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

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LXX International conference "NUCLEUS – 2020. Nuclear physics and elementary particle physics", 11-17 October 2020

This work is supported by:
the RFBR according to the research project No. 18-02-40086
the European Union's Horizon 2020 research and innovation program under grant agreement No. 871072
the Ministry of Science and Higher Education of the Russian Federation, Project "Fundamental properties of elementary particles and cosmology" No 0723-2020-0041

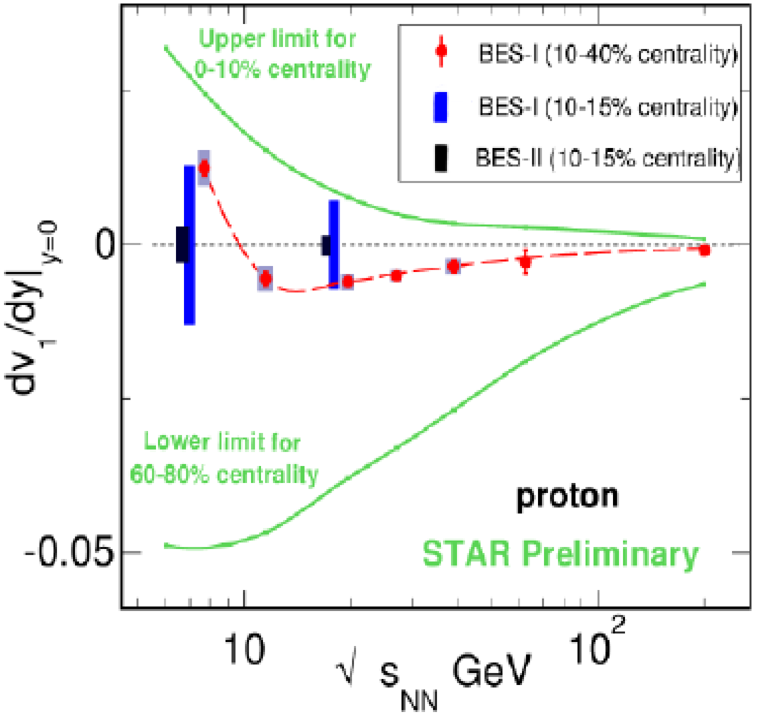
Outline

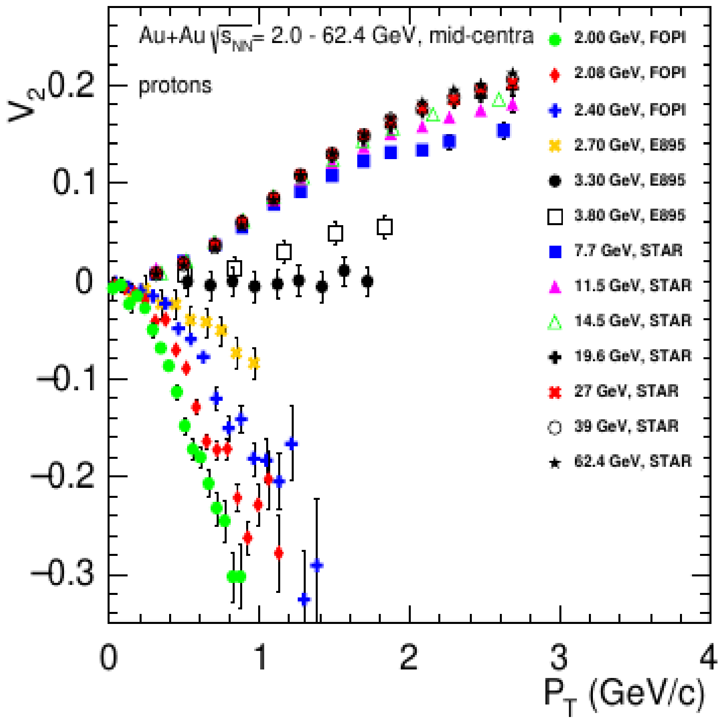
- Anisotropic flow at NICA energies
- MPD experiment at NICA
- Flow performance in MPD
  - Methods descriptions
  - Performance study for v_1 and v_2 using different methods
  - Au+Au vs. Bi+Bi comparison
- Summary and outlook

Anisotropic flow at NICA energies

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

v_1 – directed flow
v_2 – elliptic flow
v_3 – triangular flow

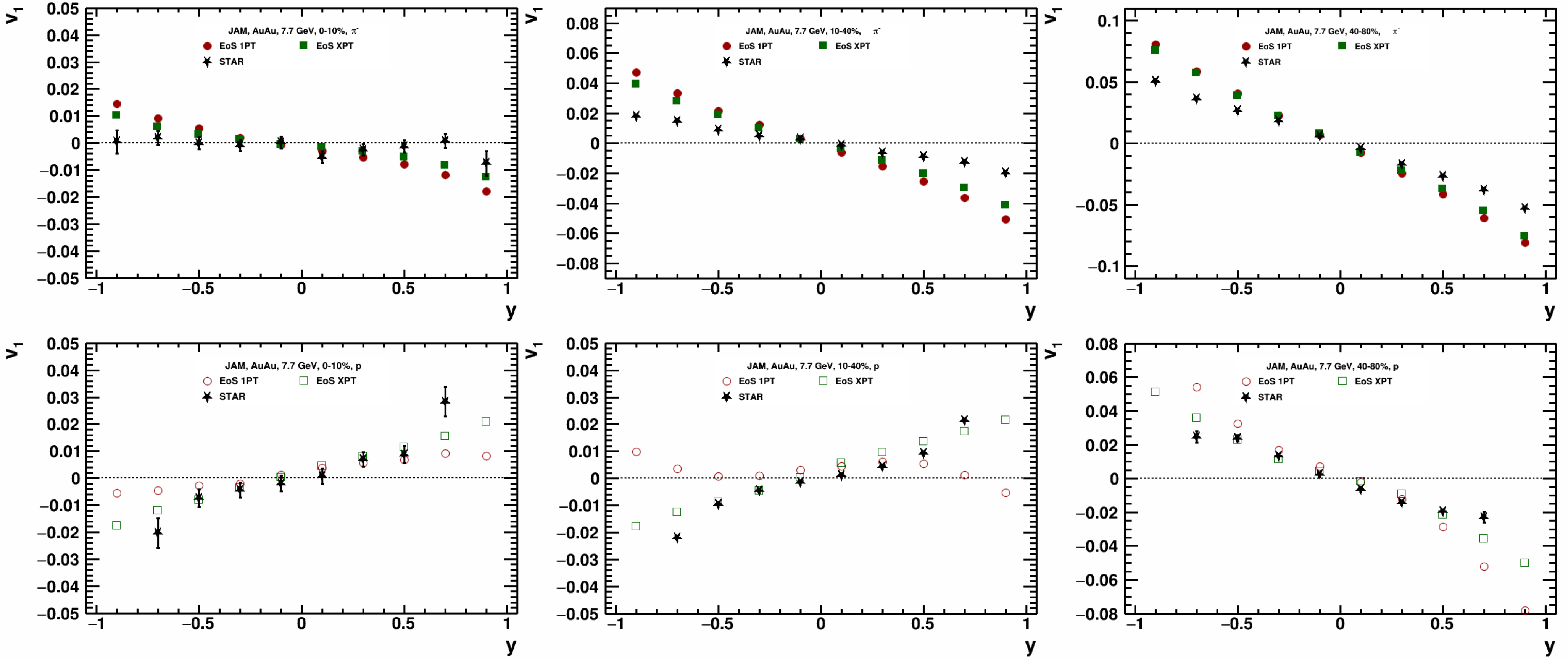




- Both directed and elliptic flow are sensitive to the transport properties of the dense matter produced in the HIC (EoS, η/s, c_s, etc.)
- Large passing time → strong spectator influence on flow signal

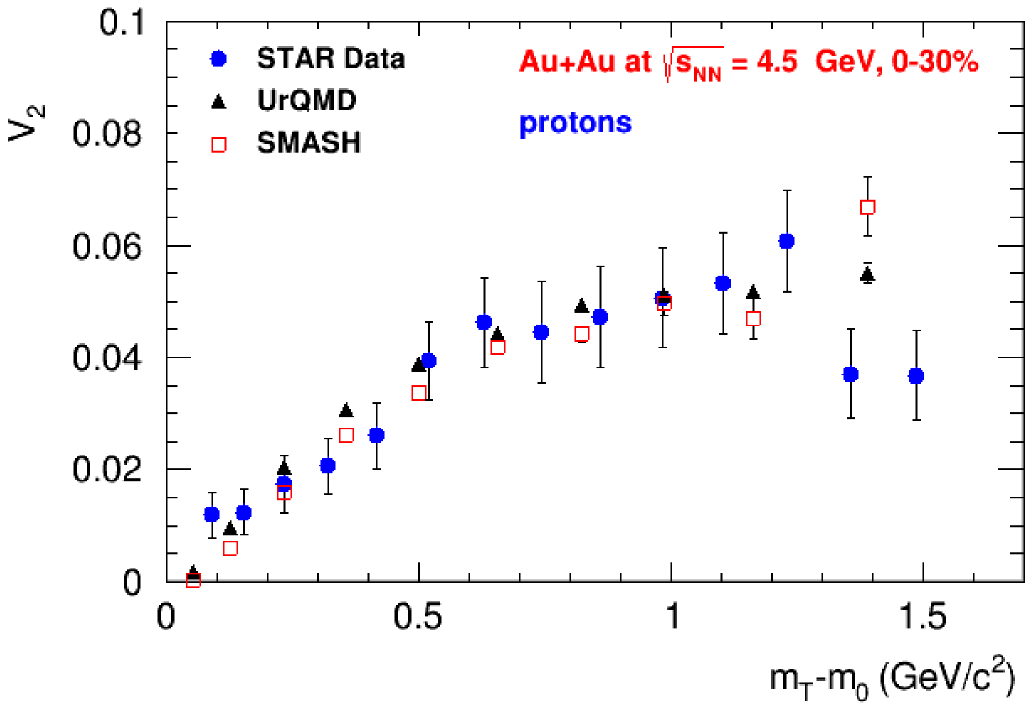
Rapidity dependence of directed flow: JAM EoS comparison

