The comparison of methods for elliptic flow measurements with the MPD Experiment at NICA

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For the MPD Collaboration

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Outline

- **Elliptic flow (v_2) at NICA energies**
- **Description of direct cumulant, event plane and scalar product methods**
- **Sensitivity of different methods to flow fluctuations and nonflow**
- **Feasibility study of elliptic flow (v_2) of identified hadrons and V0 particles in MPD (NICA):**
  - Acceptance corrections
  - Elliptic flow of identified charged particles
  - Elliptic flow of V0 particles
  - Comparison of v_2 results for Bi+Bi and Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 GeV
- **Summary and outlook**

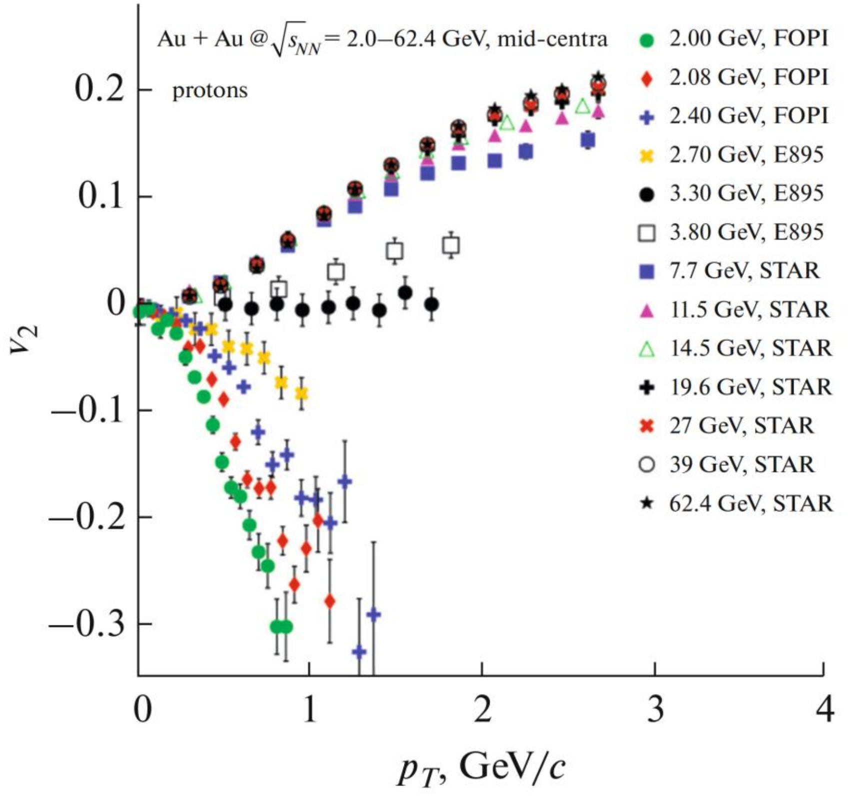
Elliptic flow at NICA energies

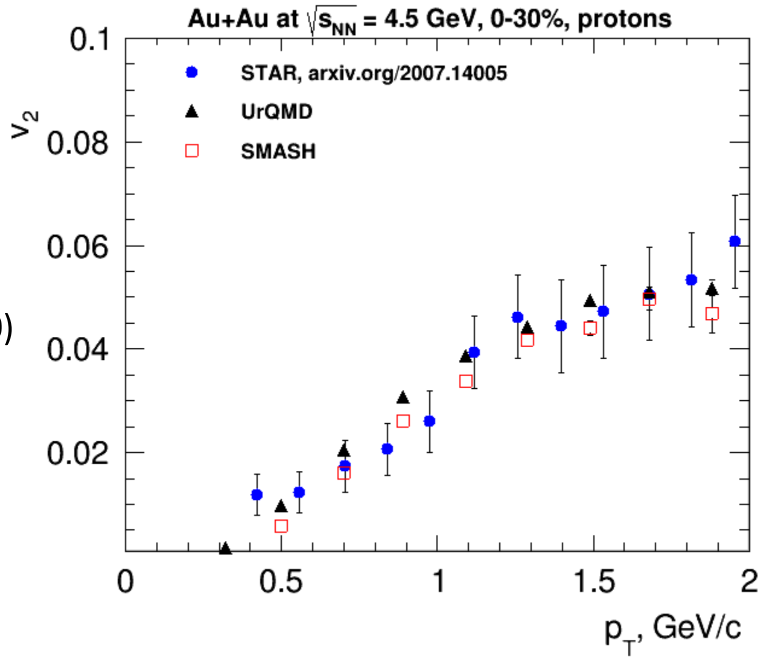
$$\frac{dN}{N_0 d(\phi-\psi_R)} = \frac{1}{2\pi}\left(1+\sum_{1}^{\infty} 2v_n \cos(n(\phi-\psi_R))\right)$$

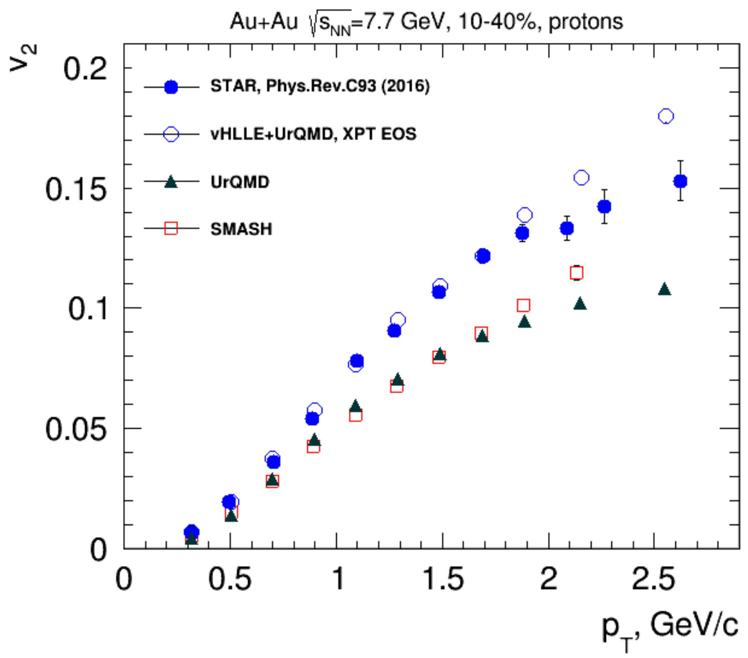
V_1 **- direct flow**

V_2 **- elliptic flow**

Taranenko et. al. Phys. Part. Nuclei 51, 309–313 (2020)



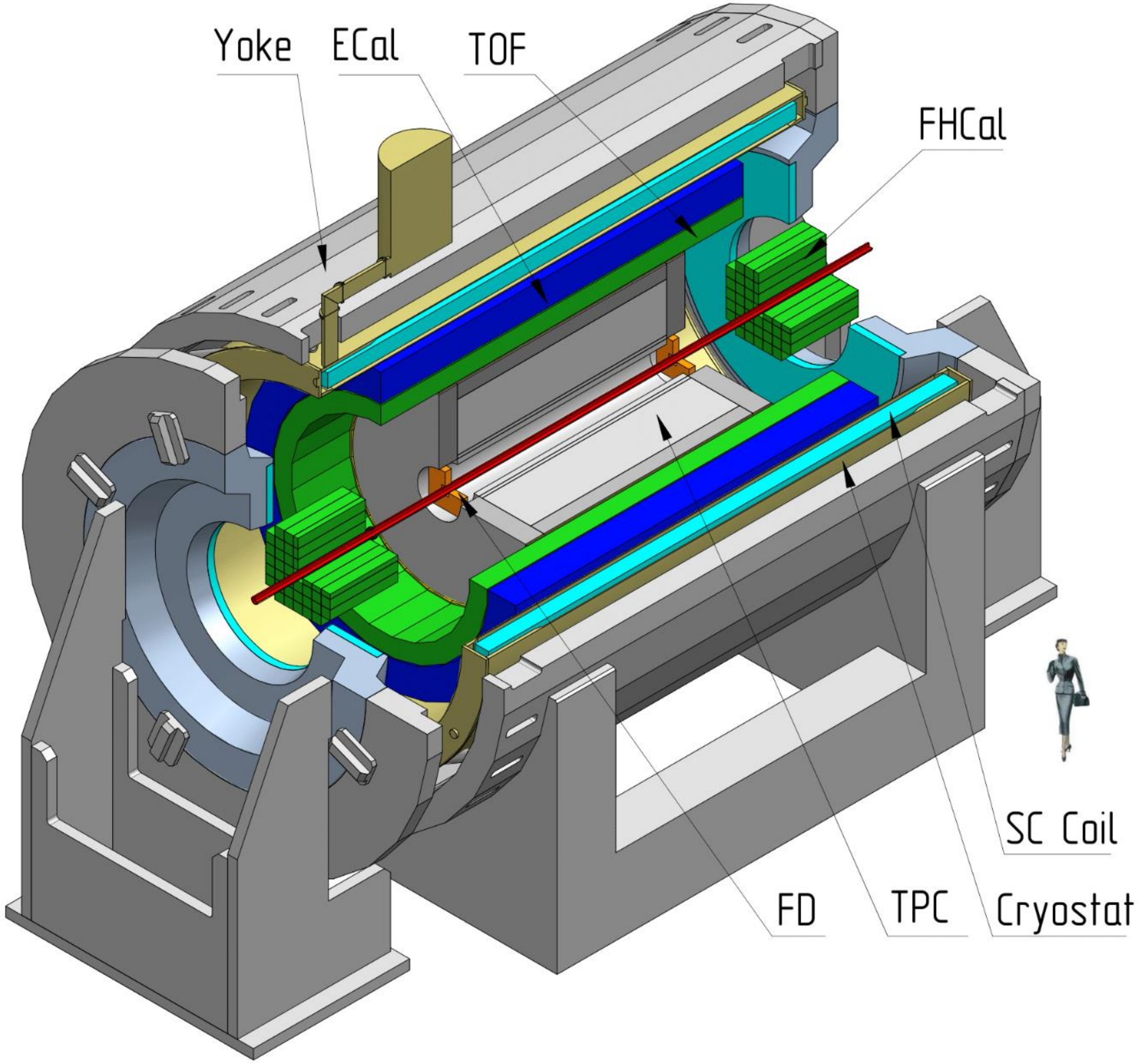




- **v_2 is sensitive to the properties of strongly interacting matter:**
  - At $\sqrt{s_{NN}}$=4.5 GeV pure string/hadronic cascade models (UrQMD, SMASH, …) give similar v_2 signal compared to STAR data
  - At $\sqrt{s_{NN}}\geq$7.7 GeV pure string/hadronic cascade models underestimate v_2 – need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting, …)
- **Strong energy dependence of v2 at $\sqrt{s_{NN}}$=3-11 GeV**
  - $v_2\approx 0$ at $\sqrt{s_{NN}}$=3.3 GeV and negative below
- **Lack of differential measurements of v_2 at NICA energies (p_T, centrality, PID, …)**

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

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

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}= 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

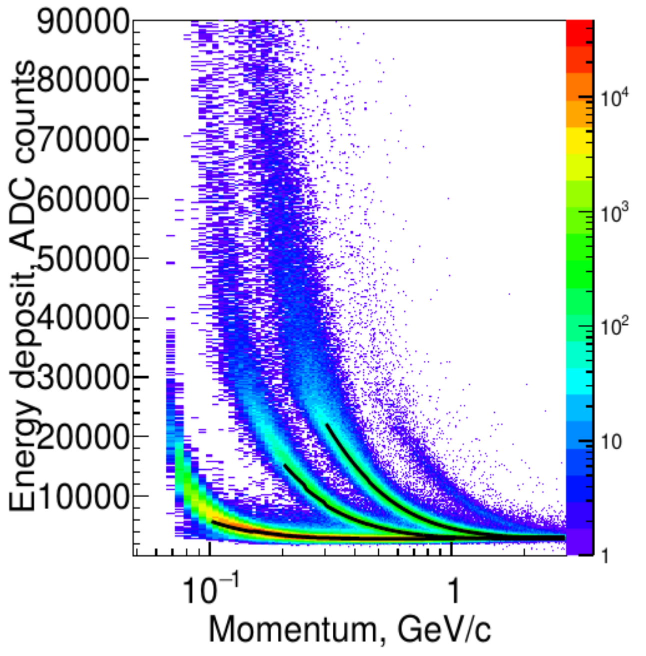
- TPC
- FHCal
- TOF
- ...

