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

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For the MPD Collaboration

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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 3.0, 4.5, 7.7 and 11.5 GeV + new results from BES-II

Anisotropic flow at NICA energies   Models:

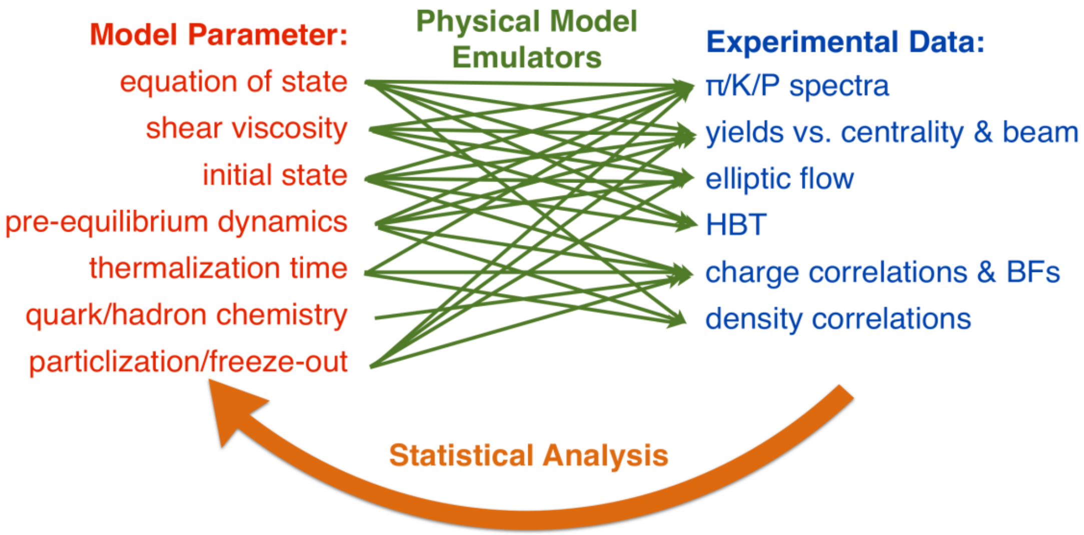
(1) String/Hadronic Cascade Models: UrQMD, HSD, SMASH, JAM, DCM-QGSM

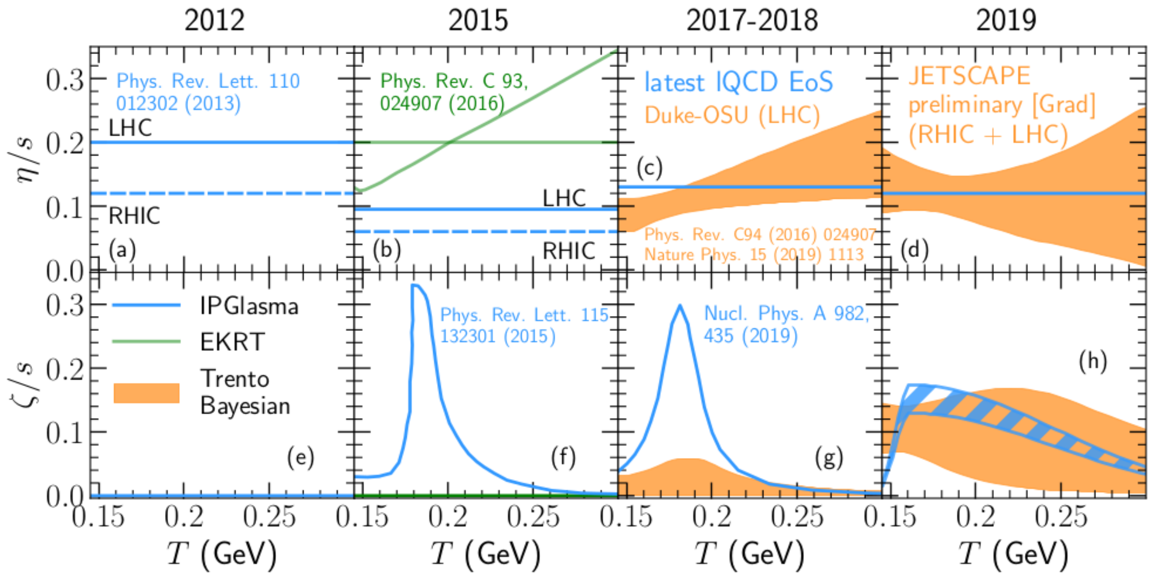
(2) Hybrid Models: viscous hydro+cascade (vHLLE+UrQMD и MUSIC+UrQMD) и parton/string models (AMPT, PHSD и PHQMD)

Goals: Reliable set of published vn results for comparison

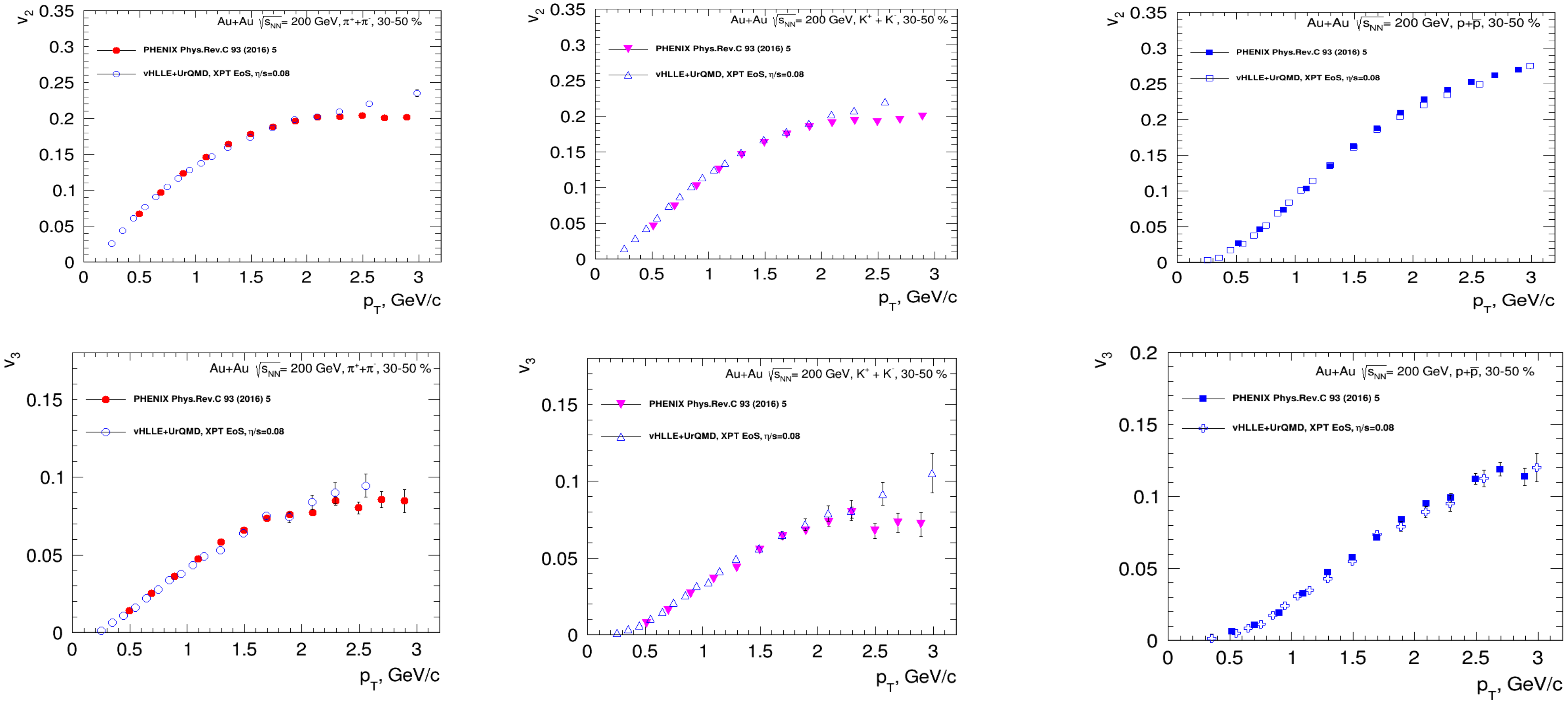
Hybrid model   constructor

Tools for a Bayesian analysis of Heavy Ion Collisions





vHLLE+UrQMD: Elliptic and triangular flow in Au + Au collisions at 200 GeV

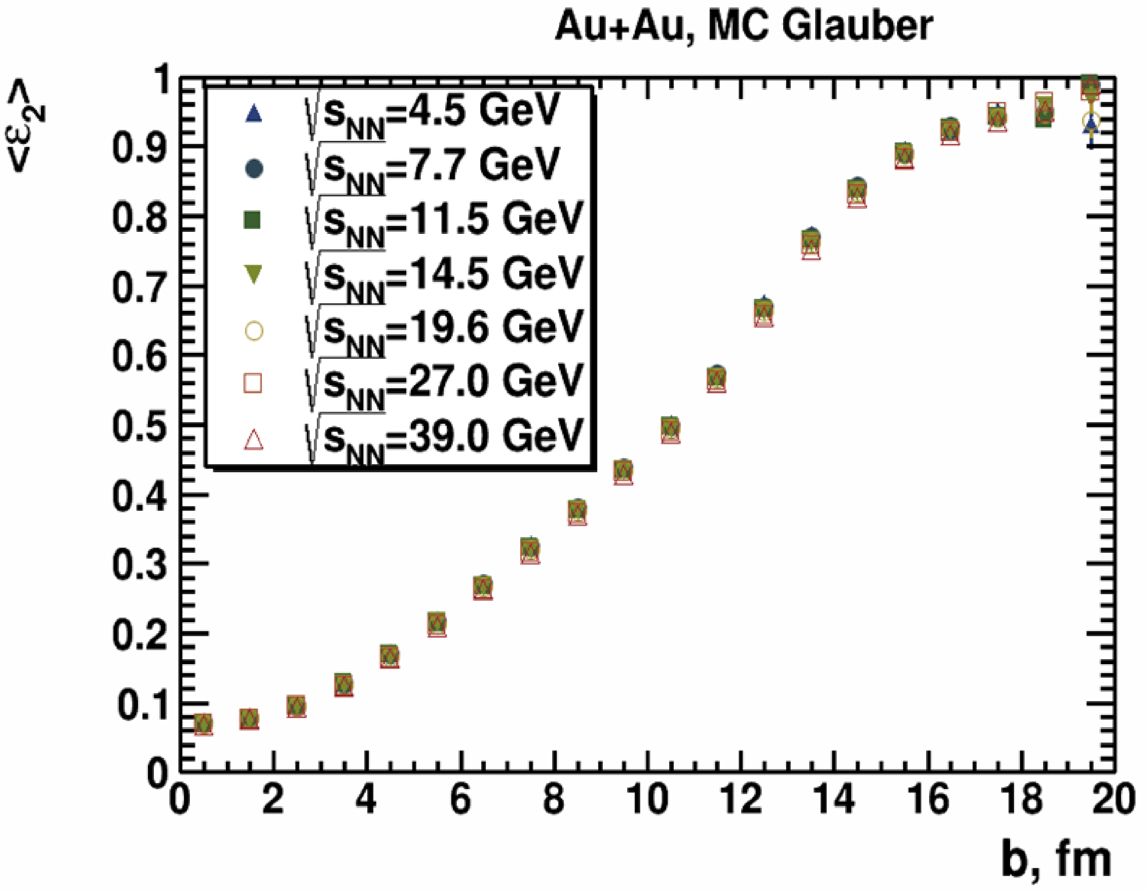


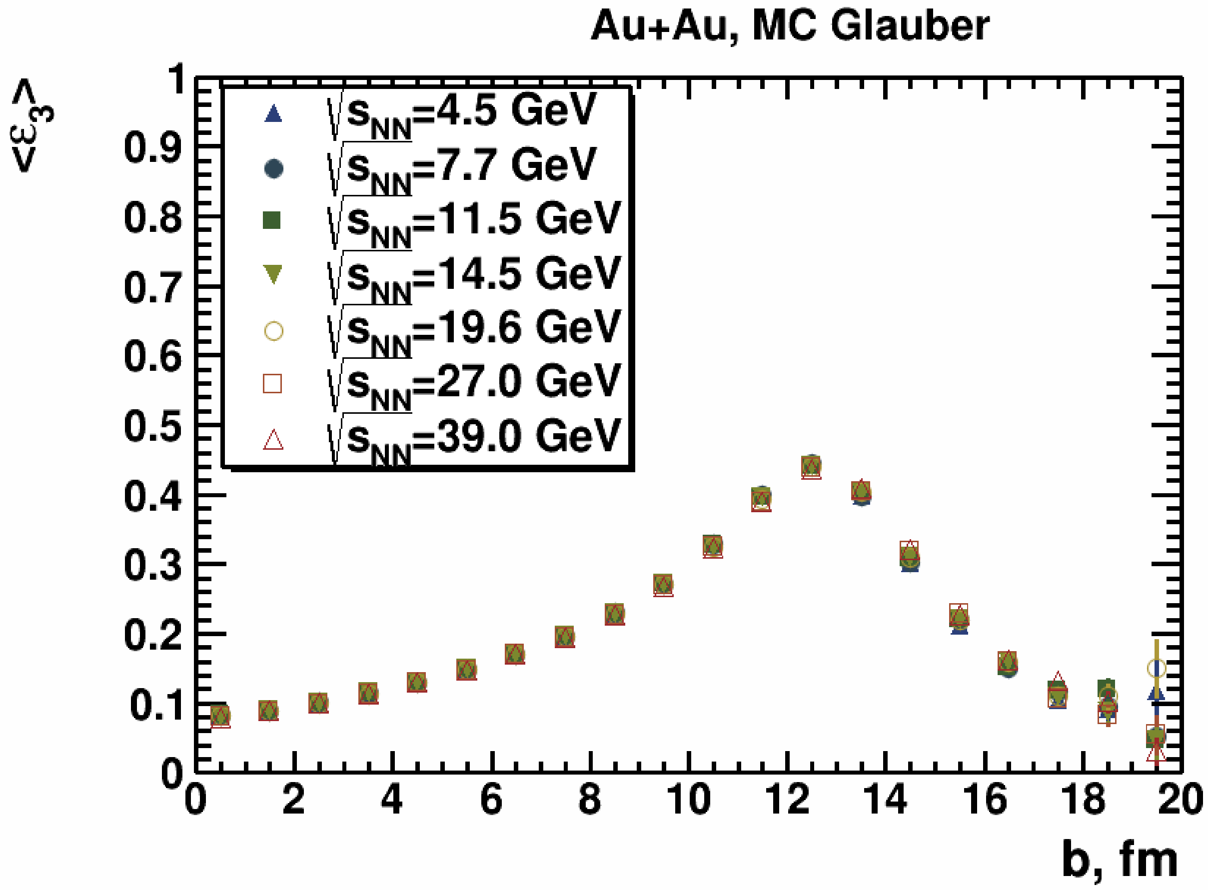
3D hydro model vHHLE + UrQMD (XPT EOS), $\eta/s = 0.08$ + param from

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

Beam Energy dependence of ε_2 and ε_3

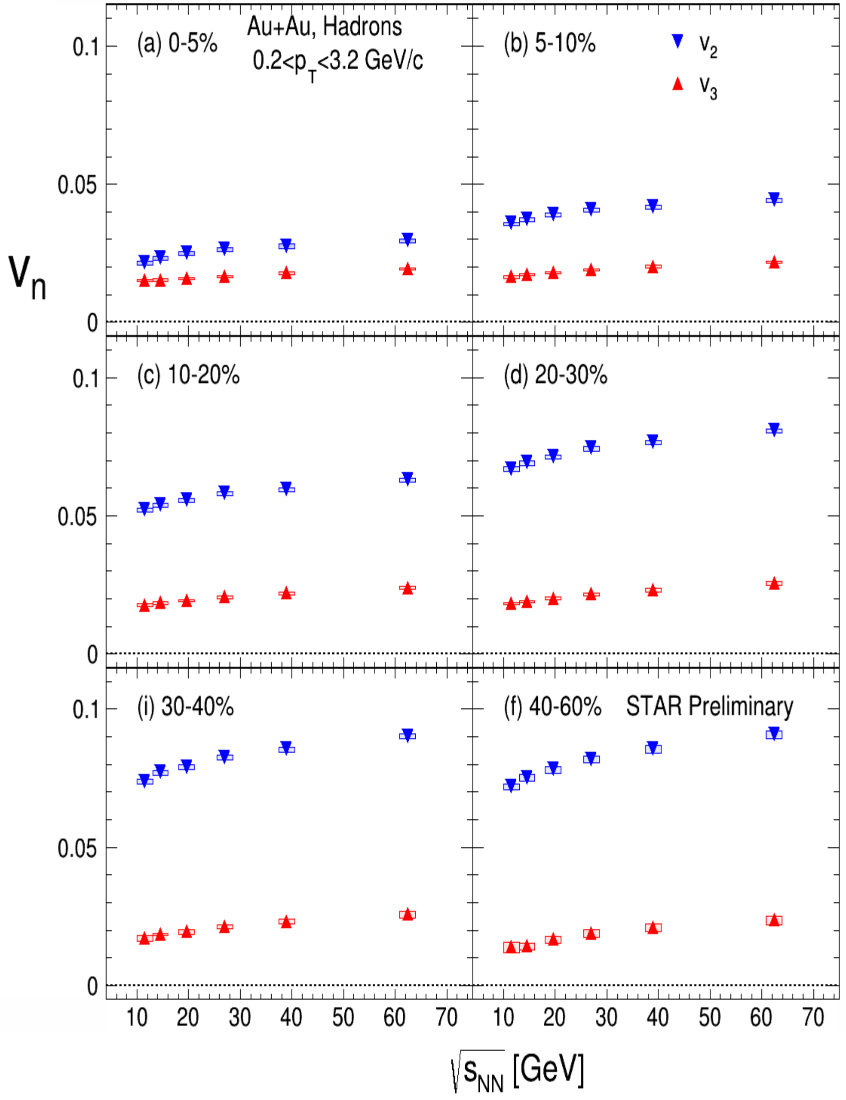


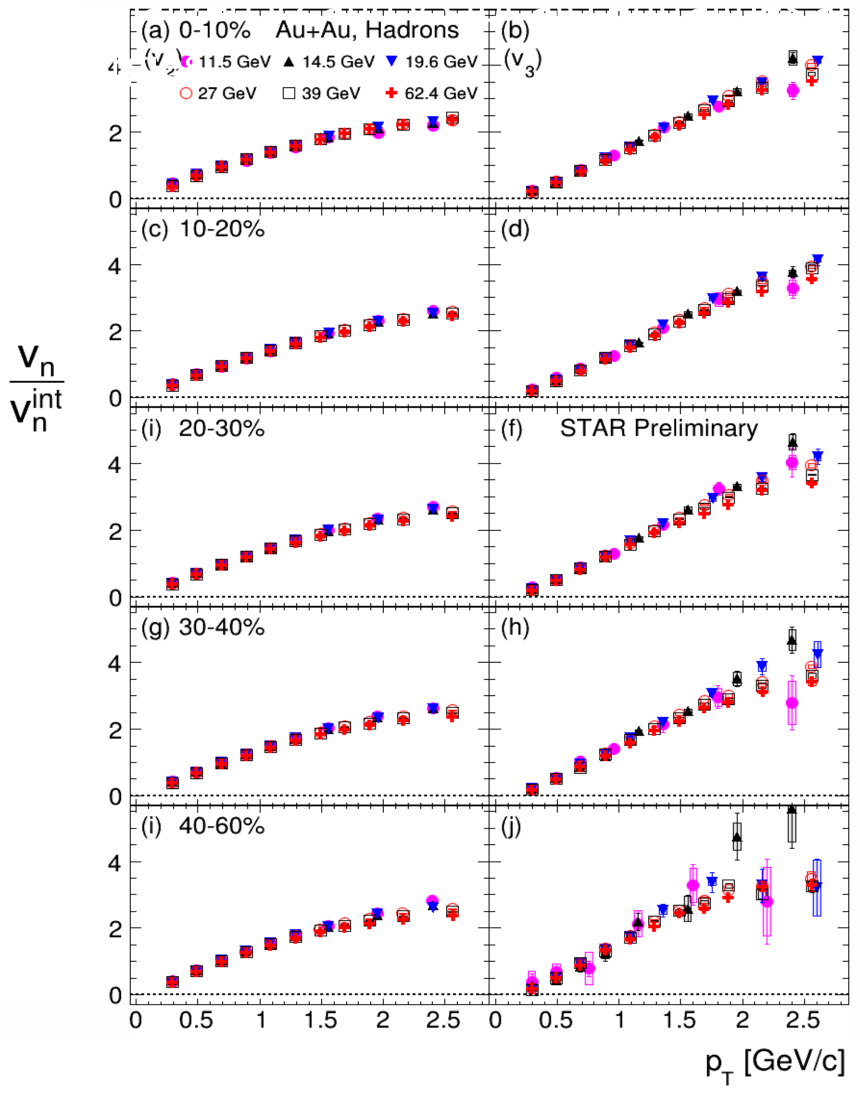


Beam-energy dependence of v_2 and v_3

*No p_T-dependent efficiency was applied

Petr Parfenov for STAR Collaboration, ICPPA 2020



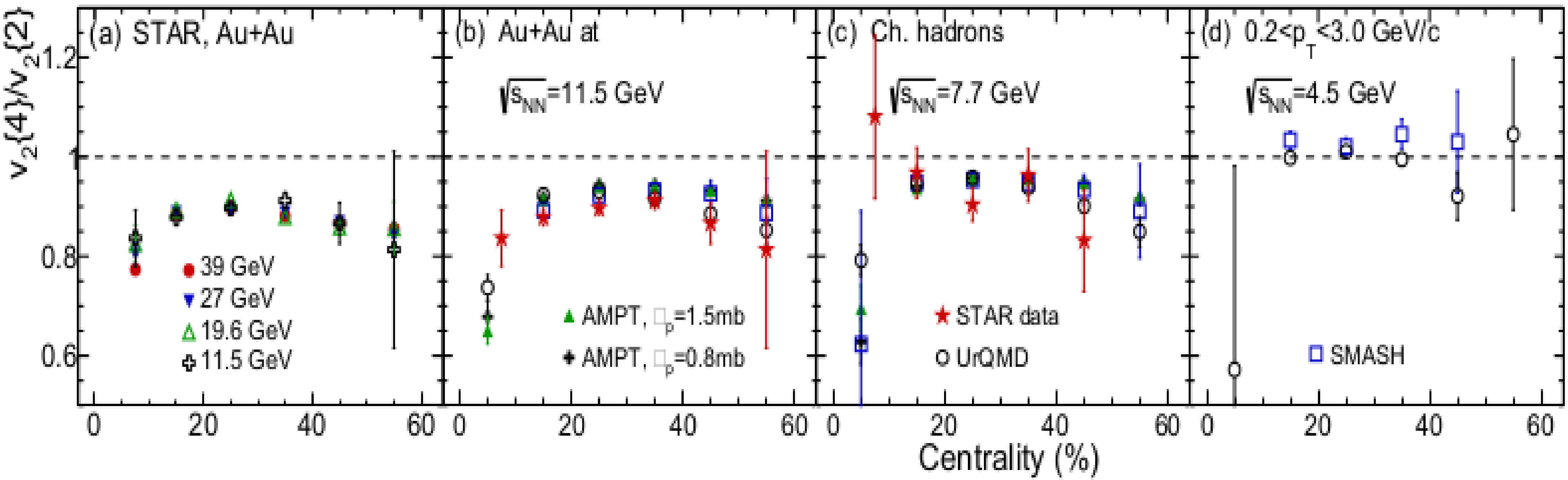


Integrated v_2 and v_3 decrease with decreasing collision energy

Similar shape of p_T dependence of normalized v_2 and v_3 for all centralities and beam energies