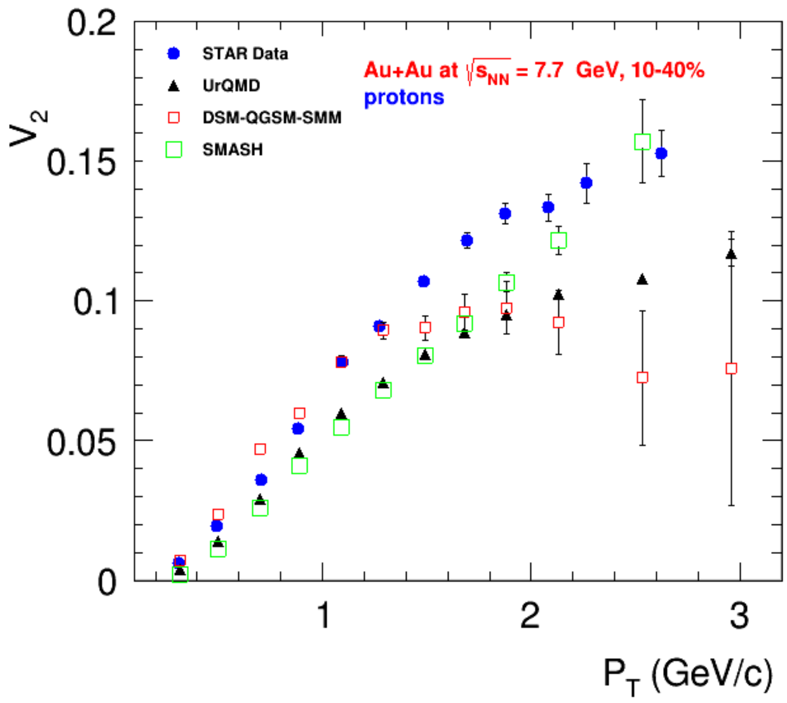
JAM model: http://www.aiu.ac.jp/~ynara/jam/, Phys. Rev. C 72 (2005) 064908; **STAR data:** Phys. Rev. Lett. 120 (2018) 62301



Directed flow is most sensitive to the EoS in mid-central collisions
Slope $dv_1/dy|_{y=0}$ changes dramatically with centrality for protons

Elliptic flow: beam-energy dependence

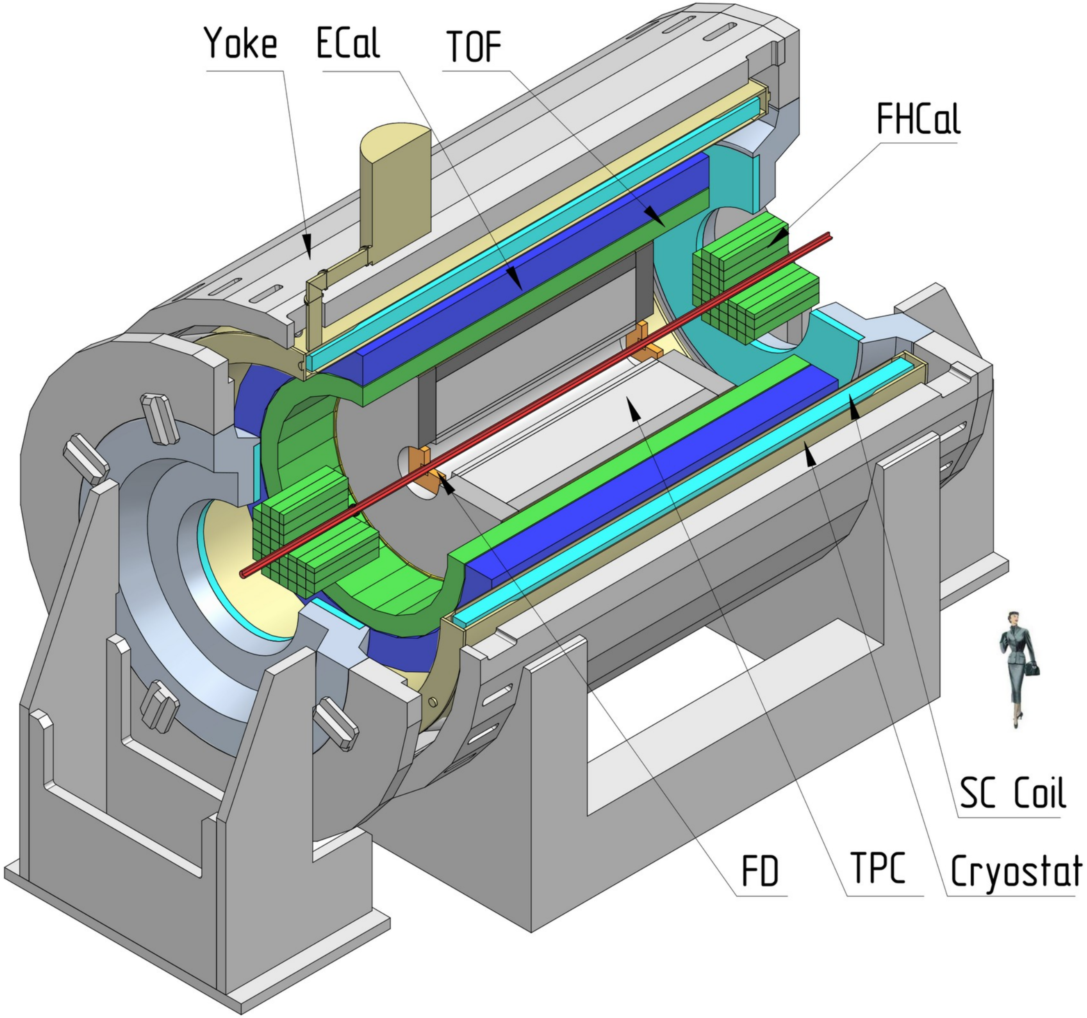




- **At $\sqrt{s_{NN}}$=4.5 GeV pure string/hadronic cascade models give similar v_2 signal compared to STAR data**
- **At $\sqrt{s_{NN}}$=7.7 GeV pure string/hadronic cascade models underpredict v_2**

Flow performance study at MPD (NICA)

Multi Purpose Detector (MPD)



EP plane

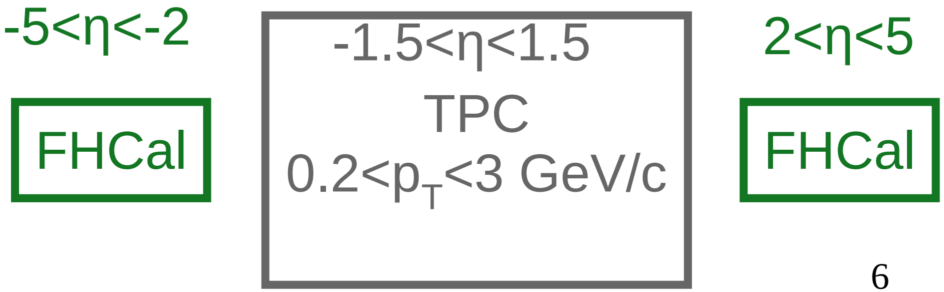
FHCal (2<|η|<5) or TPC (|η|<1.5)

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



Setup, event and track selection

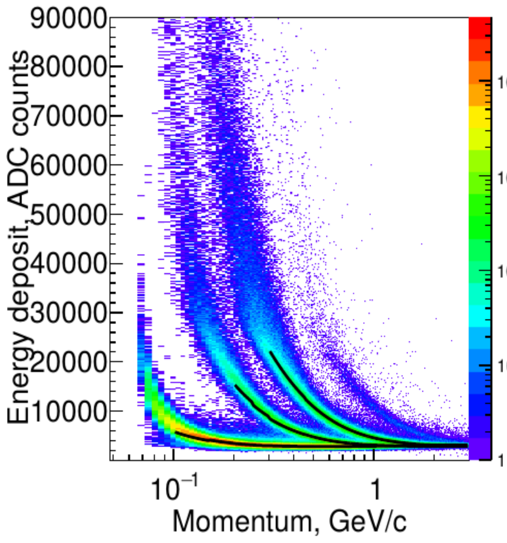
UrQMD → GEANT4 → Reconstruction → Flow analysis

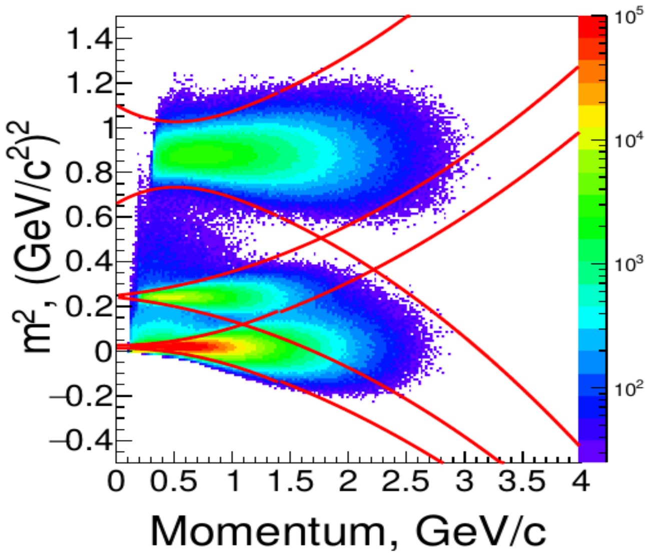
- Au+Au, N_{events}= 10 M events at $\sqrt{s_{NN}}$ = 4.5, 7.7 and 11 GeV
- Bi+Bi, N_{events}= 7 M events at $\sqrt{s_{NN}}$ = 7.7 GeV

