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

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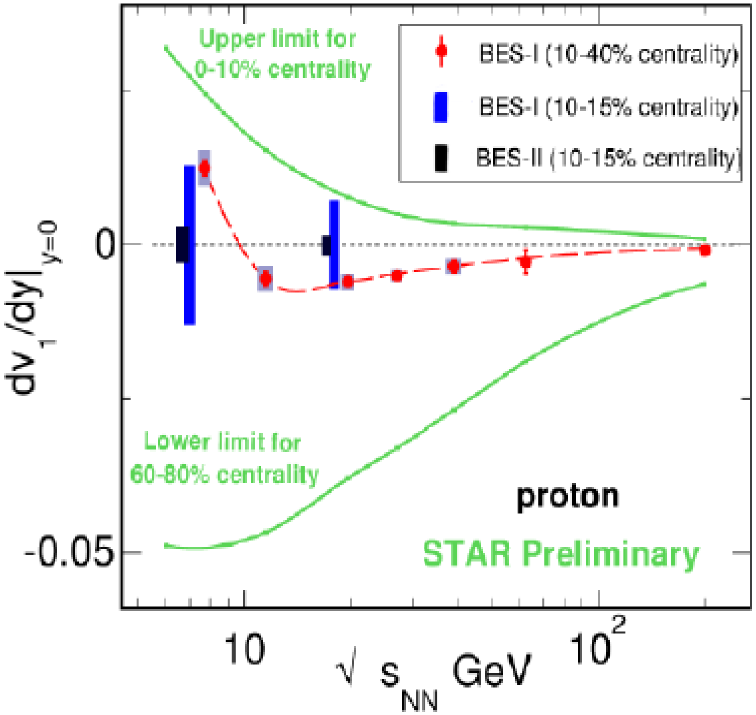
Outline

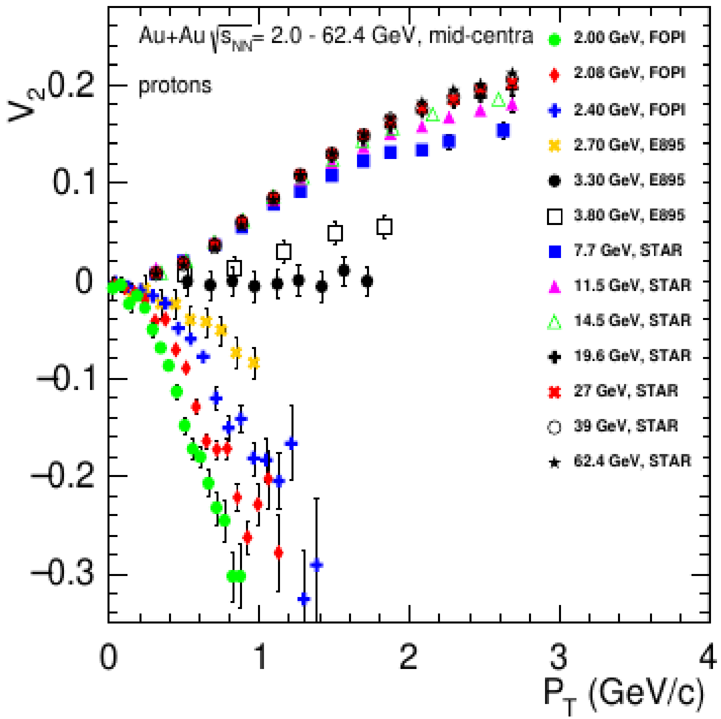
- Anisotropic flow at NICA energies
- MPD experiment at NICA
- Flow performance in MPD
  - Methods descriptions
  - Performance study for v_1 and v_2 using different methods
  - Au+Au vs. Bi+Bi comparison
- Summary and outlook

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

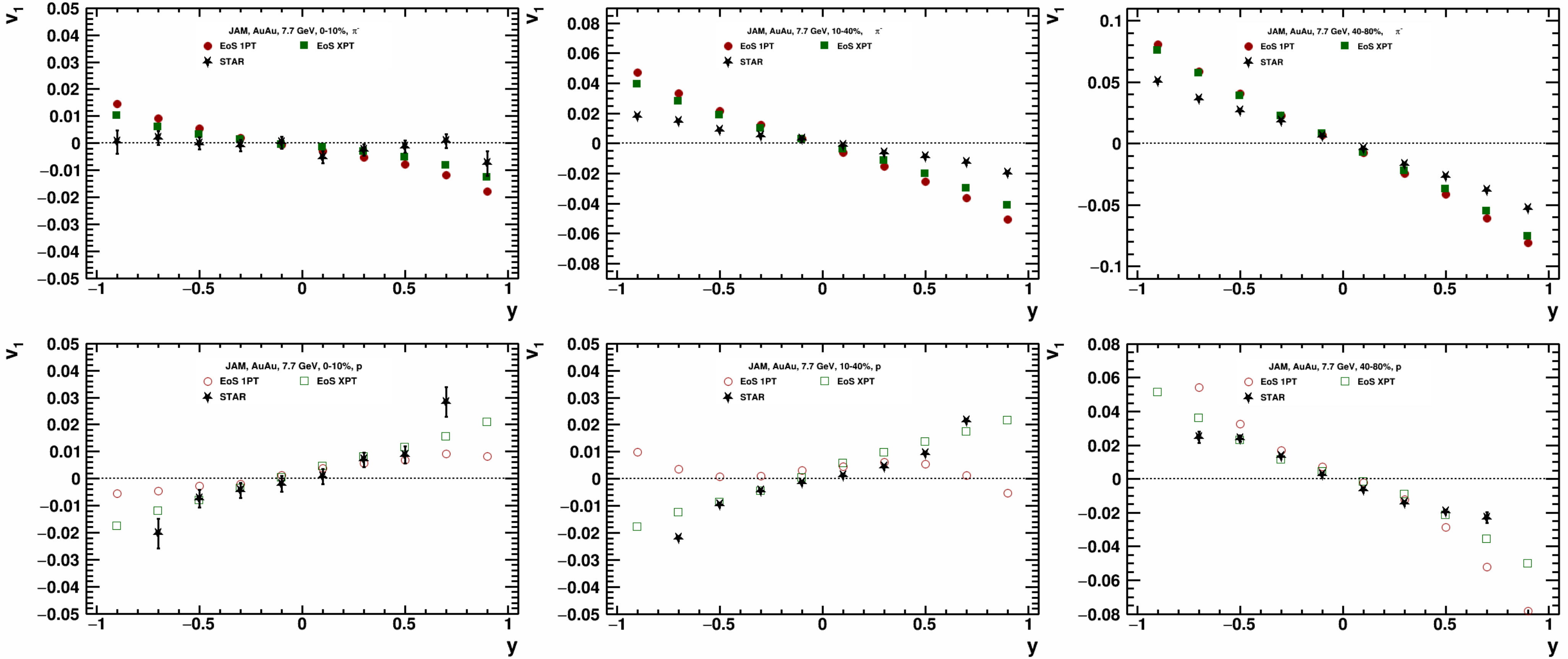




- Both directed and elliptic flow are sensitive to the transport properties of the dense matter produced in the HIC (EoS, η/s, c_s, etc.)
- Large passing time → strong spectator influence on flow signal

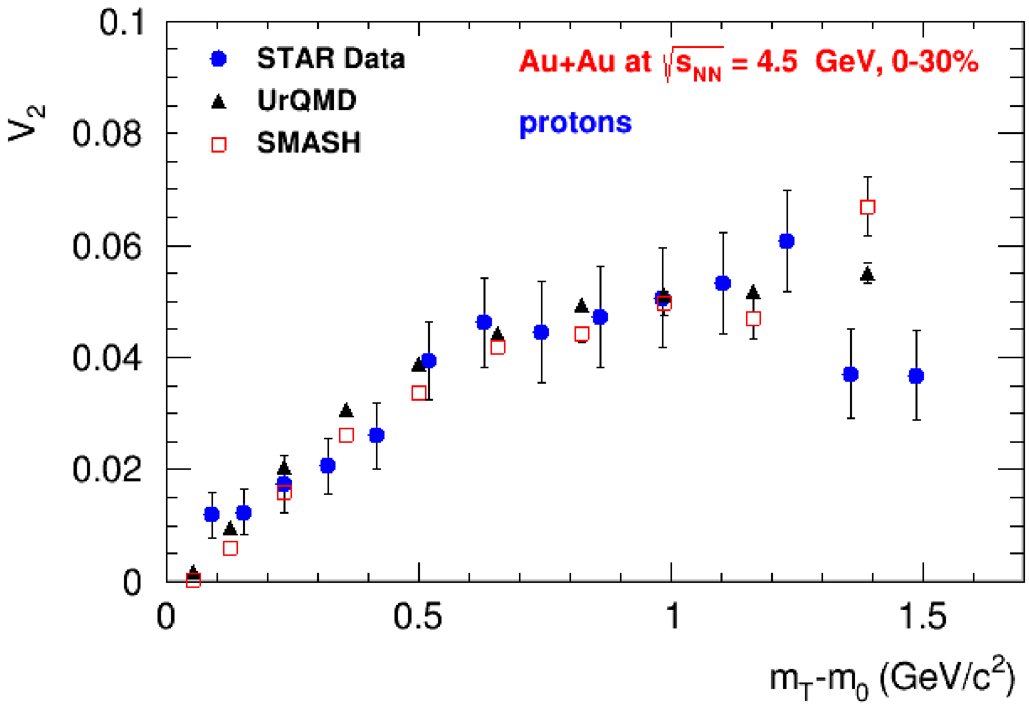
Rapidity dependence of directed flow: JAM EoS comparison

