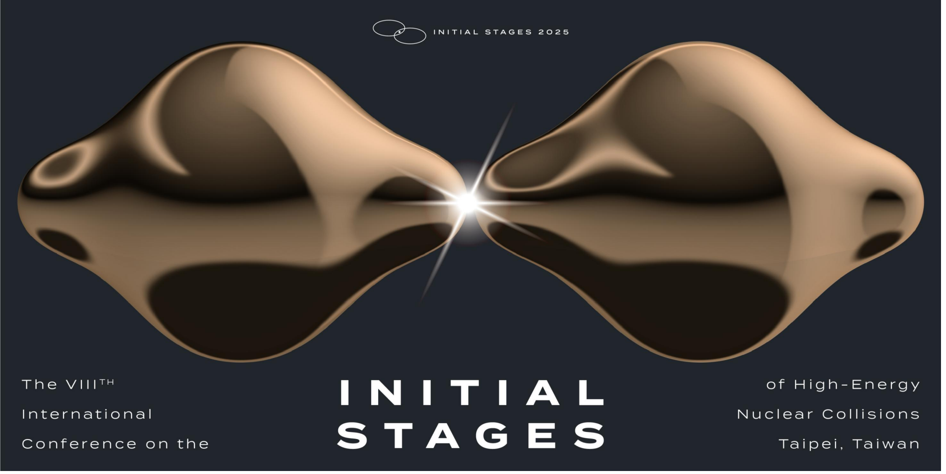


PEKING UNIVERSITY 1898

THE OHIO STATE UNIVERSITY 1870

Probing Collectivity in p+p Collisions with Viscous Anisotropic Hydrodynamics

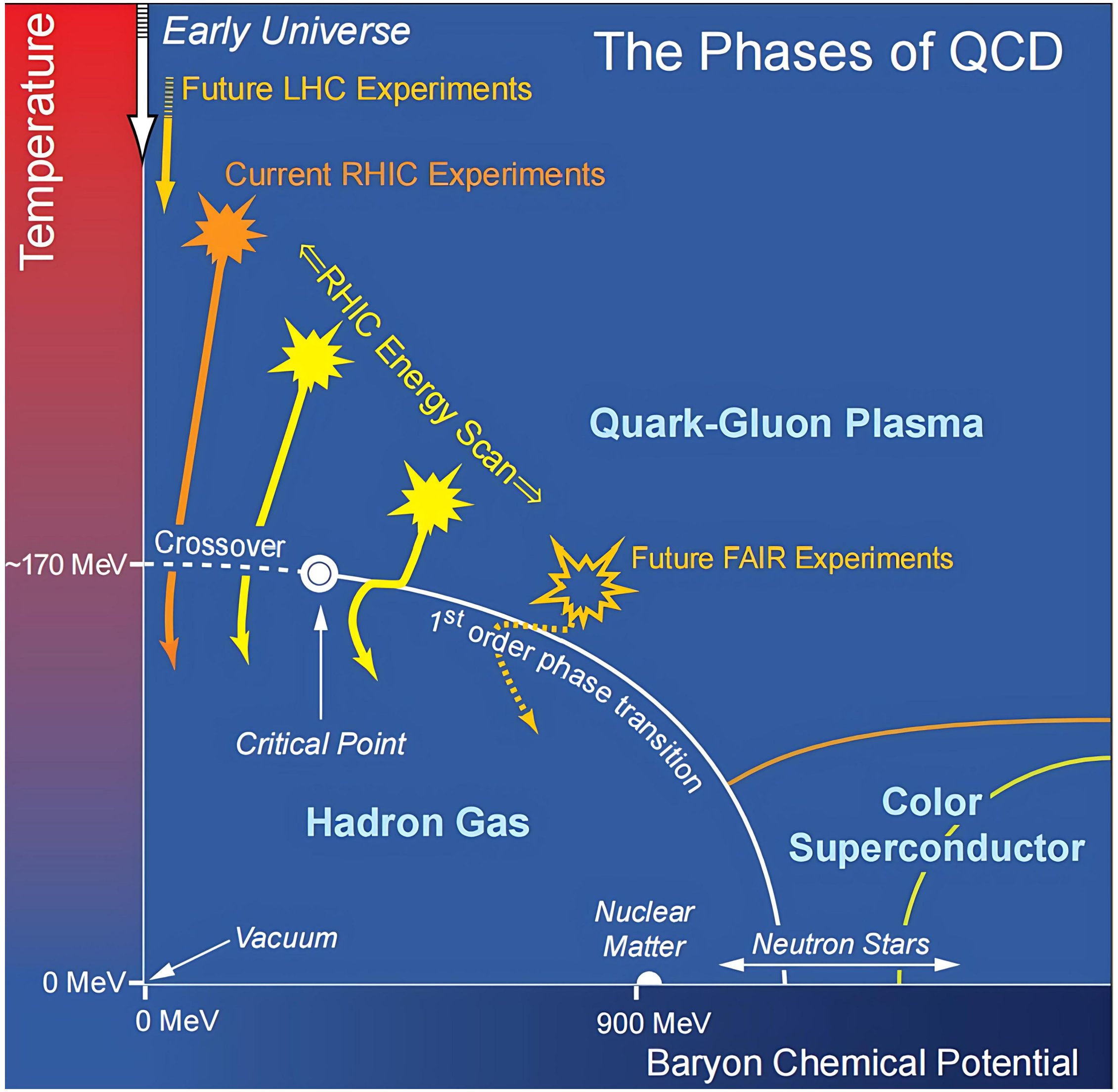
S. J. Zhao(Sophia U.), Y. Y. Peng, U. W. Heinz, H. C. Song

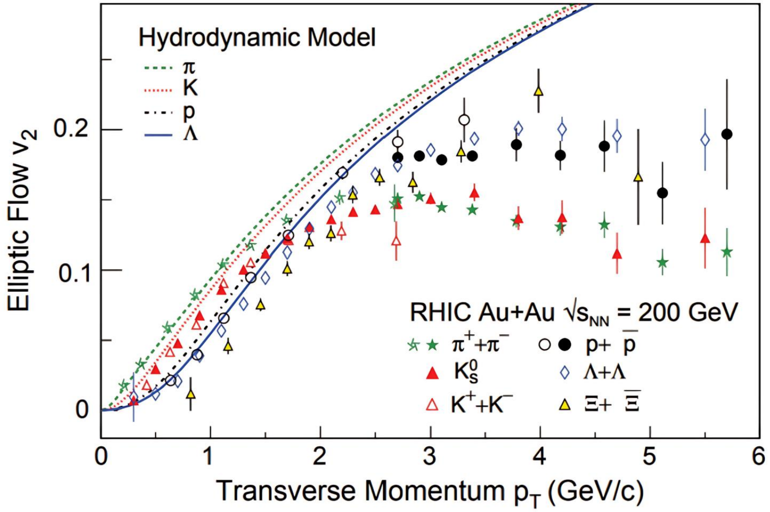
Initial Stage 2025, Taipei, Taiwan

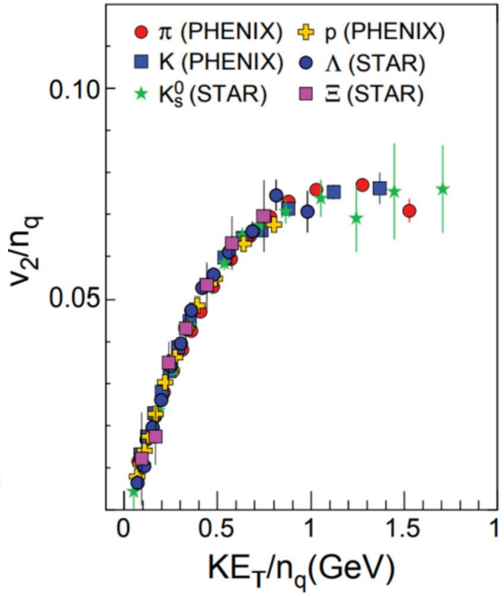
Sept. 7-12, 2025

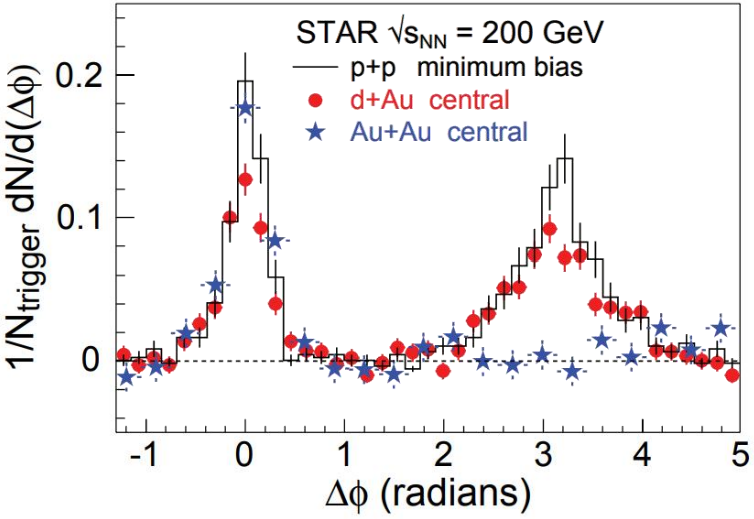
This presentation is supported by Research Fund Program for Early-career Researchers in Sophia University

