SQM2022
The 20th International Conference on Strangeness in Quark Matter
13-17 June 2022 Busan, Republic of Korea

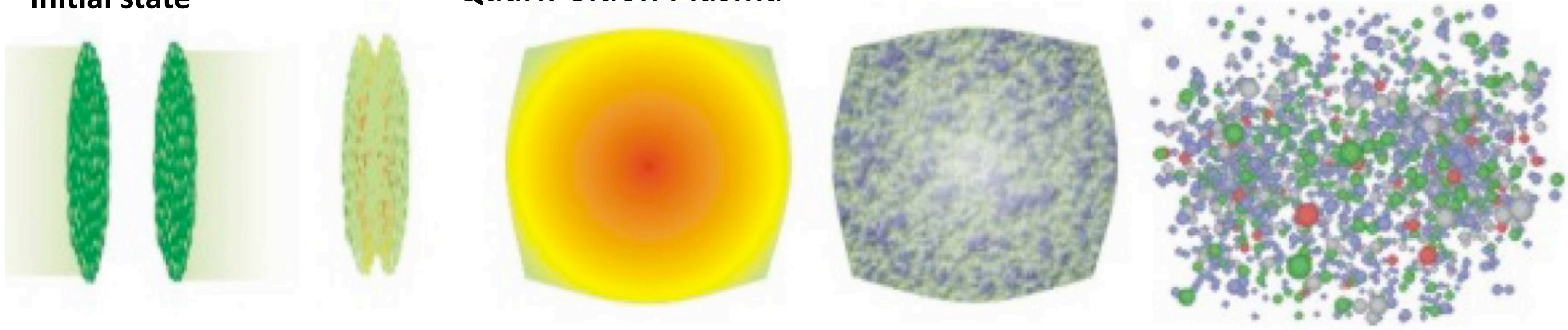
The quark number scaling of strange quark and light quarks as well as the coupled approach to solving the $R_{AA} \otimes v_2$ puzzle in heavy-ion collisions

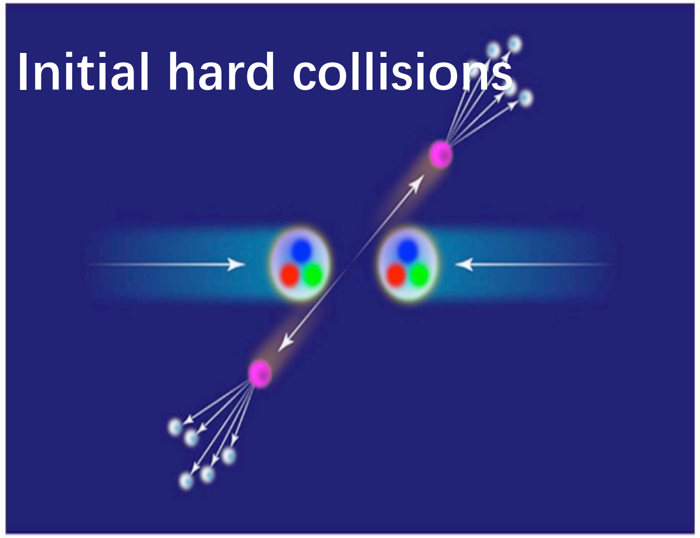
Wenbin Zhao
Central China Normal University,
Wayne State University

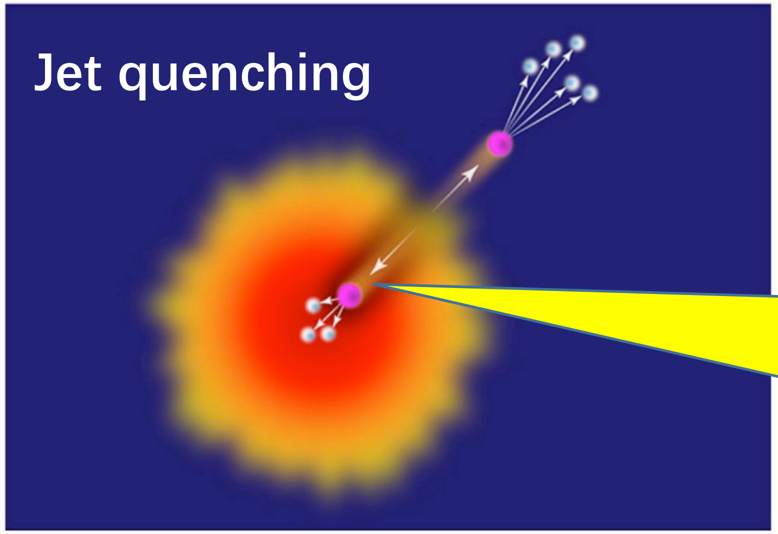
SQM, 06.14, 2022

Illustration of heavy-ion collisions

Initial state **Quark Gluon Plasma** **Hadronization** **Hadron Cascade**



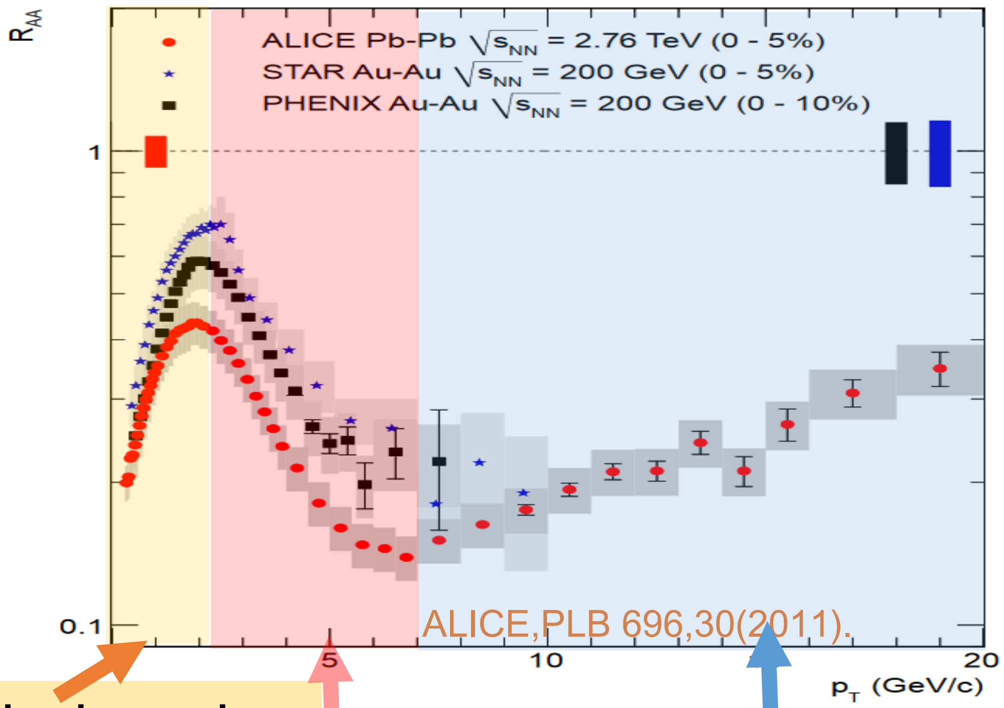


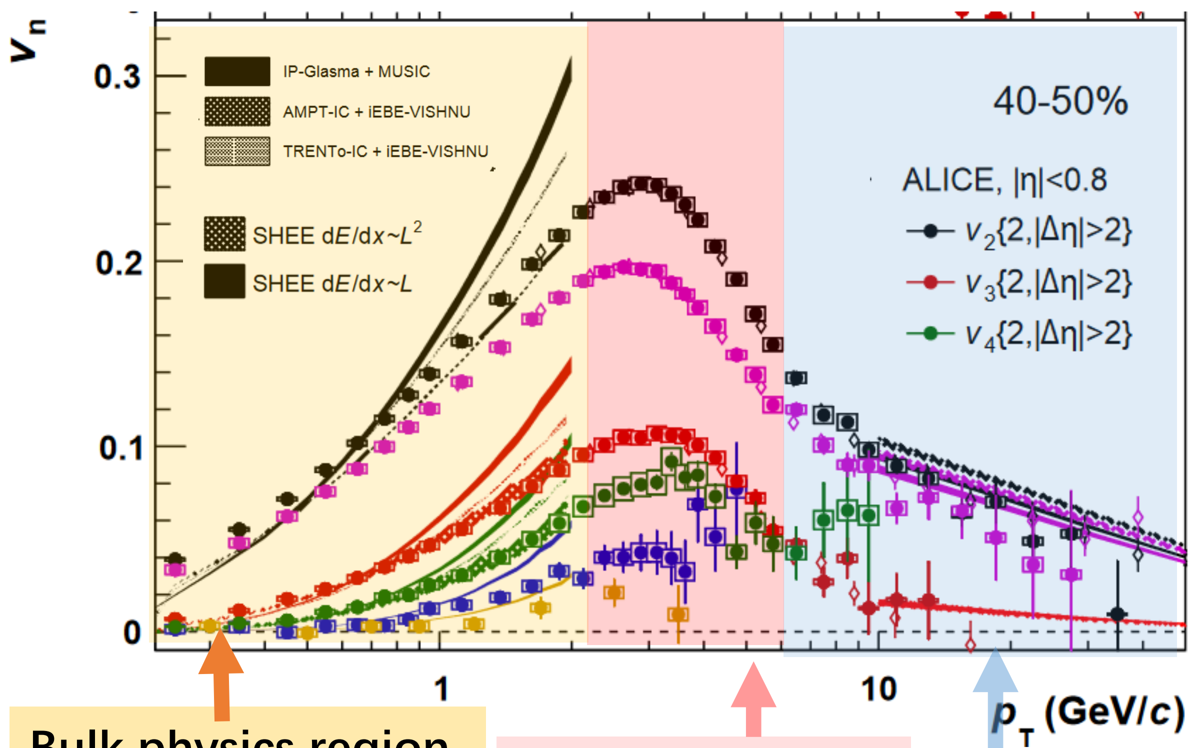


Jet quenching
Strong interaction with the energetic partons and the medium.

