Comparison of methods for elliptic flow measurements at NICA energies $\sqrt{s_{NN}}$ = 4 - 11 GeV

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For the MPD Collaboration

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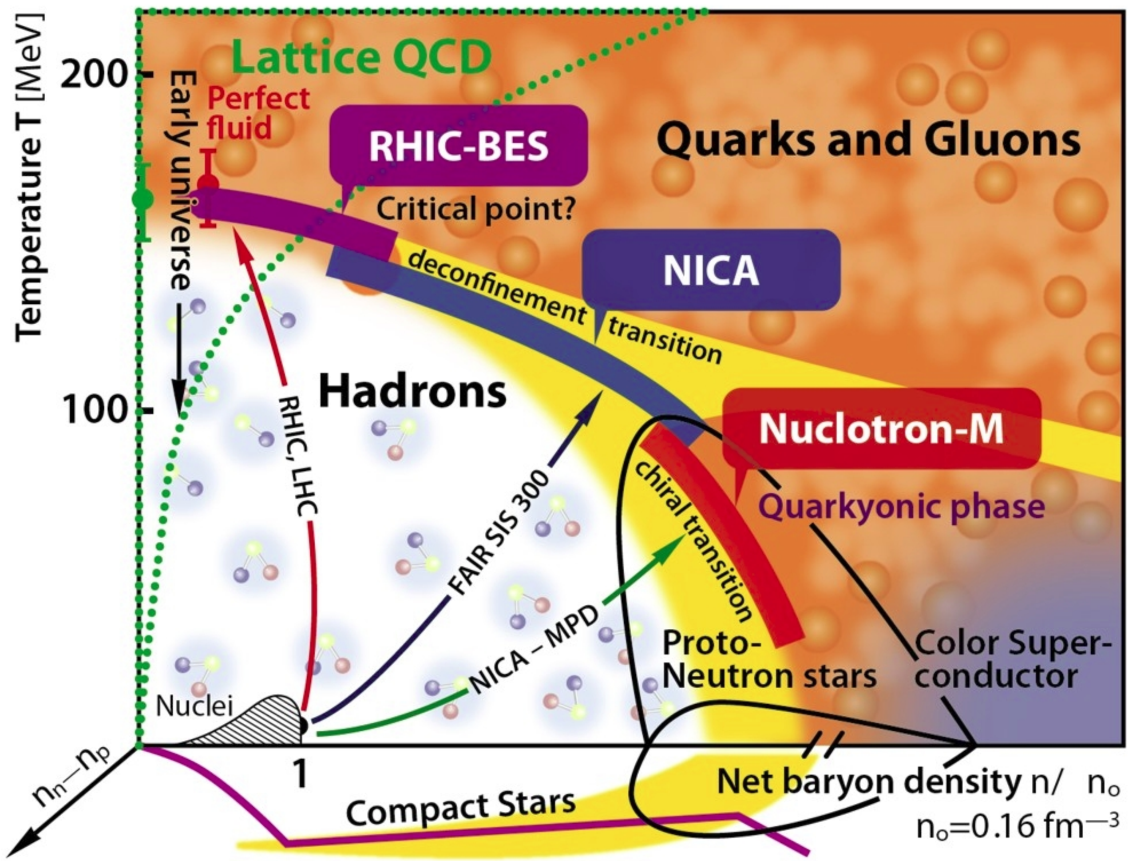
Outline

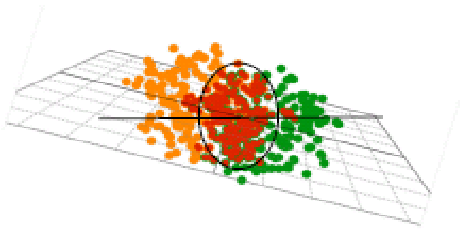
- Elliptic flow (v_2) at NICA energies
- Description of Q-Cumulant, event plane and scalar product methods
- Sensitivity of different methods to flow fluctuations and nonflow
- Performance of v_2 of inclusive charged hadrons and identified hadrons in MPD (NICA)
- Summary and outlook

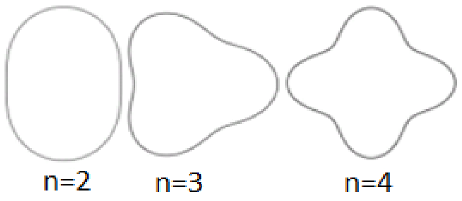
Phase Diagram of the Strongly-Interacting Matter



- **Top RHIC/LHC:**
  - validation of the cross over transition leading to the sQGP
  - access to high T and small μ_B
- **RHIC-BES/SPS/NICA/FAIR**
  - access to different systems
  - broad domain of the (μ_B,T)-plane

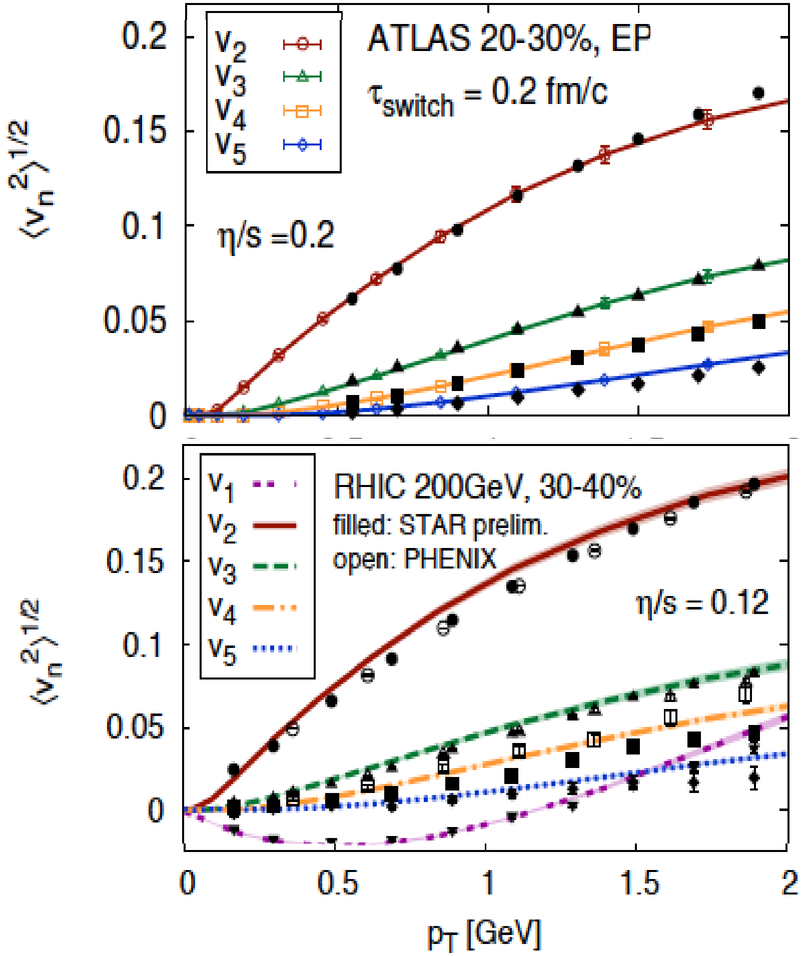
Anisotropic Collective Flow at top RHIC / LHC