Relativistic Heavy-Ion Collisions

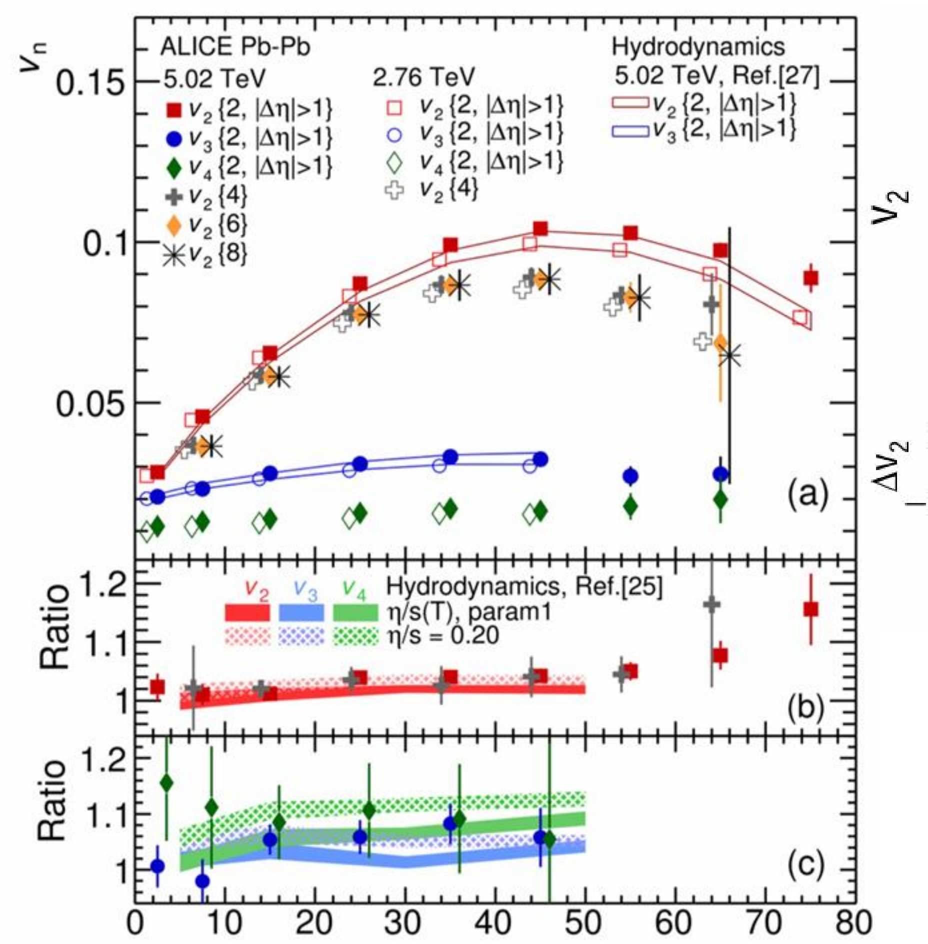




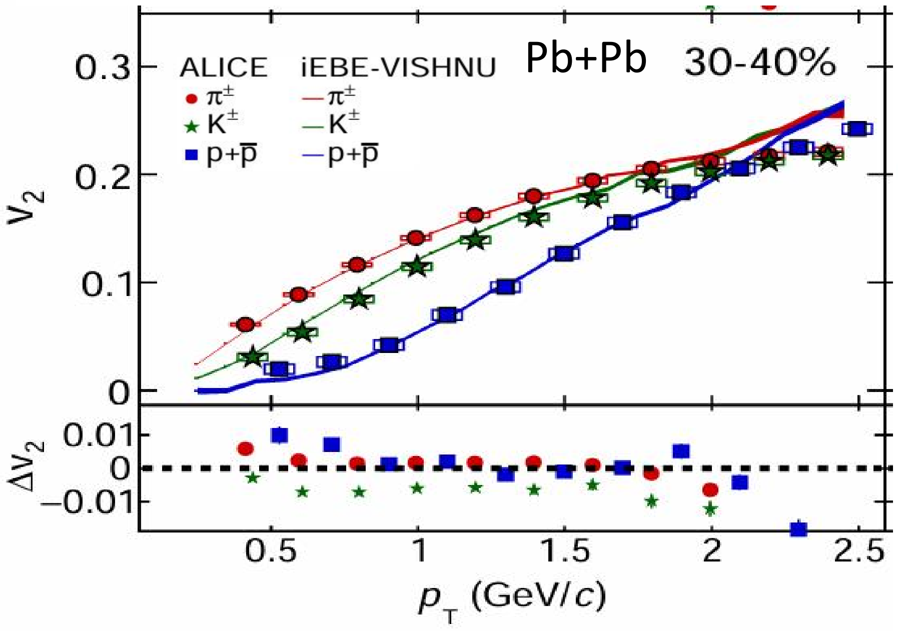




Collectivity in Relativistic Heavy-Ion Collisions

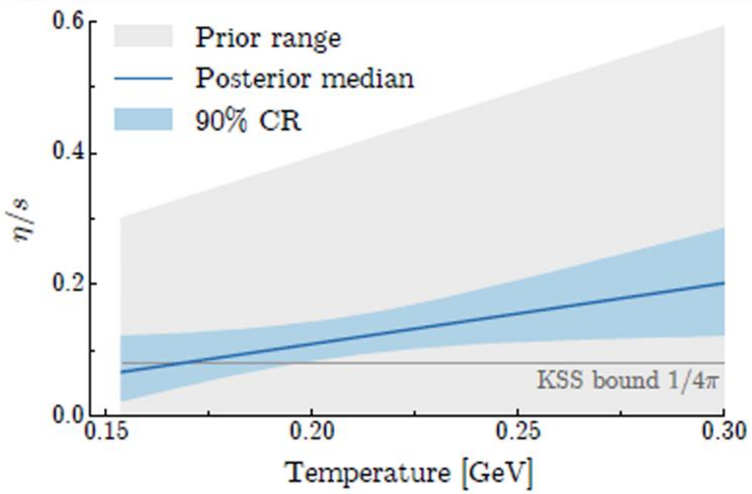


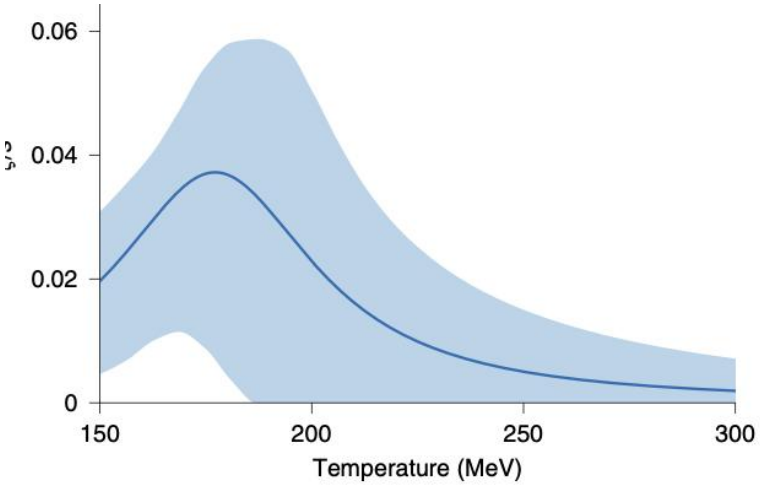
ALICE, Phys. Rev. Lett. 116(2016) 132302



ALICE, JHEP 1609 164 (2016)

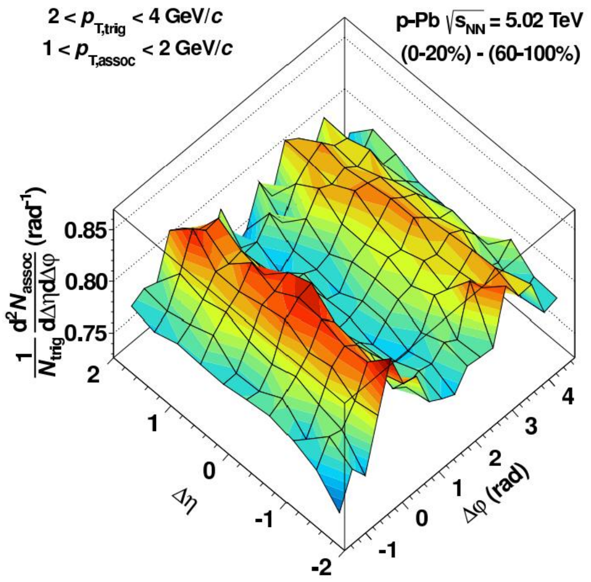
Fluid feature of created QGP medium





J.E. Bernhard, J.S. Moreland, S.A. Bass, Nature Phys. 15 1113 (2016).

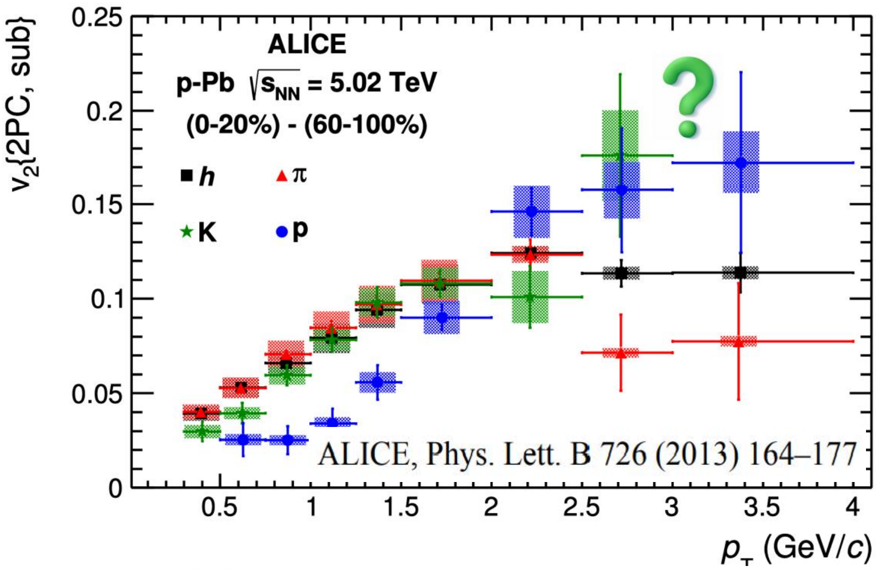
Collectivity in Small Collision Systems?



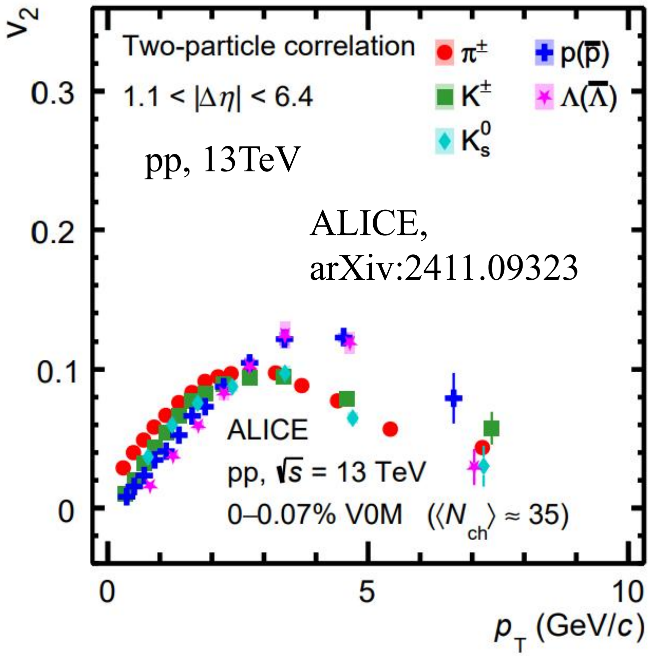
ALICE, Phys.Lett. B719 (2013) 29-41

Origin of ‘Collectivity’?

- ➢ Hydrodynamic response
- ➢ Gluon saturation
- ➢ Escape mechanism
- ➢ Multi parton interaction
- ➢ ...



