Probing the partonic degree of freedom in high multiplicity p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

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based on: **W. Zhao**, C.M. Ko, Y.X. Liu, G.Y. Qin and H. Song, arxiv:1911,00826.

Sophisticated Coalescence model

Mesons and baryons' momentum distributions by recombining of quarks:

$$\frac{dN_M}{d^3\mathbf{P}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1,\mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2,\mathbf{p}_2) \times W_M(\mathbf{y},\mathbf{k}) \delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2)\,, \quad (1)$$

and

$$\frac{dN_B}{d^3\mathbf{P}_B} = g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1,\mathbf{p}_1) \times f_{q_2}(\mathbf{x}_2,\mathbf{p}_2) f_{q_3}(\mathbf{x}_3,\mathbf{p}_3) W_B(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) \times \delta^{(3)}(\mathbf{P}_B - \mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3)\,, \quad (2)$$

$g_{B(M)}$ is the statistic factor, $f_{q,\bar{q}}(\mathbf{x}_1,\mathbf{p}_1)$ is the phase-space distribution of (anti)quarks, normalized as $\int d^3\mathbf{x} d^3\mathbf{p} f_{q,\bar{q}}(\mathbf{x},\mathbf{p}) = N_{q,\bar{q}}$, $W_{M(B)}$ is the winger function of meson(baryon).

V. Greco, C. M. Ko and P. Levai, Phys. Rev. Lett. **90**, 202302 (2003).

Framework of Hydro-Coal-Frag

-- **Thermal hadrons**: generated by hydro. with Cooper-Frye.

Meson: $P_T < 2P_1$; baryon: $P_T < 3P_1$.

-- **Coalescence hadrons**: generated by quark coalescences, including thermal-thermal, thermal-hard and hard-hard coalescence, with the corresponding ground and excited states.

a. ***Thermal partons*** **generated by hydro with $P_T > P_1$.**

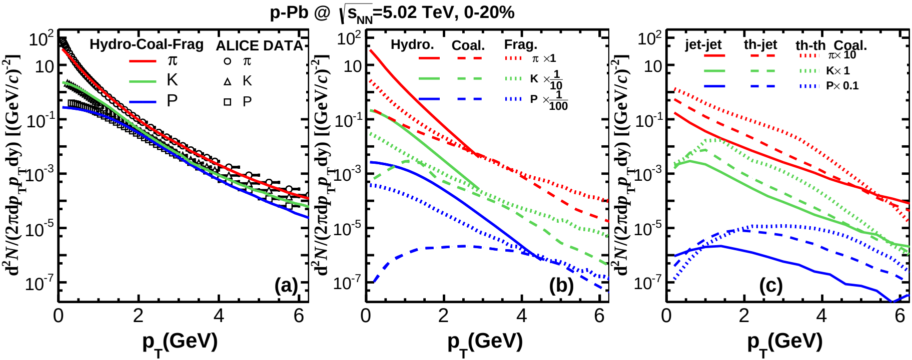
b. ***Hard partons*** **generated by PYTHIA8, then suffered with energy loss by LBT with α=0.15. Get the hard parton with $P_T > P_2$.**

-- **Fragmentation process**: the remnant hard quarks feed to fragmentation .

-- **All hadrons feed to the UrQMD model.**

NOTE: the main two parameters, $p_{T1} = 1.6GeV$ and $p_{T2} = 2.6GeV$ are fixed by spectra of pions, kaons and protons at intermediate p_T. The parameters of hydro and LBT are fixed by other places already.

