Jet quenching studies play a prominent role in our current understanding of ultra-relativistic heavy ion collisions. In this review I first present the available formalism to compute medium-induced gluon radiation. Then I discuss its effect on single particle spectra, with dedicated attention to the case of the radiating parton being a massive quark. Next I examine more differential observables like jet shapes and multiplicities, and the consequences of flow on radiative energy loss. I conclude with some remarks.

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1 Introduction and formalism

Jet quenching (Fig. 1) plays a central role in heavy ion studies \[1, 2\]. It constitutes the standard explanation of the large transverse momentum suppression of single particle spectra in nucleus-nucleus collisions with respect to the expectation from nucleon-nucleon and the disappearance of back-to-back correlations, observed at RHIC (see the reviews \[3, 4, 5, 6, 7\] for the existing formalism and comparisons with data). This phenomenon is taken as a prominent indication of the creation of a dense partonic system in ultra-relativistic heavy ion collisions \[1, 2\].

Historically, the first proposal \[8\] was based on elastic scattering. Later on it was recognized that bremsstrahlung was the dominant process for high energies of the parton traversing the medium, first in a QED form \[9\] and then taking
into account the rescattering of the emitted gluon \cite{10}. It is now widely believed that for energies of the parton (equivalent to transverse momentum in the central rapidity region) greater than $5 \div 10$ GeV, hadronization takes place outside any medium produced in the collision \cite{11} and thus gluon radiation dominates the energy loss. Medium-induced gluon radiation implies an energy degradation of the leading parton, a broadening of the associated parton shower and an increase of the associated hadron multiplicity.

The available formalism (its most general formulation can be found in \cite{12, 13}) takes into account the rescattering of the incoming and outgoing radiating parton and of the radiated gluon with the medium, see Fig. 2. Interference and mass effects on the energy spectrum of radiated gluons $\omega \frac{dI_{\text{medium}}}{d\omega d\kappa \perp}$ are given by the crossed term in Fig. 2 and contained in an exponential $\exp\left( -\Delta z \frac{k_\perp^2 + x^2 m^2}{2\omega} \right)$, with $m$ the mass of the radiating parton and $x = \frac{\omega}{E} \ll 1$. The information about the medium comes in the product density of the medium times cross section for the rescattering of the gluon inside the medium. Different approximations are taken for this product, the
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most popular one being \( n(z) \sigma(r) \propto \hat{q}(z) r^2 \). The energy loss turns out to be energy-independent and, due to the fact that the dominant process is the rescattering of the radiated gluon, proportional to the length of the medium squared, \( \Delta E \propto \int d\omega \frac{d\sigma}{d\omega} \propto \alpha_s C_R \omega_c = \alpha_s C_R \hat{q} L^2 /2 \), \( \omega_c = \hat{q} L^2 /2 \) and \( \hat{q} = \mu^2 /\lambda \) the transport coefficient defined as the mean transverse momentum squared transferred from the medium to the gluon per unit mean free path (see [14] for simple arguments).

2 Mean energy loss and single particle spectra

Two ways, at the level of either the \( p_\perp \)-spectrum or the fragmentation functions, have been proposed to compute the medium-modified particle spectrum [15, 16, 17]:

\[
\frac{d\sigma_{\text{medium}}(p_\perp)}{dp_\perp^2} = \int d\epsilon P(\Delta E) \frac{d\sigma_{\text{vacuum}}(p_\perp + \Delta E)}{dp_\perp^2}; \tag{1}
\]

\[
D_{h/p}^{\text{medium}}(z, Q^2) = \int d\epsilon \frac{P(\Delta E)}{1 - \epsilon} D_{h/p}^{\text{vacuum}} \left( \frac{z}{1 - \epsilon}, Q^2 \right), \quad \epsilon = \frac{\Delta E}{E(\approx p_\perp(y = 0))}. \tag{2}
\]

From these expressions, a strong influence of the form of the partonic spectrum is evident. The function \( P(\Delta E) \) gives the probability for the fragmenting parton to lose some energy \( \Delta E \) and is called the quenching weights. The usual approximation to compute these weights is the Poissonian one which considers each subsequent gluon emission from the parton as independent [18]. The centrality dependence of the suppression of the transverse momentum spectra can be understood in terms of nuclear geometry [19, 20]. The medium produced in the collision expands and its dynamical dilution can be absorbed in a redefinition of \( \hat{q} \) [21, 22, 23]:

\[
\hat{q}_{\text{eff}}(L) = \frac{2}{L^2} \int_{\tau_0}^{L} d\tau (\tau - \tau_0) \hat{q}(\tau), \tag{3}
\]

with \( \hat{q}(\tau) \) the transport coefficient depending on the proper time. With this formalism, a good agreement with the existing experimental data is found, see e.g. [24, 25] for recent comparisons. Several conclusions have been extracted: First, the medium is opaque at RHIC, in the sense that there is quite a large insensitivity to the value of \( \hat{q} \), and thus to the density, provided it is high enough. The emission takes place from the surface of the medium which naturally explains the absence of back-to-back correlations and the approximate scaling with number of participants. Second, uncertainties at small \( p_\perp \) due to finite energy constraints, imposed a priori on the theoretical calculations which are done in the high-energy limit, are clearly visible. As a final remark, predictions for quenching at different energies are usually done by rescaling \( \hat{q} \) according to multiplicities [26, 27, 28].

