Elliptic flow fluctuations at NICA energy regime

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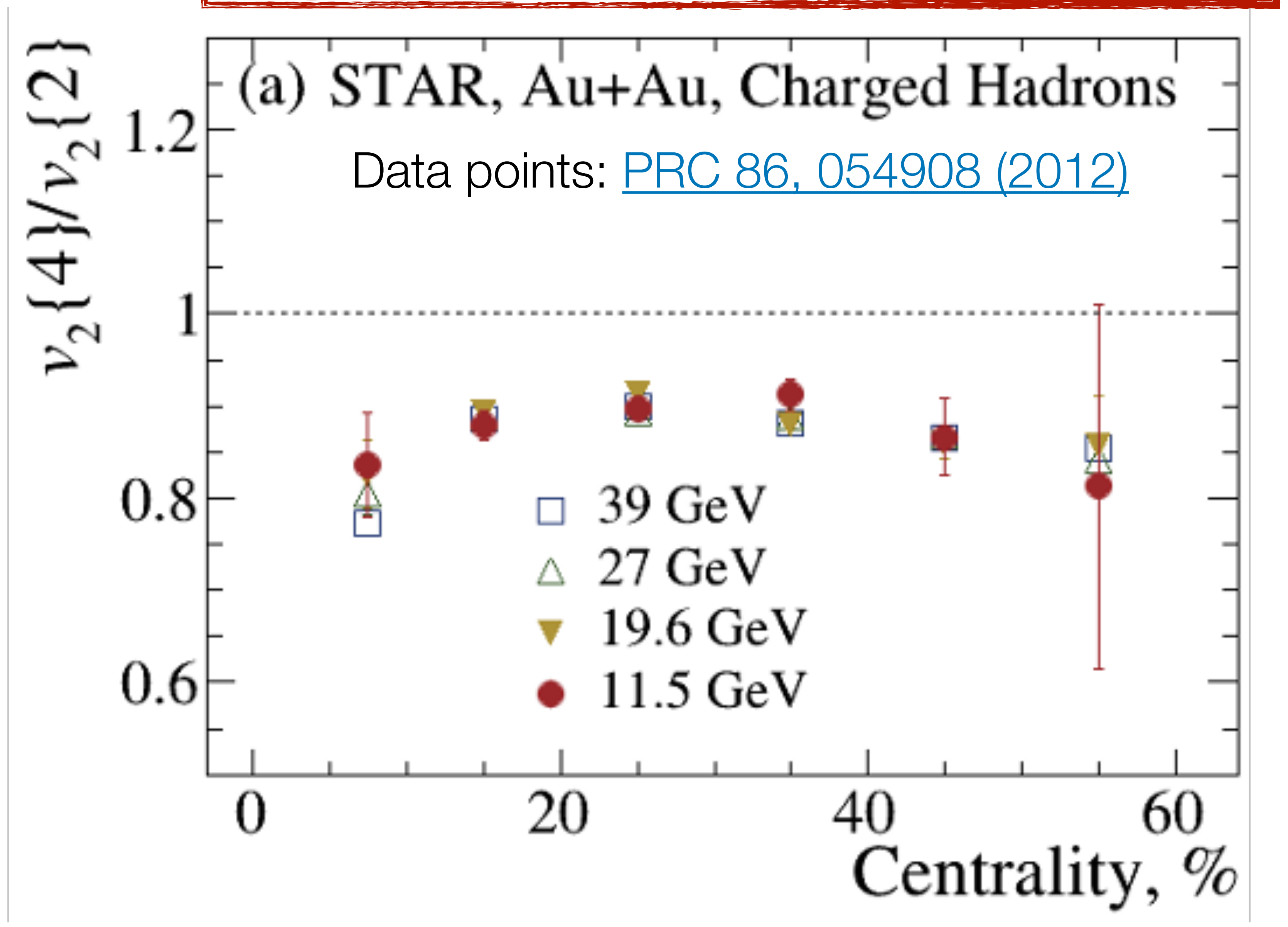
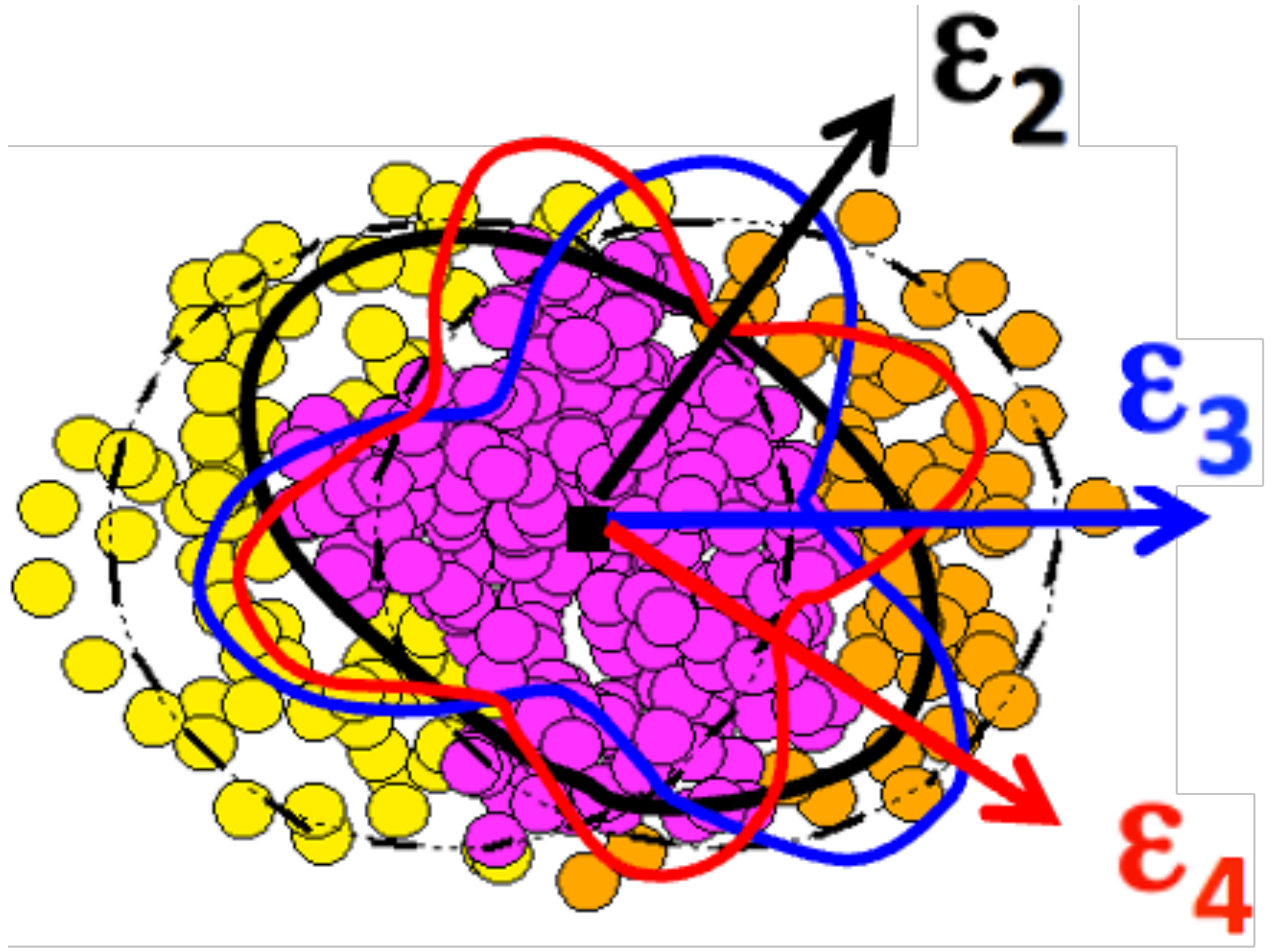
Outline

- Motivation
- Q-cumulants method
- Models & statistics
- Results
- Conclusion

Motivation of elliptic flow fluctuation study

$v_2\{4\}/v_2\{2\} \approx 1$: small v_2 fluctuations
$v_2\{4\}/v_2\{2\} \ll 1$: large v_2 fluctuations



