13th workshop in the series of workshops on QCD phase transition and relativistic heavy-ion physics (QPT 2019)

QLBT: The Linear Boltzmann Transport model for heavy quarks with a medium of quasi-particles

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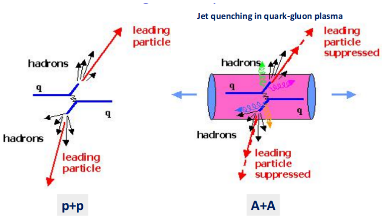
Outline

- Background
- Quasi Particle model : describe the equation of state of QGP
- QLBT model : improve the linear Boltzmann Transport (LBT)[Phys. Lett. B777 (2018) 255-259] model by modeling QGP as a collection of quasi-particles
- Numerical Results : nuclear modification factor and elliptic flow of D meson
- Summary

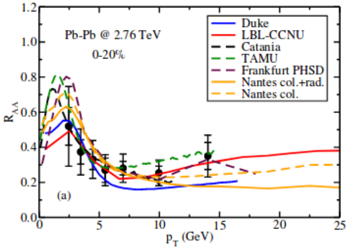
Heavy Qurak : Hard Probe in QGP



- Heavy quarks are usually produced from initial hard collisions. Due to their large mass compared to the temperature of the system, it is difficult for them to themalize.

- Explore the transport properties of QGP through the energy loss of heavy quark

Heavy quark transport models



[Shanshan Cao, Gabriele Coci, Santosh Kumar Das,arXiv:1809.07894]

- Various transport models have been developed to investigate the medium modification of heavy flavor production in heavy-ion collisions
- Different models use different transport equation
- LBT model
  - Elastic scattering: Leading order pQCD
  - Inelastic scattering: high twist model
- Catania QPM
  - Quasi Particle model
  - Only consider elastic scattering

Combined model–motivation

- In theory, heavy quarks should consider both inelastic scattering loss energy and non-perturbative effects.
- improve the linear Boltzmann Transport (LBT)() model by modeling QGP as a collection of quasi-particles(QLBT model)
  - Elastic process: leading order PQCD amplitude for elastic process, the Quasi Particle model for equation of state of QGP.
  - Inelastic process: high twist model.

Quasi Particle model：describe the state equation of QGP

- The temperature-dependent effective mass for quarks and gluons can be given by the perturbative method [S. Plumari, W. M. Alberico, V. Greco, C. Ratti, Phys. Rev. D84 (2011)]

$$m_g^2 = \frac{1}{6}g^2[(N_c + \frac{1}{2}n_f)T^2 + \frac{N_c}{2\pi^2}\Sigma_q\mu_q^2]$$

$$m_{u,d}^2 = \frac{N_c^2 - 1}{8N_c}g^2[T^2 + \frac{\mu_{u,d}^2}{\pi^2}]$$

$$m_s^2 - m_{0s}^2 = \frac{N_c^2 - 1}{8N_c}g^2[T^2 + \frac{\mu_s^2}{\pi^2}]$$

- System pressure

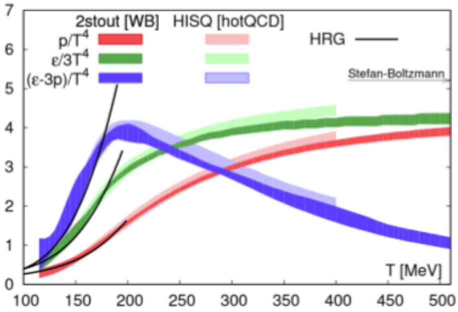
$$P_{qp}(m_u, m_d, ..T) = \Sigma_{i=u,d,s,g}d_i \int \frac{d^3p}{(2\pi)^3}\frac{\vec{p}^{\,2}}{3E_i(p)}f_i(p) - B(T)$$

