Magnitude and skewness of elliptic flow fluctuations at NICA energies

Vinh Luong[1,2,3], Dim Idrisov[2], Peter Parfenov[2],
Alexander Demanov[2], Arkadiy Taranenko[2]
[1]Joint Institute for Nuclear Research, Dubna, Russia
[2]National Research Nuclear University MEPhI, Moscow, Russia
[3]Dalat Nuclear Research Institute, Dalat, Vietnam

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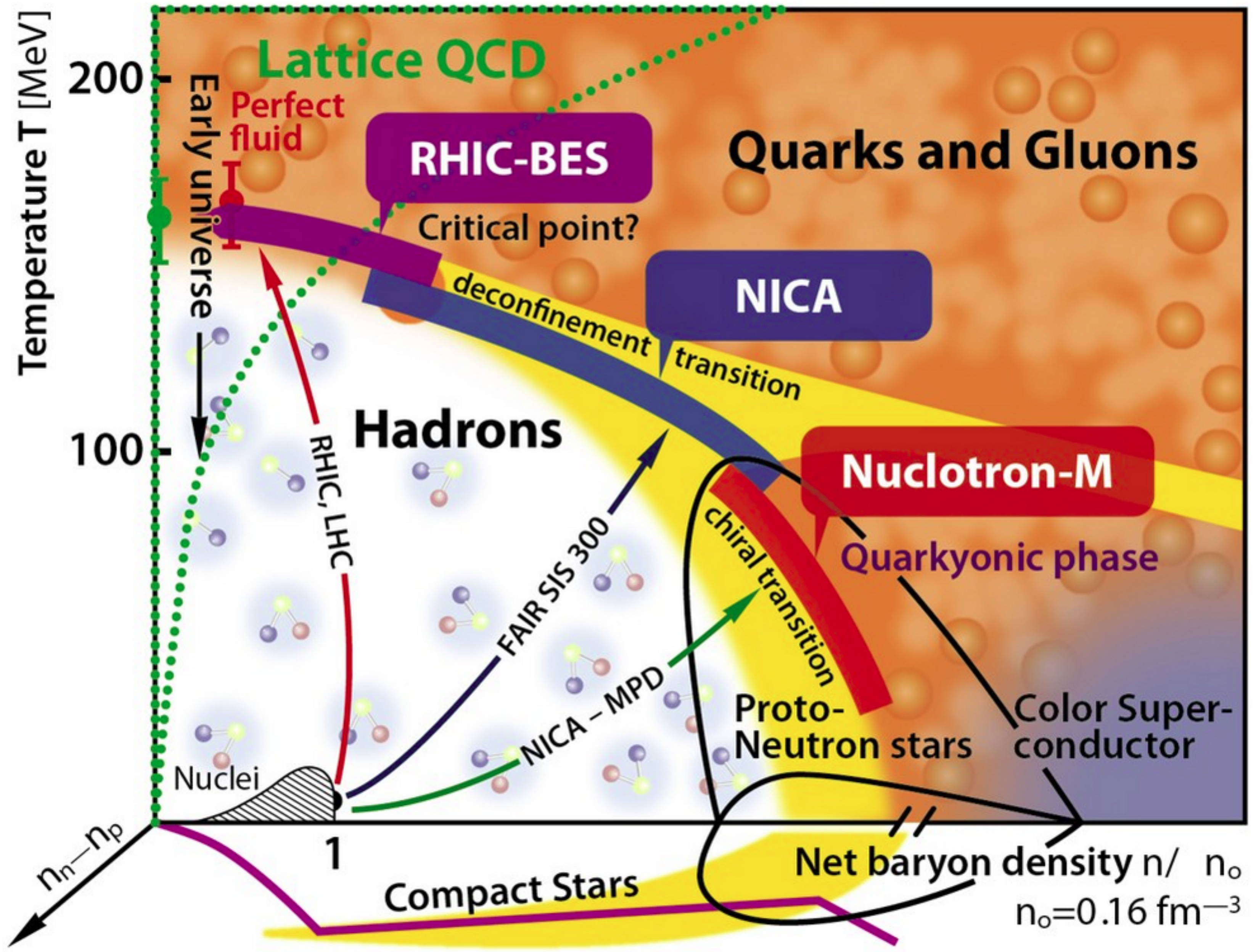
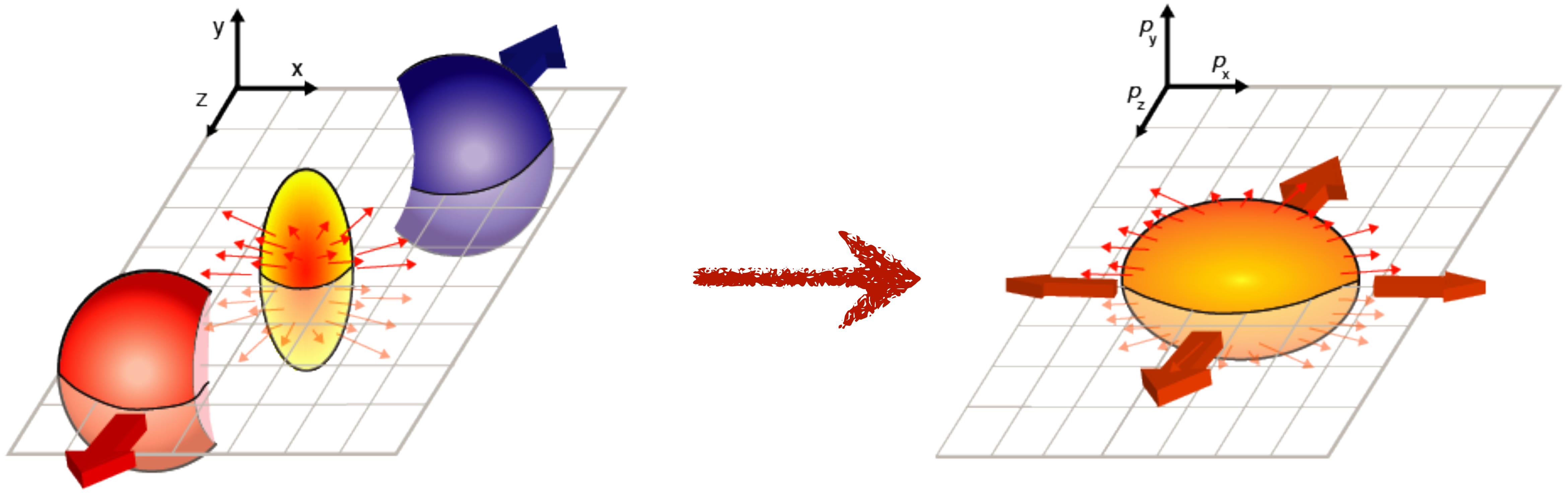
Outline

