Explaining jet quenching with perturbative QCD alone

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We present a new formulation of jet quenching in perturbative QCD beyond the eikonal approximation. Multiple scattering in the medium is modelled through infra-red-continued (2 → 2) scattering matrix elements in QCD and the parton shower describing further emissions. The interplay between these processes is arranged in terms of a formation time constraint such that coherent emissions can be treated consistently. Emerging partons are hadronised by the Lund string model. Based on this picture we obtain a good description of the nuclear modification factor at RHIC and LHC and predict its behaviour at very large $p_\perp$.

High-momentum transfer processes, such as single inclusive hadron spectra, jet-like particle correlations and reconstructed jets, have been advocated for a long time as precision tools for studying the dense QCD matter produced in ultra-relativistic nucleus-nucleus collisions. The rates and distributions of such processes can be benchmarked in the absence of medium effects both experimentally (e.g. through their measurements in proton-proton collisions) and theoretically (due to their perturbative calculability). In nucleus-nucleus collisions at RHIC and at the LHC, they show generic and strong medium modifications commonly referred to as *jet quenching*. This motivates using such hard processes as well-calibrated *hard probes* of dense QCD matter. A central challenge for theoretical work is to relate, in a quantitatively controlled and unambiguous way, the observed medium modifications to fundamental properties of the QCD matter that induces them. In this context, applying a perturbative description plays a central role.

The first measurements of jet quenching signatures at the LHC sparked an intense debate on the extent to which a purely perturbative description of jet quenching is feasible. On the one hand, it seems plausible that several features of partonic in-medium propagation may resist a perturbative formulation. This is the case, for instance, for effects of colour flow between jet and medium that modify the non-perturbative late-time dynamics of jet hadronisation. On the other hand, several perturbatively motivated jet quenching models [7–10] resting on the eikonal limit [1–6] have been shown to reproduce central features of the nuclear modification factors at RHIC and at the LHC. However, the eikonal limit is known to be plagued by large numerical uncertainties [11], and this complicates an assessment of whether a purely perturbative description can account for jet quenching.

Here, we formulate a conceptually new framework based on our understanding of perturbative QCD in non-eikonal kinematics and to document its first implementation in the medium-modified final state parton shower JEWEL. This formulation treats the scattering of an energetic parton off a medium constituent as a standard $2 \rightarrow 2$ partonic scattering process described by QCD matrix elements and valid in the full perturbative regime. Further following the standard description of all hard scattering events at colliders, large logarithms associated to collinear singularities in real emission matrix elements are resummed by the parton shower. This provides a systematically improvable approximation to extra gluon emissions that also includes radiation off the scattering centre and generates naturally configurations with any number of additional patrons. The parton shower thus introduces radiative energy loss, while the matrix elements model the collisional one. The ambiguity between elastic and inelastic scattering is thus resolved, and the distinction between vacuum and medium induced radiation becomes obsolete. Treating all emissions fundamentally in the same way introduces in a natural way the interplay of radiation from different sources.

In the following we discuss how this idea can be implemented into a Monte Carlo event generator allowing for a democratic treatment of all partonic fragments, and, at the same time, accounting in a local and probabilistic formulation not only for exact four momentum conservation including all recoils, but also with known accuracy [12, 13] for the dominant quantum interference effect in medium-induced gluon radiation, the so-called non-Abelian Landau-Pomerantchuk-Migdal (LPM) effect.

The parton shower evolution is governed by the Sudakov form factor, which can be interpreted as the probability for having no emission between two scales $Q^2$ and $Q_0^2$.

$$S_a(Q^2, Q_0^2) = \exp \left[ - \int_{Q_0^2}^{Q^2} \frac{dq^2}{q^2} \int dz \frac{\alpha_s(k_0^2)}{2\pi} \sum_b \hat{P}_{ba}(z) \right]$$

The functions $\hat{P}_{ba}(z)$ are the (unregularised) Altarelli-Parisi splitting functions describing the energy fraction $z$ taken by parton $b$ in the splitting $a \rightarrow b + c$. The coupling is evaluated at the transverse momentum of the splitting: it is given by $k_0^2 \simeq (1-z)q^2$ for initial state and by $k_1^2 \simeq z(1-z)q^2$ for final state emissions.

In order to include secondary scatters and initial state radiation off such collisions, we introduce ‘partonic pdf’s’
$f_j(x, Q^2)$, which analogously to the proton pdf’s describe \(\tau\) at leading order \(\tau\) the probability that a parton \(j\) with energy fraction \(x\) has been radiated from a parton \(i\) when the latter is resolved at a scale \(Q^2\). These pdf’s are also employed in the typical backward evolution of initial state radiation, as known, e.g., from simulating proton-proton collisions. Since the centre-of-mass energies of scatterings in the medium are typically rather small, it is unlikely that more than one initial state splitting is initiated in secondary scatterings. In this approximation\[14\] the partonic pdf’s can be integrated analytically, for instance

\[
f_i^0(x, Q^2) = \mathcal{S}_i(Q^2, Q_0^2) \delta(1-x) + \int \frac{dq^2}{q^2} \mathcal{S}_i(Q^2, q^2) \frac{\alpha_s((1-x)q^2)}{2\pi} \hat{p}_{qi}(x), \tag{2}
\]

and analogously for the other partonic pdf’s.