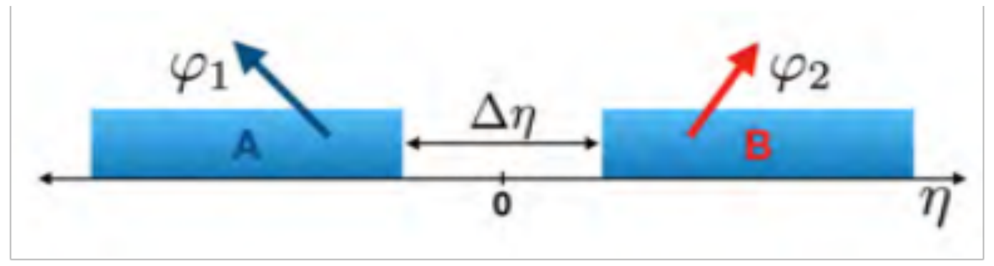


- v_2 fluctuations at $\sqrt{s_{NN}}$ = 11.5 — 39 GeV observed in STAR:
  - Weak dependence on collision energy
- Indicate a dominated initial state driven fluctuations $\sigma_{\varepsilon 2}$
- Provide constraints for IS models and shear viscosity $\eta(T/s)$

How about v_2 fluctuations at NICA energies?

Q-cumulants $v_2\{\mathrm{QC}\}$ methods

- **2-particle Q-cumulant:** $\Delta\eta$ = 0.1 is applied between 2 sub-events A and B to suppress non-flow

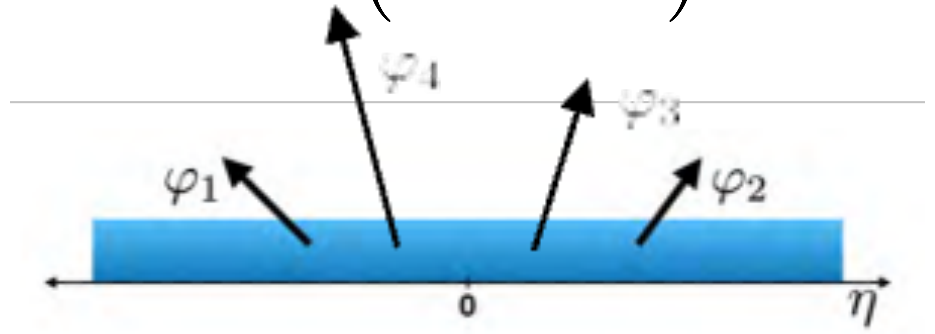


$$Q_n = \sum_{j=1}^{M} e^{in\phi_j} \qquad \langle\langle 2\rangle\rangle_{a|b} = \frac{Q_n^a Q_n^{b*}}{M_a M_b} \qquad v_2\{2\} = \sqrt{\langle\langle 2\rangle\rangle_{a|b}}$$

- **4-particle Q-cumulants**

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

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



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

- **6-particle Q-cumulants** (see PRC 83 (2011), 044913 for formula of $\langle 6\rangle$)

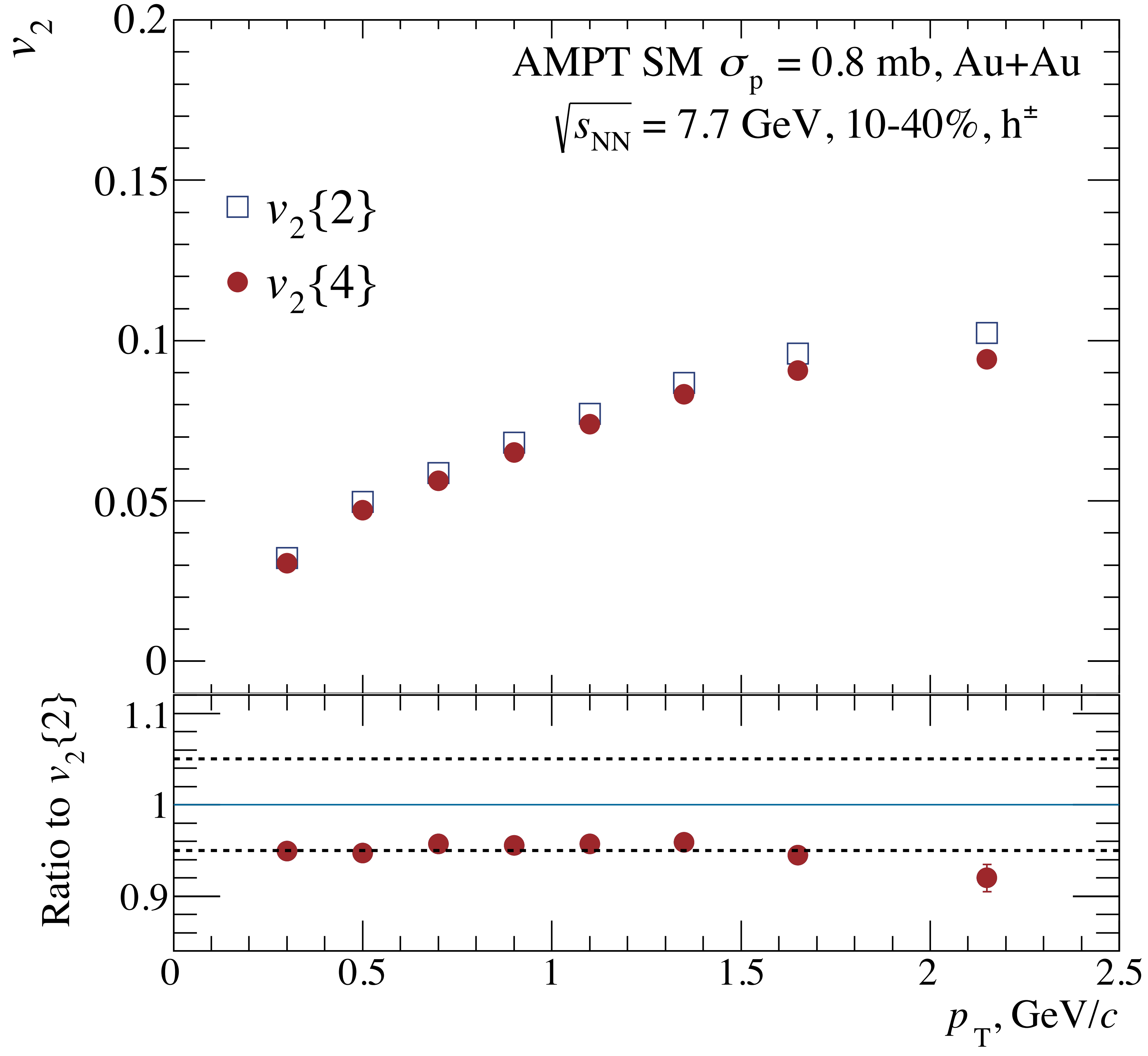
$$v_2\{6\} = \sqrt[6]{1/4\left(\langle\langle 6\rangle\rangle - 9\,\langle\langle 4\rangle\rangle\,\langle\langle 2\rangle\rangle + 12\,\langle\langle 2\rangle\rangle^3\right)}$$

Method's details described in A. Bilandzic et al, PRC 83 (2011), 044913

Sensitivity of $v_2\{\mathrm{QC}\}$ to flow fluctuations and non-flow

- Non-flow contribution for *k*-particle cumulants: $\delta_k \sim 1/M^{k-1}$
- Elliptic flow fluctuations: $\sigma_{v2}^2 = \langle v_2^2 \rangle - \langle v_2 \rangle^2$
- Assuming $\sigma_{v2} \ll \langle v_2 \rangle$, fluctuations enhance v2{2} and suppress v2{k,k=4,6} compared to $\langle v_2 \rangle$
  - $v_2\{2\} \approx \langle v_2 \rangle + \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$
  - $v_2\{4\} \approx \langle v_2 \rangle - \frac{1}{2}\frac{\sigma_{v2}^2}{\langle v_2 \rangle}$
- Assuming a Gaussian form of fluctuations
  - $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$

