Anisotropic collective flow and development of the corresponding measurement techniques for the MPD experiment

Alexander Demanov[1], Dim Idrisov[1], Vinh Ba Luong[1], Nikolay Geraksiev[2,3], Petr Parfenov[1] , Ilya Selyuzhenkov[1,5] ,Viktor Kireyeu[2] , Evgeny Volodihin[1] , Anton Truttse[1], Mikhail Mamaev[1] , Dmitri Blau[4] , Oleg Golosov[1] , Evgeni Kashirin[1] , Jovan Milošević[6] ,Laslo Nađđerđ[6], Vladimir Reković[6], Dragan Toprek[6], Dragan Manić[6], Arkadiy Taranenko[1]

[1]National Research Nuclear University MEPhI
[2]VBLHEP JINR
[3]FPT, Plovdiv University “Paisii Hilendarski”
[4]Kurchatov Institute, Moscow, [5]GSI/FAIR
[6]Vinča Institute of Nuclear Sciences, University of Belgrade, Serbia

For the MPD Collaboration

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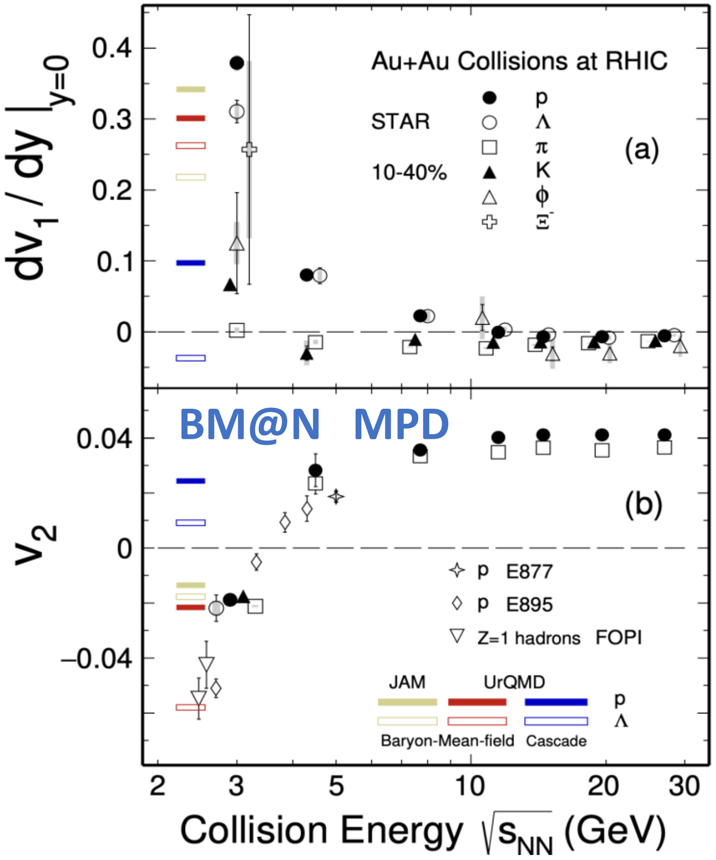
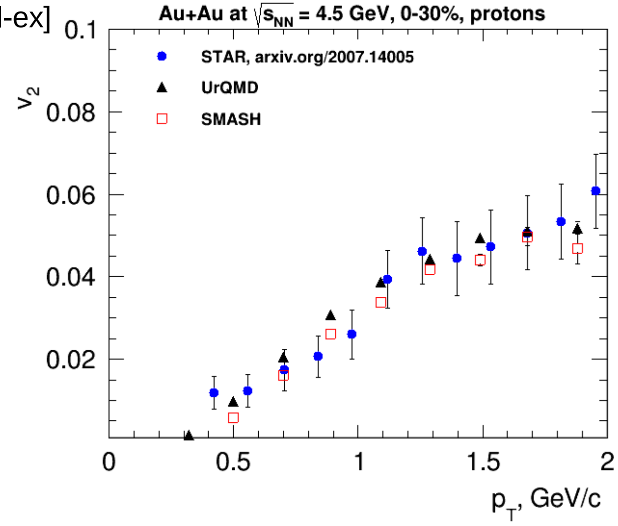
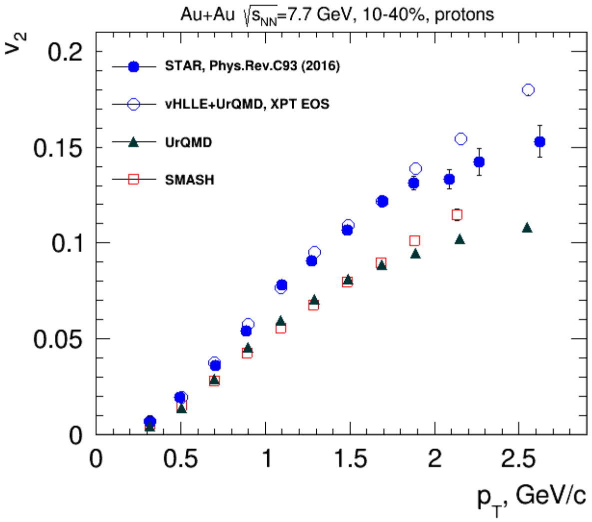
Anisotropic flow at NICA energies

M. Abdallah et al. [STAR Collaboration] 2108.00908 [nucl-ex]



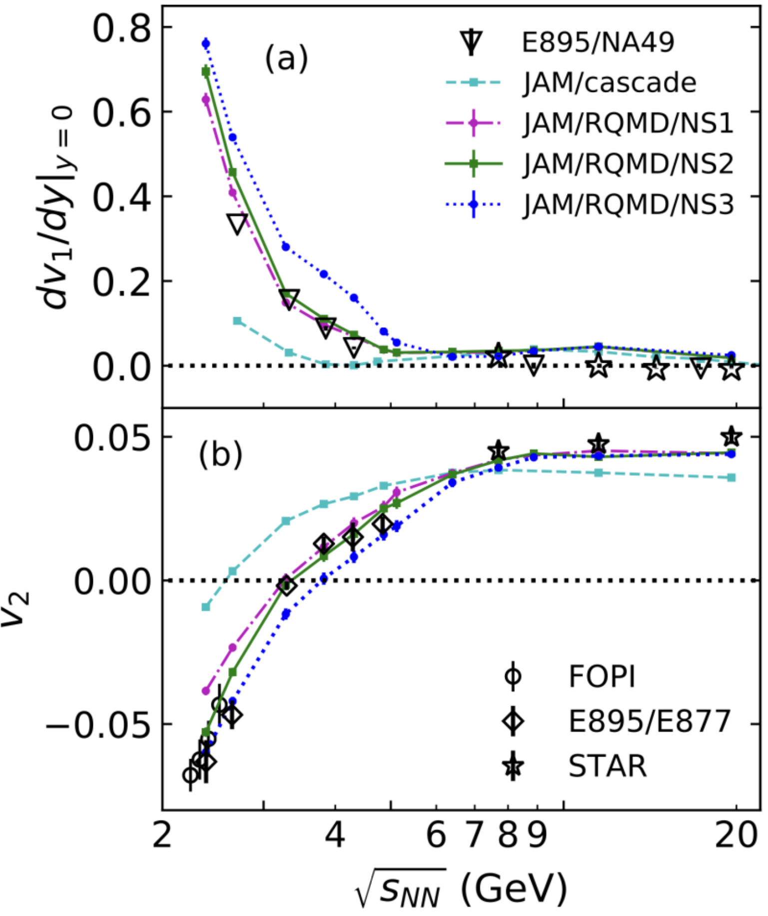




- **Strong energy dependence of v_1 and v_2 at $\sqrt{s_{NN}}$ = 3-11 GeV**
  - $v_2 \approx 0$ at $\sqrt{s_{NN}}$ = 3.3 GeV and negative below
- **Lack of differential measurements of v_2 at NICA energies (p_T, centrality, PID,…)**
- **v_2 is sensitive to the properties of strongly interacting matter:**
  - 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,…)

- Make predictions for the anisotropic flow measurements $v_n(p_T, y)$ at BM@N ($\sqrt{s_{NN}}$=2.3-3.3 GeV) and MPD ($\sqrt{s_{NN}}$=4-11 GeV) energies

Anisotropic flow study at $\sqrt{s_{NN}}$=2-4.5 GeV



To study energy dependence of v_n, JAM microscopic model was selected (ver. 1.90597)

NN collisions are simulated by:

- $\sqrt{s_{NN}}$<4 GeV: resonance production
- 4<$\sqrt{s_{NN}}$<50 GeV: soft string excitations
- $\sqrt{s_{NN}}$>10 GeV: minijet production

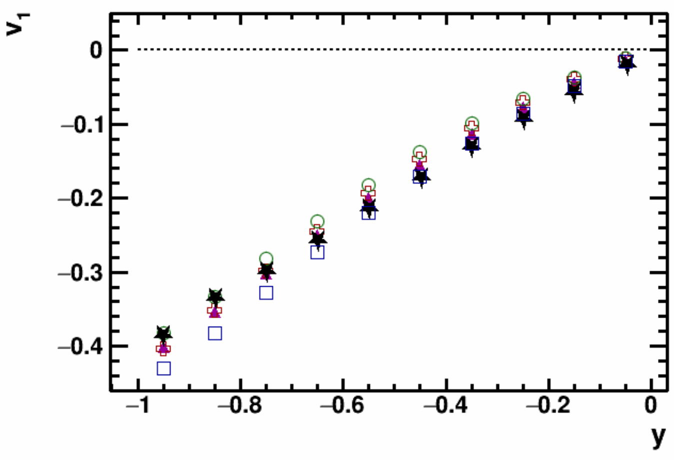
We use RQMD with relativistic mean-field theory (non-linear σ-ω model) implemented in JAM model

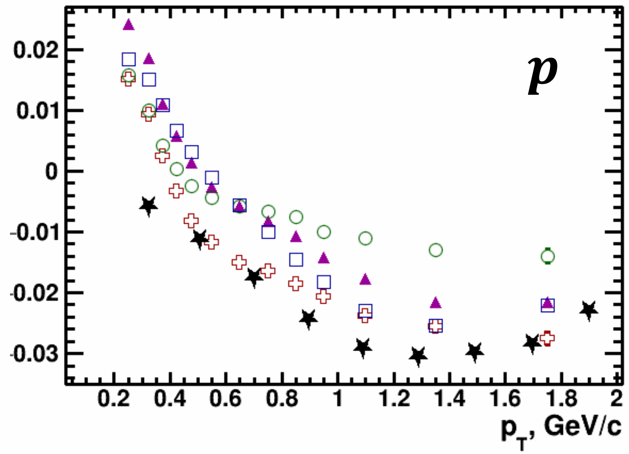
Different EOS were used:

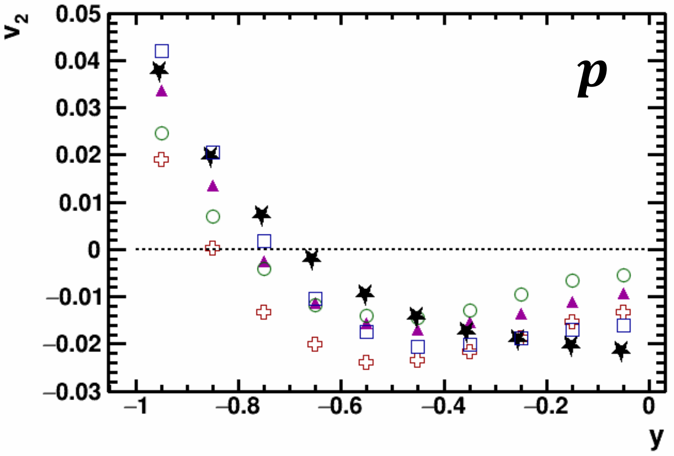
- **MD3** (momentum-dependent potential): K=210 MeV, m^*/m=0.65, $U_{opt}(\infty)$=37
- **MD2** (momentum-dependent potential): K=210 MeV, m^*/m=0.65, $U_{opt}(\infty)$=37
- **NS1** (standard potential): K=380 MeV, m^*/m=0.83
- **NS2** (standard potential): K=210 MeV, m^*/m=0.83

Y.Nara, T.Maruyama, H.Stoecker Phys. Rev. C 102, 024913 (2020)
Y.Nara, H.Stoecker Phys. Rev. C 100, 054902 (2019)

v_1 and v_2 in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data







JAM, Au+Au, 10-40% **(4.6<b<9.3 fm)**

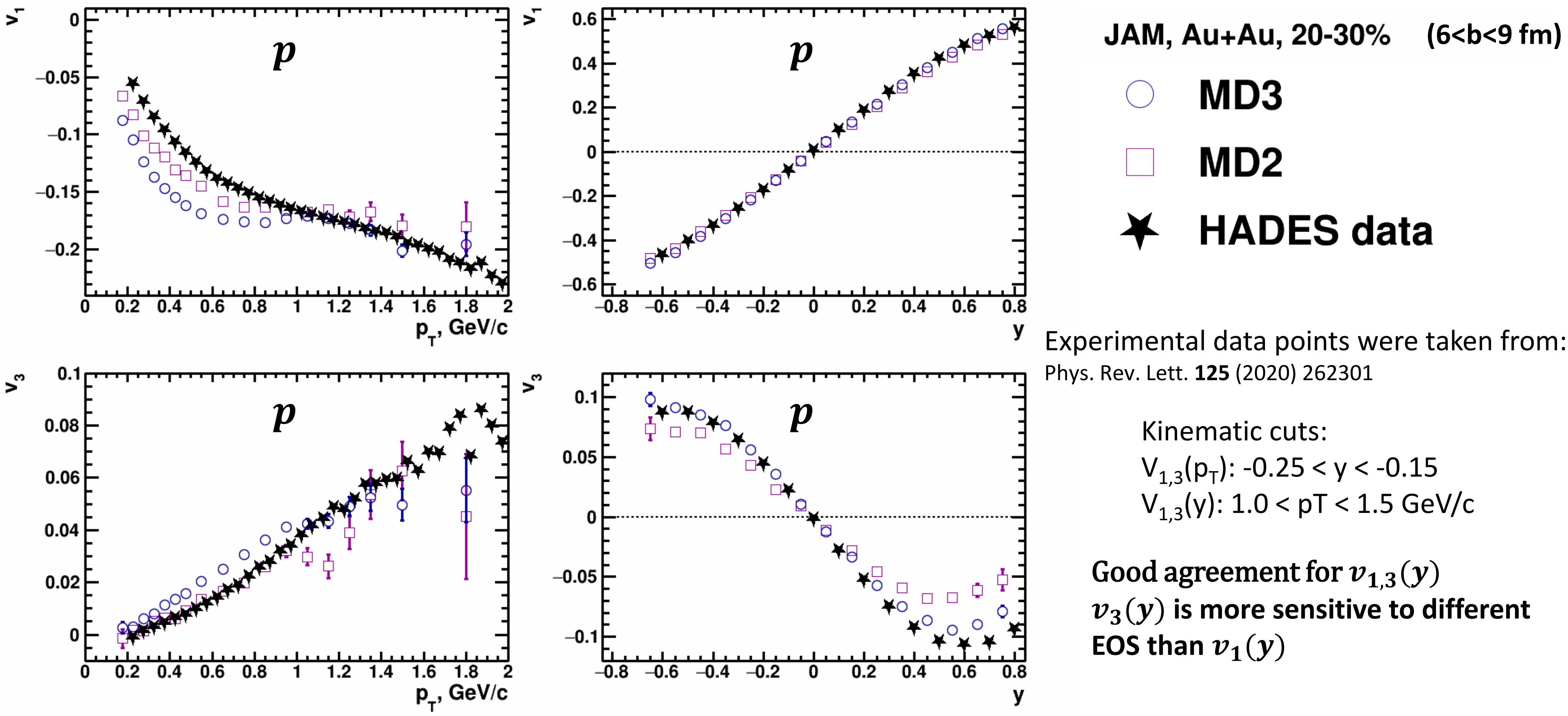
- □ **MD3**
- ▲ **MD2**
- ✚ **NS1**
- ○ **NS2**
- ★ **STAR data**

