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Jet-medium interactions in QCD matter : theory overview

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Jet-medium interaction in heavy-ion collisions has been the subject of many studies over years. To explore the phenomenon of jet quenching in detail, model builders have been focusing on the jet-induced medium response with many theoretical approaches. In this short overview, two models are introduced to illustrate the difference in two main theoretical approaches. The important effect related to the medium response have been found for jet energy loss, jet substructure and many other observables in different model calculations.

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1. Introduction

The study of the properties of quark-gluon plasma (QGP) is the main purpose of high-energy heavy-ion collisions at the Relativistic Heavy-Ion Collider (RHIC) [1, 2] and the Large Hadron Collider (LHC) [3]. One of the most dramatic phenomena observed so far is jet quenching [4–20]. As jets, sprays of particles which are correlated to initial hard scattering in the very beginning of the collision, travel through the QGP, the high energy partons will interact with the hot and dense medium and lose a large amount of energy through scattering and radiative processes. Part of the lost energy propagates outside the jet cone and leads to jet energy loss. Another effect of the jet-medium interaction is the jet-induced medium excitation. Some thermal partons from the medium get excited by the scatterings with the jet constituent partons, and their average energy is higher than that of the medium background.

The first question one may ask about jet energy loss is where does those energy go. In experimental studies of dijet transverse momentum imbalance [21] in Pb-Pb collisions one observes that the subleading jet when propagating through the medium loses a large amount of energy outside the jet cone. However, the total transverse momentum balance gets restored after the inclusion of soft particles at large angles relative to the jet axis. How does this happen? The answer is related to the problem of thermalization in heavy-ion physics that we still do not fully understand.

As the medium absorbs the energy deposited by the jet, part of the medium becomes correlated with the jet, both inside and outside the jet cone. Therefore it should not be subtracted as background energy in the jet energy correction. The challenge is to find a method to distinguish the jet correlated part from the huge background in heavy ion collisions. To study the parton energy loss, many theories have been developed based on pQCD with the assumption of weak coupling between the jet and medium, including BDMPS-Z, GLV, AMY, HT and SCETg. On the other hand Ads/CFT theory assumes that the jet and medium are strongly coupled. Almost all of them can describe the suppression of single hadrons and give a consistent temperature dependence of the jet transport coefficient $\hat{q}$ which informs about the general transport property of the medium [22]. Based on these theories, numerous models have been developed to achieve a more complete description of jet modification inside the medium.

2. Models

Various models have been developed for the study of jet-medium interaction. Some of the models have especially taken into account the effect of medium response to insure the total energy momentum conservation [23–25]. There are generally two ways to describe the jet induced medium response. One is to follow the propagation of medium recoil partons like in JEWEL [26–28], LBT [29–32], MARTINI [33]. The other is to treat the energy deposition from jets in hydrodynamics simulations such as the Jet-fluid model [34], Hybrid model [24, 35] and CoLBT-hydro model [36]. These two approaches provide insights into the jet energy loss and the induced medium response in different ways, which could be crucial for our understanding of the jet-medium interaction.

In this overview I will use two models as examples to present the details. The first one is the Linear Boltzmann Transport (LBT) model which is based on a Boltzmann equation.

$$p_a \cdot \partial f_a = \frac{\gamma_b}{2} \int \prod_{i=b,c,d} \mathrm{d}[p_i](f_c f_d - f_a f_b)|M_{ab\to cd}|^2 S_2(\hat{s},\hat{t},\hat{u})(2\pi)^4 \delta^4(p_a + p_b - p_c - p_d) + inelastic \tag{2.1}$$

where γ_b is the spin degeneracy for parton b, $f_i = 1/(e^{p_i\cdot u/T} \pm 1)(i = b,d)$ are the thermal distributions at local temperature T and fluid velocity u. The distributions of the partons before and after scattering are $f_i = (2\pi)^3\delta^3(\vec{p}-\vec{p}_i)\delta^3(\vec{x}-\vec{x}_i-\vec{v}_i t)(i = a,c)$. $S_2(\hat{s},\hat{t},\hat{u}) = \theta(\hat{s} \geq 2\mu_D^2)\theta(-\hat{s}+\mu_D^2 \leq -\mu_D^2)$ is the regulation condition where $\mu_D^2 = g^2T^2(N_c + \frac{N_f}{2})/3$ is the Debye screening mass. A high-twist approach [37,38] is used for the simulation of the radiated gluon emission,

