Anisotropic collective flow and development of the corresponding measurement techniques for the MPD experiment at NICA collider

Arkadiy Taranenko[1] , Dim Idrisov[1], Vinh Ba Luong[1], Nikolay Geraksiev[2,3], Petr Parfenov[1] , Alexander Demanov[1], Alexey Povarov[1] , Viktor Kireyeu[2] , Evgeny Volodihin[1] , Anton Truttse[1], Dmitri Blau[4] , Oleg Golosov[1] , Evgeni Kashirin[1]

[1]National Research Nuclear University MEPhI
[2]VBLHEP JINR
[3]FPT, Plovdiv University “Paisii Hilendarski”
[4]Kurchatov Institute, Moscow

For the MPD Collaboration

This work is supported by the RFBR according to the research project No. 18-02-40086

The Conference "RFBR Grants for NICA", 20-23 October 2020, Dubna, Russia

Research project No. 18-02-40086: “Anisotropic collective flow and development of the corresponding measurement techniques for the MPD experiment at NICA collider”

<u>The goal of this project is to develop and deploy experimental measurement techniques for the azimuthal collective flow measurement with the MPD experiment at the NICA collider for different types of hadrons produced in nucleus-nucleus collisions.</u>

As a result of the project implementation a numerical modelling of the anisotropic collective flow based on the modern Monte-Carlo event generators of heavy-ion collisions with subsequent simulation of the realistic response of the MPD detector subsystems based on the GEANT platform and reconstruction algorithms build in the MPDROOT will be performed.

A set of simulated heavy-ions collisions will be used for deploying of the existing and development of new algorithms for the measurement of the anisotropic collective flow which will utilize different combinations of the MPD detector subsystems.

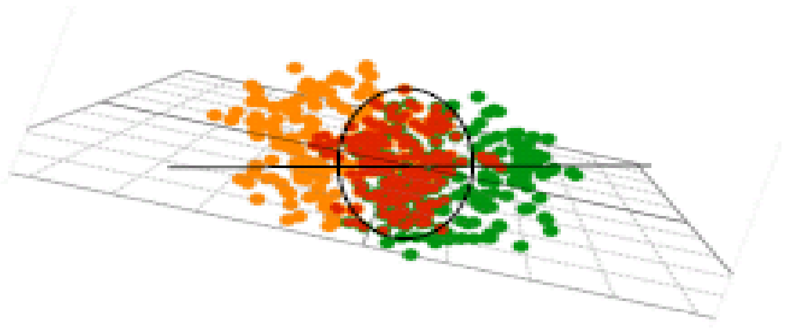
Petr Parfenov, “What do anisotropic flow measurements can tell us about the matter created in the little bang at NICA?”, Models/Data (22/10/2020, 15:10)

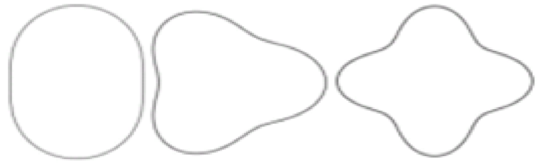
Dim Idrisov: “The comparison of methods for anisotropic flow measurements with the MPD Experiment at NICA” (22/10/2020, 15-30)

Outline

- Introduction: Why measure anisotropic flow?
- Beam energy dependence of anisotropic flow.
- What to expect for flow at NICA energies: Models vs Data
- Sensitivity of different methods to flow fluctuations and nonflow
- Feasibility study of anisotropic flow of identified hadrons and V0 particles in MPD (NICA)
- Summary and outlook

Anisotropic Collective Flow at RHIC/LHC

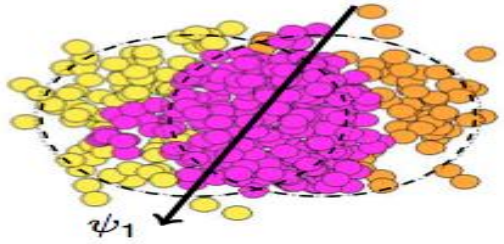




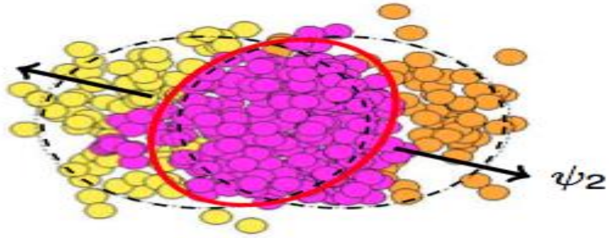
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

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

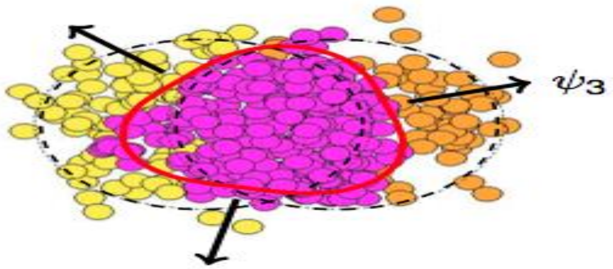
Initial eccentricity (and its attendant fluctuations), ε_n, drives momentum anisotropy, v_n, with specific viscous modulation



v_1 - directed flow

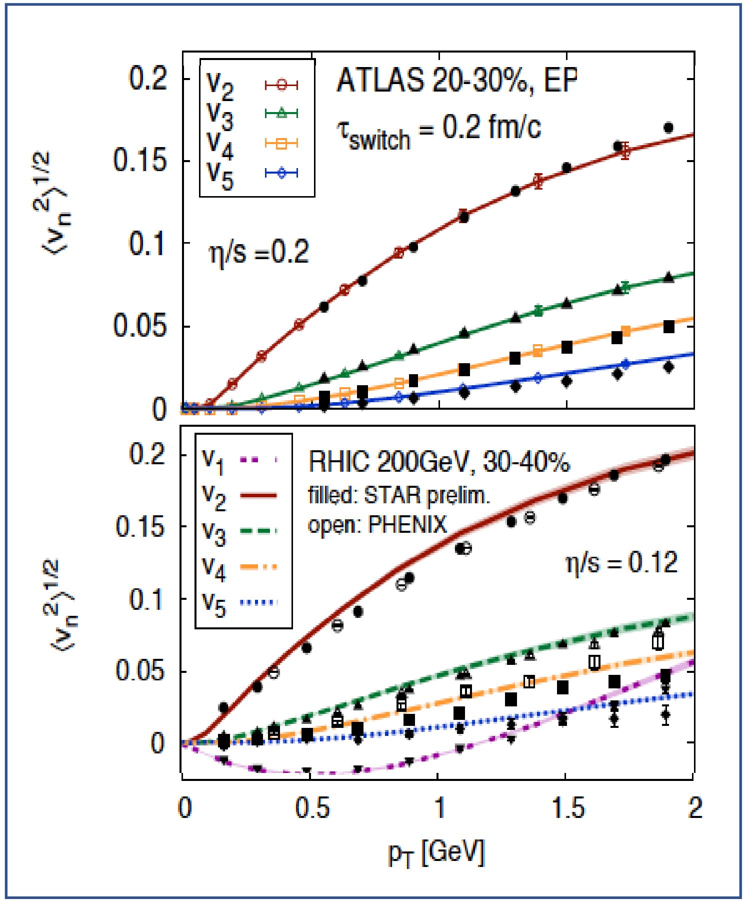


v_2 - elliptic flow

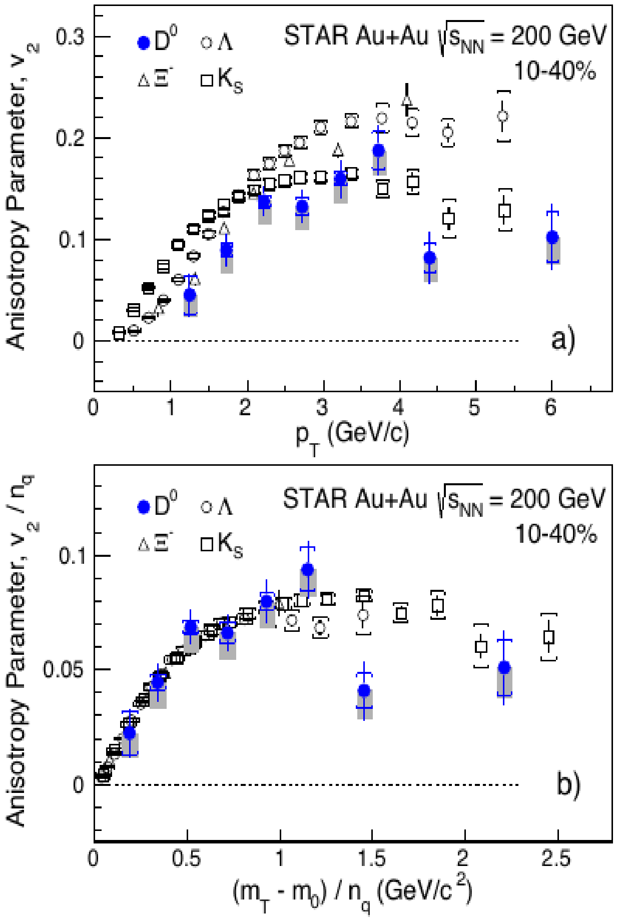


v_3 - triangular flow

Anisotropic Collective Flow at top RHIC / LHC



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



STAR PRL118 (2017) 212301

V_n (p_T, centrality) - sensitive to the early stages of collision.
Important constraint for transport properties: EOS, η/s, ζ/s, etc.

v_n of identified hadrons:

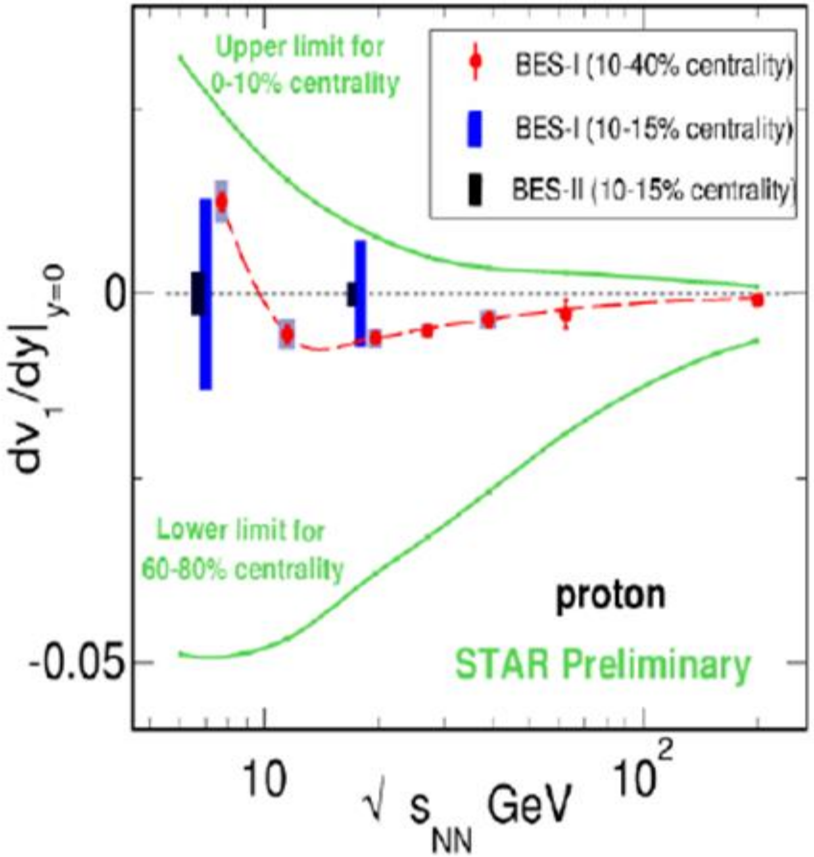
Mass ordering at p_T < 2 GeV/c
(hydrodynamic flow, hadron rescattering)

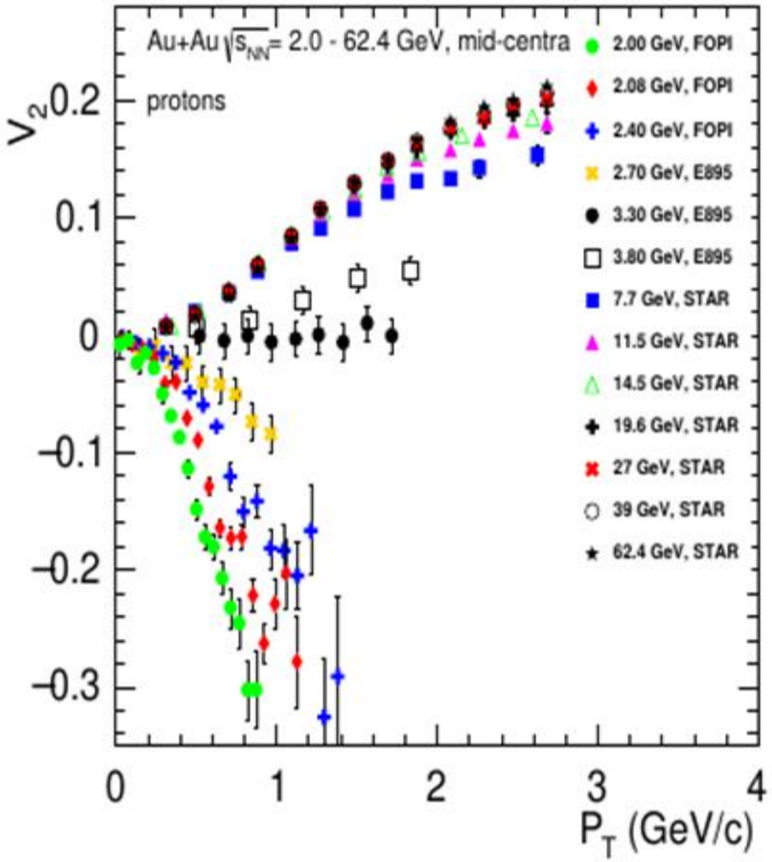
Baryon/meson grouping at p_T > 2 GeV/c
(recombination/coalescence),
Number of constituent quark (NCQ) scaling

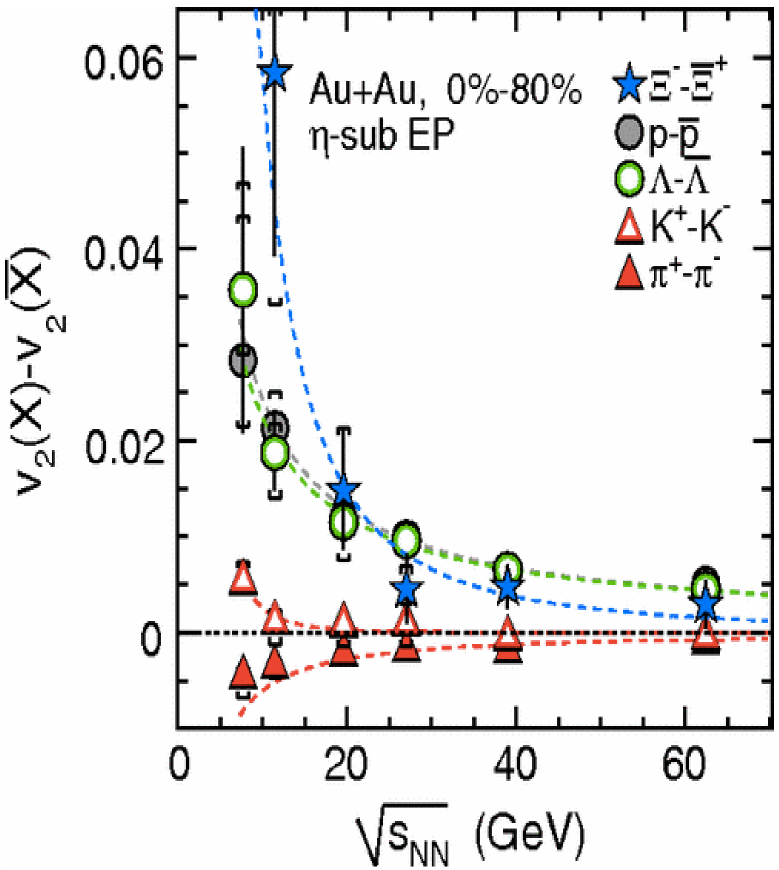
No difference between particles and antiparticles

Beam energy dependence of anisotropic flow

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







- **Minimum in slope of directed flow (dv_1/dy) as a function of beam energy for baryons**
- **Small change in v_2 (p_T) for inclusive and identified charged hadrons**
- **Substantial particle-antiparticle split in v_2 at lower energies**
- **Strong energy dependence of v2 at $\sqrt{s_{NN}}$=3-11 GeV**

Anisotropic Flow at NICA energies: Data vs Models

Anisotropic flow at NICA energies   Experimental Data:

(1) E895 Collaboration Au+Au at 2.7, 3.32, 3.85 and 4.3 GeV

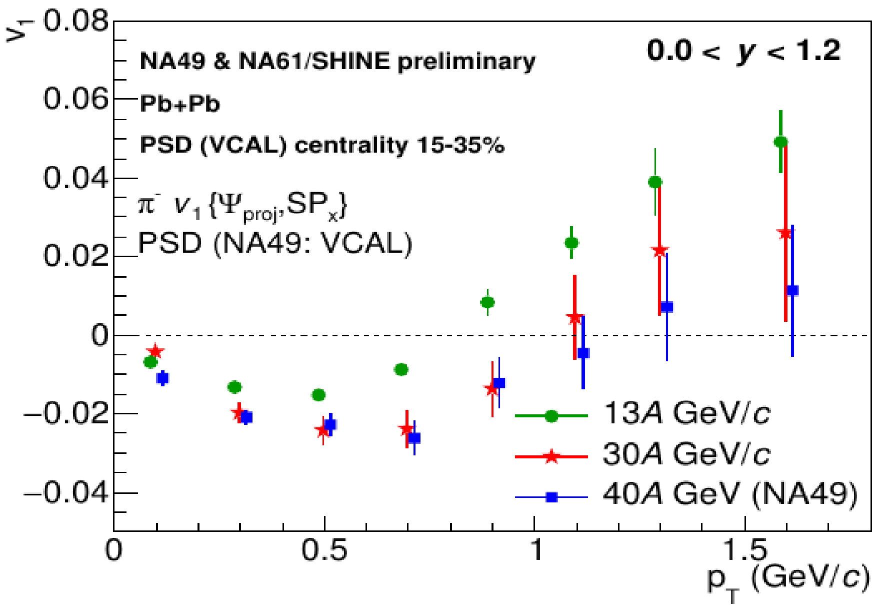
(2) NA61/NA49 Pb+Pb at 5.1, 7.6 and 8.9 GeV

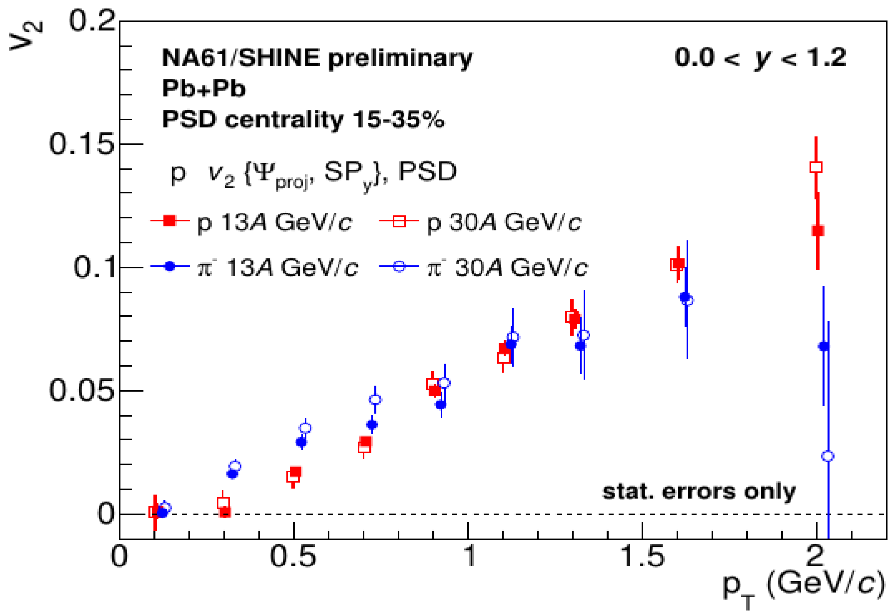
(3) STAR Collaboration Au+Au at 4.5, 7.7 and 11.5 GeV