- Q-cumulants method
- Sensitivity of different order of Q-cumulants to flow fluctuations and non-flow
- Results from models on elliptic flow fluctuations at NICA energy regime
- Conclusion

Anisotropic flow phenomenon





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

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

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

- LHC/top RHIC: cross-over phase transition to the sQGP
- Beam energy scan programs: RHIC/SPS/FAIR/**NICA**: searching for the critical end point & 1st order phase transition

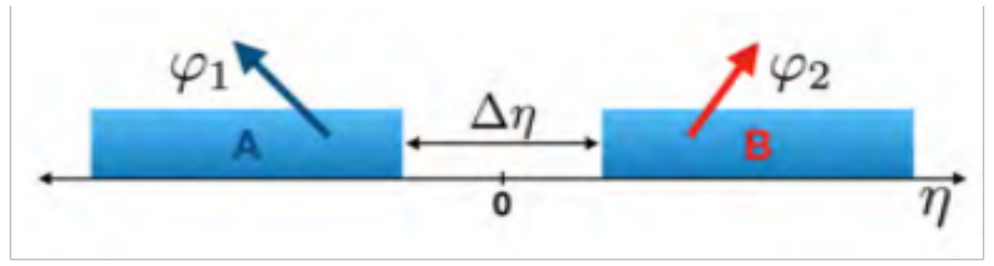
- Transfer of initial anisotropy ε_n in coordinate space to final anisotropy v_n in momentum space via the thermalized medium
- Anisotropic flow: sensitive probe to study the sQGP properties (η/s, ζ/s, EoS, …)

Q-cumulants methods for flow measurements

- Ψ_{RP} **cannot be measured directly** → Multi-particle azimuthal correlations method is used:

$$\langle\langle 2\rangle\rangle = \left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle = \left\langle\left\langle e^{in[(\phi_1-\Psi_{RP})-(\phi_2-\Psi_{RP})]}\right\rangle\right\rangle = \left\langle\left\langle e^{in(\phi_1-\Psi_{RP})}\right\rangle\left\langle e^{-in(\phi_2-\Psi_{RP})}\right\rangle + \delta_2\right\rangle = \left\langle v_n^2 + \delta_2\right\rangle$$

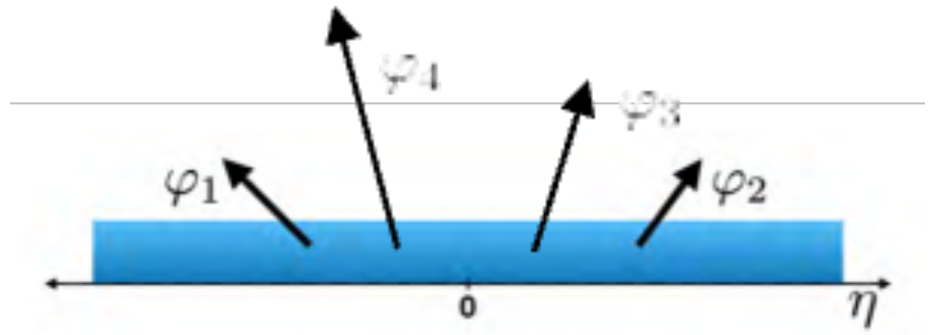
- **2-particle Q-cumulant:** $\Delta\eta$ = 0.1 is applied between 2 sub-events A and B to suppress 2-particle non-flow δ_2