$$\frac{\mathrm{d}N_g^a}{\mathrm{d}z\mathrm{d}k_\perp^2\mathrm{d}t} = \frac{6\alpha_s P_a(z)k_\perp^4}{\pi(k_\perp^2+z^2m^2)^4} \cdot \frac{p\cdot u}{p_0}\hat{q}_a(x)\sin^2(\frac{\tau-\tau_i}{\tau_f}), \tag{2.2}$$

where the mass of the mother parton a is denoted by m, energy fraction of the radiated gluon is denoted by z and $k_\perp$ is the transverse momentum transfer of the splitting. $P_a(z)$ the splitting function. $\tau_f = 2p_0z(1-z)/(k_\perp^2+z^2m^2)$ is the formation time of the radiated gluon, $\hat{q}_a$ is transport coefficient and the Deybe screening mass is used as an infrared cut-off. In this model, both the elastic scattering and radiation processes are considered and the medium recoil parton can also go through further interactions with the medium along with the jet shower parton and the radiated gluon. In particular, the propagation of the initial thermal parton is also tracked to account for the back reaction. The interactions among the recoiled partons, shower partons and radiated gluons are not considered in the calculation with the assumption of linear approximation. In this approach, all the interactions are based on the pQCD description. During the LBT simulation, the medium background information is read from a hydro profile. However, the feedback to the medium background has been neglected even though the jet-medium interaction will modify the jet and the medium background at the same time.

To overcome this limitation, another model is developed. The Coupled LBT hydro model combines the LBT model and the Clviscs Hydro model together in real time. The initial parton shower will first propagate according to the Boltzmann equation within LBT, after the interaction with the medium, the partons are divided into two parts by a momentum cut p_{cut}^0 in the comoving frame. The hard partons above p_{cut}^0 will keep propagating within LBT, and the soft partons below p_{cut}^0 will be deposited into hydro as source terms according to the following formula [39,40],

$$j^\nu = \sum_i \frac{\theta(p_{cut}^0 - p_i\cdot u)p_i^\nu/\Delta\tau}{\tau(2\pi)^{3/2}\sigma_r^2\sigma_{\eta_s}} \exp[-\frac{(\vec{x}_\perp - \vec{x}_{\perp i})^2}{2\sigma_r^2} - \frac{(\eta_s-\eta_{si})^2}{2\sigma_{\eta_s}^2}] \tag{2.3}$$

where σ_r and σ_{η_s} are Gaussian widths for the smearing. Then by solving the hydro equation with the source terms one can get the updated medium information for the next step. The hadronization of the hard part (LBT) above p_{cut}^0 is carried on by a recombination model [41] and the hadronization process of the soft part (hydro) is calculated with the Cooper-Frye formula [42]. The contribution from the background calculated by the simulation without the jet source must be subtracted to get the final result. Within this coupled approach, one can simulate the jet propagation and medium evolution with feedback simultaneously. Fig. 1 (left) shows what the medium response looks like in the CoLBT-hydro simulation with feedback. In this gamma-jet event, one can see that the energy is carried away to large angles with respect to the jet axis by a Mach cone wave front followed by a

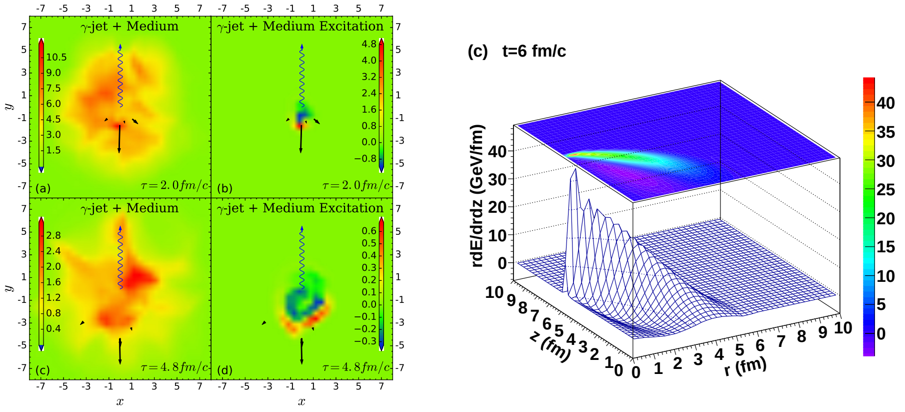

Figure 1: (Color online) Left: Energy density (GeV/fm^3) and γ-jet evolution in the transverse plane at $\eta_s = 0$, $\tau = 2.0$ (a,b) and 4.8 fm/c (c,d) in a 0-12% central Au+Au collision at $\sqrt{s} = 200$ AGeV. Straight (wavy) lines represent parton (photon) momenta. Hydrodynamic background from the same event without γ-jet is subtracted in the right panels. Right: Energy density of the medium response induced by a single parton propagation in a static medium $T = 0.4$ GeV from the LBT calculation [36]

