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

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For the MPD Collaboration

7th MPD Collaboration Meeting, JINR , Dubna, 21-23 April 2021, Dubna, Russia

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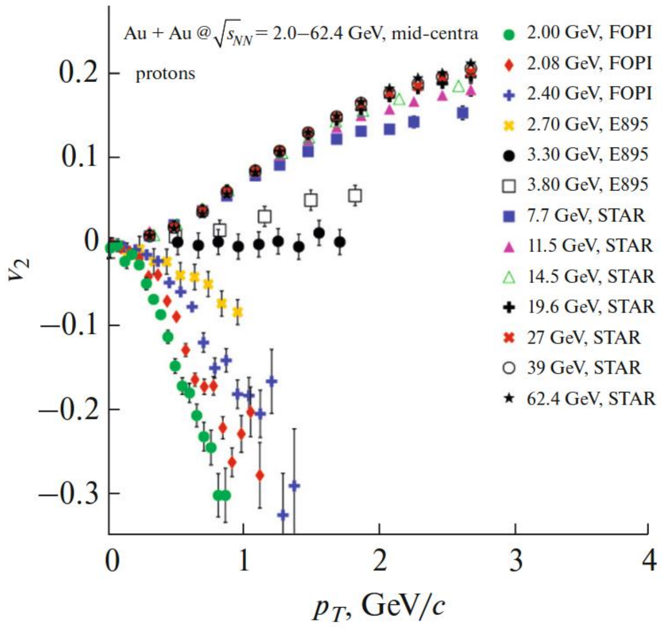
Main anisotropic flow result in 2021:

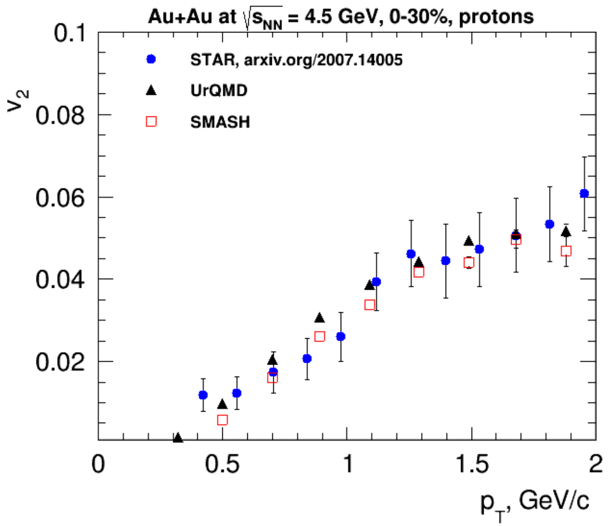
Congratulations to Ilya Seluyzhenkov who defended his Doctor of Sciences thesis in April 21, 2021 (NRNU MEPhI)

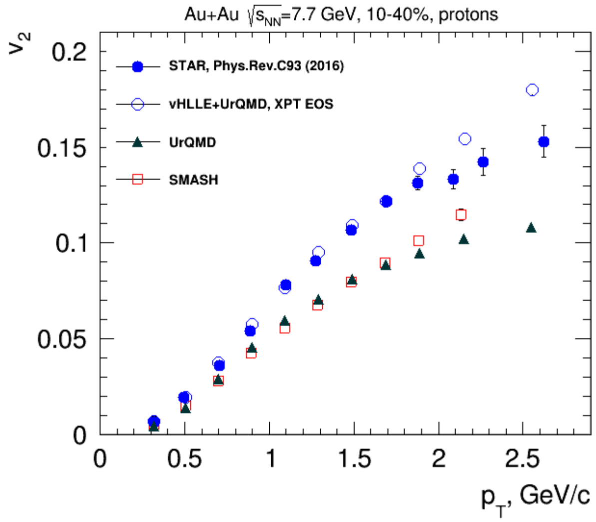
"Anisotropic flow of hadrons in heavy-ion collisions with the ALICE experiment at the CERN Large Hadron Collider"

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

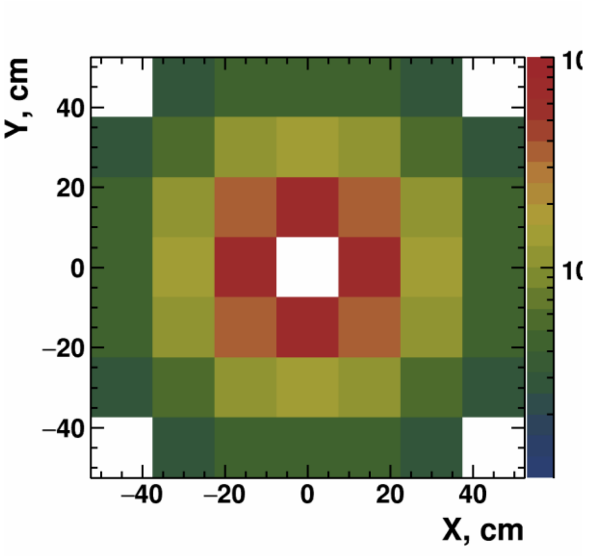
- Using v_1 of particles in FHCal to determine Q_n

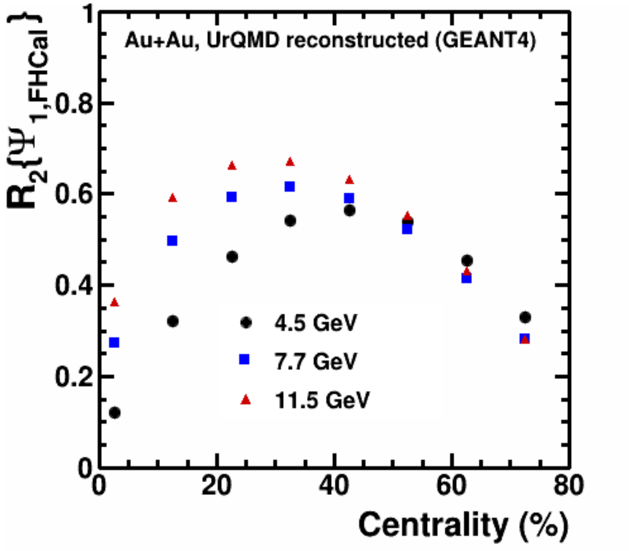
$$Q_1 = \frac{\sum_j E_i e^{i\phi_j}}{\sum_j E_j}, \ \Psi_{1,\mathrm{FHCal}} = \tan^{-1}\left(\frac{Q_{1,y}}{Q_{1,x}}\right)$$

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

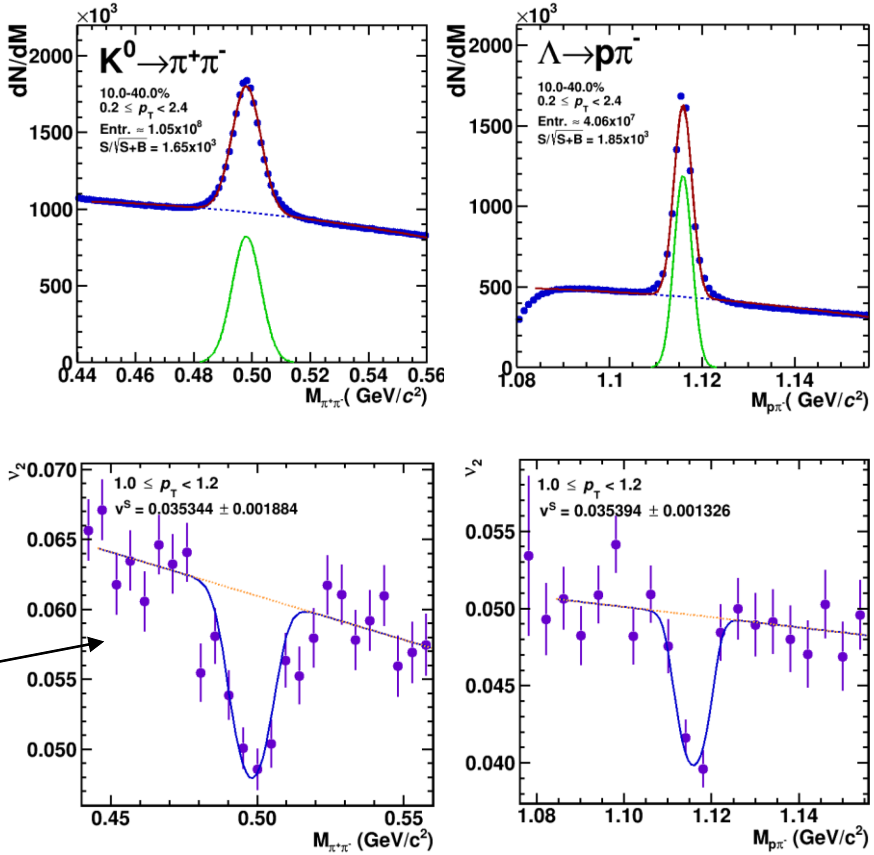
Geant4 simulation, full reconstruction with:

- TPCv7, TOFv7, FHCal

Centrality by TPC multiplicity, Event-plane method with FHCal

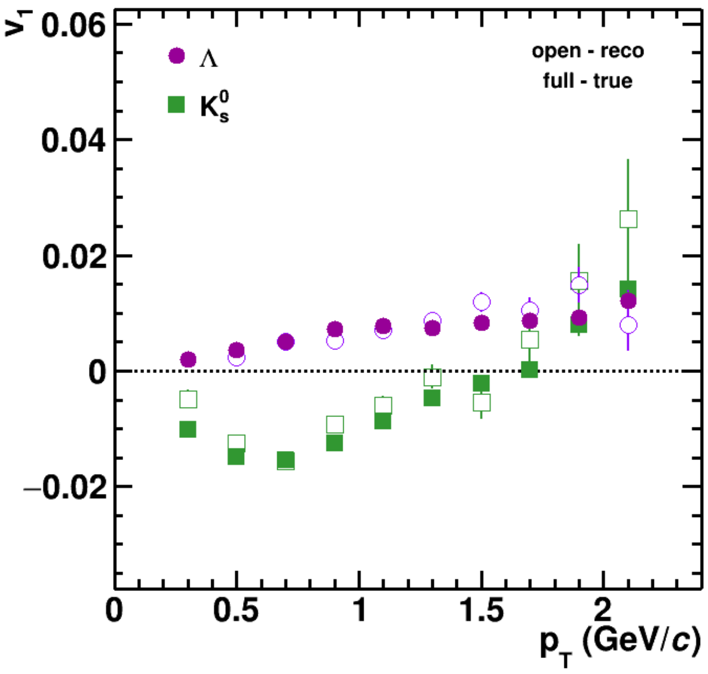
Particle decays reconstructed with MpdParticle realistic cuts
Differential flow signal extraction by bins in transverse momentum (or rapidity) with a simultaneous fit

