Relative elliptic flow fluctuations at NICA energy regime

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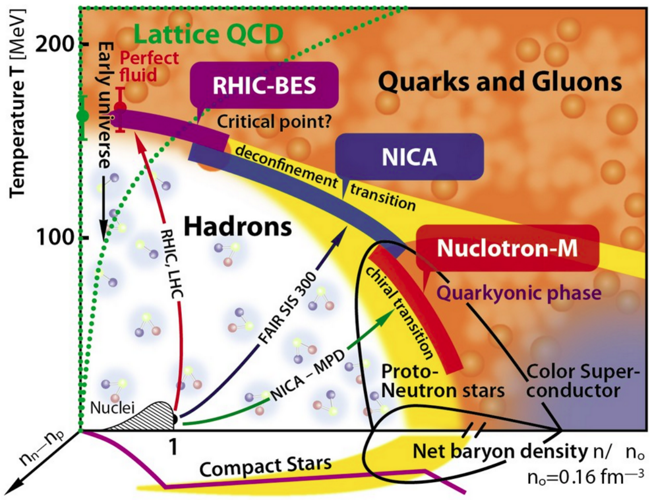
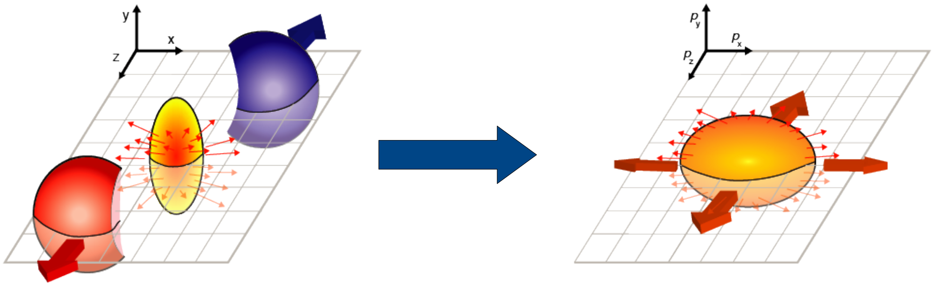
Outline

- Elliptic flow v_2 at NICA energies
- Description of methods for elliptic flow measurements
- Sensitivity of different methods to flow fluctuations and non-flow
- Relative flow fluctuations $v_2\{4\}/v_2\{2\}$
- Form of flow fluctuations
- v_2 performance of identified charged hadrons in MPD
- Summary

Anisotropic flow phenomenon





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

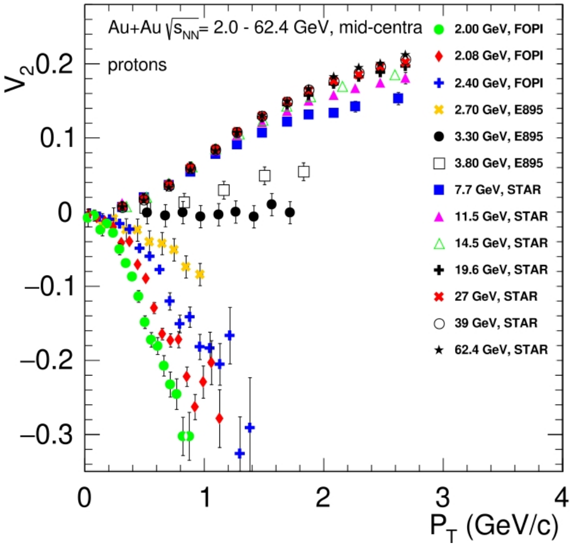
$$\frac{dN}{d\phi} \propto 1 + 2\sum_{n=1} v_n \cos\left[n\left(\phi - \Psi_{RP}\right)\right]$$

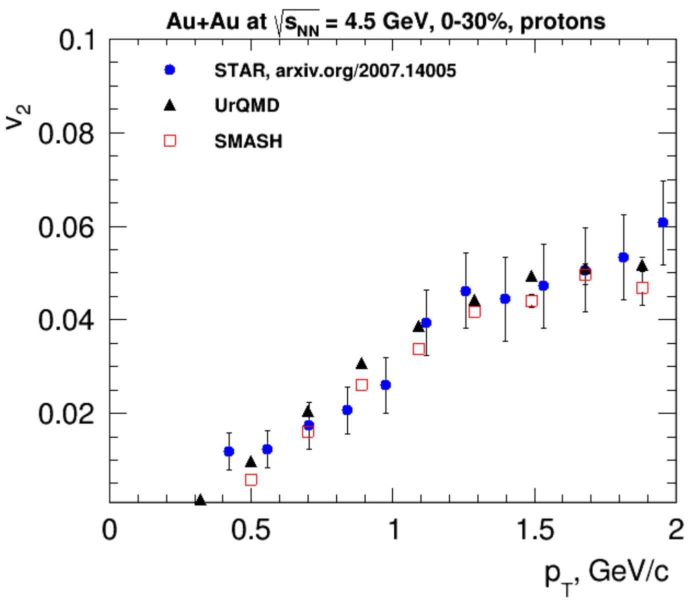
$$v_n = \langle \cos\left[n\left(\phi - \Psi_{RP}\right)\right] \rangle$$