Different domains in heavy-ion collisions

ALICE JHEP 1807,103 (2018)





Bulk physics region

Transition region

Jet physics region

Bulk physics region

Transition region

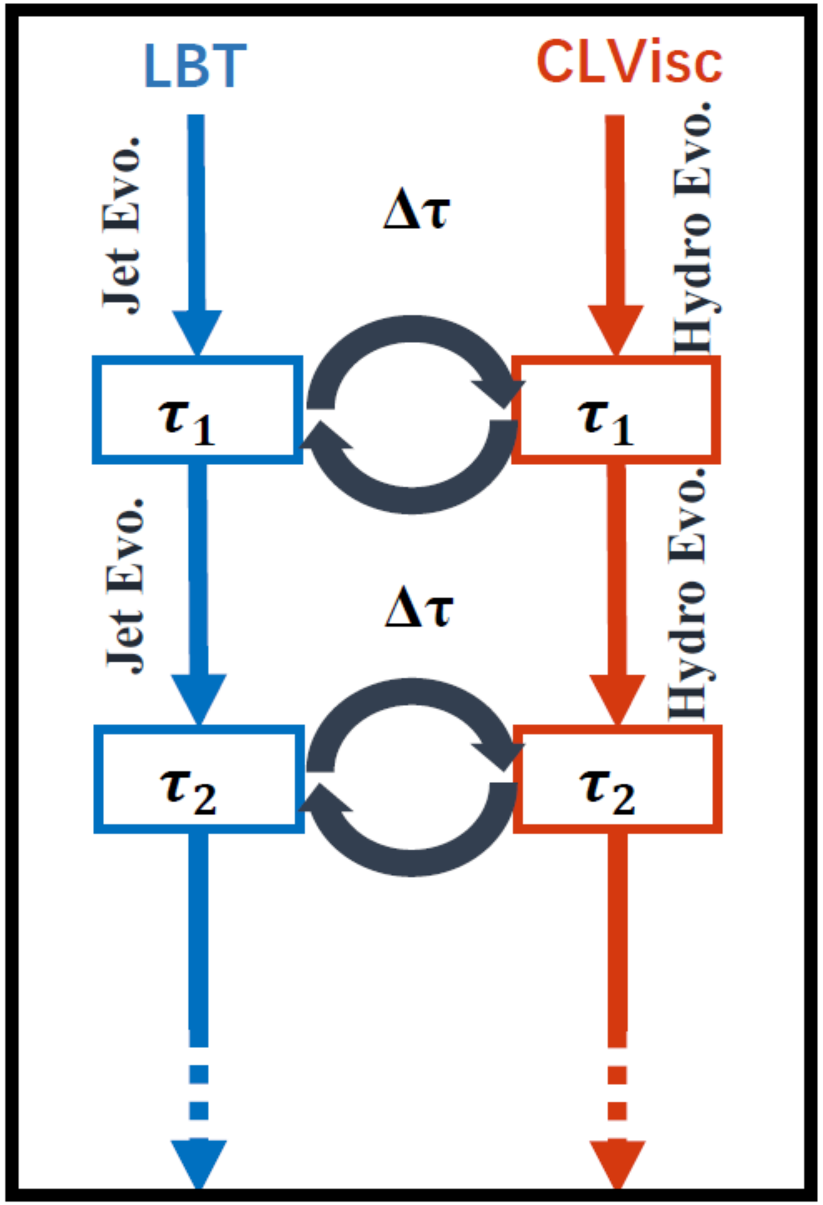
Jet physics region

$$R_{\mathrm{AA}}(p_{\mathrm{T}}, y, \phi) \equiv \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{\frac{dN_{\mathrm{AA}}}{dp_{\mathrm{T}}dyd\phi}}{\frac{dN_{\mathrm{pp}}}{dp_{\mathrm{T}}dyd\phi}},$$

$$v_2(p_{\mathrm{T}}, y) \equiv \frac{\int d\phi \cos(2\phi) \frac{dN}{dp_{\mathrm{T}}dyd\phi}}{\int d\phi \frac{dN}{dp_{\mathrm{T}}dyd\phi}}$$

- 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. B 810, 135783 (2020), 2005.09678.

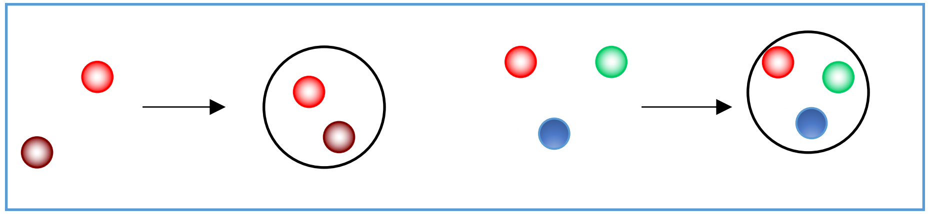
Sophisticated Coalescence model

- **Coalescence model**

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

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

$g_{B(M)}$ is statistic factor, $f_{q/\bar{q}}$ is the phase-space distribution of (anti)quarks, $W_{M/B}$ is Wigner function of meson(baryon).
Here, we use the harmonic oscillator for wave functions of hadrons, then do the Wigner transformation to get the $W_{M/B}$.



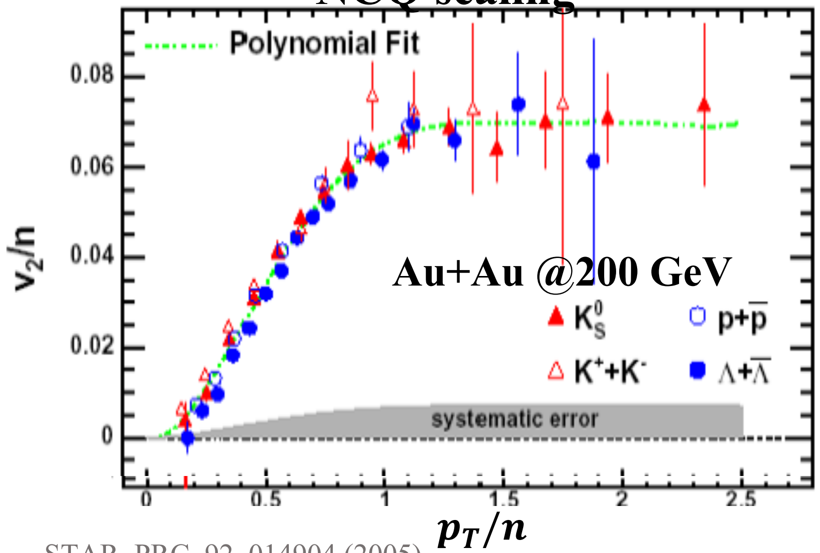
Thermal & hard Partons:

- *Thermal partons* generated by hydro
- *Hard partons* generated by PYTHIA8, then suffered with energy loss by CoLBT

Coalesence processes:

- thermal - thermal parton coalescence
- thermal - hard parton coalescence
- hard - hard parton coalescence

NCQ scaling



Han, Fries and Ko, PRC 93, 045207 (2016).
Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301 (2020).

STAR, PRC, 92, 014904 (2005).

String fragmentation

- **Colorless string fragmentation**

- Shower partons that do not coalesce will hadronize through string fragmentation using PYTHIA8.
- Shower partons have lost their original color configurations. We connect strings to minimizes the distance

$$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$$

JETSCAPE framework: Phys. Rev. C 102, 054906 (2020).
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Framework of calculations

Hydro-Coal-Frag hadronization

Thermal hadrons, low p_T (CLVis):

- generated by hydro. with Cooper-Frye.
  Meson: $p_T < 2p_{T1}$; baryon: $p_T < 3p_{T1}$.

-initial shower partons from pythia8 with $p_T > p_{T2}$

Coalescence hadrons (Coal Model):

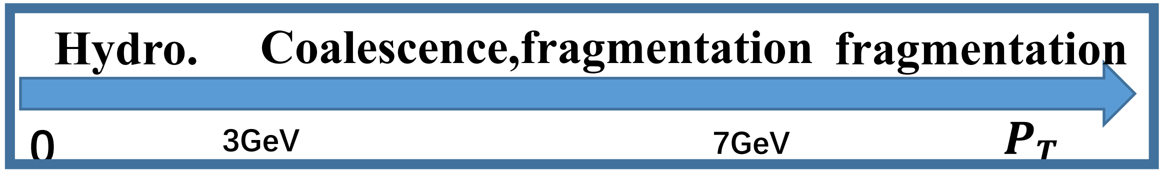
-generated by coalescence model
including thermal-thermal,
thermal-hard & hard-hard coalesence.