diffusion wake in which the energy density of medium excitation is negative. This diffusion wake is essentially the depletion of the thermal parton density along the path of the jet parton and it is also a part of the medium response. Even though there is no real-time feedback, the LBT model and other models [34, 43, 44] show approximately the same feature as one can see in the Fig. 1 (right).

3. Results from recent theoretical calculations

There are many observables that are sensitive to medium response. The most simple one is the jet energy loss. Fig. 2 shows the average transverse momentum loss as a function of the initial jet p_T for different jet cone sizes within LBT. By looking at the difference between calculations with and without the medium response one can actually see how much energy inside the jet cone is contributed from medium response. With the larger cone size, the relative contribution of the medium response to the energy loss becomes more important. And that is also the case with the diffusion wake which is also a part of medium response as we compare the calculations with the back reaction and without it. The medium response changes the p_T dependence of jet energy loss, which will have a direct effect on single jet R_{AA} especially when we look at the cone size dependence. Calculations from JEWEL [28], LBT [45] and Jet-fluid model [34] all show that jet suppression becomes smaller as one increases the jet cone size. This angular ordering is natural since with larger cone size the jet recovers more lost energy, and the cone size dependence quantitatively depends on the p_T differential energy loss which could be modified by the medium response.

The jet-medium interactions will not only modify the energy of the jet but also change the structure inside and outside the jet cone. The jet shape (left panel of Fig. 3) describes the angular distribution of p_T inside the jet cone. Generally the jet-medium interactions will lead to a broadening of the jet shape which is essentially the enhancement of soft particles close to the edge of

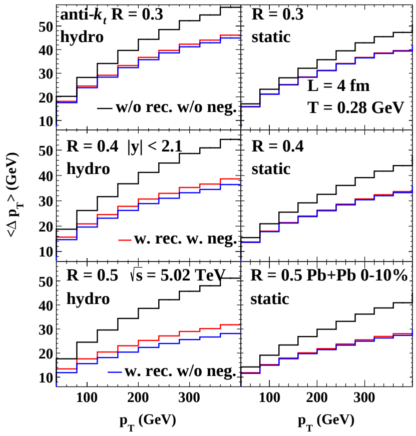

Figure 2: (Color online) LBT results on average p_T loss $\langle \Delta p_T \rangle$ for jets in $|y| < 2.1$ as a function of the vacuum jet p_T with anti-k_t algorithm and $R = 0.3, 0.4, 0.5$ for (left panel) hydrodynamic background in central 0 - 10% Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV and (right panel) static medium at $T = 0.28$ GeV with fixed length $L = 4$ fm. Black lines are results without recoil and back reaction ("negative" partons), while red lines are with recoil and back reaction and blue lines are with recoil but without back reaction [45].

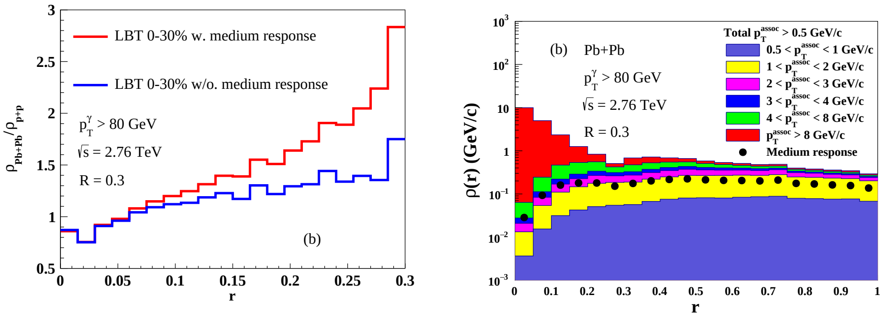

Figure 3: (Color online) Left: The ratio of transverse jet profile of γ-jets with (red) and without (blue) contributions from jet-induced medium response at $\sqrt{s} = 2.76$ TeV. Right: Extended transverse jet profile of γ-jets in central (0–30%) Pb+Pb collisions at $\sqrt{s} = 2.76$ TeV from LBT simulations. The solid circles show contributions from jet-induced medium response (recoil and back reaction) [46].

