

Evaluating the anisotropic fluid behavior and partonic degree of freedom in O+O and Ne+Ne Collisions

Yili Wang

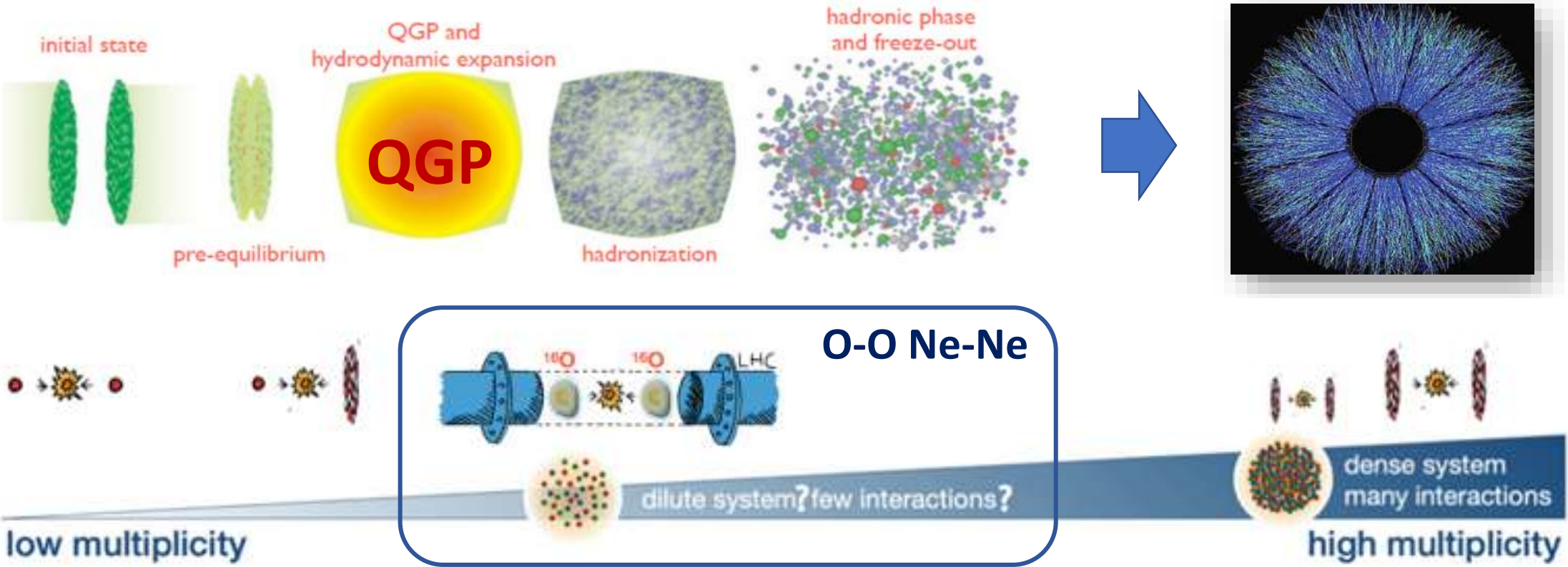
Peking University

(Spicy Gluons 2026, Oct. 18th 2026)



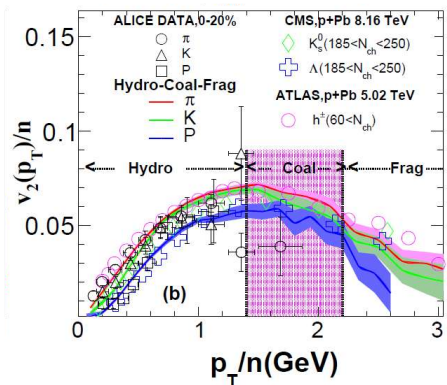
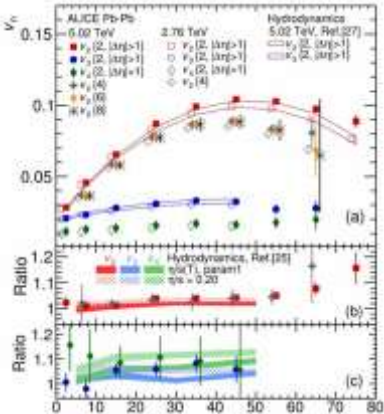
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QGP and Hydrodynamics in O-O and Ne-Ne Collisions



Fluid behavior
Assess the applicability of conventional viscous hydrodynamics

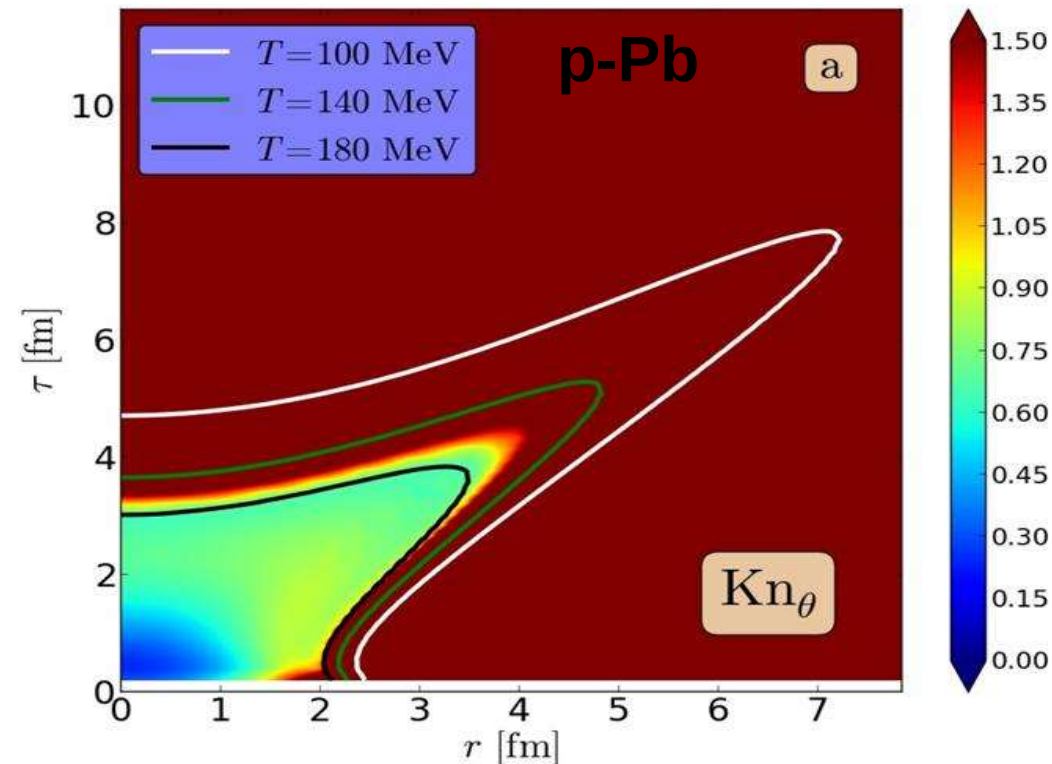
Partonic collectivity
NCQ scaling provide evidence for partonic degrees of freedom



Applicability of hydrodynamics in small systems

Knudsen number $K_n = \lambda/L \ll 1$

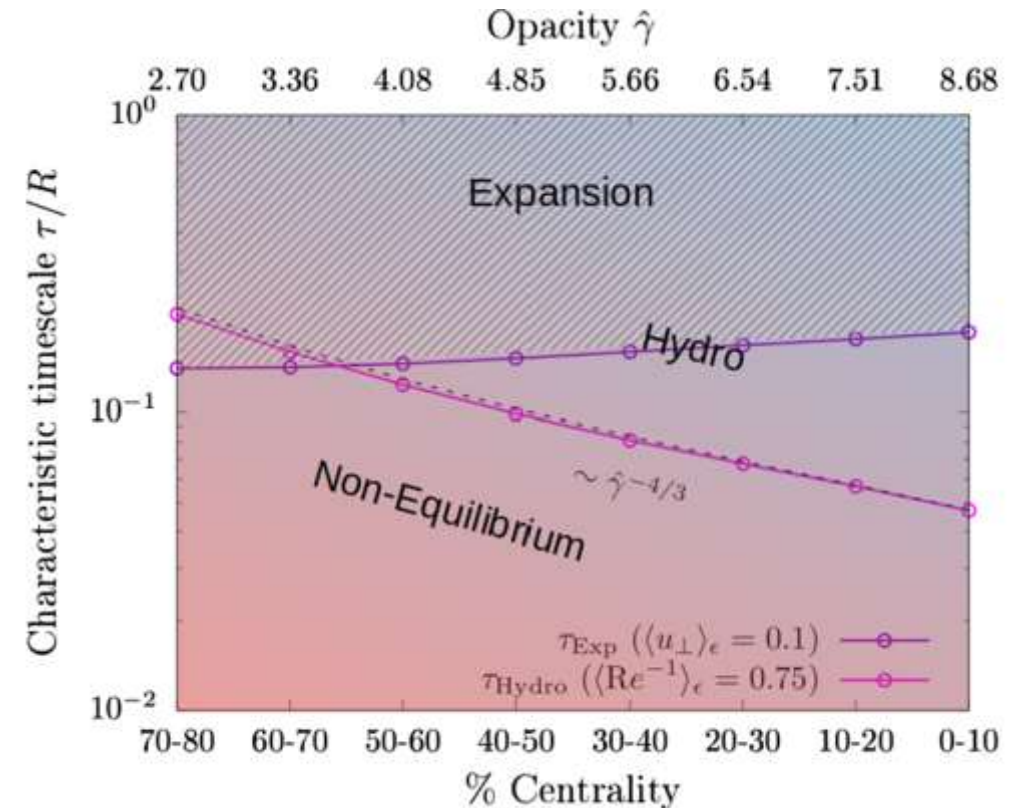
- Large local Knudsen numbers can arise in small collision systems.