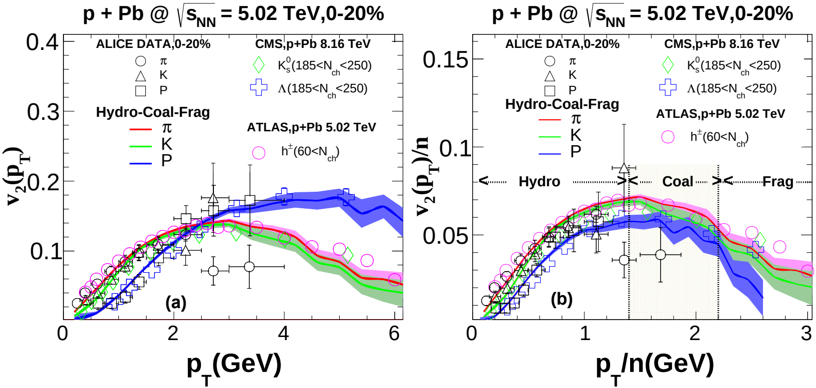
Spectra of π, K, P and P/π



- Low p_T: hydrodynamics dominates.
- Intermediate p_T: coalescence and fragmentation.
- High p_T : Fragmentation dominates.
- Coalescence hadrons: Thermal-thermal coalescence dominates.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, arxiv: 1911.00826.

$v_2(p_T)$ and NCQ scaling

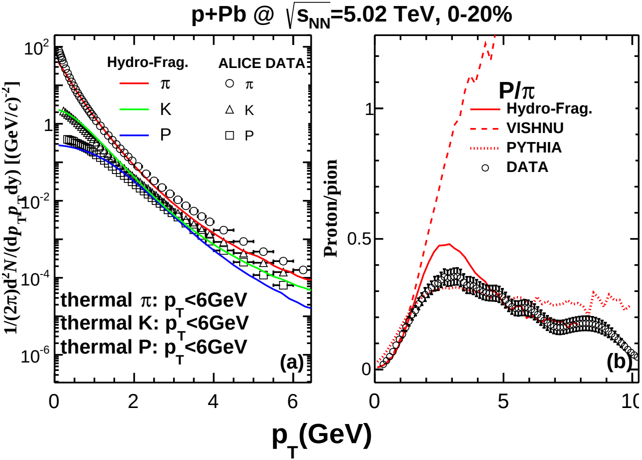


- Hydro-Coal-Frag model gives a nice description of $v_2(p_T)$ of pion, kaon and proton over p_T from 0 to 6 GeV.
- At intermediate p_T, Hydro-Coal-Frag model can get the approximately NCQ scaling at data shown.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, arxiv: 1911.00826.

The importance of quark coalescence process in p-Pb system

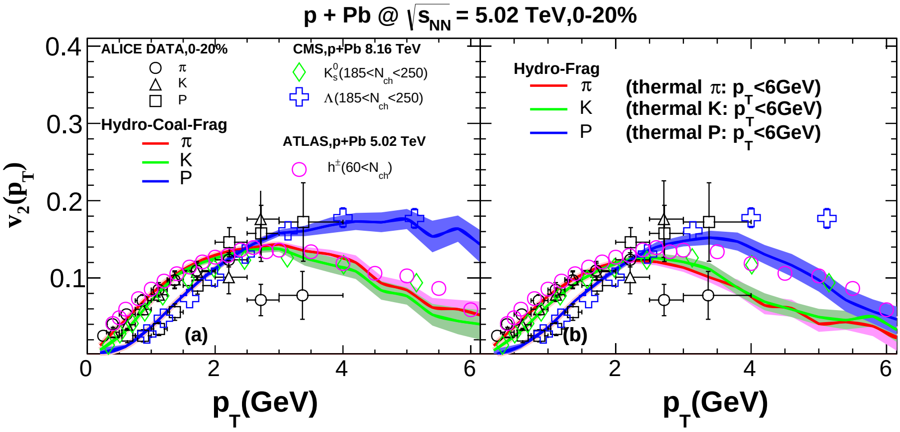
spectra of Hydro-Frag



- Hydro-Frag underestimates the spectra at intermediate p_T.
- Hydro-Frag also fail to reproduce the P/π.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, arxiv: 1911.00826.

