Model study of the energy dependence of the correlation between anisotropic flow and the mean transverse momentum in Au+Au collisions

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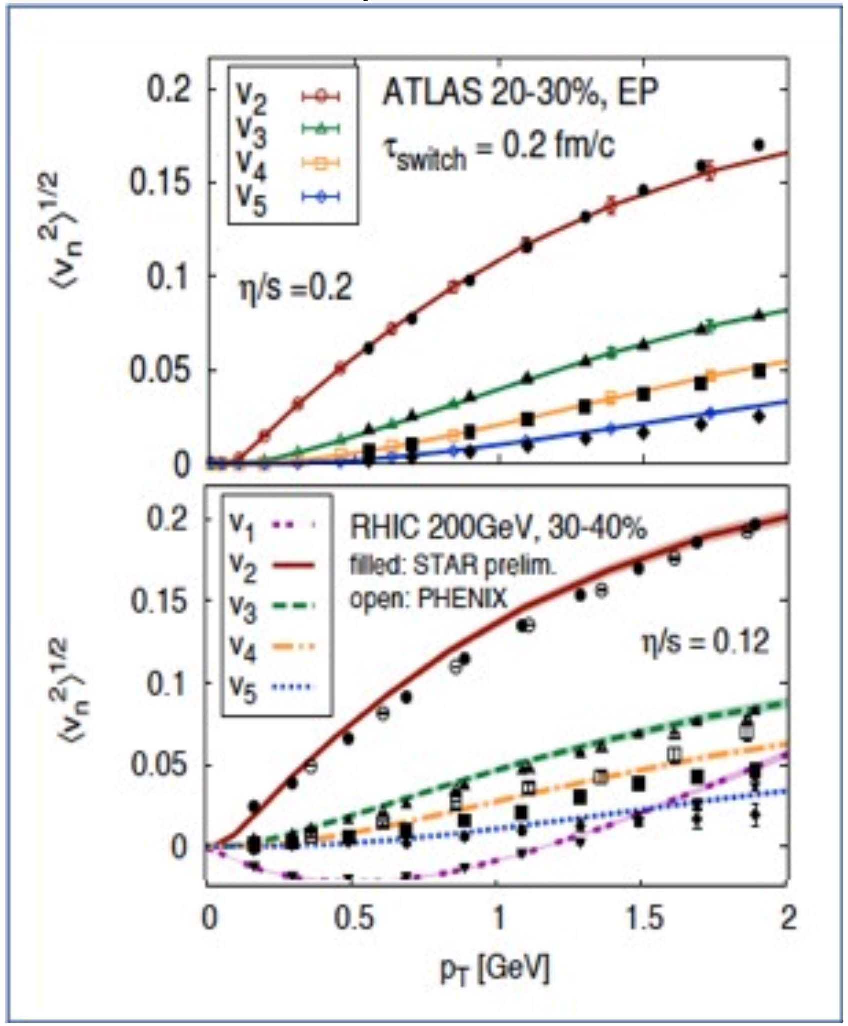
  - Beam energy dependence of $v_n - [p_T]$ correlation
  - Dependence of $v_n - [p_T]$ correlation on the event shape
- Summary and outlook

Anisotropic collective flow

Gale, Jeon, et al., Phys. Rev. Lett. 110, 012302

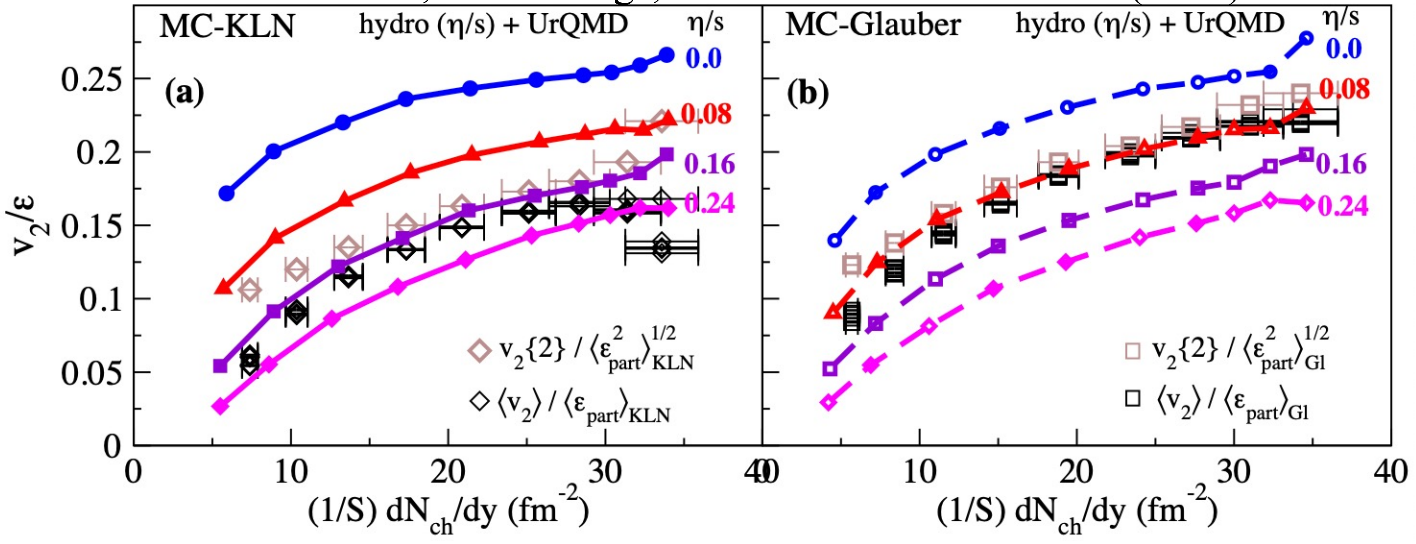


$$\frac{dN}{d\varphi} \propto 1 + 2\sum_{n=1} v_n \cos[n(\varphi - \Psi_n)], \qquad v_n = \langle \cos[n(\varphi - \Psi_n)] \rangle$$

$v_n(p_T, \text{centrality})$ - sensitive to the early stages of collision. Important constraint for transport properties (EoS, η/s, ζ/s, etc.)