H. Niemi, G.S. Denicol, arXiv:1404.7327

Inverse Reynolds number $Re^{-1} \ll 1$

- Transverse expansion may begin before the hydrodynamic regime is reached



V. Ambrus, S. Schlichting and C. Werthmann, PRL. 130, 152301 (2023)

Small Systems: shorter lifetimes and smaller size
→ Challenge near-equilibrium conditions

Viscous Anisotropic Hydrodynamics (VAH)

VH

$$f = f_{\text{eq}} + \delta f$$

$$f_{\text{eq}} = \left[\exp\left(-\sqrt{m^2 + \mathbf{p}^2}/T\right) + \Theta \right]^{-1}$$

$$T^{\mu\nu} = \boxed{\mathcal{E} u^\mu u^\nu - (\mathcal{P}_{\text{eq}} + \Pi) \Delta^{\mu\nu}} + \pi^{\mu\nu}.$$

dominant terms

small corrections

Treats pressure anisotropy as a **perturbative correction**.

VAH

$$f(x, p) = f_a(x, p) + \delta \tilde{f}(x, p)$$

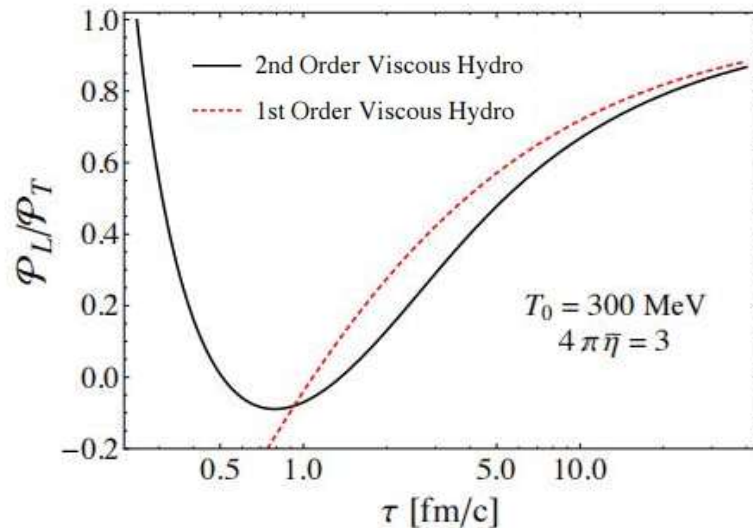
$$f_a = \left[\exp\left(-\frac{1}{\Lambda} \sqrt{m^2 + \frac{\mathbf{p}_\perp^2}{\alpha_\perp^2} + \frac{p_z^2}{\alpha_L^2}}\right) + \Theta \right]^{-1}$$

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

dominant terms

small corrections

Incorporates pressure anisotropy at **leading order**.



Return to traditional hydro with small $\mathcal{P}_{L,\perp} - \mathcal{P}_{\text{eq}}$.

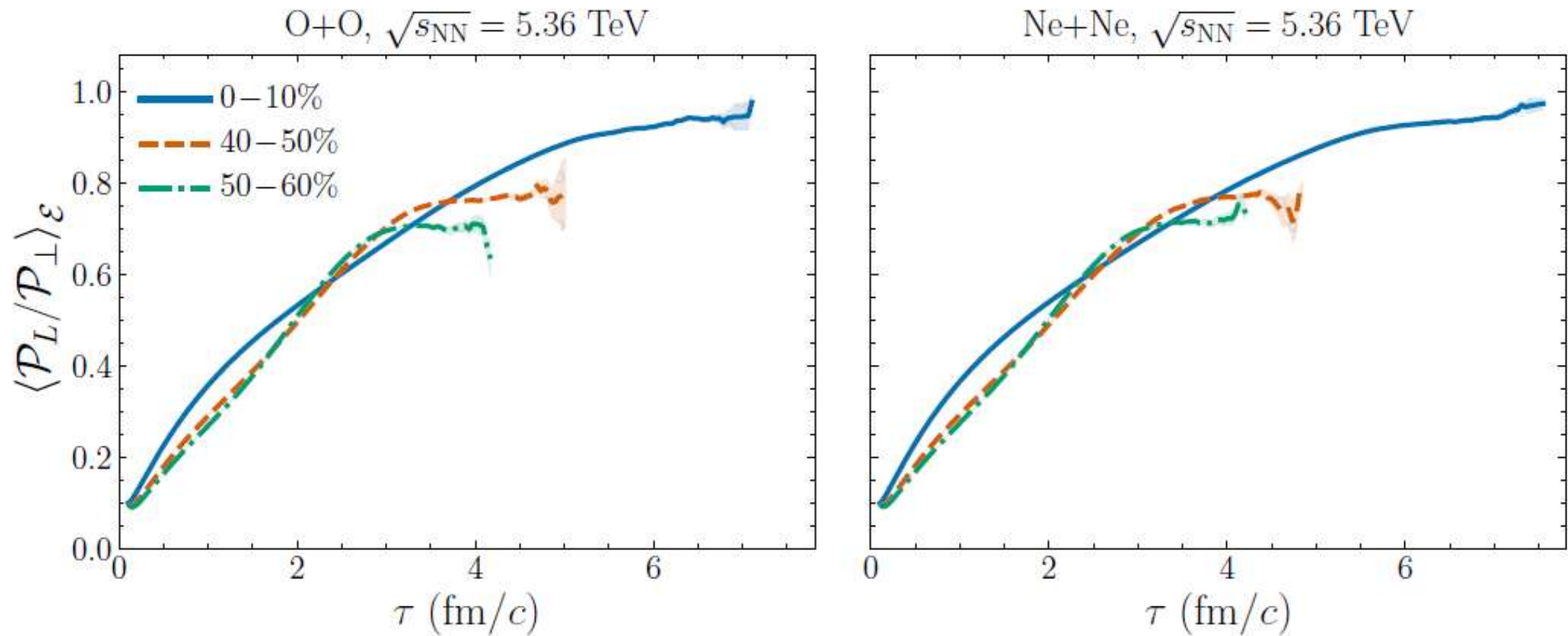
M. McNelis, D. Bazow, and U. Heinz, Com. Phys. Comm 267, 108077 (2021)

Small systems: strong pressure anisotropies can arise at early times and persist even until late in the evolution.