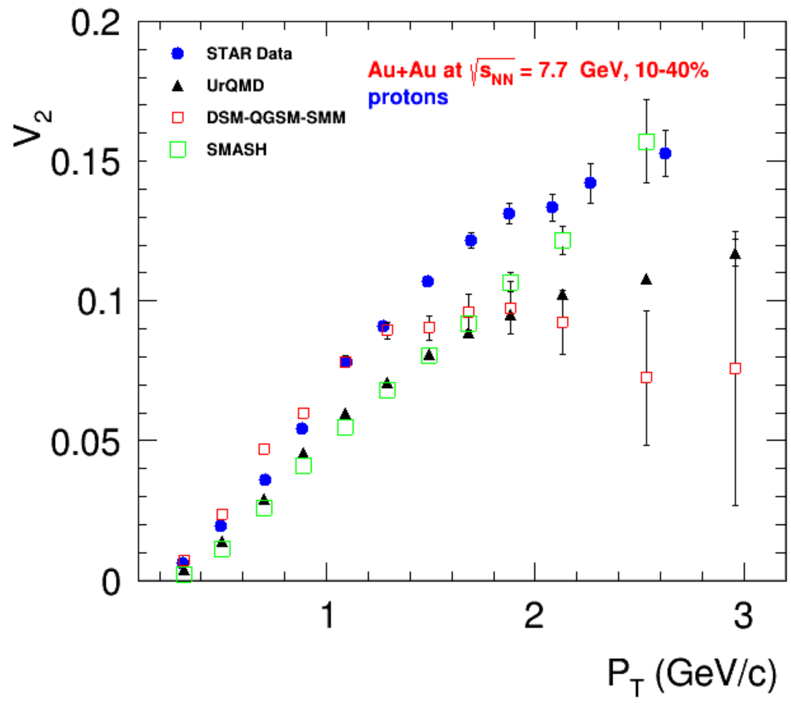
JAM model: http://www.aiu.ac.jp/~ynara/jam/, Phys. Rev. C 72 (2005) 064908; **STAR data:** Phys. Rev. Lett. 120 (2018) 62301



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

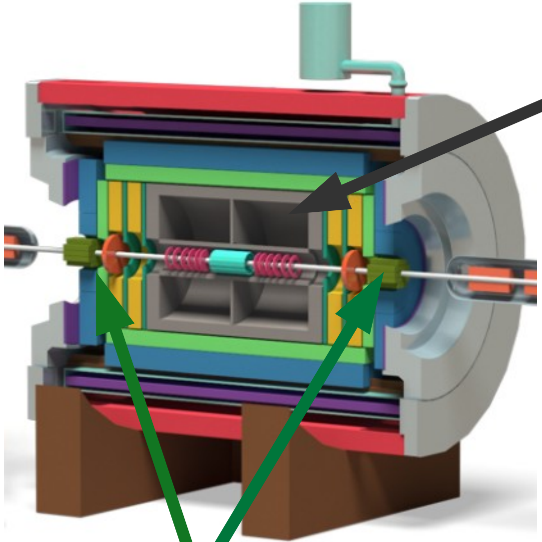




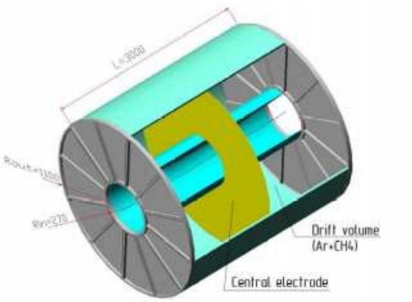
- **At $\sqrt{s_{NN}}$=4.5 GeV pure string/hadronic cascade models give similar v_2 signal compared to STAR data**
- **At $\sqrt{s_{NN}}$=7.7 GeV pure string/hadronic cascade models underpredict v_2**

Flow performance study at MPD (NICA)

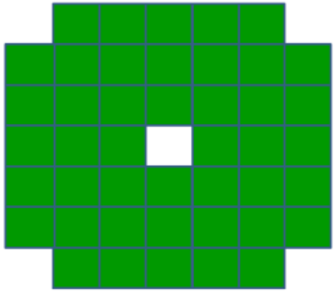
Multi Purpose Detector (MPD)



Time projection chamber (TPC)



Forward Hadron Calorimeter (FHCal)



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

-5<η<-2 FHCal

-1.5<η<1.5 TPC $0.2<p_T<3$ GeV/c

2<η<5 FHCal

Setup, event and track selection

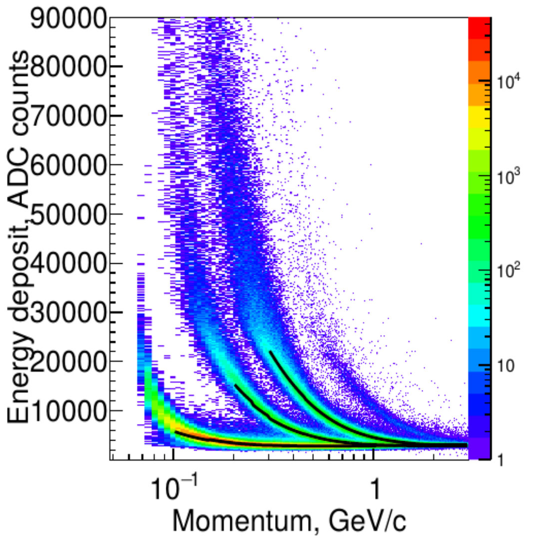
UrQMD → GEANT4 → Reconstruction → Flow analysis

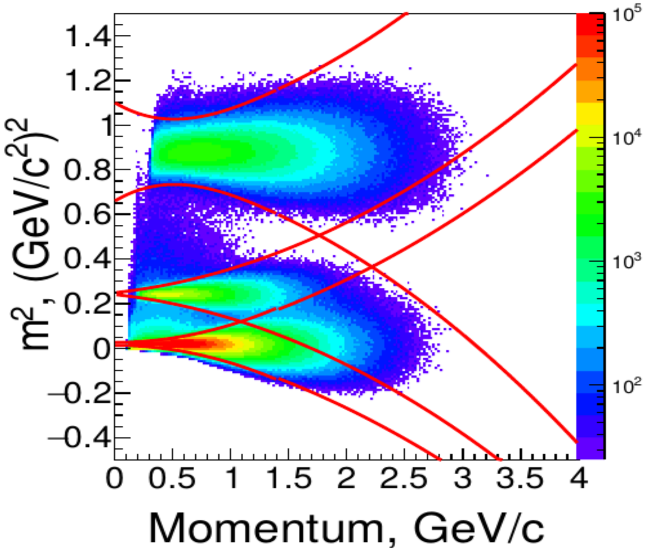
- Au+Au, N_{events} = 10 M events
  at $\sqrt{s_{NN}}$ = 4.5, 7.7 and 11 GeV
- Bi+Bi, N_{events} = 7 M events
  at $\sqrt{s_{NN}}$ = 7.7 GeV

- 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, 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: $m=1,\ \omega=E$

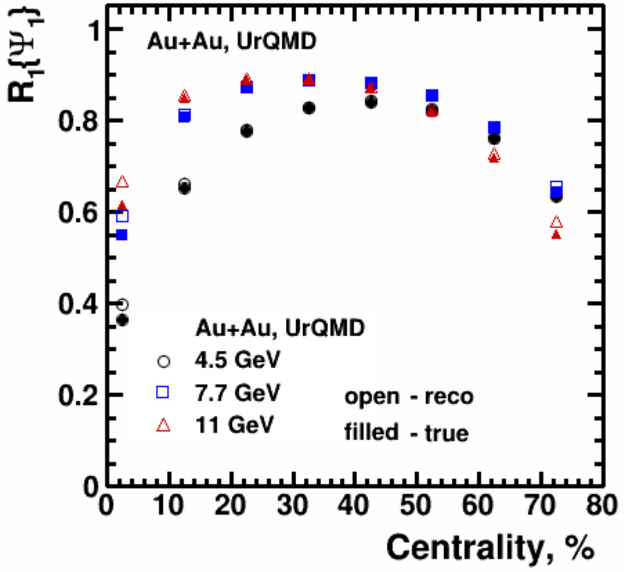
TPC EP: $m=2,\ \omega=p_T$

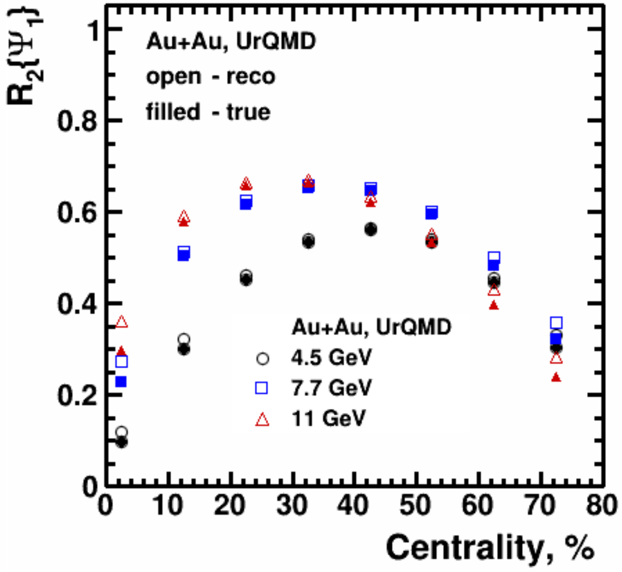
$$Res_n^2\{\Psi_m^{EP,L},\Psi_m^{EP,R}\}=\langle\cos[n(\Psi_m^{EP,L}-\Psi_m^{EP,R})]\rangle$$