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

- **4-, 6-particle Q-cumulants**

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

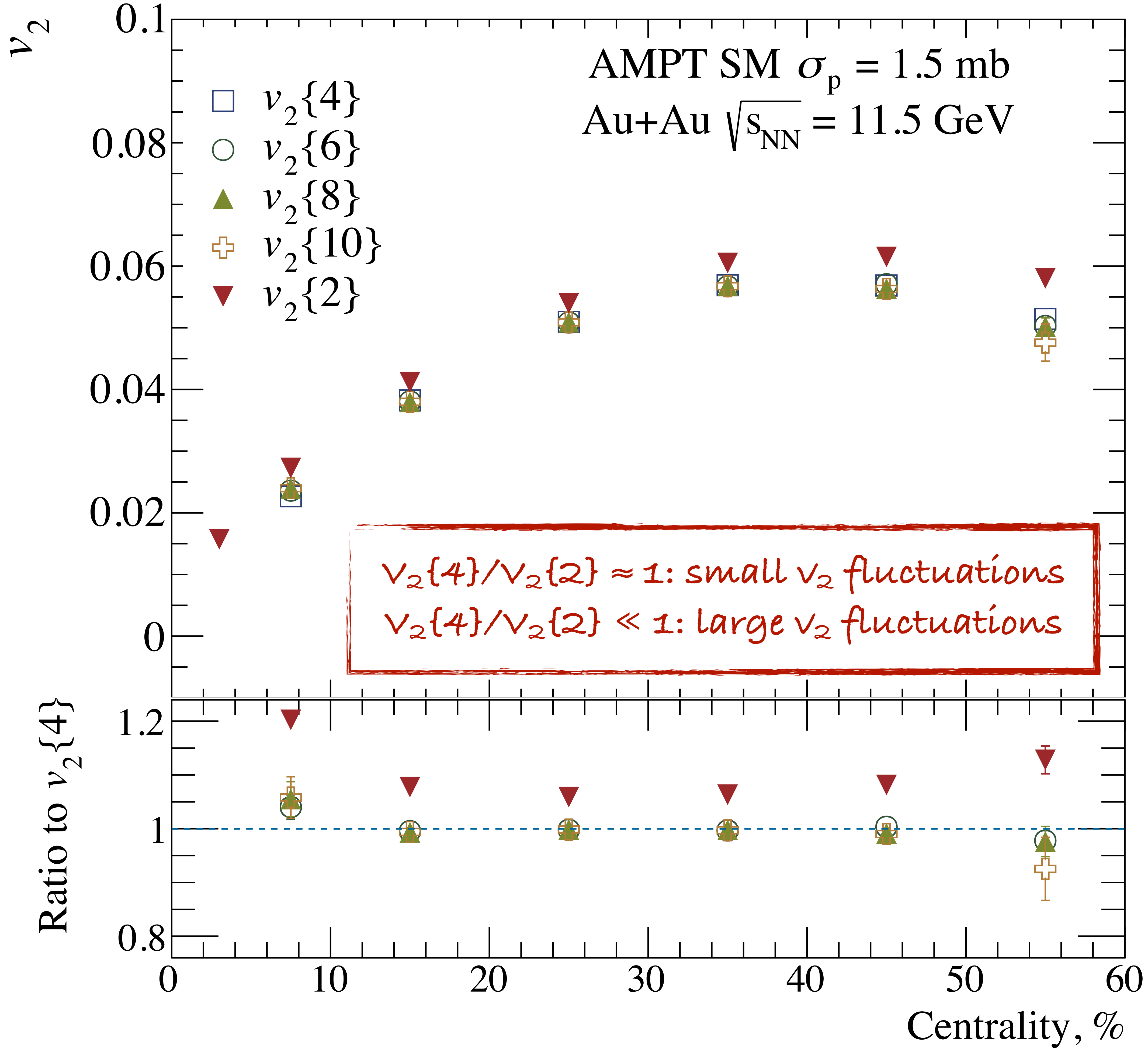


$$v_n\{4\} = \sqrt[4]{2\,\langle\langle 2\rangle\rangle^2 - \langle\langle 4\rangle\rangle} \qquad v_n\{6\} = \sqrt[6]{1/4\left(\langle\langle 6\rangle\rangle - 9\,\langle\langle 4\rangle\rangle\,\langle\langle 2\rangle\rangle + 12\,\langle\langle 2\rangle\rangle^3\right)}$$

Formulae for $\langle 6\rangle$ can be found in A. Bilandzic et al, PRC 83 (2011), 044913

Sensitivity of $v_2\{2k\}$ 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 $v_2\{2\}$ and suppress $v_2\{2k, k > 1\}$ compared to $\langle v_2 \rangle$
  - $v_2\{2\} \approx \langle v_2 \rangle + \dfrac{1}{2}\dfrac{\sigma_{v2}^2}{\langle v_2 \rangle}$
  - $v_2\{4\} \approx \langle v_2 \rangle - \dfrac{1}{2}\dfrac{\sigma_{v2}^2}{\langle v_2 \rangle}$
- Assuming a Gaussian form of fluctuations
  - $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{10\}$