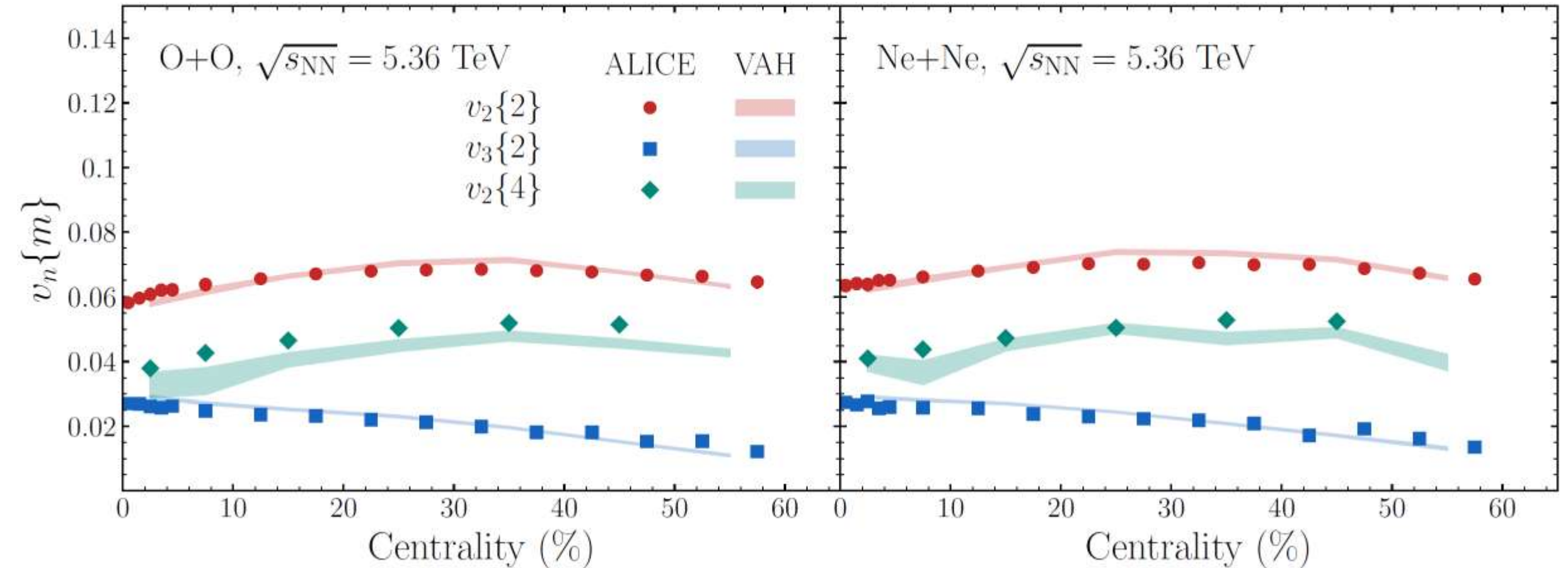
VAH is better suited

Pressure Anisotropy in O+O and Ne+Ne Collisions



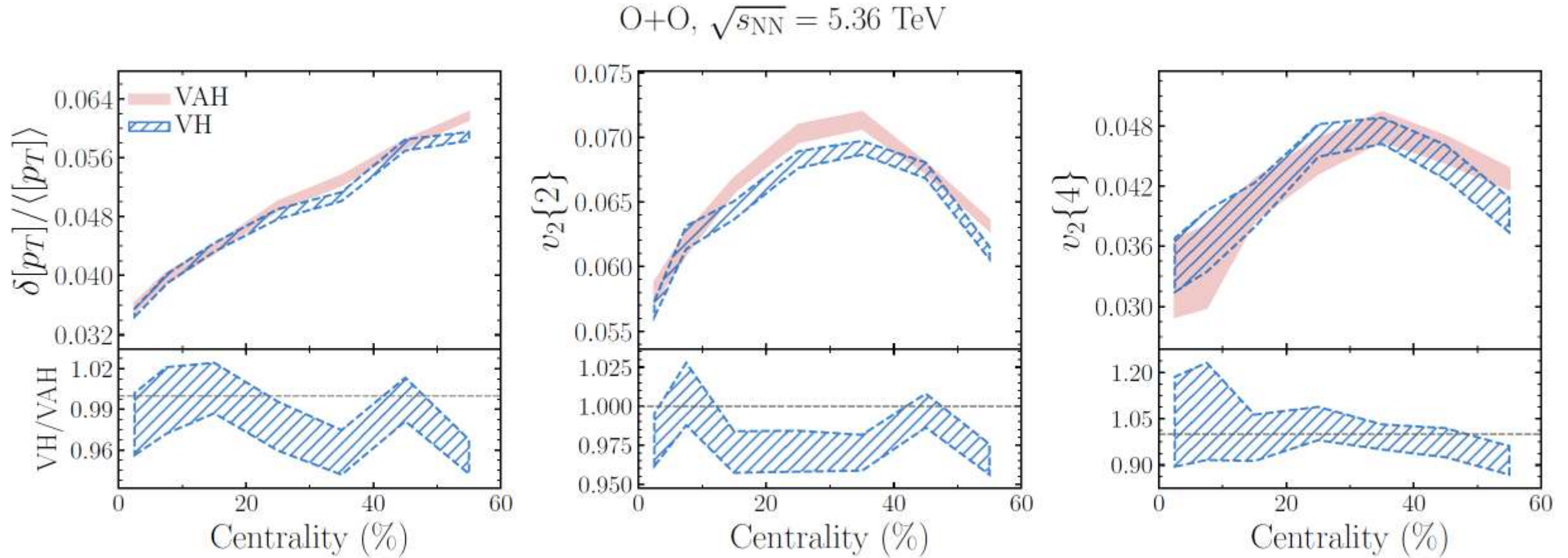
- Strong pressure anisotropy at early times across all centralities
- Pressure anisotropy persists toward the end of the evolution, particularly in peripheral collisions.
 - This motivates VAH in O+O and Ne+Ne collisions.

Flow Harmonics in O+O and Ne+Ne Collisions



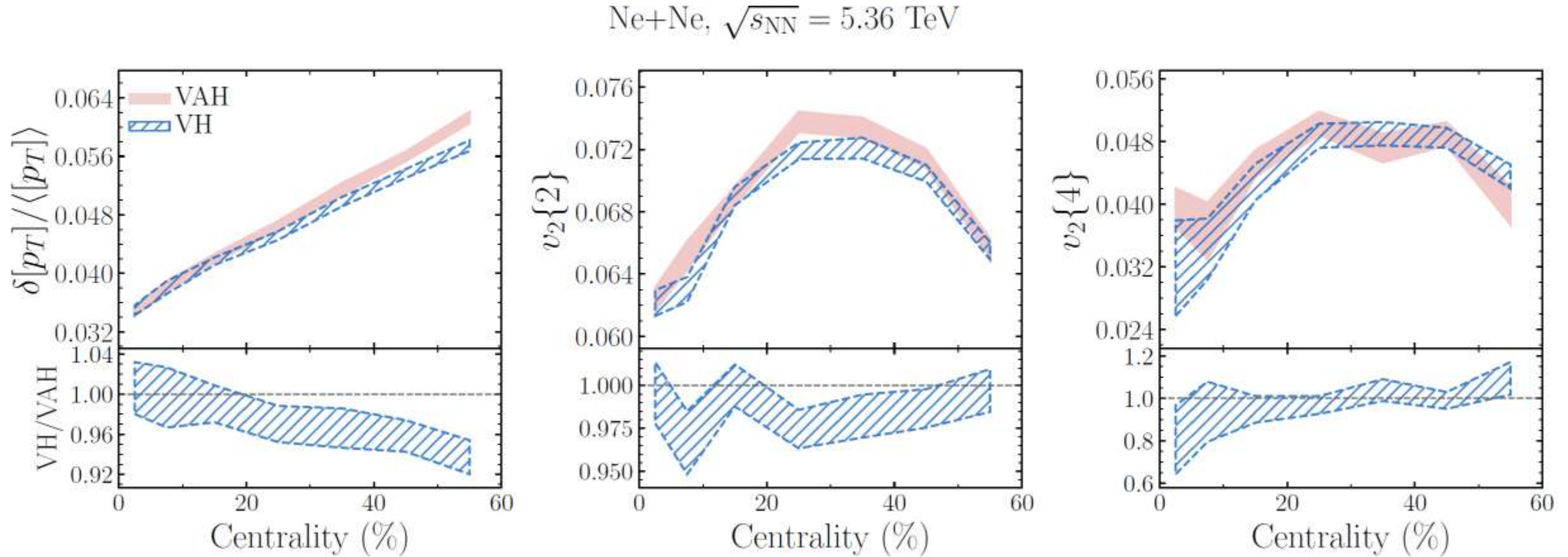
- We tune a common set of parameters to ALICE data, describing $v_2\{2\}$, $v_3\{2\}$, and $v_2\{4\}$ in both O+O and Ne+Ne collisions.

Comparison of VH and VAH in O+O Collisions



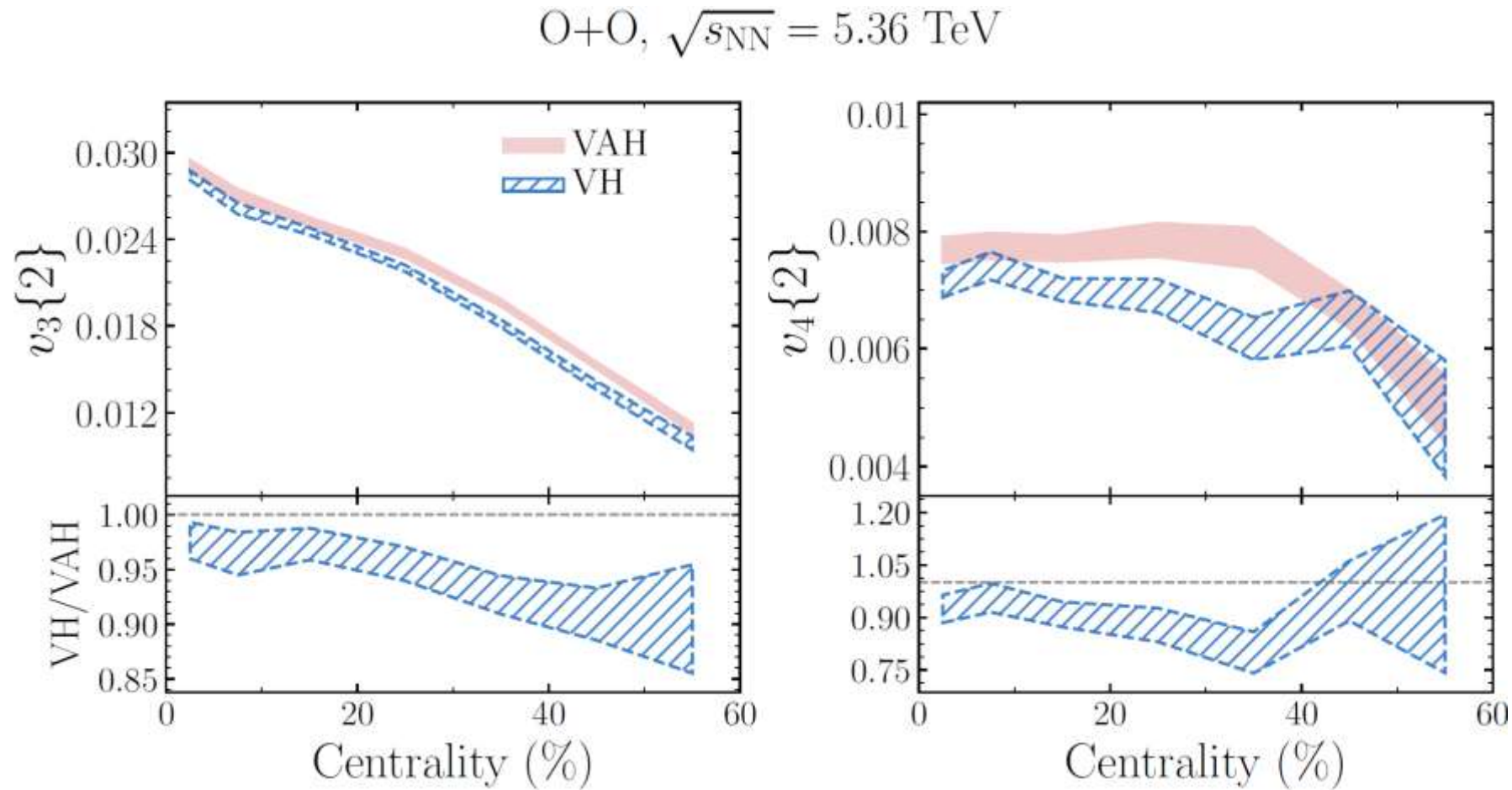
- VH and VAH give similar predictions for relative mean- p_T fluctuations and elliptic flow $v_2\{2\}$ and $v_2\{4\}$.