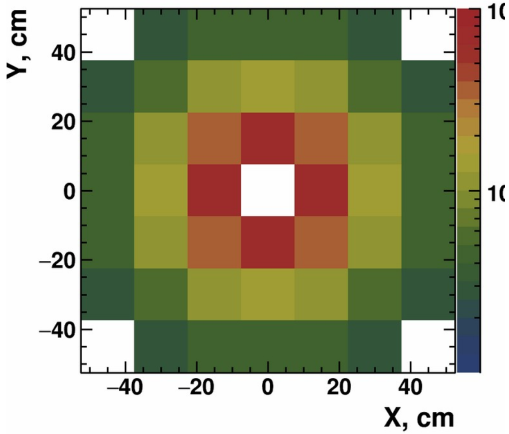
$$Res_n\{\Psi_m^{EP,true}\}=\langle\cos[n(\Psi_{RP}-\Psi_m^{EP})]\rangle$$

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

- 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

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

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

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):

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

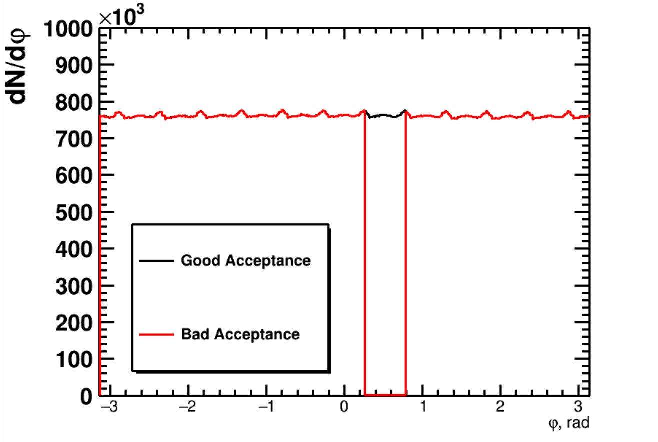
$$v_n\{4'\} = \frac{2\langle\langle 2'\rangle\rangle_n\langle\langle 2\rangle\rangle_n - \langle\langle 4'\rangle\rangle_n}{\left(2\langle\langle 2\rangle\rangle_n^2 - \langle\langle 4\rangle\rangle_n\right)^{3/4}}$$

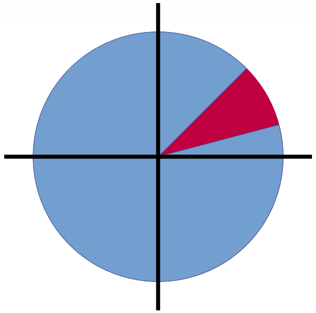
- Reference Flow Particle (RFP) – integrated flow over the event (centrality dependence)
- Particle Of Interest (POI) – differential flow (centrality, p_T, ...)