GEANT4:
- 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, September 2020

Event plane method implementation in MPD (NICA)

$$Q_x^m = \frac{\sum \omega_i \cos(m\varphi_i)}{\sum \omega_i}, Q_y^m = \frac{\sum \omega_i \sin(m\varphi_i)}{\sum \omega_i}, \Psi_m^{EP} = \frac{1}{m} \mathrm{ATan2}(Q_y^m, Q_x^m)$$

FHCal EP: $m=1,\ \omega=E$

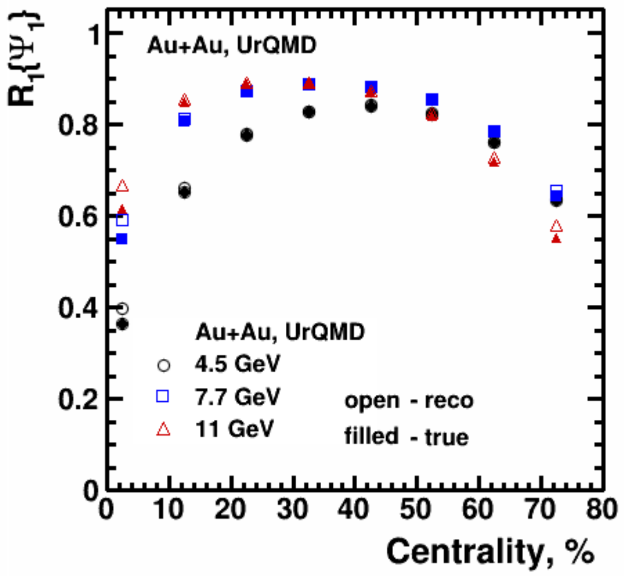
TPC EP: $m=2,\ \omega=p_T$

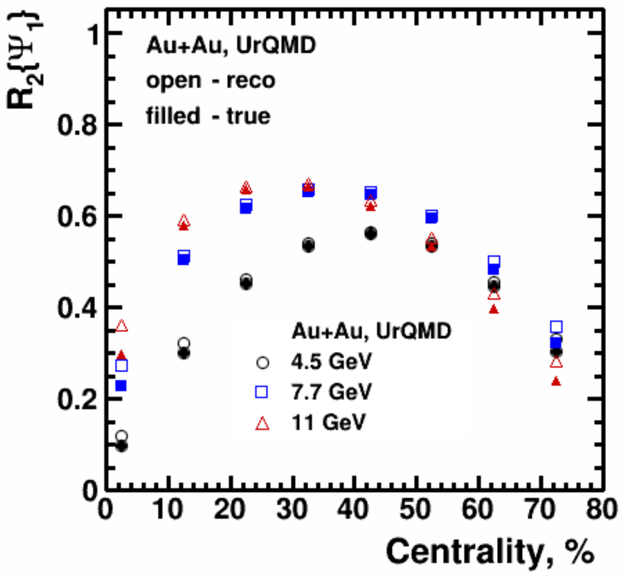
$$Res_n^2\{\Psi_m^{EP,L}, \Psi_m^{EP,R}\} = \langle \cos[n(\Psi_m^{EP,L} - \Psi_m^{EP,R})] \rangle$$

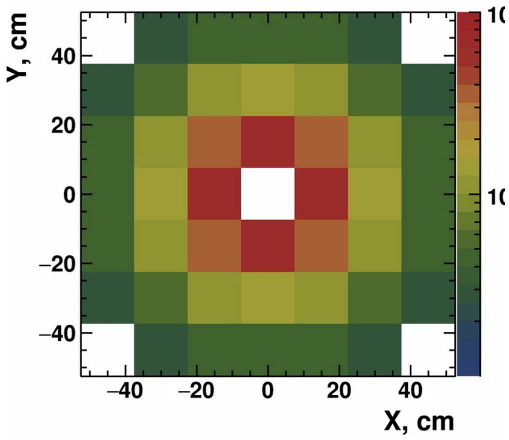
$$Res_n\{\Psi_m^{EP,true}\} = \langle \cos[n(\Psi_{RP} - \Psi_m^{EP})] \rangle$$

$$v_n = \frac{\langle \cos[n(\Psi_{RP} - \Psi_m^{EP})] \rangle}{Res_n\{\Psi_m^{EP,true}\}}$$

- Both FHCal and TPC detecors were used for EP:
  - Δη-gap>0.05 for TPC EP
  - Δη-gap>0.5 for FHCal EP







Energy distribution in FHCal

Direct cumulants method

Particle azimuthal moments:

$$\langle 2\rangle_n = \langle e^{in(\varphi_i-\varphi_j)}\rangle \approx v_n^2 + \delta_n$$

$$\langle 4\rangle_n = \langle e^{in(\varphi_i+\varphi_j-\varphi_k-\varphi_l)}\rangle \approx v_n^4 + 4v_n^2\delta_n + 2\delta_n^2$$

δ - is nonflow

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

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

Average over all events (RFP):

$$v_n\{2\}^2 = \langle\langle 2\rangle\rangle_n$$

$$v_n\{4\}^4 = 2\langle\langle 2\rangle\rangle_n^2 - \langle\langle 4\rangle\rangle_n$$

For exclusive region (POI):

$$v_n\{2'\} = \frac{\langle\langle 2'\rangle\rangle_n}{\sqrt{\langle\langle 2\rangle\rangle_n}}$$

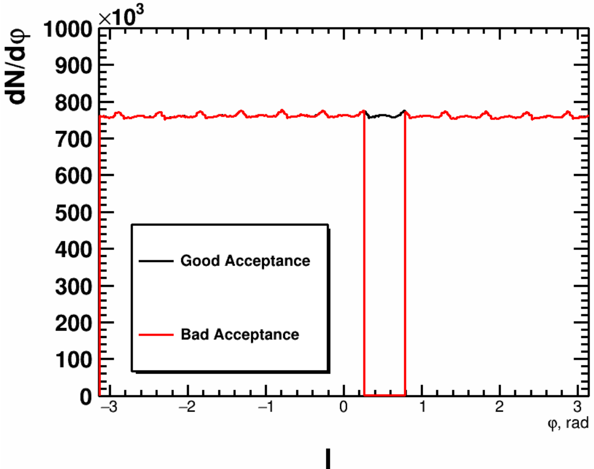
$$v_n\{4'\} = \frac{2\langle\langle 2'\rangle\rangle_n\langle\langle 2\rangle\rangle_n - \langle\langle 4'\rangle\rangle_n}{\left(2\langle\langle 2\rangle\rangle_n^2 - \langle\langle 4\rangle\rangle_n\right)^{3/4}}$$

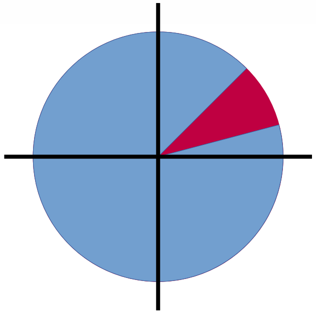
- Reference Flow Particle (RFP) – integrated flow over the event (centrality dependence)
- Particle Of Interest (POI) – differential flow (centrality, p_T, ...)

