第十三届全国粒子物理学术会议

（2021）

From hydro to jet quenching, coalescence and hadron cascade

A coupled approach to solving the $R_{AA} \otimes v_2$ puzzle

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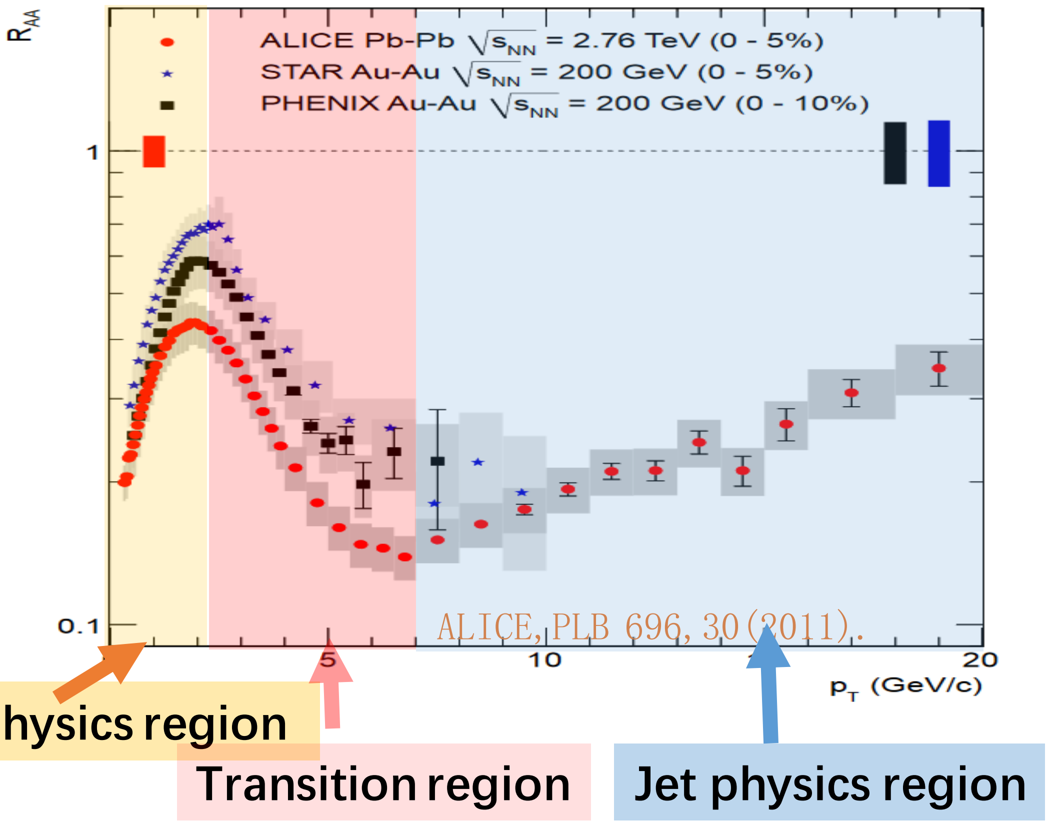
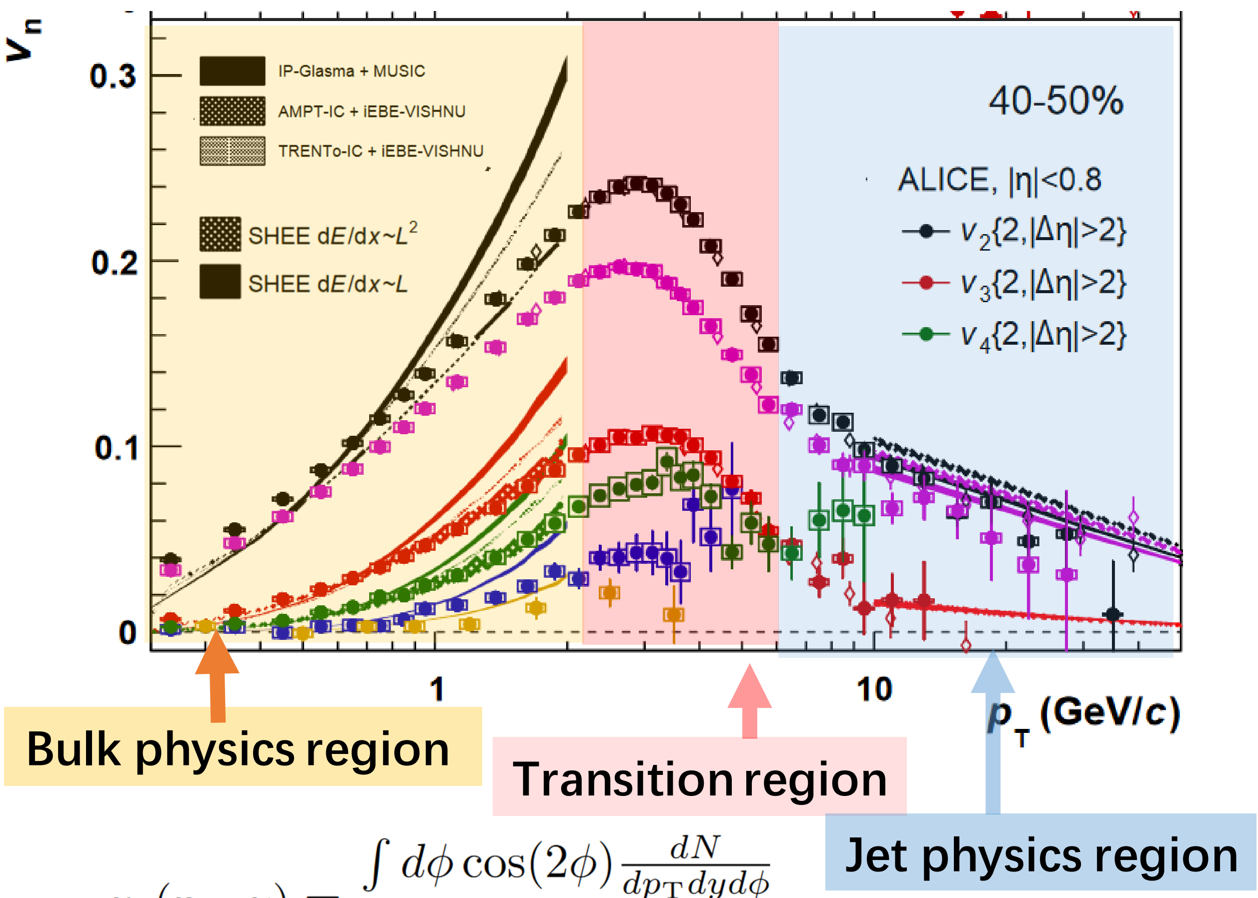
青岛 online, 2021.08.16

Based on: **W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657 [hep-ph].**

Different domains in heavy-ion collisions



ALICE JHEP 1807, 103 (2018)

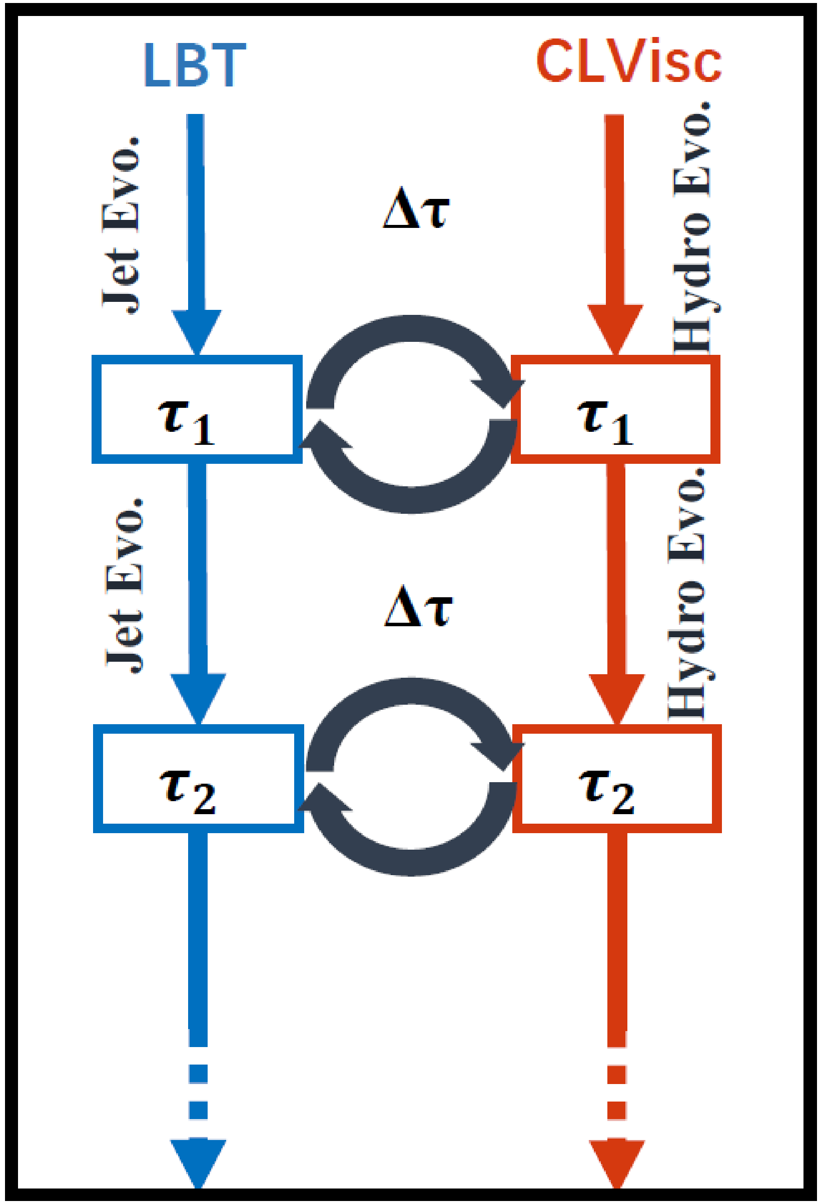


$$R_{AA}(p_T, y, \phi) \equiv \frac{1}{\langle N_{coll}\rangle} \frac{\frac{dN_{AA}}{dp_T dy d\phi}}{\frac{dN_{pp}}{dp_T dy d\phi}},$$

$$v_2(p_T, y) \equiv \frac{\int d\phi \cos(2\phi) \frac{dN}{dp_T dy d\phi}}{\int d\phi \frac{dN}{dp_T dy d\phi}}$$

- Different domains are clearly observed in data in heavy-ion collisions.
- Low p_T (p_T<2-3 GeV): bulk physics; High p_T (p_T>10 GeV): jet physics.
- Intermediate p_T (3<p_T<8-10 GeV): transition regime; (Not well studied.)