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

Acceptance filter

TPC

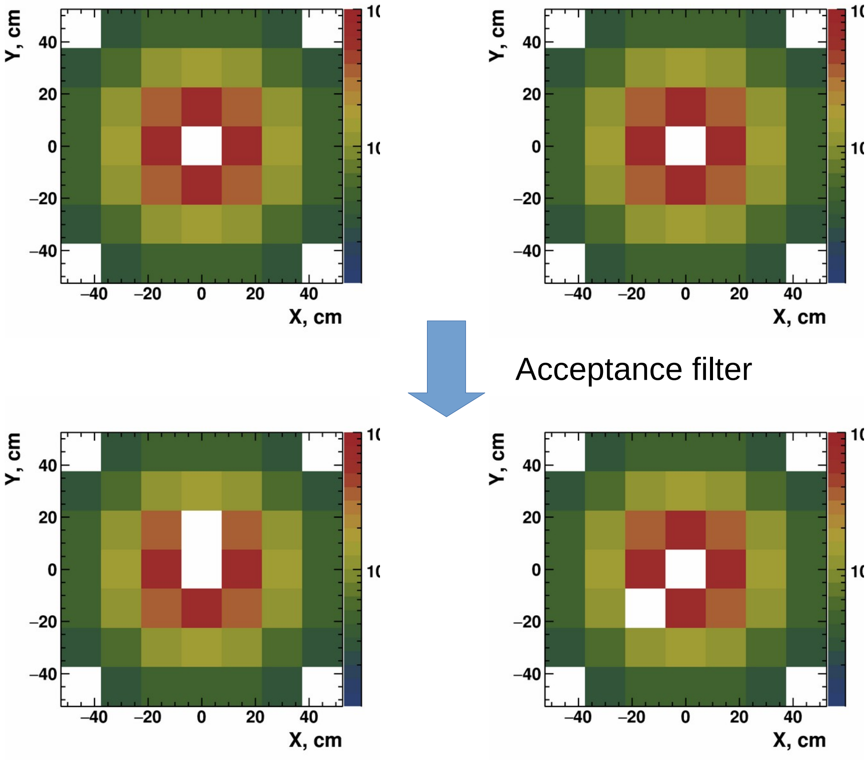




Area 15°< φ < 45° is off

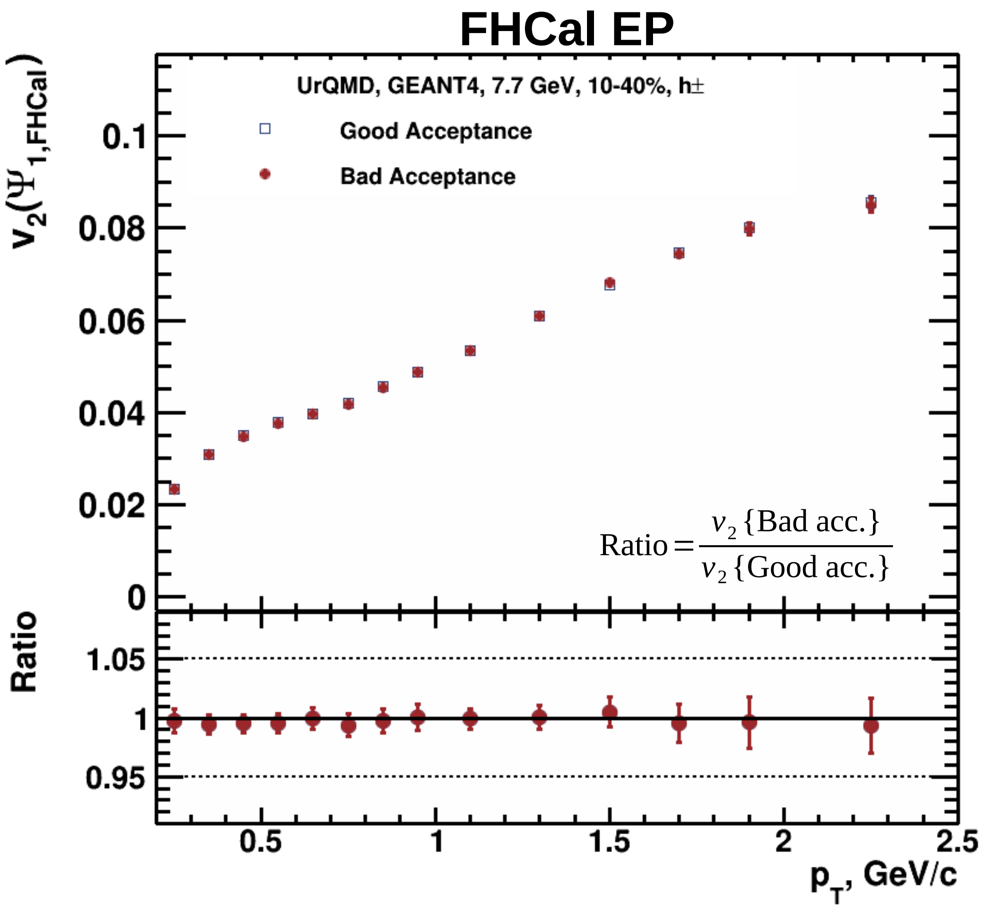
FHCal L

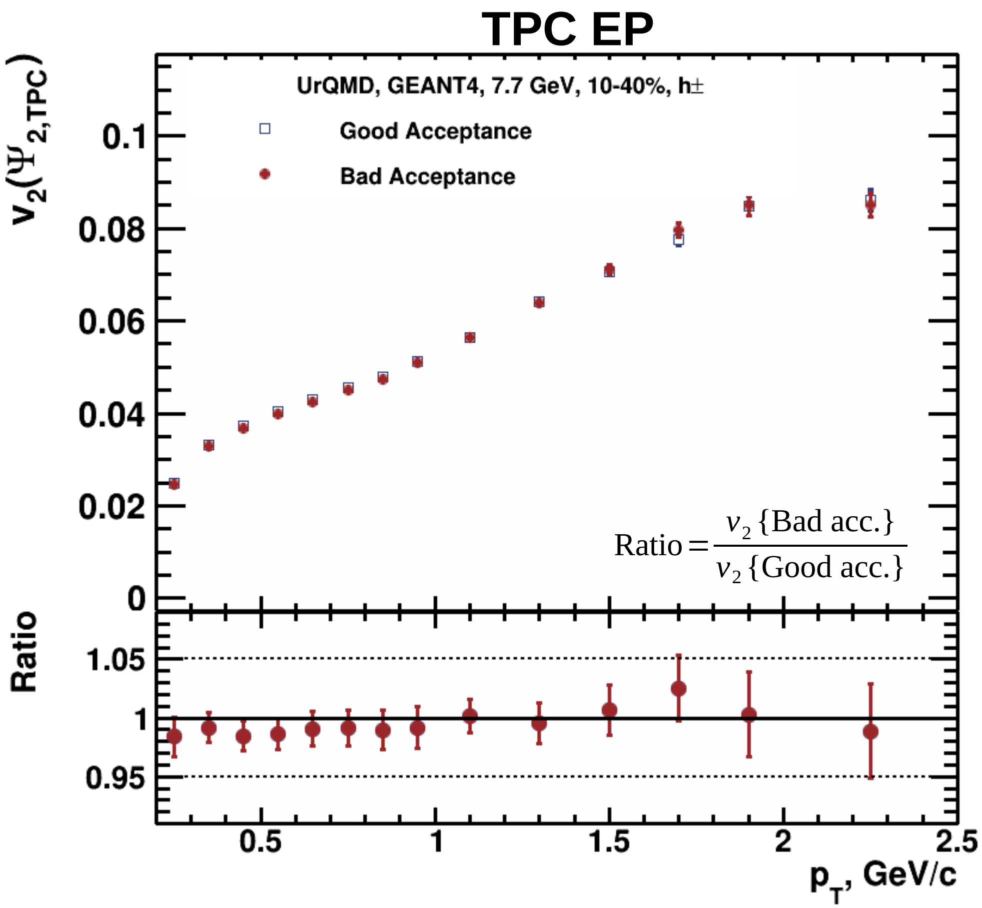
FHCal R



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

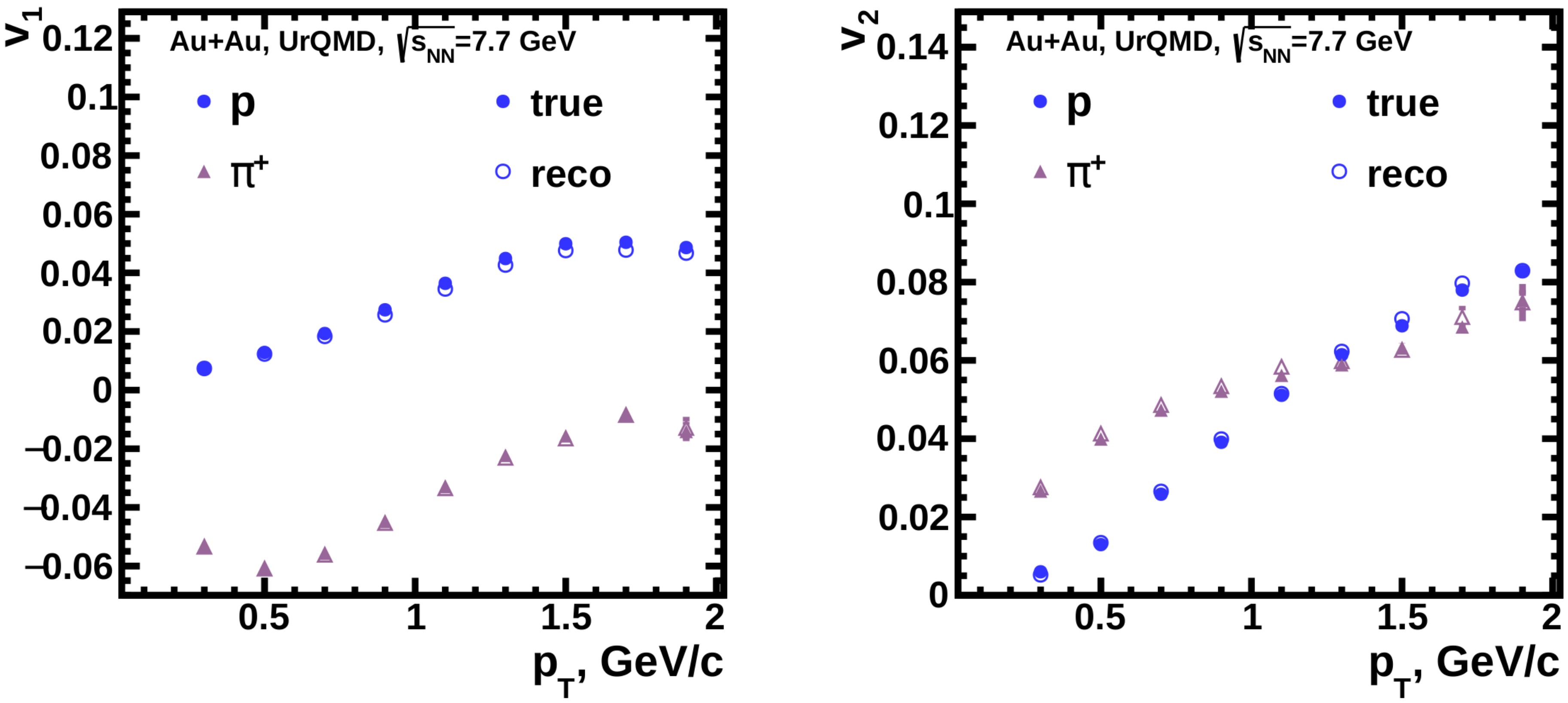
$v_2(p_T)$: check of corrections





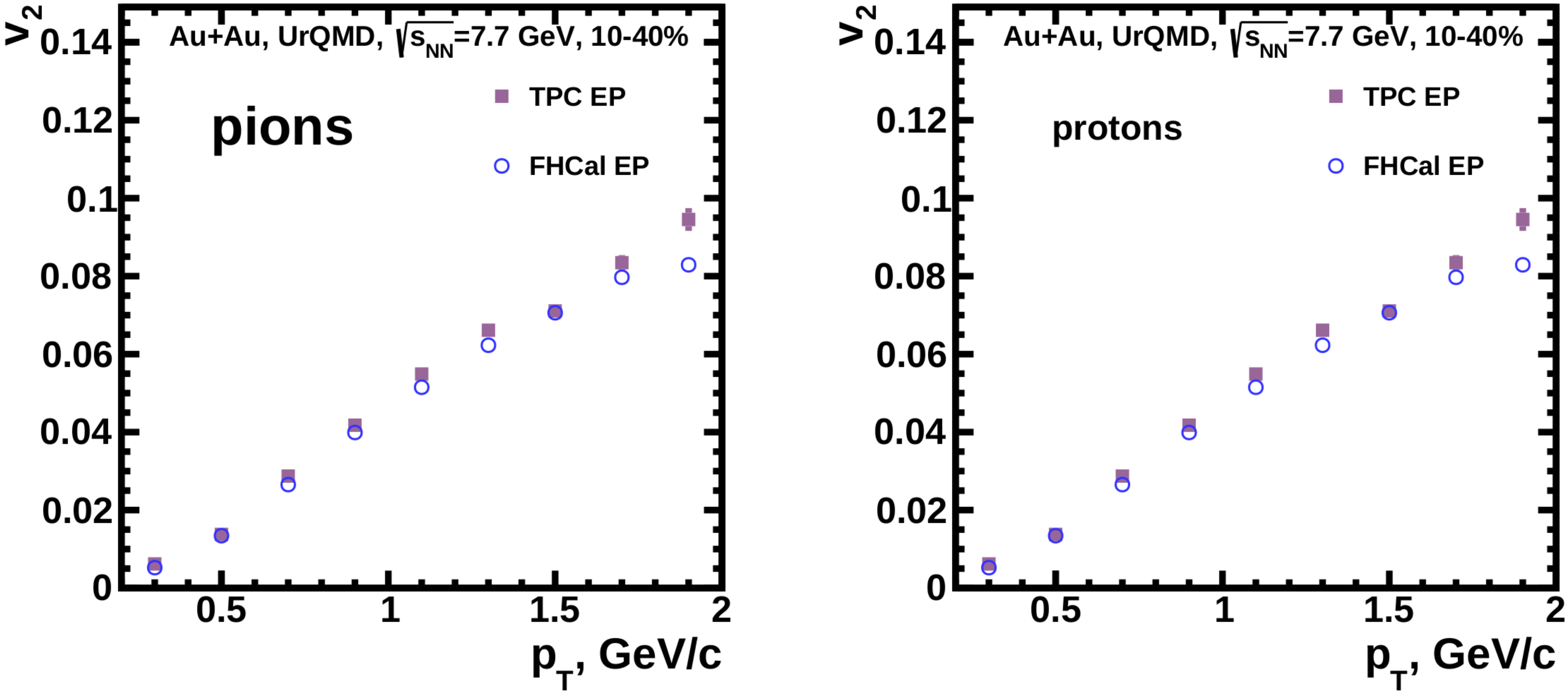
Good agreement with results for ideal (Good) acceptance