The method was introduced by Ante Bilandzic in Phys.Rev.C 83 (2011) 044913

Acceptance filter

TPC

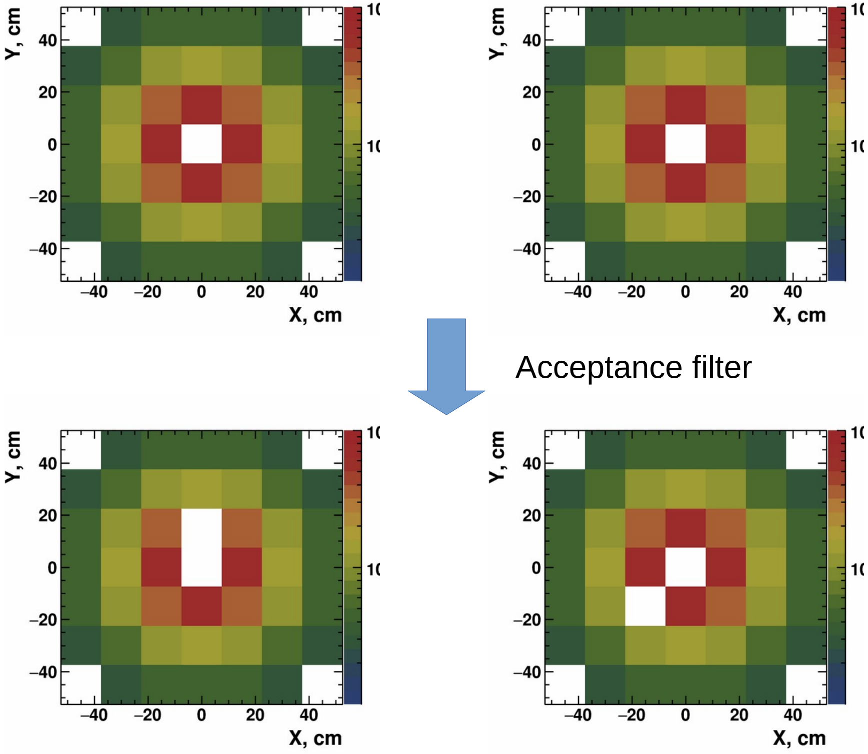




Area 15°< φ < 45° is off

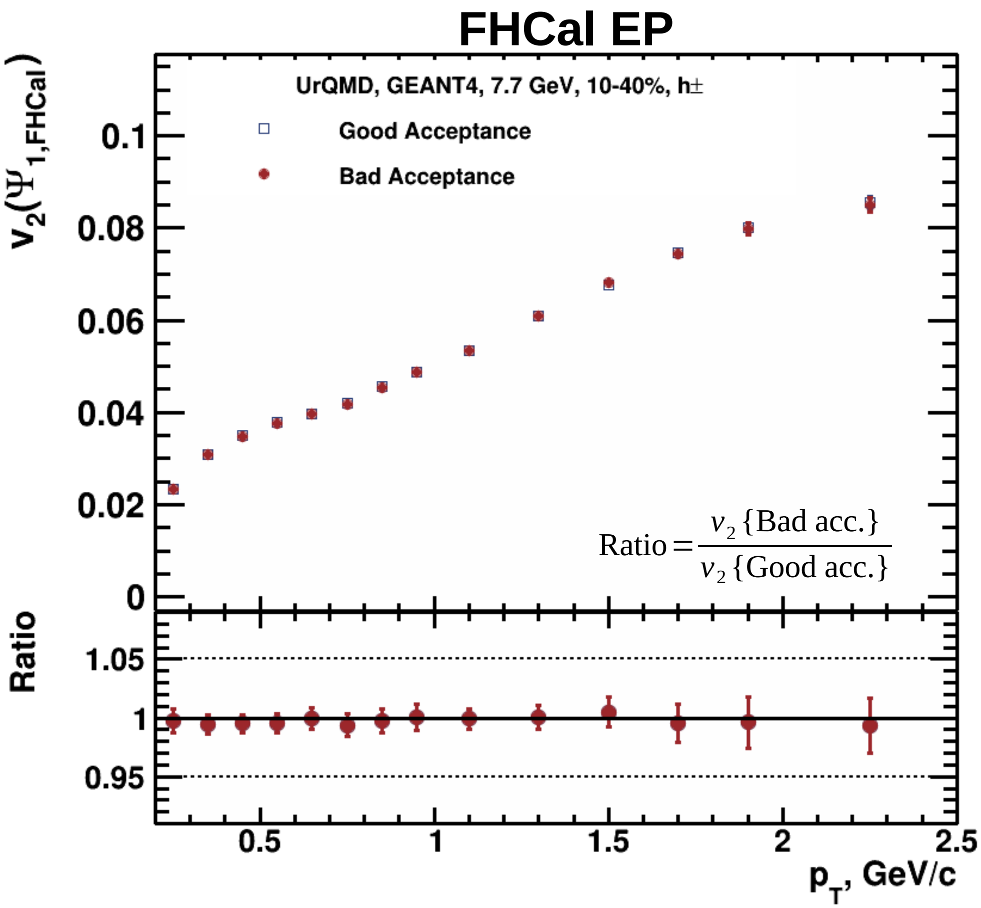
FHCal L

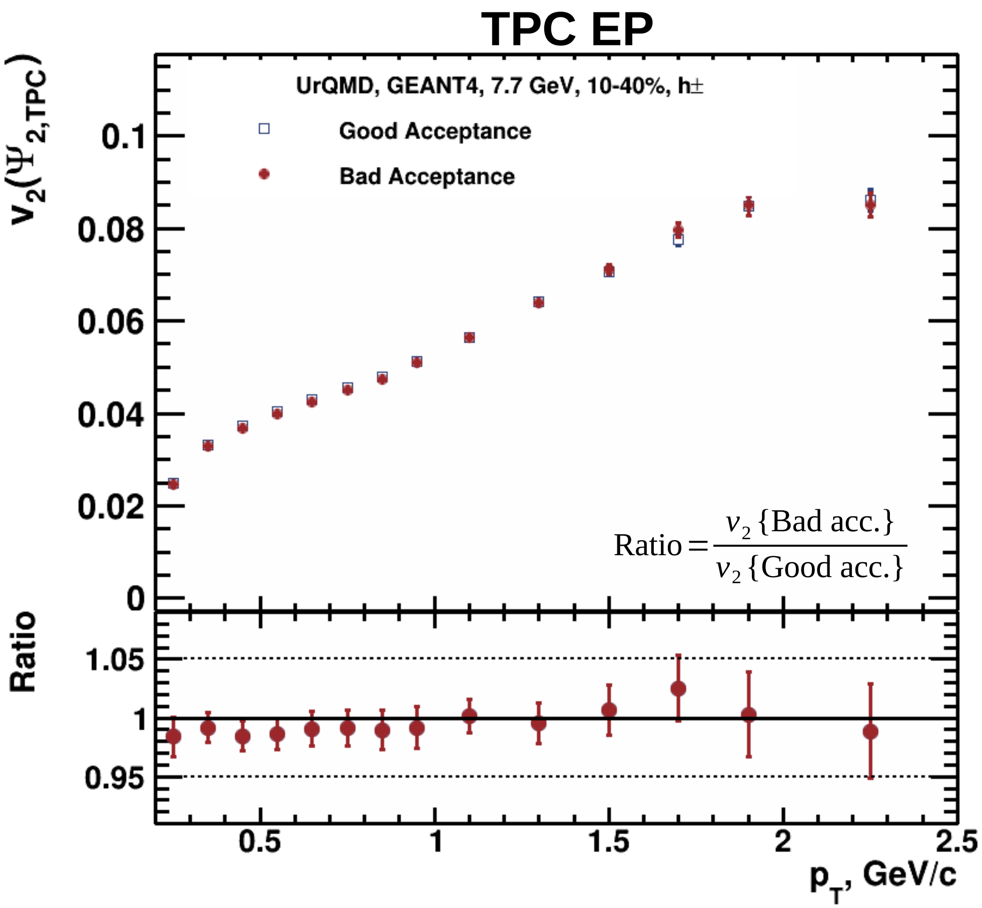
FHCal R



Modules 15 (L) and 28 (R) are off

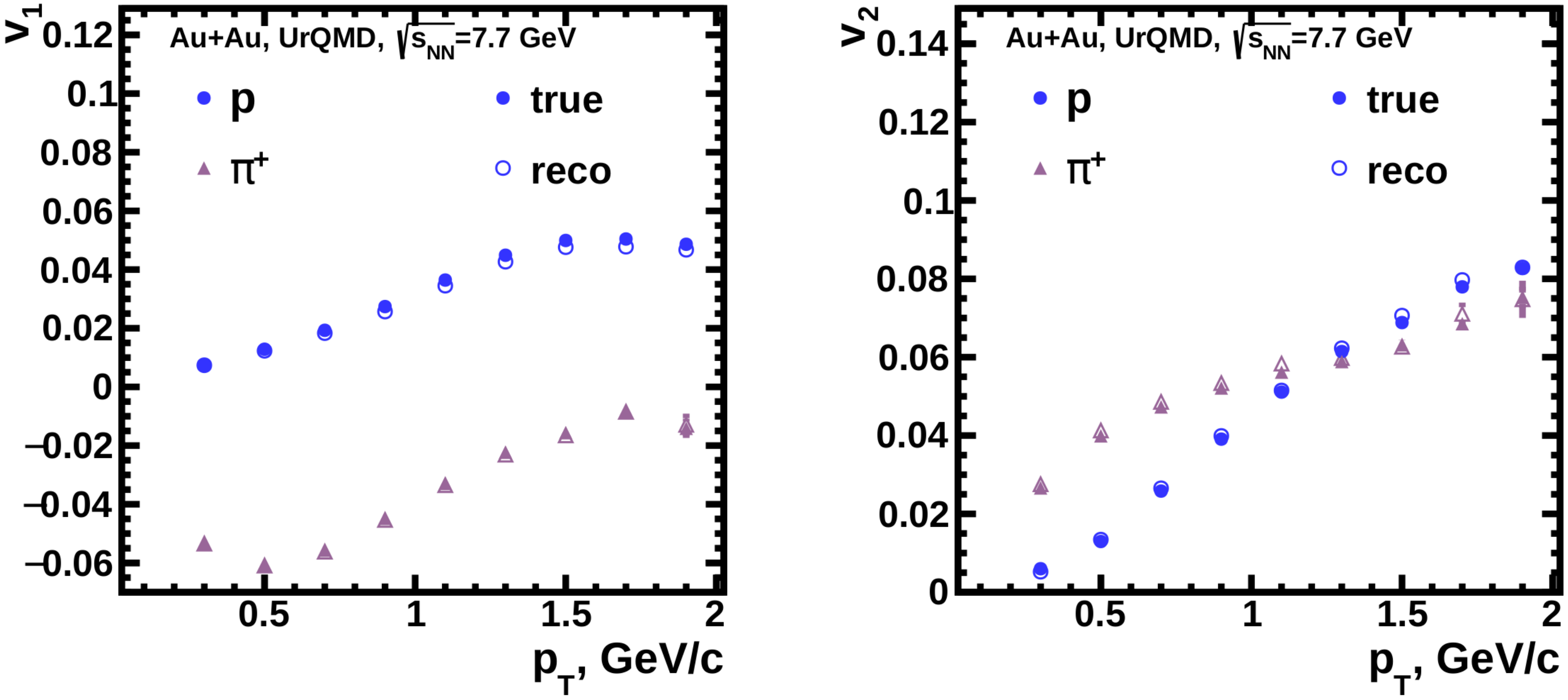
$v_2(p_T)$: check of corrections





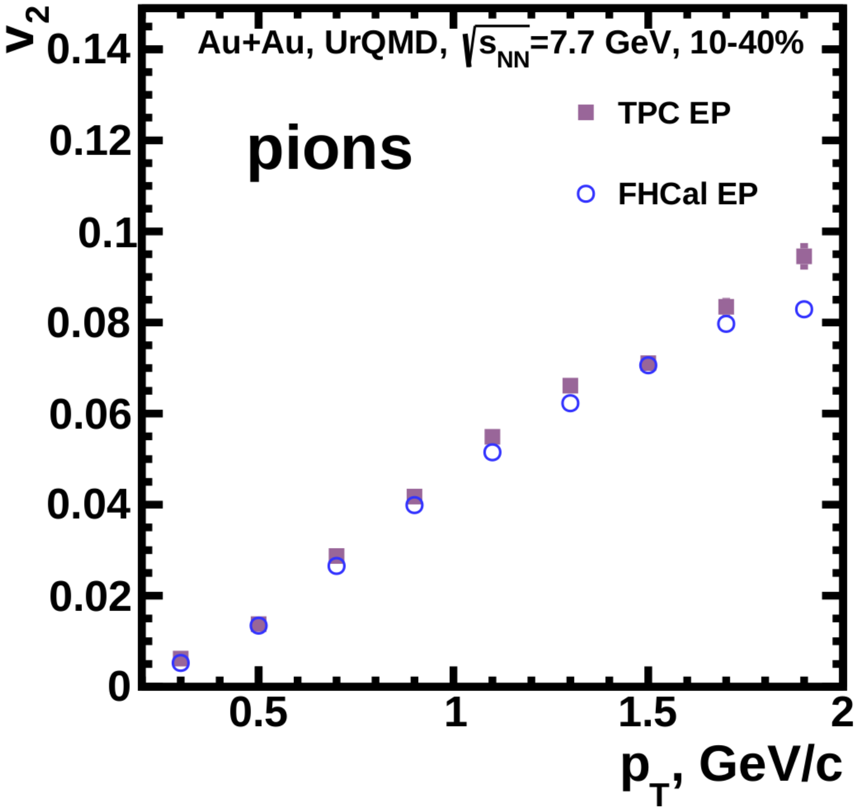
Good agreement with results for ideal (Good) acceptance

