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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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

- Different domains are clearly observed in data in heavy-ion collisions.
- Intermediate $p_T$ ($3<p_T<8$-10 GeV): transition regime; (Not well studied.)
CoLBT-hydro model

CoLBT-Hydro model

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

Evolve the energetic partons and the bulk medium concurrently.

Hydrodynamics equations with the source terms:

\[ \partial_\mu T_{\text{fluid}}^{\mu\nu} = J^{\nu} \]

\( T_{\text{fluid}}^{\mu\nu} \): Energy-momentum tensor of the QGP fluid;
\( J^{\nu} \): Energy-momentum density deposited by energetic partons.

with the Gaussian smearing:

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

\( p^0_{\text{cut}} \) separates the soft and hard partons

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.

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W. Zhao, Ko, Liu, Qin and Song, PRL. 125, 072301 (2020).
Verification of the hadronization code in p-p

\[ p-p@\sqrt{s_{NN}}=5.02\text{TeV} \]

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

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

CoLBT-hydro with Hydro-Cool-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 $p_T$

- CoLB-T-hydro nicely describes the spectra of charged from 0 to 20 GeV.
- Transition $p_T$ is higher in central collisions.

Transverse momentum spectra of identified hadrons

- CoLBT-hydro nicely describes the spectra of identified hadrons from 0 to 20 GeV.
- CoLBT nicely describes the particle ratios. $P/\pi$ peak moves to higher $p_T$ in central collision.
- $P/\pi$ and $K/\pi$ 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 $\pi$ 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.

Predictions for Au-Au at RHIC
With parameters fixed at LHC, CoLBT-hydro nicely predicts the spectra of $\pi^0$ and of $\pi^\pm$, K and P from low $p_T$ to high $p_T$ in Au-Au at 200 GeV.

$R_{AA}$ 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 $\pi$, $K$ and $P$ from 0 to 6 GeV in RHIC.

NCQ scaling at RHIC and LHC

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

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
Initialization of hard partons

• Transverse locations of hard collisions $r_\perp$ are sampled from the binary collision density

$$\frac{dN_{\text{coll}}}{dr^2_\perp}(r_\perp; b) = T_{Pb}(r_\perp + b/2)T_{Pb}(r_\perp - b/2)$$

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

$$\tau_f = 2x(1-x)\frac{E}{k^2_\perp}$$

Hadron cascade effects

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

- Hydro. works at low $p_T$ range ($p_T<2-3$ GeV).
- Quark coalescence generates large $v_2$ at intermediate $p_T$ ($3<p_T<8$ GeV)
- 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 $W_{q,\bar{q}}$:

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

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

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

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

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

$$\overline{W}_{M,n}(y, k) = \frac{v^n}{n!} e^{-v}.$$  \hspace{1cm} (5)

with

$$v = \frac{1}{2} \left( \frac{y^2}{\sigma^2_M} + k^2 \sigma^2_M \right).$$  \hspace{1cm} (6)

Similarly, the Gaussian smeared Wigner function for baryon is:

$$\overline{W}_{B,n_1,n_2}(y_1, k_1; y_2, k_2) = \frac{v_1^{n_1}}{n_1!} e^{-v_1} \cdot \frac{v_2^{n_2}}{n_2!} e^{-v_2},$$  \hspace{1cm} (7)

with

$$v_i = \frac{1}{2} \left( \frac{y_i^2}{\sigma^2_{B_i}} + k_i^2 \sigma^2_{B_i} \right), \hspace{0.5cm} i = 1, 2.$$  \hspace{1cm} (8)