Experimental data points were taken from:
Mohamed Abdallah et al. [STAR Collaboration]
2108.00908 [nucl-ex]

Kinematic cuts:
$v_2(p_T)$: -1 < y < 0
v_2(y) of $\pi^{\pm}$: 0.2 < pT < 1.6 GeV/c
v_2(y) of p: 0.4 < pT < 2.0 GeV/c

v_2 of pions and protons is more sensitive to different EOS than v_1

$v_{1,3}(p_T, y)$ in Au+Au $\sqrt{s_{NN}}$=2.4 GeV: model vs. HADES data

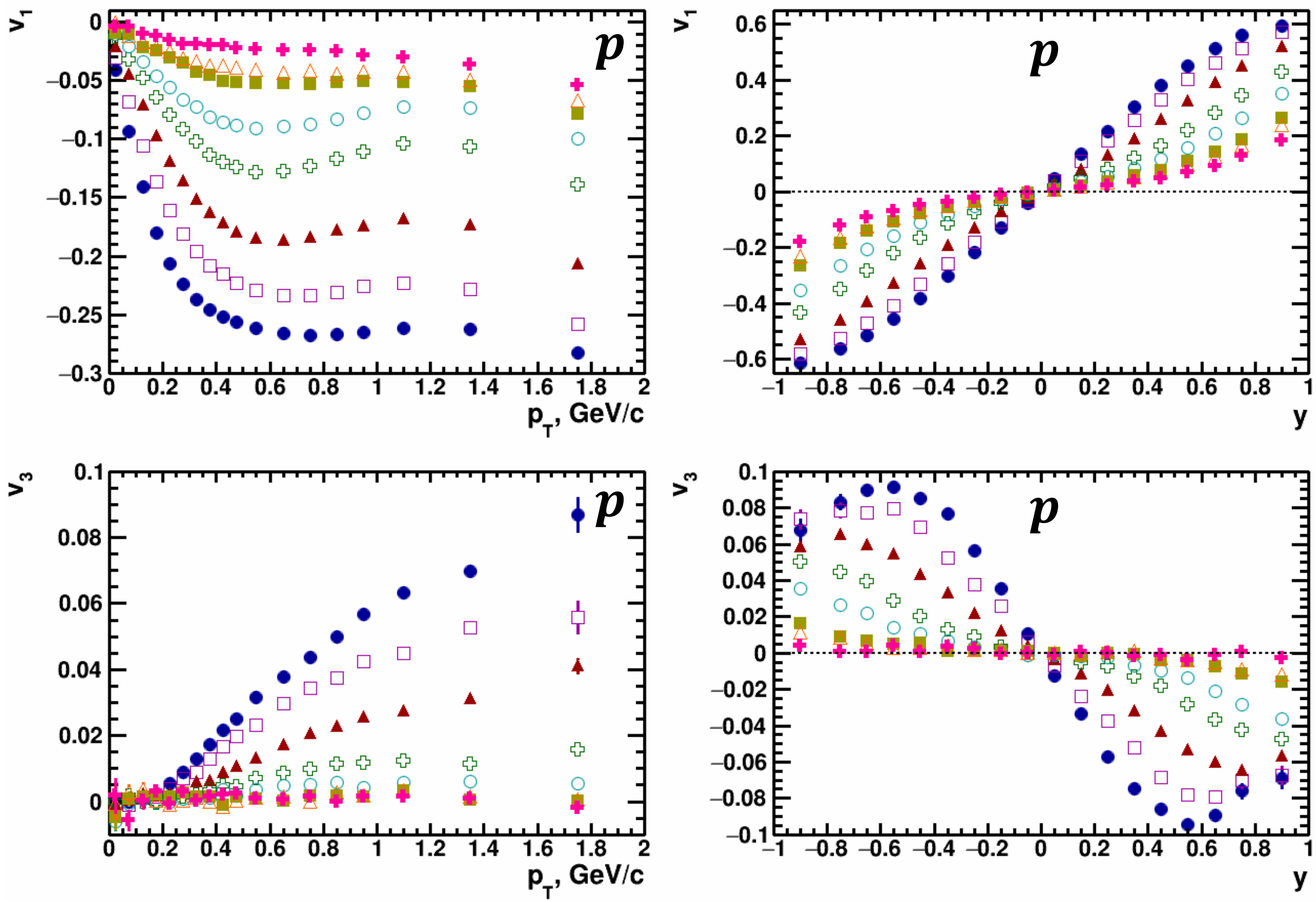


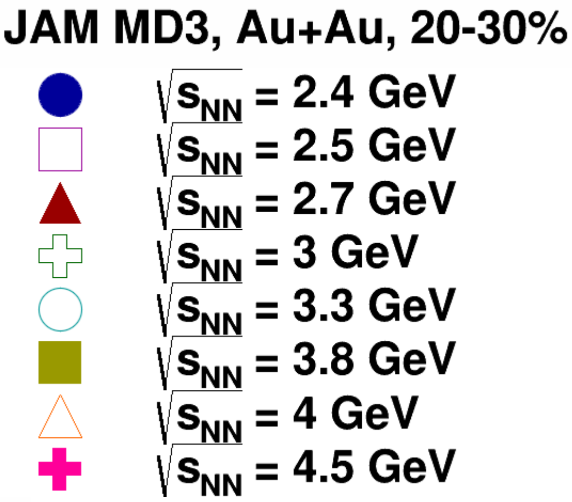
Experimental data points were taken from:
Phys. Rev. Lett. **125** (2020) 262301

Kinematic cuts:
$V_{1,3}(p_T)$: -0.25 < y < -0.15
$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c

Good agreement for $v_{1,3}(y)$
$v_3(y)$ is more sensitive to different EOS than $v_1(y)$

$v_{1,3}(p_T, y)$ Au+Au $\sqrt{s_{NN}}$=2.4-4.5 GeV: JAM





Protons:

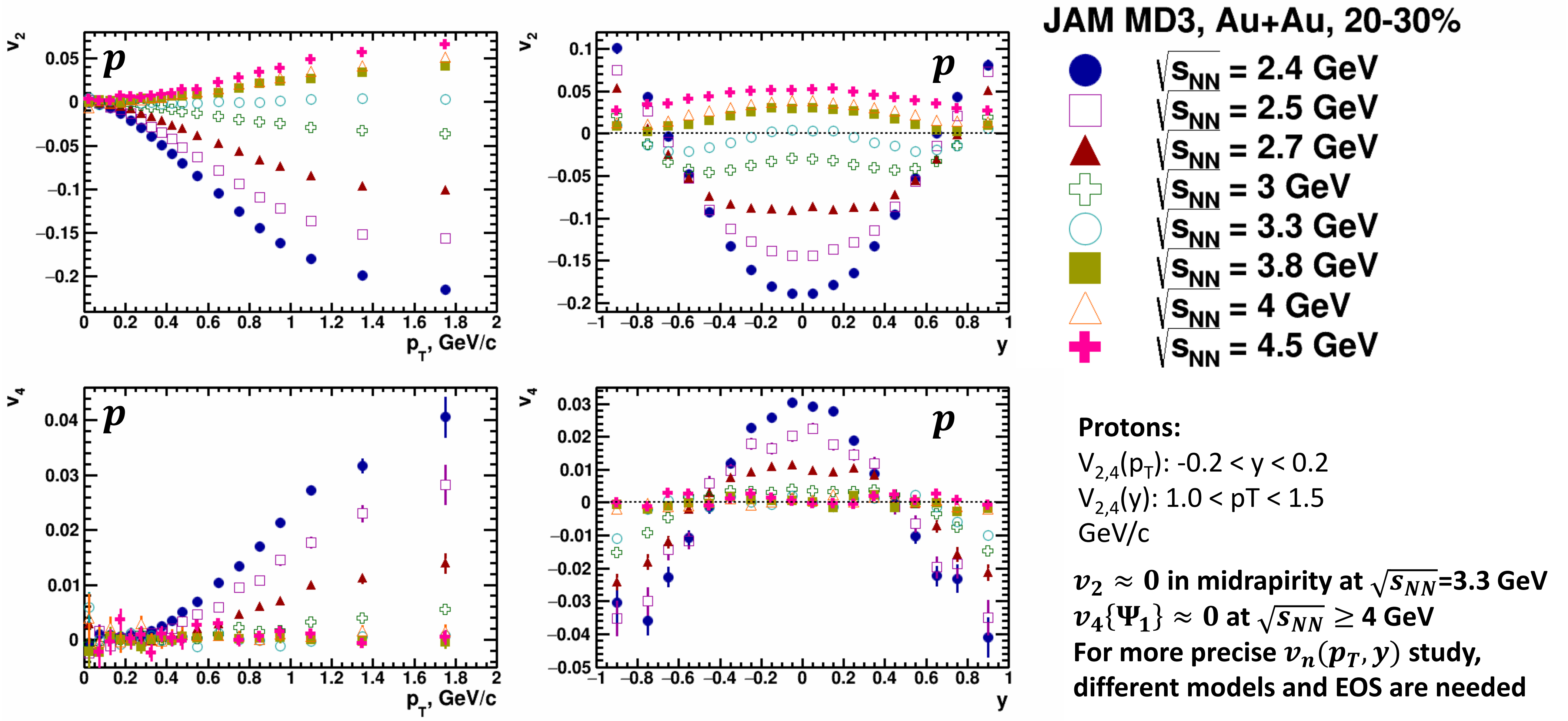
$V_{1,3}(p_T)$: -0.5 < y < -0.15

$V_{1,3}(y)$: 1.0 < pT < 1.5 GeV/c

$|v_{1,3}\{\Psi_1\}|$ decreases with increasing collision energy

$v_3 \approx 0$ at $\sqrt{s_{NN}} \geq 4$ GeV

$v_{2,4}(p_T, y)$ Au+Au $\sqrt{s_{NN}}$=2.4-4.5 GeV: JAM



Protons:

$V_{2,4}(p_T)$: -0.2 < y < 0.2

$V_{2,4}(y)$: 1.0 < pT < 1.5 GeV/c

$v_2 \approx 0$ in midrapirity at $\sqrt{s_{NN}}$=3.3 GeV

$v_4\{\Psi_1\} \approx 0$ at $\sqrt{s_{NN}} \geq 4$ GeV

For more precise $v_n(p_T, y)$ study, different models and EOS are needed

Event plane method using FHCal

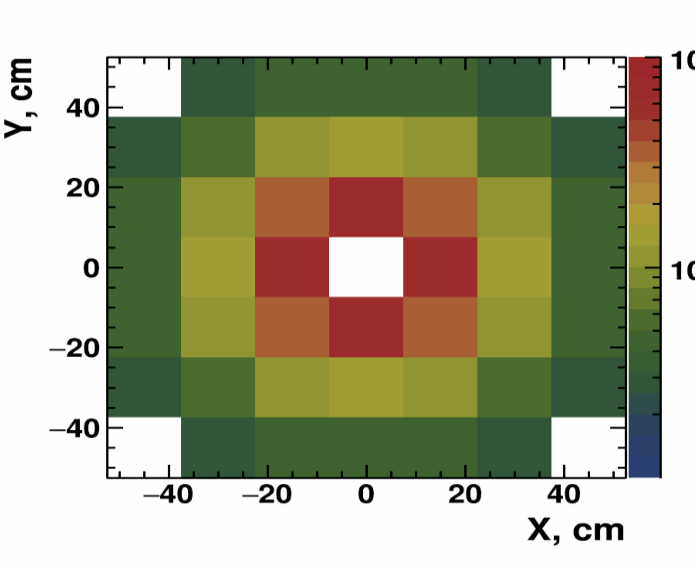
- Using v_1 of particles in FHCal to determine Q_n

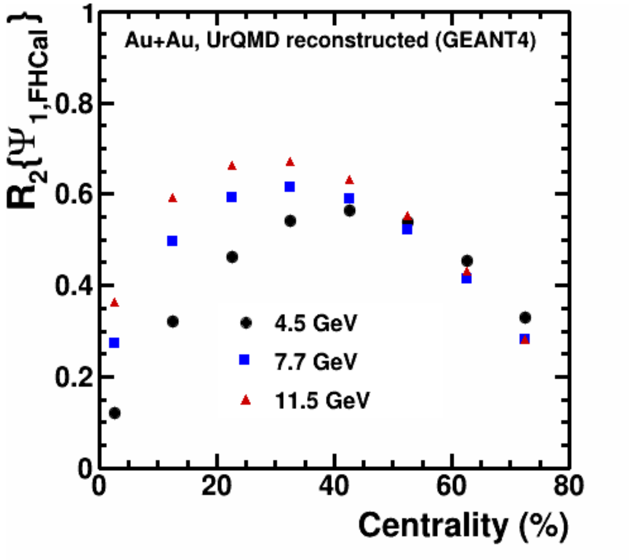
$$Q_1 = \frac{\sum_j E_i e^{i\phi_j}}{\sum_j E_j}, \quad \Psi_{1,\mathrm{FHCal}} = \tan^{-1}\left(\frac{Q_{1,y}}{Q_{1,x}}\right)$$

E – energy deposited in FHCal modules $(2 < |\eta| < 5)$

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

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





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

v_n of V0 particles: invariant mass fit method (Nikolay Geraksiev)

Data set:

- 25 million events, UrQMD 3.4 non-hydro, 11.0 GeV, minbias

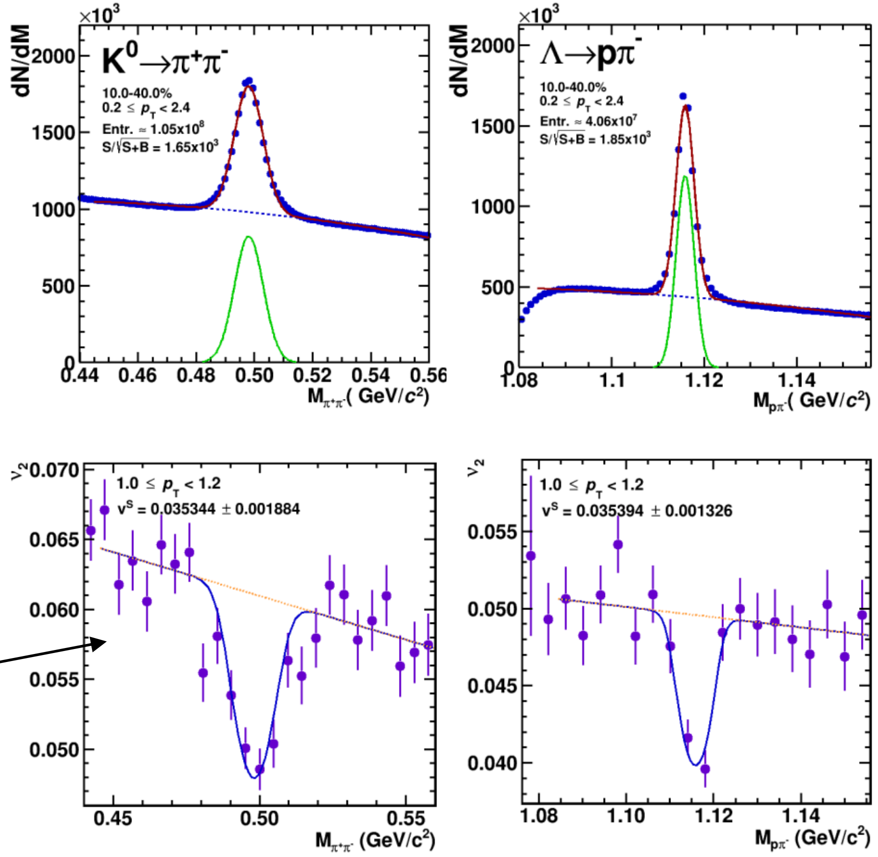
Geant4 simulation, full reconstruction with:

- 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

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



Outlook:
* Larger statistics with vHLLE (hydrodynamic evolution)
* Larger signal magnitude due to hydro (realistic input)
* Latest versions of detector geometry

- Multi-variate analysis for reconstructed particle selection (TMVA)
- KFParticle

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

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

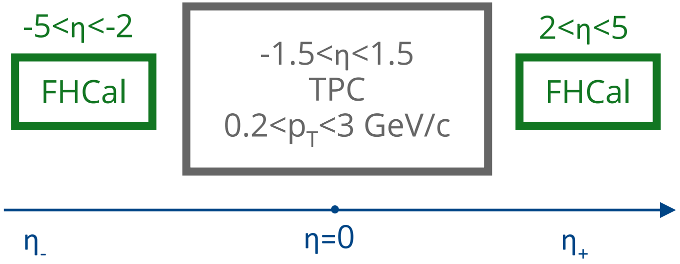
$$Q_2 = \sum_{j=1}^{M} \omega_j u_{2,j}, \; \Psi_{2,\mathrm{TPC}} = \frac{1}{2}\tan^{-1}\left(\frac{Q_{2,y}}{Q_{2,x}}\right)$$

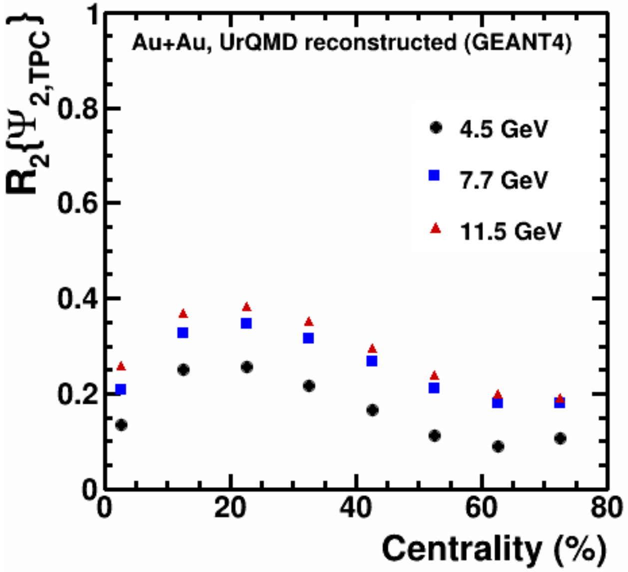
- **Scalar product:** $$v_2^{\mathrm{SP}}\{Q_{2,\mathrm{TPC}}\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp}\rangle}{\sqrt{\langle Q_{2,\eta+} Q_{2,\eta-}\rangle}}$$

- **TPC Event-plane:**

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

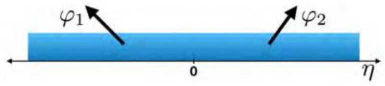
$$\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \sqrt{\langle \cos\left[2(\Psi_{2,\eta+} - \Psi_{2,\eta-})\right]\rangle}$$

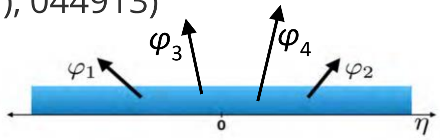




Elliptic flow measurements using TPC: Q-Cumulants

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





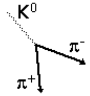
$$\langle 2\rangle_n = \frac{|Q_n|^2 - M}{M(M-1)} \approx v_2^2 + \delta$$

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

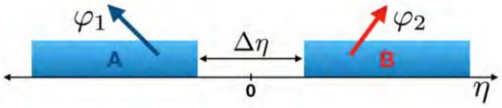
$$v_2\{4\} = \sqrt[4]{2\langle\langle 2\rangle\rangle^2 - \langle\langle 4\rangle\rangle}$$

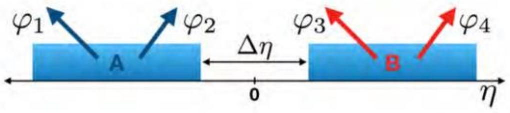
δ – nonflow contribution

- resonance decay
- jets



- **Subevent Q-Cumulants:** (J. Jia et al., Phys. Rev. C **96** (2017), no. 3, 0





$$\langle 2\rangle_{a|b} = \frac{Q_{n,a}Q_{n,b}^*}{M_aM_b},\ v_2\{2{,}2-\mathrm{sub}\} = \sqrt{\langle\langle 2\rangle\rangle_{a|b}}$$

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

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

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)

$$v_2\{2\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$$

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

- **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**:

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

$v_n\{2k\}$ (k=1,…,5) from JAM model

Group members:
Jovan Milošević
Laslo Nađđerđ
Vladimir Reković
Dragan Toprek
Dragan Manić
University of Belgrade
Vinča Institute of Nuclear Sciences,
Belgrade, Serbia

- For the first time $v_n\{10\}$

$$v_n\{10\} = \sqrt[10]{\frac{1}{456} c_n\{10\}}$$

- $v_n\{2k\}$ (k=1,…,5) cumulant's statistical uncertainties are calculated analytically using the data: Phys. Rev. C 104 (2021) 034906, arXiv:2104.00588 [nucl-th].
- First time introduced a new (second) hydrodynamics probe that includes $v_2\{10\}$
  - First hydrodynamics probe:

$$\frac{v_2\{6\} - v_2\{8\}}{v_2\{4\} - v_2\{6\}} = \frac{1}{11}$$

  - Second hydrodynamics probe:

$$\frac{v_2\{8\} - v_2\{10\}}{v_2\{6\} - v_2\{8\}} = \frac{3}{19}$$

- Codes for both, with and without efficiency corrections are developed
- Q-cumulants technique is applied as it is enable very fast calculations
- Difficulties when flow magnitude, or particle multiplicity is too small

$v_n\{10\}$ from Q-cumulants

10-th order Q-cumulant $\langle\langle 10\rangle\rangle = \langle\langle e^{in(f_1+f_2+f_3+f_4+f_5-f_6-f_7-f_8-f_9-f_{10})}\rangle\rangle$

$$c_n\{10\} = \langle\langle 10\rangle\rangle - 25\times\langle\langle 2\rangle\rangle\langle\langle 8\rangle\rangle - 100\times\langle\langle 4\rangle\rangle\langle\langle 6\rangle\rangle$$
$$+400\times\langle\langle 6\rangle\rangle\langle\langle 2\rangle\rangle^2 + 900\times\langle\langle 2\rangle\rangle\langle\langle 4\rangle\rangle^2$$
$$-360\times\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle^3 + 2880\times\langle\langle 2\rangle\rangle^5$$

- **For the first time $v_n\{10\}$** $\quad v_n\{10\} = \sqrt[10]{\frac{1}{456}c_n\{10\}}$

Statistical uncertainties of the $v_n\{2k\}$ (k=1,…,5) cumulants are calculated analytically using the data [Phys. Rev. C 104 (2021) 034906 arXiv:2104.00588 [nucl-th]]

$$s^2[v_n\{10\}]\times 4560^2(v_n\{10\})^{18} = A^2 s^2_{\langle\langle 2\rangle\rangle} + B^2 s^2_{\langle\langle 4\rangle\rangle}$$
$$+C^2 s^2_{\langle\langle 6\rangle\rangle} + D^2 s^2_{\langle\langle 8\rangle\rangle} + s^2_{\langle\langle 10\rangle\rangle} + 2ABs_{\langle\langle 2\rangle\rangle,\langle\langle 4\rangle\rangle}$$
$$+2ACs_{\langle\langle 2\rangle\rangle,\langle\langle 6\rangle\rangle} + 2ADs_{\langle\langle 2\rangle\rangle,\langle\langle 8\rangle\rangle} + 2As_{\langle\langle 2\rangle\rangle,\langle\langle 10\rangle\rangle}$$
$$+2BCs_{\langle\langle 4\rangle\rangle,\langle\langle 6\rangle\rangle} + 2BDs_{\langle\langle 4\rangle\rangle,\langle\langle 8\rangle\rangle} + 2Bs_{\langle\langle 4\rangle\rangle,\langle\langle 10\rangle\rangle}$$
$$+2CDs_{\langle\langle 6\rangle\rangle,\langle\langle 8\rangle\rangle} + 2Cs_{\langle\langle 6\rangle\rangle,\langle\langle 10\rangle\rangle} + 2Ds_{\langle\langle 8\rangle\rangle,\langle\langle 10\rangle\rangle}$$

$$A = 14400\langle\langle 2\rangle\rangle^4 - 10800\langle\langle 2\rangle\rangle^2\langle\langle 4\rangle\rangle$$
$$+800\langle\langle 6\rangle\rangle\langle\langle 2\rangle\rangle + 900\langle\langle 4\rangle\rangle^2 - 25\langle\langle 8\rangle\rangle$$
$$B = 1800\langle\langle 4\rangle\rangle\langle\langle 2\rangle\rangle - 3600\langle\langle 2\rangle\rangle^3 - 100\langle\langle 6\rangle\rangle$$
$$C = 400\langle\langle 2\rangle\rangle^2 - 100\langle\langle 4\rangle\rangle$$
$$D = -25\langle\langle 2\rangle\rangle$$

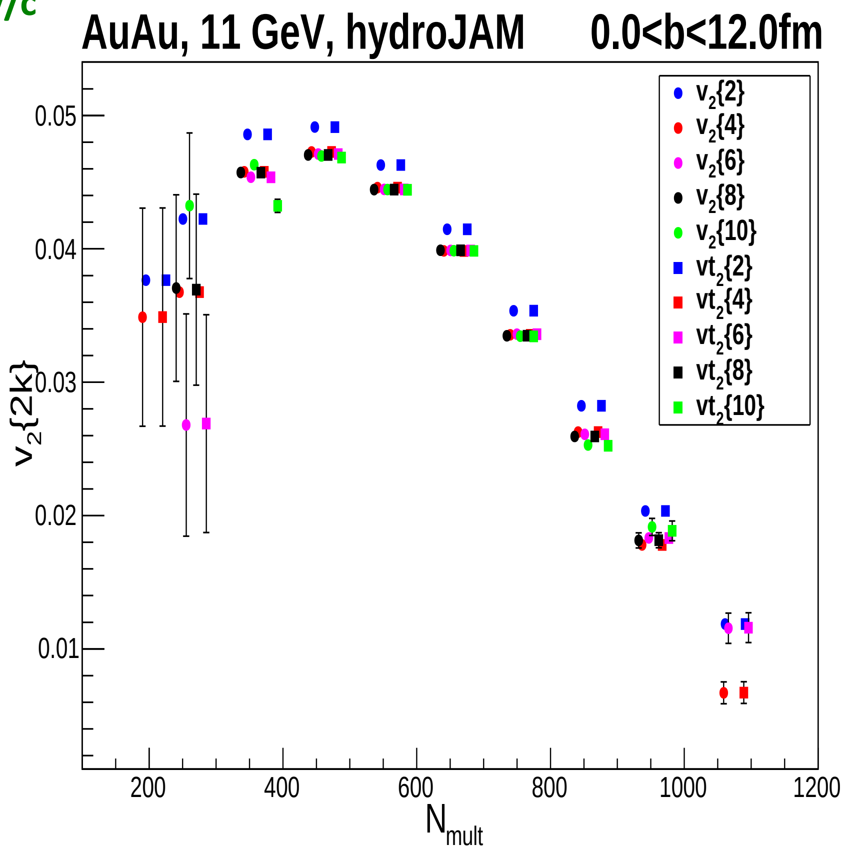
v_2 from cumulants of different orders - NICA

✧ AuAu collisions at $\sqrt{s_{NN}}$ = 11.0 GeV

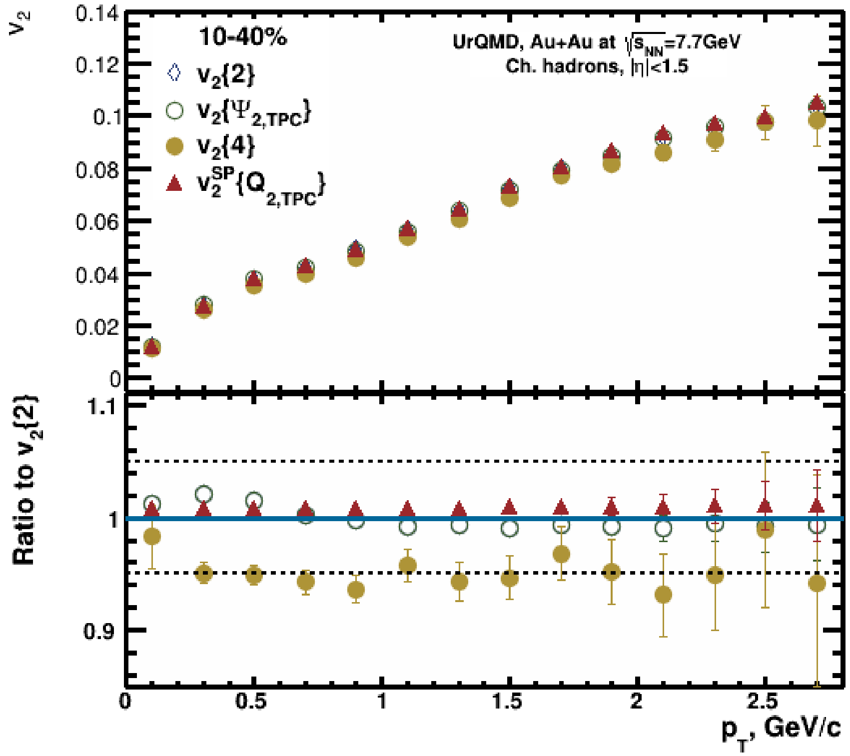
- In 10 multiplicity classes from 100 up to 1200
- PID: p, π^+, π^- , $|\eta|$ < 1.5, p_T > 200 MeV/c

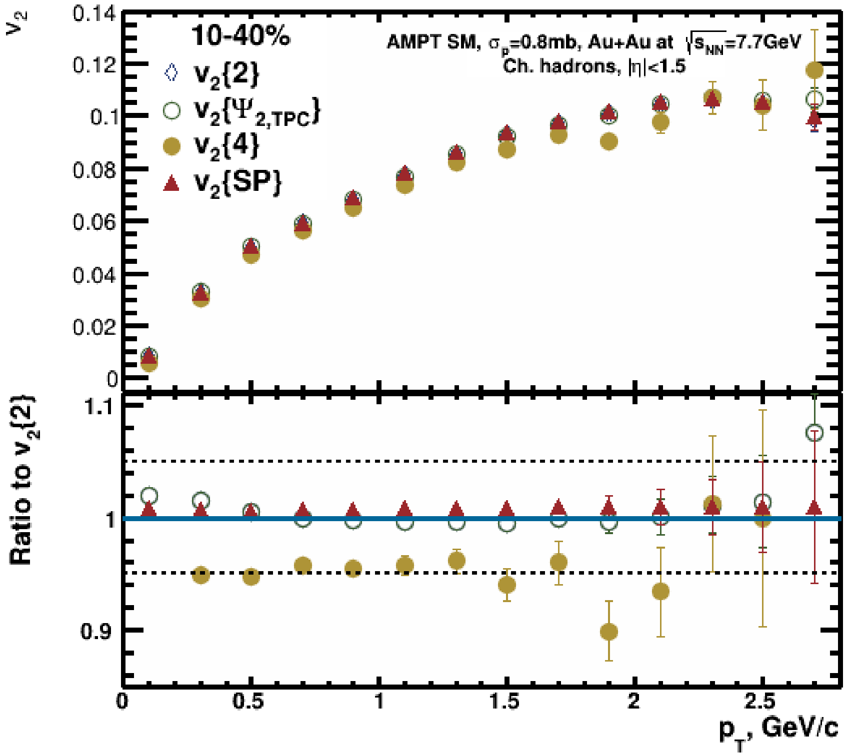
- 0.0 < b < 12.0 fm
- stat.: 1.068 B events

- $v_2\{2k\}$ are well measured in semicentral collisions
- $v_2\{2k\}$ are not well enough ordered. It could be a problem with JAM itself.
- We developed codes for calculations with and without efficiency corrections both.
- closed circles (squares): results without (with) efficiency corrections (efficiency randomly distributed between 95 and 100%)
- With real data and efficiencies the two results will differ.