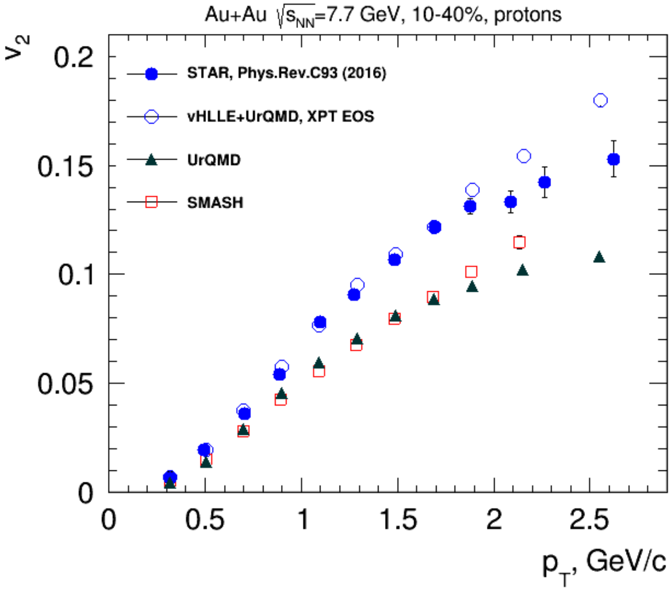
- **LHC/top RHIC:** cross-over transition leading to the sQGP
- Beam-energy scan programs (**RHIC/SPS/NICA/FAIR**): search for 1^{st} order phase transition, critical end point

- Transfer of anisotropy from the initial coordinate space into the final momentum space via the thermalized medium
- Anisotropic flow is a sensitive probe of the sQGP properties (η/s, ζ/s, EoS)

Elliptic flow at NICA energies







Lack of differential v_2 at NICA energies

$v_2(\mathrm{UrQMD,\ SMASH}) \approx v_2(\mathrm{STAR})$

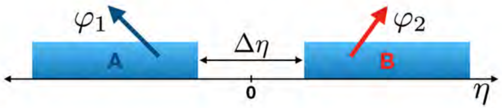
$v_2(\mathrm{UrQMD,\ SMASH}) < v_2(\mathrm{STAR})$

$v_2(\mathrm{vHLLE+UrQMD}) \approx v_2(\mathrm{STAR})$

v_2 is sensitive to the properties of the strongly interacting matter produced in relativistic heavy-ion collisions

Q-cumulants method for v_2 measurements

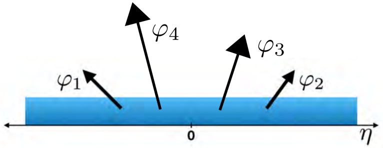
- **Sub-event 2-particle Q-cumulants** $v_2\{2\}$



$$Q_n = \sum_{i=1}^{M} e^{in\phi} \qquad \langle 2 \rangle_{a|b} = \frac{Q_{n_a} Q^*_{n,b}}{M_a M_b} \qquad v_2\{2\} = \sqrt{\langle\langle 2 \rangle\rangle_{a|b}}$$

  - $\Delta\eta = 0.1$ is applied between 2 sub-events A, B to suppress non-flow

- **4-particle Q-cumulants** $v_2\{4\}$



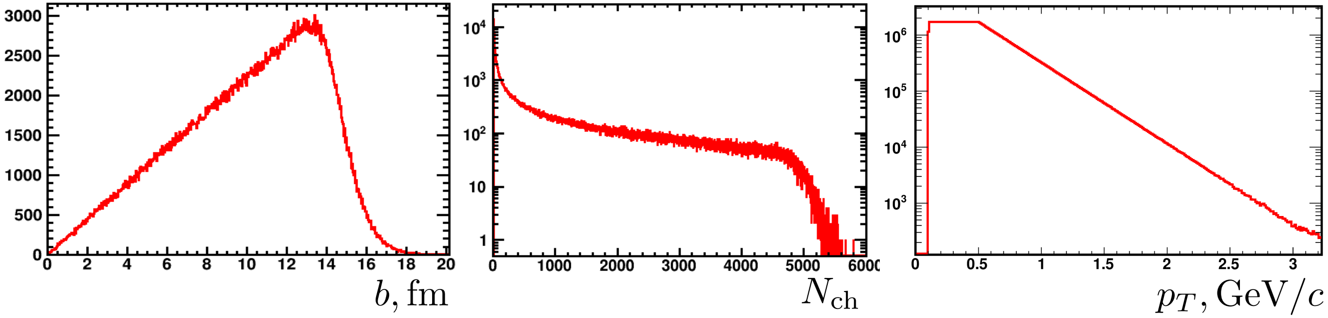
$$\langle 2 \rangle = \frac{|Q_n|^2 - M}{M(M-1)}$$