Uncertainty in the extraction of η/s originate from uncertainty in the estimates for the initial-state eccentricities in the model – a new observable must be constructed

U. Heinz, R. Snellings, *Ann.Rev.Nucl.Part.Sci.* 63 (2013) 123-151



$v_n - [p_T]$ correlation coefficient

- Pearson correlation coefficient (PCC) R and modified PCC ρ:

$$R = \frac{cov(v_n^2, [p_T])}{\sqrt{Var(v_n^2)}\sqrt{Var([p_T])}} \qquad \rho = \frac{cov(v_n^2, [p_T])}{\sqrt{Var(v_n^2)_{dyn}\sqrt{c_k}}}$$

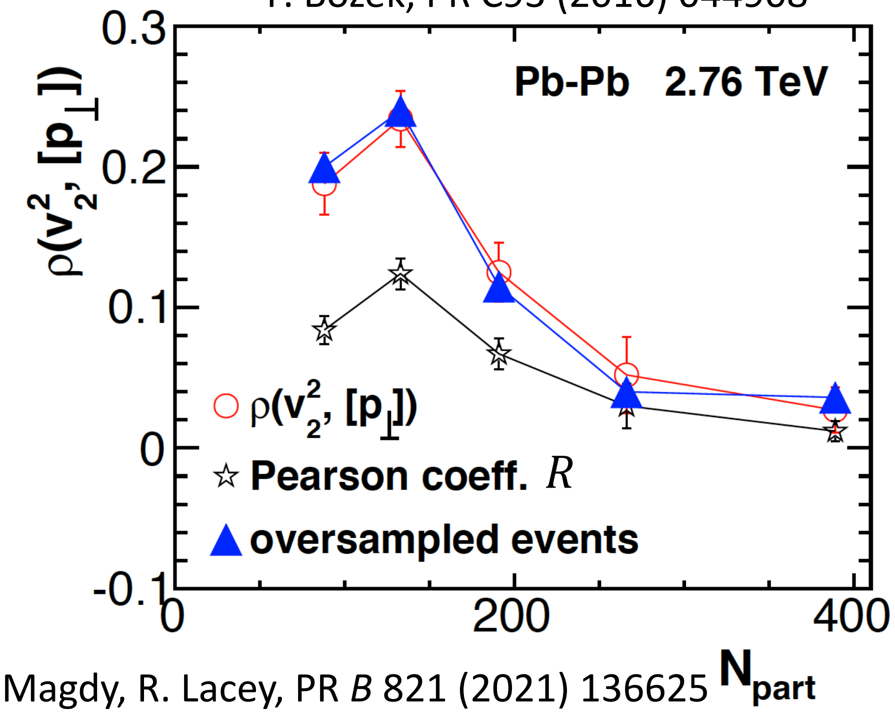
$$cov(v_n^2, [p_T]) = \left\langle \frac{1}{N_A N_C} \sum_{a \neq b \neq c} e^{in(\varphi_a - \varphi_c)} \left(p_{T,b} - \langle [p_T] \rangle\right) \right\rangle$$

$$Var(v_n^2)_{dyn} = \langle corr_n\{4\} \rangle - \langle corr_n\{2\} \rangle^2 = v_n\{2\}^4 - v_n\{4\}^4$$

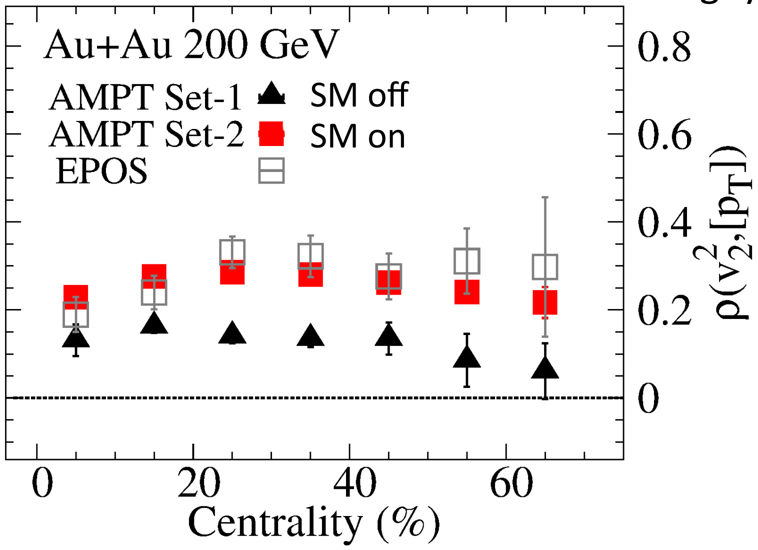
$$c_k = \left\langle \frac{1}{N_B(N_B - 1)} \sum_{b \neq b'} \left(p_{T,b} - \langle [p_T] \rangle\right)\left(p_{T,b'} - \langle [p_T] \rangle\right) \right\rangle$$

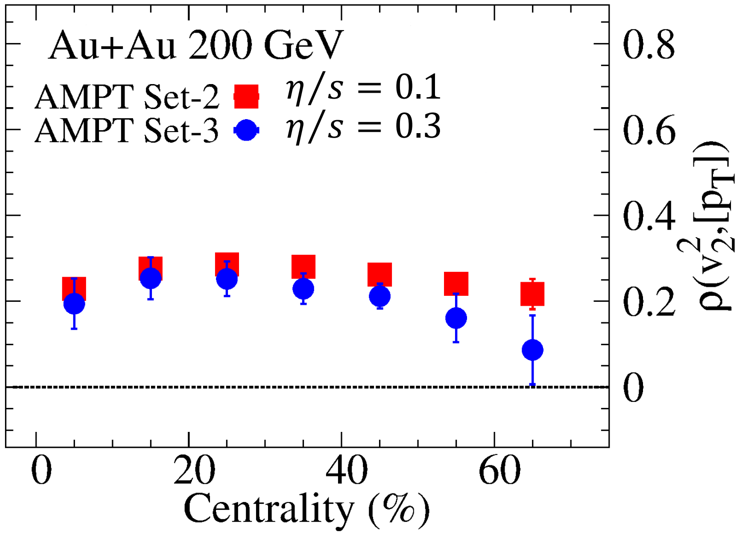
- Modified PCC ρ is multiplicity independent
- ρ is sensitive to the initial-state and insensitive to the η/s