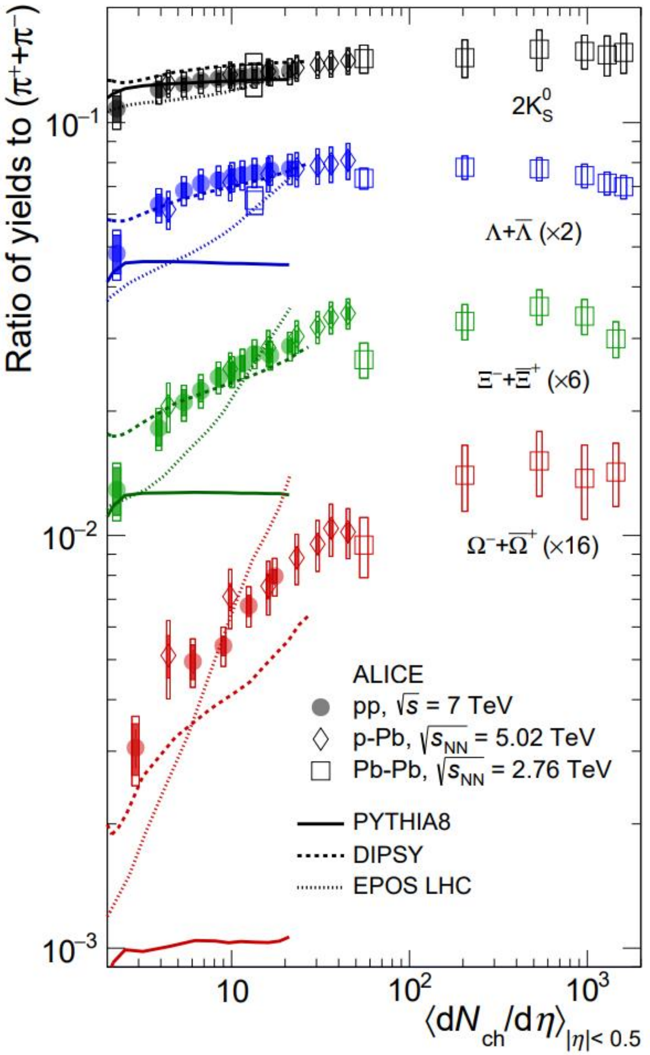
ALICE, Phys. Lett. B 726 (2013) 164–177



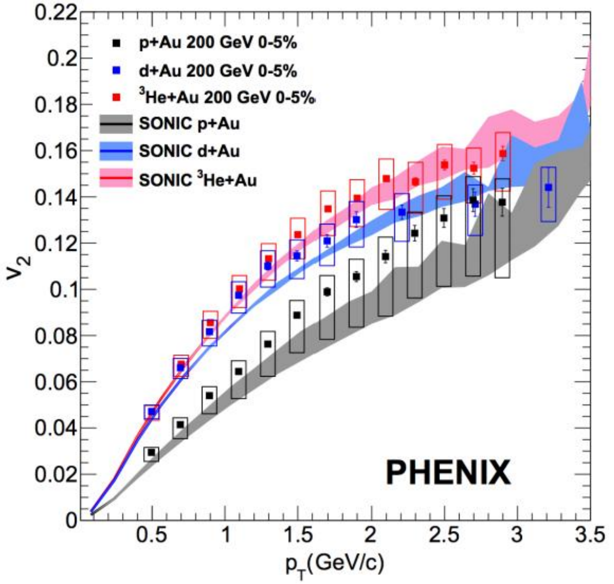
pp, 13TeV

ALICE, arXiv:2411.09323

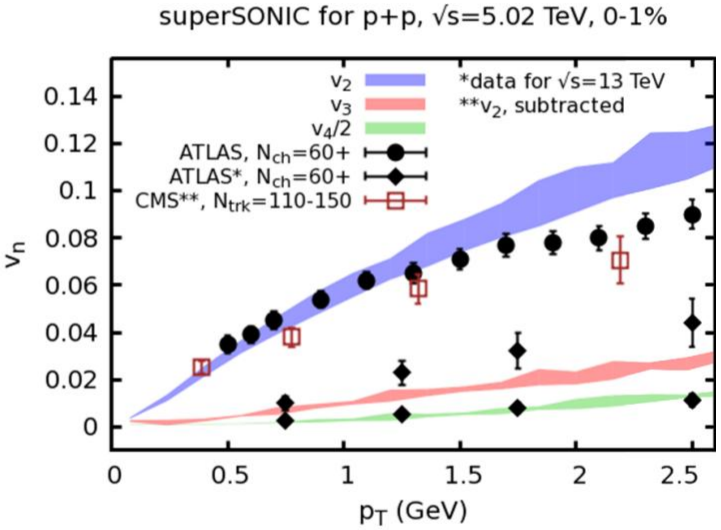
ALICE, Nature Phys. 13 (2017) 535-539



Applying Hydrodynamics in Small Collision Systems



J. Carlson, et. al. Phys. Rev. Lett. 113 (2014) no. 11, 112301,

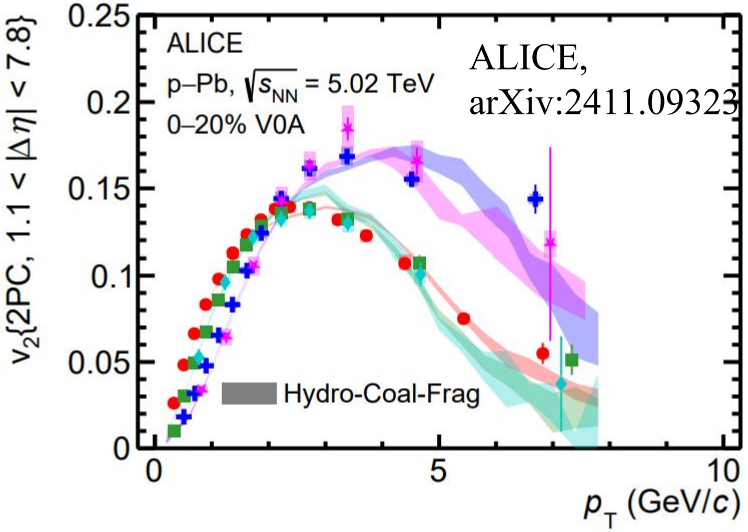


Weller, et. al. Phys.Lett.B 774 (2017) 351-356

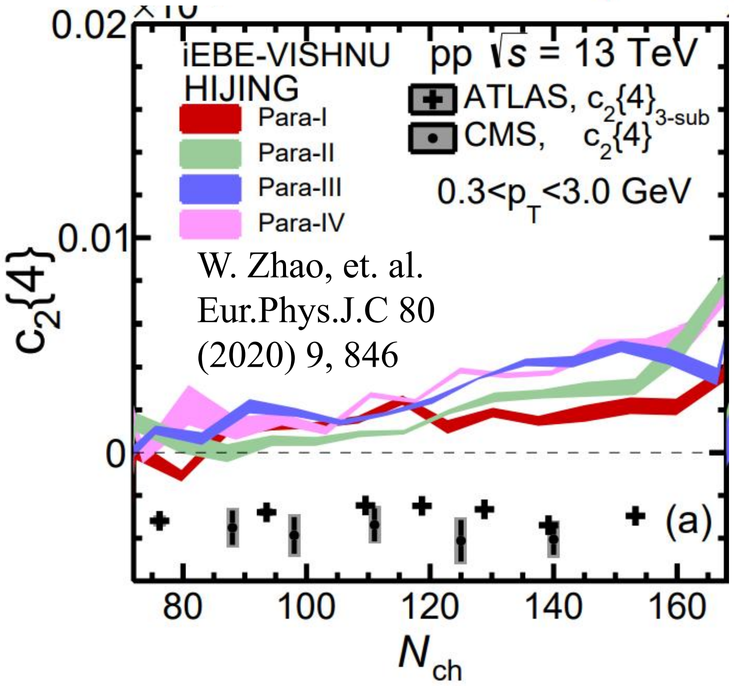
- ➢ Experimental side:
  Non-flow subtrction
  Multiplicity fluctuations
  Kinetic acceptance
  ...

- ➢ Phenomenological side:
  Subnuclonic structure
  Early stage dynamics
  Hybrid approach
  ...

Hydro partially works and debet remains

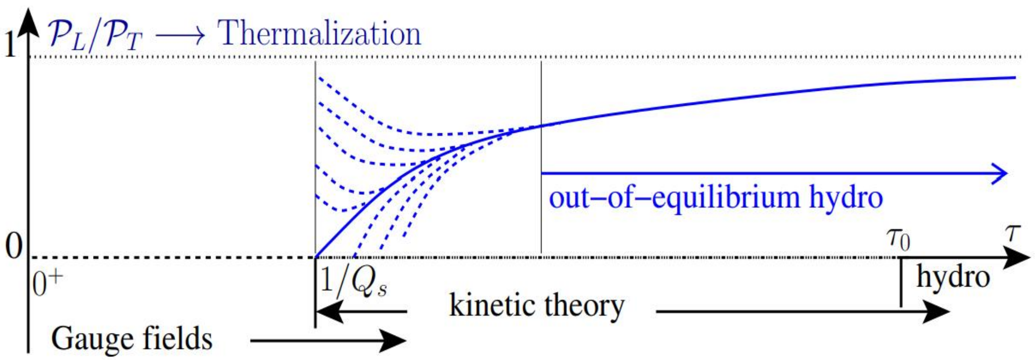


ALICE, arXiv:2411.09323



W. Zhao, et. al. Eur.Phys.J.C 80 (2020) 9, 846

Validaty of Hydrodynamics?



- ➢ Large Deviations from Equilibrium

Initial anisotropic expansion

Small system size

Large shear viscous correction

…

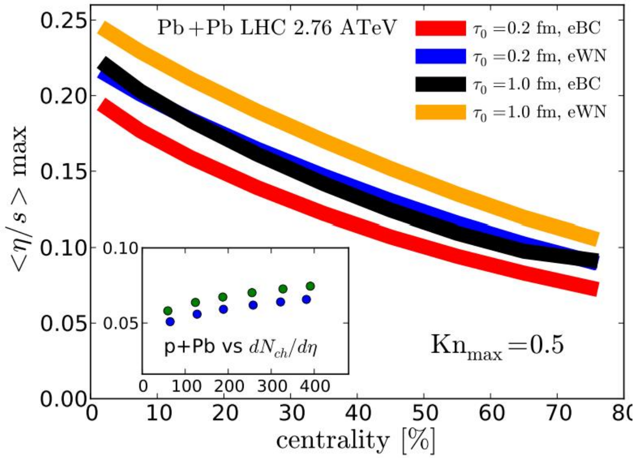
- ➢ Extending the Applicability of Hydro

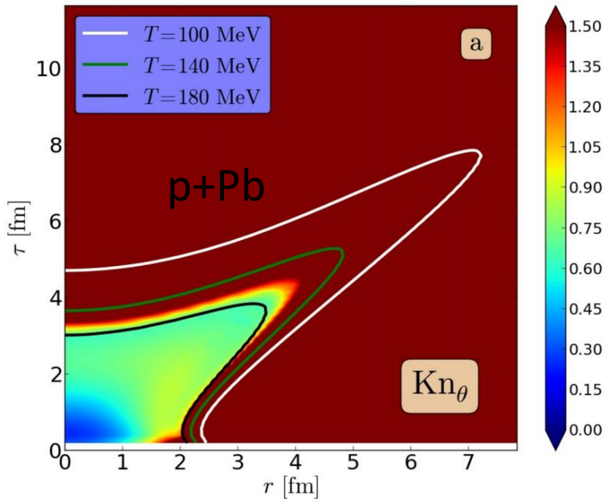
Attractor behavior

Anisotropic hydrodynamics

Resummed hydrodynamics

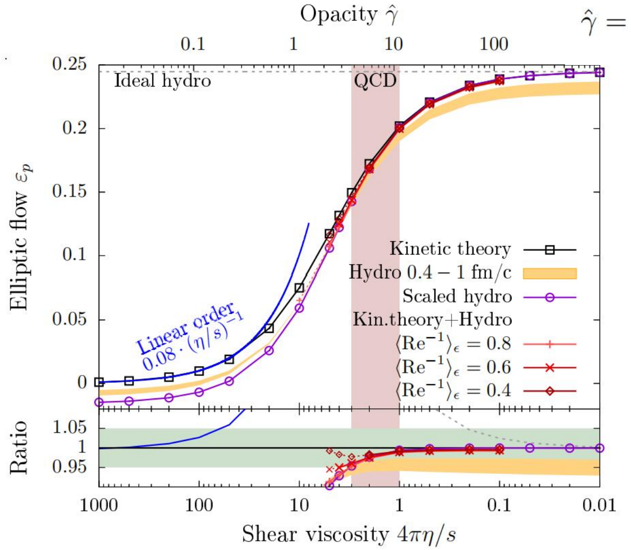
…

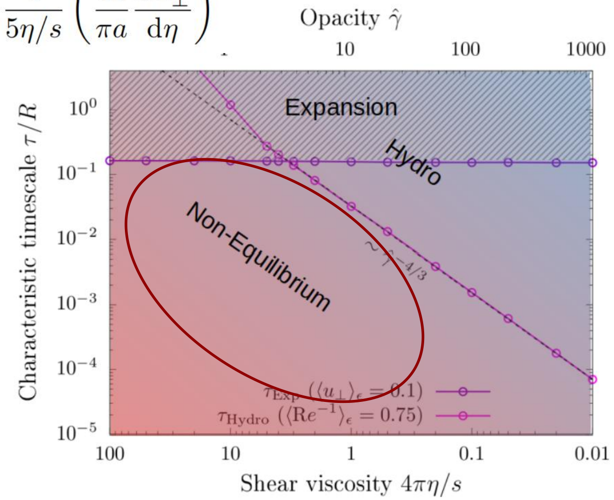




H. Niemi, et. al. arXiv: 1404.7327

$$\hat{\gamma} = \frac{1}{5\eta/s}\left(\frac{R}{\pi a}\frac{\mathrm{d}E_\perp^0}{\mathrm{d}\eta}\right)^{1/4}$$





V. E. Ambrus, et. al. Phys.Rev.Lett. 130 (2023) 15, 152301

Viscous Anisotropic Hydrodynamics (VAH)

- Traditional hydro: $T^{\mu\nu} = \mathcal{E}u^\mu u^\nu - (\mathcal{P}+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu},$
- Redecomposition of $T^{\mu\nu}$:

$$T^{\mu\nu} = \mathcal{E}u^\mu u^\nu \boxed{+ \mathcal{P}_L z^\mu z^\nu - \mathcal{P}_T \Xi^{\mu\nu}} + 2W^{(\mu}_{\perp z} z^{\nu)} + \pi^{\mu\nu}_{\perp}$$

- Redecomposition of viscous terms

$$\pi^{\mu\nu} = \frac{1}{3}(\mathcal{P}_L - \mathcal{P}_T)(2z^\mu z^\nu + \Xi^{\mu\nu}) + 2W^{(\mu}_{\perp z} z^{\nu)} + \pi^{\mu\nu}_{\perp}$$

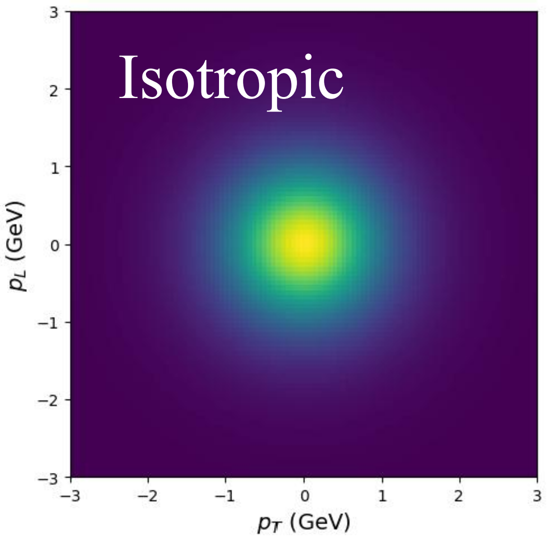
$$\Pi = \frac{1}{3}(\mathcal{P}_L + 2\mathcal{P}_T) - \mathcal{P}_{\mathrm{eq}}$$

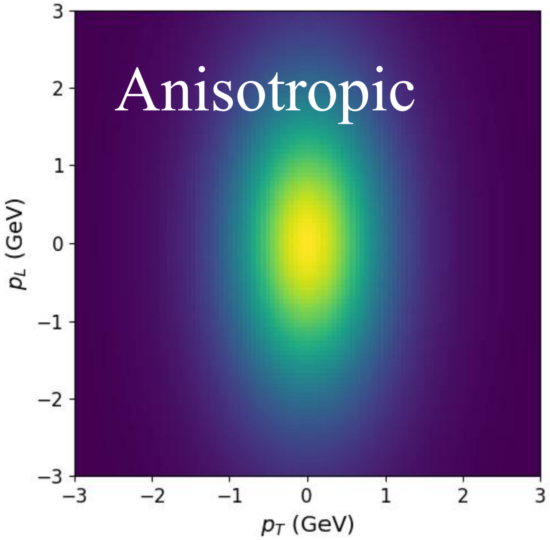
- Anisotropic particle distribution:

$$f_a(x,p) = f_{\mathrm{eq}}\left(\frac{\sqrt{\Omega_{\mu\nu}p^\mu p^\nu}}{\Lambda(x)}\right).$$