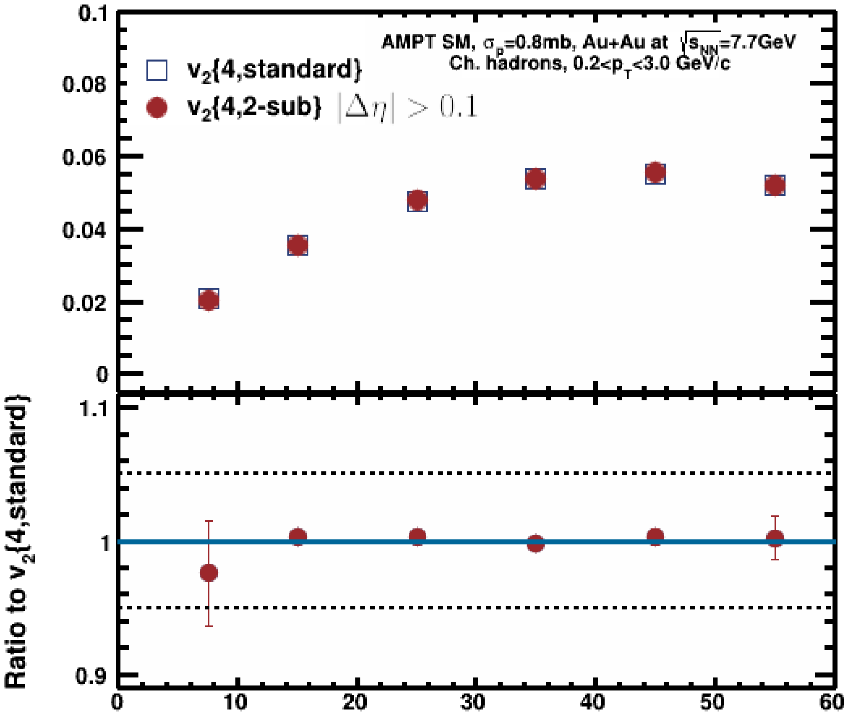
Sensitivity of different methods to flow fluctuations

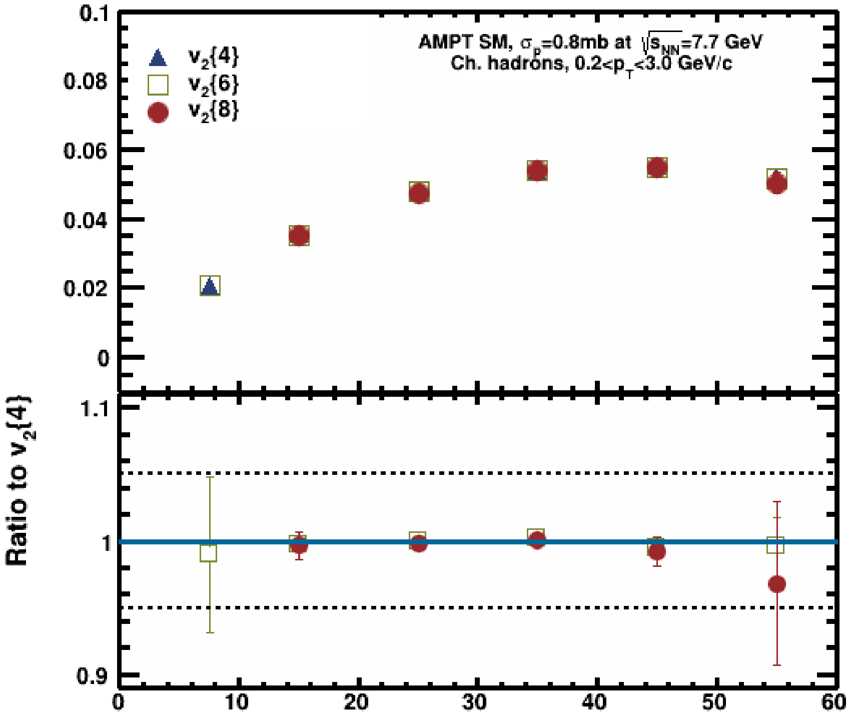




$$v_2\{2\} \approx v_2^{\rm SP}\{Q_{2,\rm TPC}\}, v_2\{4\} < v_2\{2\}$$

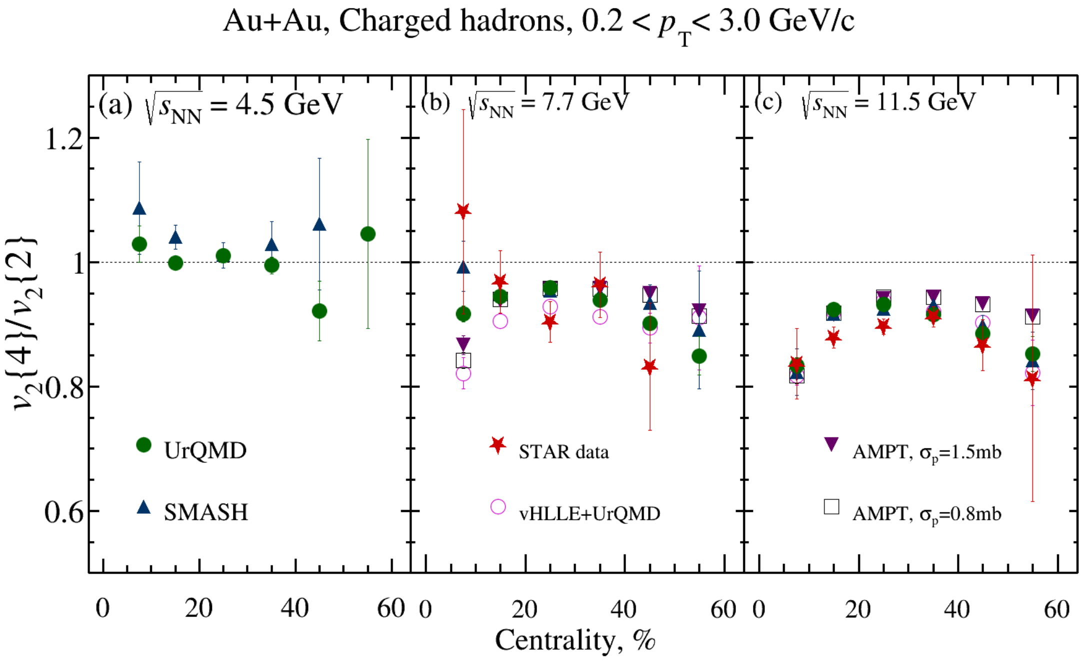
Comparison of high-order Q-Cumulants



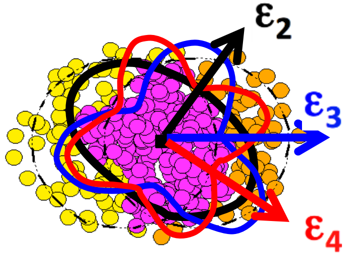


Reasonable agreement between
v_2{4,standard}, v_2{4,2-sub}, v_2{6}, v_2{8}

Relative flow fluctuations of charged hadrons

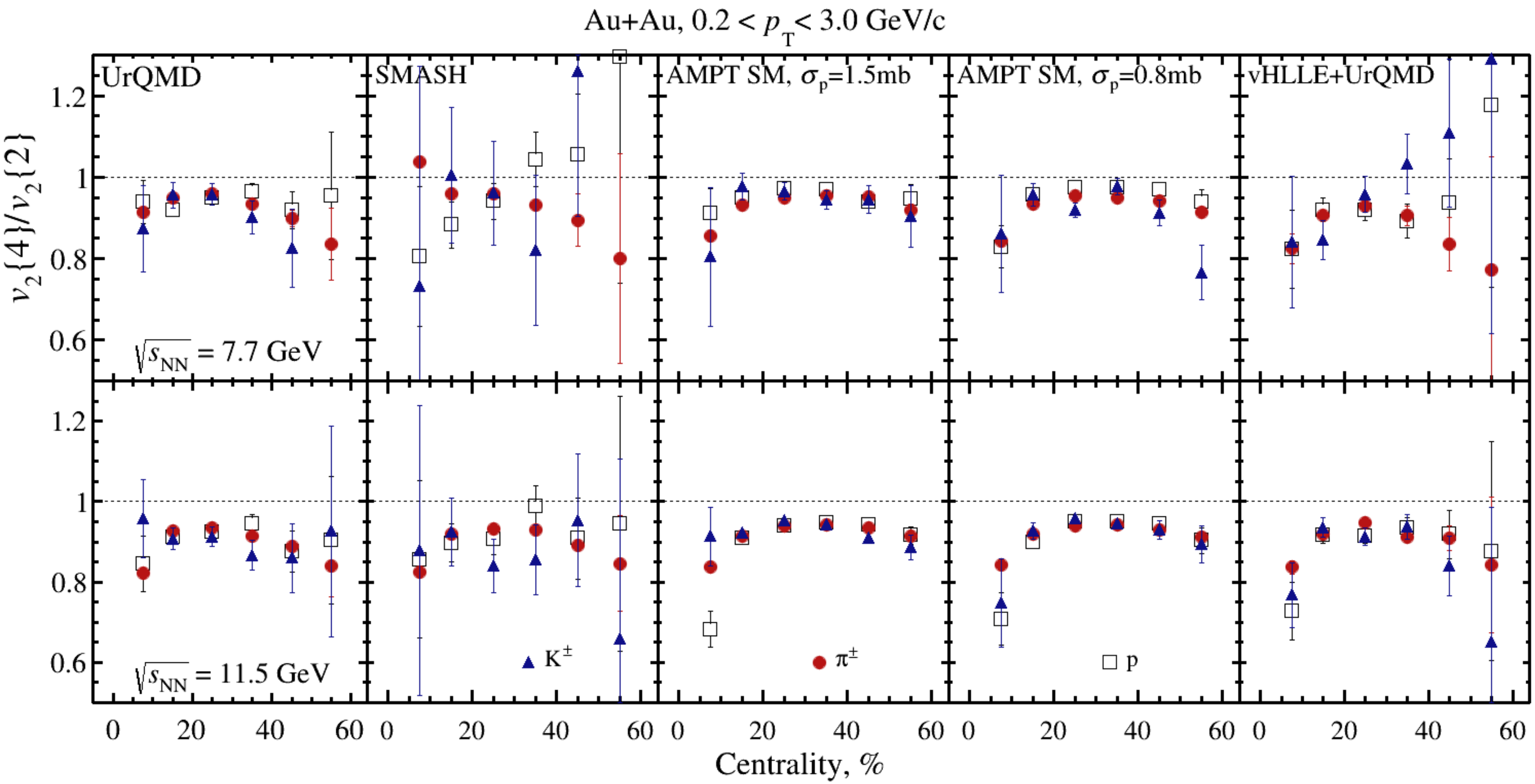


- Relative v_2 fluctuations ($v_2\{4\}/v_2\{2\}$) observed by STAR experiment can be reproduced both in the string/cascade models (UrQMD, SMASH) and model with QGP phase (AMPT SM, vHLLE+UrQMD)
- Dominant source of v_2 fluctuations: **participant eccentricity fluctuations** in the initial geometry
- Are there non-zero v_2 fluctuations at $\sqrt{s_{NN}}$= 4.5 GeV?



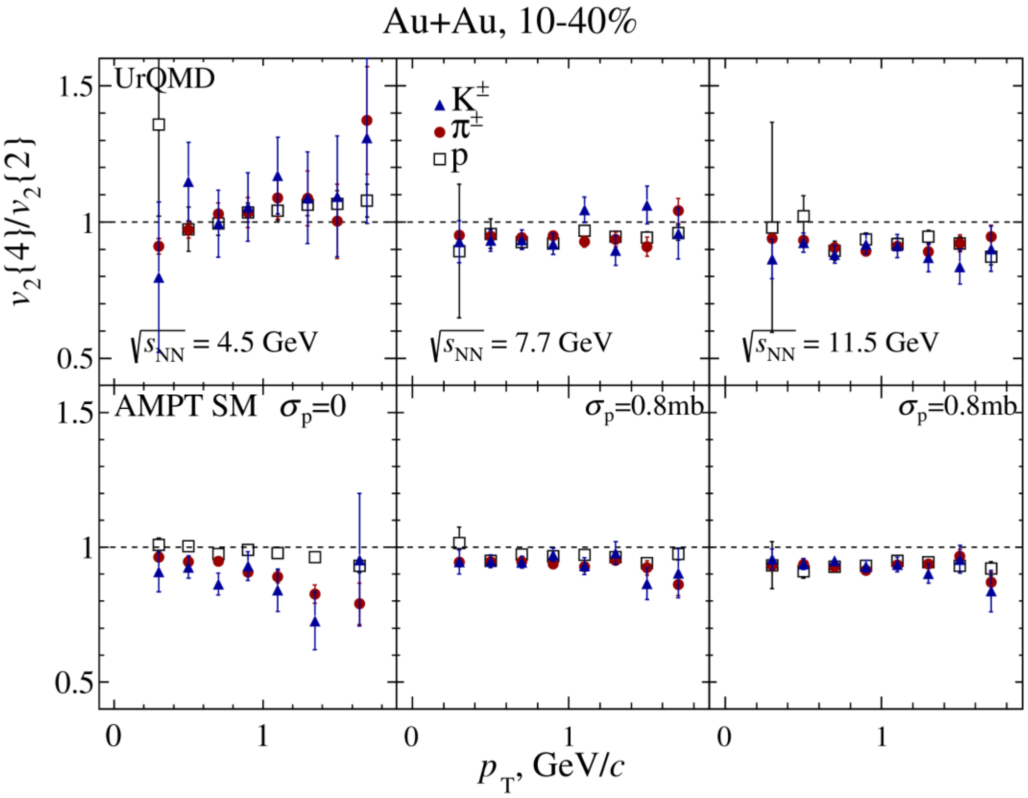
STAR data: Phys.Rev.C **86**, 054908 (2012)
After quality cuts, 0-80%: 4M at 7.7 GeV, 11M at 11.5 GeV

Relative flow fluctuations of identified charged hadrons



Elliptic flow fluctuations show weak dependence on particle species
Need more statistics

Relative flow fluctuations of identified charged hadrons



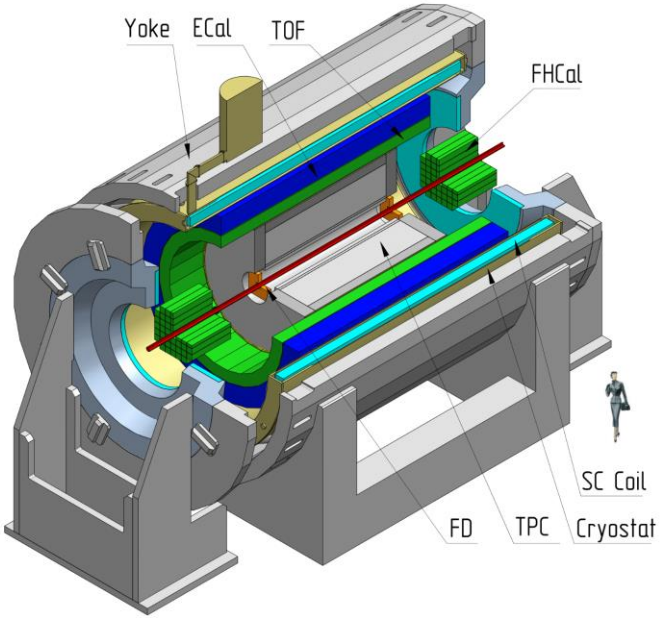
- $v_2\{4\}/v_2\{2\}$ ratio in 10-40% mid-central Au+Au collisions predicted by UrQMD and AMPT SM:
  - $\sqrt{s_{NN}}$ = **7.7, 11.5 GeV:** weak PID/p_T-dependence
  - $\sqrt{s_{NN}}$ = **4.5 GeV:** zero relative fluctuations for protons predicted by AMPT

