Correlation between mean transverse momentum and anisotropic flow in models at NICA energy range

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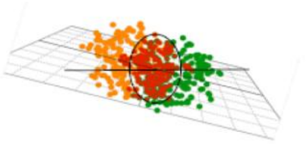
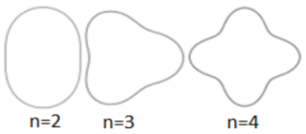
Outline

- Introduction
- Method for the transverse momentum-flow correlations measurements
- Comparison with published data
- The results at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV for different models
- Summary and outlook

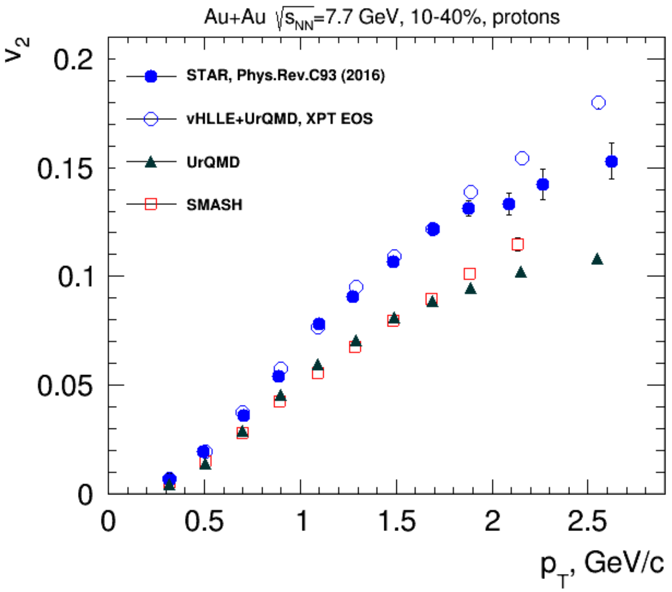
Elliptic flow at NICA energies

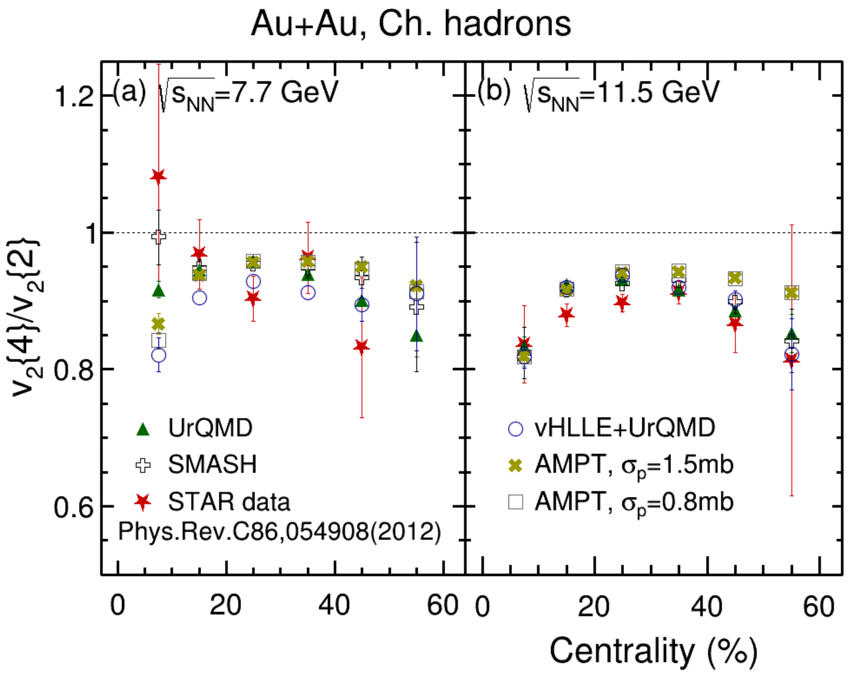
$$\frac{dN}{d\varphi} \sim 1 + \sum_{n=1} v_n \cos\left[n\left(\varphi - \Psi_n\right)\right],$$





$$v_2\{2\} = \sqrt{\left\langle e^{i2(\varphi_1-\varphi_2)} \right\rangle}, \quad v_2\{4\} = \sqrt[4]{\left\langle e^{i2(\varphi_1+\varphi_2-\varphi_3-\varphi_4)} \right\rangle - 2\left\langle e^{i2(\varphi_1-\varphi_2)} \right\rangle^2}$$





- **v_2 is sensitive to the properties of strongly interacting matter:**
  - 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 SM)

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

The correlation coefficient

The correlation coefficient defined as

$$\rho(\mathrm{v}_2^2,[p_T]) = \frac{\mathrm{cov}\left(\mathrm{v}_2^2,[p_T]\right)}{\sqrt{\mathrm{var}\left(\mathrm{v}_2^2\right)_{dyn}}\sqrt{c_k}}$$

where $\mathrm{var}\left(\mathrm{v}_2^2\right)_{\mathrm{dyn}} = \left\langle \mathrm{v}_2^4 \right\rangle - \left\langle \mathrm{v}_2^2 \right\rangle^2 = \left\langle\left\langle 4 \right\rangle\right\rangle\Big|_{A,C} - \left\langle\left\langle 2 \right\rangle\right\rangle^2\Big|_{A,C}$

$$\left\langle\left\langle 2 \right\rangle\right\rangle\Big|_{A,C} = \left\langle\left\langle e^{i\cdot 2\left(\varphi_1^A - \varphi_2^C\right)} \right\rangle\right\rangle = \frac{\boldsymbol{Q}_{2,A}\boldsymbol{Q}_{2,C}^*}{M_A M_C},$$

$$\left\langle\left\langle 4 \right\rangle\right\rangle\Big|_{A,C} = \left\langle\left\langle e^{i\cdot 2\left(\varphi_1^A + \varphi_2^A - \varphi_3^C - \varphi_4^C\right)} \right\rangle\right\rangle = \frac{\left(\boldsymbol{Q}_{2,A}^2 - \boldsymbol{Q}_{4,A}\right)\left(\boldsymbol{Q}_{2,C}^2 - \boldsymbol{Q}_{4,C}\right)^*}{M_A\left(M_A - 1\right)M_C\left(M_C - 1\right)}$$

$\boldsymbol{Q}_{n,A/C} = \sum_k e^{\mathrm{i}\cdot\mathrm{n}\varphi_k^{A/C}}$ - flow vector for A/C sub event

$M_{A/C}$ - multiplicity of particles

$-1 < \eta < -0.35$ $\quad |\eta| < 0.35$ $\quad 0.35 < \eta < 1$

to suppress non-flow effects,
the two sub-events method was used

In the study were used charged particles with $0.2 < p_T < 2.0$ GeV/c

Magdy, Niseem & Lacey, Roy. (2021). Physics Letters B. 821. 136625. 10.1016/j.physletb.2021.136625.

The correlation coefficient 2

The variance of the mean transvers momentum, taking into account autocorrelations, is defined as

$$c_k = \left\langle \frac{1}{M_B(M_B-1)} \sum_B \sum_{B' \neq B} \left(p_{T,B} - \langle [p_T] \rangle \right) \left(p_{T,B'} - \langle [p_T] \rangle \right) \right\rangle$$

where $[p_T] = \sum_{i=1}^{M_B} p_{T,i} \Big/ M_B$

to suppress non-flow and autocorrelation effects in the $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ the three-subevents method was used

$$\mathrm{cov}\left(\mathrm{v}_2^2, [p_T]\right) = \left\langle \frac{\sum_{A,C} e^{i \cdot 2\left(\varphi_1^A - \varphi_2^C\right)} \sum_B \left(p_{T,B} - \langle [p_T] \rangle \right)}{M_A M_C M_B} \right\rangle$$

$-1 < \eta < -0.35$ $\quad |\eta| < 0.35$ $\quad 0.35 < \eta < 1$

Magdy, Niseem & Lacey, Roy. (2021). Physics Letters B. 821. 136625. 10.1016/j.physletb.2021.136625.