Fragmentation hadrons :

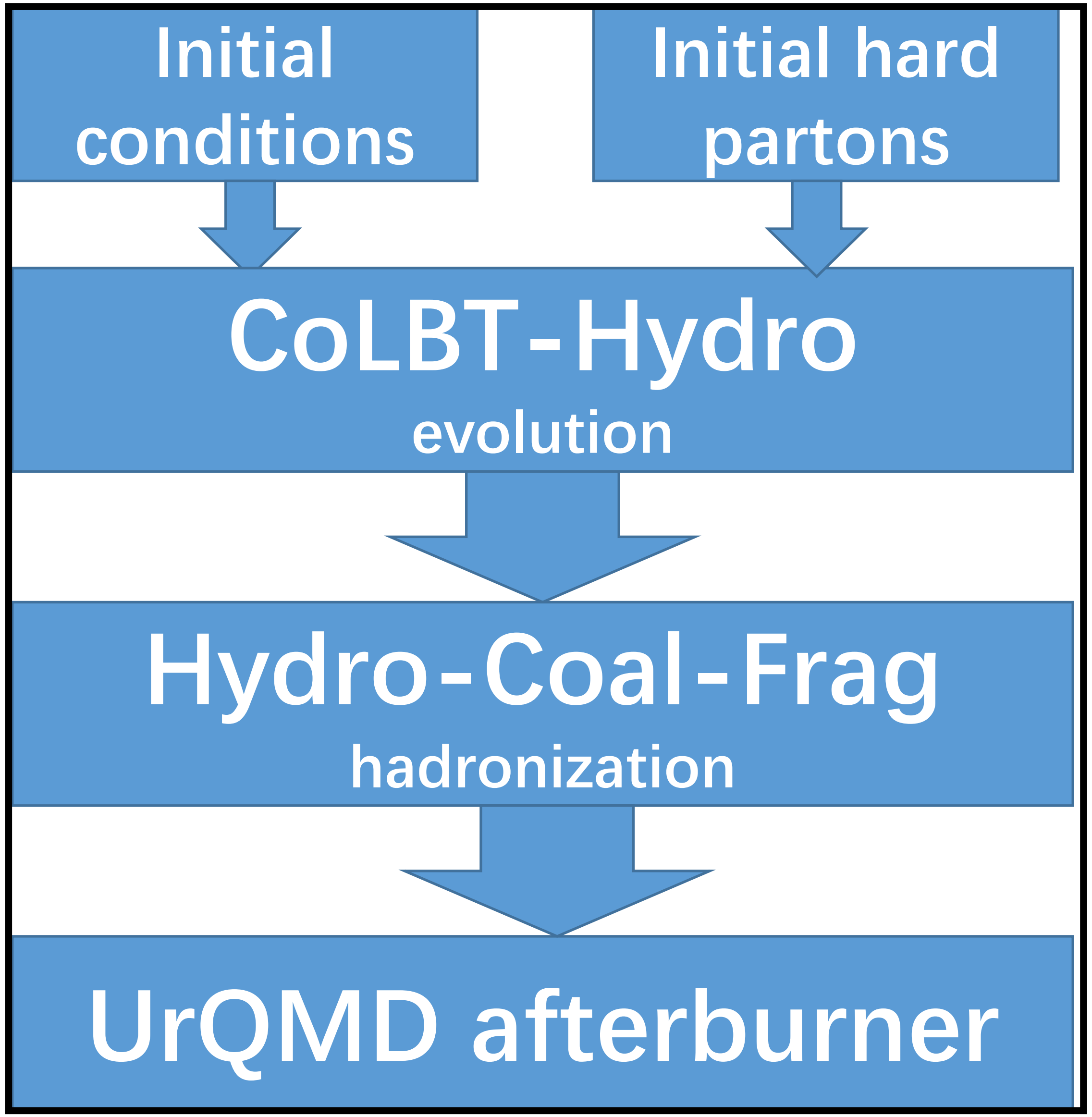
-the remnant hard quarks feed to fragmentation.

UrQMD afterburner:

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

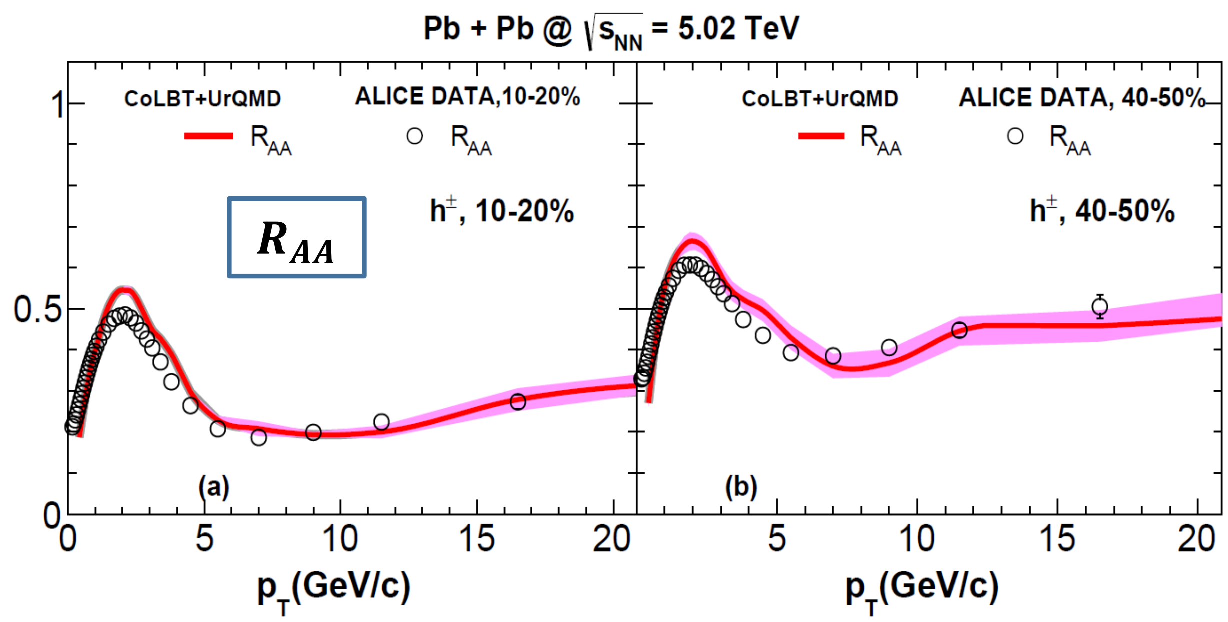


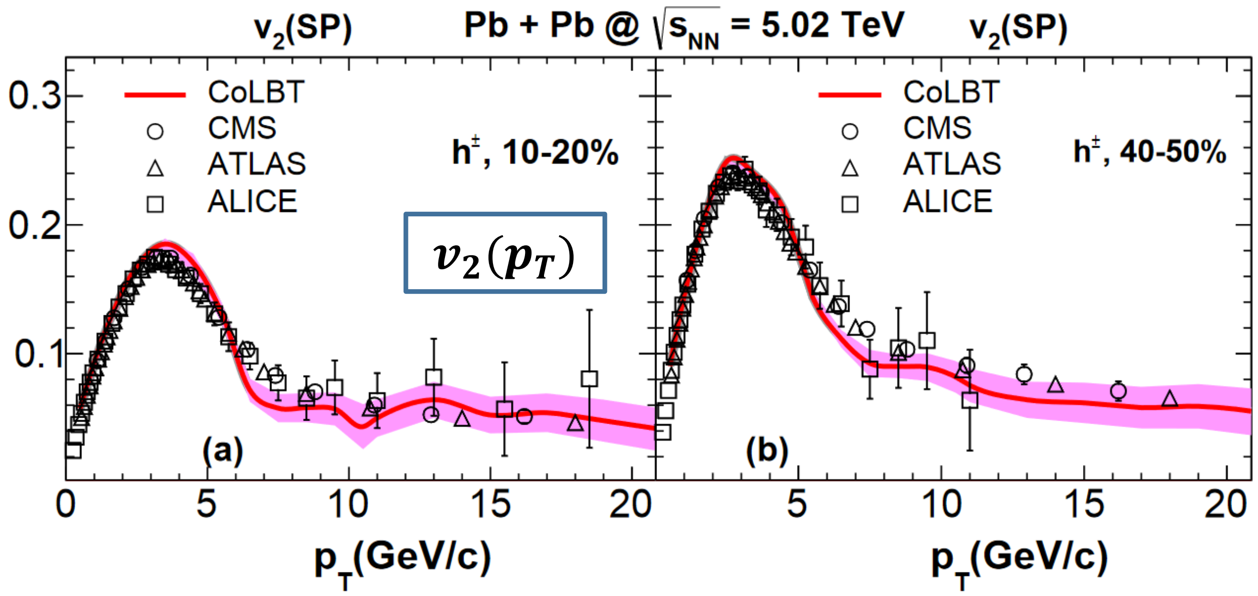
Framework



W. Zhao, Ko, Liu, Qin and Song, PRL. 125, 072301 (2020). W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

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

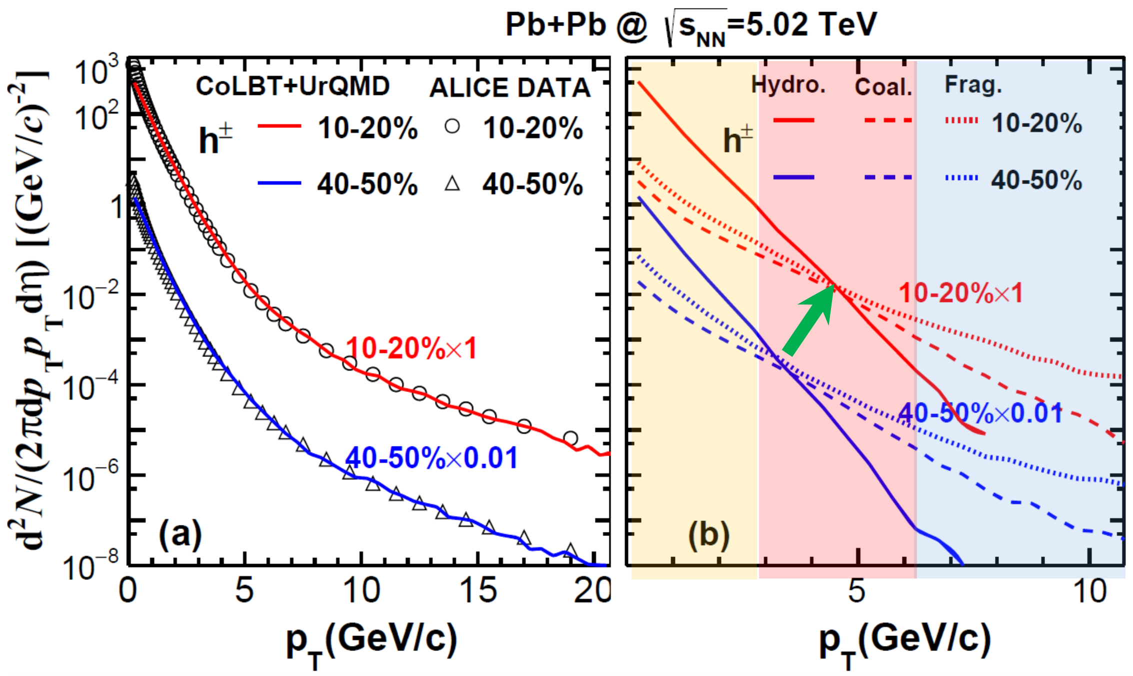


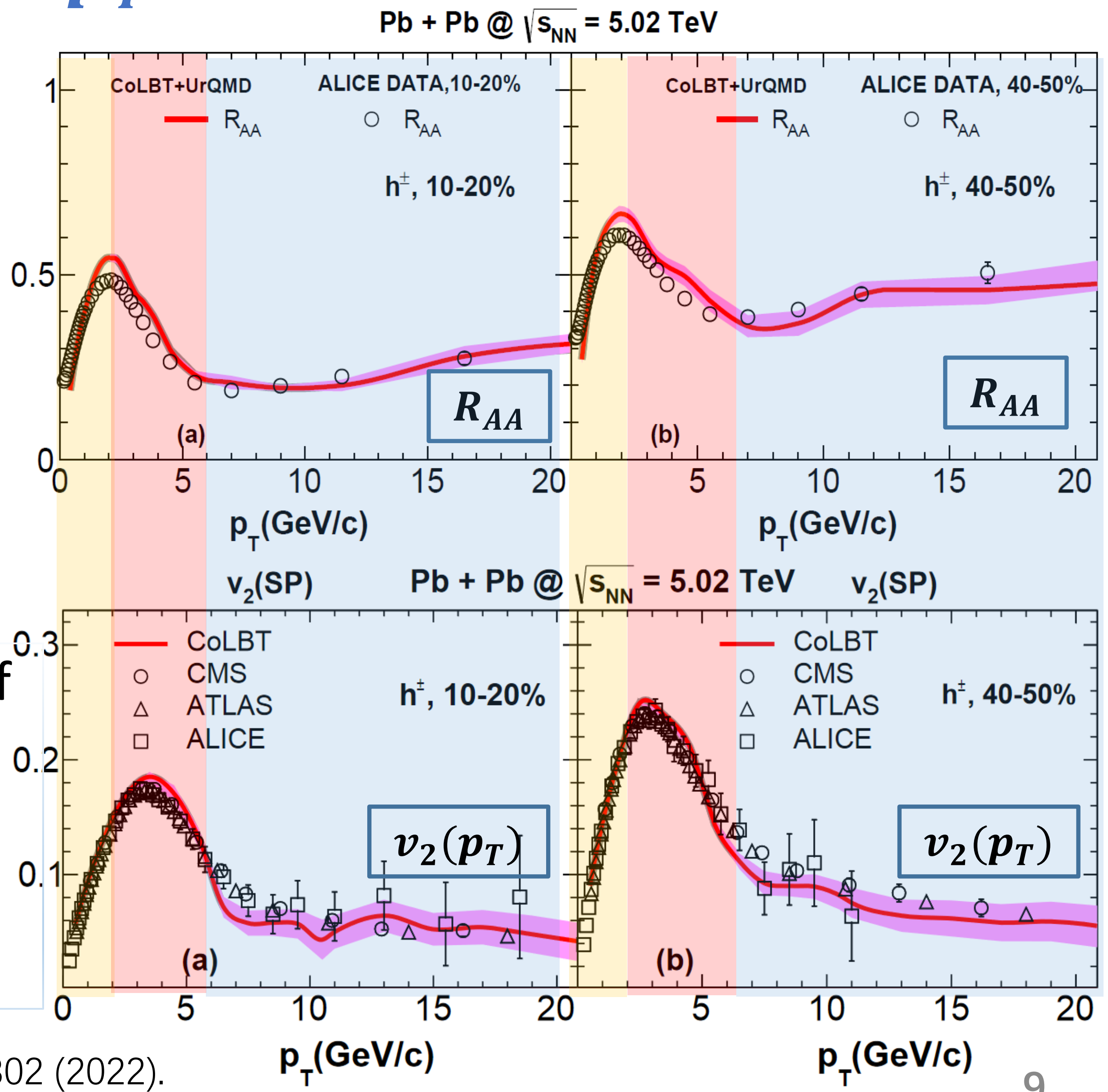


- CoLBT-hydro with Hydro-Coal-Frag hadronizations can simultaneously describe the R_{AA} and collective flow from low p_T to high p_T regions in Pb+Pb collisions.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Transition from low p_T to high p_T