Comparison of VH and VAH in Ne+Ne Collisions



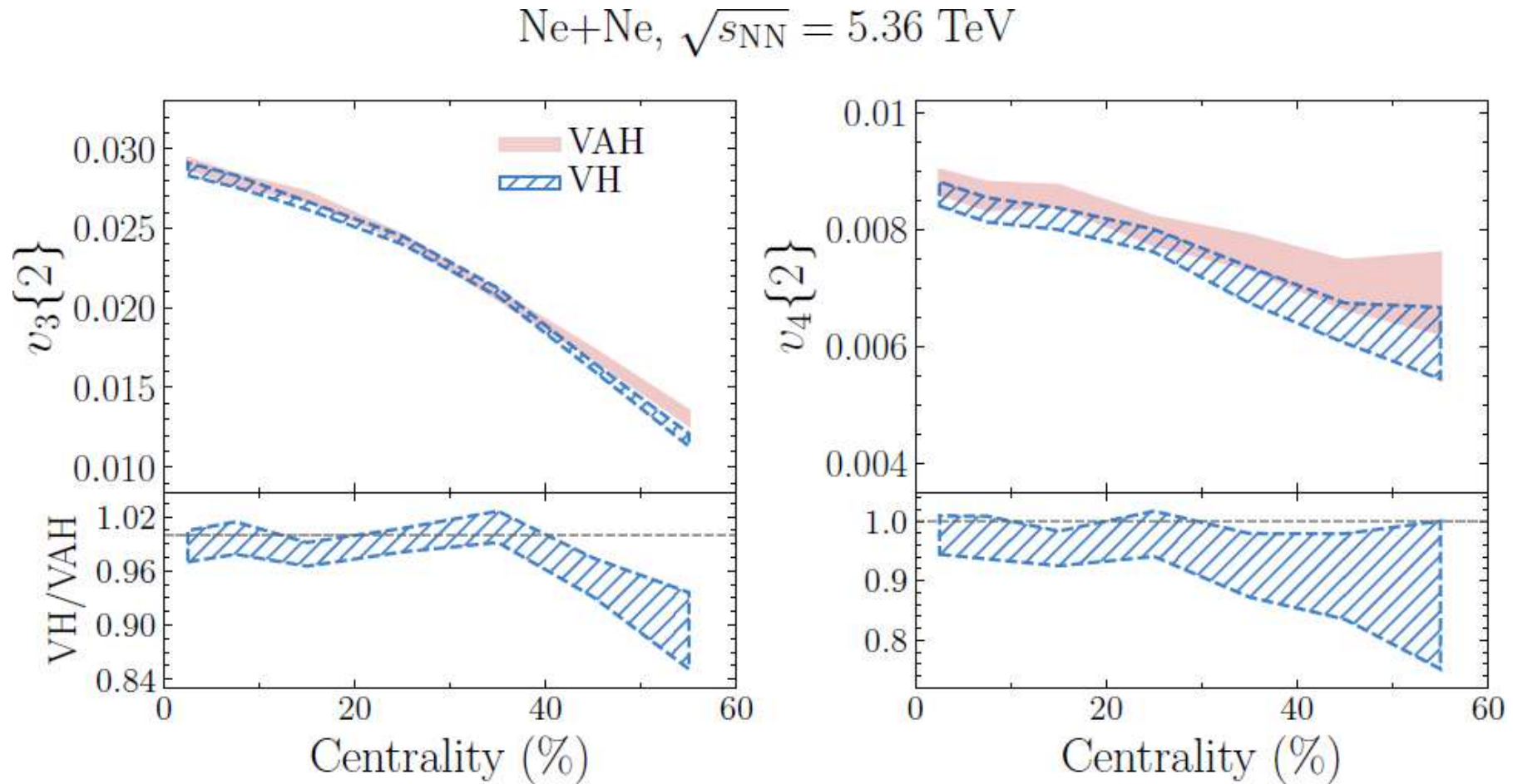
- VH and VAH give similar predictions for relative mean- p_T fluctuations and elliptic flow $v_2\{2\}$ and $v_2\{4\}$.

Higher-Order Flow Harmonics in O+O Collisions



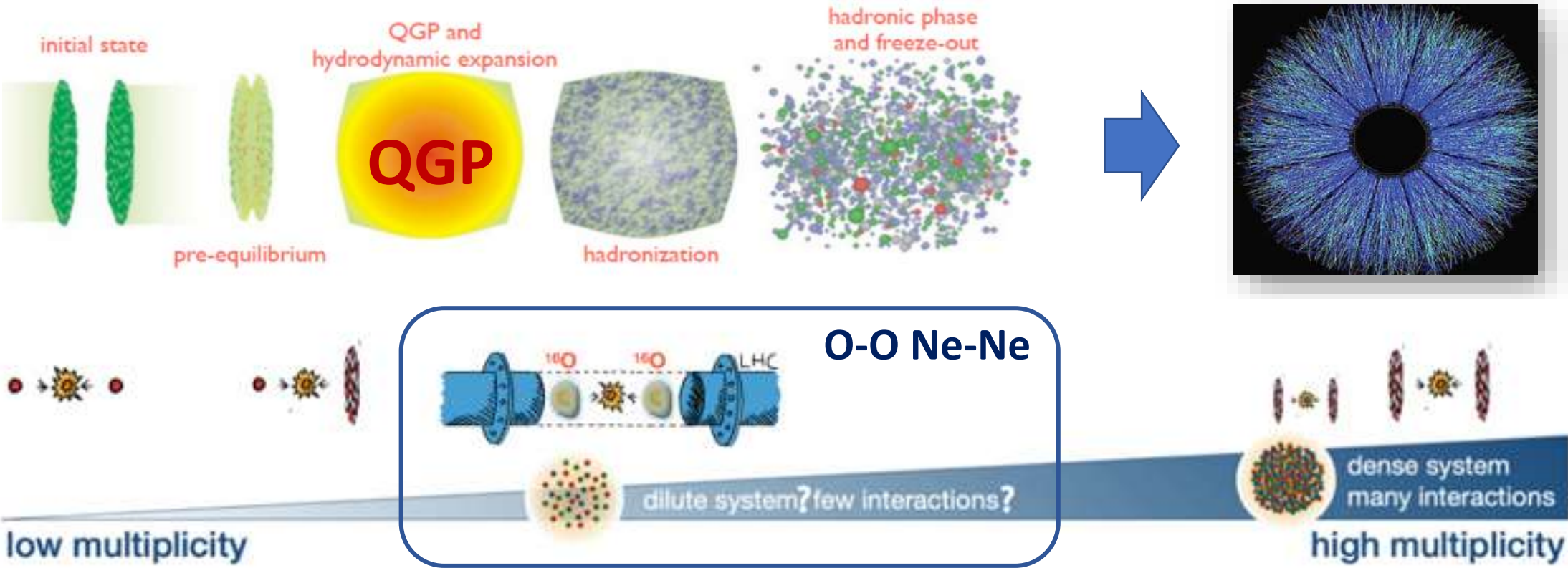
- Higher-order flow harmonics show larger VH–VAH differences, particularly in peripheral collisions.
- Further studies of other higher-order observables with increased statistics are ongoing.

Higher-Order Flow Harmonics in Ne+Ne Collisions



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- Further studies of other higher-order observables with increased statistics are ongoing.

QGP and Hydrodynamics in O-O and Ne-Ne Collisions

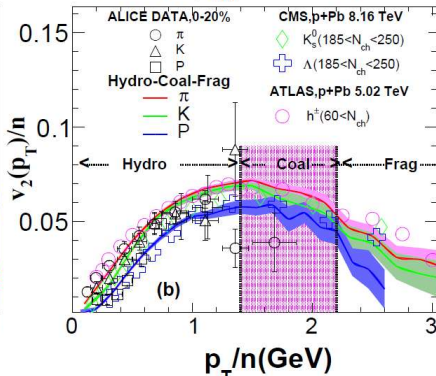
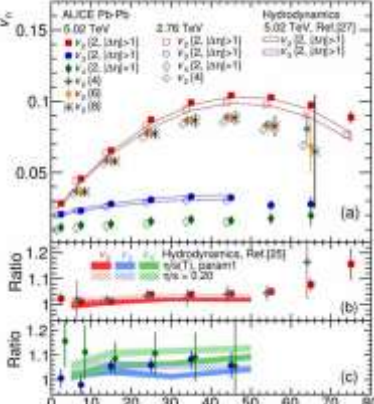


Fluid behavior

Assess the applicability of conventional viscous hydrodynamics

Partonic collectivity

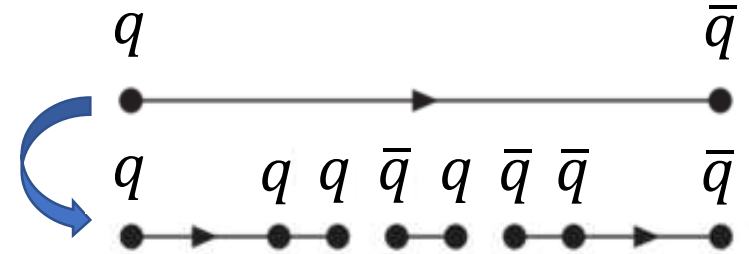
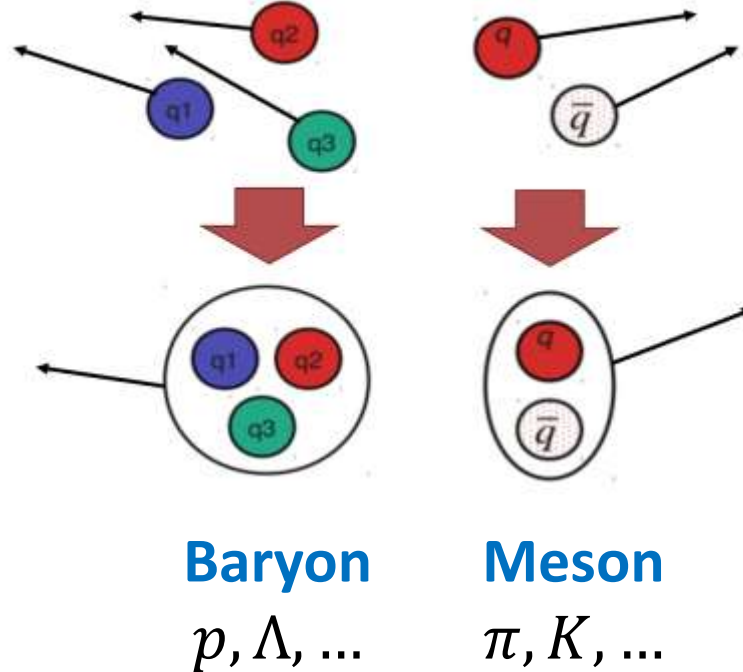
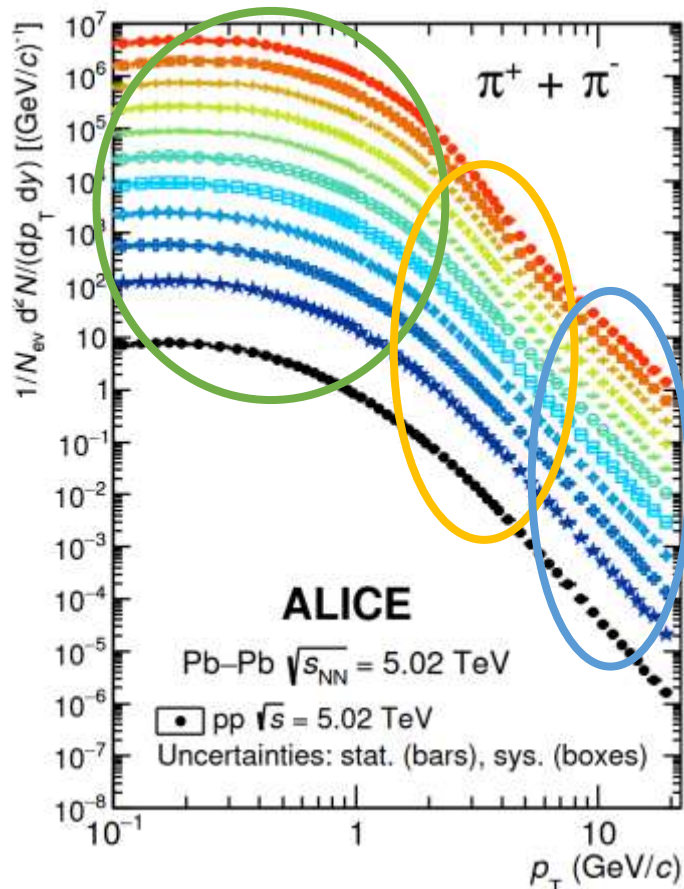
NCQ scaling provide evidence for partonic degrees of freedom