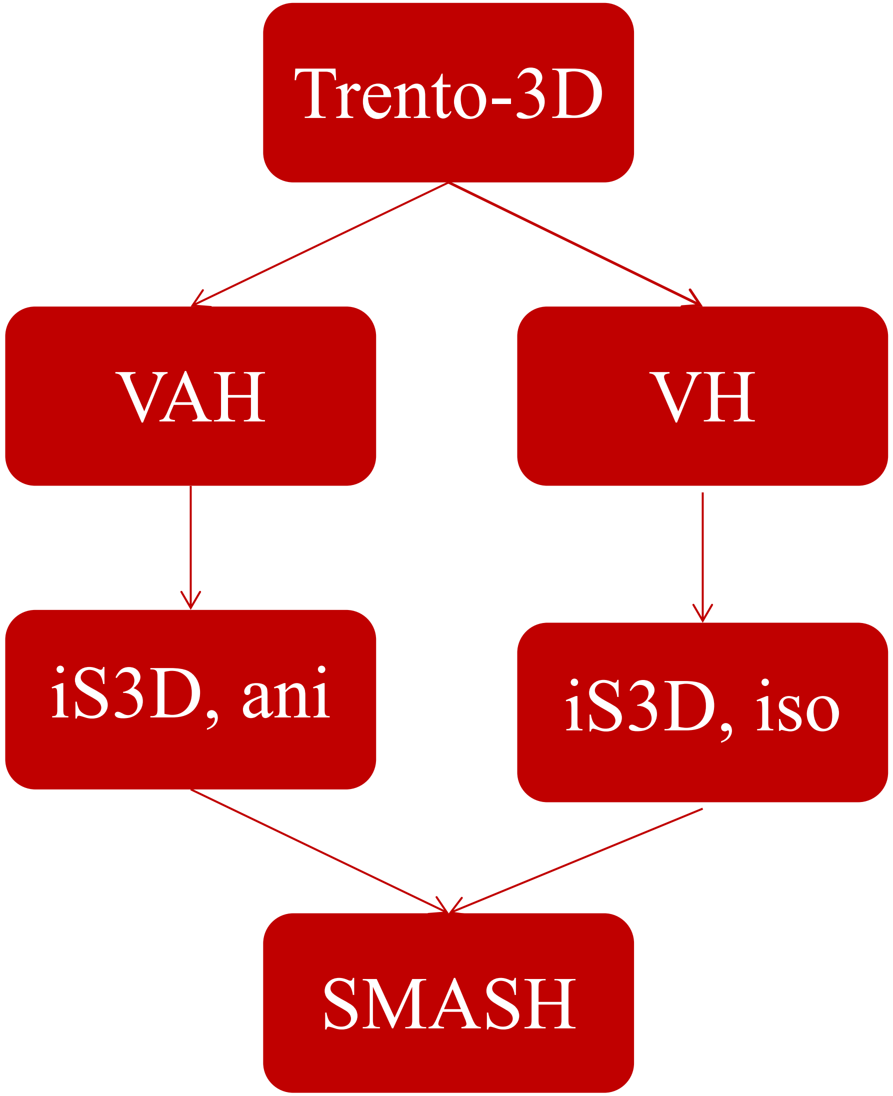
$$\Omega_{\mu\nu}p^\mu p^\nu = m^2 + \frac{p^2_{\perp,\mathrm{LRF}}}{\alpha^2_\perp} + \frac{p^2_{z,\mathrm{LRF}}}{\alpha^2_L}.$$

$(\Lambda, \alpha_L, \alpha_\perp)$ determined from the generalized Landau matching condition.





Model Framework



- Initial energy deposition

$$\mathcal{E}_{\mathrm{tot}} = \mathcal{E}_{\mathrm{fb}} + \mathcal{E}_{\mathrm{frag,A}} + \mathcal{E}_{\mathrm{frag,B}}$$

- Hydro evolution

$$T^{\mu\nu} \sim (\mathcal{E}, u^{\mu}, \mathcal{P}, \pi^{\mu\nu}, \Pi)$$

$$T^{\mu\nu} \sim (\mathcal{E}, u^{\mu}, \mathcal{P}_L, \mathcal{P}_T, W^{\mu}_{\perp z}, \pi^{\mu\nu}_{\perp})$$

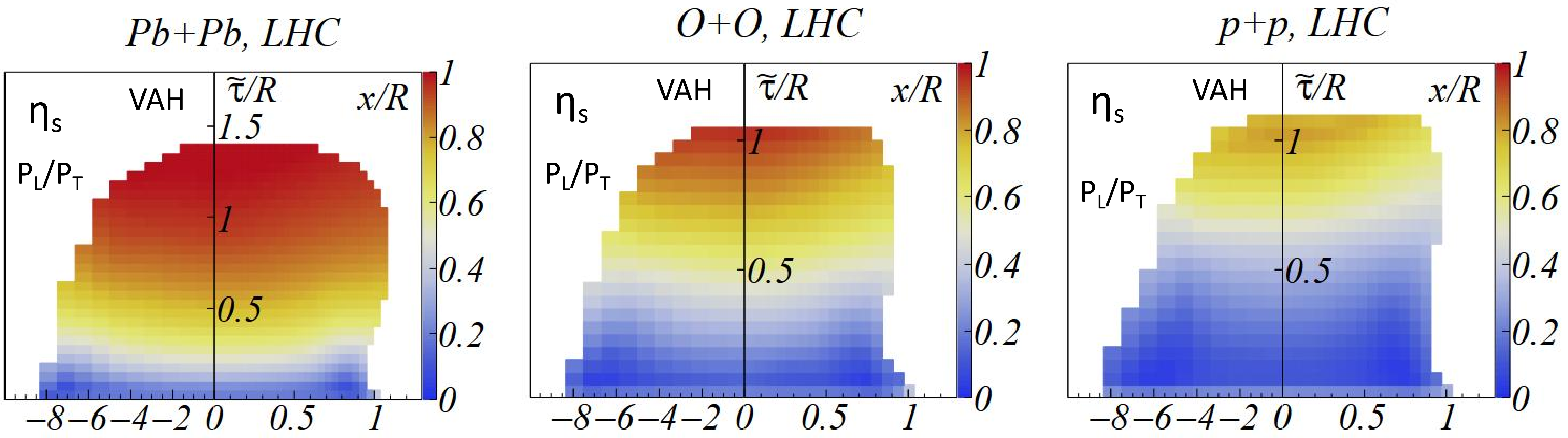
- Particle Sampling

$$E\frac{\mathrm{d}N_i}{\mathrm{d}^3p} = \frac{g_i}{(2\pi^3)}\int_{\Sigma} \mathrm{d}^3\sigma_{\mu}(x)p^{\mu} f_i(x;p),$$

- Hadronic afterburner

$$p^{\mu}\partial_{\mu} f_i(x,p) \; = \; C_i[f]$$

Isotropization in VAH Framework



Strong anisotropic expansion at the early stage.

Heavy-ion collisions: Near-isotropization.

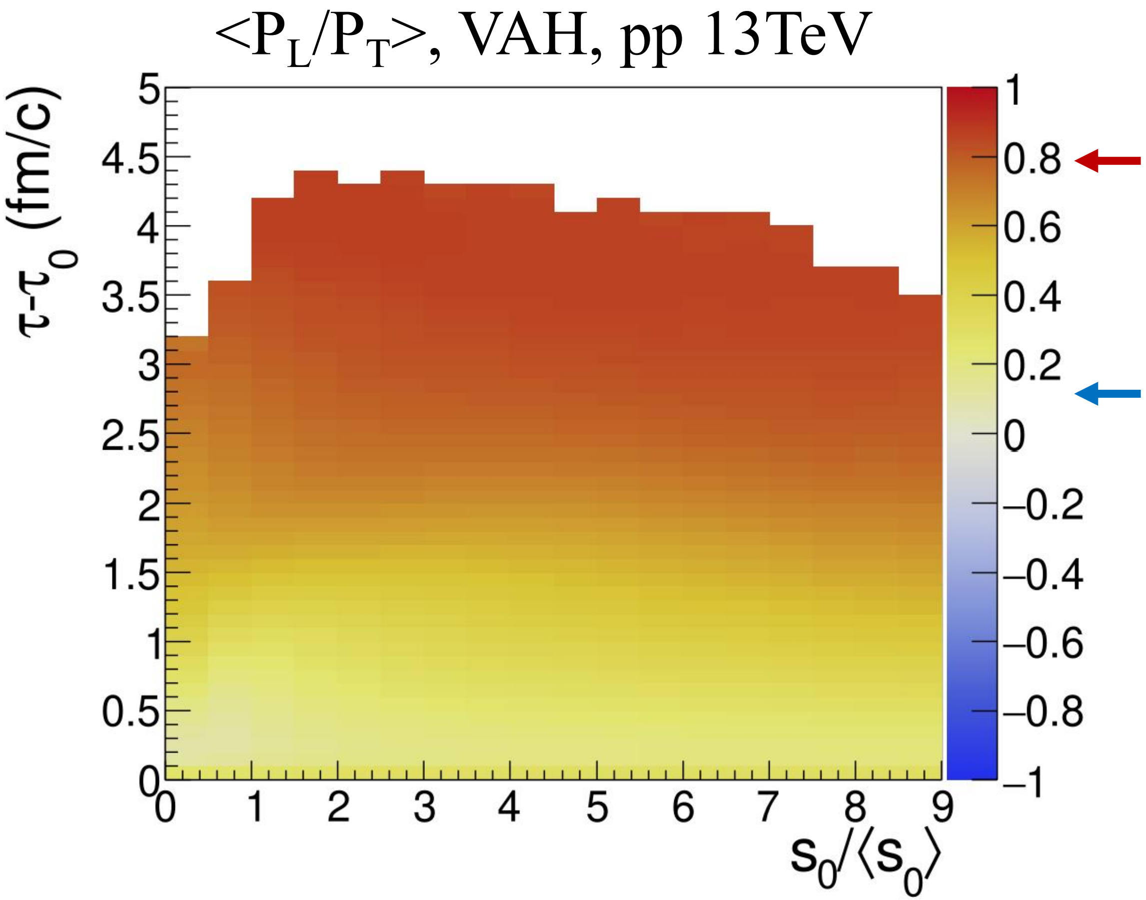
O+O collisions: Critical case.

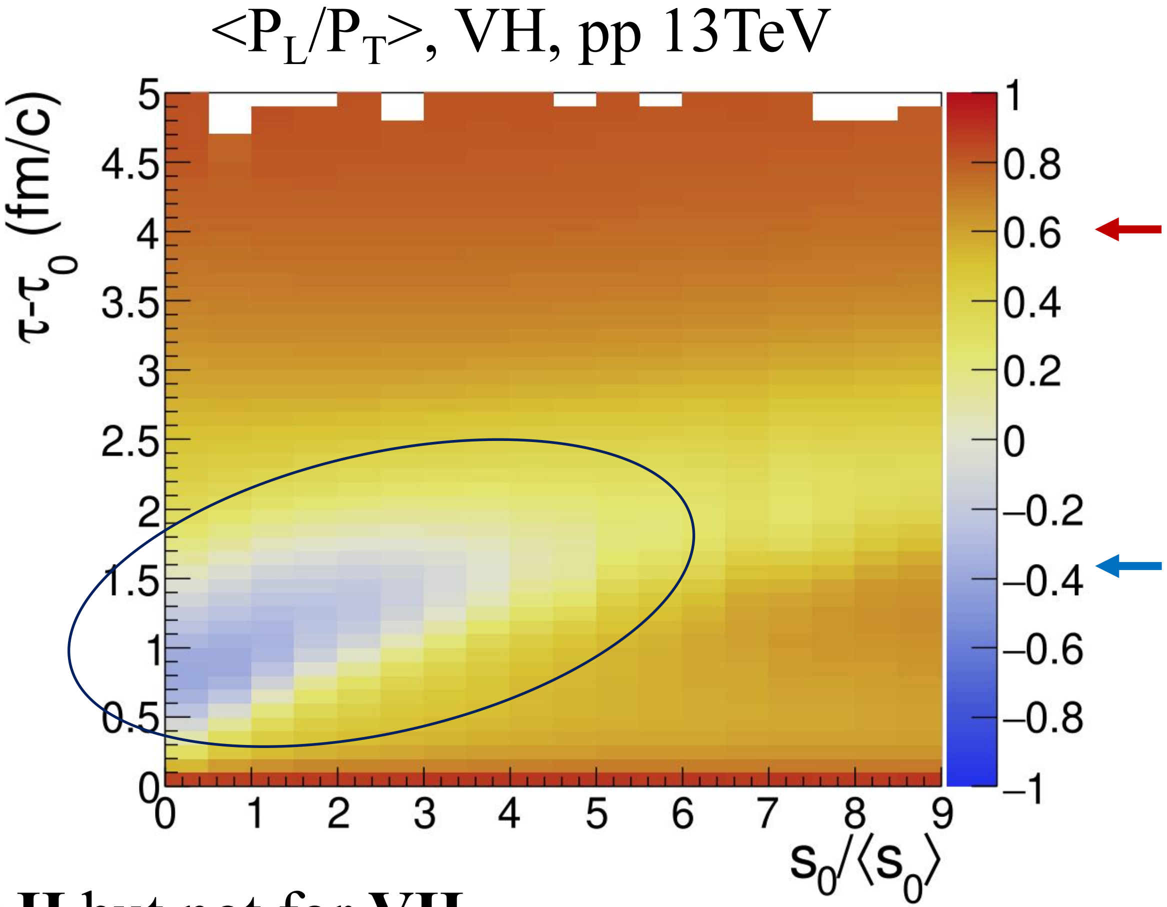
p+p collisions: Remain anisotropic.

Small collision systems as probes of early-stage dynamics

Zhao, Y. Peng, U. Heinz, H. Song. Paper in preparation.

