SOPHIA HADRON PHYSICS GROUP

上智大学 SOPHIA UNIVERSITY

Exploring the Existance of QGP Droplet in p-p Collisions at LHC

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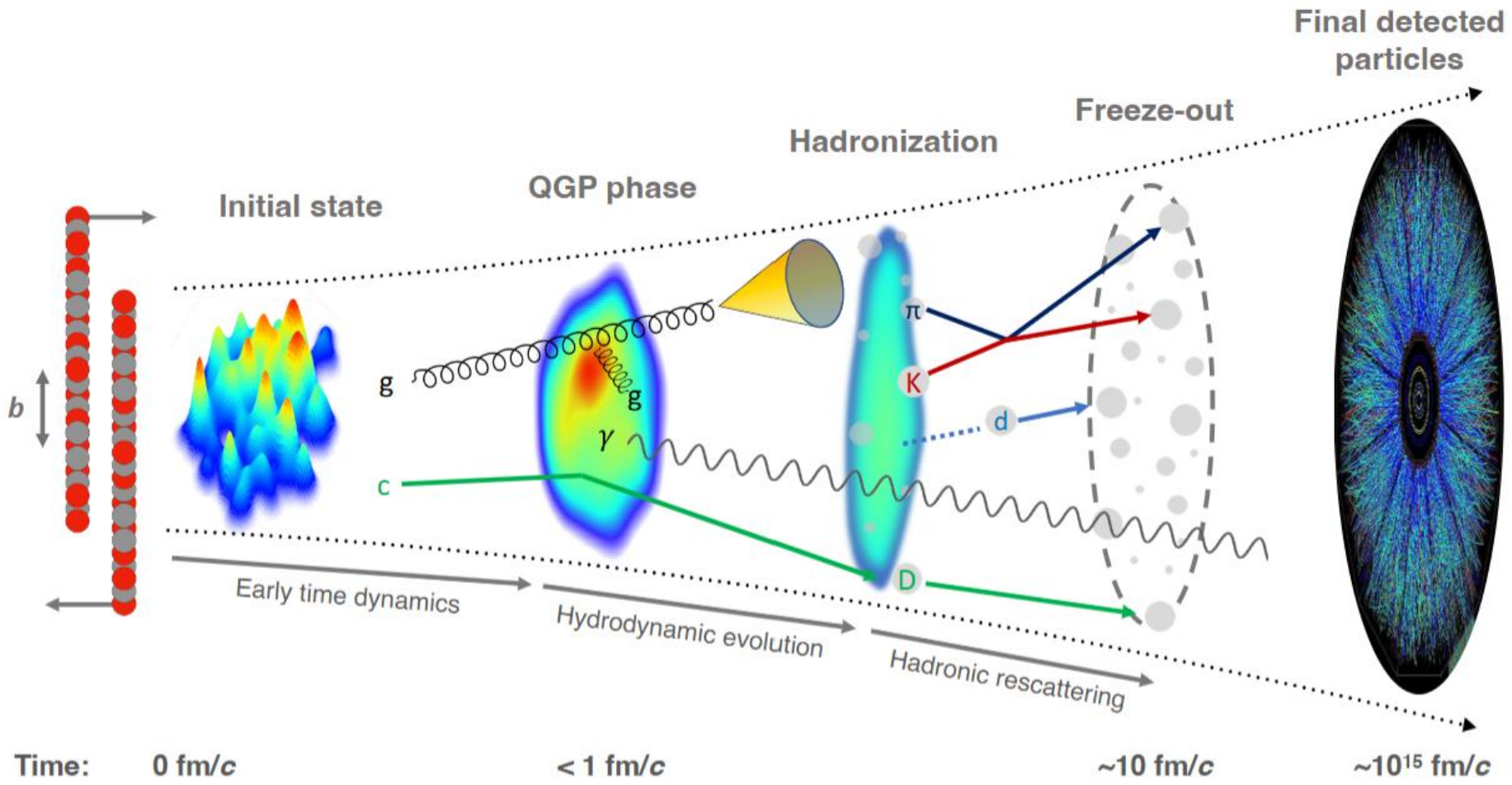
In collaborate with Yiyang Peng, Ulrich W. Heinz, and Huichao Song
22/10/2026

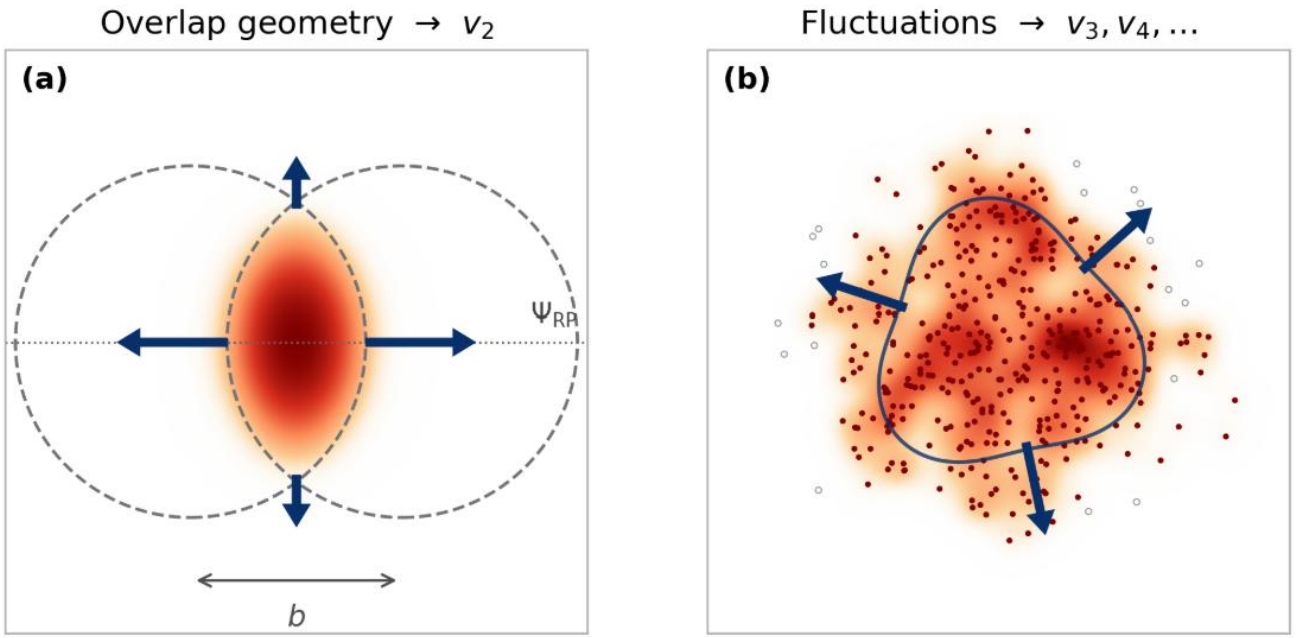
Relativistic Heavy-ion Collisions

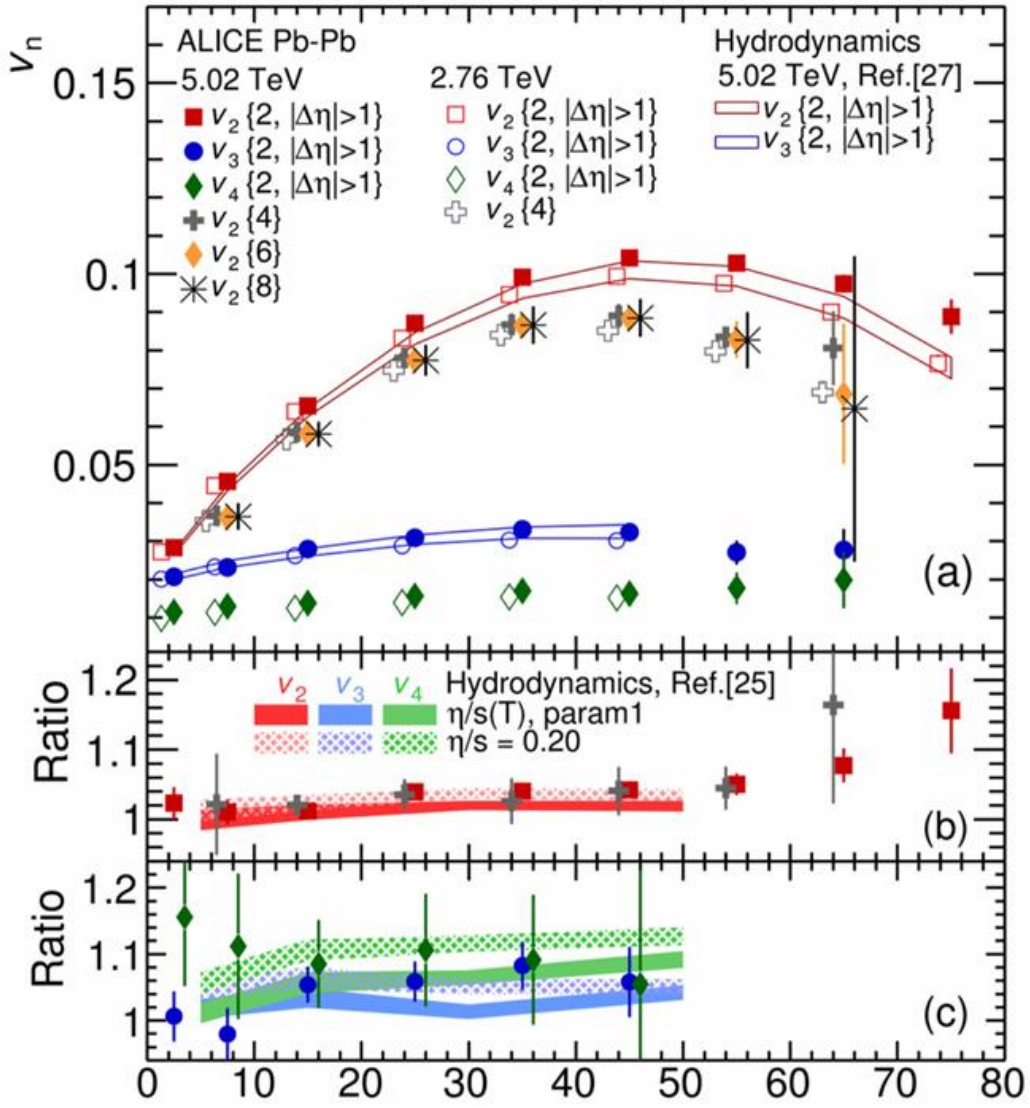


Well-established multi-stage description of heavy-ion collisions.