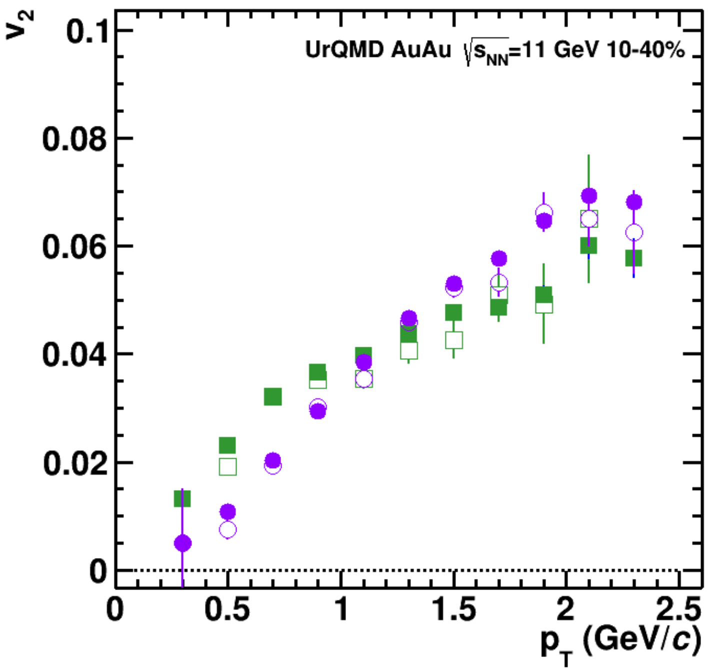
$$v_2^{SB}(m_{inv},p_T) = v_2^{S}(p_T)\frac{N^{S}(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)} + v_2^{B}(m_{inv},p_T)\frac{N^{B}(m_{inv},p_T)}{N^{SB}(m_{inv},p_T)}$$



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)

Performance study for v_n of V0 particles



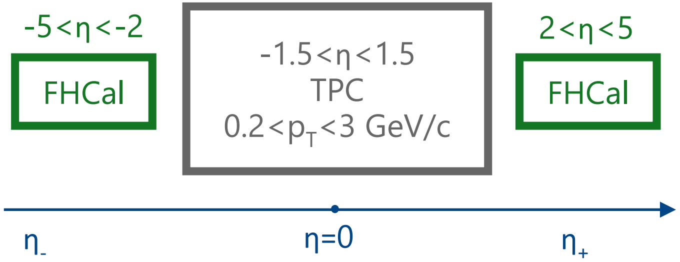


Reasonable agreement between reconstructed and generated v_n signals for both K^0 and Λ

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

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

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

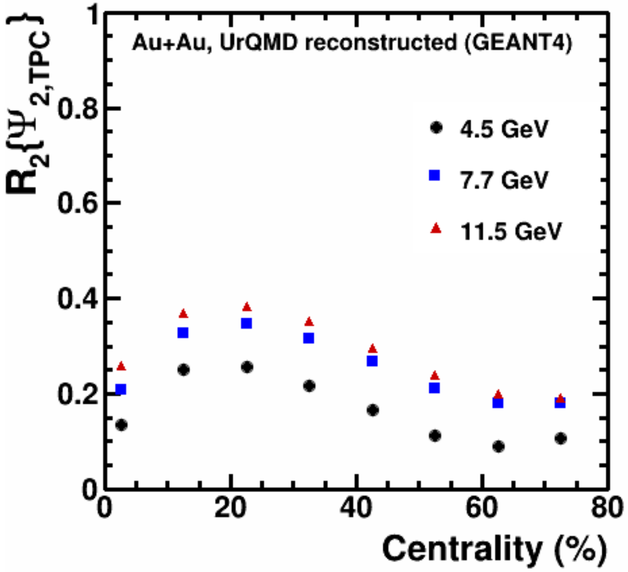


- **Scalar product:** $$v_2^{\mathrm{SP}}\{Q_{2,\mathrm{TPC}}\} = \frac{\langle u_{2,\eta\pm} Q^*_{2,\eta\mp}\rangle}{\sqrt{\langle Q_{2,\eta+} Q_{2,\eta-}\rangle}}$$

- **TPC Event-plane:**

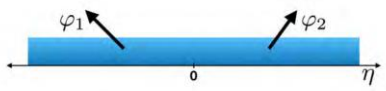
$$v_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \frac{\langle \cos\left[2(\phi_{\eta\pm} - \Psi_{2,\eta\mp})\right]\rangle}{\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\}}$$

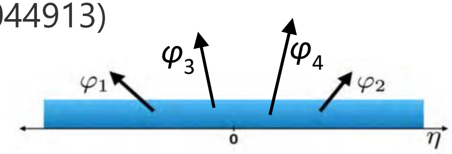
$$\mathrm{R}_2^{\mathrm{EP}}\{\Psi_{2,\mathrm{TPC}}\} = \sqrt{\langle \cos\left[2(\Psi_{2,\eta+} - \Psi_{2,\eta-})\right]\rangle}$$



Elliptic flow measurements using TPC: Q-Cumulants

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



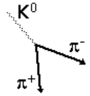


$$\langle 2\rangle_n = \frac{|Q_n|^2 - M}{M(M-1)} \approx v_2^2 + \delta \qquad \langle 4\rangle_n = \frac{[Q_n]^4 + [Q_{2n}]^2 - 2\Re[Q_{2n}Q_n^*Q_n^*] - 4(M-2)[Q_n]^2 - 2M(M-3)}{M(M-1)(M-2)(M-3)} \approx v_2^4 + 4v_2^2 + 2\delta^2$$

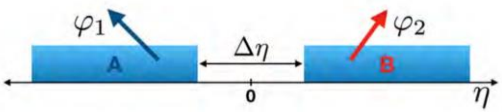
$$v_2\{4\} = \sqrt[4]{2\langle\langle 2\rangle\rangle^2 - \langle\langle 4\rangle\rangle}$$

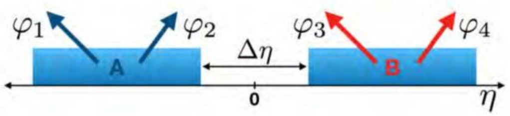
δ – nonflow contribution

- resonance decay
- jets



- **Subevent Q-Cumulants:** (J. Jia et al., Phys. Rev. C **96** (2017), no. 3, 0349





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

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

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**:

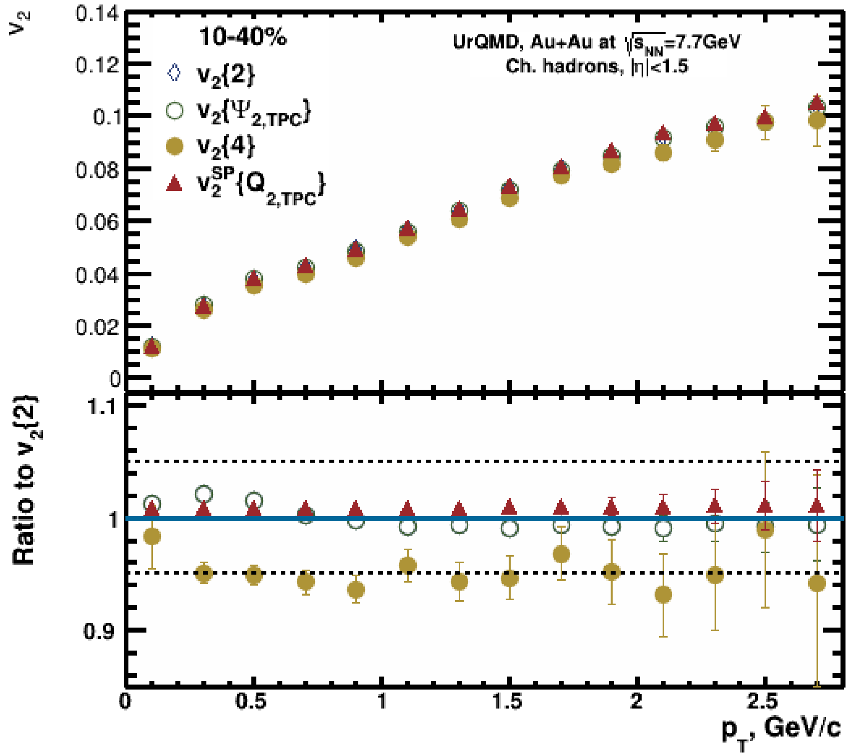
$$v_2^{SP}\{Q_{2,\mathrm{TPC}}\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$$