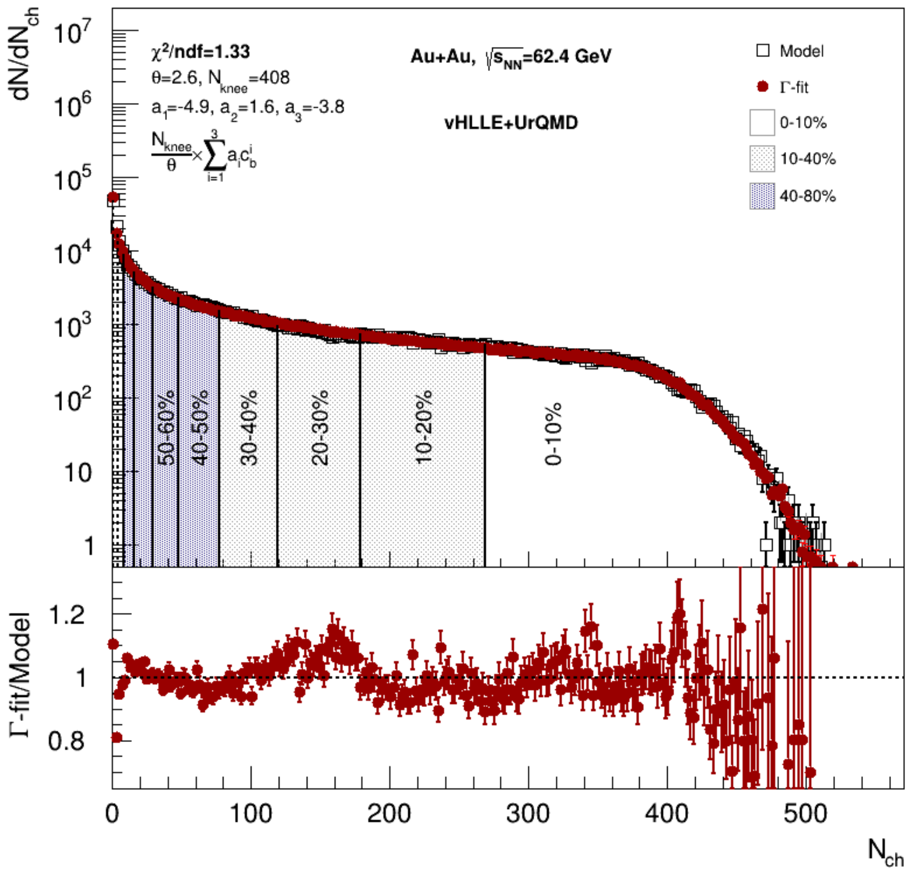
Motivation of the work

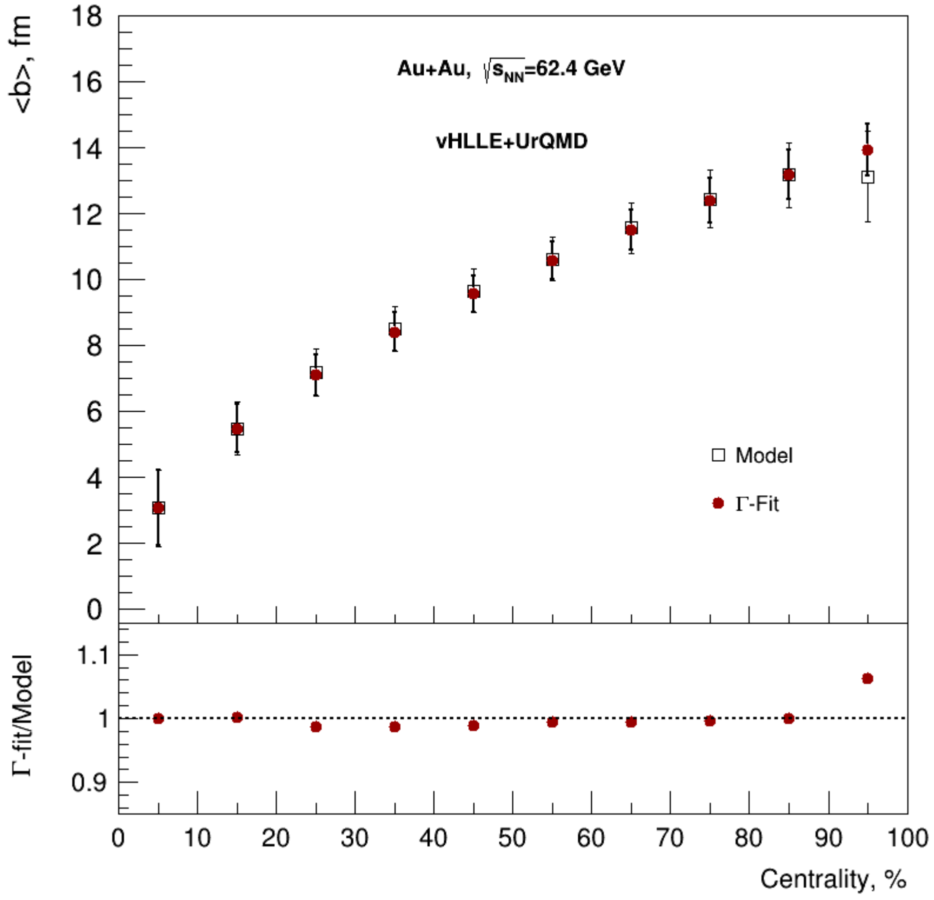
- The $\rho(\mathrm{v}_2^2, [p_T])$ is sensitive to initial state and its entropy density profile

- The $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ and $\mathrm{var}(\mathrm{v}_2^2)$ are sensitive to η/s

- The precise set of measurements for $\mathrm{var}([p_T])$, $\mathrm{var}(\mathrm{v}_2^2)$, $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ and $\rho(\mathrm{v}_2^2, [p_T])$ as a function of beam-energy and centrality, could help precision extraction of the temperature and baryon chemical-potential dependence of η/s

Centrality for Au+Au collisions at $\sqrt{S_{NN}} = 62.4$ GeV in vHLLE+UrQMD



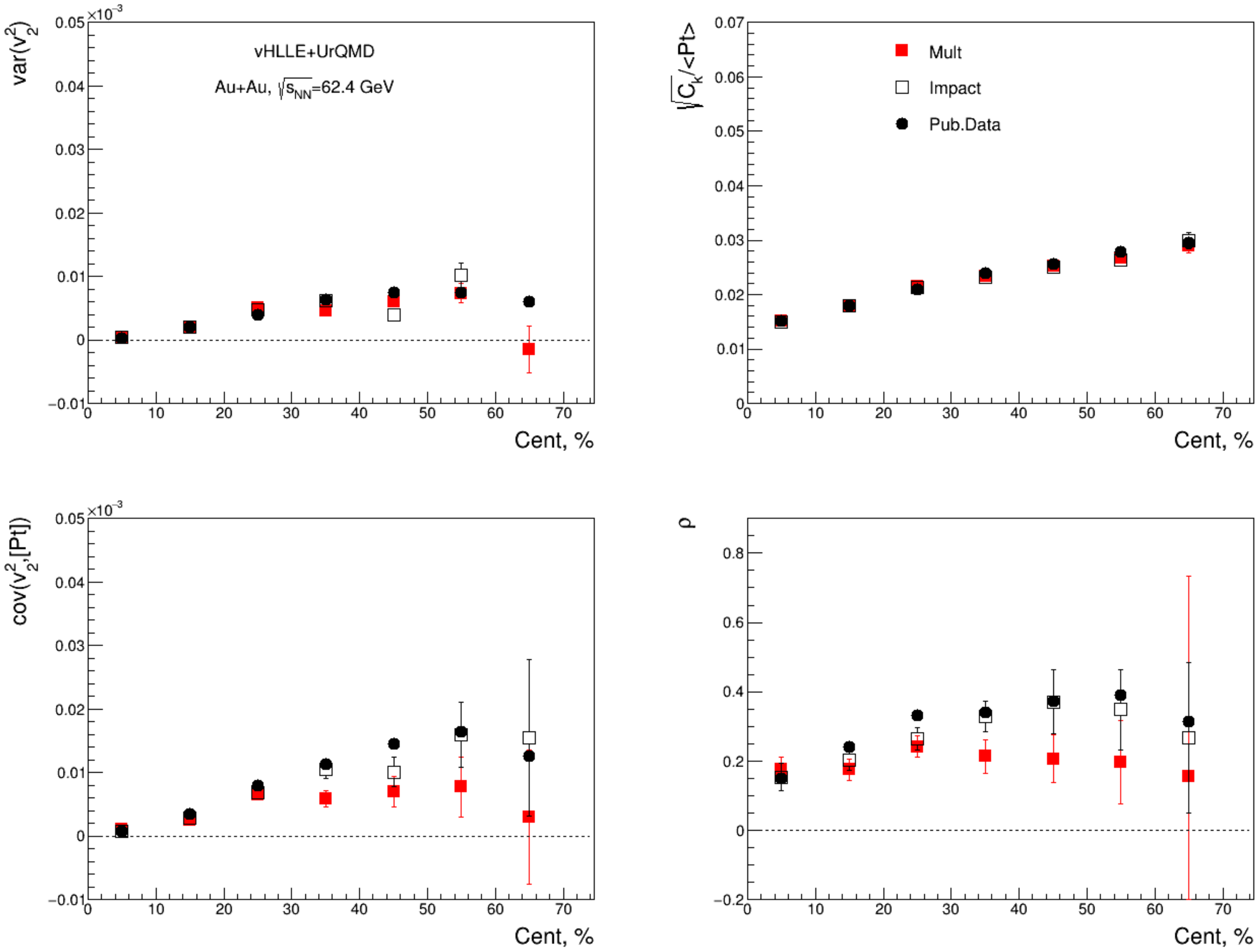


The reasonable fit quality and good agreement of the impact parameter distribution with the model data.
For centrality determination the Inverse Bayes approach was used.

Parfenov, P.et.al; *Particles* 2021, *4*, 275-287. https://doi.org/10.3390/particles4020024

Comparison of correlation coefficient with published results

The published data taken from: **Niseem Magdy et. al. Published in: Phys.Rev.C 105 (2022) 4, 044901**



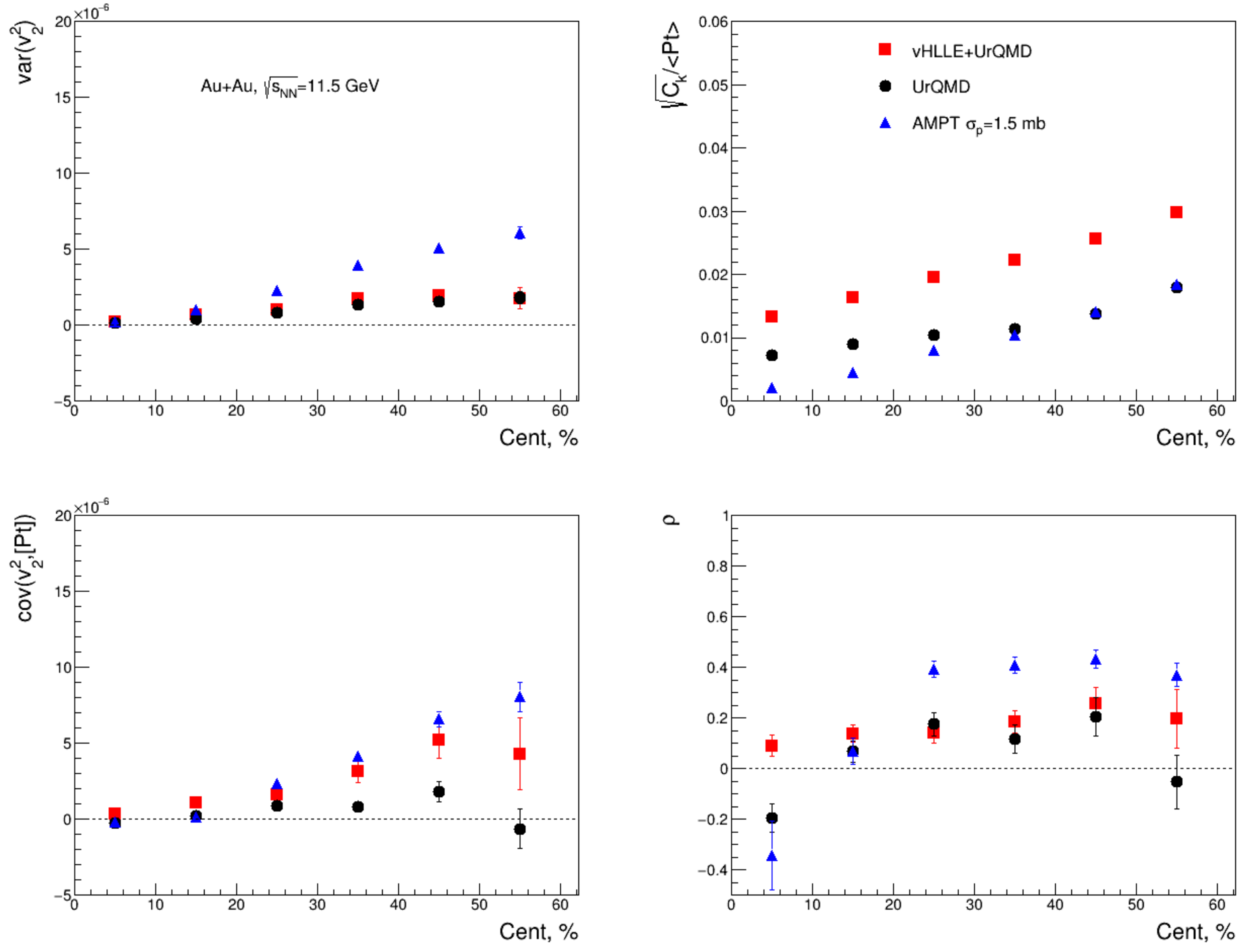
Filled red squares: multiplicity-based centrality