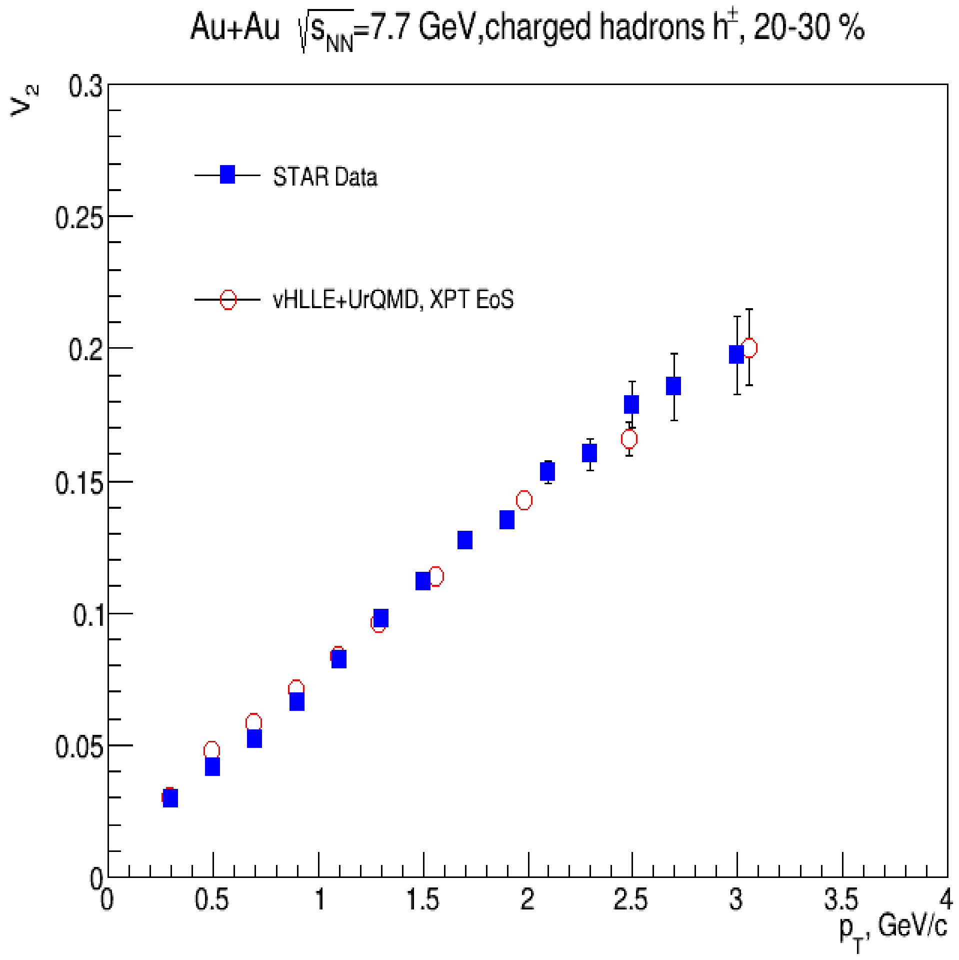
Beam energy dependence of Relative elliptic flow fluctuations

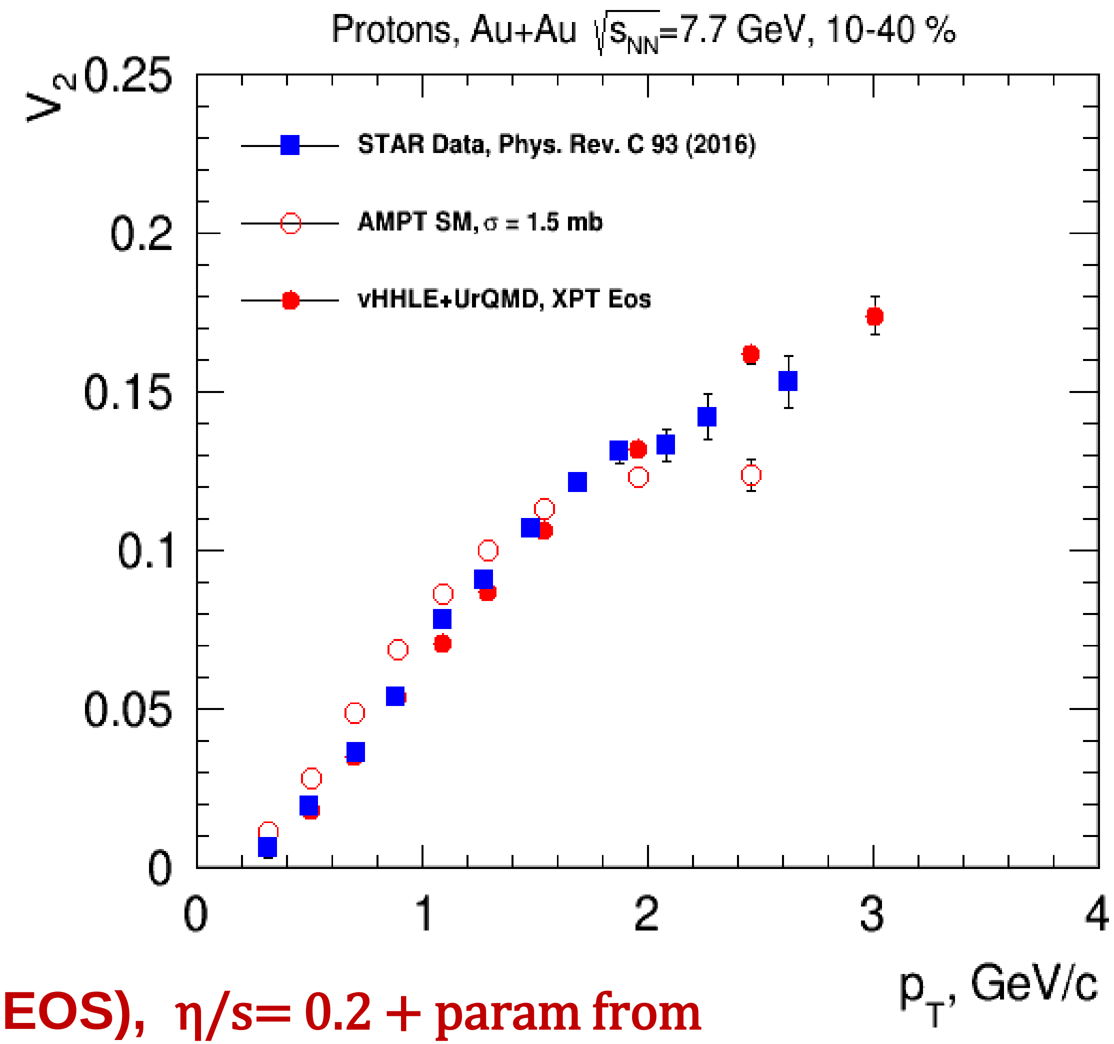
Star data: L. Adamczyk et al. (STAR Collaboration). Phys. Rev. C 86, 054908 (2012)
Analysis of the model data: Vinh Ba Luong, Dim Idrisov (MEPhI)



- 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

Elliptic flow at NICA energies: Models vs Data comparison





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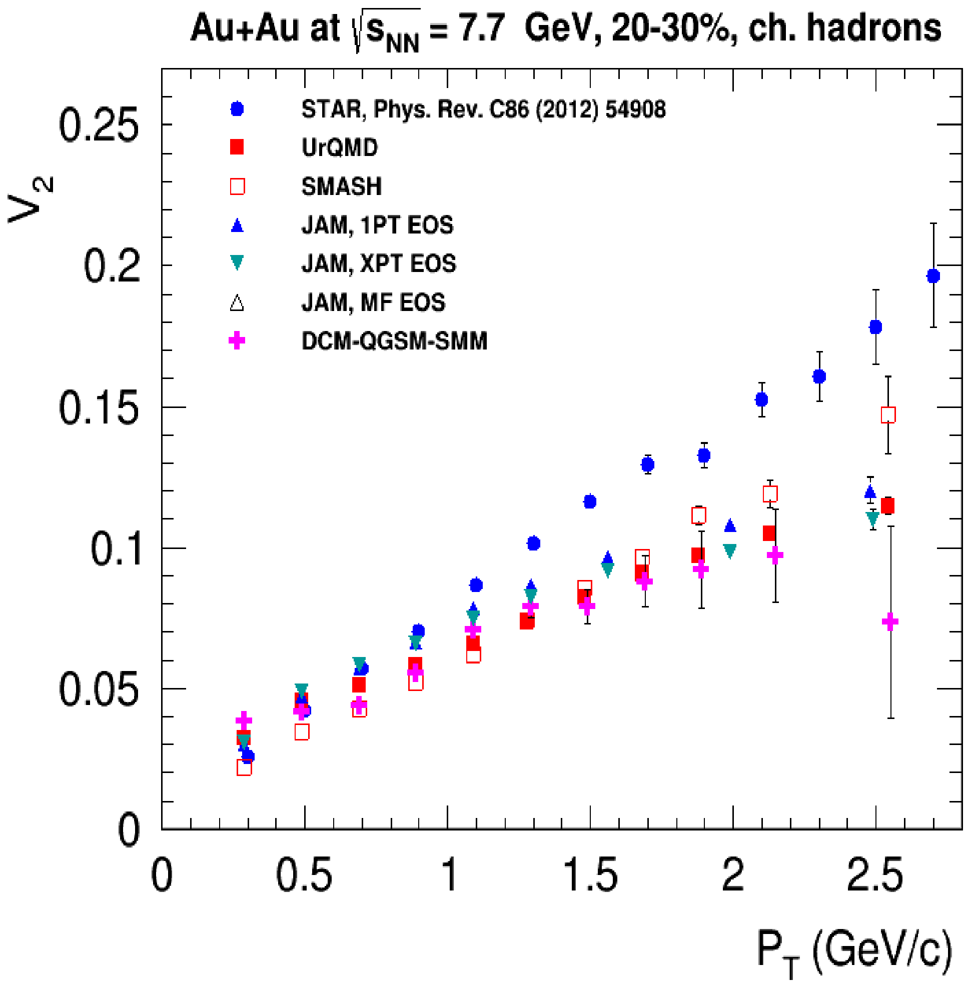
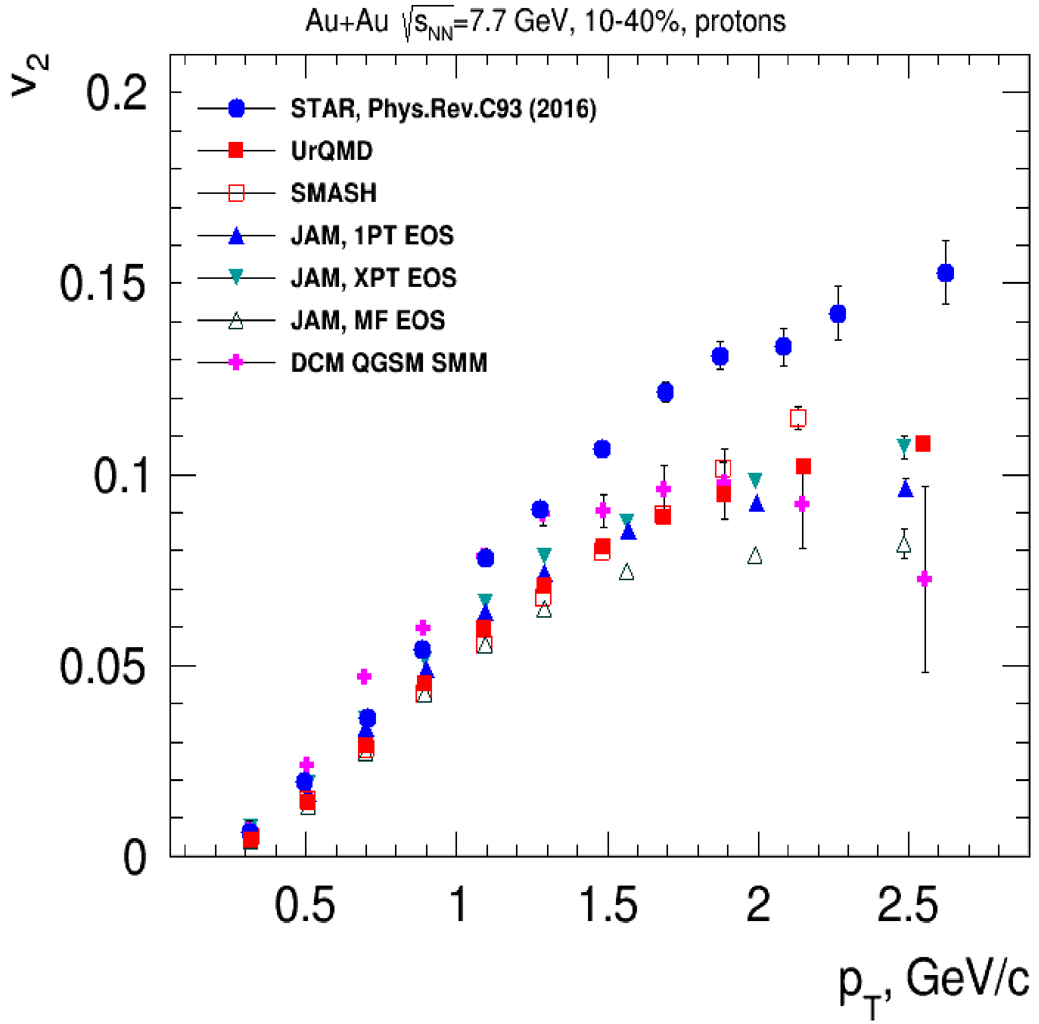
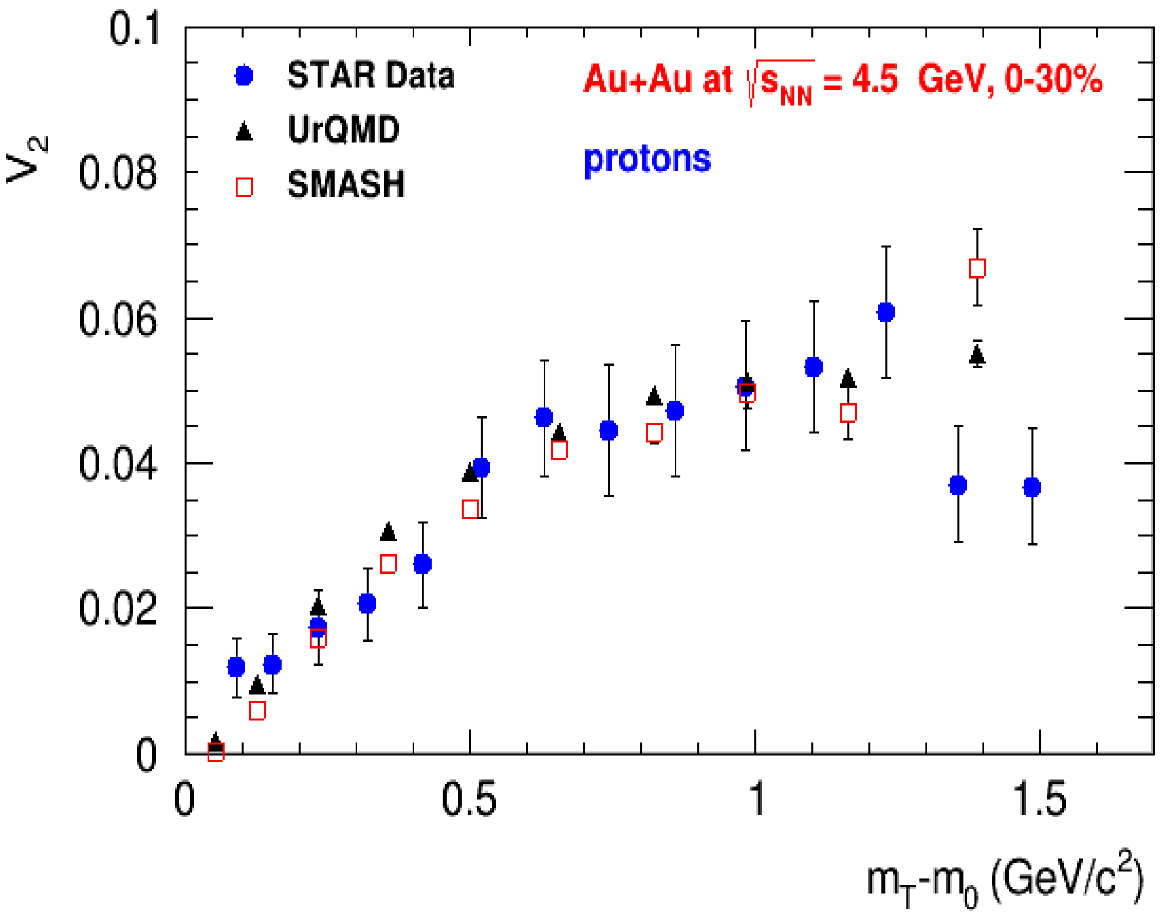