CoLBT-hydro model



CoLBT-Hydro model

Linear Boltzmann Transport model (LBT) + 3+1D hydrodynamic model (CLVis)

Evolve the energetic partons and the bulk medium concurrently.

Hydrodynamics equations with the source terms:

$$\partial_\mu T^{\mu\nu}_{\text{fluid}} = J^\nu$$

$T^{\mu\nu}_{\text{fluid}}$: Energy-momentum tensor of the QGP fluid;

J^ν : Energy-momentum density deposited by energetic partons. with the Gaussian smearing:

$$J^\nu(\vec{x}_\perp, \eta_s) = \sum_i \frac{\theta(p^0_{\text{cut}} - p_i \cdot u)p^\nu}{\tau(2\pi)^{3/2}\sigma_r^2\sigma_{\eta_s}\Delta\tau} e^{-\frac{(\vec{x}_\perp - \vec{x}_{\perp i})^2}{2\sigma_r^2} - \frac{(\eta_s - \eta_{si})^2}{2\sigma_{\eta_s}^2}}$$

p^0_{cut} separates the soft and hard partons

W. Chen, S. Cao, T. Luo, L.-G. Pang, and X.-N. Wang,Phys. Lett. B810, 135783 (2020), 2005.09678.

Framework of calculations

Hydro-Coal-Frag hadronization

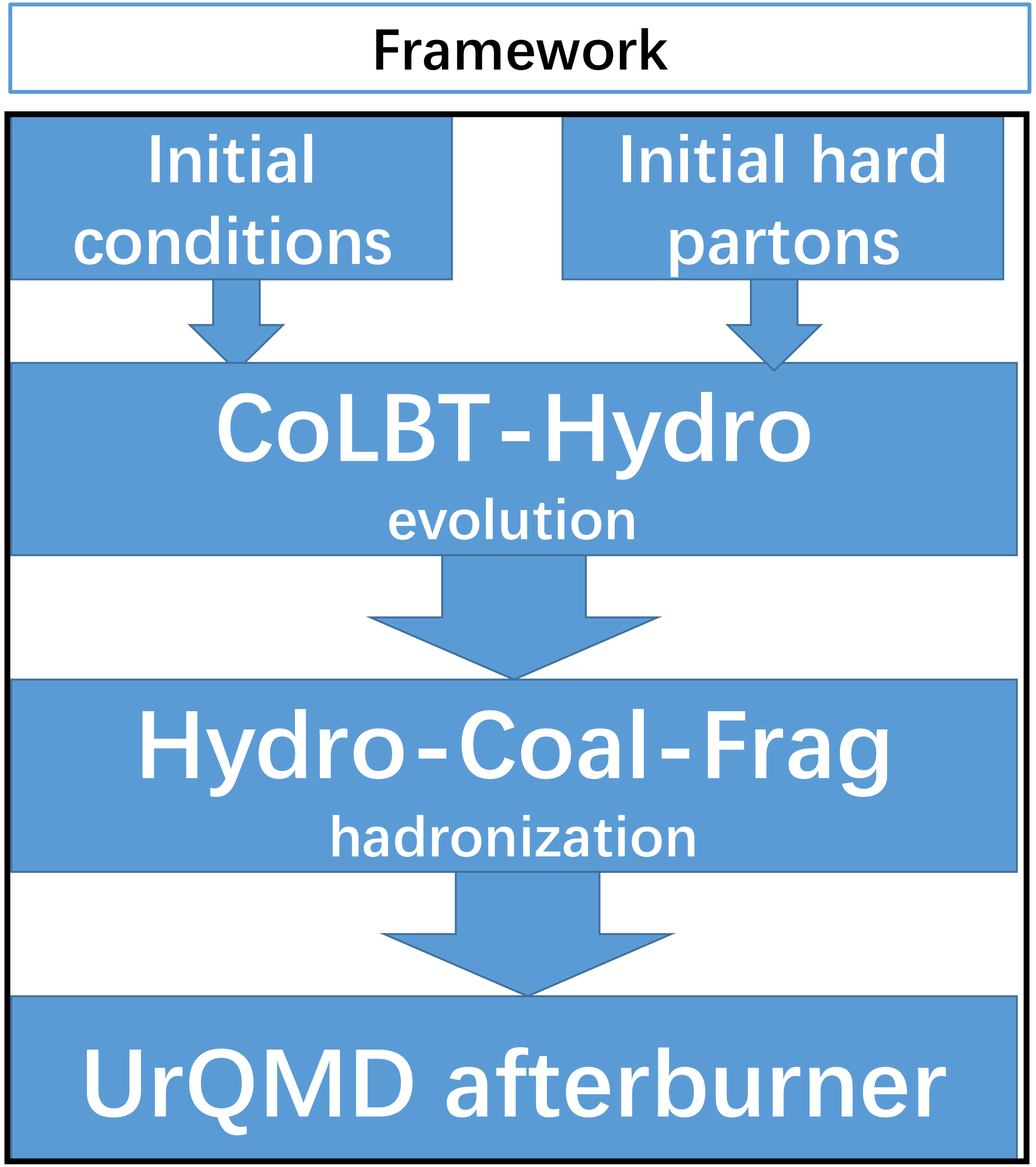
Thermal hadrons, low p_T (CLVis):
- generated by hydro. with Cooper-Frye.

Coalescence hadrons (Coal Model):
-generated by coalescence model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

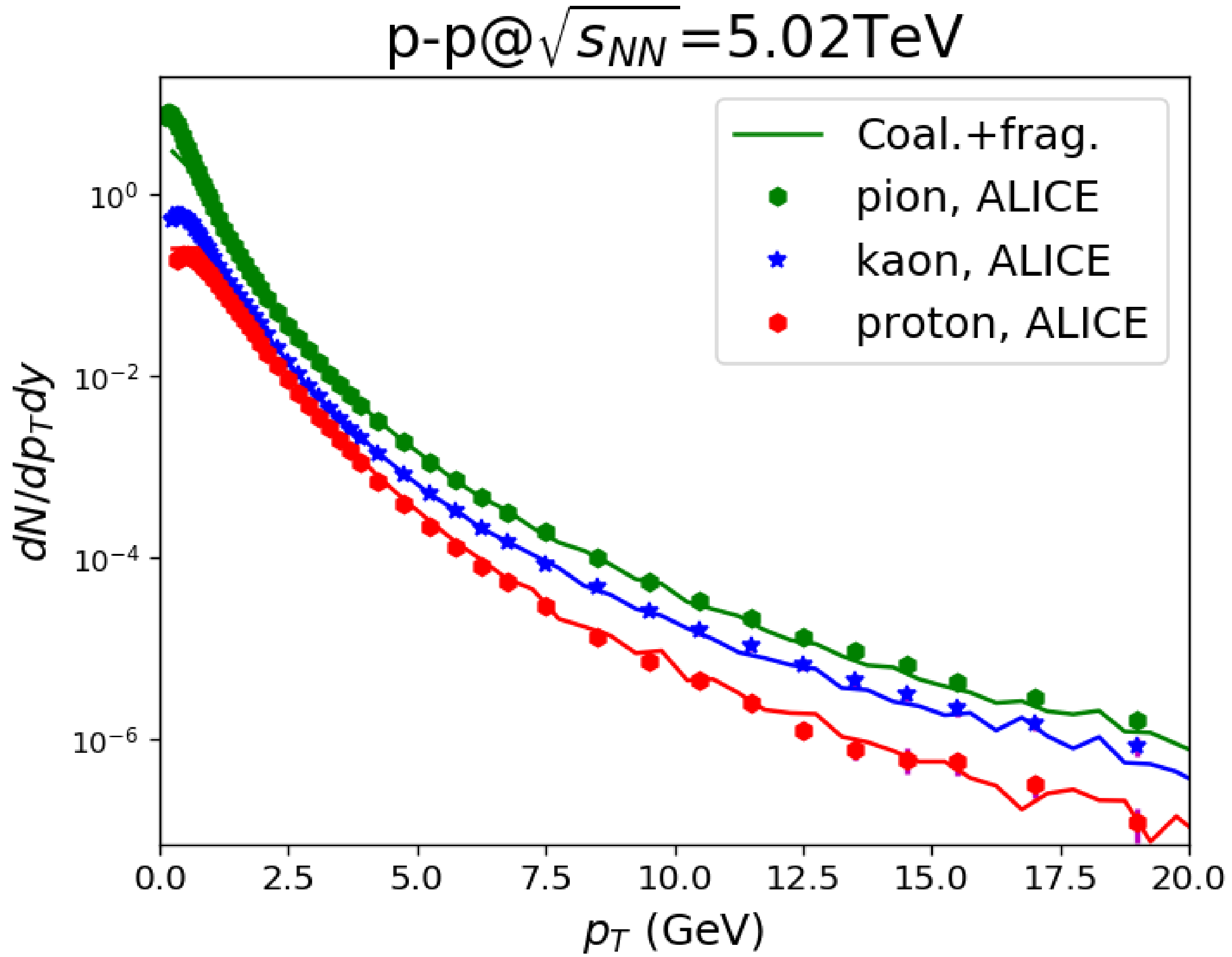
Fragmentation hadrons :
-the remnant hard quarks feed to fragmentation .