P. Bożek, PR C93 (2016) 044908



N. Magdy, R. Lacey, PR *B* 821 (2021) 136625





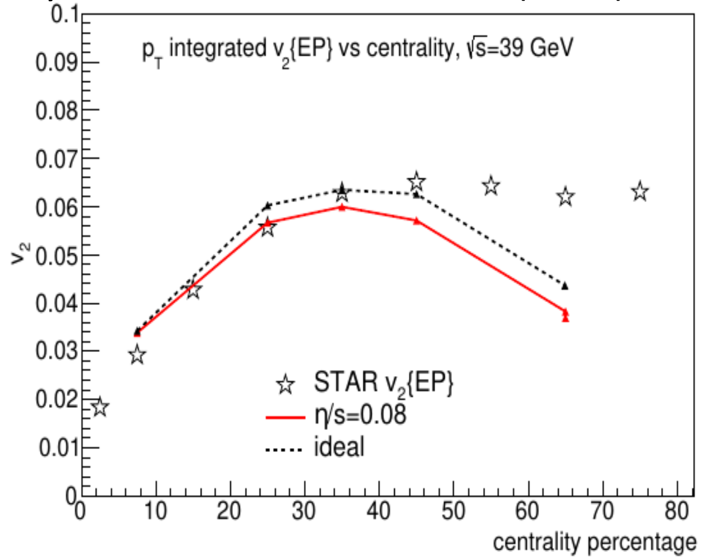
vHLLE+UrQMD model for anisotropic flow at RHIC/LHC

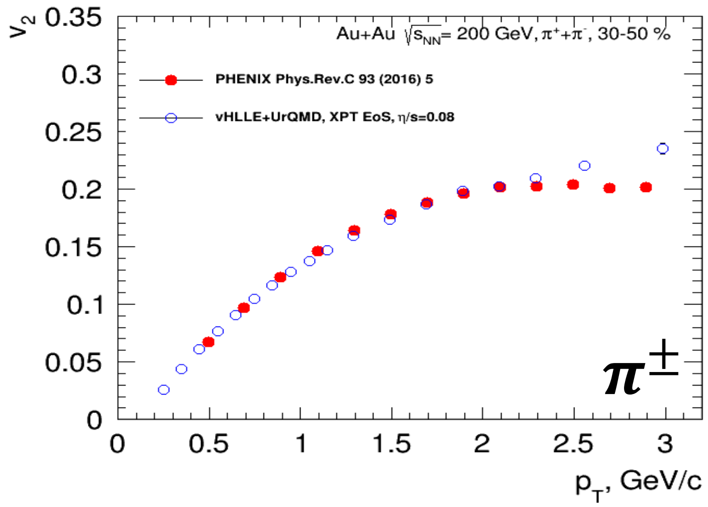
UrQMD + 3D viscous hydro model vHLLE+UrQMD

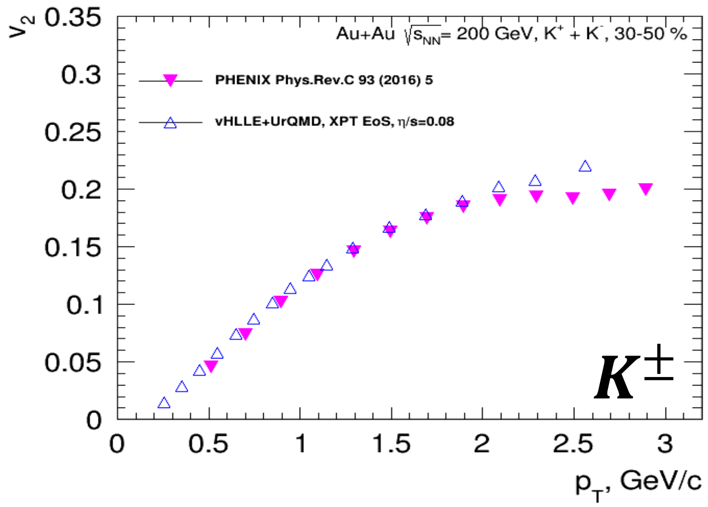
Iurii Karpenko, Comput. Phys. Commun. 185 (2014), 3016
https://github.com/yukarpenko/vhlle
Parameters: from Iu. A. Karpenko, P. Huovinen, H. Petersen, M. Bleicher, Phys. Rev. C91 (2015) no.6, 064901 – good description of STAR BES results for v_2 of inclusive charged hadrons (7.7-62.4 GeV)

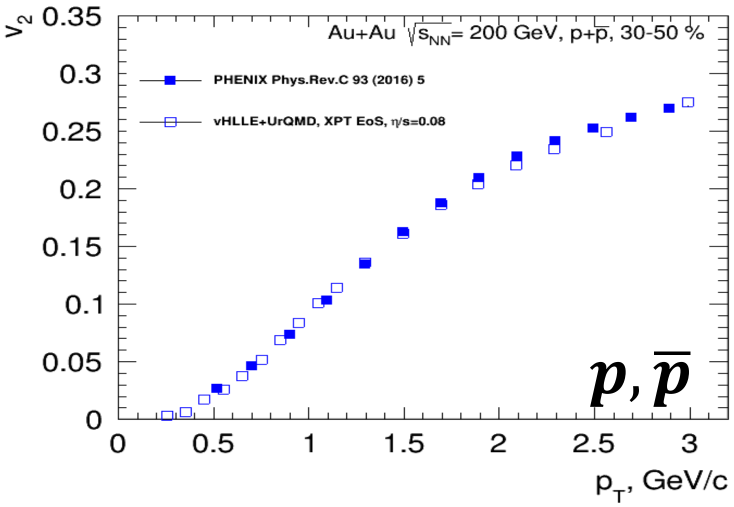
Initial conditions: model UrQMD
QGP phase: 3D viscous hydro (vHLLE) with crossover EOS (XPT)
Hadronic phase: model UrQMD

Z.W. Lin, C. M. Ko, B.A. Li, B. Zhang and S. Pal: Physical Review C 72, 064901 (2005).