Anisotropic flow at NICA energies   Models:

(1) String/Hadronic Cascade Models: UrQMD, HSD, SMASH, JAM, DCM-QGSM

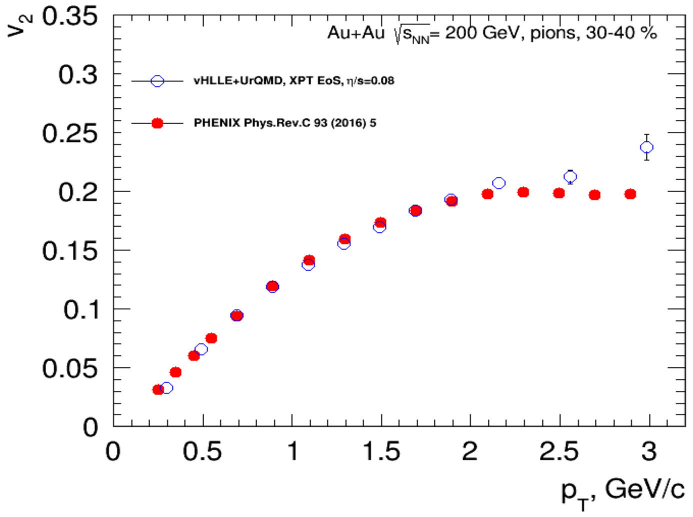
(2) Hybrid Models: viscous hydro+cascade (vHLLE+UrQMD и MUSIC+UrQMD) и parton/string models (AMPT, PHSD и PHQMD)

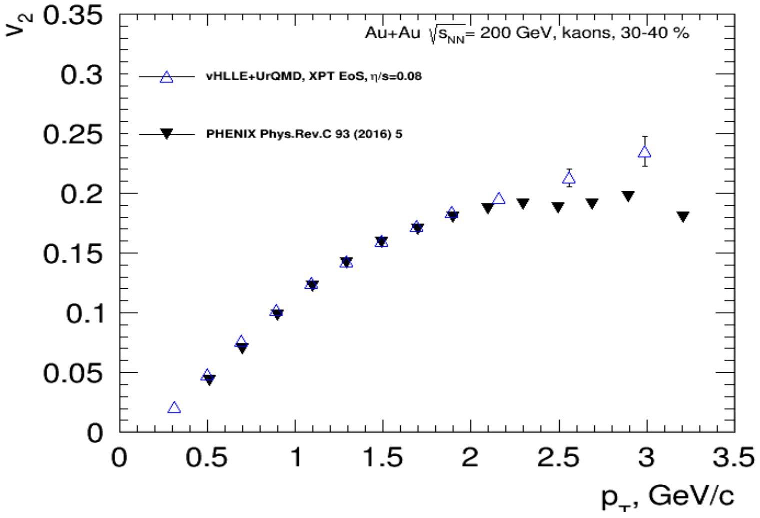




MEPhI in NA61/SHINE: Golosov. O , Kashirin E, (ICPPA 2020)

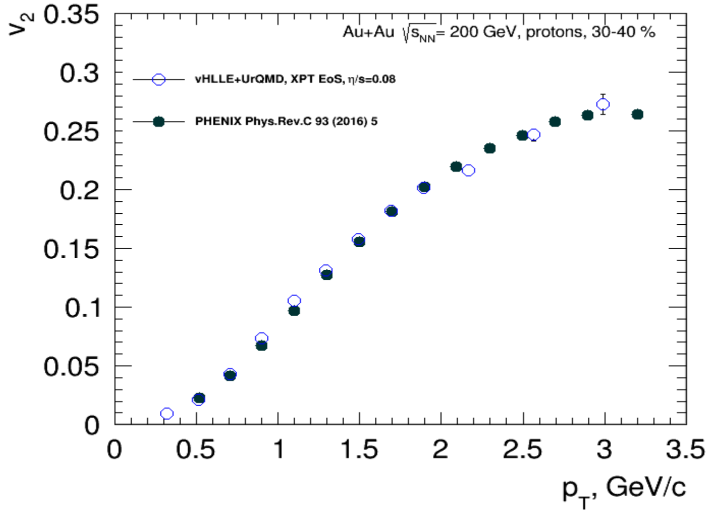
vHLLE+UrQMD: Elliptic flow at top RHIC energy

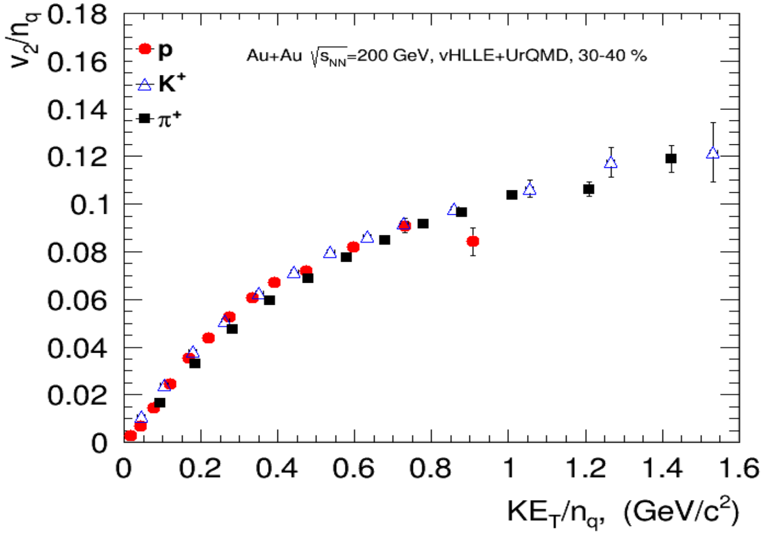




3D hydro model vHHLE + UrQMD (XPT EOS), η/s= 0.08 + param from

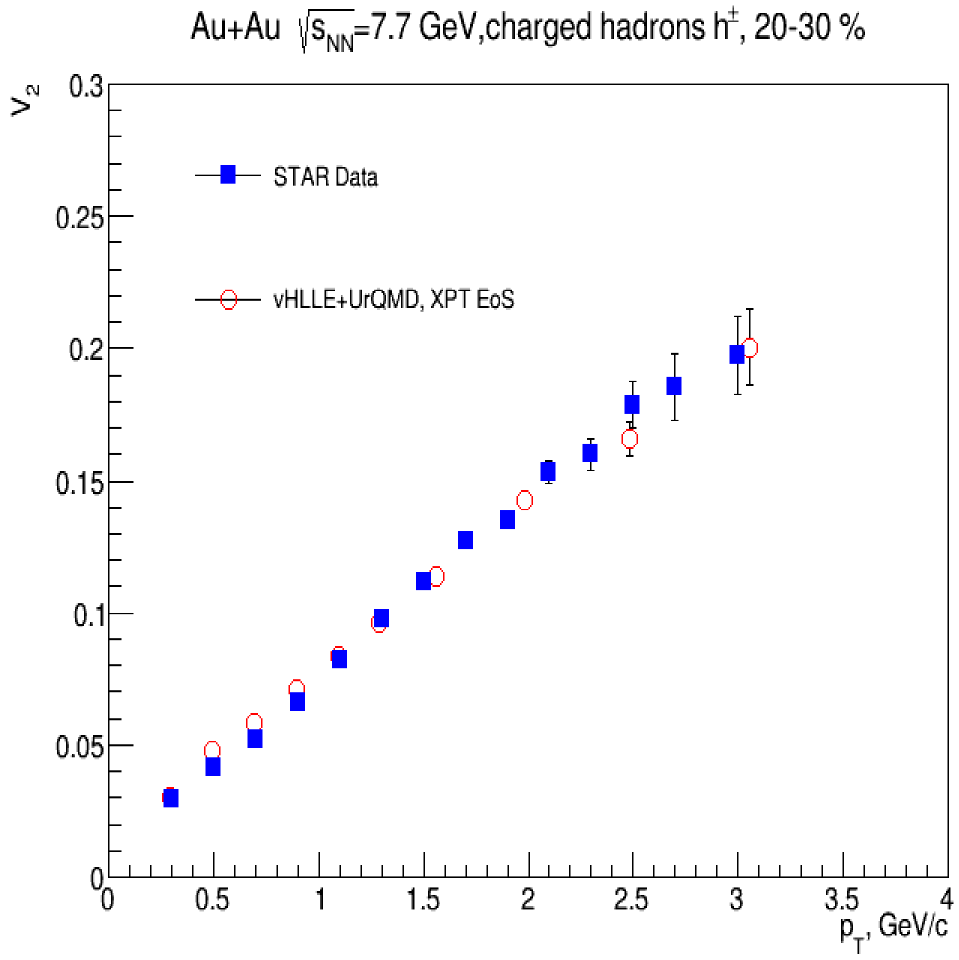
Iu.A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher , Phys.Rev. C91 (2015) no.6, 064901

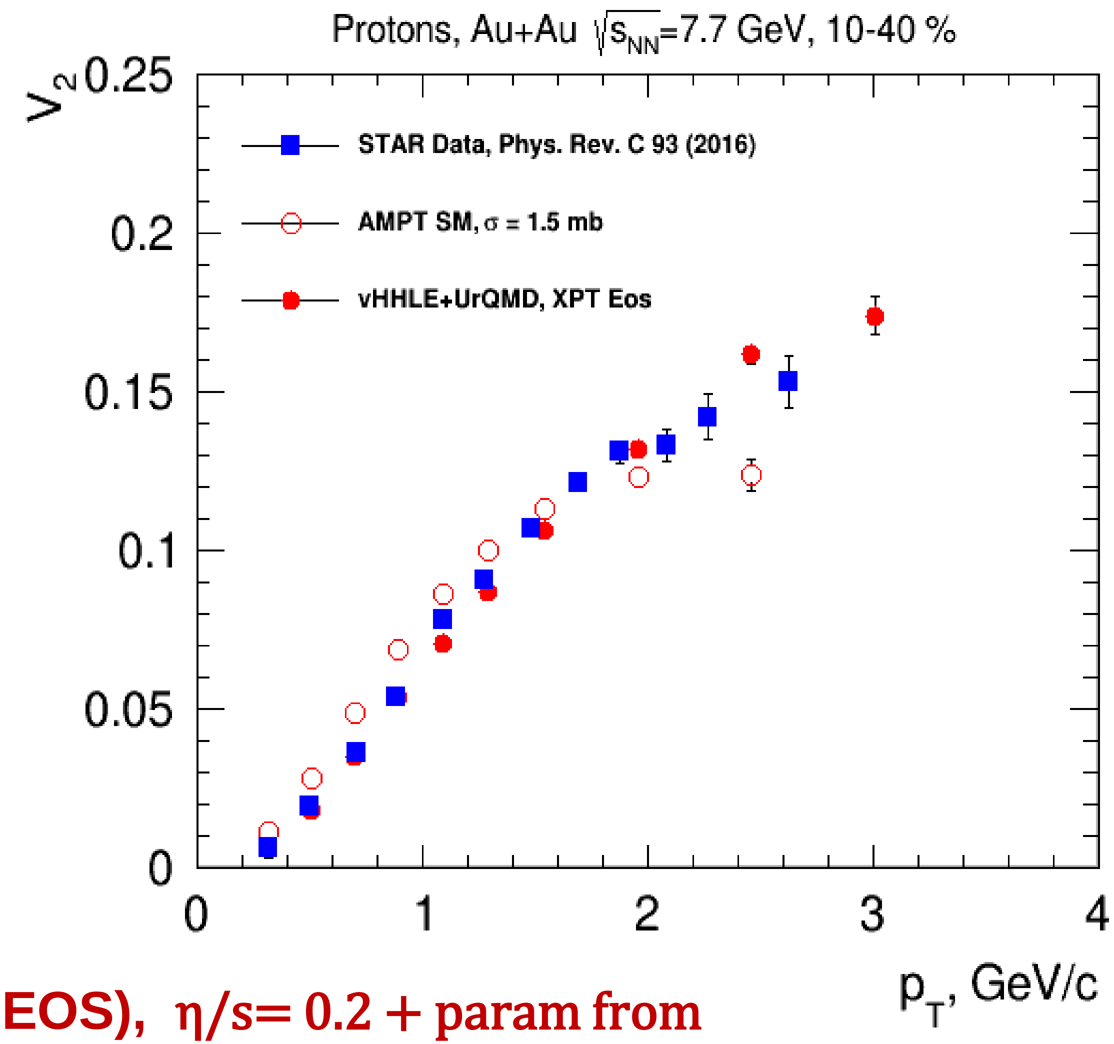




Reasonable agreement between results of vHLLE+UrQMD model and published PHENIX data for 200 GeV including KET/nq scaling

Elliptic flow at NICA energies: Models vs Data comparison

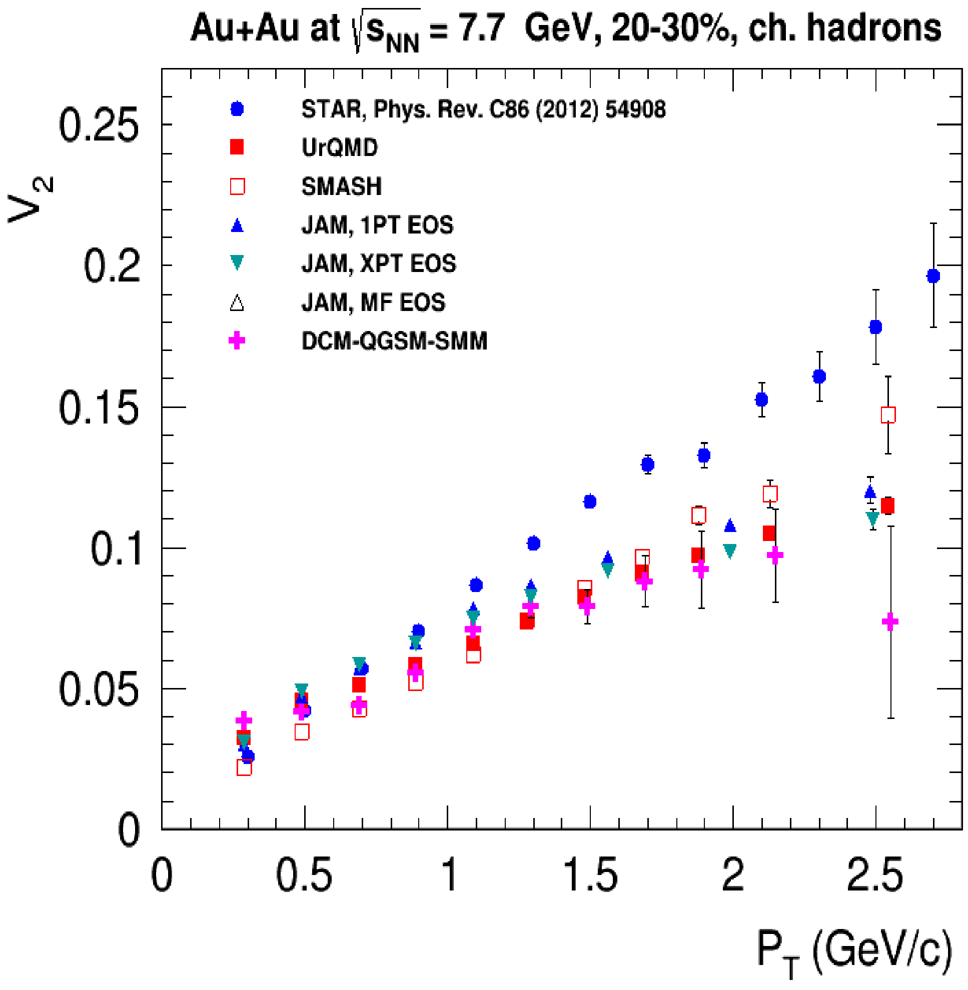


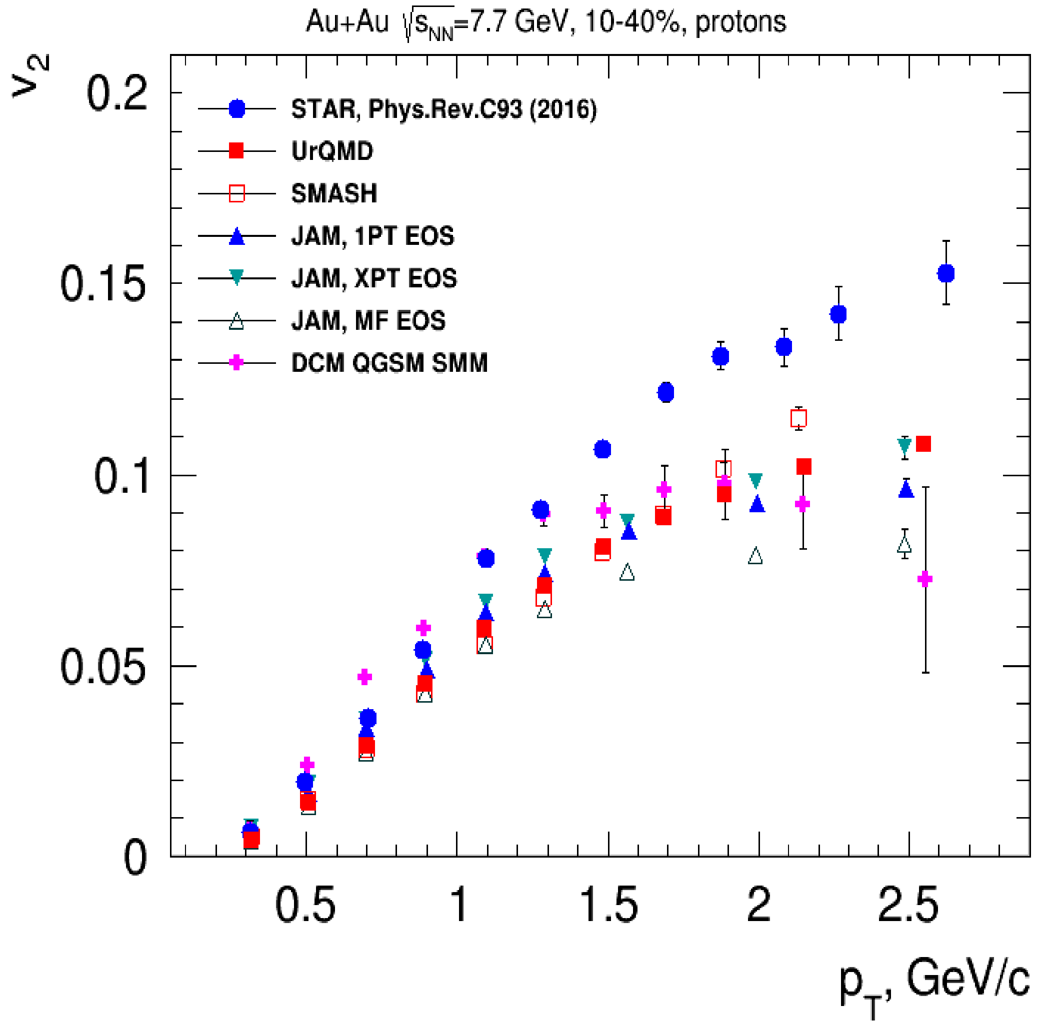


3D hydro model vHHLE + UrQMD (XPT EOS), $\eta/s = 0.2$ + param from

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

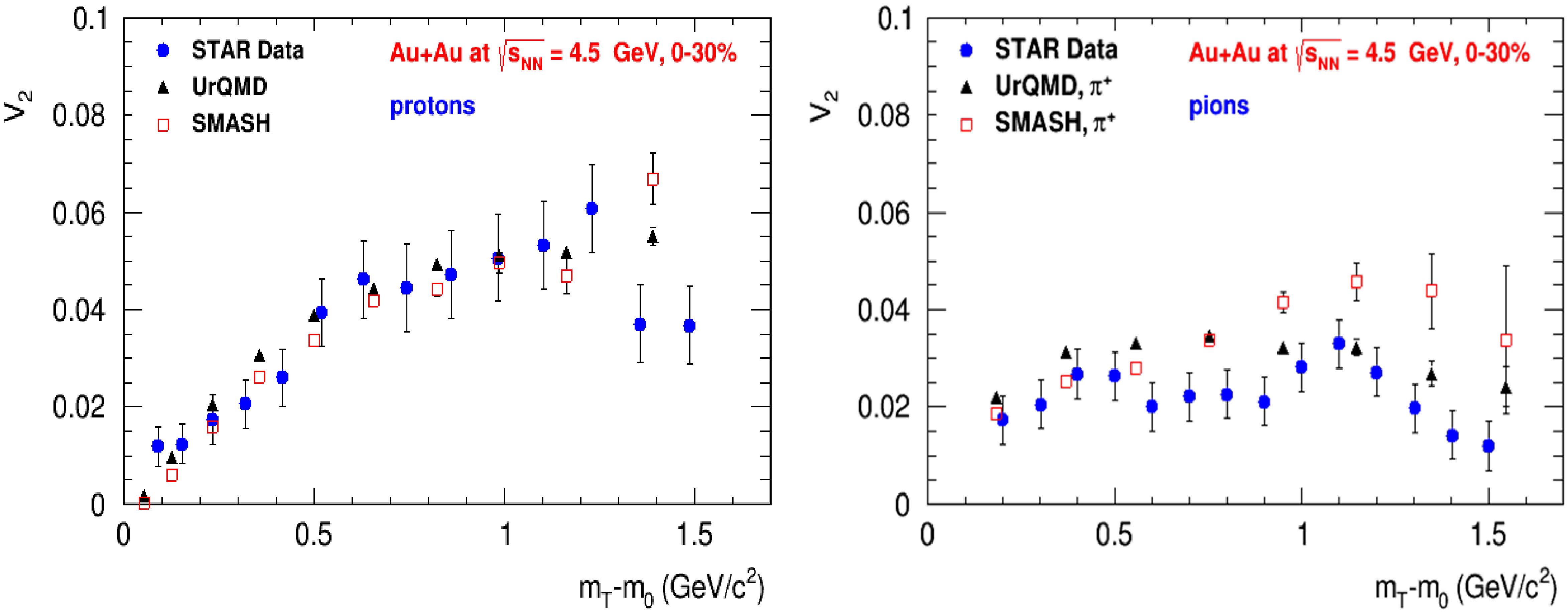
Elliptic flow at NICA energies: Models vs Data comparison