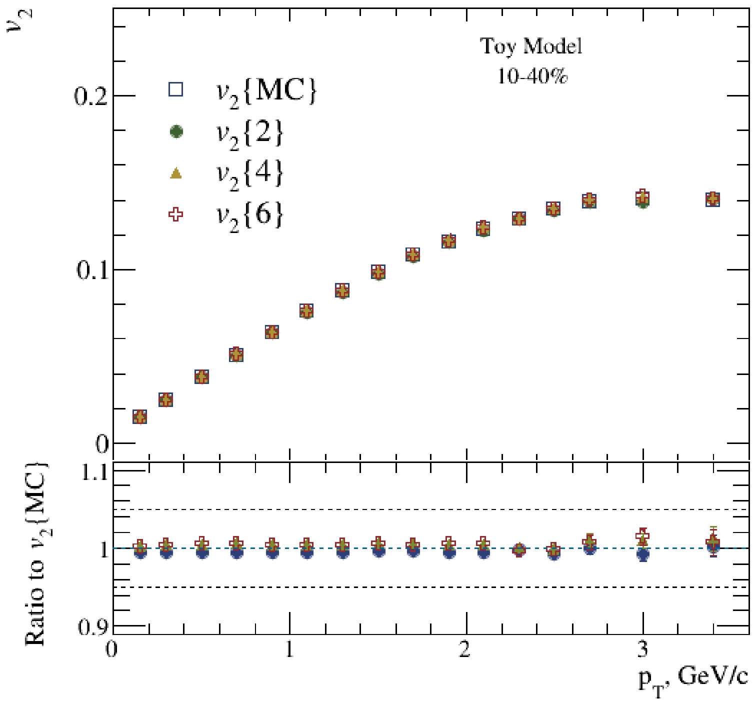
$$\langle 4 \rangle = \frac{|Q_n|^4 + |Q_{2n}|^2 - 2\Re[Q_{2n} Q^*_n Q^*_n] - 4(M-2)\,|Q_n|^2 - 2M(M-3)}{M(M-1)(M-2)(M-3)} \qquad v_2\{4\} = \sqrt[4]{2\,\langle\langle 2 \rangle\rangle^2 - \langle\langle 4 \rangle\rangle}$$

- **6,8-particle Q-cumulants** $v_2\{6\}$, $v_2\{8\}$
  - $\langle 6 \rangle, \langle 8 \rangle$ calculated using recursive algorithm in PRC 89 (2014) 064904 to get rid of long stand-alone formulae

Method's details described in PRC 83 (2011), 044913

Testing Q-cumulant code on MC Toy Model





- v_2 is generated based on the parameterized function $v_2(b, \eta, p_T)$ of RHIC data
- **Simulated events:** 100 M
- **Selection criteria for flow analysis:** same selection is used for analyzing flow from heavy-ion collision generators
  - **Centrality selection:** based on b
  - **Track selection:**
    - $|\eta| < 1.5$
    - Reference particles: $0.2 < p_T^{\mathrm{RFPs}} < 3.0$ GeV/c, charged hadrons

Good agreement between $v_2\{MC\}$ and all $v_2\{2k\}$ (k=1,2,3)
→ Code works properly

Models & statistics

Au+Au, min. bias

- **Without QGP phase:**
  - **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
  - **AMPT σ_p = 0:**
    - $\sqrt{s_{NN}}$ = 4.5 GeV: 120M

- **With QGP phase:**
  - **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

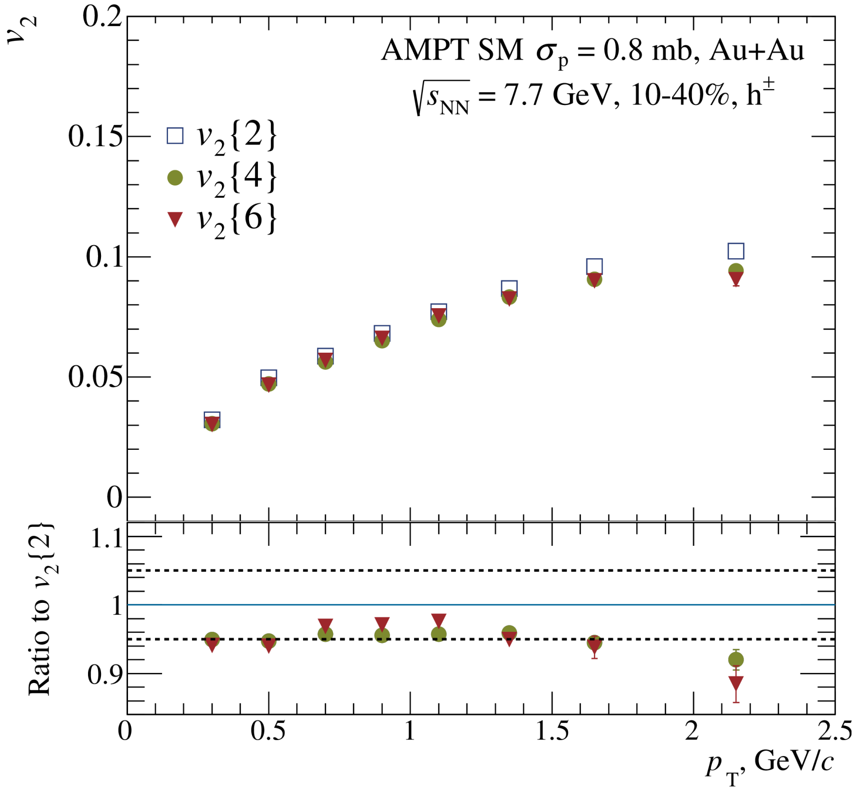
Sensitivity of Q-cumulants to flow fluctuations and non-flow