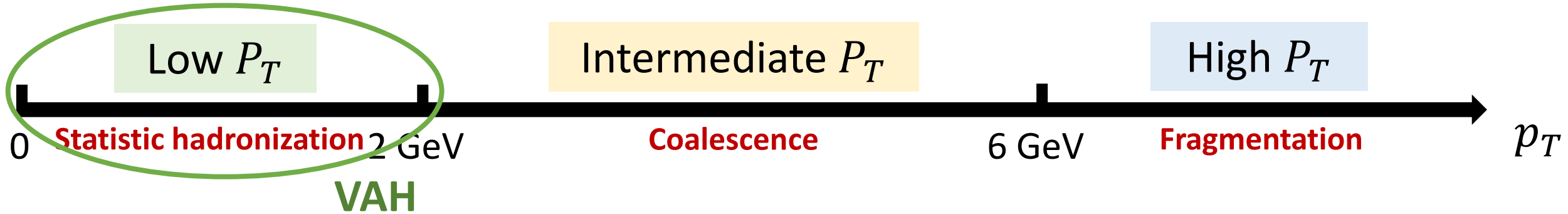
Particle production in different p_T region



~ 99% Hydrodynamics



Hydrodynamics with statistic hadronization at low p_T



$$T^{\mu\nu} = \mathcal{E} u^\mu u^\nu + \mathcal{P}_L z^\mu z^\nu - \mathcal{P}_\perp \Xi^{\mu\nu} + 2 W_{\perp z}^{(\mu} z^{\nu)} + \pi_\perp^{\mu\nu}$$

Conservation laws

$$\partial_\mu T^{\mu\nu}(x) = 0,$$

Relaxation equations

$$T^{\tau\mu}, \quad P_L, \quad P_\perp, \quad W_{\perp z}^\mu, \quad \pi_\perp^{\mu\nu}$$

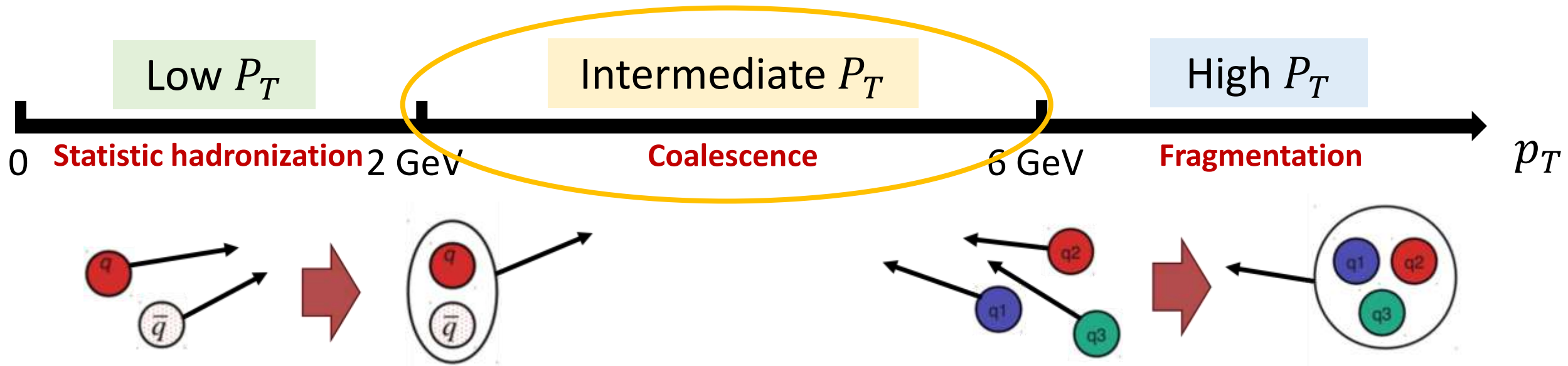
Input: EOS & Initial & final conditions

Output with statistic hadronization:

Cooper-Frye formula

$$\begin{aligned} E \frac{d^3 N_i}{d^3 p} &= \frac{g_i}{(2\pi)^3} \int_\Sigma p^\mu d^3 \sigma_\mu f_i(x, p) \\ &= \frac{g_i}{(2\pi)^3} \int_\Sigma p^\mu d^3 \sigma_\mu \left[f_{a,i}(x, p) + \delta \tilde{f}_i(x, p) \right]. \end{aligned}$$

Quark coalescence process at intermediate p_T



Instantaneous projection

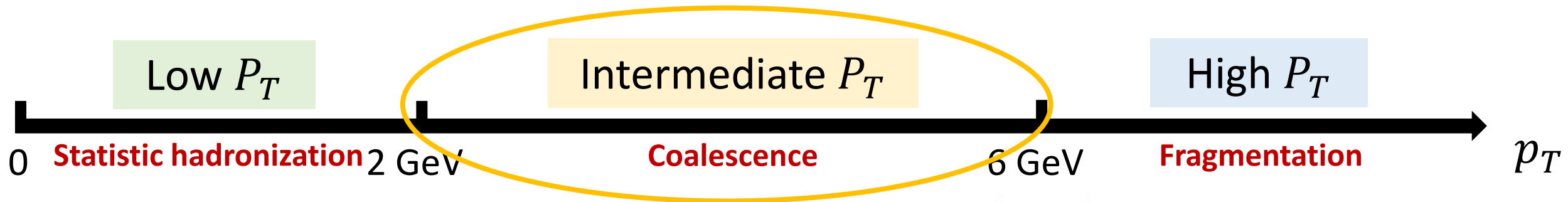
$$N_h = \int \frac{d^3 P}{(2\pi)^3} \langle h; \mathbf{P} | \rho | h; \mathbf{P} \rangle .$$

$$\underline{f_q(\mathbf{x}_1, \mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2, \mathbf{p}_2)}$$

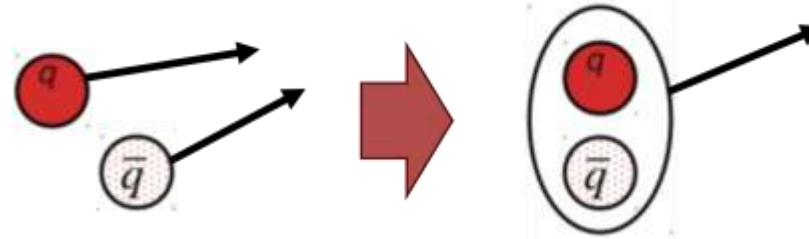
$$\frac{dN_M}{d^3 P} = \sum_{a,b} \int \frac{d^3 R}{(2\pi)^3} \frac{d^3 q d^3 r}{(2\pi)^3} W_{ab} \left(\mathbf{R} - \frac{\mathbf{r}}{2}, \frac{\mathbf{P}}{2} - \mathbf{q}; \mathbf{R} + \frac{\mathbf{r}}{2}, \frac{\mathbf{P}}{2} + \mathbf{q} \right) \Phi_M(\mathbf{r}, \mathbf{q}).$$

$$\Phi_M(\mathbf{r}, \mathbf{q}) = \int d^3 s e^{-i\mathbf{s} \cdot \mathbf{q}} \varphi_M \left(\mathbf{r} + \frac{\mathbf{s}}{2} \right) \varphi_M^* \left(\mathbf{r} - \frac{\mathbf{s}}{2} \right)$$