the jet cone. Calculations from different models all show an important contribution from medium response especially at large radius [25, 28, 33, 34, 46]. However, due to the different theory implementation, the effect is somehow different. The extended jet shape measurement allows us to look at the p_T distribution both inside and outside the jet cone. As one compares the medium response effect between Jet-fluid [34, 47] and LBT (right panel of Fig. 3), one can see that in the jet-fluid calculation the medium response completely dominates at large radius. But in the LBT calculation, even at very large angle, there is a sizable contribution from large angle radiation, which could also be caused by the different implementation of medium response. Looking at even larger angles, the measurement of missing p_T shows that the energy is recovered at large angles by soft particles and the calculation using the Hybrid model [25] gives an example showing that adding medium response to jets is essential to regain p_T balance of the whole event.

The study of angular structure tells us that the medium response to jet generally leads to

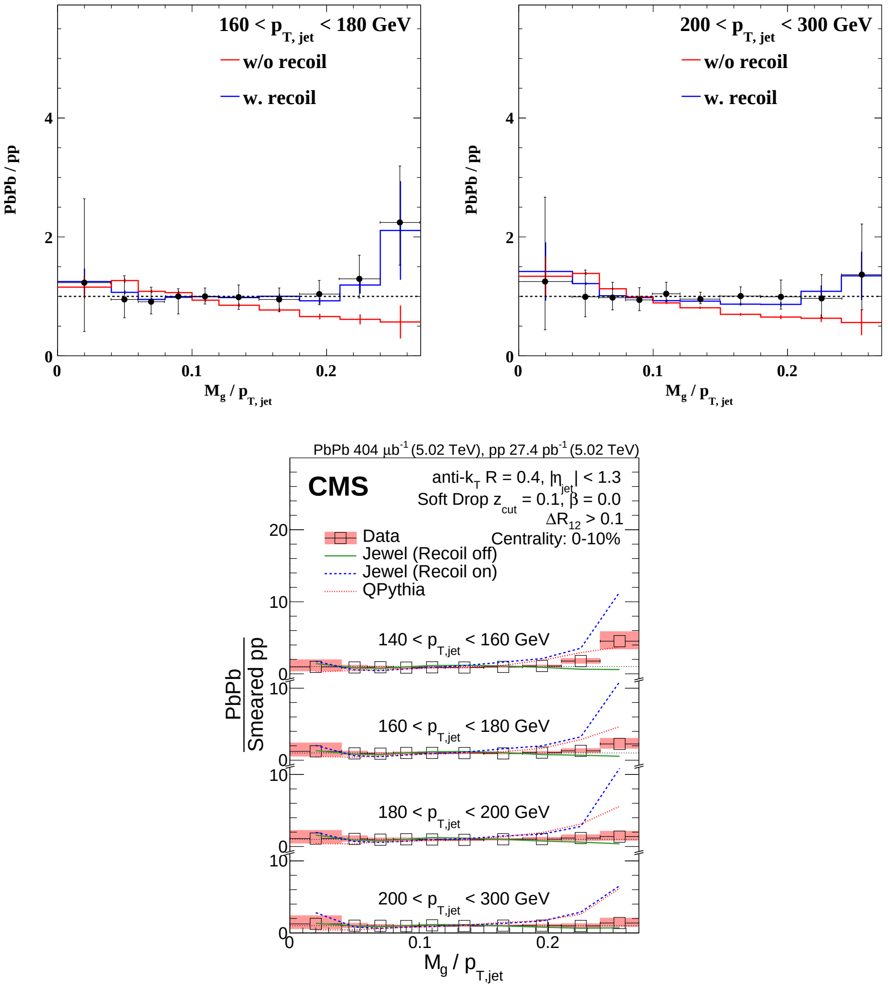

Figure 4: (Color online) Upper: The ratio of M_g/p_T^{jet} in PbPb over pp from LBT, Lower: CMS data compared to JEWEL(blue) and Q-PYTHIA(red) [48].

enhancement at large angles. However, this kind of enhancement could also be caused by large angle radiation as we can see in many theoretical calculations which neglect medium response. So it is important to find a way to separate the effects from medium response and large angle radiation. In a recent groomed jet study, both calculations from JEWEL (lower panel of Fig. 4) and LBT (upper panel of Fig. 4) show that the enhancement of the large groomed jet mass tail comes from the medium recoil. Without contribution from the medium response, one actually can see that there is a slight suppression instead of enhancement at the large groomed mass in Jewel and LBT. However, another calculation from QPythia [49] (lower panel of Fig. 4) which has no medium response effect can also present a similar feature. Further study is needed to see if one can find some unique signal for the jet-medium recoil scattering in the groomed jet study.