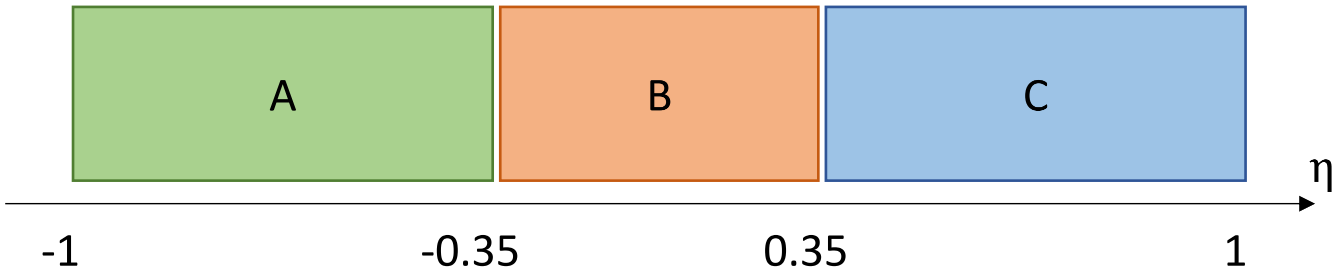






Analysis method

- A + C: v_n^2 measurements
- B: $[p_T]$ measurements



Covariance is calculated using 3 subevents:

$$cov(v_n^2, [p_T]) = \left\langle \frac{1}{N_A N_C} \sum_{A,C} e^{in(\varphi_a - \varphi_c)} \left([p_{T,b}] - \langle [p_T] \rangle \right) \right\rangle$$

Dynamical variance of v_n^2:

$$Var(v_n^2)_{dyn} = v_n\{2\}^4 - v_n\{4\}^4 = C_2^2\{2\} - C_2\{4\},$$

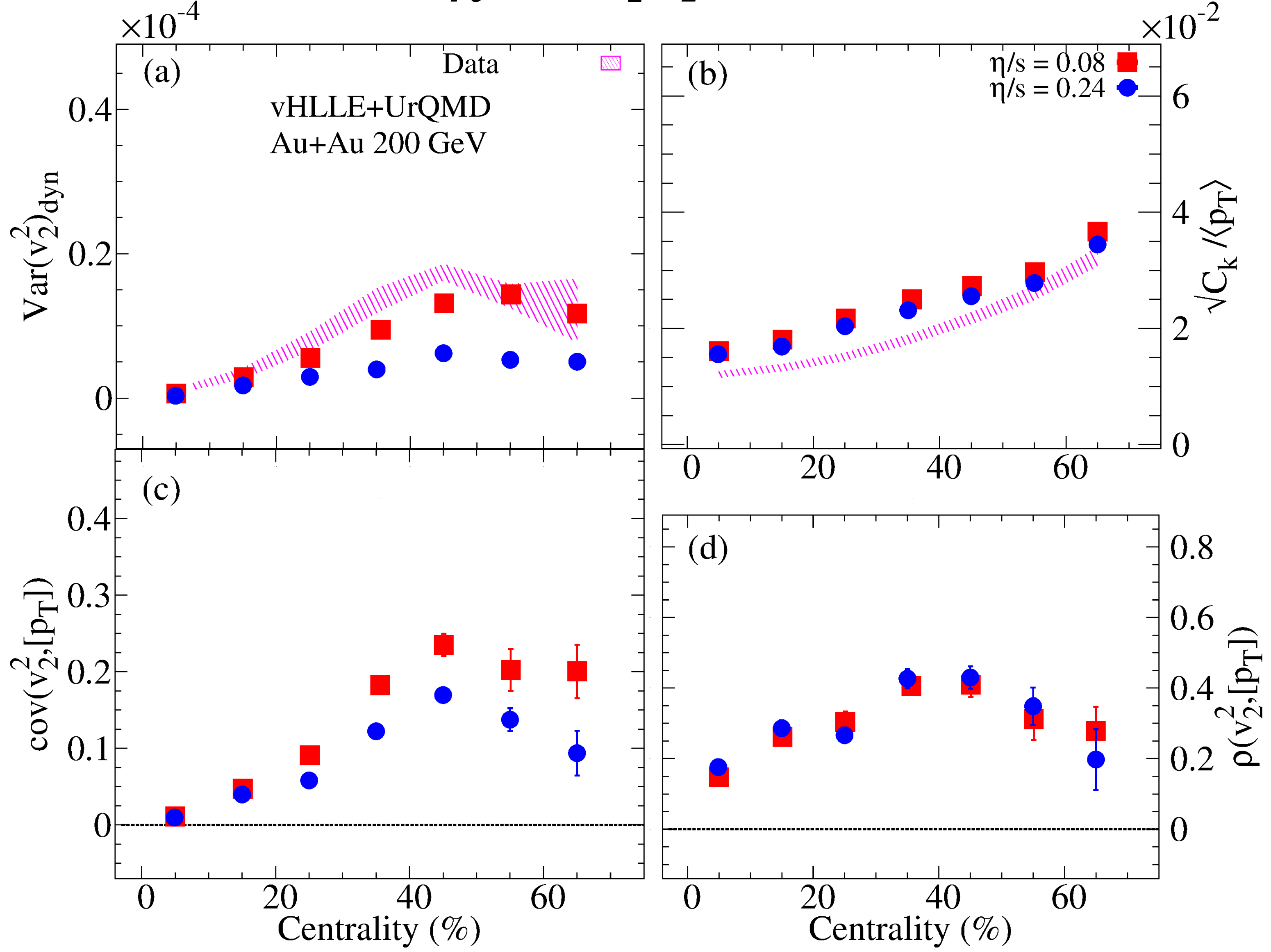
$$C_2^2\{2\} = \langle\langle 2 \rangle\rangle\Big|_{A,C} = \left\langle\left\langle e^{2i(\varphi_1^A - \varphi_2^C)} \right\rangle\right\rangle, C_2^2\{4\} = \langle\langle 4 \rangle\rangle\Big|_{A,C} - 2\,\langle\langle 2 \rangle\rangle^2\Big|_{A,C},$$

$$\langle\langle 4 \rangle\rangle\Big|_{A,C} = \left\langle\left\langle e^{2i(\varphi_1^A + \varphi_2^A - \varphi_3^C - \varphi_4^C)} \right\rangle\right\rangle$$

Variance of the mean transverse momentum:

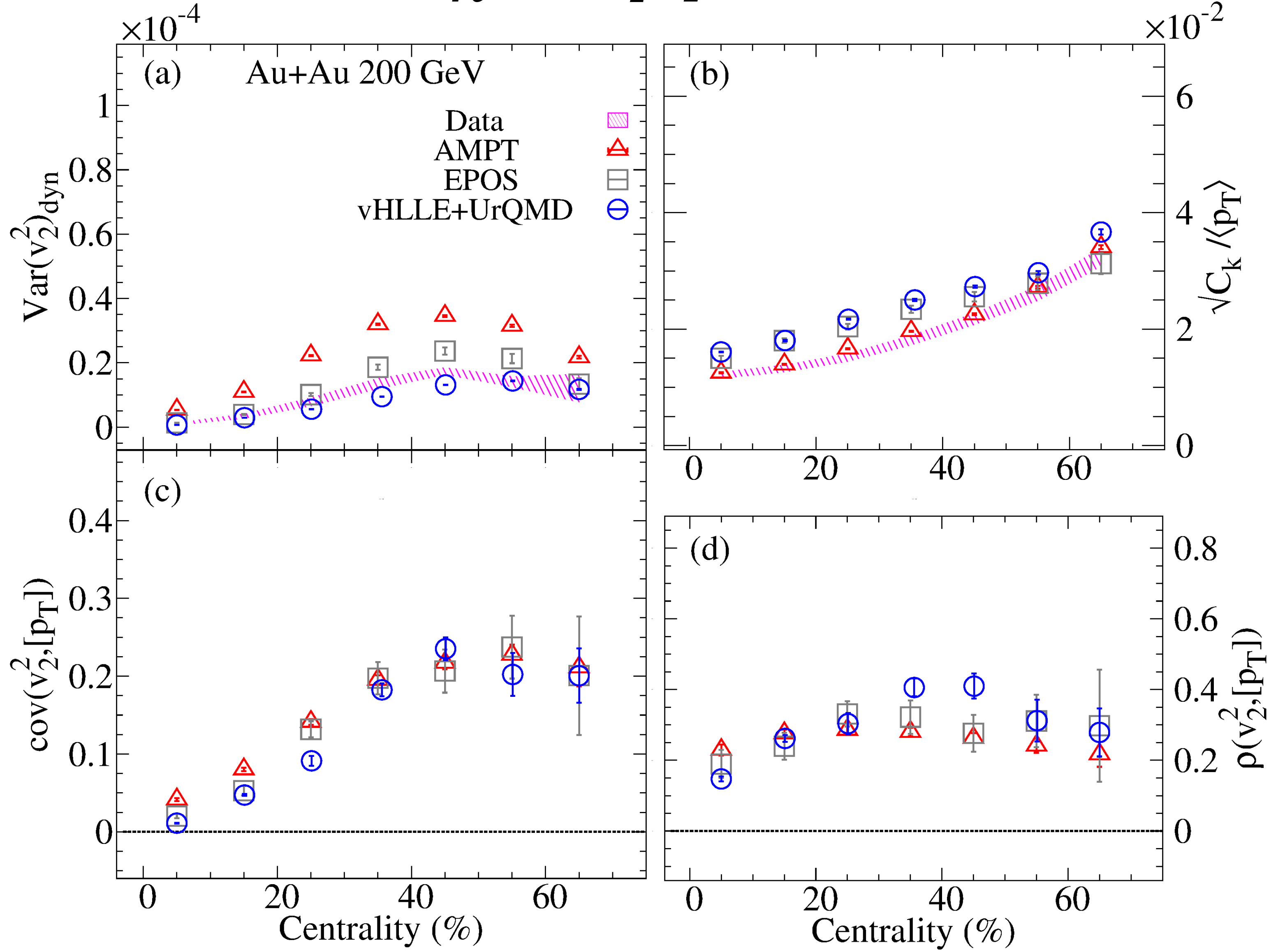
$$c_k = \left\langle \frac{1}{N_B(N_B - 1)} \sum_{b \neq b'} \left(p_{T,b} - \langle [p_T] \rangle \right)\left(p_{T,b'} - \langle [p_T] \rangle \right) \right\rangle, [p_T] = \frac{1}{N_B} \sum_b p_T, b$$

Results: $v_n - [p_T]$ correlation for different η/s



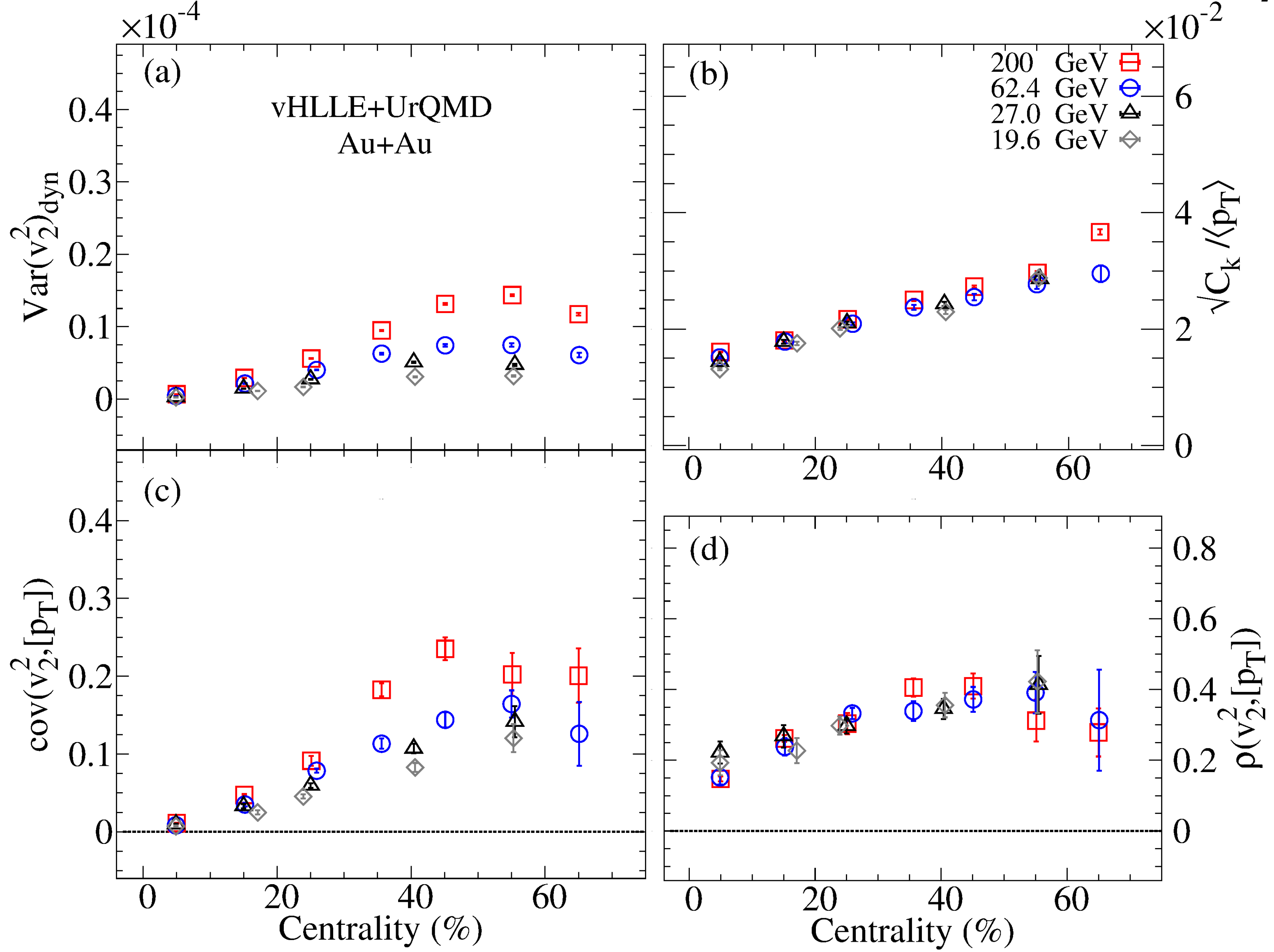
- $Var(v_n^2)_{dyn}$ and $cov(v_n^2,[p_T])$decrease with increasing values of η/s
- $\sqrt{c_k}/\langle p_T\rangle$ and $\rho(v_n^2,[p_T])$ show weak dependence on η/s