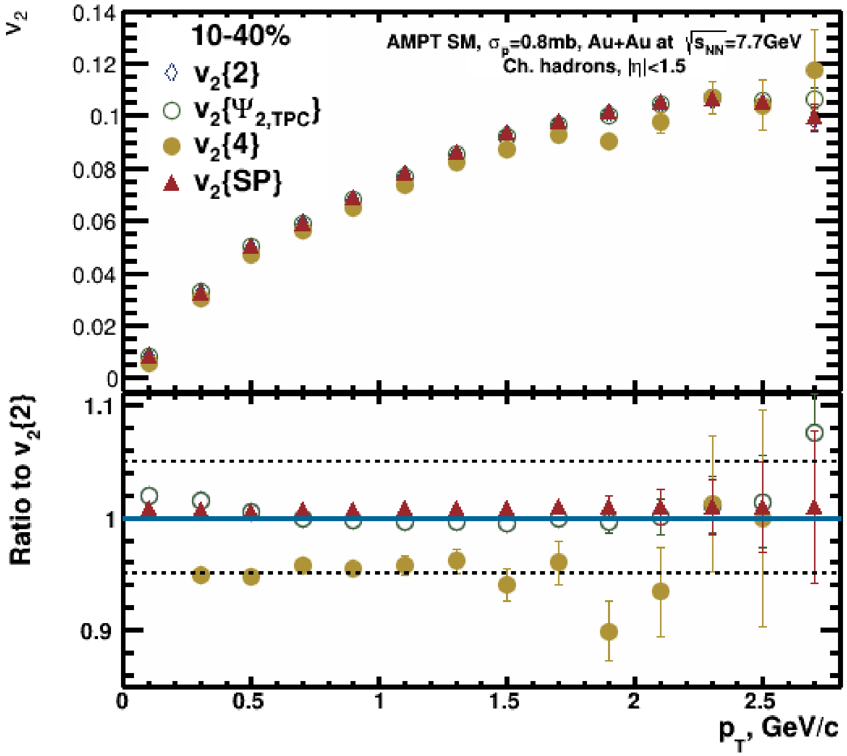
Models & statistics

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

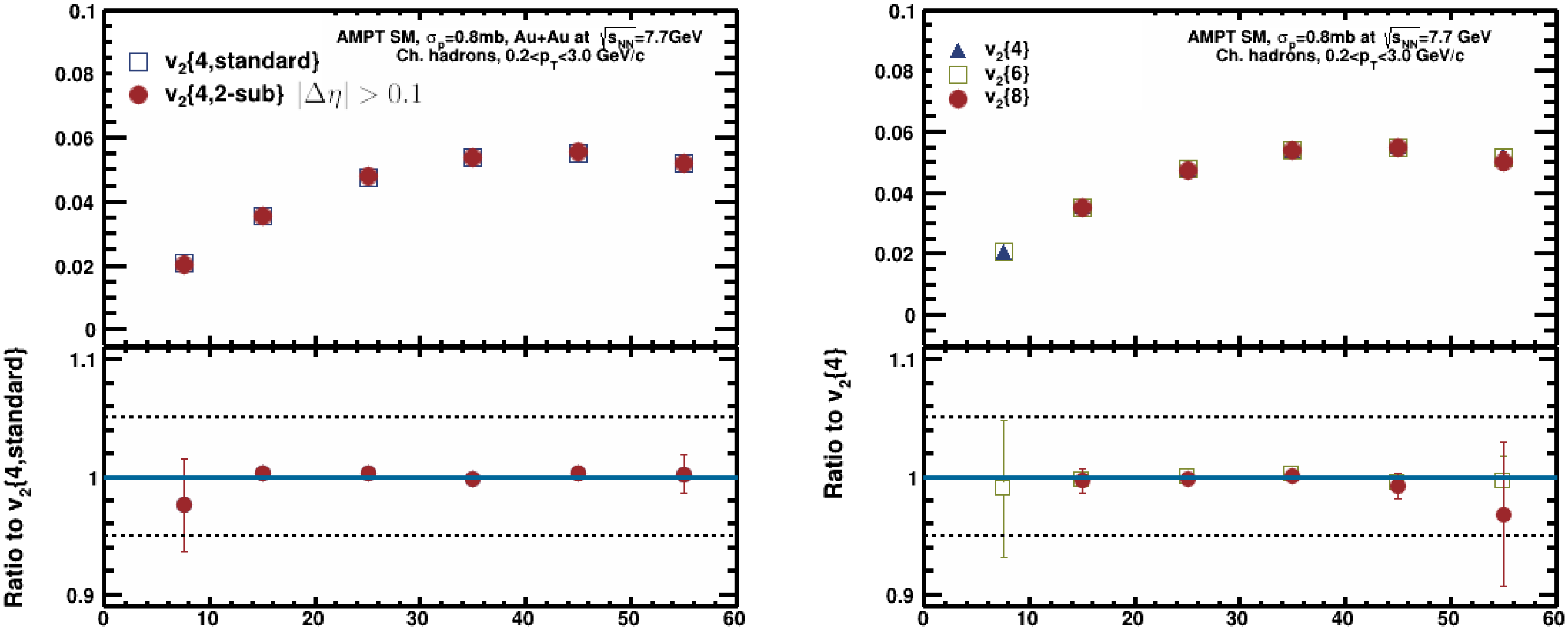
Sensitivity of different methods to flow fluctuations





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

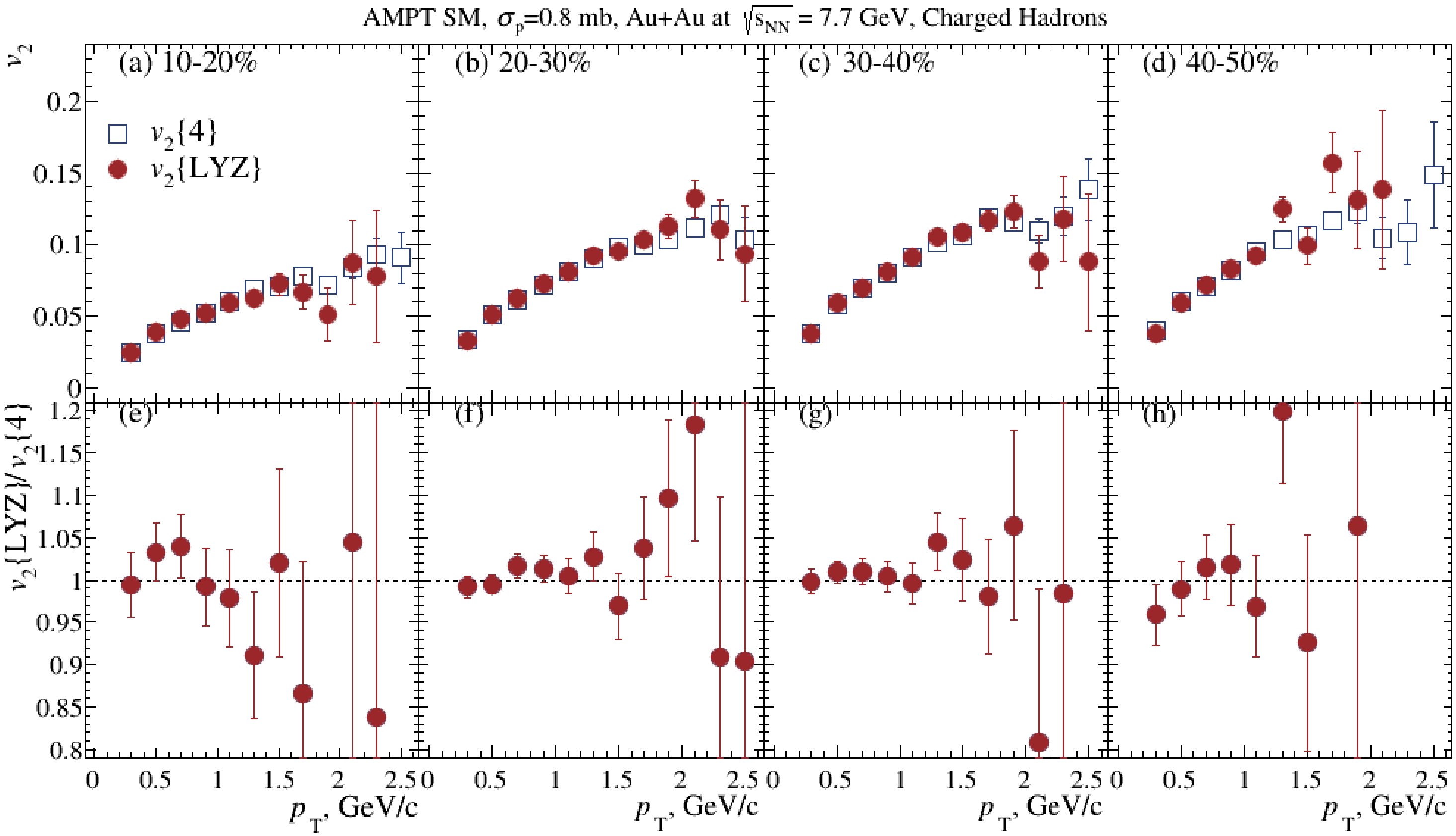
Comparison of high-order Q-Cumulants



Reasonable agreement between

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

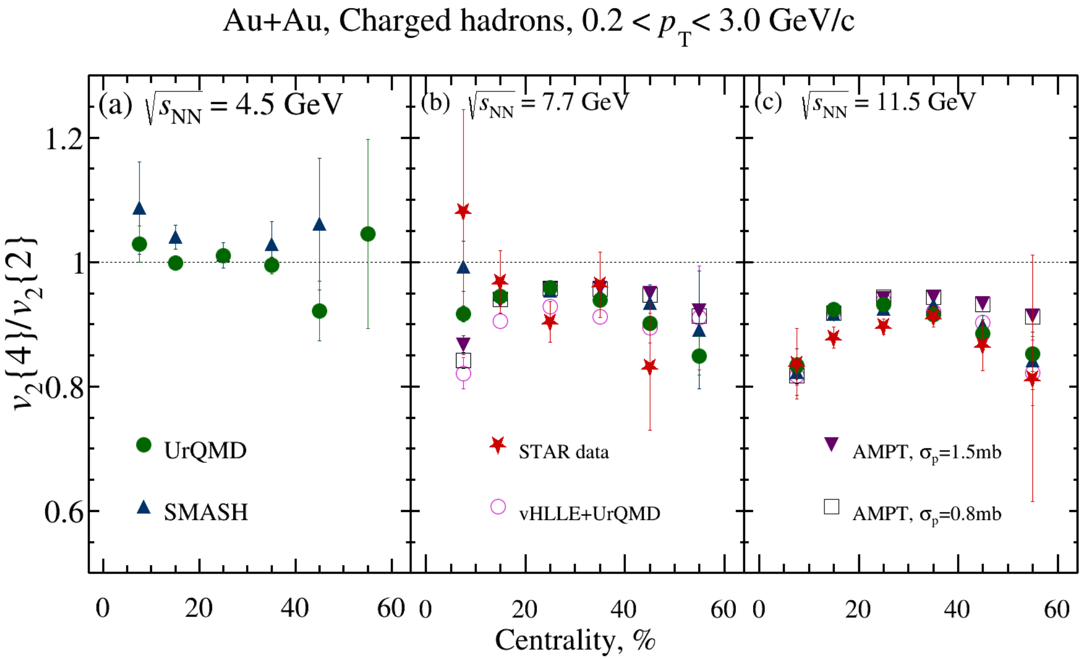
Comparison between $v_2\{4\}$ and $v_2\{LYZ\}$



