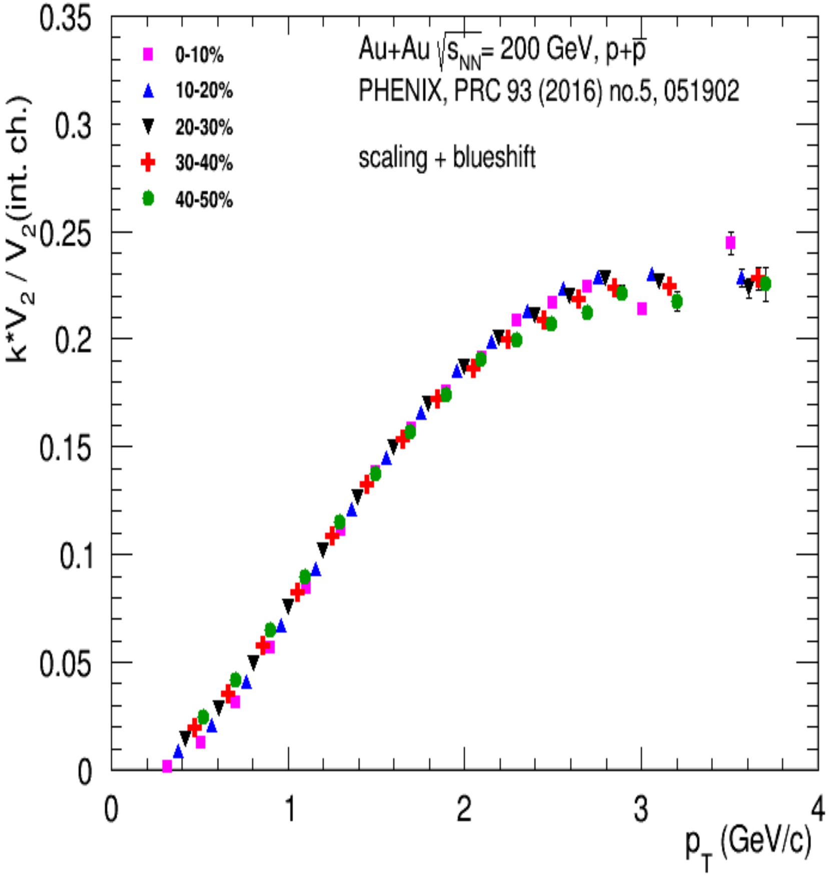
**for protons the strong radial flow “blueshifts” the entire flow signal to higher $p_T$ : $p_T \sim p_T^{th} + mc\beta$**

# $V_2$ of identified hadrons at top RHIC energy: protons

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

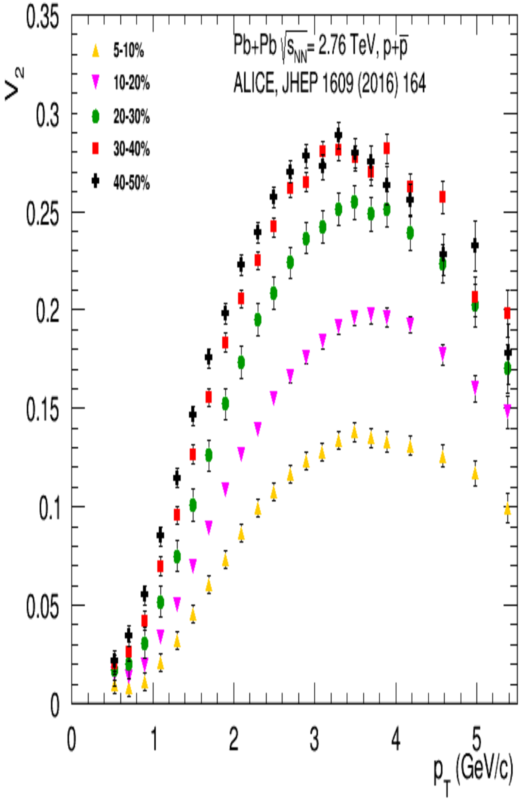
M. Petrovici at el, Phys Rev C 98 (2018)

