Comparison of methods for elliptic flow measurements at NICA energies

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MPD Physics Forum

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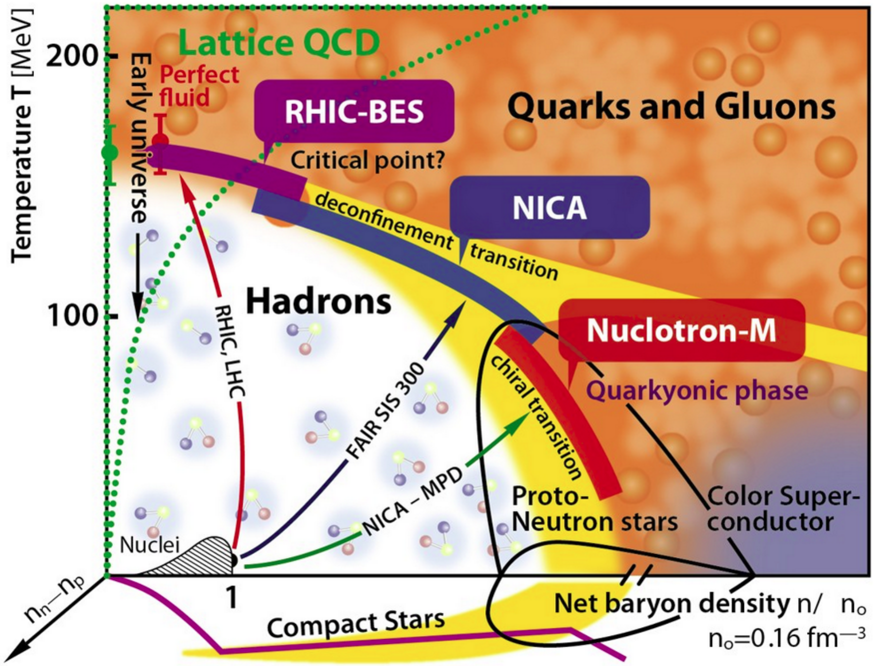
Outline

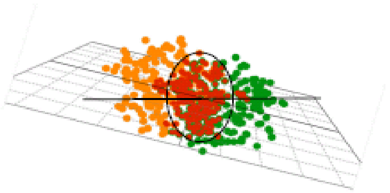
- Elliptic flow v_2 at NICA energies
- Description of event plane, scalar product, Q-Cumulants, and Lee-Yang Zeros methods for flow measurements
- Sensitivity of different methods to flow fluctuations and non-flow
- Effect of non-uniform acceptance
- Performance of v_2 of identified charged hadrons in MPD
- Comparison of Au+Au and Bi+Bi colliding systems
- Summary and outlook

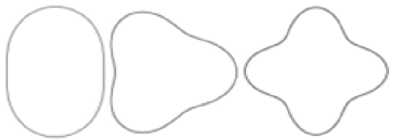
Phase Diagram of the Strongly-Interacting Matter



- **Top RHIC/LHC:**
  - Validation of the cross-over transition leading to the sQGP
  - Access to high T, small μ_B
- **Beam-energy scan programs: RHIC/SPS/NICA/FAIR:**
  - Broad domain of the (T,μ_B)-plane
  - Access to different systems, search for first-order phase transition and critical end point

Anisotropic Collective Flow at top RHIC/LHC

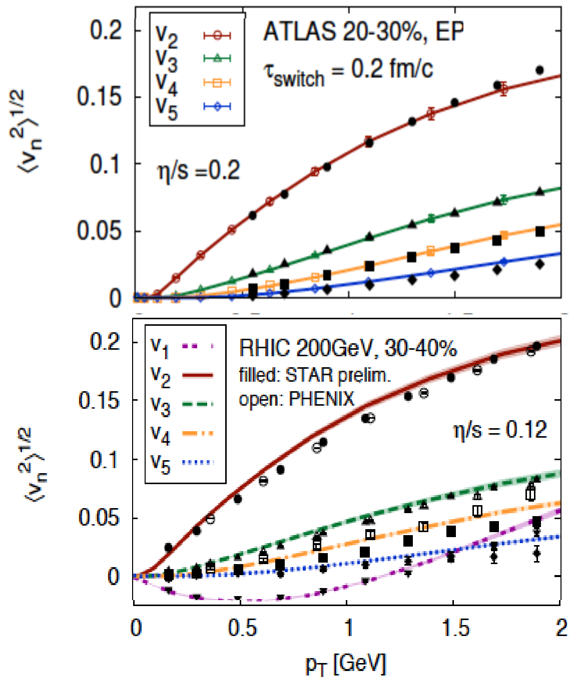




$$\epsilon_n = \sqrt{\frac{\langle r^n \cos n\phi\rangle + \langle r^n \sin n\phi\rangle}{\langle r^n\rangle}}$$

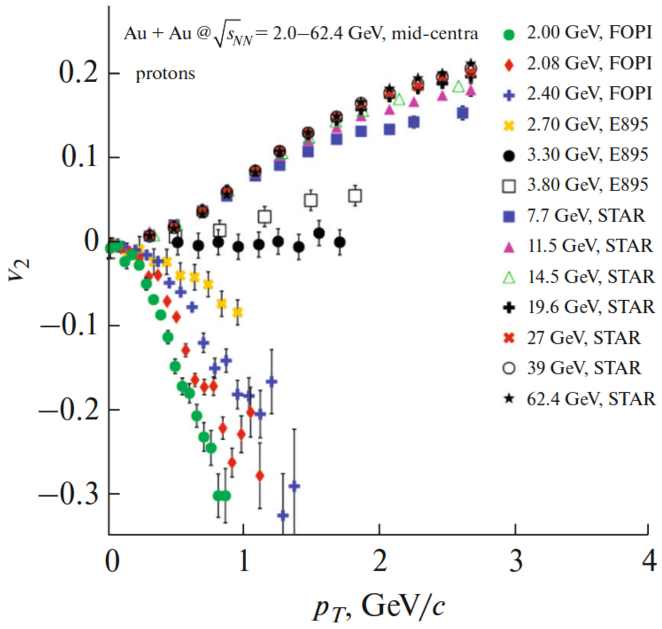
$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_n\right)\right]$$

Phys. Rev. Lett. **110** (2013) no.1, 012302

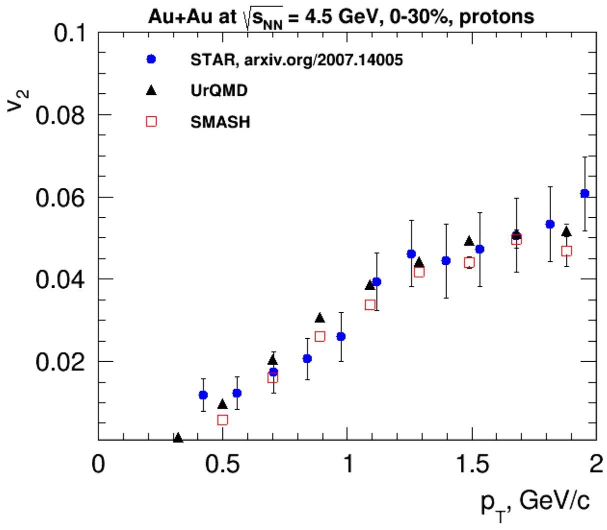


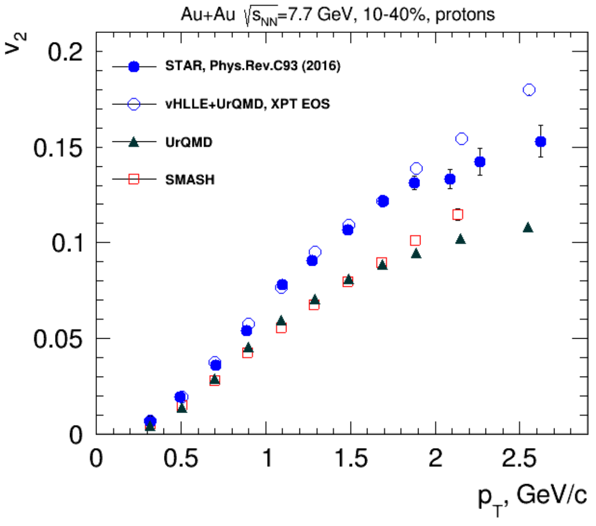
- Initial eccentricity (and its attendant fluctuations) ε_n drives momentum anisotropy v_n with specific viscous modulation
- v_1 - directed flow, v_2 - elliptic flow, v_3 - triangular flow
- v_n (p_T, centrality):
  - sensitive to the early stages of collision
  - important constraint for transport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

Elliptic flow at NICA energies



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





- **Strong energy dependence of v_2 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,…)

Event plane method using FHCal

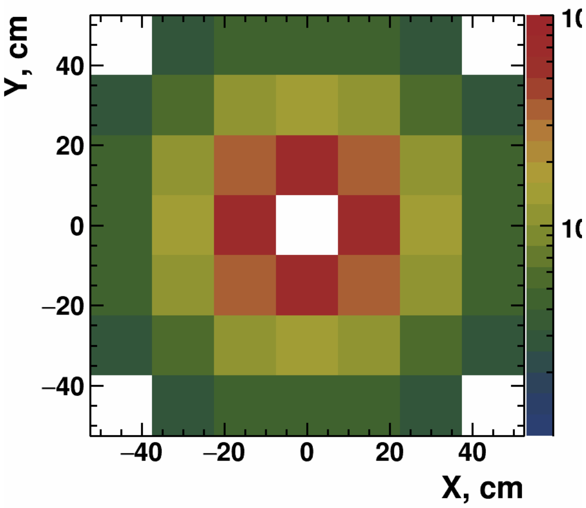
- Using v_1 of particles in FHCal to determine Q_n