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

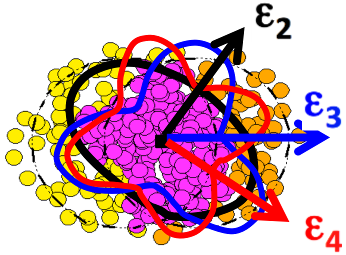
Need more statistics

Relative flow fluctuations of charged hadrons

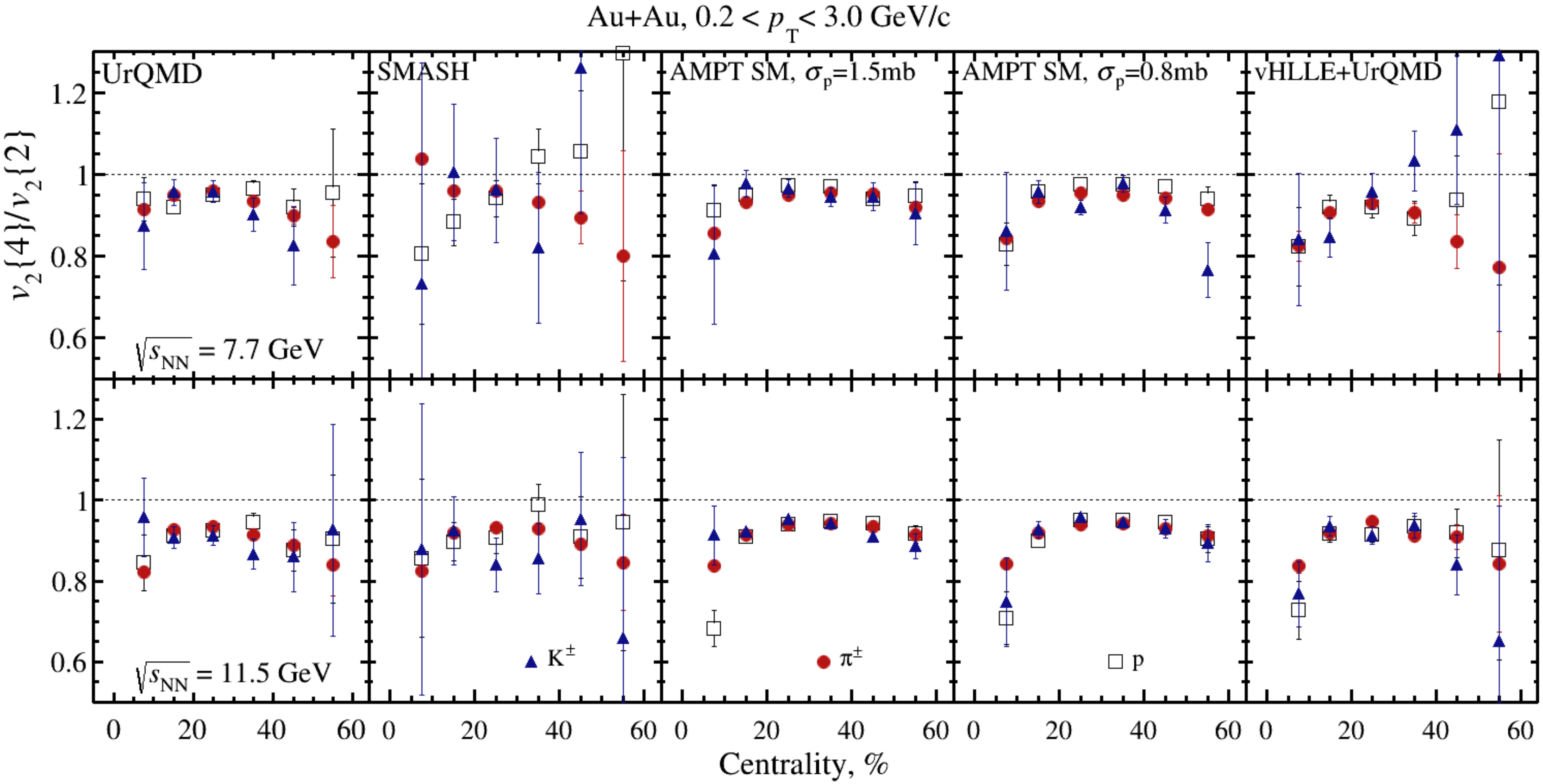


- Relative v_2 fluctuations ($v_2\{4\}/v_2\{2\}$) observed by STAR experiment can be reproduced both in the string/cascade models (UrQMD, SMASH) and model with QGP phase (AMPT SM, vHLLE+UrQMD)
- Dominant source of v_2 fluctuations: **participant eccentricity fluctuations** in the initial geometry
- Are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



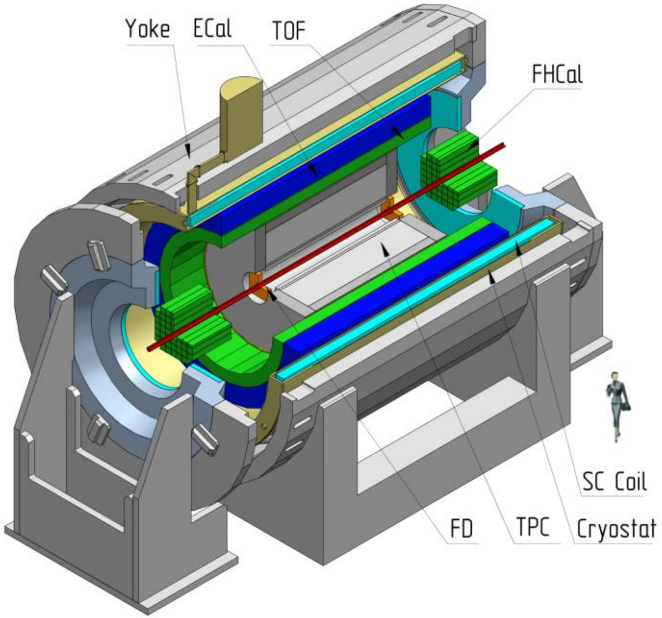
Elliptic flow fluctuations show weak dependence on particle species
Need more statistics

MPD Experiment at NICA

UrQMD → GEANT4 → Reconstruction → Flow analysis

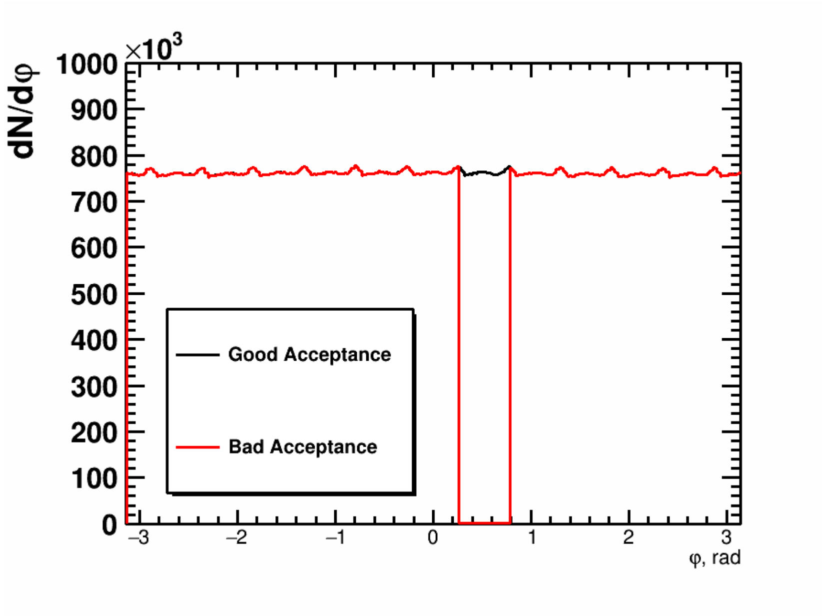
- Au+Au: 20M at $\sqrt{s_{NN}}$ = 7.7 GeV, 10M at $\sqrt{s_{NN}}$ = 11.5 GeV, Bi+Bi: 7M at $\sqrt{s_{NN}}$ = 7.7 GeV
- Centrality determination: Impact parameter b
- Event plane determination: TPC, FHCal
- Track selection:
  - Primary tracks
  - $N_{TPC\ hits} \geq 16$
  - $0.2 < p_T < 3.0$ GeV/c
  -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