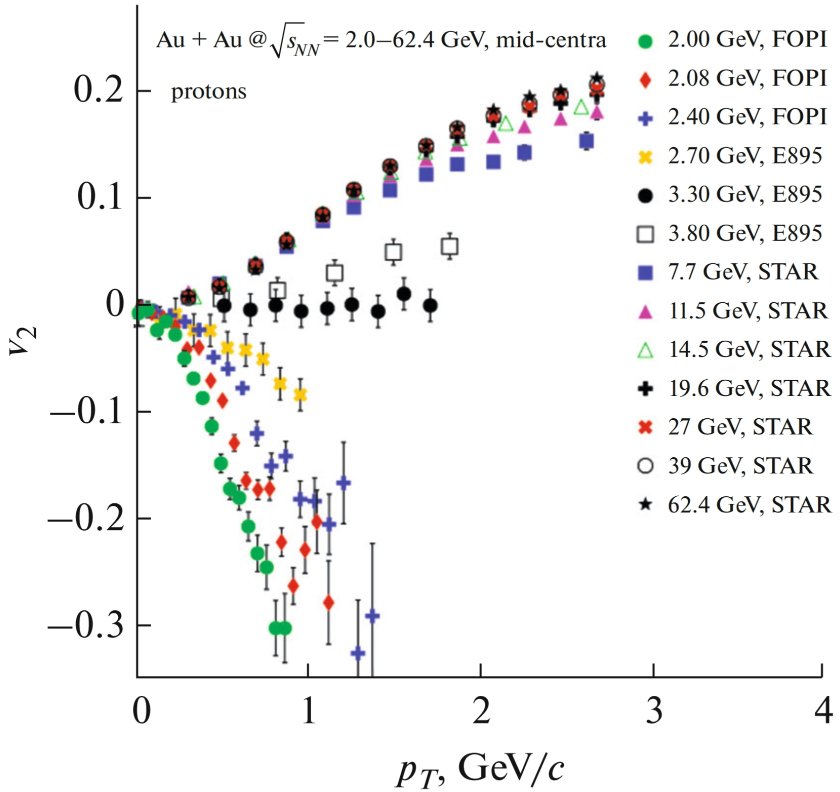
$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}} \Rightarrow \frac{dN}{d\phi} \propto \left(1 + 2\sum_{n=1} v_n \cos\left[n(\phi - \Psi_n)\right]\right)$$

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

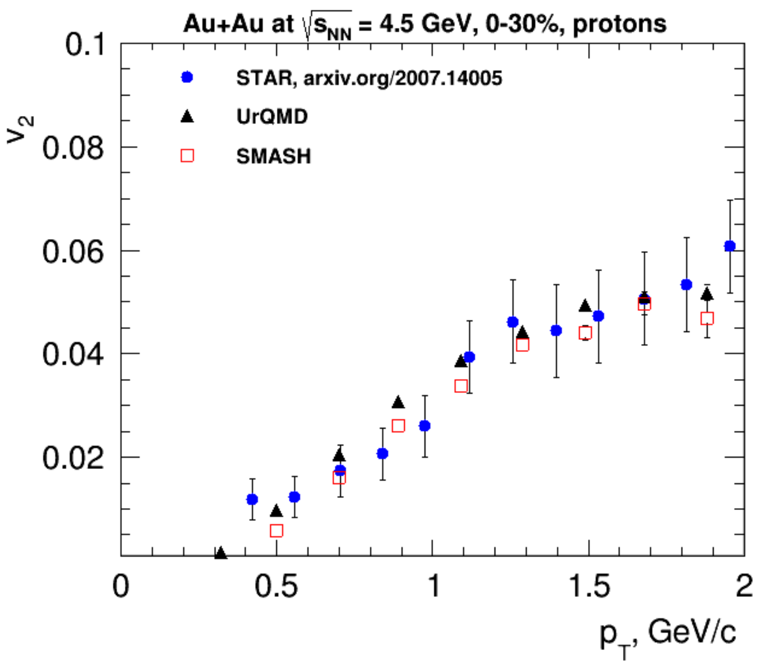


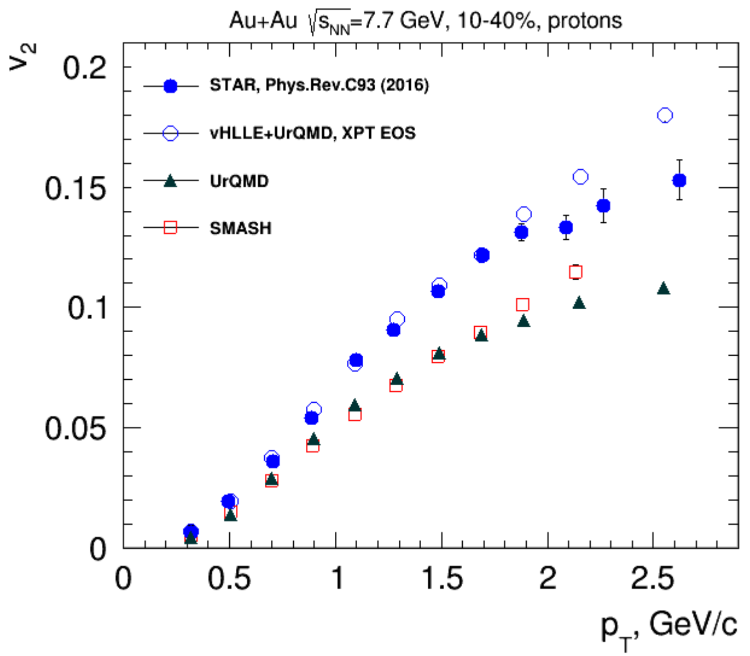
- Initial eccentricity (and its attendant fluctuations) ε_n drives momentum anisotropy v_n with specific viscous modulation
- v_1 - directed flow, v_2 - elliptic flow, v_3 - triangular flow
- v_n ($p_{T,}$ centrality):
  - sensitive to the early stages of collision
  - important constraint for transport properties: EoS, η/s, ζ/s, etc.

Elliptic flow at NICA energies



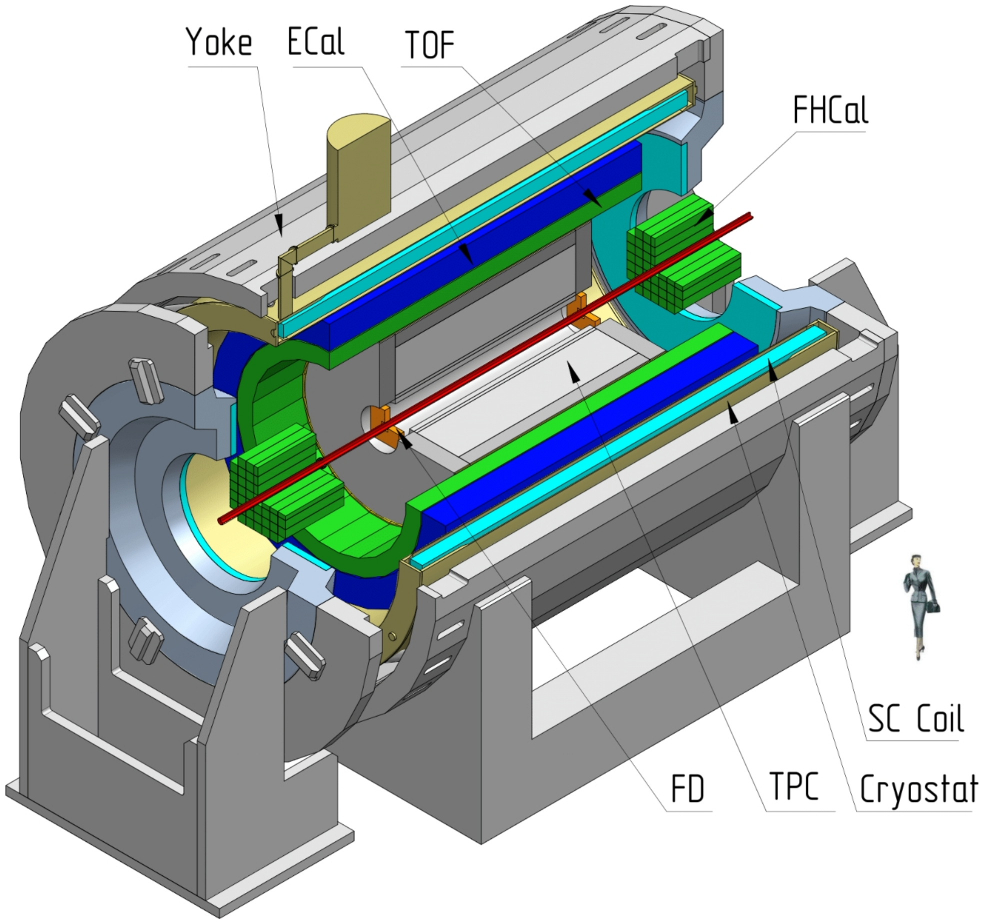
Taranenko et. al.,
Phys. Part. Nuclei **51**, 309–313 (2020)