  - B(T)：the temperature-dependent bag constant

- System energy density

$$\epsilon = T\frac{dP}{dT} - P(T)$$

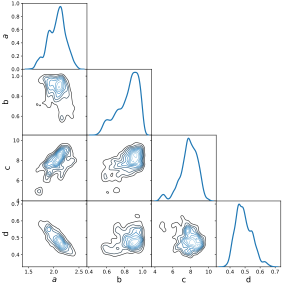
Two set of lattice data

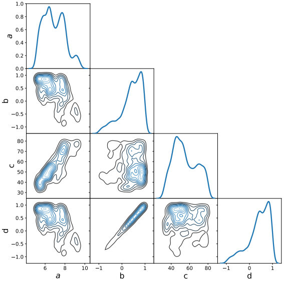


[A. Bazavov, et al., Phys. Rev. D90 (2014) and S. Borsanyi, Z. Fodor, C. Hoelbling, S. D. Katz, S. Krieg, K. K. Szabo, Phys. Lett. B730 (2014)]

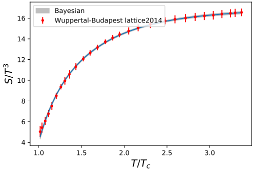
- 2014 Hot QCD and Wuppertal-Budapest(WB) lattice thermal results.

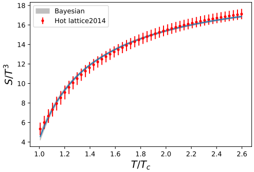
Quasi Particle model
Extract g(T) coupling constant





$$g^2(T) = \frac{48\pi^2}{(11N_c - 2N_f)ln(\frac{1}{ce^{-d(T/T_c)^2}+1}(a\frac{T}{T_c} + b)^2)}$$

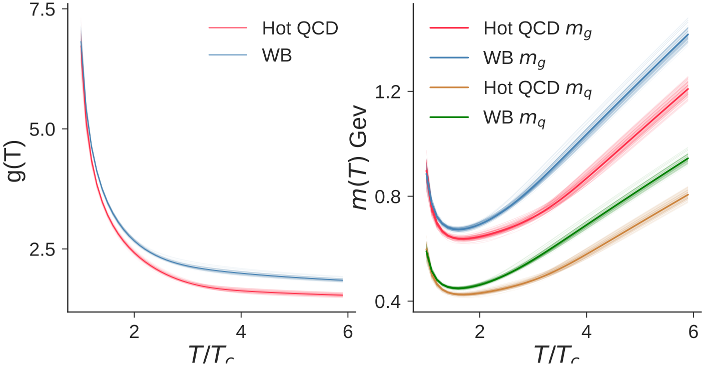




- The top left denote g(T) from Wuppertal-Budapest lattice data. The bottom left denote g(T) from Hot QCD lattice data.

Quasi Particle model

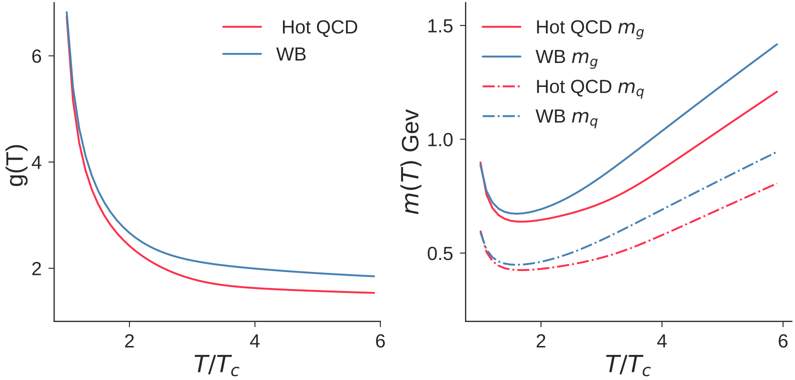
$g(T)$ and Quasi Particle mass



- Extract the lattice data to get $g(T)$ and the corresponding thermal mass.