Hydro phase dominates the evolution: $\Delta\tau_{\text{hydro}} >> \Delta\tau_{\text{pre-eq}}$

Collectivity in Relativistic Heavy-Ion Collisions



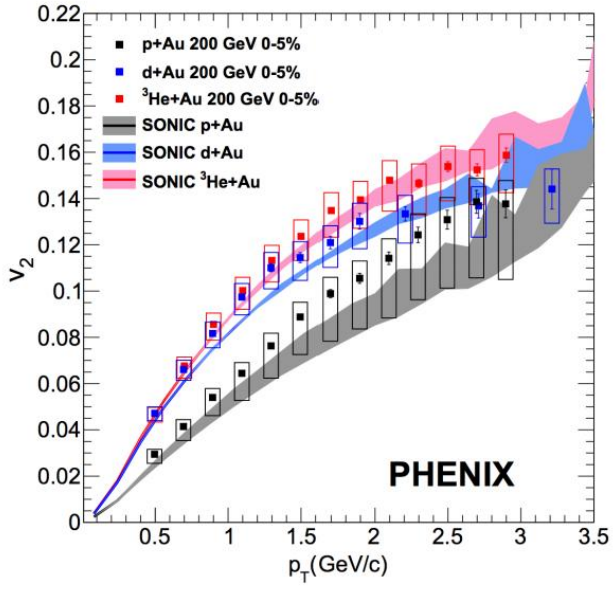


Pressure gradients convert spatial anisotropy into momentum anisotropy:

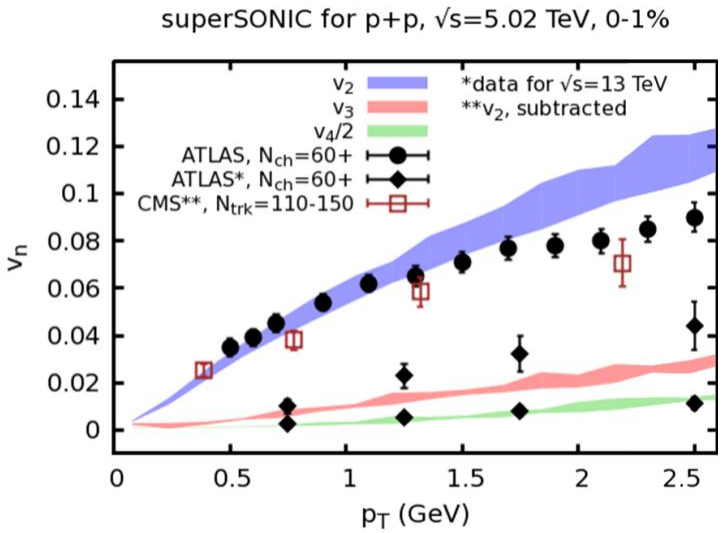
$v_n \sim \kappa(\eta/s, T, R, \ldots)\ \varepsilon_n$

Hydro quantitatively describes the measured flow

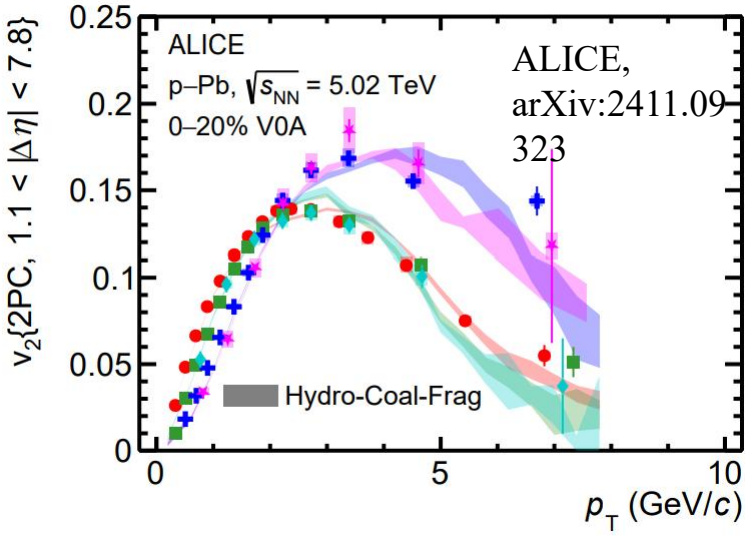
Hydrodynamics Approach in Small Collision Systems

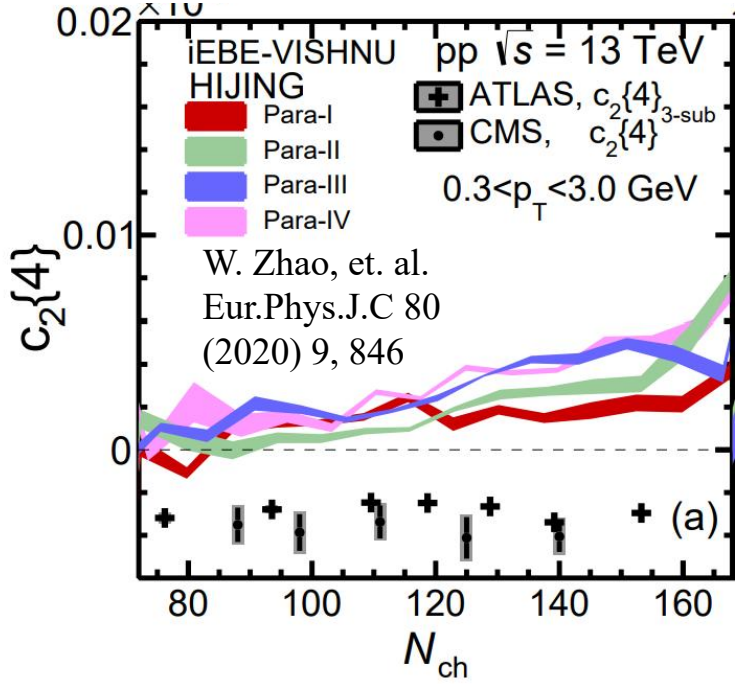


J. Carlson, et. al. Phys. Rev. Lett. 113 (2014) no. 11, 112301,



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





Hydro partially works, but…

Same mechanism as in A–A?

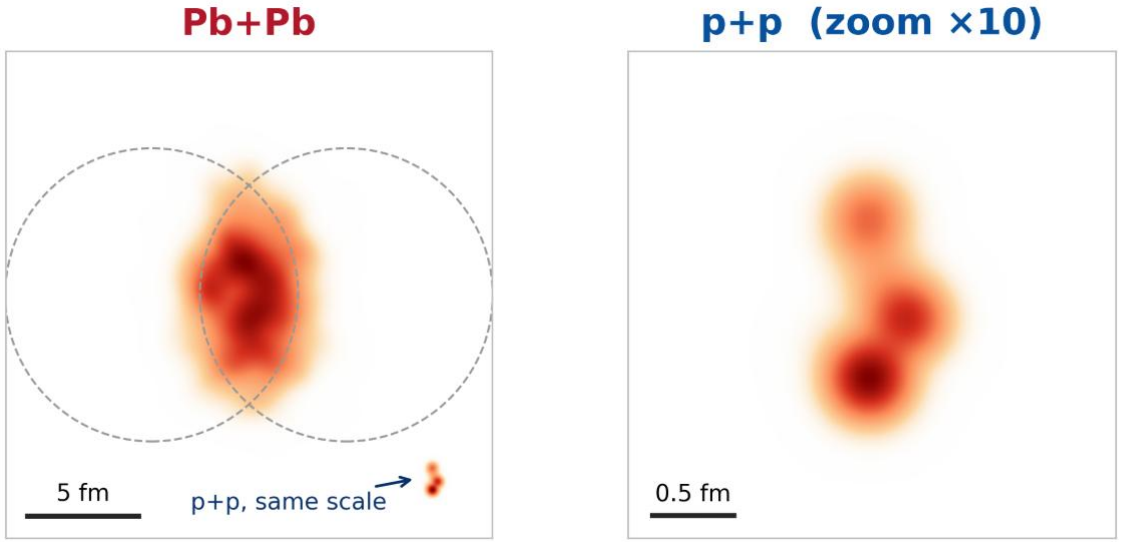
Is hydro valid in small systems?

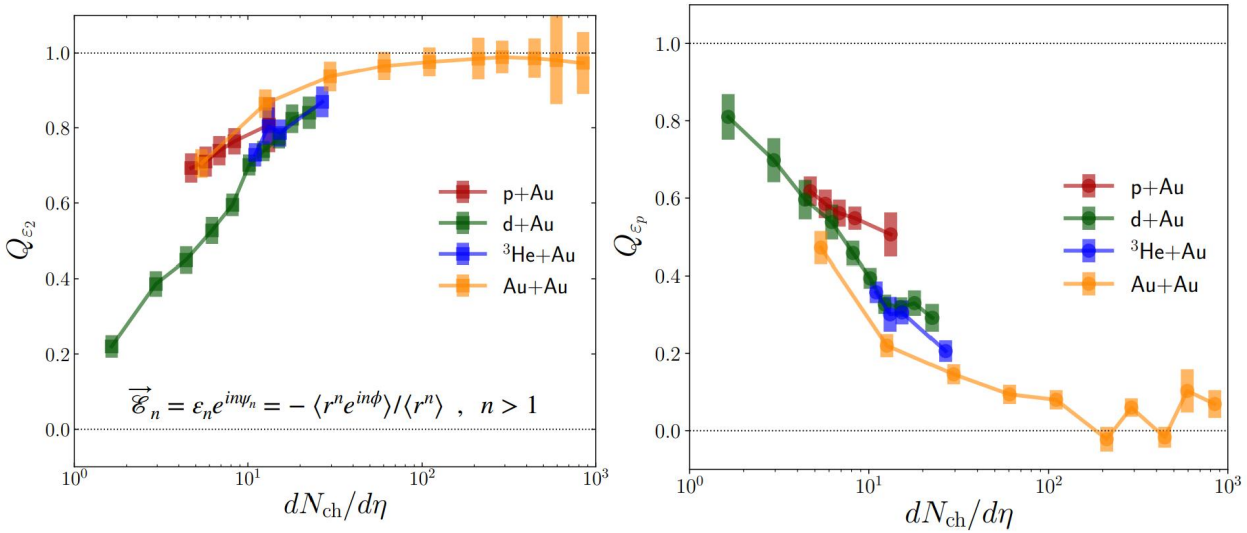
What makes small systems different?