3 Gluon radiation off massive quarks

Gluon radiation in the vacuum is modified by a mass of the parent quark. Radiation for angles \( \theta < m/E \) is suppressed, which constitutes the so-called dead
cone effect \cite{29}. It leads to the modification of the spectrum of the radiated gluon

$$\frac{1}{k_1^\perp} \rightarrow \frac{1}{k_1^\perp} \left[ \frac{k_2^\perp}{k_1^\perp + (\frac{m\omega}{E})^2} \right]^2 \equiv \frac{1}{k_1^\perp} F\left(k_1^\perp, \frac{m\omega}{E}\right). \tag{4}$$

Dokshitzer and Kharzeev \cite{30} proposed that medium-induced gluon radiation is reduced by the same effect. In this first exploratory study, in absence of a fully differential spectrum they considered

$$\omega \frac{dI_{\text{medium}}^{m>0}}{d\omega} = \omega \frac{dI_{\text{medium}}^{m=0}}{d\omega} F\left(\langle k_1^\perp \rangle, \frac{m\omega}{E}\right), \quad \langle k_1^\perp \rangle \approx \sqrt{q\omega}. \tag{5}$$

Naively one would expect that the gluon may move into the dead cone due to multiple scattering, and thus the dead cone may be filled, see Fig. 3. Technically, there is a competition between interference and rescattering which demands numerical studies, done in \cite{31, 32, 33} for fragmentation functions and the mean energy loss, and in \cite{34} for the fully differential spectrum.

In Fig. 4 it is shown \cite{34} on the left the differential spectrum of radiated gluons, and on the right the mean induced energy loss \(\langle \Delta E_{\text{ind}} \rangle\) for parameters extracted from a comparison with RHIC data \cite{18}. Some conclusions can be drawn: The dead cone is filled, but it constitutes a small fraction of the available phase space. The energy loss for charm quarks at RHIC is a factor \(\sim 2\) smaller than for light quarks, but should still be observable. And the uncertainties due to energy constraints imposed a posteriori are significant. The experimental situation on charm in AuAu collisions at RHIC \cite{35, 36} is unclear, as the available single electron spectra constrain weakly the energy loss \cite{37} and the measured \(p_\perp\) is small so hadronization effects may play a significant role.

### 4 More differential observables

Medium-induced radiation may modify the energy deposition (i.e. the jet definition and profile) and the distribution of sub-leading particles from that in usual...
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Fig. 4. Left: differential spectrum of radiated gluons versus \( \kappa^2 = k^2_\perp / (\hat{q} L) \) for \( R = \omega_c L = 1000, \omega_c = \hat{q} L^2 / 2 \), for different \( \gamma = \omega_c / \omega \). Right: relative mean induced energy loss \( \langle \Delta E_{\text{ind}} \rangle / E \) for \( L = 6 \text{ fm} \) and \( \hat{q} = 0.8 \text{ GeV}^2 / \text{fm} \), versus \( E \).

Fig. 5. Schematic effects of medium-induced gluon radiation on jet shapes.

fragmentation in the vacuum, see Fig. 5. Such studies have been performed in [38]. The conclusions are: The jet definition is stable, as most energy is deposited at small \( R = \sqrt{\eta^2 + \phi^2} \) with \( \eta \) and \( \phi \) the pseudorapidity and azimuth with respect to the center of the jet, which gives good chances to measure jets in a heavy ion environment at the LHC. There is little sensibility to the infra-red contribution from the medium. And the background is apparently under control (the vacuum contribution is taken from [39] and may be fixed at the LHC from pp and pA). These studies may also have important consequences for RHIC, see below.
Until now, I have considered a medium which expands and dilutes but shows no momentum anisotropy. In heavy ion collisions, flow is strongly suggested by the success of relativistic hydrodynamics to explain particle production at small transverse momenta \[1\[2\]. Hydrodynamics implies strong position-momentum correlations. At high energies, energy loss is determined by momentum transferred perpendicularly to the parton trajectory. Thus, in the presence of collective flow these momentum exchanges acquire a preferred direction which will influence gluon radiation off the fast parton (if it is created decoupled from the medium i.e. not at rest in the local co-moving frame of the medium), see Fig. 6. In \[40\] we have examined the effect of flow on the jet profile, see Fig. 7. With the parameters used in this Fig., the induced mean energy loss is 23 GeV, which is a conservative estimate for the LHC \[38, 41\]. Also the magnitude of the directed component, equal in these results to the isotropic one, could be considerably larger. The displacement of the calorimetric center of the jet is small, \(\langle \Delta \eta \rangle = 0.04\), and should not spoil the jet definition which is done using much larger cone sizes. The effect of flow also leads to different jet widths in different \(\eta - \phi\) directions, a feature which could be explored in experimental analysis e.g. \[42\], and to a moderate increase in \(v_2\). A possible influence of flow has to be considered to extract densities from quenching studies as flow may mimic the effect of a higher density. It may also help to understand the space-time picture of the collision.

5 Remarks

To conclude, let me briefly highlight some points. First, energy constraints create large uncertainties for small \(p_\perp\), which motivates the computation of sub-leading energy corrections to the existing formalism. Second, an implementation of medium-
induced gluon radiation in a Monte Carlo simulation is needed, see [41]. Third, the opaqueness of the medium at RHIC makes the determination of densities difficult; flow effects should also be considered. Fourth, until now the main focus of the phenomenological analysis is on single particle spectra, but more differential observables like jet shapes and multiplicities offer valuable information; this demands a better understanding of the vacuum (pp and pA). To conclude, at the LHC high-\(E_T\) jets (\(E_T > 50\) GeV) will be very abundant [43], so jet quenching studies will play a prominent role in the heavy ion program [19, 41, 44, 45].

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