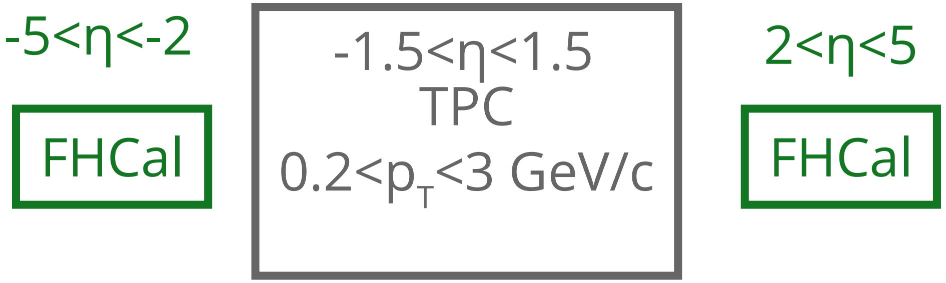
- **Strong energy dependence of v2 at $\sqrt{s_{NN}}$ = 3-11 GeV**
  - $v_2 \approx 0$ at $\sqrt{s_{NN}}$ = 3.3 GeV and negative below
- **Lack of differential measurements of v_2 at NICA energies (p_T, centrality, PID,…)**
- **v_2 is sensitive to the properties of strongly interacting matter:**
  - 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,…)

MPD Experiment at NICA



Multi-Purpose Detector (MPD) Stage 1

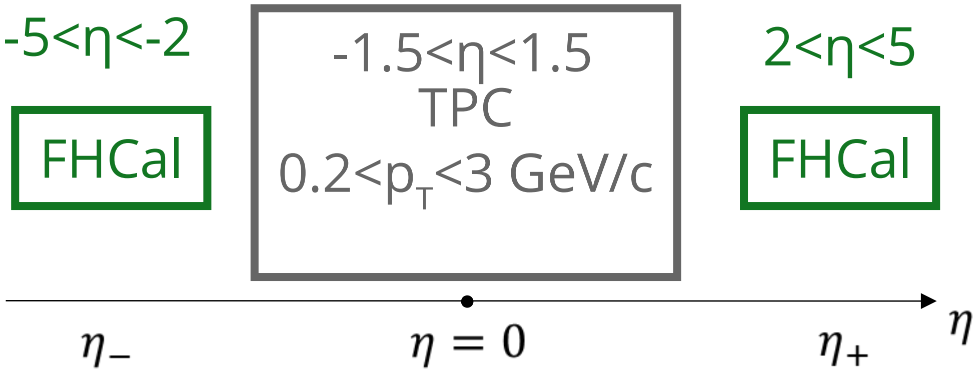
- **Centrality determination:** Impact parameter b
- **Event plane determination:** TPC, FHCal
- **Track selection:**
  - Primary tracks
  - $N_{\text{TPC hits}} \geq 16$
  - $0.2 < p_T < 3.0$ GeV/c
  - $|\eta| < 1.5$
  - PID based on PDG



Elliptic flow measurements using v2 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: $v_2^{\mathrm{SP}}\{Q_{2,\mathrm{TPC}}\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp}\rangle}{\sqrt{\langle Q_{2,\eta+} Q^*_{2,\eta-}\rangle}}$ (3)

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

Q-cumulants:

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

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

δ – nonflow contribution

Description of event plane method using FHCal

Using v_1 of particles in FHCal to determine Q_n

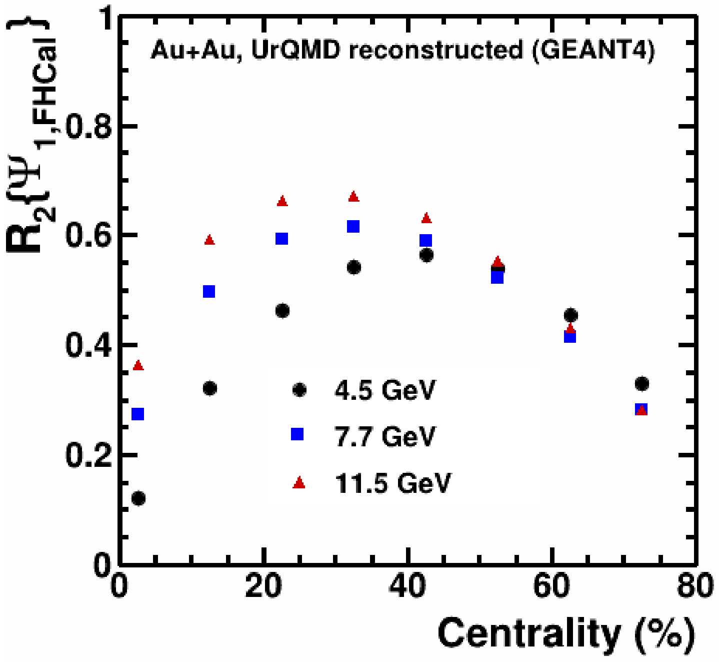
$$Q_{1,x}=\frac{\sum E_i\cos(\varphi_i)}{\sum E_i},\ Q_{1,y}=\frac{\sum E_i\sin(\varphi_i)}{\sum E_i} \quad (1)$$

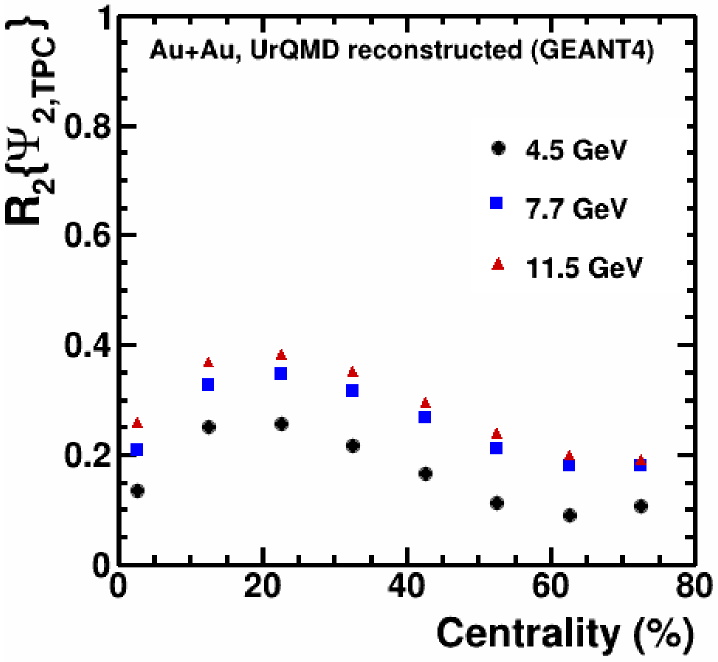
$$\Psi_{1,\mathrm{FHCal}}=\mathrm{ATan2}(Q_{1,y},Q_{1,x}) \quad (2)$$