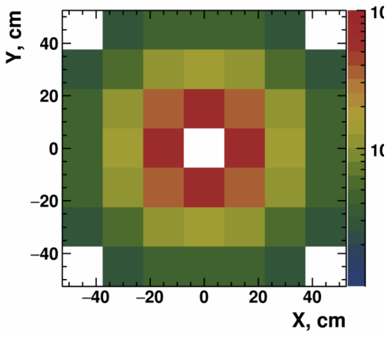
Multi-Purpose Detector (MPD) Stage 1

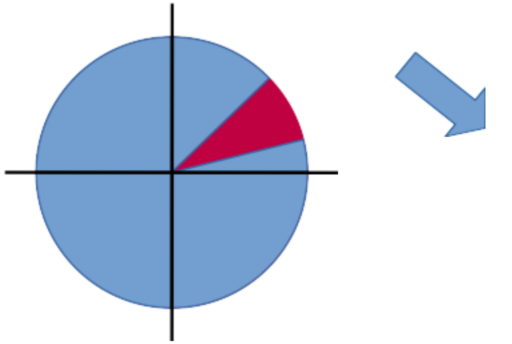
Non-uniform acceptance



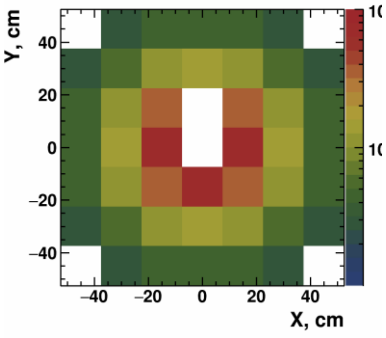
Area 15°< ϕ < 45° is off

FHCal L,R

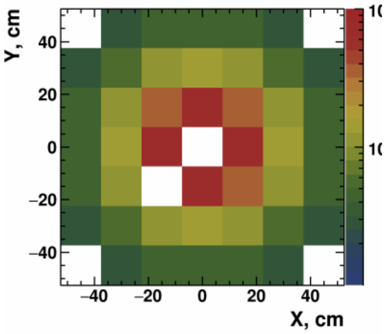




FHCal L

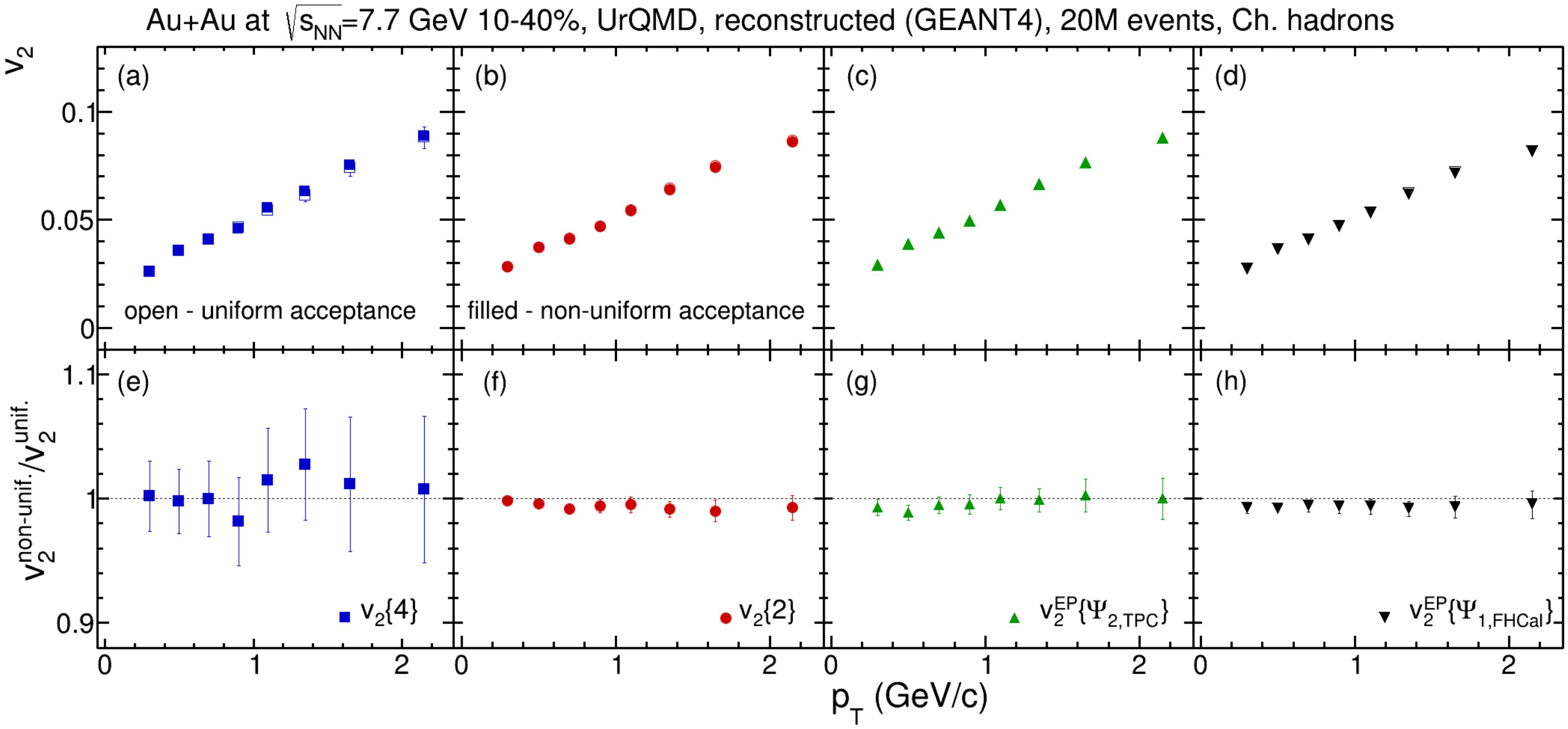


FHCal R



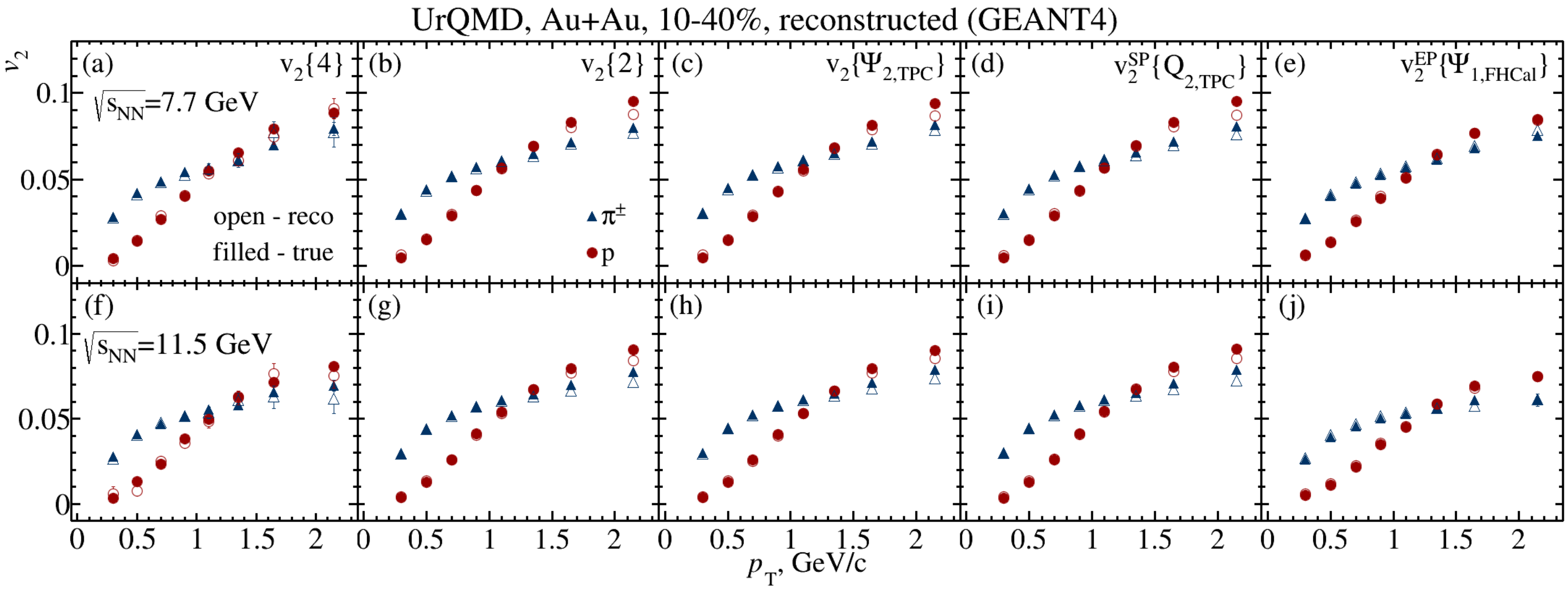
How robust are the future measurements against non-uniform acceptance?