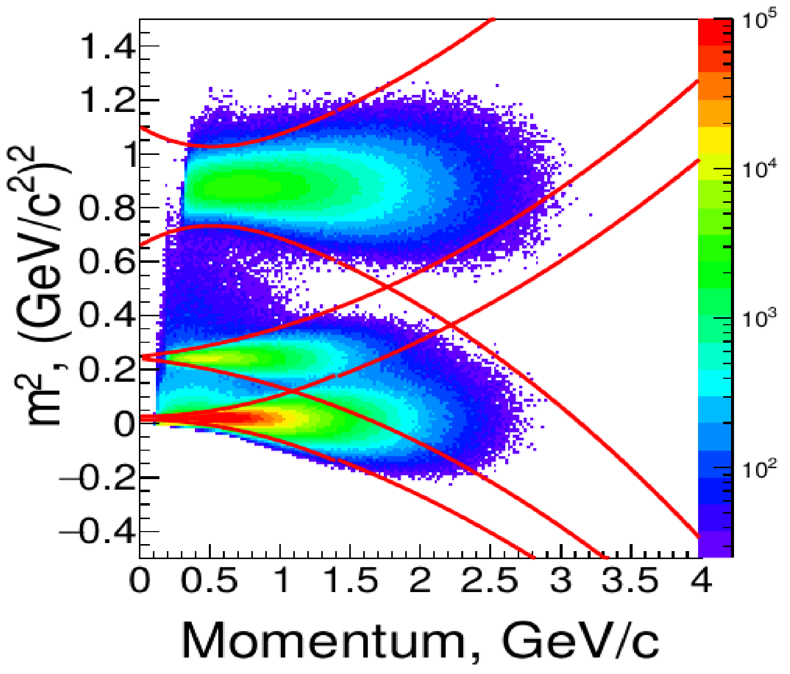
Event classification:
- Track multiplicity
- FHCal energy

Track selection:

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

MPDRoot, August 2020





Description of event plane and scalar product methods using TPC

Using v_2 of produced particles in TPC to determine Q_n

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

$$Q_n = \sum_{j=1}^{M} \omega_j e^{in\varphi_j}, \quad X_n = \mathrm{Re}(Q_n), \quad Y_n = \mathrm{Im}(Q_n) \qquad (2)$$

$$\Psi_n = \tan^{-1}\left(\frac{Y_n}{X_n}\right) \Big/ n \qquad (3)$$

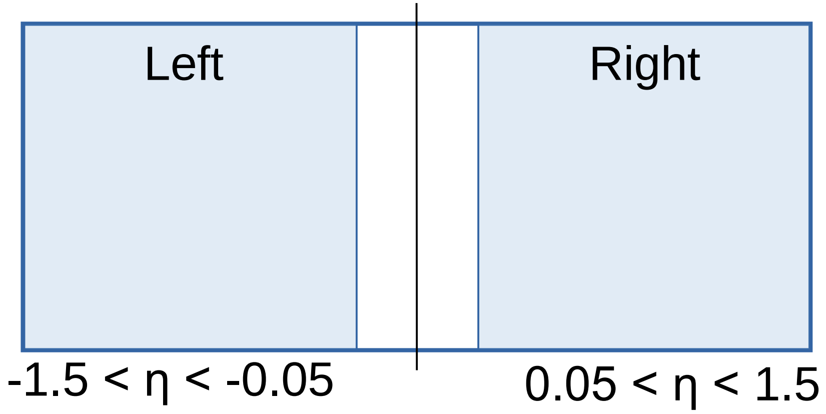
Event Plane:

$$R_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \sqrt{\left\langle \cos\left[2\left(\Psi_{2,\eta+} - \Psi_{2,\eta-}\right)\right]\right\rangle} \qquad (4)$$

$$v_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \frac{\left\langle \cos\left[2\left(\varphi_{2,\eta\pm} - \Psi_{2,\eta\mp}\right)\right]\right\rangle}{R_2^{EP}\{\Psi_{2,\mathrm{TPC}}\}} \qquad (5)$$

Scalar Product:

$$v_2^{\mathrm{SP}}\{Q_{2,\mathrm{TPC}}\} = \frac{\left\langle u_{2,\eta\pm} Q^*_{2,\eta\mp}\right\rangle}{\sqrt{\left\langle Q_{2,\eta+} Q^*_{2,\eta-}\right\rangle}} \qquad (6)$$



Left half (η<-0.05) → η_-

Right half (η>0.05) → η_+

Similar to methods used in L. Adamczyk, et al., Phys.Rev.C 86 (2012) 054908

Description of event plane method using FHCal

Using v_1 of particles in FHCal to determine Q_n

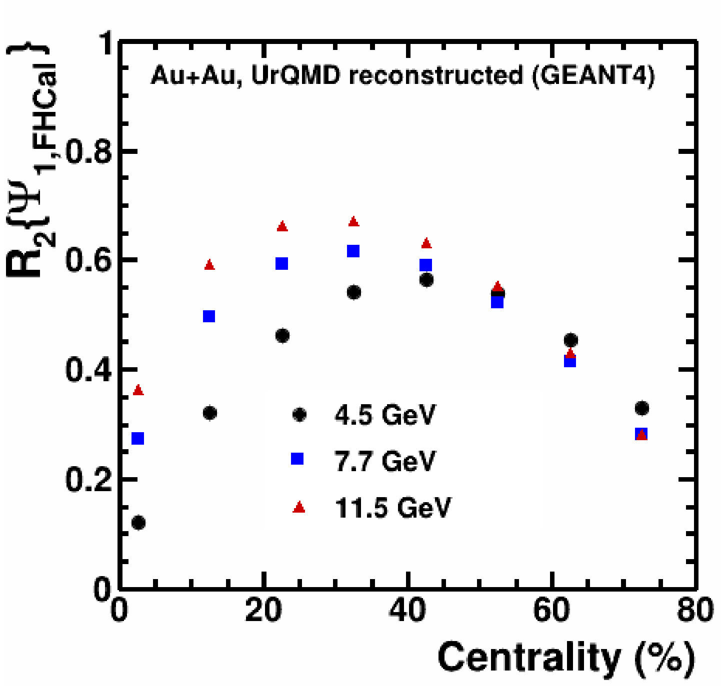
$$Q_{1,x} = \frac{\sum E_i \cos(\varphi_i)}{\sum E_i}, Q_{1,y} = \frac{\sum E_i \sin(\varphi_i)}{\sum E_i} \quad (1)$$

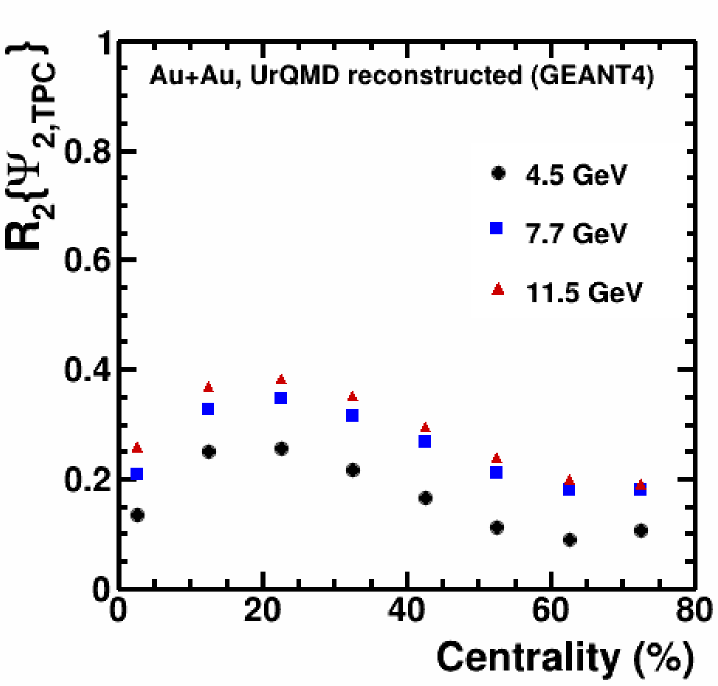
$$\Psi_{1,\mathrm{FHCal}} = \mathrm{ATan2}(Q_{1,y}, Q_{1,x}) \quad (2)$$

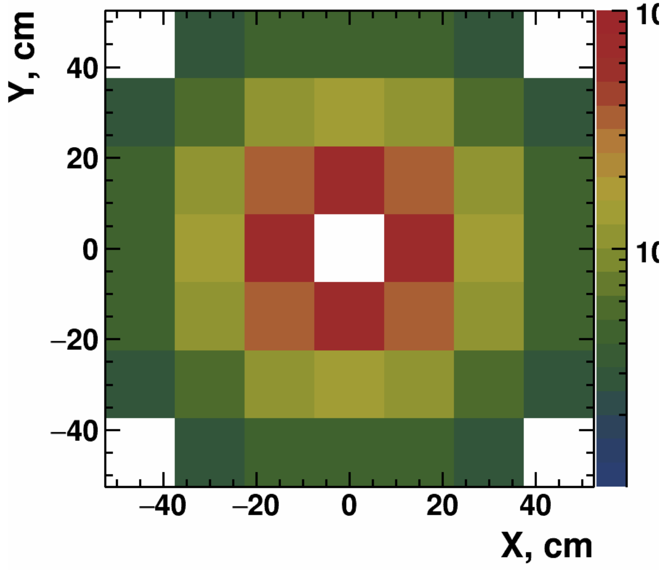
E – energy deposition in FHCal modules (2<|η|<5)

$$R_2\{\Psi_{1,\mathrm{FHCal}}\} = \left\langle \cos\left[2\left(\Psi_{RP} - \Psi_{1,\mathrm{FHCal}}\right)\right]\right\rangle \quad (3)$$

$$v_2\{\Psi_{1,\mathrm{FHCal}}\} = \frac{\left\langle \cos\left[2\left(\varphi - \Psi_{1,\mathrm{FHCal}}\right)\right]\right\rangle}{R_2\{\Psi_{1,\mathrm{FHCal}}\}} \quad (4)$$







Energy distribution in FHCal

Description of direct cumulant method for flow measurements

2 and 4 particle azimuthal correlations

$$\langle 2 \rangle_n = \frac{|Q_n|^2 - M}{M(M-1)} \quad (1) \quad \text{where} \quad Q_n = \sum_{i=1}^{M} e^{in\varphi_i} \quad (2)$$

$$\langle 4 \rangle_n = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2|Q_{2n}Q_n^*Q_n^*| - 4M(M-2)|Q_n|^2 + 2M(M-3)}{M(M-1)(M-2)(M-3)} \quad (3)$$

Elliptic flow estimate with direct cumulant method

$$\langle 2 \rangle_n = \mathrm{v}_n^2 + \delta_n \qquad \langle 4 \rangle_n = \mathrm{v}_n^4 + 4\mathrm{v}_n^2\delta_n + 2\delta_n^2 \quad (4)$$

$$\mathrm{v}_n\{2\} = \sqrt{\langle\langle 2 \rangle\rangle} \qquad \mathrm{v}_n\{4\} = \sqrt[4]{2\langle\langle 2 \rangle\rangle^2 - \langle\langle 4 \rangle\rangle} \quad (5)$$

δ – nonflow contribution (Bose-Einstein correlations, resonance decays, …)

This method was introduced by Ante Bilandzic in Phys. Rev. C83:044913, 2011

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:

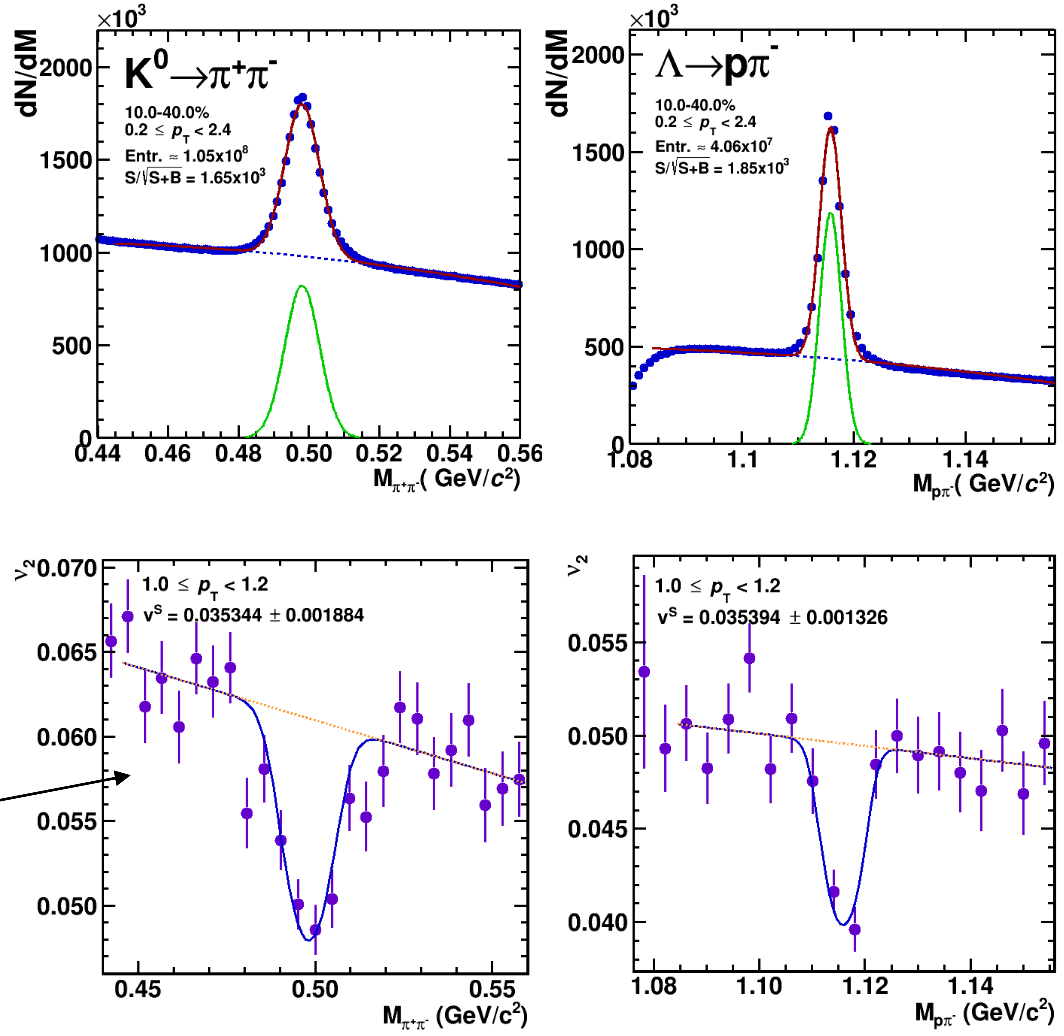
- TPCv7, TOFv7, FHCal

Centrality by TPC multiplicity, Event-plane method with FHCal

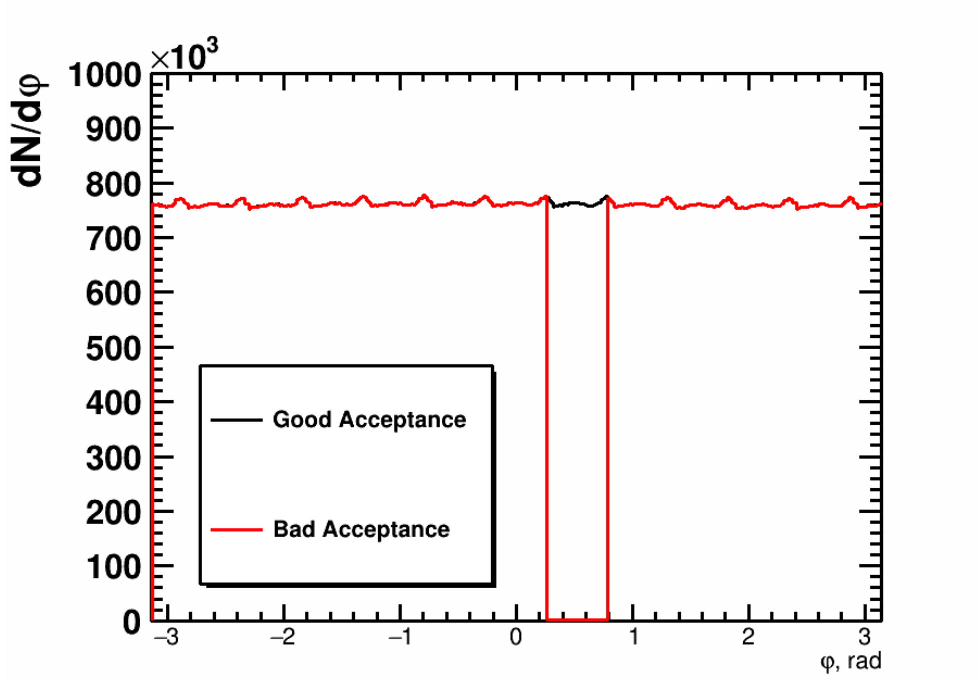
Particle decays reconstructed with MpdParticle realistic cuts

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

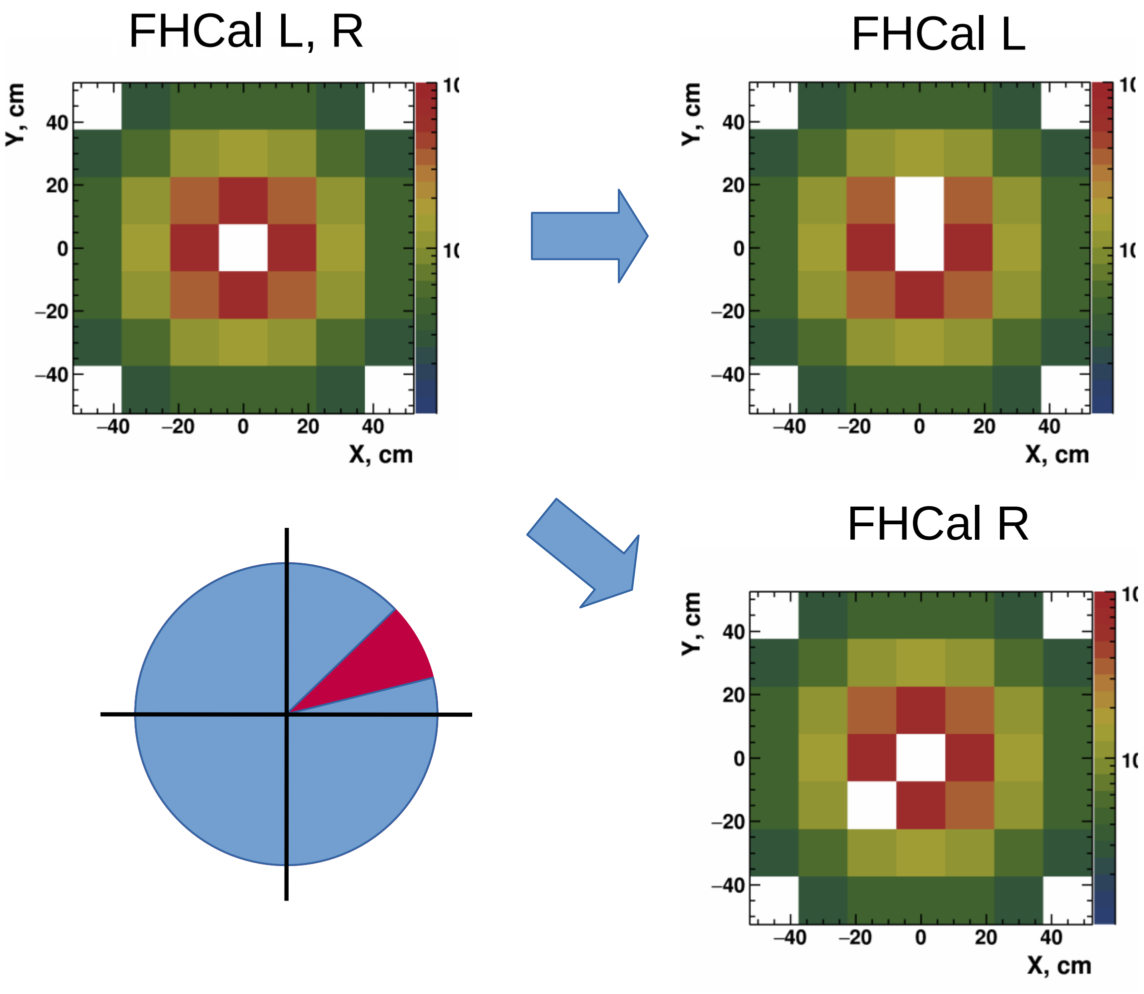
$$v_2^{SB}(m_{inv},p_T) = v_2^{S}(p_T)\frac{N^{S}(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)} + v_2^{B}(m_{inv},p_T)\frac{N^{B}(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)}$$



Non-uniform acceptance

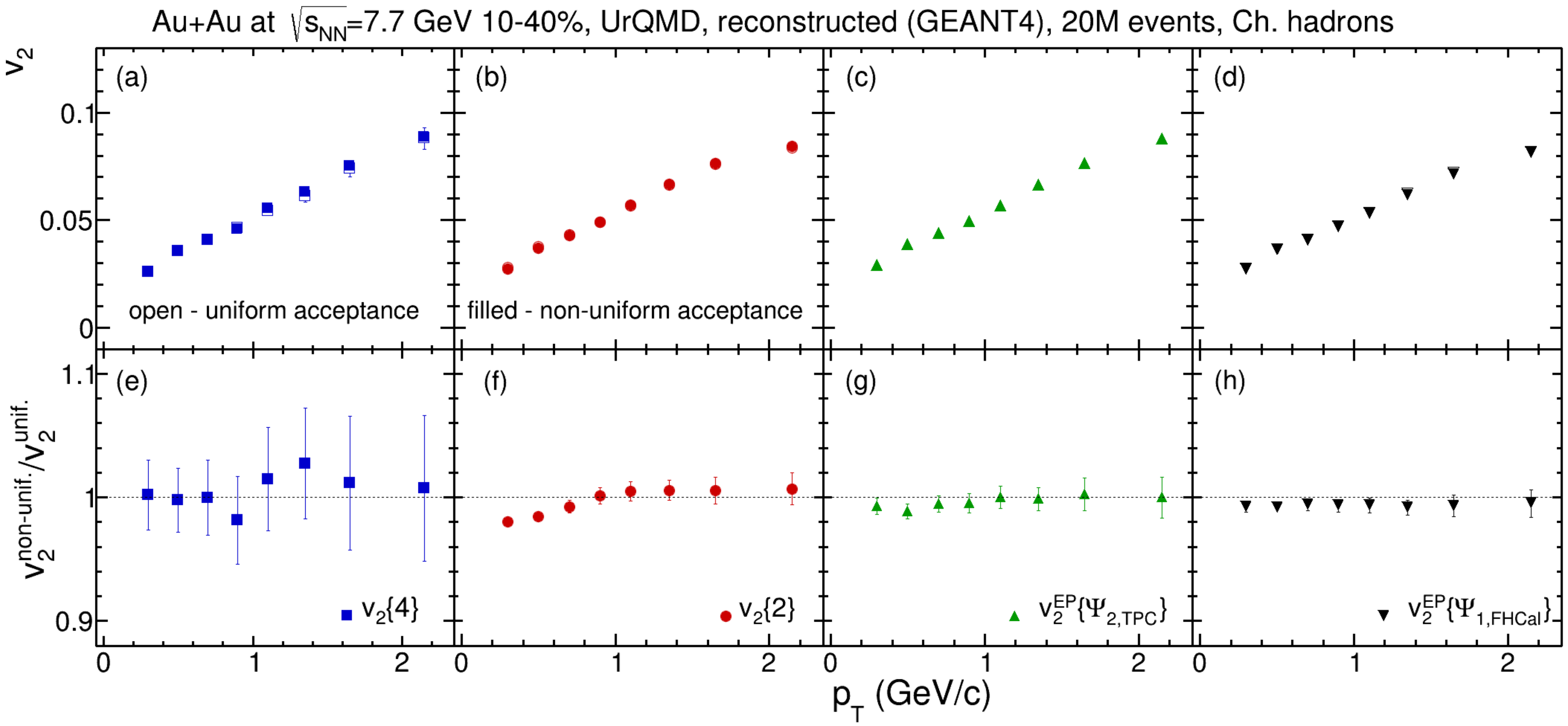


Area 15°< φ < 45° is off



How robust the future measurements against non-uniform acceptance?