Open black squares: b-based centrality

- A good agreement between published data and results with b-based centrality
- The $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ is sensitive to the **multiplicity fluctuations**

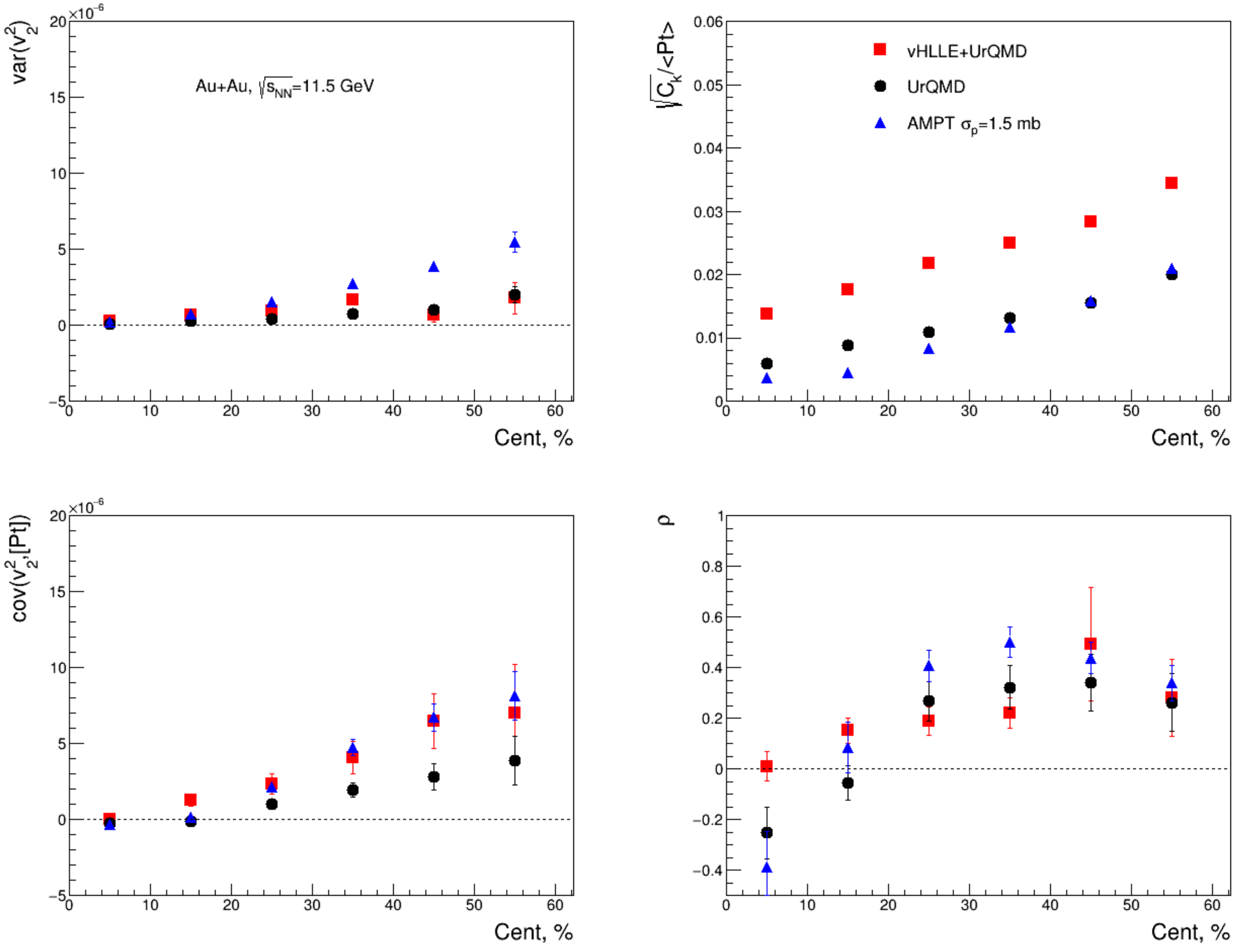
The $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ and $\rho(\mathrm{v}_2^2, [p_T])$ depend on the centrality determination method.

The transverse momentum-flow correlations at $\sqrt{S_{NN}}$=11.5 GeV



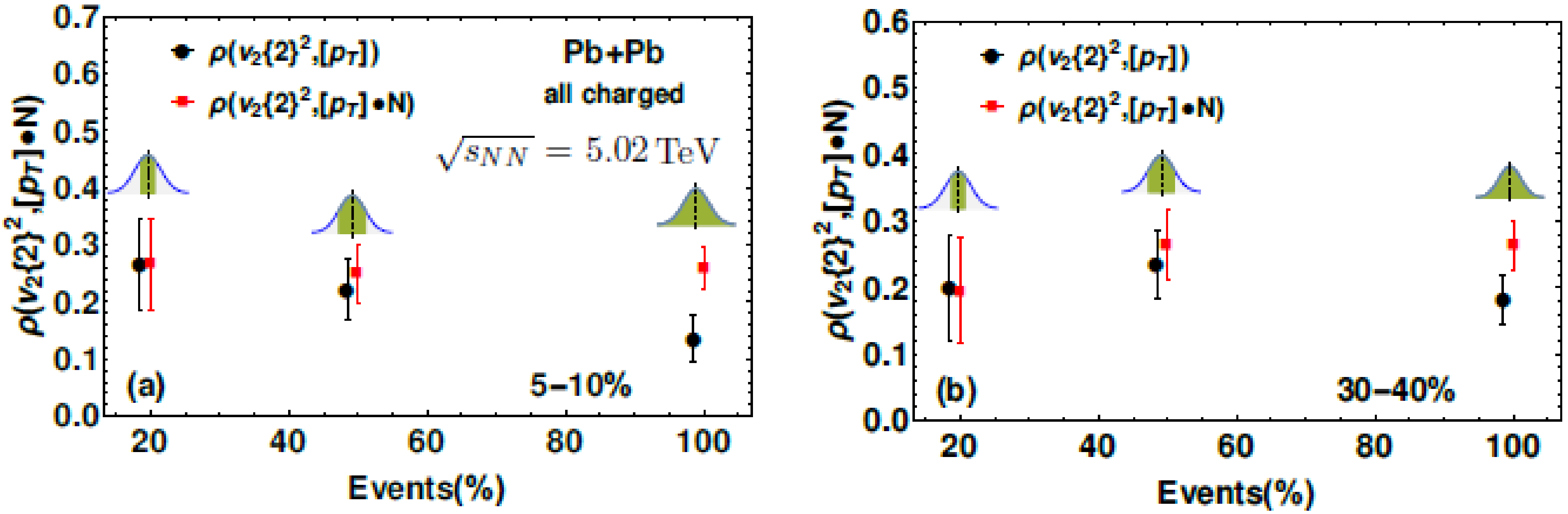
- $\rho(\mathrm{v}_2^2, [p_T])$ decreases in the most central collisions due to the eccentricity decreases faster compared to changes in elliptic area.
- $\rho(\mathrm{v}_2^2, [p_T])$ from vHLLE+UrQMD and UrQMD are consistent with each other due to the same initial state
  - $\rho(\mathrm{v}_2^2, [p_T])$ is sensitive to initial state
- $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ from vHLLE+UrQMD and AMPT are consistent due to QGP phase
  - $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ is sensitive to thermalization (η/s, etc.)

The transverse momentum-flow correlations at $\sqrt{S_{NN}}$=7.7 GeV



- The same trends as for $\sqrt{S_{NN}}$=11.5 GeV
- The $\mathrm{var}(v_2^2)$ decrease with decreasing energy
- More statistics are needed to get more accurate results

The partial correlation coefficient



The partial correlation coefficient defined as

$$\rho(\mathrm{v}_2^2,[p_T]\bullet N) = \frac{\mathrm{cov}\left(\mathrm{v}_2^2,[p_T]\bullet N\right)}{\sqrt{\mathrm{var}\left(\mathrm{v}_2^2\bullet N\right)}\sqrt{\mathrm{var}([p_T]\bullet N)}}$$

takes into account the **fluctuations of the multiplicity**

where $\mathrm{cov}\left(\mathrm{v}_2^2,[p_T]\bullet N\right) = \mathrm{cov}\left(\mathrm{v}_2^2,[p_T]\right) - \frac{\mathrm{cov}\left(\mathrm{v}_2^2,N\right)\mathrm{cov}\left([p_T],N\right)}{\mathrm{var}\left(N\right)}$, $\mathrm{var}\left([p_T]\bullet N\right) = \mathrm{var}\left([p_T]\right) - \frac{\mathrm{cov}\left([p_T],N\right)^2}{\mathrm{var}\left(N\right)}$

Bozek, P, Mehrabpour, H. Phys. Rev. C 2020; 101:064902.

