New Challenges for open HF physic in URHICs

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Outline

✧ HF dynamics in QGP: estimates of T dependence of $D_s$

✧ Hadronization mechanism on $\Lambda_c/D$ ratios

✧ New observables: $v_n(\text{light}) - v_n(\text{heavy})$, $\sigma_{vn}/v_n$

✧ Impact of initial stages on HF dynamics: EM field, vorticity and Glasma
HF dynamics in QGP and estimates of T dependence of $D_s$
Specific of Heavy Quarks

- $m_{c,b} >> \Lambda_{QCD}$ production by pQCD hard processes
- $m_{c,b} >> T_{RHIC,LHC}$ negligible thermal production
- $m_{c,b} >> q^2 \sim gT_{RHIC,LHC}$ soft scatterings $\rightarrow$ Brownian motion
- $\tau_0 \approx 1/2m_Q << \tau_{QGP}$ witness of all the QGP evolution
- $\tau_{th} \approx \tau_{QGP} >> \tau_{q,g}$ carry more information of their evolution
HF in all stages of URHICs

- Dynamics in QGP
  - Transp. coeff. of QGP
  - Thermalization time

- Hadronization mechanism
  - coalescence and/or fragm.

- Formation of QGP with large vorticity

HQs in:
- Glasma
- EM field

HQs prod.

Adapted from R. Rapp
Relativistic Boltzmann at finite $\eta/s$

\begin{align*}
p^\mu \partial_\mu f_q(x, p) + m(x) \partial_\mu m(x) \partial_\mu f_q(x, p) &= C[f_q, f_g] \\
p^\mu \partial_\mu f_g(x, p) + m(x) \partial_\mu m(x) \partial_\mu f_g(x, p) &= C[f_q, f_g]
\end{align*}

Free streaming $\ 3p \neq 0$ Interaction $\epsilon - 3p \neq 0$ Collision term gauged to some $\eta/s \neq 0$

**Heavy Quarks evolution**

\[ p^\mu \partial_\mu f_Q(x, p) = C[f_q, f_g, f_Q](x, p) \]

$\mathcal{M}$ scattering matrix by QPM model fit to lQCD thermodynamics

**Hadronization by coalescence plus fragmentation**

S. Plumari et al., EPJC78 (2018) no.4, 348

\[
\begin{align*}
\frac{dN_{\text{Hadron}}}{d^2p_T} &= g_s \int \int d^3p_i \frac{d^3d_i}{(2\pi)^3} f_q(x_i, p_i) f_w(x_1, x_n, p_1, ..., p_n) \delta(p_T - \sum_i p_{iT}) \\
\frac{dN_h}{d^2p_h} &= \sum_f \int d\varepsilon \frac{dN_f}{d^2p_f} D_{f \rightarrow h}(\varepsilon)
\end{align*}
\]

Good description of spectra $D^0, D^+, D_s, \Lambda_c, B, \Lambda_b$
What is the underlying $D_s$?

- Get close AdS/CFT at $T \approx T_c$
- We have a probe with $\tau_{\text{therm}} \approx \tau_{\text{QGP}}$

$$\tau_{\text{th}} = \frac{M}{2\pi T^2} \left(2\pi T D_s\right) \simeq 1.8 \frac{2\pi T D_s}{(T/T_c)^2} \text{ fm/c}$$

Not a model fit to lQCD data!
The result is gotten from the simultaneous discription of $R_{AA}(p_T)$ & $v_2(p_T)$

Scardina et al., PRC96(2017) 044905
Hadronization mechanism on $\Lambda_c/D$ ratio
\( \Lambda_c/D \) from hadronization mechanism

With the same coalescence plus fragmentation model we describe the \( \Lambda_c/D^0 \) for RHIC and LHC

- This opens a new paradigm in studying HF
- The effect will be even larger for because larger \( \Lambda_b/B \)
New observables: $v_n$(light) - $v_n$(heavy), $\sigma_{vn}/v_n$
Sensitivity of $C(n,n)$ and $\nu_n$ variances on $D_s(T)$

- $C(n,n)$ and $\sigma_{\nu_n}/\nu_n$ is sensitive to $T$ dependence of $D_s$. 

\[ C(\nu^l_n, \nu^m_n) = \frac{(\nu^l_n - \langle \nu^l_n \rangle)(\nu^m_n - \langle \nu^m_n \rangle)}{\sigma_{\nu^l_n} \sigma_{\nu^m_n}} \]
Impact of initial stages on HF dynamics by EM field, vorticity and Glasma
HF dynamics in vorticity and EM field

We solve the relativistic Boltzmann eq coupled with the external EM field.

\[ p^\mu \partial_\mu f_q(x, p) + m(x) \partial_x m(x) \partial_\mu f_q(x, p) + \frac{q}{2} F^\mu_\nu \partial_\mu f_q(x, p) = C[f_q, f_g] \]
\[ p^\mu \partial_\mu f_g(x, p) + m(x) \partial_x m(x) \partial_\mu f_g(x, p) = C[f_q, f_g] \]

Heavy quark evolution

\[ p^\mu \partial_\mu f_Q(x, p) + \frac{q}{2} F^\mu_\nu \partial_\mu f_Q(x, p) = C[f_q, f_g, f_Q] \]

- Charm transport coefficient constrained by experimental data on the \( R_{AA}(p_T) \) and \( v_2 \) of D meson
- Vorticity employed for \( \Lambda \) polarization and \( v_1 \) of light particles
- EM field is calculated with fast moving protons in colliding nuclei assuming a constant conductivity of medium
Impact of EM Field + Vorticity on D

- Large average $v_1$ of D meson due to vorticity, a lot larger than for charged particles
- A sizable $v_1$ splitting for D meson than for charged particles predicted $v_1 \approx 10^{-3} - 10^{-4}$ [Gursoy et al., PRC89 (2014)] using the same EM field

- At LHC energy we get much less than experimental data (???)
HQ in Glasma

\[ \frac{dx_i}{dt} = \frac{p_i}{E} , \]

\[ E \frac{dp_i}{dt} = Q_a F_{iv}^a p^v , \]

\[ E \frac{dQ_a}{dt} = -Q_c \varepsilon^{cba} A_b \cdot p , \]

Y. Sun et al., PLB 798 (2019) 134933

✧ Enhancement of \( R_{AA}(p_T) \)

✧ The effect is similar to Fokker-Planck with only diffusion and negligible drag

✧ Gain in \( v_2 \): larger interaction in the QGP to have same \( R_{AA}(p_T) \)
Prediction of both $R_{AA}, \nu_2$ gives us $D_s(T)$ of QGP $\approx l_{QCD}$

$\Lambda_c/D$ from Coal.+Fragm. explained in AA (RHIC & LHC)

$v_n(HQ) - v_n(QGP)$ and $\sigma_{vn}/v_n$, new observables probing $D_s(T)$

Charm directed flow can probe the initial strong EM field and vorticity

Glasma effect on HF

There are more things to do and to learn than expected!