Acceptance correction



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

Sensitivity of different methods to flow fluctuations

Elliptic flow fluctuations:

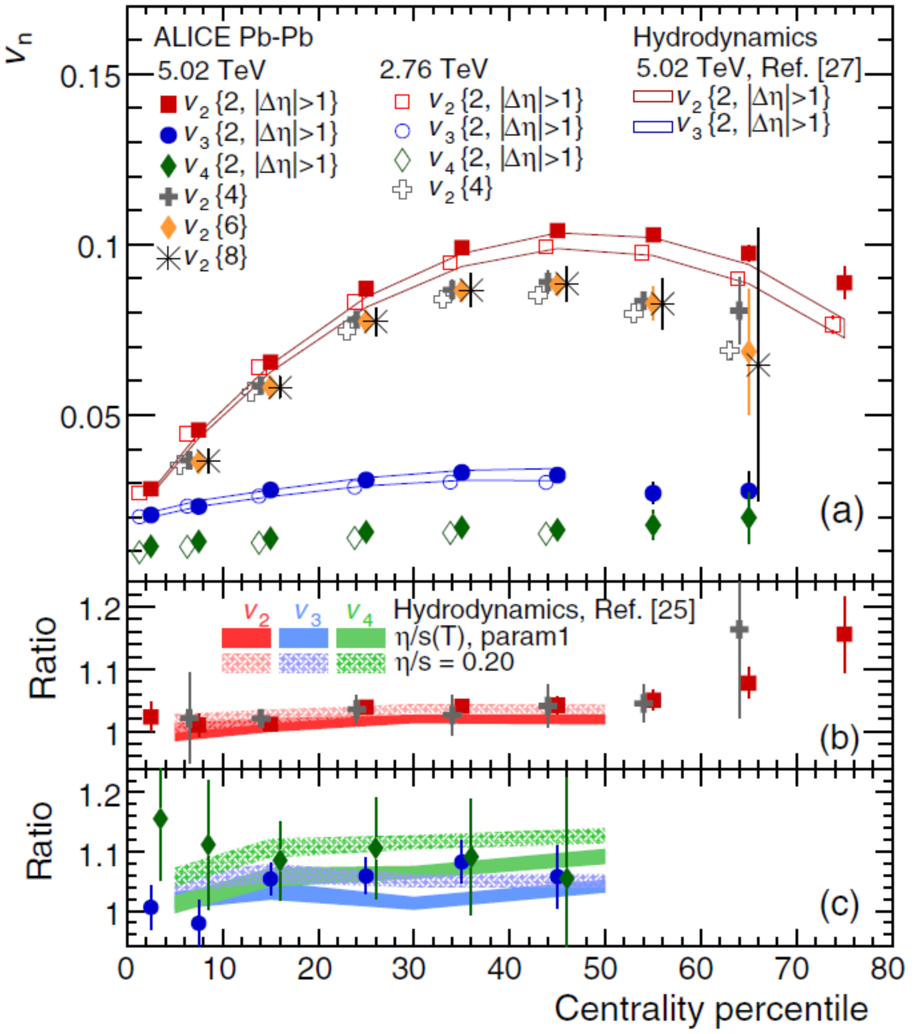
$$\sigma_{v_2}^2 = \langle v_2^2 \rangle - \langle v_2 \rangle^2$$

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

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

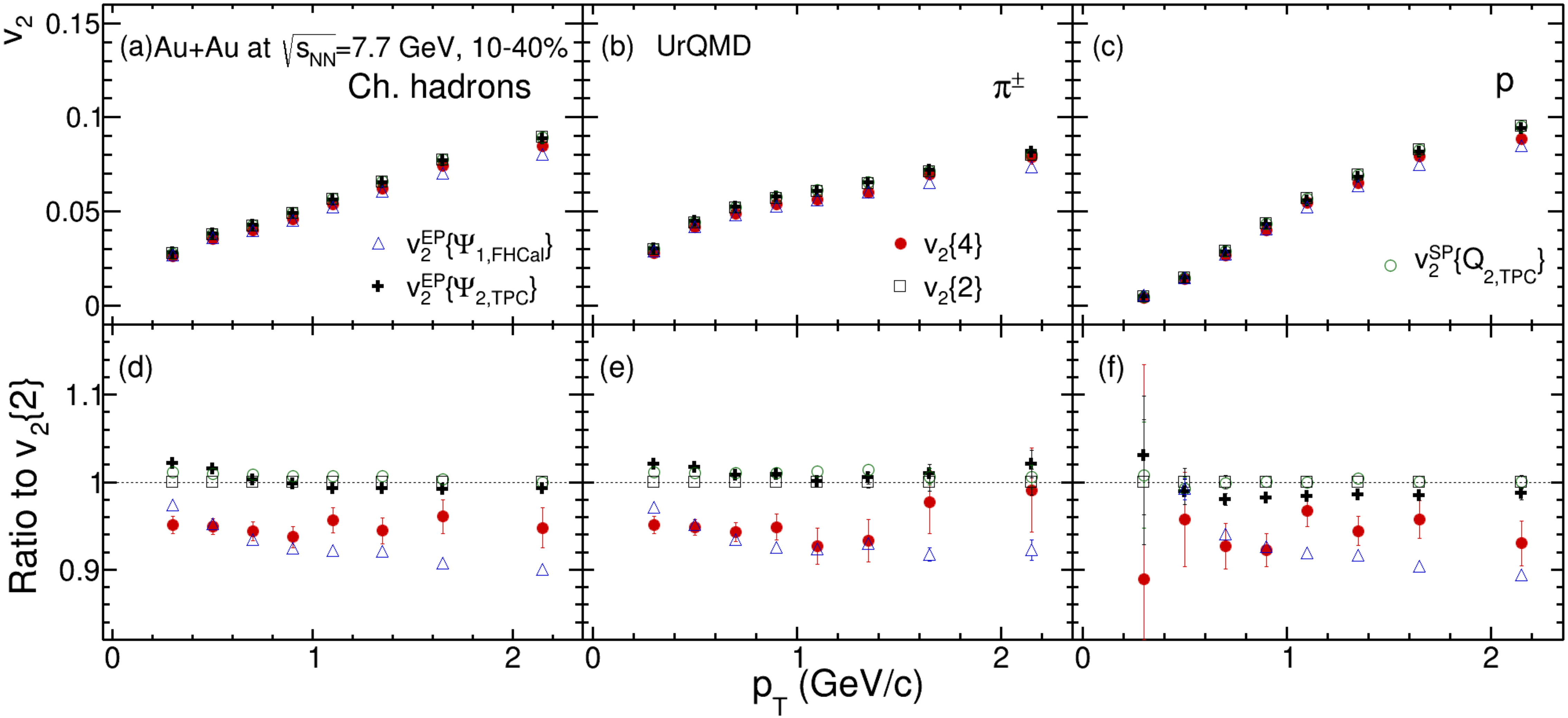
The difference between $v_2^{EP}\{\Psi_{1,FHCal}\}$ and $v_2^{EP}\{\Psi_{2,TPC}\}$:

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



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

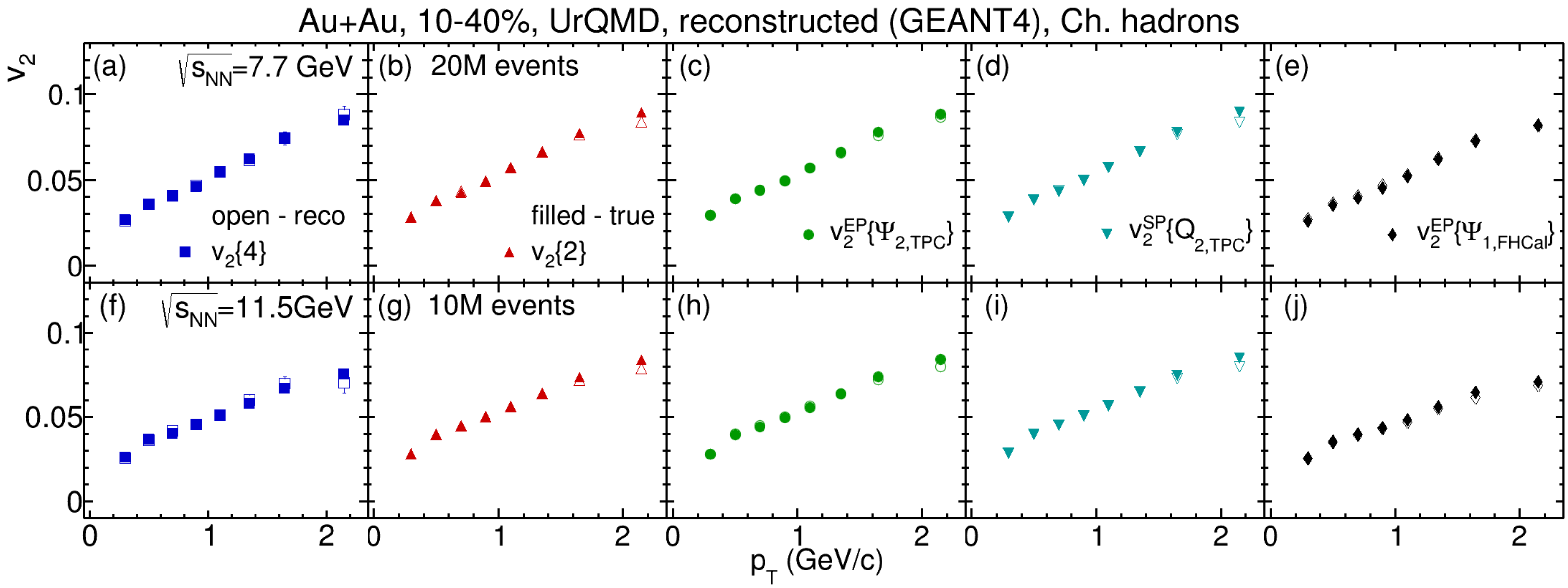
Comparison of v2 measurements using different method



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

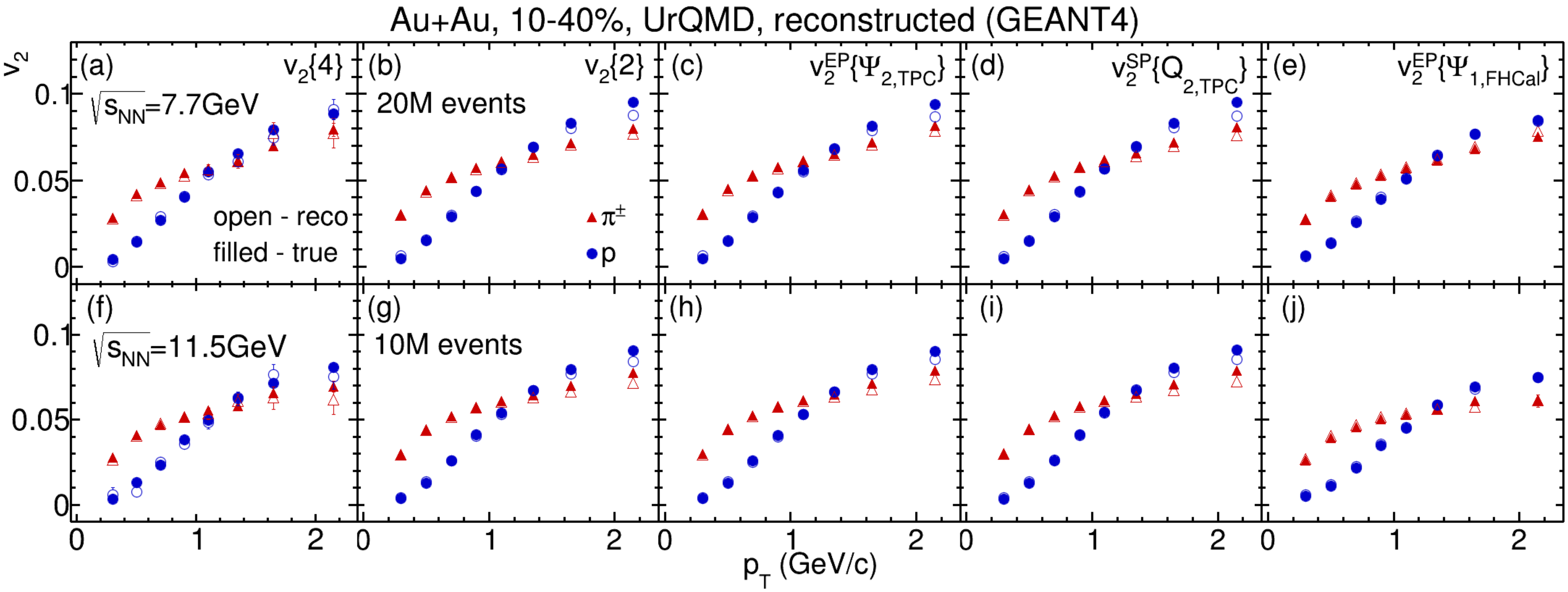
$v_2\{4\}$ and $v_2^{EP}\{\Psi_{1,\mathrm{FHCal}}\}$ are smaller than $v_2\{2\}$ due to fluctuation and nonflow