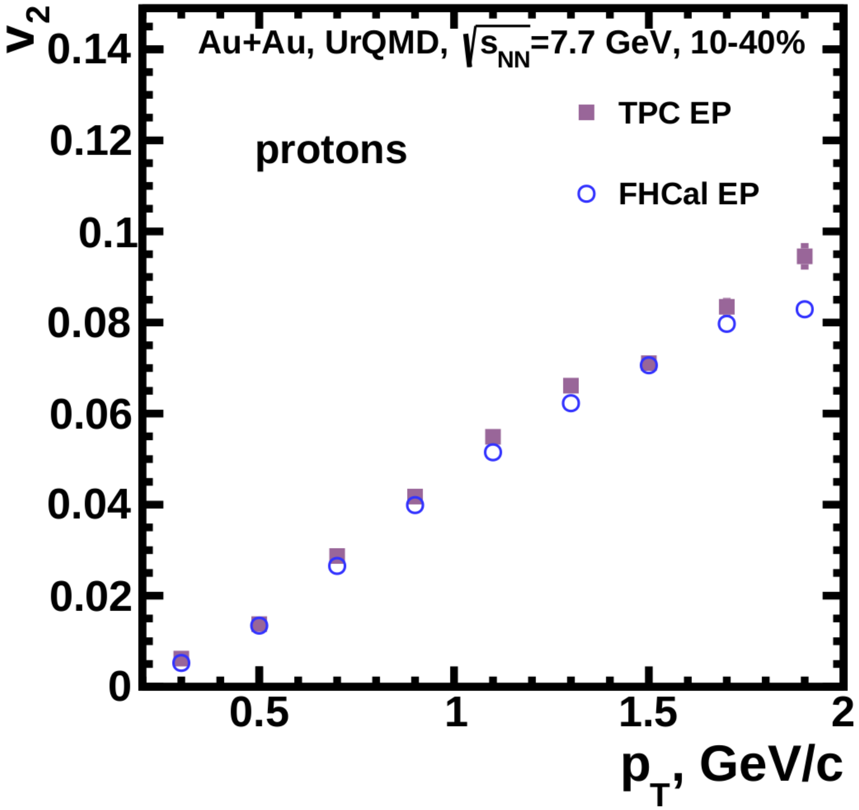
p_T-dependence of v_1 and v_2 of reconstructed signal



Both directed and elliptic flow results after reconstruction and resolution correction are consistent to that of MC simulation

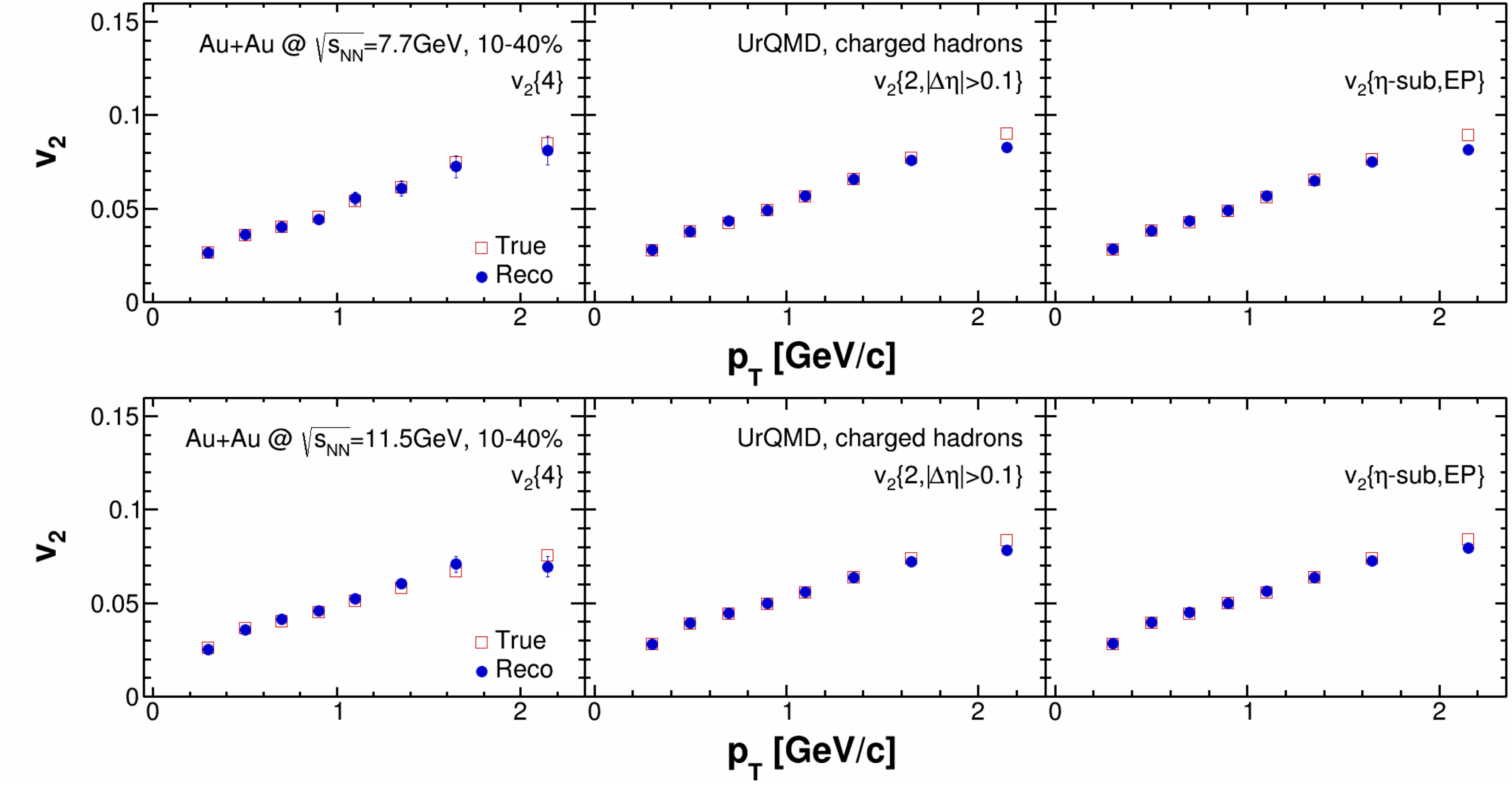
$v_2(p_T)$: FHCal EP vs TPC EP





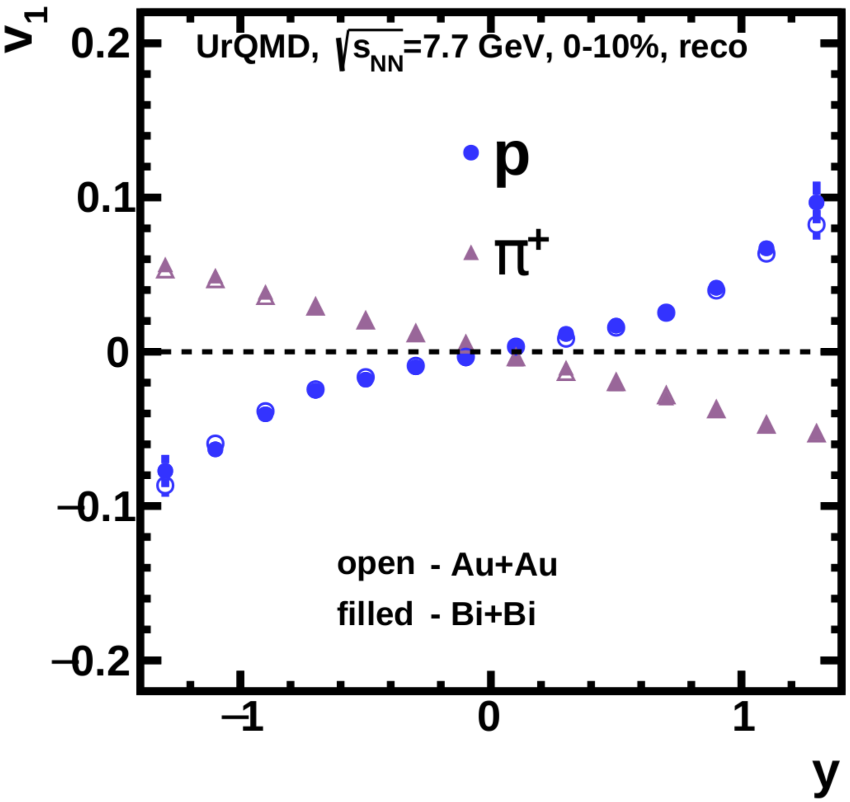
Expected small difference between v_2 measured with respect TPC ($\Psi_{2,EP}$) and FHCal ($\Psi_{1,EP}$)