Acceptance correction



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

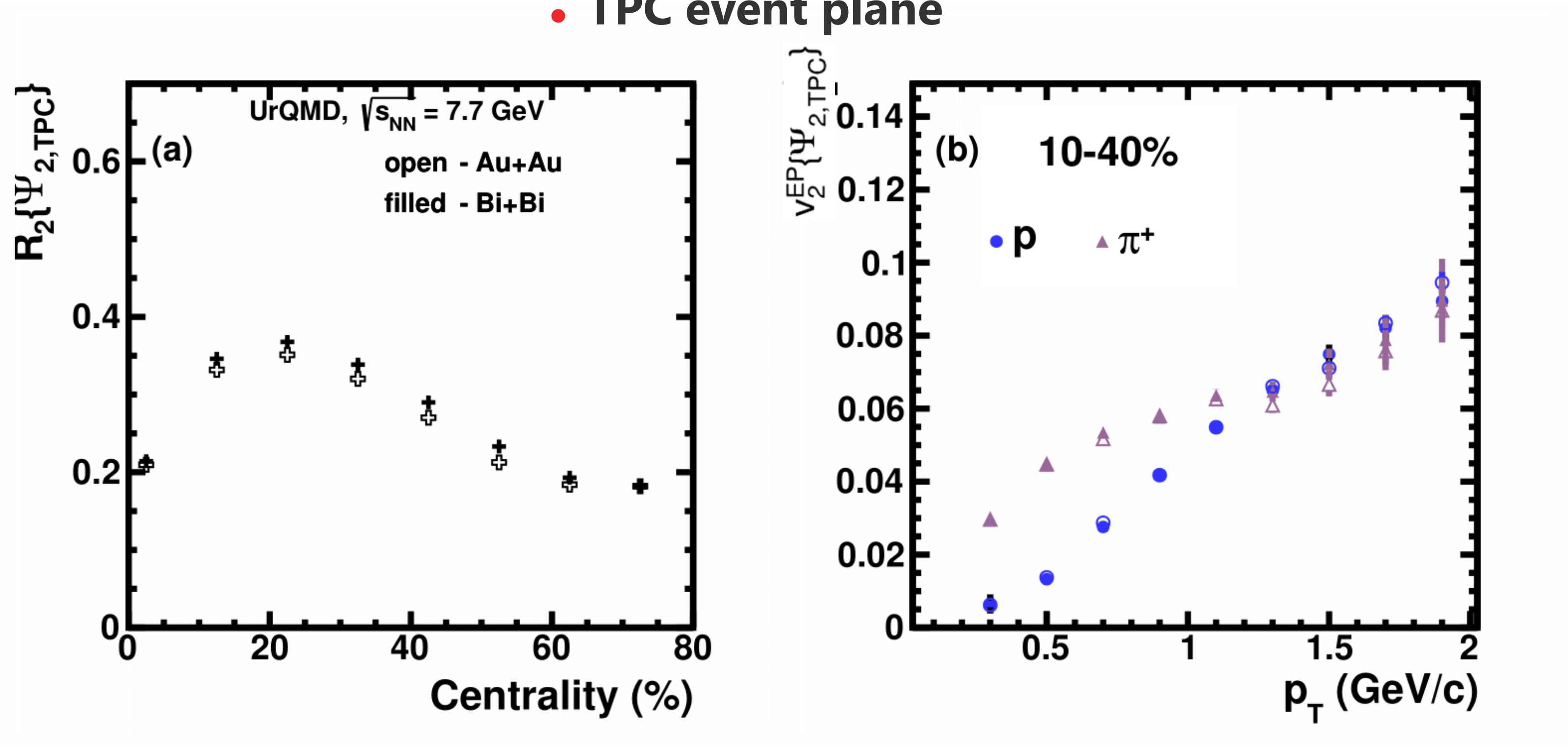
Performance of v_2 of pions and protons in MPD



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

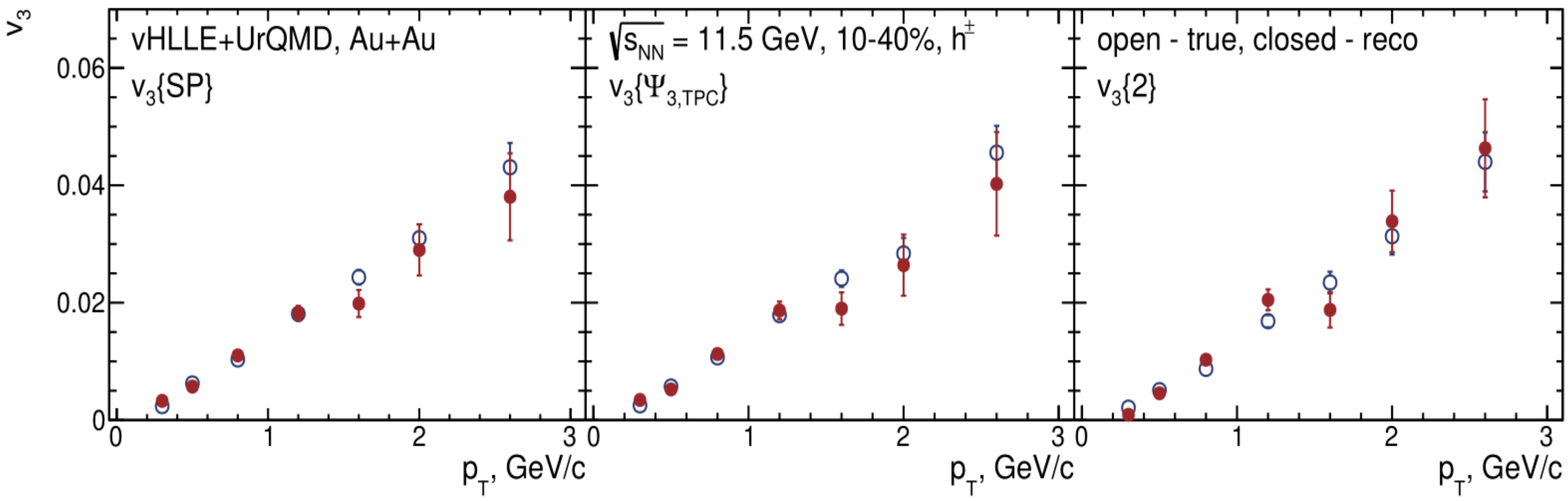
Au+Au vs. Bi+Bi collisions for MPD reconstructed data

- TPC event plane



- Expected small difference between two colliding systems

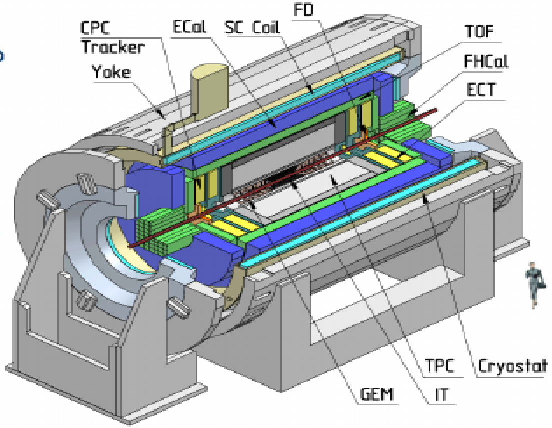
Triangular flow with MPD at NICA



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



Use of the KFParticle formalism within the MPD experiment: status and first promising results obtained

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[1]Joint Institute for Nuclear Research, Dubna, Russia
[2]National Research Nuclear University MEPhI, Moscow, Russia
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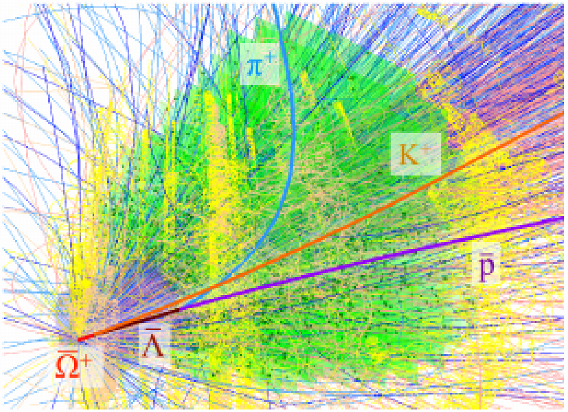
KFParticle formalism

Particles in heavy-ion collision:

STAR ALICE CBM



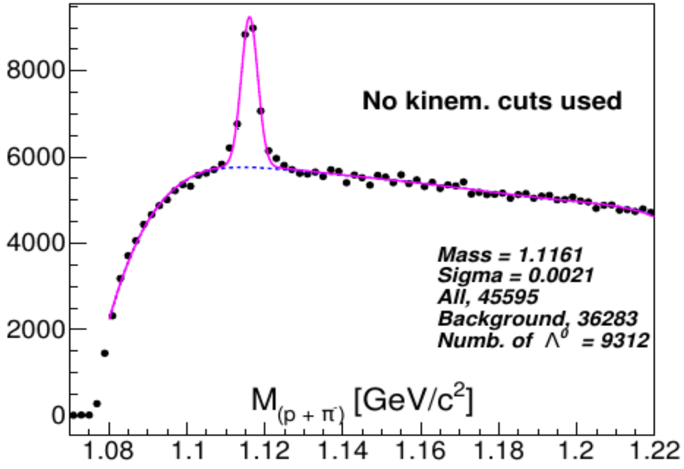
KFParticle:

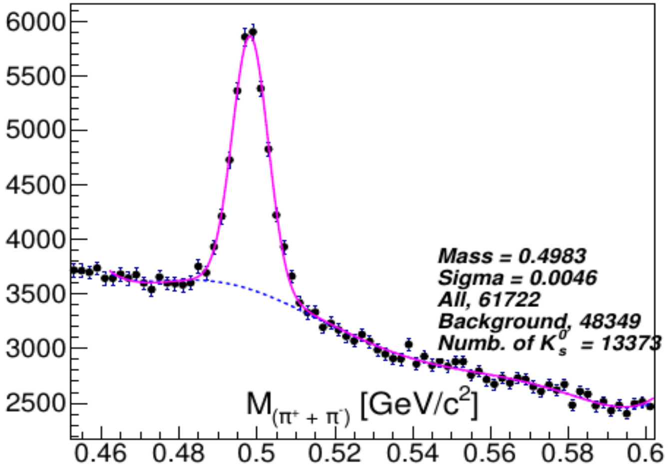
- developed for complete reconstruction of short-lived particles with their P, E, m, $c\tau$, L, Y

Main benefits:

- based on the Kalman filter mathematics
- idependent in sense of experimental setup (collider, fixed target)
- allows one reconstruction of decay chains (cascades)
- daughter and mother particles are described and considered the same way
- daughter particles are added to the mother particle independently

Reconstructed mass spectra





KF Particle Finder scheme assumes that each mass spectrum consists of:

- Signal (S) (daughter particles come from real decaying particle)
- Background related to misidentification (MB) (daughter particles come from decaying particle, but either pdg (PID) hypothesis is incorrect or not all daughters from decay are reconstructed)
- Combinatorial background (CB) (tracks do not form a real secondary vertex)

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
  - Lack of existing differential measurements of v_2 (p_T, centrality, PID, …)
- **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
  - v_n of K^0 and Λ particles: results from reconstructed (using invariant mass fits) and generated data are in a good agreement
- **Small differences in v_n for 2 colliding systems (Au+Au, Bi+Bi) were observed as expected**