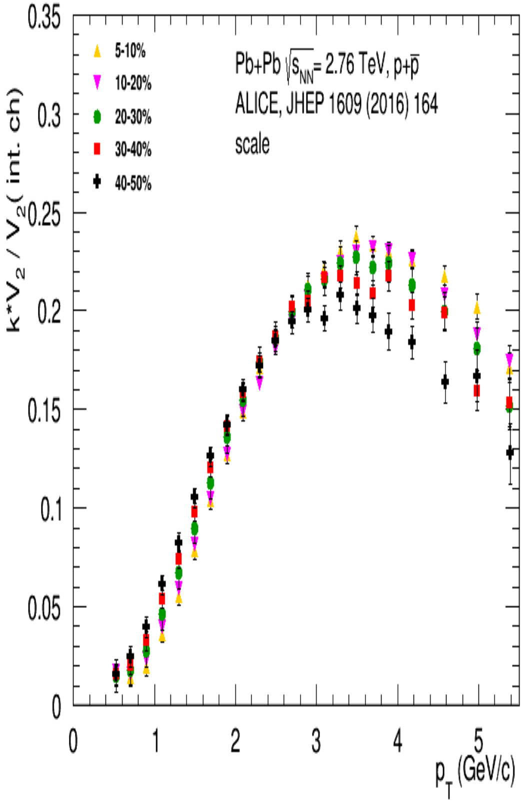


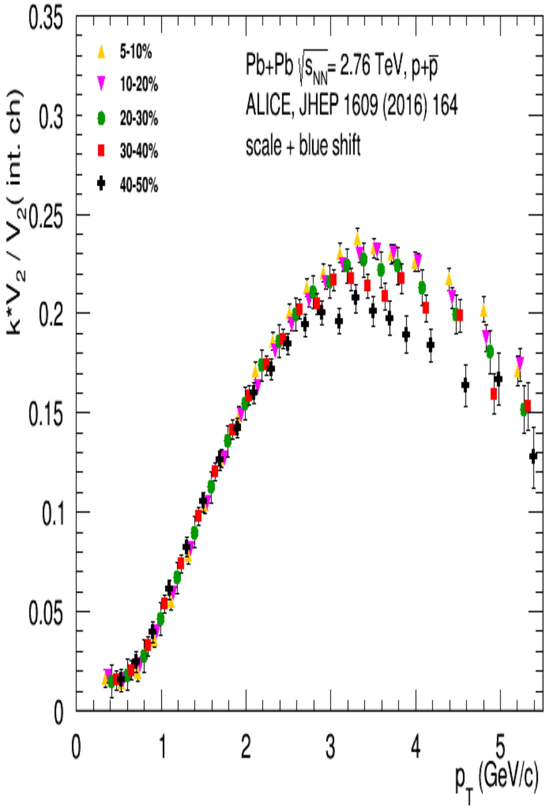


# Elliptic flow of identified hadrons at LHC : protons

**Scaling with integral flow of charged hadrons + correction for "blue shift"**



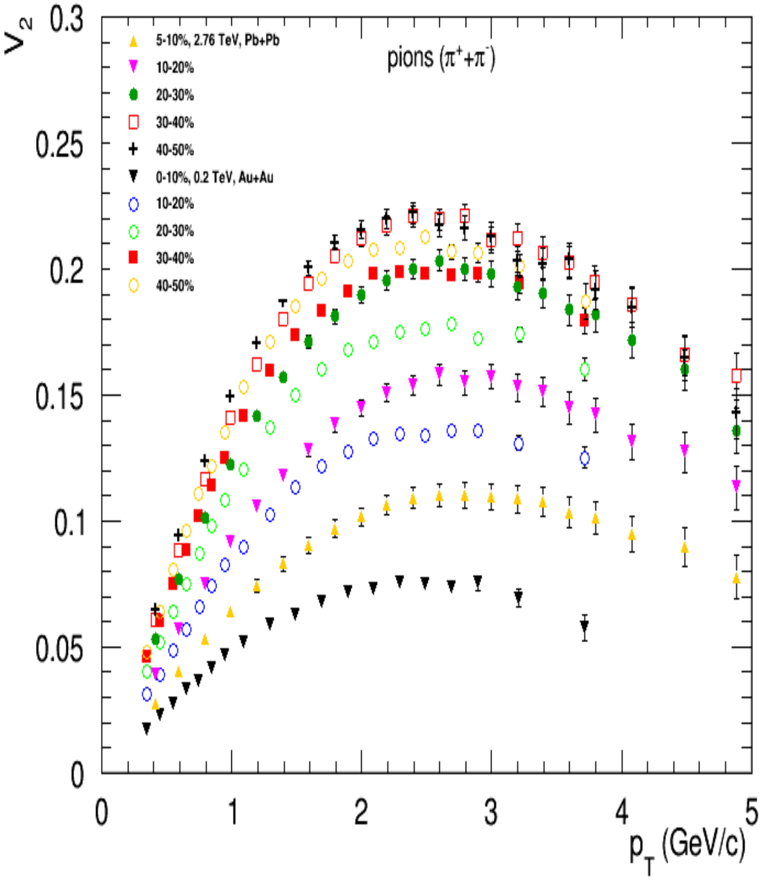


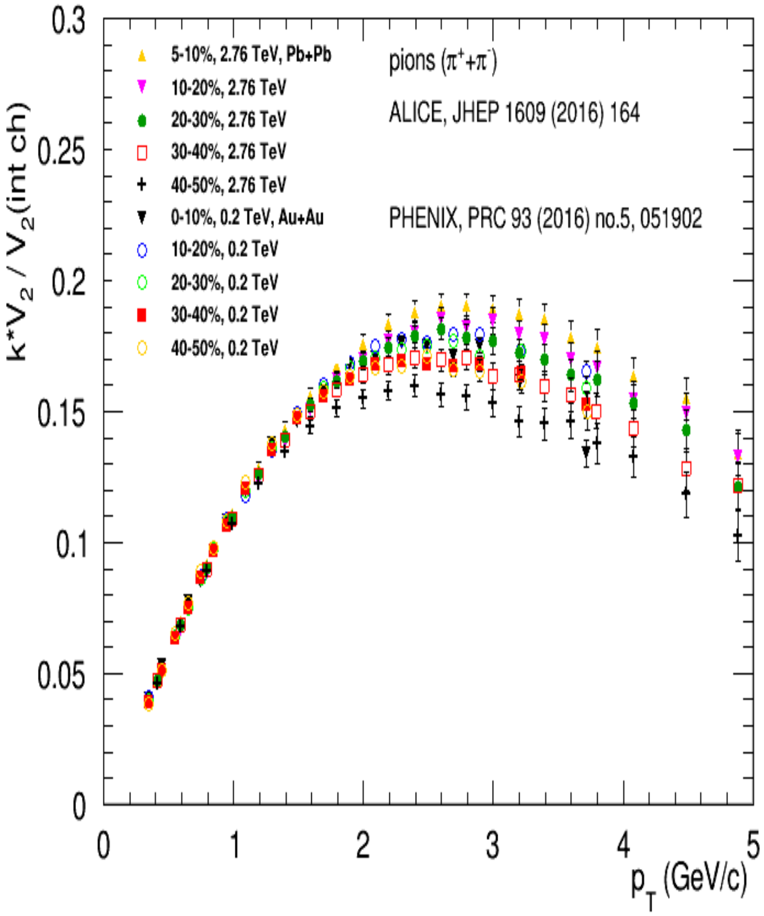


$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* \, V_2(PID, p_T)???$$

# Elliptic flow of identified hadrons at RHIC/LHC : pions

## Scaling with integral flow of charged hadrons

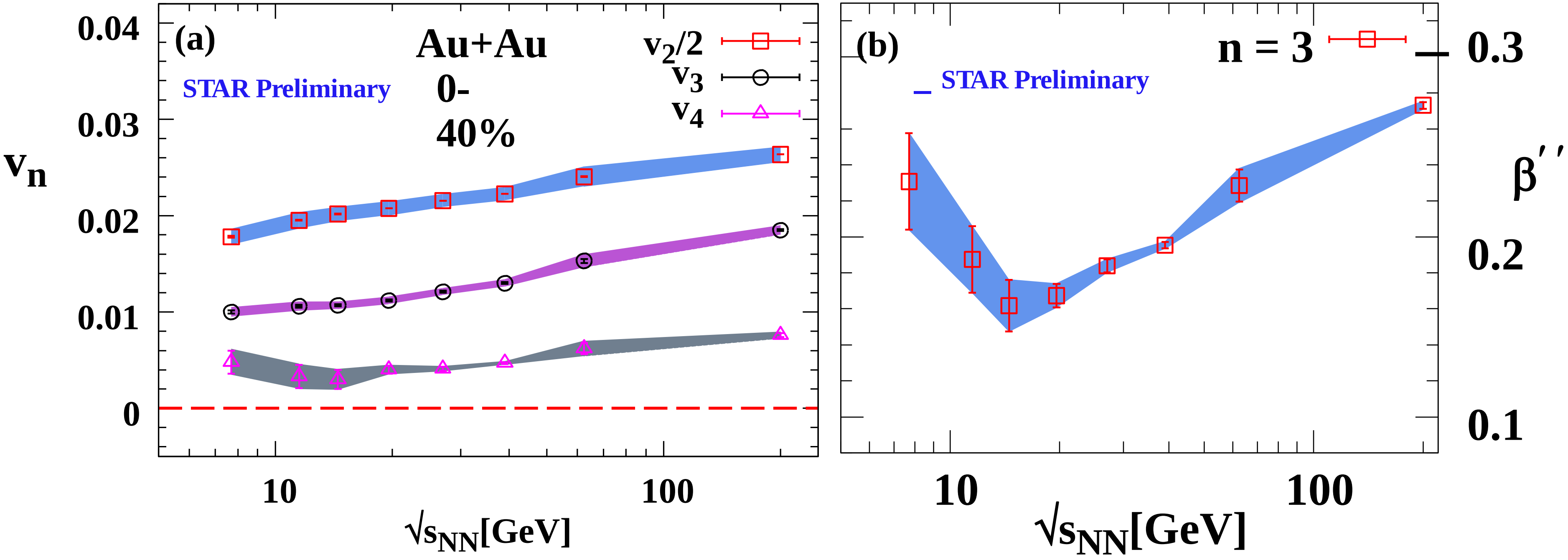




$$V_2(PID, p_T, centrality, \sqrt{s_{NN}}) = V_2(h, centrality, \sqrt{s_{NN}})^* \, V_2(PID, p_T)???$$

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

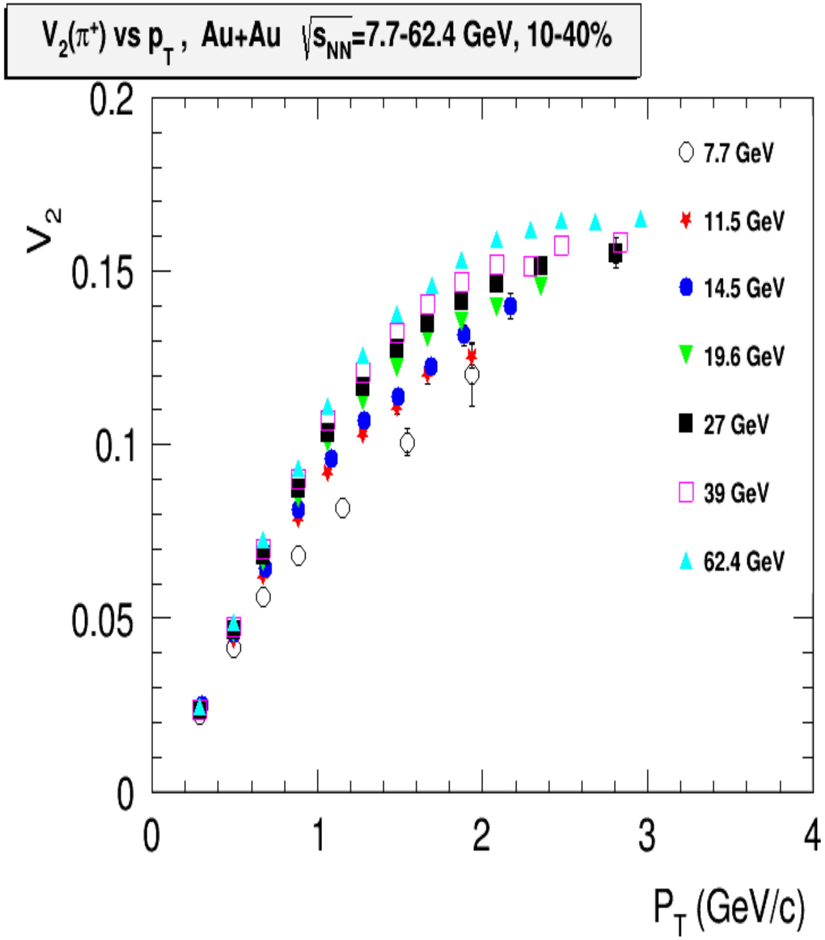
$$\mathrm{VC} \propto \frac{\eta}{s}$$



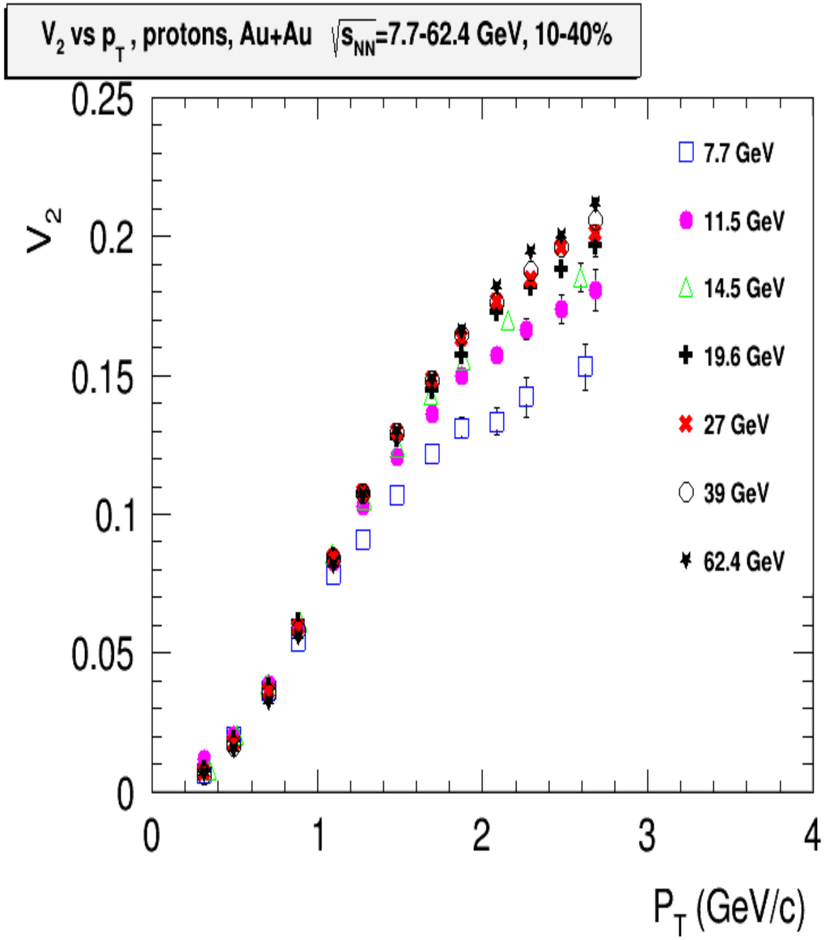
**$V_n$ shows a monotonic increase with beam energy. The viscous coefficient, which encodes the transport coefficient ($\eta/s$), indicates a non-monotonic behavior as a function of beam energy.**