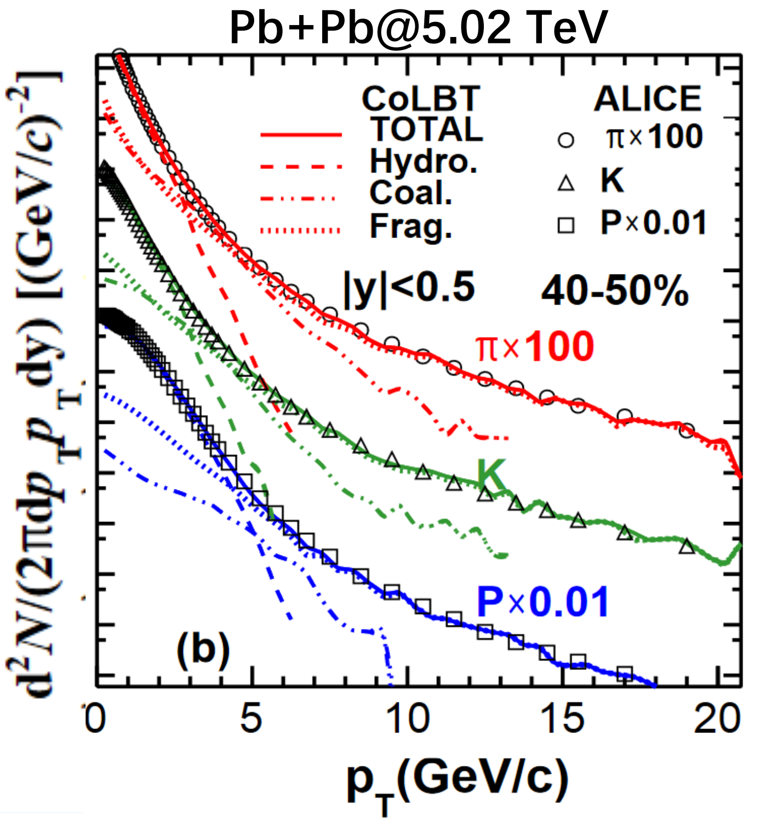


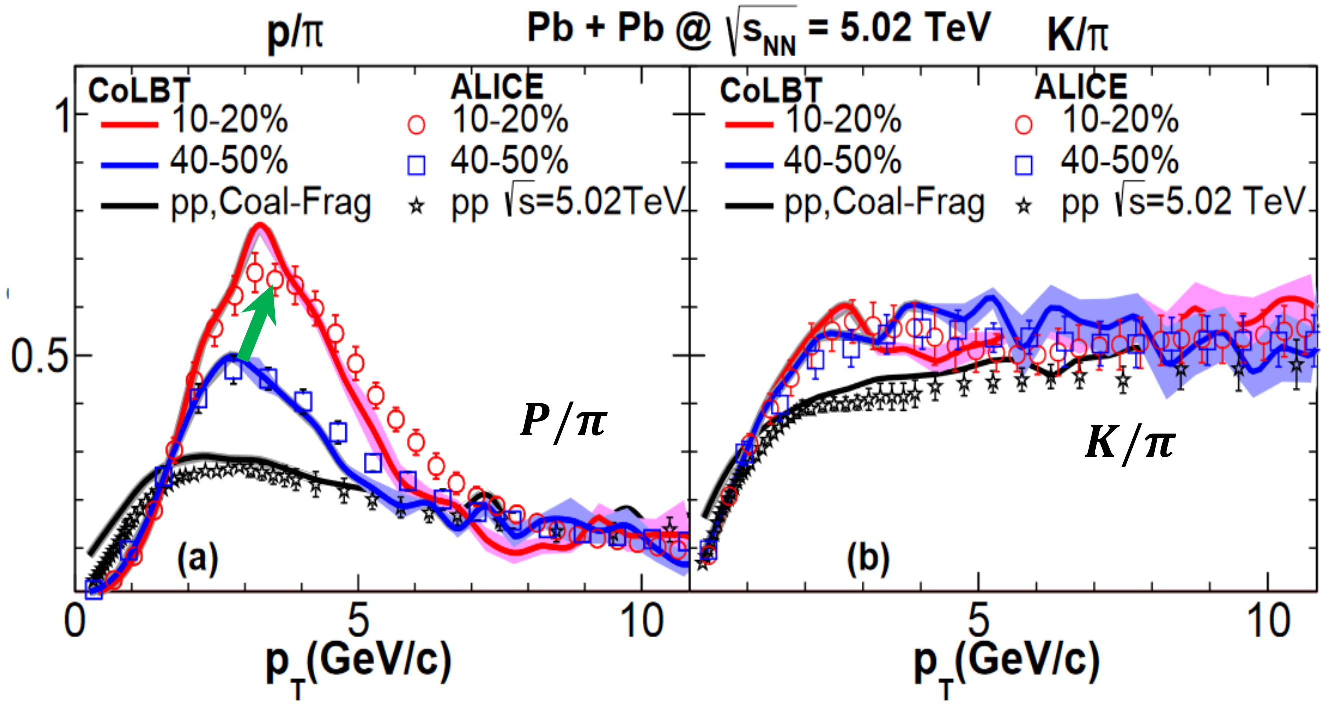


- CoLBT-hydro nicely describes the spectra of charged from 0 to 20 GeV.
- Low p_T: hydro; Intermediate p_T: transition regime; High p_T: jet physics.
- Transition p_T is higher in central collisions.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Transverse momentum spectra of identified hadrons

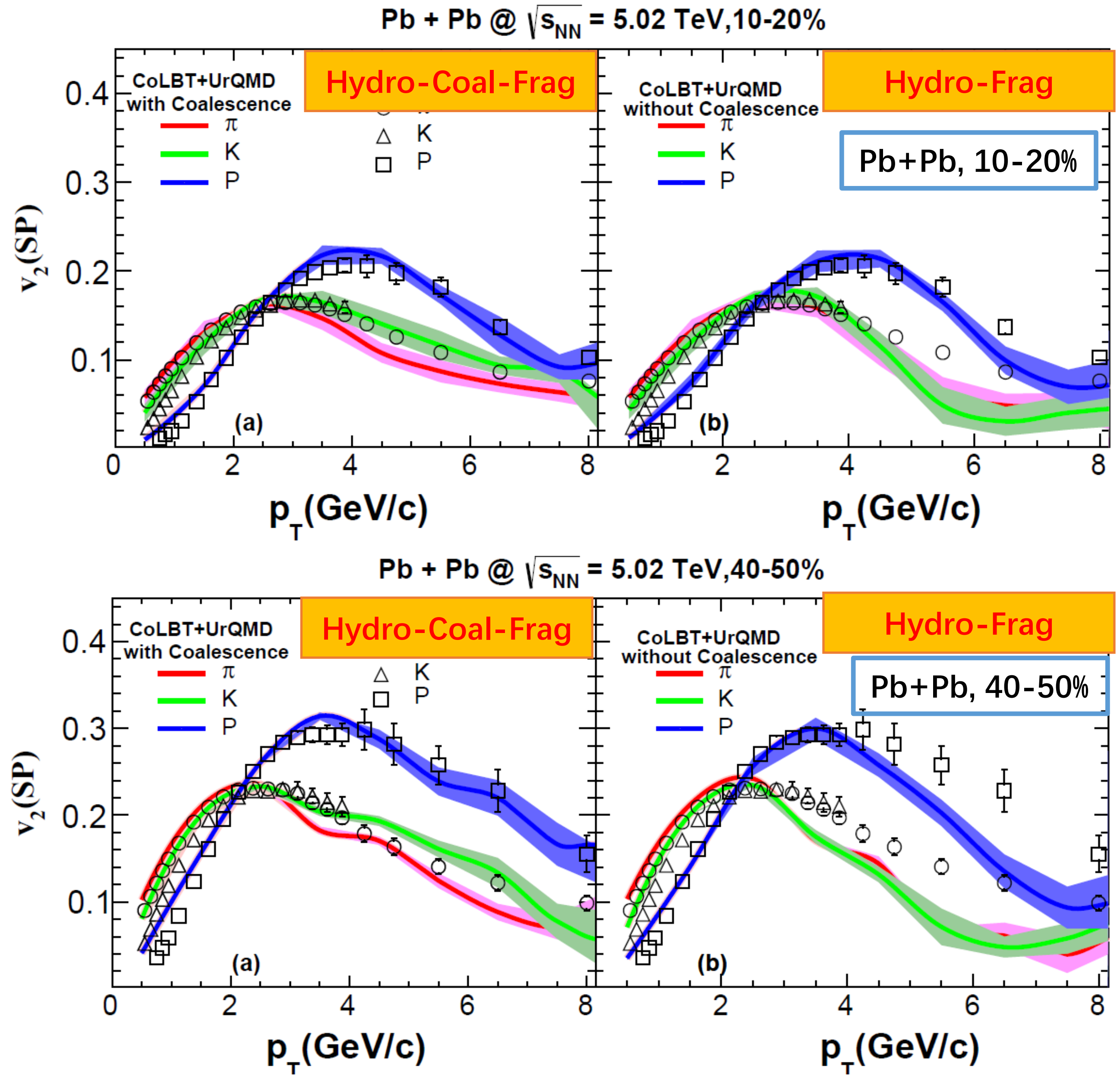




- CoLBT-hydro nicely describes the spectra of identified hadrons, $\boldsymbol{P/\pi}$ and $\boldsymbol{K/\pi}$ from 0 to 20 GeV.
- $\boldsymbol{P/\pi}$ in Pb+Pb is higher than pp; $\boldsymbol{P/\pi}$ peak moves to higher p_T in central collision.
- $\boldsymbol{P/\pi}$ and $\boldsymbol{K/\pi}$ approach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

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Collective flow of identified hadrons

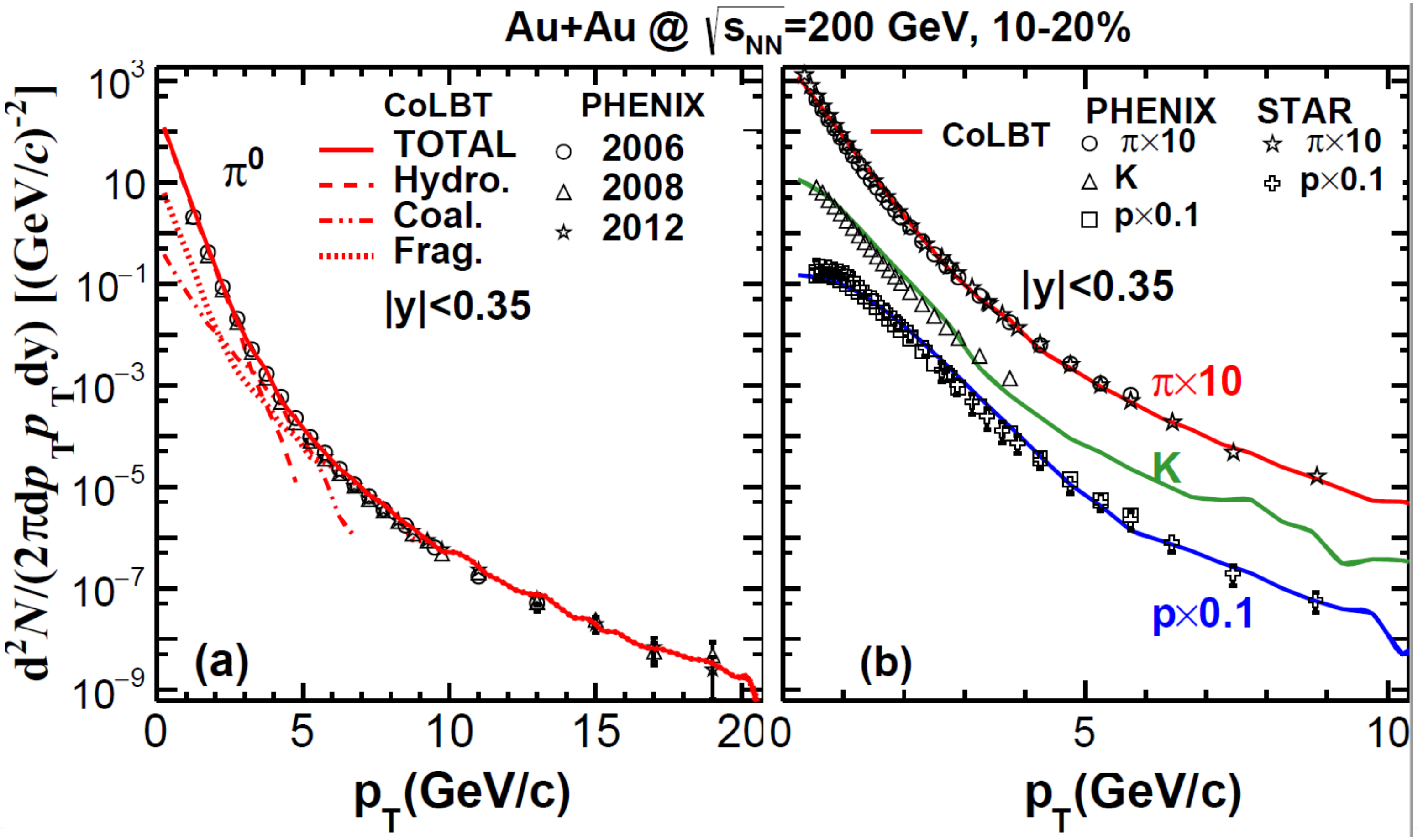


- CoLBT-hydro with Hydro-Coal-Frag works well for PID flow from 0 to 8 GeV.
- $v_2(p_T)$ of P larger than π and K at 3 GeV, caused by interplay between hydro. Coal. and frag.
- Quark coalescence is important for Pb+Pb collisions at intermediate p_T range.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