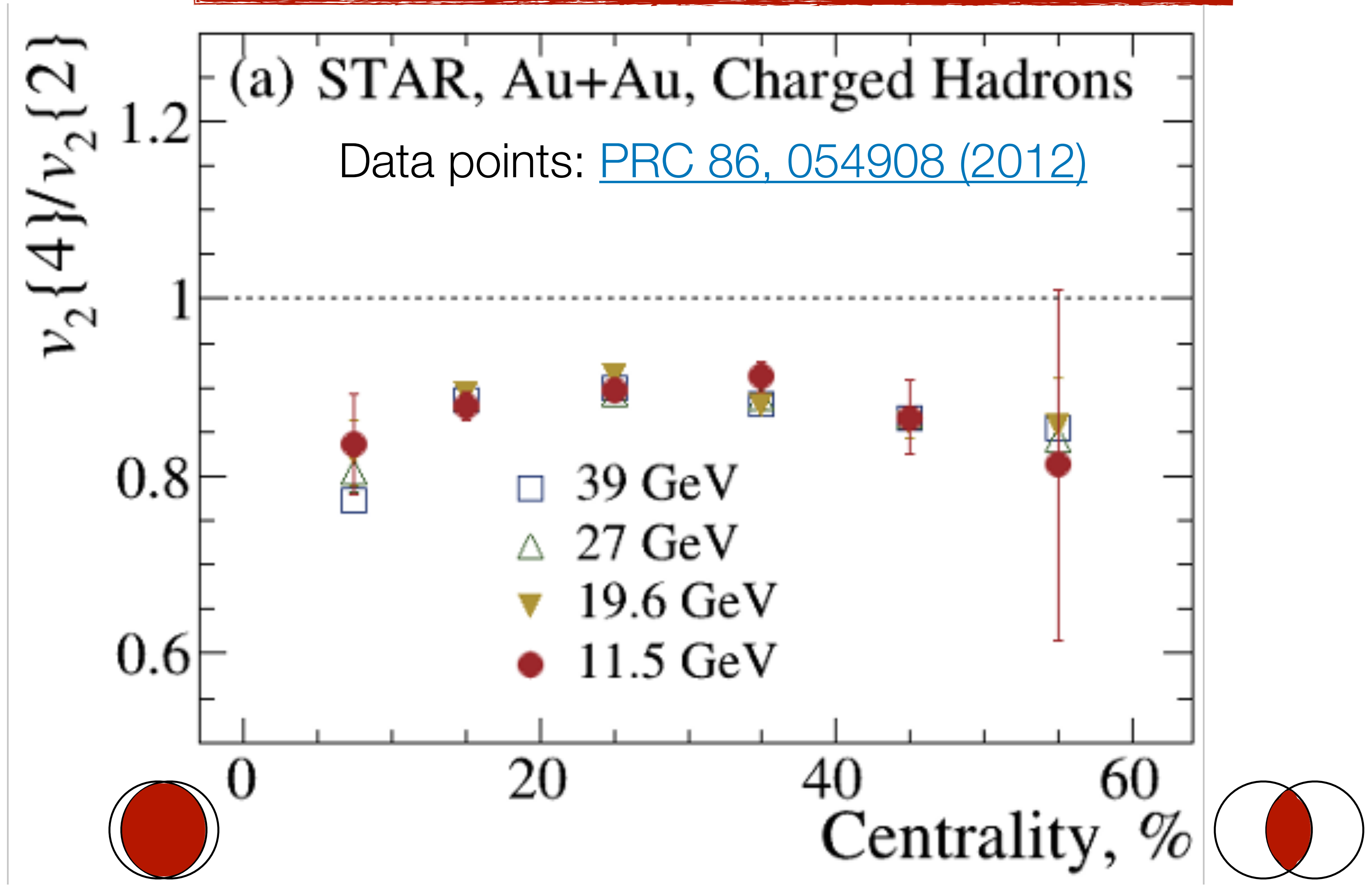


$v_2\{4\}/v_2\{2\} \approx 1$: small v_2 fluctuations
$v_2\{4\}/v_2\{2\} \ll 1$: large v_2 fluctuations

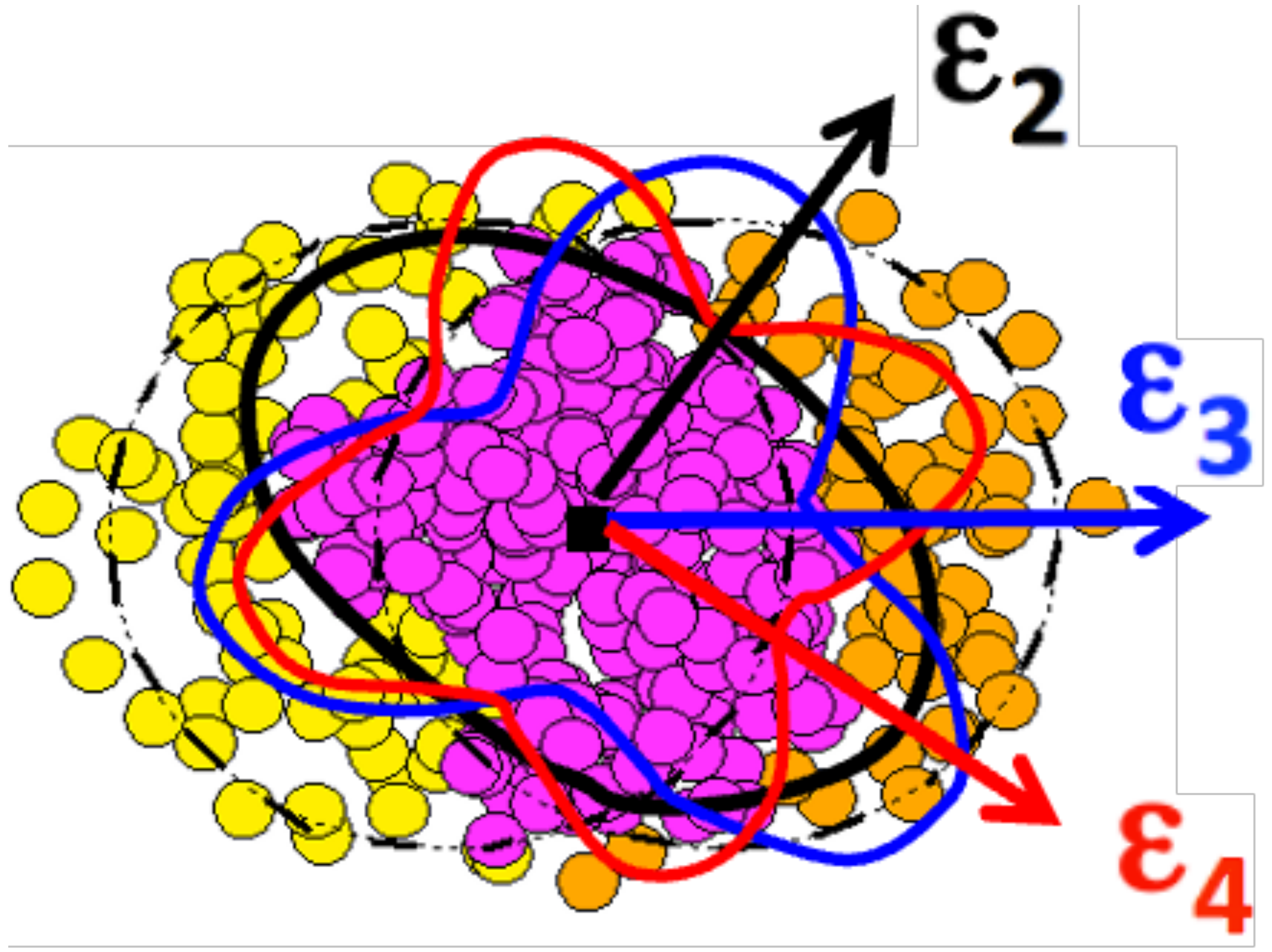
$$v_2\{2\} > v_2\{4\} \approx v_2\{6\} \approx v_2\{8\} \approx v_2\{10\}$$