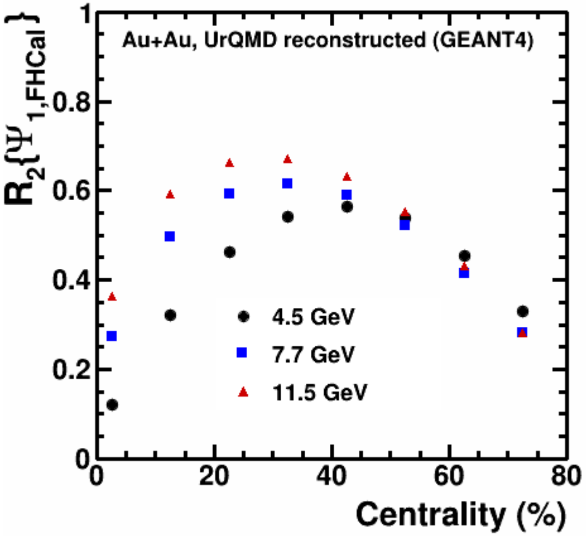
$$Q_1 = \frac{\sum_j E_i e^{i\phi_j}}{\sum_j E_j}, \quad \Psi_{1,\mathrm{FHCal}} = \tan^{-1}\left(\frac{Q_{1,y}}{Q_{1,x}}\right)$$

$$E - \text{energy deposited in FHCal modules}\,(2 < |\eta| < 5)$$

$$\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{1,\mathrm{FHCal}}\} = \langle \cos\left[2(\Psi_{1,\mathrm{FHCal}} - \Psi_{\mathrm{RP}})\right]\rangle$$

$$v_2^{\mathrm{EP}}\{\Psi_{1,\mathrm{FHCal}}\} = \frac{\langle \cos\left[2(\phi - \Psi_{1,\mathrm{FHCal}})\right]\rangle}{\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{1,\mathrm{FHCal}}\}}$$





Recent results of $v_2\{\Psi_{1,FHCal}\}$: Particles **4** (2021), no.2, 146-158

Elliptic flow measurements using TPC: Scalar product, Event-plane

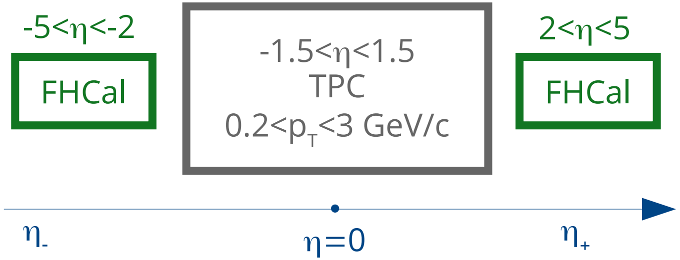
$$u_2 = \cos 2\phi + i \sin 2\phi = e^{2i\phi}$$

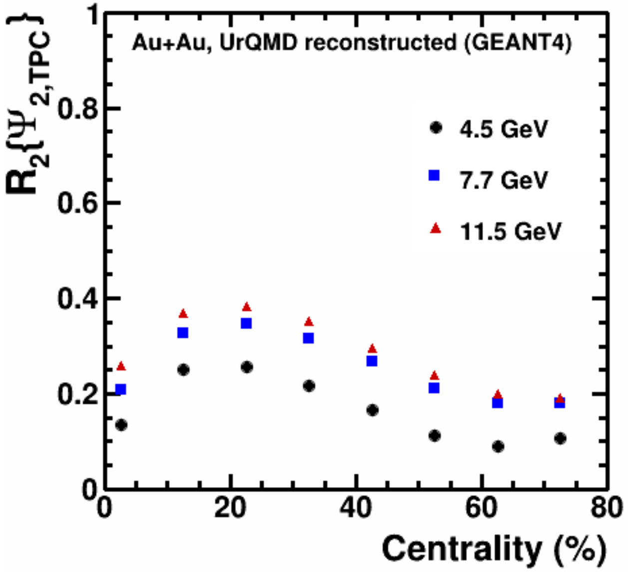
$$Q_2 = \sum_{j=1}^{M} \omega_j u_{2,j}, \ \Psi_{2,\mathrm{TPC}} = \frac{1}{2} \tan^{-1}\left(\frac{Q_{2,y}}{Q_{2,x}}\right)$$

- **Scalar product:** $$v_2^{\mathrm{SP}}\{Q_{2,\mathrm{TPC}}\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp} \rangle}{\sqrt{\langle Q_{2,\eta+} Q_{2,\eta-} \rangle}}$$
- **TPC Event-plane:**

$$v_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \frac{\langle \cos\left[2(\phi_{\eta\pm} - \Psi_{2,\eta\mp})\right] \rangle}{\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\}}$$

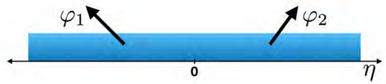
$$\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \sqrt{\langle \cos\left[2(\Psi_{2,\eta+} - \Psi_{2,\eta-})\right] \rangle}$$

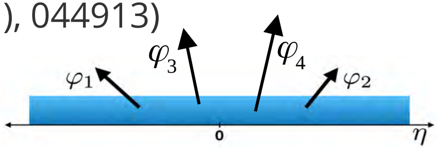




Elliptic flow measurements using TPC: Q-Cumulants

- **Standard Q-Cumulants:** (A. Bilandzic et al., Phys. Rev. C **83** (2011), 044913)





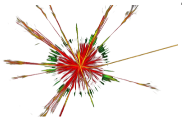
$$\langle 2\rangle_n = \frac{|Q_n|^2 - M}{M(M-1)} \approx v_2^2 + \delta$$

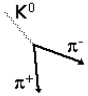
$$\langle 4\rangle_n = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2\Re[Q_{2n}Q_n^*Q_n^*] - 4(M-2)\,|Q_n|^2 - 2M(M-3)}{M(M-1)(M-2)(M-3)} \approx v_2^4 + 4v_2^2\delta + 2\delta^2$$

$$v_2\{4\} = \sqrt[4]{2\,\langle\langle 2\rangle\rangle^2 - \langle\langle 4\rangle\rangle}$$

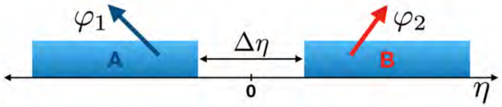
δ – non-flow contribution :

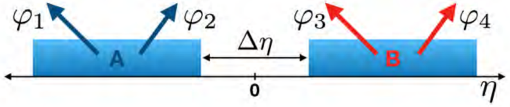
- resonance decay
- jets





- **Subevent Q-Cumulants:** (J. Jia et al., Phys. Rev. C **96** (2017), no. 3, 034906)





$$\langle 2\rangle_{a|b} = \frac{Q_{n_a}Q_{n,b}^*}{M_a M_b},\ v_2\{2, 2\text{-sub}\} = \sqrt{\langle\langle 2\rangle\rangle_{a|b}}$$

$$\langle 4\rangle_{a,a|b,b} = \frac{(Q_{n,a}^2 - Q_{2n,a})(Q_{n,b}^2 - Q_{2n,b})^*}{M_a(M_a-1)M_b(M_b-1)},\ v_2\{4, 2\text{-sub}\} = \sqrt[4]{2\,\langle\langle 2\rangle\rangle_{a|b}^2 - \langle\langle 4\rangle\rangle_{a,a|b,b}}$$

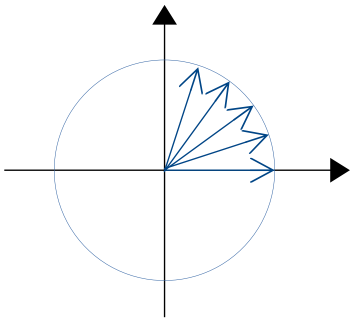
Note: In this presentation, all of $v_2\{2\}$ result is obtained by subevent method to suppress non-flow contribution

Elliptic flow measurements using TPC: High-order QC and Lee-Yang Zeros

- **Lee-Yang Zeros: considers all-particle correlations**
  (N. Borghini et al., J. Phys. G **30** (2004), S1213-S1216)

$$G^{\theta}(\mathrm{i}r) = \left\langle \prod_{j=1}^{M} [1 + \mathrm{i}r\omega_j \cos(2(\phi_j - \theta))] \right\rangle_{\text{events}}$$

$$\theta \in \left\{0, \frac{\pi}{10}, \frac{\pi}{5}, \frac{3\pi}{10}, \frac{2\pi}{5}\right\}$$



r – real positive variable,

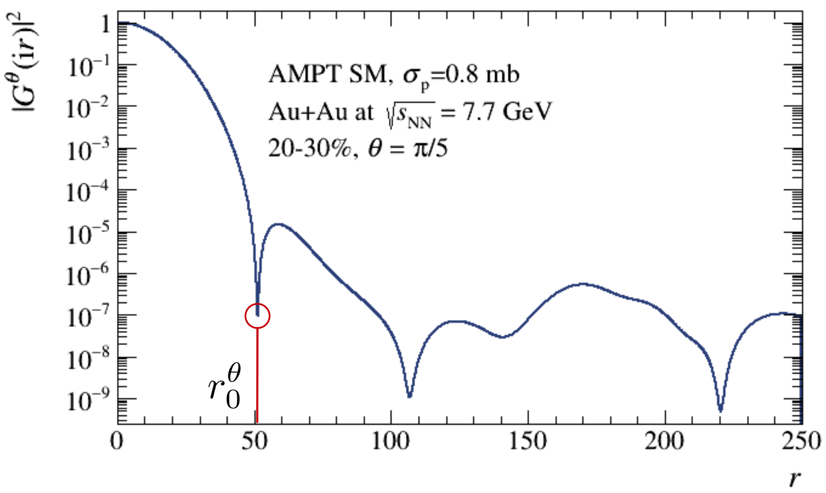
ω_j – particle weight, $\omega_j = 1/M$

θ – arbitrary reference azimuthal angle, $0 \leq \theta < \pi/2$

$$v_2\{\text{LYZ}\} = V_2\{\infty\} = \left\langle \frac{j_{01}}{r_0^{\theta}} \right\rangle_{\theta}$$

j_{01} – first root of Bessel functions of the 1-st kind

j_{01} = 2.405



Sensitivity of different methods to flow fluctuations

- Elliptic flow fluctuations: $\sigma_{v2}^2 = \langle v_2^2 \rangle - \langle v_2 \rangle^2$
- Assuming $\sigma_{v2} \ll \langle v_2 \rangle$ and a Gaussian form for flow fluctuations
- Fluctuations enhance $v_2\{2\}$ and suppress high-order **Q-Cumulants** compared to $\langle v_2 \rangle$:

  (S. A. Voloshin, A. M. Poskanzer, and R. Snellings, Landolt-Bornstein **23** (2010), 293)

$$v_2\{2\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle} \qquad v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{\mathrm{LYZ}\} \approx \langle v_2 \rangle - \frac{1}{2}\frac{\sigma_{v_2}^2}{\langle v_2 \rangle}$$

- **TPC EP method**: (M. Luzum et al., Phys. Rev. C **87** (2013) 4, 044907)

$$\langle v_2 \rangle \leq v_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} \leq \sqrt{\langle v_2^2 \rangle} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$$

- **Scalar product**:

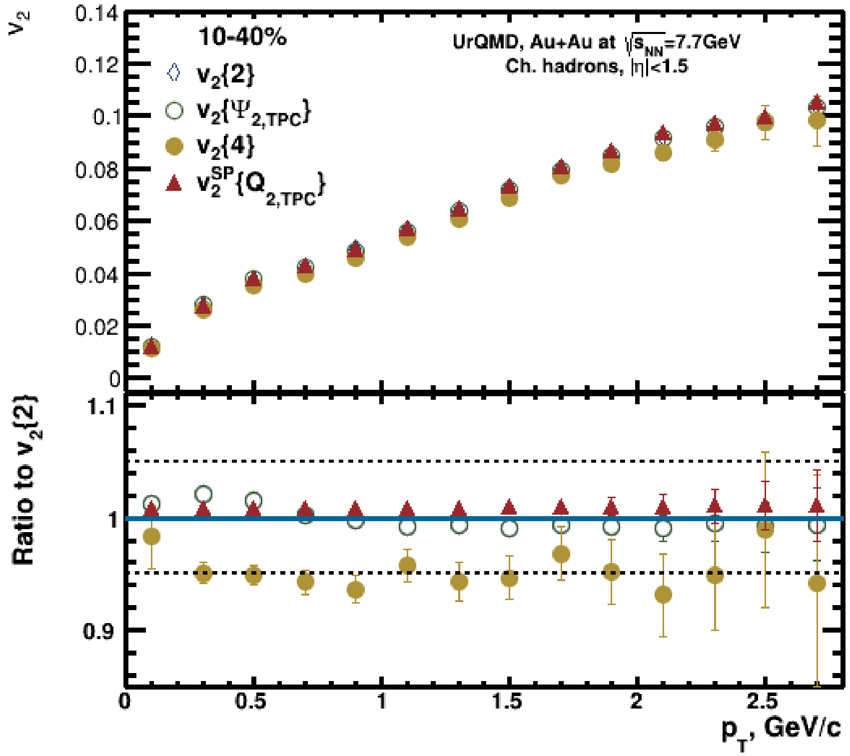
$$v_2^{SP}\{Q_{2,\mathrm{TPC}}\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$$

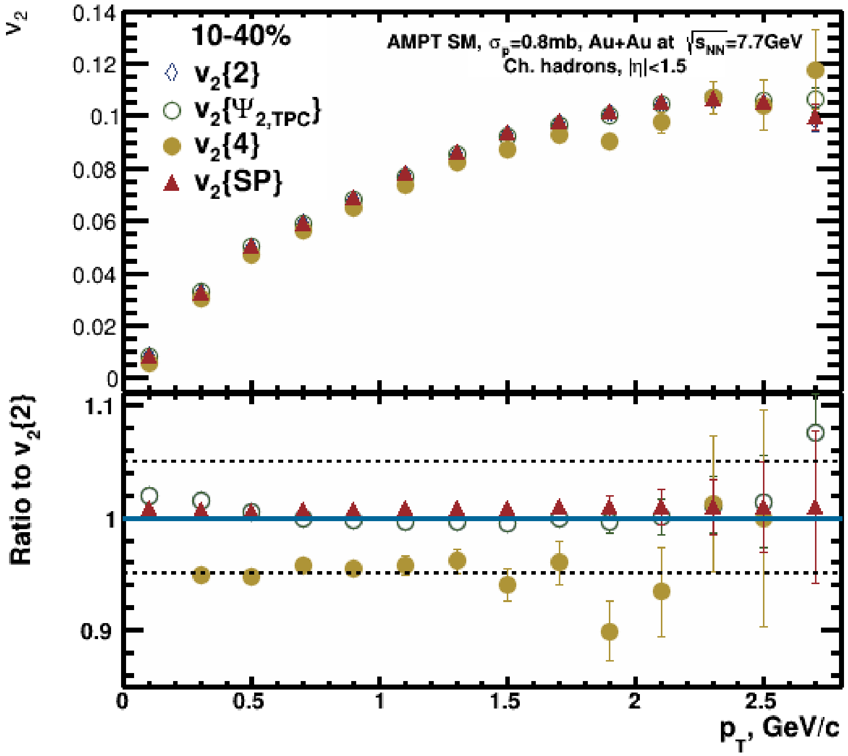
Models & statistics

Au+Au, min. bias

- UrQMD:
  - $\sqrt{s_{NN}}$ = 7.7 GeV: 88M
  - $\sqrt{s_{NN}}$ = 11.5 GeV: 50M
  - $\sqrt{s_{NN}}$ = 4.5 GeV: 115M
- SMASH: $\sqrt{s_{NN}}$ = 4.5-11.5 GeV: 64M
- vHLLE+UrQMD: $\sqrt{s_{NN}}$ = 7.7-11.5 GeV: 27M
- AMPT SM, σ_p = 0.8 mb:
  - $\sqrt{s_{NN}}$ = 11.5 GeV: 35M
  - $\sqrt{s_{NN}}$ = 7.7 GeV: 72M
- AMPT SM, σ_p = 1.5 mb:
  - $\sqrt{s_{NN}}$ = 11.5 GeV: 60M
  - $\sqrt{s_{NN}}$ = 7.7 GeV: 42M

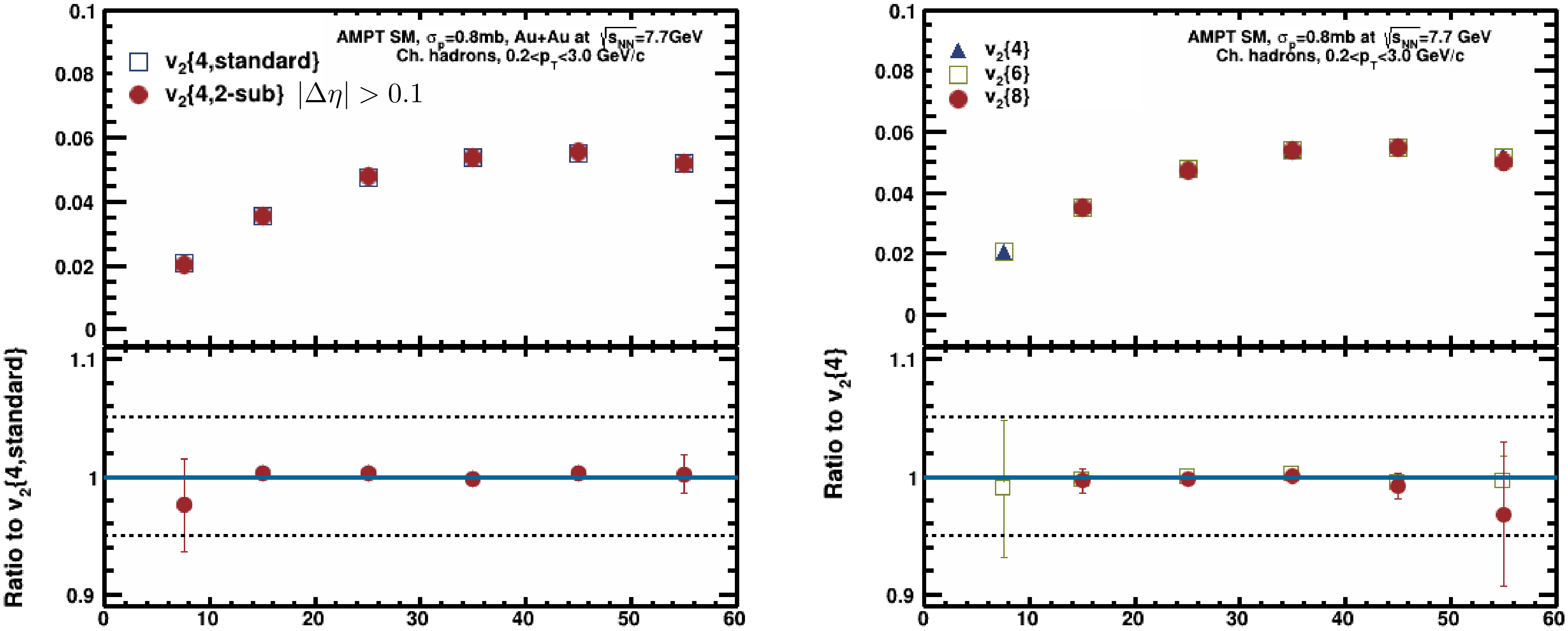
Sensitivity of different methods to flow fluctuations





$$v_2\{2\} \approx v_2^{\mathrm{SP}}\{Q_{2,\mathrm{TPC}}\}, v_2\{4\} < v_2\{2\}$$