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

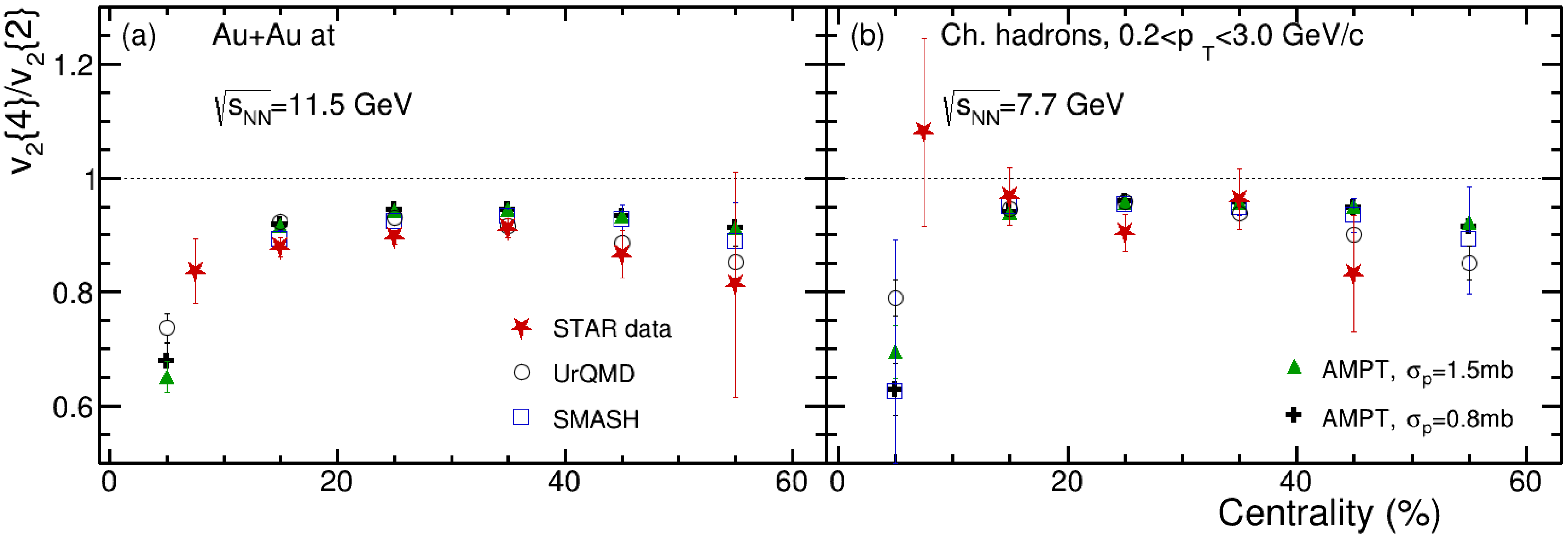
Elliptic flow at NICA energies: Models vs Data comparison



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

Relative elliptic flow fluctuations at 11.5 GeV and 7.7 GeV

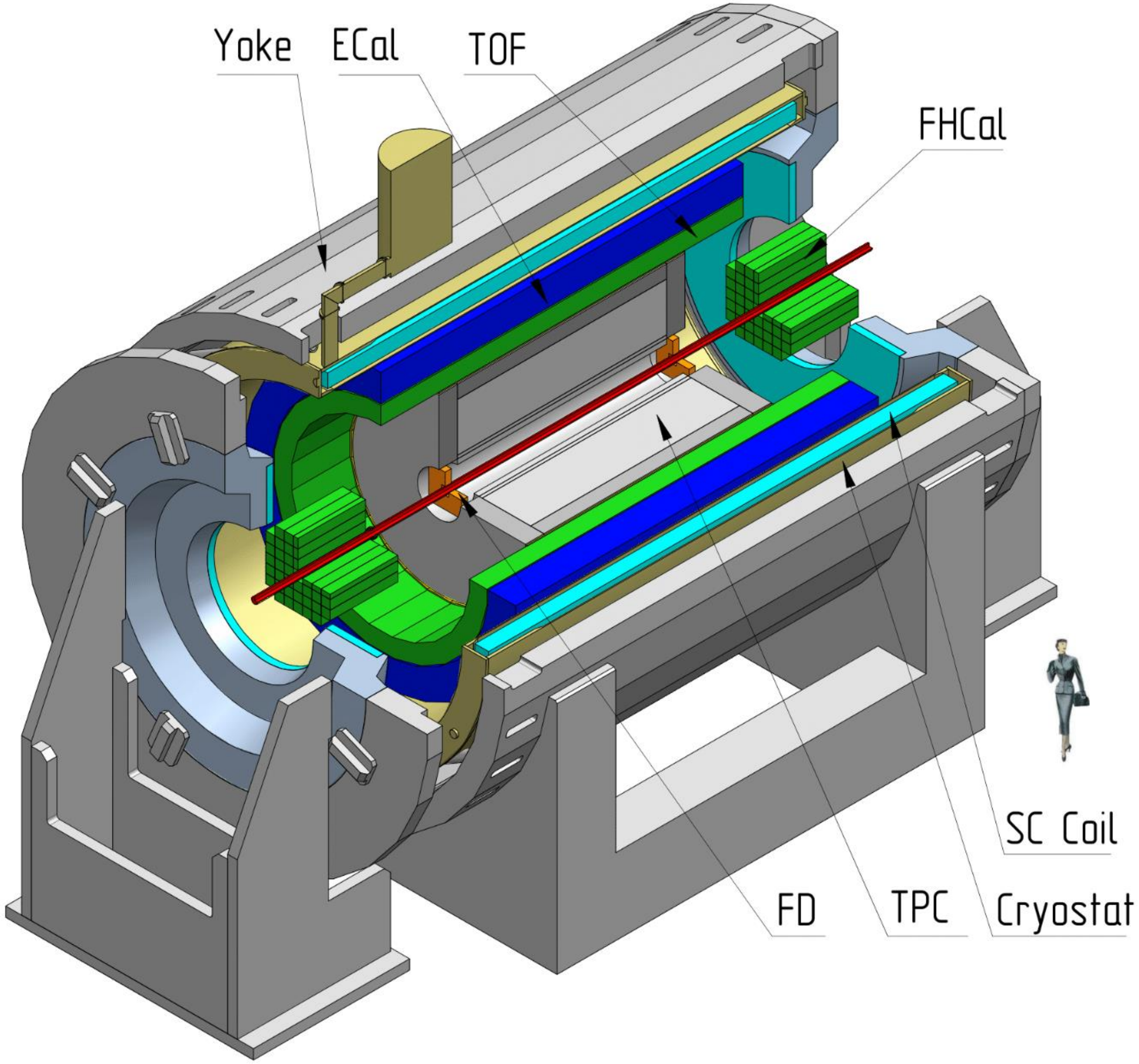
Star data: L. Adamczyk et al. (STAR Collaboration). Phys. Rev. C 86, 054908 (2012)



- Relative v_2 fluctuations ($v_2\{4\}/v_2\{2\}$) observed by STAR experiment can be reproduced both in the string/cascade models (UrQMD, SMASH) and hybrid model (AMPT with string melting)
- Dominant source of v_2 fluctuations: participant eccentricity fluctuations in the initial geometry

MPD Experiment at NICA

Multi-Purpose Detector (MPD) Stage 1



Event plane, centrality:

FHCal (2<|η|<5) or TPC (|η|<1.5)

Time Projection Chamber (TPC)

- Tracking of charged particles within (|η| < 1.5, 2π in φ)
- PID at low momenta

Time of Flight (TOF)

- PID at high momenta

-5<η<-2	-1.5<η<1.5	2<η<5
FHCal	TPC $0.2<p_T<3$ GeV/c	FHCal

Setup, event and track selection

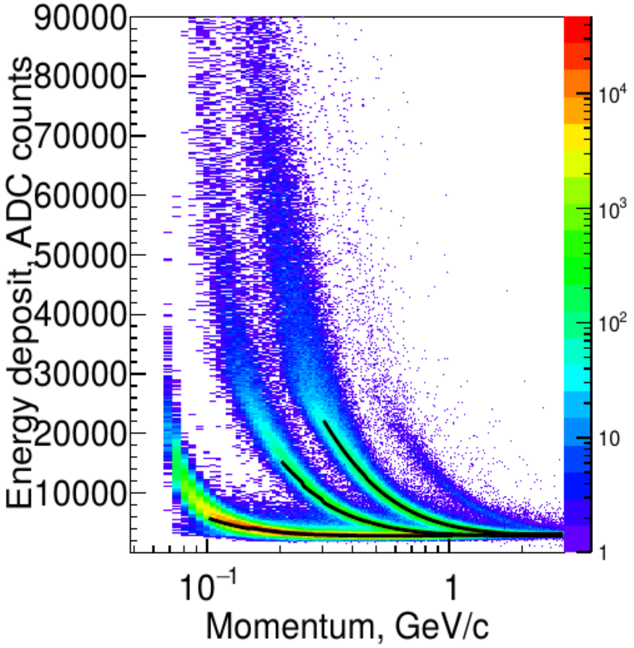
Model → GEANT4 → Reconstruction → Flow analysis

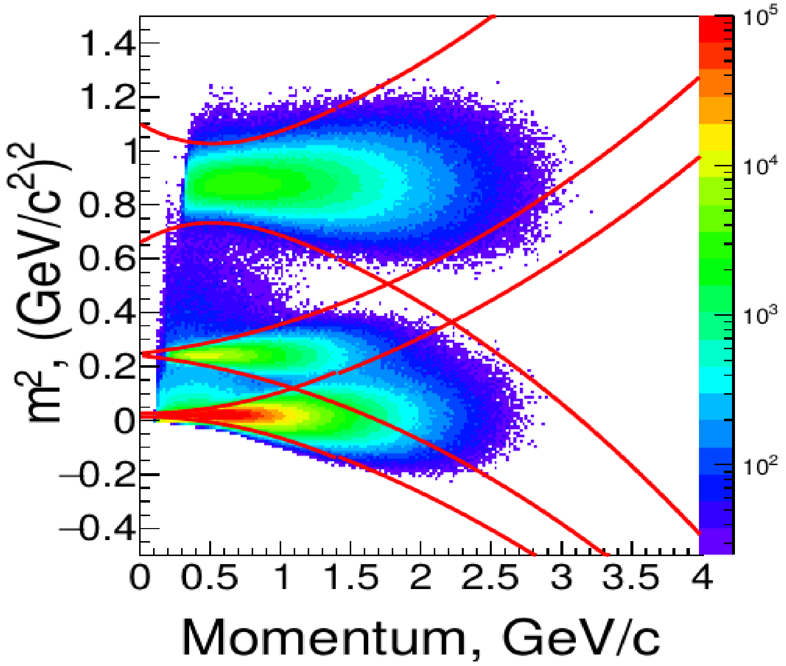
- Au+Au: UrQMD
  - N_{events}= 10 M *at* $\sqrt{s_{NN}}$ = 4.5, 11.5 GeV
  - N_{events}= 25 M *at* $\sqrt{s_{NN}}$ = 11 GeV (for K^0, Λ)
  - N_{events}= 20 M at $\sqrt{s_{NN}}$ = 7.7 GeV
- Bi+Bi:
  - N_{events}= 17 M *at* $\sqrt{s_{NN}}$ = 7.7 GeV

- TPC
- FHCal
- TOF
- ...

Event classification:
- Track multiplicity
- FHCal energy

Track selection:
- $N_{TPC\ hits}$ > 16
- 0.2 < p_T< 3 GeV/c
- $|\eta|$ < 1.5
- PID based on TPC+TOF (MpdPid)



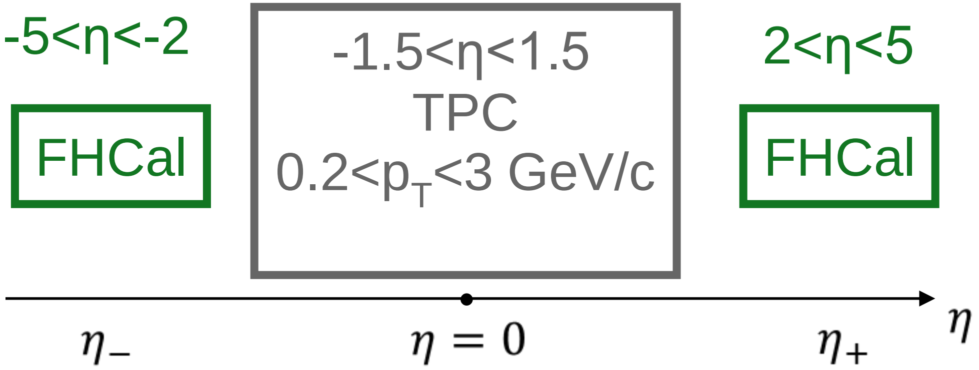


MPDRoot, August 2020

Elliptic flow measurements using v_2 of produced particles in TPC

$$u_2 = \cos 2\varphi + i \sin 2\varphi = e^{2i\varphi} \qquad (1)$$

$$Q_2 = \sum_{j=1}^{M} \omega_j u_{2,j}\,, \Psi_{2,\mathrm{TPC}} = \frac{1}{2}\tan^{-1}\left(\frac{Q_{2,y}}{Q_{2,x}}\right) \qquad (2)$$



Scalar Product: $$v_2^{\mathrm{SP}}\{Q_{2,\mathrm{TPC}}\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp}\rangle}{\sqrt{\langle Q_{2,\eta+} Q^*_{2,\eta-}\rangle}} \qquad (3)$$

Event Plane: $$R_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \sqrt{\langle \cos[2(\Psi_{2,\eta+} - \Psi_{2,\eta-})]\rangle} \qquad v_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \frac{\langle \cos[2(\varphi_{\eta\pm} - \Psi_{2,\eta\mp})]\rangle}{R_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\}} \qquad (4)$$

Q-cumulants:

$$\langle 2\rangle_2 = \frac{|Q_n|^2 - M}{M(M-1)} \approx v_2^2 + \delta \qquad \langle 4\rangle_2 = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2|Q_{2n}Q_n^*Q_n^*| - 4M(M-2)|Q_n|^2 + 2M(M-3)}{M(M-1)(M-2)(M-3)} \approx v_2^4 + 4v_2^2\delta + 2\delta^2$$

$$v_2\{2\} = \sqrt{\langle\langle 2\rangle\rangle} \qquad v_2\{4\} = \sqrt{2\langle\langle 2\rangle\rangle^2 - \langle\langle 4\rangle\rangle} \qquad (5)$$

Event plane method using v_1 of particles in FHCal

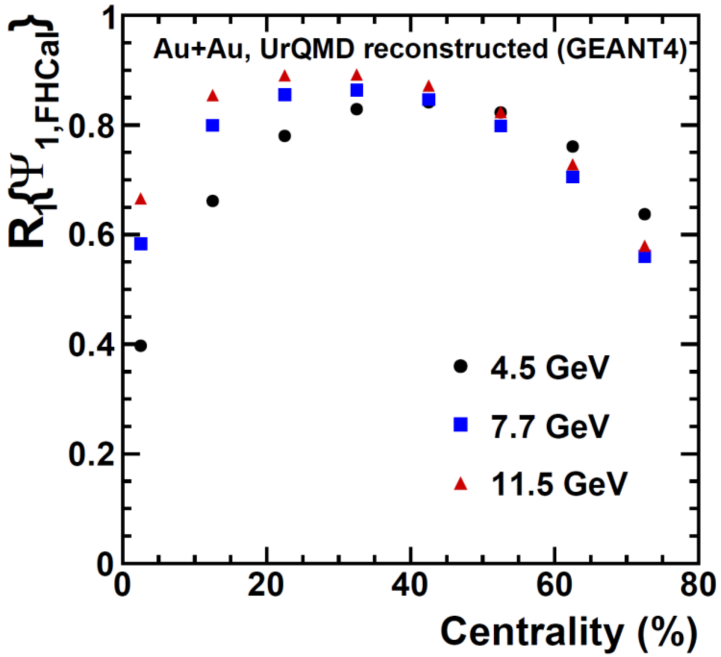
Using v_1 of particles in FHCal to determine Q_n

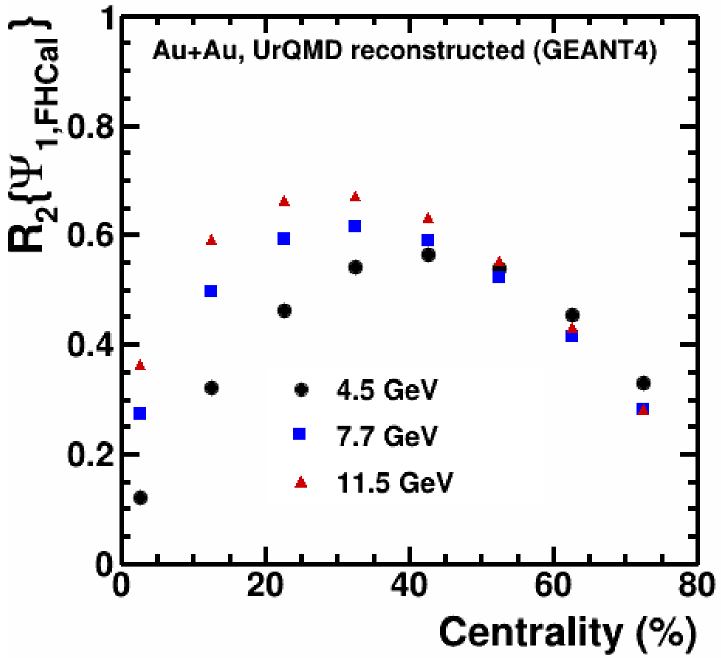
$$Q_1 = \frac{\sum E_i e^{i\varphi_i}}{\sum E_i}, \Psi_{1,\mathrm{FHCal}} = \tan^{-1}\left(\frac{Q_{1,y}}{Q_{1,x}}\right) \qquad (1)$$