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

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



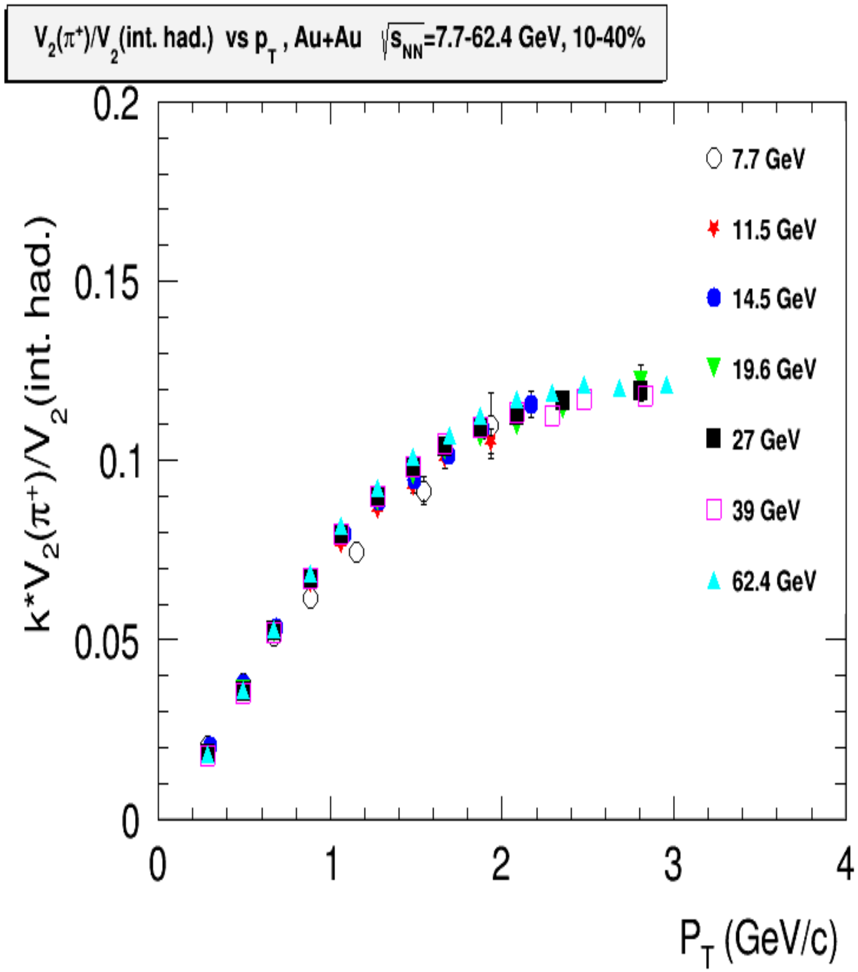
$V_2(\pi^+)$ vs $p_T$ , Au+Au $\sqrt{s_{NN}}$=7.7-62.4 GeV, 10-40%



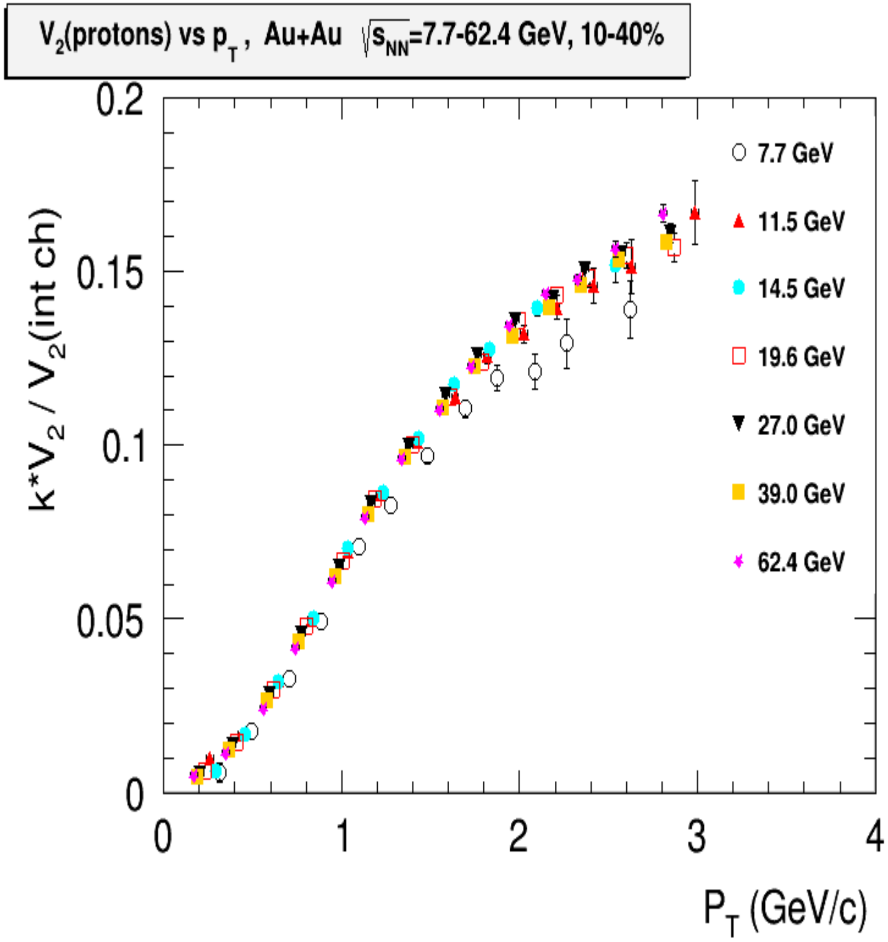
$V_2$ vs $p_T$ , protons, Au+Au $\sqrt{s_{NN}}$=7.7-62.4 GeV, 10-40%

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

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



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



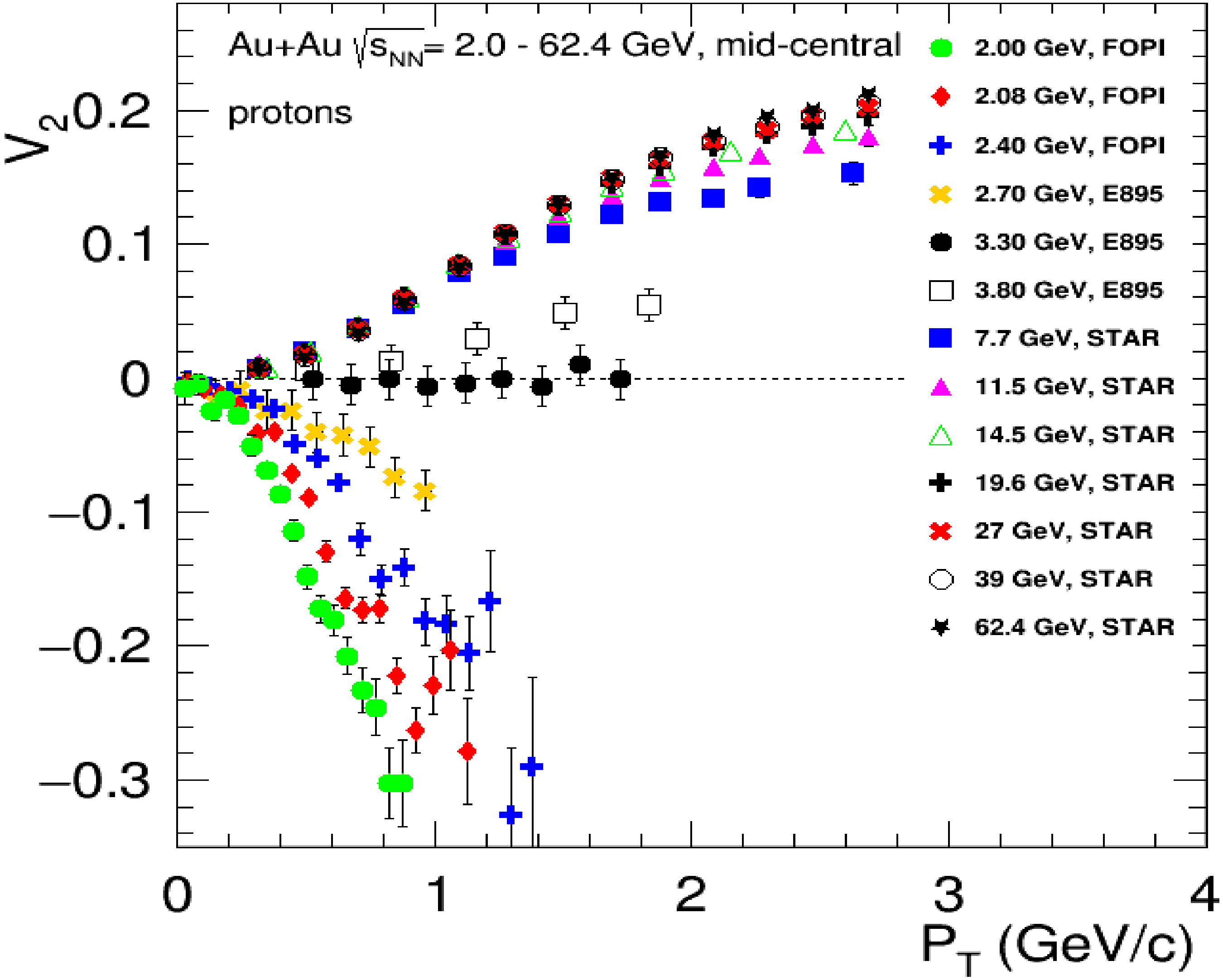
$V_2$(protons) vs $p_T$ , Au+Au $\sqrt{s_{NN}}$=7.7-62.4 GeV, 10-40%

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

# Excitation function of differential elliptic flow

EPJ Web Conf. 204 (2019) 03009

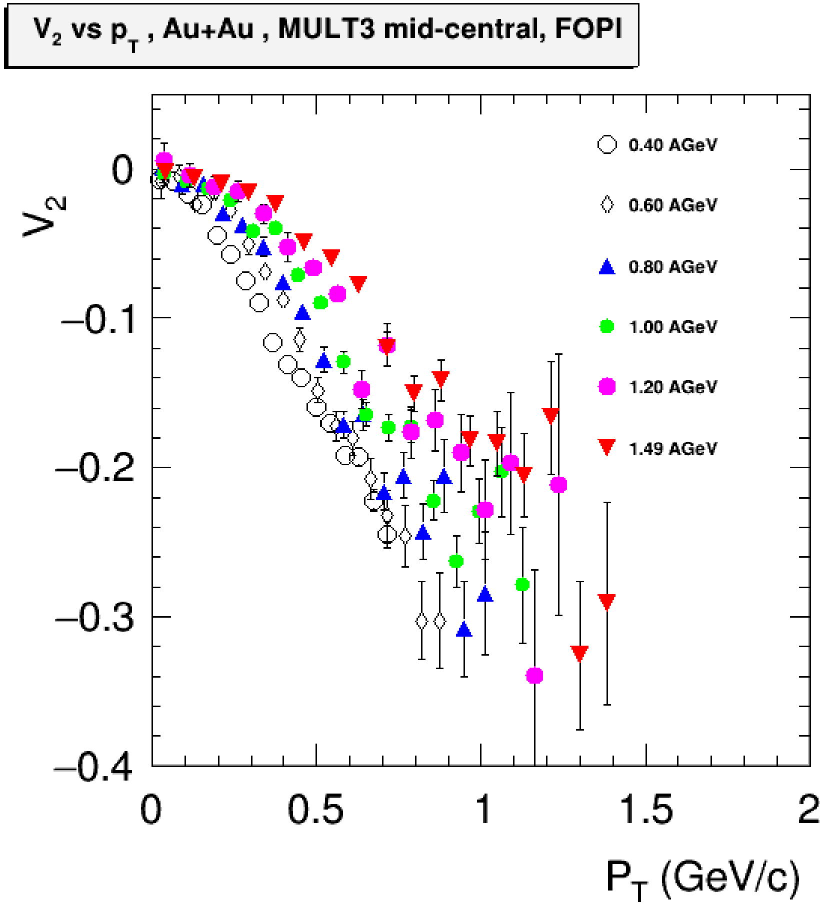
**FOPI (15-29%)**
**E895 (12-25%)**
**STAR (10-40%)**