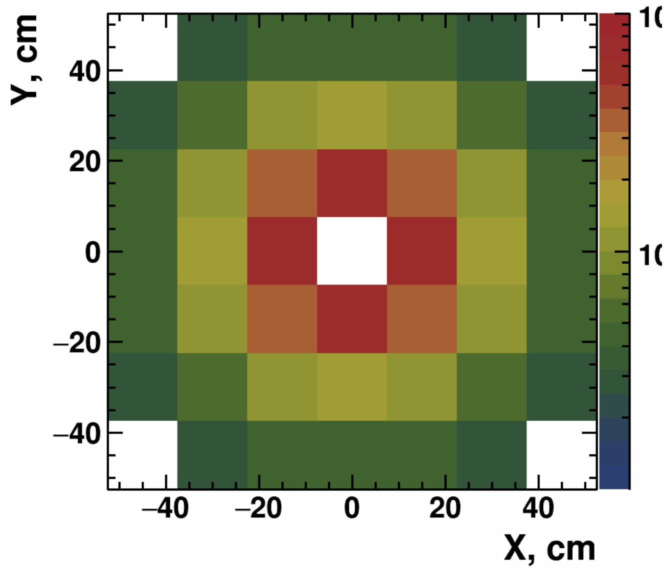
$$R_2\{\Psi_{1,\mathrm{FHCal}}\}=\langle\cos[2(\Psi_{RP}-\Psi_{1,\mathrm{FHCal}})]\rangle \quad (3)$$

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

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







Energy distribution in FHCal

Sensitivity of different methods to flow fluctuations

- Elliptic flow fluctuations:

$$\sigma_{v_2}^2 = \langle v_2^2 \rangle - \langle v_2 \rangle^2 \qquad (1)$$

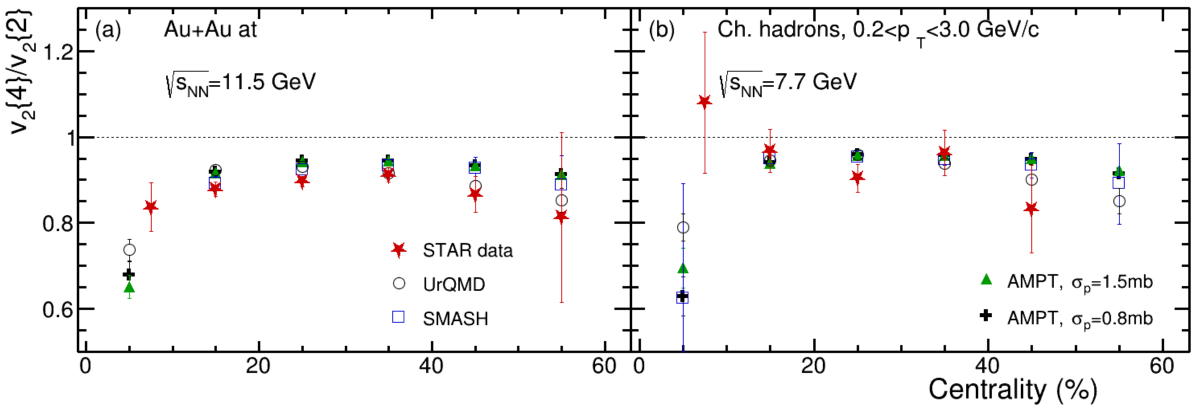
- The difference between $v_2\{2\}$ and $v_2\{4\}$:

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

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

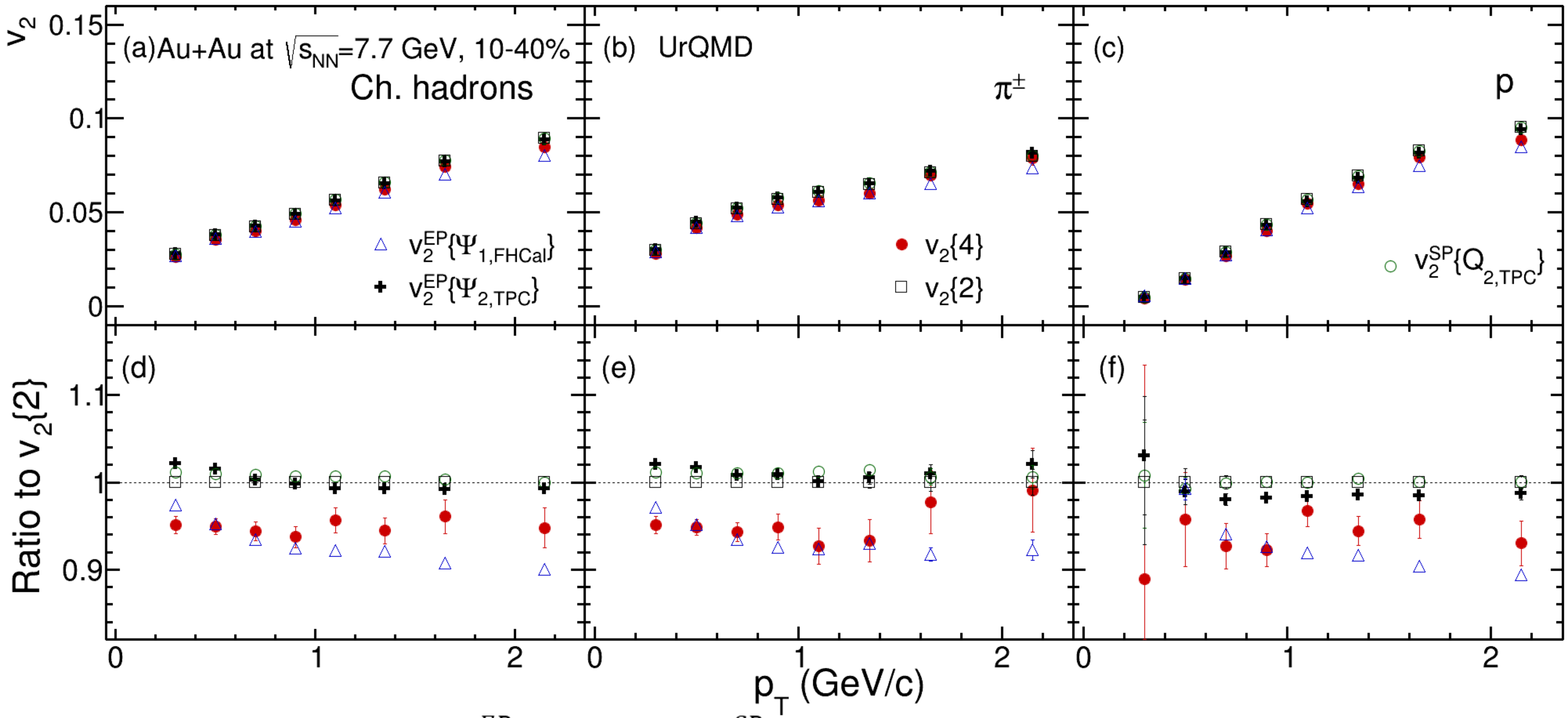
$$v_2^{EP}\{\Psi_{1,\mathrm{FHCal}}\} \approx \langle v_2 \rangle, v_2^{EP}\{\Psi_{2,\mathrm{TPC}}\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v_2}^2}{\langle v_2 \rangle} \qquad (3)$$