$v_2\{4\}/v_2\{2\} \approx 1$: small v_2 fluctuations
$v_2\{4\}/v_2\{2\} \ll 1$: large v_2 fluctuations



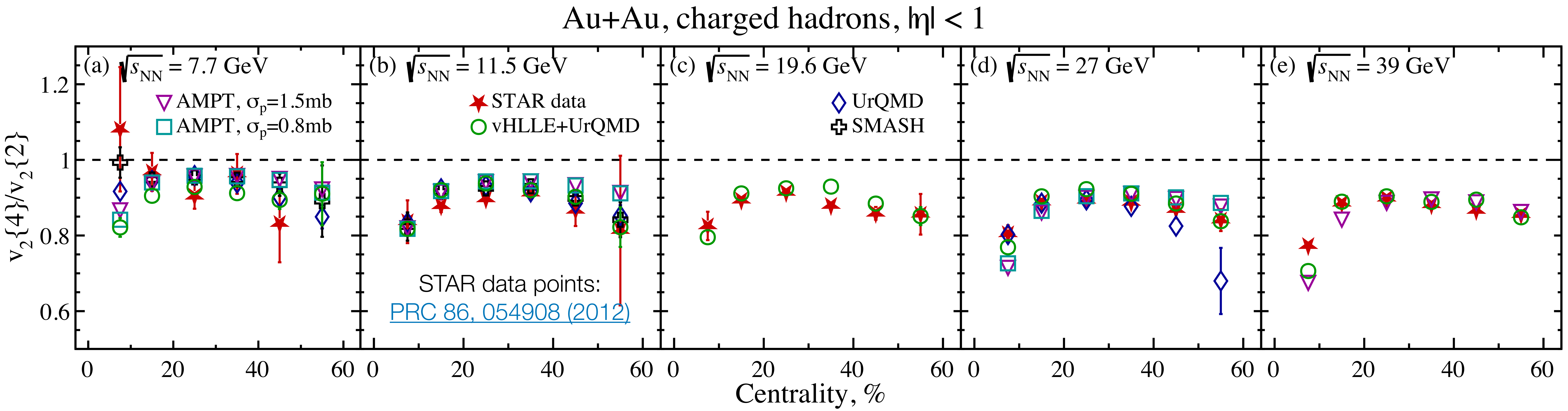
$v_2\{2\} > v_2\{4\}$

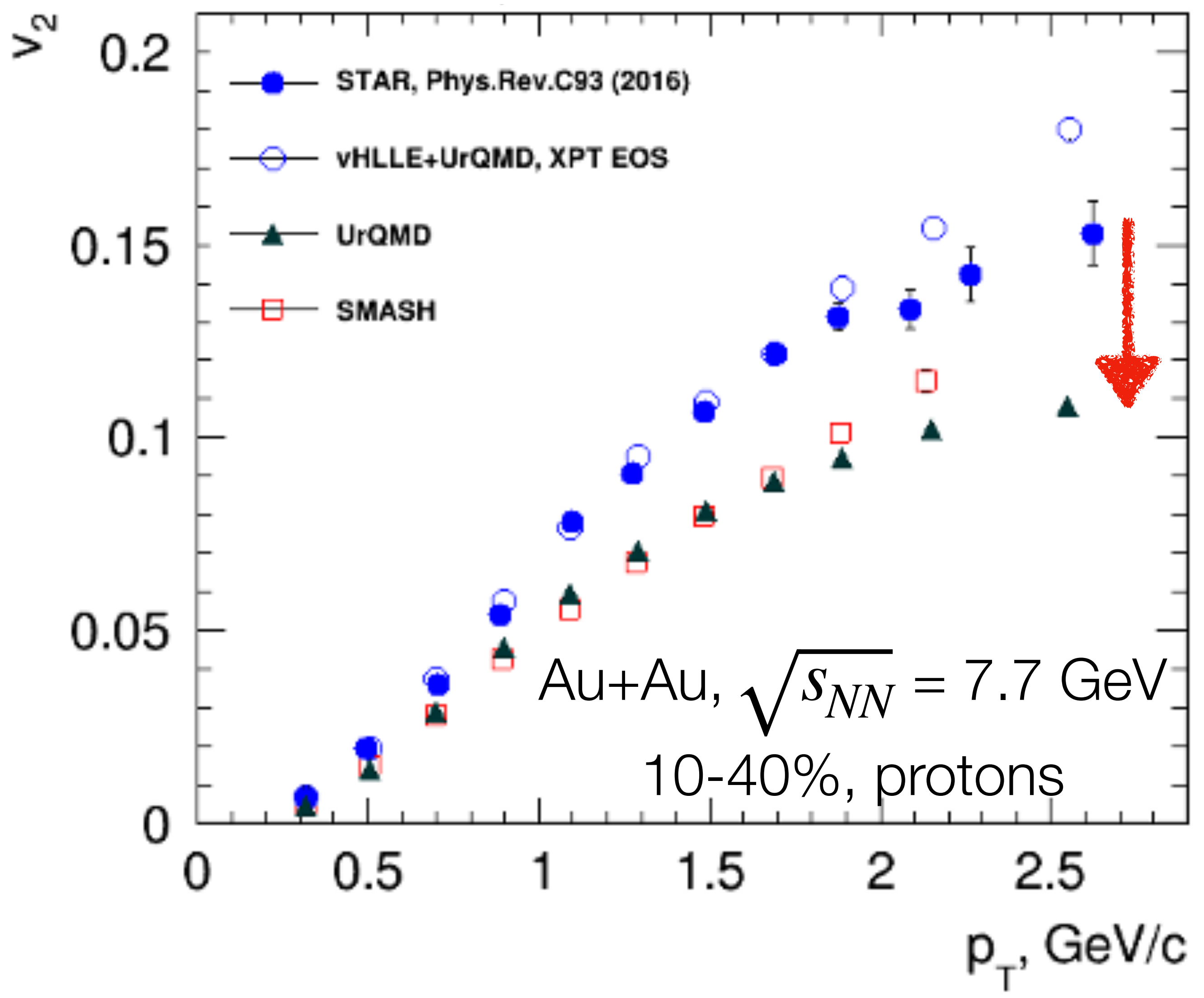
Models & statistics

Au+Au min. bias

- **Without QGP phase**
  - UrQMD v3.4 (cascade)
    - $\sqrt{s_{NN}}$ = 4.5 GeV: 115M
    - $\sqrt{s_{NN}}$ = 7.7 GeV: 88M
    - $\sqrt{s_{NN}}$ = 11.5 GeV: 50M
  - SMASH v1.8
    - $\sqrt{s_{NN}}$ = 4.5—11.5 GeV: 64M
  - AMPT SM $\sigma_p = 0$
    - $\sqrt{s_{NN}}$ = 4.5, 7.7 GeV: 120M
  - JAM v1.90597 (cascade)
    - $\sqrt{s_{NN}}$ = 4.5 GeV: 49M
- **With QGP phase**
  - vHLLE+UrQMD
    - $\sqrt{s_{NN}}$ = 7.7, 11.5 GeV: 27M
  - AMPT SM $\sigma_p = 0.8$ mb
    - $\sqrt{s_{NN}}$ = 7.7 GeV: 72M
    - $\sqrt{s_{NN}}$ = 11.5 GeV: 35M
  - AMPT SM $\sigma_p = 1.5$ mb
    - $\sqrt{s_{NN}}$ = 7.7 GeV: 42M
    - $\sqrt{s_{NN}}$ = 11.5 GeV: 60M