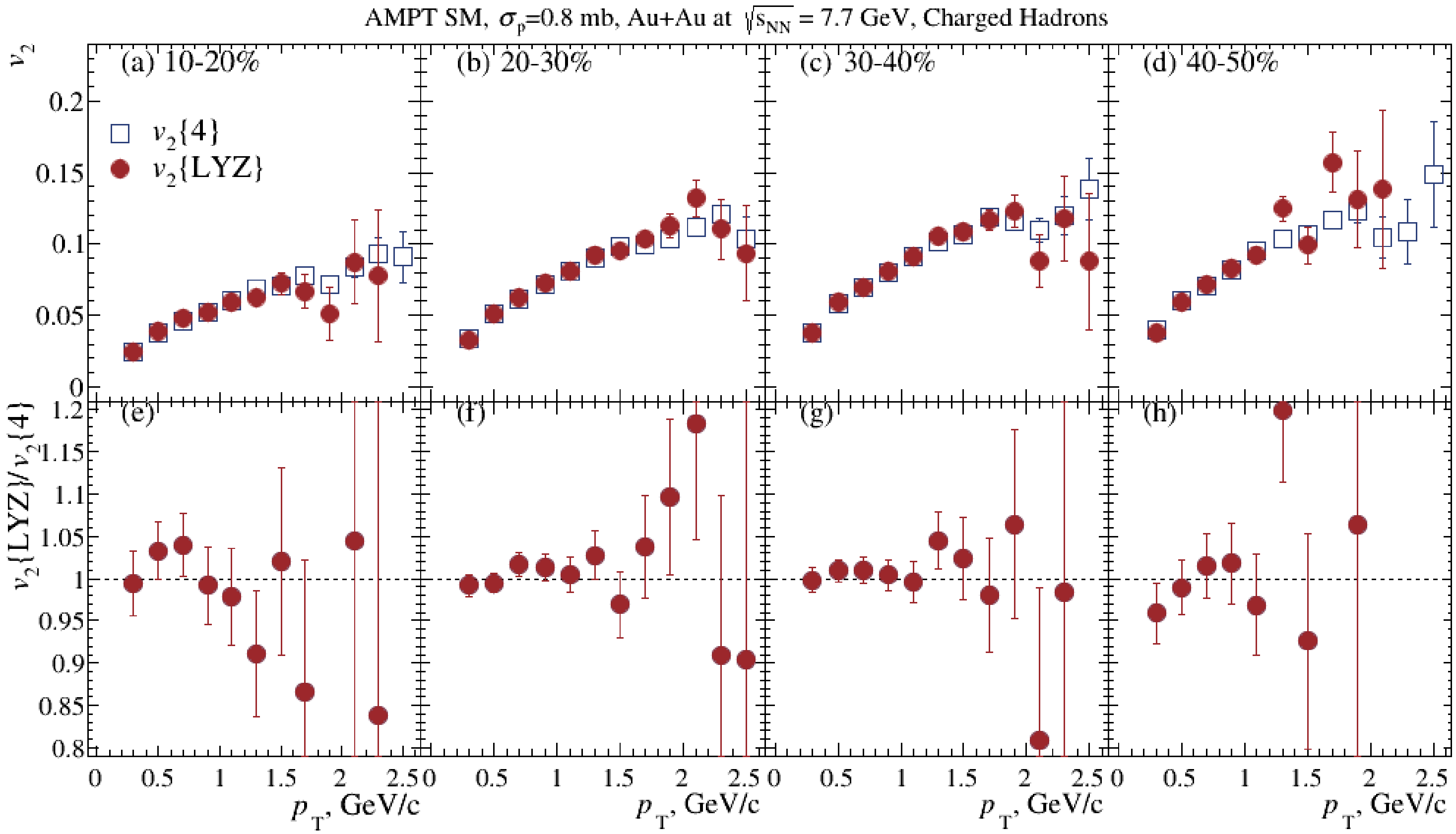
Comparison of high-order Q-Cumulants



Reasonable agreement between

$v_2\{4,\text{standard}\}$, $v_2\{4,\text{2-sub}\}$, $v_2\{6\}$, $v_2\{8\}$

Comparison between $v_2\{4\}$ and $v_2\{LYZ\}$

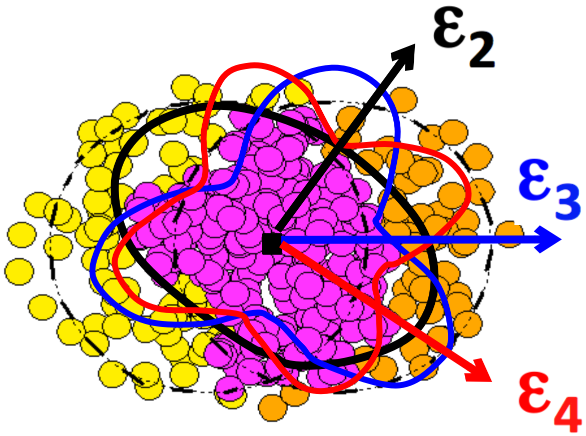


$v_2\{4\} \approx v_2\{LYZ\}$ at mid-centrality

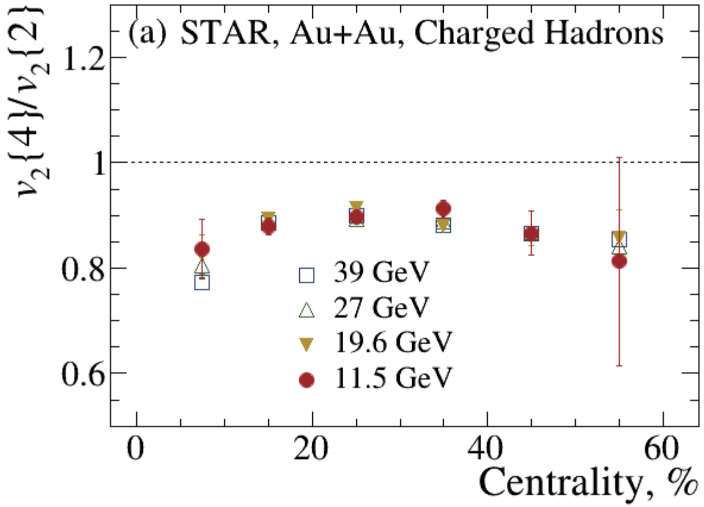
Need more statistics

Motivation of elliptic flow fluctuation study

- Indicate a dominant role for initial-state-driven fluctuation $\sigma_{\epsilon 2}$
- Provide further constraints for initial-state models, precision extraction of the temperature-dependent specific shear viscosity η/s(T) $(v_2 = \kappa_2 \epsilon_2)$



Phys.Rev.C **86**, 054908 (2012)

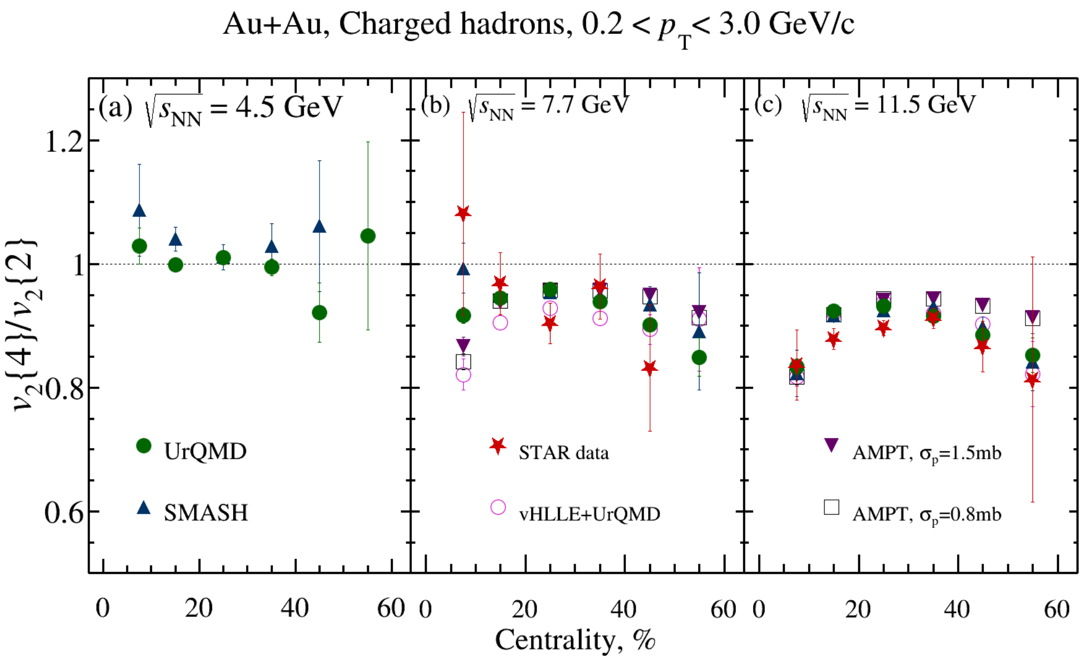


Note: small value of the $v_2\{4\}/v_2\{2\}$ ratio corresponds to large fluctuations

v_2 fluctuations at STAR BES:

- **weak dependence on collision energy**
- **main source: ϵ_2 fluctuations**

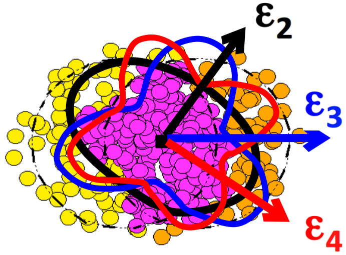
Relative flow fluctuations of charged hadrons