Results: $v_n - [p_T]$ correlation for different models



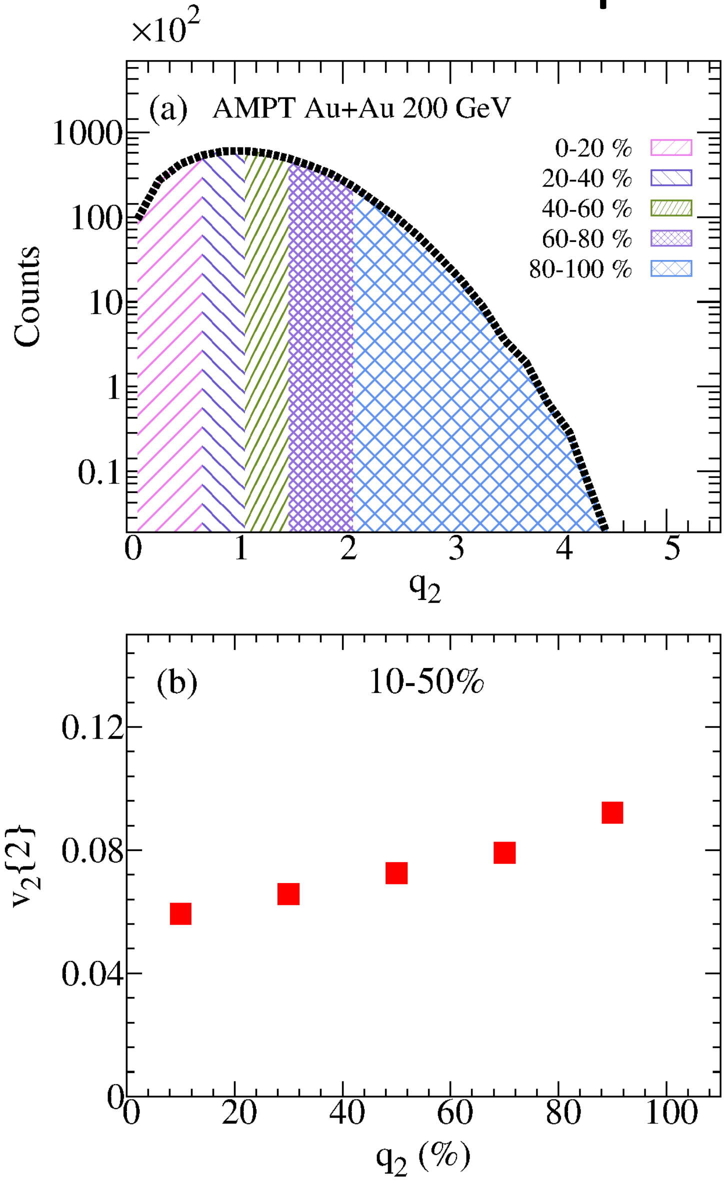
- Good overall agreement between vHLLE+UrQMD, AMPT and EPOS models
- Reasonable agreement with the values estimated from the experimental measurements

Results: energy dependence of $v_n - [p_T]$ correlation



- $Var(v_n^2)_{dyn}$ and $cov(v_n^2, [p_T])$ increase with increasing beam energy $\sqrt{s_{NN}}$
- $\sqrt{c_k}/\langle p_T\rangle$ and $\rho(v_n^2, [p_T])$ show weak dependence on $\sqrt{s_{NN}}$

Event shape engineering (ESE)