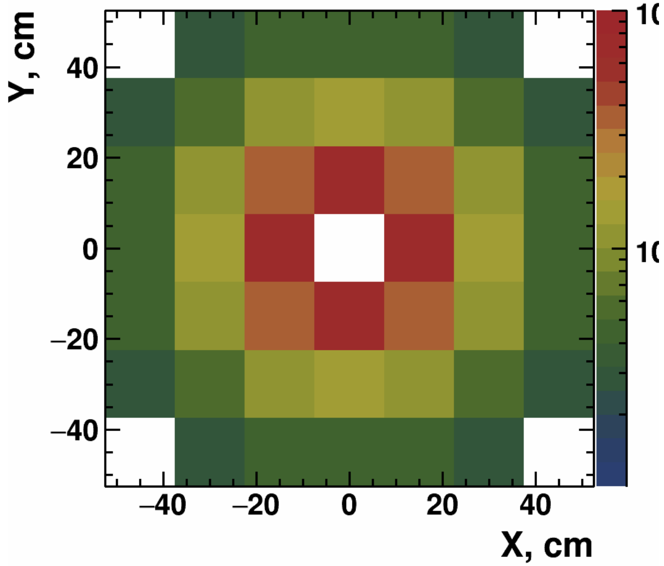
E – energy deposition in FHCal modules (2<|η|<5)

$$R_n\{\Psi_{1,\mathrm{FHCal}}\} = \langle\cos[n(\Psi_{\mathrm{RP}} - \Psi_{1,\mathrm{FHCal}})]\rangle \qquad (2)$$

$$v_2\{\Psi_{1,\mathrm{FHCal}}\} = \frac{\langle\cos[n(\varphi - \Psi_{1,\mathrm{FHCal}})]\rangle}{R_n\{\Psi_{1,\mathrm{FHCal}}\}} \qquad (3)$$







Energy distribution in FHCal

v_2 of V0 particles: invariant mass fit method

Data set:

- 25 million events, UrQMD 3.4 non-hydro, 11.0 GeV, minbias

Geant4 simulation, full reconstruction with:

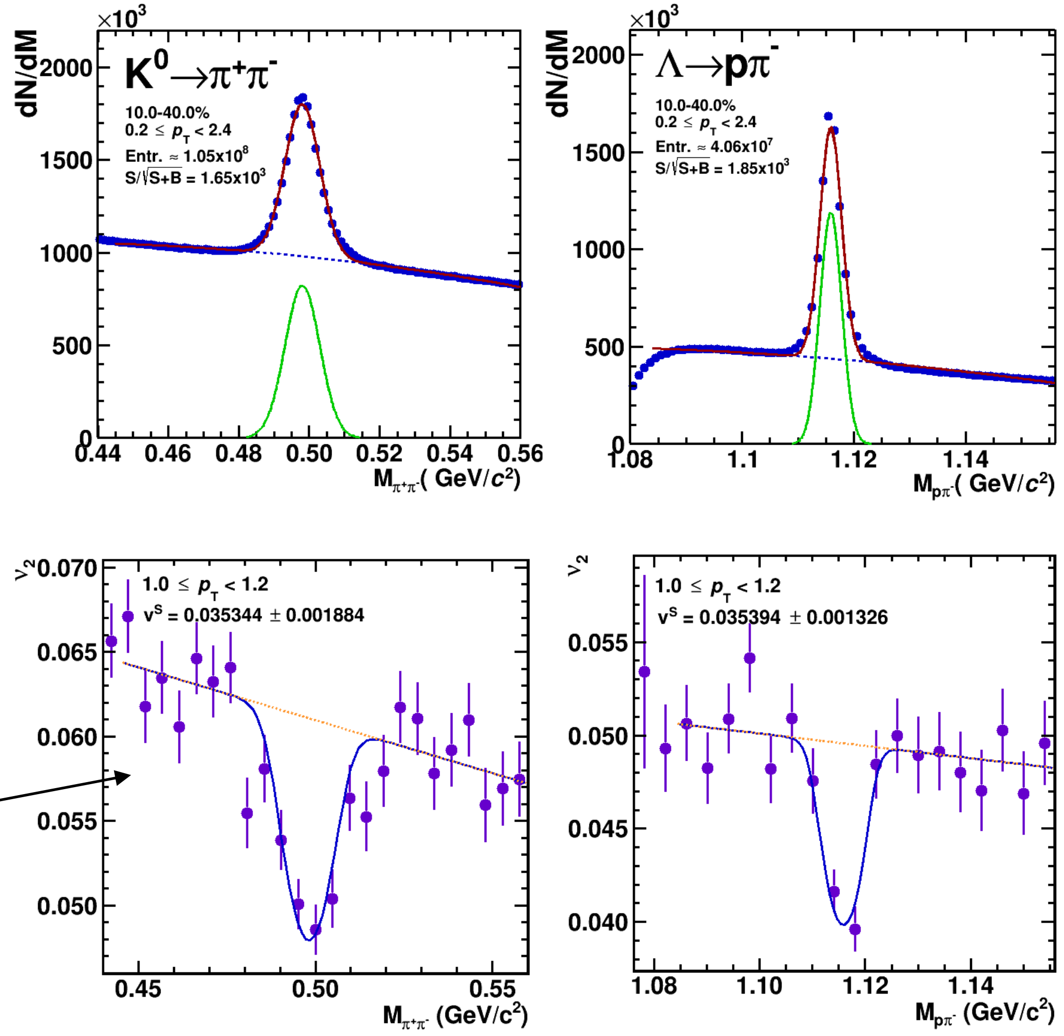
- TPCv7, TOFv7, FHCal

Centrality by TPC multiplicity, Event-plane method with FHCal

Particle decays reconstructed with MpdParticle realistic cuts

Differential flow signal extraction by bins in transverse momentum (or rapidity) with a simultaneous fit

$$v_2^{SB}(m_{inv},p_T) = v_2^S(p_T)\frac{N^S(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)} + v_2^B(m_{inv},p_T)\frac{N^B(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)}$$



Sensitivity of different methods to flow fluctuations

Elliptic flow fluctuations:

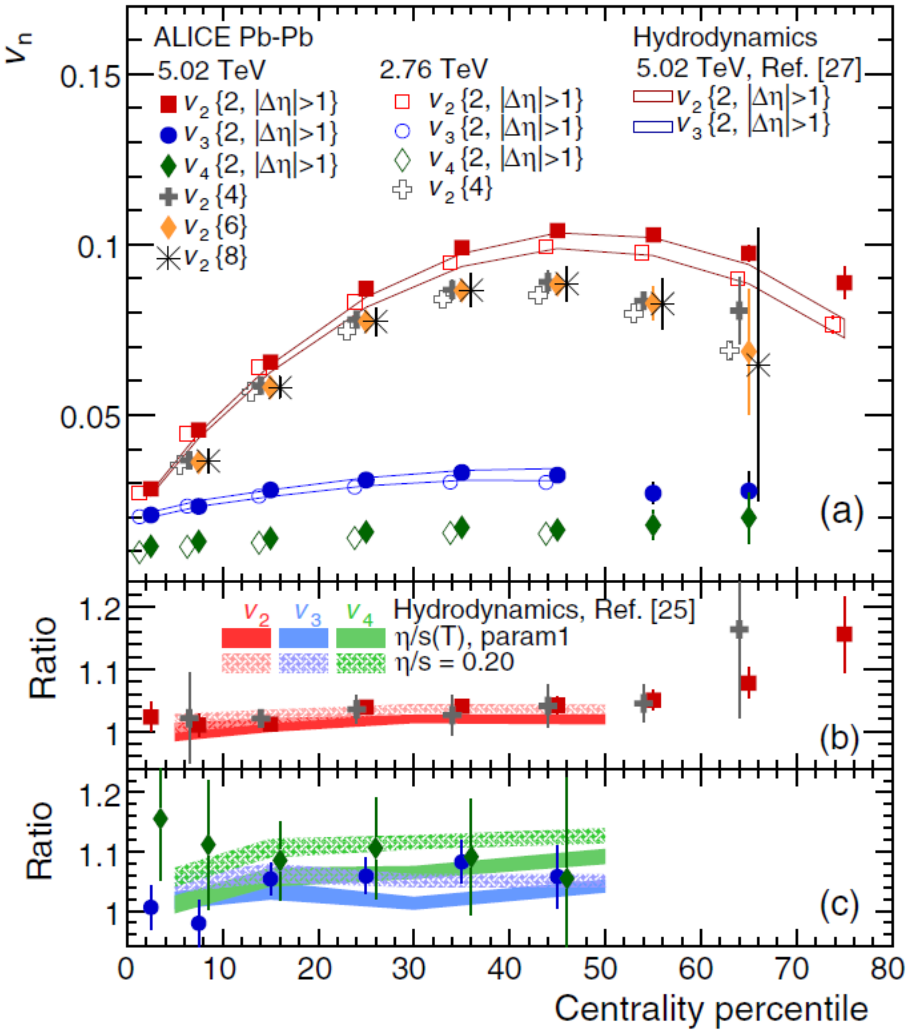
$$\sigma_{v_2}^2 = \langle v_2^2 \rangle - \langle v_2 \rangle^2$$

The difference between $v_2\{2\}$ and $v_2\{4\}$:

$$v_2\{2\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v_2}^2}{\langle v_2 \rangle}, v_2\{4\} \approx \langle v_2 \rangle - \frac{1}{2}\frac{\sigma_{v_2}^2}{\langle v_2 \rangle}$$

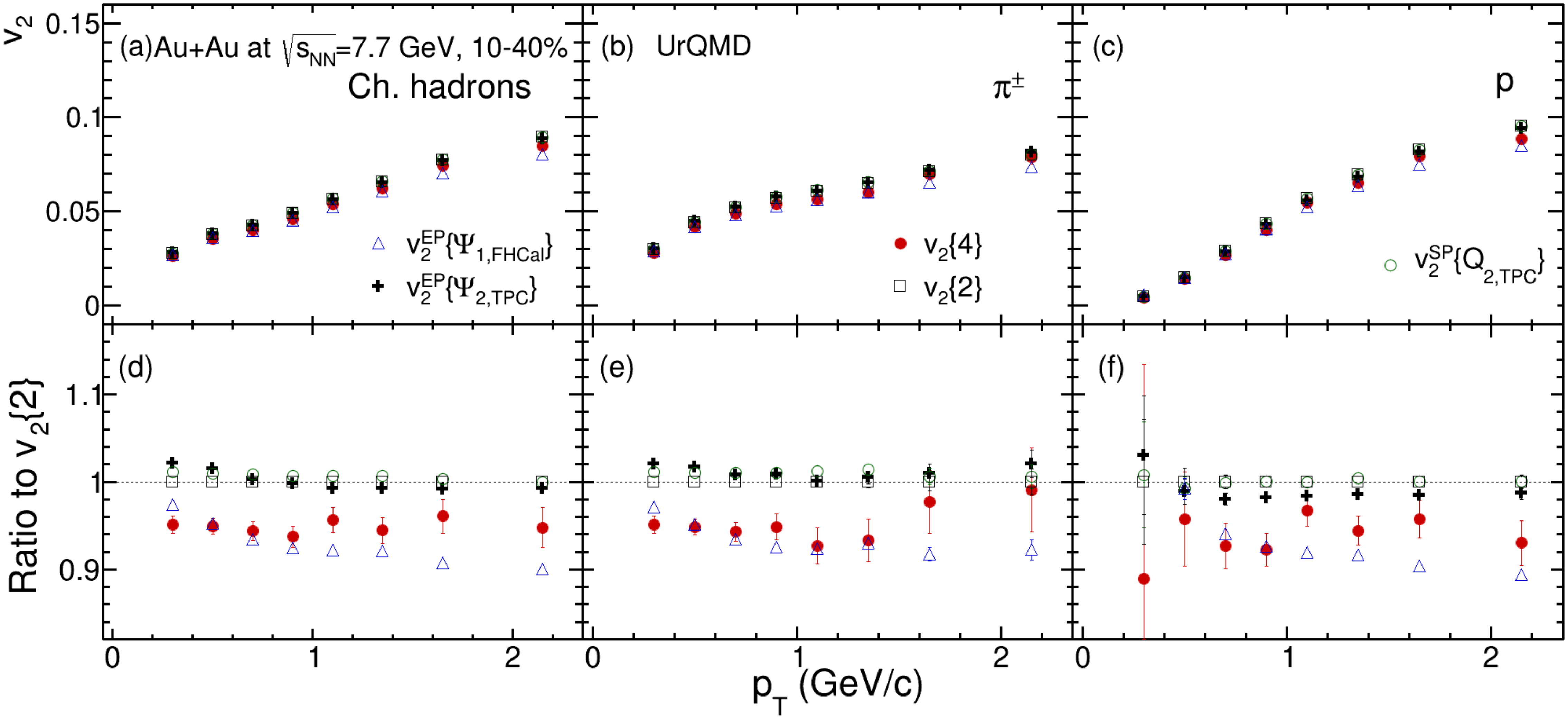
The difference between $v_2^{EP}\{\Psi_{1,FHCal}\}$ and $v_2^{EP}\{\Psi_{2,TPC}\}$:

$$v_2^{EP}\{\Psi_{1,\mathrm{FHCal}}\} \approx \langle v_2 \rangle, v_2^{EP}\{\Psi_{2,\mathrm{TPC}}\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v_2}^2}{\langle v_2 \rangle}$$



J. Adam et al. The ALICE Collaboration Phys. Rev. Lett. 116 (2016) 132302

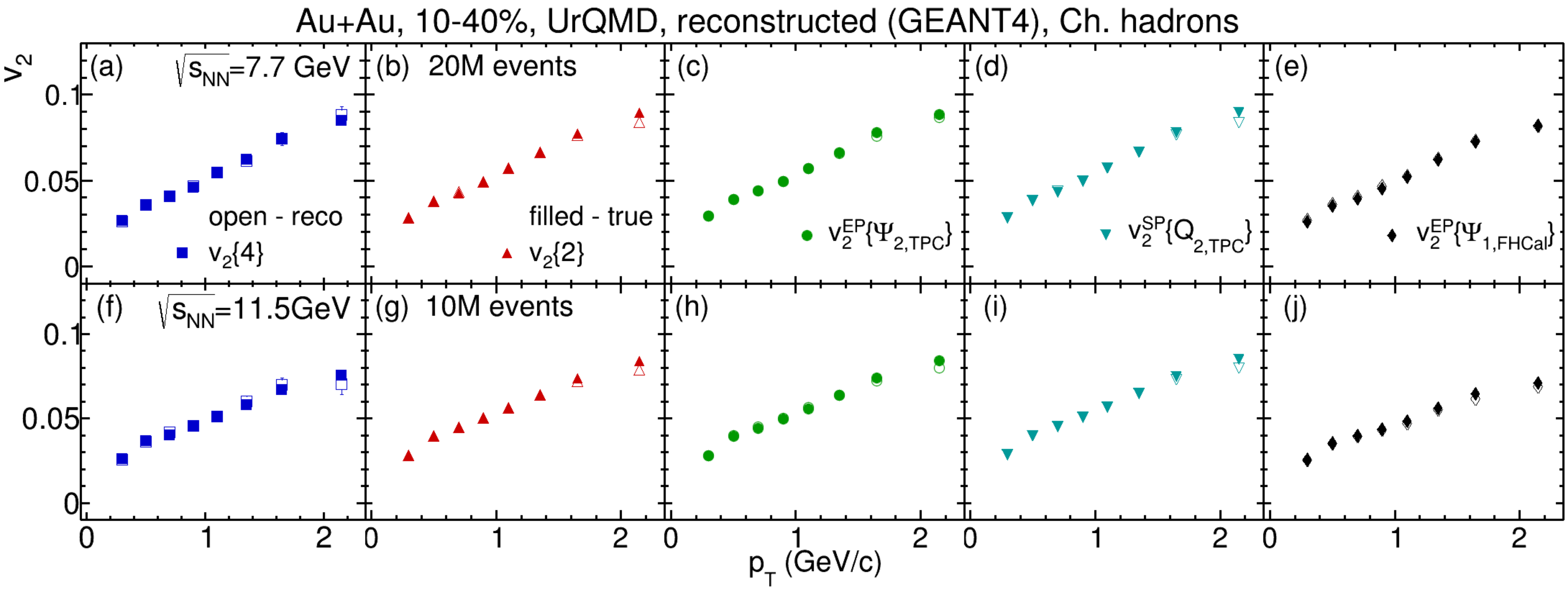
Comparison of v2 measurements using different method



$v_2\{2\}$, $v_2^{EP}\{\Psi_{2,\mathrm{TPC}}\}$ and $v_2^{SP}\{Q_{2,\mathrm{TPC}}\}$ are in a good agreement

$v_2\{4\}$ and $v_2^{EP}\{\Psi_{1,\mathrm{FHCal}}\}$ are smaller than $v_2\{2\}$ due to fluctuation and nonflow

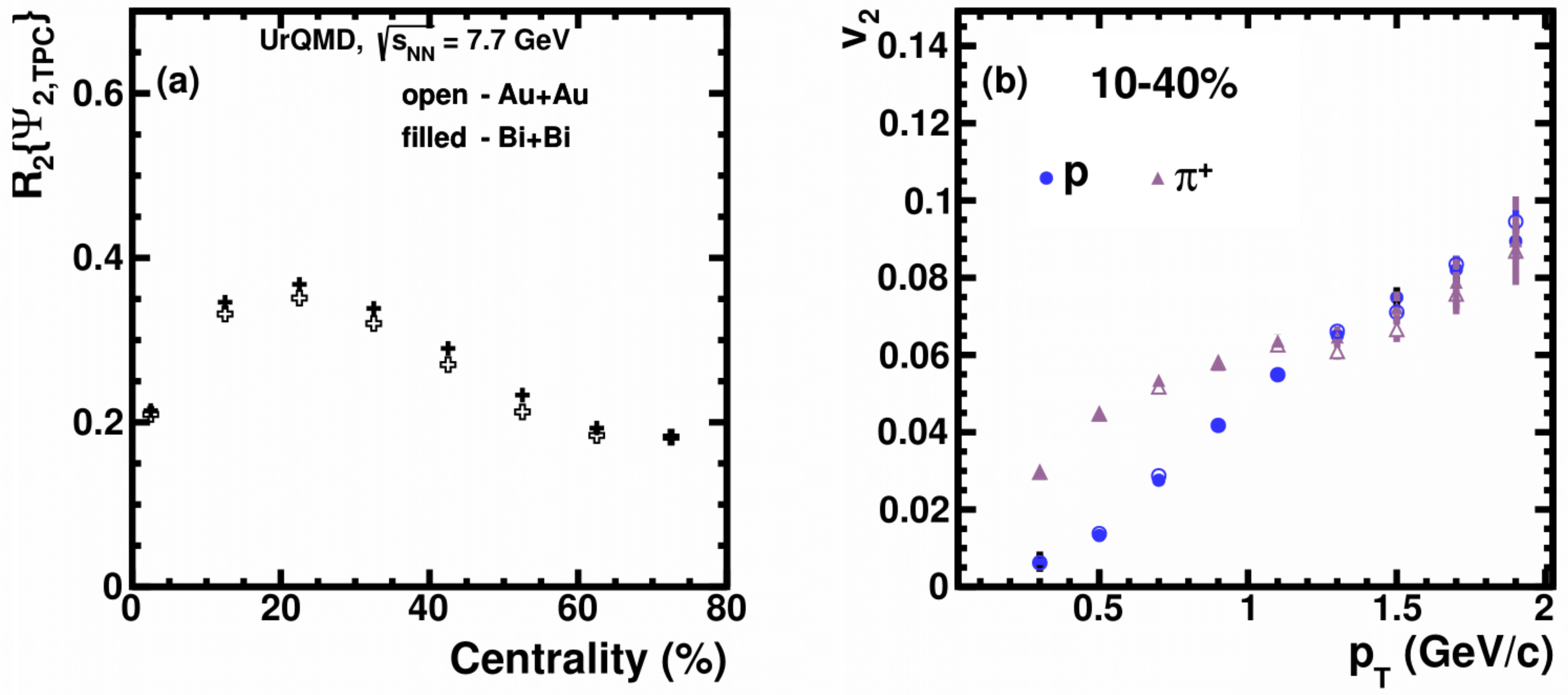
Performance study of v_2 of charged hadrons in MPD