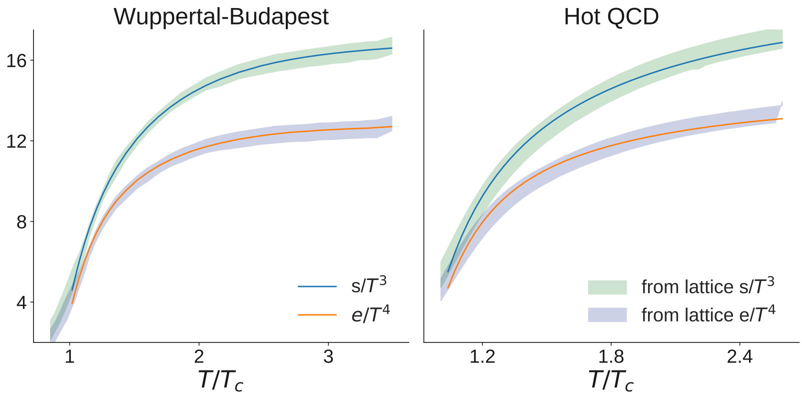
Quasi Particle model

$g(T)$ and Quasi Particle mass mean value



- $g(T)$ take parameter mean value.

Calculate thermodynamic quantities versus lattice data



- $g(T)$ takes the average of the parameters, and the calculated result represents the blue line (QGP entropy density) and the red line (QGP energy density).

QLBT model

Heavy quark elastic scattering process

- Boltzmann equation

$$P_1 \cdot \partial f_1(x_1, p_1) = E_1 C[f_1]$$

  - p_1 represent the 4-momentum of the jet parton ,$C[f_1]$ represent collision term.

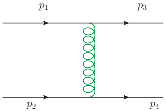
- Solve the Boltzmann equation to obtain the scattering rate

$$\begin{aligned}\Gamma_{12\longrightarrow 34}(p_1, T) = \frac{\gamma_2}{16E_1(2\pi)^4} & \int dE_2 d\theta_2 d\theta_4 d\theta_4 d\phi_4 \\ & \times f_2(E_2, T)(1 \mp f_4(E_4, T))S_2(s, t, u)|M_{12\rightarrow 34}|^2 \\ & \times \frac{p_2 p_4 sin\theta_2 sin\theta_4}{E_1 + E_2 - p_1 cos\phi_4 \frac{E_4}{p_4} - p_2 cos\theta_{24} \frac{E_4}{p_4}}\end{aligned}$$

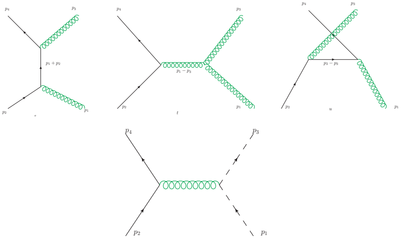
  - f denote partons distribution function. the parton 1 and 3 are intial and final heavy quarks. parton 2 adn 4 denote intial and final Quasi Particle.
  - pQCD Scattering amplitude

Heavy quark elastic scattering process
scattering channels

$cq \to cq$



$cg \to cg$



- we use Feynman gauge plus Ghost field to caculate scattering amplitude.
- q and g denote Quasi paricle in QGP which scatter with heavy qaurk.