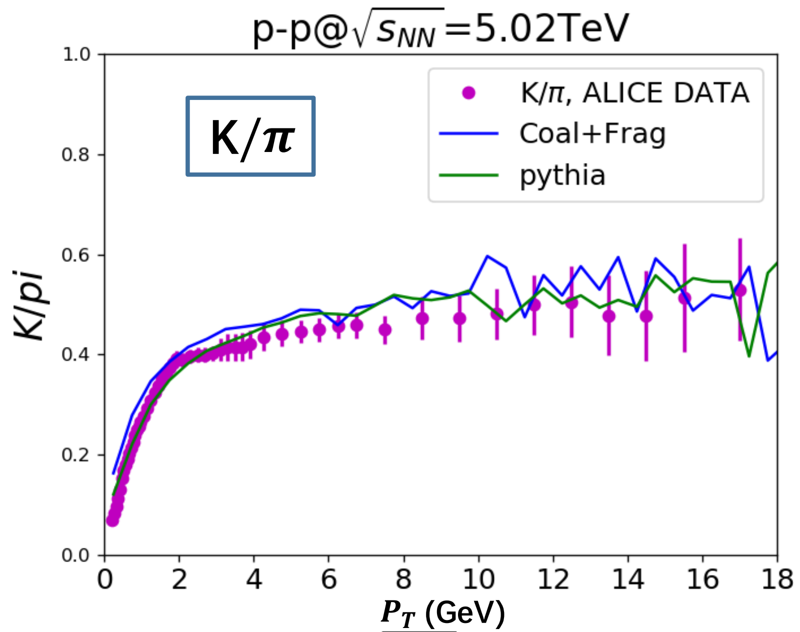
UrQMD afterburner:
-All hadrons are feed into UrQMD for hadronic evolution, scatterings and decays

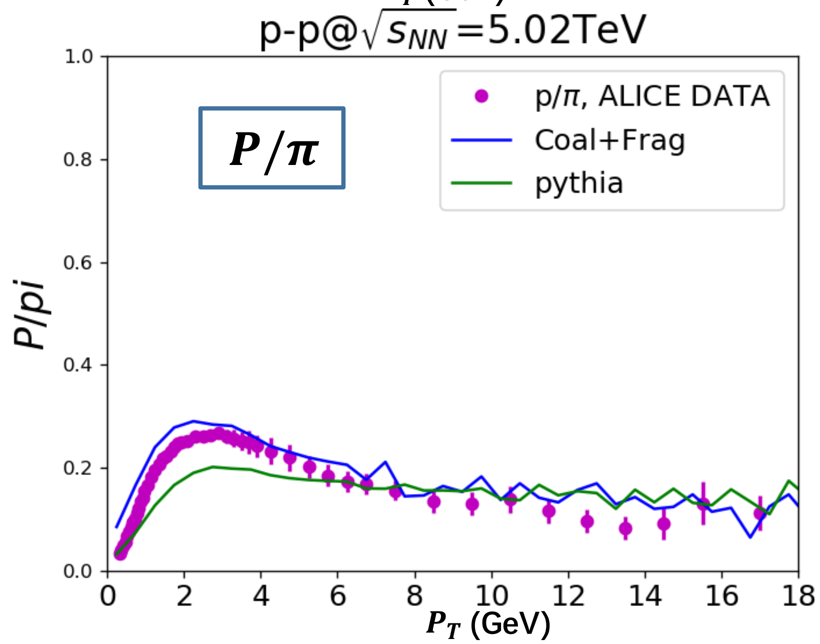
W. Zhao, Ko, Liu, Qin and Song, PRL. 125, 072301 (2020).
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657.



Verification of the hadronization code in p-p



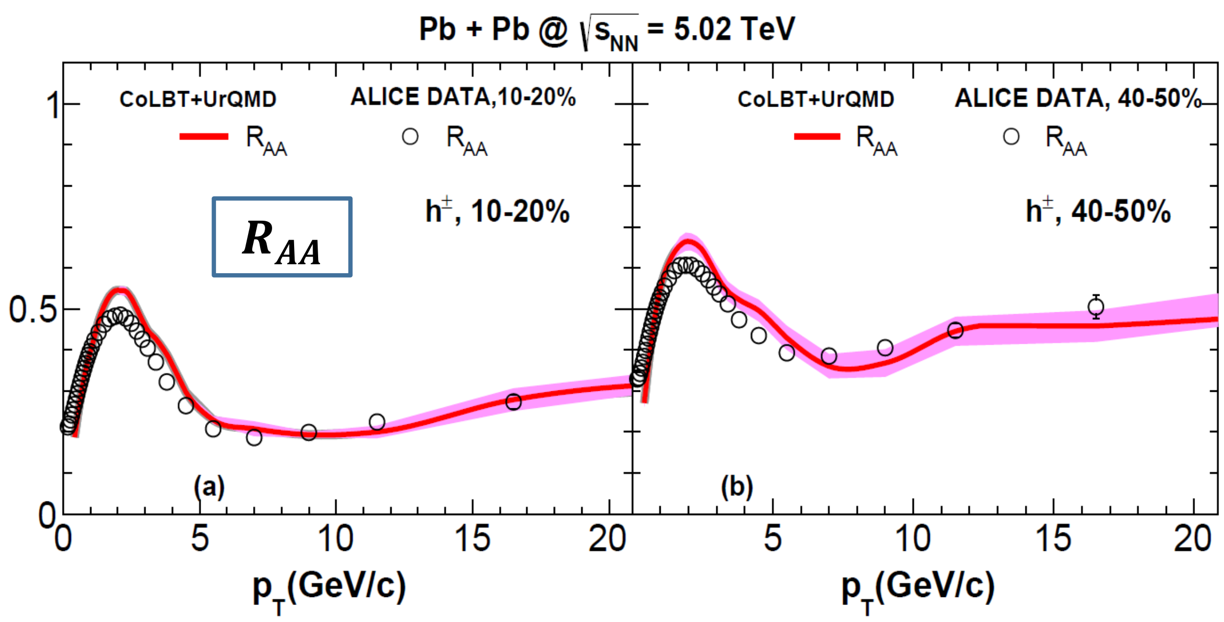


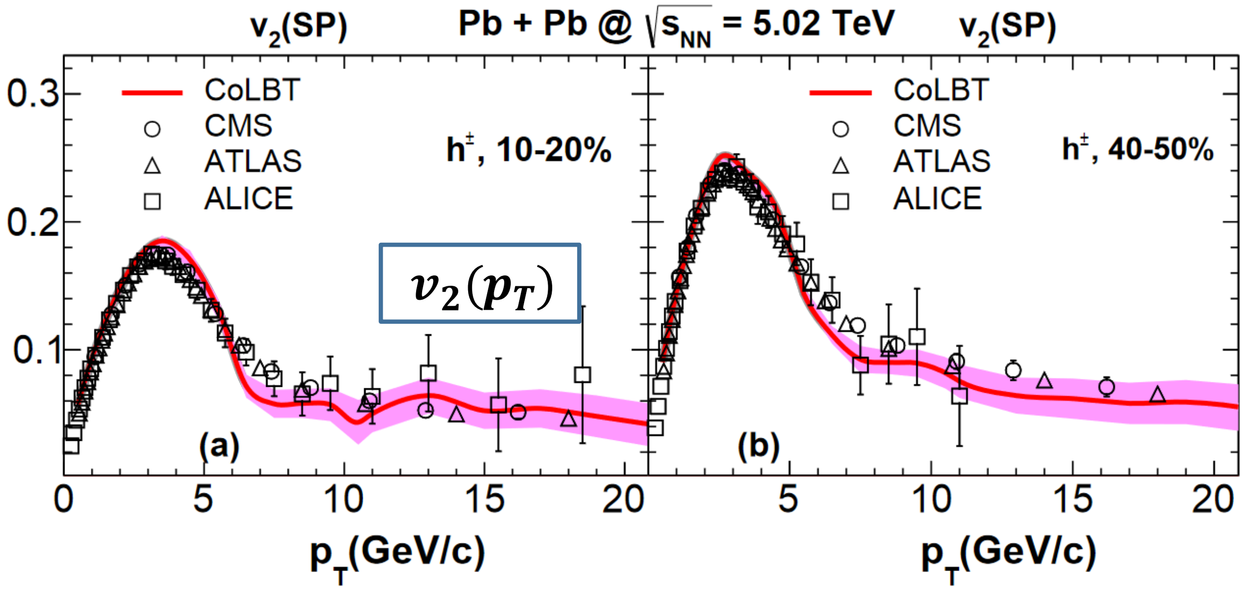


- Coal-Frag model can well reproduce the p_T-spectra of π, K and P as well as the K/π and P/π in p-p collisions.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657 [hep-ph].