Quark coalescence process at intermediate p_T

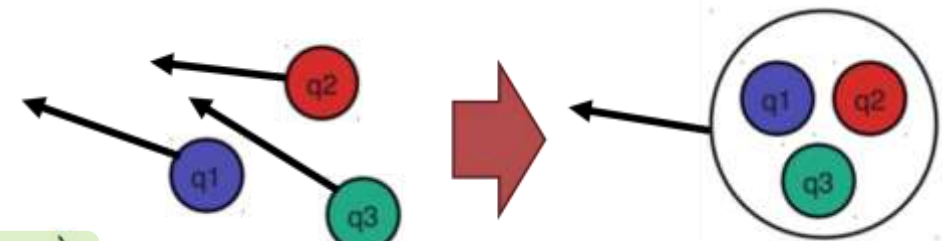


Meson



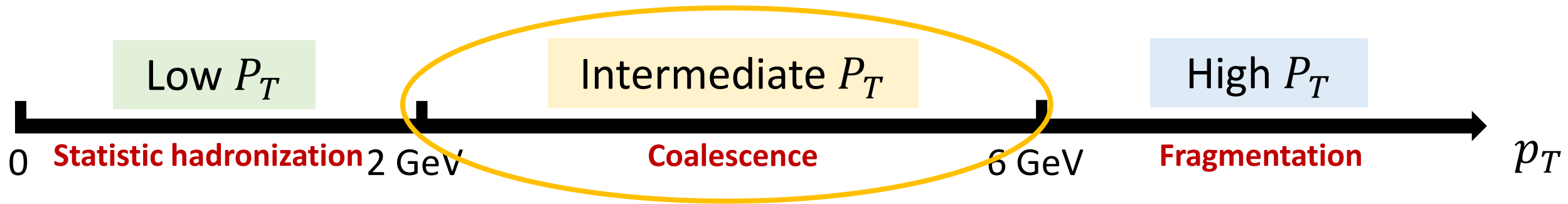
$$\frac{dN_M}{d^3\mathbf{P}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1, \mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2, \mathbf{p}_2) \times W_M(\mathbf{y}, \mathbf{k}) \delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2)$$

Baryon



$$\begin{aligned} \frac{dN_B}{d^3\mathbf{P}_B} = & g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1, \mathbf{p}_1) \\ & \times f_{q_2}(\mathbf{x}_2, \mathbf{p}_2) f_{q_3}(\mathbf{x}_3, \mathbf{p}_3) W_B(\mathbf{y}_1, \mathbf{k}_1; \mathbf{y}_2, \mathbf{k}_2) \times \delta^{(3)}(\mathbf{P}_B - \mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3) \end{aligned}$$

Quark coalescence process at intermediate p_T

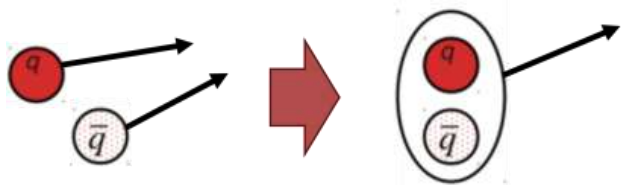


Thermal partons

- From hydrodynamics
- Via the Cooper–Frye formula

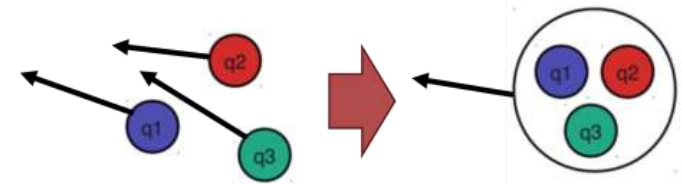
Hard partons

- Generated by PYTHIA 8
- Suffered energy loss by LBT



Thermal - Thermal

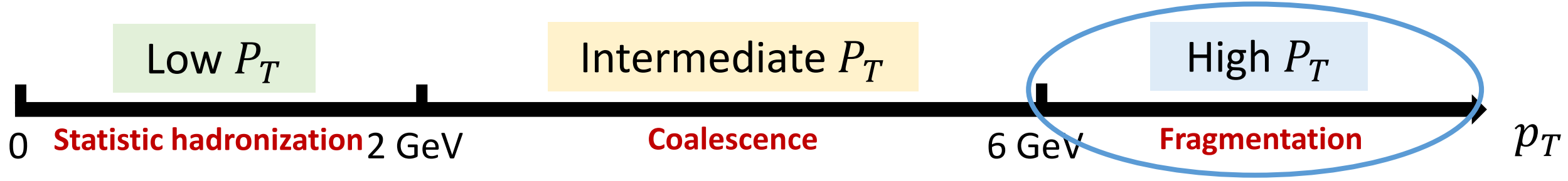
Quark Coalescence



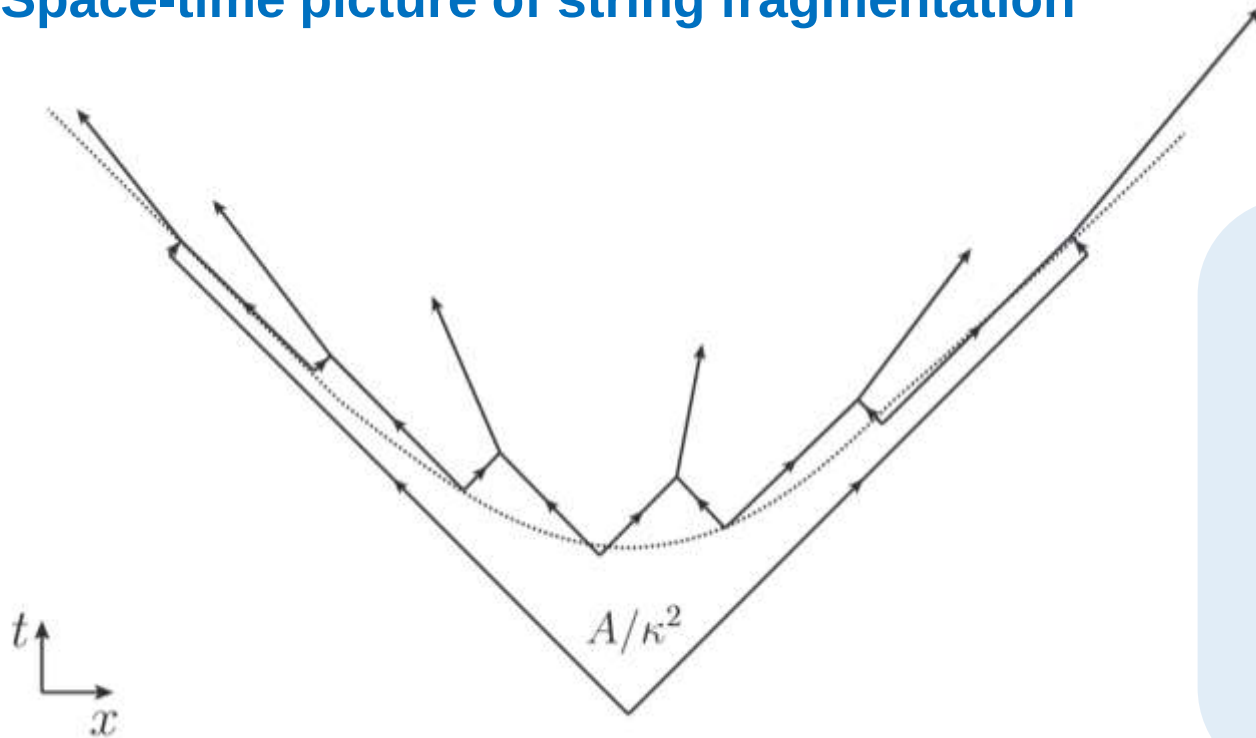
Thermal - Hard

Hard - Hard

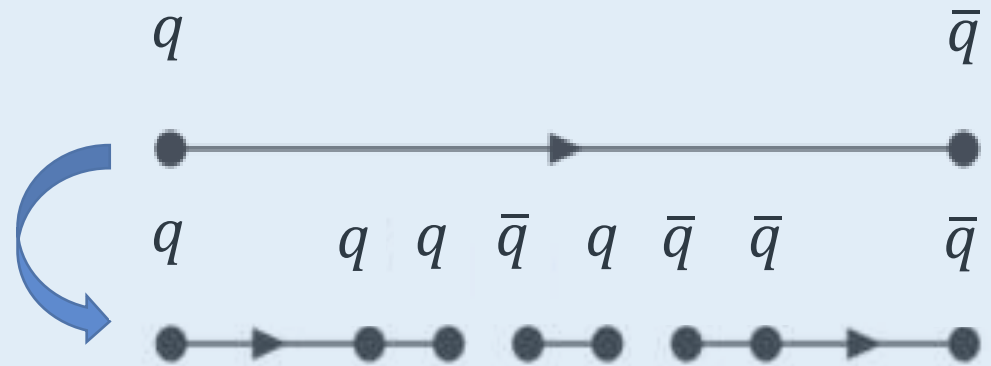
String fragmentation at high p_T



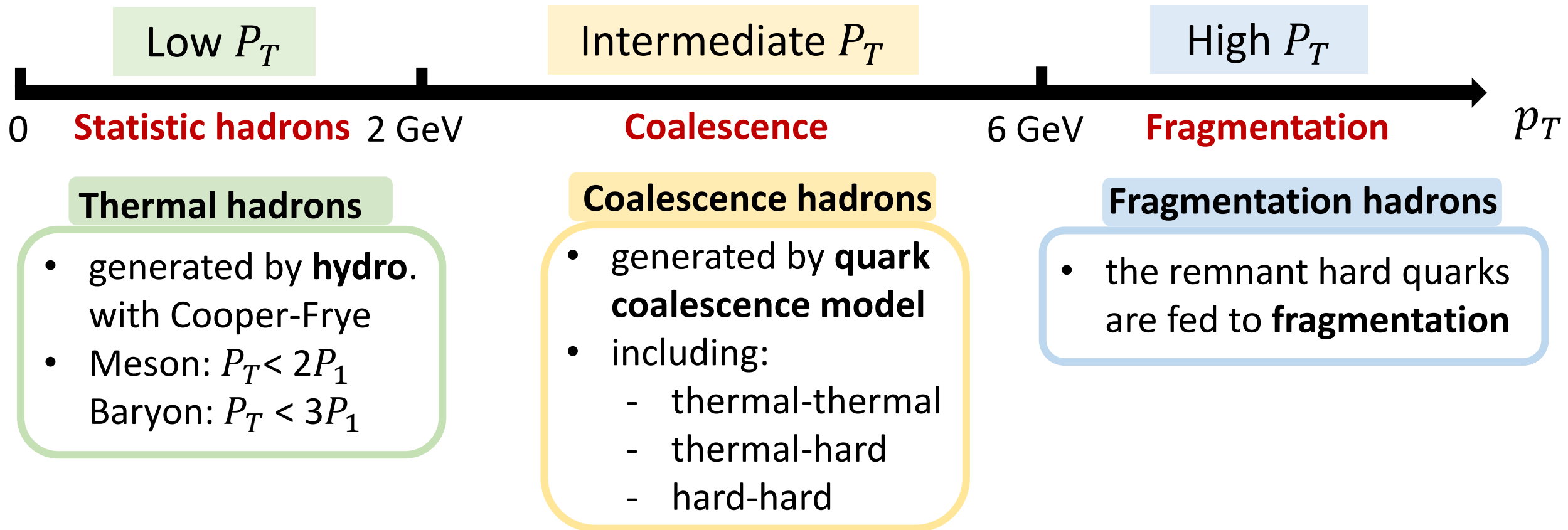
Space-time picture of string fragmentation