Heavy quark inelastic scattering process

- the average number of radiated gluons from single heavy quark

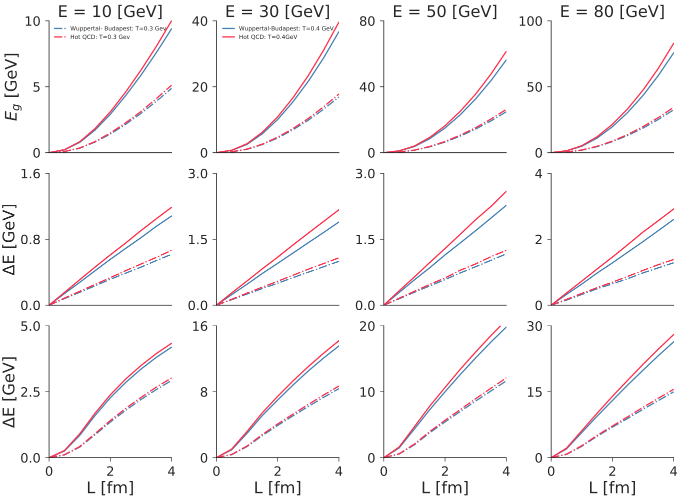
$$< N_g > (E, T, t, \delta t) = \delta t \int dx dk_\perp^2 \frac{dN_g}{dx dk_\perp^2 dt}$$

- The distribution function of radiated gluon（hight twist） [X.-F. Guo and X.-N. Wang, Phys. Rev. Lett. 85, 3591 (2000)][A. Majumder, Phys. Rev. D85, 014023 (2012)][B.-W. Zhang, E. Wang, and X.-N. Wang, Phys. Rev. Lett. 93, 072301 (2004)]

$$\frac{dN_g}{dx dk_\perp^2 dt} = \frac{2\alpha_s C_A P(x)}{\pi k_\perp^4} \widehat{q} (\frac{k_\perp^2}{k_\perp^2 + x^2 M^2})^4 sin(\frac{t - t_i}{2\tau_f})^2$$

  - τ_f is the formation time of the radiated gluon deined as $\tau_f = 2Ex(1-x)/(k_\perp^2 + x^2 M^2)$.
  - $k_\perp$ is the gluon transverse momentum.
  - x is the fractional energy of the emitted gluon taken from its parent parton， P(x) is splitting function。

Heavy quark energy loss in two static medium

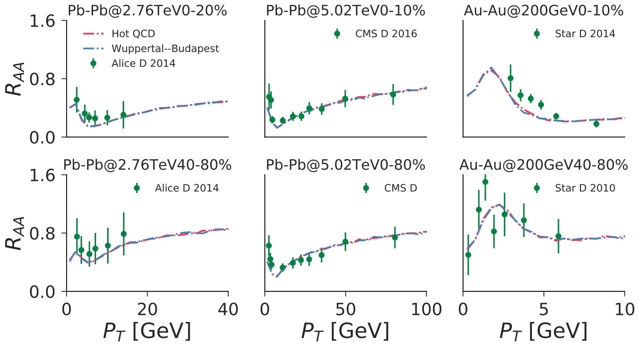


- Monte Carlo results : In two set static medium, the first row: heavy quark radiated gluon energy. Second row: heavy quark elastic scattering energy loss, third row: heavy quark inelastic scattering energy loss.

The generation and evolution of heavy quarks and the generation of final state hadrons

- Stage of production: use the CTEQ factorization form, combined with the EPS09 factorization form containing the nuclear shadowing effect, to obtain the initial P_T distribution of the Heavy quark.
- Evolutionary stage:use linear Boltzmann transport and quasi-particle models to describe the evolution of heavy quarks in the medium. The relativistic Hydrodynamics model (CLvisc and VISnew) provides the flow velocity and temperature in evolution.
- Hadronization of heavy quarks
    - use hybrid model of fragmentation and coalescence mechanisms to describe the hadronization of heavy quarks.

Numerical Results
D meson nuclear modifiacation factor



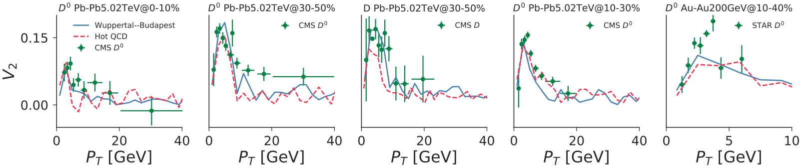
- The nuclear modifiacation factor of the meson is defined as follows

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN^{AA}/dp_T}{dN^{pp}/dp_T}$$

.