Another way to search for unique properties of medium response is to look at jet-hadron correlations. The recent calculation of the gamma hadron fragmentation function using the CoLBT-hydro model [36] shows agreement with the experiment data (left panel of Fig. 5). Since soft hadrons from jet induced medium excitation carry an average thermal energy that is independent of

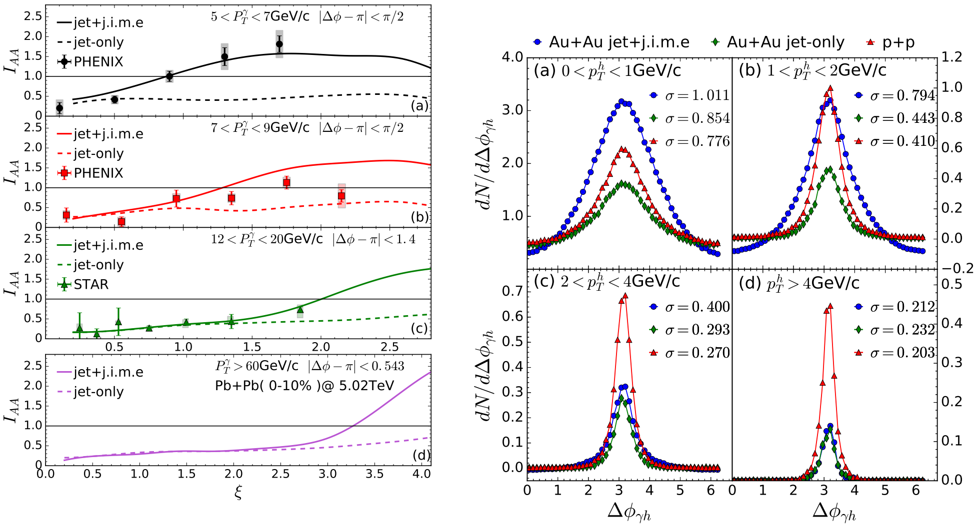

Figure 5: Left: Modification factor for γ-hadron correlation as a function of $\xi = \log(1/z)$ for $|\eta_{h,\gamma}| < 0.35$ and different p_T^γ in 0-40% and 0-12% Au+Au collisions at $\sqrt{s} = 200$ GeV with (solid) and without jet induced medium excitation (dashed) as compared to the STAR [50] and PHENIX data [51]. Right: γ-hadron azimuthal correlation for $|\eta_{h,\gamma}| < 1.0$, $12 < p_T^\gamma < 20$ GeV/c and different p_T^h in p+p (triangle) and 0-12% central Au+Au collisions with (circle) and without (diamond) jet induced medium excitation at $\sqrt{s} = 200$ AGeV. The half width σ is obtained via a Gaussian fit within $|\Delta\phi_{h\gamma} - \pi| < 1.4$ [36].

the jet energy, an important feature of the CoLBT-hydro results is that the transition point from the hard suppression to the soft hadron enhancement due to medium excitation appears at a constant p_T range. The γ-hadron angular correlation shows another feature of medium response. As we can see in Fig. 5(right) the angular distributions for the enhanced soft hadrons around the jet direction get significantly broadened. However the most interesting feature is the depletion of soft hadrons in the near γ side due to the diffusion wake, which is a unique identification of medium response.

4. Discussion

The medium response is crucial to understand the full story of jet quenching. Currently, to carry out such studies there are two ways like LBT (recoil particles) and Hydro (Hydro response). The important effect of jet induced medium response has been observed in various jet observables including jet energy loss, jet substructure and jet-hadron correlation. Many model calculations show that medium response generally leads to the enhancement of soft particles at large angles around jets. However, challenges have been presented on distinguishing the effects from large angle radiation and medium response. Therefore it is important to search for the unique signals of medium response such as the diffusion wake. The recent measurement of jet chemistry might give us more significant signals. The medium response inside the jet cone leads to the enhancement of the baryon/meson ratios inside jets in AA collisions compared to pp collisions. One can imagine that if we look at the angular dependence of baryon/meson ratios, we might be able to identify the evidence of medium response at large angle. However, this represents a huge challenge for the jet hadronization in any theoretical calculation.

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