v_2 fluctuations at $\sqrt{s_{NN}} = 7.7 - 39$ GeV

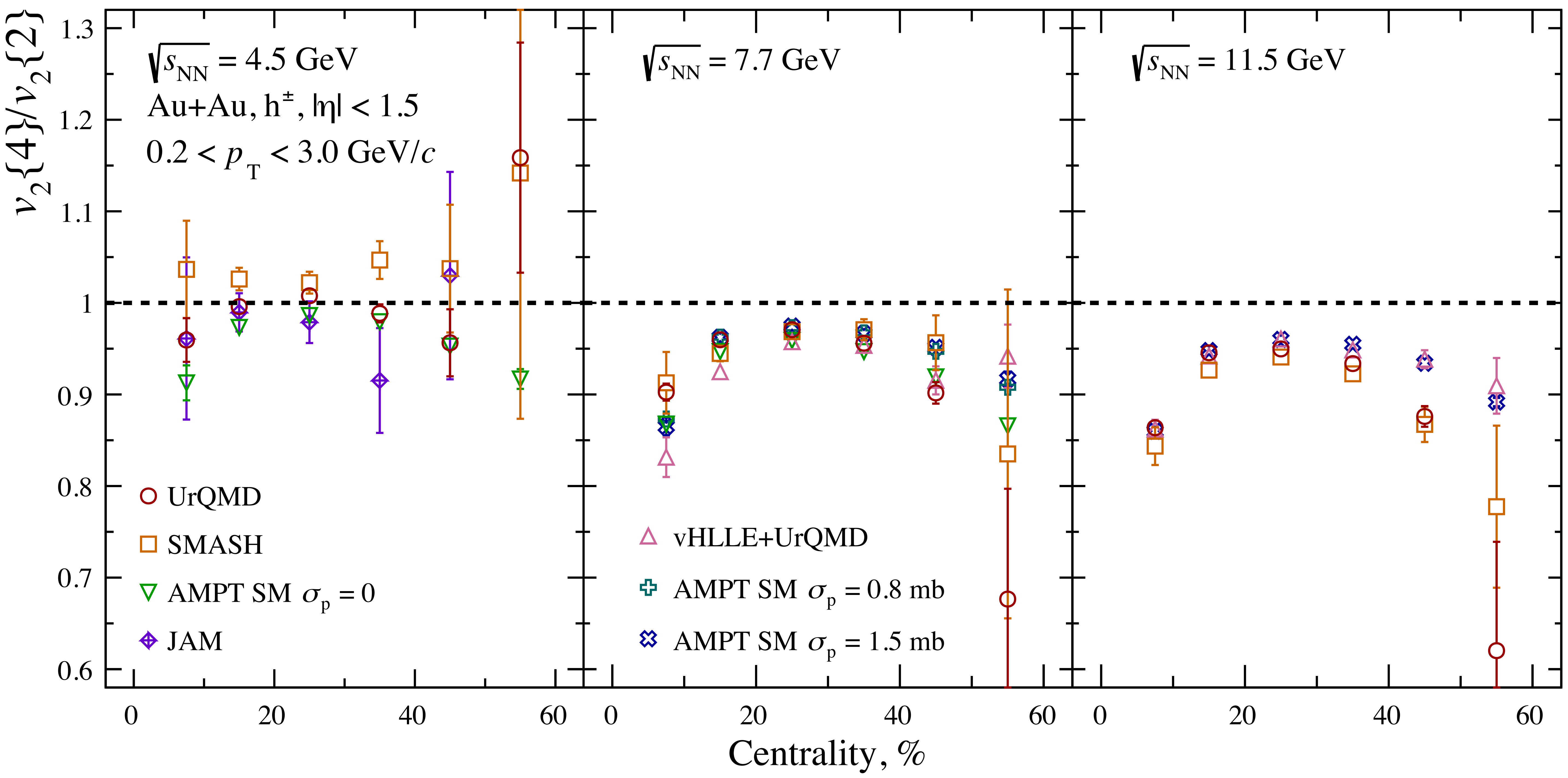




- At $\sqrt{s_{NN}} \geq 7.7$ GeV pure string/cascade models without QGP phase underestimate v_2
- v_2 fluctuations observed in STAR can be reproduced by model either with QGP phase or without QGP phase
  - v_2 fluctuations dominated by ε_2 fluctuations
  - $v_2\{4\}/v_2\{2\}$: direct probe for the initial state conditions

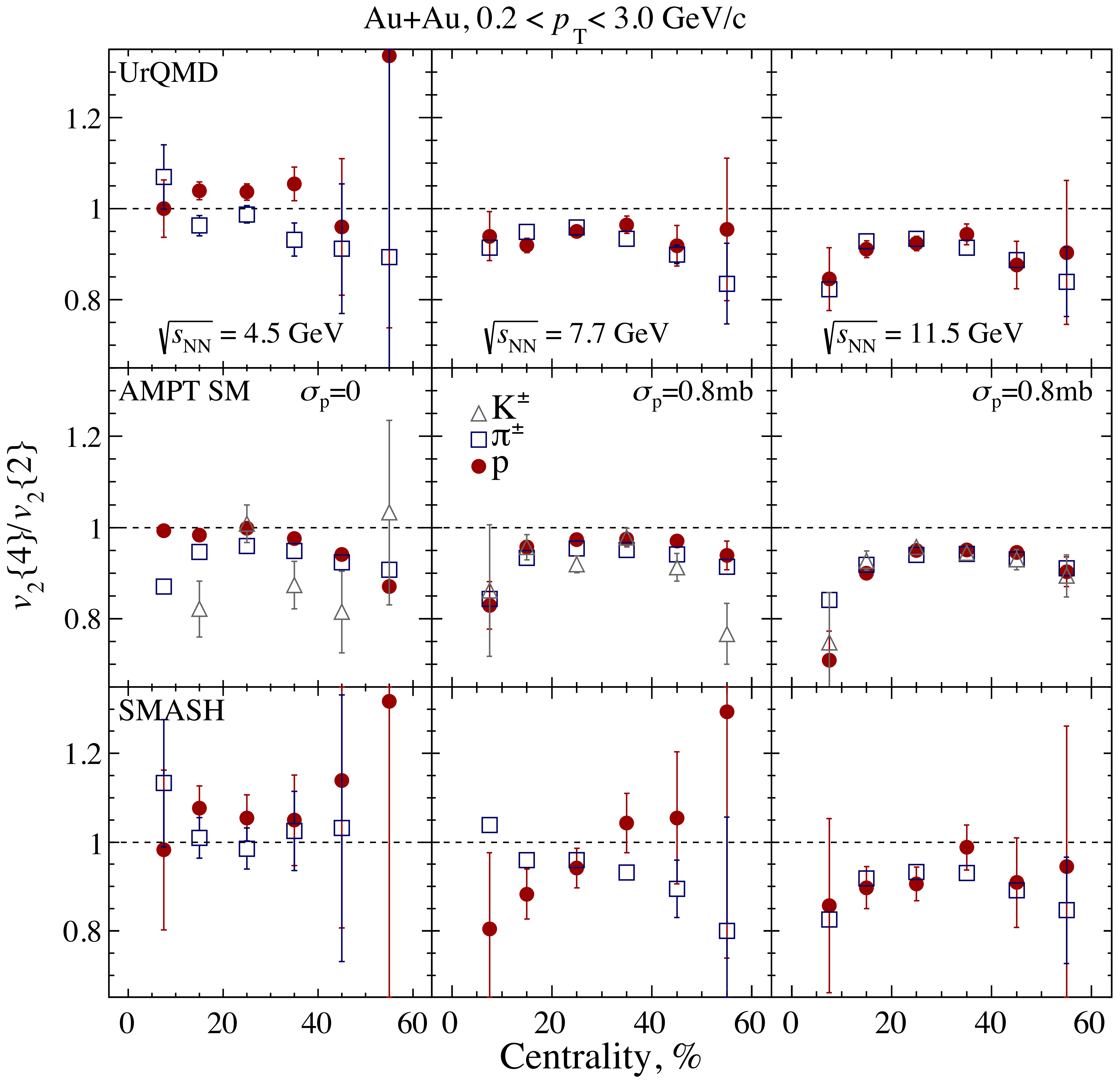
Relative v_2 fluctuations of charged hadrons

$v_2\{4\}/v_2\{2\} \approx 1$: small v_2 fluctuations
$v_2\{4\}/v_2\{2\} \ll 1$: large v_2 fluctuations