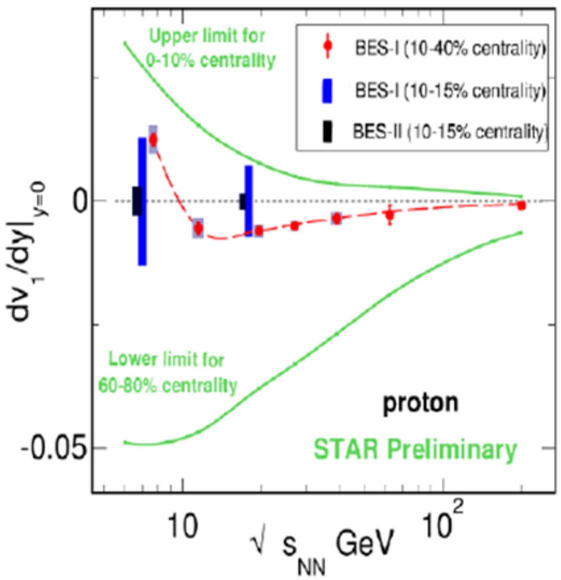
Outlook:

- Detailed differential measurements v_1,v_2 and v_3 measurements for the charged hadrons, V0 particles and resonances
- Detailed analysis note
- Github repository: https://github.com/FlowNICA/CumulantFlow

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

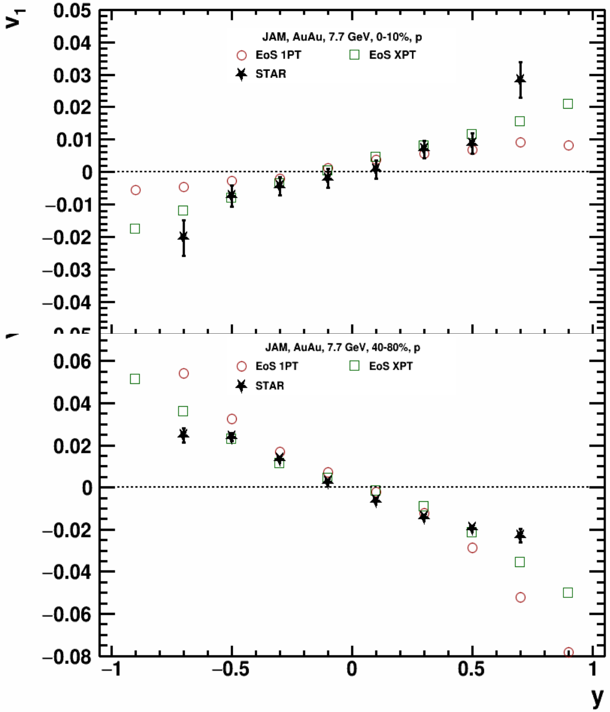
(16-20 August 2020)

v_1 study at NICA energies



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

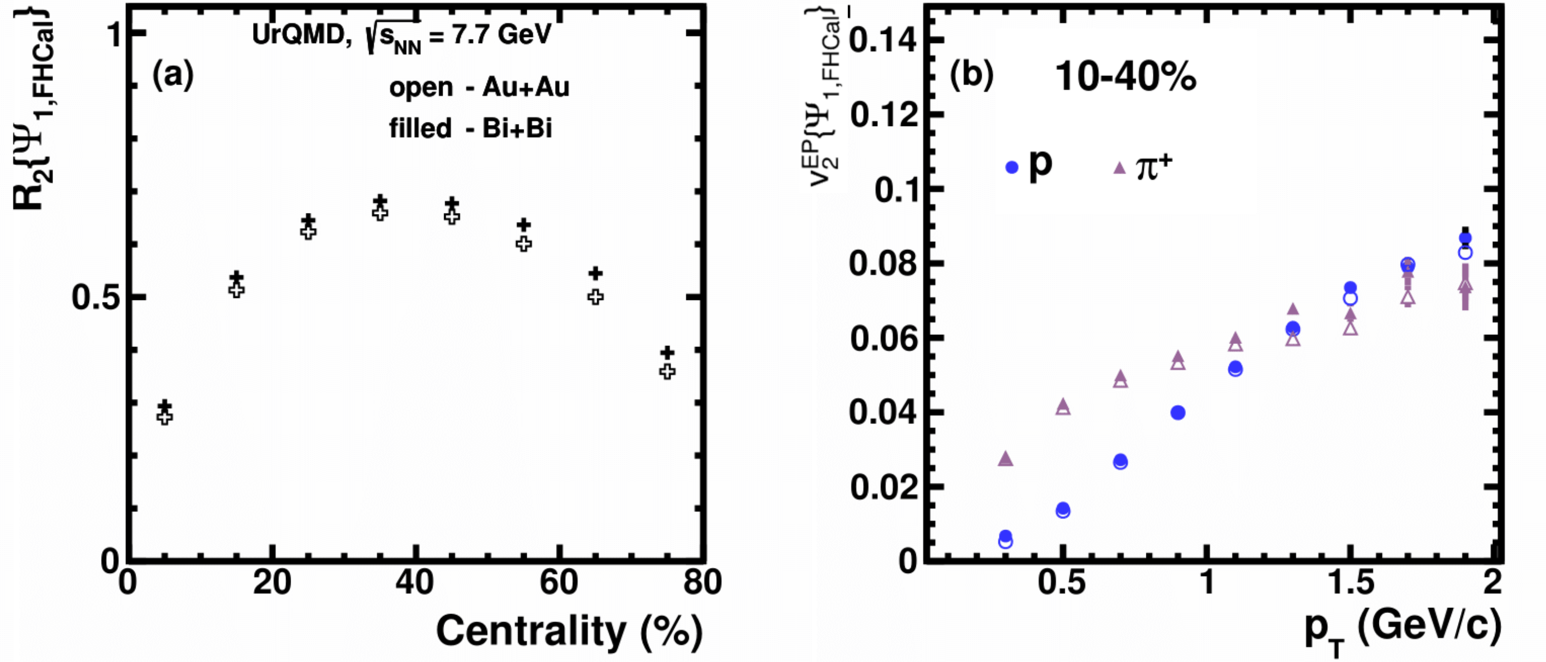
P. Parfenov, The Conference "RFBR Grants for NICA", Dubna (2020)