- Initial stage:

1. Significant geometric size difference
2. Initial geometry purely driven by unknown sub-nucleonic fluctuation inside proton
3. Contribution from the initial stage momentum anisotropy:

$$V_2 \sim \kappa_2 \varepsilon_2 + \kappa_{2,p} \varepsilon_{2,p}$$





Schenke, et. al. PLB 2020

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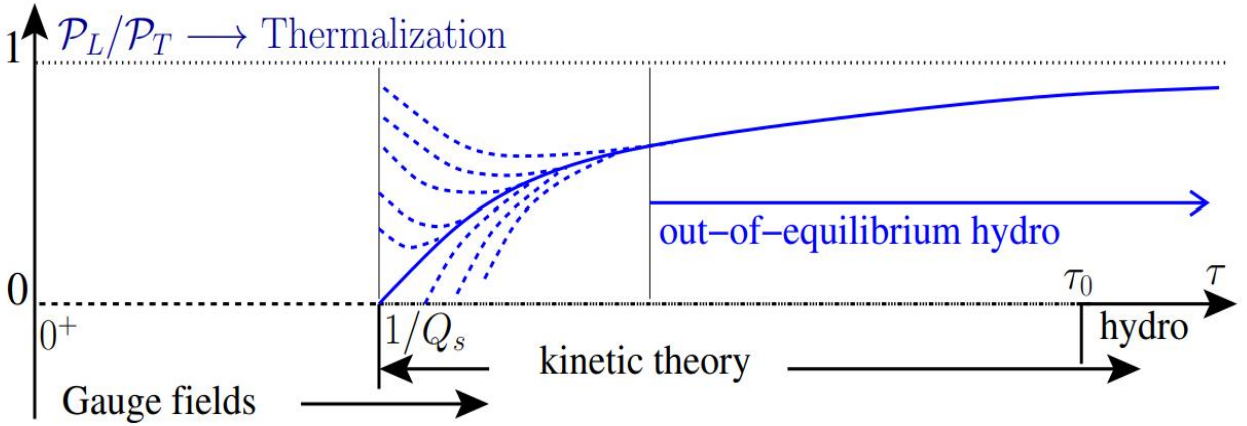
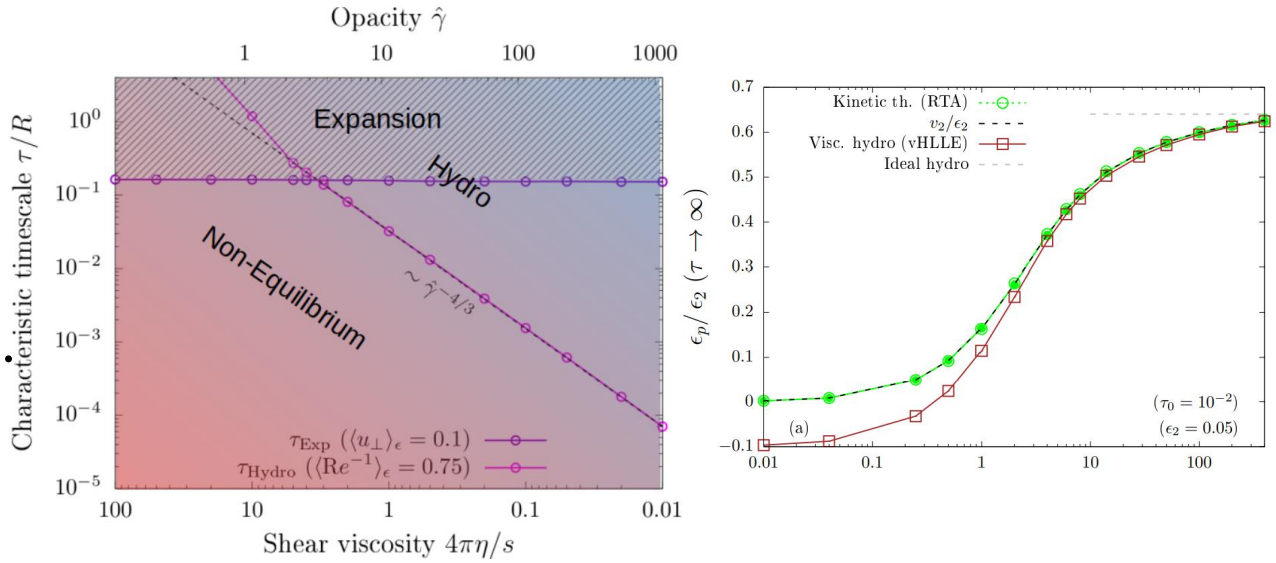
- Pre-equilibrium & Hydro:

1. Shorter evolution time, non-equilibrium evolution is important in small collision systems.

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





Schlichting, et. al. PRL (2023), PRD (2022)

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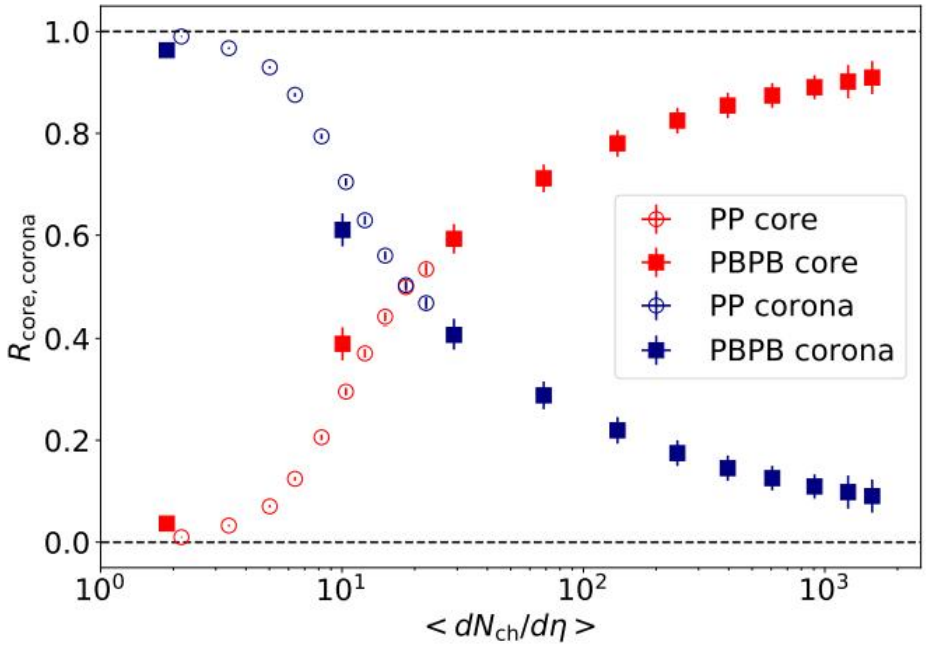

Hirano, et. al. PRC (2022)

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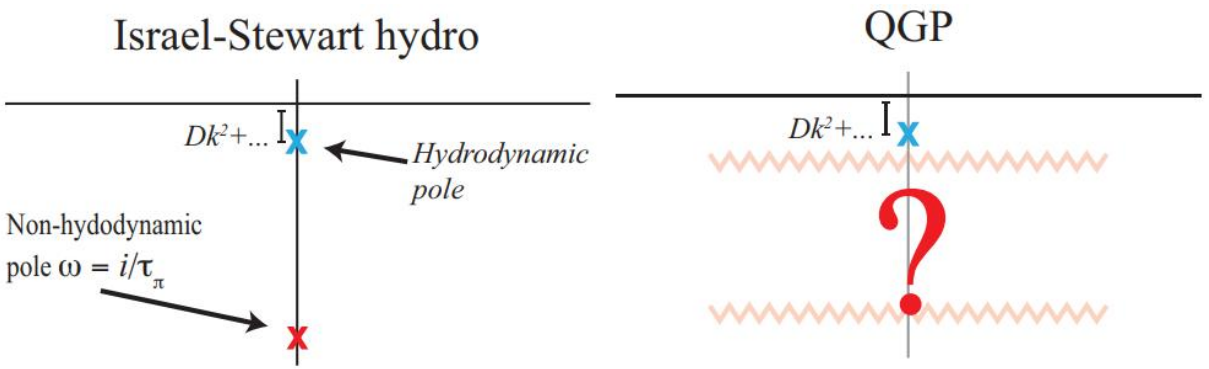
2. Not all medium can be described by fluid:

$v_n \sim v_{n,\mathrm{hydro}} + v_{n,\mathrm{non\text{-}hydro}}$



Wiedemann, et. al. EPJC (2019)

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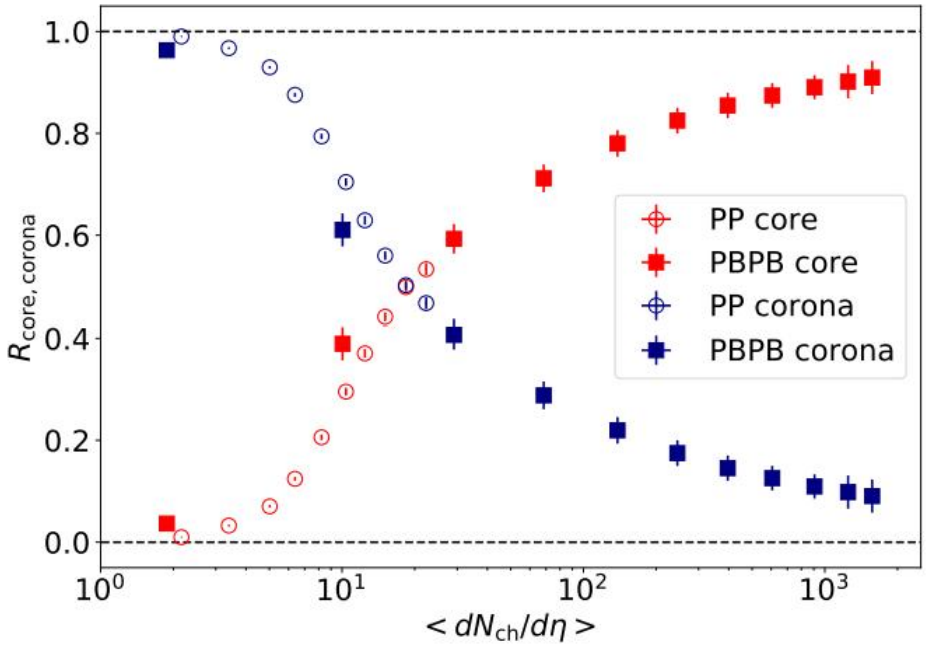

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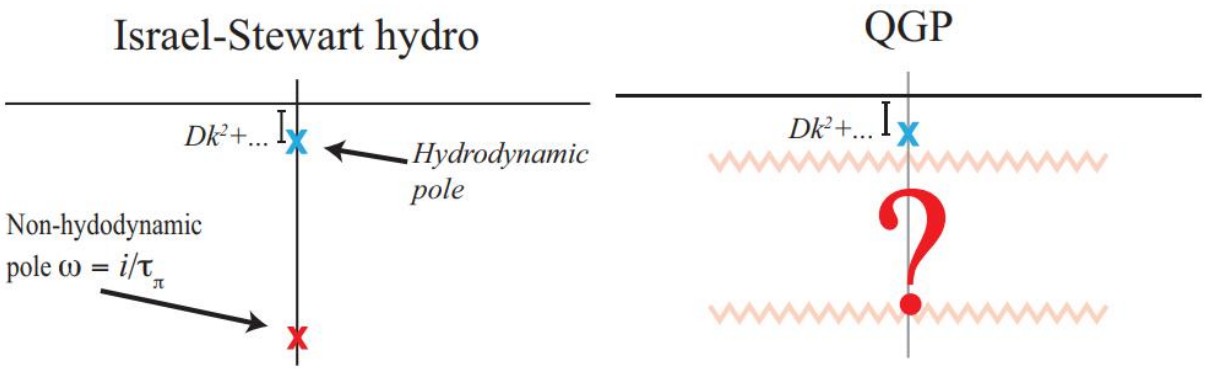