Reconstructed (reco) and generated (true) v_2 values are in a good agreement for all methods

Au+Au vs. Bi+Bi collisions for reconstructed data in MPD

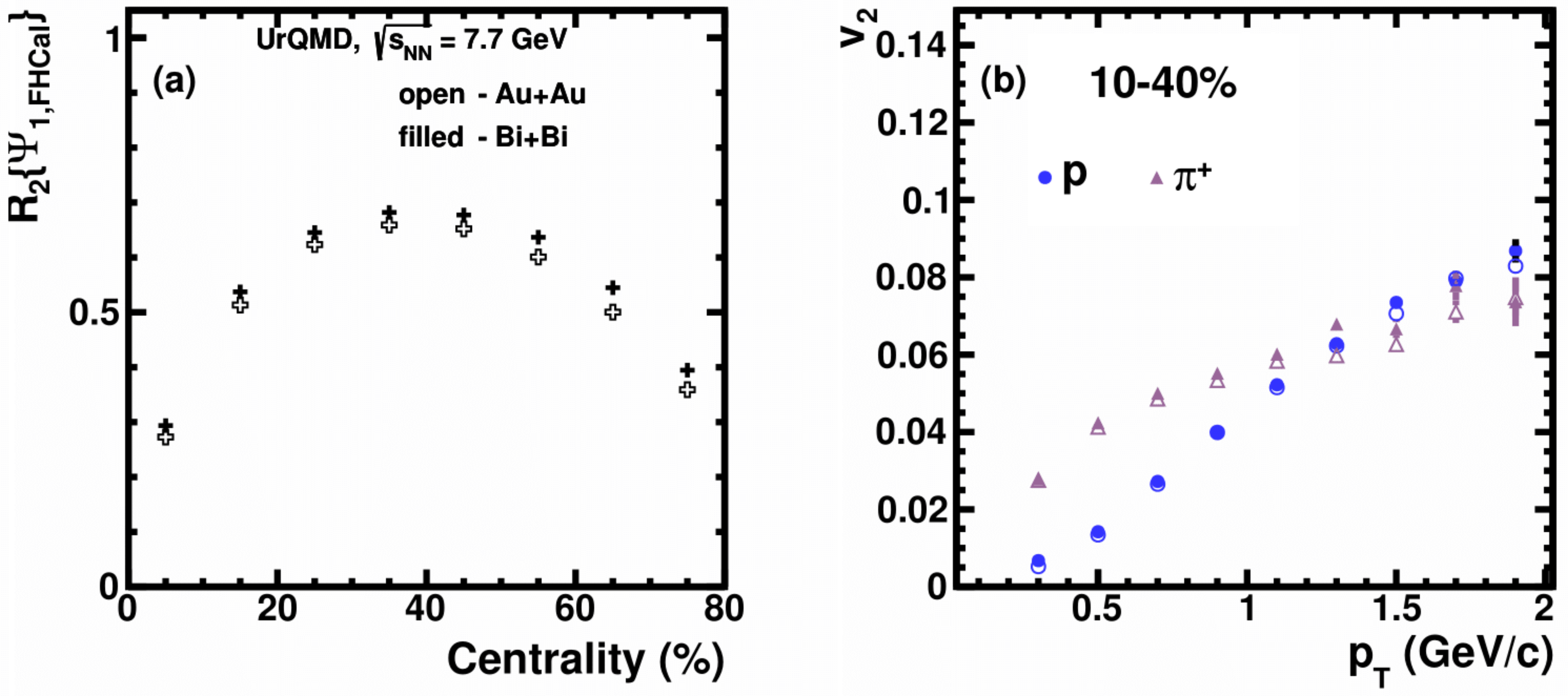
TPC event plane



The results show a little difference for resolution and elliptic flow between two colliding systems

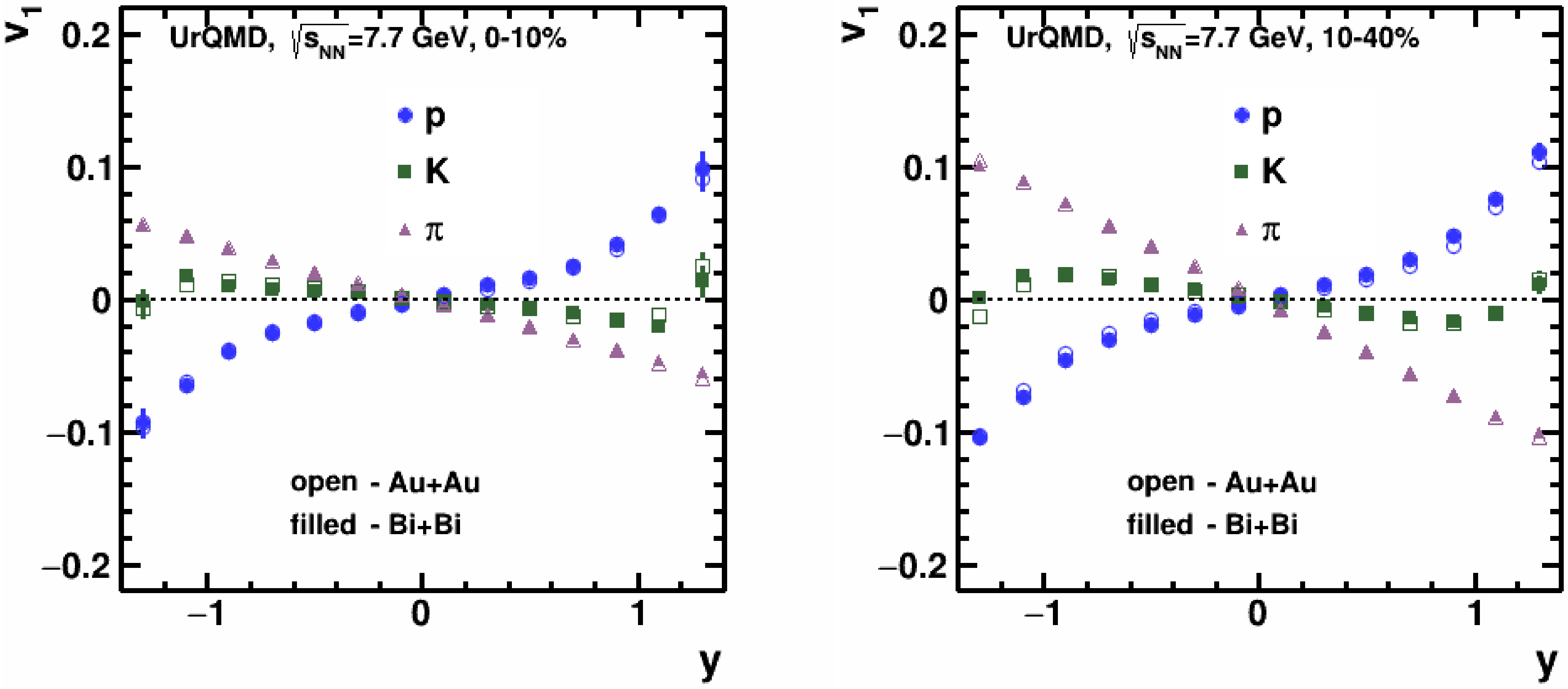
Au+Au vs. Bi+Bi collisions for reconstructed data in MPD

FHCal event plane



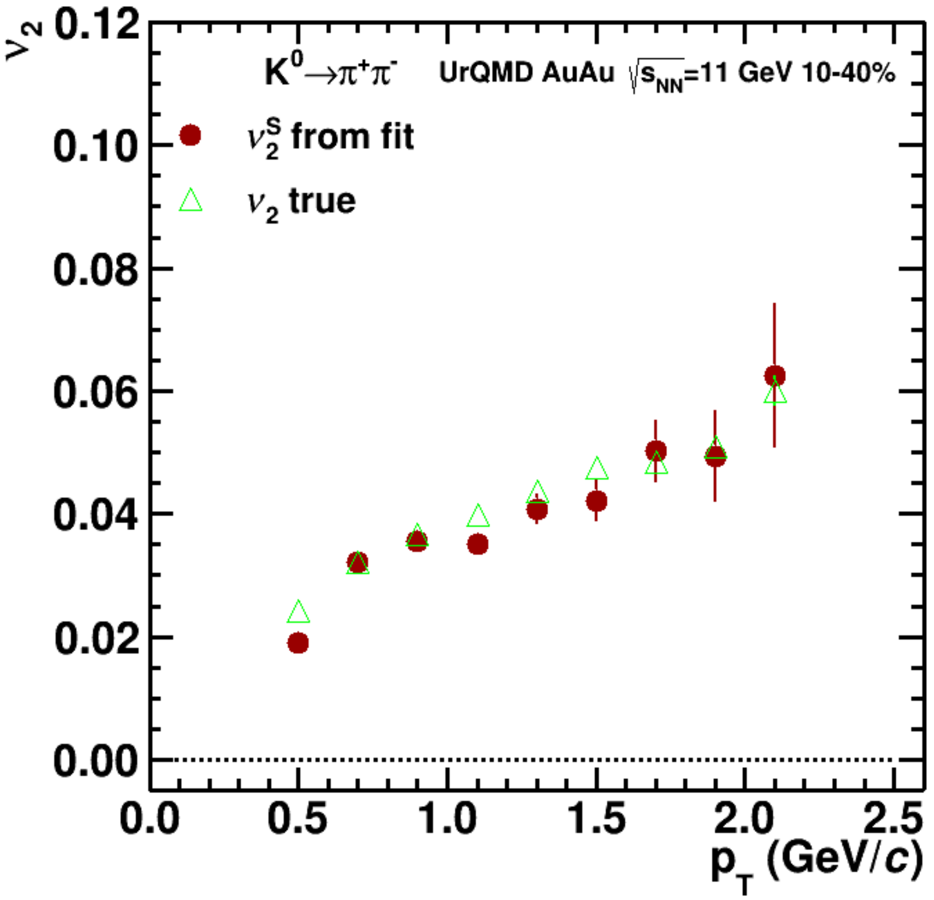
Expected small difference between colliding systems

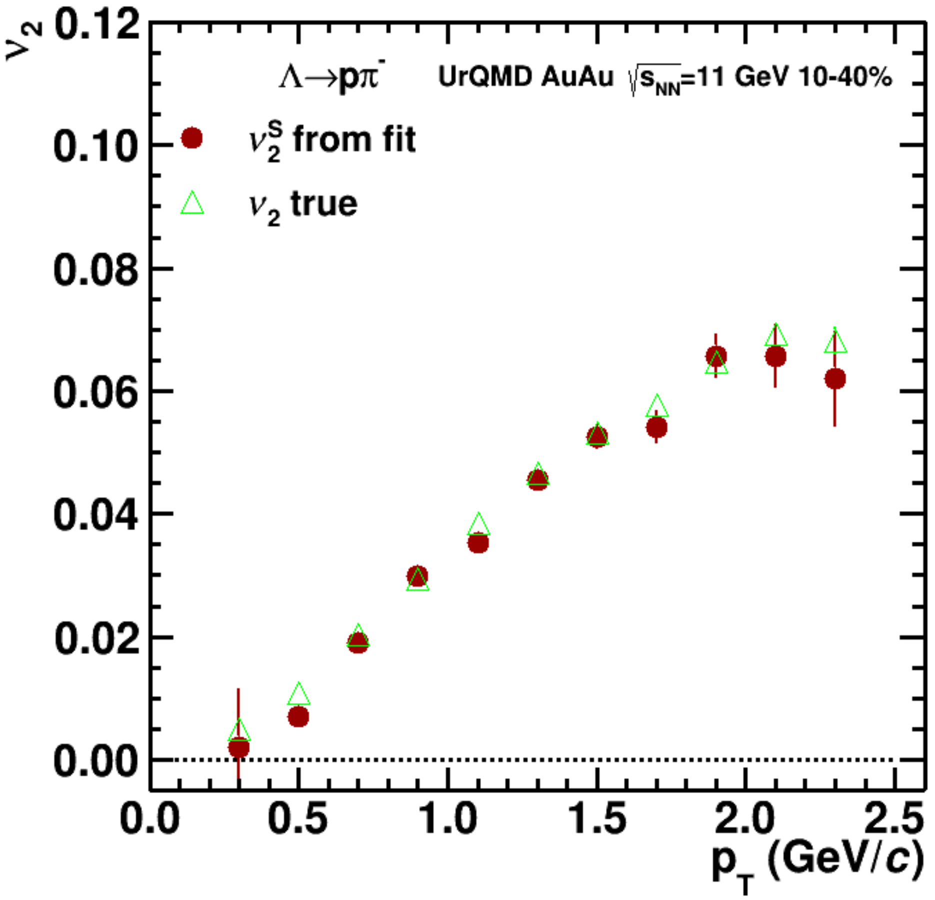
$v_1(y)$: Bi+Bi vs Au+Au



Expected small difference for v1 (y) for particles produced in Au+Au and Bi+Bi collisions.

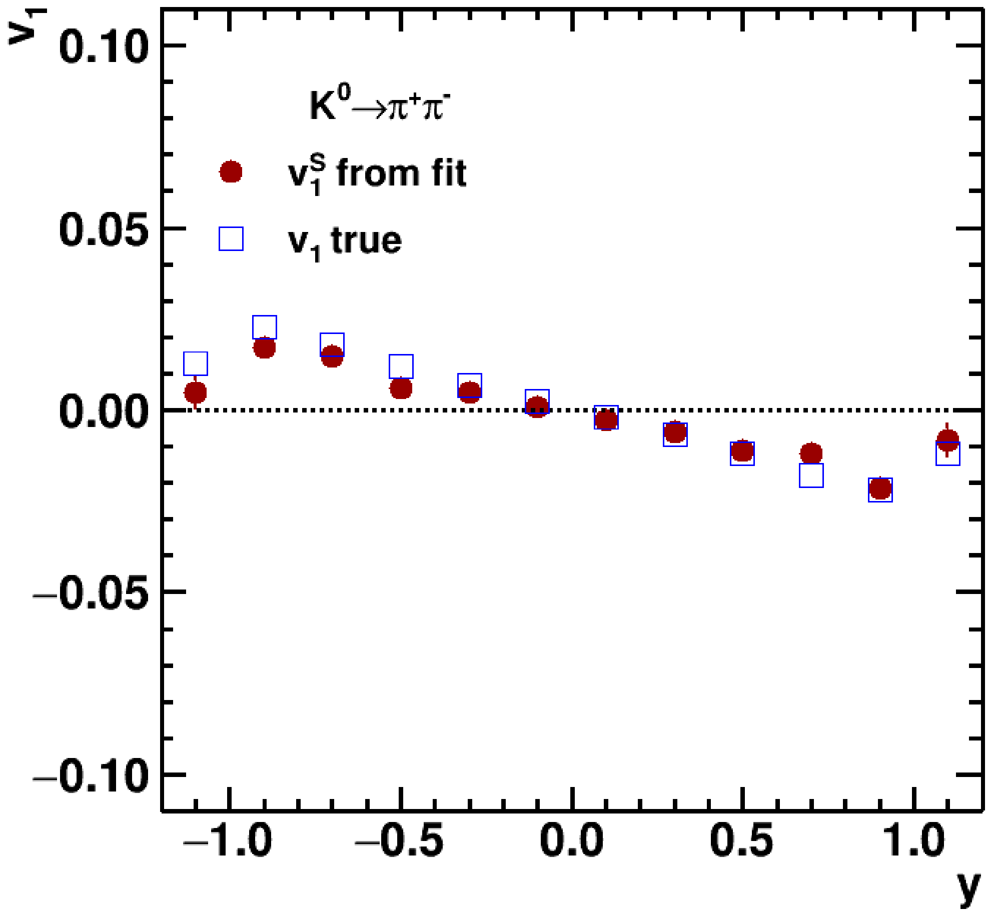
Performance study for v_2 of V0 particles

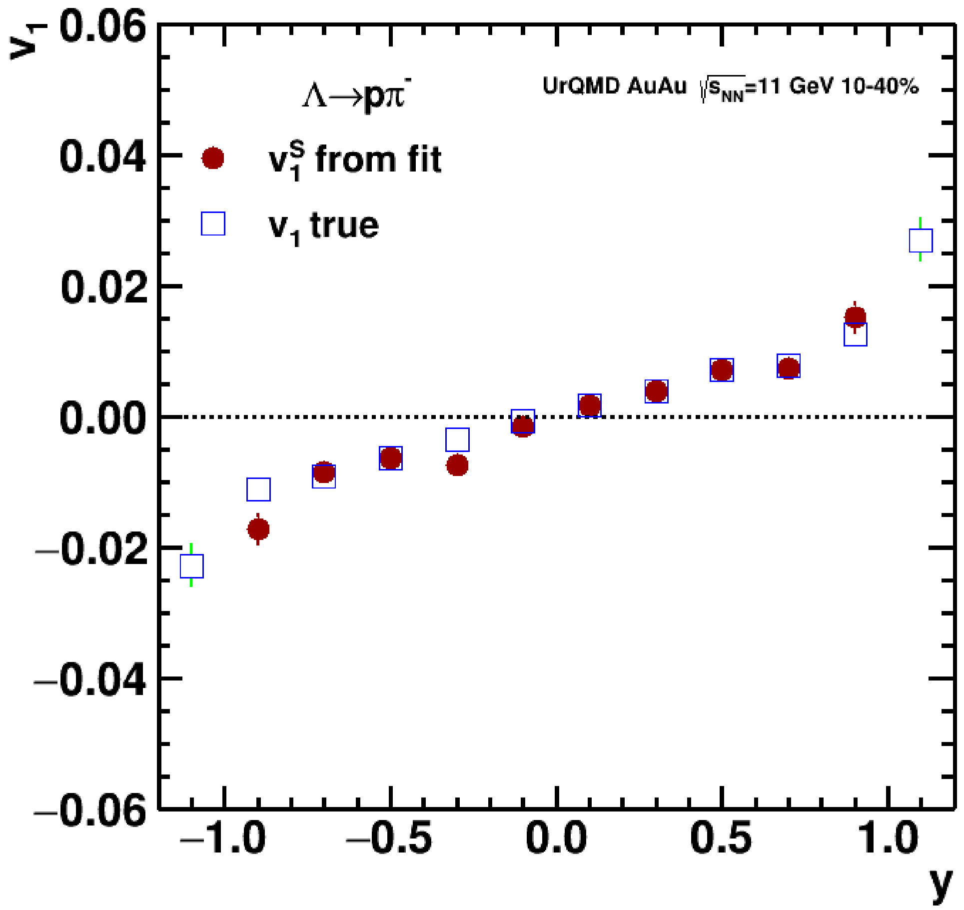




Reasonable agreement between reconstructed and generated v_2 signals for both K^0 and Λ