Summary and outlook

- A good agreement between published data and results for vHLLE+UrQMD at $\sqrt{S_{NN}}$= 62.4 GeV with b-based centrality for $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ and $\rho(\mathrm{v}_2^2, [p_T])$

- The $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ and $\rho(\mathrm{v}_2^2, [p_T])$ depend on the centrality determination method due to the multiplicity fluctuates

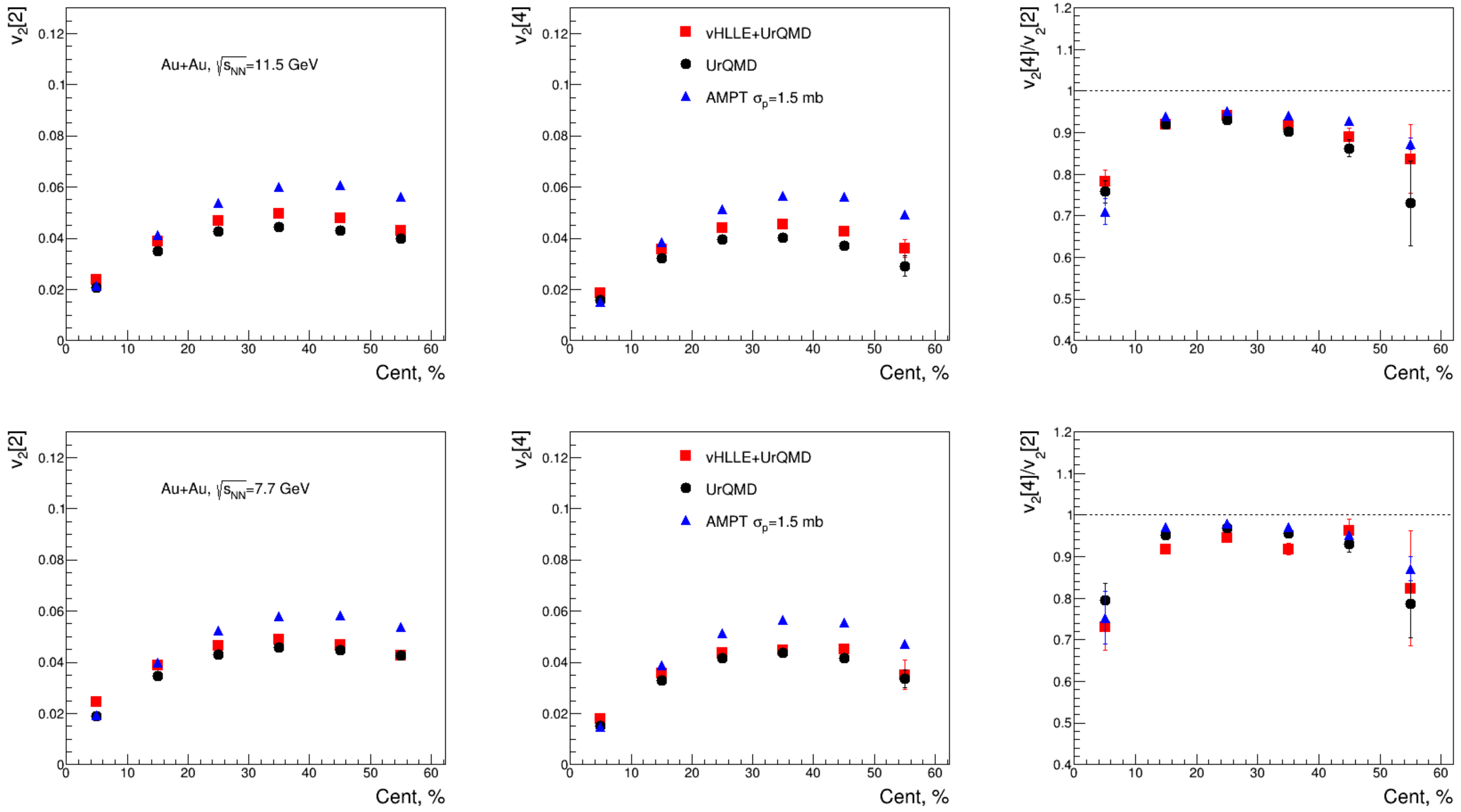
- The results at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV for AMPT, UrQMD, and vHLLE+UrQMD
    - $\rho(\mathrm{v}_2^2, [p_T])$ from vHLLE+UrQMD and UrQMD are consistent with each other due to the same initial state
    - $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ from vHLLE+UrQMD and AMPT are consistent due to QGP phase simulation
    - $\rho(\mathrm{v}_2^2, [p_T])$ decreases in the most central collisions

- To compare results for partial and non-partial correlation coefficient at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV for AMPT, UrQMD, and vHLLE+UrQMD models

- Study sensitivity of $\mathrm{v}_2^2 - [p_T]$ **partial** correlation coefficient to different equation of states in models within mean-field approach at lower beam energies

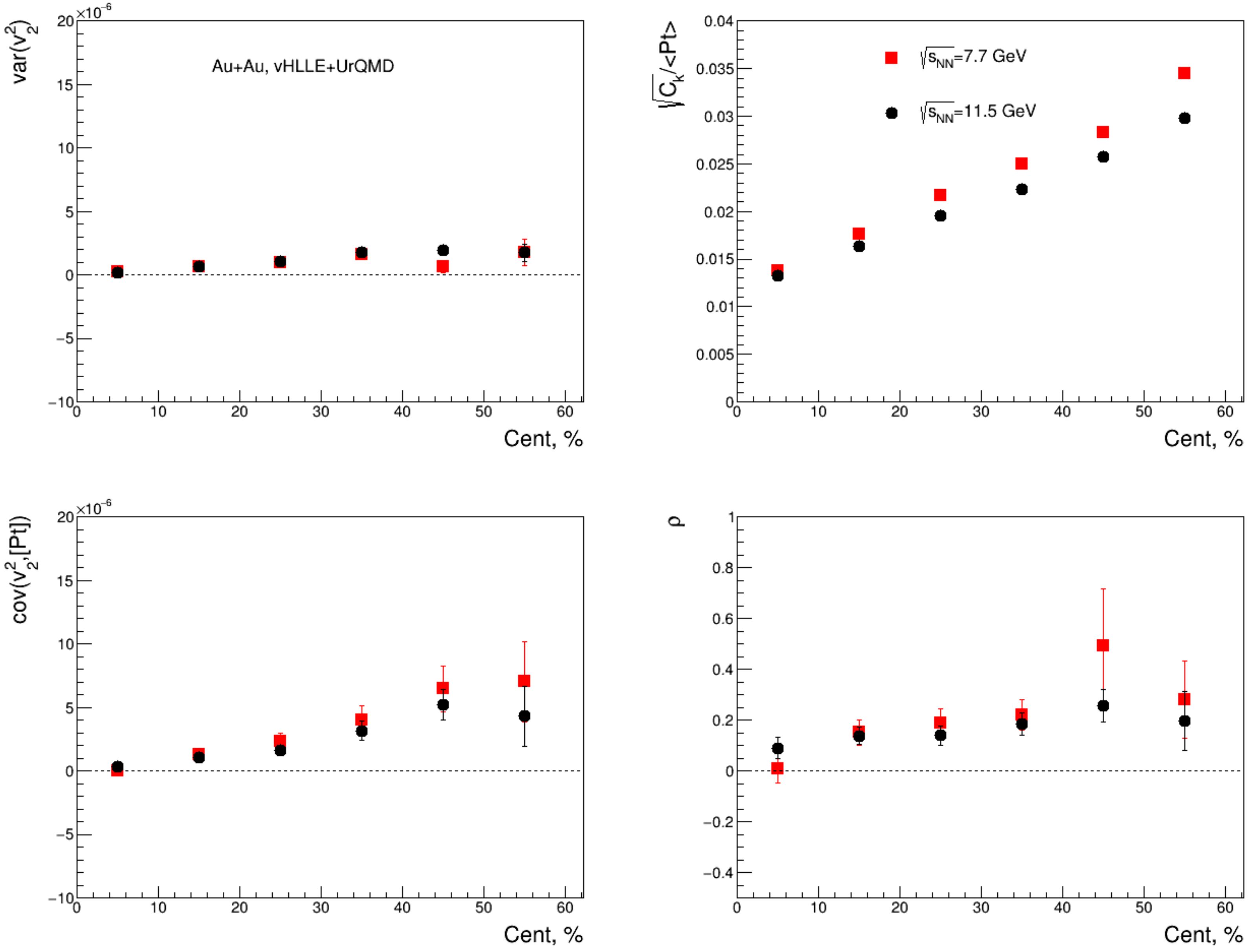
Thank you for your attention!

Elliptic flow and its fluctuations at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV



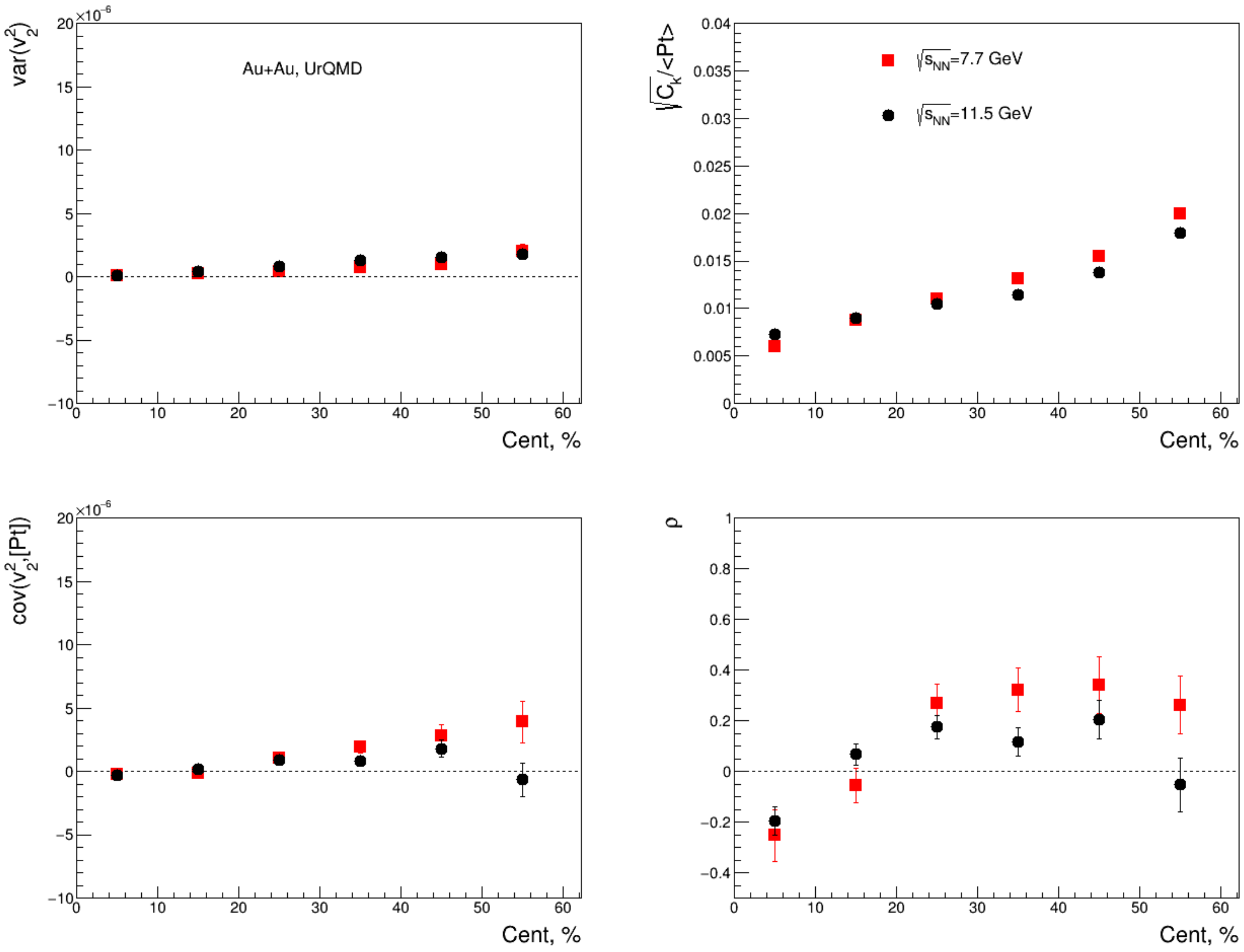
The flow fluctuations are model independent and decrease with decreasing energy.