Wiedemann, et. al. EPJC (2019)

Viscous Anisotropic Hydrodynamics

- Redecomposition of $T^{\mu\nu}$:

$$T^{\mu\nu} = \mathcal{E} u^\mu u^\nu + \underbrace{\mathcal{P}_L z^\mu z^\nu - \mathcal{P}_\perp \Xi^{\mu\nu}}_{\text{Pressure Anisotropy}} + \underbrace{2W_{\perp z}^{(\mu} z^{\nu)} + \pi_\perp^{\mu\nu}}_{\text{Residual Shear Stress}},$$

$$T^{ij}_{\text{LRF}} = \begin{pmatrix} P_\perp + \pi_\perp^{xx} & \pi_\perp^{xy} & W_{\perp z}^x \\ \pi_\perp^{xy} & P_\perp + \pi_\perp^{yy} & W_{\perp z}^y \\ W_{\perp z}^x & W_{\perp z}^y & P_L \end{pmatrix}$$

- Redecomposition of viscous term

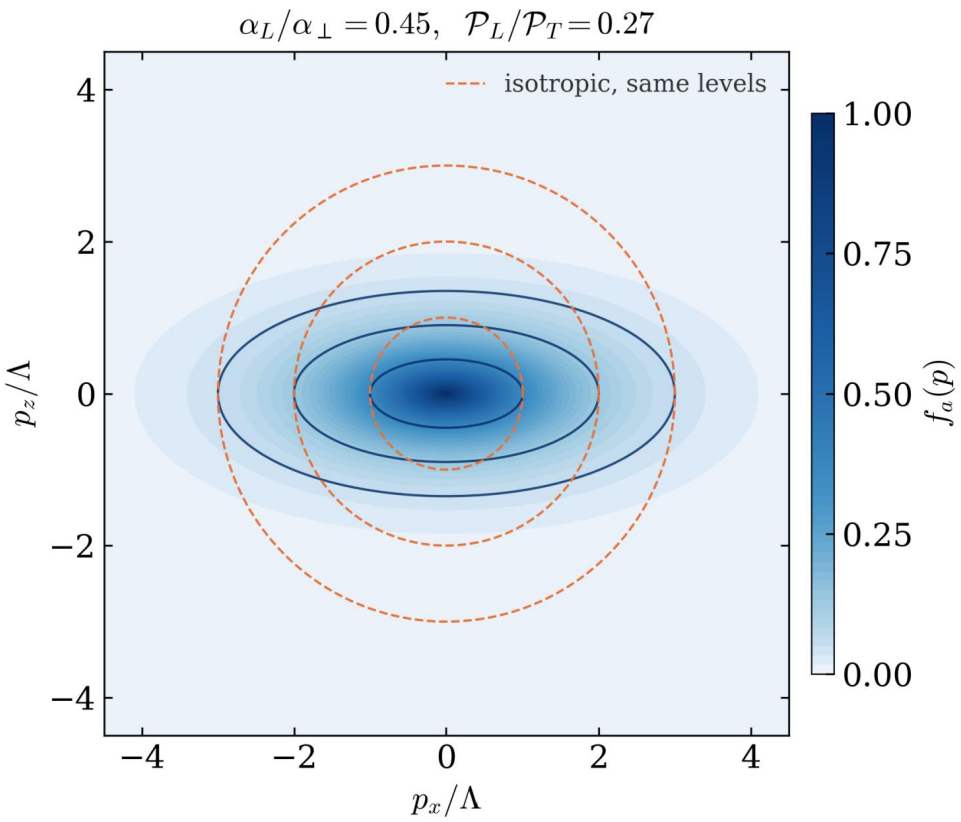
$$\pi^{\mu\nu} = \frac{1}{3}(\mathcal{P}_L - \mathcal{P}_T)(2z^\mu z^\nu + \Xi^{\mu\nu}) + 2W_{\perp z}^{(\mu} z^{\nu)} + \pi_\perp^{\mu\nu}$$

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

- Anisotropic particle distribution:

$$f_a(x,p) = f_{\text{eq}}\left(\frac{\sqrt{\Omega_{\mu\nu}p^\mu p^\nu}}{\Lambda(x)}\right) + \delta\tilde{f}(x,p)$$

$$\Omega_{\mu\nu}p^\mu p^\nu = m^2 + \frac{p^2_{\perp,\text{LRF}}}{\alpha_\perp^2} + \frac{p^2_{z,\text{LRF}}}{\alpha_L^2}.$$



Viscous Anisotropic Hydrodynamics

- EoM

$$\partial_\mu T^{\mu\nu} = 0$$

$$\dot{\mathcal{P}}_L = -\frac{\bar{\mathcal{P}} - \mathcal{P}_{\rm eq}}{\tau_\Pi} - \frac{\mathcal{P}_L - \mathcal{P}_\perp}{3\tau_\pi} + \bar{\zeta}_z^L \theta_L + \bar{\zeta}_\perp^L \theta_\perp + \cdots$$

$$\dot{\mathcal{P}}_\perp = -\frac{\bar{\mathcal{P}} - \mathcal{P}_{\rm eq}}{\tau_\Pi} + \frac{\mathcal{P}_L - \mathcal{P}_\perp}{3\tau_\pi} + \bar{\zeta}_z^\perp \theta_L + \bar{\zeta}_\perp^\perp \theta_\perp + \cdots$$

$$\dot{B} = -\frac{B - B_{\rm eq}}{\tau_\Pi} - \cdots$$

$$\dot{W}^\mu_{\perp z} = -\frac{W^\mu_{\perp z}}{\tau_\pi} + (\bar{\eta}_u^W, \bar{\eta}_\perp^W, \cdots)$$

$$\dot{\pi}^{\mu\nu}_\perp = -\frac{\pi^{\mu\nu}_\perp}{\tau_\pi} + (\bar{\eta}_\perp, \cdots).$$

- Anisotropic transport coefficients resum in the pressure anisotropy

$$\begin{aligned}
\bar{\zeta}_z^L &= -c_s^2(\mathcal{E} + \mathcal{P}_L) - \frac{4\eta}{3\tau_\pi} - \frac{\zeta}{\tau_\Pi} - \delta_{\Pi\Pi}(\bar{\mathcal{P}} - \mathcal{P}_{\rm eq}) - \frac{2}{3}\delta_{\pi\pi}(\mathcal{P}_L - \mathcal{P}_\perp) + \cdots \\
\bar{\zeta}_\perp^L &= -c_s^2(\mathcal{E} + \mathcal{P}_\perp) + \frac{2\eta}{3\tau_\pi} - \frac{\zeta}{\tau_\Pi} - \delta_{\Pi\Pi}(\bar{\mathcal{P}} - \mathcal{P}_{\rm eq}) - \frac{2}{3}\delta_{\pi\pi}(\mathcal{P}_L - \mathcal{P}_\perp) + \cdots \\
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\bar{\zeta}_\perp^\perp &= -c_s^2(\mathcal{E} + \mathcal{P}_\perp) + \frac{2\eta}{3\tau_\pi} - \frac{\zeta}{\tau_\Pi} - \delta_{\Pi\Pi}(\bar{\mathcal{P}} - \mathcal{P}_{\rm eq}) + \frac{1}{3}\delta_{\pi\pi}(\mathcal{P}_L - \mathcal{P}_\perp) + \cdots \\
&\cdots \quad \cdots
\end{aligned}$$

Anisotropic enthalpy density

Isotropic transport coefficients

Anisotropic transport coefficients

Model Setup

- Initial stage: Trento with subnucleonic fluctuation
- Hydro stage: $\partial_\mu T^{\mu\nu}_{\mathrm{VAH(VH)}} = 0$
- Freeze-out: Cooper-Frye

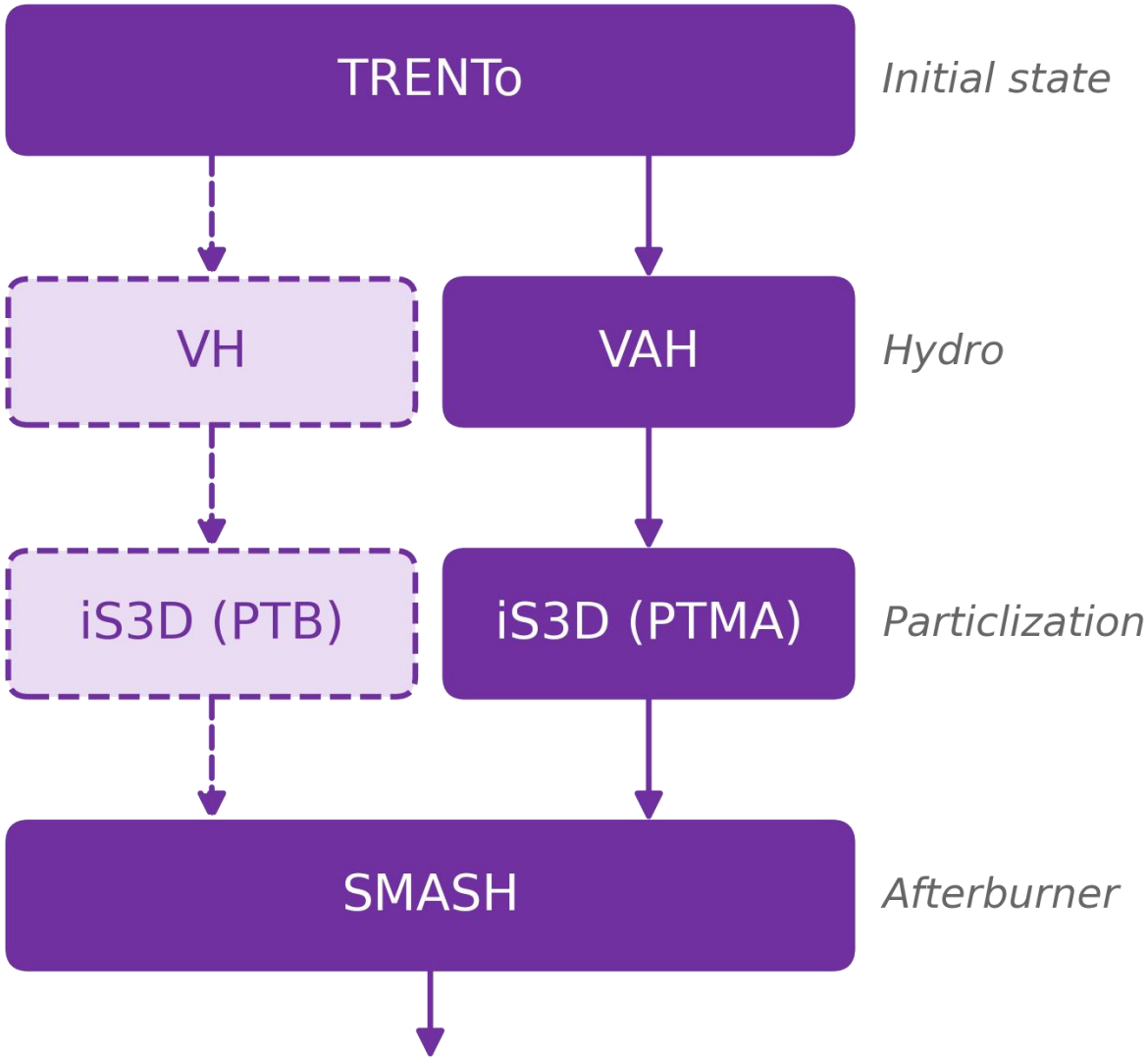
$$E\frac{\mathrm{d}N_i}{\mathrm{d}^3p} = \frac{g_i}{(2\pi^3)}\int_\Sigma \mathrm{d}^3\sigma_\mu(x)p^\mu f_i(x;p),$$