String breaking via $q\bar{q}$ pair production



Hydro-Coal-Frag Hybrid Model

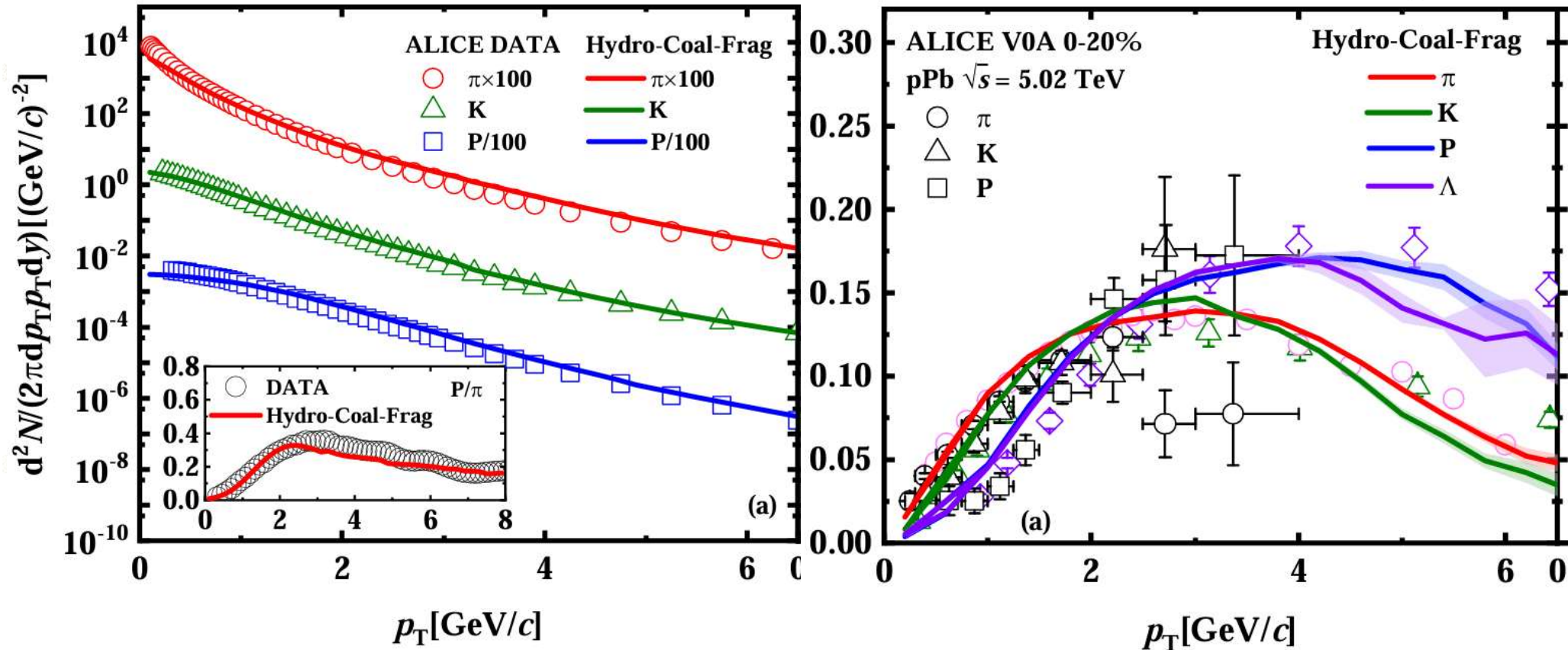


UrQMD afterburner:

- All produced hadrons are fed into UrQMD for hadronic evolution, scatterings and decays.

p_T spectra and elliptic flow of π, K, p from Hydro-Coal-Frag Model

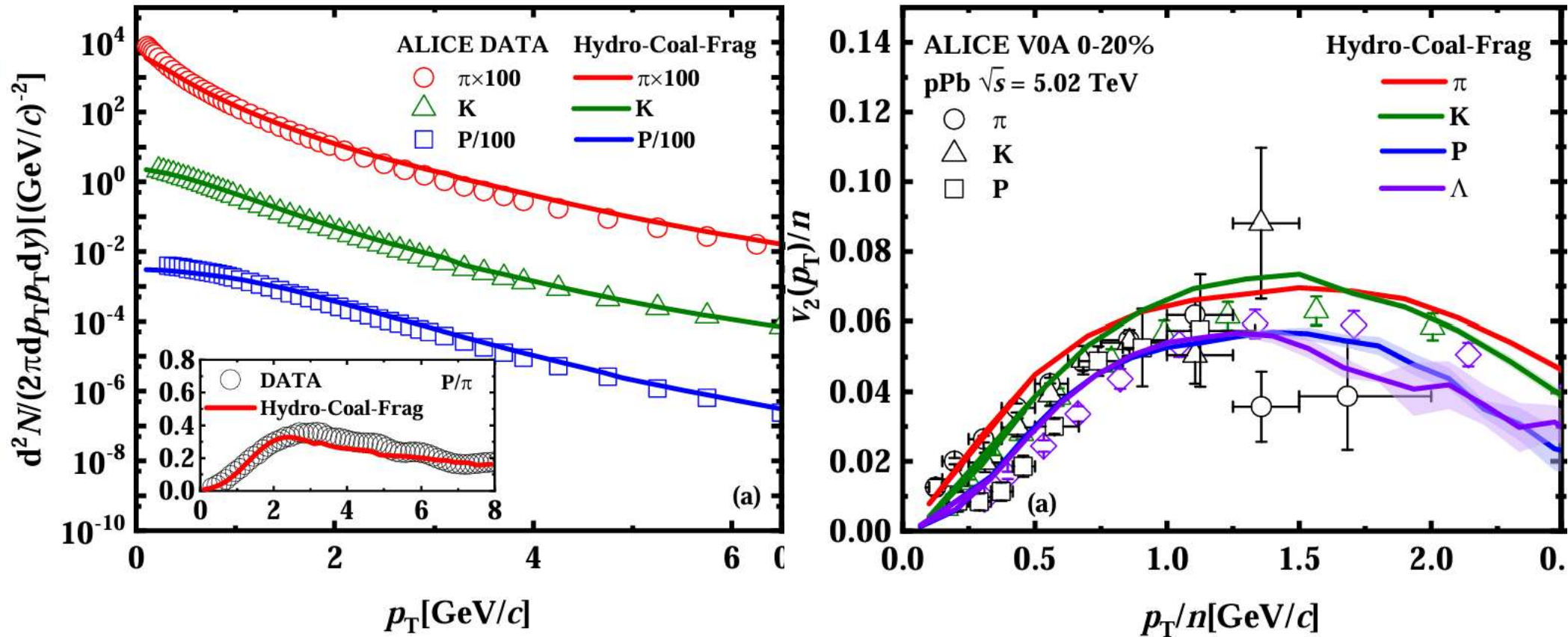
p+Pb @ $\sqrt{s_{NN}}=5.02$ TeV, 0-20%



- With coalescence at partonic level, we can nicely reproduce p_T spectra and elliptic flow of these stable hadrons (π K p ...) from 0 to 6 GeV