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



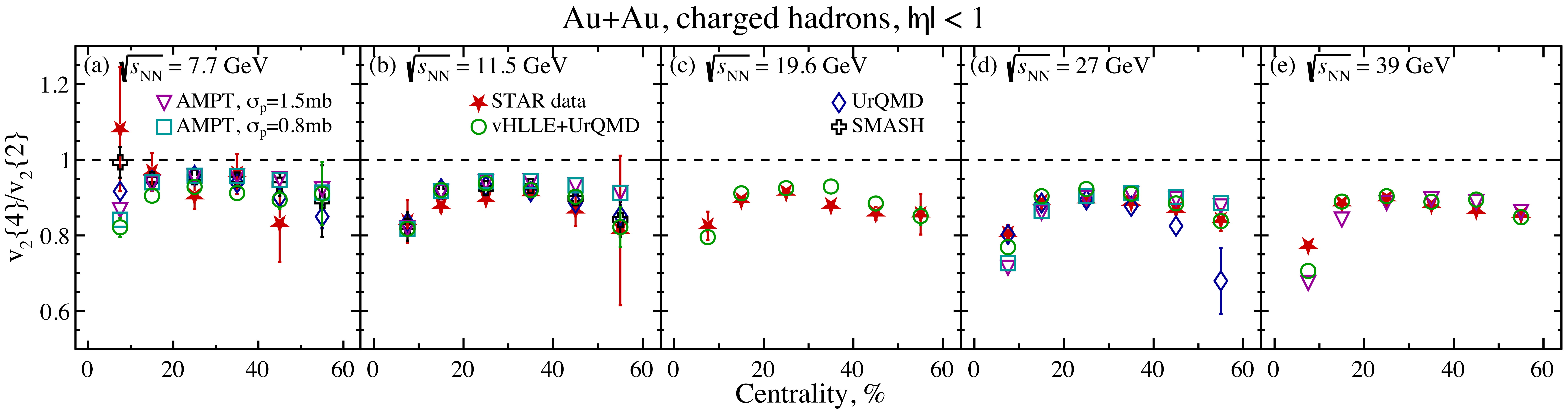
Data points: PRC 86, 054908 (2012)

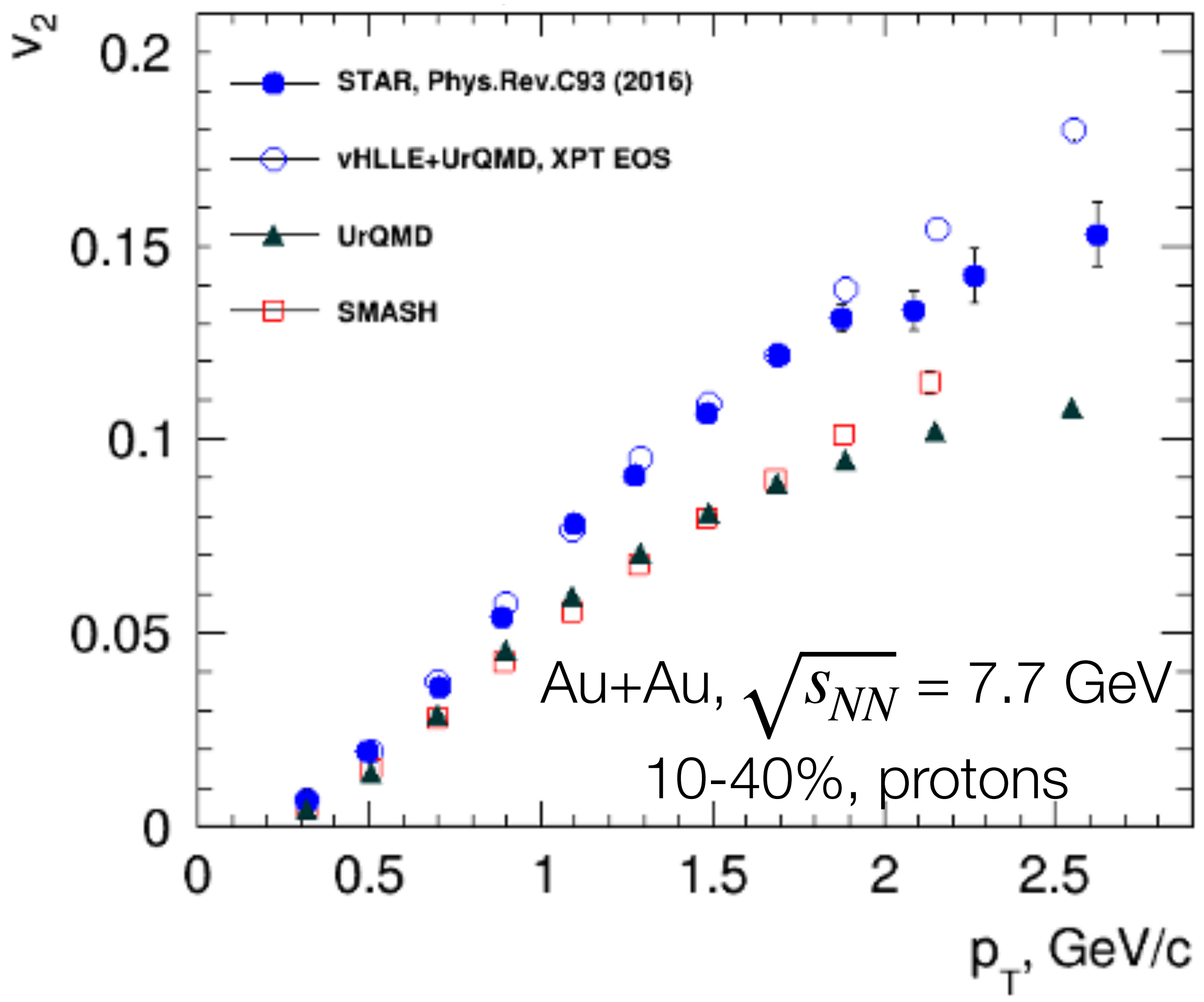


- v_2 fluctuations at $\sqrt{s_{NN}}$ = 11.5 — 39 GeV observed in STAR:
  - Weak dependence on collision energy
- Indicate a dominated initial state driven fluctuations $\sigma_{\varepsilon 2}$
- Provide constraints for IS models and shear viscosity $\eta(T/s)$

How about v_2 fluctuations at NICA energies?