Performance study of v_2 of charged hadrons in MPD



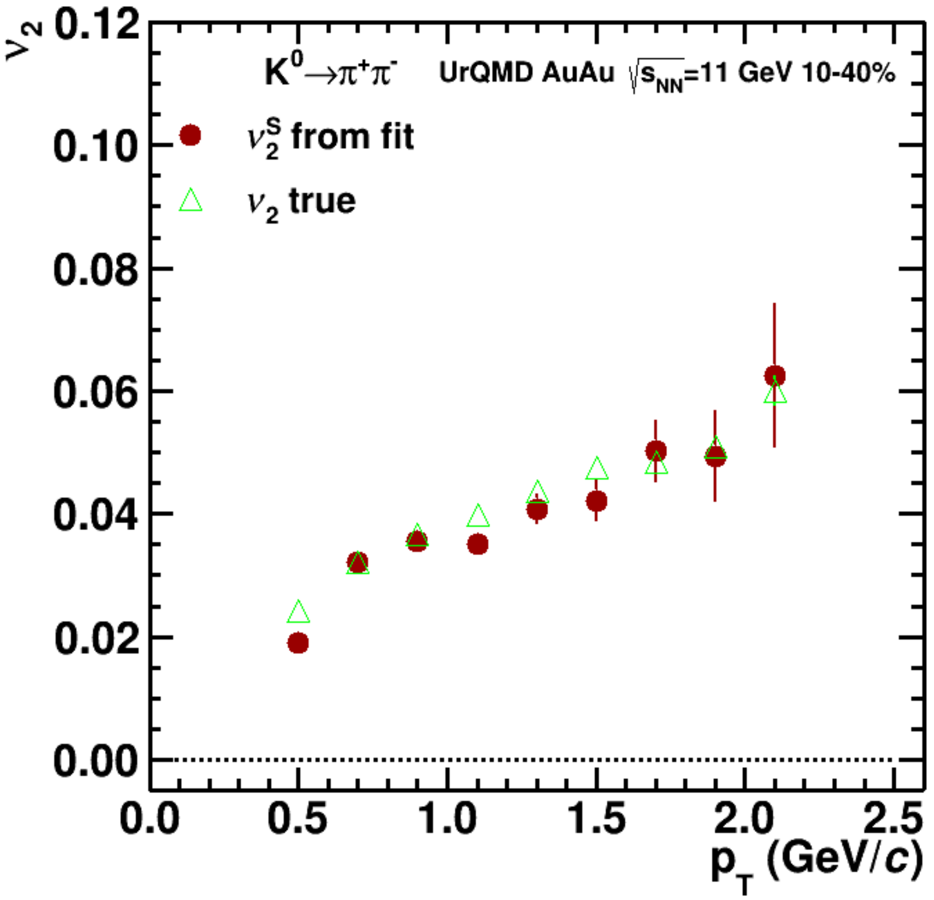
Reconstructed (reco) and generated (true) v_2 values are in a good agreement for all methods

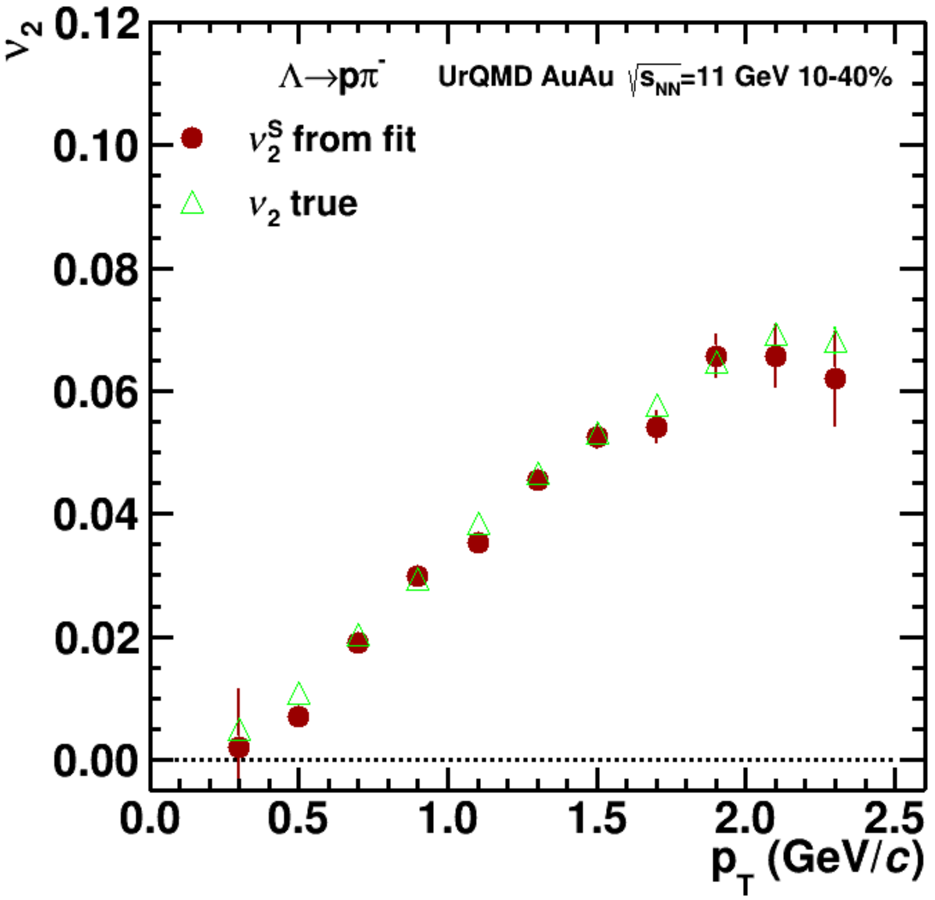
Performance study of v_2 of pions and protons in MPD



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

Performance study for v_2 of V0 particles

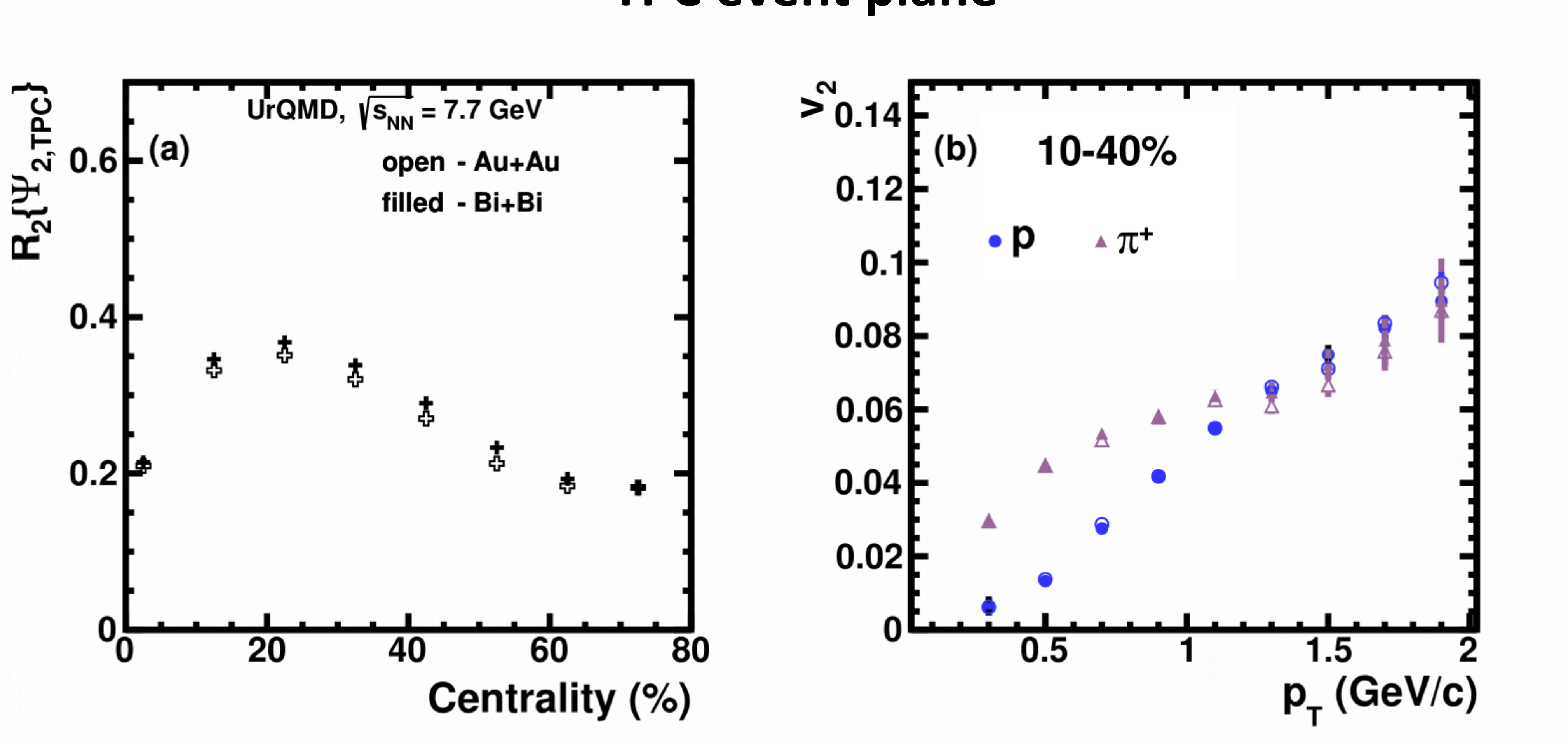




Reasonable agreement between reconstructed and generated v_2 signals for both K^0 and Λ

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

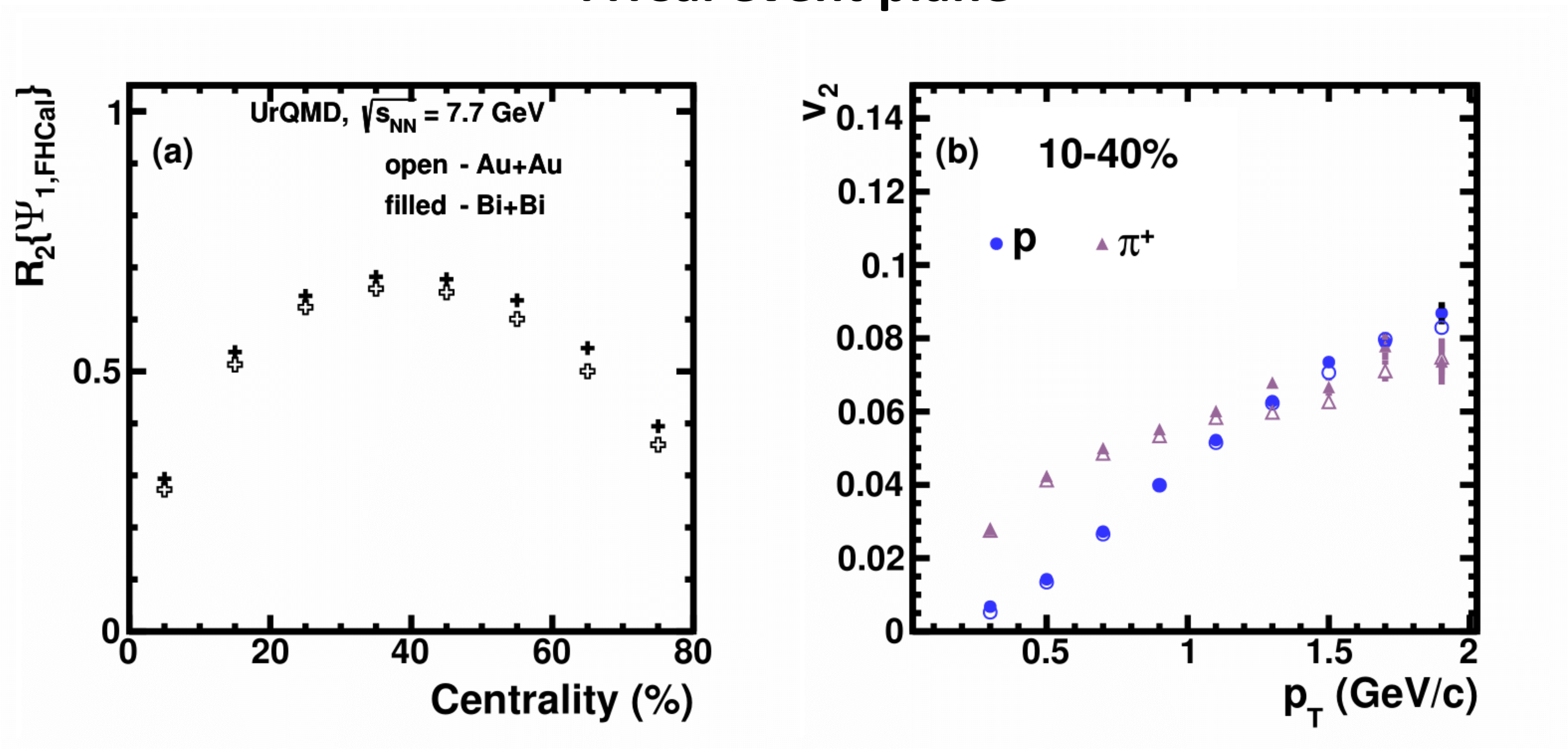
TPC event plane



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

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:**
  - Acceptance corrections allows one to perform v_2 measurements with non-uniform acceptance 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