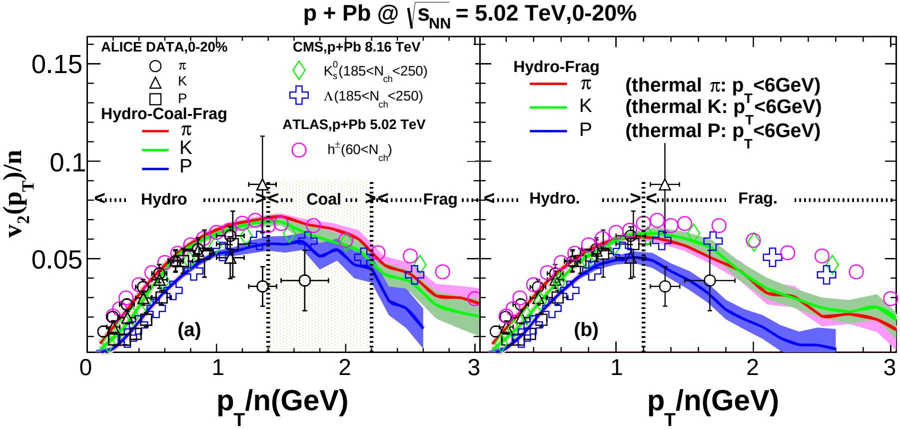
$v_2(p_T)$ of Hydro-Coal-Frag, and Hydro-Frag



- Without coalescence, Hydro-Frag greatly underestimates the $v_2(p_T)$ at intermediate p_T.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, arxiv: 1911.00826.

NCQ scaling of Hydro-Coal-Frag, and Hydro-Frag



- Without coalescence, Hydro-Frag will greatly violate the NCQ scaling at intermediate p_T, with the deviation of NCQ scaling at the level of $\pm 50\%$.

W. Zhao, C.M.Ko, Y.X.Liu, G,Y.Qin and H. Song, arxiv: 1911.00826.

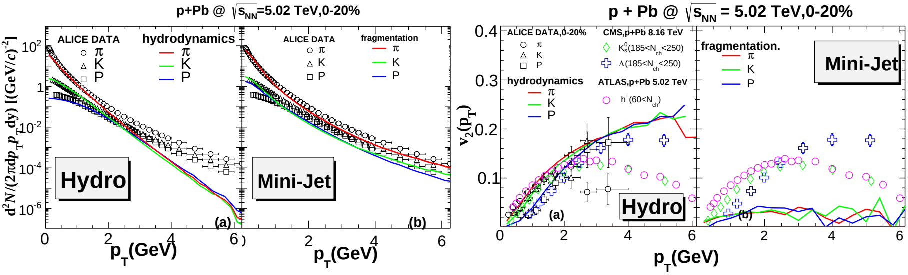
Summary

- NCQ scaling is a very important signal to probe the partonic degree of freedom in small system.
- Our model, `Hydro-Coal-Frag`, that combines `Hydro.`, `Coal.` and `Frag.` together can well describe the spectra, $v_2(p_T)$ and the approximately NCQ scaling at intermediate p_T.
- Quark coalescence is necessary in high multiplicity p+Pb collisions. Without quark coalescence, it would not only underestimate the magnitude of $v_2(p_T)/n$ but also greatly violate the NCQ scaling behavior at intermediate p_T, no matter how we tune the related parameters.
- This implies the possible formation of QGP in high multiplicity p-Pb collisions at LHC.

Thanks

Back up

Further explore p-Pb system by hydro or min-jet



- Hydrodynamics works at low p_T, but fails at intermediate and high p_T.
- Mini-jet can't generate enough flow at low and intermediate p_T.
- At intermediate p_T: one need to combine soft and hard parts.

Wigner function for excited states

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, $W_{q,\bar{q}}$:

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

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

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

$\xi = \sqrt{\frac{m\omega}{\hbar}}x$, $H_n(\xi)$ 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).

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).

Decay of excited states

Excited states decay into multiple pions in the case of light quark mesons, to kaon and pion in the case of light and strange mesons, to (anti)nucleon and pion in the case of light flavor (anti)baryons, and to Λ and pion in the case of strangeness ± 1 baryons. For decays into multiple pions, the relative probabilities are determined through the available phase space:

$$P_l(M) \sim \left[\frac{1}{6\pi^2}\left(\frac{M}{m_\pi}\right)^3\right]^l \frac{(4l-4)!(2l-1)}{(2l-1)!^2(3l-4)!} \, . \tag{9}$$

Here l is the number of pions, M is the mass of the excited state, or the invariant mass of the light quark-antiquark pair.

Excited states decay into kaon or Λ in a similar way.

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