- No longer need to adjust α_s parameter.
- The more the center collision, the more obvious suppression.
- $K_p = 1 + A_p e^{-|\vec{p}^2|/2\sigma_p^2}$ (A_p=5 σ_p=5), is placed on scattering rate and $\hat{q}$.

Numerical Results
D meson elliptic flow



- elliptic flow of the meason is defined as (smooth hydro)

$$v_2(P_T) =< cos(2\phi) >= \left\langle \frac{P_x^2 - P_y^2}{P_x^2 + P_y^2} \right\rangle$$

.

- The elliptical flow is related to the initial geometry.
- Low p_T interval has a peak, high p_T becomes flat.
- same K_p factor.

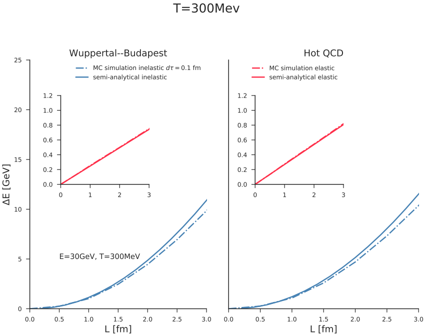
Summary

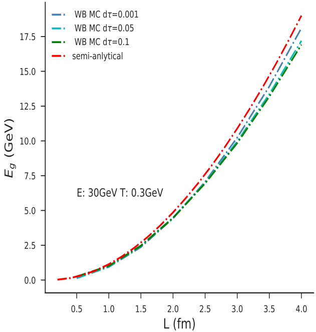
- In order to be accurate, two sets of lattice data were used, and the quasi-particle model was used to describe the equation of state of QGP.
- The quasi-particle $g(T)$ factor cancels the positive and negative effects of the energy loss caused by the coupling strength and the quasi-particle distribution. as a result, D meason nuclear modifiacation factor is the same.
- No longer need to adjust α_s parameter.
- The quasi-particle model combined with the linear Boltzmann model (QLBT model) can better describe the D meson nuclear modifiacation factor and elliptic flow data at RHIC and LHC.
- In the current model, only the k_P factor is reserved to describe the low p_T non-perturbative effect.
- Future work
  - Use event by event hydro
  - forward (backward) rapidty region
  - Compare the different transport models and explore the connections between the models

Thanks

Backup

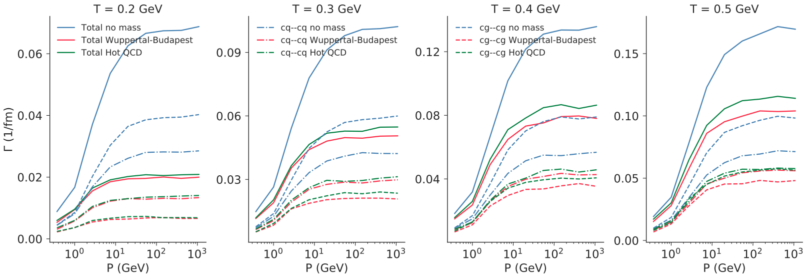
heavy quarks Energy loss of elastic and inelastic scattering: Monte Carlo results vesus semi-analytical results





- Compare Monte Carlo and semi-analytical results with two $g(T)$
  - red line denote heavy quark elastic scattering energy loss in static medium, and blue line denote heavy quark radiated gluon energy in static medium.
- The Monte Carlo results are consistent with the semi-analytical results to verify the correctness of the program.
  - Error comes from time step.

Backup
rate compare



- blue line denote rate without theraml mass. red denote g(T) from Wuppertal-Budapest, green denote g(T) from Hot QCD.
  - solid line denote total rate. Dotted line denote cg-cg channel rate. Point line denote cq-cq channel rate.