$$f^{\mathrm{PTMA}}_{a,i}(x,p) = \frac{\mathcal{Z}(x)g_i}{\exp\left[\frac{\sqrt{p\cdot(\Omega(x)+\delta\Omega(x))\cdot p+m_i^2}}{\Lambda(x)}\right]+\Theta_i},$$

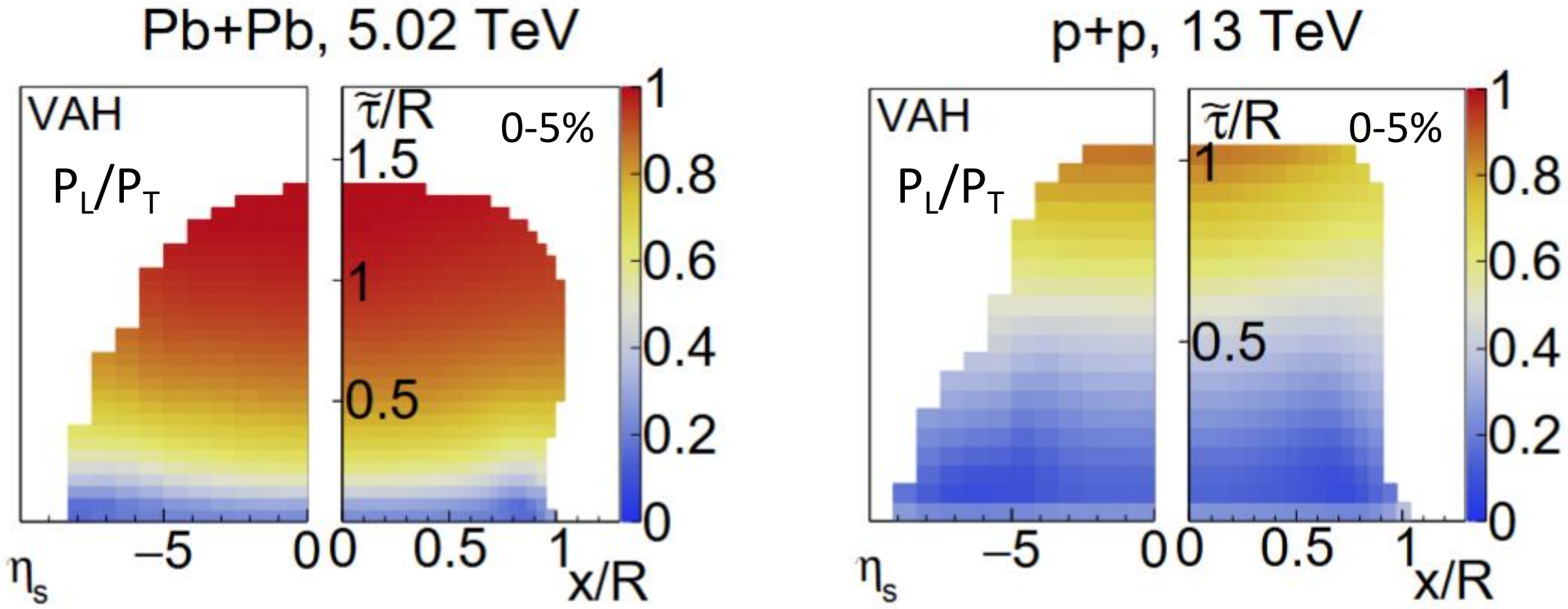
$$f^{\mathrm{PTB}}_i(x,p) = \frac{z_\Pi}{\det A}\frac{g_i}{\exp\left[\frac{\sqrt{\mathbf{p}'^2+m_i^2}}{T}\right]+\Theta_i},$$

- Afterburner: SMASH (cascade)

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



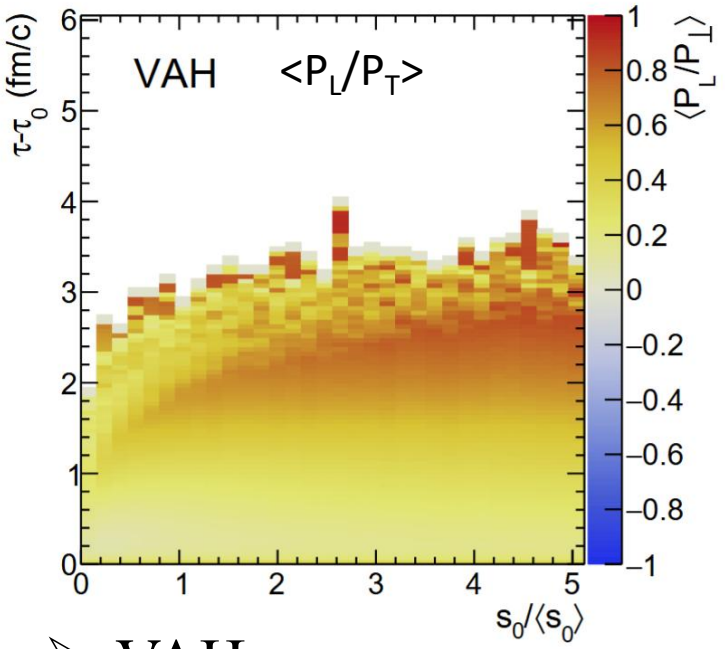
Development of Pressure Anisotropy: System Size Dependence

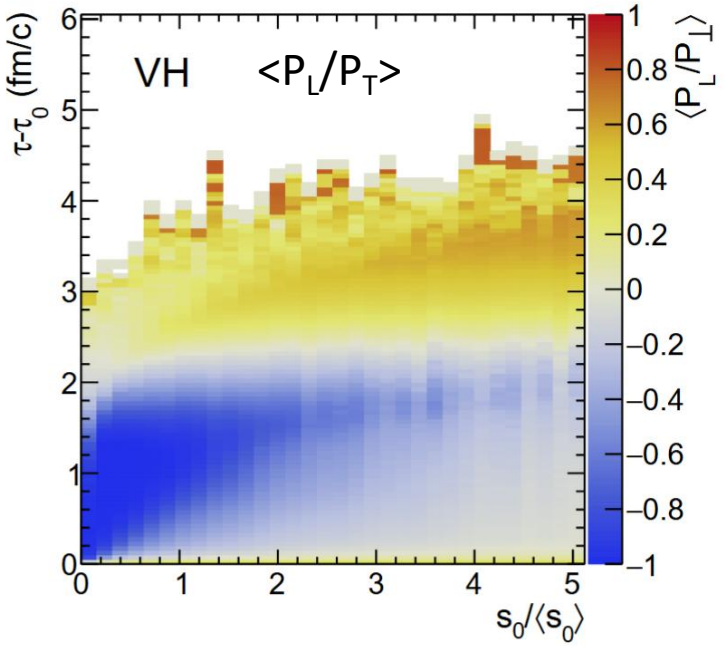


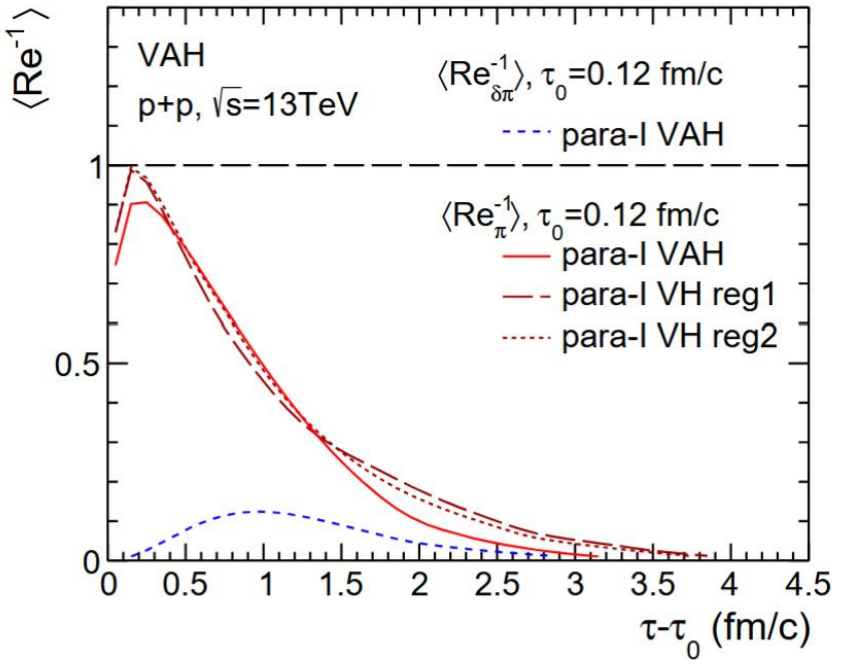
Strongly anisotropic expansion at early times
Rapid isotropization in heavy-ion collisions
Deviation from equilibrium persists in small systems

SJZ, Y. Peng, U. Heinz, H. Song. Paper in Progress

Development of Pressure Anisotropy: VAH v.s. VH







- VAH

  Anisotropic distribution guarantees $P_L > 0$

  Large anisotropy treated non-perturbatively; small residual corrections keep the gradient expansion valid