p_T-dependence of v_1 and v_2 of reconstructed signal



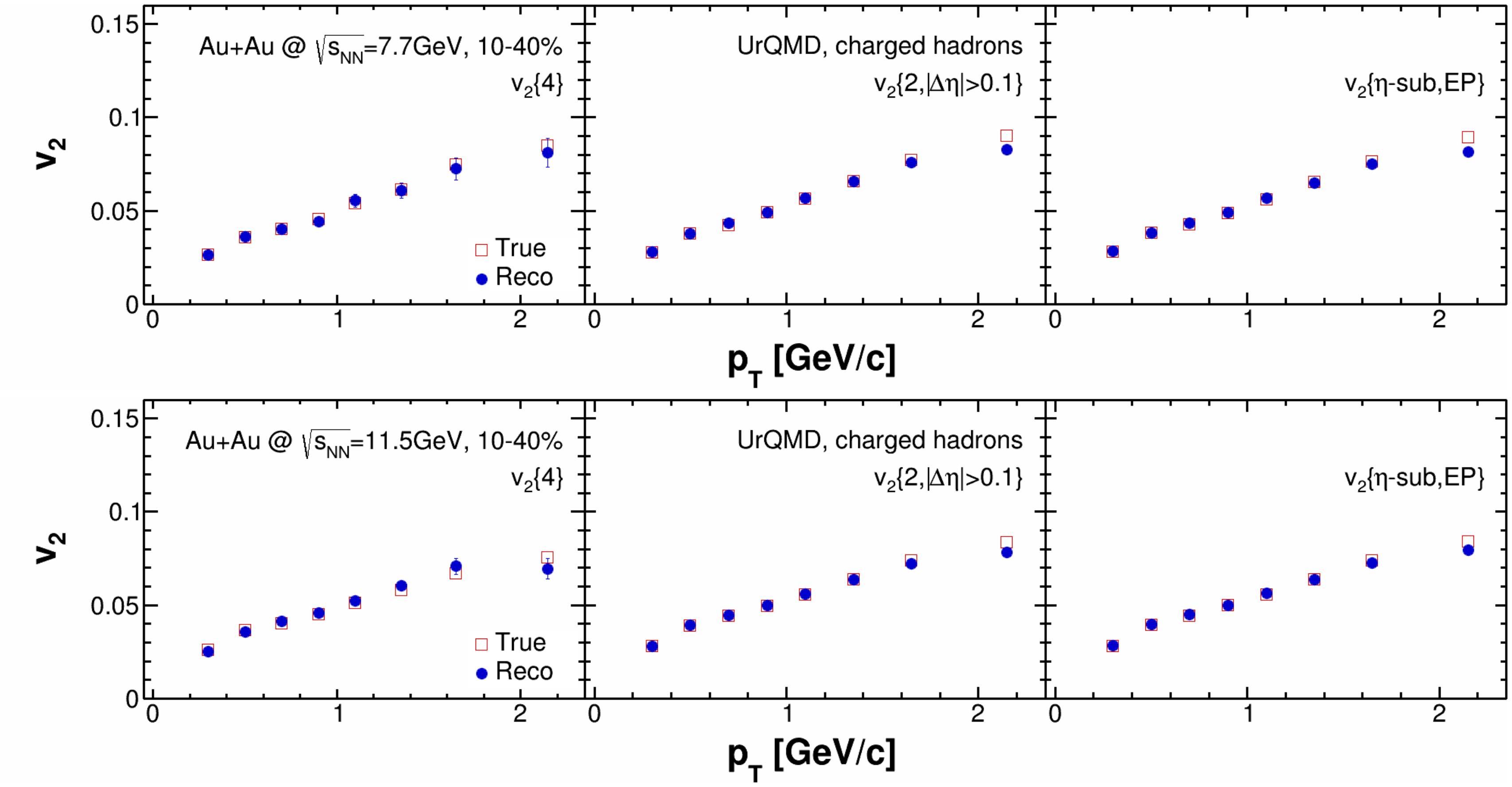
Both directed and elliptic flow results after reconstruction and resolution correction are consistent to that of MC simulation

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



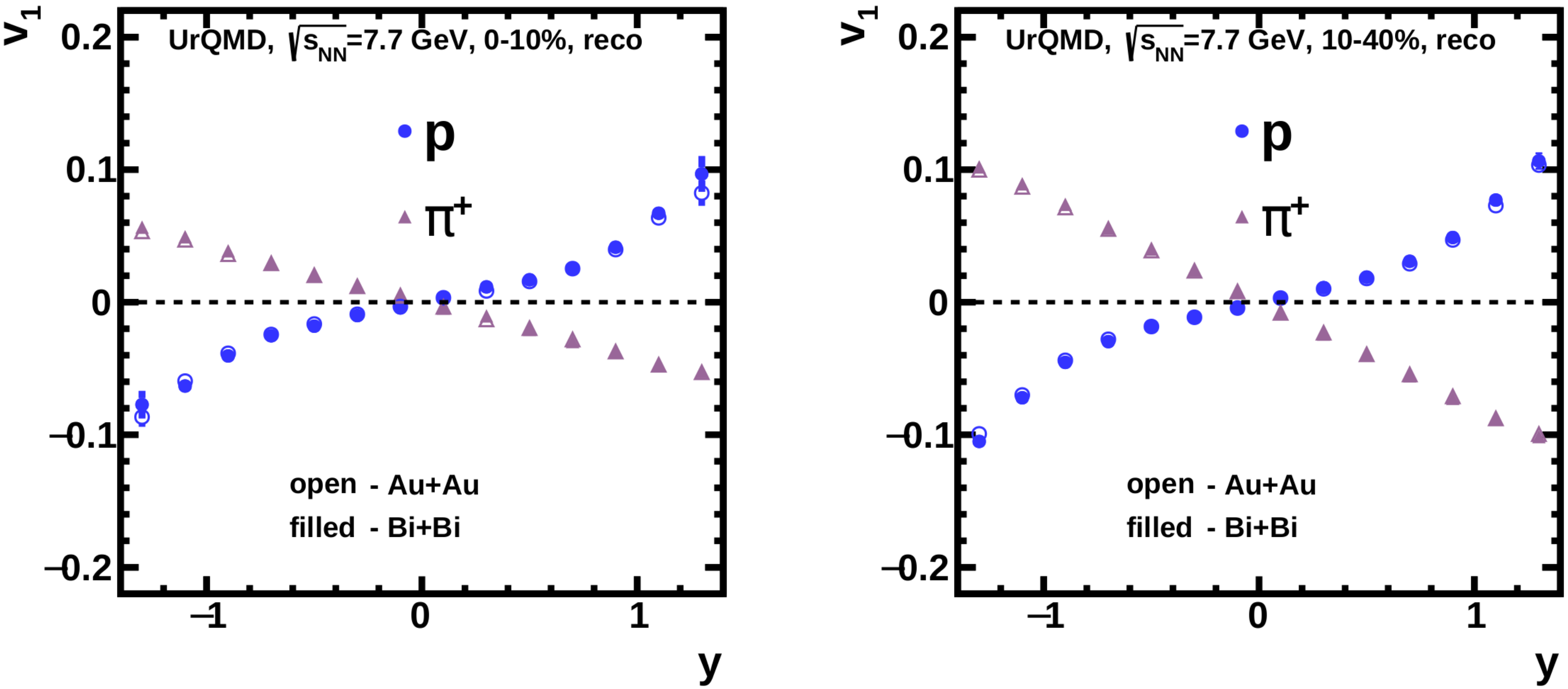
Expected small difference between v_2 measured with respect TPC ($\Psi_{2,EP}$) and FHCal ($\Psi_{1,EP}$)

Direct cumulant measurements in MPD (NICA)