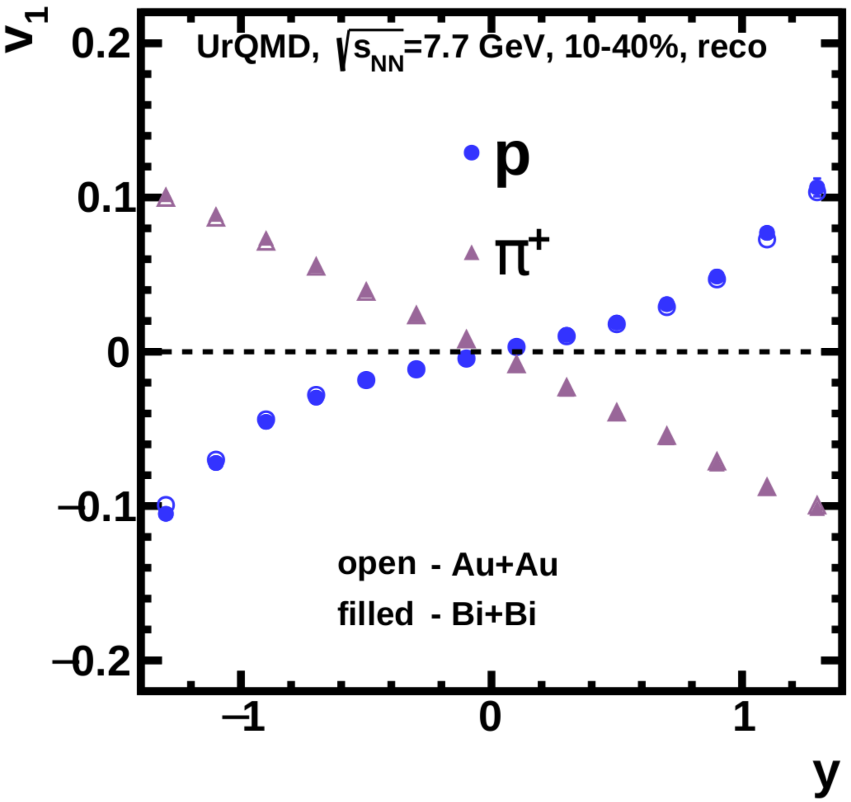
Direct cumulant measurements in MPD (NICA)



Elliptic flow results using direct cumulant and EP methods after reconstruction are consistent to that of MC simulation

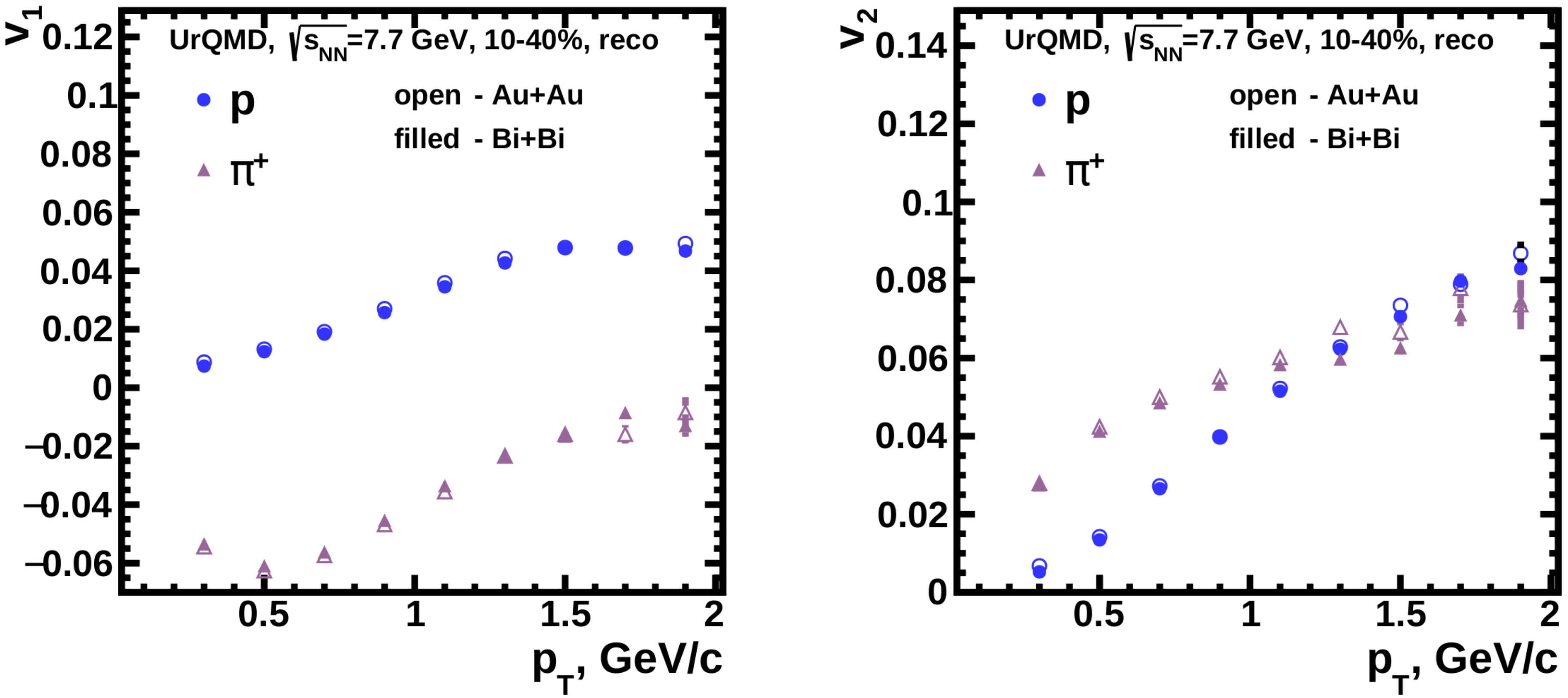
$v_1(y)$: Bi+Bi vs Au+Au





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

$v_n(p_T)$: Bi+Bi vs Au+Au



Expected small difference for v1 and v2 for particles produced in Au+Au and Bi+Bi collisions.

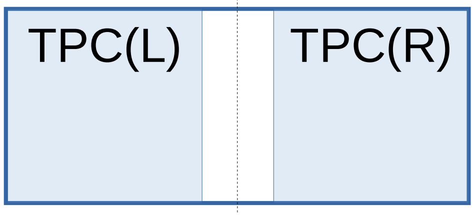
Summary

- Comparison of models with STAR data shows that at NICA energy range:
  - Slope $dv_1/dy|_{y=0}$ of protons changes sign with centrality
  - v_2 shows non-monotonic growth with increasing beam energy (from $\sqrt{s_{NN}}$ = 4.5 to 7.7 GeV)
- Full reconstruction chain was implemented in MPD:
  - Combined particle identification based on TPC and TOF
  - Realistic hadronic simulation (GEANT4)
  - Corrections allow us to perform flow measurements even with non-uniform acceptance
- Reconstructed v_1, v_2 are in an agreement with MC generated data for both event plane and direct cumulant methods
- v_1 and v_2 show small difference between Au+Au and Bi+Bi collisions

Thank you for your attention!

Backup

$v_2(p_T)$: EP vs. SP methods



-1.5 < η < -0.05   0.05 < η < 1.5

Left TPC half $(\eta < -0.05) \rightarrow \eta_-$

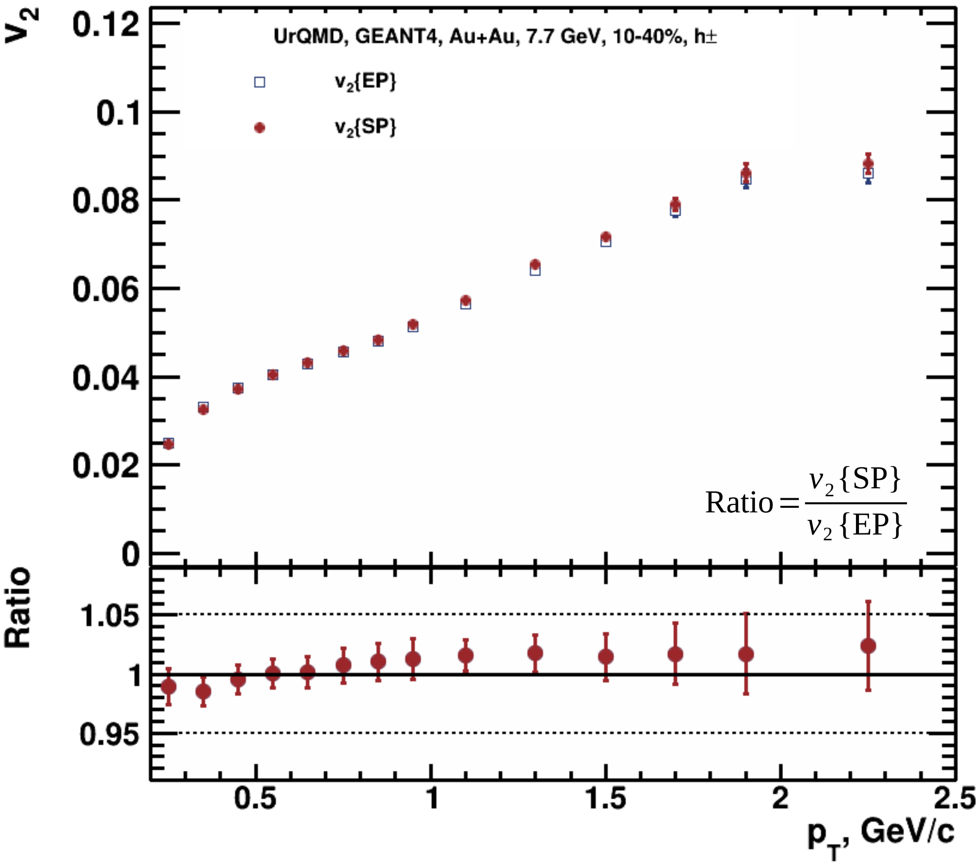
Right TPC half $(\eta > 0.05) \rightarrow \eta_+$