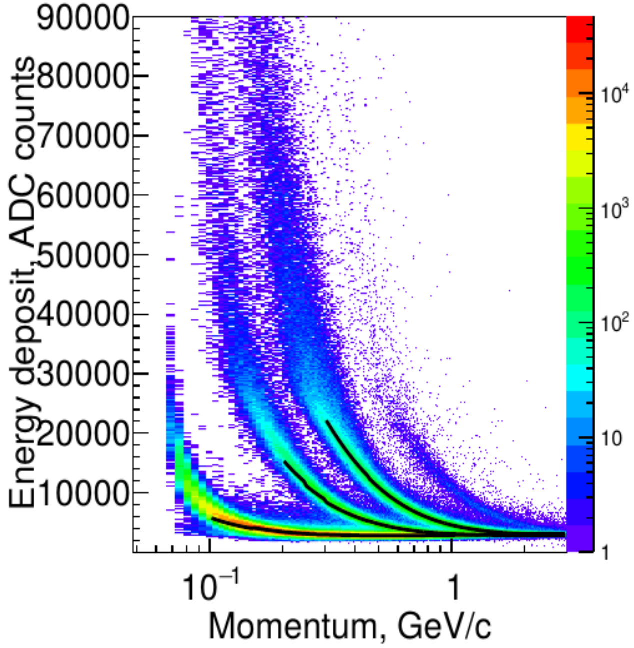
UrQMD → GEANT4 → Reconstruction → Flow analysis

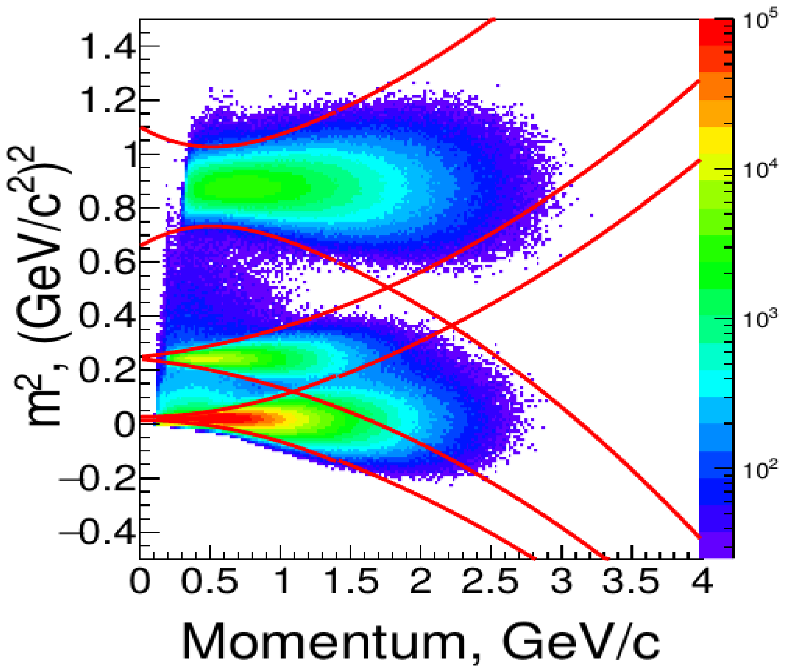
- Au+Au:
  - N_{events} = 10 M *at* $\sqrt{s_{NN}}$ = 4.5, 11.5 GeV
  - N_{events} = 20 M at $\sqrt{s_{NN}}$ = 7.7 GeV
- Bi+Bi:
  - N_{events} = 7 M *at* $\sqrt{s_{NN}}$ = 7.7 GeV

- 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)

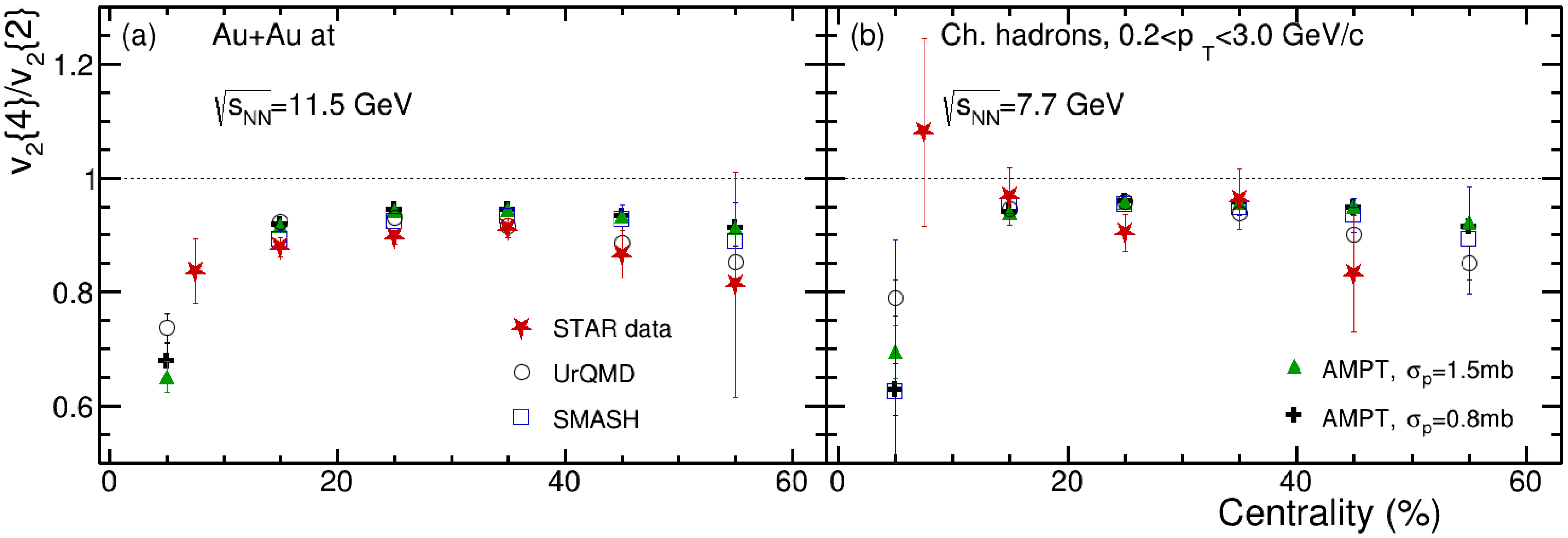




MPDRoot, August 2020

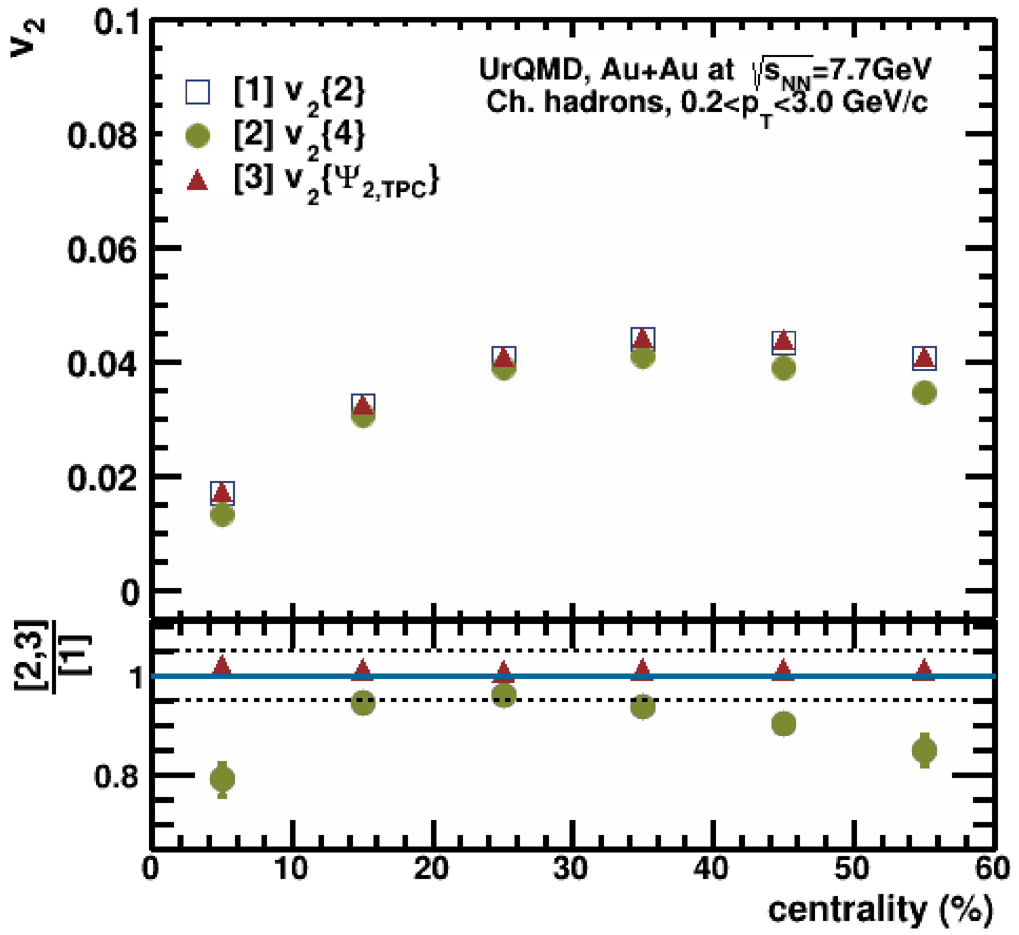
Relative elliptic flow fluctuations at 11.5 GeV and 7.7 GeV

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

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

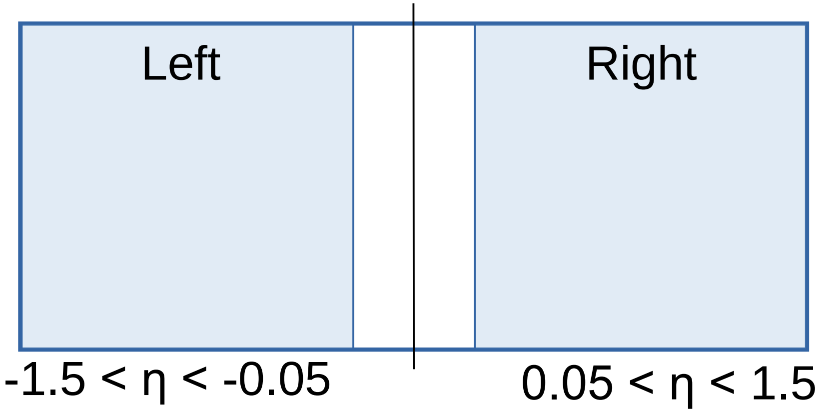
Description of event plane method

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

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

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

- 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_+

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

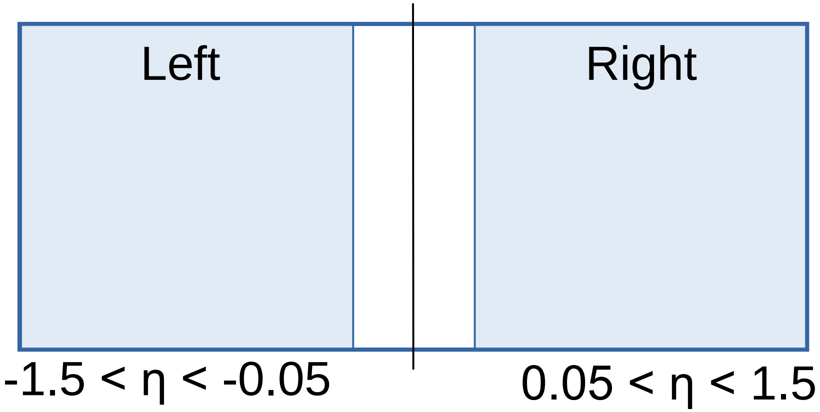
STAR Collaboration: B.I. Abelev, et al., Phys.Rev.C77:054901,2008