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

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



Multi-Purpose Detector (MPD) Stage 1

Results of fit for UrQMD model

Simulated data sets:

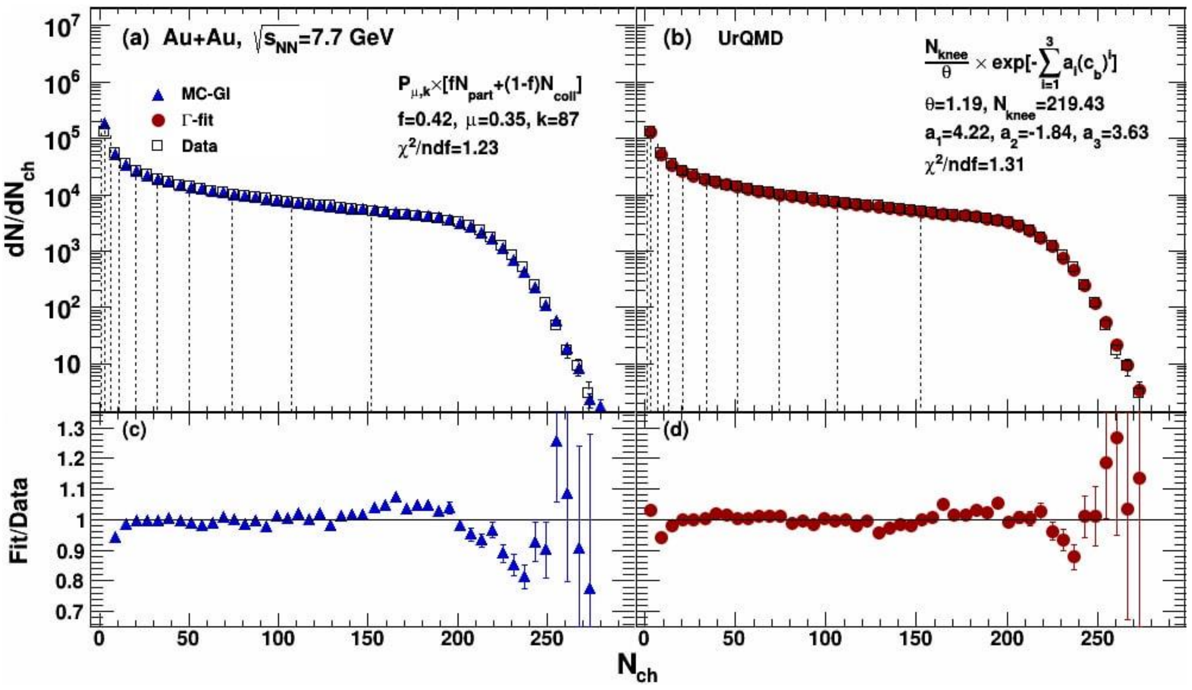
- Au+Au, N_{ev}=500k, $\sqrt{s_{NN}}$=7.7 GeV

Hadron selection:

- Charged particles only
- $|\eta|<0.5$
- p_T>0.15 GeV/c

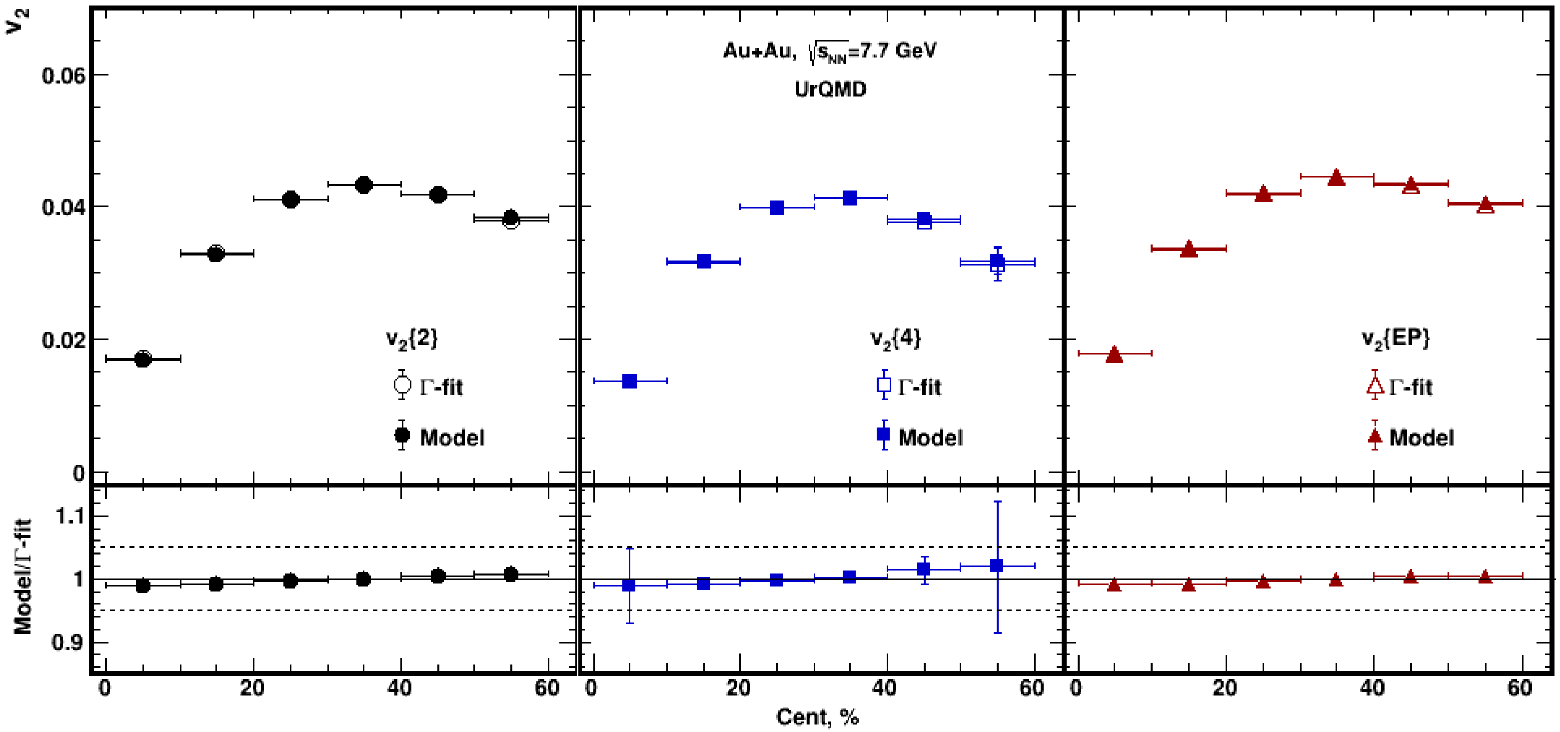
The model version:

- UrQMD ver. 3.4 in cascade mode



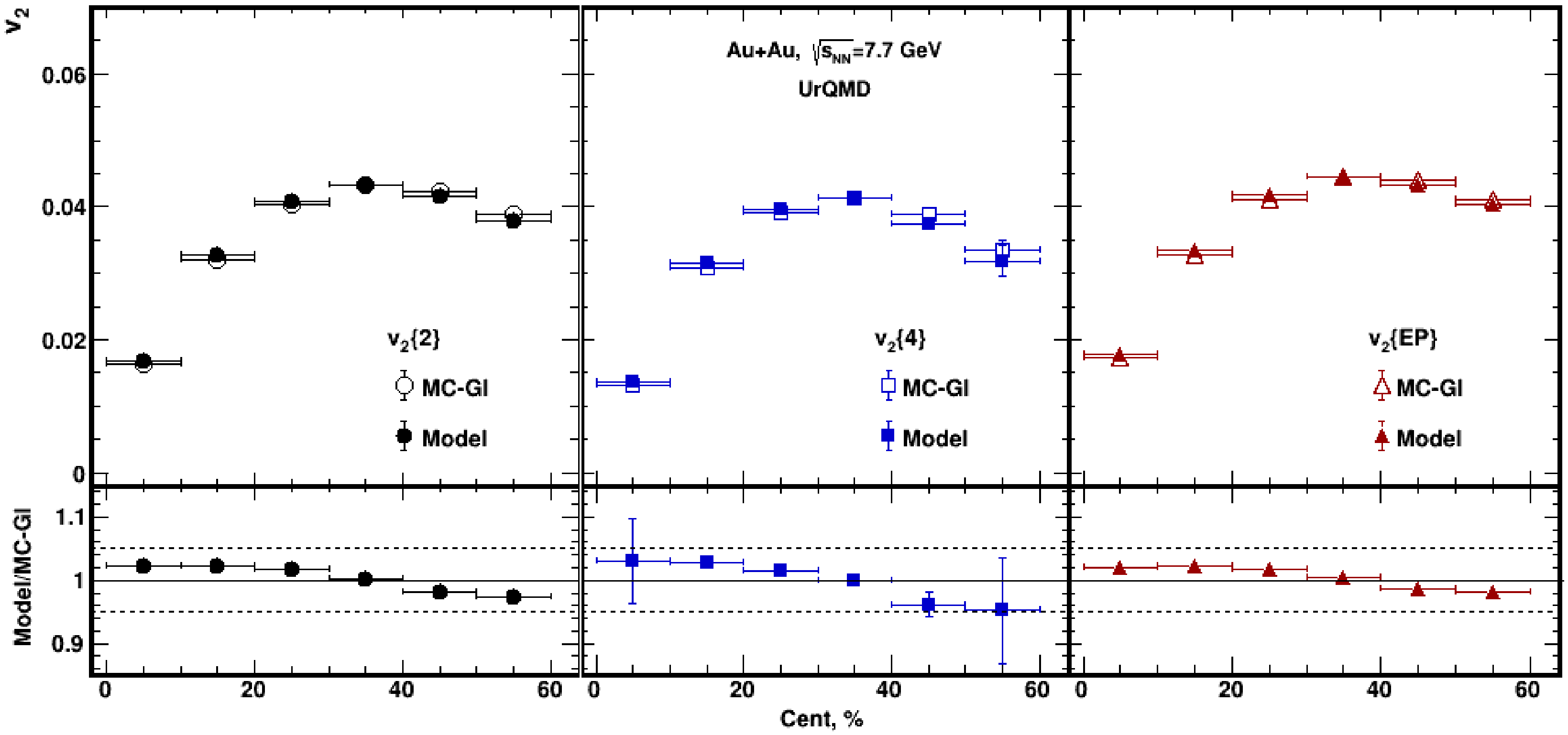
Good fit quality for both methods

The effect of the bias in centrality determination in flow measurements for UrQMD model (Γ-fit)



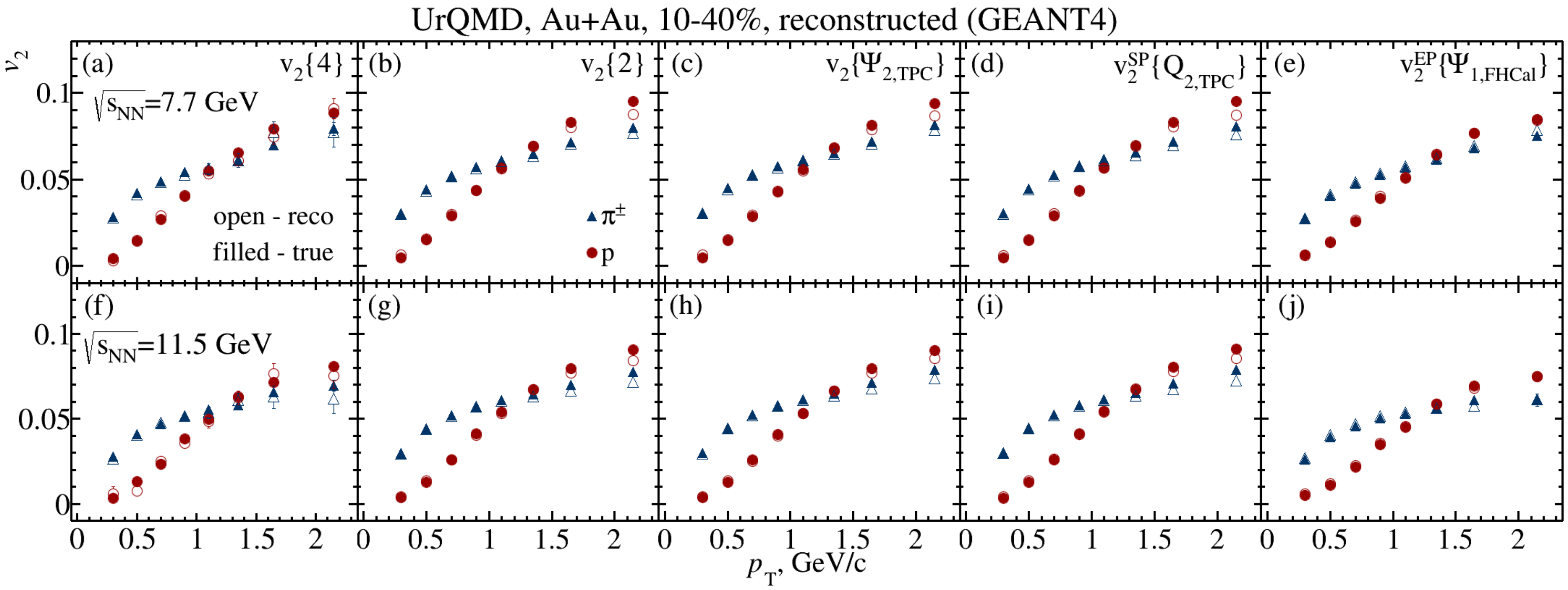
The effect of the bias caused by different centrality determination methods is within 1-2%.

The effect of bias in centrality determination in flow measurements for UrQMD model(MC-Glauber)



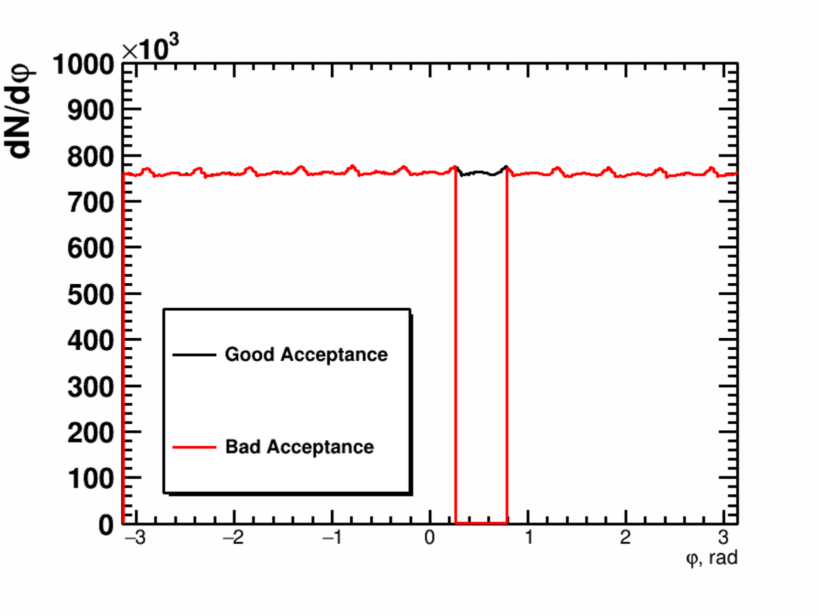
The effect of the bias caused by different centrality determination methods is within 4%.