Predictions for Au-Au at RHIC

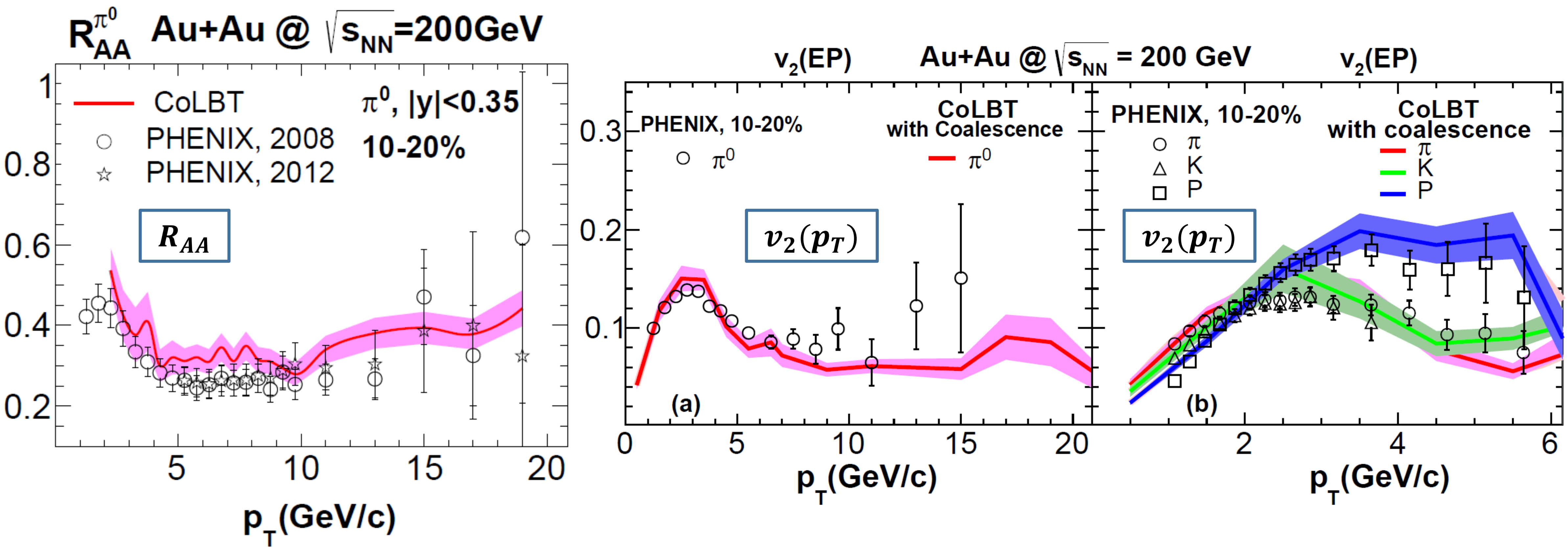
Spectra at Au-Au at RHIC



- 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, PRL. 128, 022302 (2022).
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, in preparation.

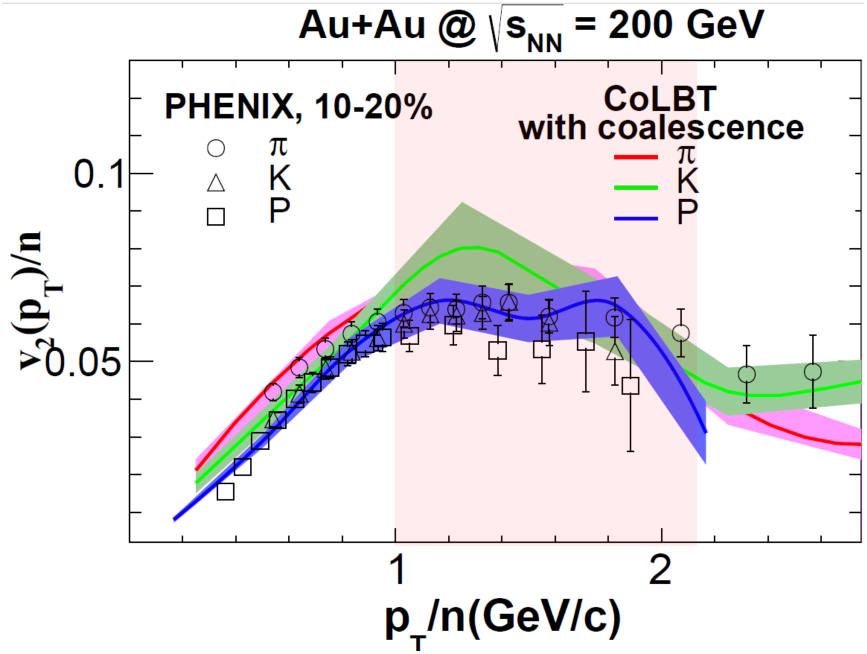
R_{AA} and $v_2\ (p_T)$ at Au-Au at RHIC