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

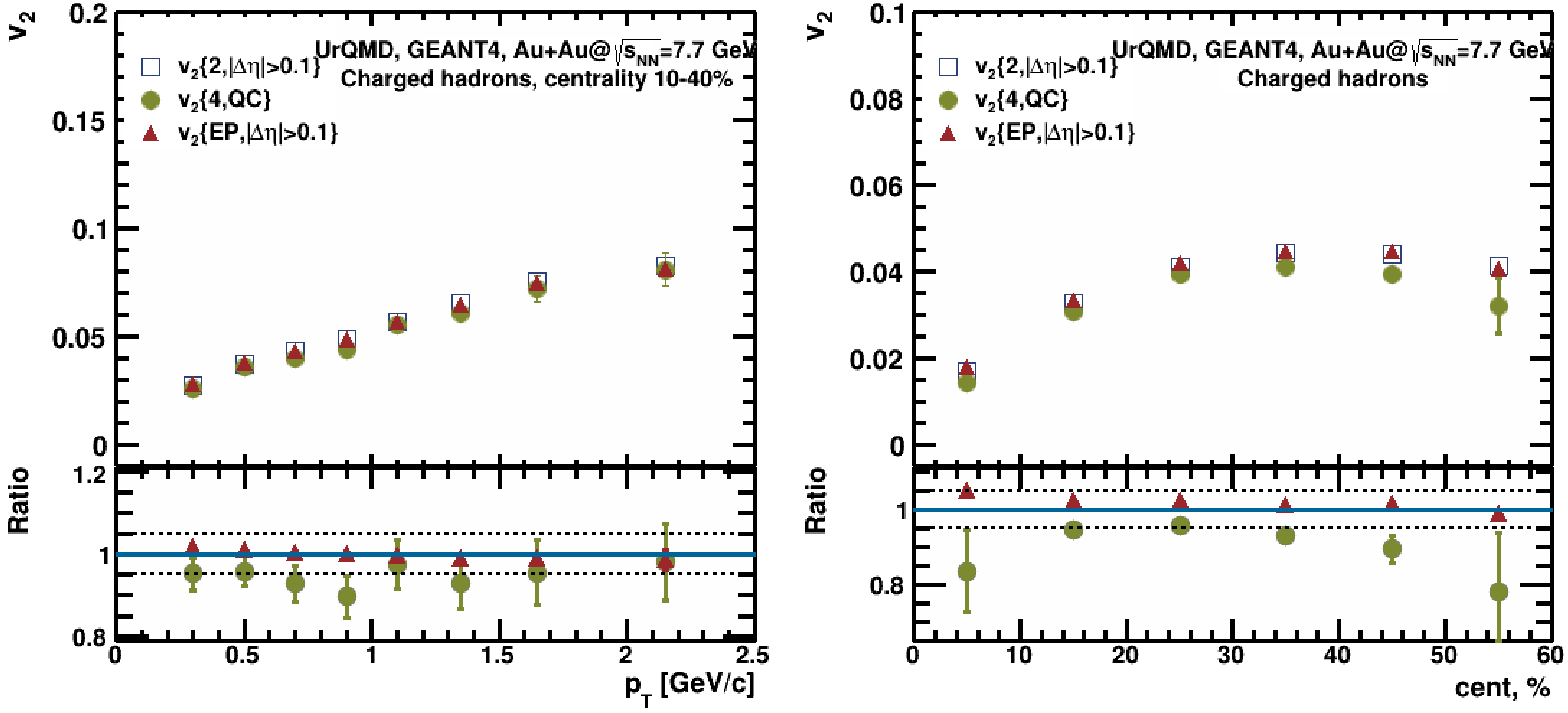


Left half (η<-0.05) → η_-

Right half (η>0.05) → η_+

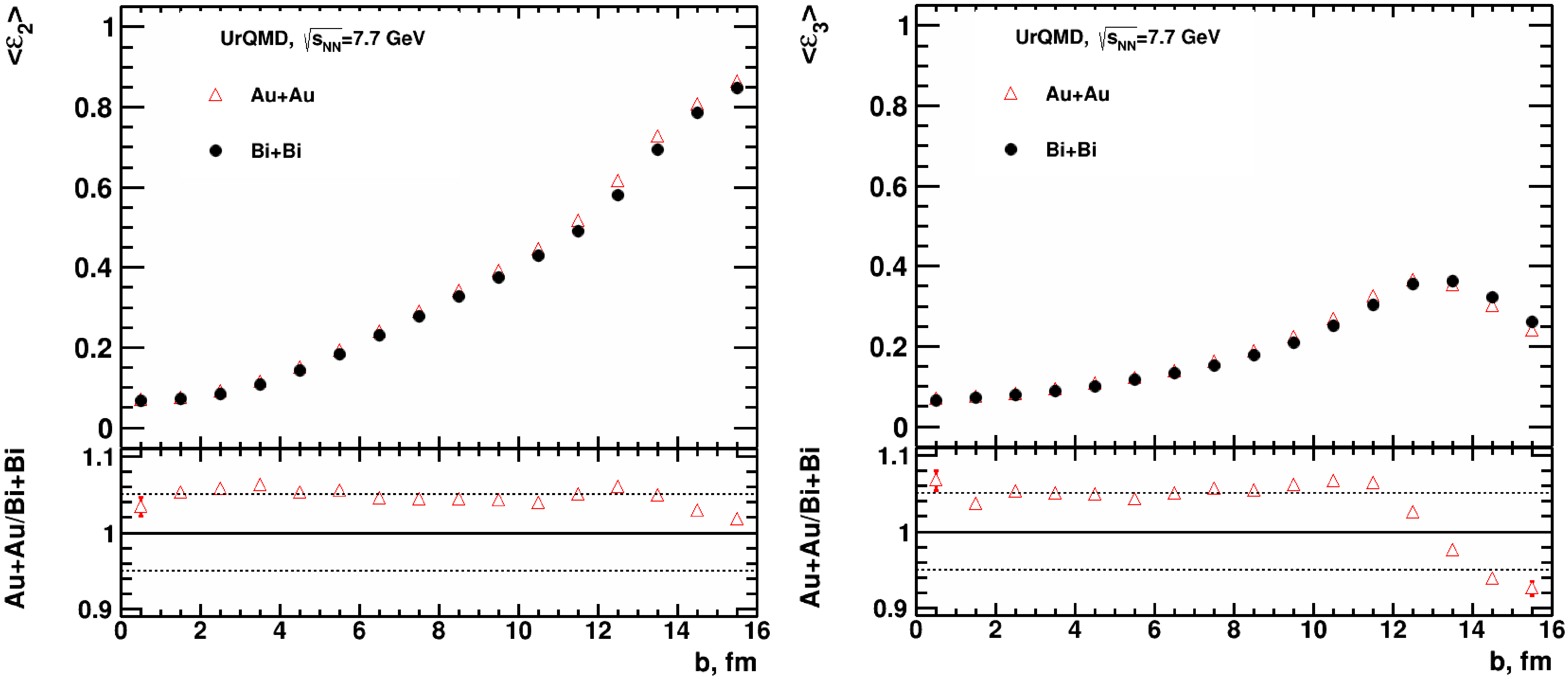
$$v_2^{SP}\{Q_{2,\mathrm{TPC}}\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp} \rangle}{\sqrt{\langle Q_{2,\eta+} Q^*_{2,\eta-} \rangle}} \qquad (3)$$

Results for v_2 for reconstructed events of MPD



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

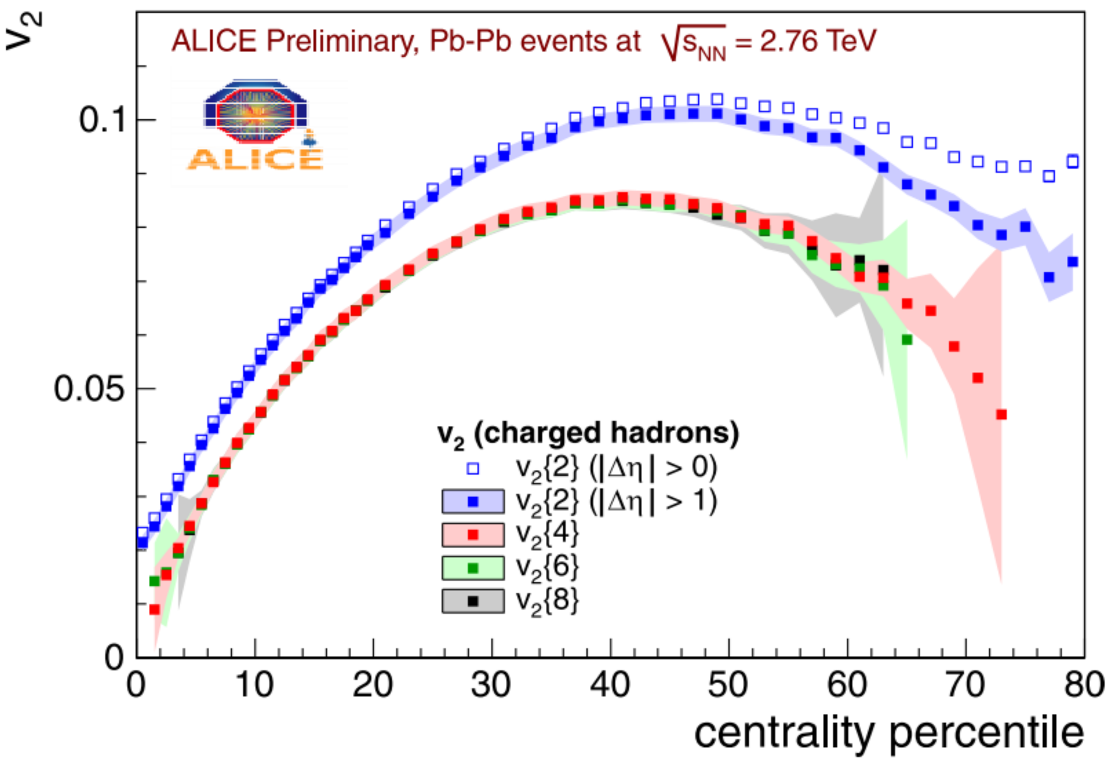
- How fluctuations affect the measured values of v_n. The effect of the fluctuations on v_n estimates can be obtained from

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

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

- 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.

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

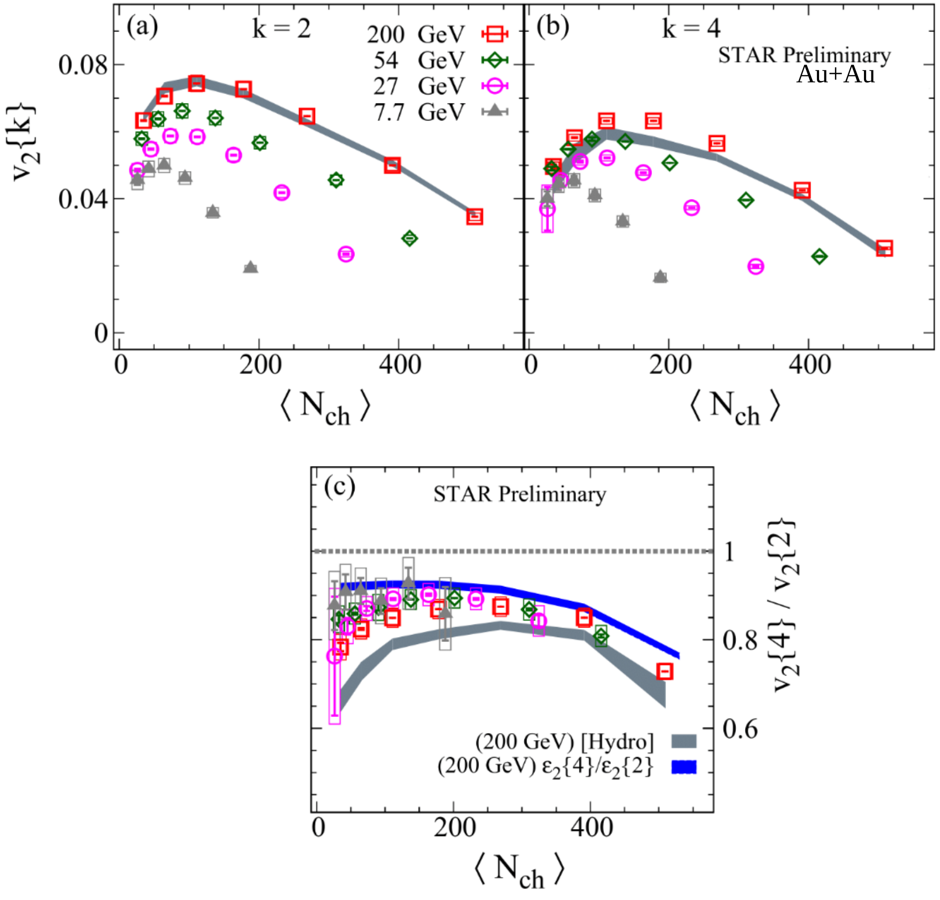


The difference between $v_n\{2\}$ with and without $\Delta\eta$ gap is driven by the contribution from nonflow