R_{AA} v.s. $v_2(p_T)$ from low p_T to high p_T

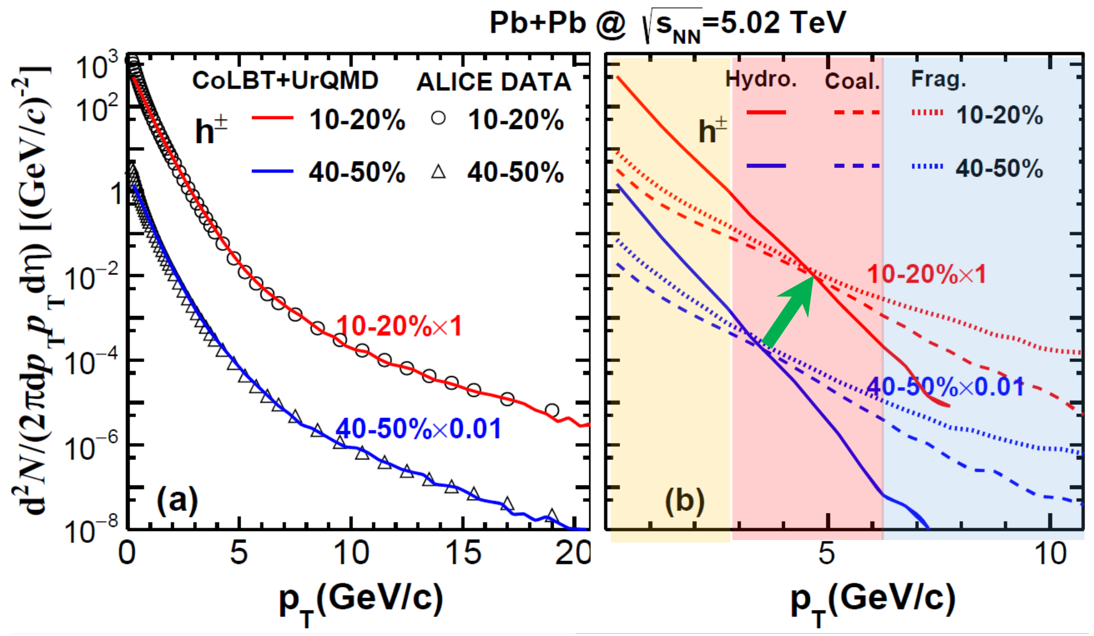


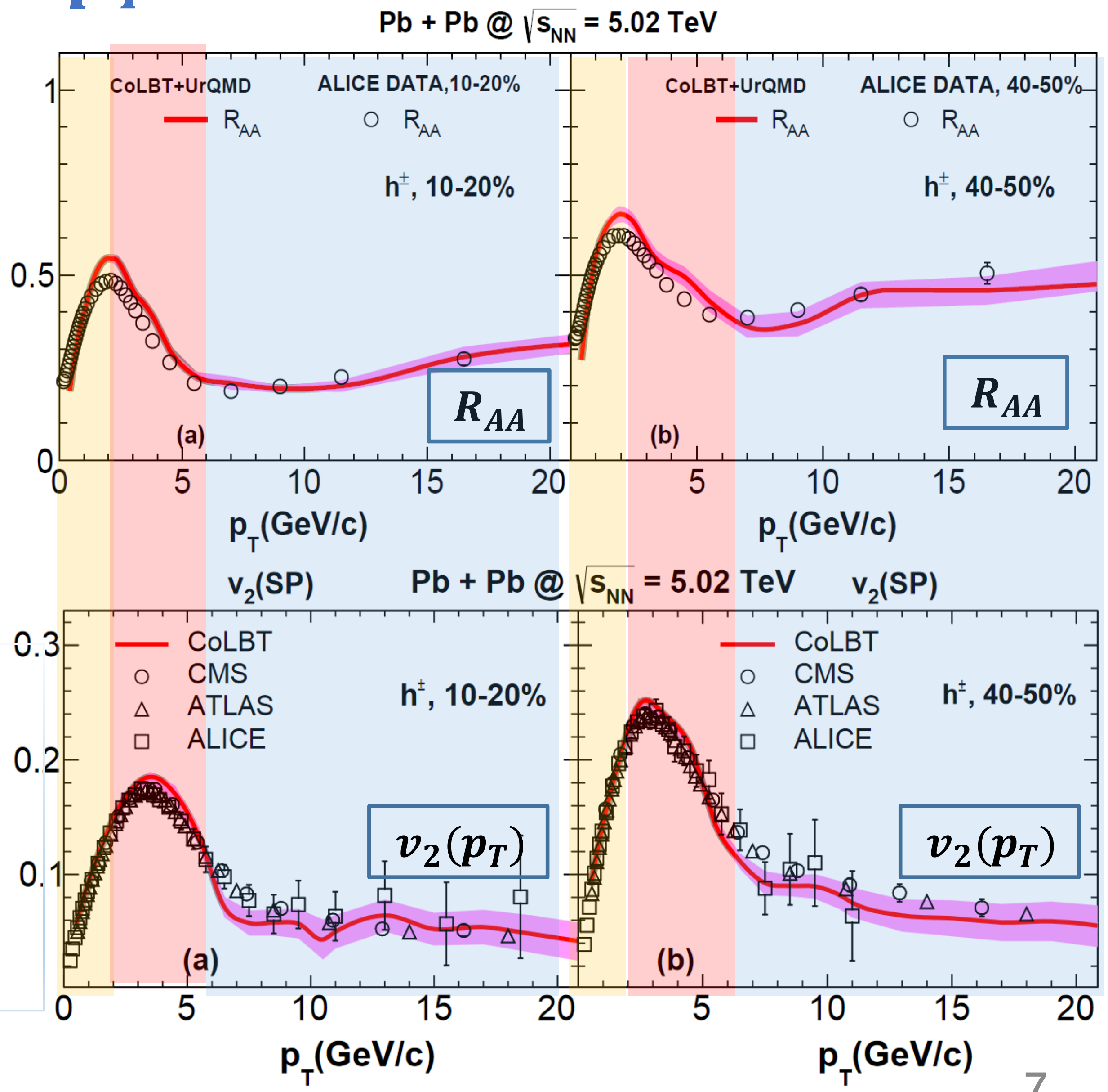


W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657 [hep-ph].

- CoLBT-hydro with Hydro-Coal-Frag hadronizations can simultaneously describe the R_{AA} and collective flow from low p_T to high p_T regions in Pb+Pb collisions.

Transition from low p_T to high p_T

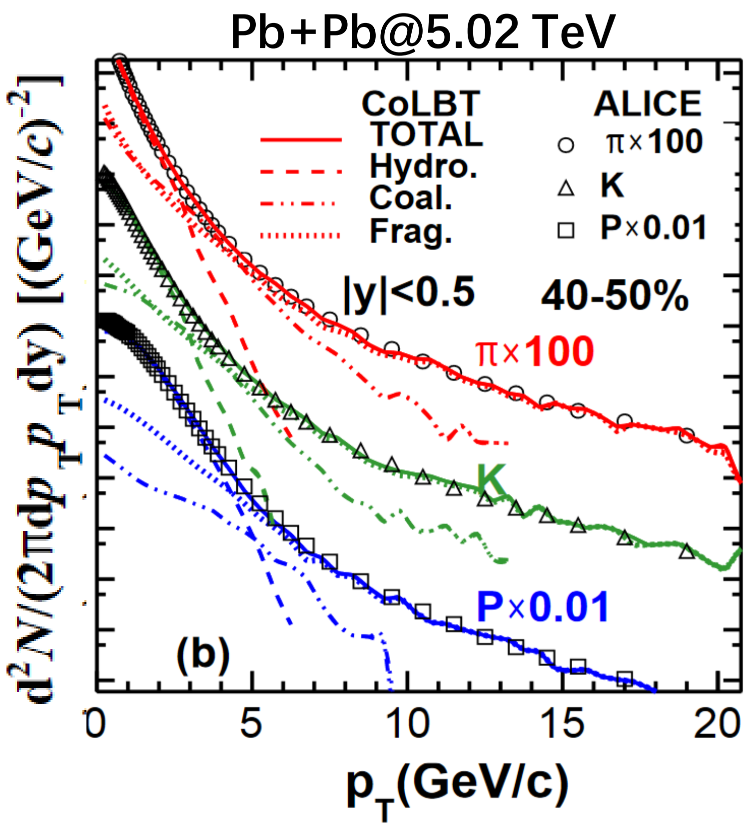


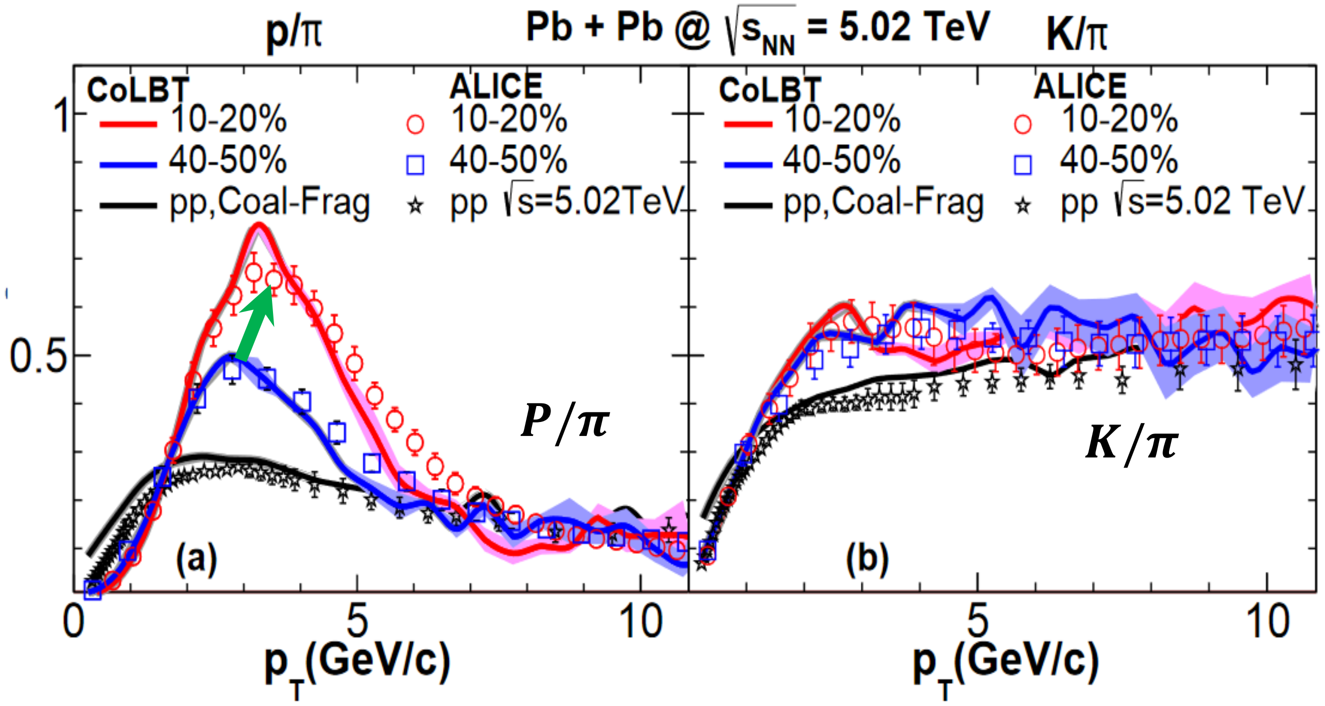


- CoLBT-hydro nicely describes the spectra of charged from 0 to 20 GeV.
- Low p_T: hydro; Intermediate p_T: transition regime; High p_T: jet physics.
- Transition p_T is higher in central collisions.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657.