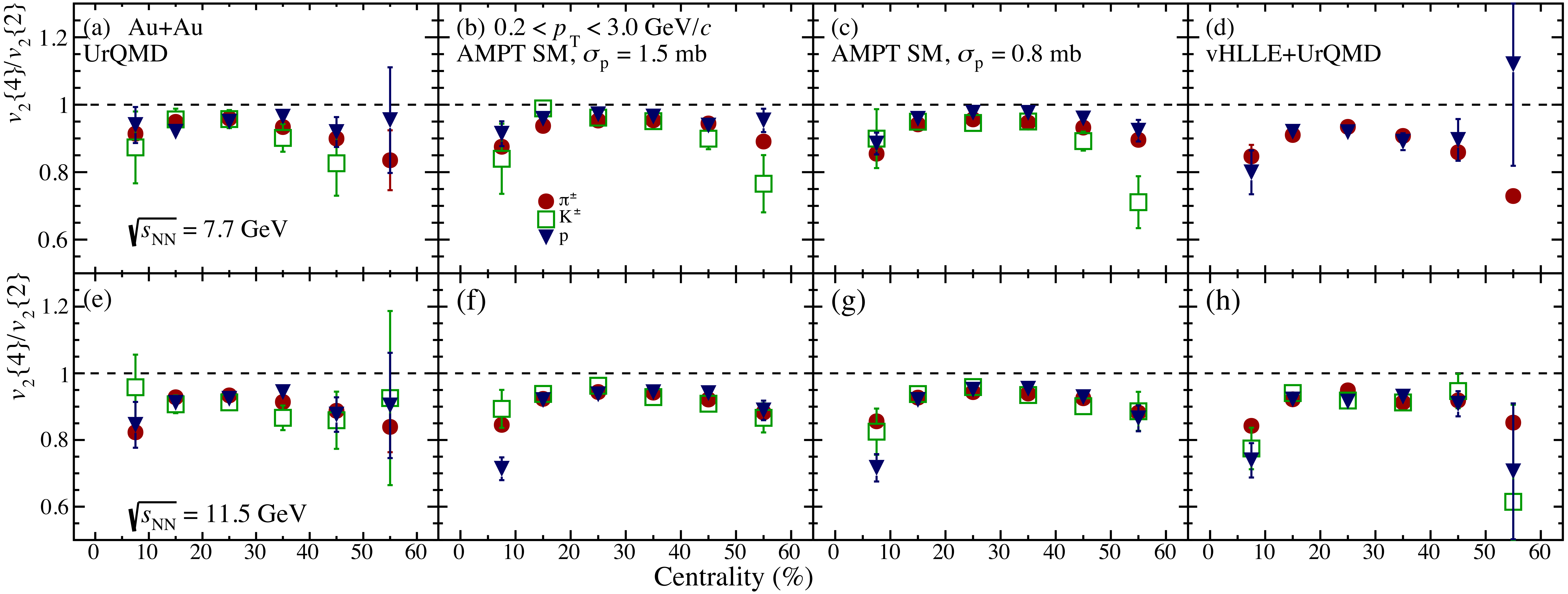
v_2 fluctuations at $\sqrt{s_{NN}} = 7.7 - 39$ GeV





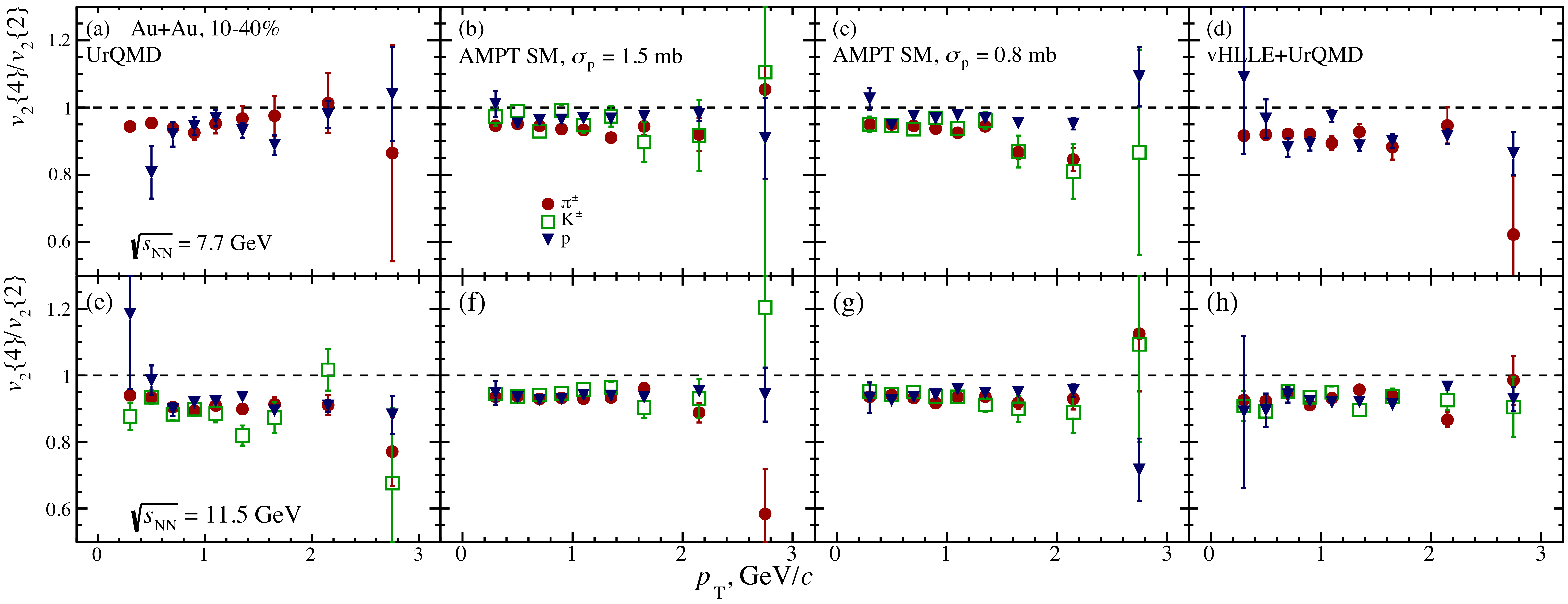
- At $\sqrt{s_{NN}} \geq 7.7$ GeV pure string/cascade models without QGP phase underestimate v_2
- v_2 fluctuations observed in STAR can be reproduced by model either with or without partonic phase description
  - v_2 fluctuations dominated by ε_2 fluctuations
  - $v_2\{4\}/v_2\{2\}$: direct probe for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