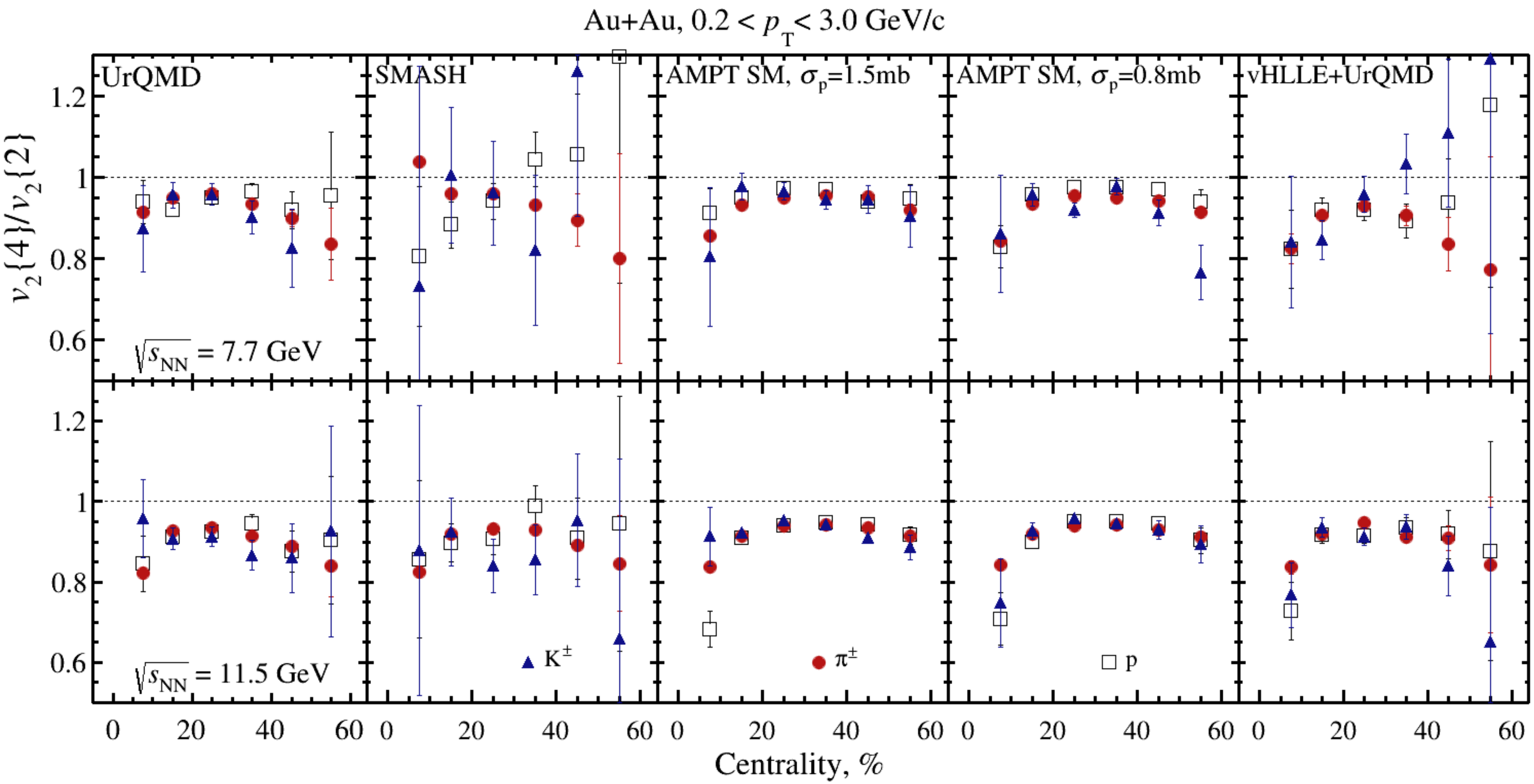
STAR data: Phys.Rev.C **86**, 054908 (2012)

After quality cuts, 0-80%: 4M at 7.7 GeV, 11M at 11.5 GeV

- 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 model with QGP phase (AMPT SM, vHLLE+UrQMD)
- Dominant source of v_2 fluctuations: **participant eccentricity fluctuations** in the initial geometry
- Are there non-zero v_2 fluctuations at $\sqrt{s_{NN}}$= 4.5 GeV?



Relative flow fluctuations of identified charged hadrons



Elliptic flow fluctuations show weak dependence on particle species

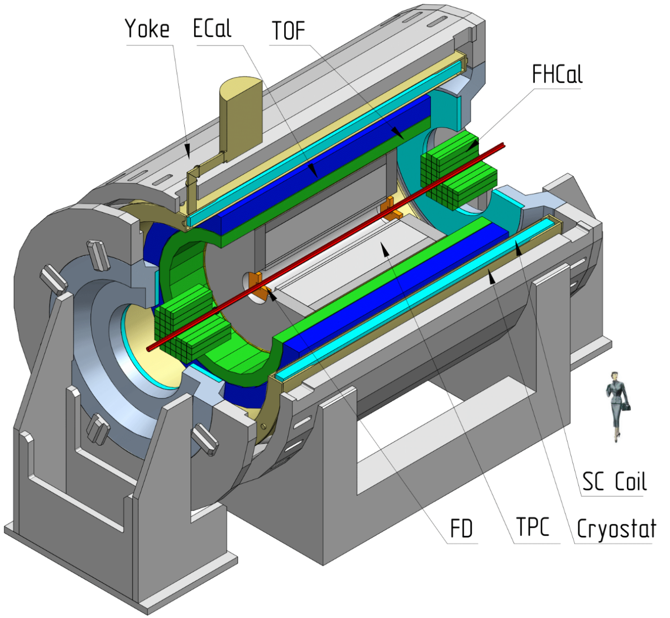
Need more statistics

MPD Experiment at NICA

UrQMD → GEANT4 → Reconstruction → Flow analysis

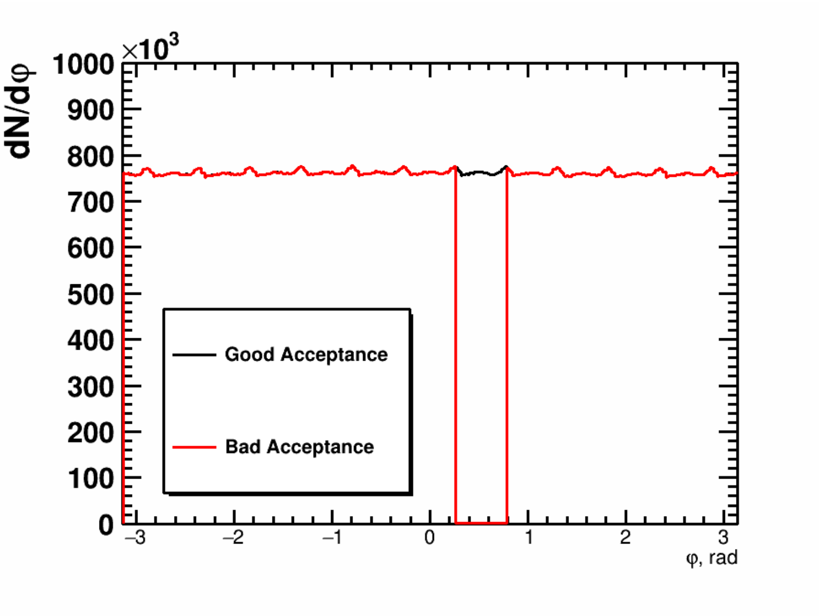
- Au+Au: 20M at $\sqrt{s_{NN}}$ = 7.7 GeV, 10M at $\sqrt{s_{NN}}$ = 11.5 GeV, Bi+Bi: 7M at $\sqrt{s_{NN}}$ = 7.7 GeV
- Centrality determination: Impact parameter b
- Event plane determination: TPC, FHCal
- Track selection:
  - Primary tracks
  - $N_{TPC\ hits} \geq 16$
  - $0.2 < p_T < 3.0$ GeV/c
  - $|\eta| < 1.5$
  - PID based on PDG