The results for vHLLE+UrQMD at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV



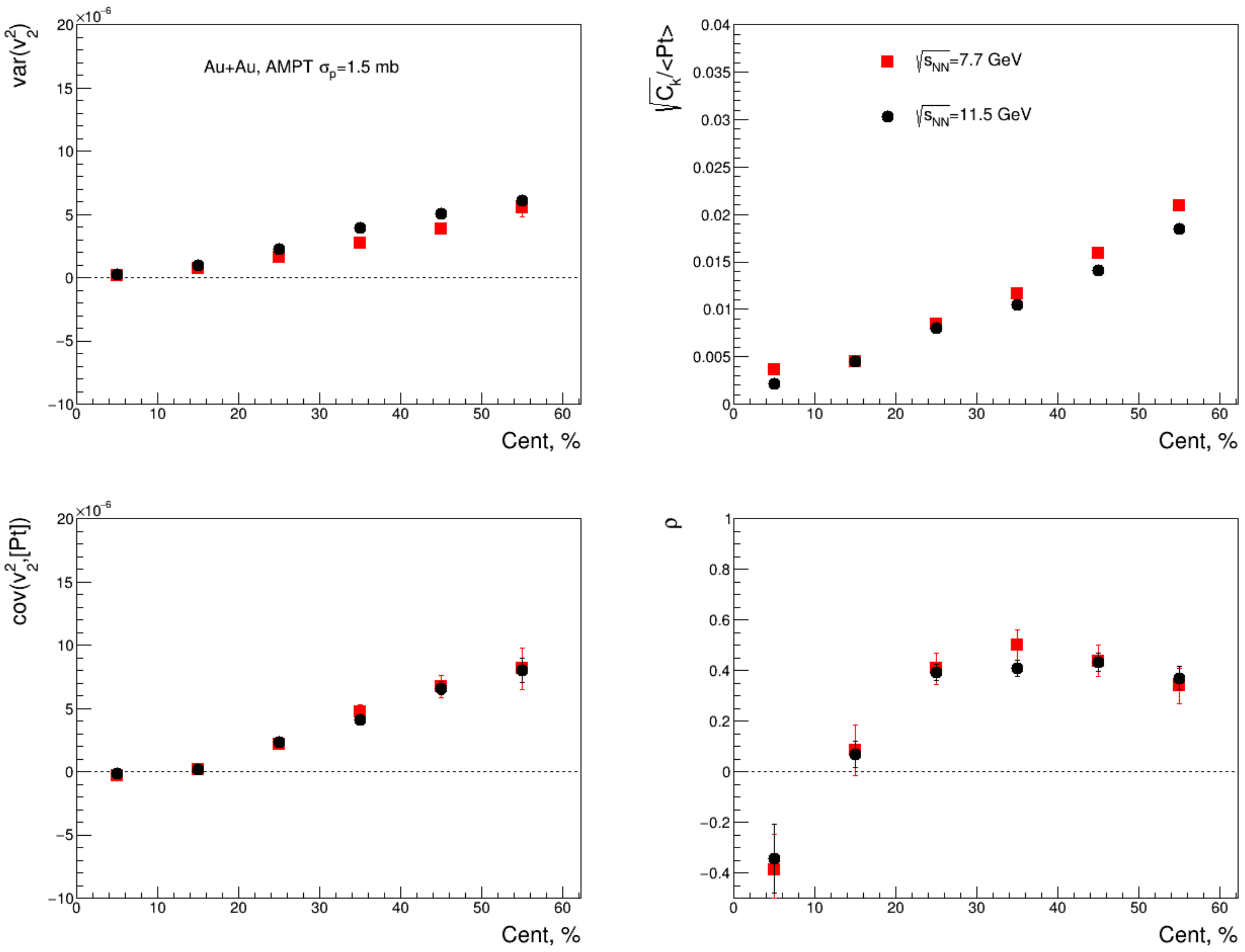
- The $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ and $\rho(\mathrm{v}_2^2, [p_T])$ changes weakly at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV
- The $\sqrt{c_k}/\langle p_T\rangle$ increases with decreasing energy.

The results for UrQMD at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV



- Do the $cov(v_2^2, [p_T])$ and $\rho(v_2^2, [p_T])$ increases with decreasing energy due to non-flow effects?

The results for AMPT at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV



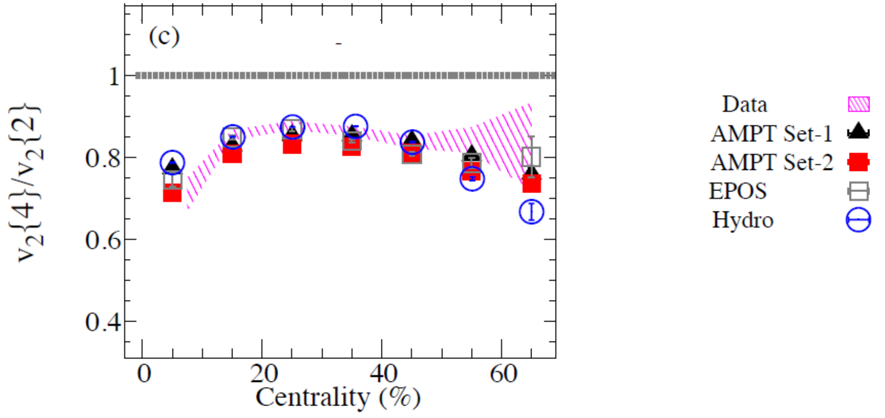
- The set of measurements for $\mathrm{var}([p_T])$, $\mathrm{var}(\mathrm{v}_2^2)$, $\mathrm{cov}(\mathrm{v}_2^2,[p_T])$ and $\rho(\mathrm{v}_2^2,[p_T])$ changes weakly at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV

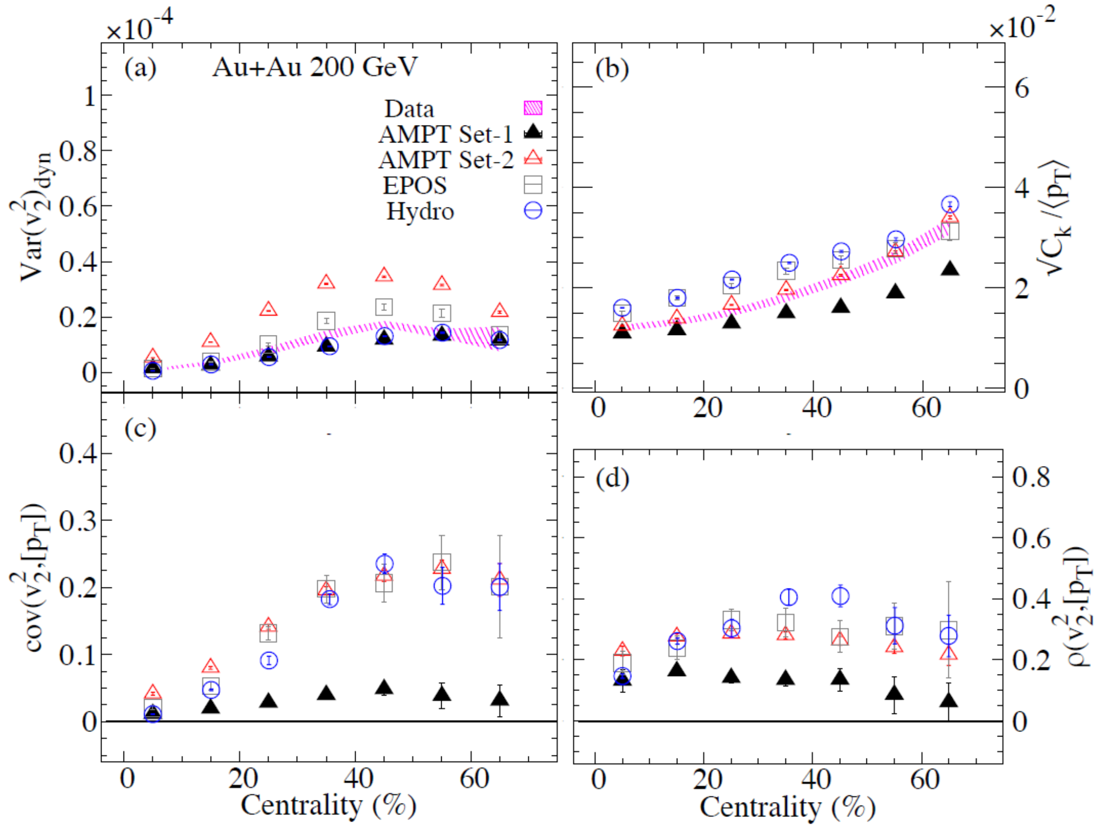
Summary and outlook

- A good agreement between published data and results for vHLLE+UrQMD at $\sqrt{S_{NN}}$= 62.4 GeV with b-based centrality for $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ and $\rho(\mathrm{v}_2^2, [p_T])$
  - The $\mathrm{cov}(\mathrm{v}_2^2, [p_T])$ and $\rho(\mathrm{v}_2^2, [p_T])$ depend on the centrality determination method
- The results at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV for AMPT, UrQMD, and vHLLE+UrQMD
  - The $\rho(\mathrm{v}_2^2, [p_T])$ vs. centrality for vHLLE+UrQMD at $\sqrt{S_{NN}}$=7.7 and 11.5 shows the similar trends as for BES energies.
  - $\rho(\mathrm{v}_2^2, [p_T])$<0 for the most central collisions in UrQMD and AMPT models at $\sqrt{S_{NN}}$=7.7 and 11.5 GeV
- Investigate beam-energy and event-shape dependence of the $\mathrm{v}_3^2 - [p_T]$ correlation using vHLLE+UrQMD model
- Study sensitivity of $\mathrm{v}_2^2 - [p_T]$ correlation to different equation of states in models within mean-field approach at lower beam energies