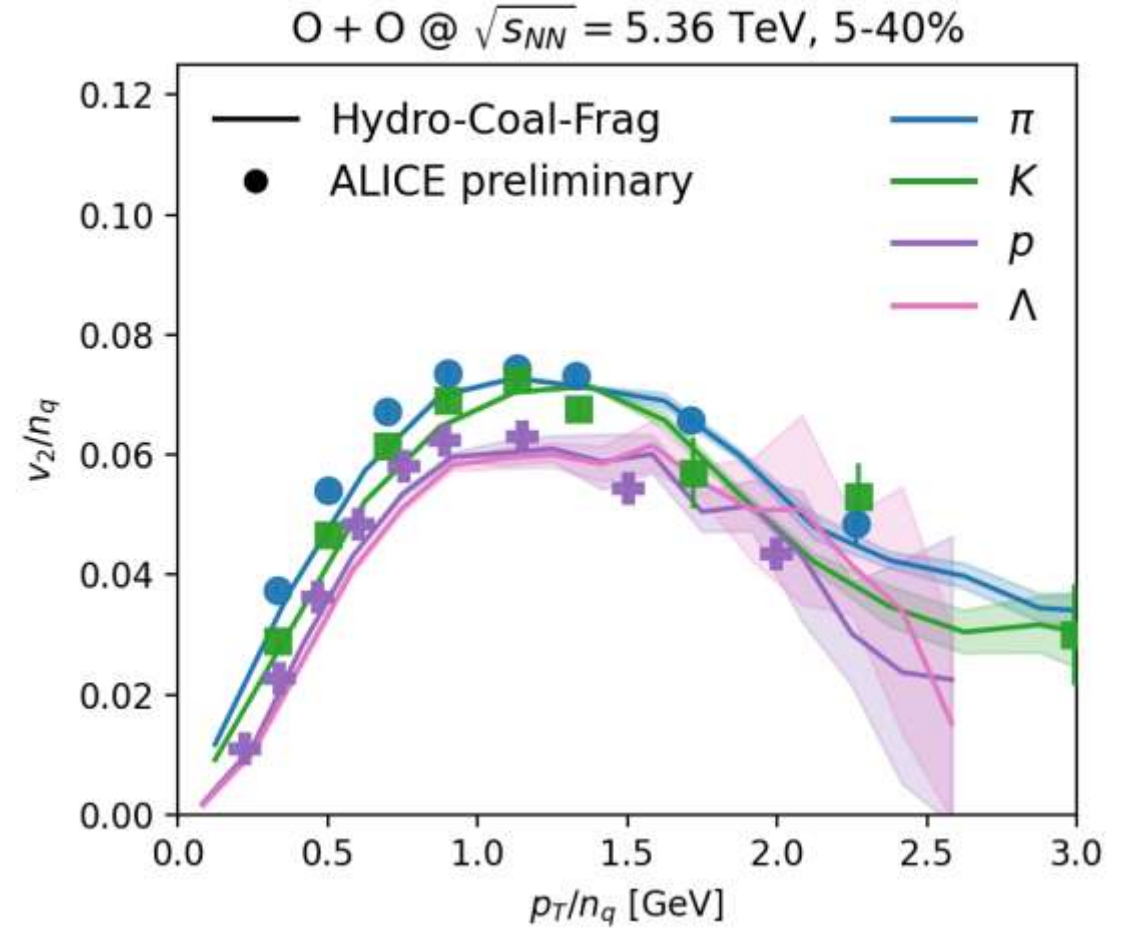
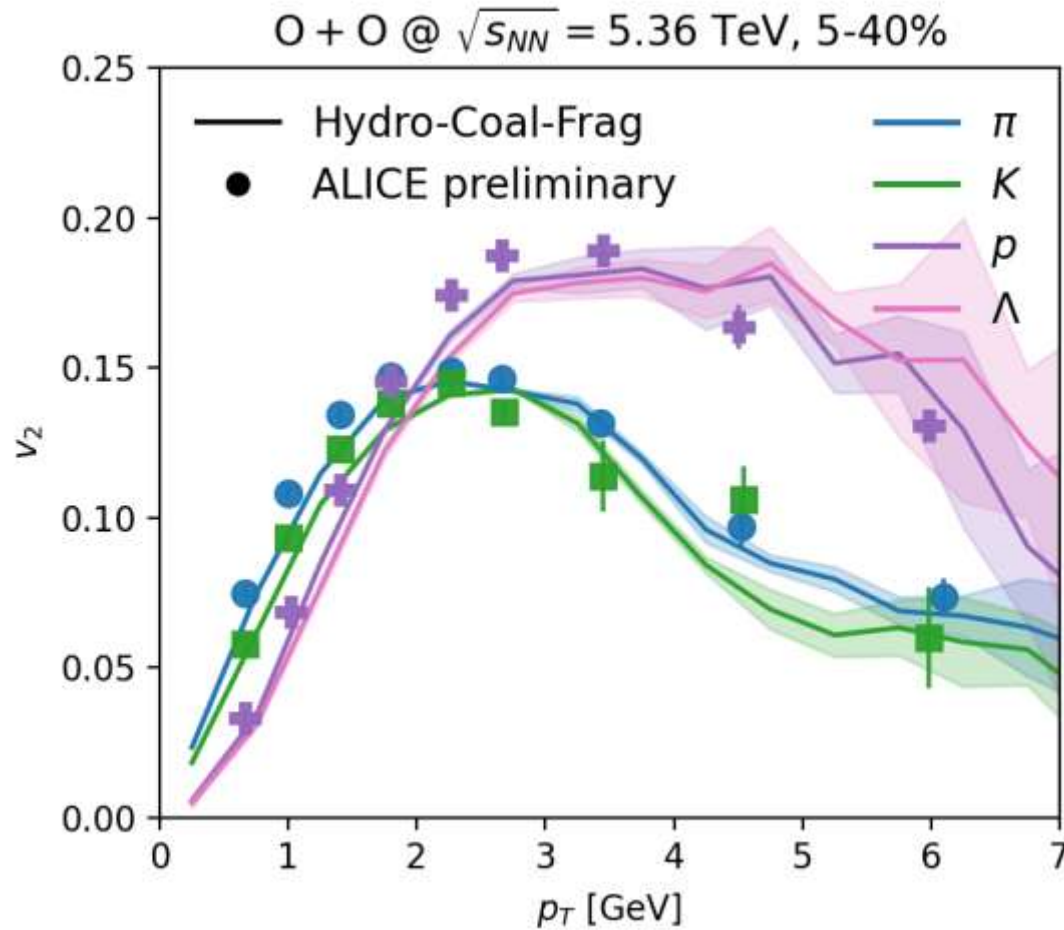
p_T spectra and elliptic flow of π, K, p from Hydro-Coal-Frag Model

p+Pb @ $\sqrt{s_{NN}}=5.02$ TeV, 0-20%



- With coalescence at partonic level, we can nicely reproduce p_T spectra and elliptic flow of these stable hadrons (π K p ...) from 0 to 6 GeV
- Approximate NCQ scaling behavior at intermediate p_T

Elliptic flow of π, K, p in O+O Collisions



- With the same framework, we predict the elliptic flow of these stable hadrons in O+O collisions.
- Also give NCQ scaling behavior at intermediate p_T

Summary

Hydrodynamic applicability:

- The P_L/P_T ratio remains far from unity at late times in peripheral O+O and Ne+Ne collisions, challenging the applicability of conventional viscous hydrodynamics.
- VH–VAH differences are small for elliptic flow but more pronounced for higher-order harmonics, particularly $v_4\{2\}$, toward peripheral collisions.

Partonic collectivity:

- Hydro-Coal-Frag describes identified-particle elliptic flow in O+O collisions, with approximate NCQ scaling at intermediate p_T supporting partonic collectivity.

Thanks !

Viscous Anisotropic Hydrodynamics (VAH)

Relaxation equations of VAH:

$$\begin{aligned}\dot{\mathcal{P}}_L = & -\frac{\bar{\mathcal{P}} - \mathcal{P}_{\text{eq}}}{\tau_\Pi} - \frac{\mathcal{P}_L - \mathcal{P}_\perp}{3\tau_\pi/2} + \bar{\zeta}_z^L z_\mu D_z u^\mu + \bar{\zeta}_\perp^L \theta_\perp - 2W_{\perp z}^\mu \dot{z}_\mu + \bar{\lambda}_{Wu}^L W_{\perp z}^\mu D_z u_\mu \\ & + \bar{\lambda}_{W\perp} W_{\perp z}^\mu z_\nu \nabla_{\perp\mu} u^\nu - \bar{\lambda}_\pi^L \pi_{\perp}^{\mu\nu} \sigma_{\perp,\mu\nu},\end{aligned}$$

Longitudinal Pressure

$$\begin{aligned}\dot{\mathcal{P}}_\perp = & -\frac{\bar{\mathcal{P}} - \mathcal{P}_{\text{eq}}}{\tau_\Pi} + \frac{\mathcal{P}_L - \mathcal{P}_\perp}{3\tau_\pi} + \bar{\zeta}_z^\perp z_\mu D_z u^\mu + \bar{\zeta}_\perp^\perp \theta_\perp + W_{\perp z}^\mu \dot{z}_\mu + \bar{\lambda}_{Wu}^\perp W_{\perp z}^\mu D_z u_\mu \\ & - \bar{\lambda}_{W\perp}^\perp W_{\perp z}^\mu z_\nu \nabla_{\perp\mu} u^\nu + \bar{\lambda}_\pi^\perp \pi_{\perp}^{\mu\nu} \sigma_{\perp,\mu\nu}.\end{aligned}$$

Transverse Pressure

$$\begin{aligned}\dot{W}_{\perp z}^{\{\mu\}} = & -\frac{W_{\perp z}^\mu}{\tau_\pi} + 2\bar{\eta}_u^W \Xi^{\mu\nu} D_z u_\nu - 2\bar{\eta}_\perp^W z_\nu \nabla_\perp^\mu u^\nu - (\bar{\tau}_z^W \Xi^{\mu\nu} + \pi_{\perp}^{\mu\nu}) \dot{z}_\nu + \bar{\delta}_W^W W_{\perp z}^\mu \theta_\perp \\ & - \bar{\lambda}_{Wu}^W W_{\perp z}^\mu z_\nu D_z u^\nu + \bar{\lambda}_{W\perp}^W \sigma_\perp^{\mu\nu} W_{\perp z,\nu} + \omega_\perp^{\mu\nu} W_{\perp z,\nu} + \bar{\lambda}_{\pi u}^W \pi_{\perp}^{\mu\nu} D_z u_\nu - \bar{\lambda}_{\pi\perp}^W \pi_{\perp}^{\mu\nu} z_\alpha \nabla_{\perp\nu} u^\alpha,\end{aligned}$$

Longitudinal momentum diffusion

$$\begin{aligned}\dot{\pi}_\perp^{\{\mu\nu\}} = & -\frac{\pi_{\perp}^{\mu\nu}}{\tau_\pi} + 2\bar{\eta}_\perp \sigma_\perp^{\mu\nu} - 2W_{\perp z}^{\{\mu} \dot{z}^{\nu\}} - \bar{\delta}_\pi^\pi \pi_{\perp}^{\mu\nu} \theta_\perp - \bar{\tau}_\pi^\pi \pi_{\perp}^\alpha \{\mu \sigma_{\perp,\alpha}^{\nu\}} + 2\pi_{\perp}^\alpha \{\mu \omega_{\perp,\alpha}^{\nu\}} + \bar{\lambda}_\pi^\pi \pi_{\perp}^{\mu\nu} z_\alpha D_z u^\alpha \\ & - \bar{\lambda}_{Wu}^\pi W_{\perp z}^{\{\mu} D_z u^{\nu\}} + \bar{\lambda}_{W\perp}^\pi W_{\perp z}^{\{\mu} z_\alpha \nabla_\perp^{\nu\}} u^\alpha.\end{aligned}$$

Transverse shear stress tensor