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

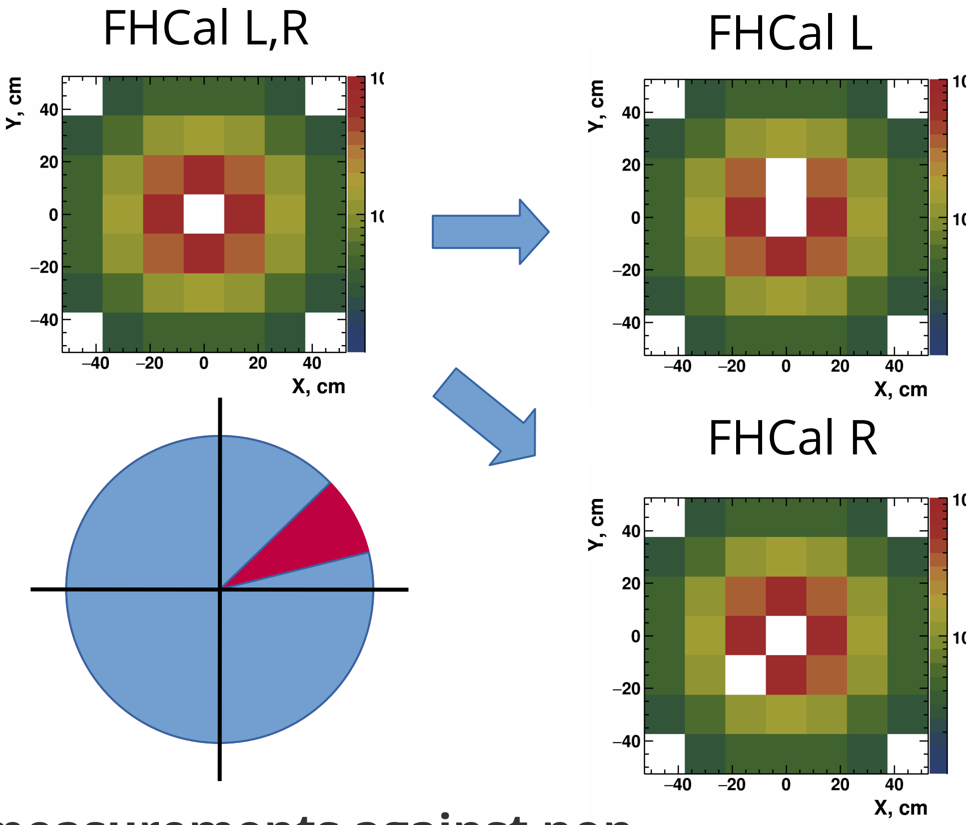


Multi-Purpose Detector (MPD) Stage 1

Non-uniform acceptance

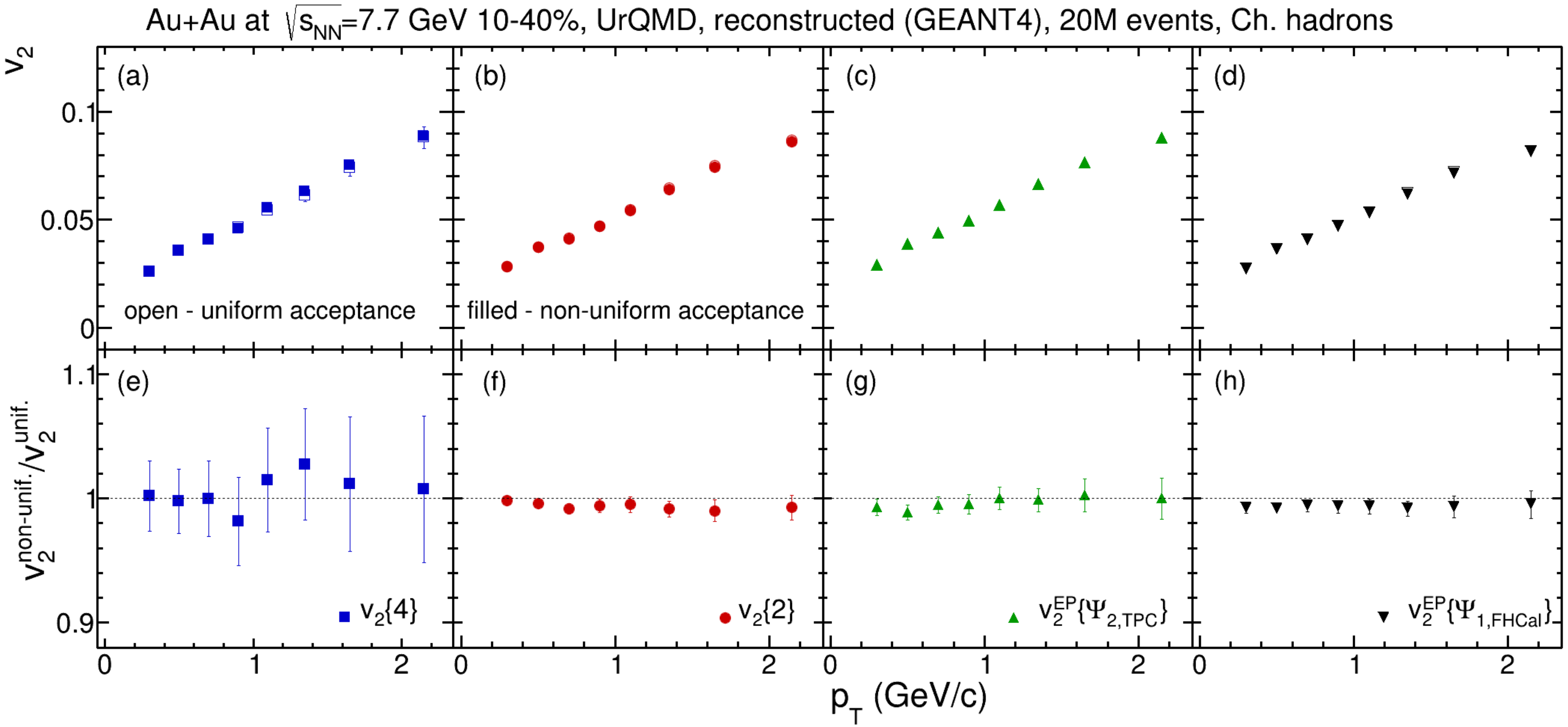


Area 15°< φ < 45° is off



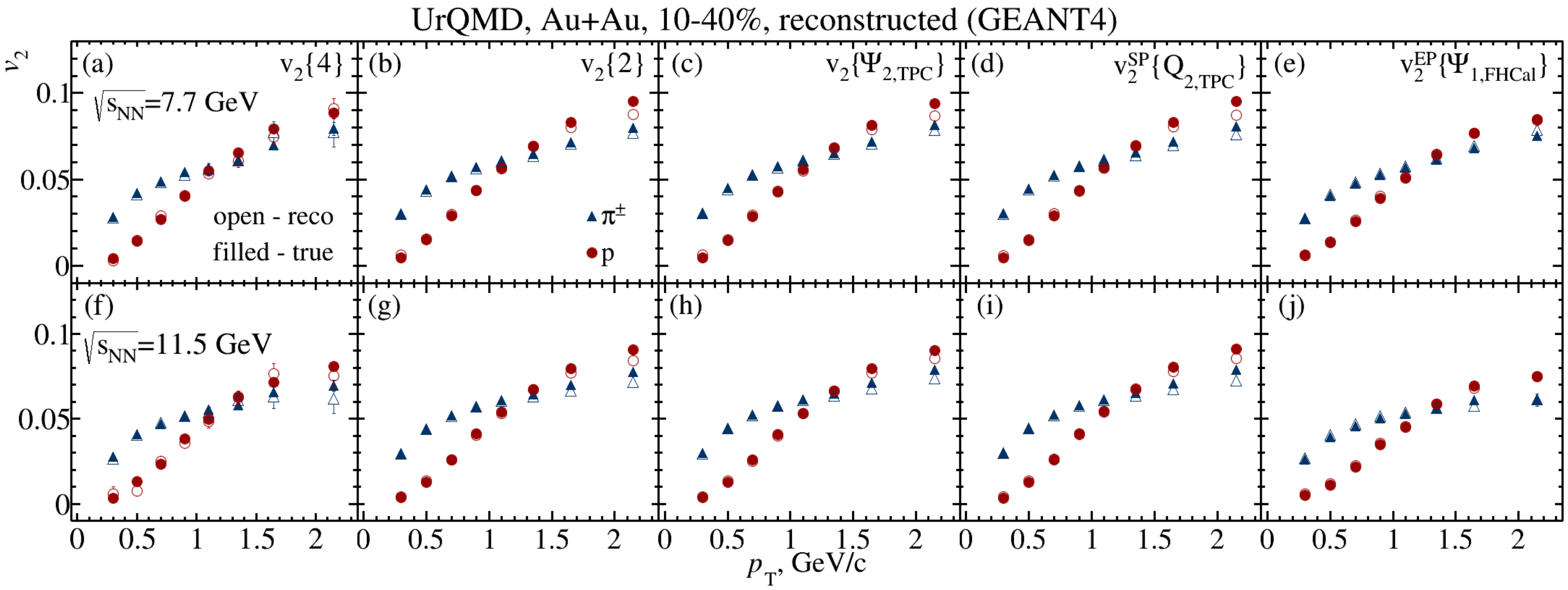
How robust are the future measurements against non-uniform acceptance?

Acceptance correction



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

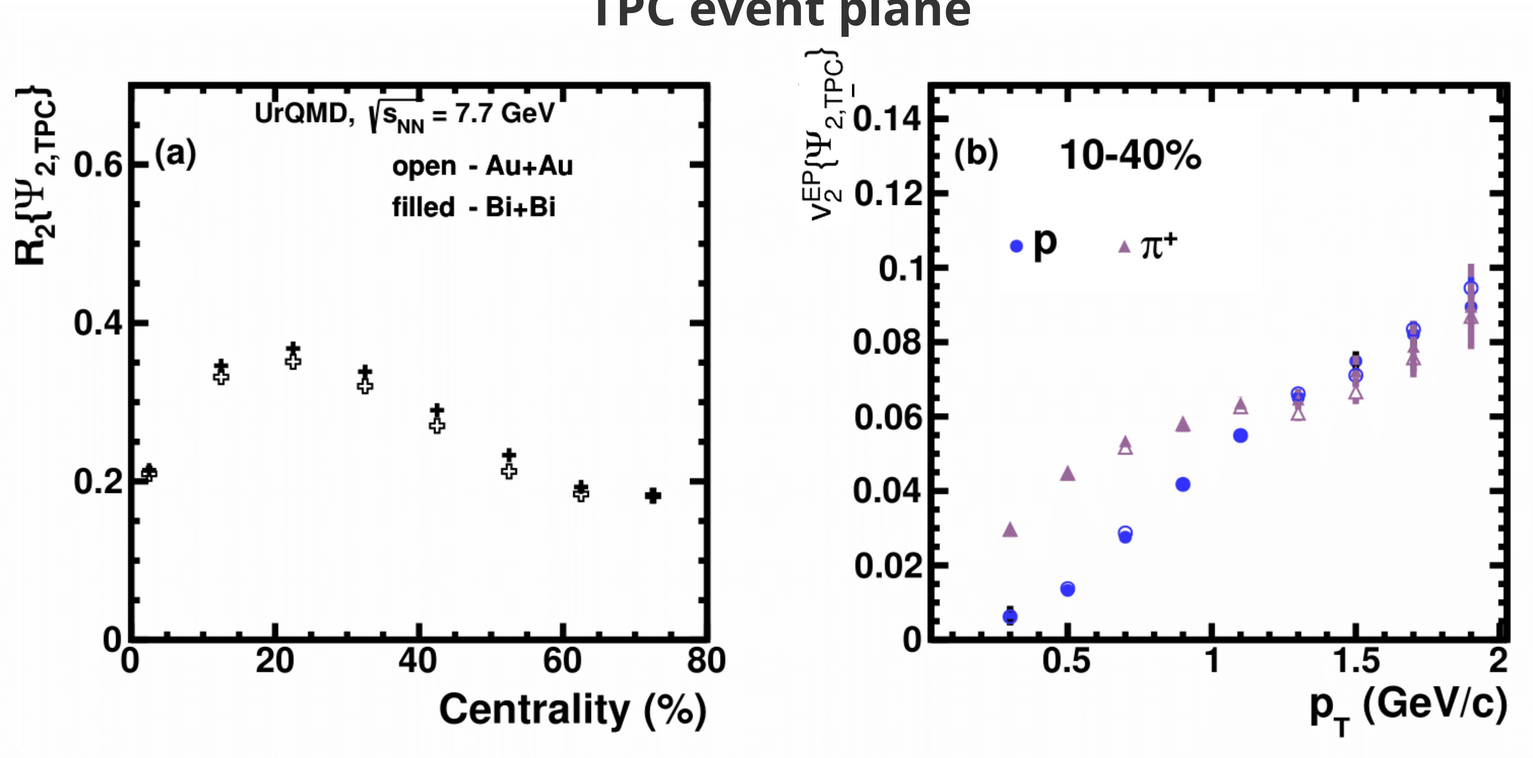
Performance of v_2 of pions and protons in MPD