- Strong energy dependence of v_2 fluctuations at low NICA energies
- $v_2\{4\}/v_2\{2\} \approx 1$ at $\sqrt{s_{NN}}$ = 4.5 GeV
  - Zero v_2 fluctuations

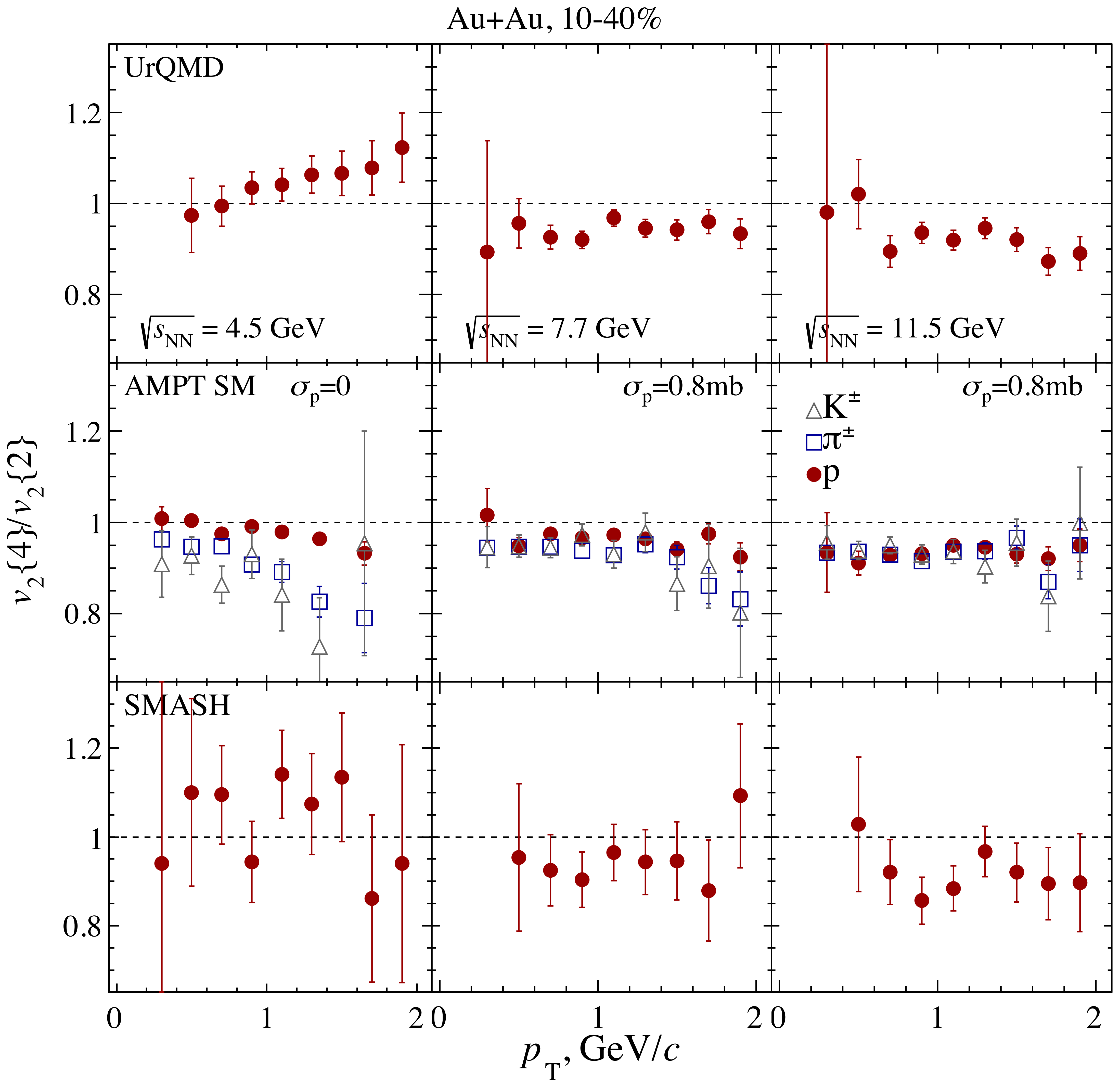
Relative v_2 fluctuations of identified hadrons



Row - same model, column - same colliding energy

- $v_2\{4\}/v_2\{2\} \approx 1$ for protons in 0-40% predicted by UrQMD, AMPT & SMASH at $\sqrt{s_{NN}}$ = 4.5 GeV
- Weak dependence on particle species (protons, pions, kaons)

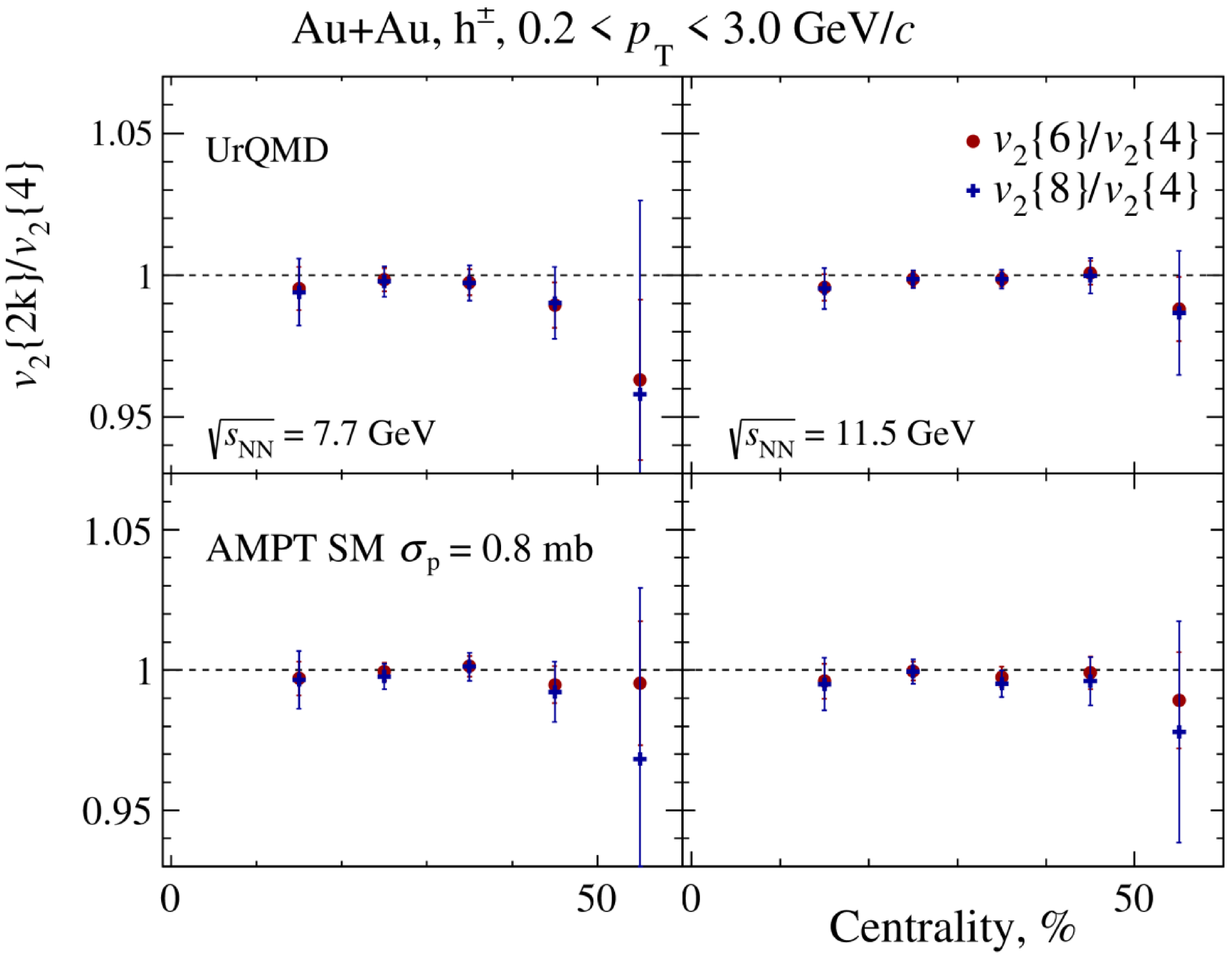
Relative v_2 fluctuations of identified hadrons