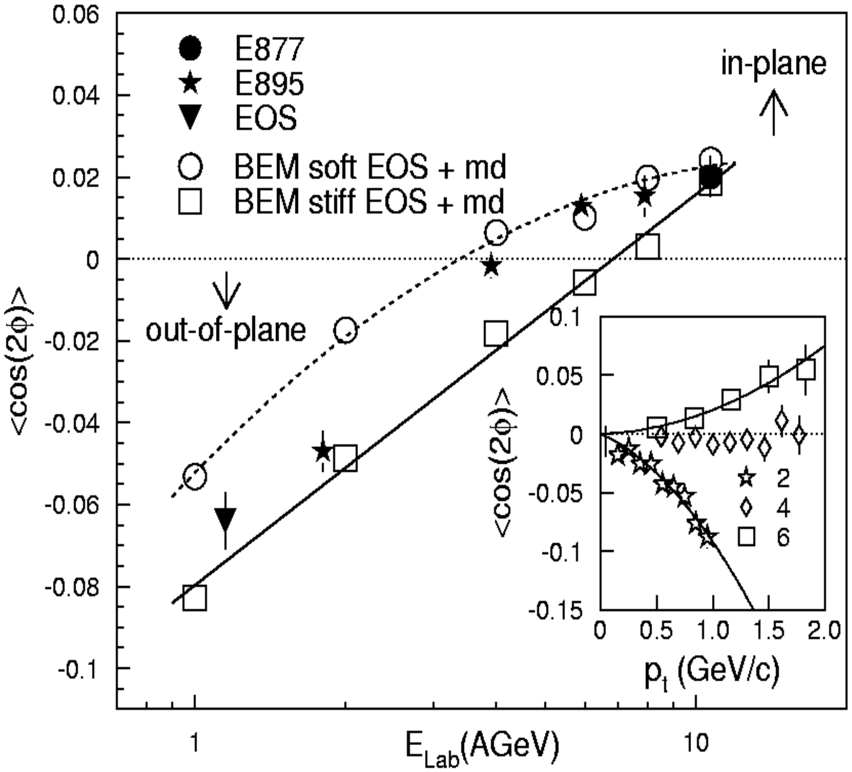
**High precision differential measurements of anisotropic flow?**

# Elliptic Flow at SIS-AGS: interactions with spectators

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



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

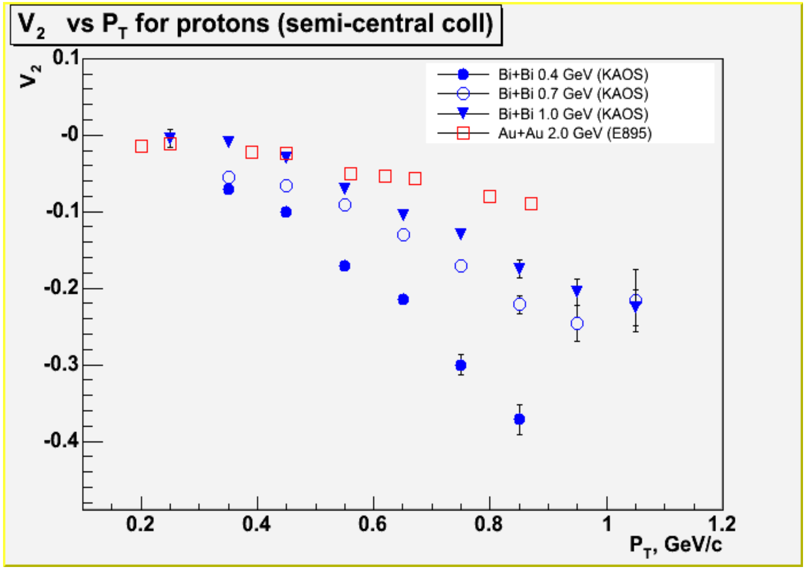


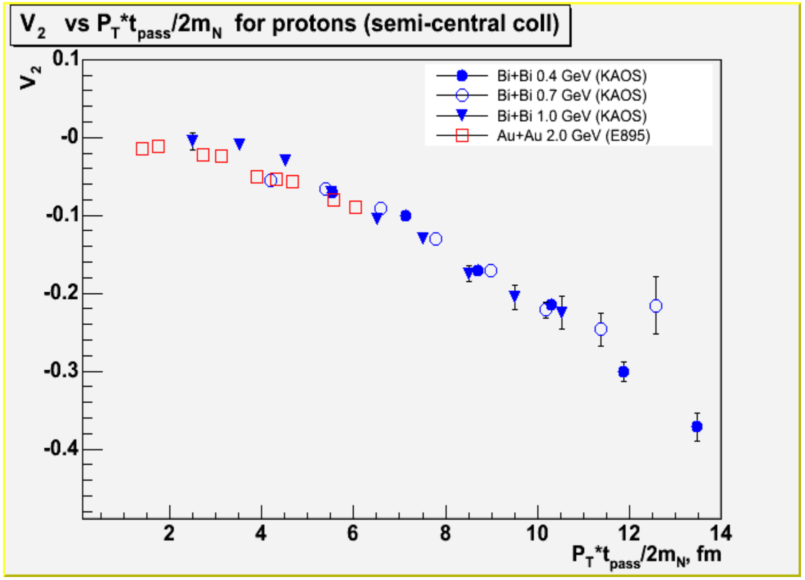
**Passage time: $2R/(\beta_{cm}\gamma_{cm})$**
**Expansion time: $R/c_s$**
**$c_s=c\sqrt{dp/d\varepsilon}$ - speed of sound**

**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**

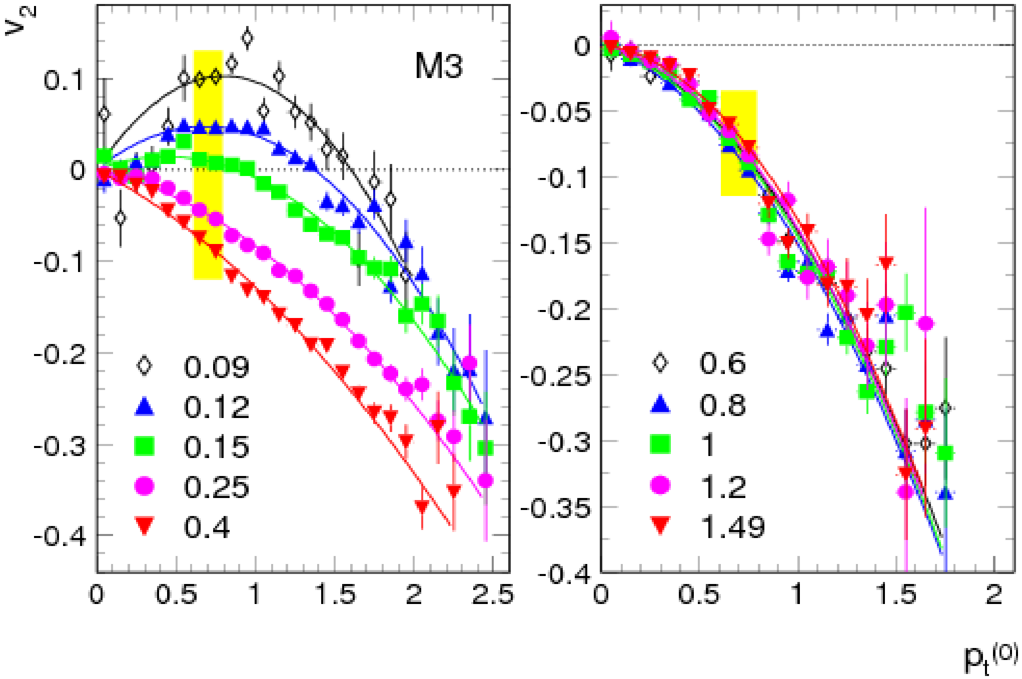
# $v_2$ Flow at SIS-AGS: scaling relations