Relative v_2 fluctuations of identified hadrons



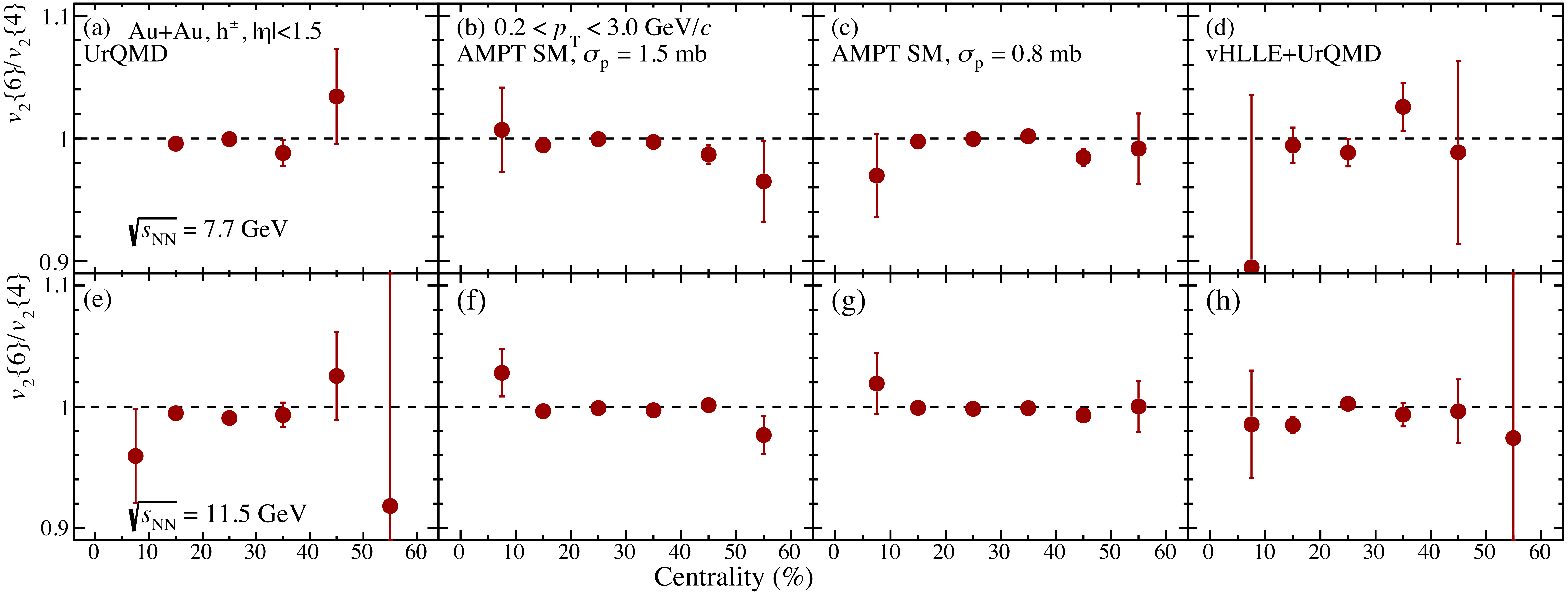
Weak dependence on particle species (pions, kaons, protons)

Relative v_2 fluctuations of identified hadrons



Weak dependence on p_T and particle species (pions, kaons, protons)