Transverse momentum spectra of identified hadrons

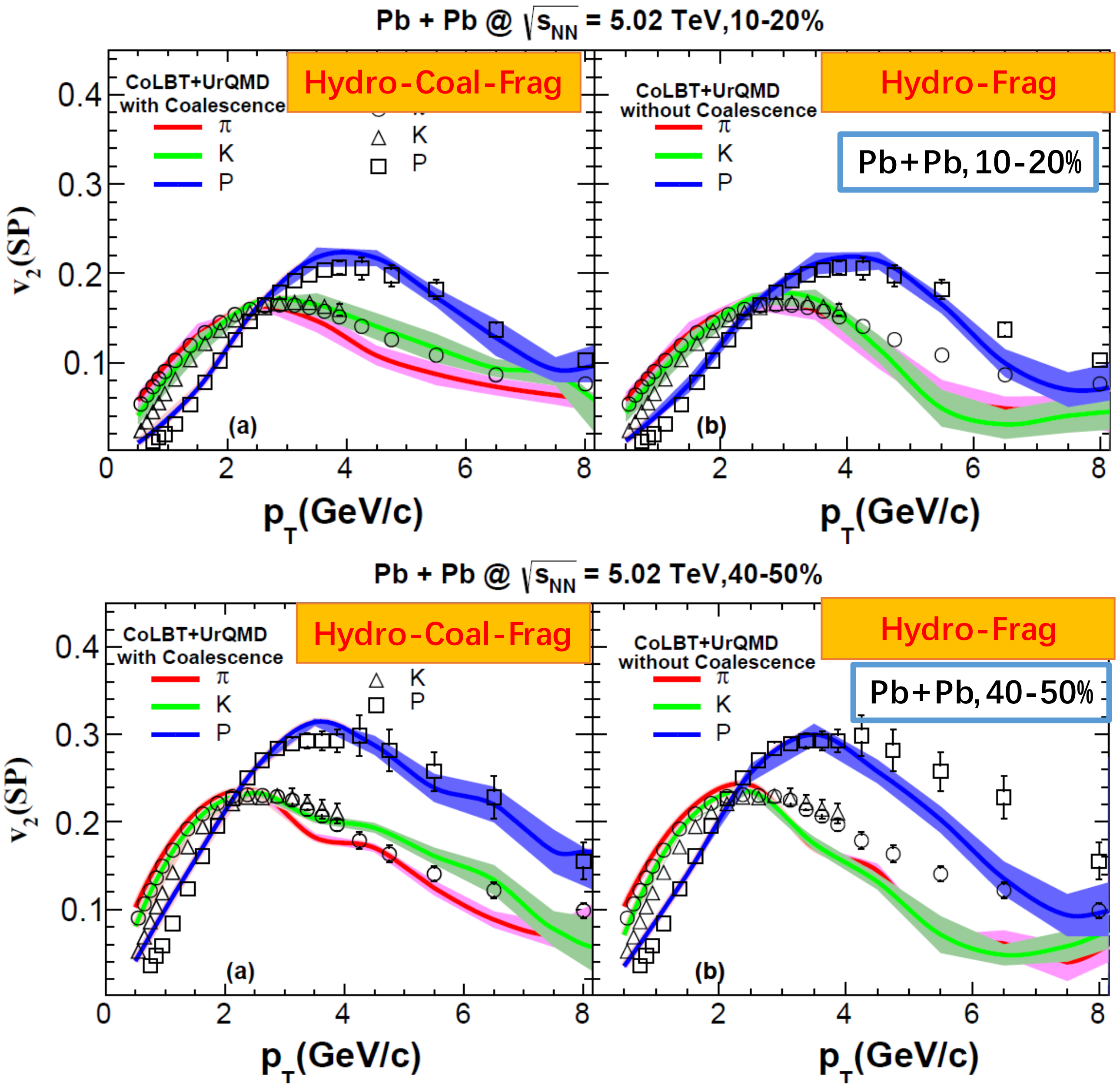




W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657 [hep-ph].

- CoLBT-hydro nicely describes the spectra of identified hadrons, P/π and K/π from 0 to 20 GeV.
- P/π in Pb+Pb is higher than pp; P/π peak moves to higher p_T in central collision.
- P/π and K/π approach to the p-p value at high p_T.

Collective flow of identified hadrons

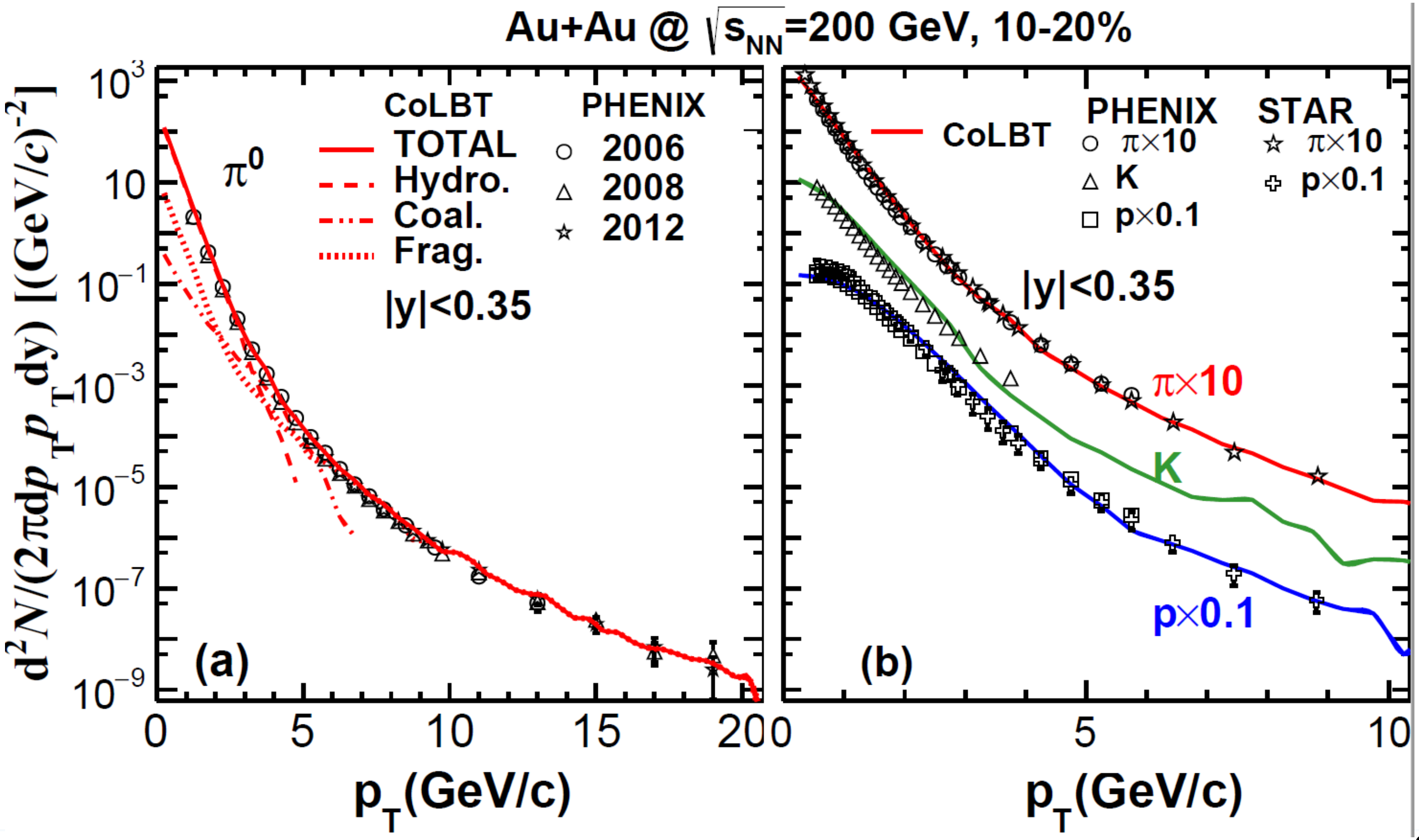


- CoLBT-hydro with Hydro-Coal-Frag works well for PID flow from 0 to 8 GeV.
- $v_2(p_T)$ of P larger than π and K at 3 GeV, caused by interplay between hydro. Coal. and frag.
- Quark coalescence is important for Pb+Pb collisions at intermediate p_T range.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657 [hep-ph].