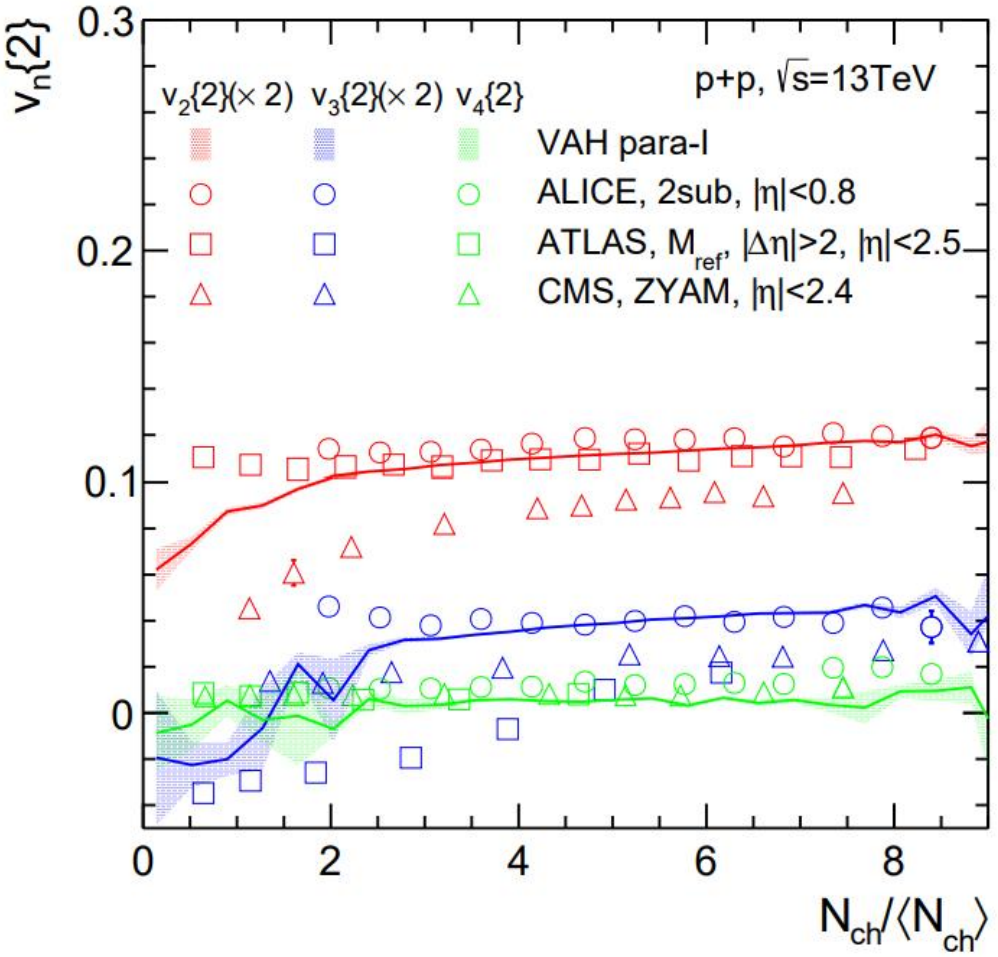
- VH

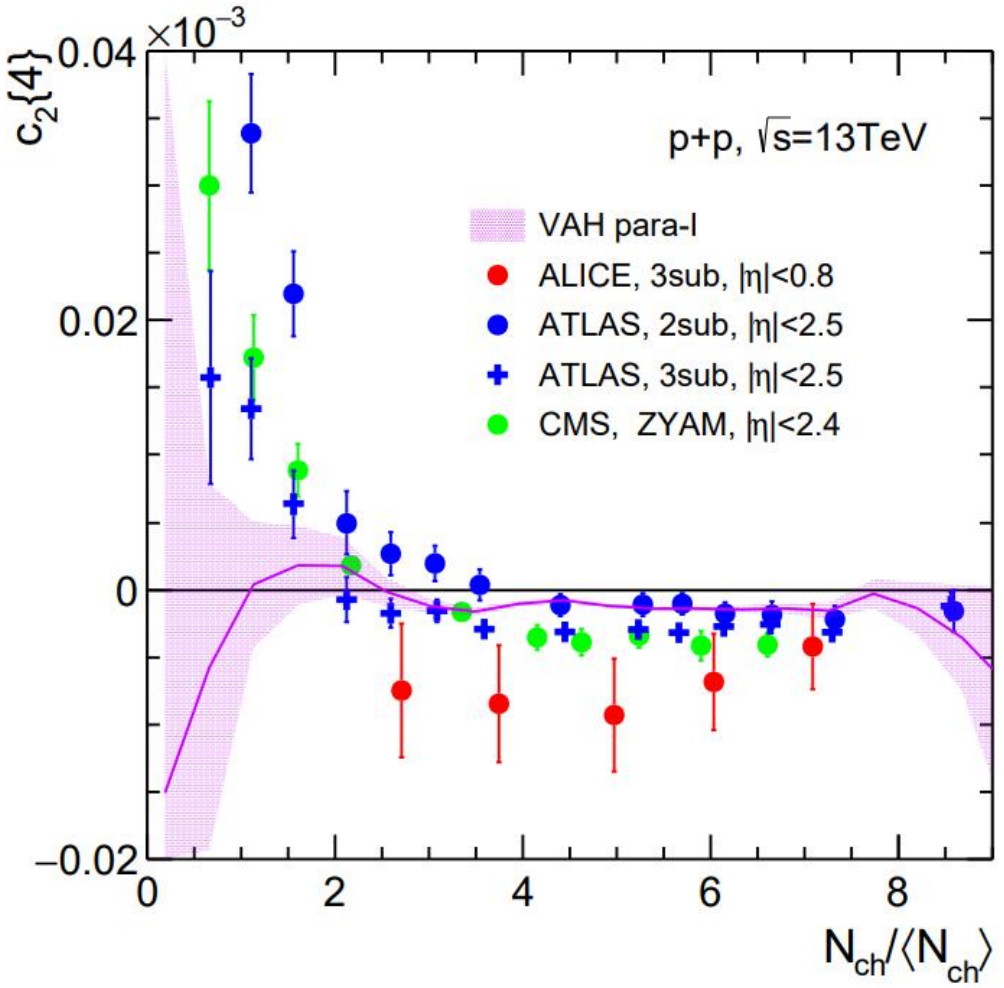
  Negative P_L prolongs the evolution, final stage result in lower P_L/P_T

  Early dynamics dominated by regions with $Re^{-1} > 0.5$

SJZ, Y. Peng, U. Heinz, H. Song. Paper in Progress

Description of Flow Measurement in p-p Collisions



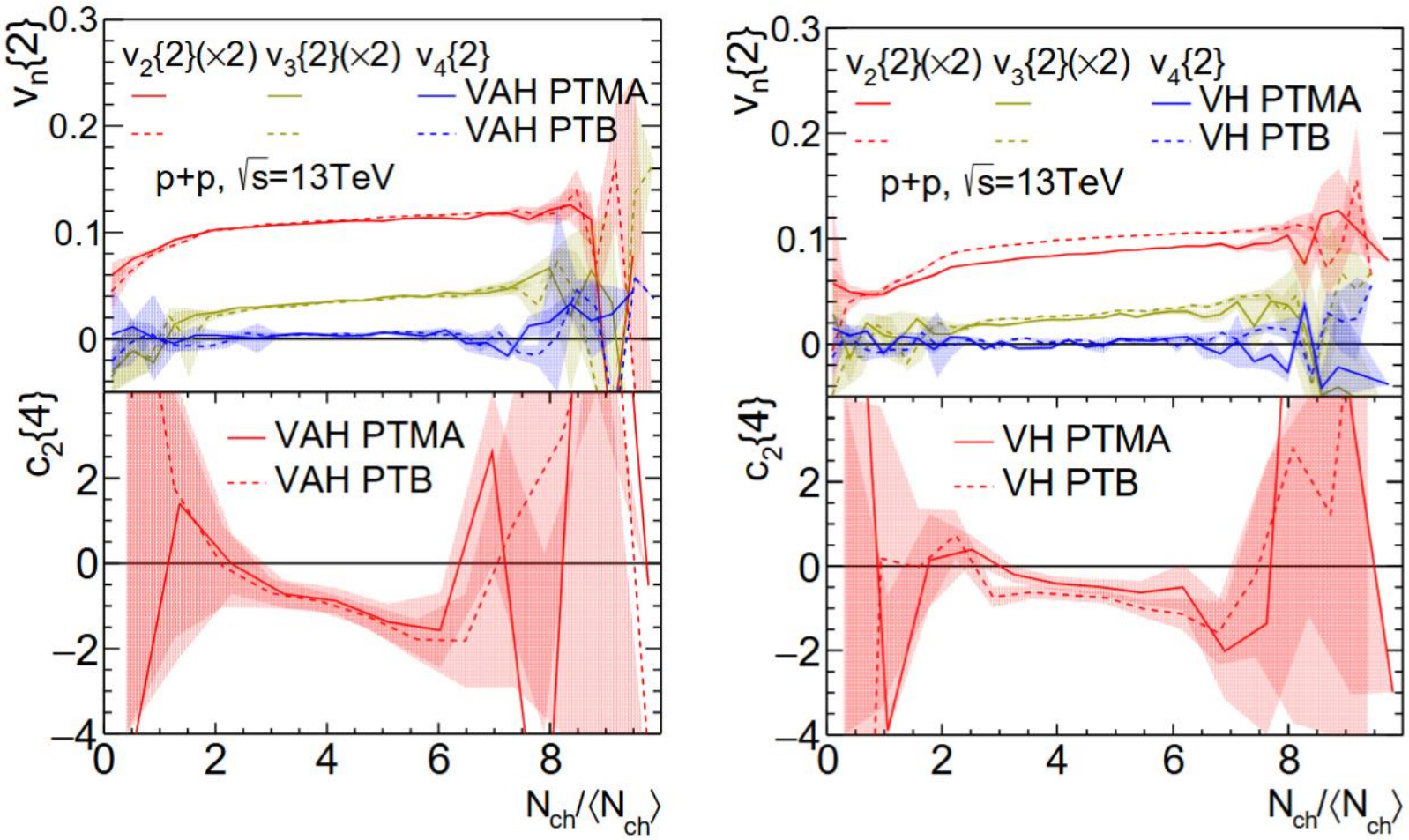


Two-particle correlations reproduced down to low multiplicity.

Correct $c_2\{4\}$ sign reproduced, but magnitude need more mechanism.