Transverse momentum-flow correlations

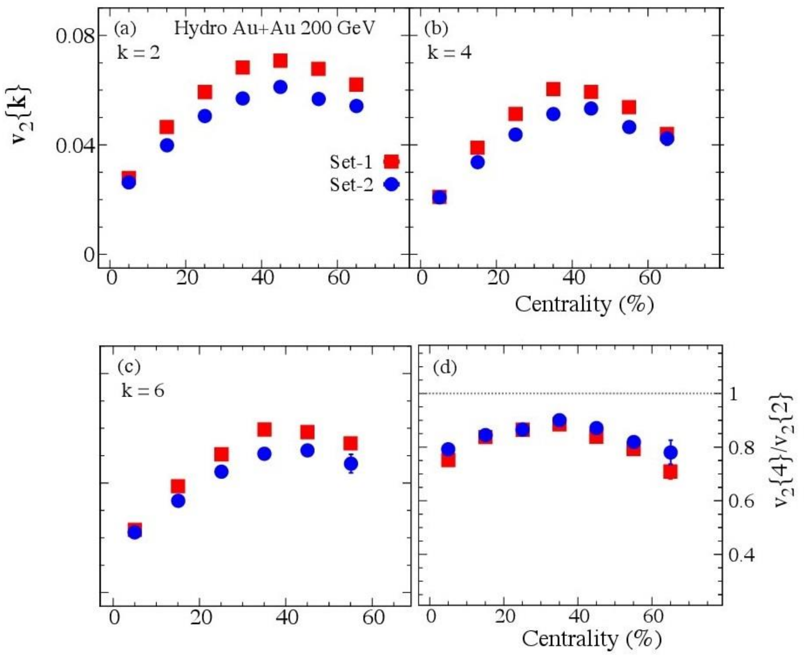
Models	Initial stage conditions	η/s
AMPT	Glauber-like & SM-ON	0.10
AMPT	Glauber-like & SM-OFF	0.10
EPOS	Described in terms of flux tubes computed based on Gribov-Regge multiple scattering theory	0.08
Hydro	Woods-Saxon distributions Glauber-like Initial conditions	(BES)

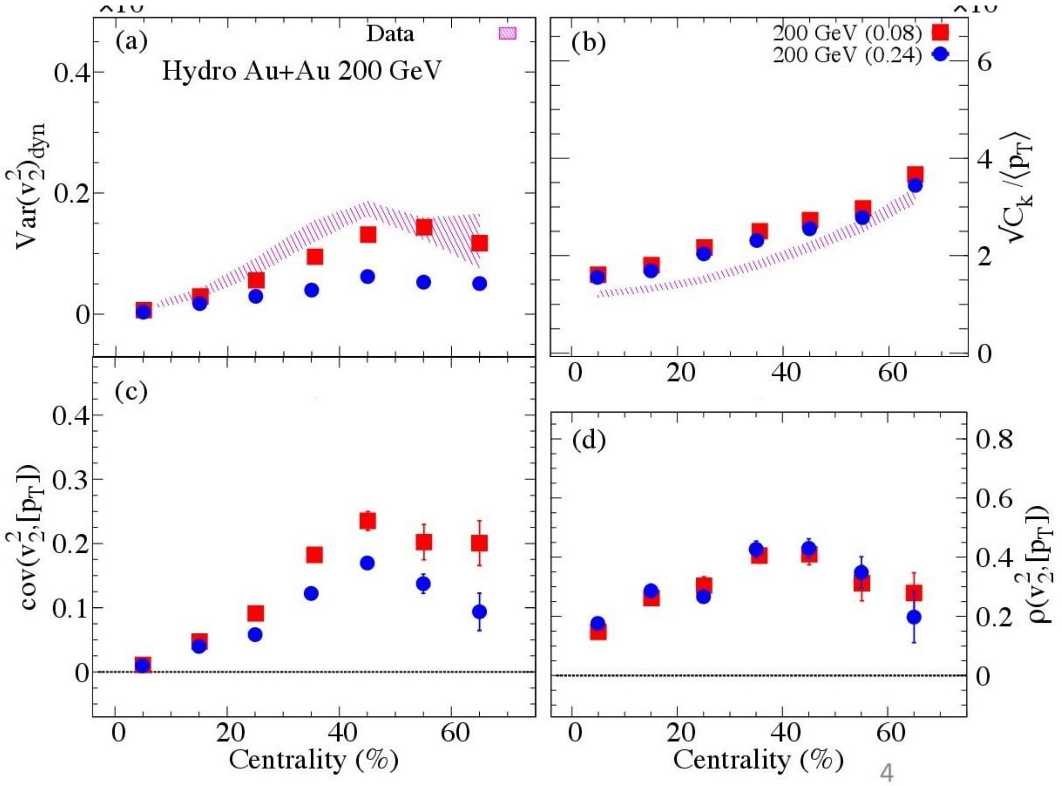




- The $cov(v_2^2, [p_T])$ and $\rho(v_2^2, [p_T])$ show agreement between AMPT (SM) and EPOS
- Smaller $cov(v_2^2, [p_T])$ and $\rho(v_2^2, [p_T])$, from AMPT without SM

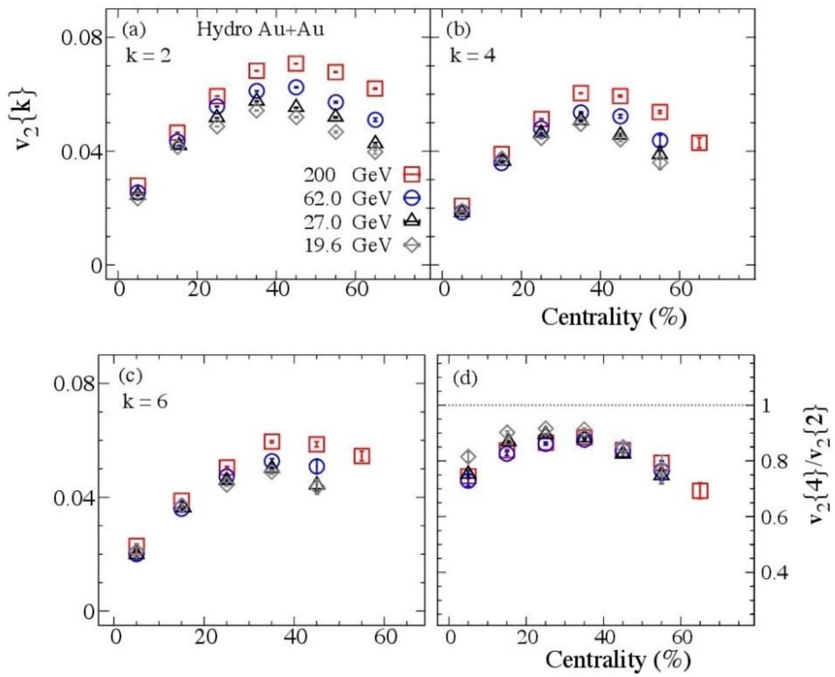
Transverse momentum-flow correlations

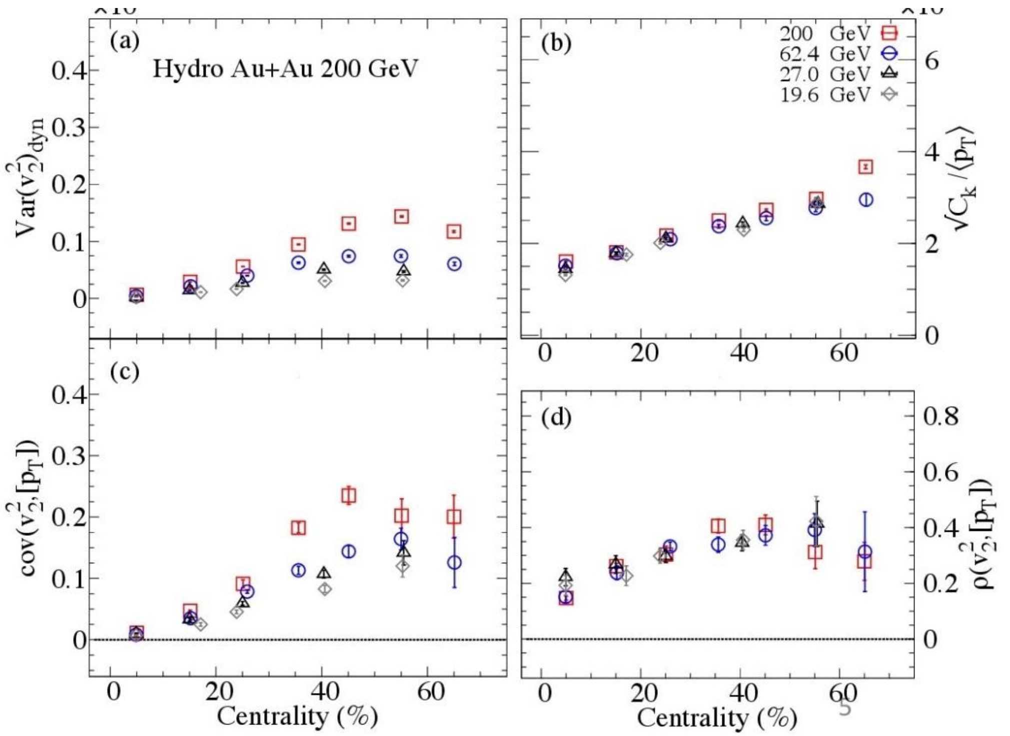




- The $cov(v_2^2,[p_T])$ decreas with η/s
- The $\rho(v_2^2,[p_T])$, show weak dependance on η/s