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

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

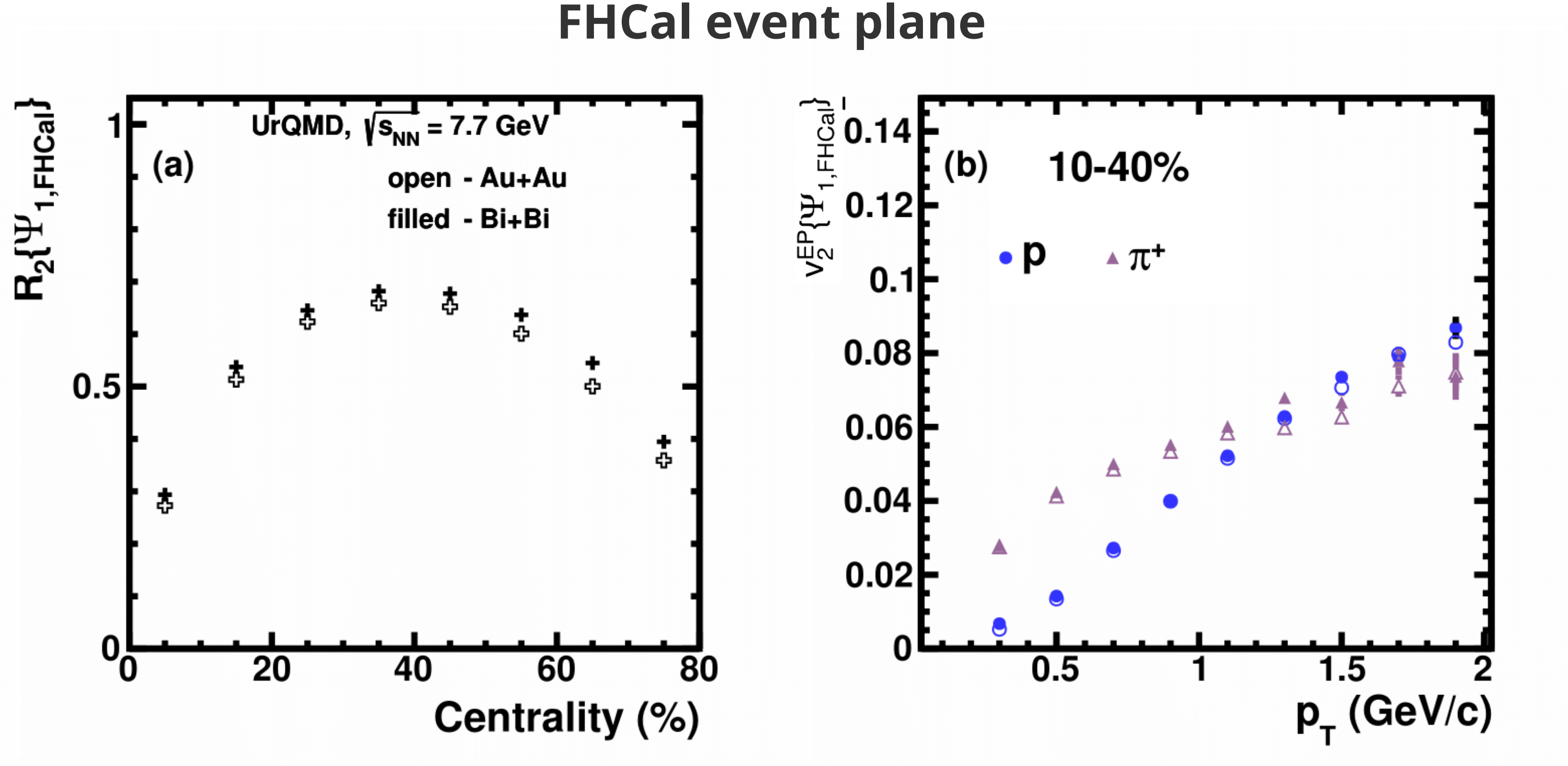
TPC event plane



Expected small difference between two colliding systems

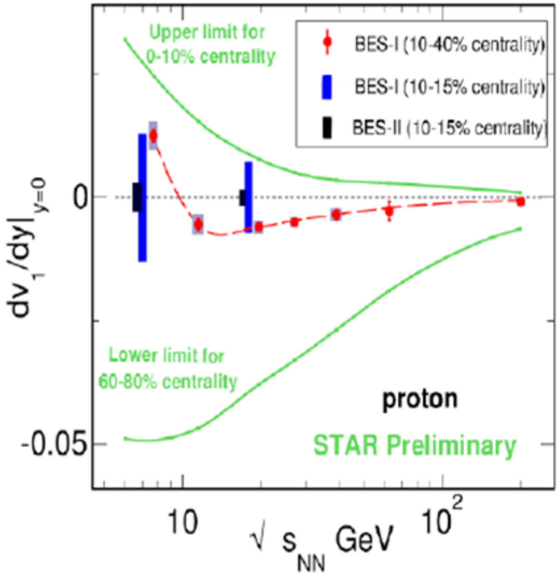
Au+Au vs. Bi+Bi collisions for MPD reconstructed data

FHCal event plane



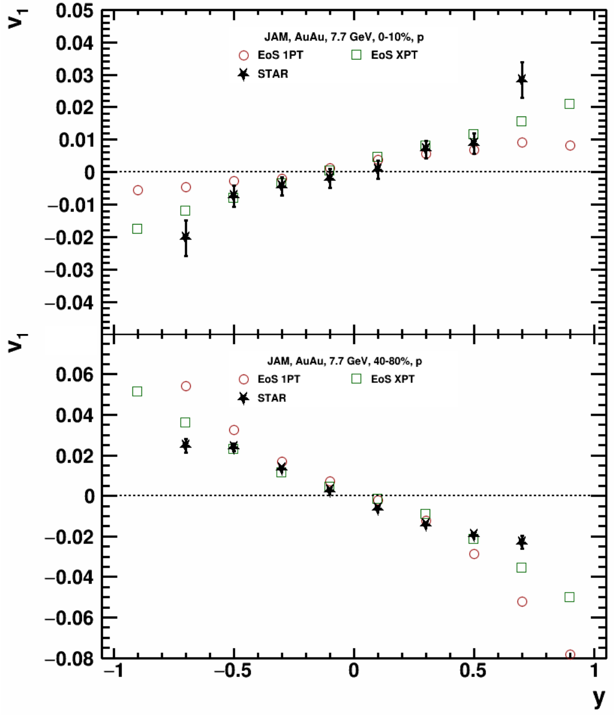
Expected small difference between two colliding systems

Outlook – v_1 study at NICA energies



Slope dv_1/dy has non-monotonic behavior and strong centrality dependence

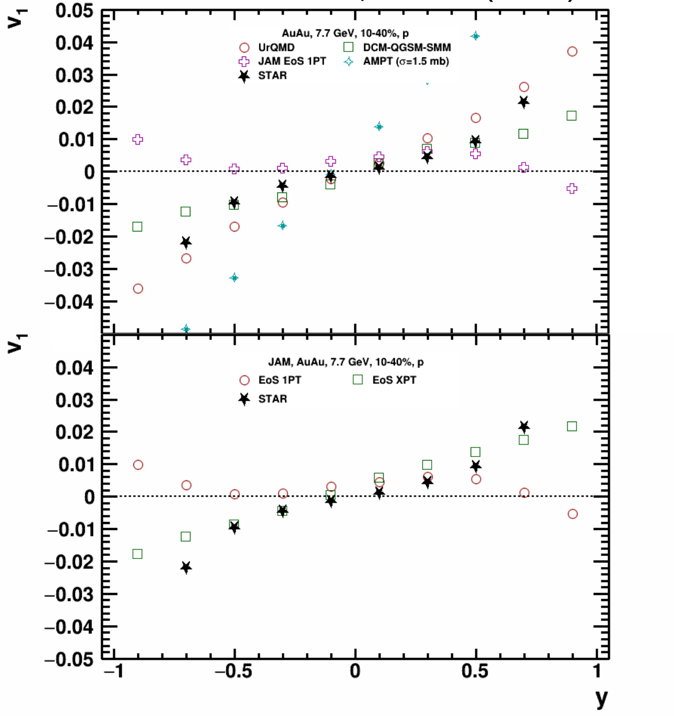
P. Parfenov, The Conference "RFBR Grants for NICA", Dubna (2020)