Predictions for Au-Au at RHIC

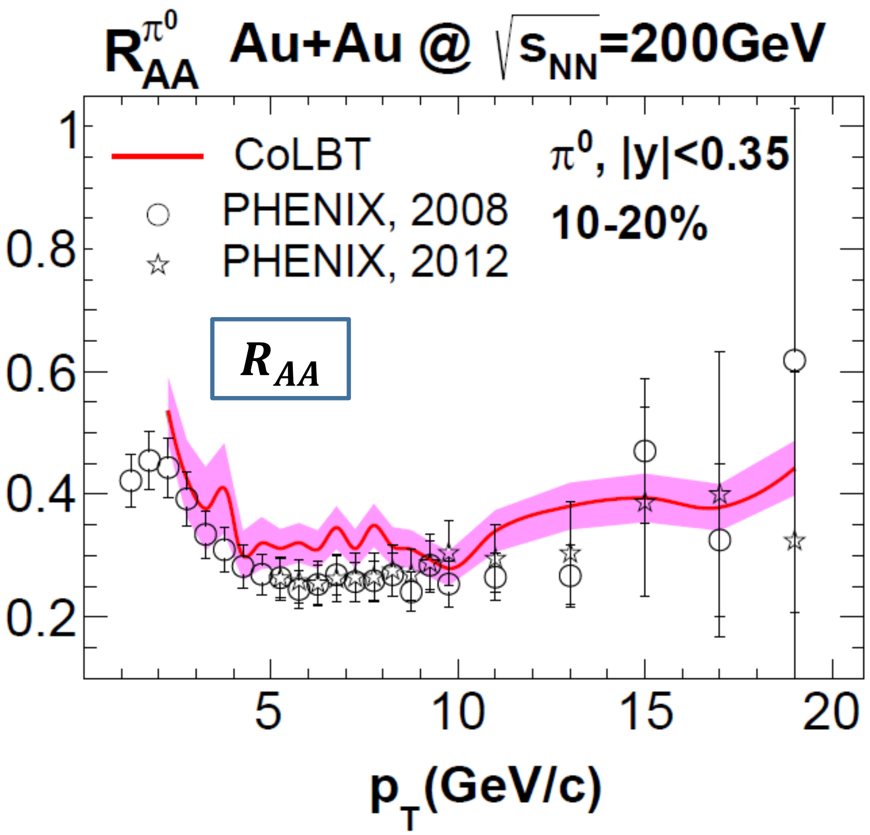
Spectra at Au-Au at RHIC

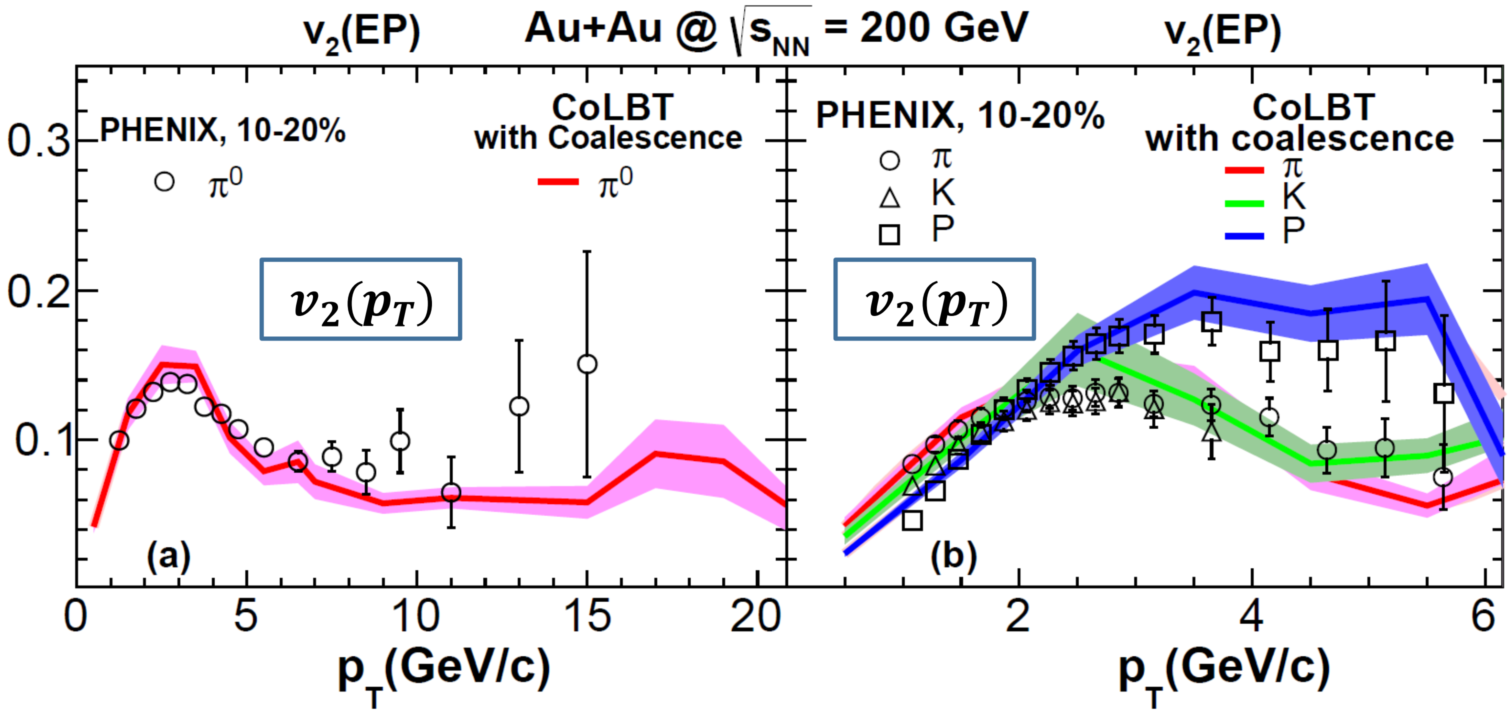


- With parameters fixed at LHC, CoLBT-hydro nicely predicts the spectra of π^0 and of $\pi^{\pm}$, K and P from low p_T to high p_T in Au-Au at 200 GeV.
- Low p_T: hydro; Intermediate p_T: transition region; High p_T: fragmentation.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657.
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, in preparation.