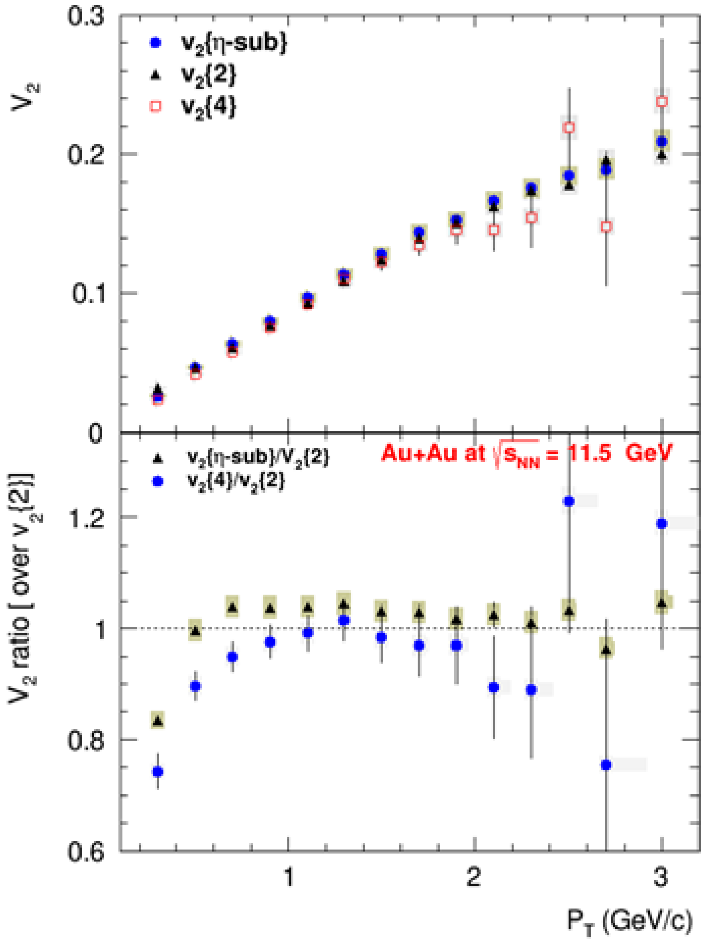
Ilya Selyuzhenkov for the ALICE collaboration, Prog.Theor.Phys.Suppl. 193 (2012) 153-158

Cumulant results from Beam Energy Scans

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



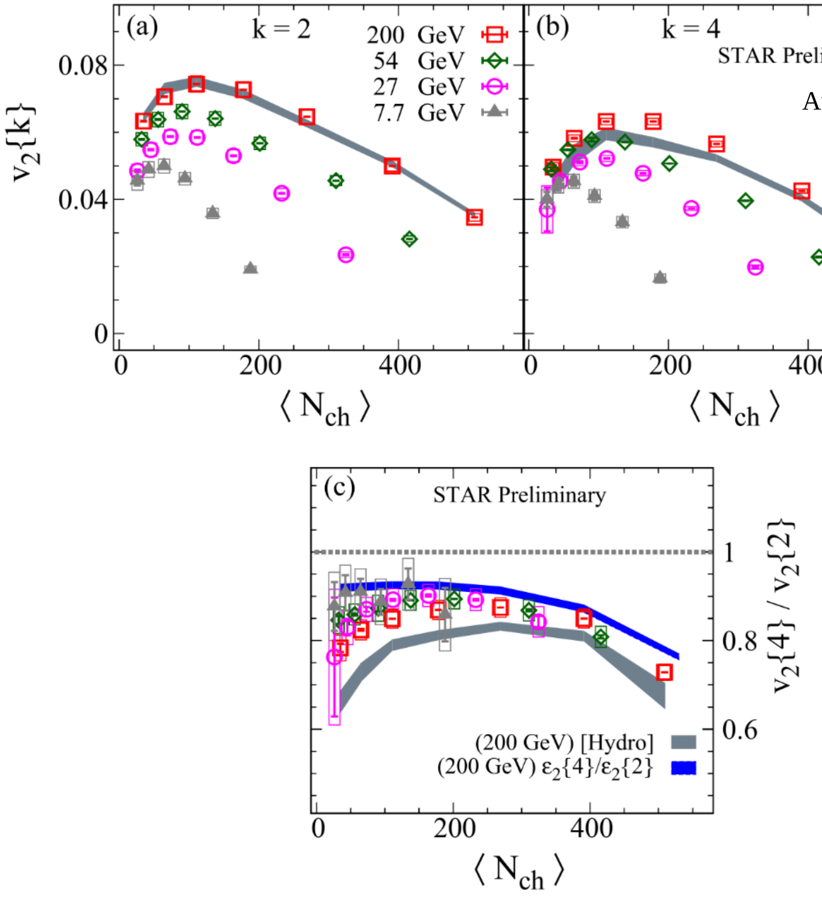
L. Adamczyk et al. (STAR Collaboration). Phys. Rev. C 86, 054908 (2012)



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

Methods of flow measurements have different sensitivity to flow fluctuations

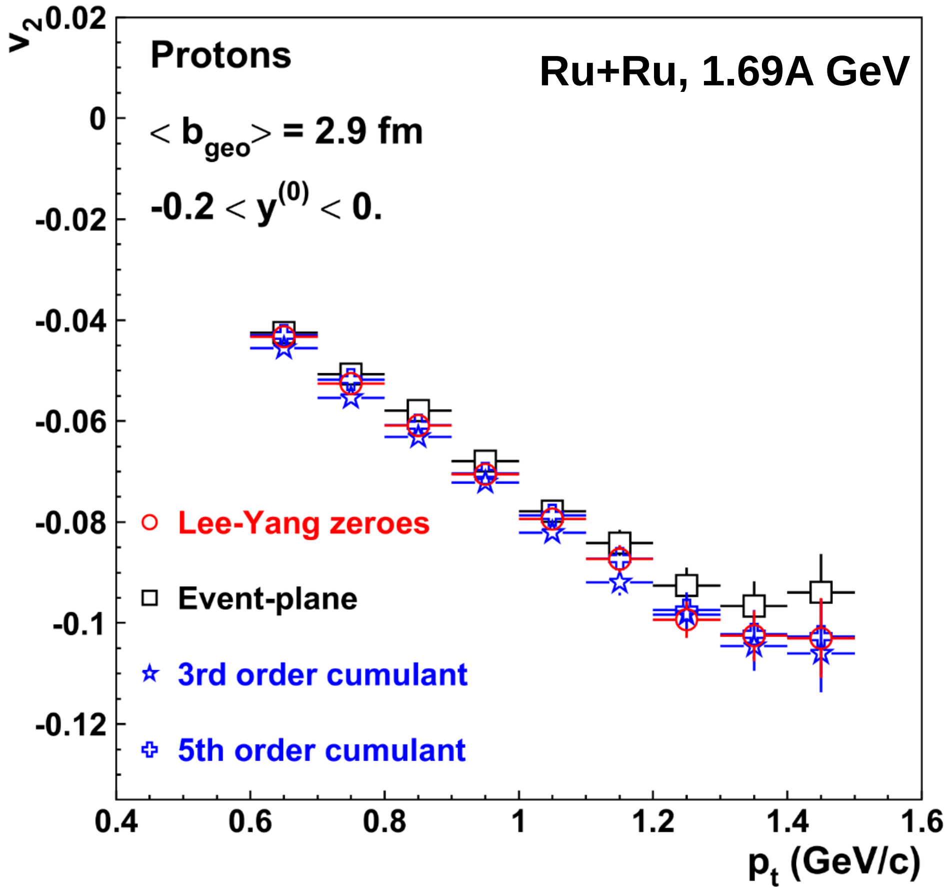
Cumulant results from Beam Energy Scans



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



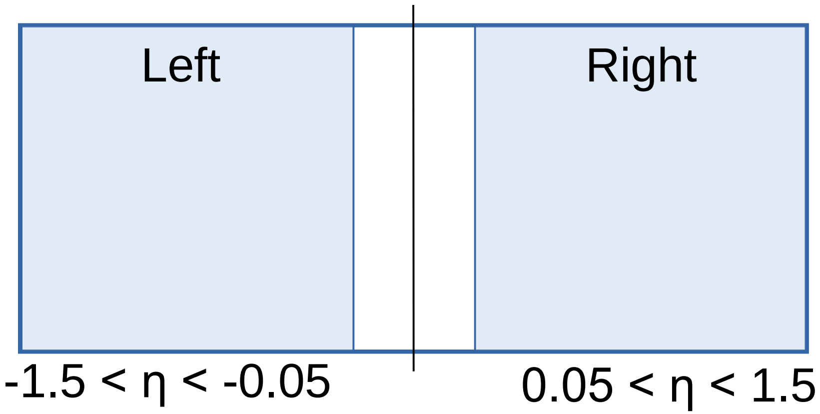
v_2 versus transverse momentum for protons measured in semi-central events and around mid-rapidity.

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

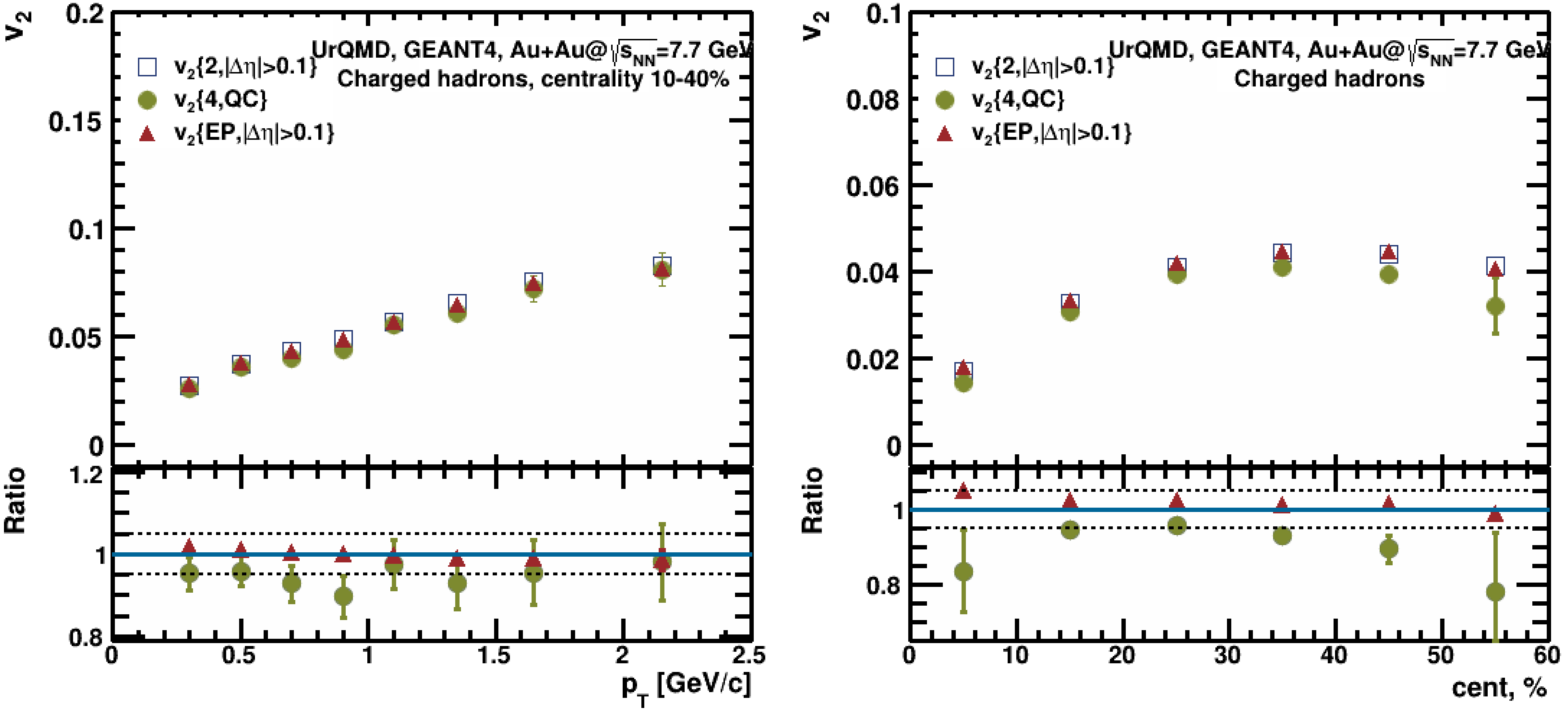
- Total number of generated minimum bias events - 88 M
- Particle selection: charged hadrons, $0.2<p_T<3$ GeV/c
- Configuration of cumulant method:
  1. RFP and POI: charged hadrons;
  2. calculations were performed taking into account the effect of autocorrelation
- All 3 methods have the same kinematical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



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