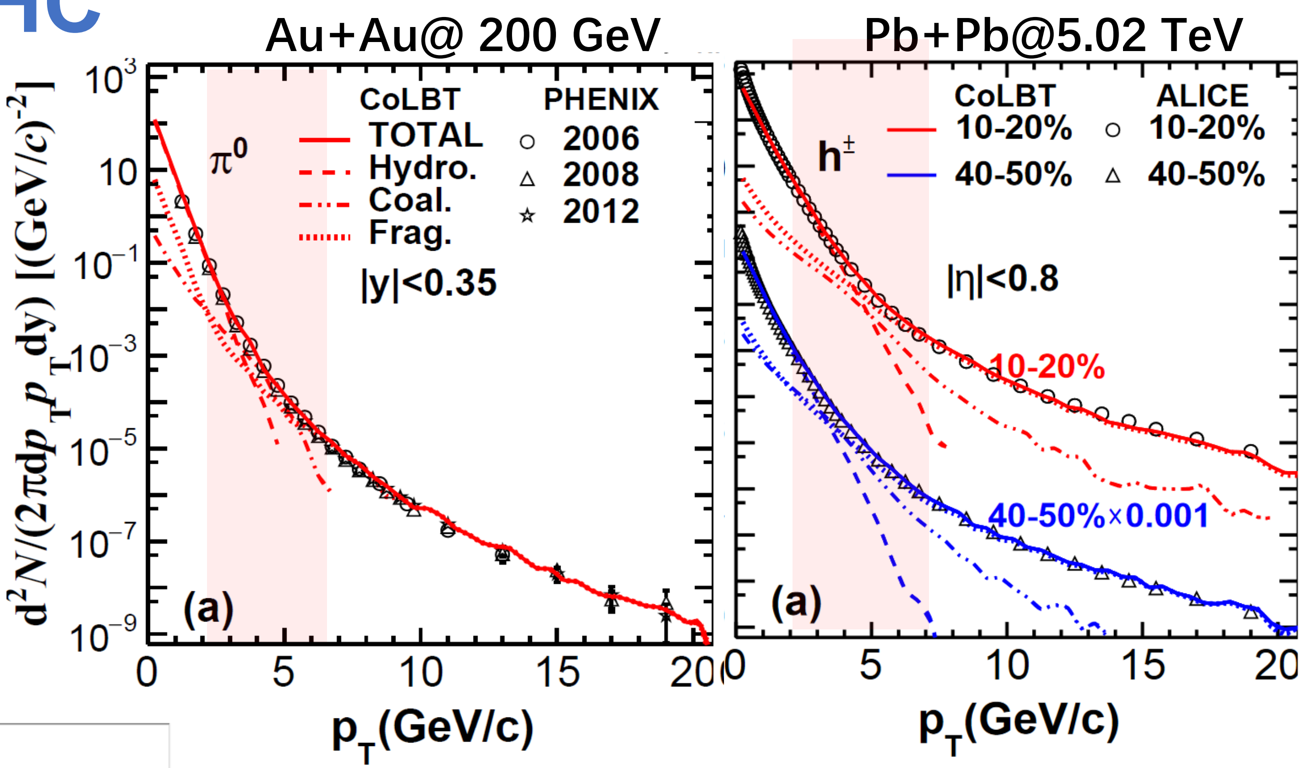


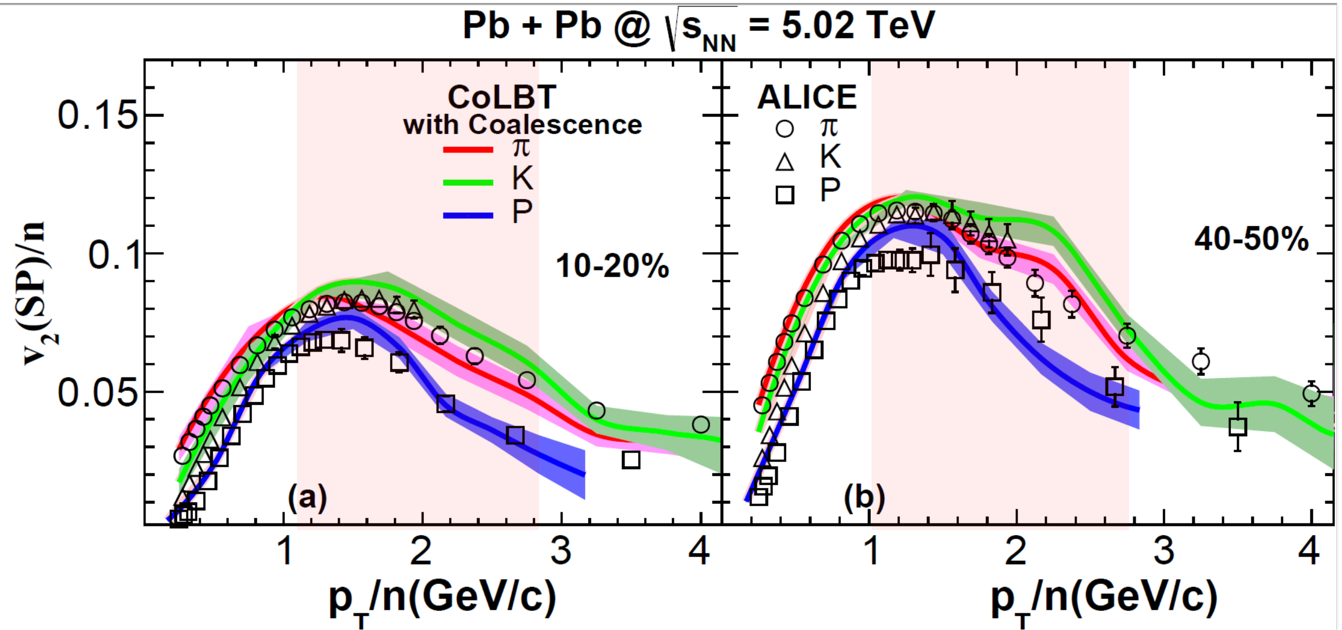
- With parameters fixed at LHC, CoLBT-hydro nicely predicts the $\mathrm{R_{AA}}$ and $v_2(p_T)$ from 0 to 20 GeV in Au-Au at 200 GeV.
- CoLBT-hydro nicely predicts the $v_2(p_T)$ of π, K and P from 0 to 6 GeV in RHIC.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).
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, PRL. 128, 022302 (2022).
W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, in preparation.

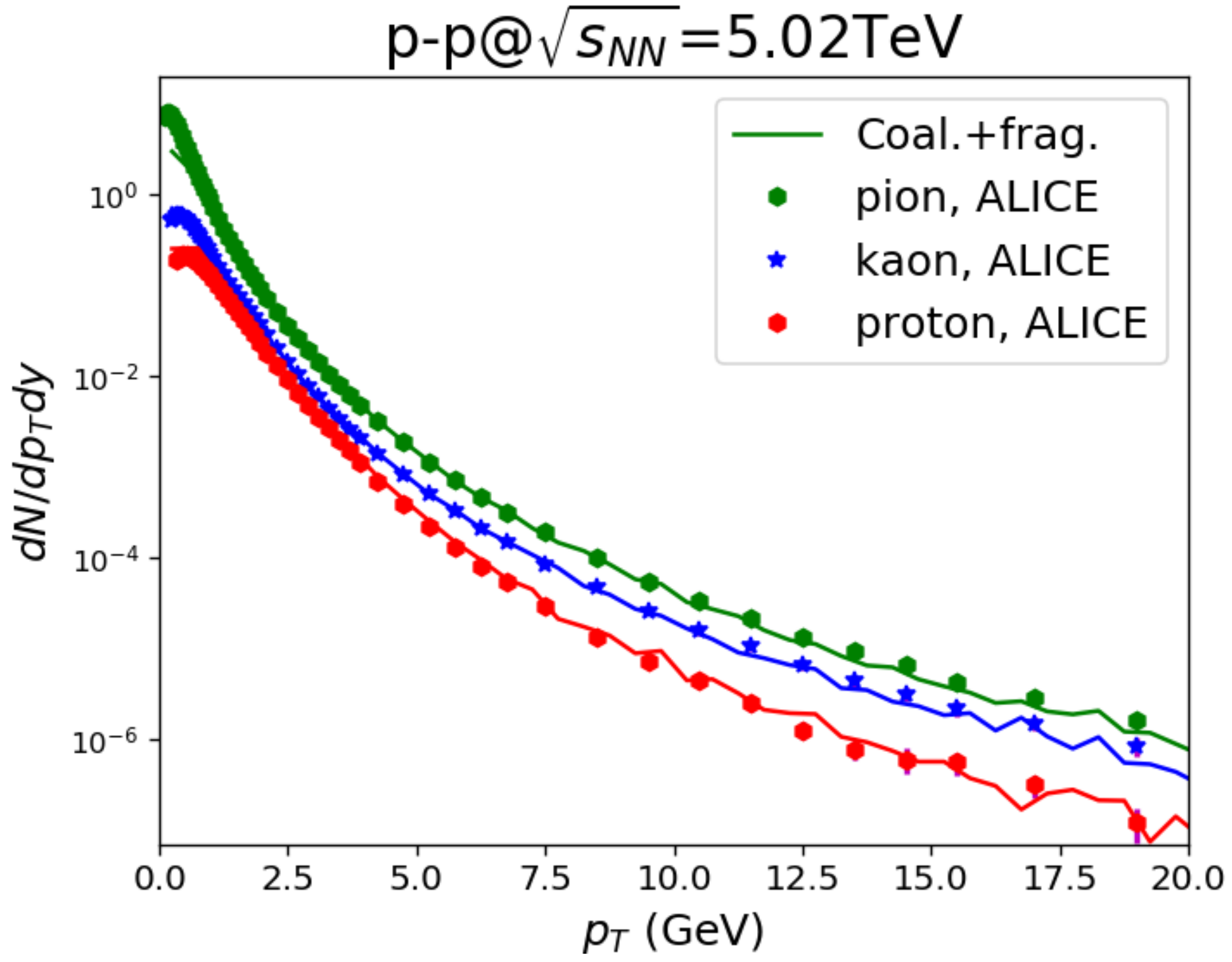
Summary

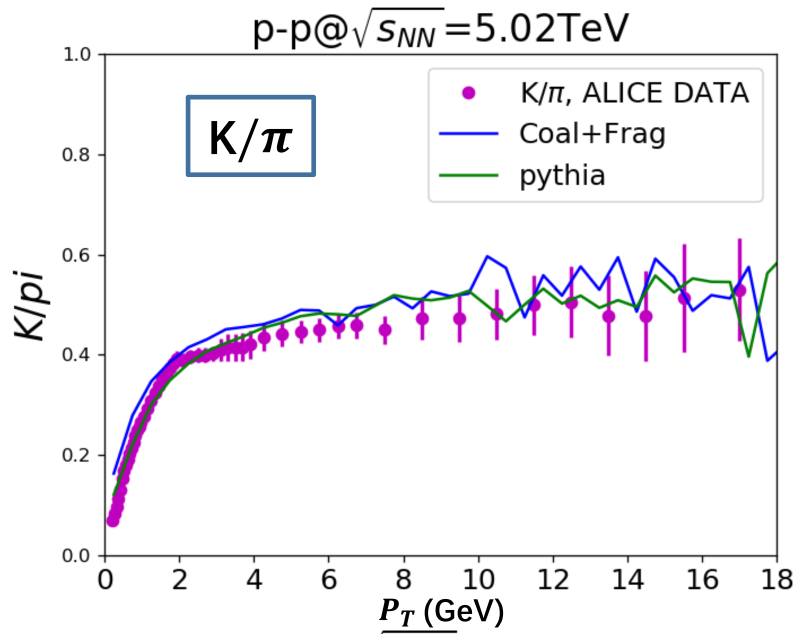
- CoLBT-hydro with Hydro-Coal-Frag hadronization simultaneously describe the R_{AA} and collective flow from low p_T to high p_T in Pb+Pb collisions.
- CoLBT-hydro also nicely describes the collective flow of identified hadrons with p_T from 0 to 8 GeV.
- Quark coalescence is important in heavy-ion collisions.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

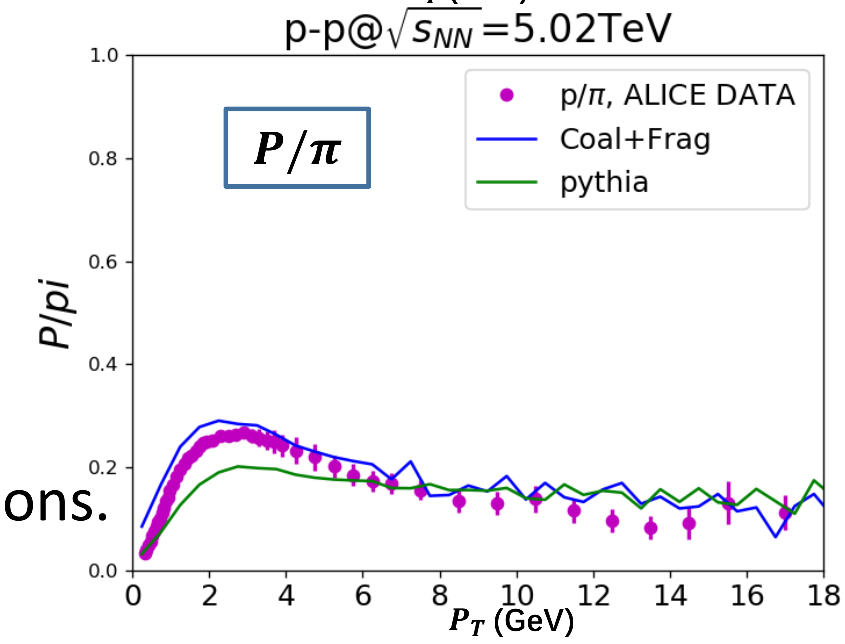
Thanks for Your Attention!