- Non-flow contribution: for k-particle correlations: $\delta_k \sim 1/M^{k-1}$
- 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 $\langle v_2 \rangle$:

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

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

    - $\frac{v_2\{4\}}{v_2\{2\}} \approx 1 \Longrightarrow \sigma_{v2}^2 \approx 0$

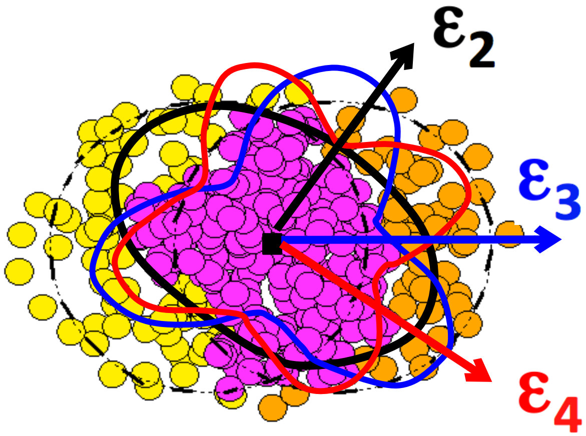


$v_2\{2\} > v_2\{4\} \approx v_2\{6\}$

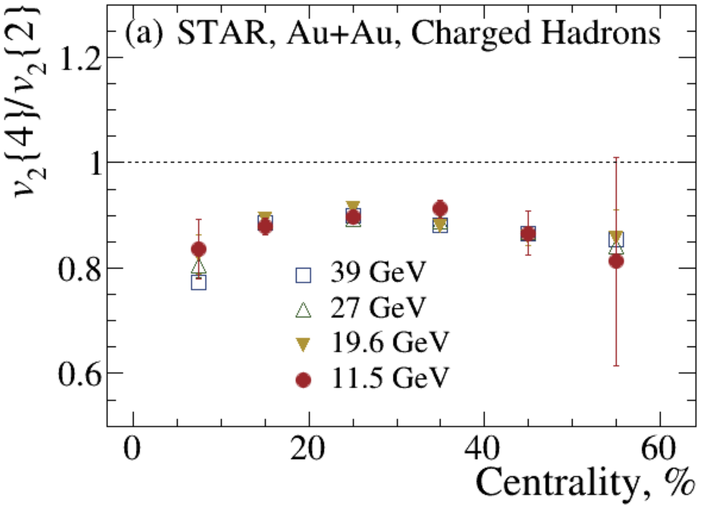
Motivation for elliptic flow fluctuation study

- 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 $\eta/s(T)$

$$(v_2 = \kappa_2 \epsilon_2)$$



Data points: PRC 86, 054908 (2012)

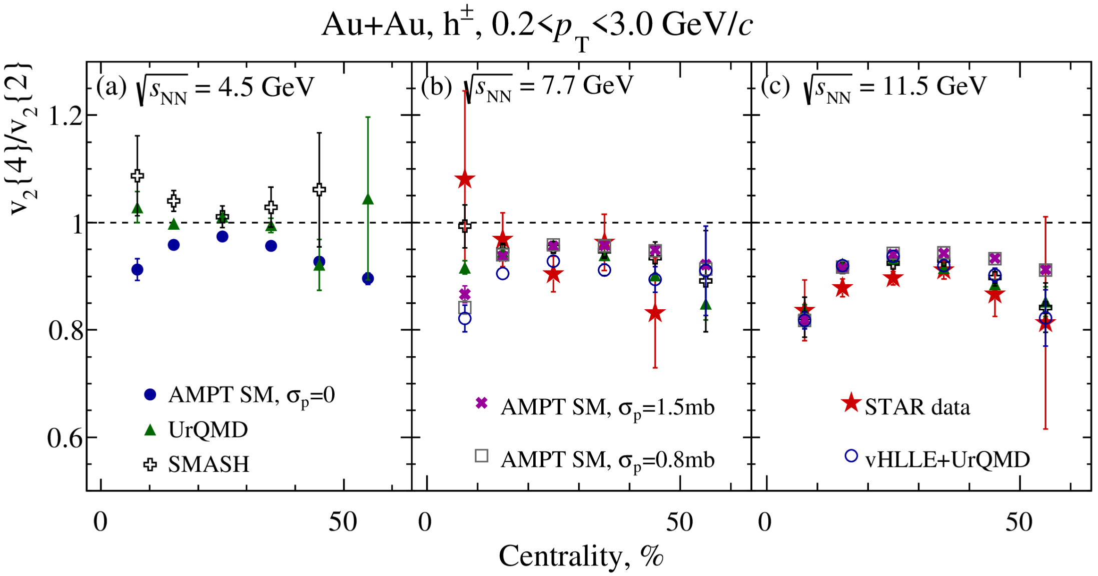


Note: small value of the $v_2\{4\}/v_2\{2\}$ ratio corresponds to large fluctuations

v_2 fluctuations at $\sqrt{s_{NN}}$=11.5–39 GeV in STAR BES:

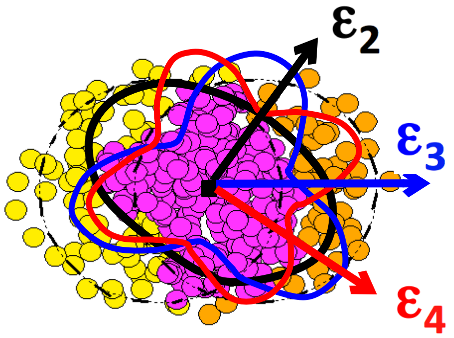
- weak dependence on collision energy
- main source: ϵ_2 fluctuations

Relative flow fluctuations of charged hadrons

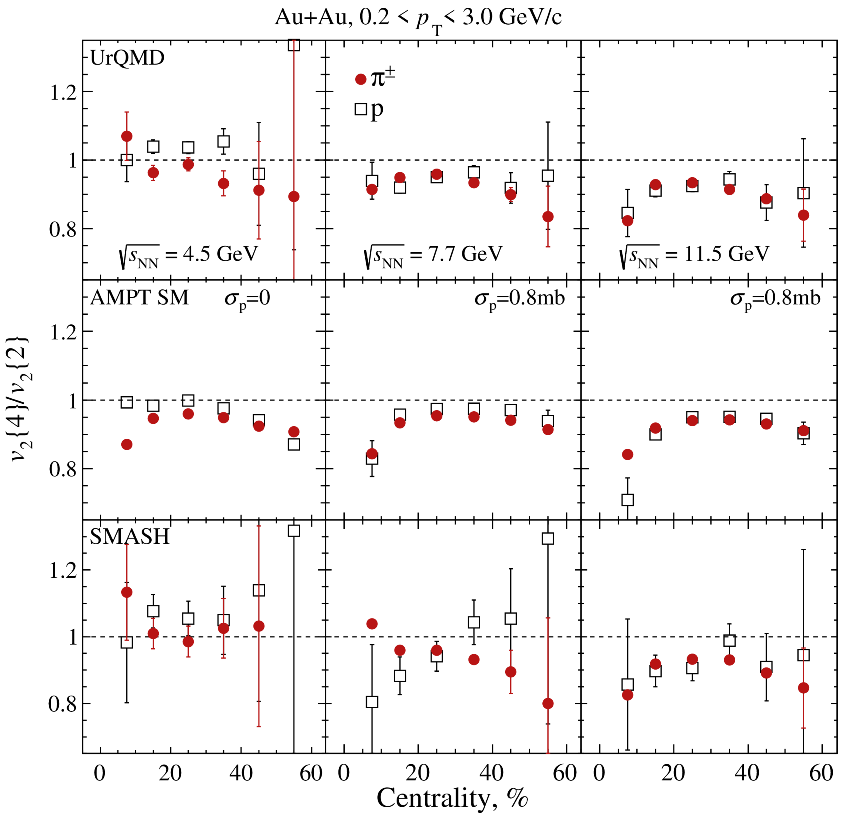


STAR data: PRC 86, 054908 (2012)
After quality cuts, 0-80%: 4M at 7.7 GeV, 11M at 11.5 GeV

- 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?



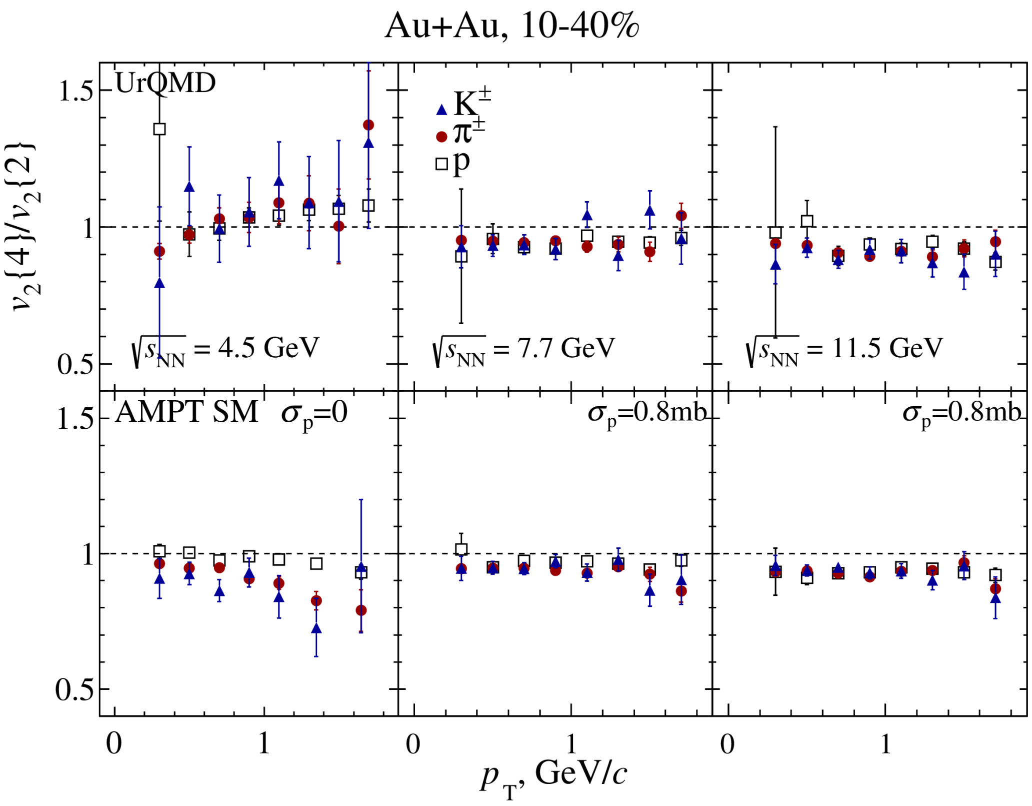
Relative flow fluctuations of identified charged hadrons