dv_1/dy slope changes dramatically with centrality for protons

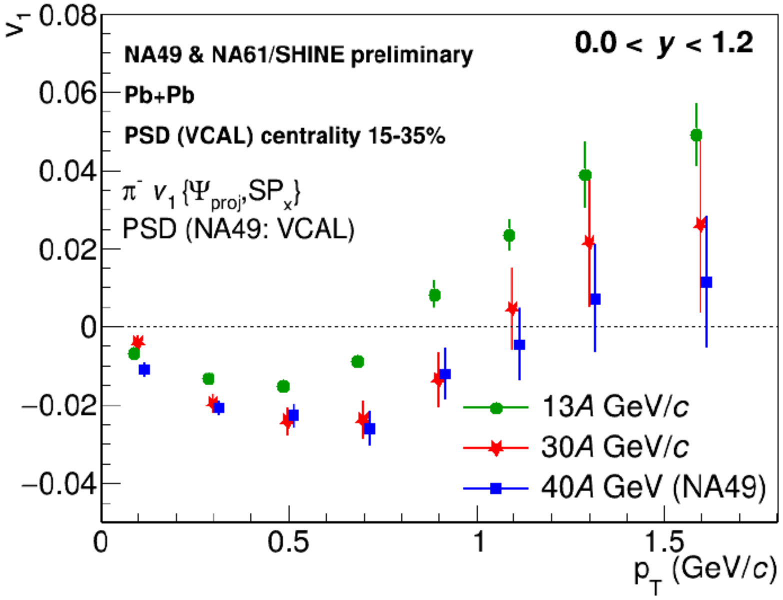
Outlook – v_1 study at NICA energies

P. Parfenov, The Conference "RFBR Grants for NICA", Dubna (2020)



DCM-QGSM-SMM and JAM XPT have the better agreement with STAR published data

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



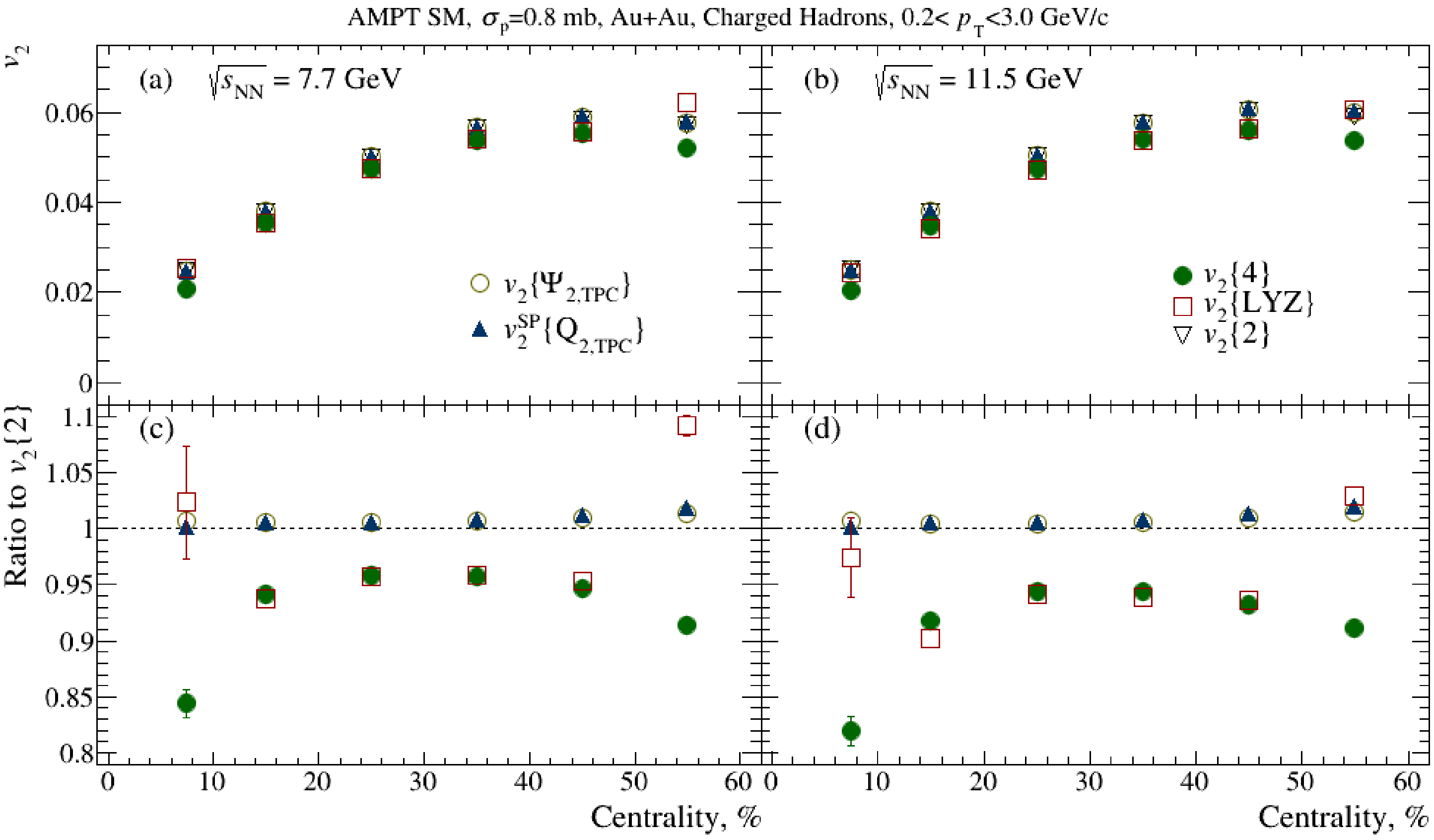
What kind of additional information can we extract from (p_T, centrality)-dependence of v_1 from comparison with DCM-QGSM-SMM and JAM (XPT & 1PT EoS) models?

Summary and outlook

- **v_2 at NICA energies shows strong energy dependence**
- **Comparison of methods for v_2 measurements from different models:**
  - The differences between methods are well understood and could be attributed to non-flow and fluctuations
  - Relative flow fluctuations $v_2\{4\}/v_2\{2\}$ measured in STAR can be reproduced by models with and without QGP, indicating main source of flow fluctuations is the participant eccentricity 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
  - v_2 measurements are robust upon non-uniform acceptance in MPD
  - Expected small difference between Bi+Bi and Au+Au colliding systems
- **Outlook:**
  - v_1, v_2, and v_3 measurements for the MPD reconstructed data from vHLLE+UrQMD model
- **Github repository:** https://github.com/FlowNICA/CumulantFlow

Back-up slides

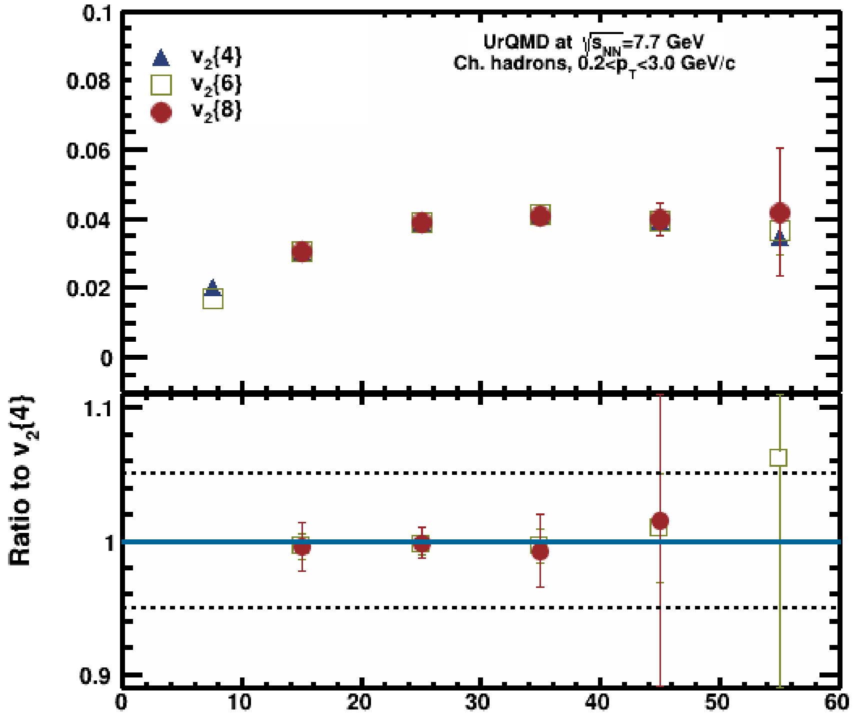
Centrality dependence of v_2\{methods\}



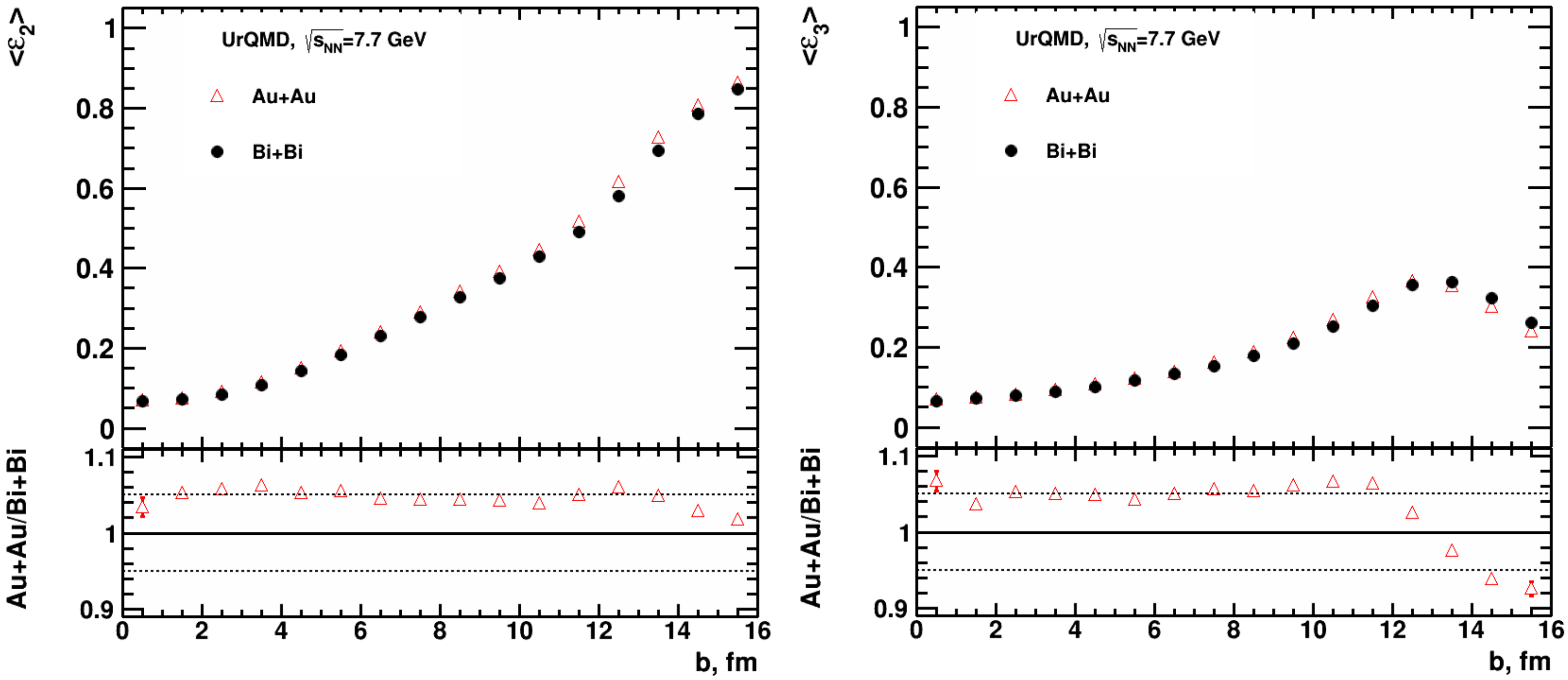
$v_2\{4\} \approx v_2\{LYZ\}$, $v_2\{2\} \approx v_2\{SP\} \approx v_2\{\Psi_{2,TPC}\}$

Description of high-order Q-Cumulants

- **Higher order Q-Cumulants $v_2\{m\}$ (m=6,8):**
  (A. Bilandzic et al., Phys. Rev. C **89** (2014), 064904)
  - number of terms in "standalone" analytical expressions increases quickly with order of correlators
  - using recursive algorithms: calculate analytically higher-order correlators in terms of lower ones



Eccentricity: Bi+Bi vs. Au+Au



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