Star data: 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

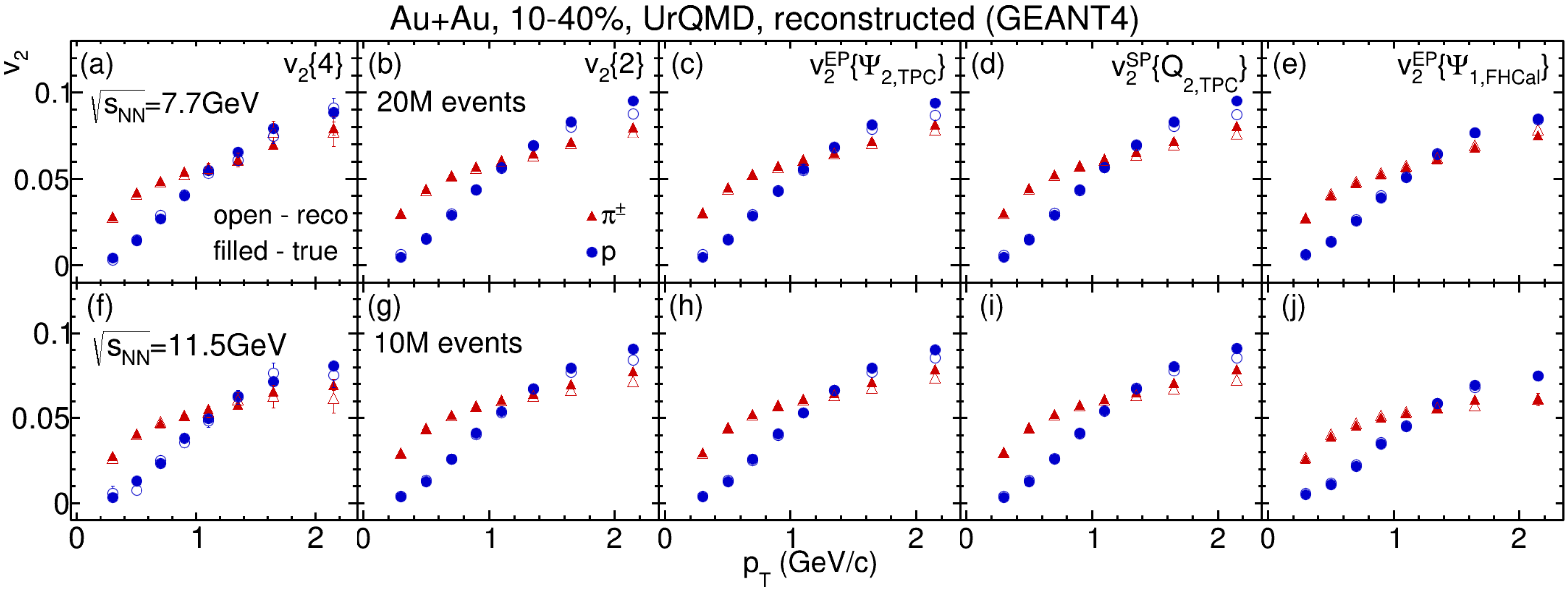
Comparison of v2 measurements using different method



$v_2\{2\}, v_2^{EP}\{\Psi_{2,\mathrm{TPC}}\}$ 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 v2 of pions and protons in MPD



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

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
- **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)

Backup

Setup, event and track selection

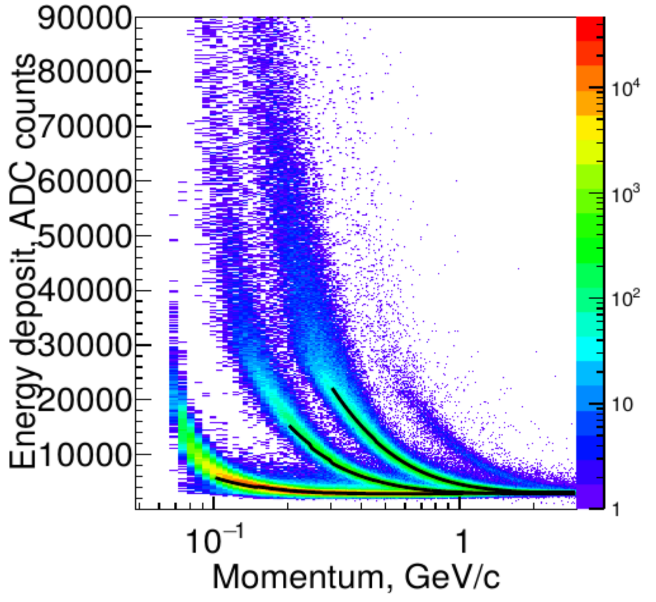
UrQMD → GEANT4 → Reconstruction → Flow analysis

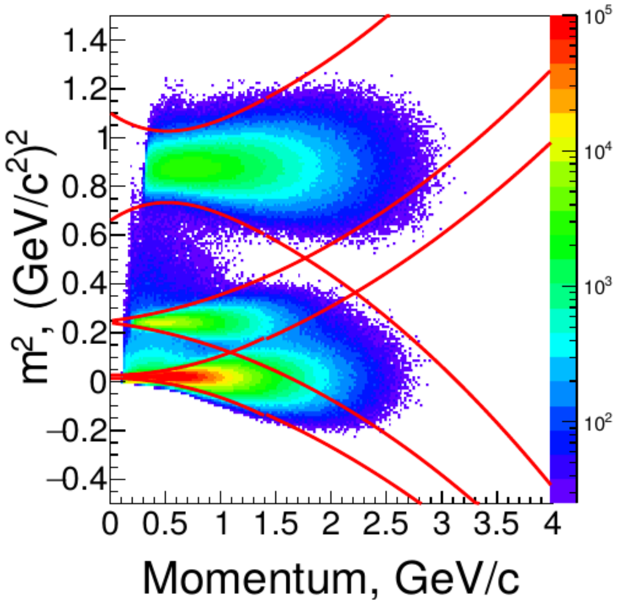
- Au+Au:
  - N_{events} = 10 M at $\sqrt{s_{NN}}$ = 4.5, 11.5 GeV
  - N_{events} = 20 M at $\sqrt{s_{NN}}$ = 7.7 GeV
- Bi+Bi:
  - N_{events} = 7 M at $\sqrt{s_{NN}}$ = 7.7 GeV