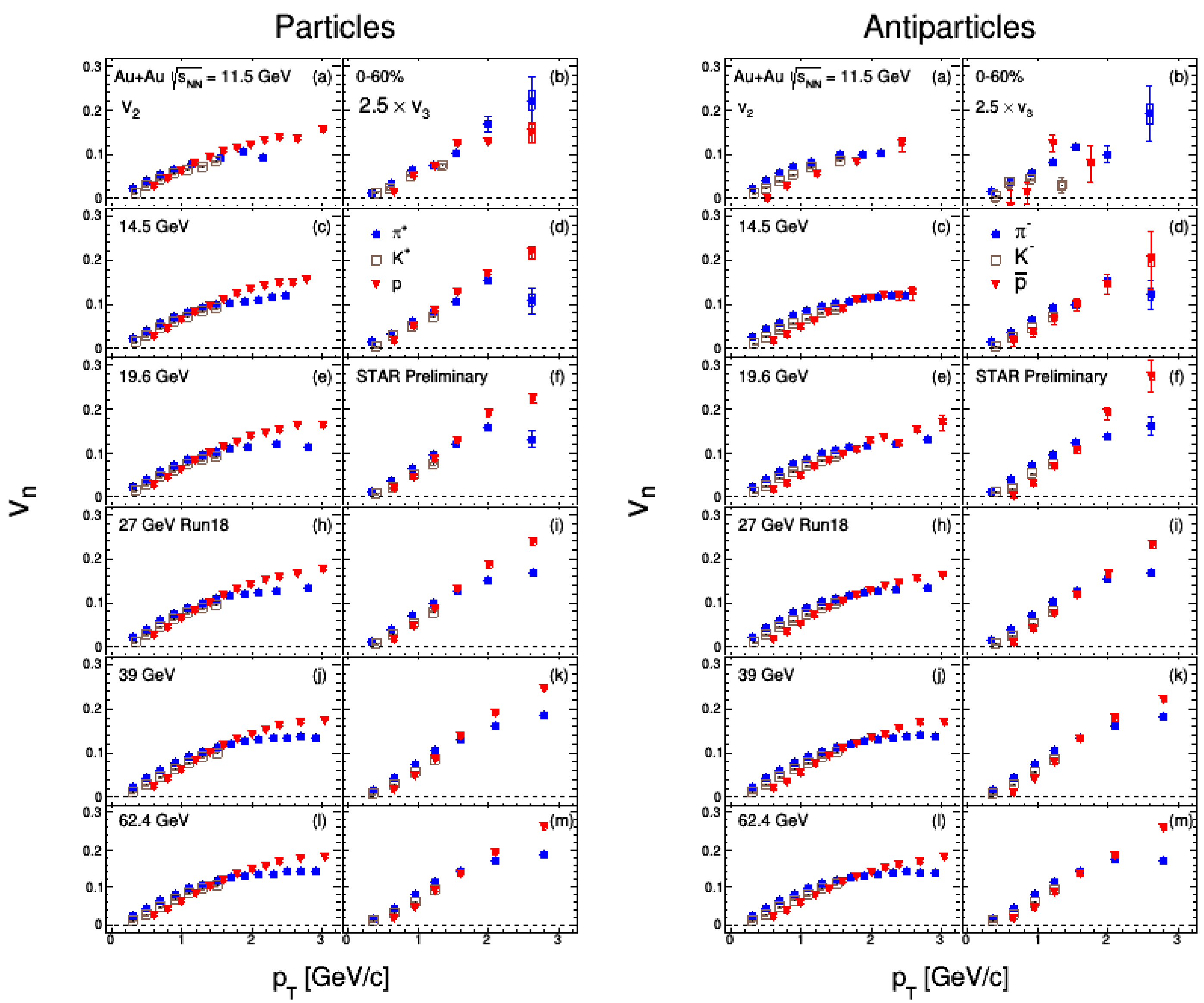
Performance study for v_1 of V0 particles

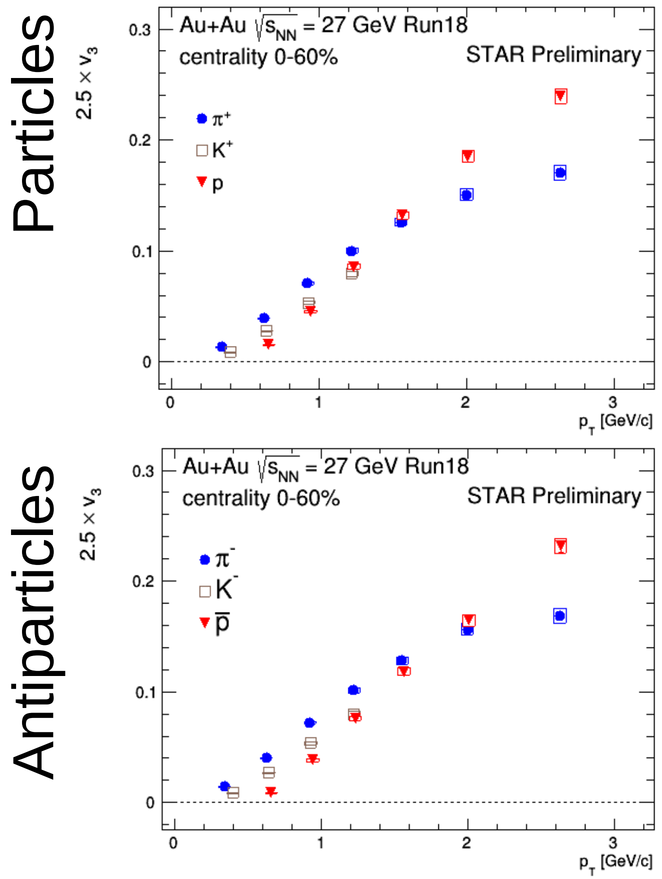




Reasonable agreement between reconstructed and generated v_1 signals for both K^0 and Λ

$v_2(p_T)$ and $v_3(p_T)$ of identified hadrons



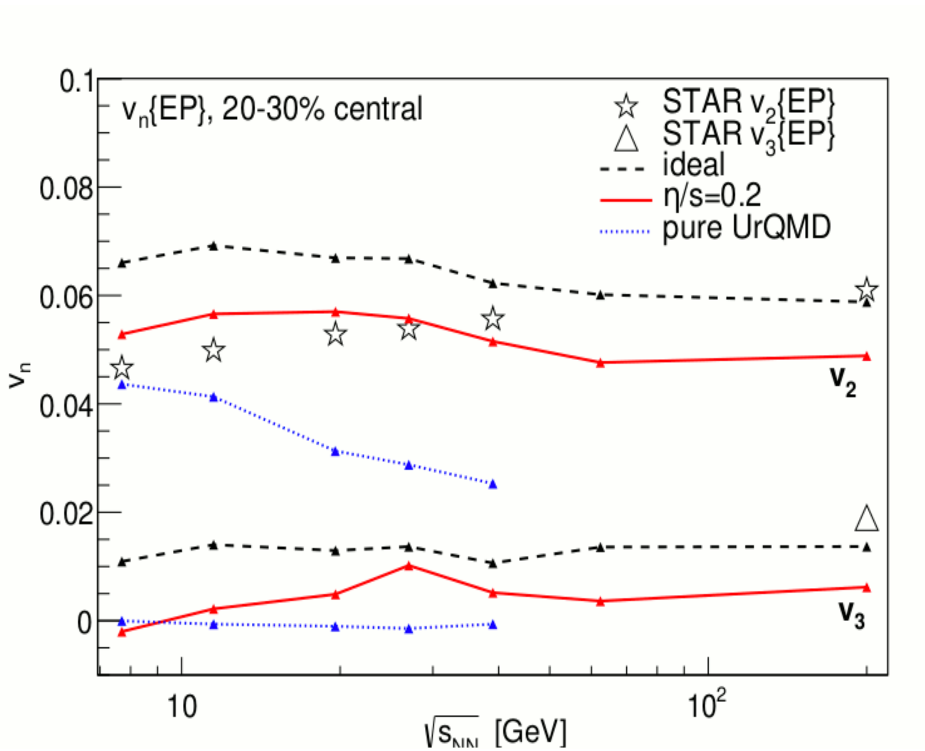


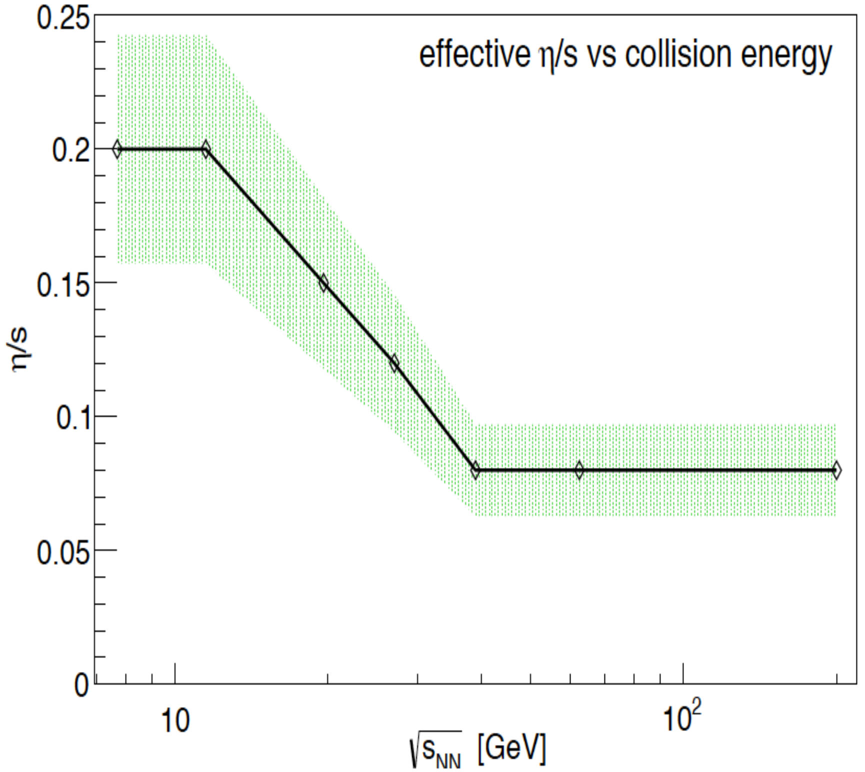
Mass ordering for p_T<1.5 GeV/c
Baryon/meson grouping for p_T>2 GeV/c

P.Parfenov "Elliptic (v_2) and triangular (v_3) anisotropic flow of identified hadrons from the STAR Beam Energy Scan program", ICPPA 2020

Outlook: triangular flow at NICA

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????

Summary and outlook

- **v_2 at NICA energies shows strong energy dependence:**
  - At $\sqrt{s_{NN}}$=4.5 GeV v_2 from UrQMD, SMASH are in a good agreement with the experimental data
  - At $\sqrt{s_{NN}}\geq$7.7 GeV UrQMD, SMASH underestimate v_2 – need hybrid models with QGP phase
  - Lack of existing differential measurements of v_2 (p_T, centrality, PID, …)
- **Comparison of methods for elliptic flow measurements using UrQMD model:**
  - The differences between methods are well understood and could be attributed to non-flow and fluctuations
- **Feasibility study for elliptic flow in MPD:**
  - v_2 of identified charged hadrons: results from reconstructed and generated data are in a good agreement for all methods
  - v_2 of K^0 and Λ particles: results from reconstructed (using invariant mass fits) and generated data are in a good agreement
- **Small differences in v_2 for 2 colliding systems (Au+Au, Bi+Bi) were observed as expected**

Outlook:

- v_1,v_2 and v_3 measurements for the hybrid models (production of 60 M events for vHLLE+UrQMD at $\sqrt{s_{NN}}$= 11 GeV is ongoing)

Thank you for you attention

Backup

Setup, event and track selection

UrQMD → GEANT4 → Reconstruction → Flow analysis

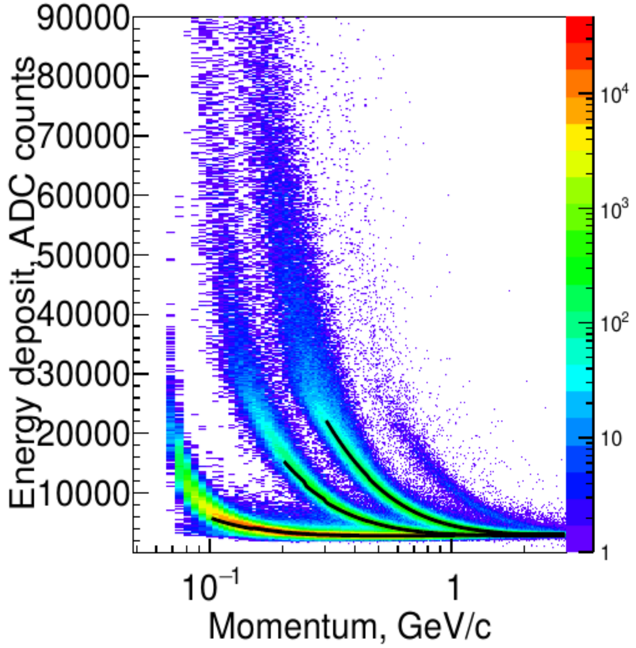
- Au+Au:
  - N_{events}= 10 M *at* $\sqrt{s_{NN}}$ = 4.5, 11.5 GeV
  - N_{events}= 20 M at $\sqrt{s_{NN}}$ = 7.7 GeV
- Bi+Bi:
  - N_{events}= 7 M *at* $\sqrt{s_{NN}}$ = 7.7 GeV

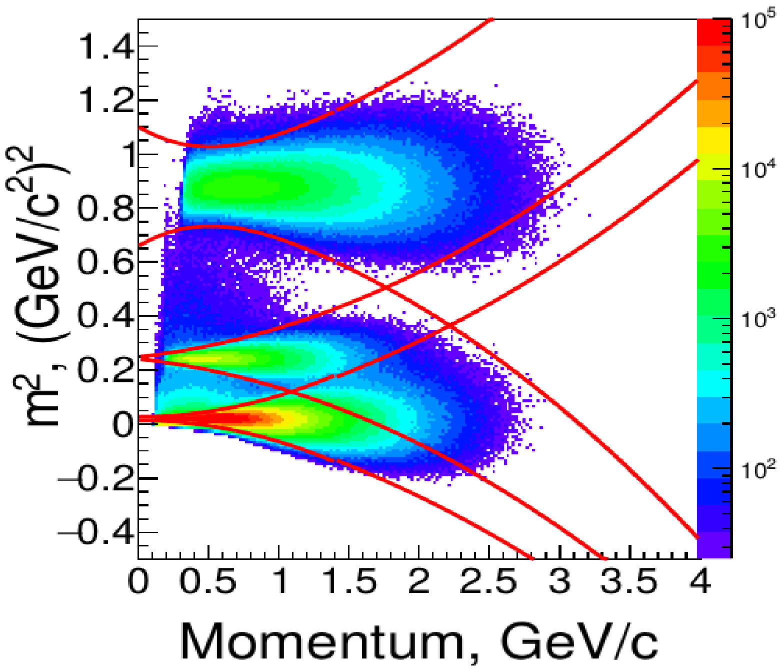
- TPC
- FHCal
- TOF
- ...

Event classification:
- Track multiplicity
- FHCal energy

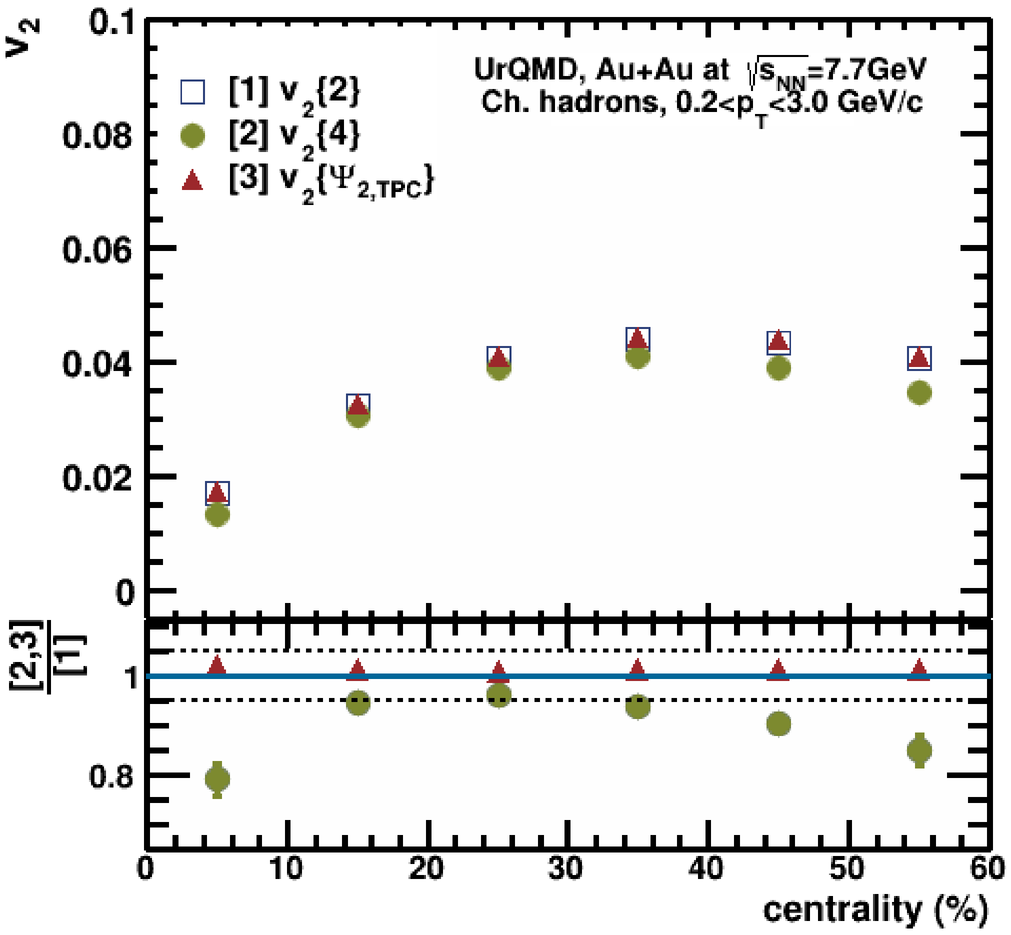
Track selection:
- Primary tracks (2σ DCA cut)
- $N_{TPC\ hits}$ > 16
- 0.2 < p_T< 3 GeV/c
- $|\eta|$ < 1.5
- PID based on TPC+TOF (MpdPid)

MPDRoot, August 2020





Results for v_2 from UrQMD model of Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV



$v_2\{4\}$ is smaller than $v_2\{2\}$ due to fluctuations and nonflow

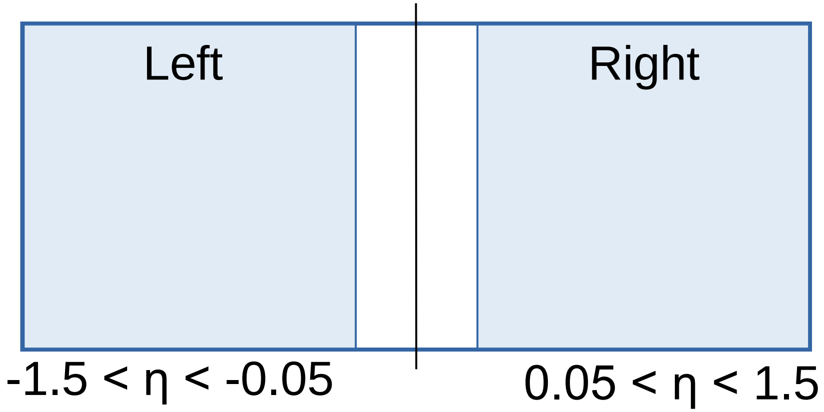
Description of event plane method

$$\mathbf{Q}_n = \sum_{j=1}^{N} w_n(j)\, e^{in\phi_j} = |\mathbf{Q}_n|\, e^{in\Phi_n} \qquad (1)$$

$$Q_n \cos(n\Psi_n) = X_n = \sum_i w_i \cos(n\phi_i),$$
$$Q_n \sin(n\Psi_n) = Y_n = \sum_i w_i \sin(n\phi_i),$$

$$\Psi_n = \left(\tan^{-1} \frac{\sum_i w_i \sin(n\phi_i)}{\sum_i w_i \cos(n\phi_i)}\right) / n \qquad (2)$$

- η-sub EP method: resolution of the reaction plane Ψ_2 obtained from 2 sub-events