Isotropization in p+p Collisions

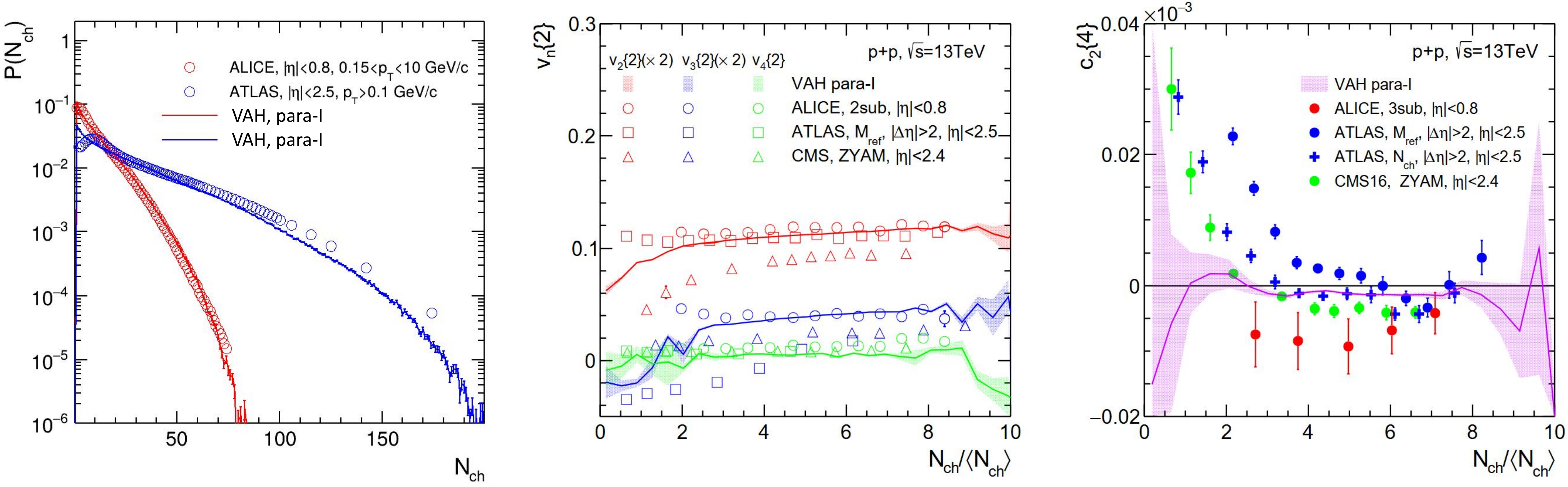

$\langle P_L/P_T \rangle$, VAH, pp 13TeV


$\langle P_L/P_T \rangle$, VH, pp 13TeV

Anisotropic evolution well captured by **VAH** but not for **VH**.
VAH extends reliable description to low-multiplicity systems.

Zhao, Y. Peng, U. Heinz, H. Song. arXiv:2509.03841

VAH Description of p+p Collisions



ALICE, Phys.Lett.B 845 (2023) 138110
ATLAS, Eur.Phys.J.C 76 (2016) 9, 502
ALICE, Phys.Rev.Lett. 123 (2019) 14, 142301
ATLAS, Eur.Phys.J.C 77 (2017) 6, 428
CMS, Phys.Lett.B 765 (2017) 193-220

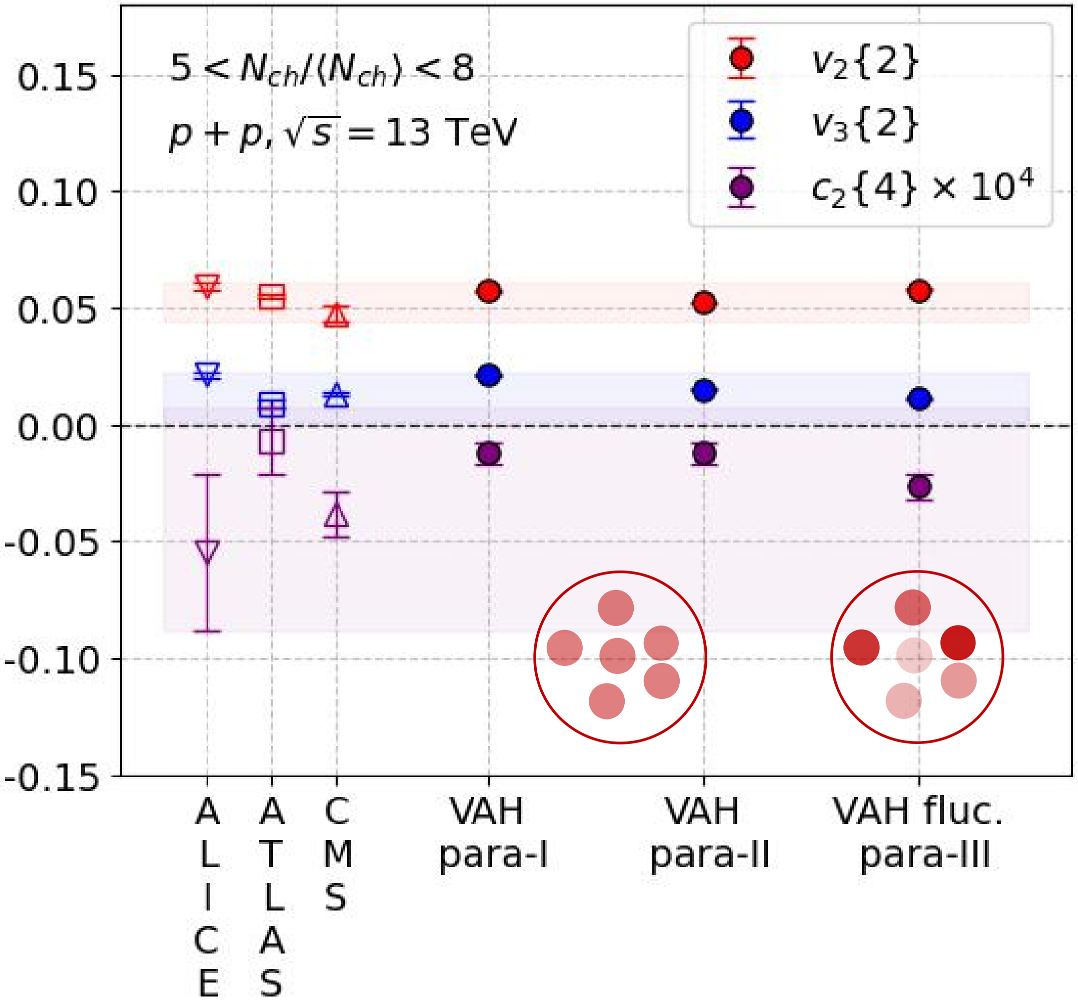
$v_n\{2\}$: Good agreement in high-multiplicity events

$v_2\{4\}$: Correct sign, Qualitative agreement

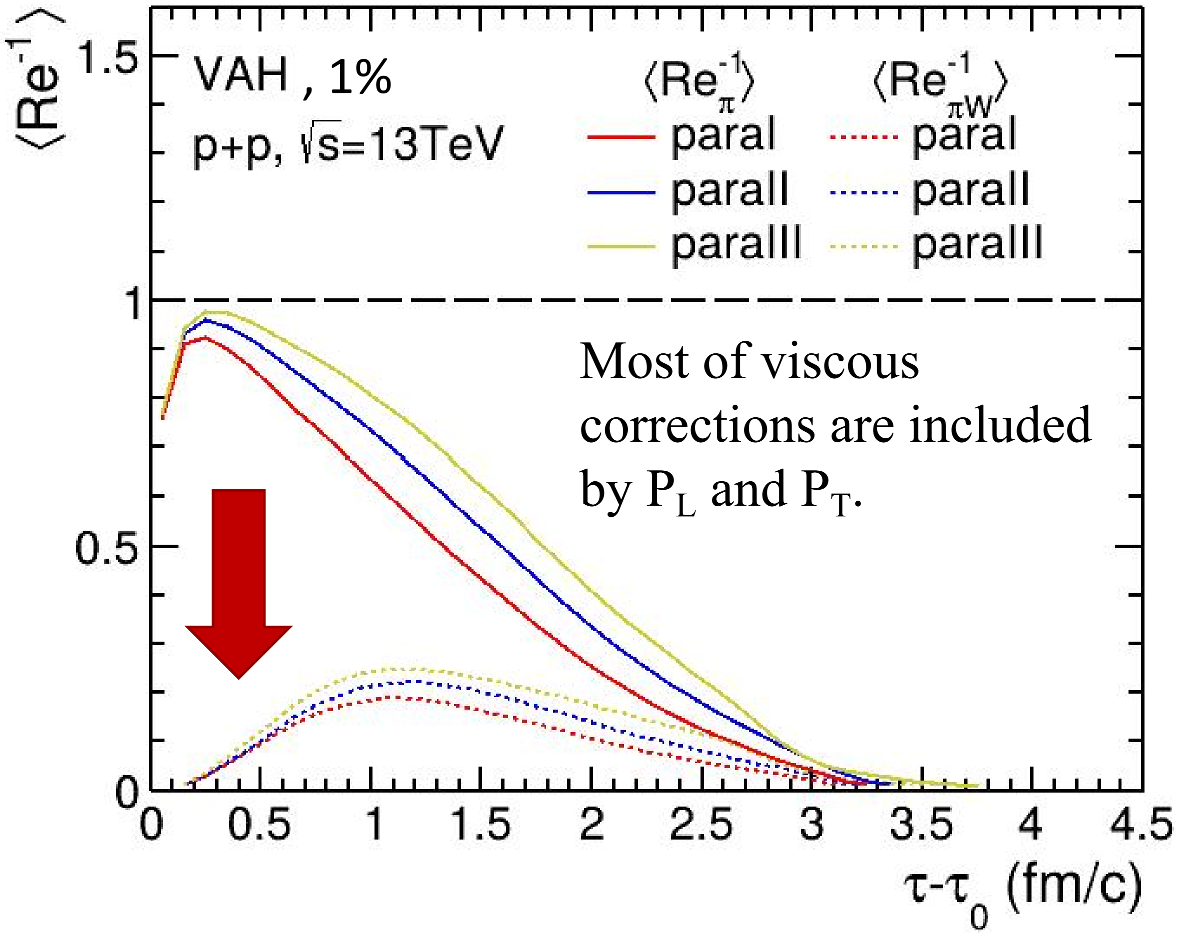
Hydrodynamic origin of collectivity ?

Zhao, Y. Peng, U. Heinz, H. Song. arXiv:2509.03841

Apply VAH in p+p Collisions



$c_2\{4\}$ remains negative across different initial conditions and parameter sets

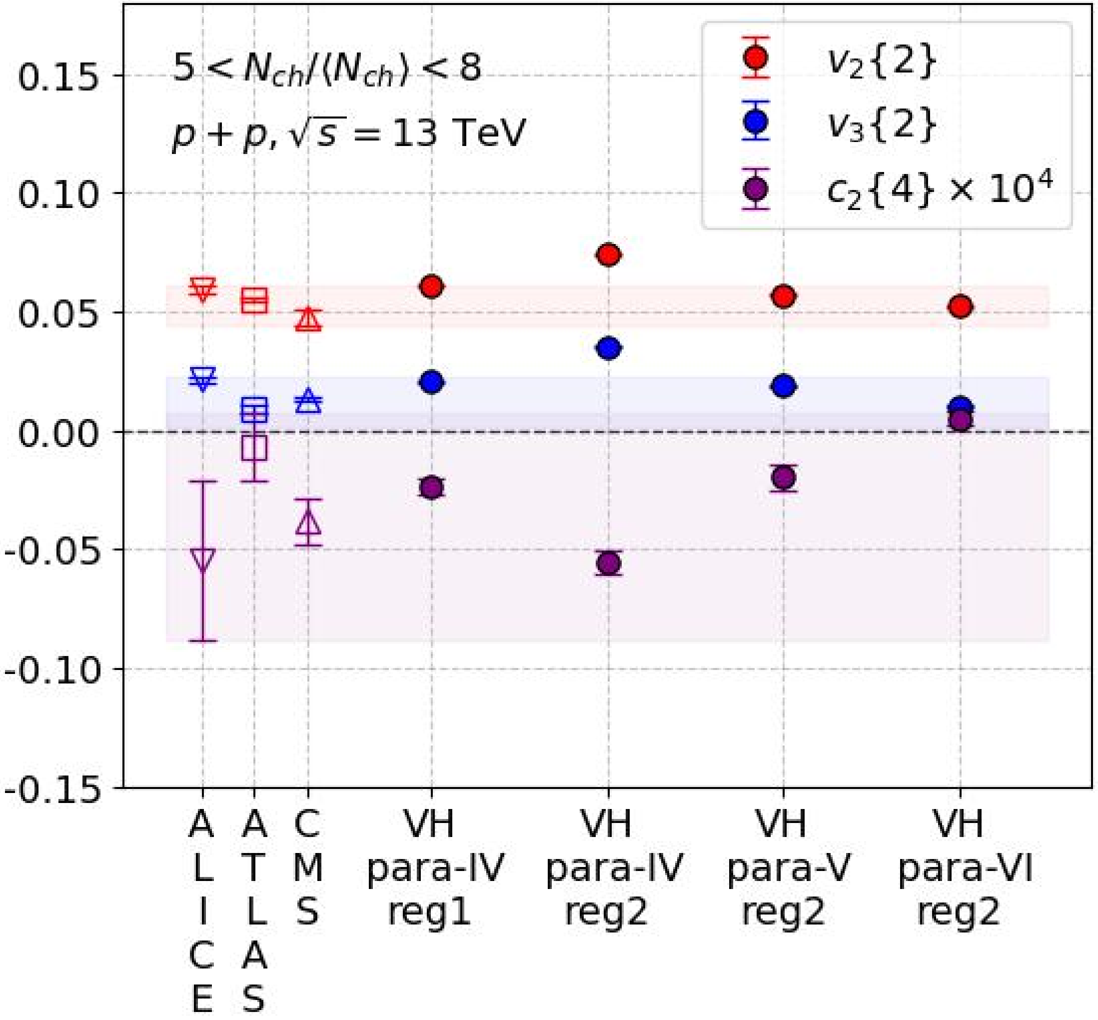


Most of viscous corrections are included by P_L and P_T.