*(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

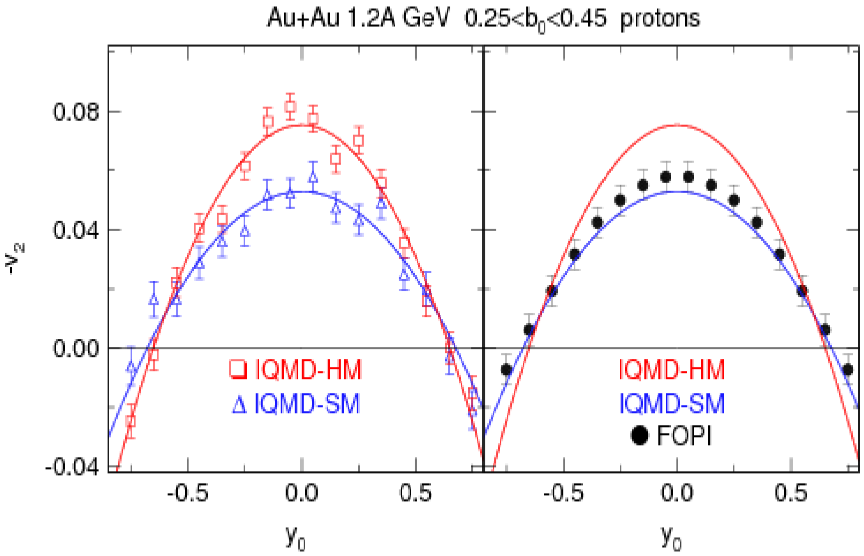


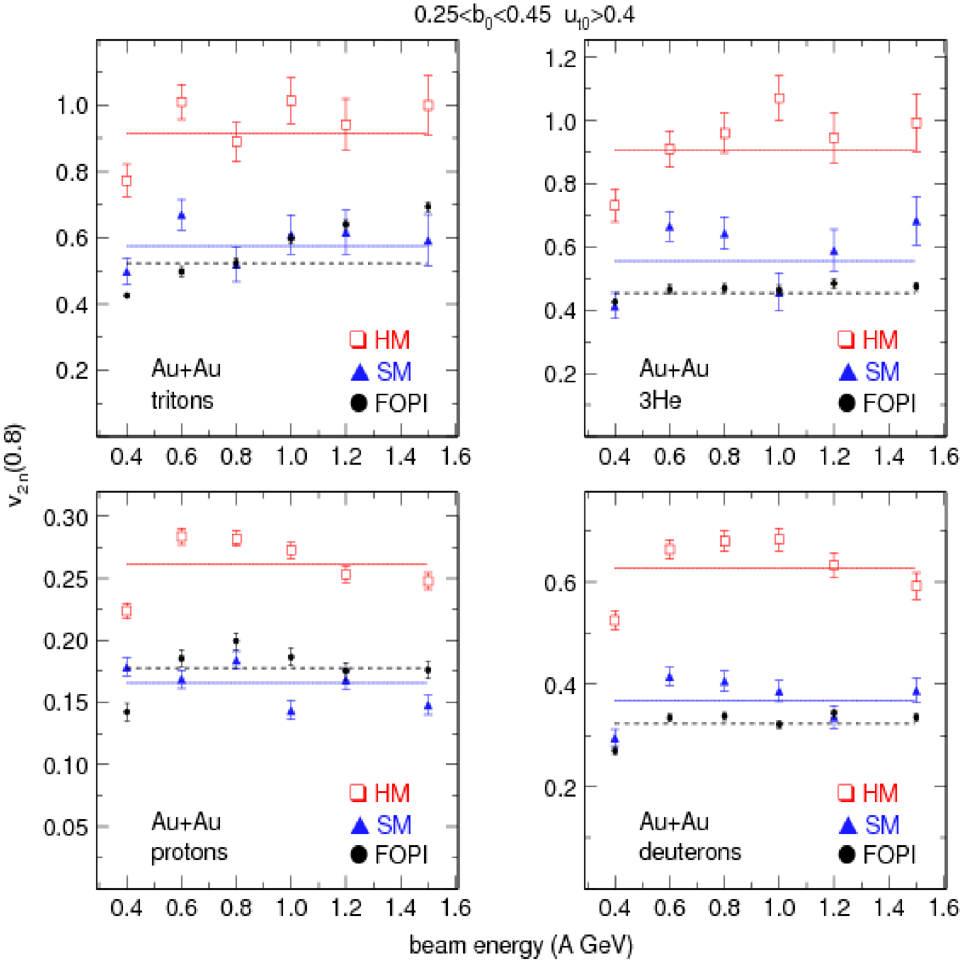
**The rather good scaling observed suggest that $c_s$ does not change significantly over beam energy range 0.4 – 2.0 AGeV. .**

# *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**

# *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**

# Flow performance study for FHCAL TDR ( 2018)

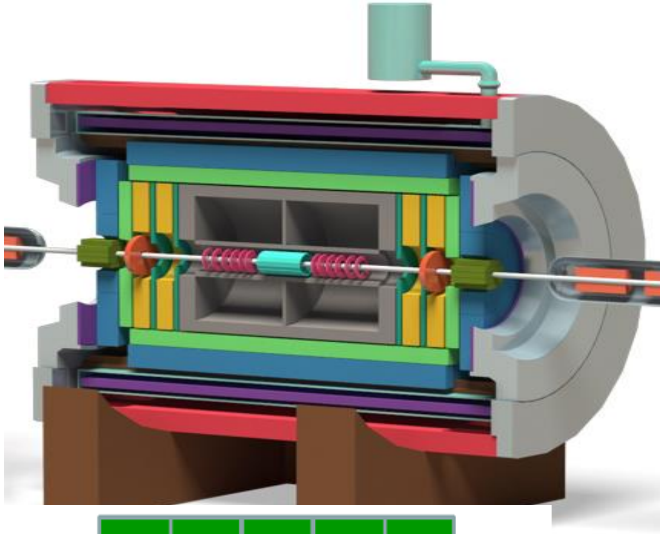
NICA

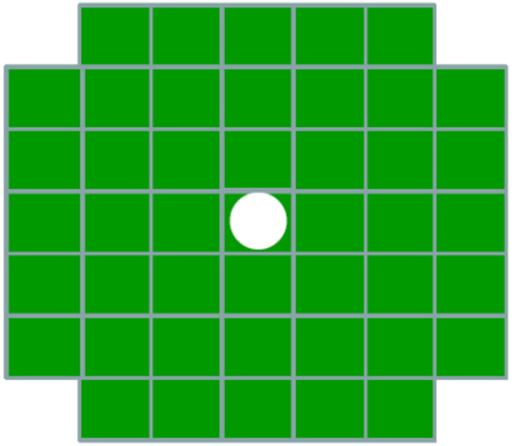
**Technical Design Report for the MPD Experiment**

Nuclotron Based Ion Collider Facility

Forward Hadron Calorimeter (FHCal)

December 2016

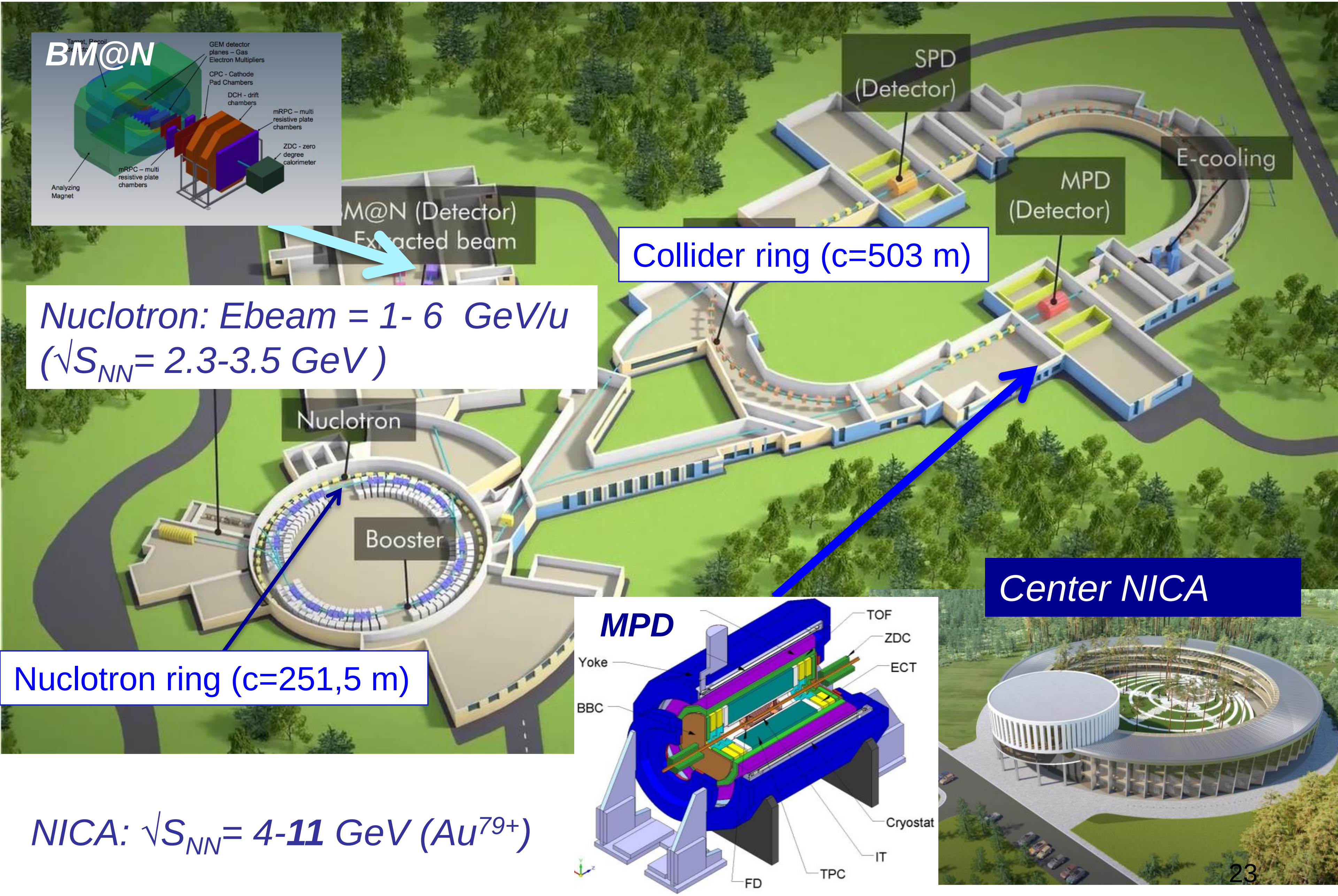




**FHCal coverage: $2.2<|\eta|< 4.8$**

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

# NICA(JINR), Dubna



Collider ring (c=503 m)