Left half (η<-0.05) → η_-

Right half (η>0.05) → η_+

$$v_2\{\eta\text{-sub,EP}\} = \frac{\langle \cos[n(\phi_{\eta\pm} - \Psi_{2,\eta\mp})]\rangle}{\sqrt{\langle \cos[n(\Psi_{2,\eta+} - \Psi_{2,\eta-})]\rangle}} \qquad (3)$$

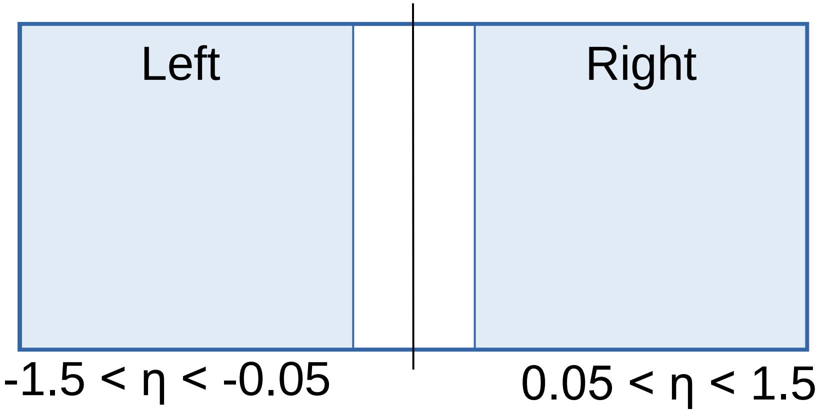
STAR Collaboration: B.I. Abelev, et al., Phys.Rev.C77:054901,2008

Description of scalar product method

$$u_n = \cos n\phi + i \sin n\phi = e^{in\varphi} \qquad (1)$$

$$Q_n = \sum_{j=1}^{M} u_{n,j} = \sum_{j=1}^{M} e^{in\varphi_j} \qquad (2)$$

- u_n – particle unit vector
- Q_n – event flow vector(Q-vector)
- Elliptic flow measured using correlation between u_n and Q_n

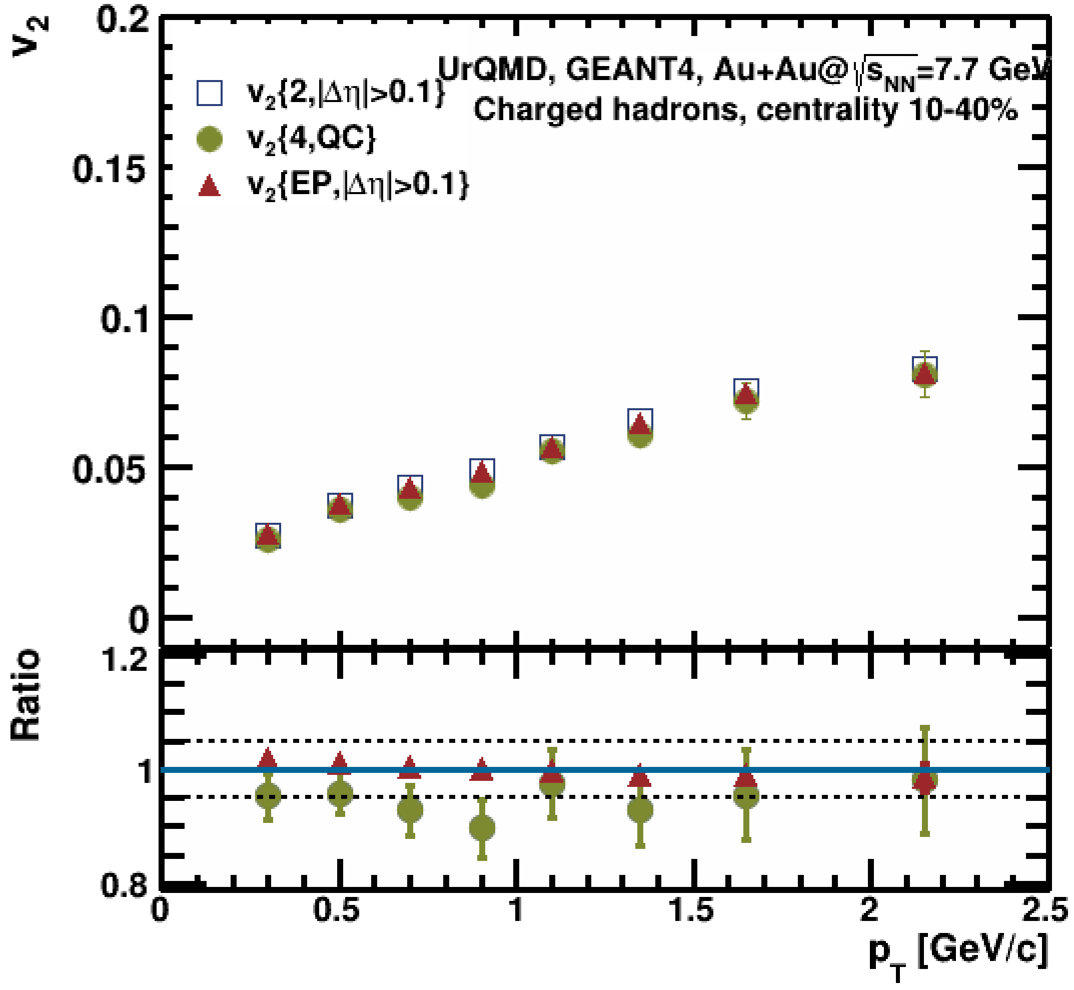


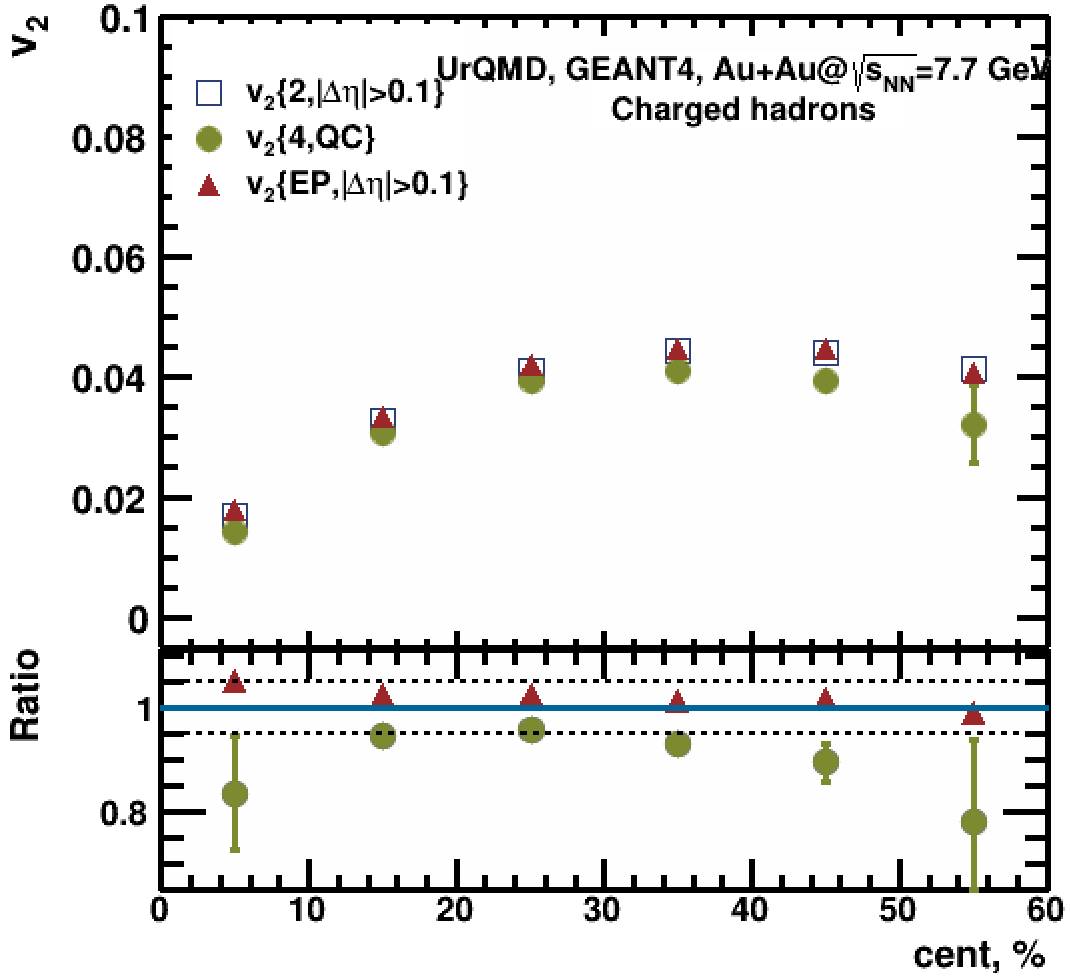
Left half (η<-0.05) → η_-

Right half (η>0.05) → η_+

$$\mathrm{v}_2^{SP}\{Q_{2,\mathrm{TPC}}\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp} \rangle}{\sqrt{\langle Q_{2,\eta+} Q^*_{2,\eta-} \rangle}} \qquad (3)$$

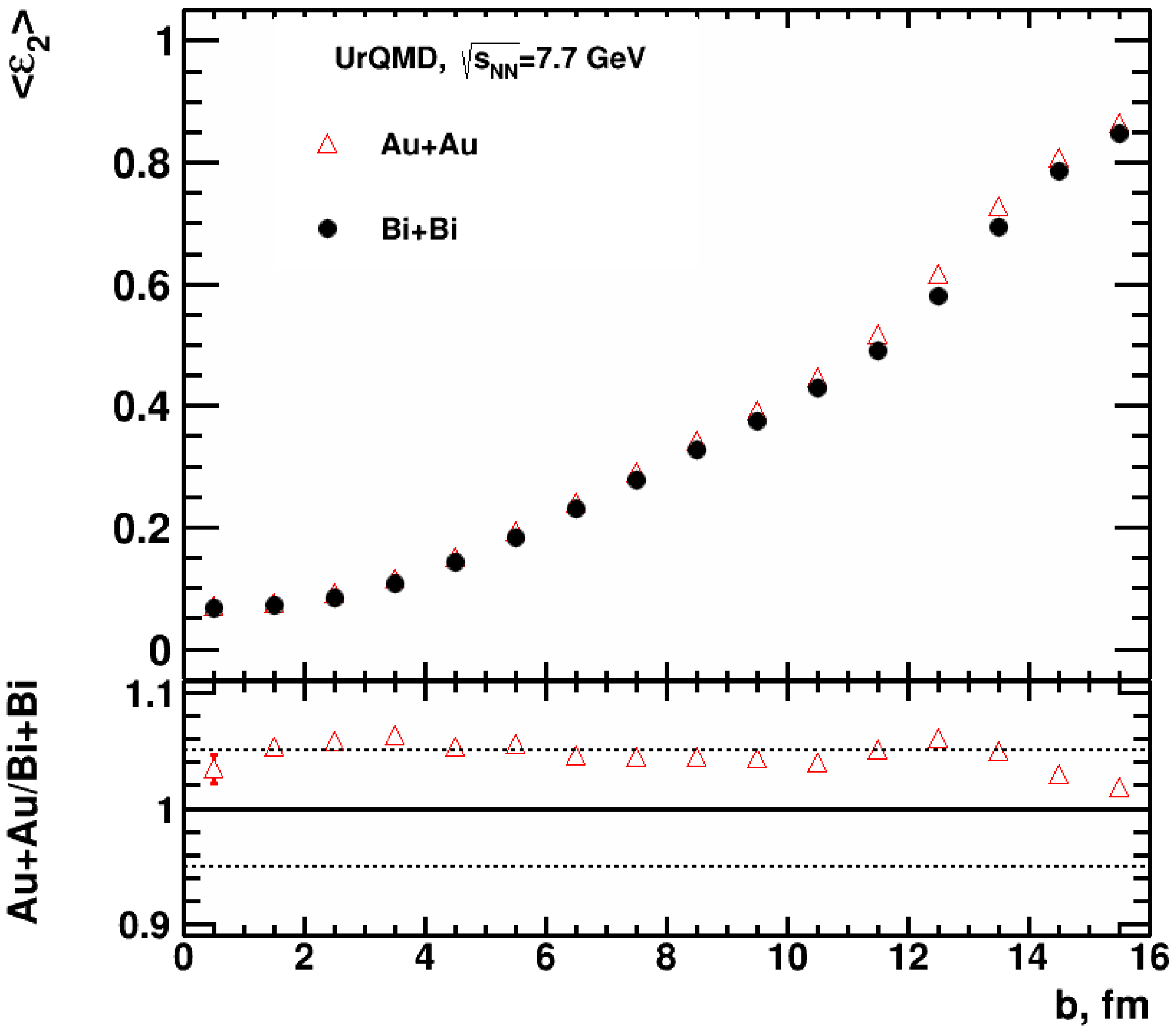
Results for v_2 for reconstructed events of MPD

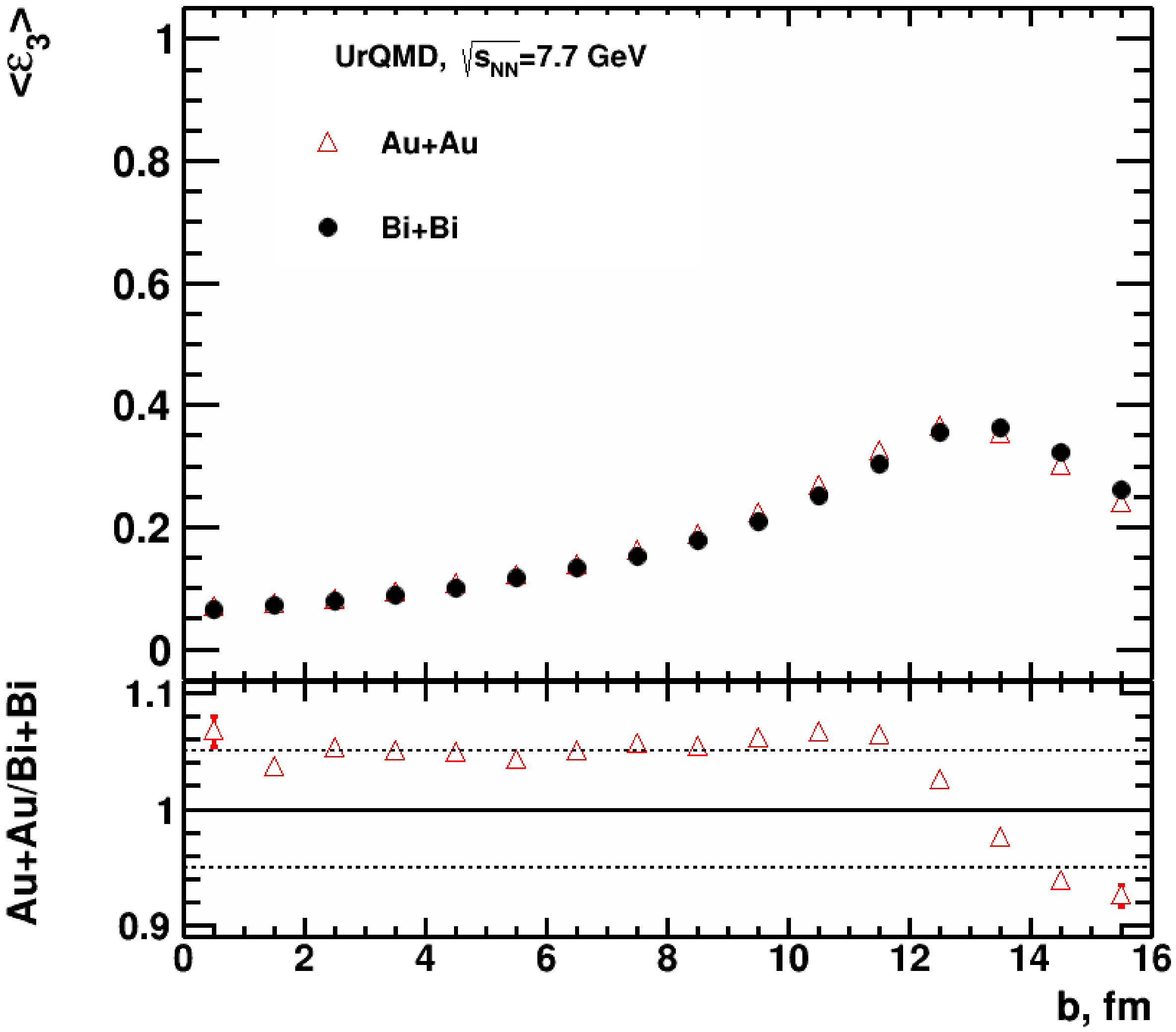




$v_2\{2\}$ and $v_2\{4\}$ are in good agreement with $v_2\{\eta\text{-sub,EP}\}$ at 10-40% centrality

Eccintricity: Bi+Bi vs Au+Au





UrQMD model predicts small difference between ε_n of Au+Au and Bi+Bi

Sensitivity of different orders cumulants to elliptic flow fluctuations

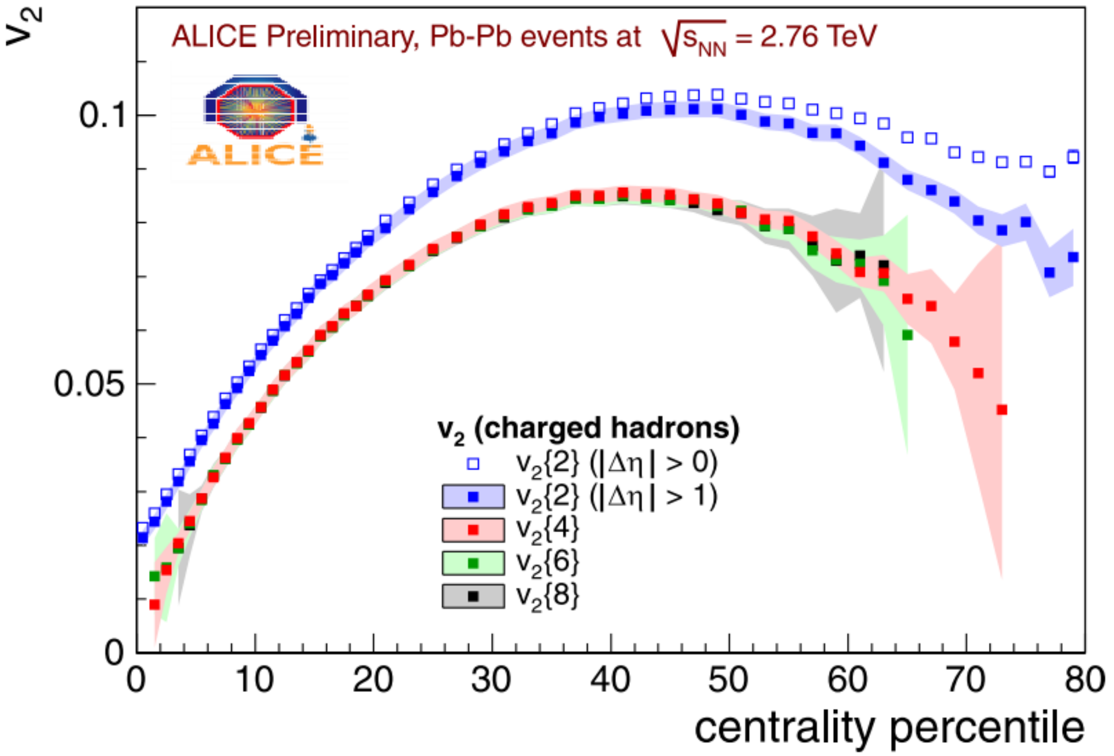
- How fluctuations affect the measured values of v_n. The effect of the fluctuations on v_n estimates can be obtained from

$$\left\langle v_n^2 \right\rangle = \bar{v}_n^2 + \sigma_{v_n}^2, \quad \left\langle v_n^4 \right\rangle = \bar{v}_n^4 + 6\sigma_{v_n}^2 \bar{v}_n^2$$

$$v_n\{2\} = \sqrt{\left\langle v_n^2 \right\rangle}, \quad v_n\{4\} = \sqrt[4]{2\left\langle v_n^2 \right\rangle^2 - \left\langle v_n^4 \right\rangle}$$