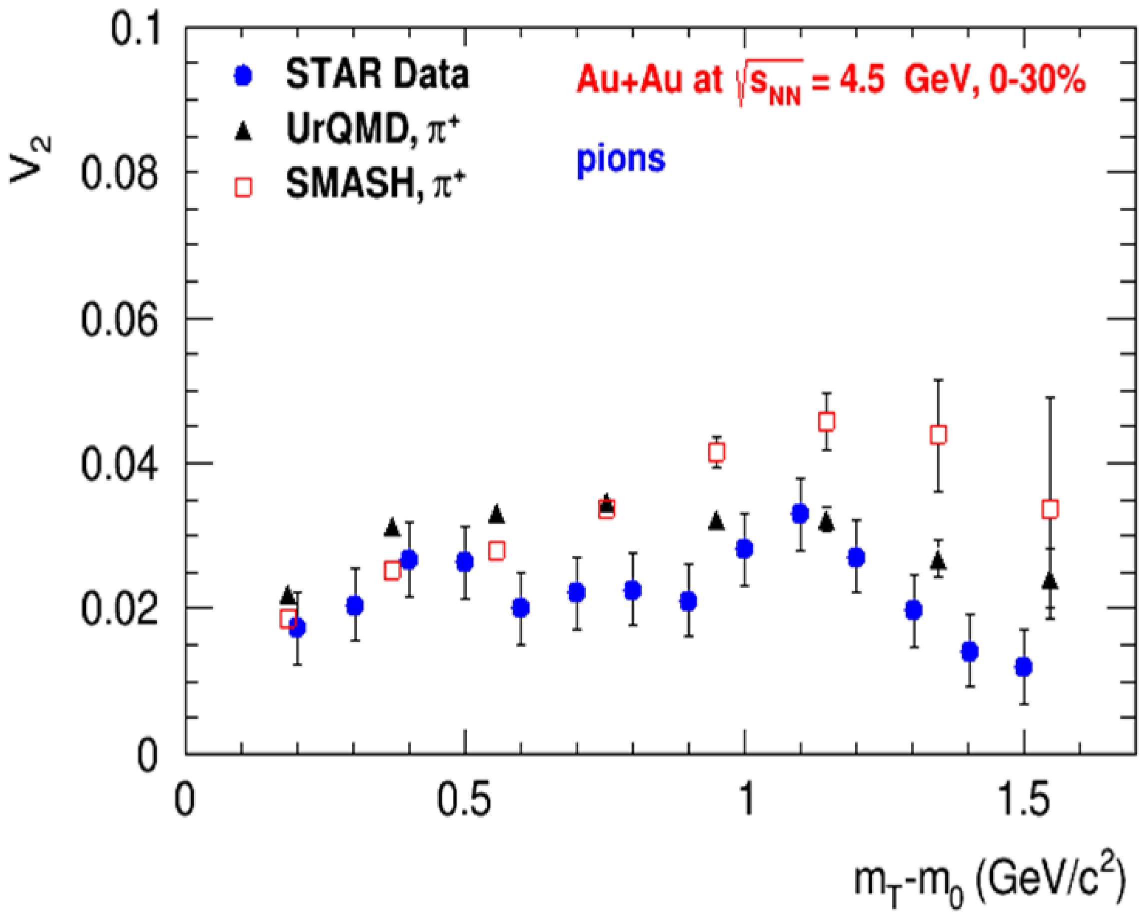


Pure String/Hadronic Cascade models give smaller v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=7.7 GeV and above

Elliptic flow at NICA energies: Models vs Data comparison

STAR Data, https://arxiv.org/abs/2007.14005



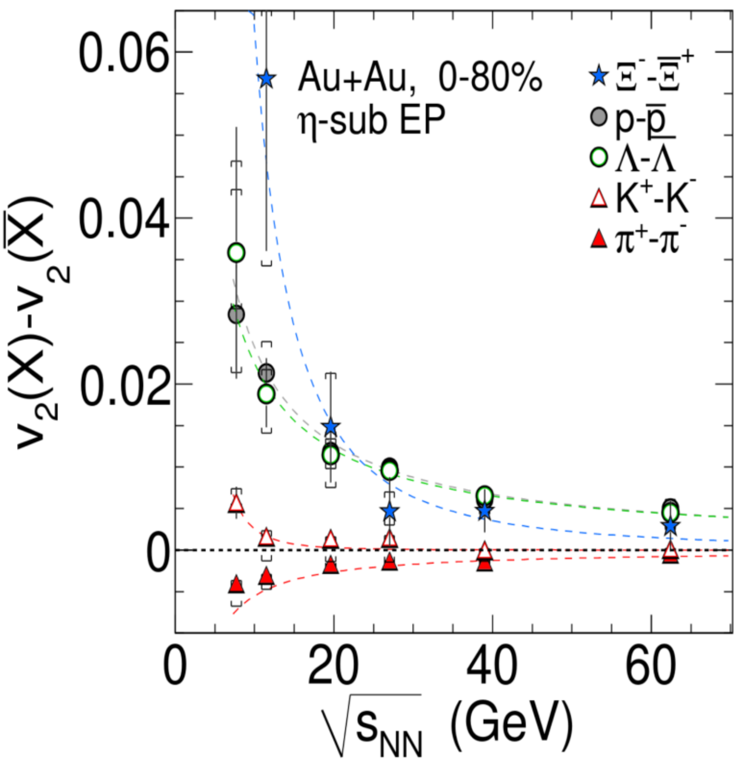


Pure String/Hadronic Cascade models give similar v_2 signal compared to STAR data for Au+Au $\sqrt{s_{NN}}$=4.5 GeV

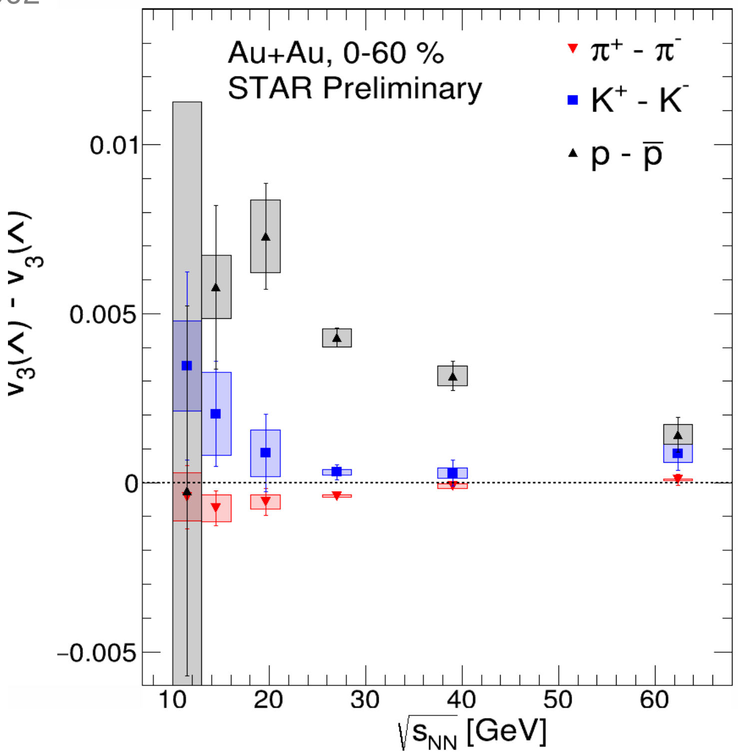
Beam-energy dependence of v_2 and v_3 particle-antiparticle difference

Petr Parfenov for STAR Collaboration (ICPPA2020)

STAR Collaboration, Phys. Rev. C 88 (2013) 14902

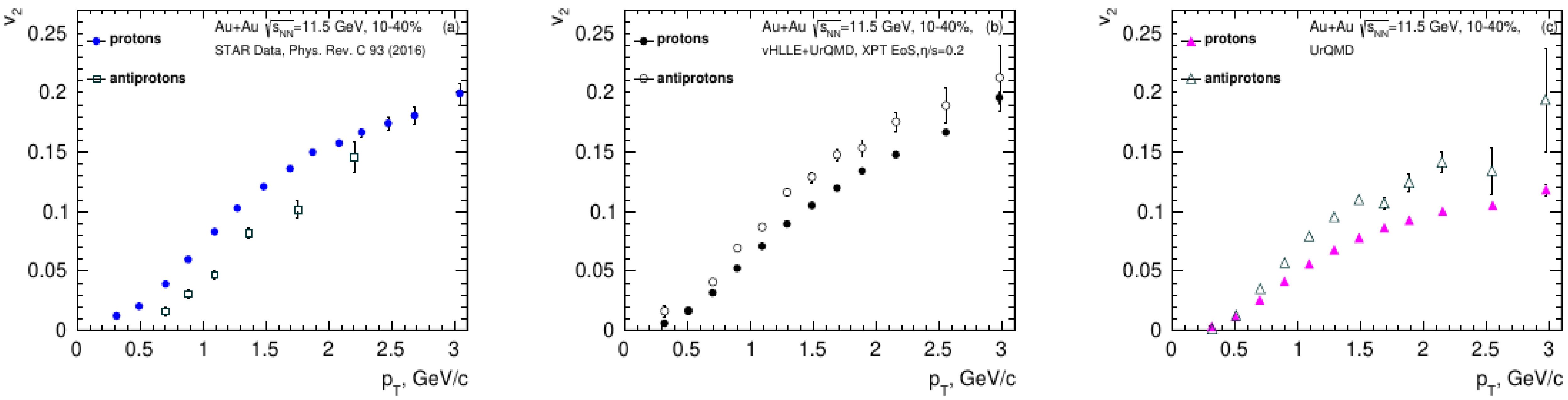


New results



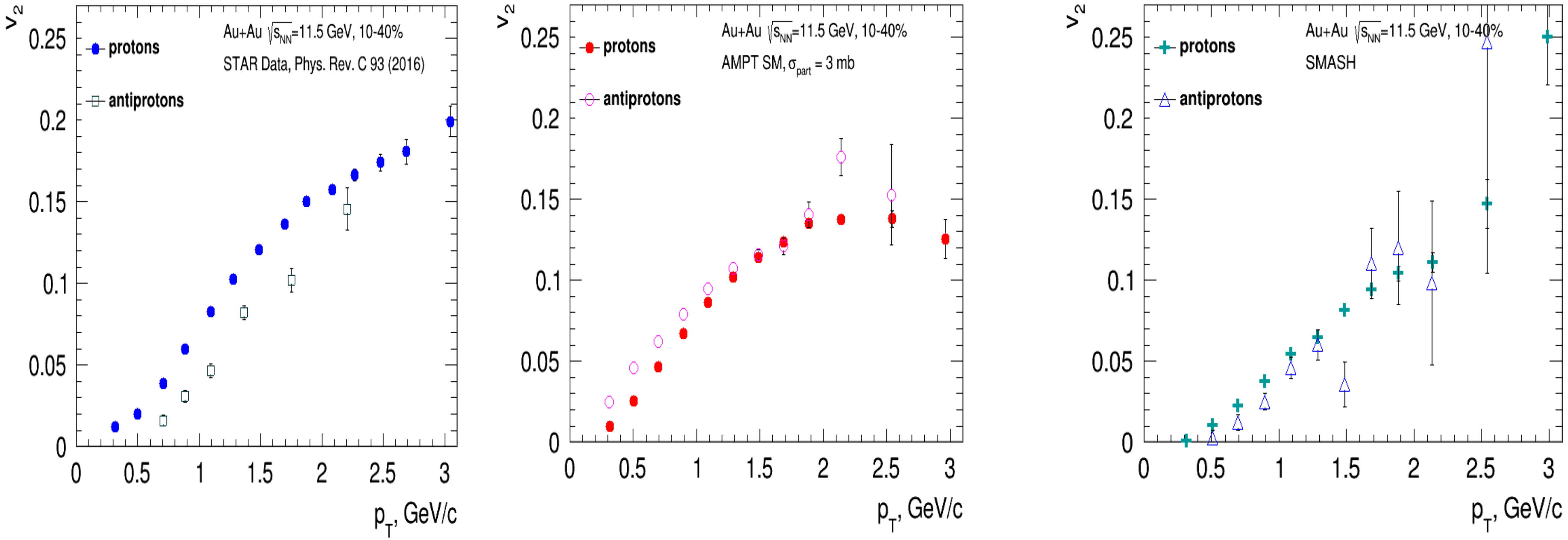
- Several theoretical scenarios of possible sources of the observed difference in v_2:
  - Transported and produced protons (or quarks) have different v_2
  - Mean-field potentials in the hadronic phase: particles feel Coulomb attraction or repulsion corresponding to their charge sign
  - Possible artificial increase of the baryon-antibaryon difference may be attributed to the way event plane is defined in the measurements
- The difference cannot be quantitively reproduced within those scenarios

Elliptic flow: protons vs. antiprotons



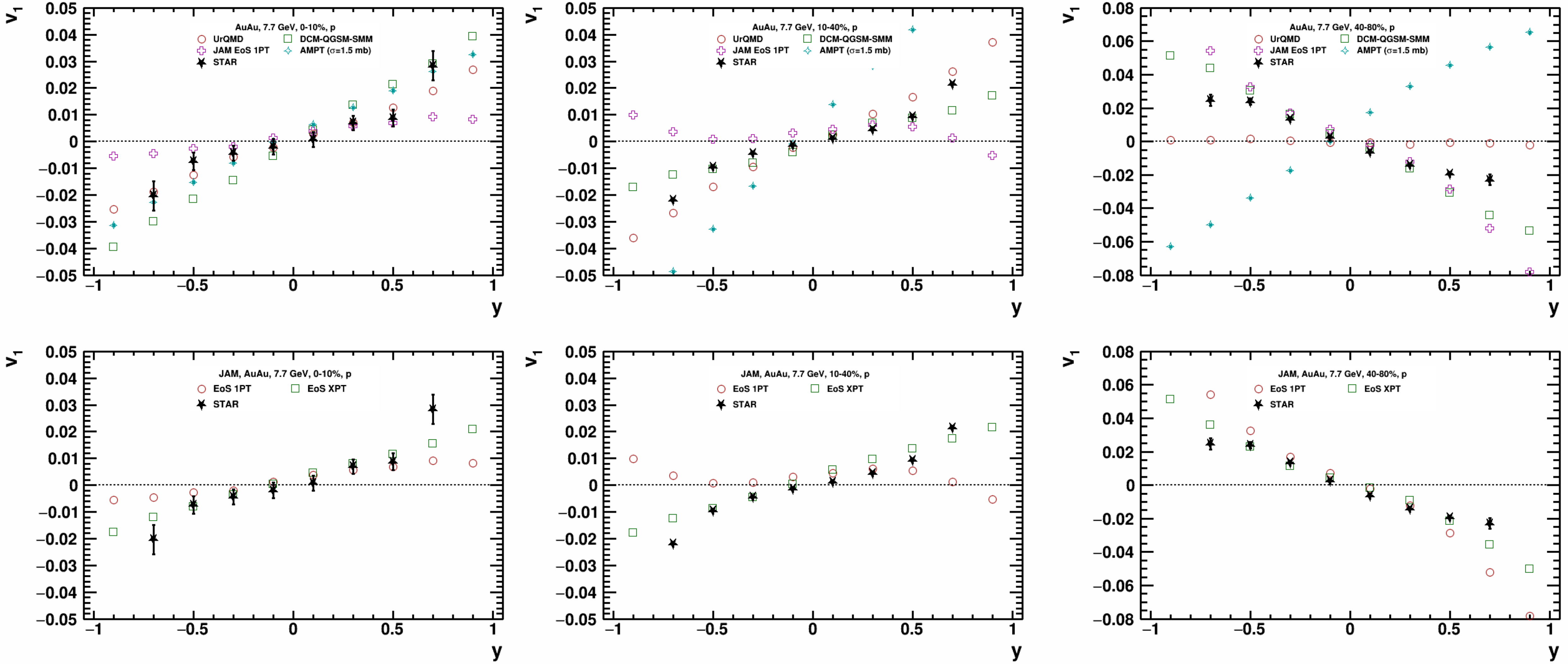
- Both vHLLE+UrQMD and UrQMD predict $v_2(p) < v_2(\bar{p})$ but experimental data shows $v_2(p) > v_2(\bar{p})$

Elliptic flow: protons vs. antiprotons



- The same trend is apparent in both UrQMD and AMPT
- SMASH gives a different trend – close to the data

Model vs. data comparison for $v_1(y)$

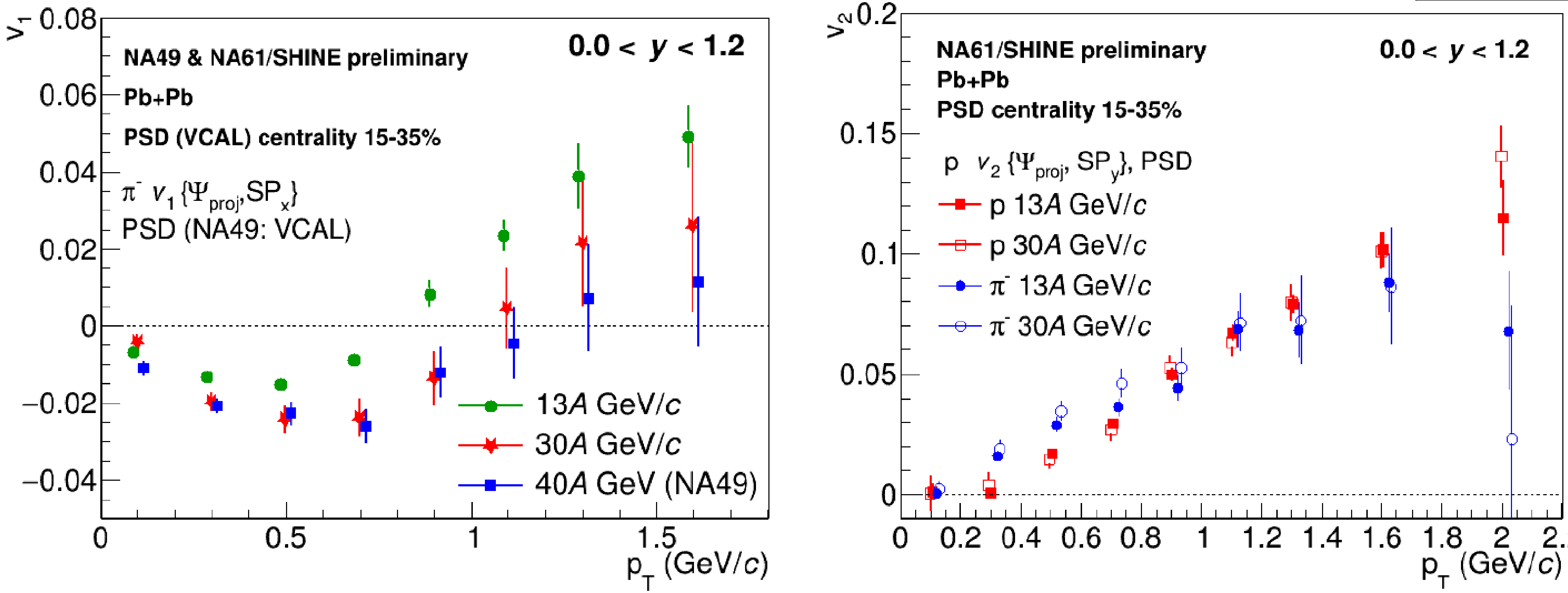


- DCM-QGSM-SMM and JAM XPT have the better agreement with STAR published data
- Slope dv_1/dy changes dramatically with centrality for protons

$v_1(p_T)$ at NICA energy range

p_{Lab}, A GeV/c	$\sqrt{s_{NN}}$, GeV
13	5.123
30	7.624
40	8.87

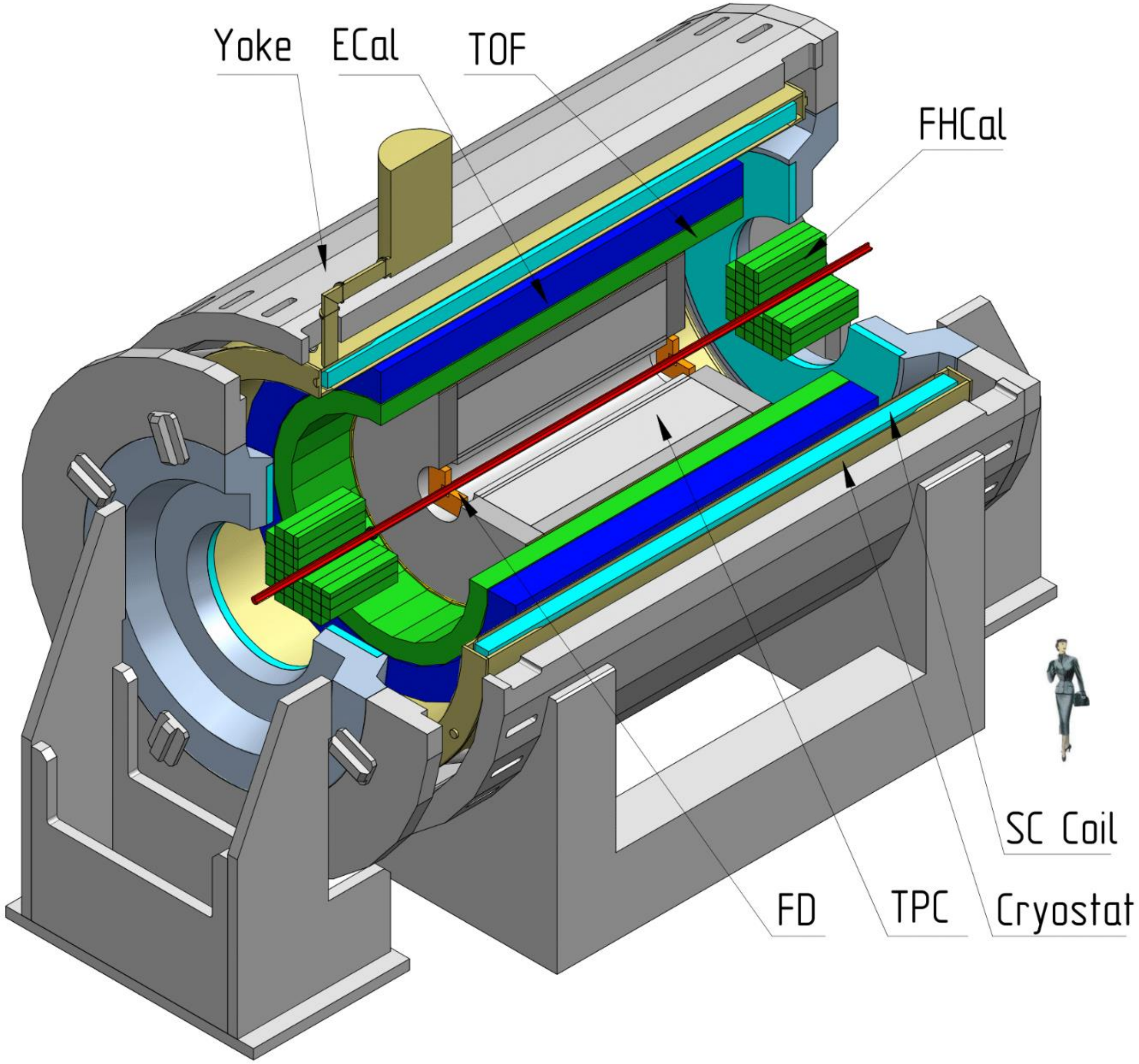
NA61/SHINE: Golosov. O., Kashirin E. (MEPhI), ICPPA 2020



- What kind of additional information can we extract from (p_T, centrality)-dependence of v_1 from comparison with DCM-QGSM-SMM and JAM (XPT & 1PT EoS) models?