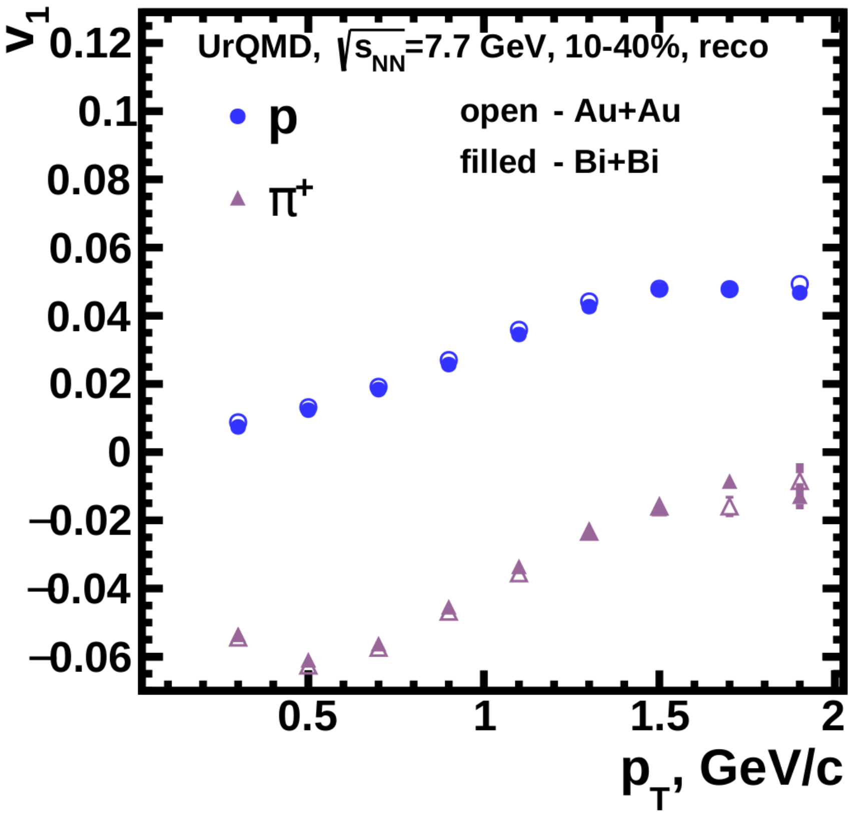
Elliptic flow results using direct cumulant and EP methods after reconstruction are consistent to that of MC simulation

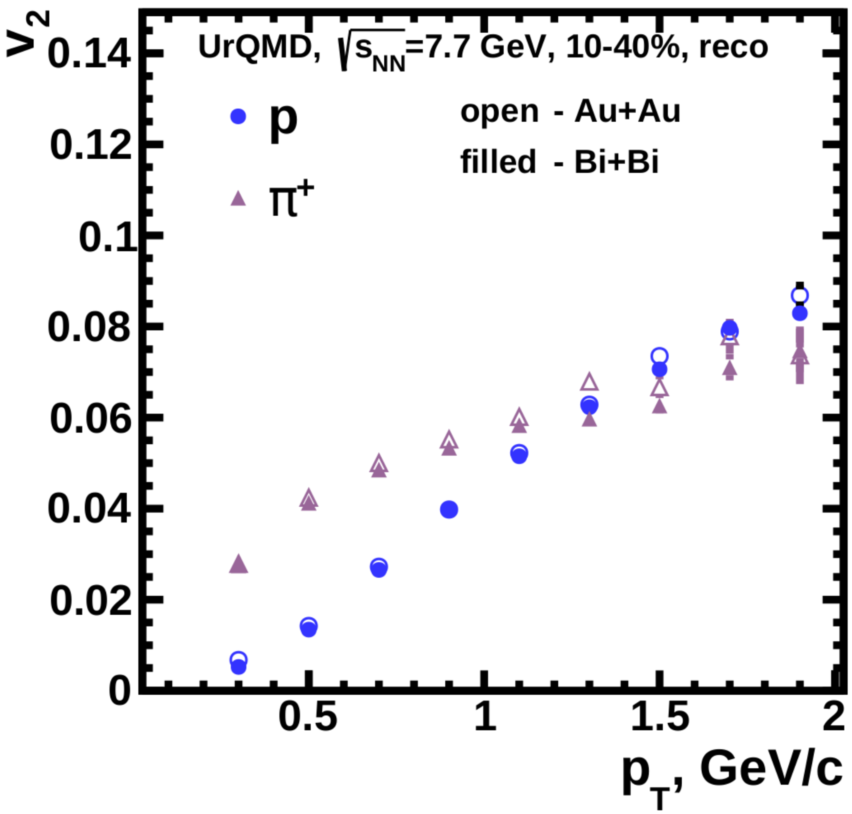
$v_1(y)$: Bi+Bi vs Au+Au



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.

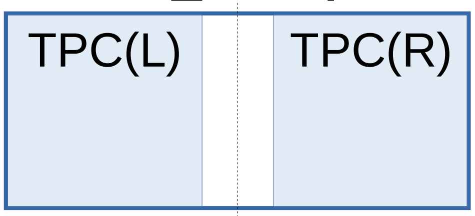
Summary

- 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 $(\eta < -0.05) \rightarrow \eta_-$

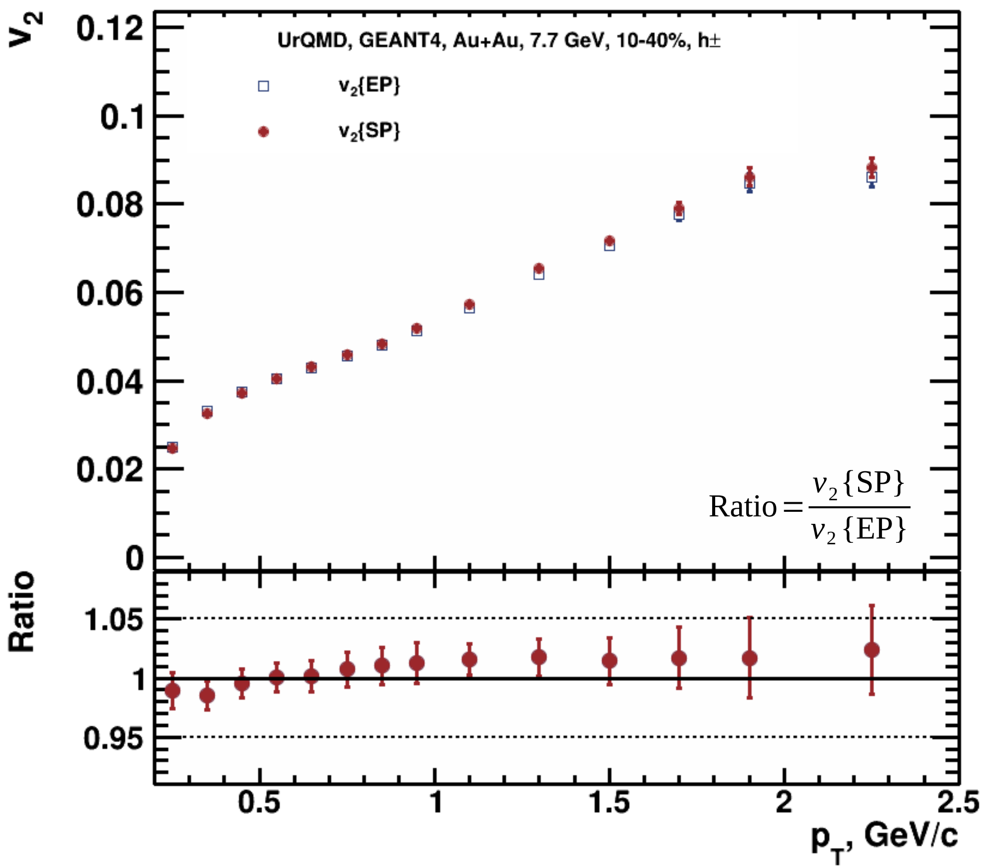
Right TPC half $(\eta > 0.05) \rightarrow \eta_+$

Event Plane (EP):

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

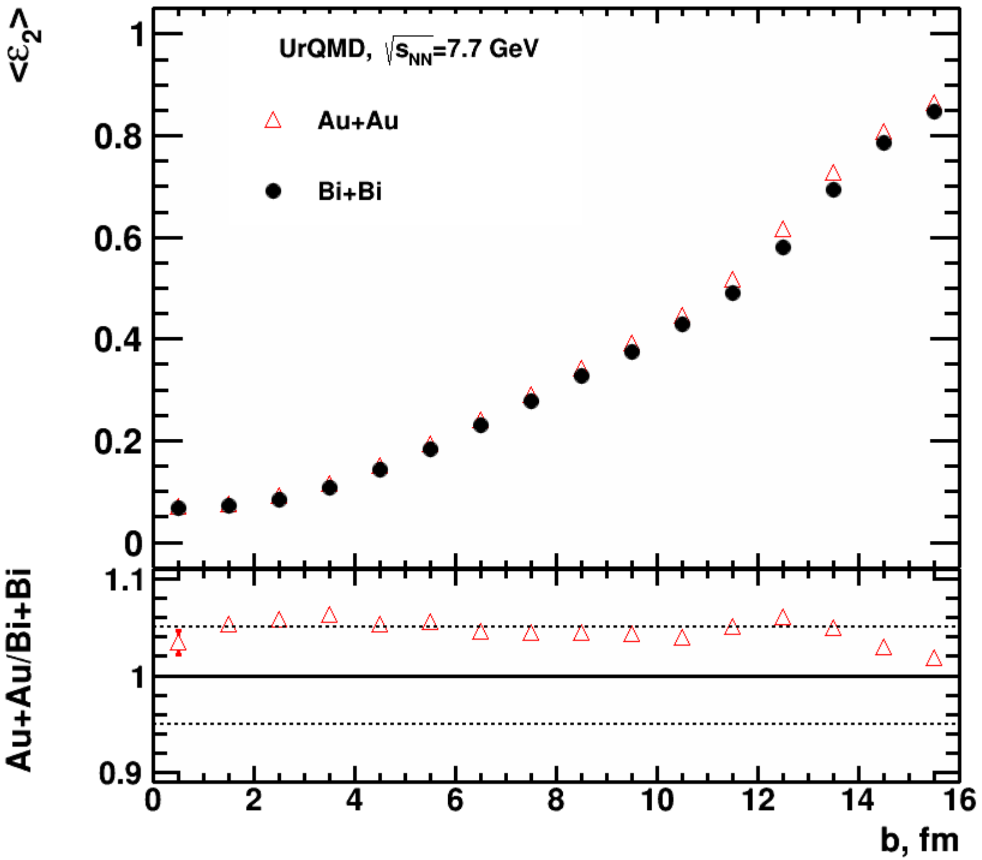
Scalar Product (SP):