- The difference between $v_n\{2\}$ and $v_n\{4\}$ is sensitive to not only nonflow but also to the event-by-event v_n fluctuations.

$$v_n\{2\} = \bar{v}_n + \frac{1}{2}\frac{\sigma_{v_n}^2}{\bar{v}_n}, \quad v_n\{4\} = \bar{v}_n - \frac{1}{2}\frac{\sigma_{v_n}^2}{\bar{v}_n}$$

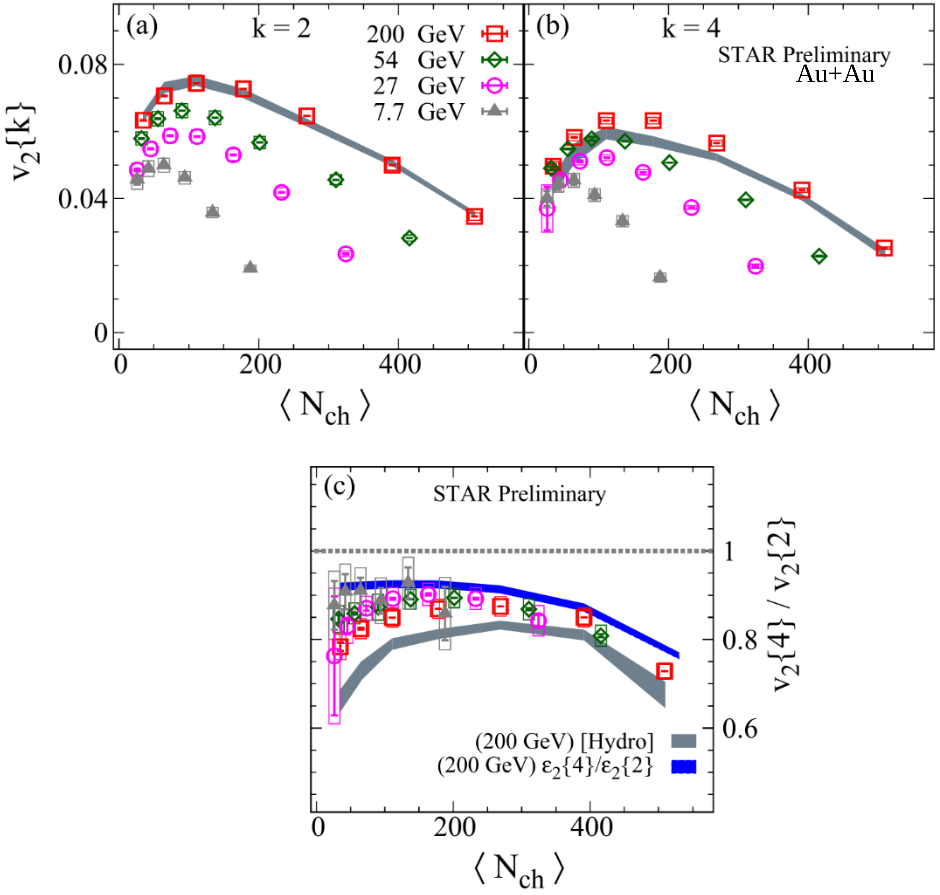


The difference between $v_n\{2\}$ with and without $\Delta\eta$ gap is driven by the contribution from nonflow

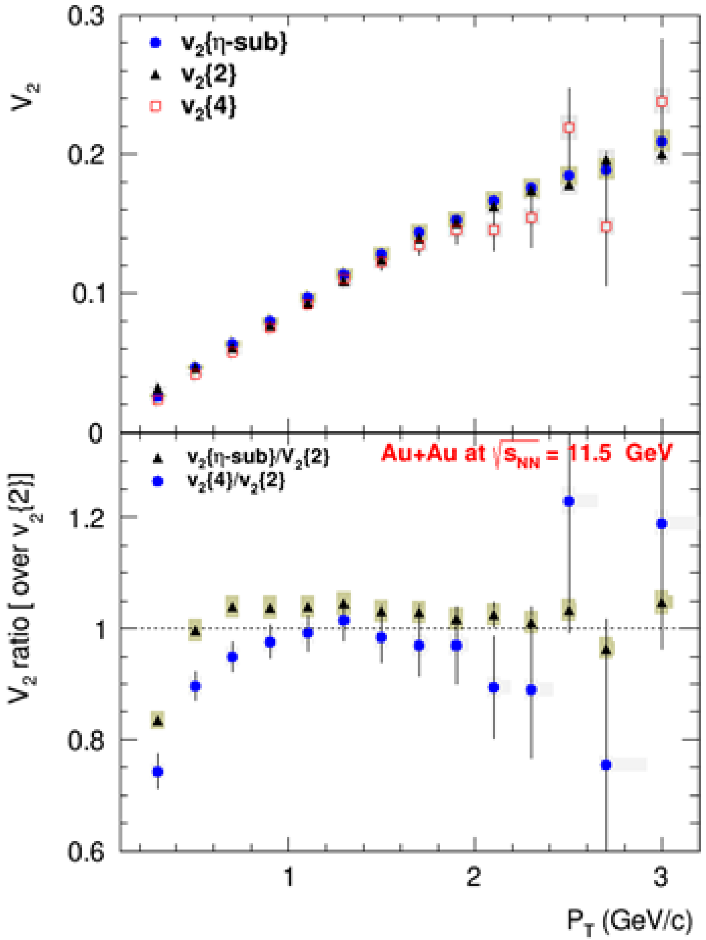
Ilya Selyuzhenkov for the ALICE collaboration, Prog.Theor.Phys.Suppl. 193 (2012) 153-158

Cumulant results from Beam Energy Scans

Niseem Magdy, Nucl.Phys.A 982 (2019) 255-258



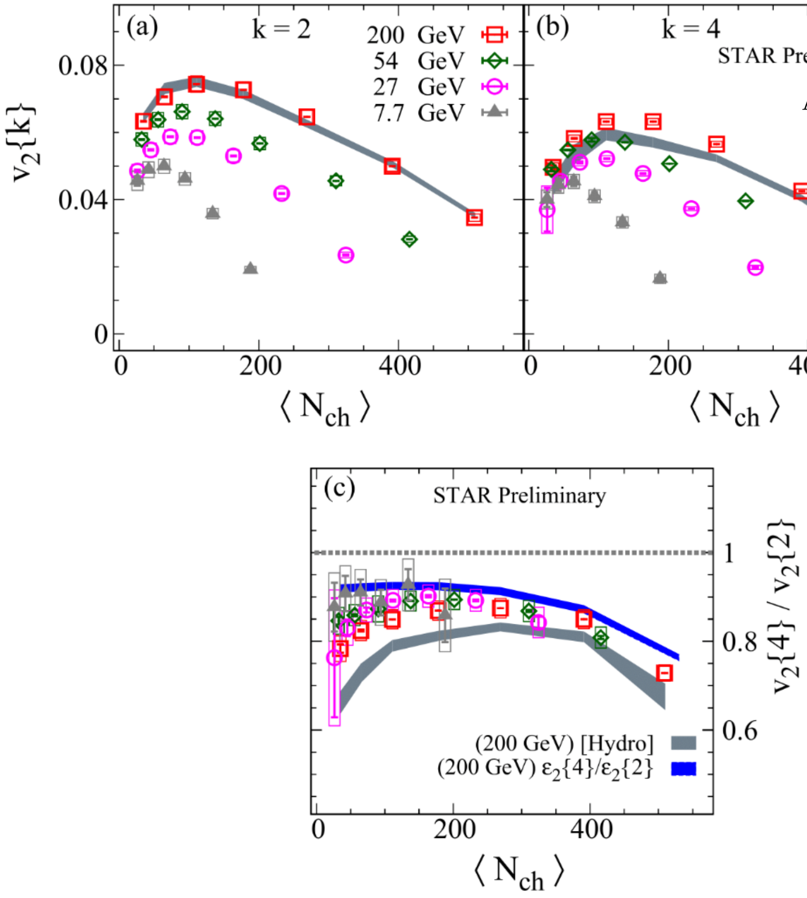
L. Adamczyk et al. (STAR Collaboration). Phys. Rev. C 86, 054908 (2012)



The magnitude and trend of the fluctuations, have weak beam energy dependence

Methods of flow measurements have different sensitivity to flow fluctuations

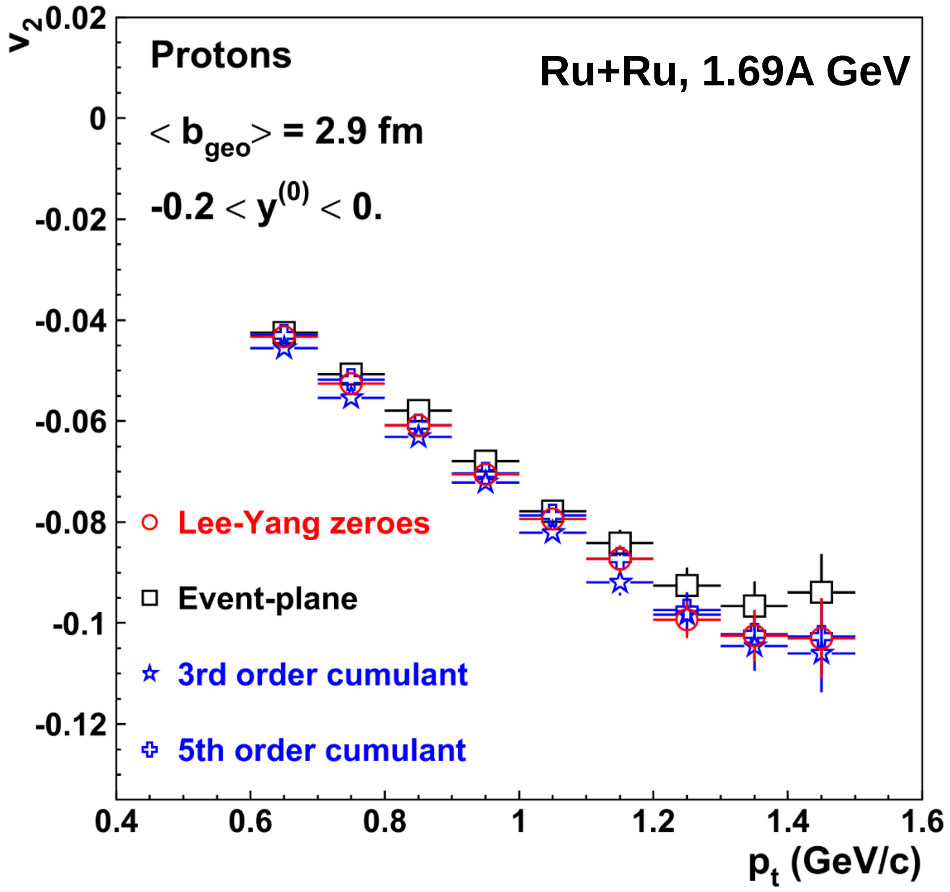
Cumulant results from Beam Energy Scans



Comprasssion of (a) $v_2\{2\}$ vs. $\langle N_{ch}\rangle$, (b) $v_2\{4\}$ vs. $\langle N_{ch}\rangle$ and (c) thir ratio for Au+Au collisions

Niseem Magdy, Nucl.Phys.A 982 (2019) 255-258

arXiv:1807.07638



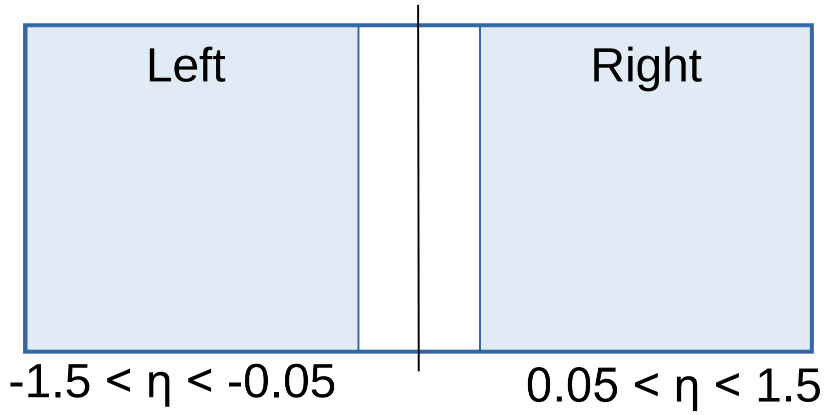
v_2 versus transverse momentum for protons measured in semi-central events and around mid-rapidity.

N. Bastid, et al., Phys.Rev. C72 (2005) 011901

arXiv:nucl-ex/0504002

Results for v_2 from UrQMD model of Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV

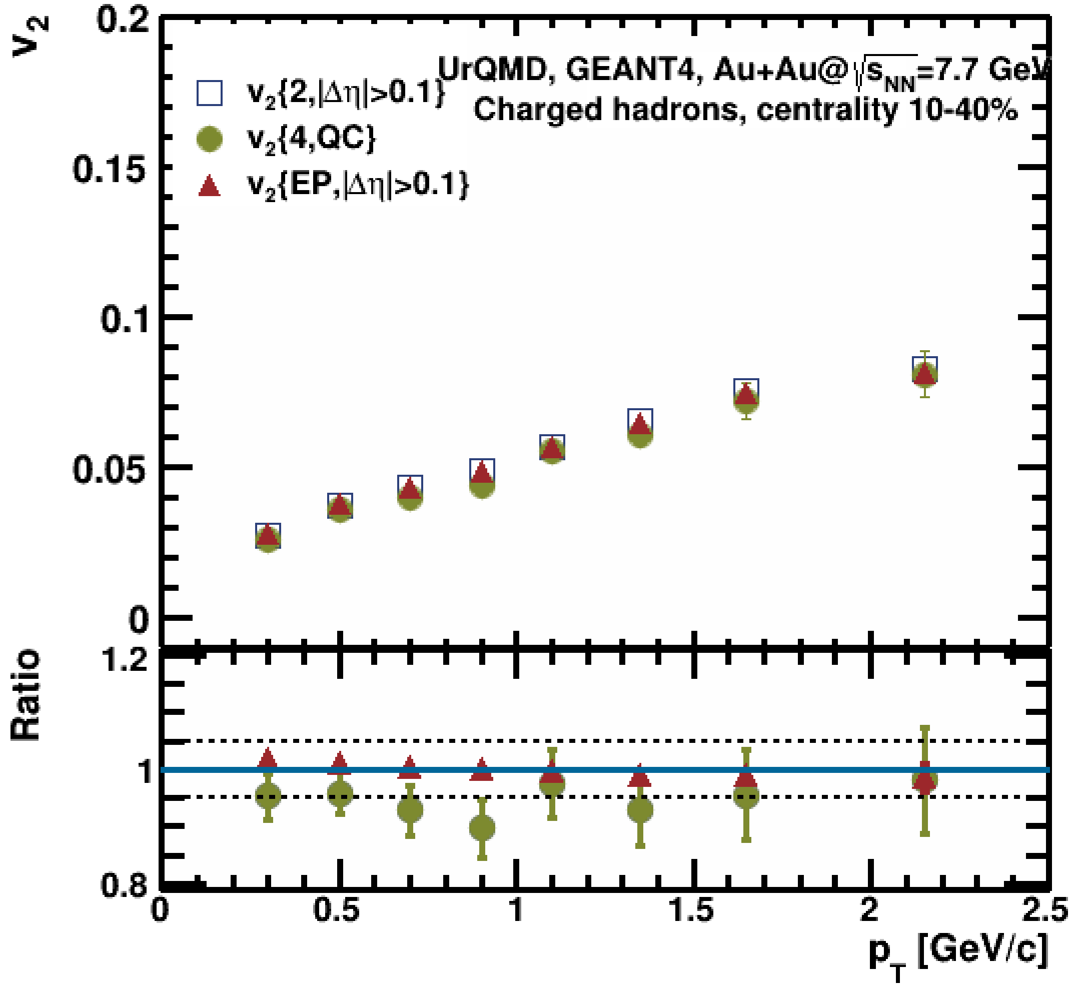
- Total number of generated minimum bias events - 88 M
- Particle selection: charged hadrons, $0.2<p_T<3$ GeV/c
- Configuration of cumulant method:
  1. RFP and POI: charged hadrons;
  2. calculations were performed taking into account the effect of autocorrelation
- All 3 methods have the same kinematical cuts

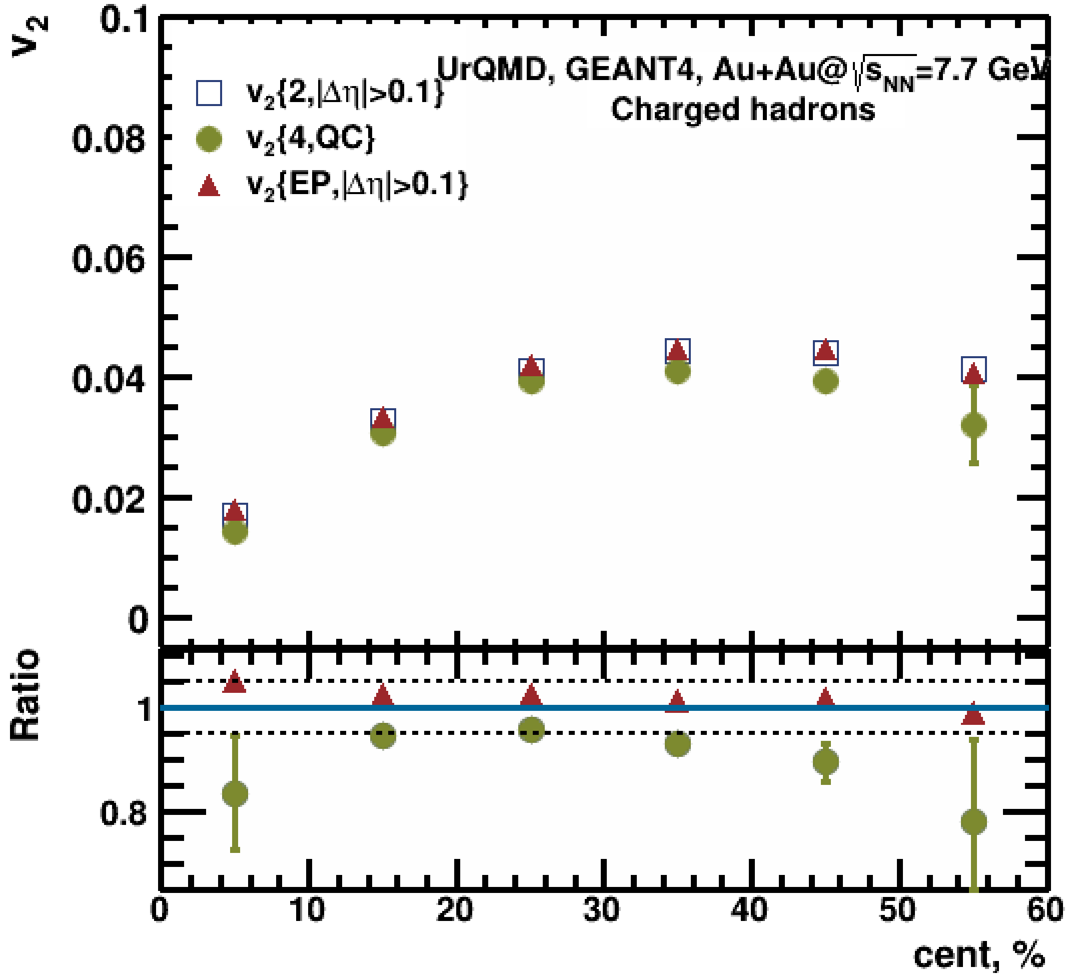


Left half ($\eta<-0.05$) → η_-

Right half ($\eta>0.05$) → η_+

Results for v_2 for reconstructed events of MPD





$v_2\{2\}$ and $v_2\{4\}$ are in good agreement with $v_2\{\eta\text{-sub,EP}\}$ at 10-40% centrality