Performance of v_2 of pions and protons in MPD

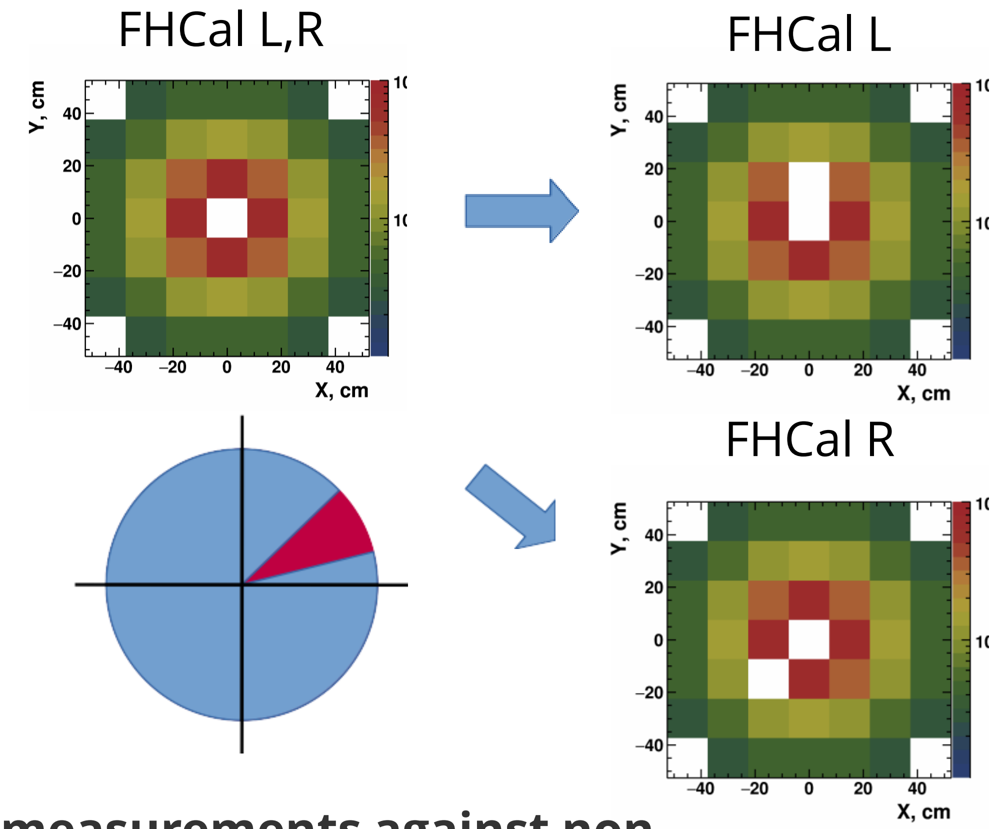


Reconstructed and generated v2 of pions and protons have a good agreement for all methods

Non-uniform acceptance

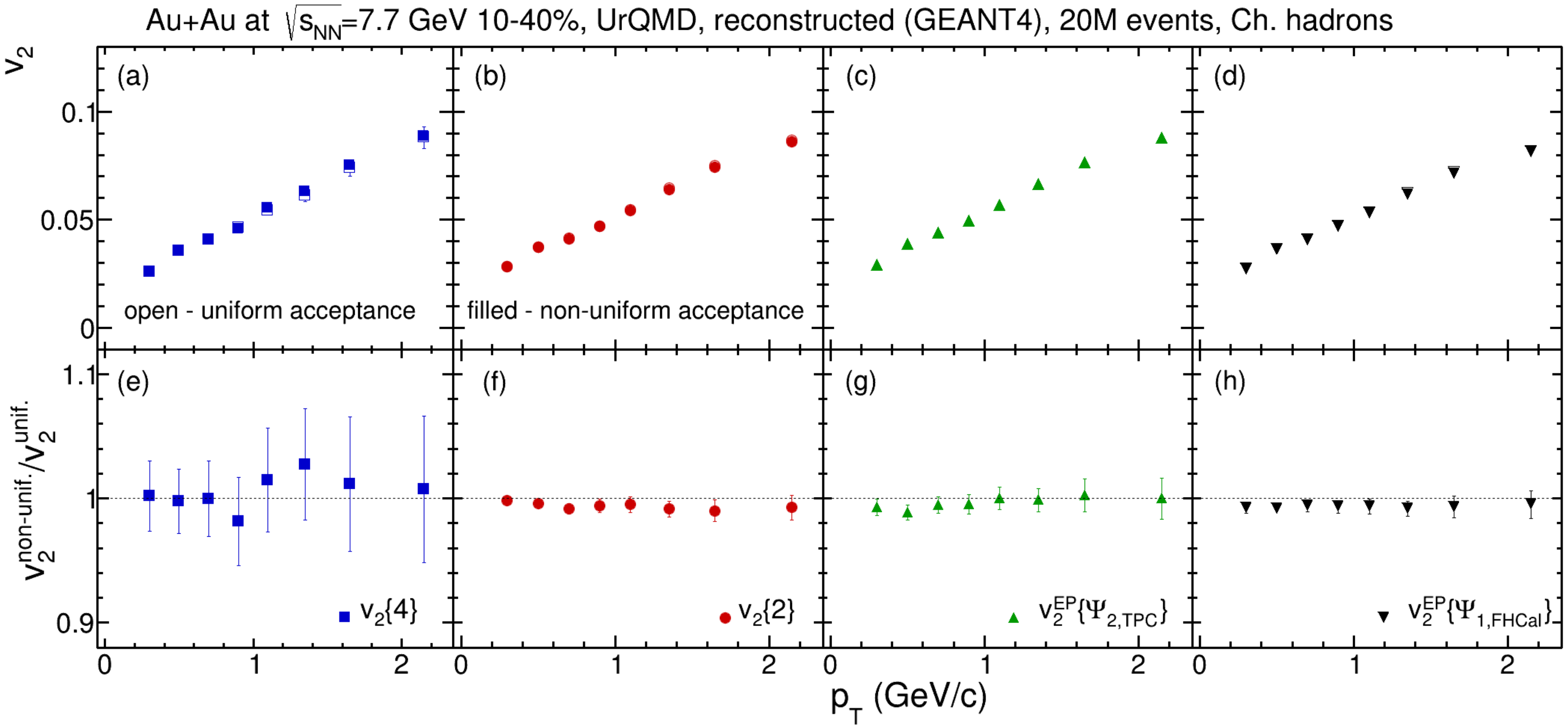


Area 15°< ϕ < 45° is off



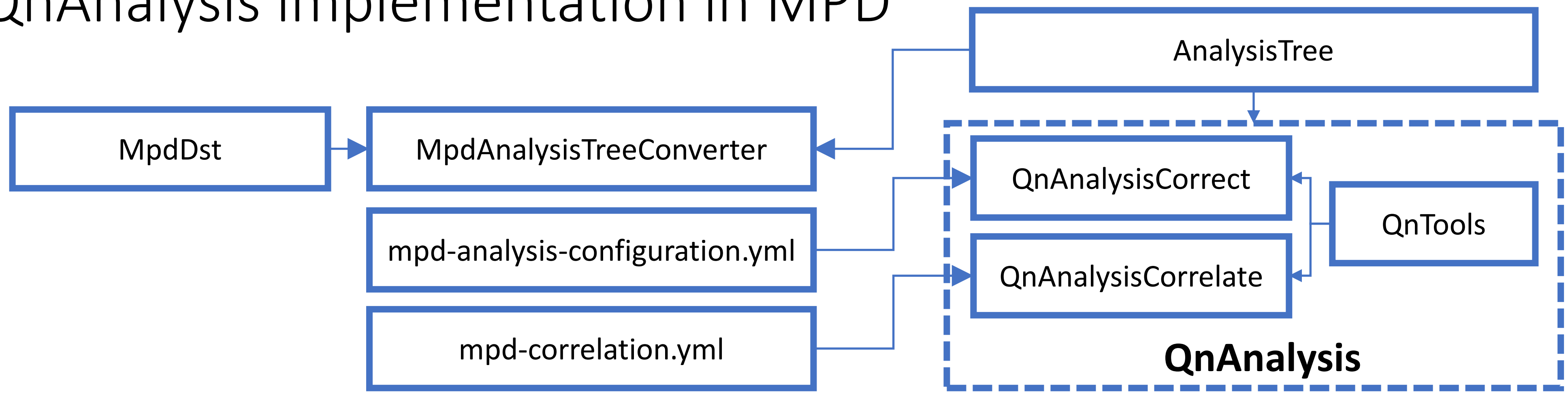
How robust are the future measurements against non-uniform acceptance?

Acceptance correction



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

QnAnalysis implementation in MPD



MPD-specific interface:

- **MpdAnalysisTreeConverter:** converter from MpdDst to AnalysisTree format
- YAML configuration files for QnAnalysis:
  - **mpd-analysis-configuration.yml**: sets up Q_n, u_n vectors to collect (cuts, correction steps, …)
  - **mpd-correlation.yml:** sets up correlations between previously collected Q_n, u_n vectors

General interface:

- **AnalysisTree:** A framework-independent, lightweight and flexible data format
- **QnTools:** set of tools for multidimentional Q-vector-based corrections and correlations:
  - **QnAnalysisCorrect**: collects Q_n, u_n vectors
  - **QnAnalysisCorrelate**: make correction between collected Q_n, u_n vectors

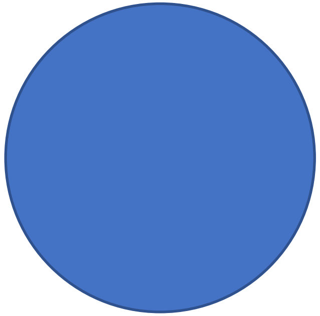
Joint development with FAIR (CBM for NICA)

QnAnalysis is already used in the current (HADES, ALICE) and future (CBM) experiments – now available for MPD

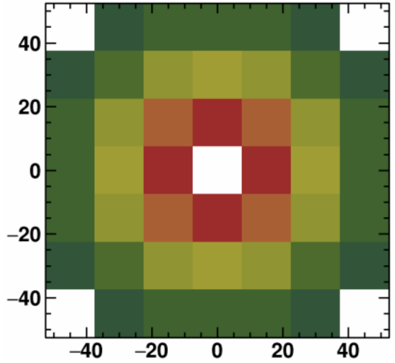
QnAnalysis git link: https://github.com/HeavyIonAnalysis/QnAnalysis
AnalysisTree git link: https://github.com/HeavyIonAnalysis/AnalysisTree

Non-uniform acceptance corrections

TPC

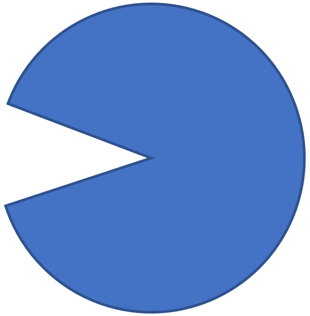


FHCal



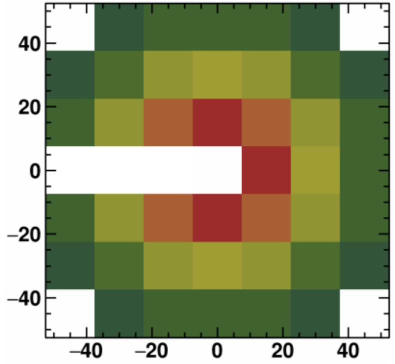
Acceptance filter

TPC



$-165° < \varphi < 165°$

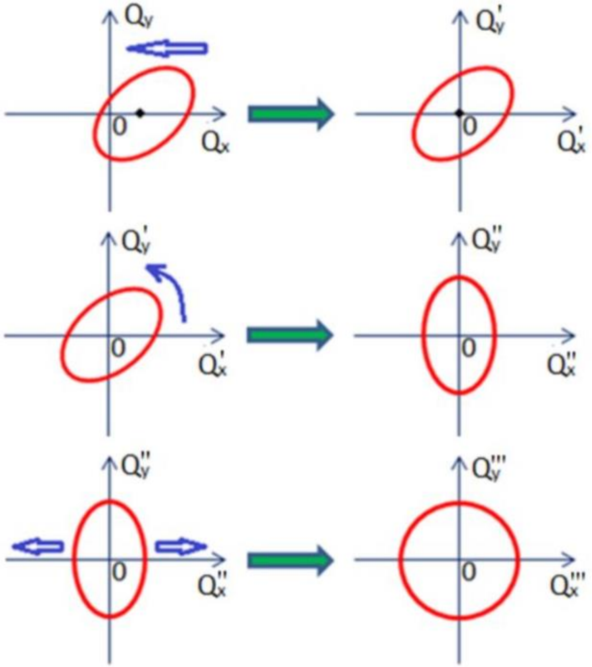
FHCal



Modules 23, 24, 25 (L) and 19, 20, 21 (R) are off

Correction for non-uniform azimuthal acceptance

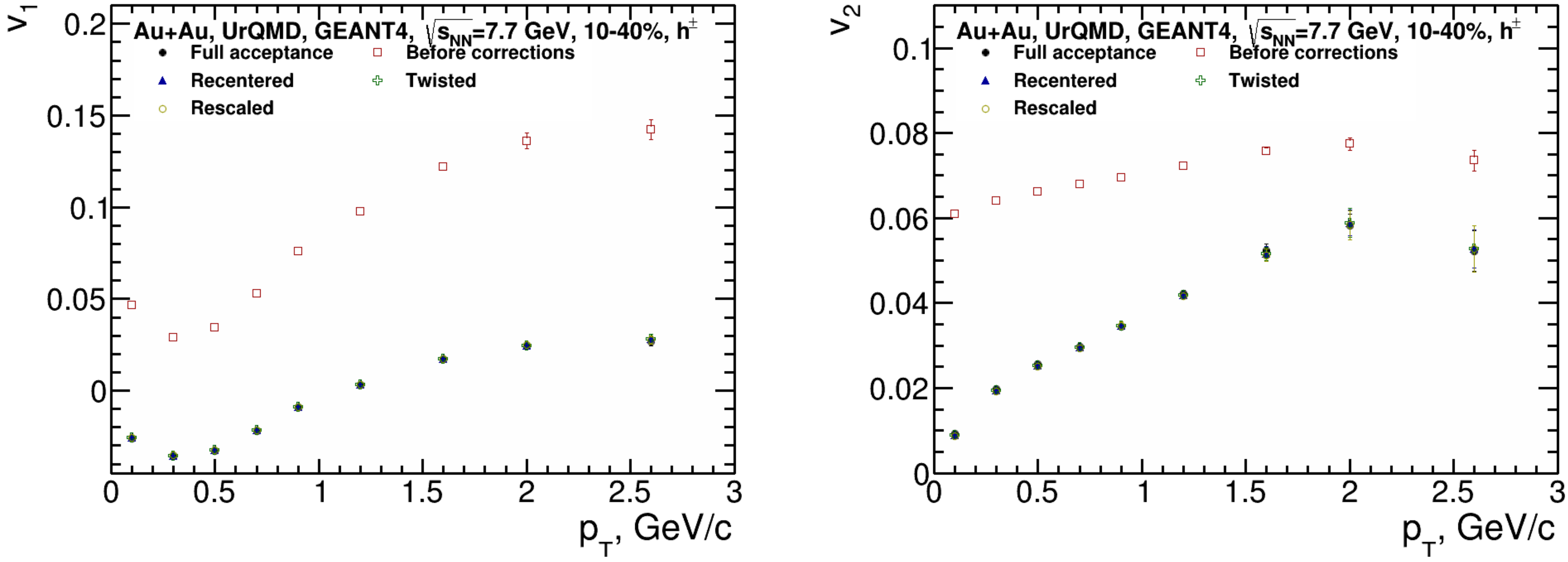
1. Recentering
2. Twist
3. Rescaling



Corrections are based on method in:

I. Selyuzhenkov and S. Voloshin PRC77, 034904 (2008)

Effects of non-uniformity corrections

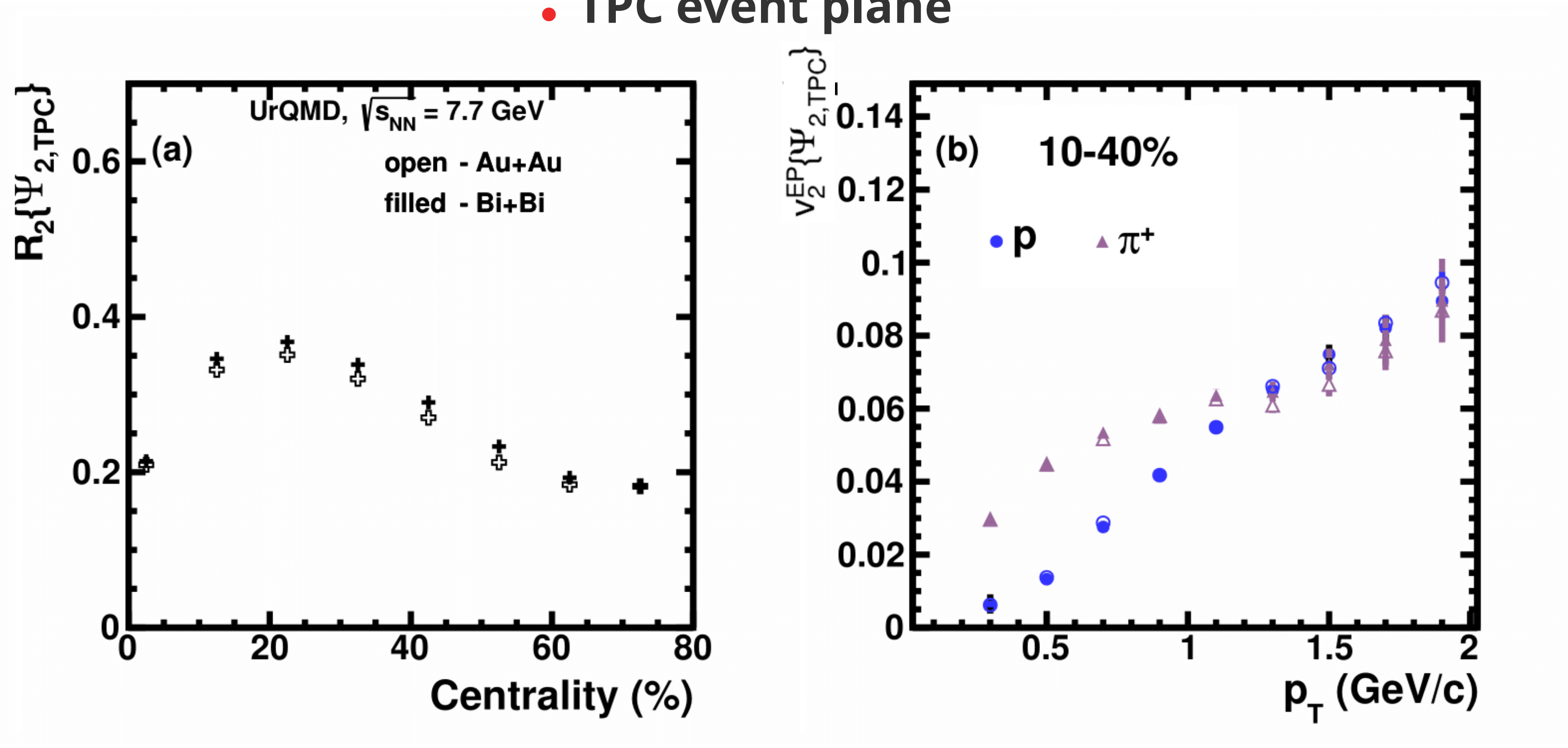


Q-vector	Q_n weight	Correction axes	Correction steps	Error calculation	Q_n normalization
Spectators (FHCal)	Module energy	b [0,12], 8 bins	Recentering Twist Rescaling	Bootstrapping, 50 samples	Sum of weights
Charged hadrons (TPC)	1	pT [0,3], 9 bins b [0,12], 8 bins			

Good agreement between v_n with acceptance non-uniformity corrections and full acceptance

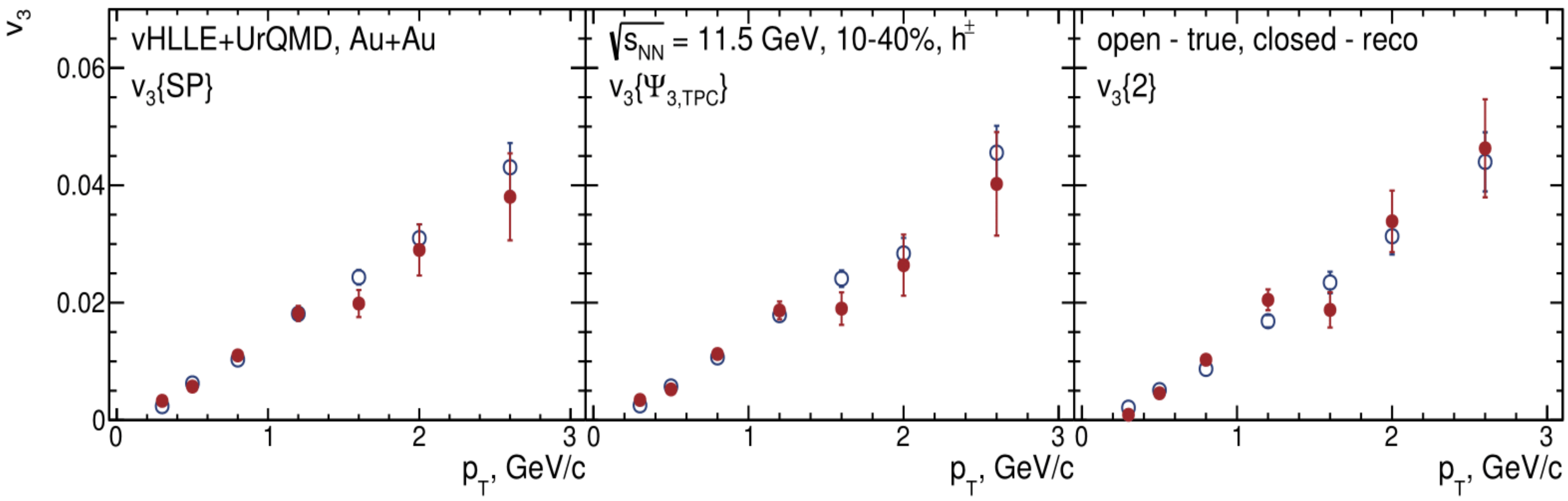
Au+Au vs. Bi+Bi collisions for MPD reconstructed data

- TPC event plane



- Expected small difference between two colliding systems

Triangular flow with MPD at NICA



Models show that higher harmonic ripples are more sensitive to the existence of a QGP phase

In models, v_3 goes away when the QGP phase disappears????

15 M of reconstructed vHLLE+UrQMD events for Au+Au at 11.5 GeV

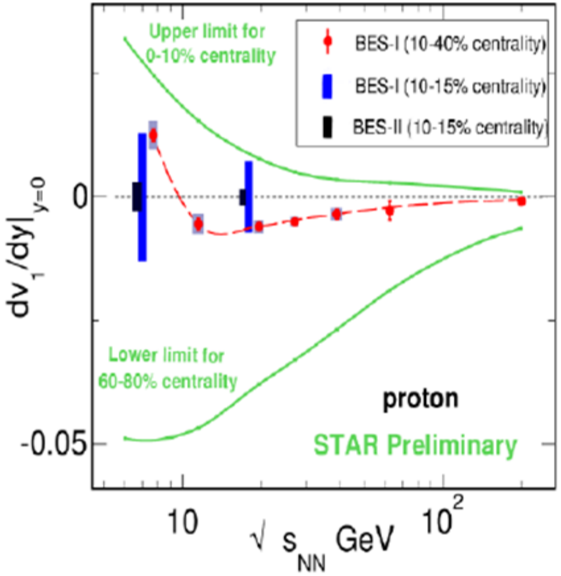
Summary and outlook

- **v_n 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
  - Detailed JAM model calculations for differential measurements of v_n at $\sqrt{s_{NN}}$ = 2.4-4.5 GeV
  - v_2 from cumulants of different orders
- **Comparison of methods for elliptic flow measurements using UrQMD and AMPT models:**
  - The differences between methods are well understood and could be attributed to non-flow and fluctuations
- **Feasibility study for directed and elliptic flow in MPD:**
  - v_n of identified charged hadrons: results from reconstructed and generated data are in a good agreement for all methods
- Small differences in v_n for 2 colliding systems (Au+Au, Bi+Bi) were observed as expected
- Programs for flow analysis are available for MPD collaboration:
  - Github repository: https://github.com/FlowNICA/CumulantFlow
  - QnAnalysis git link: https://github.com/HeavyIonAnalysis/QnAnalysis
  - AnalysisTree git link: https://github.com/HeavyIonAnalysis/AnalysisTree

Workshop on physics performance studies at FAIR and NICA, http://indico.oris.mephi.ru/event/221

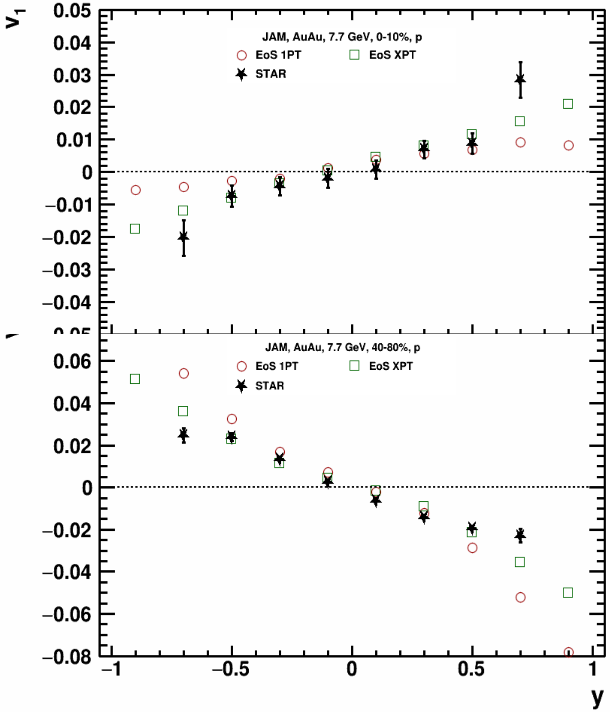
(29 November – 1 December 2021)

v_1 study at NICA energies



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

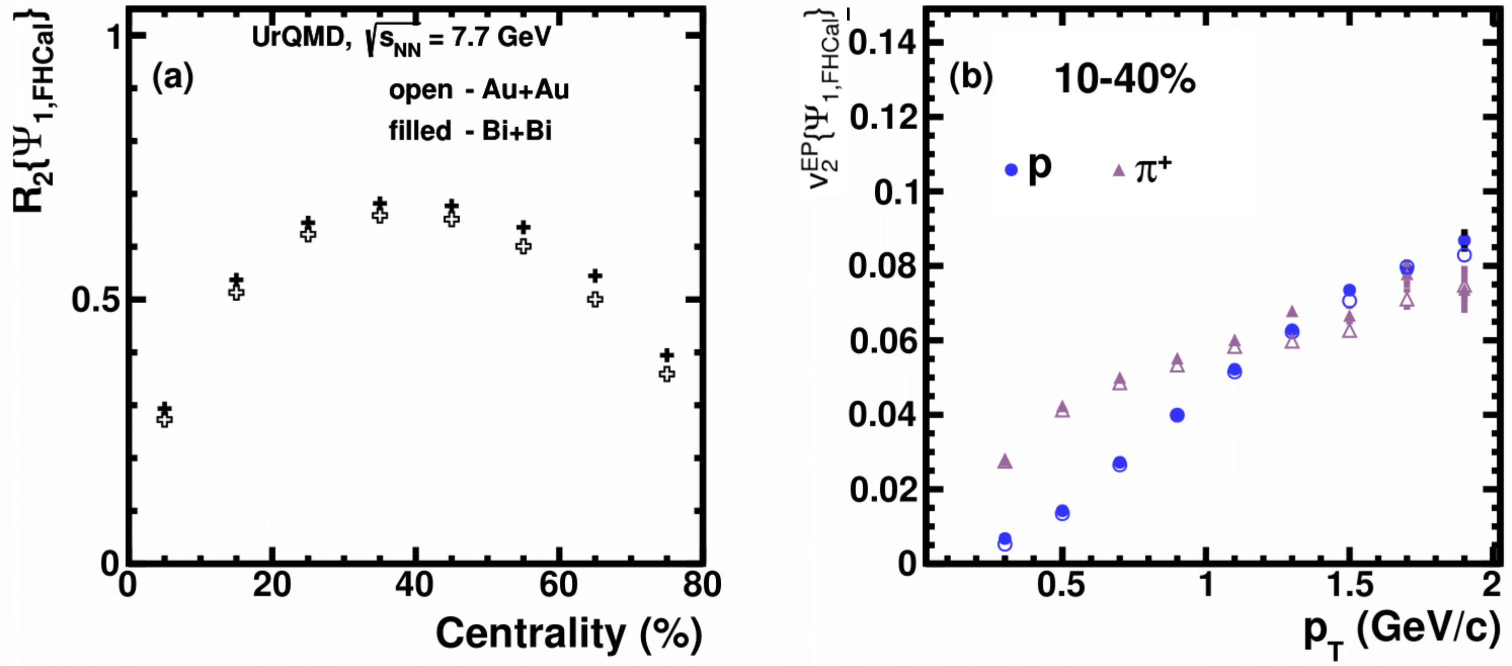
P. Parfenov, The Conference "RFBR Grants for NICA", Dubna (2020)