MPD Experiment at NICA

Multi-Purpose Detector (MPD) Stage 1



Event plane, centrality:

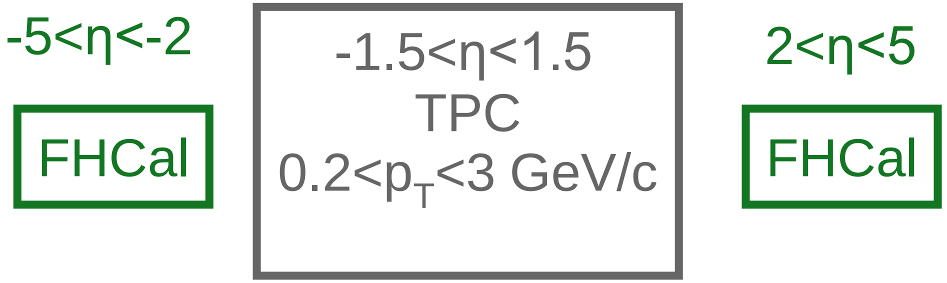
FHCal ($2<|\eta|<5$) or TPC ($|\eta|<1.5$)

Time Projection Chamber (TPC)

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

Time of Flight (TOF)

- PID at high momenta



Setup, event and track selection

Model → GEANT4 → Reconstruction → Flow analysis

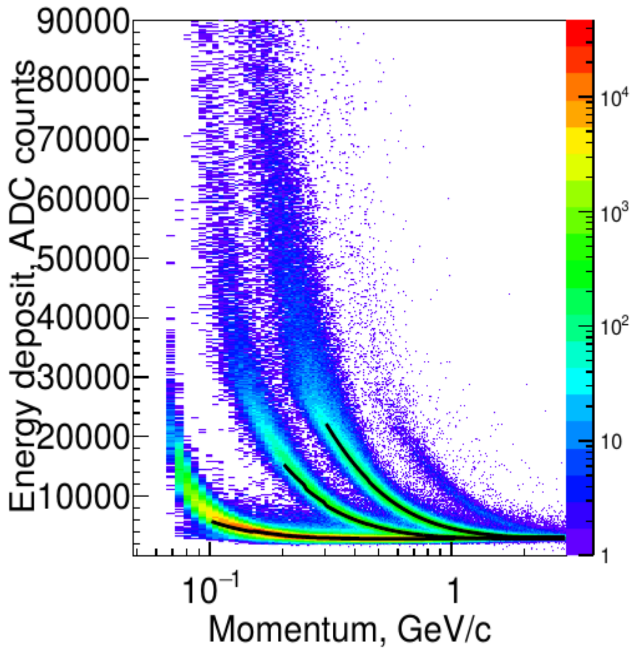
- Au+Au: UrQMD
  - N_{events}= 10 M *at* $\sqrt{s_{NN}}$ = 4.5, 11.5 GeV
  - N_{events}= 25 M *at* $\sqrt{s_{NN}}$ = 11 GeV (for K^0, Λ)
  - N_{events}= 20 M at $\sqrt{s_{NN}}$ = 7.7 GeV
- Bi+Bi:
  - N_{events}= 17 M *at* $\sqrt{s_{NN}}$ = 7.7 GeV

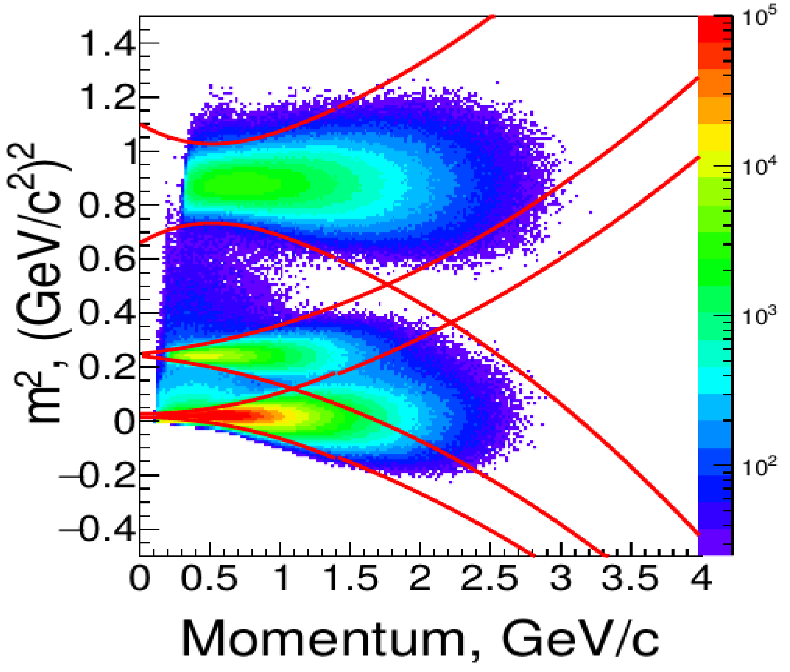
- TPC
- FHCal
- TOF
- ...

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



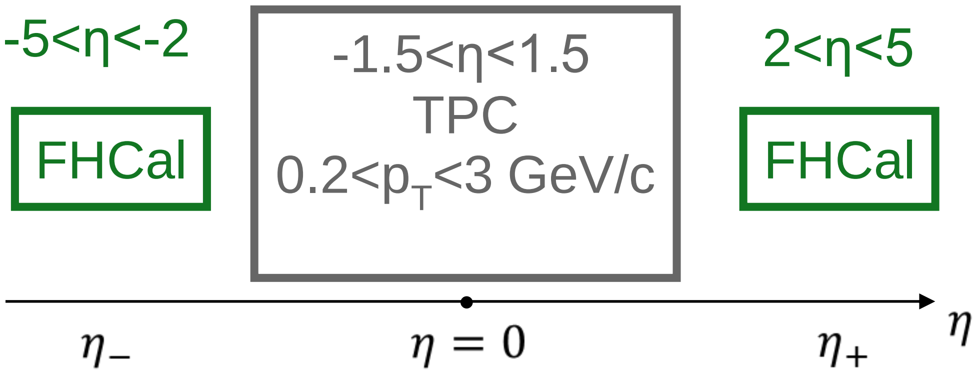


v1,v2 and v3 measurements for the hybrid models (production of 60 M events for vHLLE+UrQMD at 11 GeV is ongoing

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

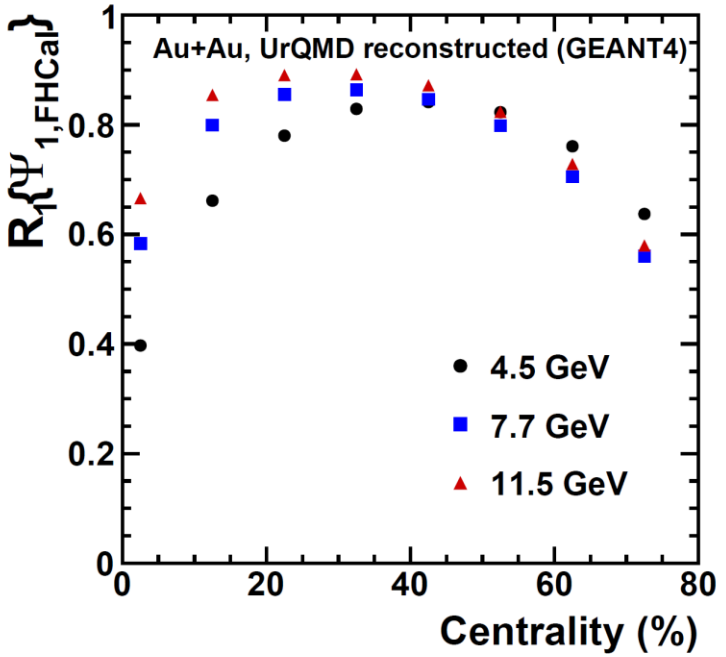
Using v_1 of particles in FHCal to determine Q_n

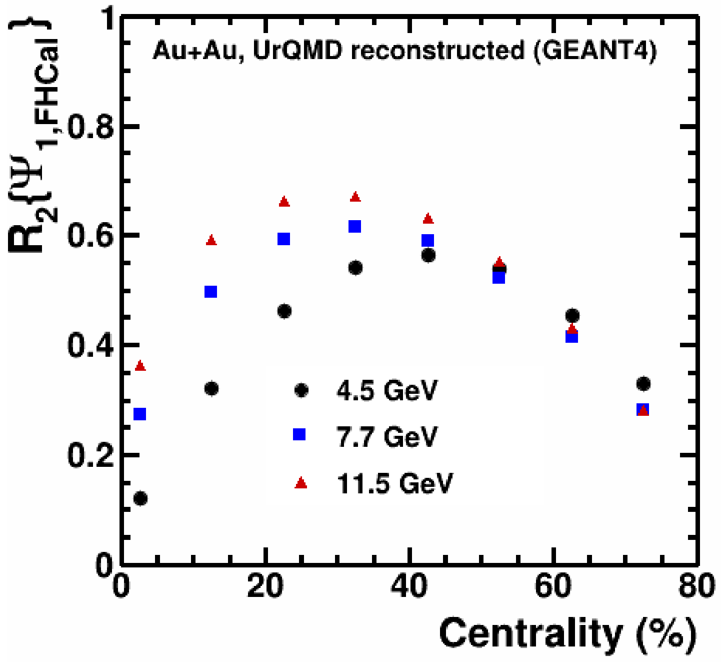
$$Q_1 = \frac{\sum E_i e^{i\varphi_i}}{\sum E_i}, \Psi_{1,\mathrm{FHCal}} = \tan^{-1}\left(\frac{Q_{1,y}}{Q_{1,x}}\right) \quad (1)$$

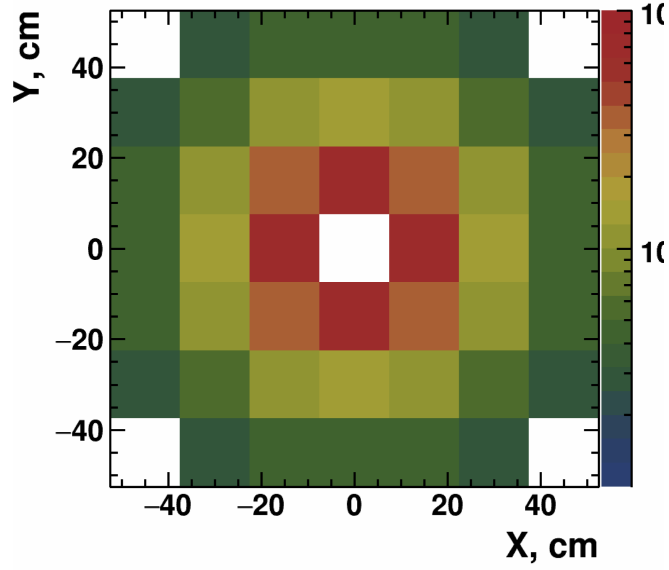
E – energy deposition in FHCal modules (2<|η|<5)

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

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







Energy distribution in FHCal

v_2 of V0 particles: invariant mass fit method (Nikolay Geraksiev)

Data set:

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

Geant4 simulation, full reconstruction with:

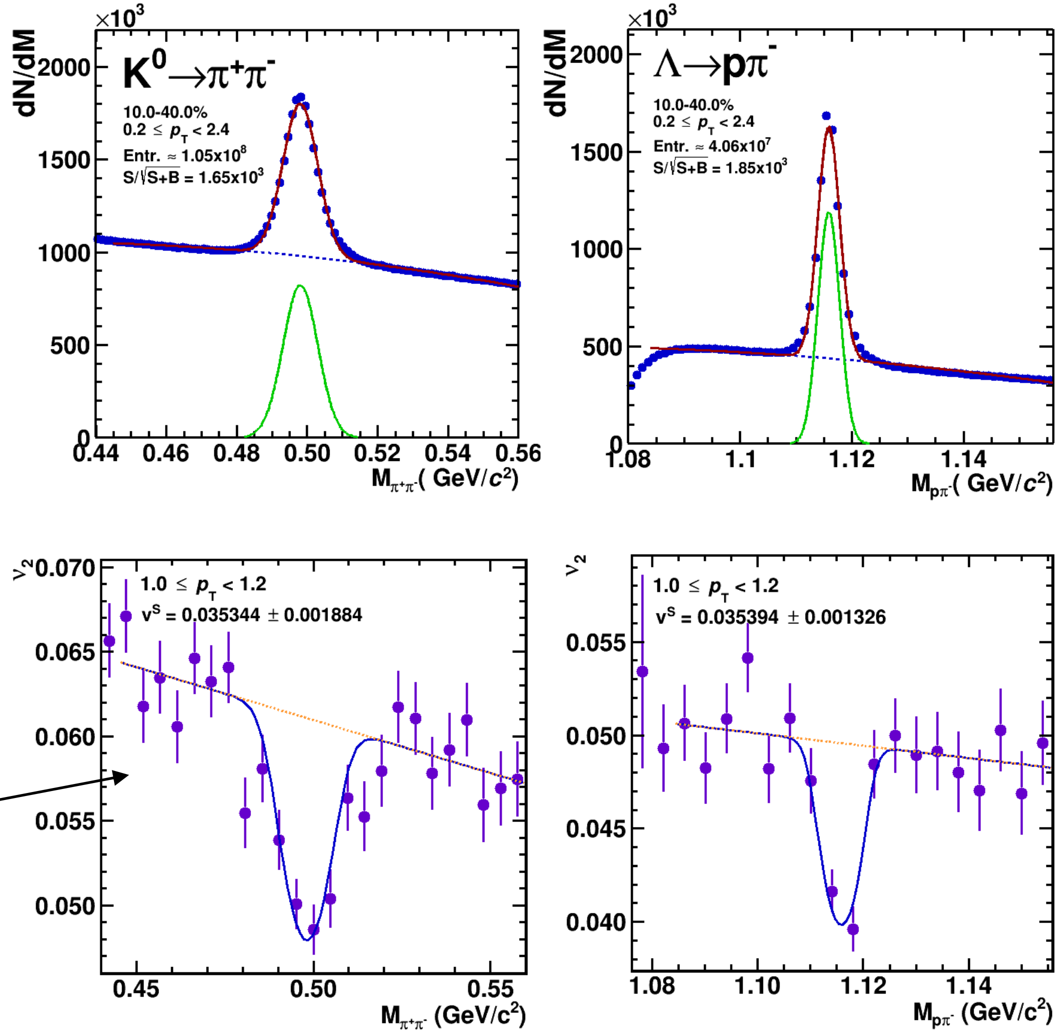
- TPCv7, TOFv7, FHCal

Centrality by TPC multiplicity, Event-plane method with FHCal

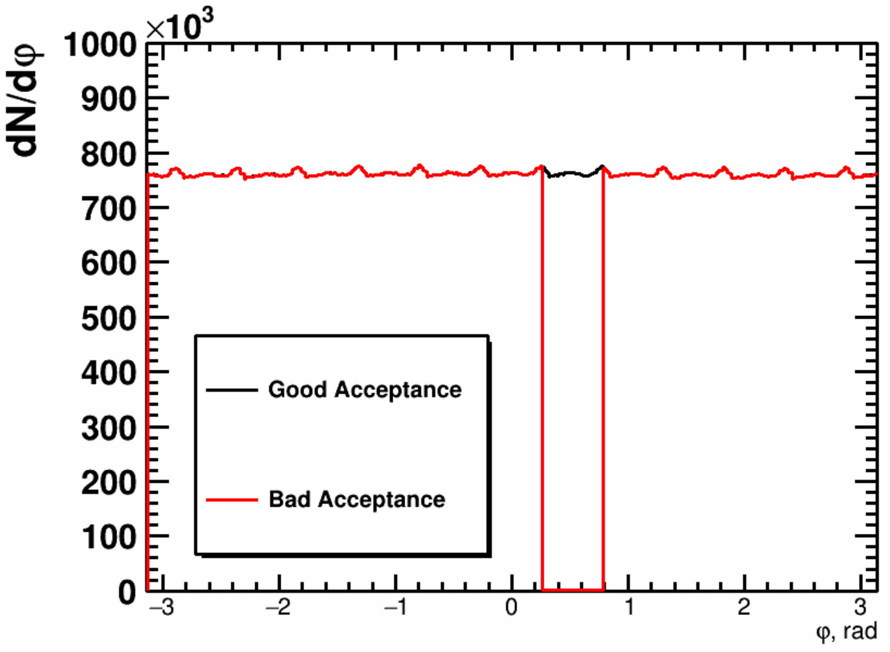
Particle decays reconstructed with MpdParticle realistic cuts

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

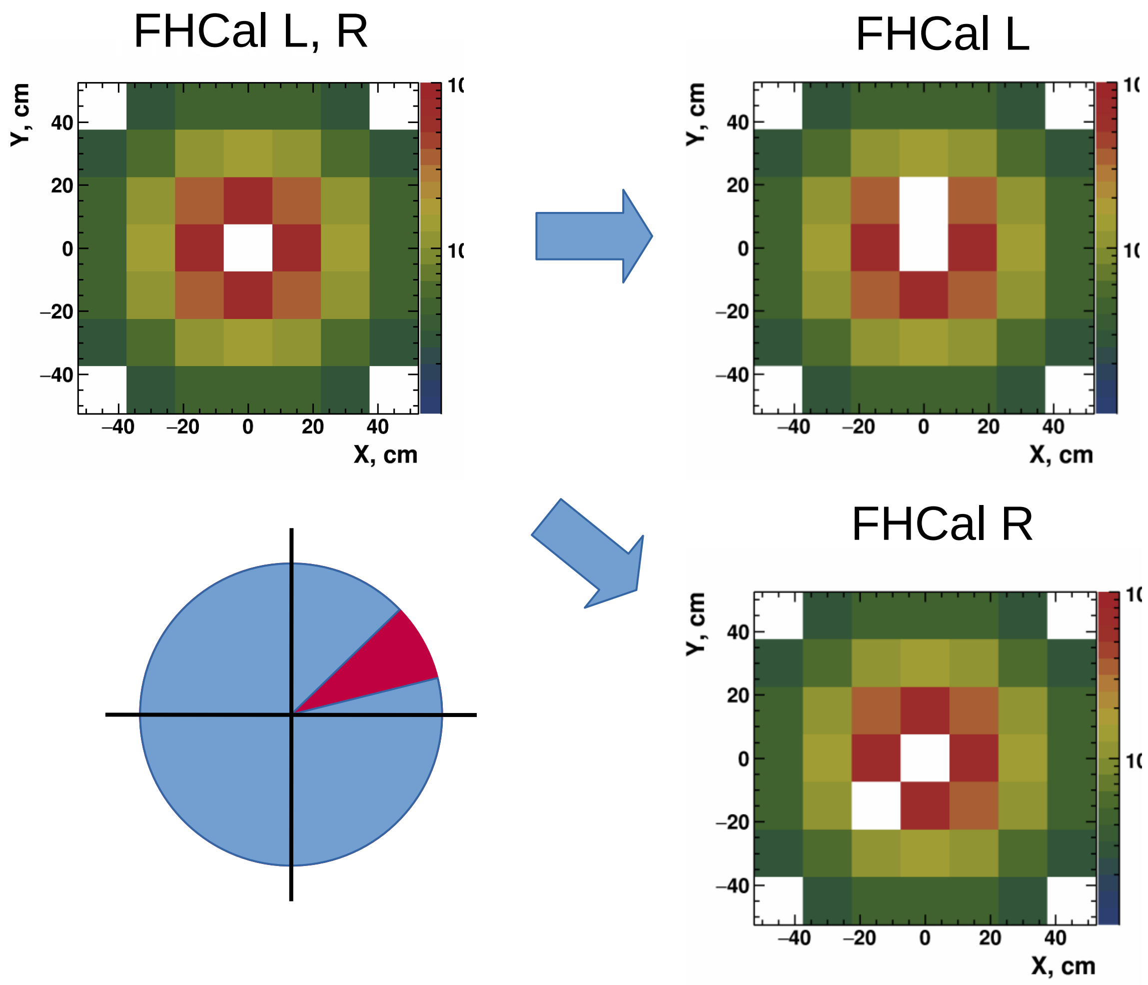
$$v_2^{SB}(m_{inv},p_T) = v_2^{S}(p_T)\frac{N^{S}(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)} + v_2^{B}(m_{inv},p_T)\frac{N^{B}(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)}$$