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

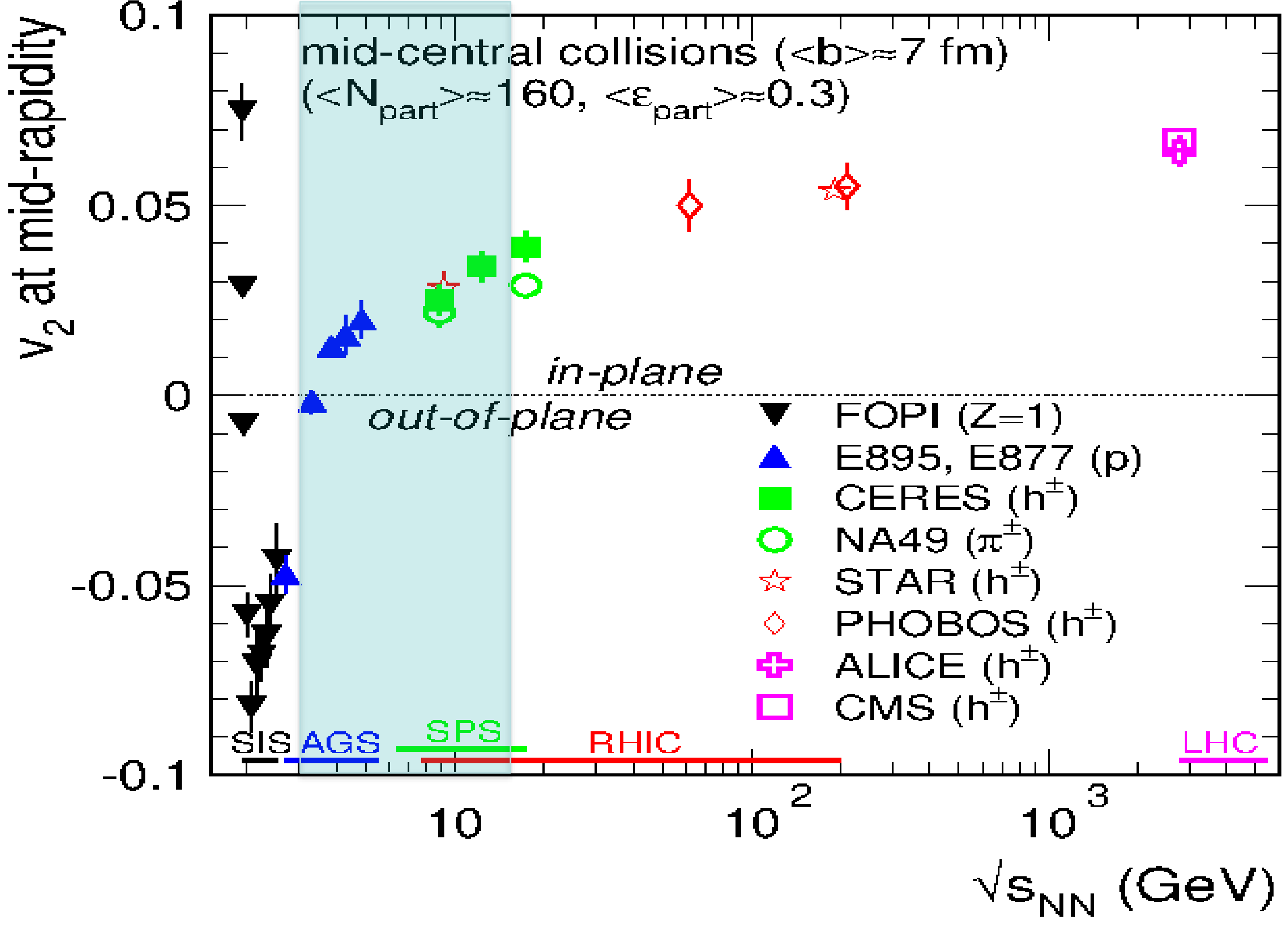
Nuclotron ring (c=251,5 m)

*Center NICA*

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

# Excitation function of integral elliptic flow

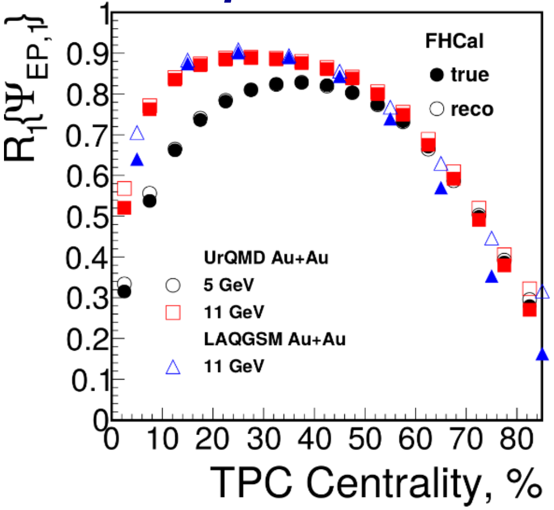
A. Andronic, Int.J.Mod.Phys. A29 (2014) 1430047

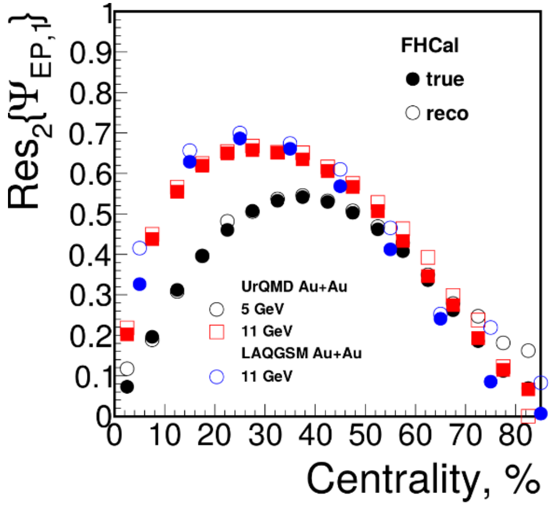


**High precision differential measurements of anisotropic flow?**

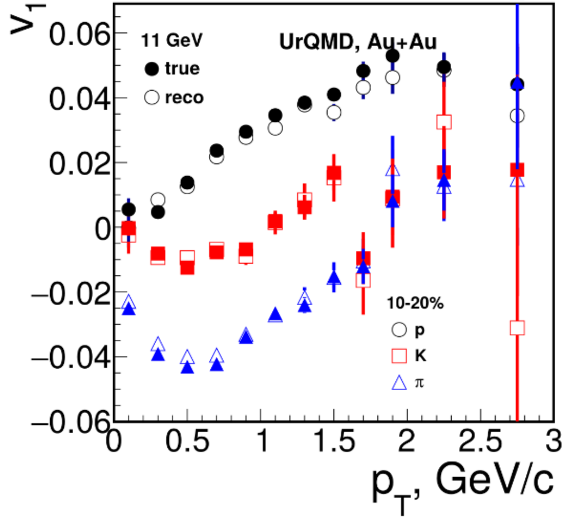
# Flow performance: *$v_n$ of charged hadrons: MPD (NICA)*