SJZ, Y. Peng, U. Heinz, H. Song. Phys.Rev.Lett. 137 (2026) 6, 062301

Particlization dependence on hydro evolution



VAH: PTMA ≈ PTB (freeze-out surface near equilibrium)

VH: PTMA ≠ PTB (larger off-equilibrium corrections at freeze-out)

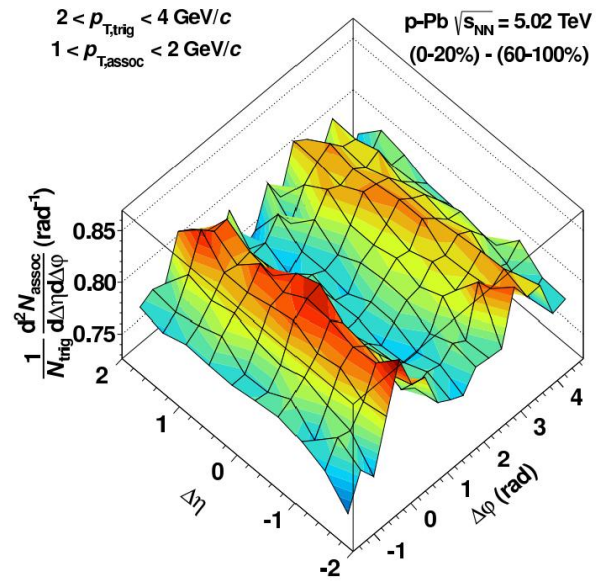
δf sensitivity reflects how far the hydro surface is from equilibrium

Summary

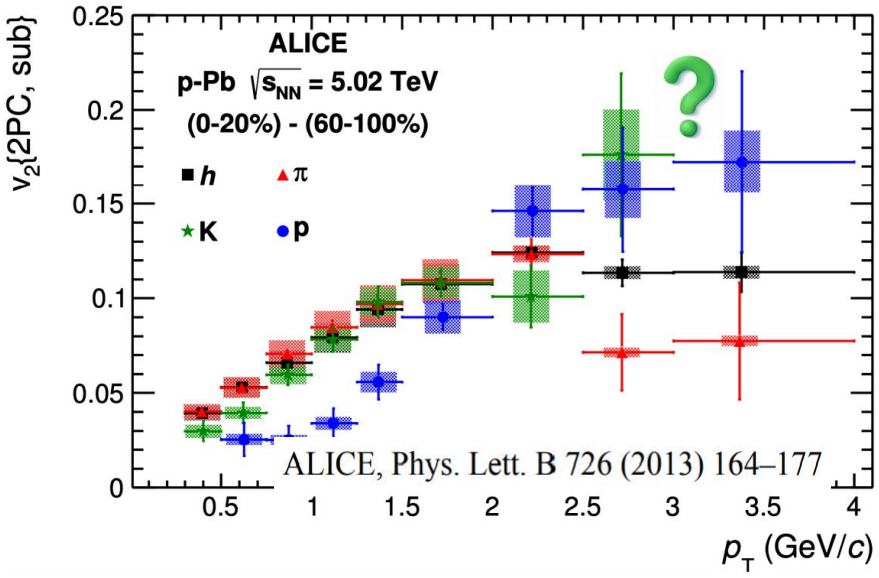
1. Hydro describes heavy-ion collisions well, but small systems differ substantially.
2. Small size and short lifetime → pre-equilibrium dynamics with large pressure anisotropy must be treated carefully. No clear separation between initial- and final-stage.
3. VAH treats the pressure anisotropy non-perturbatively → better suited for small systems, more thermalized than VH.
4. With hybrid framework developed based on VAH, the two- and four-particle flow cumulants in p-p collisions are successfully described. Further quantitative description relies on more realistic initial condition input.

Backup

Collectivity in Small Collision Systems

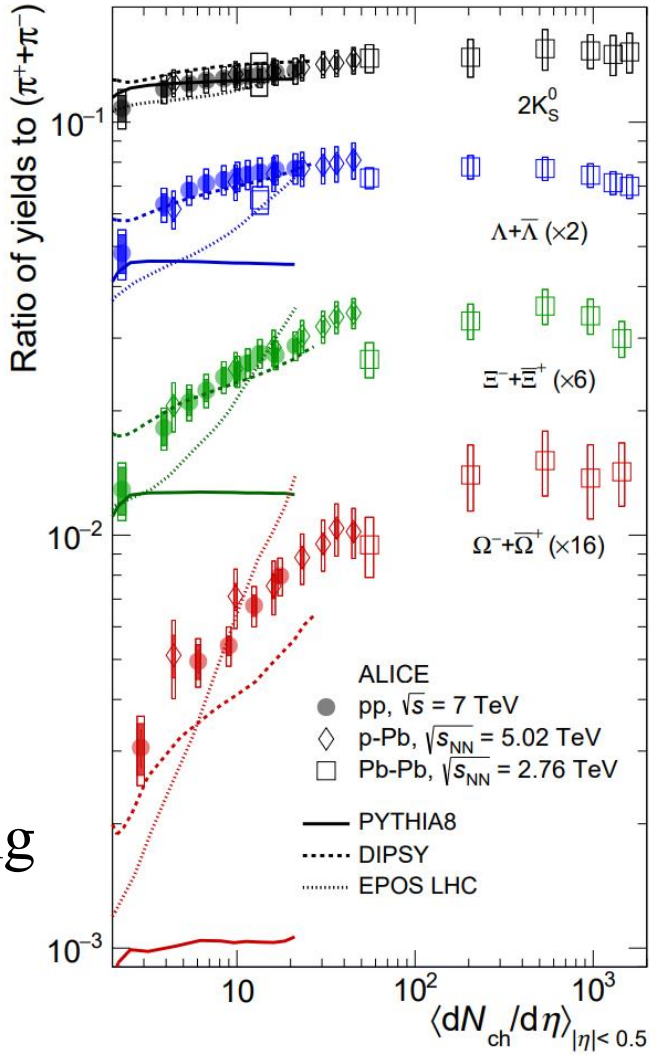


ALICE, Phys.Lett. B719 (2013) 29-41



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

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



Origin of collectivity in small systems?

- Final-state:

Hydrodynamic response

Escape mechanism

- Initial-state:

Gluon saturation (CGC)

- Microscopic / string-based

MPI + color reconnection, string shoving

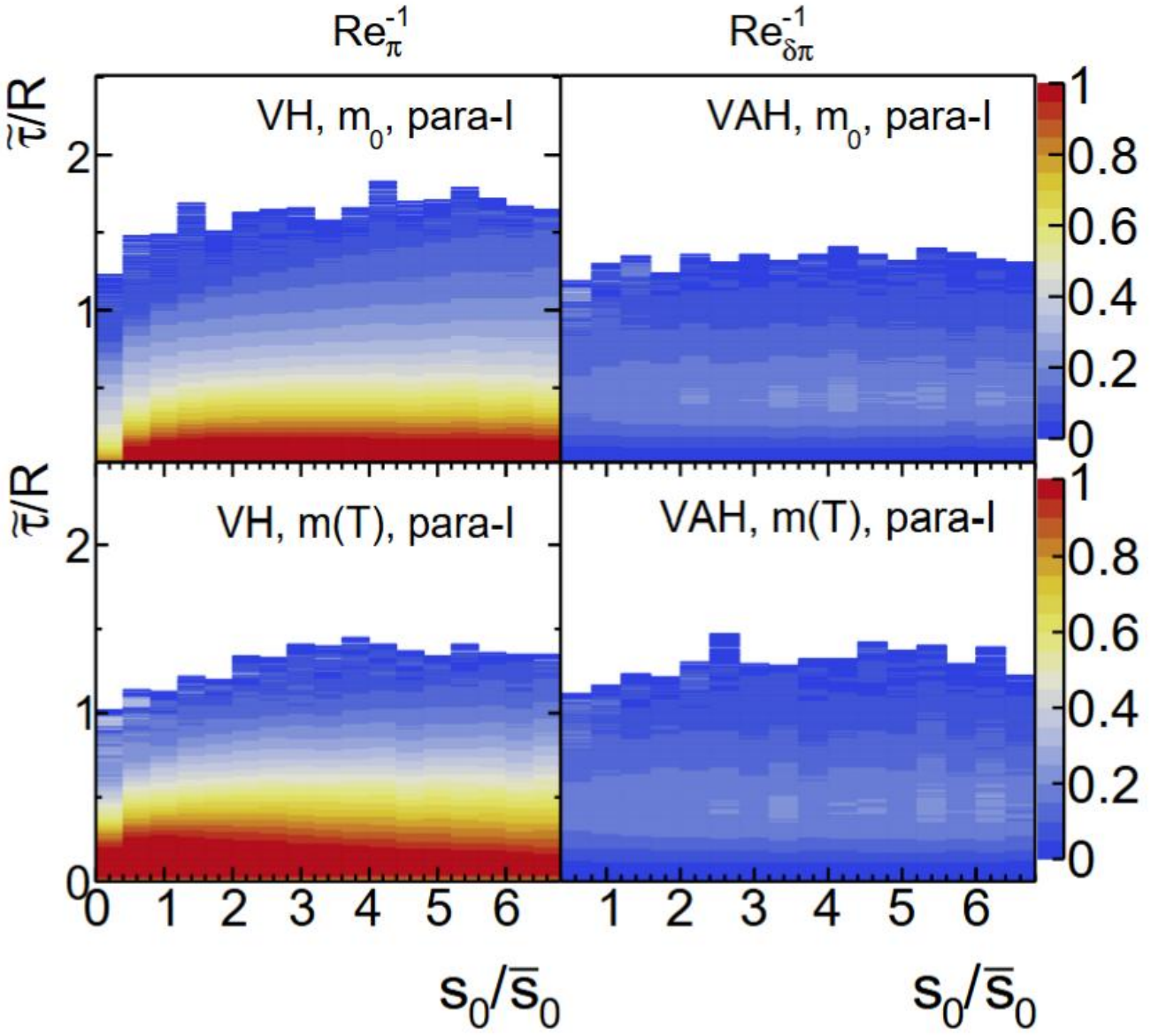
... ...