Non-uniform acceptance

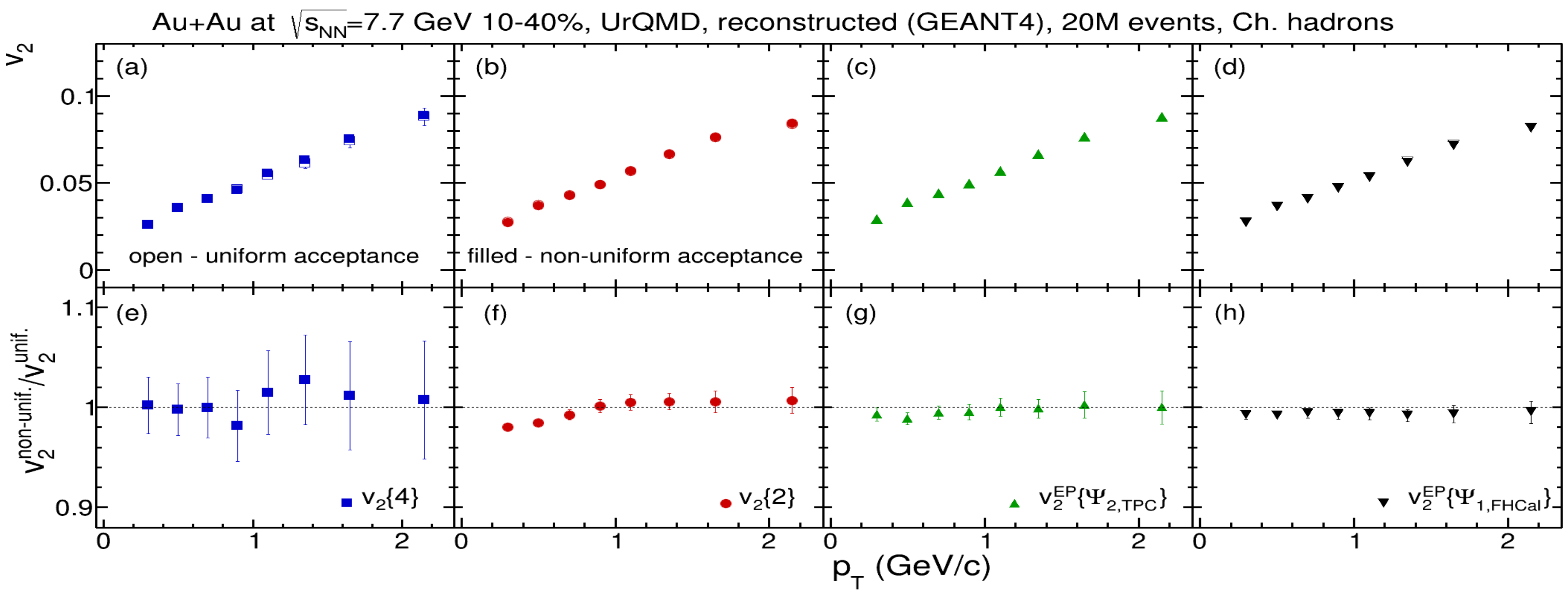


Area 15°< φ < 45° is off



How robust the future measurements against non-uniform acceptance?

Acceptance correction



The applied acceptance corrections eliminated the influence of non-uniform acceptance

Plans: QnTools Framework from CBM experiment

https://github.com/HeavyIonAnalysis/QnTools

Sensitivity of different methods to flow fluctuations

Elliptic flow fluctuations:

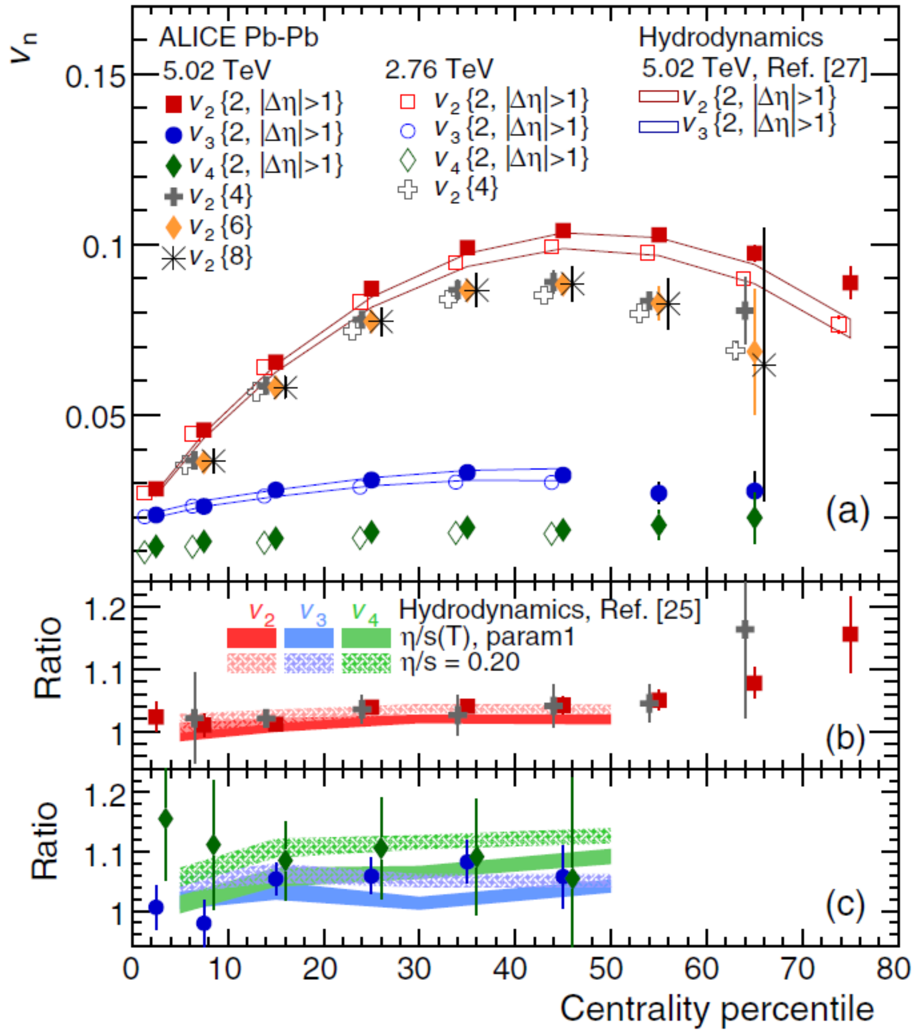
$$\sigma_{v_2}^2 = \langle v_2^2 \rangle - \langle v_2 \rangle^2$$

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

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

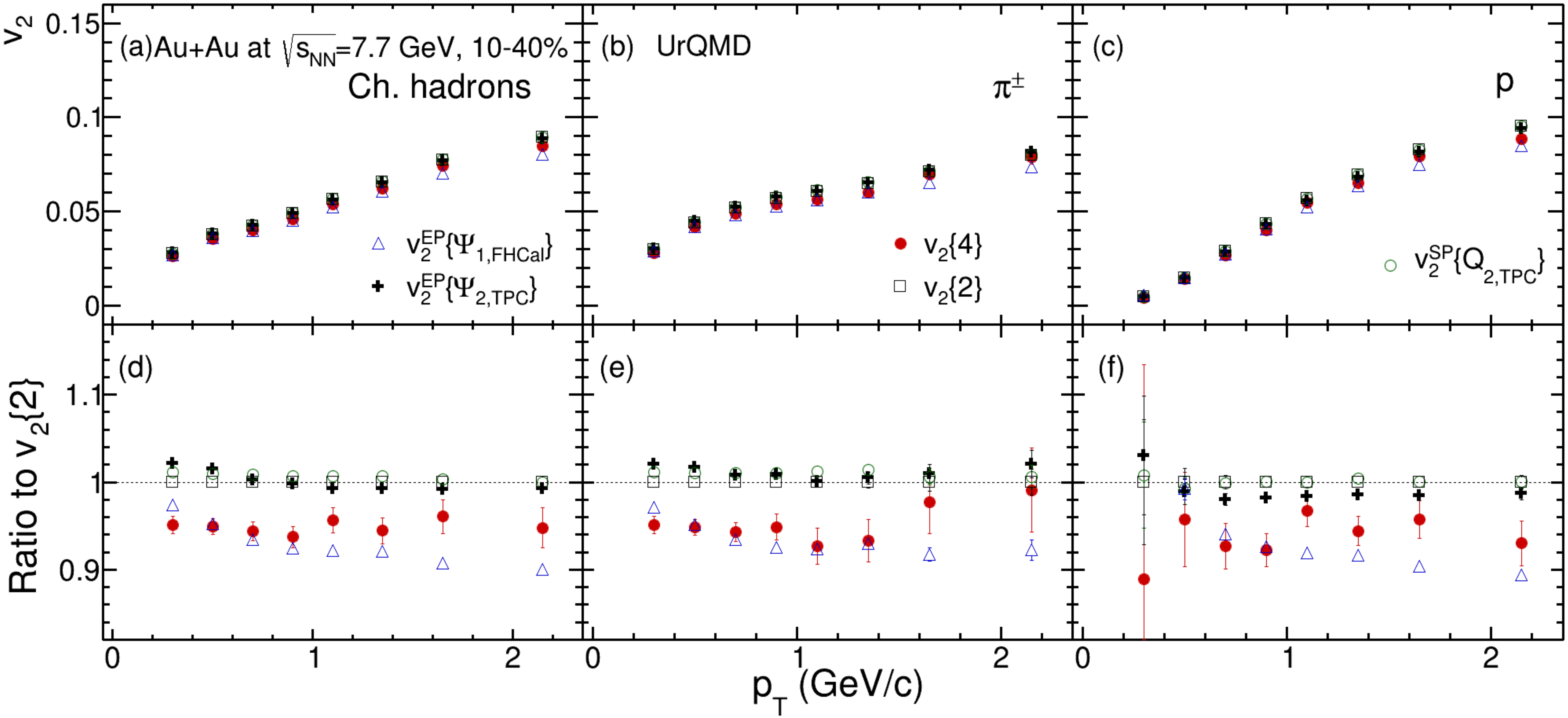
The difference between $v_2^{EP}\{\Psi_{1,FHCal}\}$ and $v_2^{EP}\{\Psi_{2,TPC}\}$:

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



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

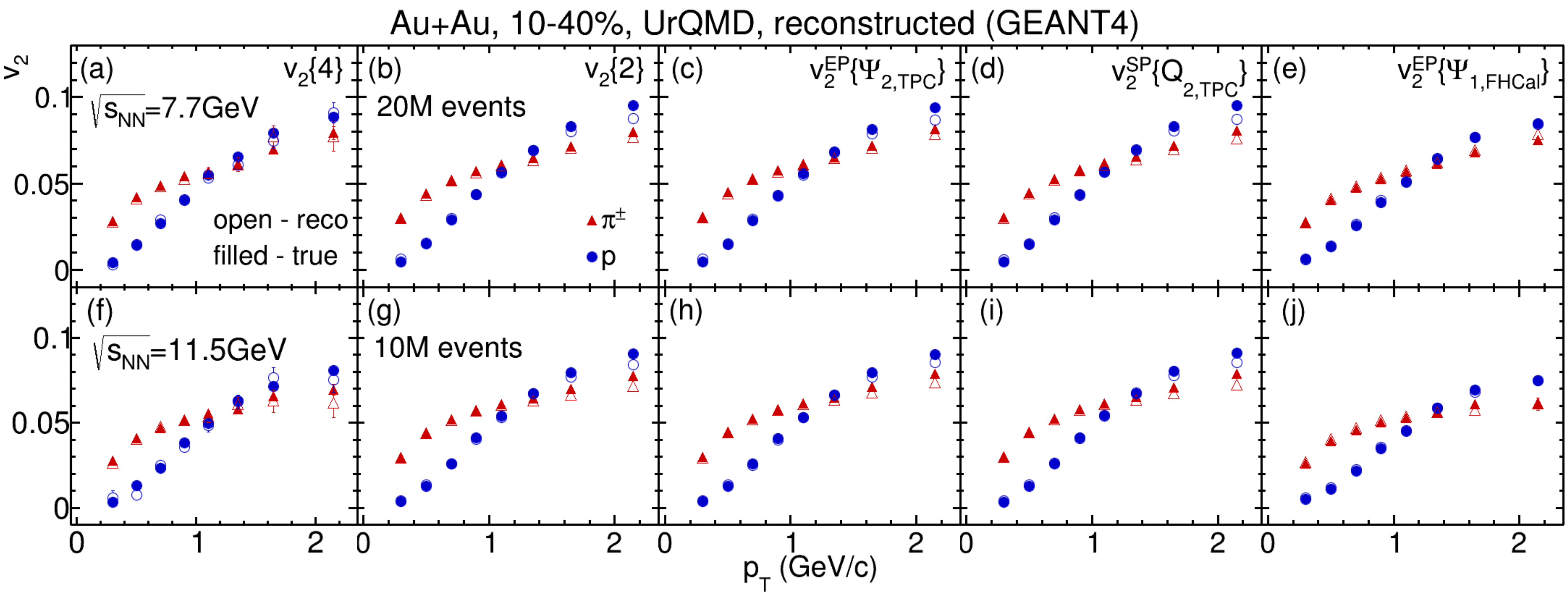
Comparison of v2 measurements using different method



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

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

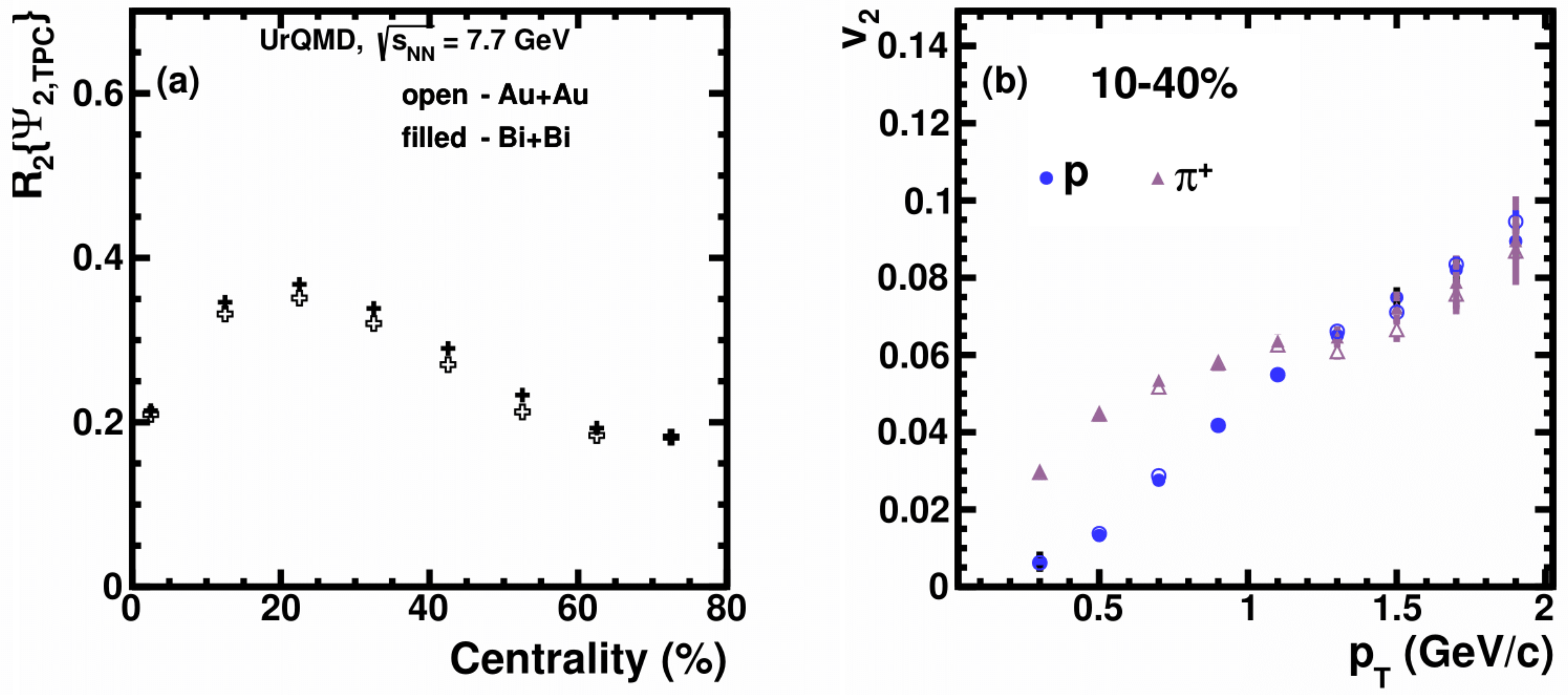
Performance study of v_2 of pions and protons in MPD



Reconstructed and generated v_2 of pions and protons have a good agreement for all methods