- Row: same model
- Column: same collision energy

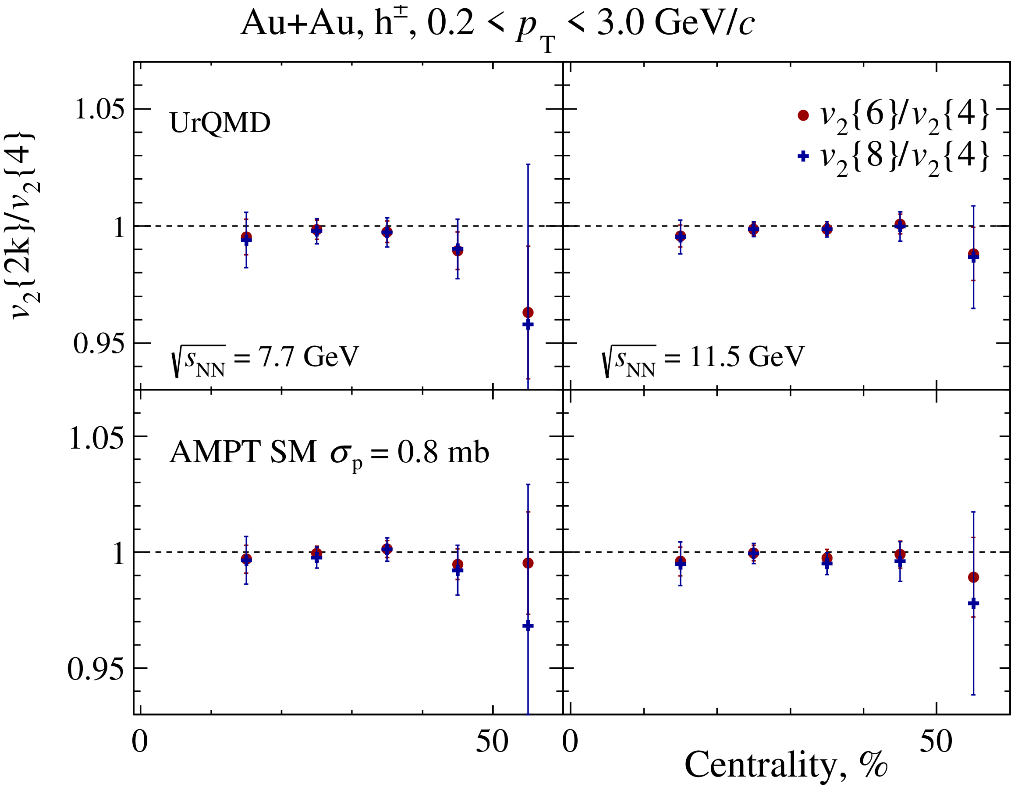
- UrQMD, AMPT SM, SMASH predict $v_2\{4\}/v_2\{2\} \approx 1$ for protons up to 30-40% centrality at 4.5 GeV
- Weak dependence on PID
- More statistics are needed