R_{AA} and $v_2\ (p_T)$ at Au-Au at RHIC

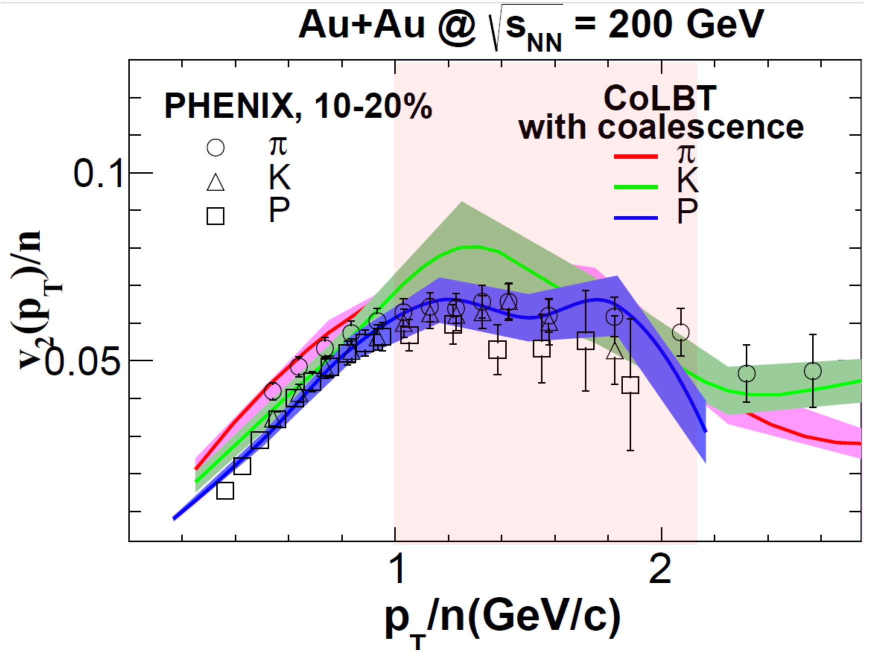


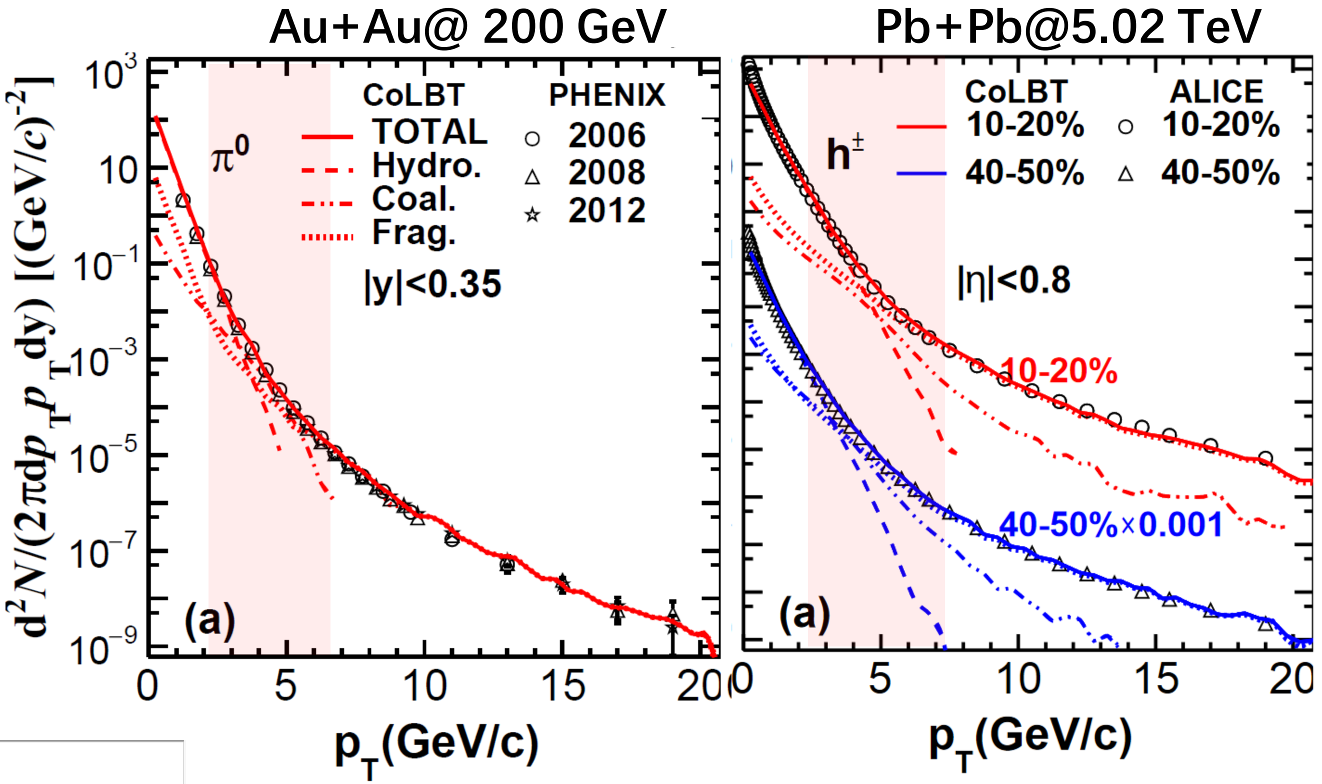


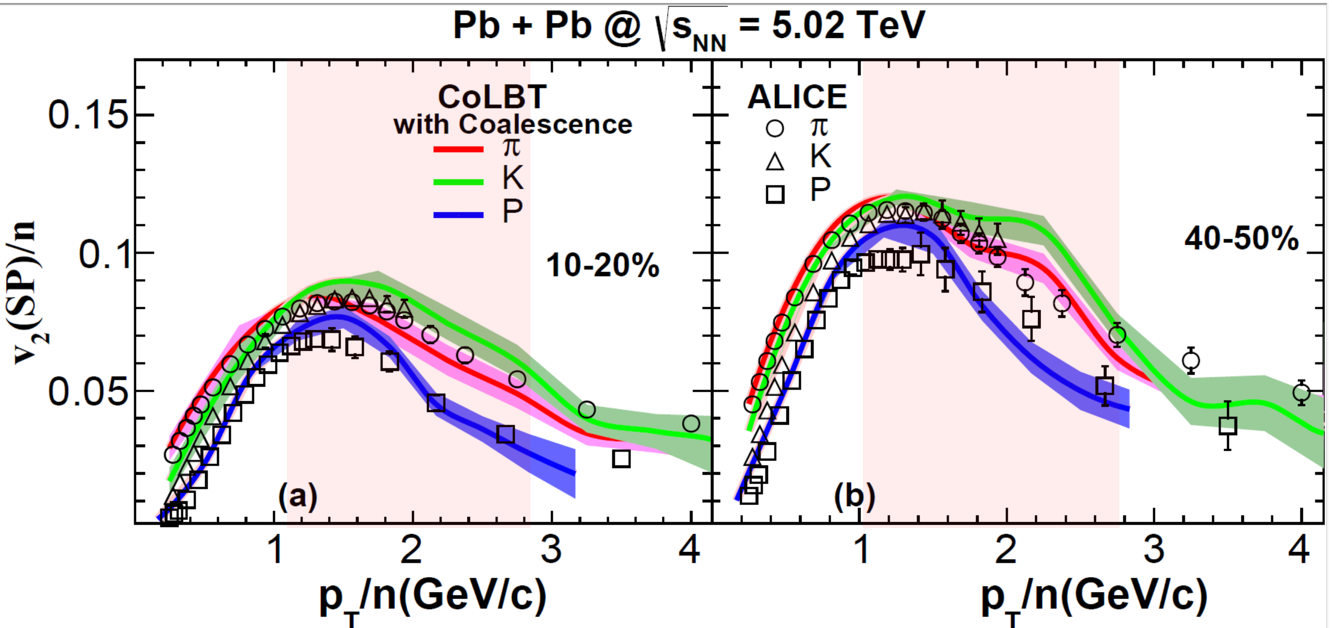
- With parameters fixed at LHC, CoLBT-hydro nicely predicts the R_{AA} and $v_2(p_T)$ from 0 to 20 GeV in Au-Au at 200 GeV.
- CoLBT-hydro nicely predicts the $v_2(p_T)$ of π, K and P from 0 to 6 GeV in RHIC.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657.
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, in preparation.

NCQ scaling at RHIC and LHC







- NCQ scaling at intermediate p_T are caused by interplay of hydro, coal. and frag.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657.
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, in preparation.

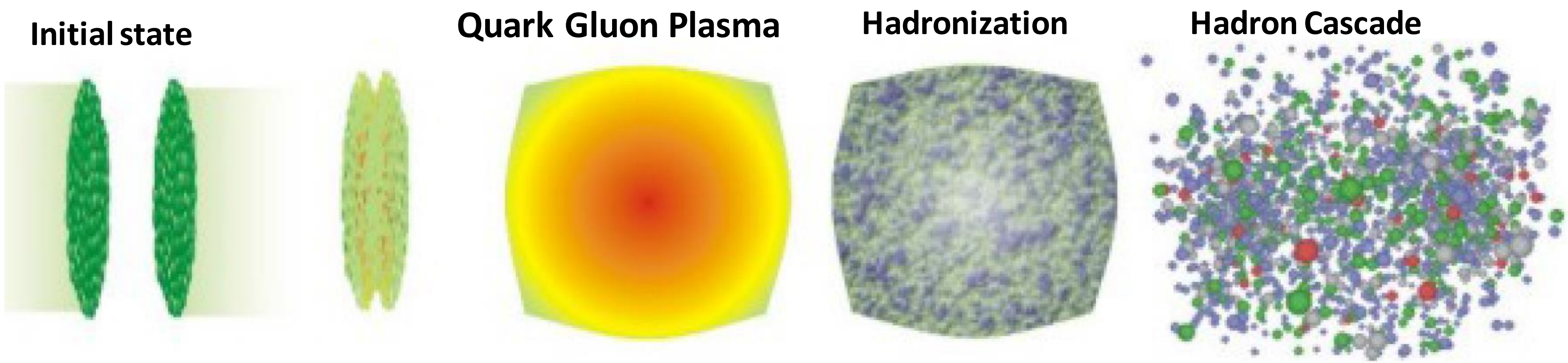
Summary

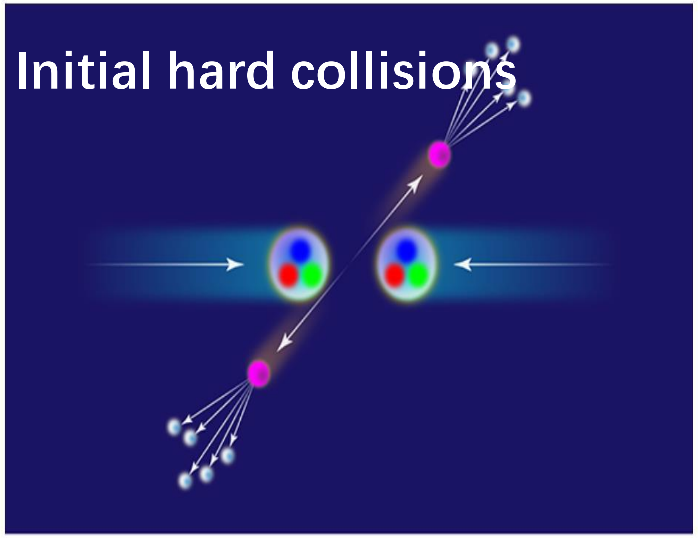
- CoLBT-hydro with Hydro-Coal-Frag hadronization simultaneously describe the R_{AA} and collective flow from low p_T to high p_T in Pb+Pb collisions.
- CoLBT-hydro also nicely describes the collective flow of identified hadrons with p_T from 0 to 8 GeV.
- Quark coalescence is important in heavy-ion collisions.
- With parameters fixed at LHC, CoLBT-hydro excellently predicts the R_{AA} and collective flow from low p_T to high p_T in Au+Au collisions at RHIC.

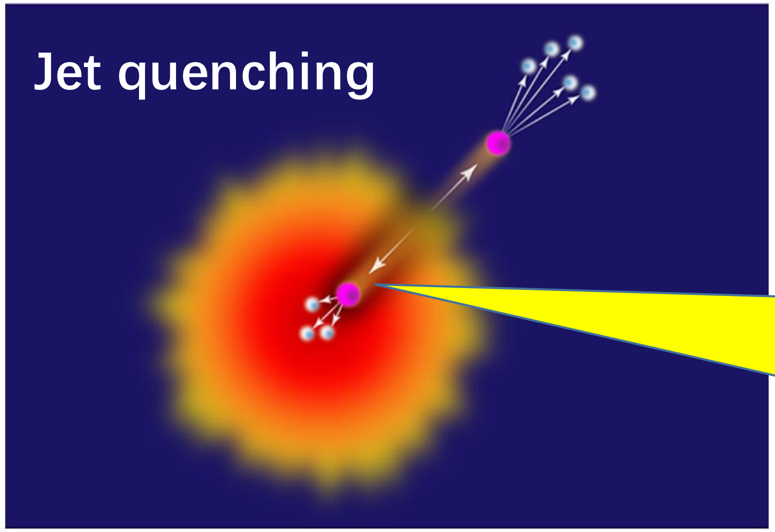
Thanks for Your Attention

Back Up

Illustration of heavy-ion collisions







Jet quenching
Strong interaction with the energetic partons and the medium.