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

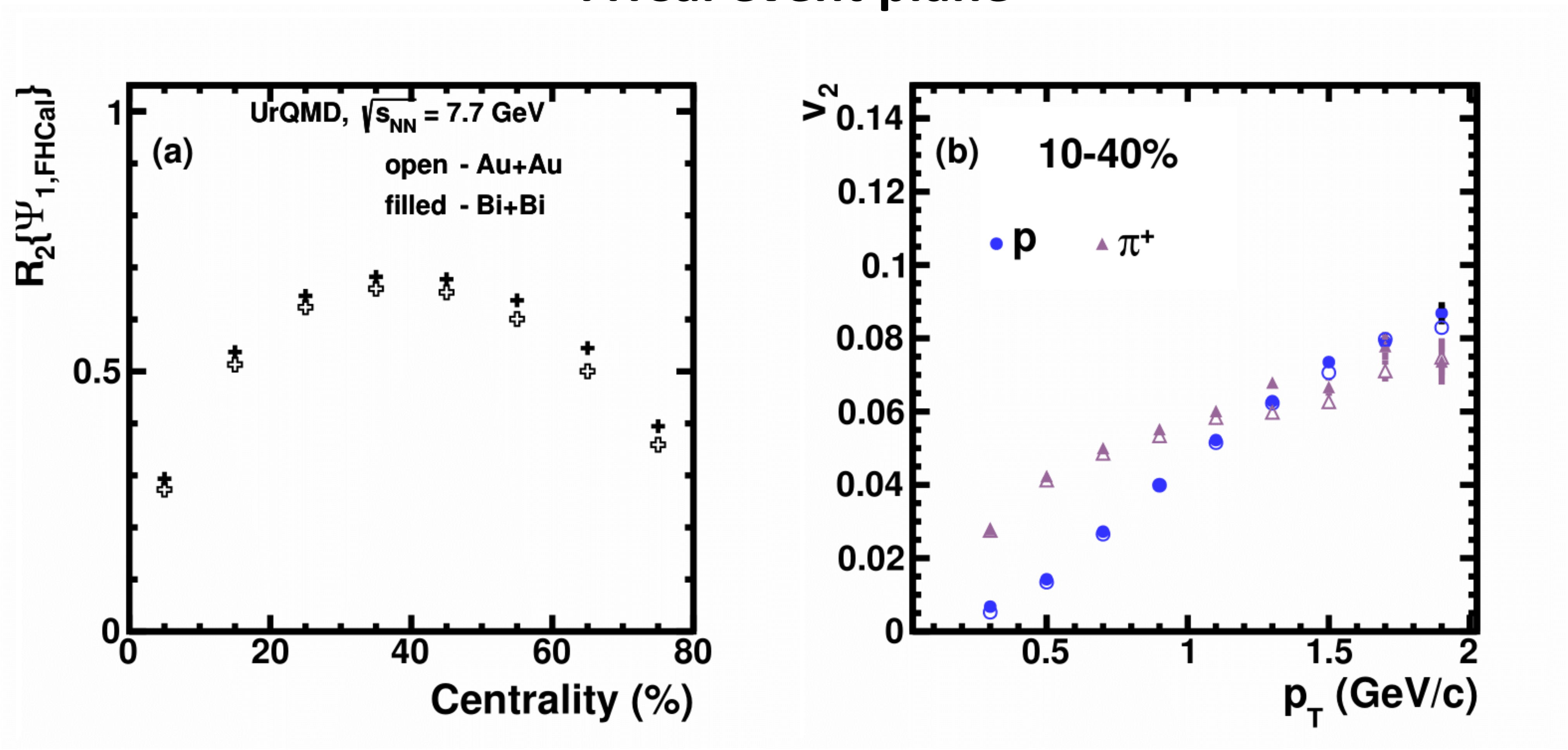
TPC event plane



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

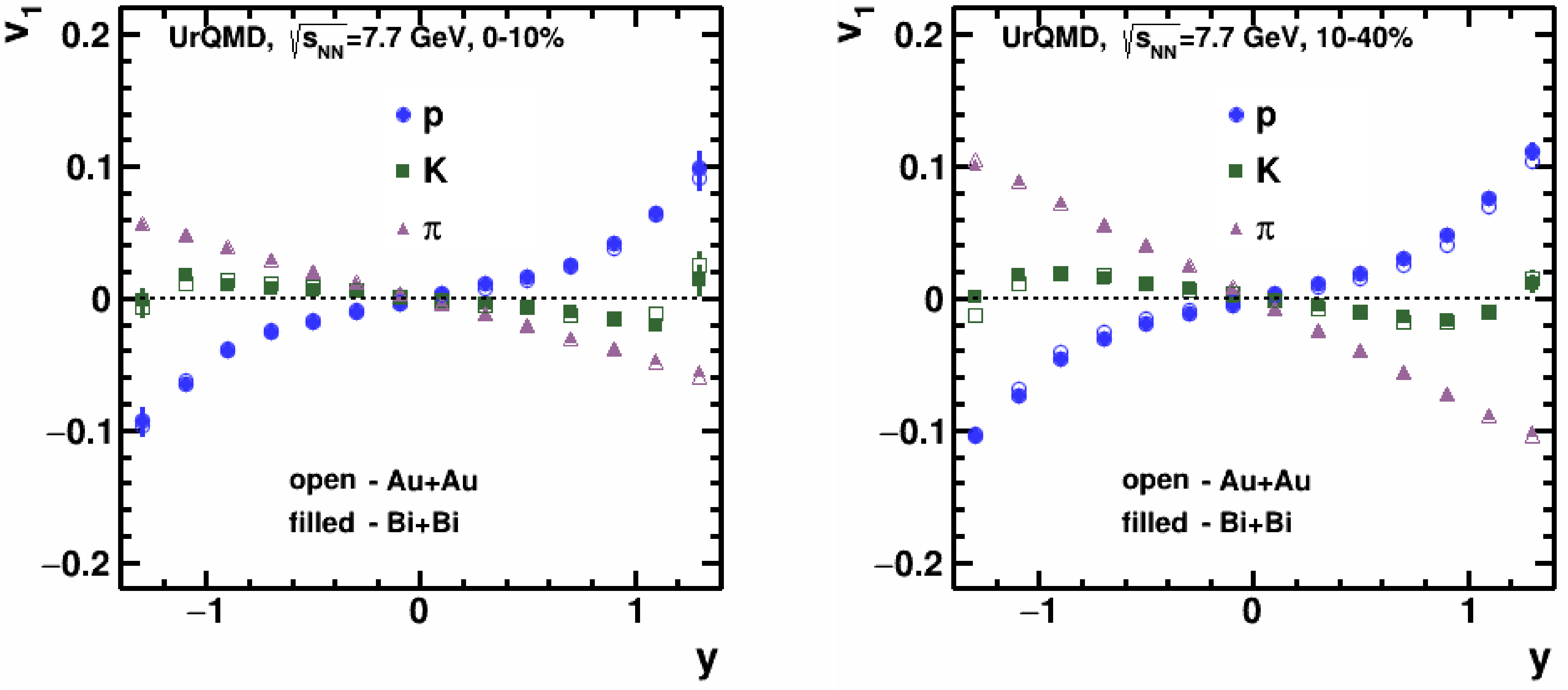
Au+Au vs. Bi+Bi collisions for reconstructed data in MPD

FHCal event plane



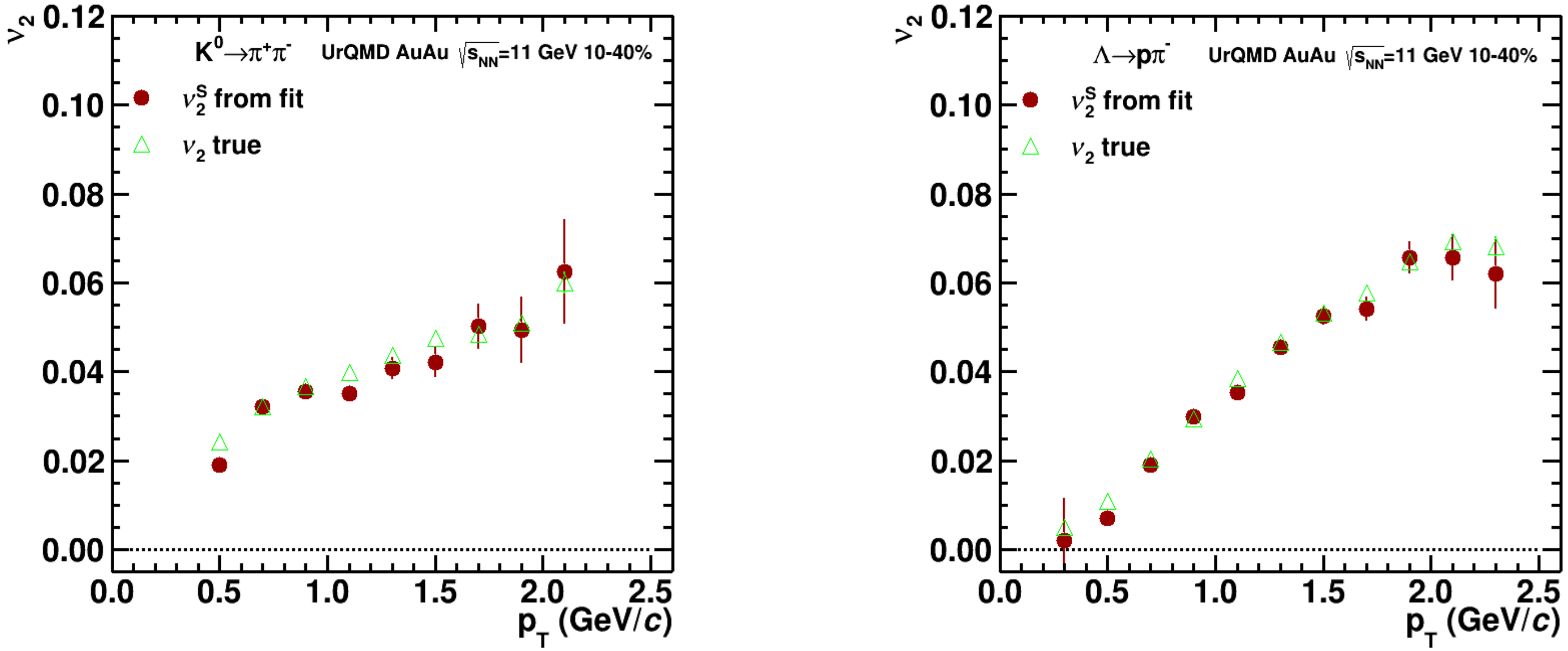
Expected small difference between colliding systems

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



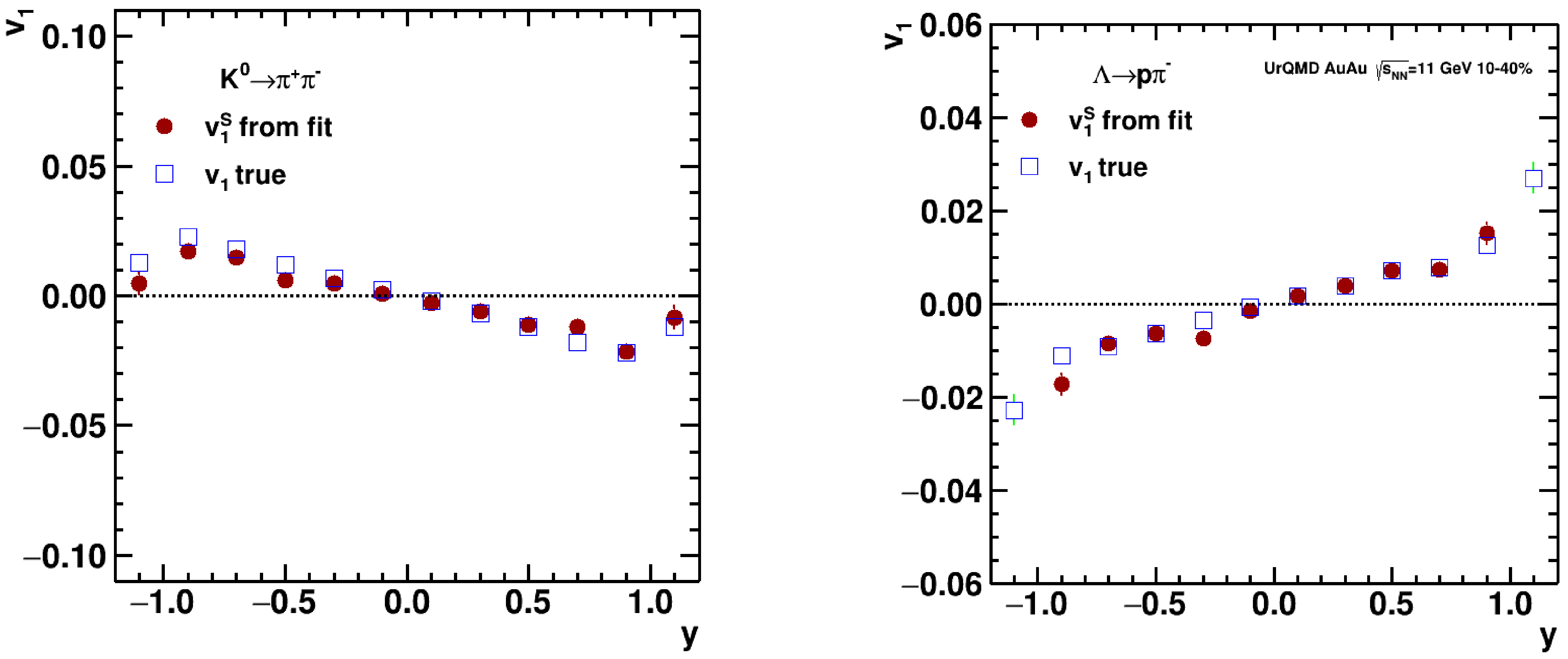
Expected small difference for v1 (y) for particles produced in Au+Au and Bi+Bi collisions.

Performance study for v_2 of V0 particles (Nikolay Geraksiev)



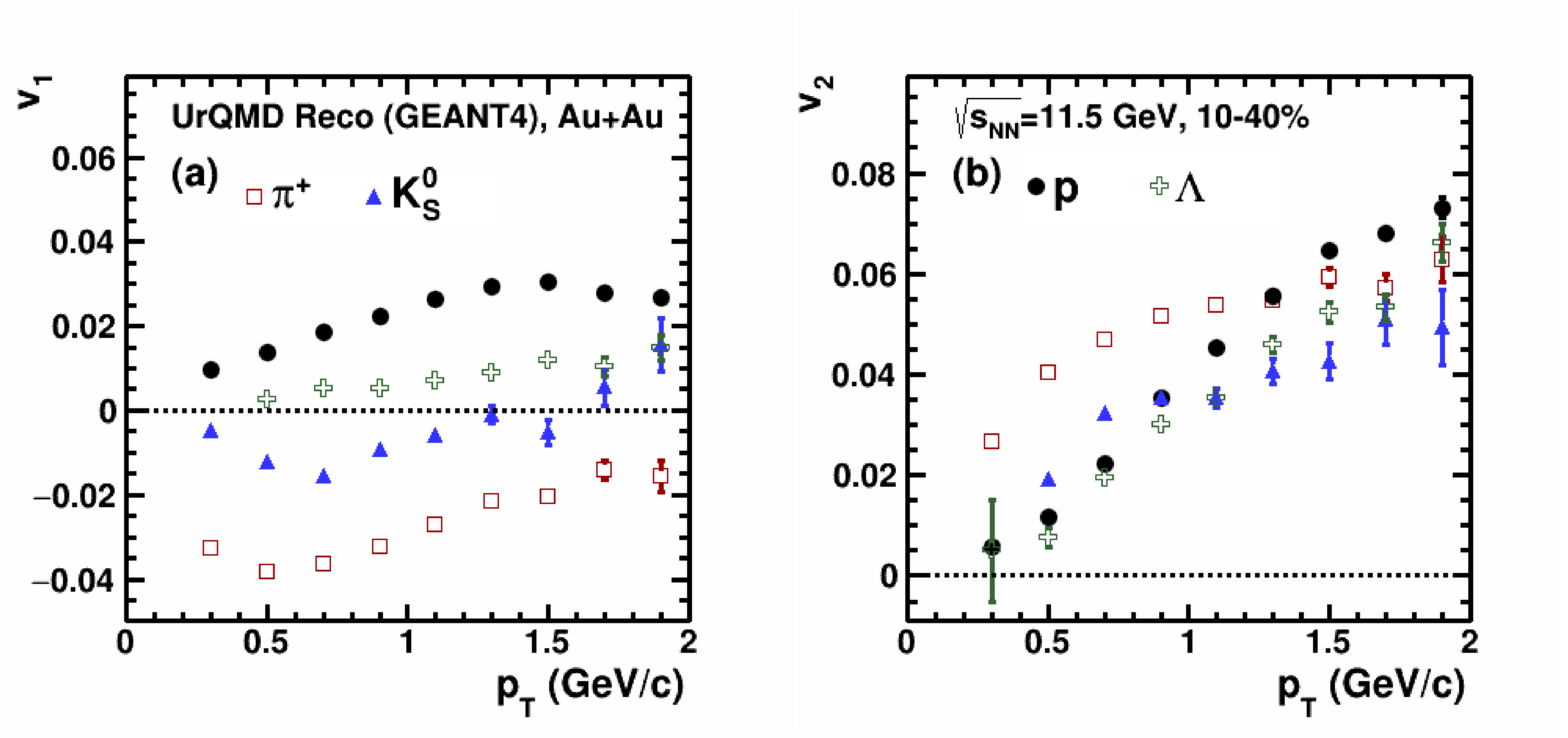
Reasonable agreement between reconstructed and generated v_2 signals for both K^0 and Λ

Performance study for v_1 of V0 particles (Nikolay Geraksiev)



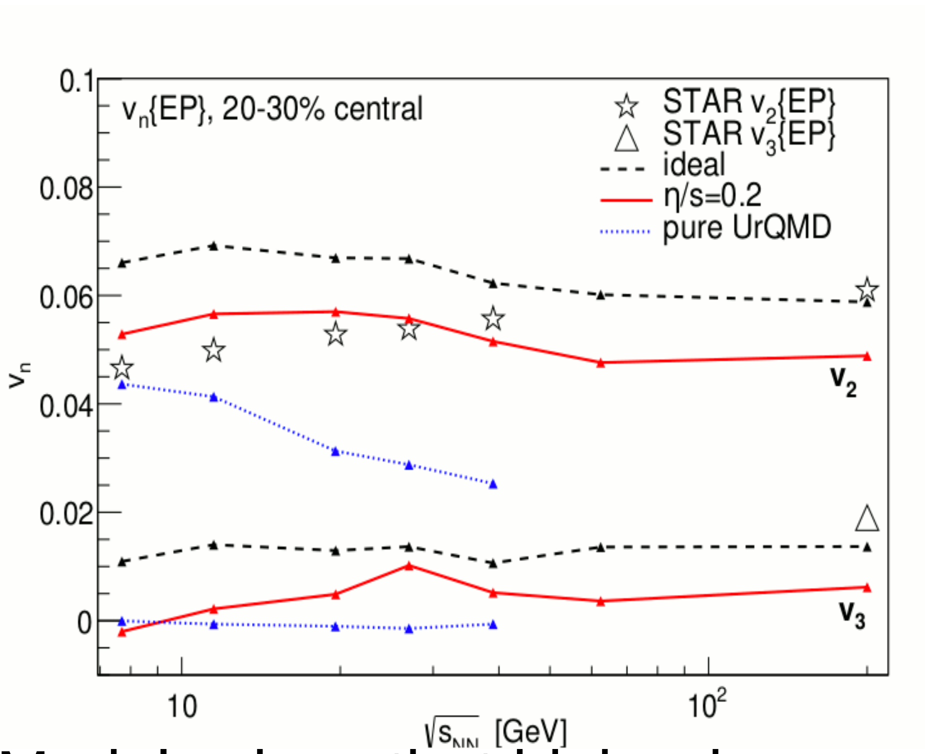
Reasonable agreement between reconstructed and generated v_1 signals for both K^0 and Λ

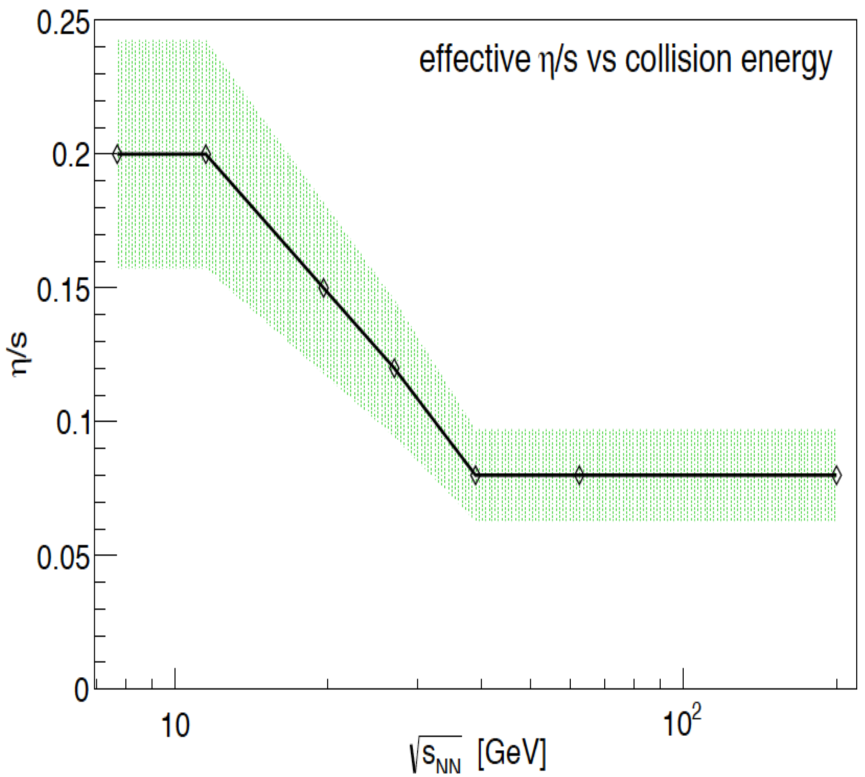
Performance study for v_1 and v_2



Outlook: triangular flow with MPD 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????