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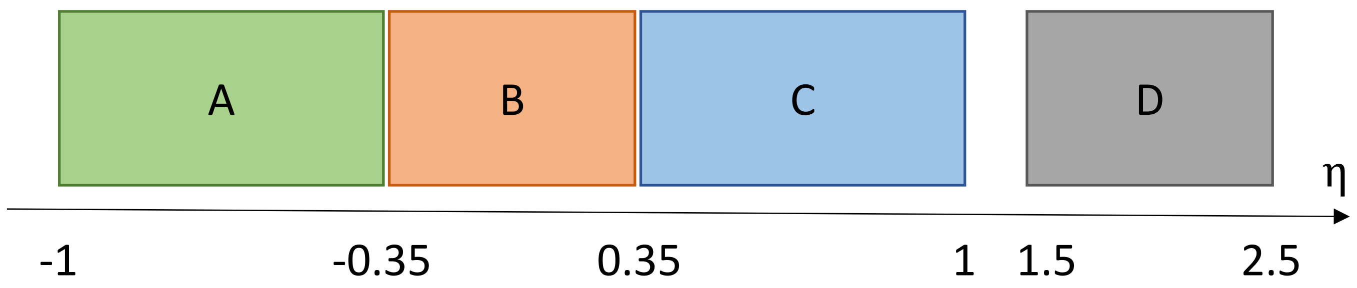
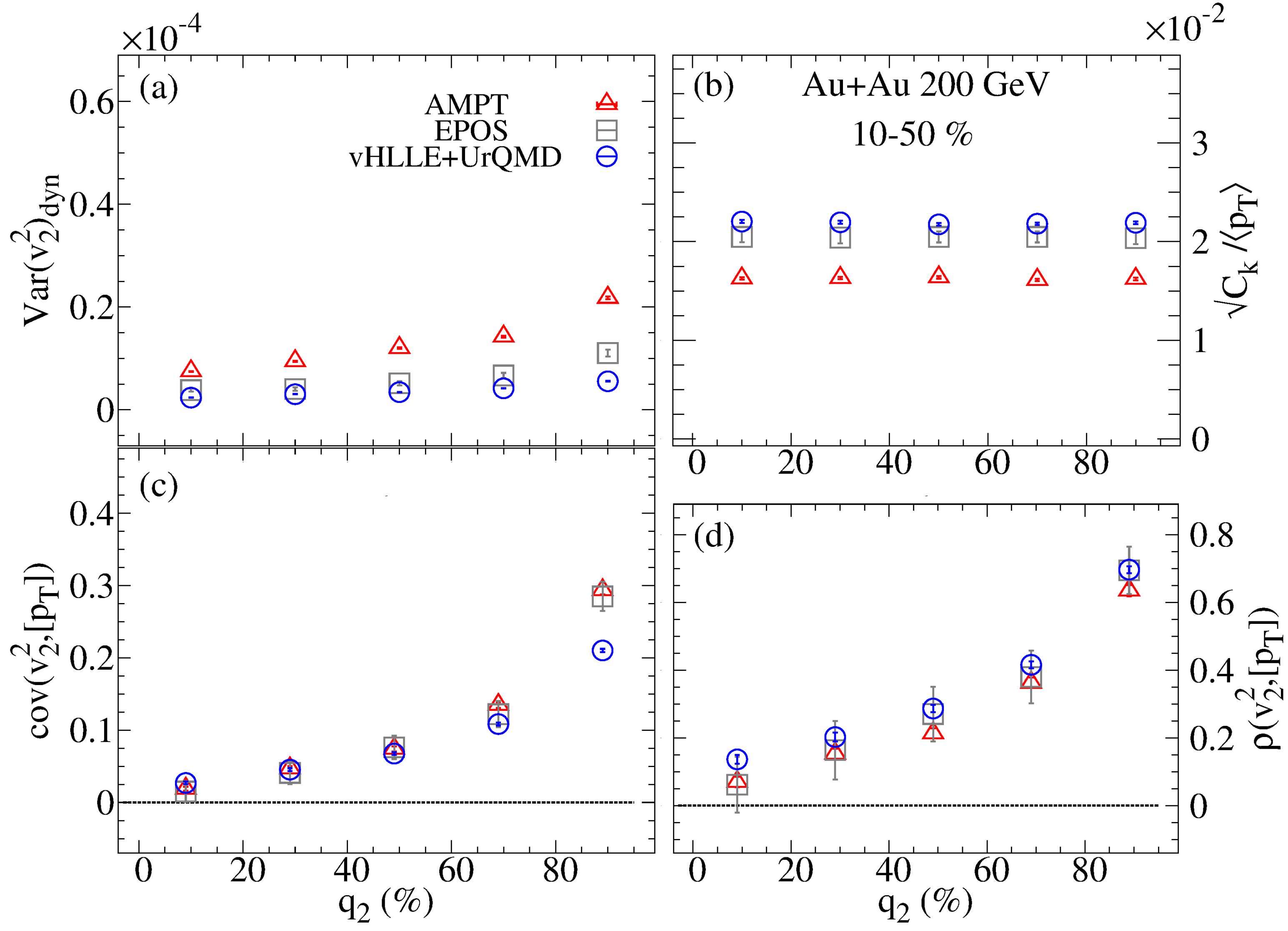


- Au+Au events with different initial-state configurations are selected using reduced flow vector for a given centrality 10-50%:

$$q_2 = \frac{\sqrt{Q_{2,x}^2 + Q_{2,y}^2}}{\sqrt{N_D}}, \qquad Q_{2,x} = \sum_D \cos(2\varphi_d) \quad Q_{2,y} = \sum_D \sin(2\varphi_d)$$

- q_2 was measured in the subevent D $(1.5 < \eta < 2.5)$

Results: q_2-dependence of $v_n - [p_T]$ correlation



- Similar results of q_2-dependence for all models
- $\sqrt{c_k}/\langle p_T\rangle$ show weak q_2 dependence
- $cov(v_n^2,[p_T])$ and $\rho(v_n^2,[p_T])$ increase with increasing q_2

Summary

The model predictions for the $\rho(v_n^2,[p_T])$, $cov(v_n^2,[p_T])$, $\sqrt{c_k}/\langle p_T\rangle$, $Var(v_n^2)_{dyn}$ in Au+Au collisions at $\sqrt{s_{NN}}$=19.6-200 GeV were investigated using vHLLE+UrQMD hybrid model

Sensitivity of $v_n - [p_T]$ correlation to η/s:

- $Var(v_n^2)_{dyn}$ and $cov(v_n^2,[p_T])$ decrease with increasing values of η/s
- $\sqrt{c_k}/\langle p_T\rangle$ and $\rho(v_n^2,[p_T])$ show weak dependence on η/s

Comparison of the results from vHLLE+UrQMD with AMPT and EPOS models:

- Good overall agreement between vHLLE+UrQMD, AMPT and EPOS models
- Reasonable agreement with the values estimated from the experimental measurements

Beam-energy dependence of $v_n - [p_T]$ correlation:

- $Var(v_n^2)_{dyn}$ and $cov(v_n^2,[p_T])$ increase with increasing beam energy $\sqrt{s_{NN}}$
- $\sqrt{c_k}/\langle p_T\rangle$ and $\rho(v_n^2,[p_T])$ show weak dependence on $\sqrt{s_{NN}}$

Event-shape dependence of $v_n - [p_T]$ correlation:

- $\sqrt{c_k}/\langle p_T\rangle$ show weak q_2 dependence
- $cov(v_n^2,[p_T])$ and $\rho(v_n^2,[p_T])$ increase with increasing q_2

Outlook

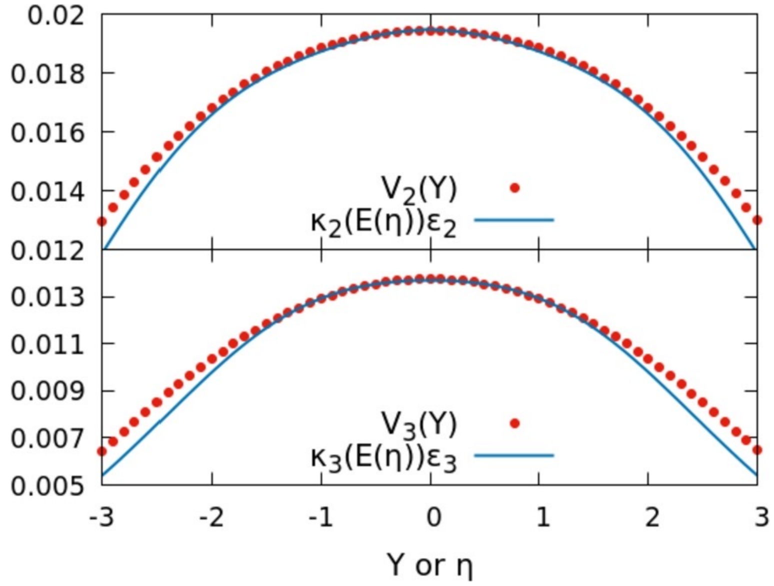
- Investigate beam-energy and event-shape dependence of the $v_3 - [p_T]$ correlation using vHLLE+UrQMD model
- Investigate feasibility of $v_2 - [p_T]$ correlation measurements for lower beam energies where effect of spectators shadowing is prevalent in the development of v_2
- Study sensitivity of $v_2 - [p_T]$ correlation to different equation of states in models within mean-field approach at lower beam energies

Thank you for your attention!

Backup slides

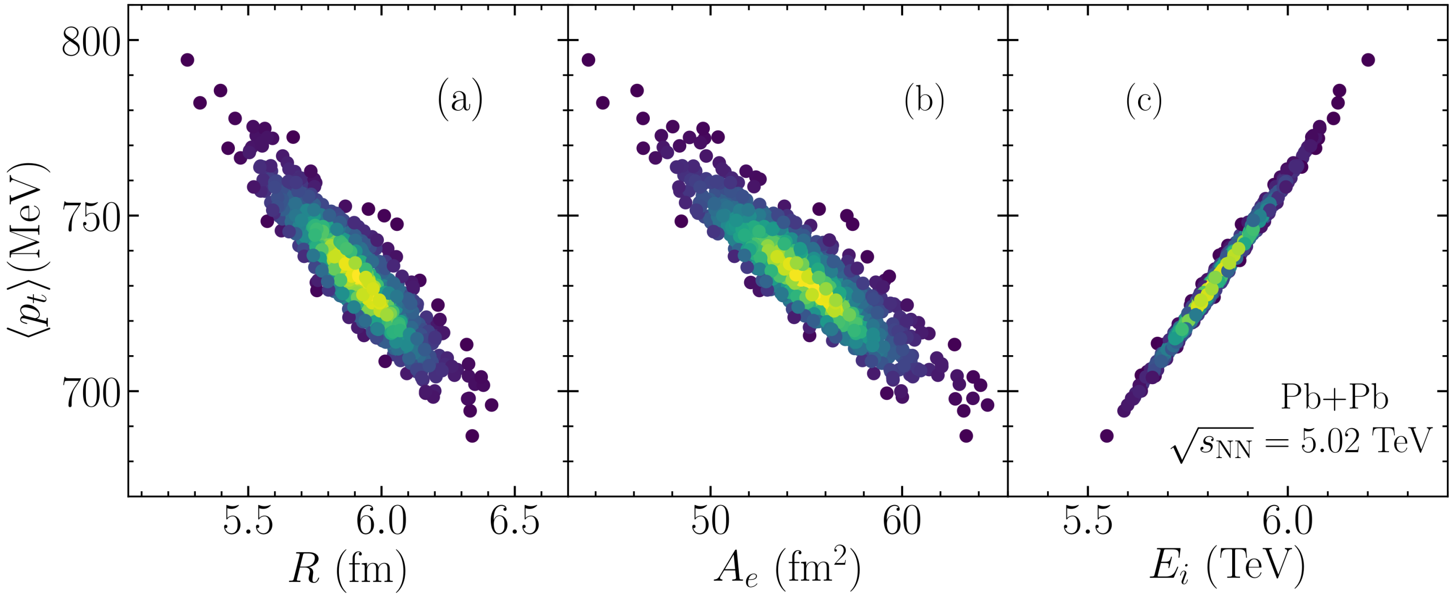
Relations with initial-state variables for v_n and $[p_T]$

- For v_2 and v_3:
  - $v_n = \kappa_n \varepsilon_n$
- For $[p_T]$:
  - $[p_T] \propto R, R^2 = 2\frac{\int (x^2+y^2) s(\tau_0,x,y)dxdy}{\int s(\tau_0,x,y)dxdy}$
  - $[p_T] \propto A_e, A_e = \frac{\pi}{2}R^2\sqrt{1-\varepsilon_2^2}$
  - $[p_T] \propto E_i, E_i = \tau_0 \int \epsilon(\tau_0,x,y)dxdy$



In hydrodynamical approach:

- At fixed total entropy S (i.e. fixed collision centrality) mean transverse momentum $[p_T]$ is determined by the energy of the fluid per unit rapidity E_i at the initial time τ_0
- In more general cases (S is not fixed), $[p_T] \propto E_i/S$



R. Franco, M. Luzum, Phys. Lett. B 806 (2020) 135518
G. Giacalone, et. al., Phys. Rev. C 103 (2021) 2, 024909