Row - same model, column - same colliding energy

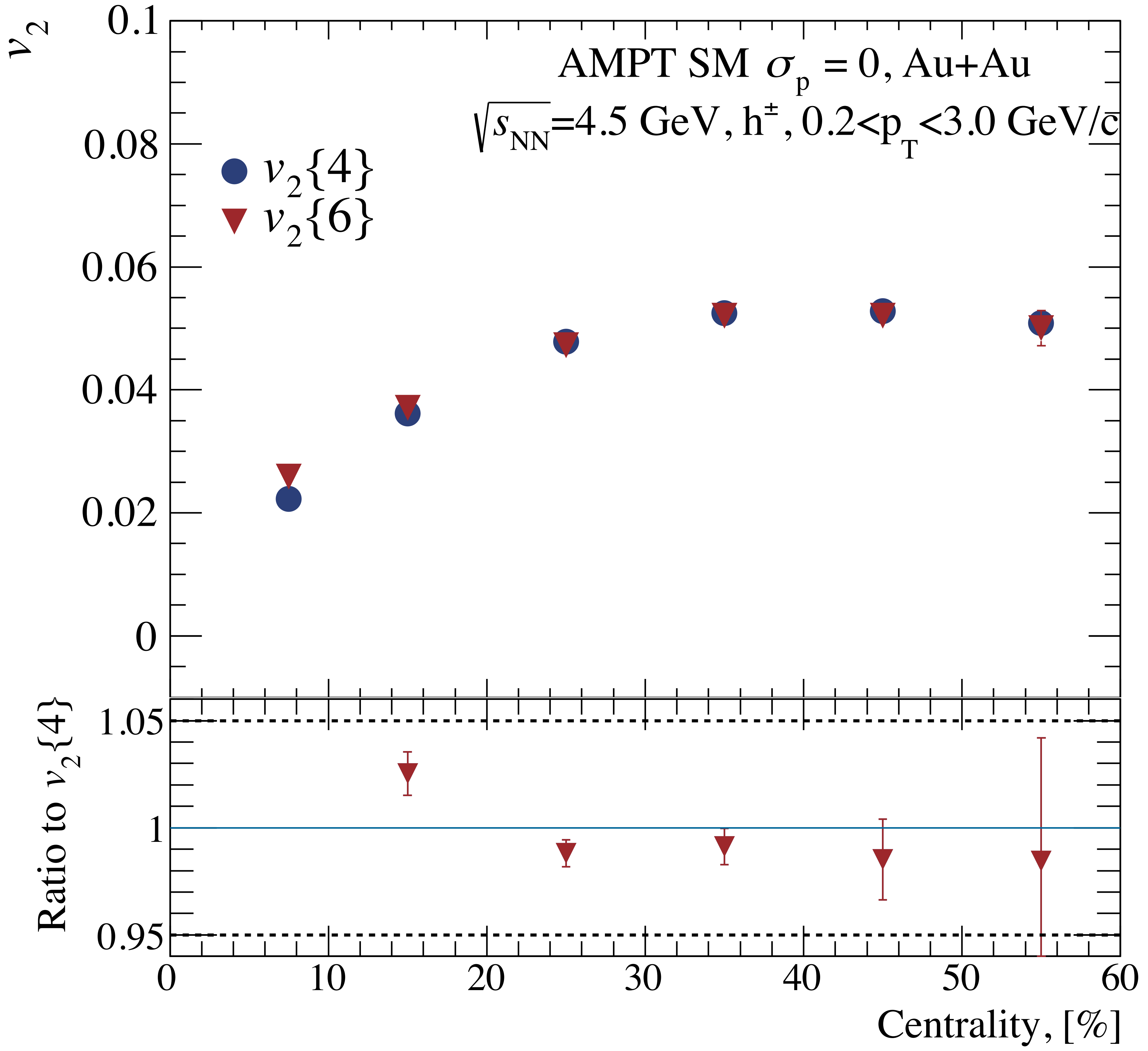
- $v_2\{4\}/v_2\{2\}$ ratio in 10-40% mid-central Au+Au collision:
  - $\sqrt{s_{NN}}$ = 7.7, 11.5 GeV: weak PID/p_T-dependence
  - $\sqrt{s_{NN}}$ = 4.5 GeV: zero relative fluctuations for proton in AMPT

Skewness of v_2 fluctuations

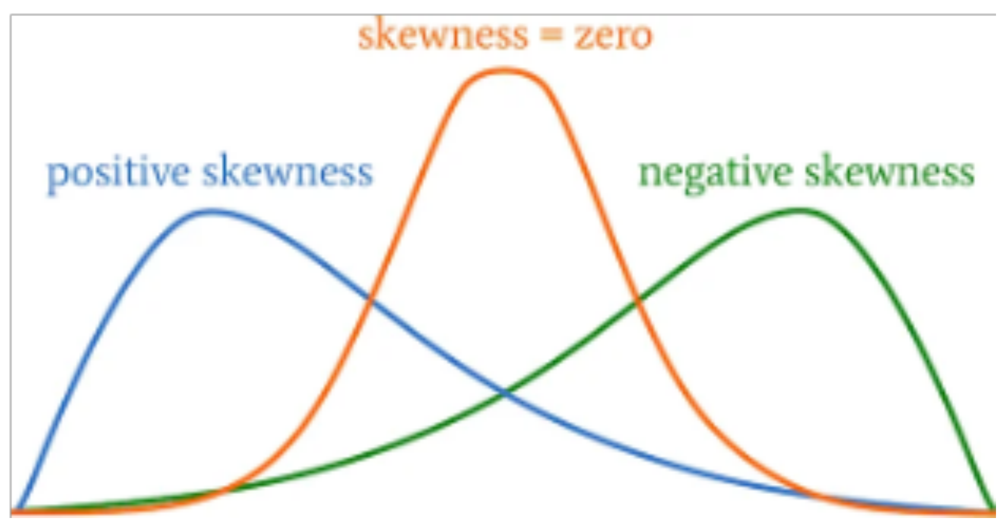


- $v_2\{6\}/v_2\{4\} \neq 1$ indicates a deviation of $P(v_2)$ from Gaussian form
- Large statistics required for v_2 skewness study