The transverse momentum-flow correlations dependence on beam energy in vHLLE+UrQMD model

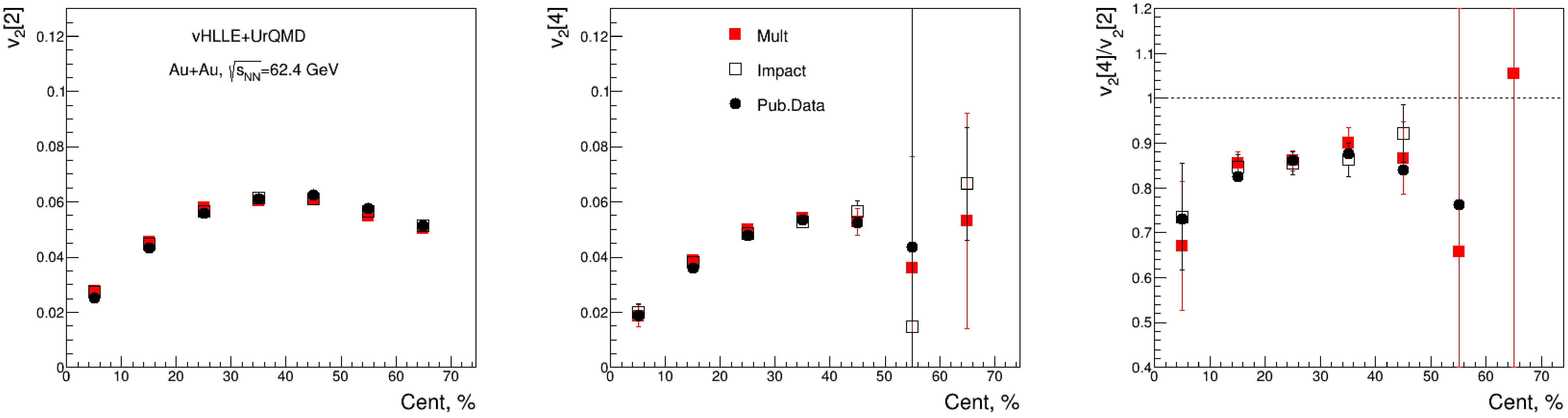




- The $cov(v_2^2,[p_T])$ decreas with beam energy
- The $\rho(v_2^2,[p_T])$, show weak dependance on beam energy

Comparison of elliptic flow measurements with published results

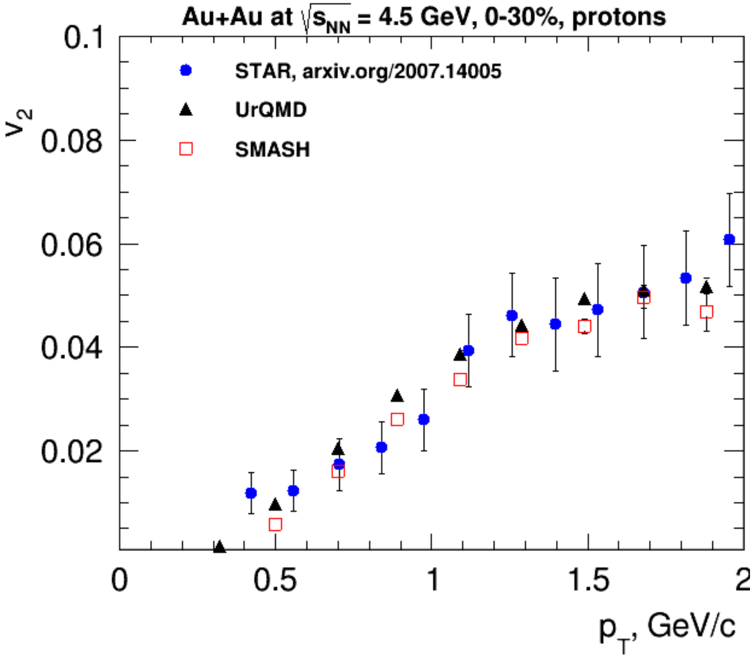
Filled red squares: multiplicity-based centrality
Open black squares: impact parameter (b) based centrality

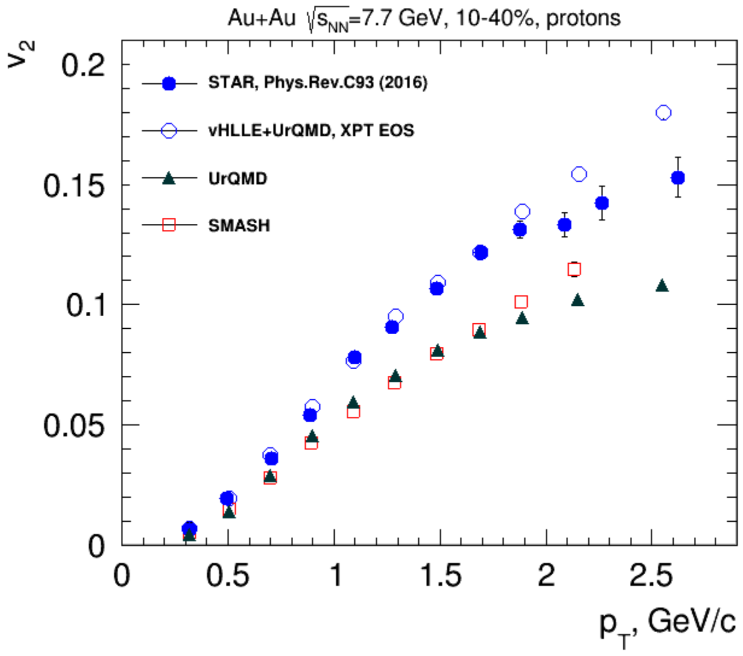


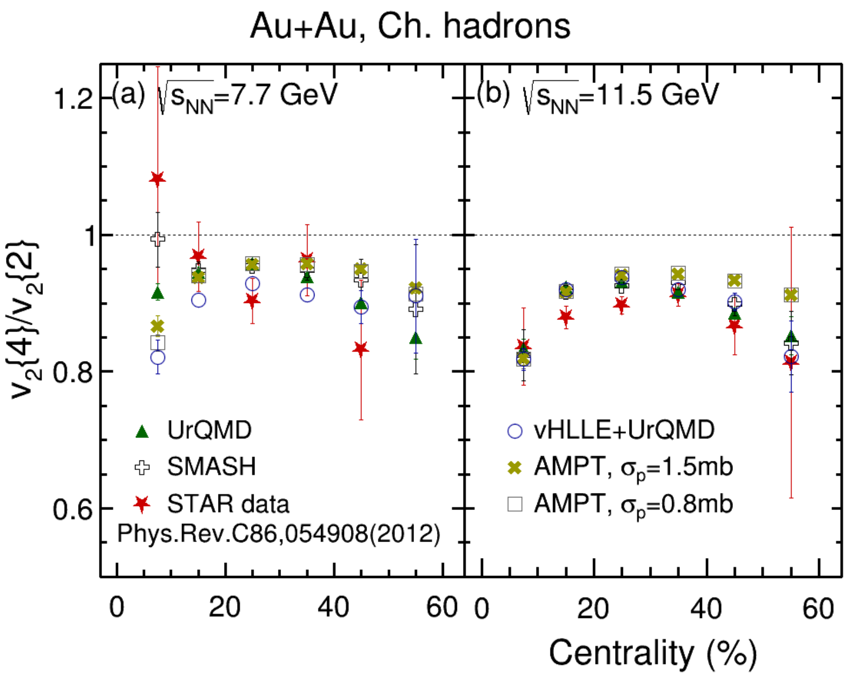
A good agreement with published data.
$v_2[2]$ and $v_2[4]$ are insensitive to centrality determination method.

The published data taken from: **Niseem Magdy et. al. Published in: Phys.Rev.C 105 (2022) 4, 044901**