Viscous Correction in Small Collision Systems

p+p collisions in LHC:
Small system size
→ Large pressure gradient
→ Fast evolution
→ Non-eq correction may remain

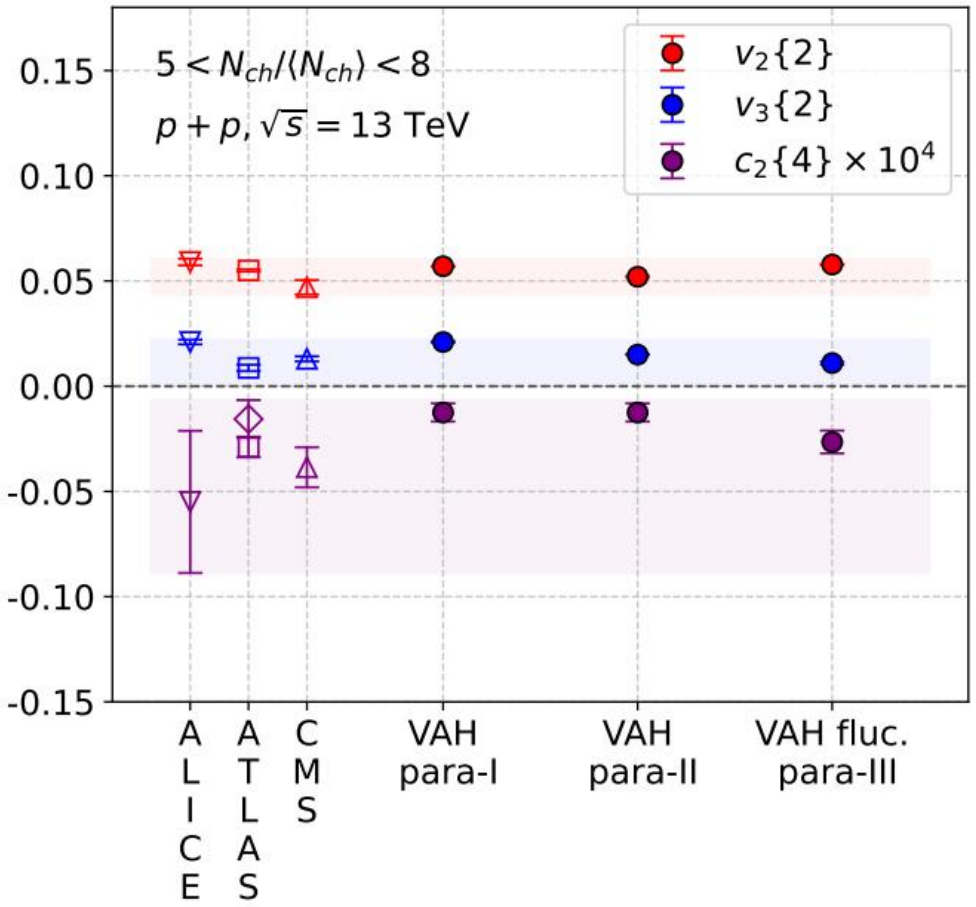
Standard VH:
Pressure gradient incoporate into viscous expansion ~ Convergence?

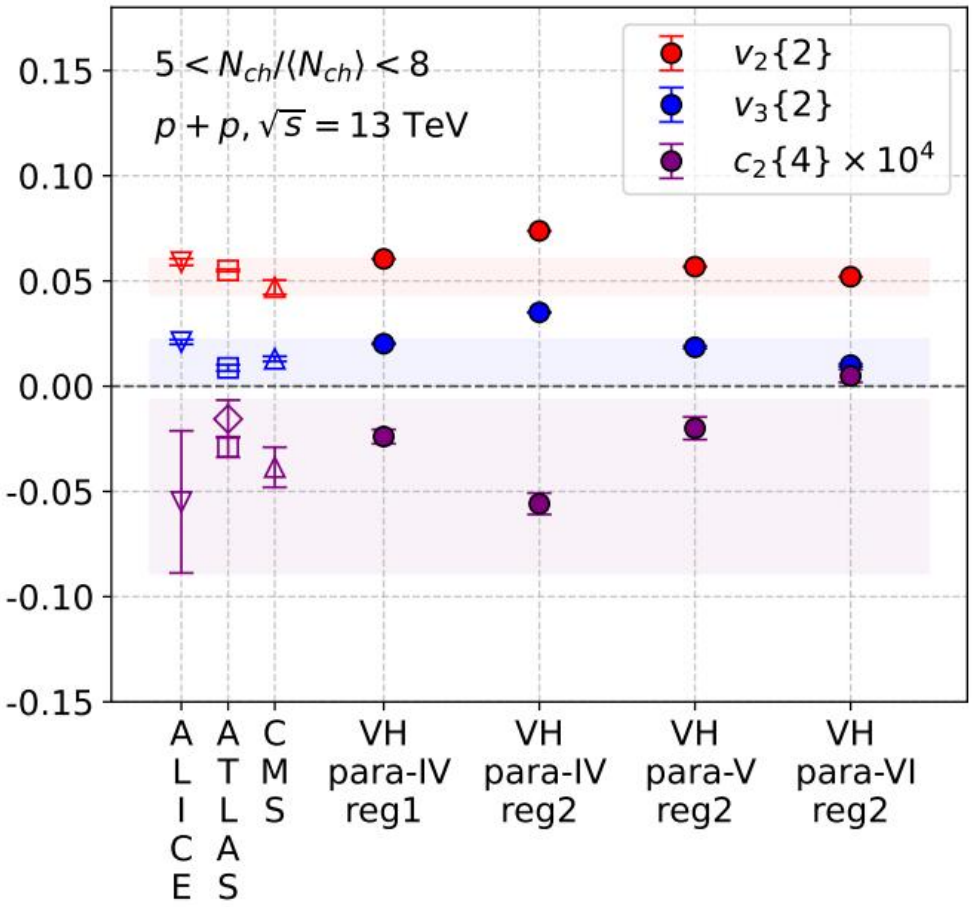
VAH: Validity determined by residual corrections



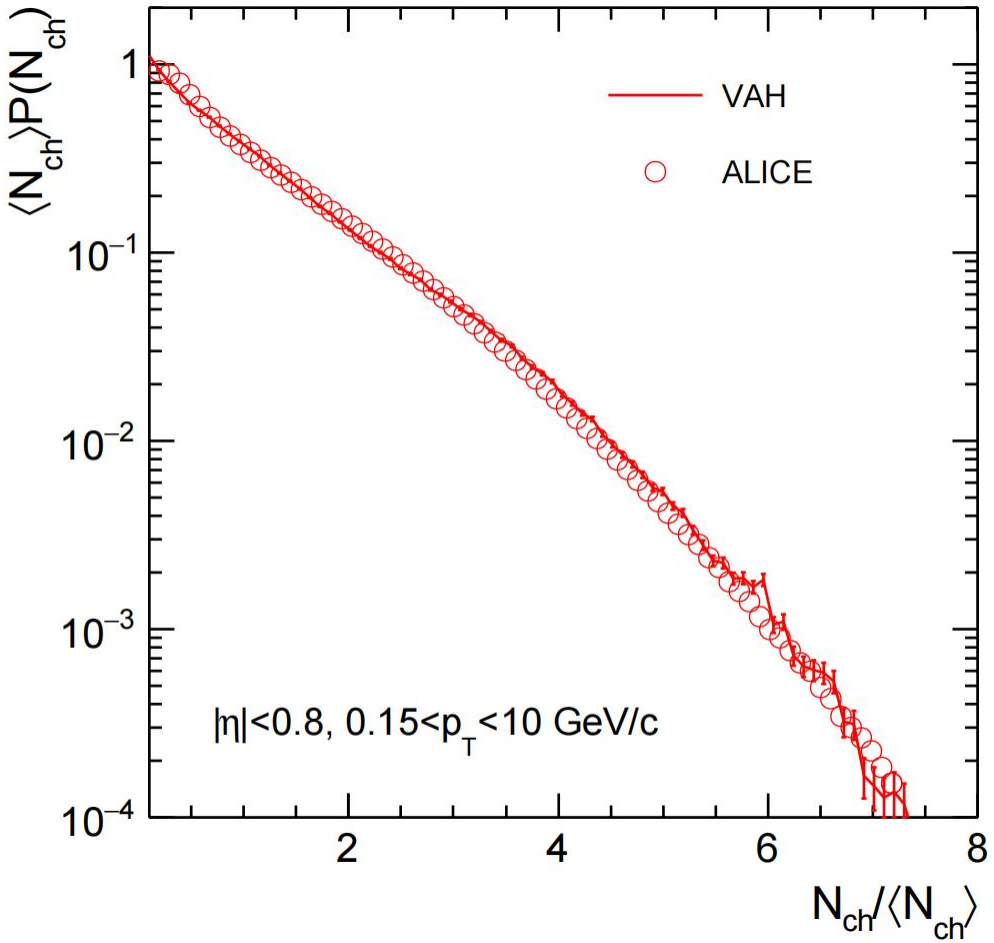
Zhao, Y. Peng, U. Heinz, H. Song. Paper in Progress

Comparison between VH and VAH





Multiplicity Distribution



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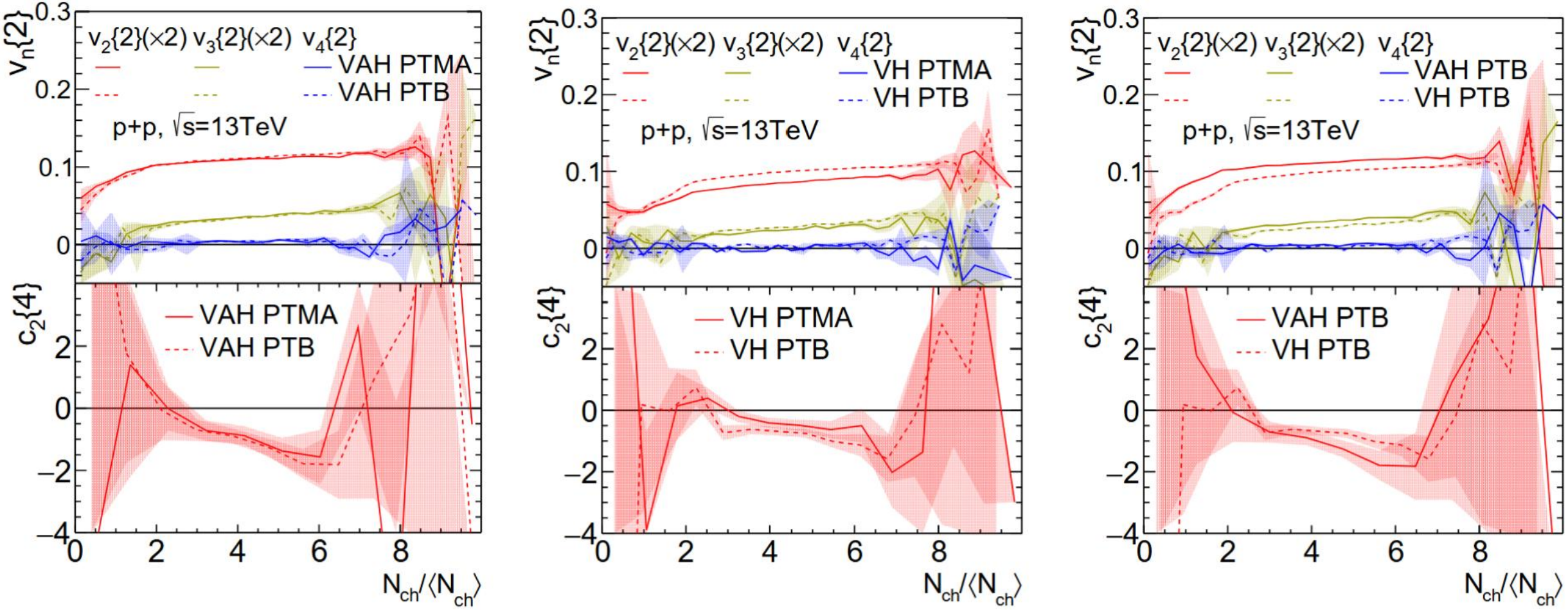

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