dv_1/dy slope changes dramatically with centrality for protons

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

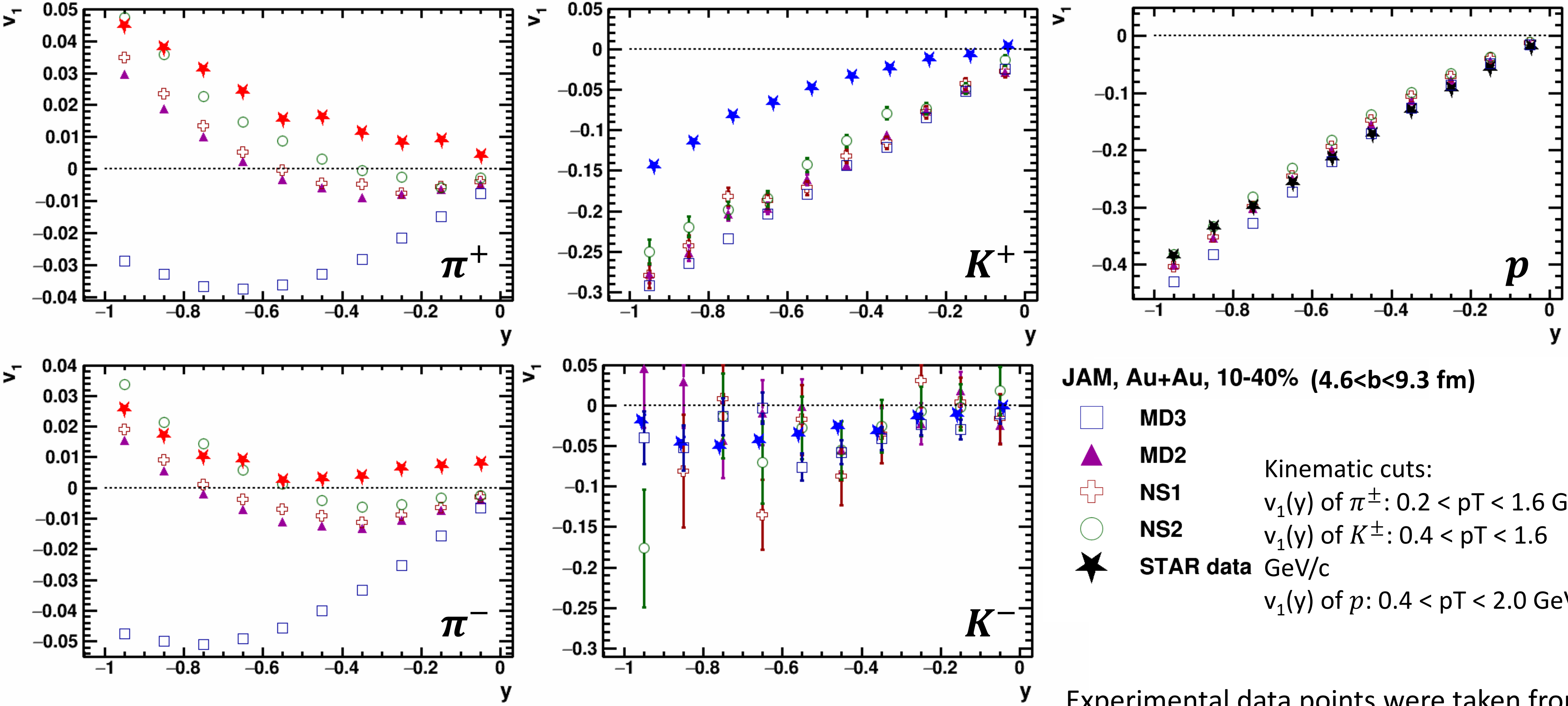
- FHCal event plane



- Expected small difference between two colliding systems

Back-up slides

$v_1(y)$ in Au+Au $\sqrt{s_{NN}}$=3 GeV: model vs. STAR data

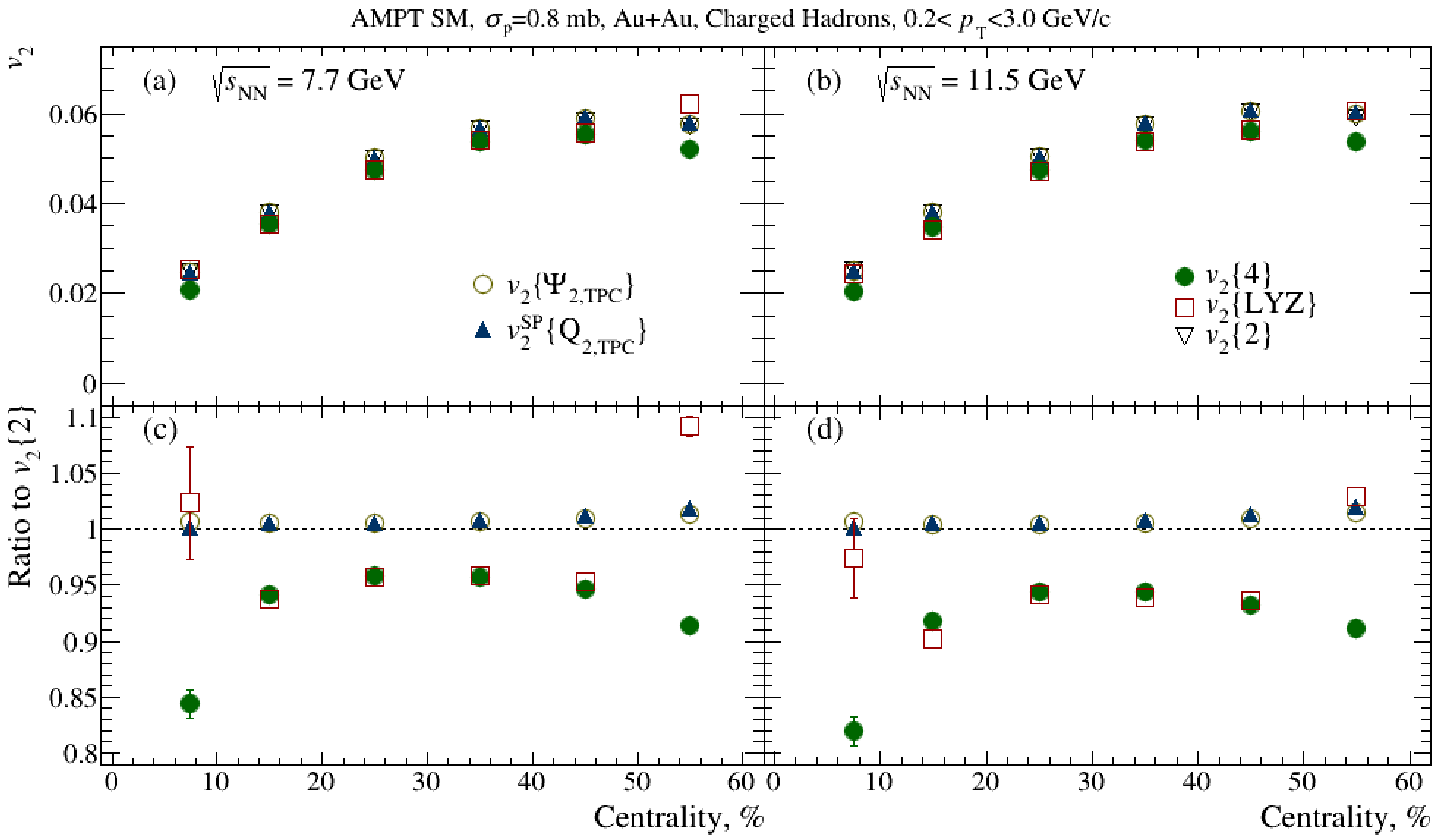


Kinematic cuts:
v_1(y) of $\pi^{\pm}$: 0.2 < pT < 1.6 GeV/c
v_1(y) of $K^{\pm}$: 0.4 < pT < 1.6 GeV/c
v_1(y) of p: 0.4 < pT < 2.0 GeV/c

JAM does not describe all particle species equally well
v_1 of pions is most sensitive to different EOS

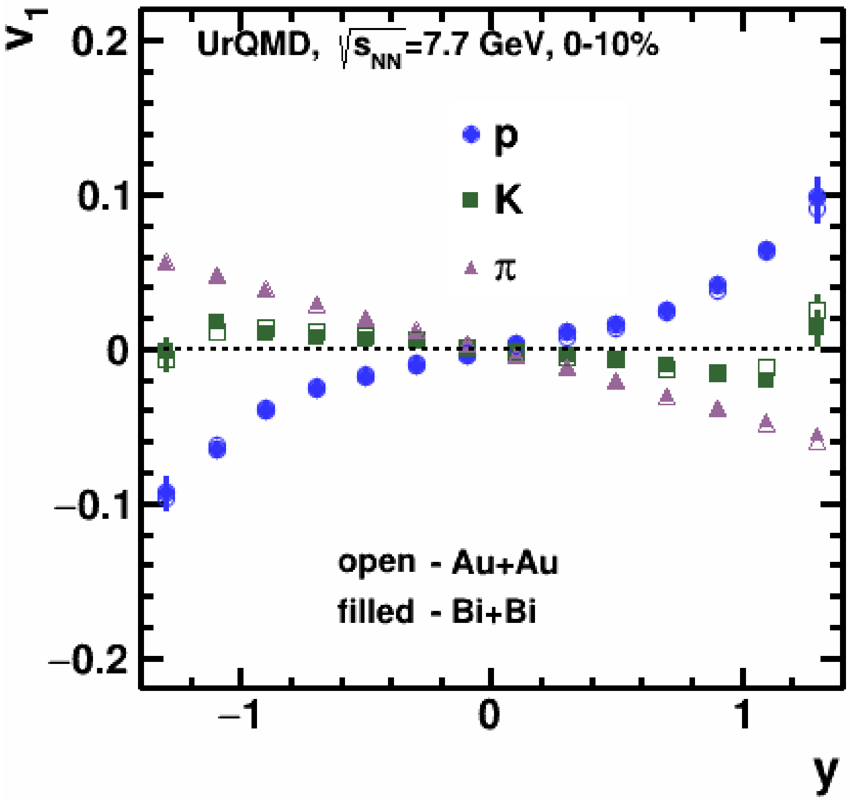
Experimental data points were taken from:
Mohamed Abdallah et al. [STAR Collaboration] 2108.00908 [nucl-ex]

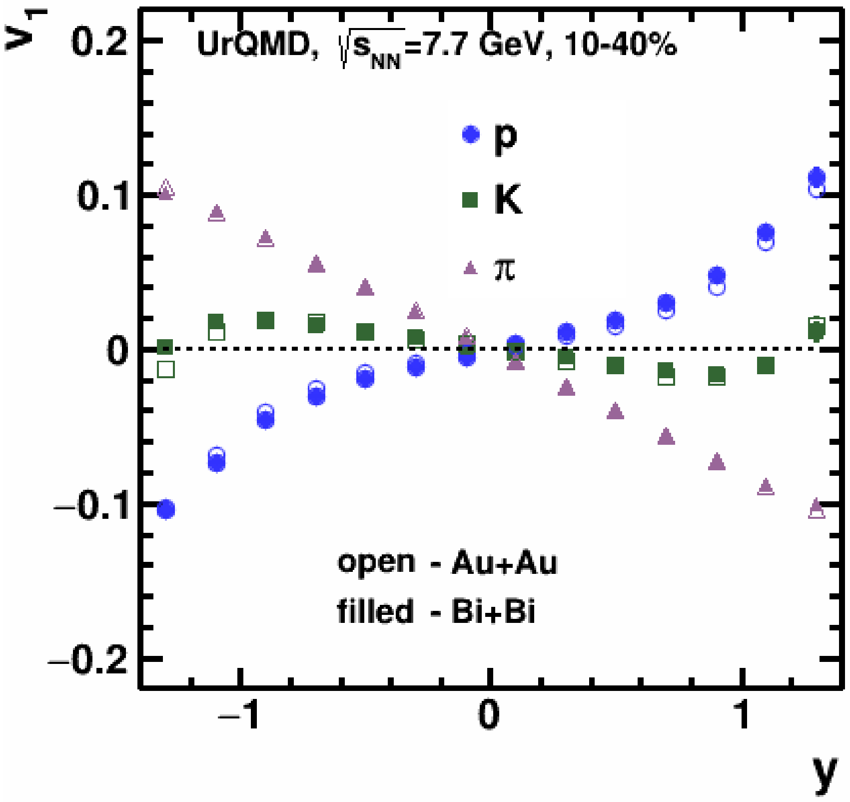
Centrality dependence of v_2\{methods\}



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

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

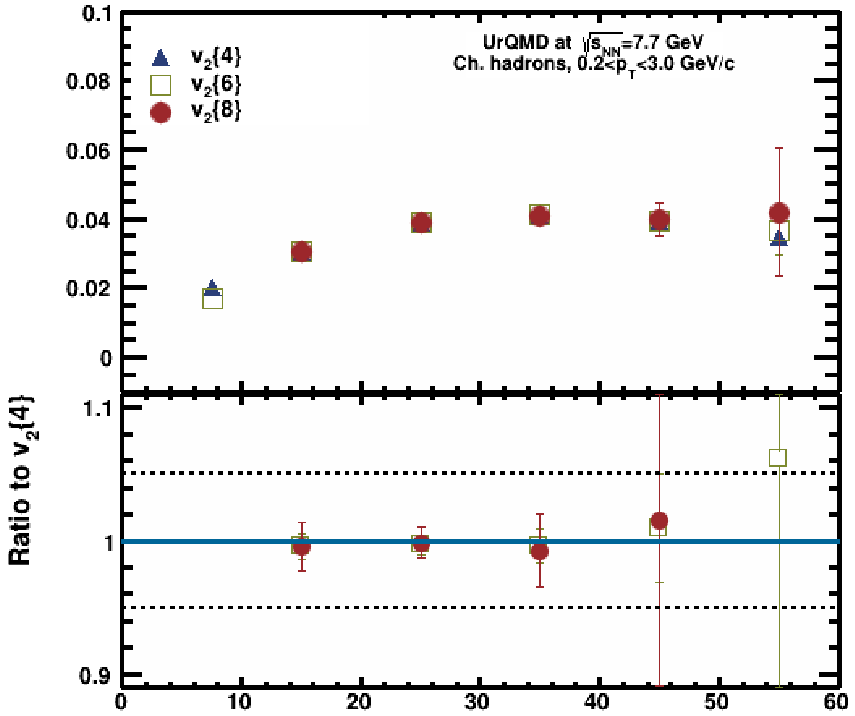




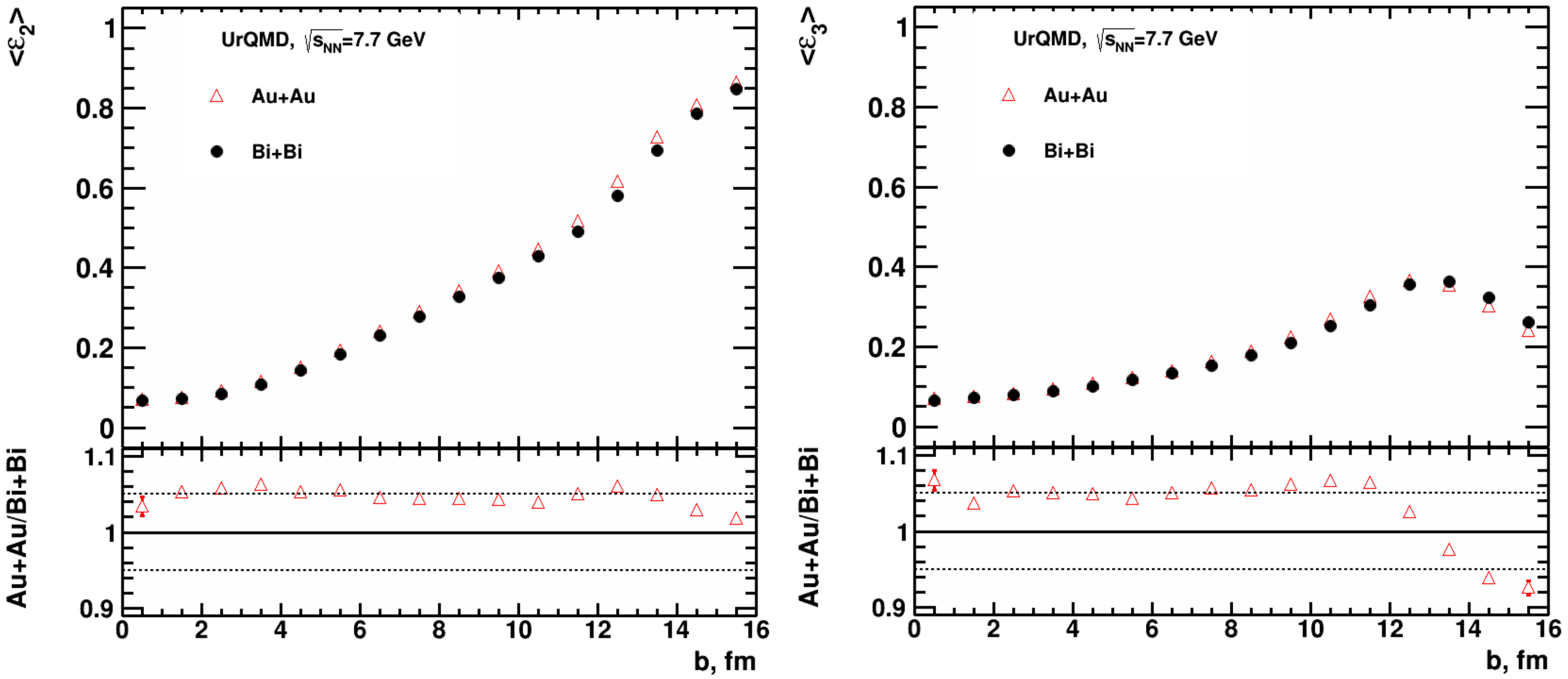
Expected small difference for v1 (y) for particles produced in Au+Au and Bi+Bi collisions.

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