VAH can be safely applied in p+p collisions

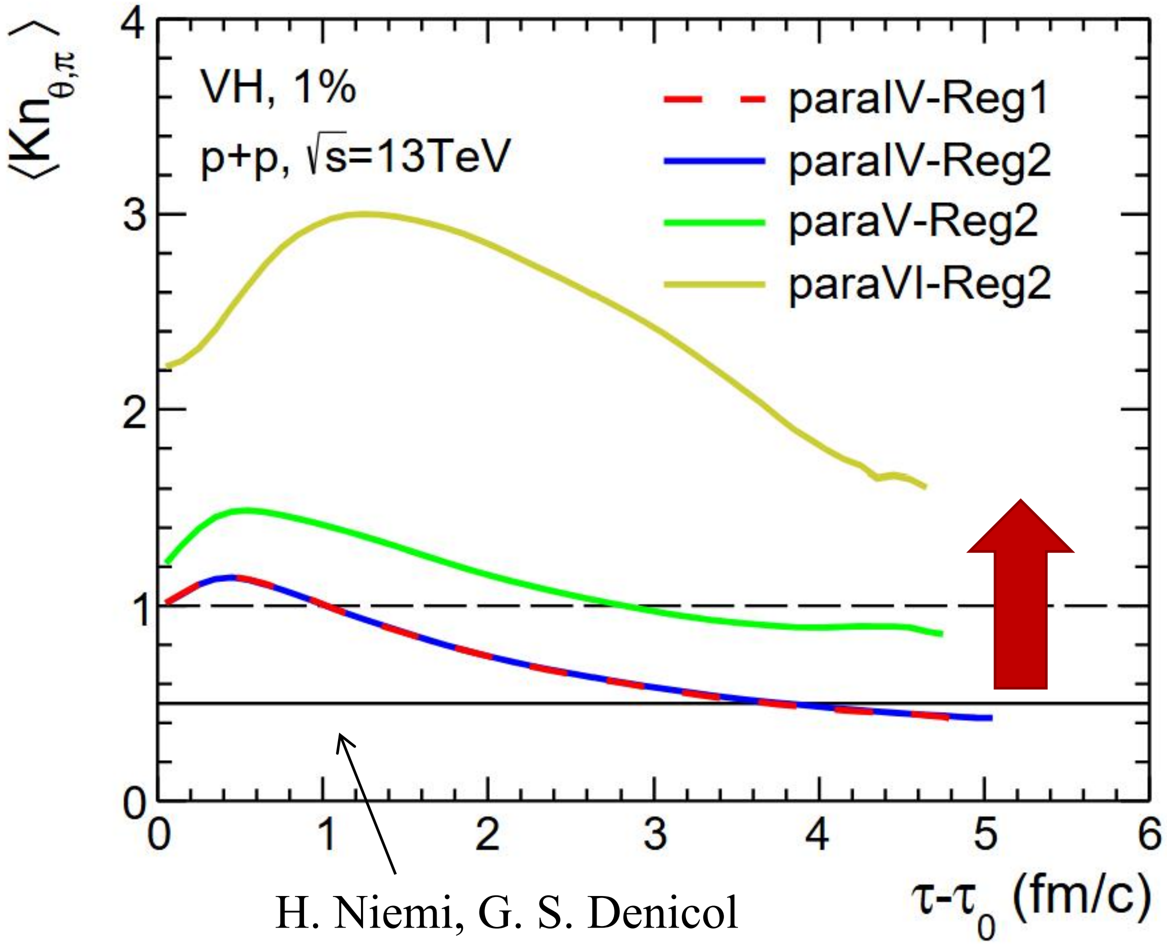
Zhao, Y. Peng, U. Heinz, H. Song. arXiv:2509.03841

Apply VH in p+p Collisions



VH requires a proper regulation scheme..
Large viscousity can lead to positive $c_2\{4\}$.

Zhao, Y. Peng, U. Heinz, H. Song. arXiv:2509.03841



H. Niemi, G. S. Denicol

Negative $c_2\{4\}$ with large Knudsen number.

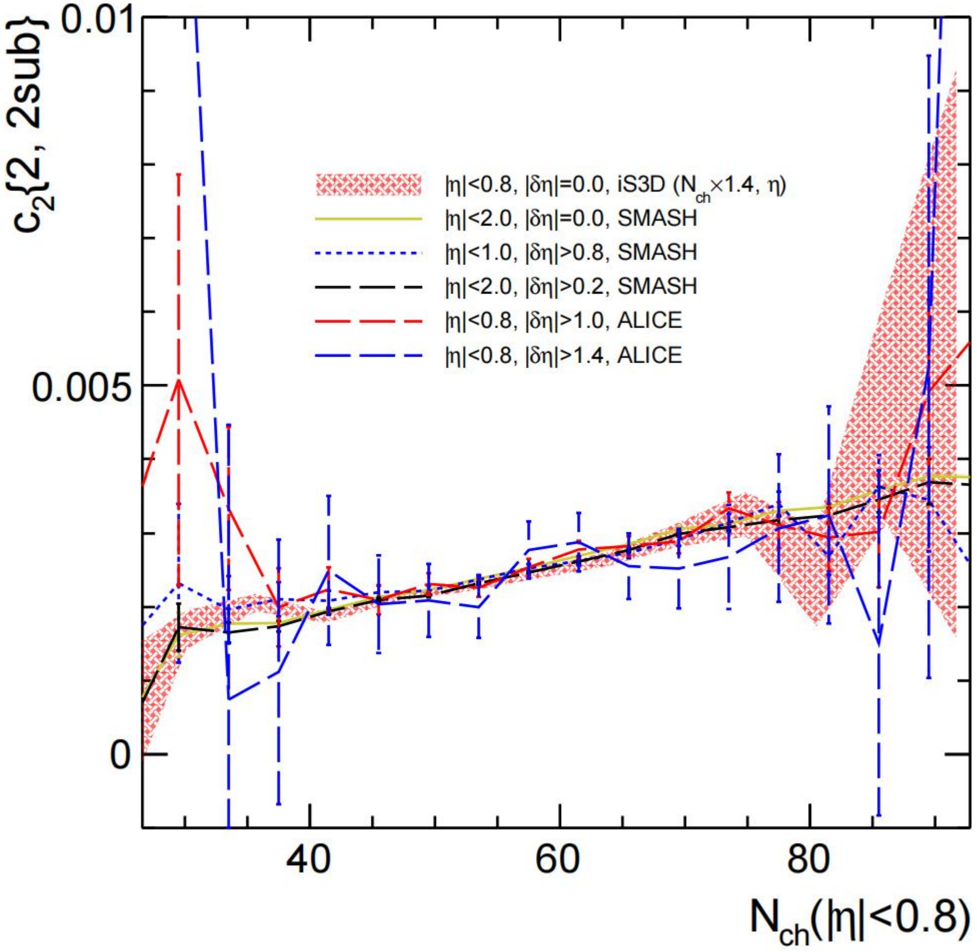
Unsafety for applying VH
in p+p collisions.

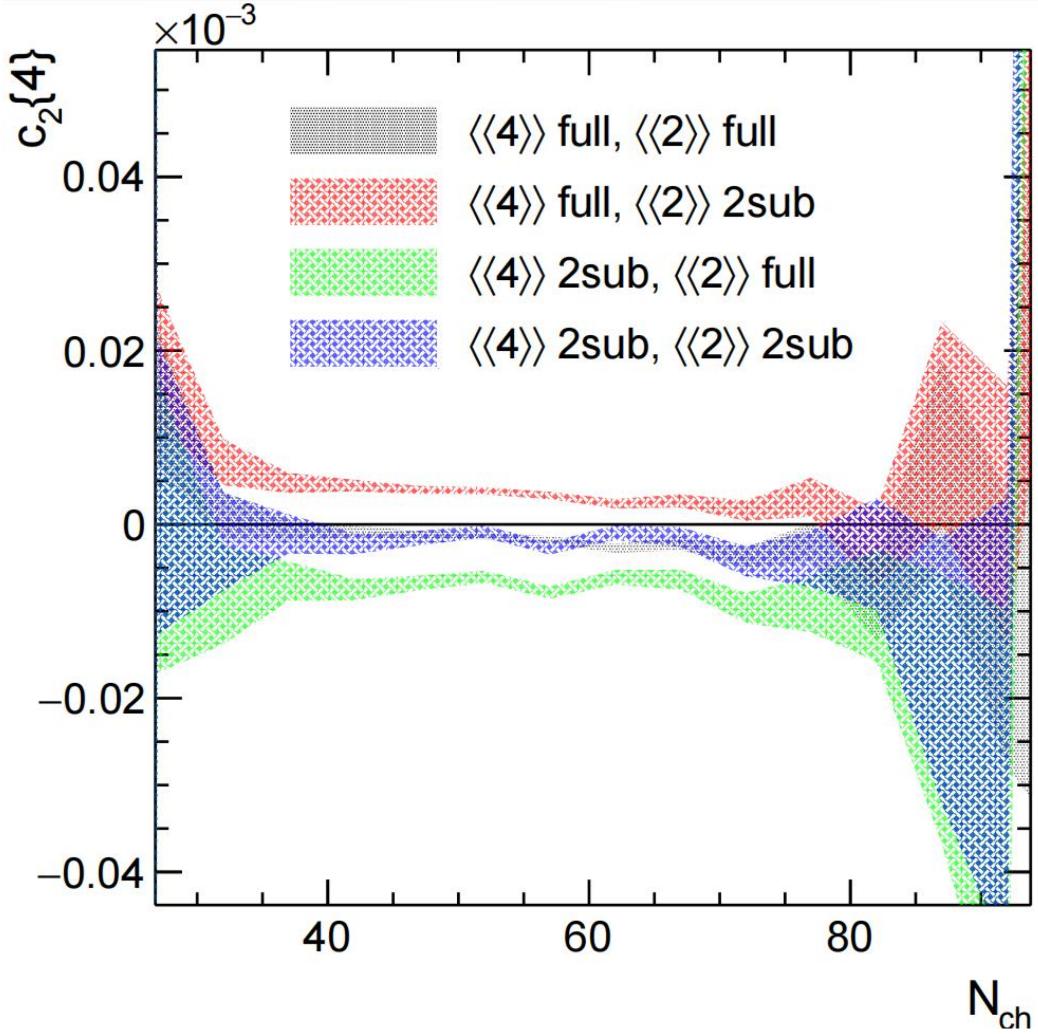
Summary

- Large anisotropic pressure gradients limit the applicability of standard hydrodynamics at the early stages
- VAH: Non-perturbative treatment of anisotropic QGP expansion; extends hydrodynamic applicability
- Small collision systems serve as sensitive probe of early-stage dynamics
- Hydrodynamic origin of collectivity in 13 TeV p+p collisions within the VAH framework

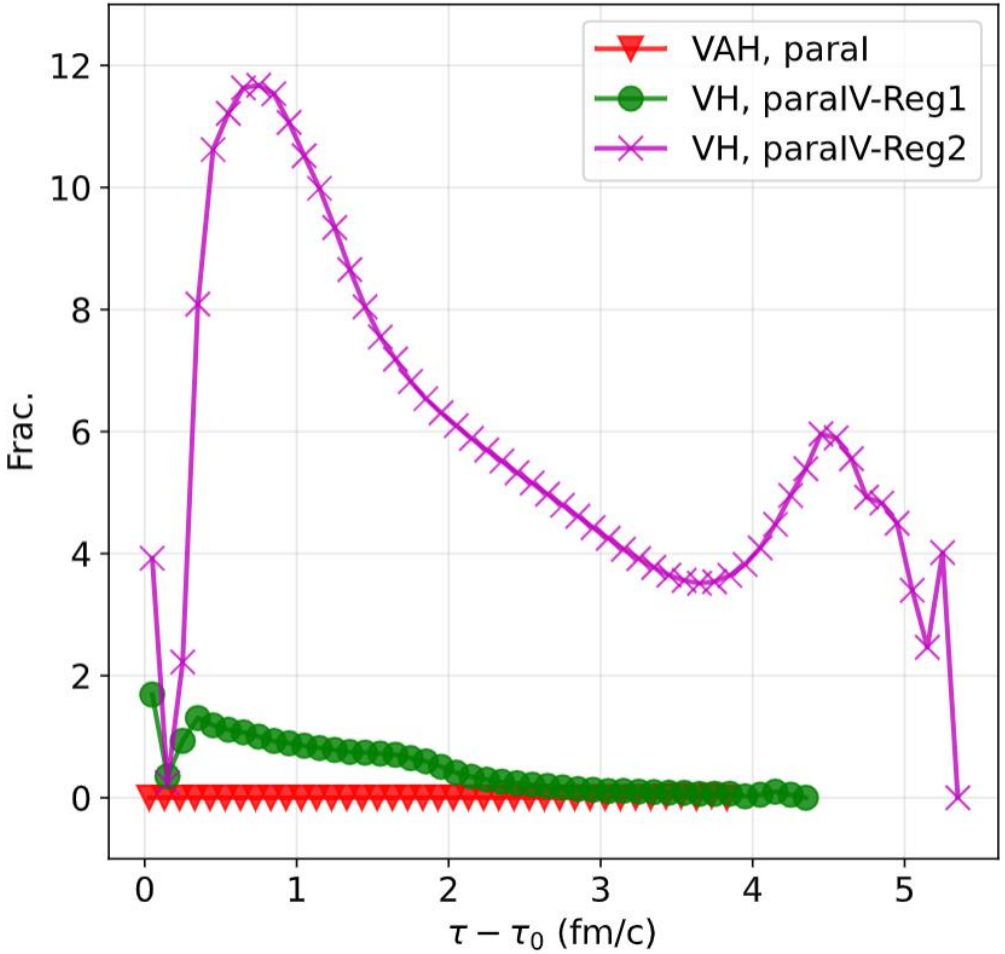
Backup

Kinetic Cuts and Sub-event Method





Regulation Scheme in VAH and VH



$$\pi^{\mu}_{\text{phys},\nu} \equiv \Delta^{\mu}_{\alpha}\Delta^{\nu}_{\beta}\pi^{\alpha\beta} - \frac{1}{3}\Delta^{\mu\nu}\Delta_{\alpha\beta}\pi^{\alpha\beta}$$

$$\text{Frac.} = \left(\frac{|\pi_{\text{phys}}|_{\text{after regulation}}}{|\pi_{\text{phys}}|_{\text{before regulation}}}\right)_{\epsilon > \epsilon_{\text{sw}}}$$