- TPC
- FHCal
- TOF
- …

Event classification:
- Track multiplicity
- FHCal energy

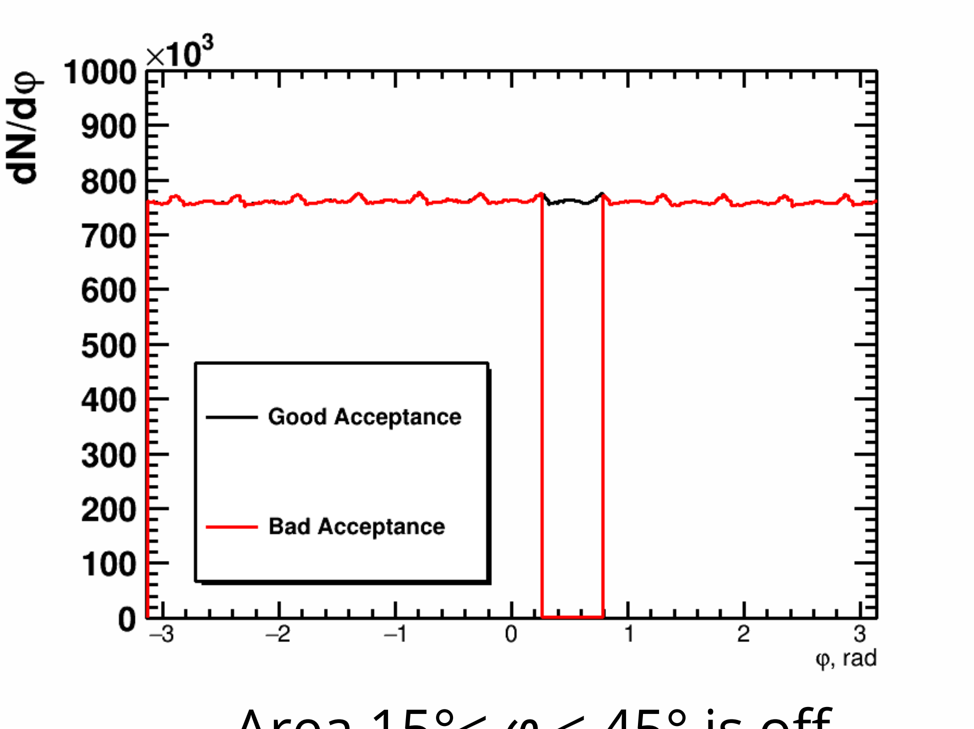
Track selection:
- Primary tracks
- $N_{TPC\ hits} > 16$
- $0.2 < p_T < 3$ GeV/c
- $|\eta| < 1.5$
- PID based on info from MC tracks