Skewness of v_2 fluctuations



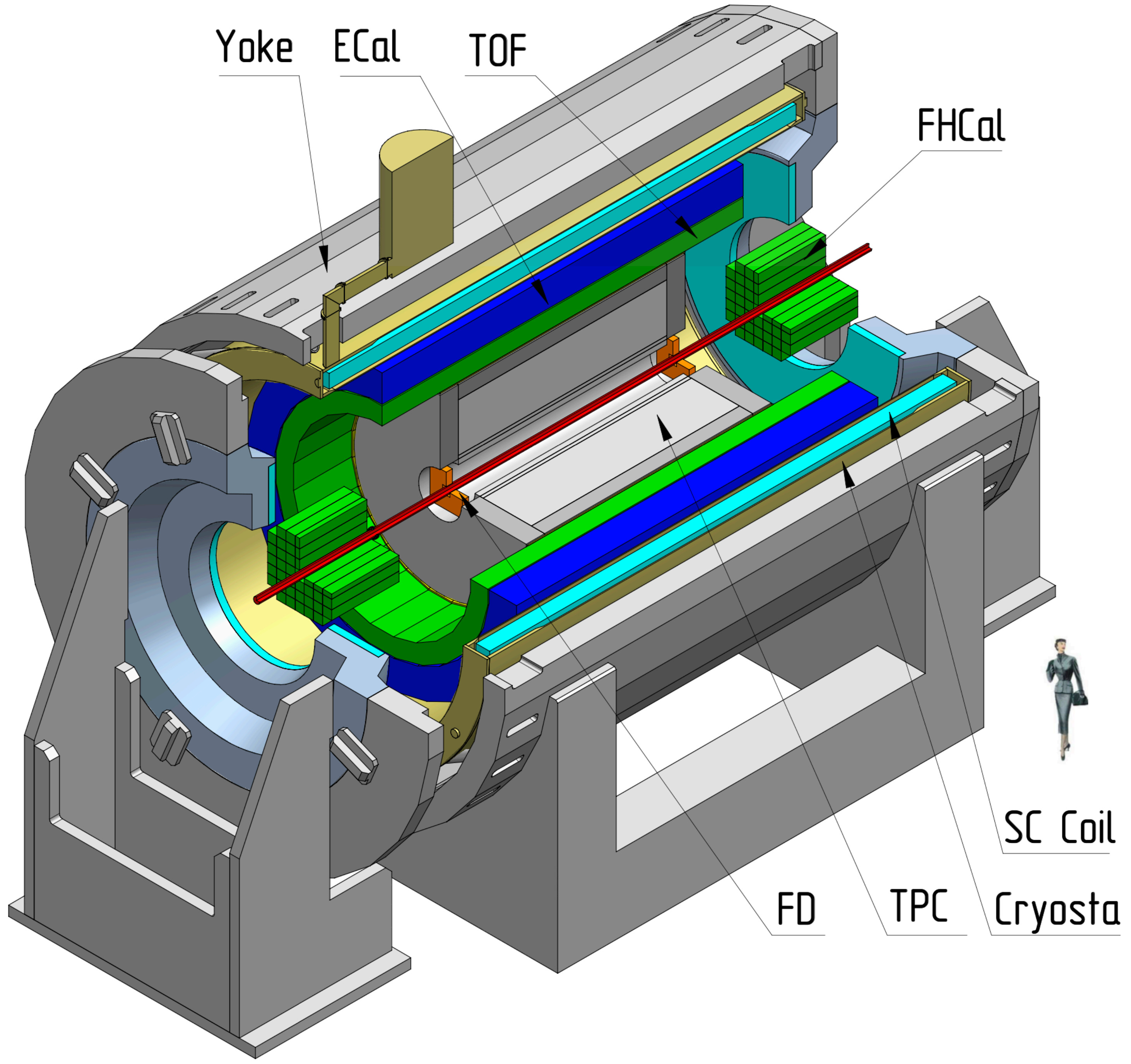
- AMPT predicts a ~1% split between $v_2\{6\}$ and $v_2\{4\}$ in 20-40% Au+Au at $\sqrt{s_{NN}}$ = 4.5 GeV
  - Negative skewness of $P(v_2)$
  - $v_2 = \kappa_2 \varepsilon_2,\ \varepsilon_2 < 1$: $P(v_2)$ right-bounded



MPD experiment at NICA

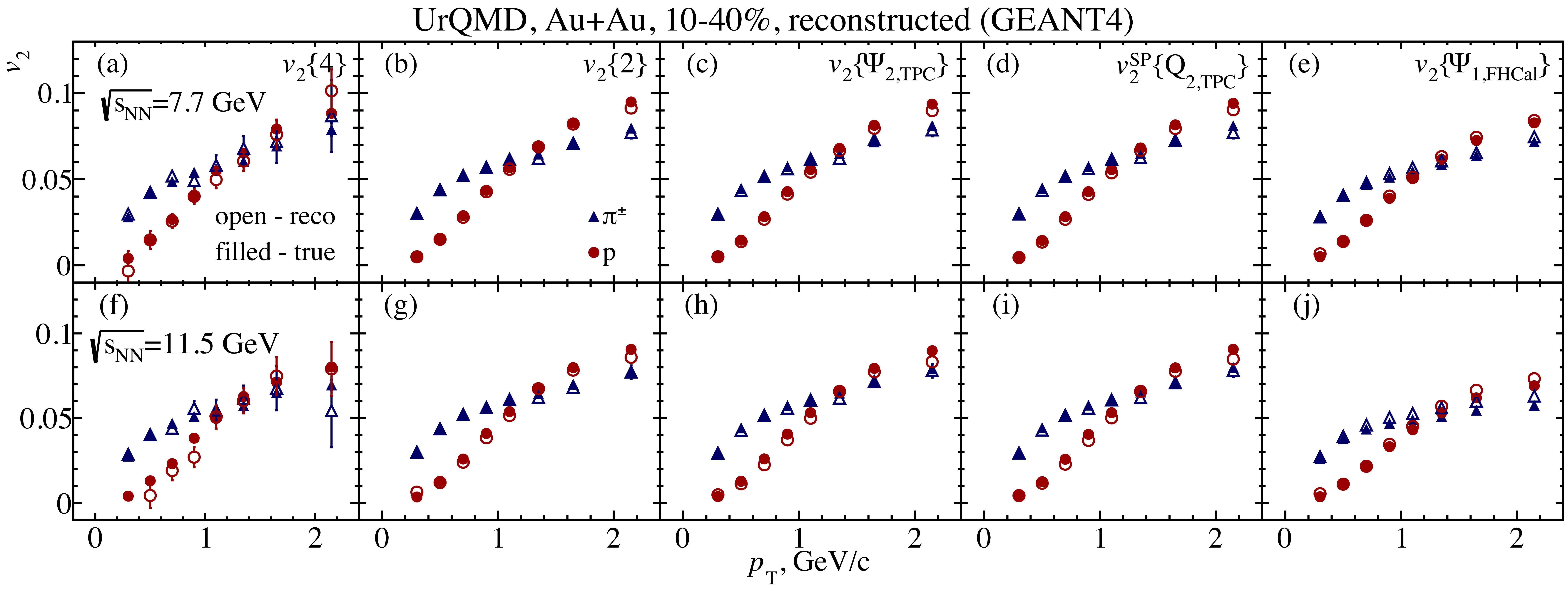
UrQMD → GEANT4 → Reconstruction → Flow Analysis

- Colliding system: Au-Au
- Colliding energy: $\sqrt{s_{NN}}$ = 7.7, 11.5 GeV
- Centrality determination: *b*-based
- Event plane: $\Psi_{1,\mathrm{FHCal}}$ and $\Psi_{2,\mathrm{TPC}}$
- Track selection:
    - $N^{\mathrm{TPC}}_{hits} > 16$
    - $|DCA| < 2\sigma$
    - $0.2 < p_T < 3.0\ \mathrm{GeV}/c$
    - $|\eta| < 1.5$
    - PID based on MpdPid



Multi-Purpose Detector at stage 1

Performance of proton & pion v_2 in MPD



Good agreement of v_2 from reconstructed and generated data for all particle species and methods