Regulation in VISHNU

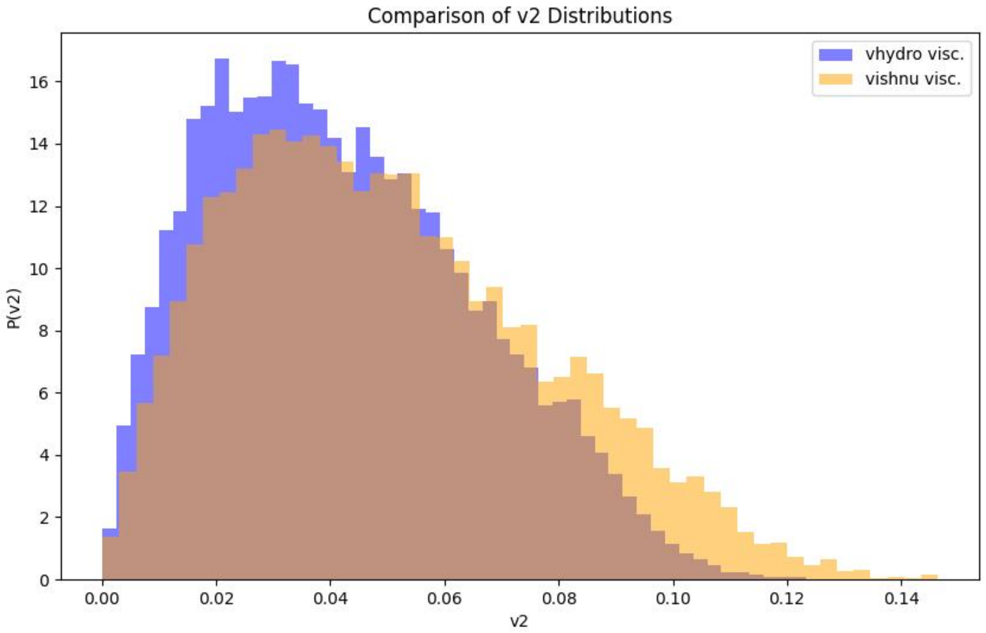
Reg1: Tanh regularization:

$$|\pi| \equiv \sqrt{\pi_{\mu\nu}\pi^{\mu\nu}} \qquad r_0 = \frac{|\pi^{\mu}_{\mu}|}{10X_0|\pi|} \qquad r_1 = \frac{|u_\mu \pi^{\mu 1}|}{10X_0|\pi|},\ r_2 = \frac{|u_\mu \pi^{\mu 2}|}{10X_0|\pi|},\ r_3 = \frac{|u_\mu \pi^{\mu 0}|}{10X_0|\pi|} \qquad r_4 = \frac{|\pi|}{10X_0\sqrt{e^2 + 3\mathcal{P}^2}}$$

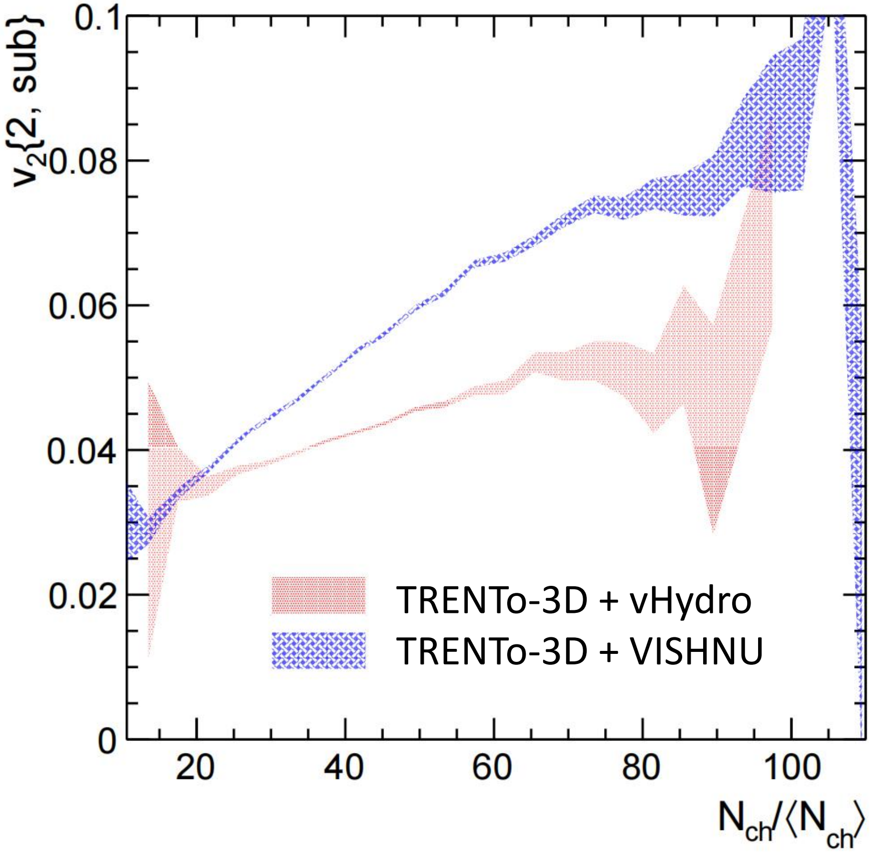
$$\pi^{\mu\nu} \leftarrow \pi^{\mu\nu}\frac{\tanh(R_\pi)}{R_\pi}. \qquad R_\pi \equiv \max\{r_i\}_0^4 \qquad \Pi \leftarrow \Pi\frac{\tanh(R_\Pi)}{R_\Pi}, \quad R_\Pi \equiv \frac{|\Pi|}{10|\mathcal{P}|}$$

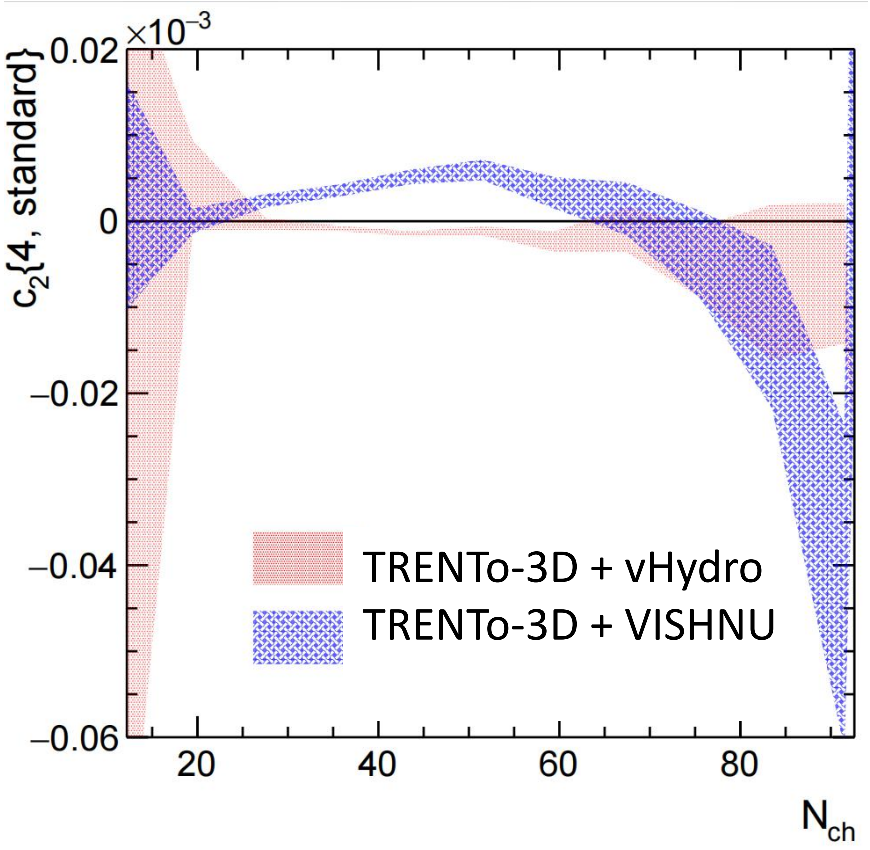
Reg2: F-D regularization:

$$\{\pi^{\mu\nu}, \Pi\} \leftarrow \{\pi^{\mu\nu}.\Pi\} \times \frac{1}{e^{(r-R_0)/A+1}}$$



Predictions from Different VH Models





With the same initial condition, same transport coefficients, predictions from two VH frameworks are different.

New Regulation Scheme in VISHNU (VISHNU*)

Regularization in VISHNU*

$$\pi^{\tau x} \leftarrow \pi^{xx} v^x + \pi^{xy} v^y,$$
$$\pi^{\tau\eta} \leftarrow \pi^{xy} u^x + \pi^{yy} u^y,$$
$$\pi^{\tau\tau} \leftarrow \pi^{\tau x} v^x + \pi^{\tau y} v^y.$$

$$|\pi| \equiv \sqrt{\pi_{\mu\nu}\pi^{\mu\nu}}$$

$$\boxed{r_0 = \frac{|\pi^\mu_\mu|}{10X_0|\pi|} \qquad r_4 = \frac{|\pi|}{10X_0\sqrt{e^2+3\mathcal{P}^2}}}$$

$$\pi^{\mu\nu} \leftarrow \pi^{\mu\nu}\frac{\tanh(R_\pi)}{R_\pi}. \quad R_\pi \equiv \min\{1, \max\{r_0, r_4\}\}$$

$$\Pi \leftarrow \Pi\frac{\tanh(R_\Pi)}{R_\Pi}, \quad R_\Pi \equiv \min\left\{1, \frac{|\Pi|}{10|\mathcal{P}|}\right\}$$