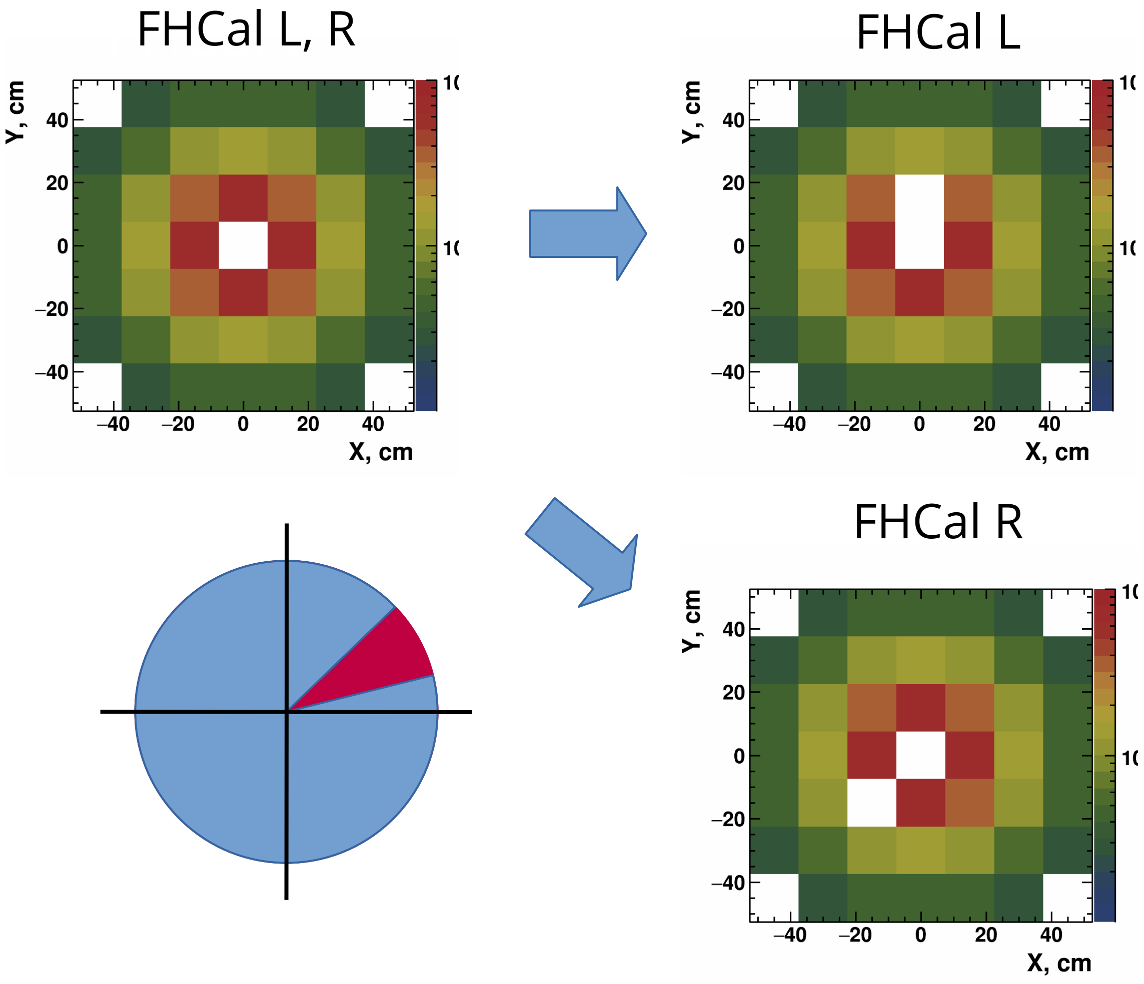


MPDRoot, August 2020

Non-uniform acceptance

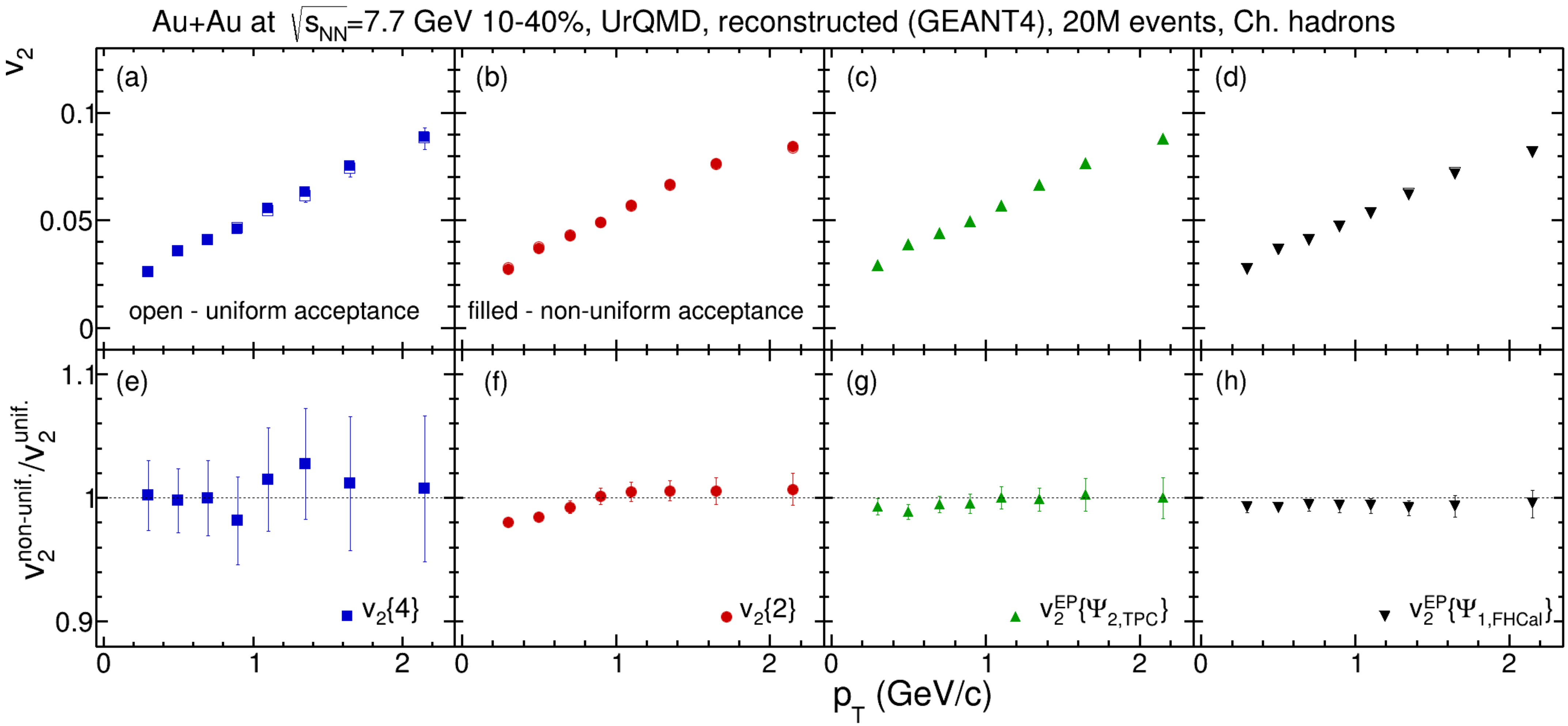


Area 15°< φ < 45° is off



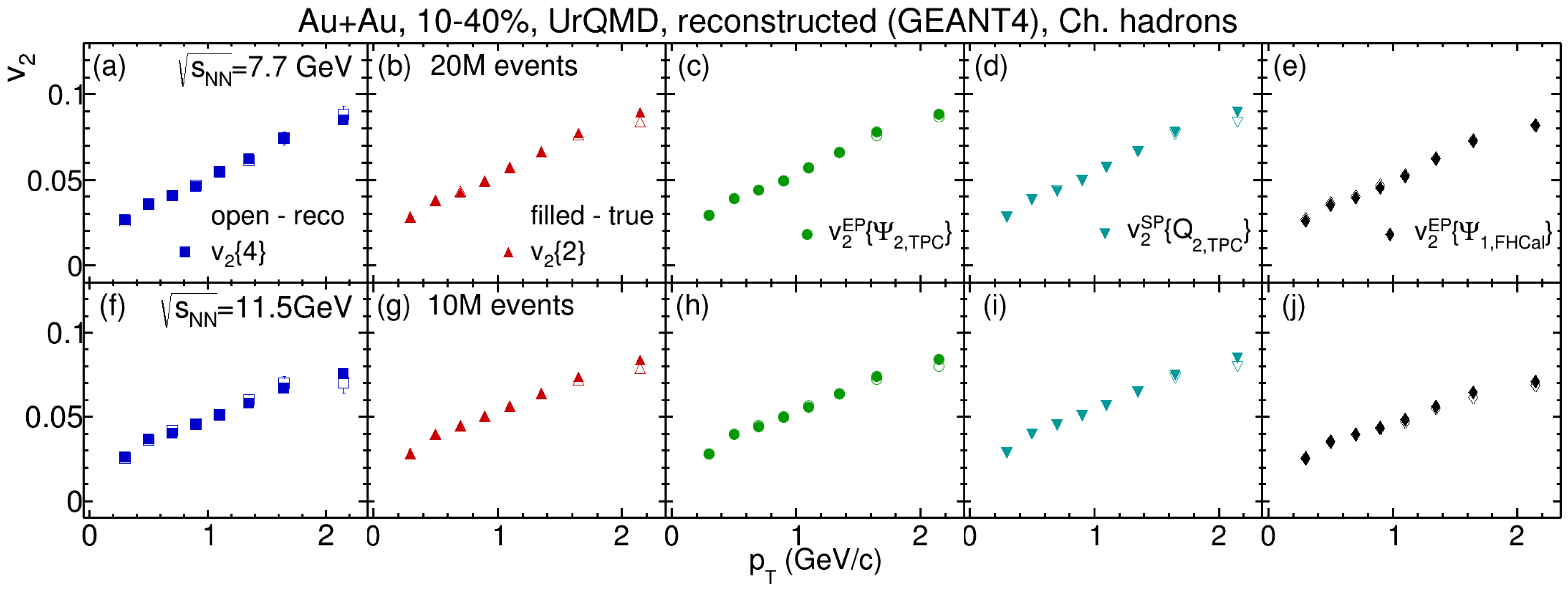
How robust the future measurements against non-uniform acceptance?

Acceptance correction



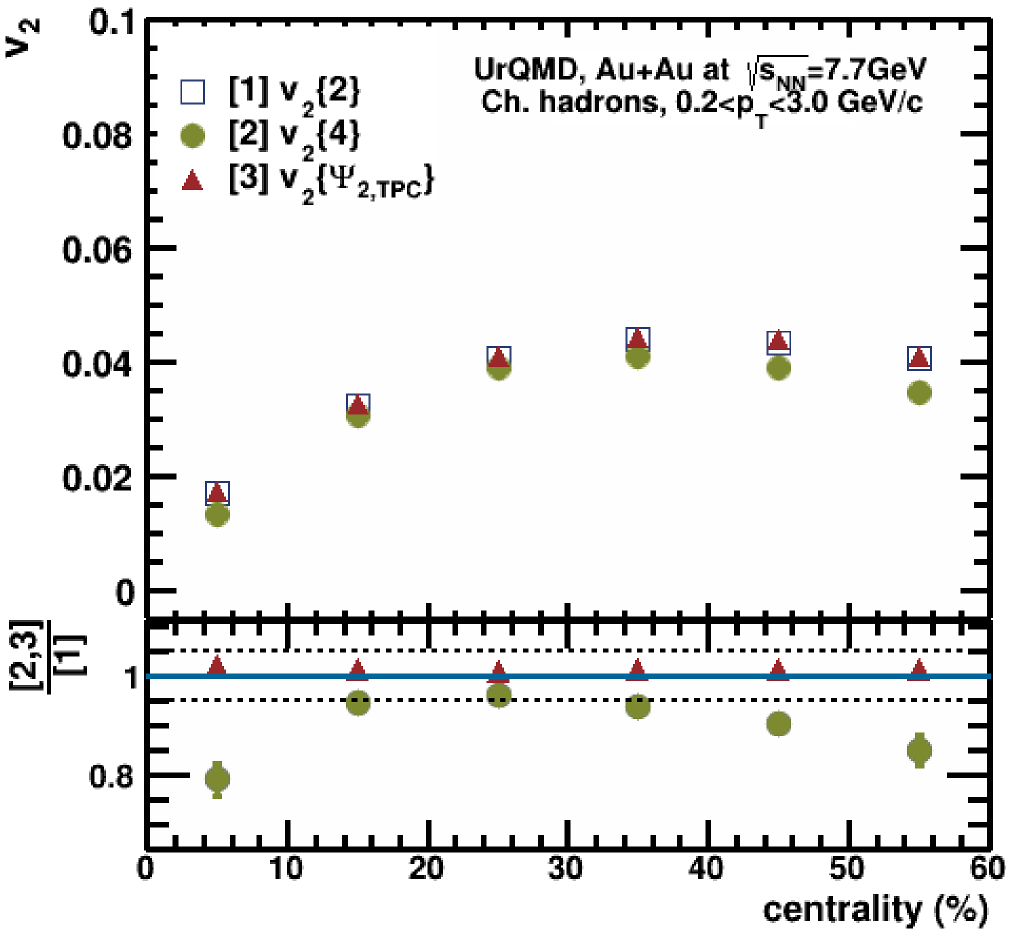
The applied acceptance corrections eliminated the influence of non-uniform acceptance