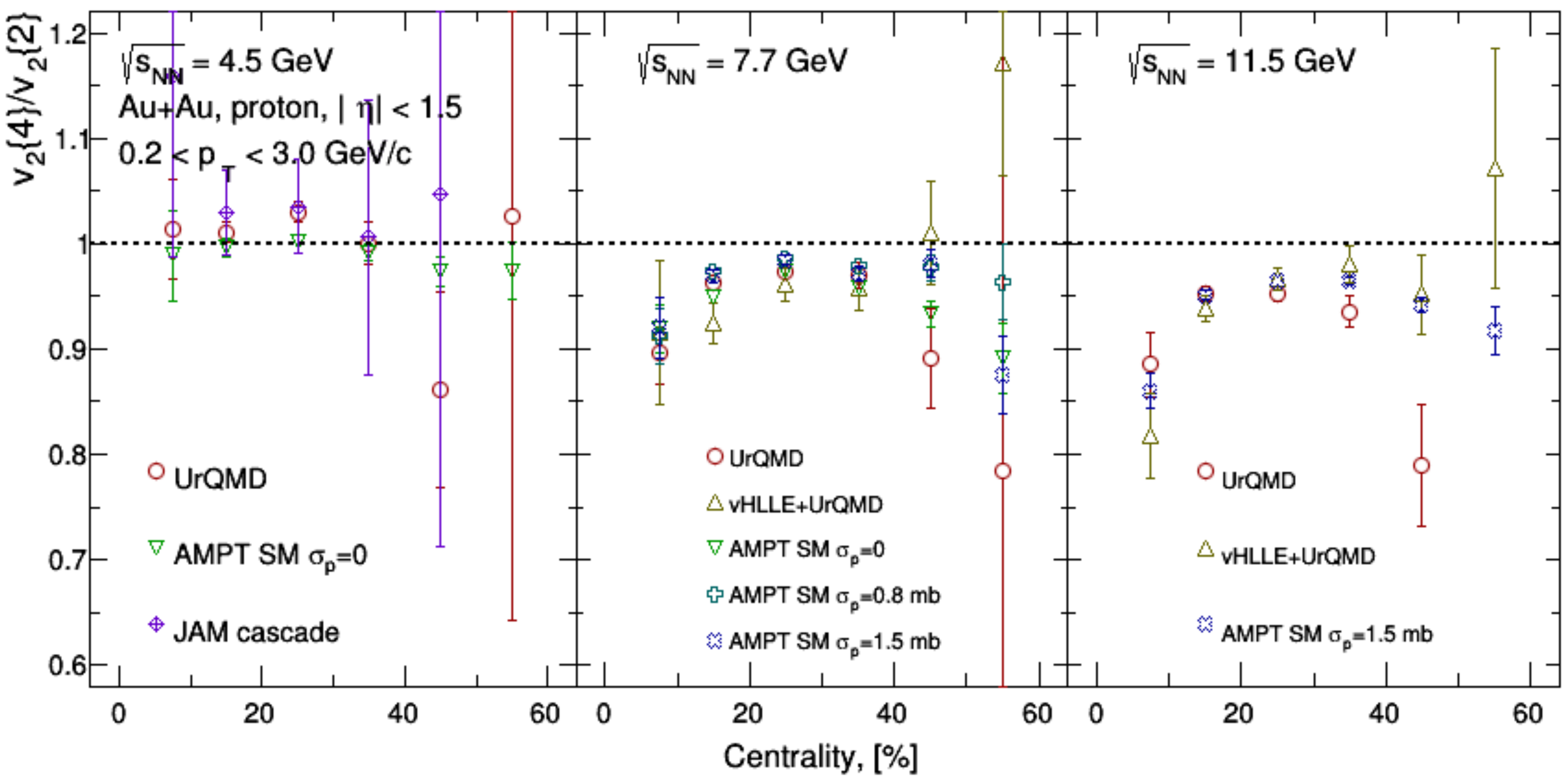
Conclusion

- Models with & without QGP predict similar magnitude for v_2 fluctuations at $\sqrt{s_{NN}}$ = 4.5—11.5 GeV/c
  - v_2 fluctuations are mainly driven from ε_2 fluctuations
- UrQMD, AMPT, SMASH models predict zero v_2 fluctuations for protons in 0-40% Au+Au collisions at $\sqrt{s_{NN}}$ = 4.5 GeV
- AMPT predicts a negative skewness of $P(v_2)$ for 20-40% Au+Au collisions
- v_2 of pions and protons from MPD reconstructed and generated data are in a good agreement

Thanks for your attention!

Back-up slides

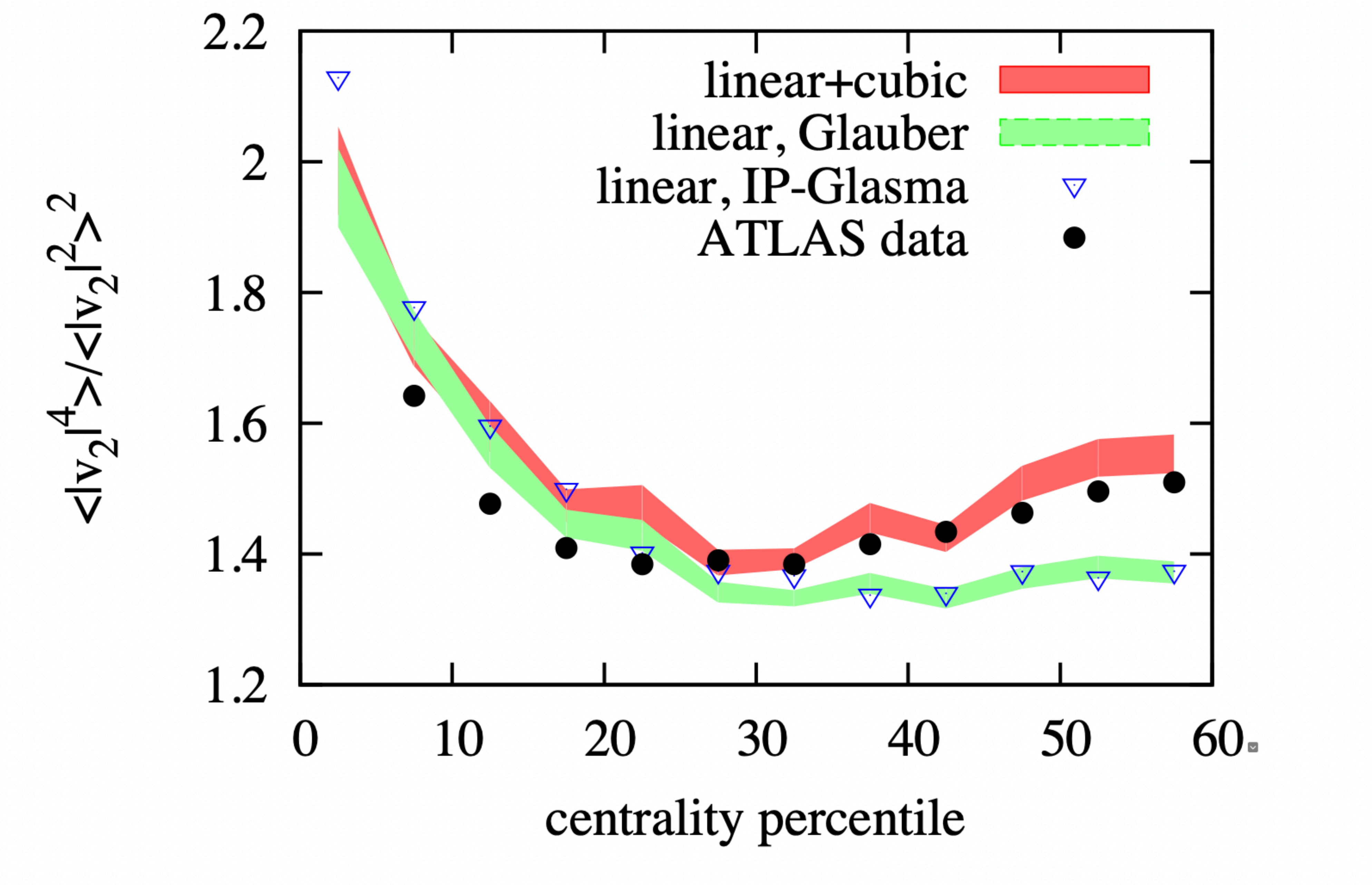
$v_2\{4\}/v_2\{2\}$ for proton



Linear & cubic response terms

- Good agreement for 5-30% centrality
  - Fluctuations dominates in central collisions
  - $v_2 = \kappa_2 \varepsilon_2 \rightarrow \frac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}} = \frac{v_2\{4\}}{v_2\{2\}}$
- $\frac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}} > \frac{v_2\{4\}}{v_2\{2\}}$ for 35-70%
  - Large non-flow contribution for $v_2\{2\}$
  - $v_2 = \kappa_2 \varepsilon_2 + \boxed{\kappa_2' |\varepsilon_2|^2 \varepsilon_2} \rightarrow \frac{\varepsilon_2\{4\}}{\varepsilon_2\{2\}} \neq \frac{v_2\{4\}}{v_2\{2\}}$

    Cubic response term
- The linear response coefficient κ_2 decreases & cubic response coefficient κ_2' increases with centrality



Figures from [PRC 93, 014909 (2016)](#)

κ_2 and κ_2' contain η/s