Event Plane (EP):

$$v_2\{EP\} = \frac{\langle \cos[2(\varphi_{\eta\pm} - \Psi_{2,\eta\mp})] \rangle}{\sqrt{\langle \cos[2(\Psi_{2,\eta+} - \Psi_{2,\eta-})] \rangle}}$$

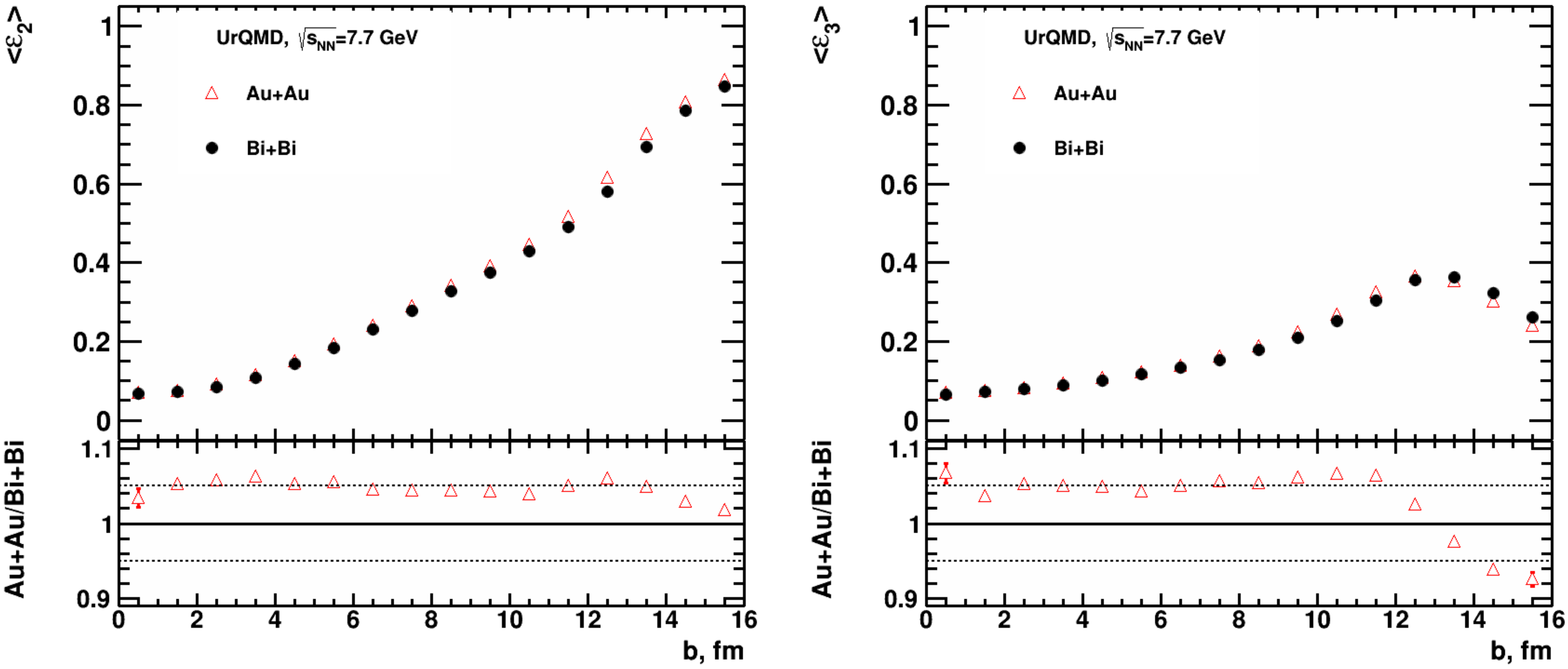
Scalar Product (SP):

$$v_2\{SP\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp} \rangle}{\sqrt{\langle Q_{2,\eta-} Q^*_{2,\eta+} \rangle}}, \quad u_2 = e^{i(2\varphi)}, \quad Q_2 = \sum_k^{k_{\text{tracks}}} u_{2,k}$$



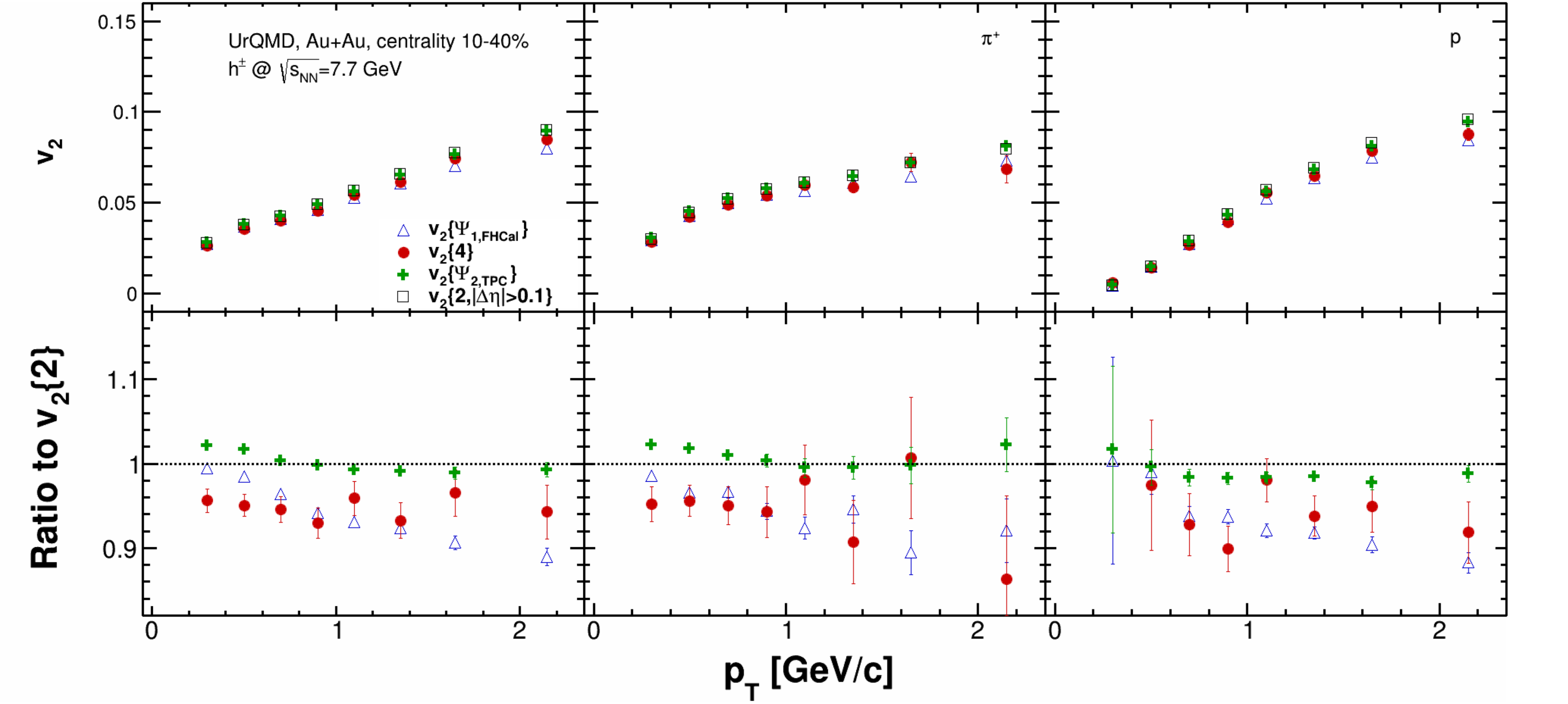
Good agreement between Event Plane and Scalar Product methods