Relative flow fluctuations of identified charged hadrons



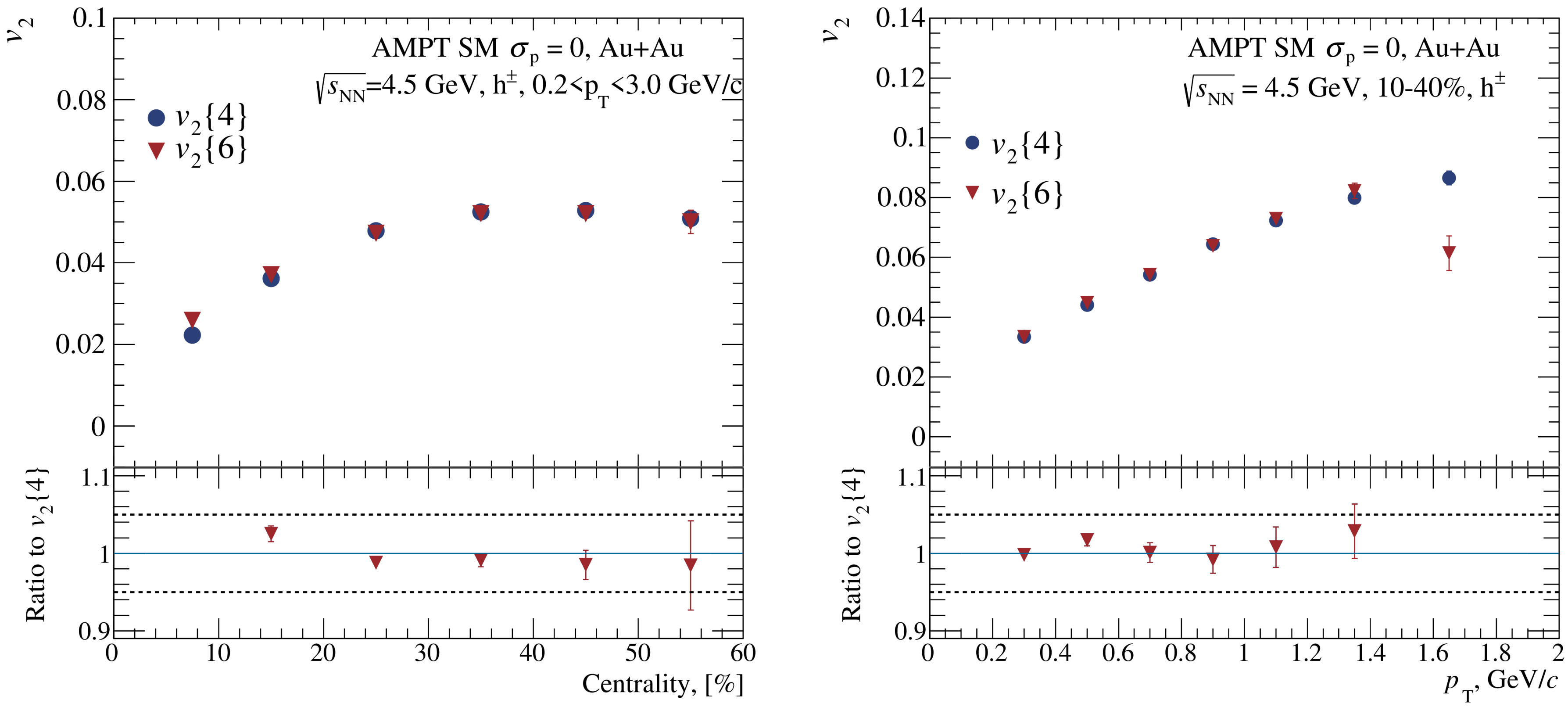
- $v_2\{4\}/v_2\{2\}$ ratio in 10-40% midcentral Au+Au collisions predicted by UrQMD and AMPT SM:
  - At 7.7, 11.5 GeV: weak PID/p_T-dependence
  - At 4.5 GeV: zero relative fluctuations for protons predicted by AMPT

Form of flow fluctuations



- $v_2\{2k\}/v_2\{4\} \approx 1\ (k = 3, 4)$ in 10-50% midcentral Au+Au collisions predicted by UrQMD & AMPT SM
  - **Gaussian form** of flow fluctuations in midcentral collisions at NICA energy regime?