Skewness of $P(v_2)$

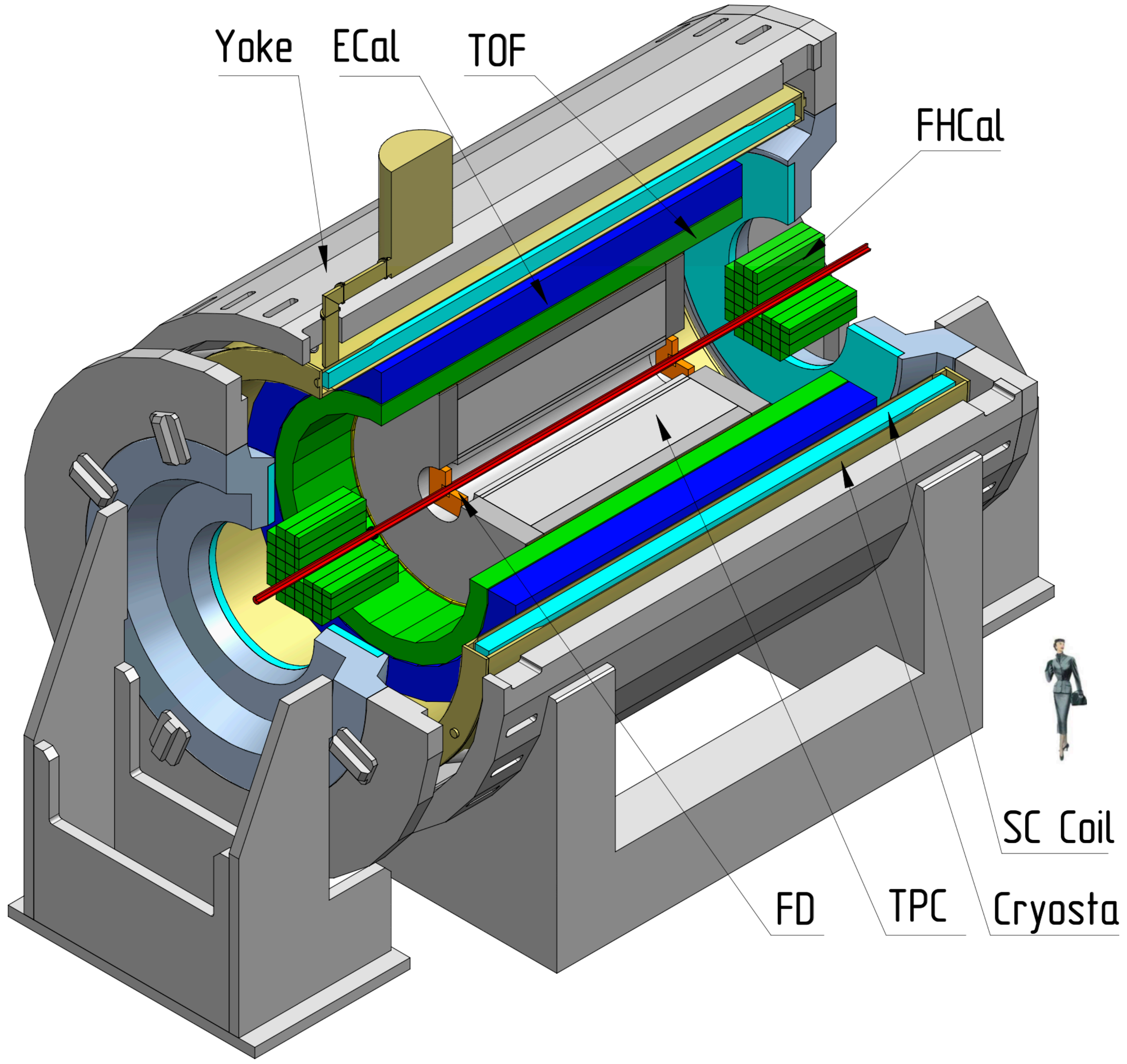


$v_2\{6\}/v_2\{4\} \approx 1 \rightarrow P(v_2)$ is likely to be Gaussian. Higher statistic is needed

MPD experiment at NICA

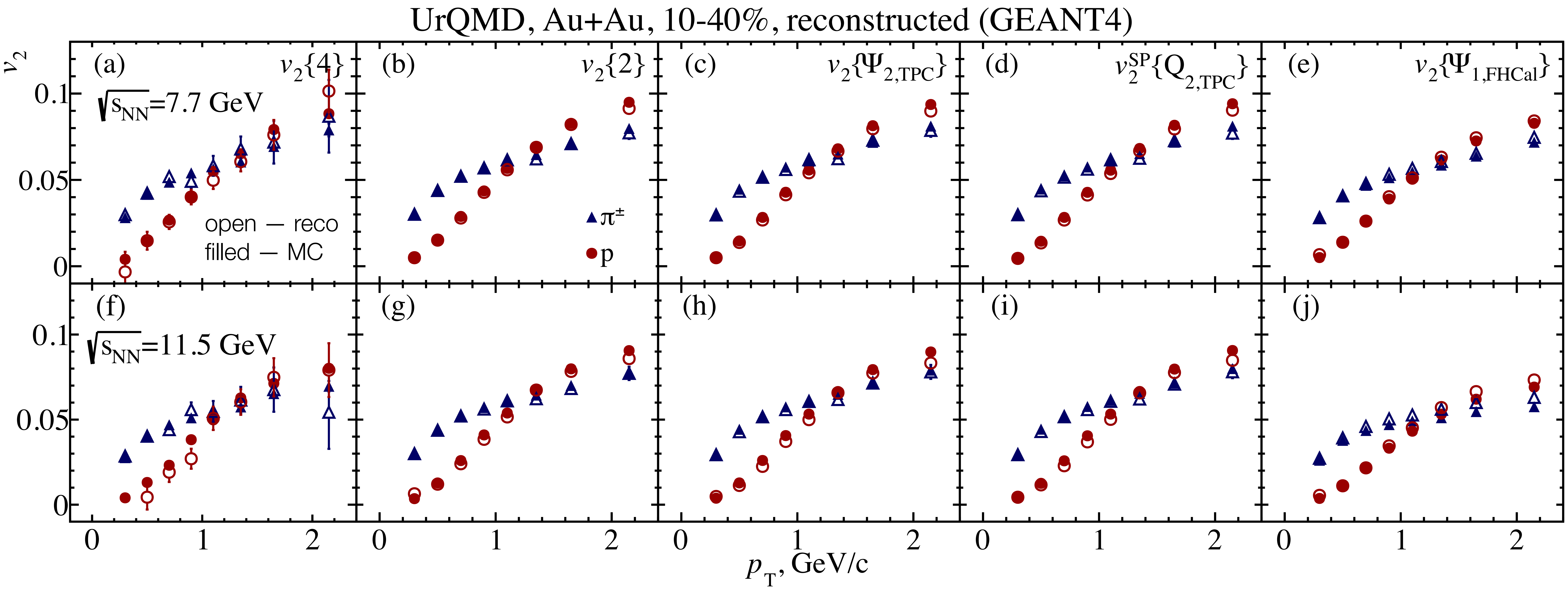
UrQMD → GEANT4 → Reconstruction → Flow Analysis

- 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:
  - $N_{hits}^{\mathrm{TPC}} > 16$
  - $|DCA| < 2\sigma$
  - $0.2 < p_T < 3.0\ \mathrm{GeV}/c$
  - $|\eta| < 1.5$
  - 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 reproduce the similar magnitude of v_2 fluctuations at $\sqrt{s_{NN}}$ = 7.7, 11.5 GeV observed in STAR experiment at RHIC
  - v_2 fluctuations are mainly driven from ε_2 fluctuations
- High order cumulant ratio $v_2\{6\}/v_2\{4\} \approx$ 1
  - $P(v_2)$ is likely to be Gaussian → more statistic needed
- Outlook: increase the statistic for the $v_2(p_T, \mathrm{PID})$ fluctuations study

Back-up slides

Models & statistics

Au+Au min. bias

- **Without partonic phase**
  - UrQMD v3.4 (cascade)
    - $\sqrt{s_{NN}}$ = 7.7 GeV: 88M
    - $\sqrt{s_{NN}}$ = 11.5 GeV: 50M
  - SMASH v1.8
    - $\sqrt{s_{NN}}$ = 7.7—11.5 GeV: 64M

- **With partonic phase**
  - vHLLE+UrQMD
    - $\sqrt{s_{NN}}$ = 7.7, 11.5 GeV: 27M
  - AMPT SM σ_p = 0.8 mb
    - $\sqrt{s_{NN}}$ = 7.7 GeV: 72M
    - $\sqrt{s_{NN}}$ = 11.5 GeV: 35M
  - AMPT SM σ_p = 1.5 mb
    - $\sqrt{s_{NN}}$ = 7.7 GeV: 42M
    - $\sqrt{s_{NN}}$ = 11.5 GeV: 60M

Effect of centrality bin width

- 0-80% min bias:
  - 9 bins: (0,5,10,20,30,40,50,60,70,80)
  - 16 bins: 5%-bin width
- Similar results for $v_2\{4\}/v_2\{2\}$ cumulant ratio