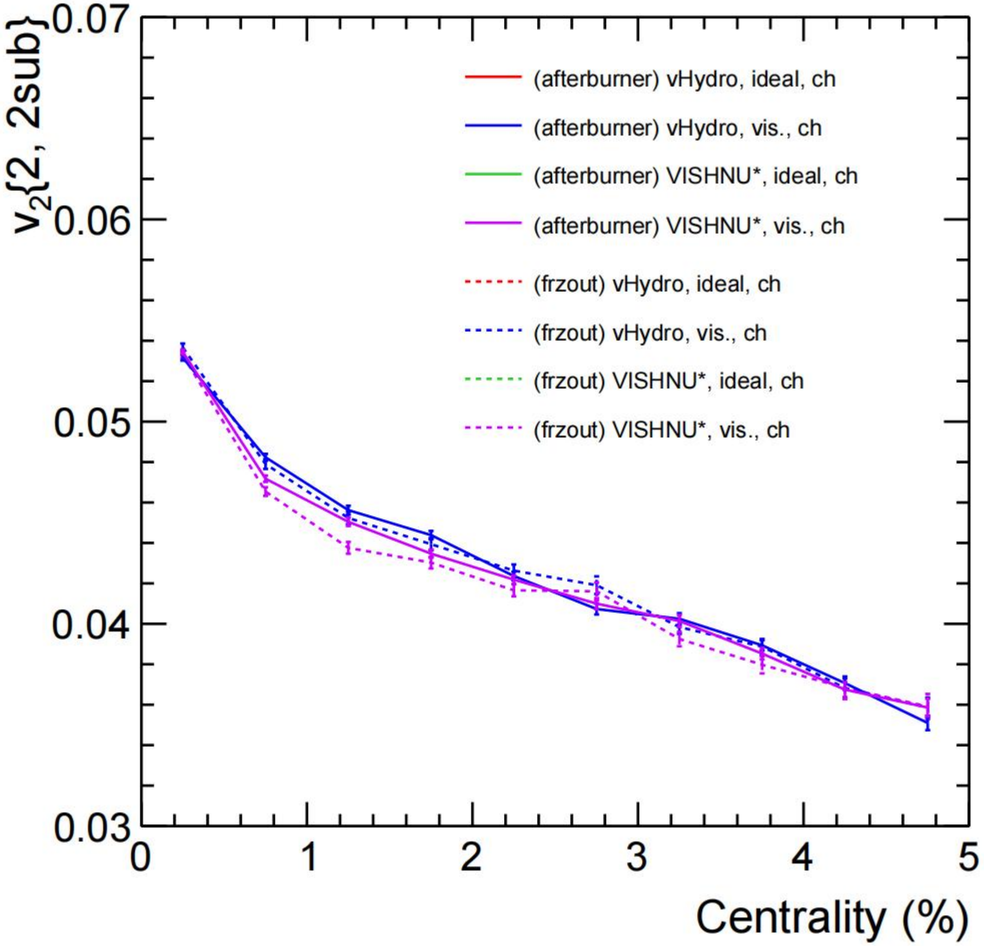
Regularization in vHydro

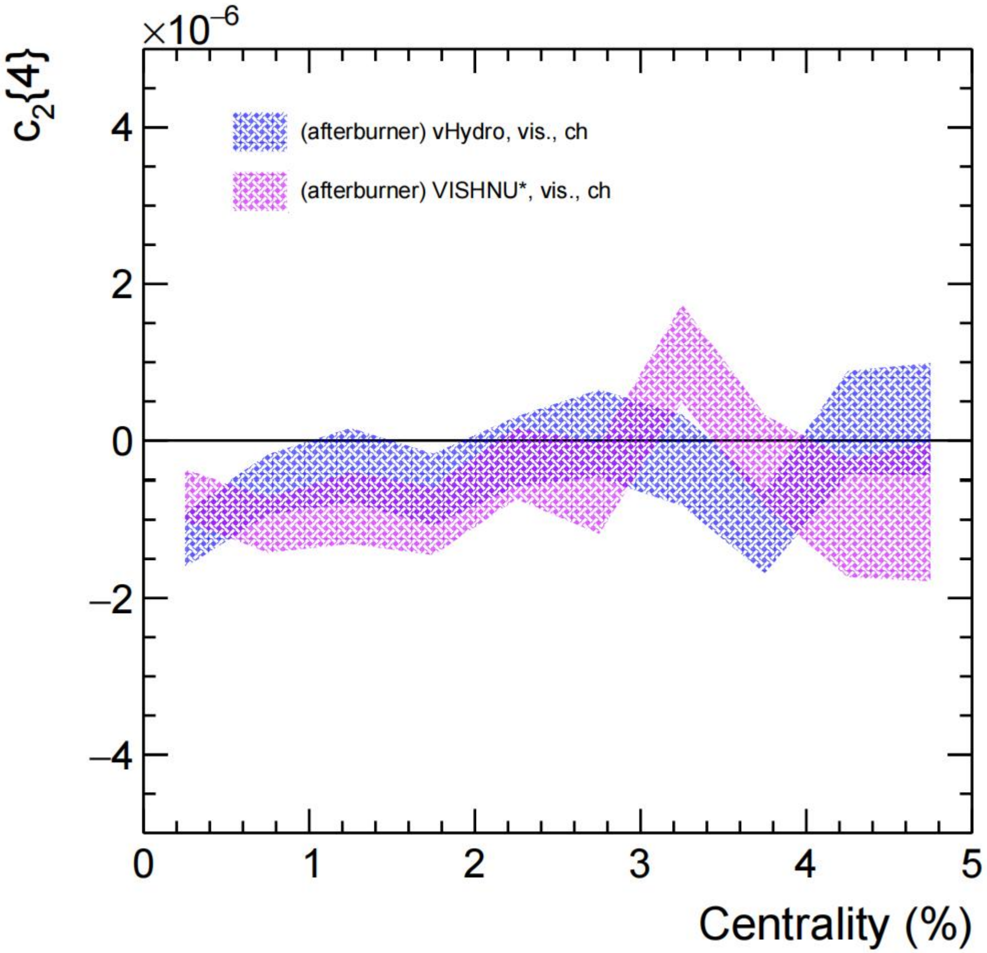
$$\pi^{\eta\eta} \leftarrow \frac{1}{\tau^2}\left[\pi^{xx}((v^x)^2-1) + \pi^{yy}((v^y)^2-1) + 2\pi^{xy}v^x v^y\right]$$
$$\pi^{\tau x} \leftarrow \pi^{xx} v^x + \pi^{xy} v^y,$$
$$\pi^{\tau\eta} \leftarrow \pi^{xy} u^x + \pi^{yy} u^y,$$
$$\pi^{\tau\tau} \leftarrow \pi^{\tau x} v^x + \pi^{\tau y} v^y.$$

$$\pi^{\mu\nu} \leftarrow \pi^{\mu\nu}\frac{\tanh(R)}{R} \qquad R = \min\left\{1, \frac{|\pi|}{10\sqrt{3}\mathcal{P}}\right\}$$

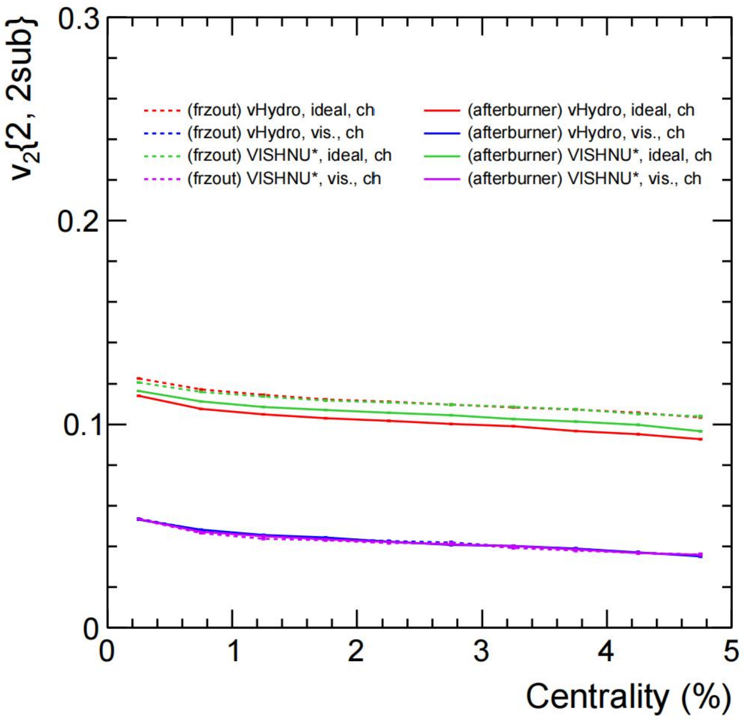
$$\Pi \leftarrow \Pi\frac{\tanh(R_\Pi)}{R_\Pi}, \quad R_\Pi \equiv \frac{|\Pi|}{10|\mathcal{P}|}$$

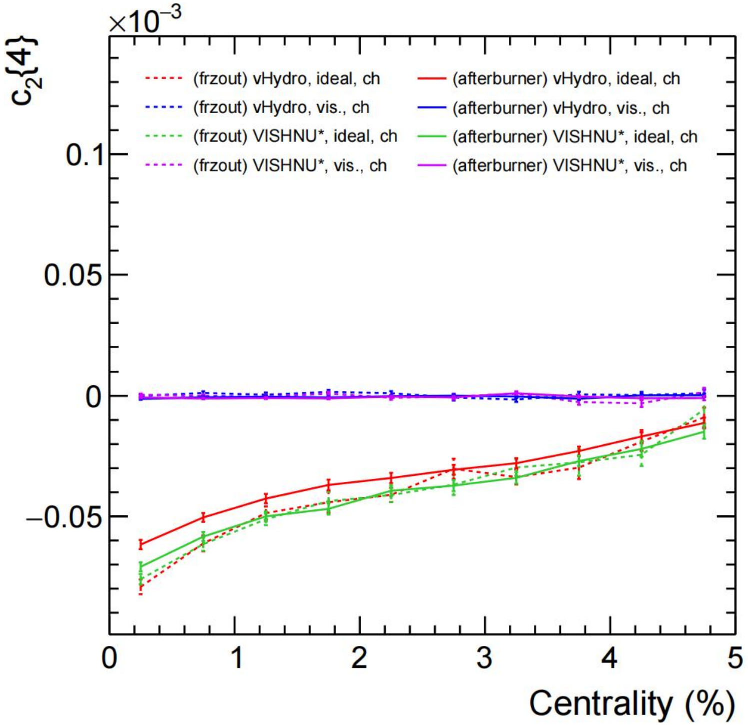
Consistent Predictions with the New Regulation Scheme

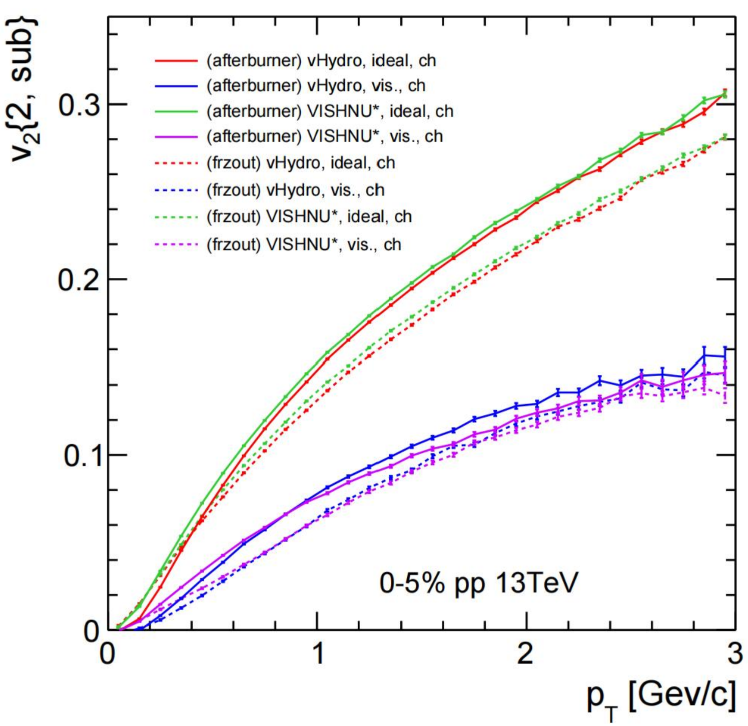




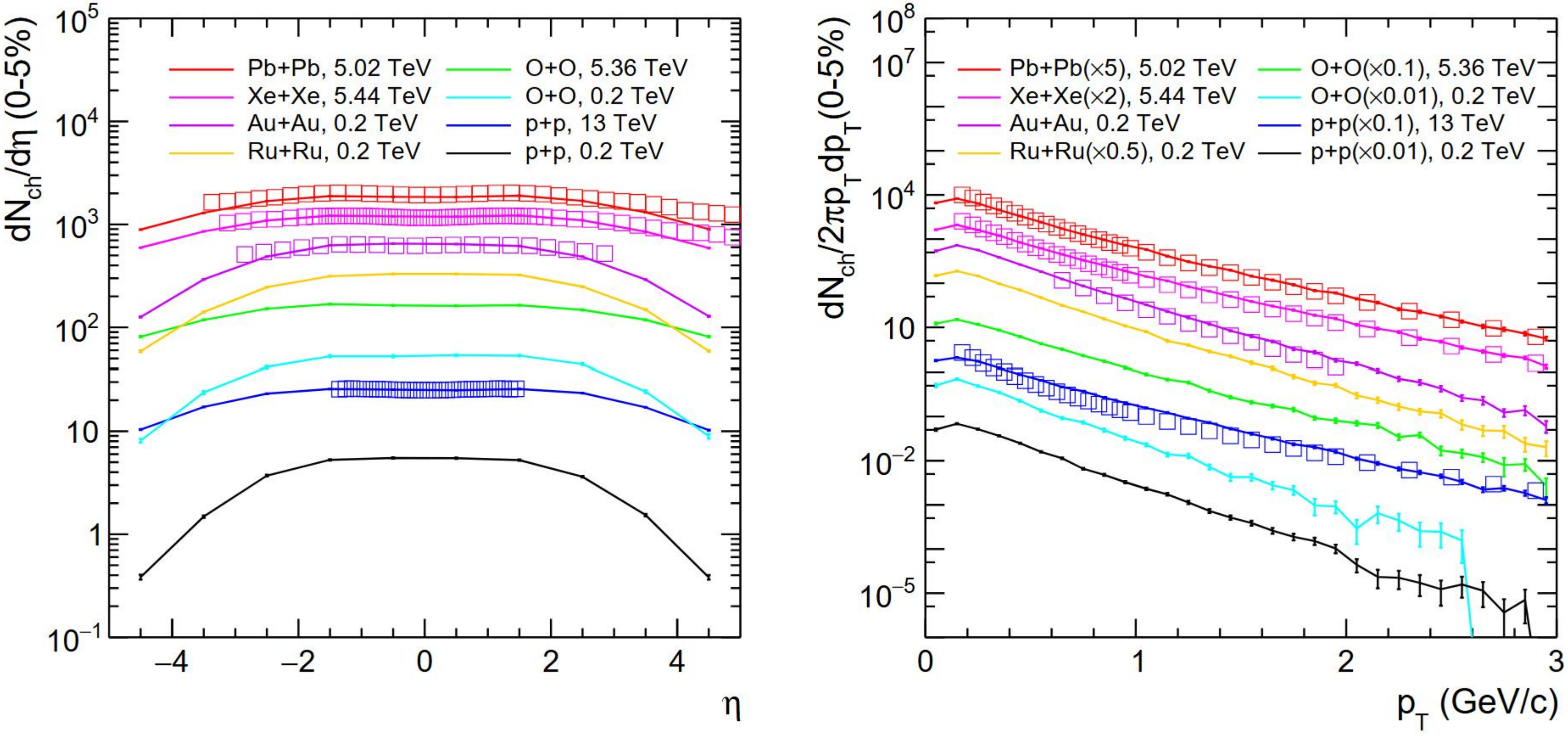
Large Viscous Correction Affect Flow Prediction







Bulk Properties Across Different Collision Systems



Describe various collision systems with one parameter set.