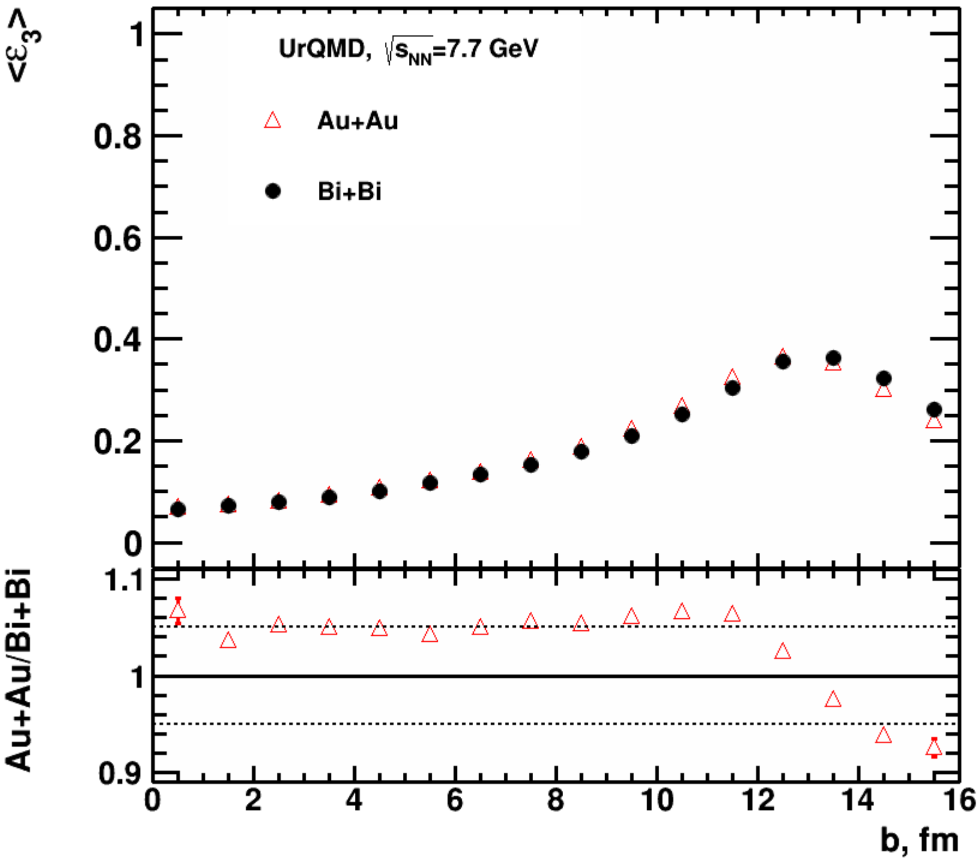
$$v_2\{SP\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp} \rangle}{\sqrt{\langle Q_{2,\eta-} Q^*_{2,\eta+} \rangle}}, \quad u_2 = e^{i(2\varphi)}, \quad Q_2 = \sum_k^{k_{\text{tracks}}} u_{2,k}$$