Performance study of v2 of inclusive charged hadrons in MPD



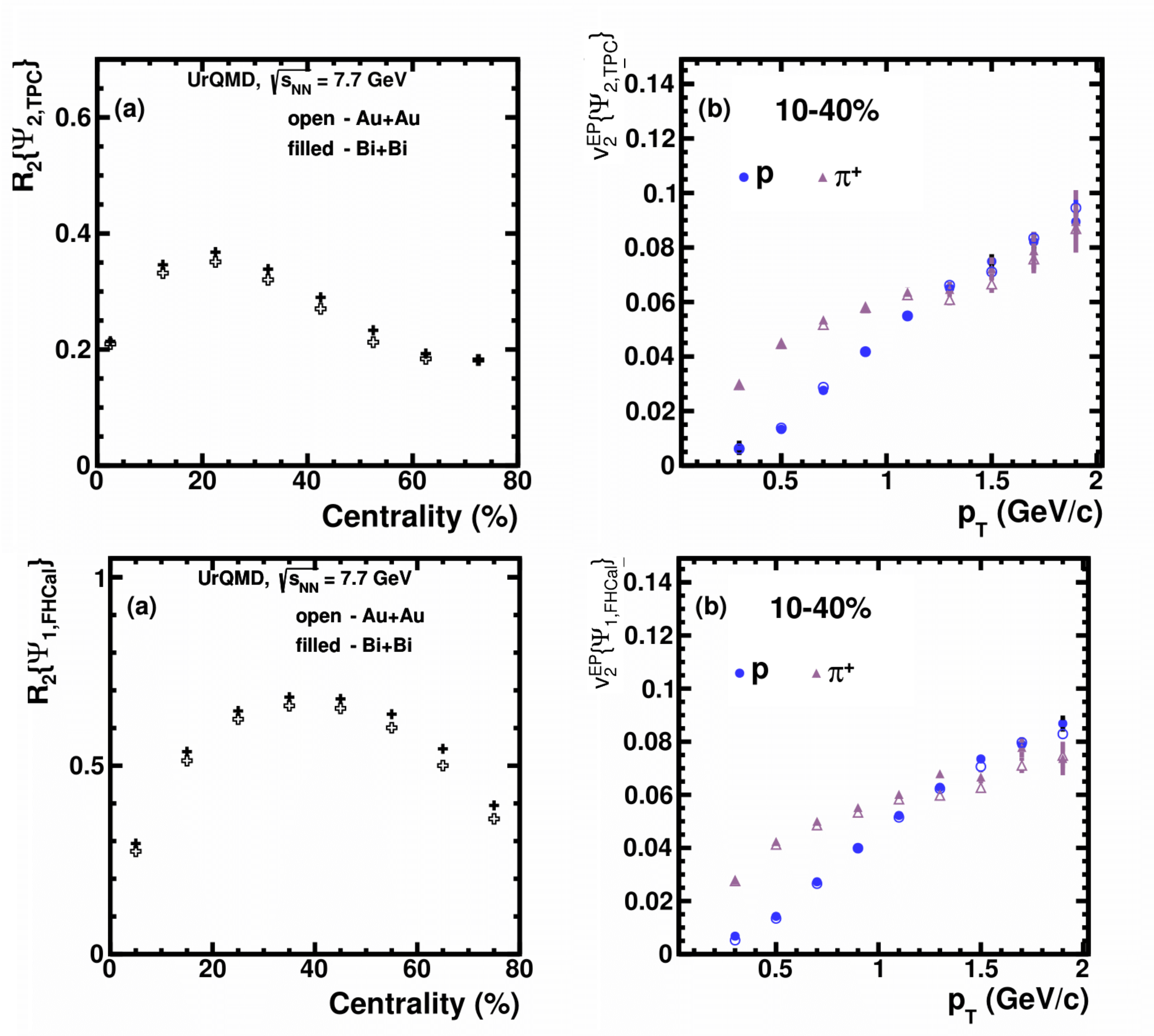
Reconstructed (reco) and generated (true) v_2 values are in a good agreement for all methods

Results from UrQMD model of Au+Au collisions at √sNN = 7.7 GeV



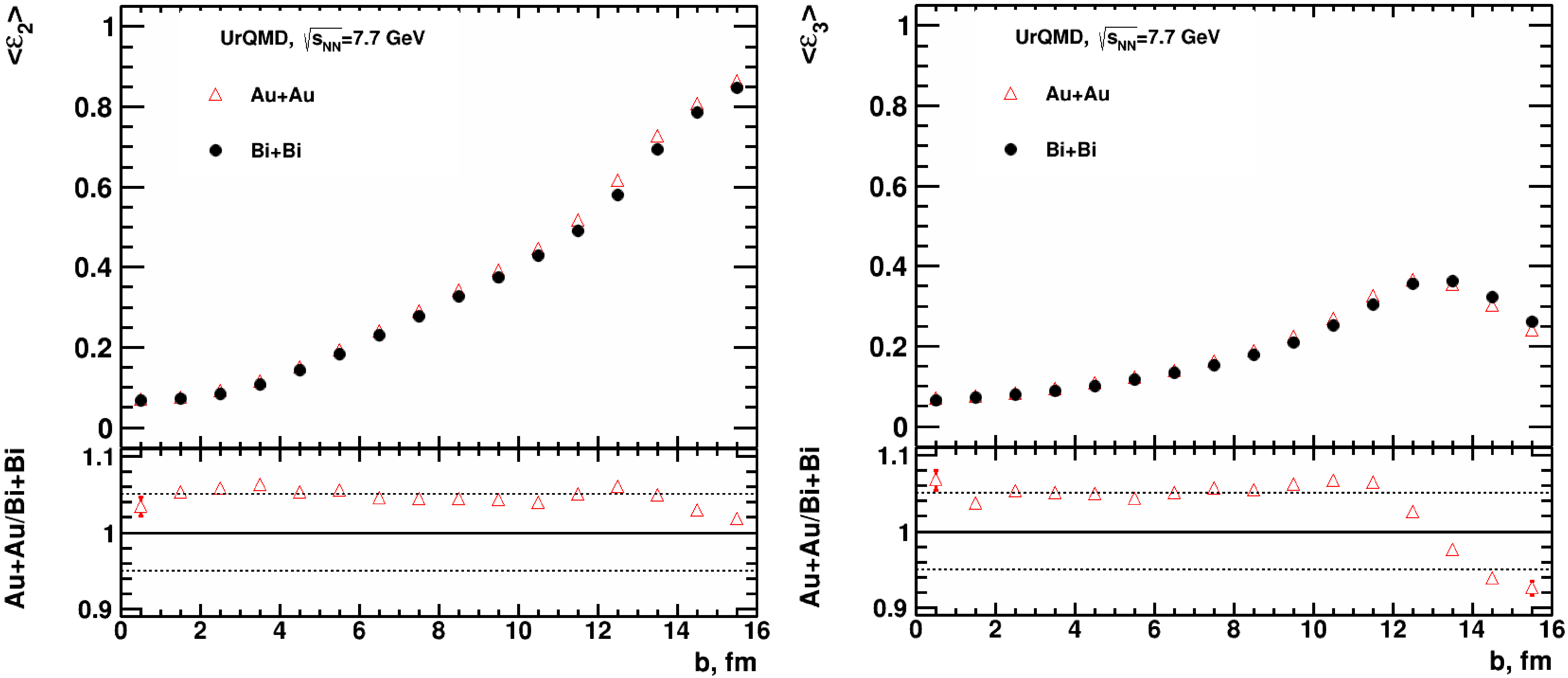
$v_2\{4\}$ is smaller than $v_2\{2\}$ due to fluctuations and non-flow

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



Expected small difference between colliding systems

Eccentricity: Bi+Bi vs Au+Au



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