Back Up

Verification of the hadronization code in p-p



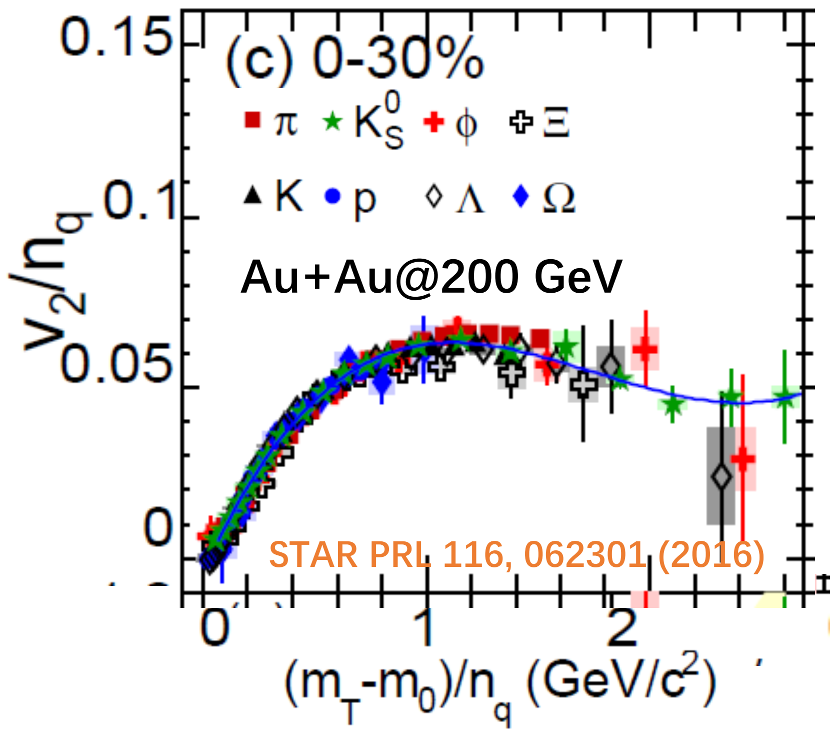


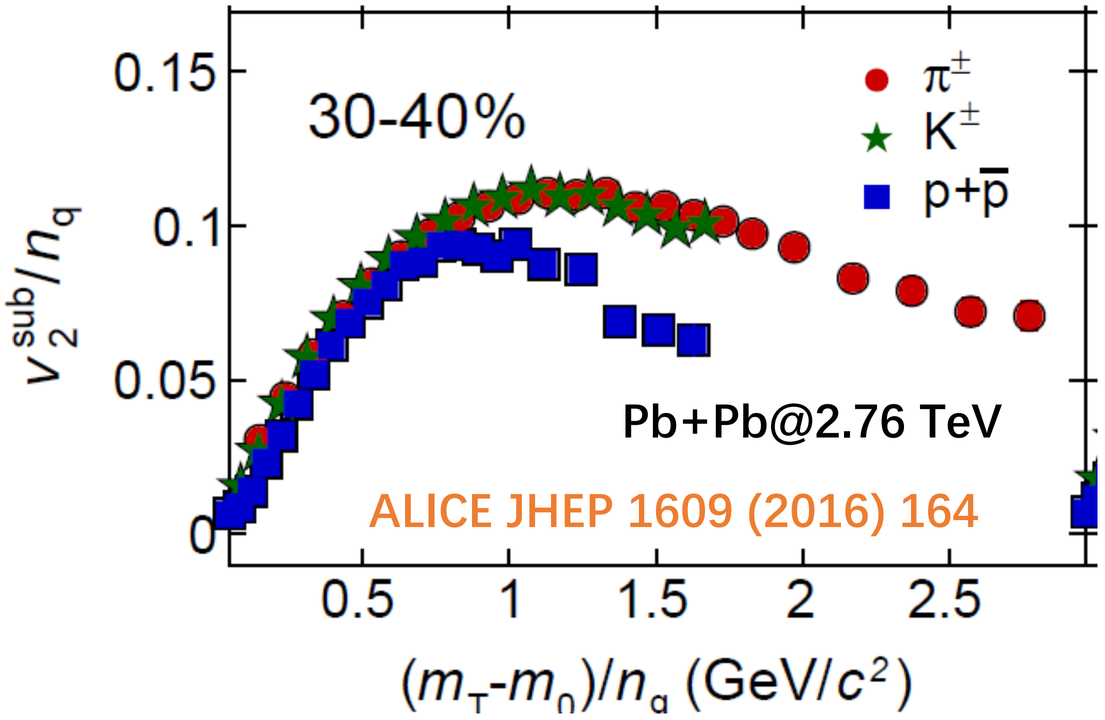


- Coal-Frag model can well reproduce the p_T-spectra of π, K and P as well as the K/π and P/π in p-p collisions.

W. Zhao, W. Ke, W. Chen, T. Luo and X. N.Wang, PRL. 128, 022302 (2022).

"NCQ scaling puzzle" between RHIC and LHC





- **At intermediate p_T range, NCQ scaling behavior is prefect at Au-Au@200 GeV collisions, how it's greatly violated at Pb-Pb@2.76 TeV.**
- **What causes such discrepancy between RHIC and LHC?**

Initialization of hard partons

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

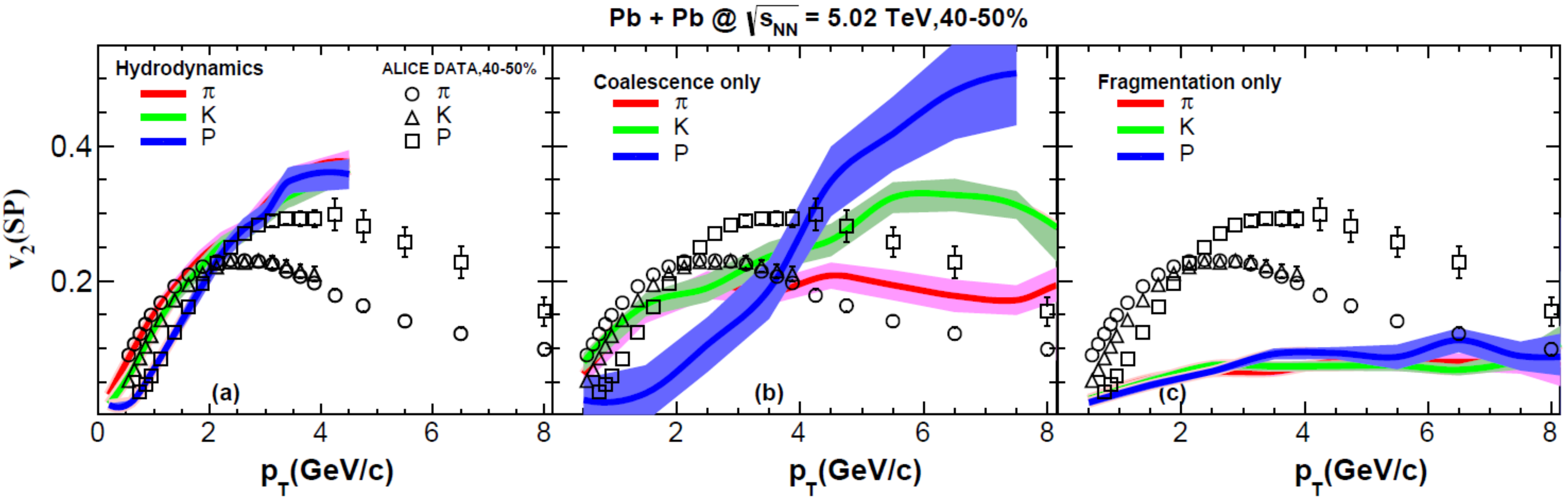
$$\frac{dN_{\rm coll}}{d\mathbf{r}_\perp^2}(\mathbf{r}_\perp; b) = T_{\rm Pb}(\mathbf{r}_\perp + \mathbf{b}/2) T_{\rm Pb}(\mathbf{r}_\perp - \mathbf{b}/2)$$

- **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.

$v_2(p_T)$ 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).

Positions of fragmented hadron

the center of mass of a string r_s and the time of the latest born remnant parton t_s. The formation time of a hadron with E and m_T is

$$t_f = E/m_T^2,$$

The position and time of each hadron produced from the string fragmentation are written by

$$t_H = t_s + t_f$$

$$\mathbf{r}_H = \mathbf{r}_s + \mathbf{v}t_f$$

Where **v** is the speed of the center-of-mass of the partons in the lab frame

Han, Fries and Ko, PRC 93, 045207 (2016).
Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301 (2020).
.