Initialization of hard partons

- Transverse locations of hard collisions $\mathbf{r}_\perp$ are sampled from the binary collision density

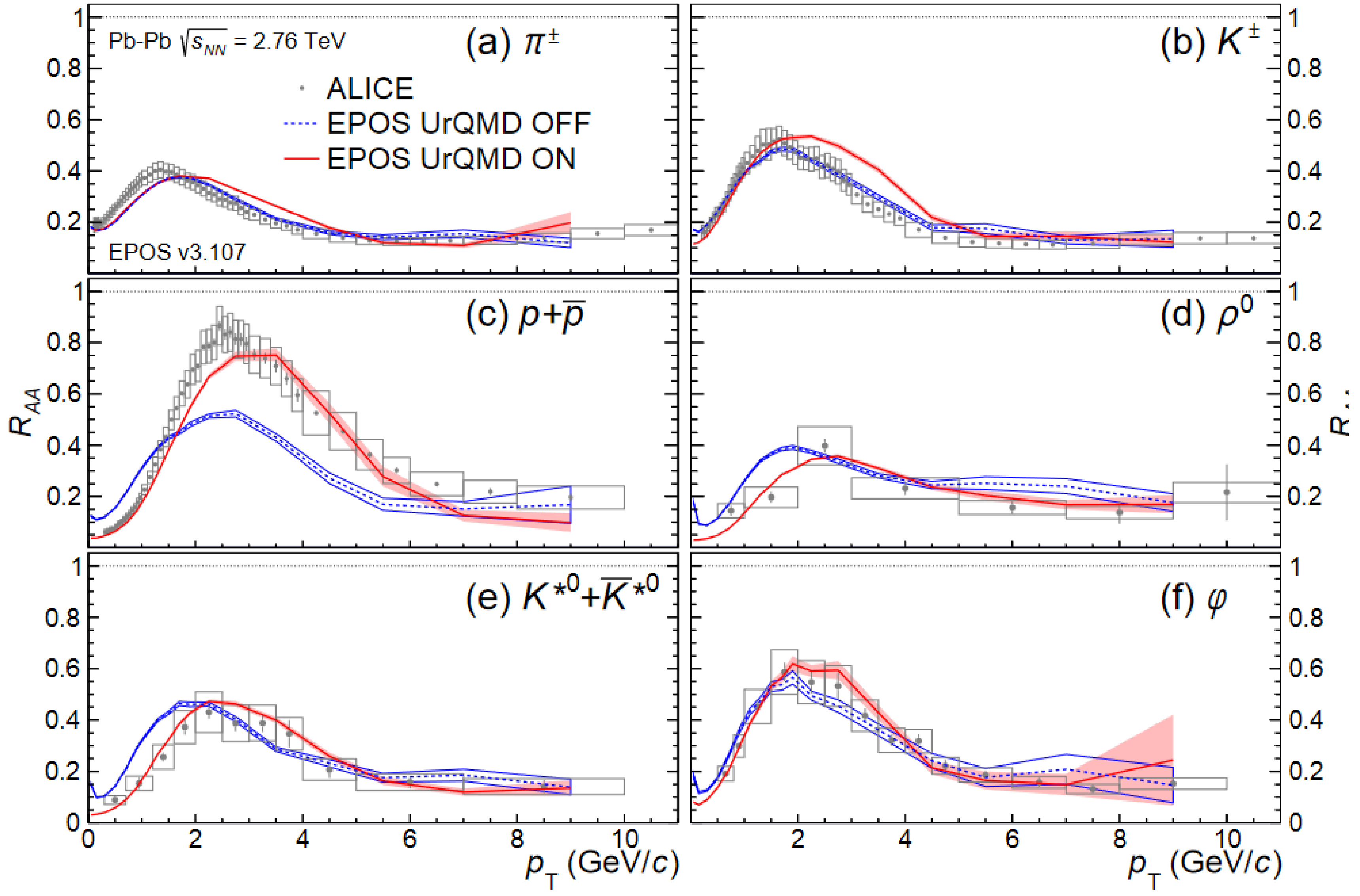
$$\frac{dN_{\mathrm{coll}}}{d\mathbf{r}_\perp^2}(\mathbf{r}_\perp; b) = T_{\mathrm{Pb}}(\mathbf{r}_\perp + \mathbf{b}/2)T_{\mathrm{Pb}}(\mathbf{r}_\perp - \mathbf{b}/2)$$

- Initial partons in the initial vacuum showers free-streams during the formation time of vacuum splittings

$$\tau_f = 2x(1-x)E/k_\perp^2$$

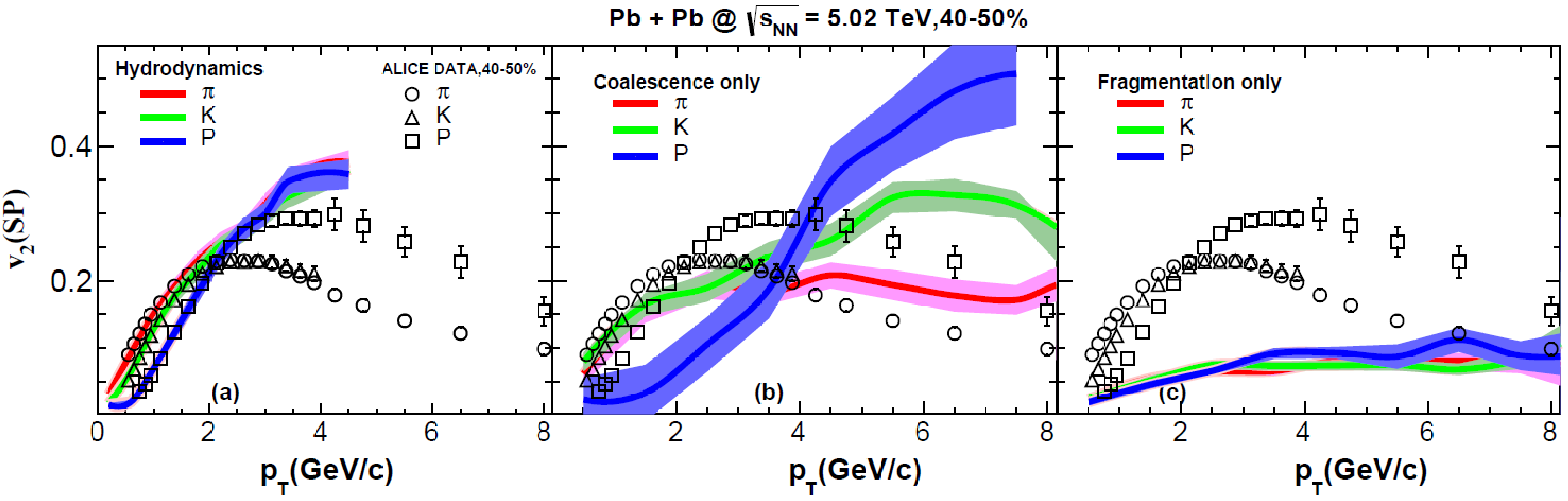
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657.

Hadron cascade effects



A. G. Knospe, C. Markert, K. Werner, J. Steinheimer, M. Bleicher arXiv:2102.06797

$v_2(p_T)$ of hydro. Coal. and Frag. parts



W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, arXiv:2103.14657.

- Hydro. works at **low** p_T range (p_T<2-3 GeV).
- Quark coalescence generates large v_2 at intermediate p_T (3<p_T<8GeV)
- Fragmentation can't generate enough v_2 below 8 GeV.

Wigner functions of hadrons

To guarantee positive value of Wigner function for stable Monto Carlo sampling, the Wigner function replaced by the overlap of hadron Wigner function W_M with parton's Wigner function, $W_{q,\bar{q}}$:

$$\overline{W}_M(\mathbf{y},\mathbf{k}) = \int d^3\mathbf{x}'_1 d^3\mathbf{k}'_1 d^3\mathbf{x}'_2 d^3\mathbf{k}'_2 \times W_q(\mathbf{x}'_1,\mathbf{k}'_1) W_{\bar{q}}(\mathbf{x}'_2,\mathbf{k}'_2) W_M(\mathbf{y}',\mathbf{k}'). \quad (3)$$

Using harmonic oscillator for wave functions of excited stated of hadrons,

$$\phi_n(x) = \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \frac{1}{\sqrt{2^n n!}} H_n(\xi) e^{-\xi^2/2}, \quad (4)$$

$\xi = \sqrt{\frac{m\omega}{\hbar}}x$, $H_n(\xi)$ are Hermite polynomials, ω is the oscillator frequency.

K. C. Han, R. J. Fries and C. M. Ko, Phys. Rev. C **93**, no. 4, 045207 (2016).

Wigner functions of hadrons

The quark wave function to be Gaussian wave packet, the wigner function of a meson in n-th excited state is

$$\overline{W}_{M,n}(\mathbf{y},\mathbf{k}) = \frac{v^n}{n!}e^{-v}. \tag{5}$$

with

$$v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2\sigma_M^2\right). \tag{6}$$

Similarly, the Gaussian smeared Wigner function for baryon is:

$$\overline{W}_{B,n_1,n_2}(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) = \frac{v_1^{n_1}}{n_1!}e^{-v_1}\cdot\frac{v_2^{n_2}}{n_2!}e^{-v_2}, \tag{7}$$

with

$$v_i = \frac{1}{2}\left(\frac{\mathbf{y}_i^2}{\sigma_{Bi}^2} + \mathbf{k}_i^2\sigma_{B_i^2}\right), \quad i = 1,2. \tag{8}$$

K. C. Han, R. J. Fries and C. M. Ko, Phys. Rev. C 93, no. 4, 045207 (2016).