30 M of reconstructed vHLLE+UrQMD events

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 $\sqrt{s_{NN}}$≥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 directed and elliptic flow in MPD:**
  - v_n of identified charged hadrons: results from reconstructed and generated data are in a good agreement for all methods
  - v_n 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_n 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)

Workshop on analysis techniques for centrality determination and flow measurements at FAIR and NICA, http://indico.oris.mephi.ru/event/181/ (24-28 August 2020)

Thank you for you attention

Backup

Setup, event and track selection

UrQMD → GEANT4 → Reconstruction → Flow analysis

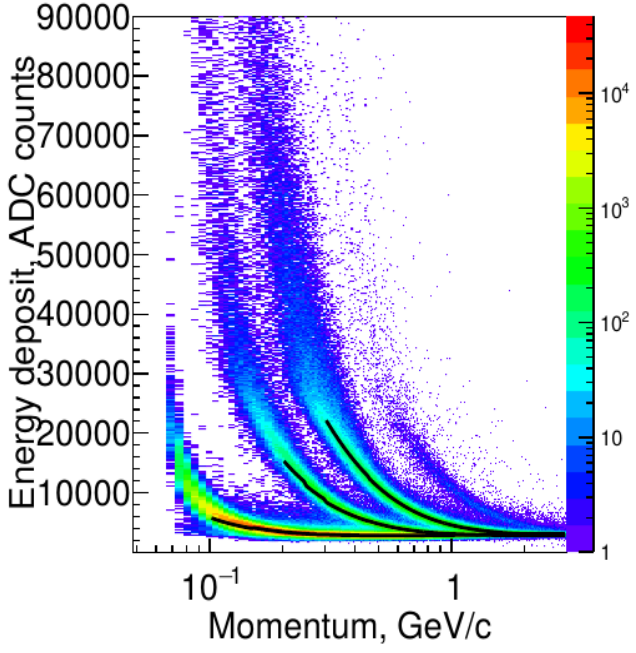
- Au+Au:
  - N_{events}= 10 M *at* $\sqrt{s_{NN}}$ = 4.5, 11.5 GeV
  - N_{events}= 20 M at $\sqrt{s_{NN}}$ = 7.7 GeV
- Bi+Bi:
  - N_{events}= 7 M *at* $\sqrt{s_{NN}}$ = 7.7 GeV

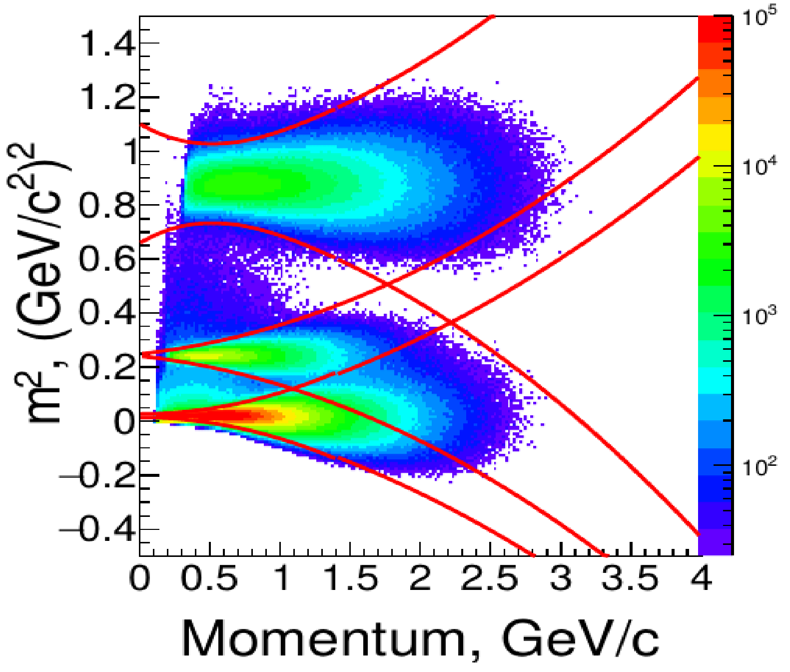
- TPC
- FHCal
- TOF
- ...

Event classification:
- Track multiplicity
- FHCal energy

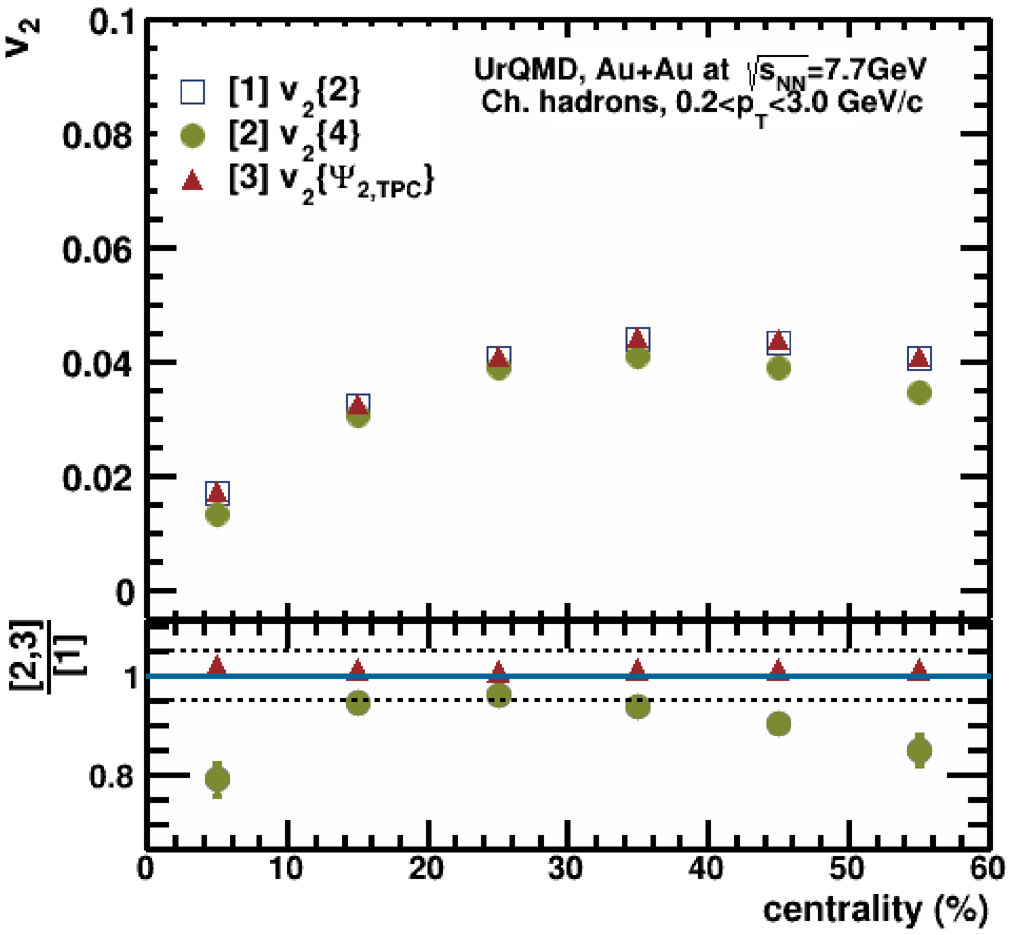
Track selection:
- Primary tracks (2σ DCA cut)
- $N_{TPC\ hits}$ > 16
- 0.2 < p_T< 3 GeV/c
- |η| < 1.5
- PID based on TPC+TOF (MpdPid)

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

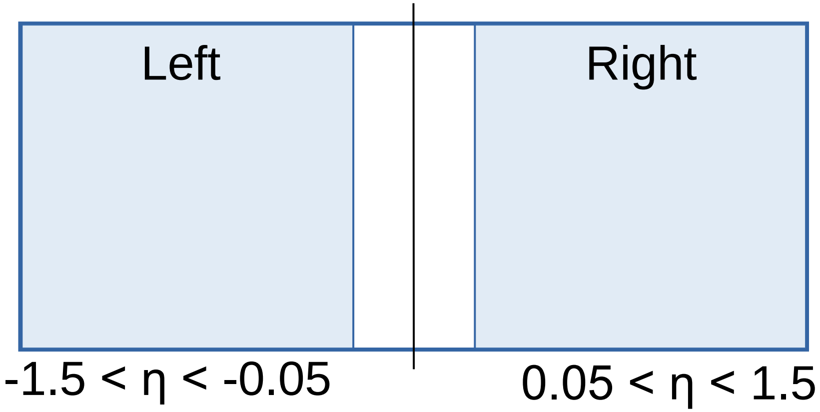
Description of event plane method

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

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

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

- 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_+

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

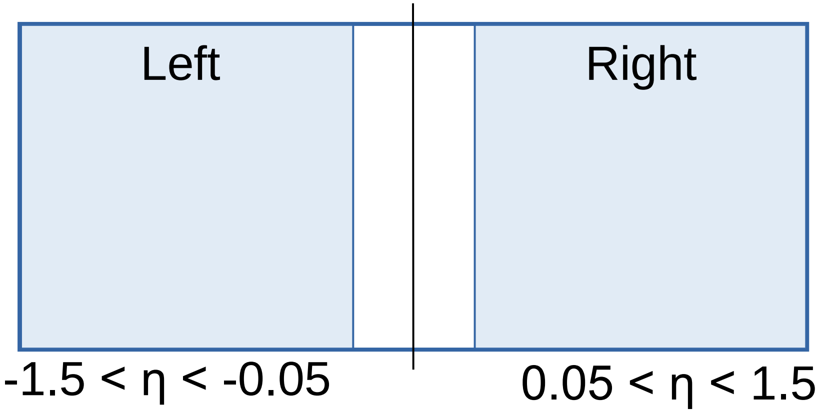
STAR Collaboration: B.I. Abelev, et al., Phys.Rev.C77:054901,2008

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

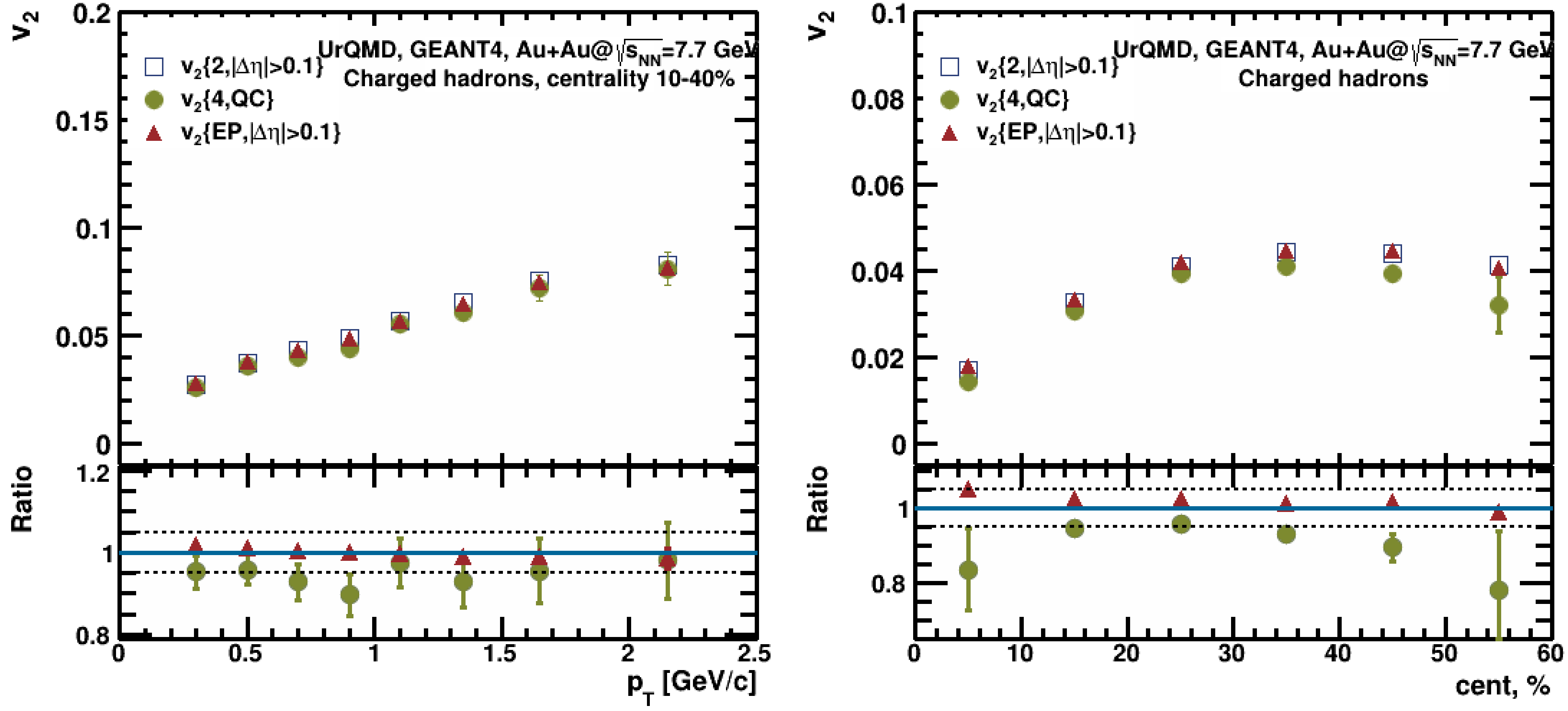


Left half (η<-0.05) → η_-

Right half (η>0.05) → η_+

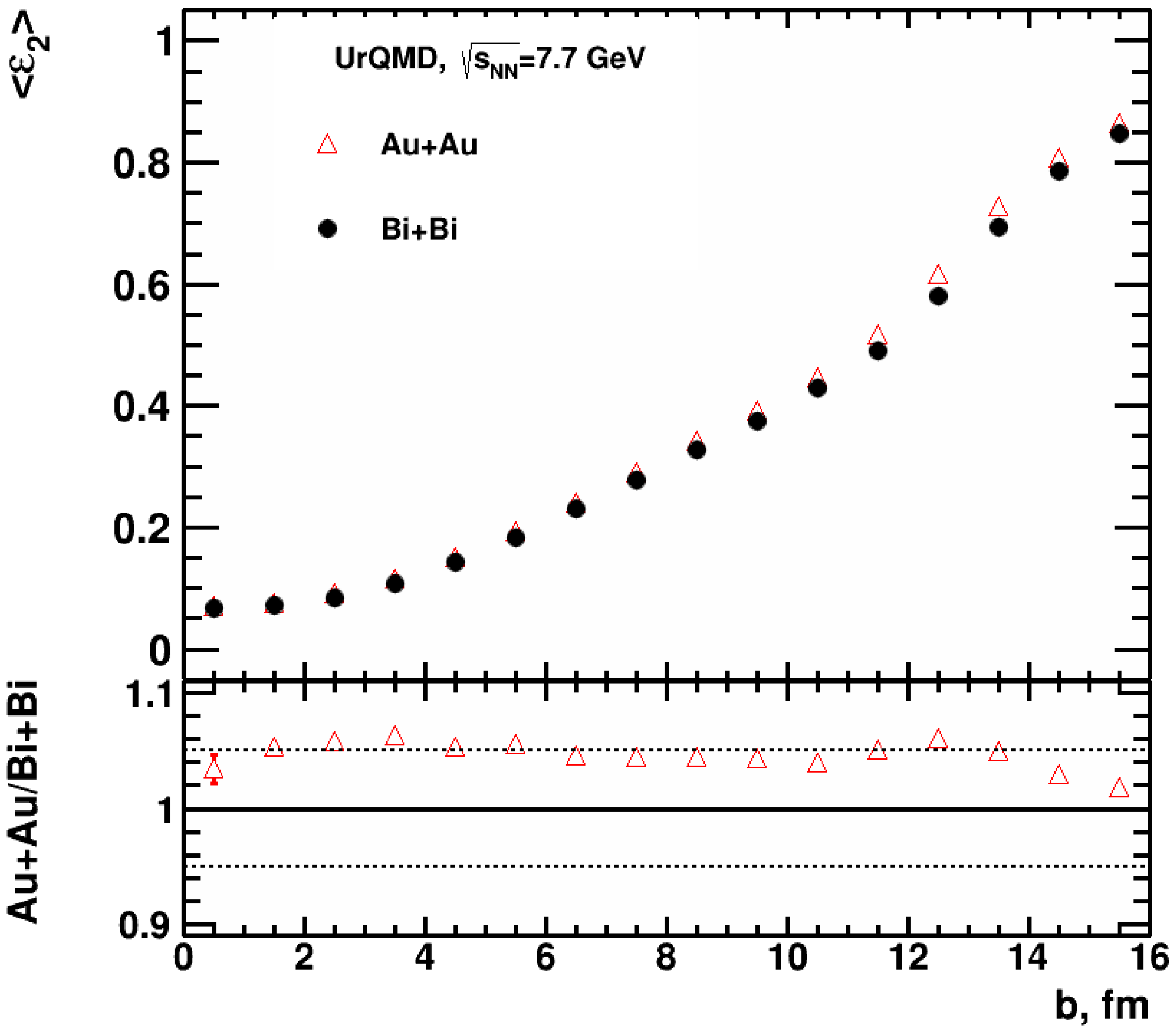
$$v_2^{SP}\{Q_{2,\mathrm{TPC}}\} = \frac{\left\langle u_{2,\eta\pm} Q^*_{2,\eta\mp} \right\rangle}{\sqrt{\left\langle Q_{2,\eta+} Q^*_{2,\eta-} \right\rangle}} \qquad (3)$$

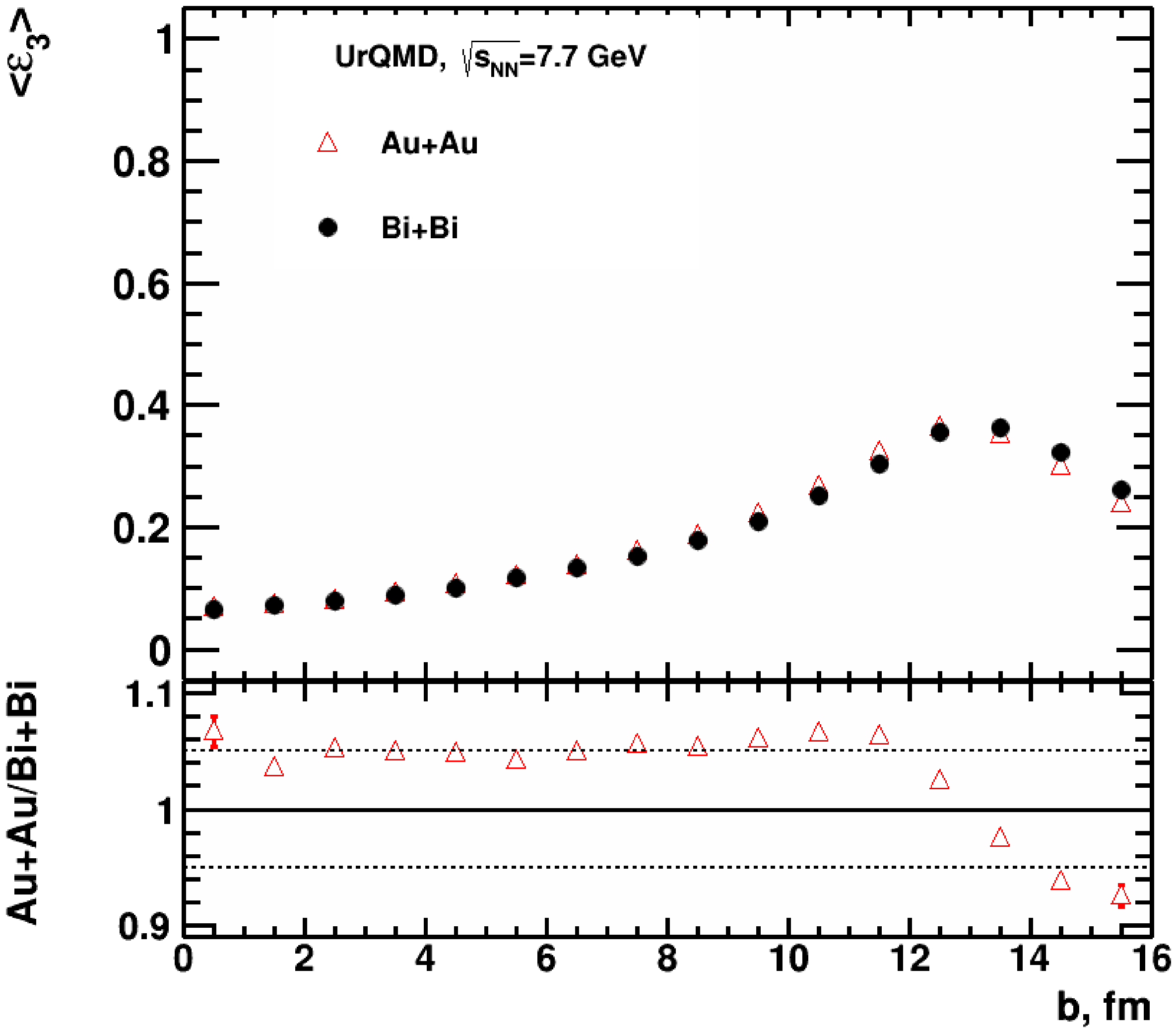
Results for v_2 for reconstructed events of MPD



v_2\{2\} and v_2\{4\} are in good agreement with v_2\{η-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

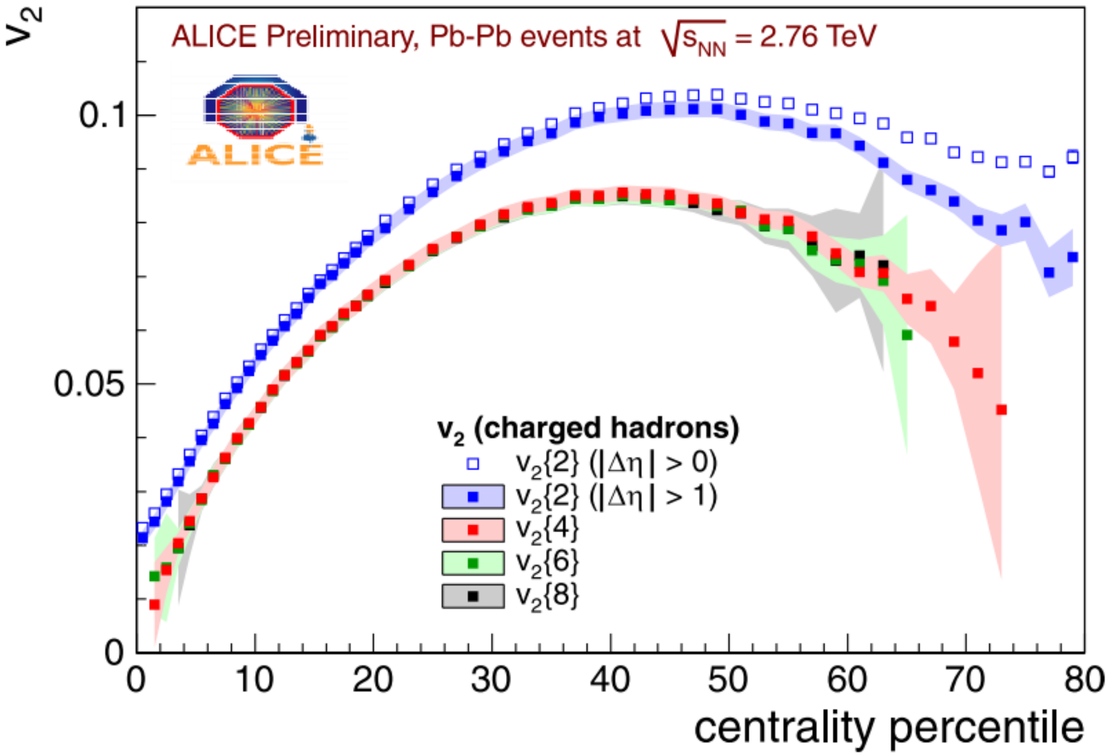
- How fluctuations affect the measured values of v_n. The effect of the fluctuations on v_n estimates can be obtained from

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

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

- 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.