Good agreement between Event Plane and Scalar Product methods

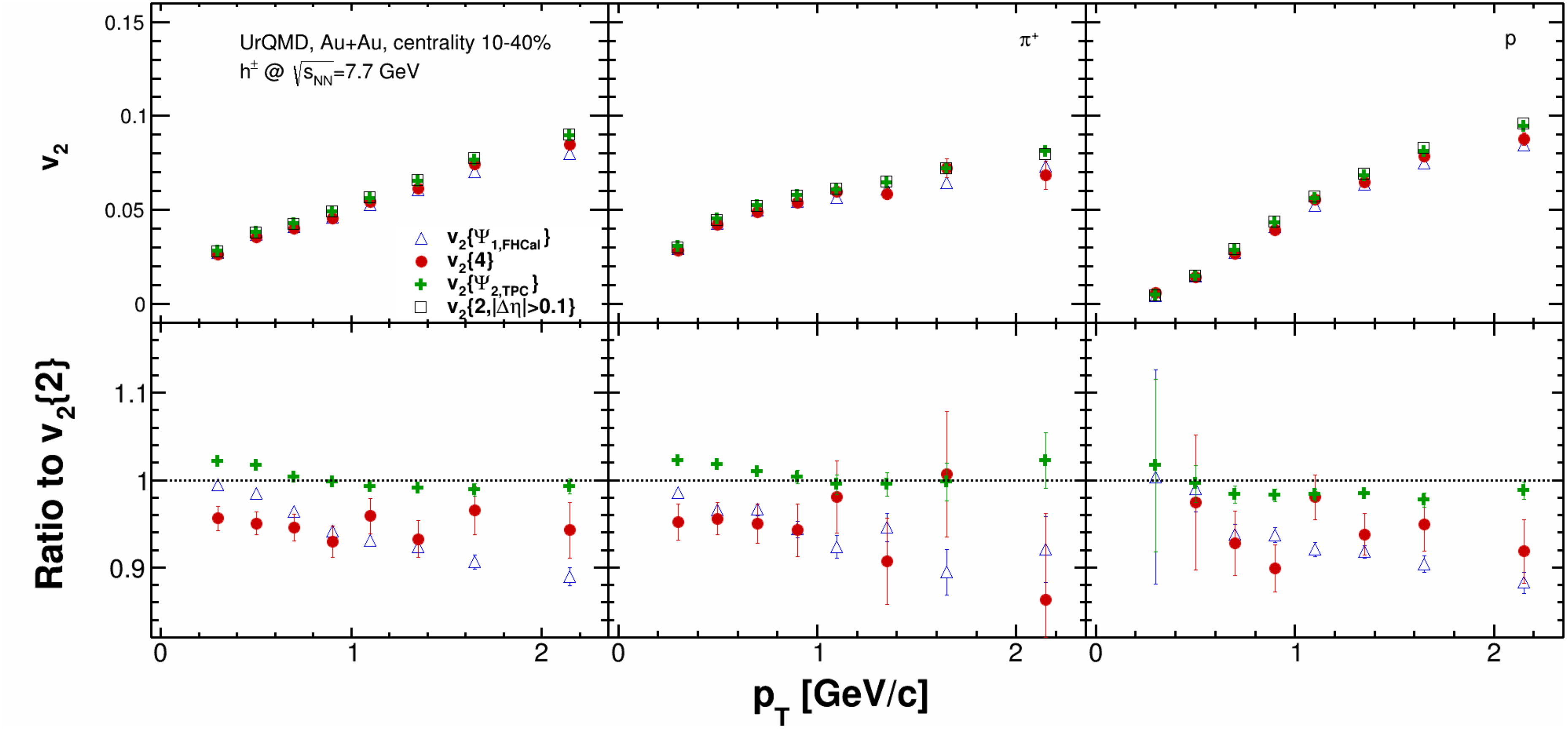
Eccintricity: Bi+Bi vs Au+Au





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

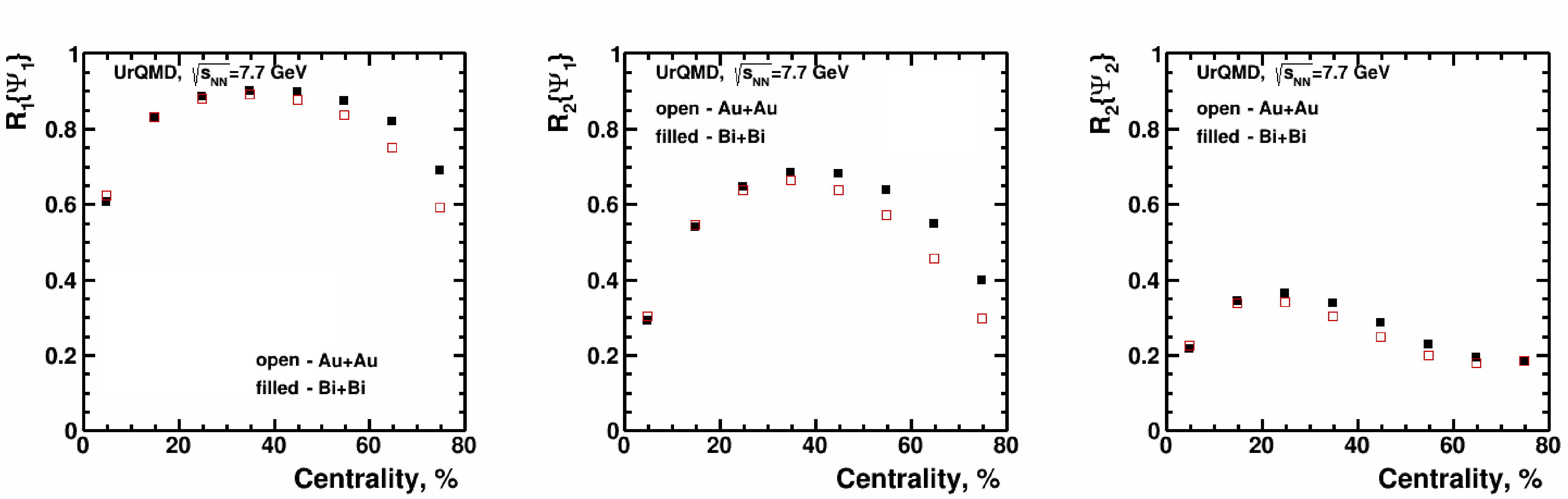
Direct cumulants in MPD



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

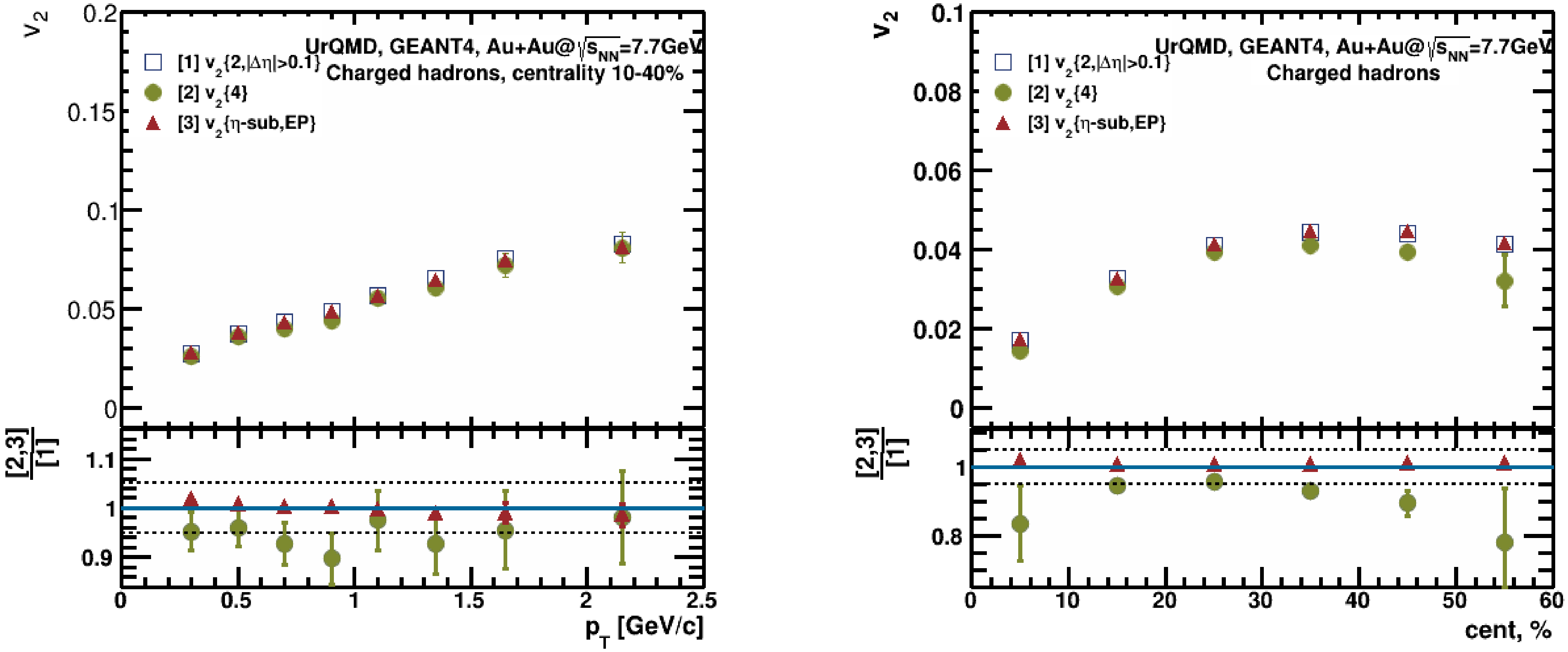
$v_2\{4\}$ and $v_2(\Psi_{1,EP})$ are smaller compared to $v_2\{2\}$ due to fluctuations and nonflow

EP Resolution: Bi+Bi vs Au+Au



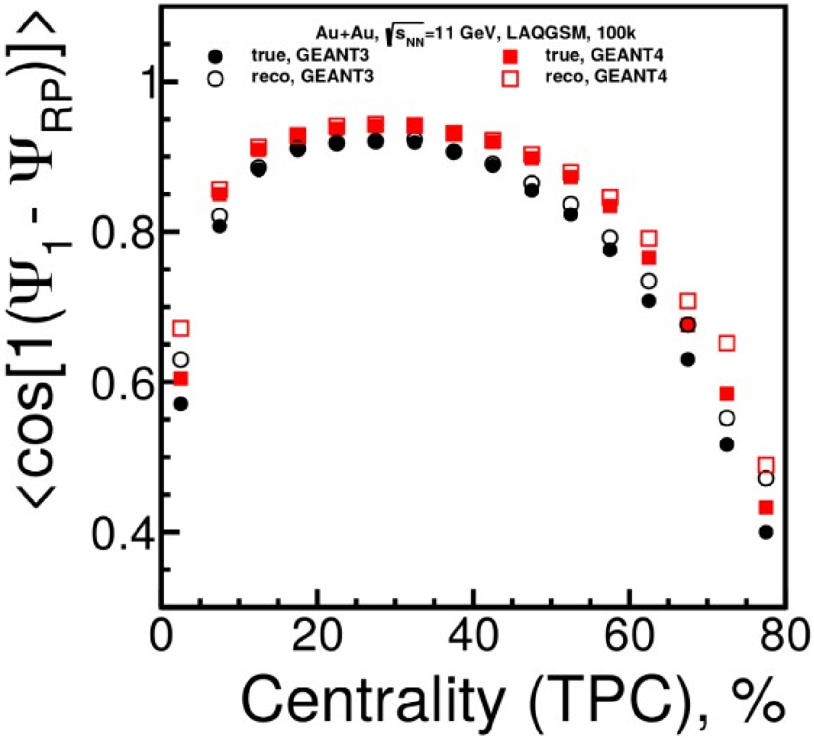
Expected small difference between EP resolutions for Au+Au and Bi+Bi

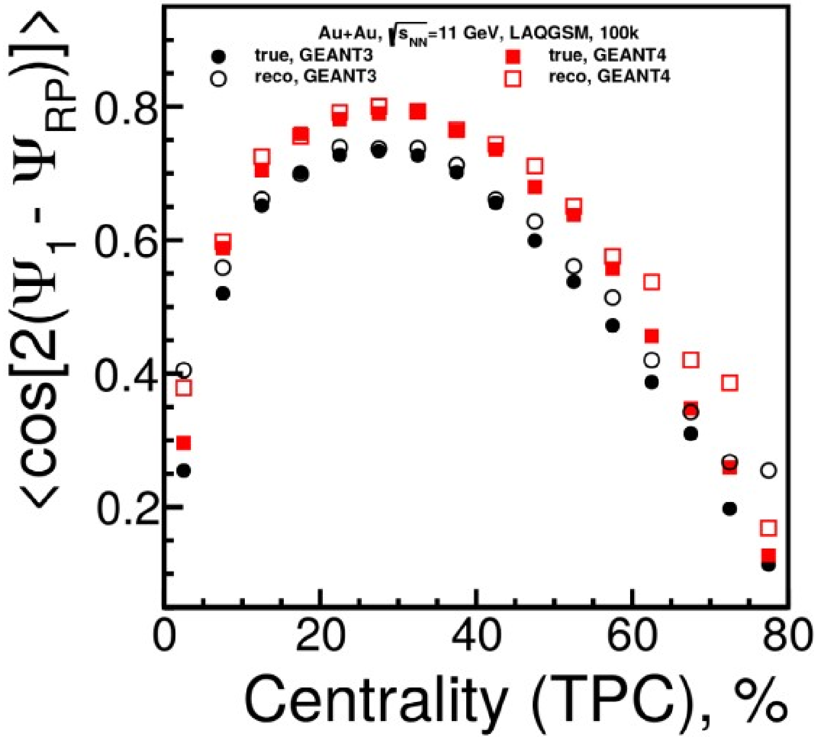
Direct cumulant measurements in MPD (NICA)



- $v_2\{2\}$ **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