Elliptic flow at NICA energies



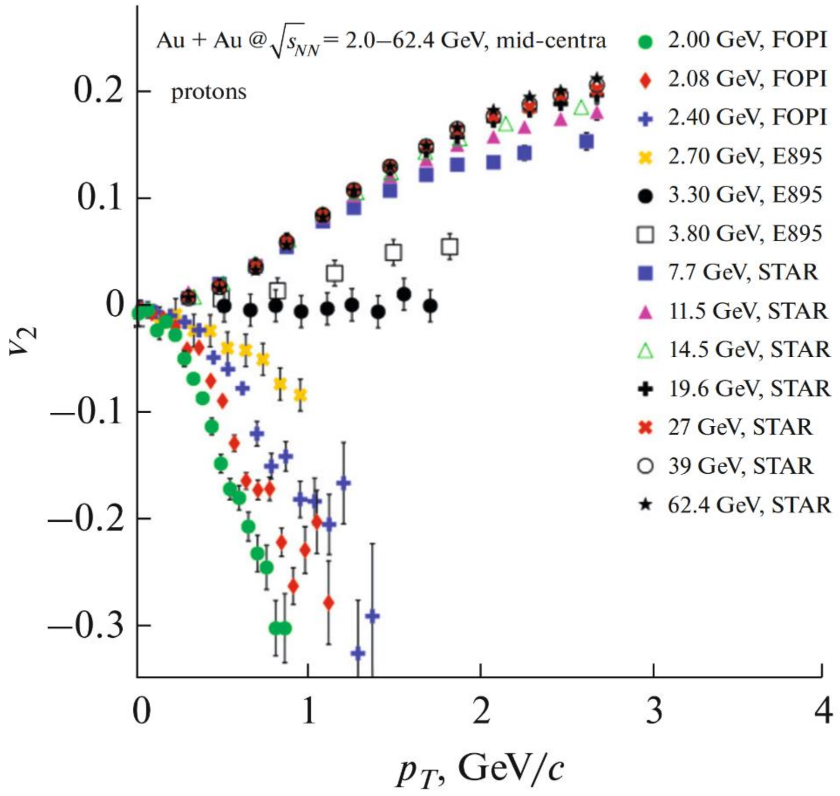




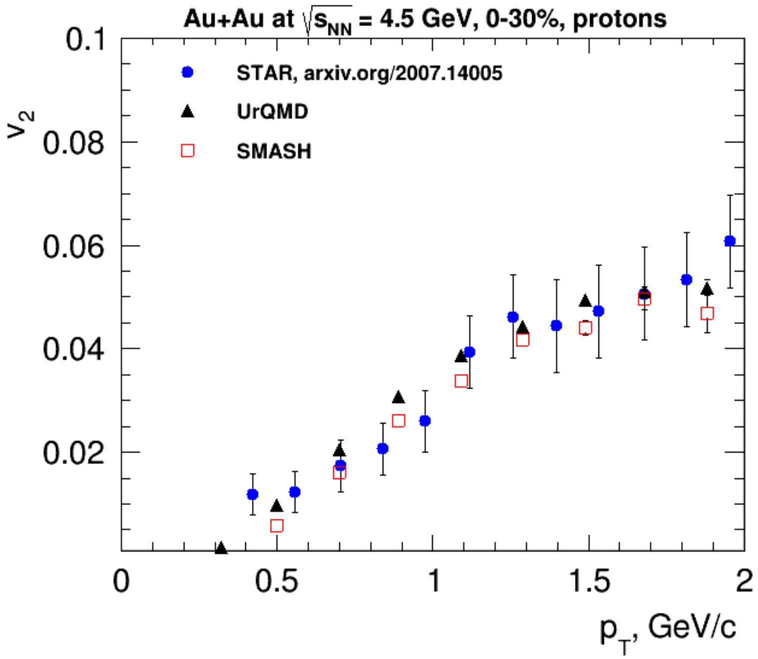
- **v_2 is sensitive to the properties of strongly interacting matter:**
  - At $\sqrt{s_{NN}}$ = 4.5 GeV pure string/hadronic cascade models (UrQMD, SMASH,…) give similar v_2 signal compared to STAR data
  - At $\sqrt{s_{NN}} \geq$ 7.7 GeV pure string/hadronic cascade models underestimate v_2 – need hybrid models with QGP phase (vHLLE+UrQMD, AMPT with string melting,…)

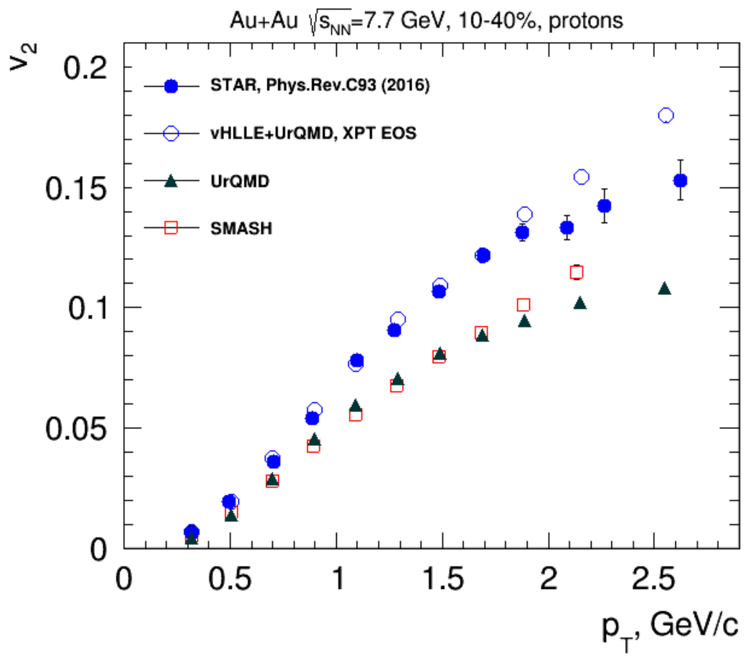
- Relative v_2 fluctuations ($v_2\{4\}/v_2\{2\}$) observed by STAR experiment can be reproduced both in the string/cascade models (UrQMD, SMASH) and hybrid model (AMPT SM, vHLLE+UrQMD)
- Dominant source of v_2 fluctuations: **participant eccentricity fluctuations** in the initial geometry

Elliptic flow at NICA energies



Taranenko et. al.,
Phys. Part. Nuclei **51**, 309–313 (2020)





- **Strong energy dependence of v2 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:**
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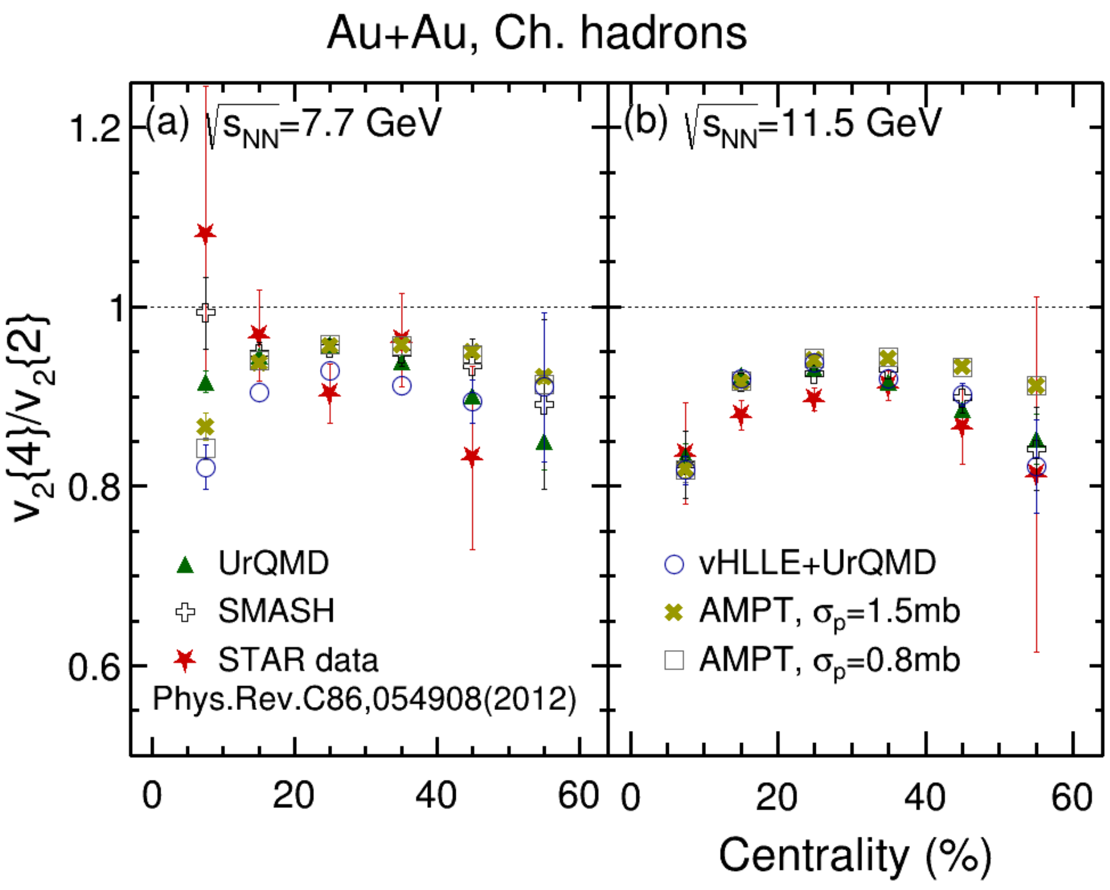
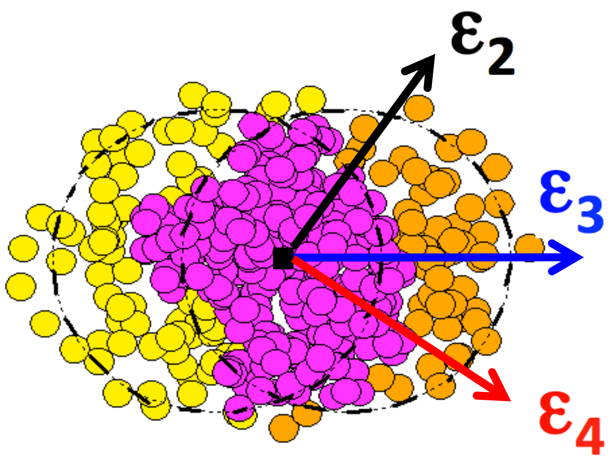
Relative elliptic flow fluctuations

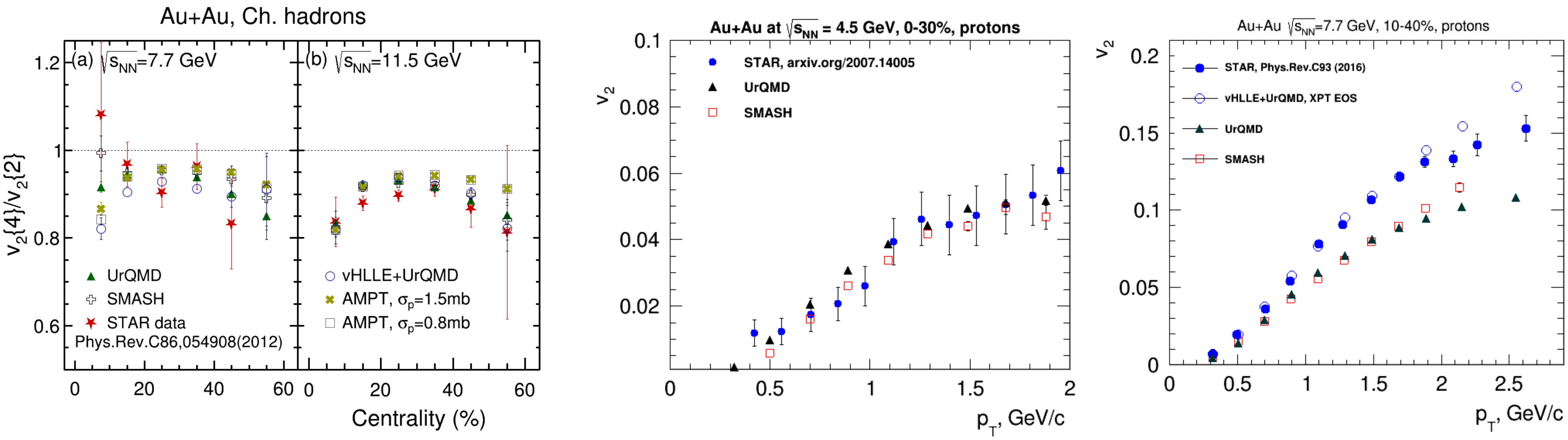


Small value for the $v_2\{4\}/v_2\{2\}$ ratio corresponds to large fluctuation

- 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 hybrid model (AMPT with string melting, vHLLE+UrQMD)
- Dominant source of v_2 fluctuations: **participant eccentricity fluctuations** in the initial geometry



Elliptic flow at NICA energies



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