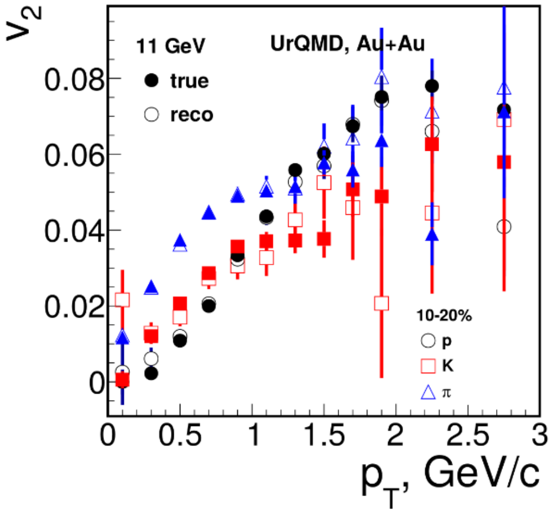
***event plane resolution***

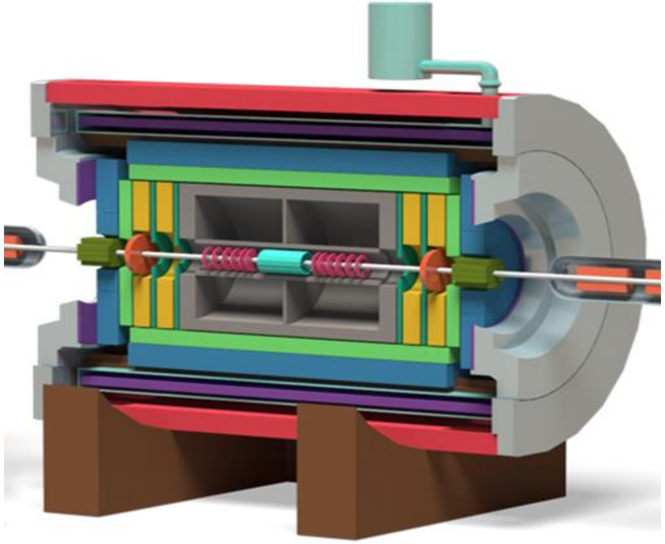


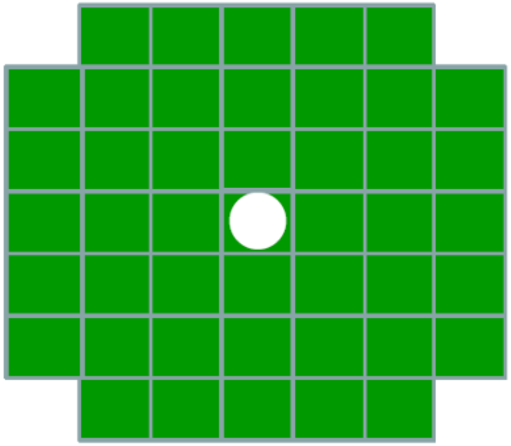


***flow harmonics ($v_1$/$v_2$)***





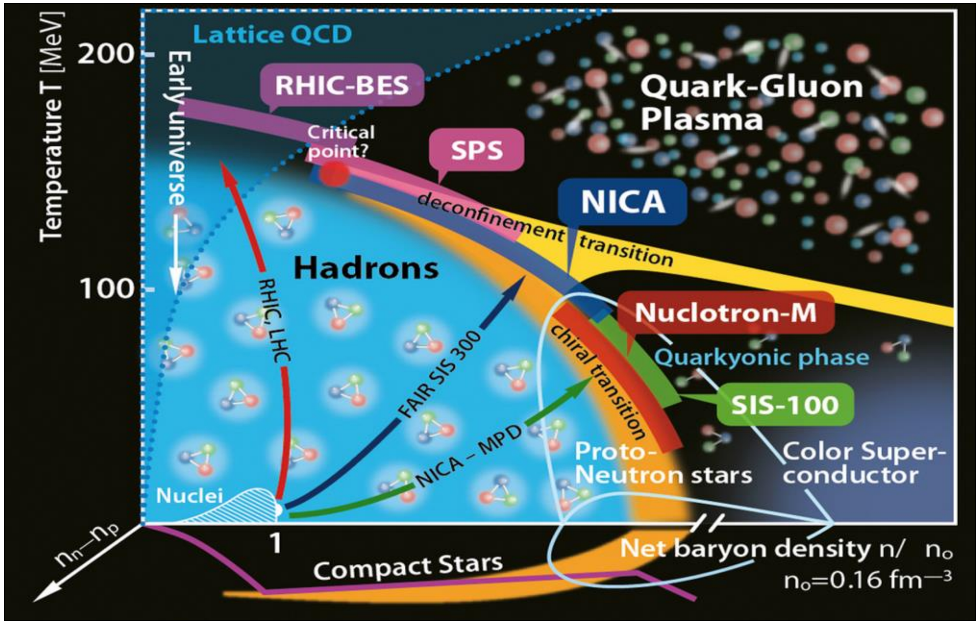




**FHCal coverage:**
**2.2<|η|< 4.8**

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

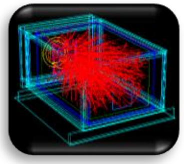
# Phase diagram



## Past measurements

Observation of the phase transition

**BNL AGS**



**CERN SPS**

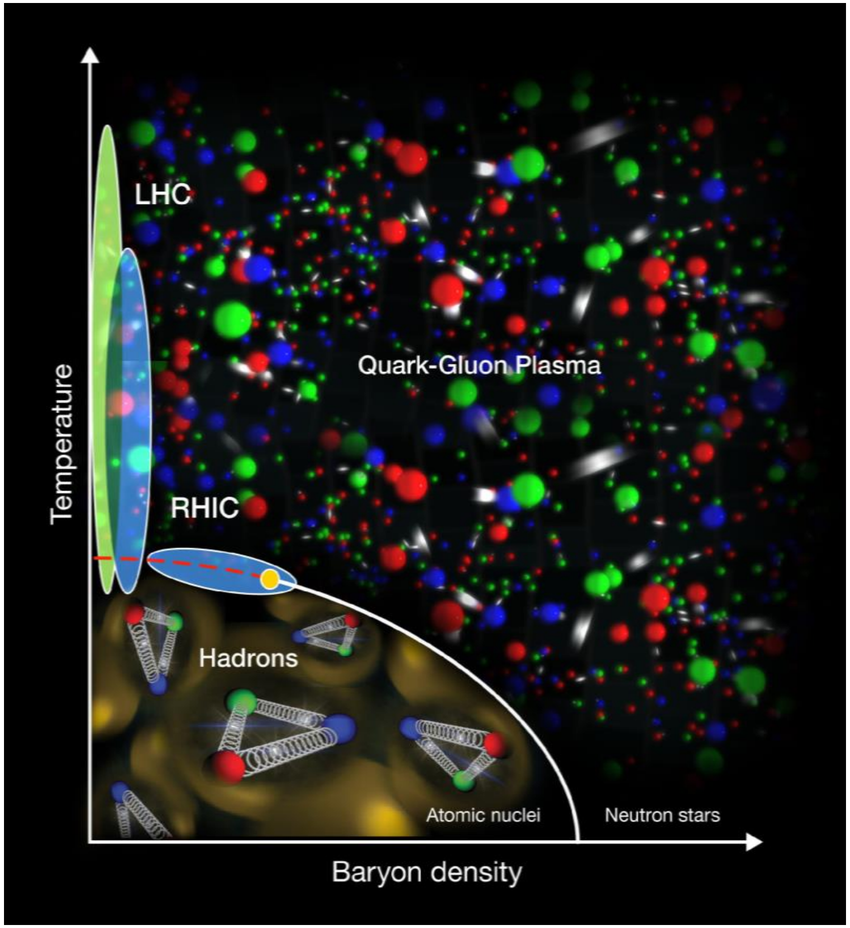
**BNL RHIC**

**CERN LHC**

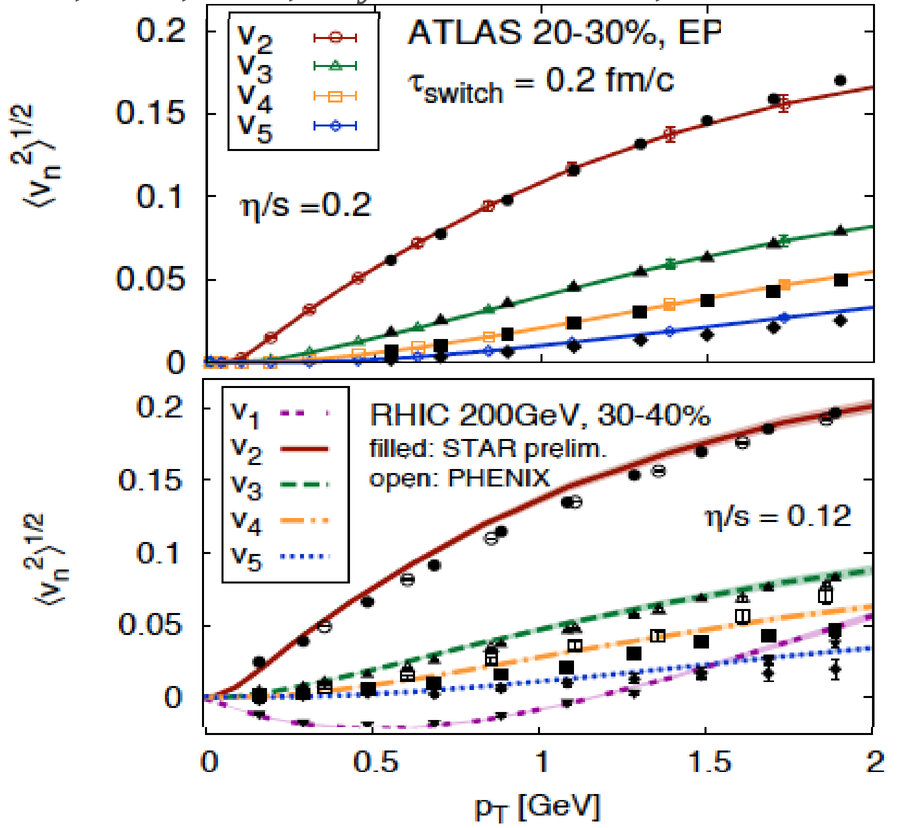
## Current & future measurements

| 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<br>MPD | HADES<br>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<br>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 |

# Perfect Liquid at RHIC and LHC



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

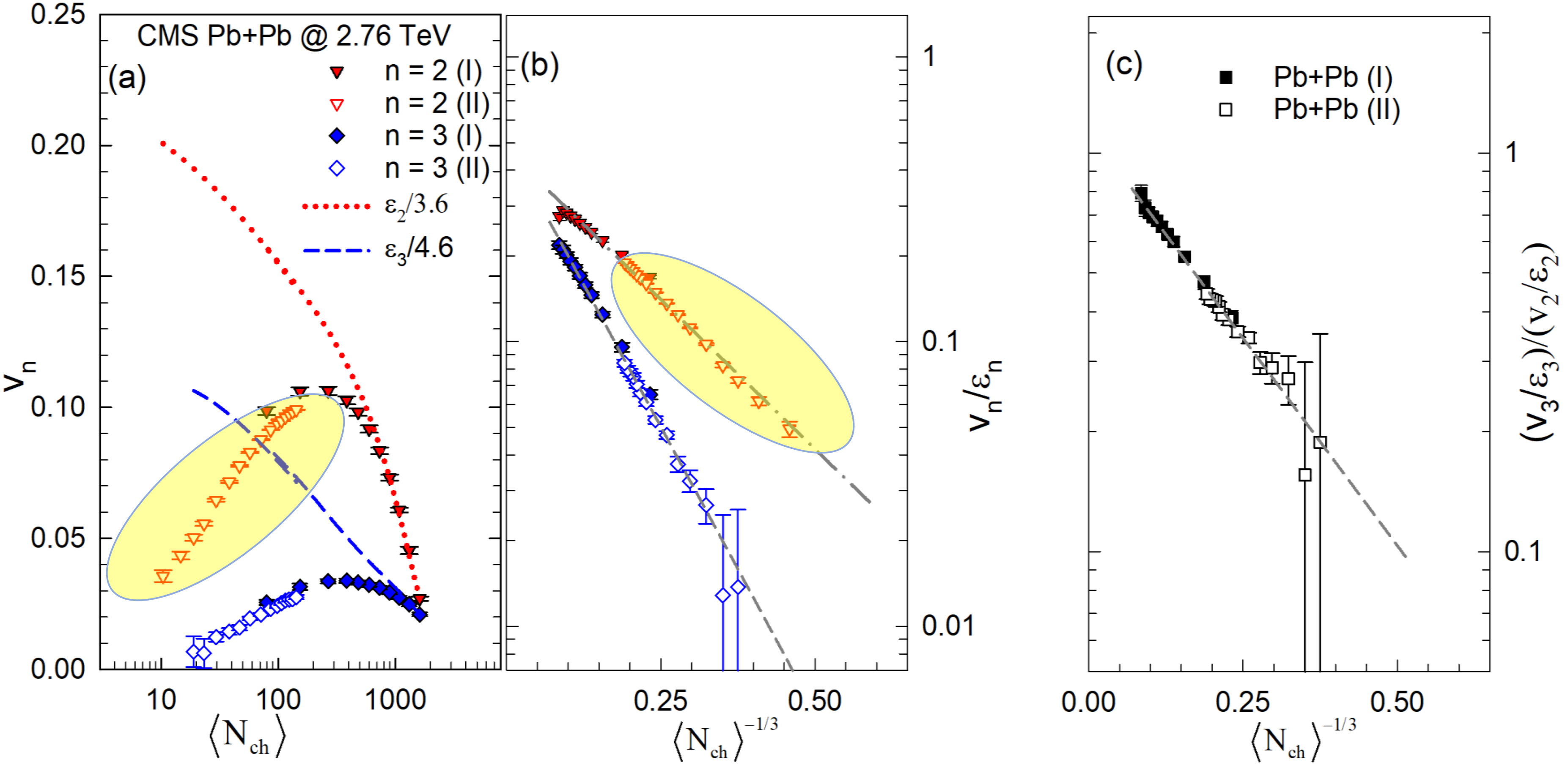


$$\frac{\eta}{s}(T,\mu),\ \frac{\zeta}{s}(T,\mu),\ c_s(T),\ \hat{q}(T),\ \alpha_s(T),\ \text{etc}$$