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

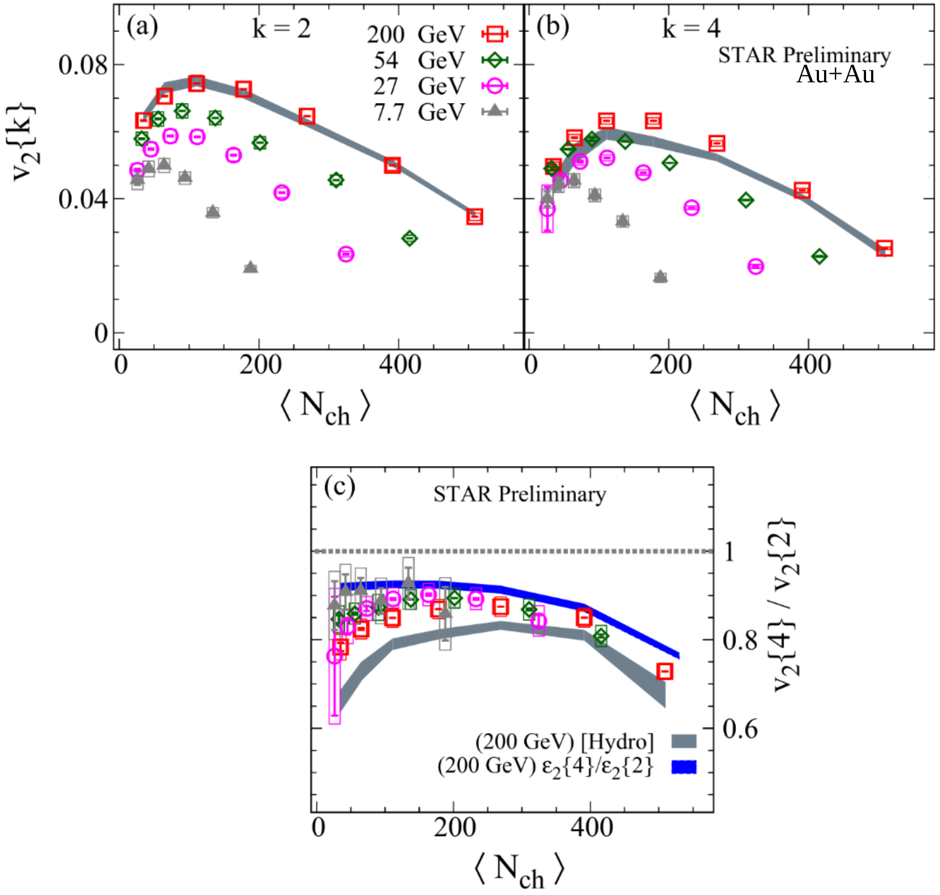


The difference between $v_n\{2\}$ with and without $\Delta\eta$ gap is driven by the contribution from nonflow

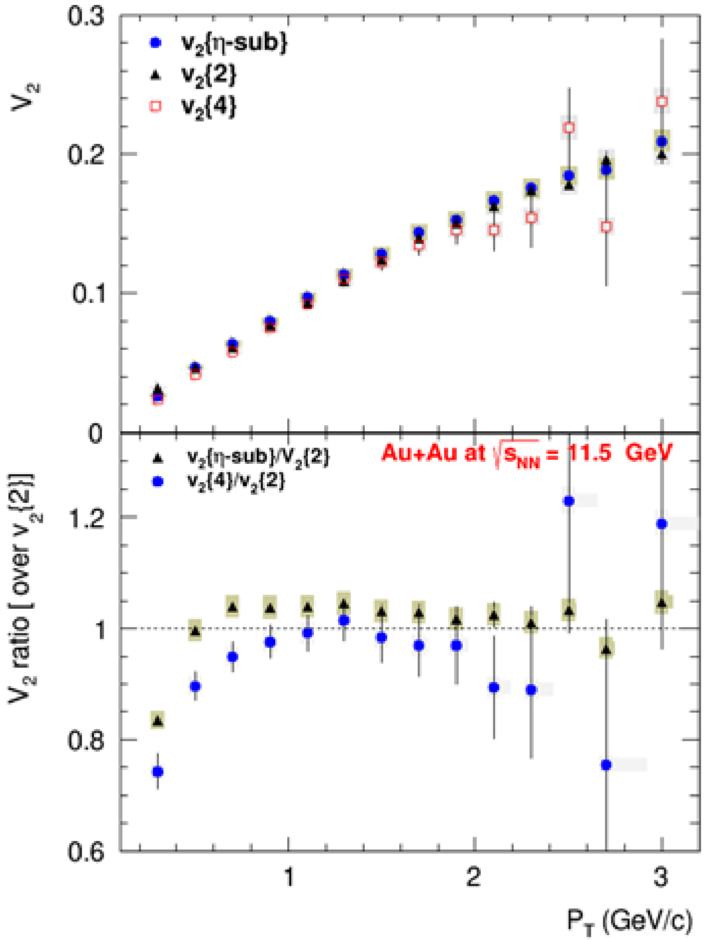
Ilya Selyuzhenkov for the ALICE collaboration, Prog.Theor.Phys.Suppl. 193 (2012) 153-158

Cumulant results from Beam Energy Scans

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



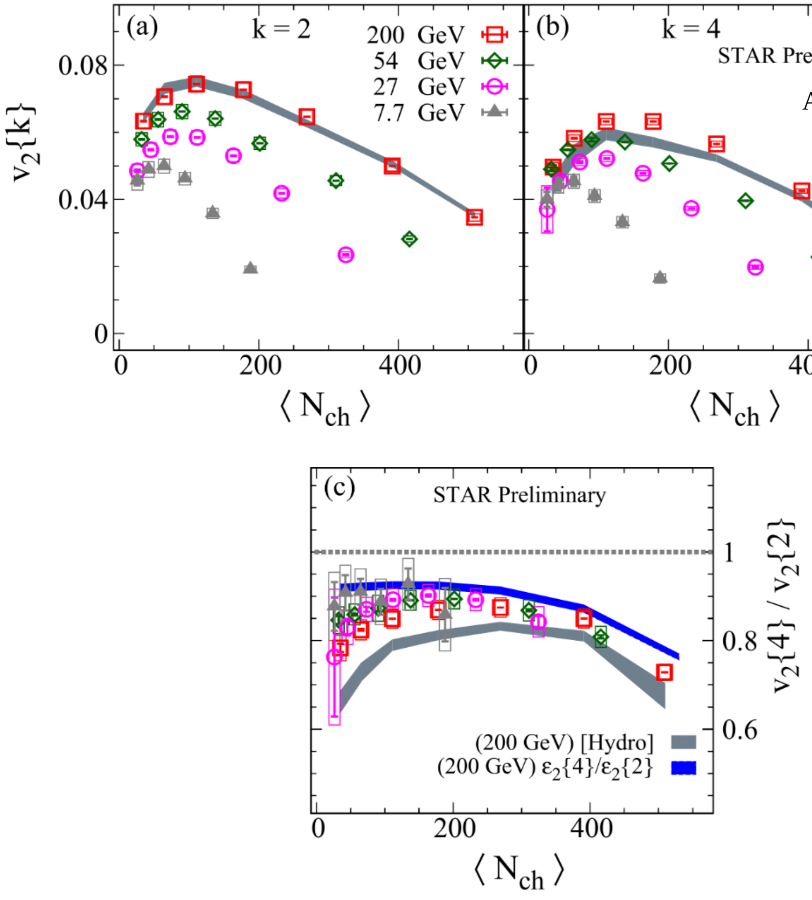
L. Adamczyk et al. (STAR Collaboration). Phys. Rev. C 86, 054908 (2012)



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

Methods of flow measurements have different sensitivity to flow fluctuations

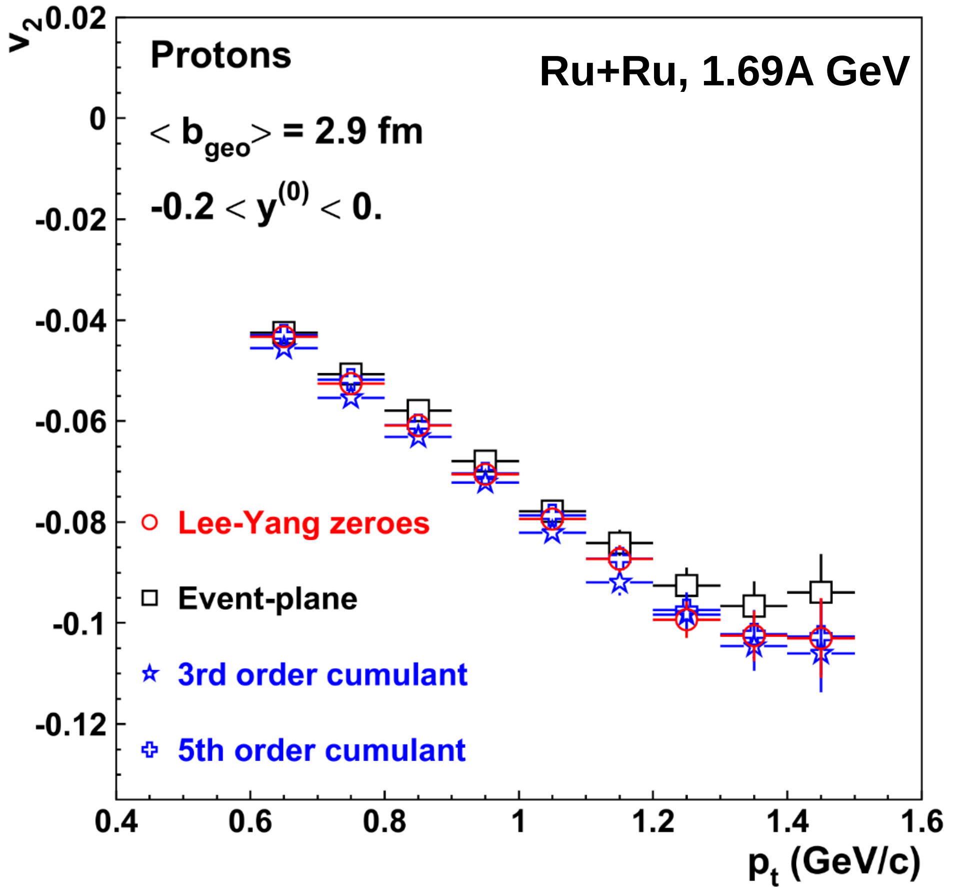
Cumulant results from Beam Energy Scans



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



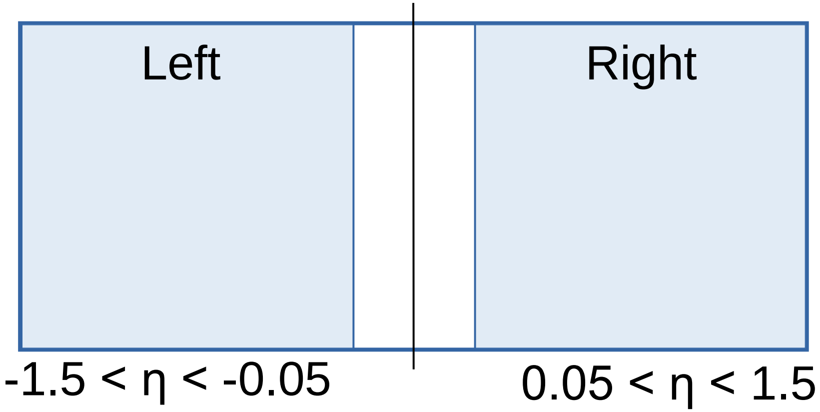
v_2 versus transverse momentum for protons measured in semi-central events and around mid-rapidity.

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



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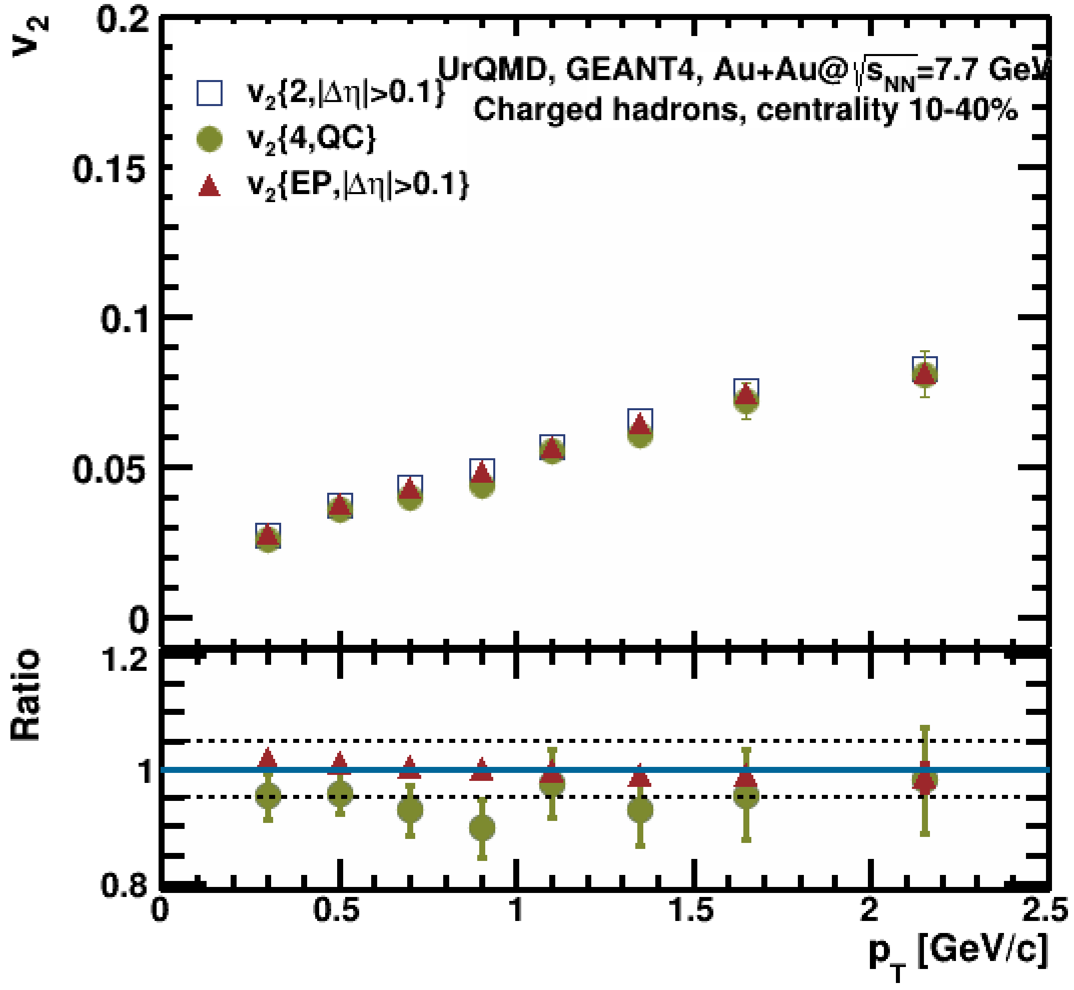

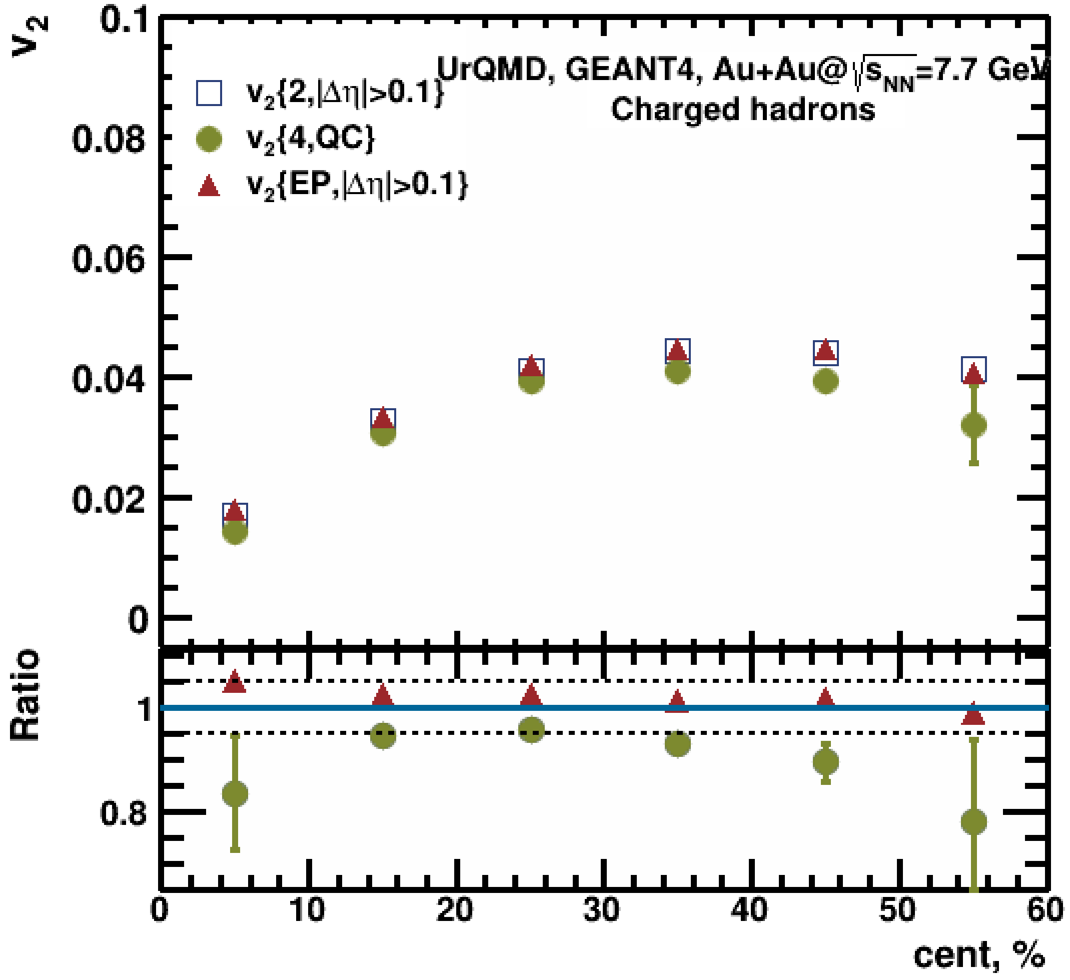

$v_2\{2\}$ and $v_2\{4\}$ are in good agreement with $v_2\{\eta\text{-sub,EP}\}$ at 10-40% centrality