Eccintricity: Bi+Bi vs Au+Au



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

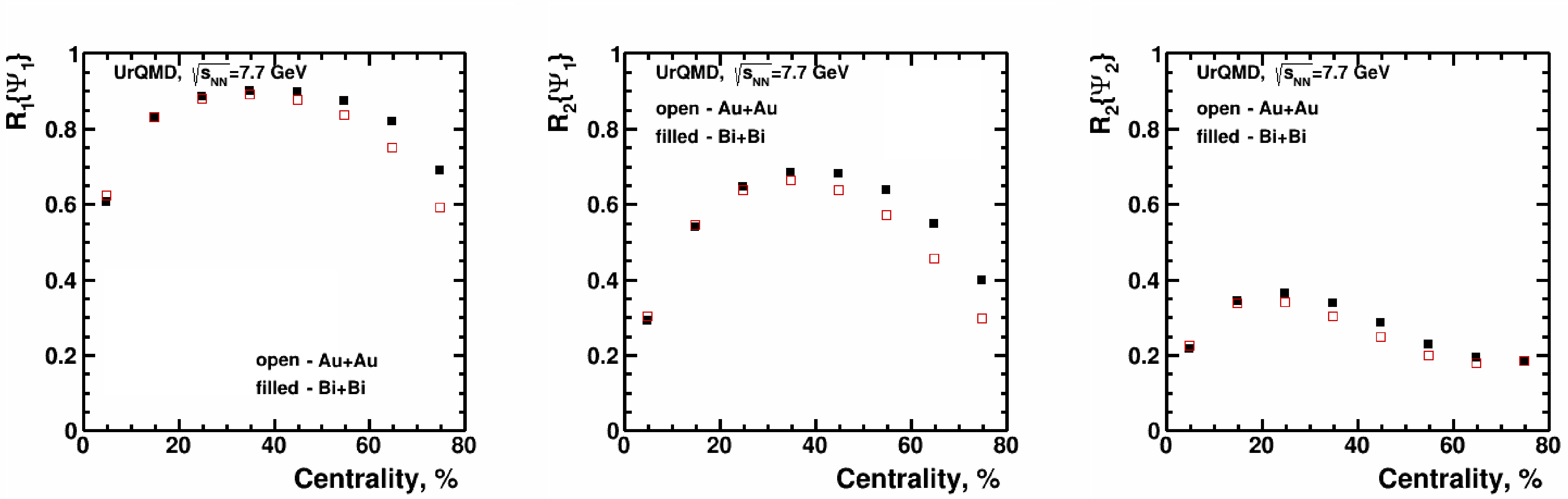
Direct cumulants in MPD



$v_2\{2\}$ and $v_2(\Psi_{2,EP})$ are in a good agreement

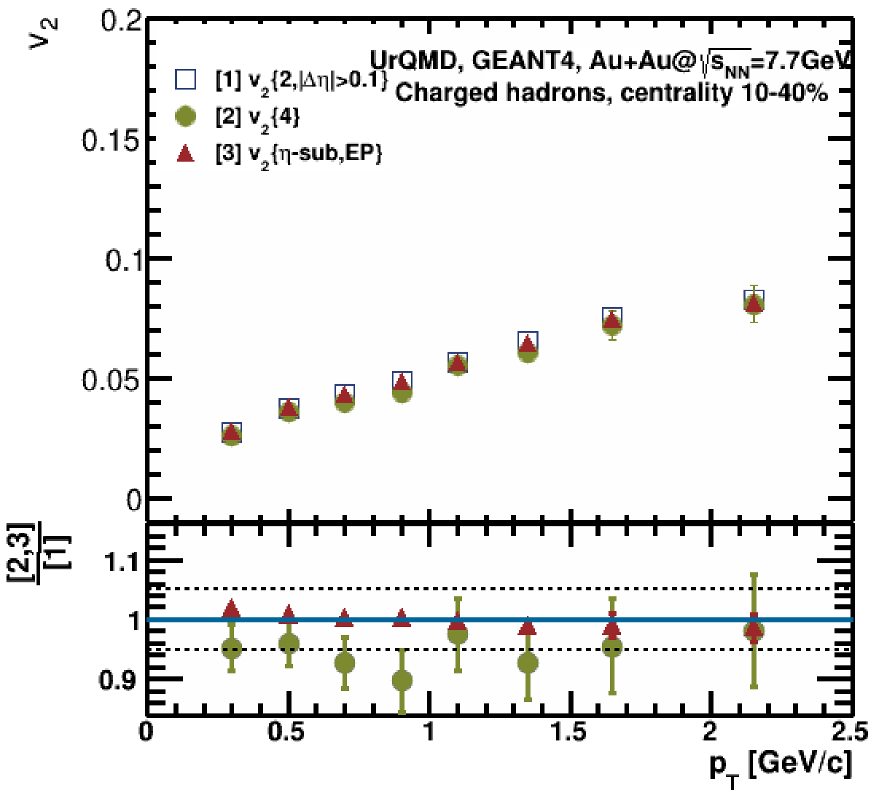
$v_2\{4\}$ and $v_2(\Psi_{1,EP})$ are smaller compared to $v_2\{2\}$ due to fluctuations and nonflow

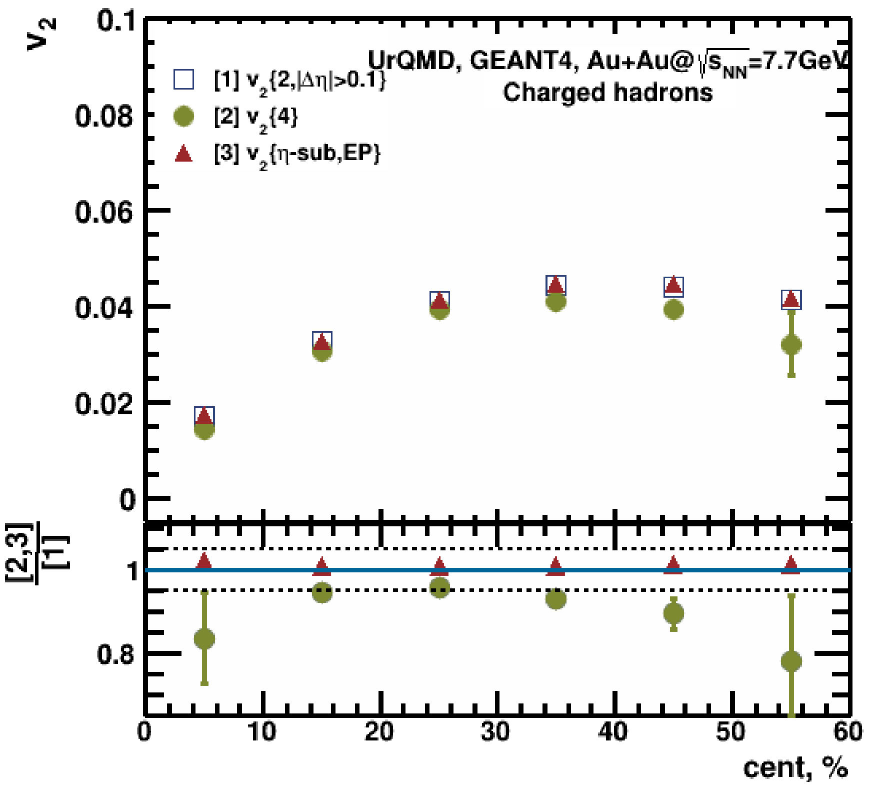
EP Resolution: Bi+Bi vs Au+Au



Expected small difference between EP resolutions for Au+Au and Bi+Bi

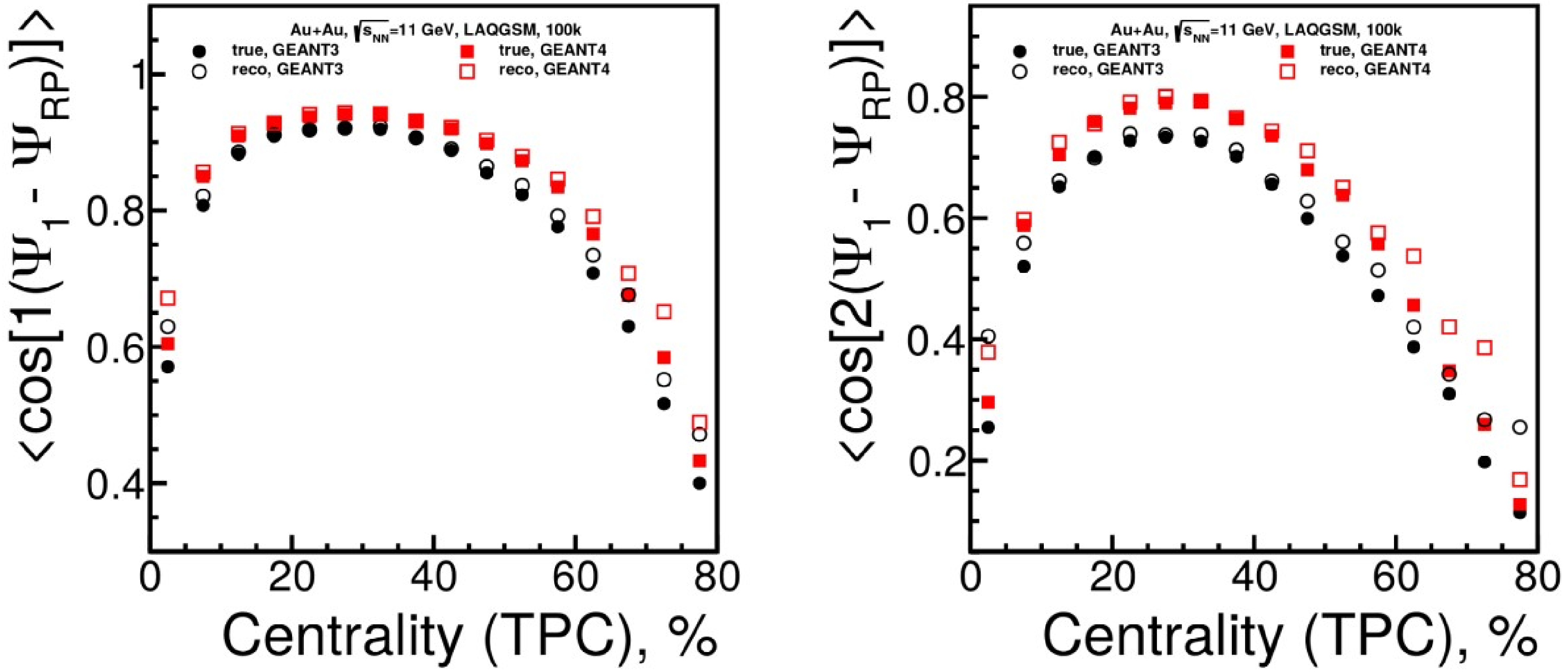
Direct cumulant measurements in MPD (NICA)





- **$v_2\{2\}$ and $v_2(\Psi_{2,EP})$ are in a good agreement**
- **$v_2\{4\}$ is smaller compared to $v_2\{2\}$ and $v_2(\Psi_{2,EP})$**

Resolution correction factor: GEANT3 vs GEANT4 comparison



GEANT4 has more realistic hadronic shower simulation
In the future: use models with fragments in the spectator area