# Acoustic Scaling - RT

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

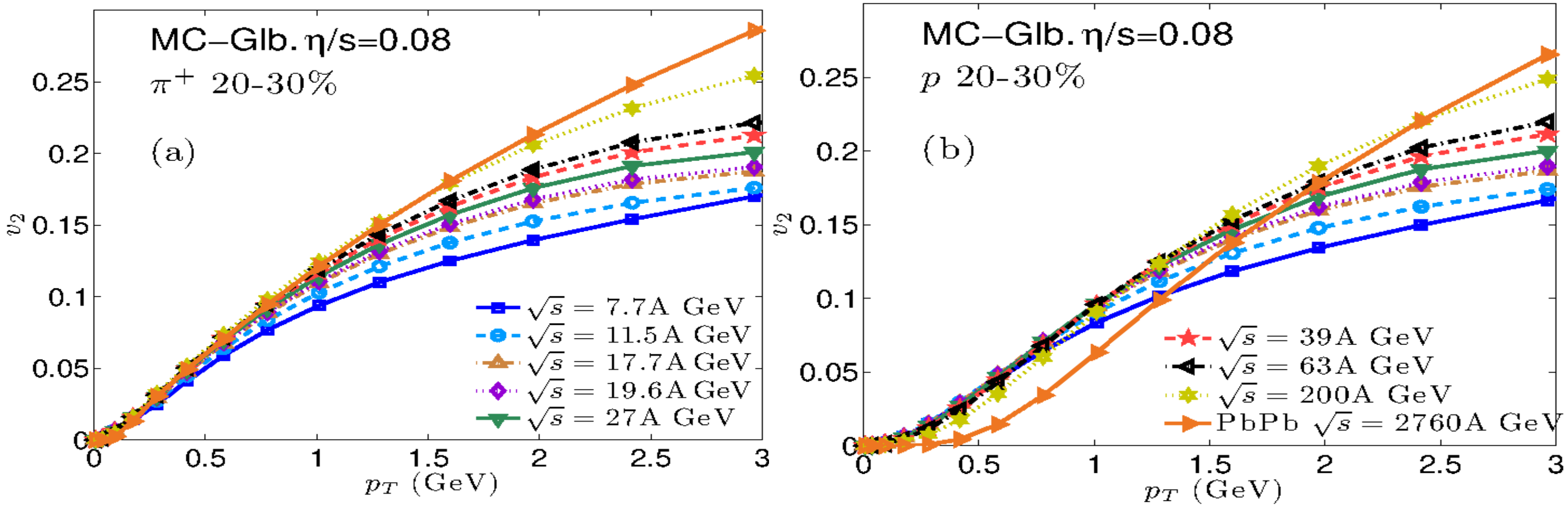
R.A. Lacey et al Phys. Rev. C **98**, 031901(R), 2018



- ✓ 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)

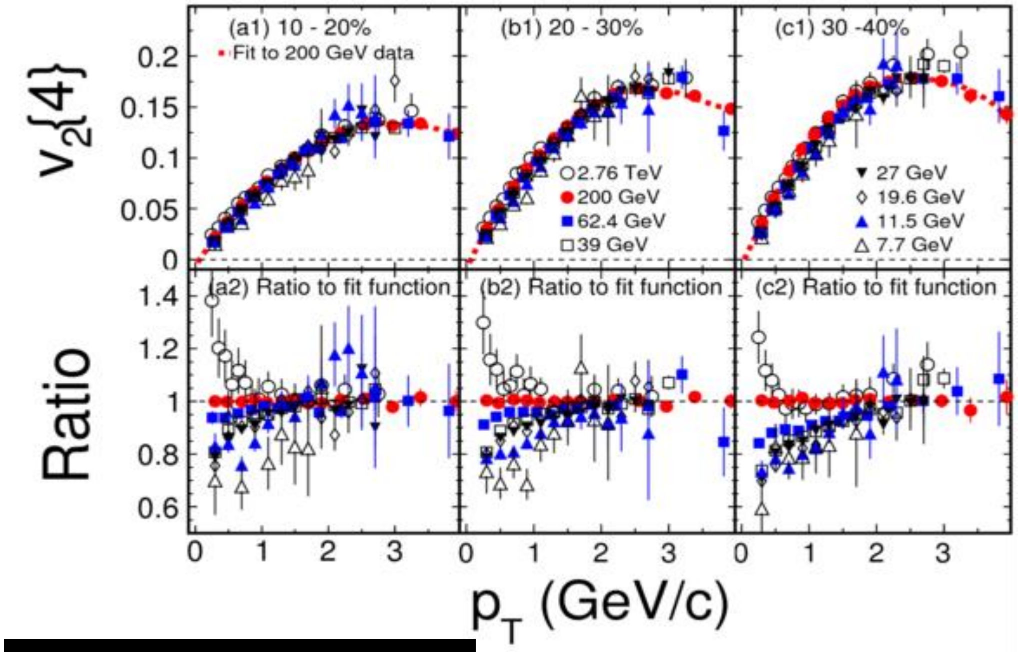
Chun Shen and Ulrich Heinz, Phys. Rev. C 85, 054902(2012), VISH2+1 model calculations



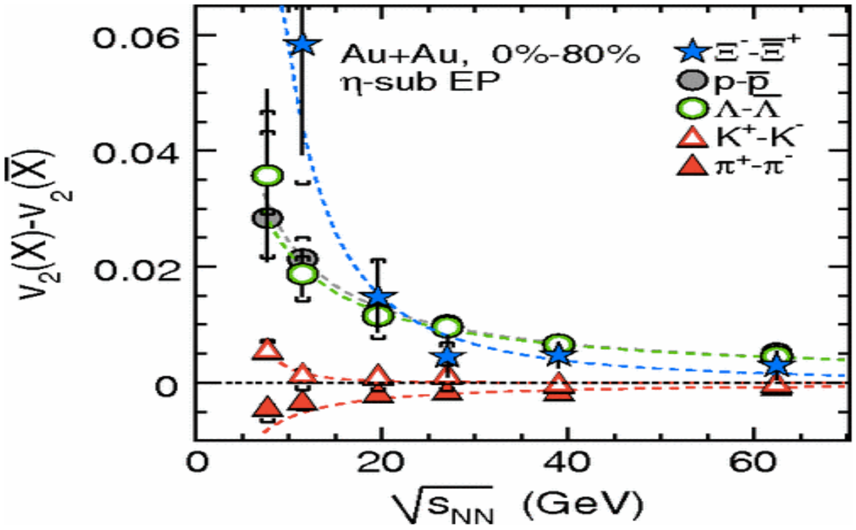
- ✓ **For pions $v_2(p_T)$ varies with $\sqrt{s_{NN}}$ very similarly to the total charged hadron $v_2(p_T)$.**
- ✓ For protons the strong radial flow “blueshifts” the entire flow signal to higher $p_T$ .

# Beam Energy Dependence of Elliptic Flow ($v_2$)

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



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



Surprisingly consistent as the energy changes by a factor ~400

Initial energy density changes by nearly a factor of 10

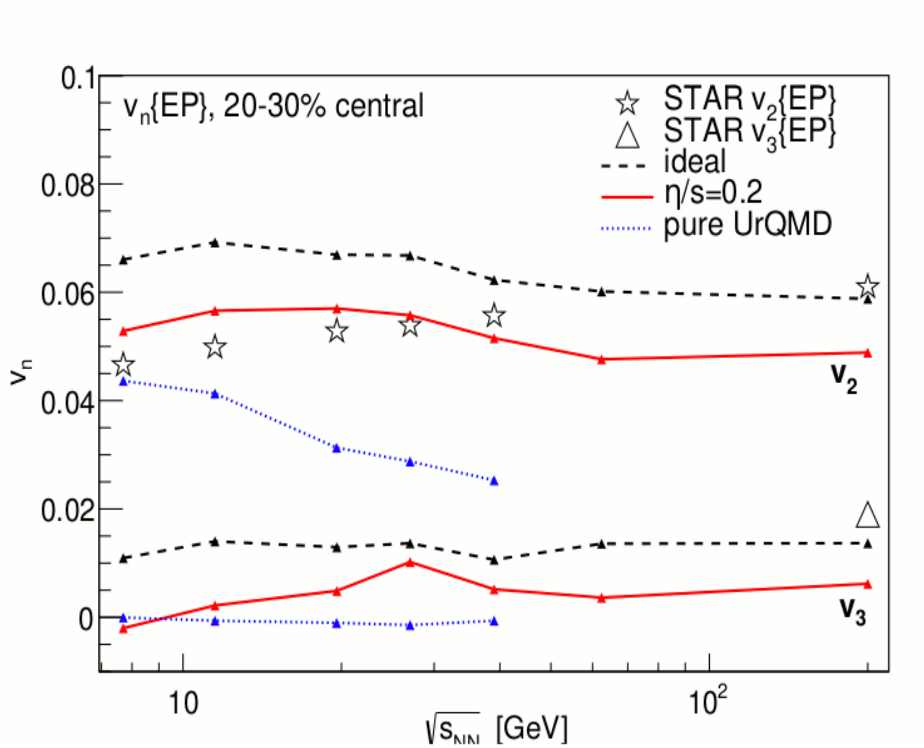
No evidence from v2 of charged hadrons for a turn off of the QGP

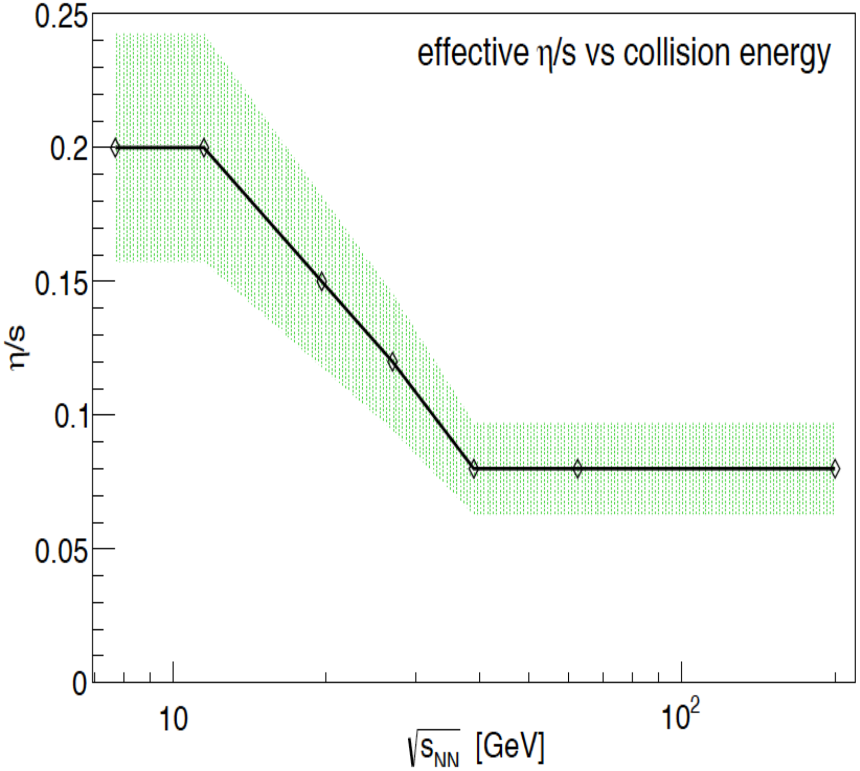
***How sensitive is $v_2$ to QGP?***

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