Form of flow fluctuations

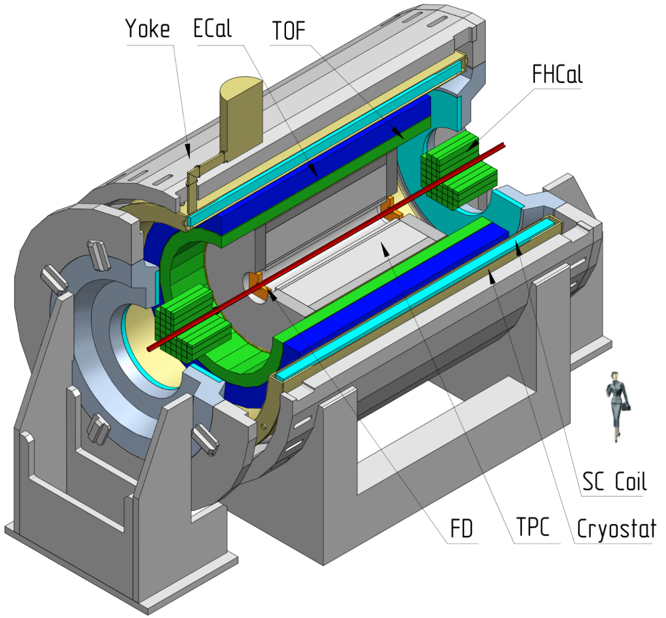


$v_2\{6\}/v_2\{4\}$=1 within statistical errors in mid-central collisions

MPD Experiment at NICA

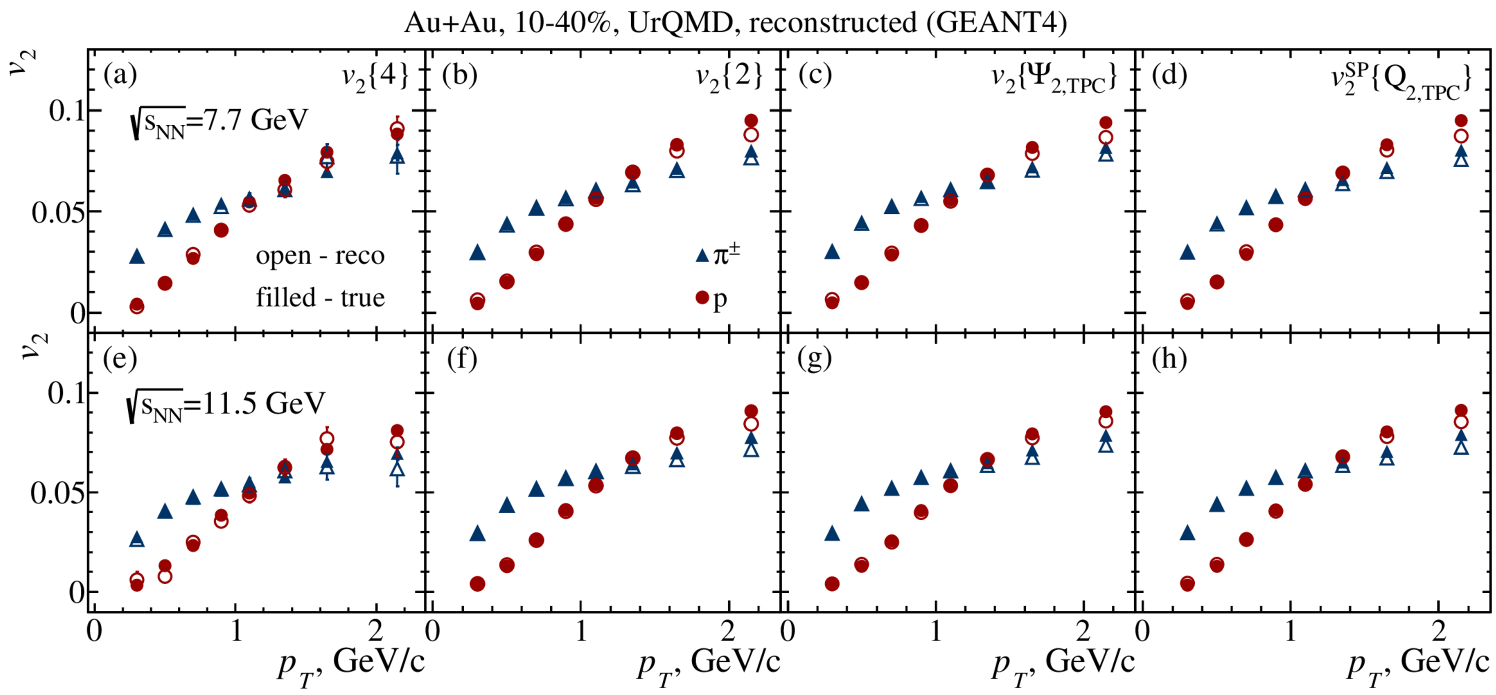
UrQMD → GEANT4 → Reconstruction → Flow analysis

- **Au+Au:**
  - 20M at $\sqrt{s_{NN}}$ = 7.7 GeV
  - 10M at $\sqrt{s_{NN}}$ = 11.5 GeV
- **Centrality determination:**
  - b based on MC-Glauber method (see Idrisov's talk)
- **Event plane determination:** TPC
- **Track selection:**
  - Primary tracks
  - $N_{\text{hits}}^{\text{TPC}} > 15$
  - $0.2 < p_T^{\text{RFPs}} < 3.0\ \text{GeV}/c$
  - $|\eta| < 1.5$
  - PID based on PDG



Multi-Purpose Detector (MPD) Stage 1

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

Summary

- Strong energy dependence of v_2 at NICA energies
  - At $\sqrt{s_{NN}}$ = 4.5 GeV: v_2 from SMASH, UrQMD are in good agreement with experimental data
  - At $\sqrt{s_{NN}} \geq$ 7.7 GeV: hadronic cascade model underestimate v_2 – need models with QGP phase (vHLLE+UrQMD, AMPT, etc.)
  - Lack of existing differential measurements of $v_2(p_T, \mathrm{PID})$
- Relative flow fluctuations $v_2\{4\}/v_2\{2\}$:
  - $v_2\{4\}/v_2\{2\}$ measured in STAR can be reproduce by models with and without QGP phase, indicating main source of flow fluctuations: the participant eccentricity fluctuations
  - Weak dependence on p_T and particle species
  - AMPT predicts zero flow fluctuations for protons in midcentral collisions at 4.5 GeV
- AMPT & UrQMD predict $v_2\{6\}/v_2\{4\}$ and $v_2\{8\}/v_2\{4\} \approx$ 1 in mid-central collisions, indicating a Gaussian form of v_2 fluctuations
- v_2 of identified charged hadrons from MPD reconstructed and from generated data are in good agreement