dv_1/dy slope changes dramatically with centrality for protons

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

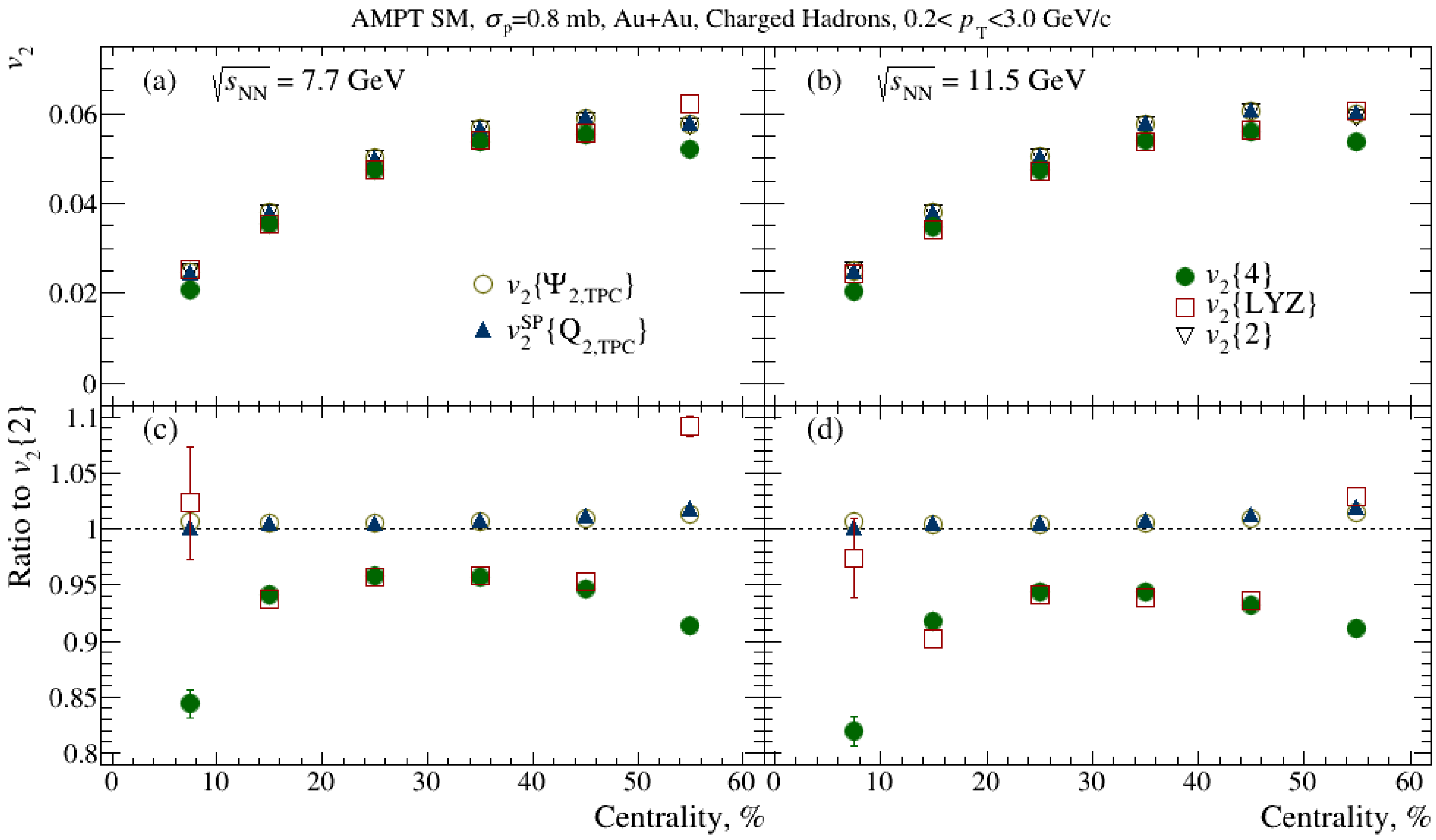
- FHCal event plane



- Expected small difference between two colliding systems

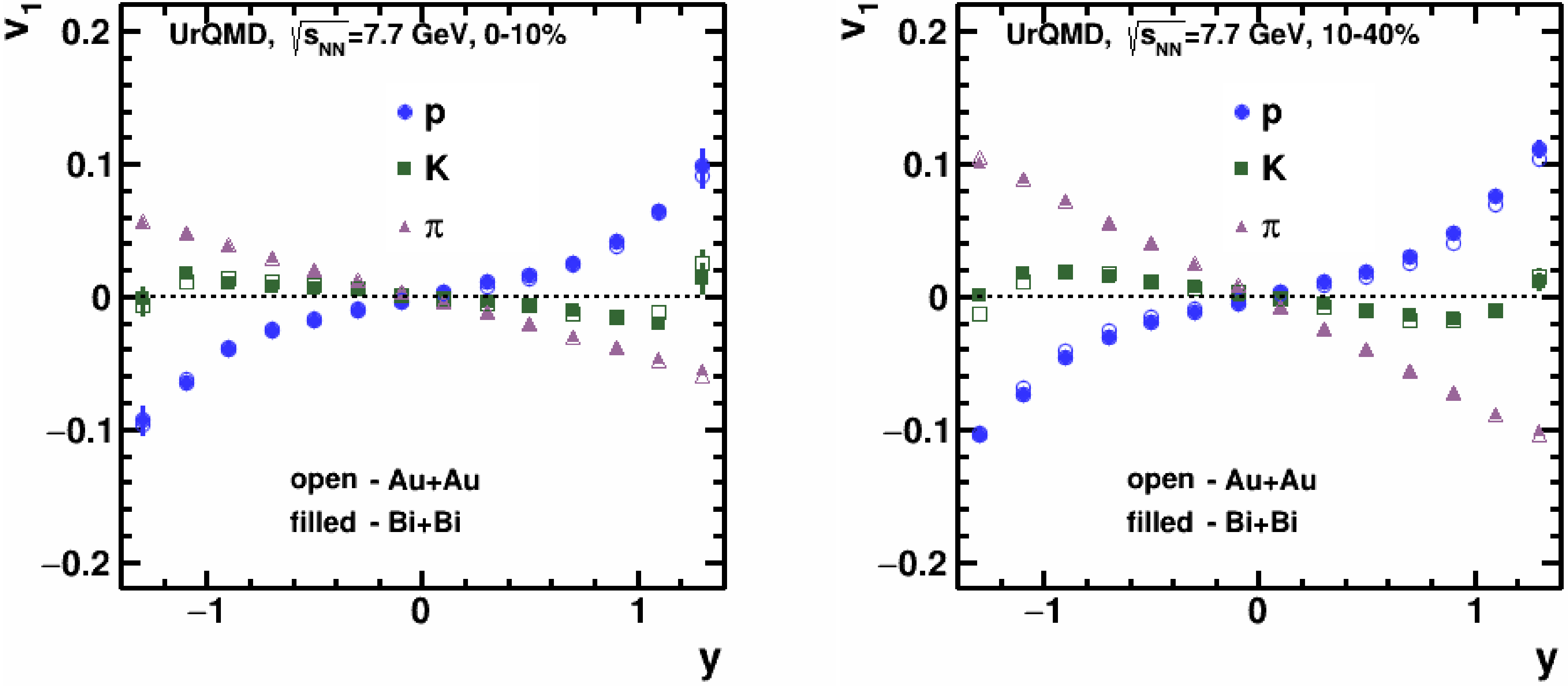
Back-up slides

Centrality dependence of v_2\{methods\}



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

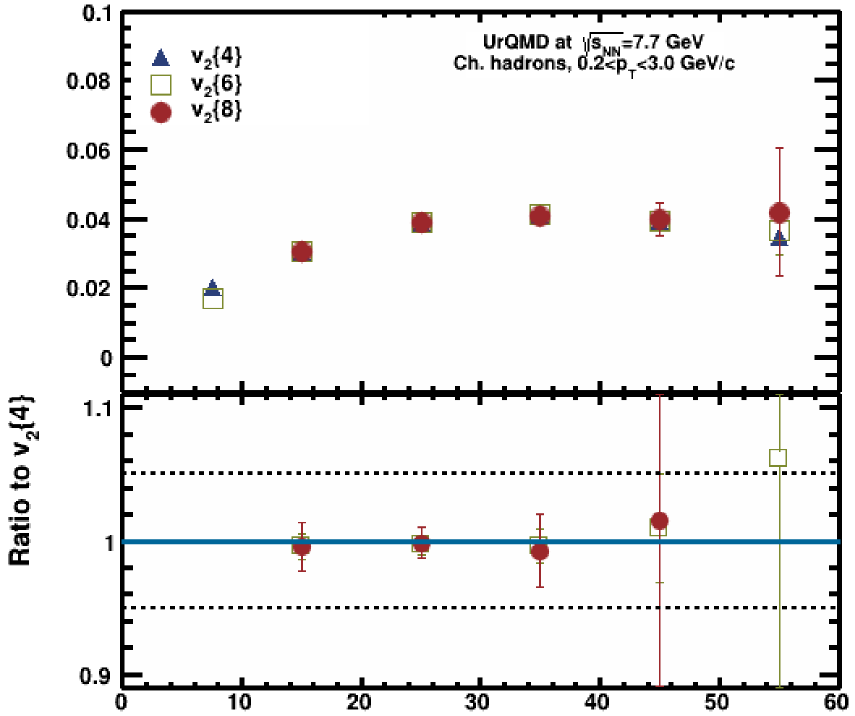
$v_1(y)$: Bi+Bi vs Au+Au



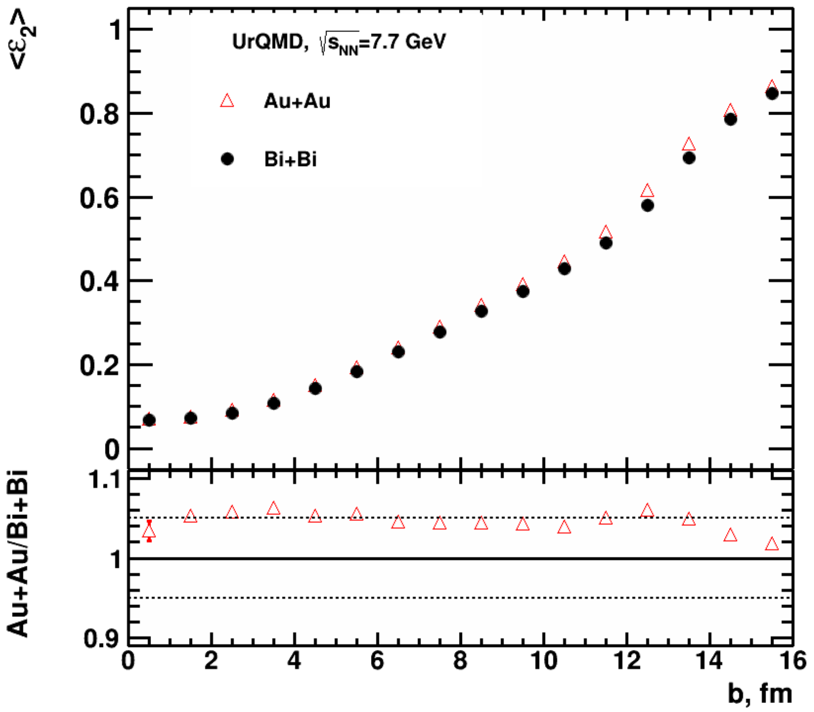
Expected small difference for v1 (y) for particles produced in Au+Au and Bi+Bi collisions.

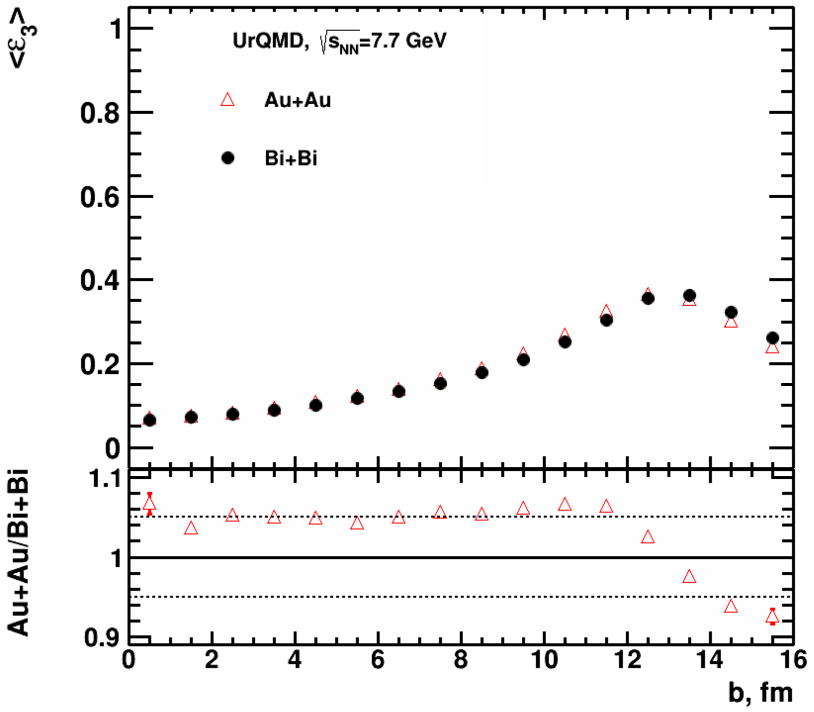
Description of high-order Q-Cumulants

- **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