The interaction of the parton shower with the parton constituents in the medium depends on properties of the medium. We specify the cross sections for \(2 \rightarrow 2\) processes as

\[
\sigma_i(E, T) = \int_0^{t_{\text{max}}(E, T)} d|\hat{t}| \int dx \sum_{j \in \{q, q, g\}} f_j^i(x, |\hat{t}|) \frac{d\sigma_j}{dT}(x, |\hat{t}|), \tag{3}
\]

where the pdf takes into account possible initial state radiation off the energetic projectile. Note that here, implicitly, we neglected a similar evolution experienced by the target, i.e. there is no initial state radiation off the medium parton. The maximum momentum transfer \(|\hat{t}|_{\text{max}}\) is determined by the kinematics of the scattering. Neglecting the scattering centre’s momentum one finds \(|\hat{t}|_{\text{max}} = 2m_p(T)|E_p - m_p|\), where \(m_p(T)\) stands for the (temperature dependent) scattering centre’s mass and \(E_p\) and \(m_p\) are the projectile parton’s energy and mass, respectively. The boundaries on the \(x\)-integral are obtained from the requirement that \(k_\perp^2 \geq Q_0^2/4\) and are given by \(x_{\text{min}}(|\hat{t}|) = Q_0/(4|\hat{t}|)\) and \(x_{\text{max}}(|\hat{t}|) = 1 - Q_0/(4|\hat{t}|)\). For the partonic cross section we keep leading terms only, but we regularise them with a Debye mass \(\mu_D \approx 3T\). They therefore read

\[
\frac{d\hat{\sigma}}{dT}(\hat{s}, |\hat{t}|) = C_R \pi s^2 \sigma_2^2(|\hat{t}| + \mu_D^2) \frac{\hat{s}^2 + (\hat{s} - |\hat{t}|)^2}{(|\hat{t}| + \mu_D^2)^2} \rightarrow C_R 2\pi \sigma_2^2(|\hat{t}| + \mu_D^2)^2 \frac{1}{(|\hat{t}| + \mu_D^2)^2}. \tag{4}
\]

Each parton emitted in subsequent parton showering has a finite formation time that is parametrically given by \(\tau \approx \omega/k_\perp^2 \approx (x)E/Q^2\). When the formation time is larger than the mean free path in the medium, emissions from all scattering centres within in the formation time interfere destructively giving rise to the non-Abelian Landau-Pomerantchuk-Migdal (LPM) effect. This has been incorporated following the algorithm of [12, 13], with the only difference that in the current framework gluon formation times cannot overlap. Compared to the original algorithm, this amounts to a mild and well understood suppression of induced radiation compared to the analytic result without changing the shapes of the gluon distributions \[15\].

When emissions from different sources, i.e. initiated by different hard scatterings (where one may be the ‘vacuum’ parton shower) compete with each other, it is solely the gluon with the shortest formation time that will be emitted. This criterion is enough to regulate the interplay of all (vacuum and medium induced) emissions.

To obtain the example results below, the following setup has been used: In all cases, the final state parton shower is generated by JEWEL \[16\], where elastic scattering and medium-induced radiation is implemented as discussed above. Initial dijet production is simulated using the matrix elements and initial state parton shower of PYTHIA 6.4 \[17\], the latter running in a virtuality-ordered mode to provide the best fit to the JEWEL simulation. In all results, the strong coupling is running at one loop with \(\alpha_s(m_Z) = 0.128\), consistent with findings of other leading order calculations. The infra-red cut-off of the parton shower was chosen as \(Q_0 = 1.5\, \text{GeV}\) to yield a good description of LEP data. The CTEQ6L1 \[18\] pdf’s as provided by LHAPDF \[19\] are used; simulating nuclear collisions the nuclear modification of EPS09LO \[20\] is employed. The medium is modelled using a simple variant of the Bjorken model \[21\], which roughly accounts for the main features of the produced matter. It describes the boost-invariant longitudinal expansion of an ideal quark-gluon-gas. The transverse profile is chosen such that the energy density is proportional to the density of wounded nucleons. JEWEL can in principle be interfaced with any medium model. For the hadronisation the strings are built by JEWEL and then handed over to the PYTHIA hadronisation routine \[22, 23\]. The colour flow and consequently the strings can be constructed in different ways. The default choice reported here is to treat the struck scattering centres as if they were gluon emissions. The scattering centre is then always colour-connected to the projectile, before the parton shower sets in.

In principle, the modelling of interactions in the medium is free of parameters, as the parton shower and its infra-red cut-off \(Q_0\), hadronisation and the couplings are fixed from \(e^+e^-\) and \(pp\) collisions. In practice, however, the infra-red regulator in the cross section \(\tau\) adds an additional freedom. Here, we choose \(\mu_D \approx 3T\), in accordance with parametric estimates. The uncertainties related to this choice will be discussed in detail elsewhere, but they do not affect the conclusions drawn in the present study.

In the absence of a medium the JEWEL parton shower reduces to a standard (vacuum) parton shower. The parton shower implementation in JEWEL was thoroughly
tested in $e^+e^-$ collisions at LEP and $pp$ reactions at RHIC and LHC. As an example for the generally good performance, Fig. 1 shows a comparison with the neutral pion spectrum measured by PHENIX [24], which forms the baseline for the measurement of the nuclear modification factor $R_{AA}$. Above $p_\perp \simeq 4 \text{ GeV}$, the JEWEL+PYTHIA results agree with the data on a level of roughly 15\% over about 6 decades.

FIG. 1. Neutral pion spectrum in $pp$ collisions at $\sqrt{s} = 200 \text{ GeV}$ simulated with JEWEL+PYTHIA and compared to PHENIX data [24]. The Analysis of Monte Carlo events and plots were made with Rivet [25].

Turning to medium-modifications of hadron spectra, we fix the critical temperature $T_c = 165 \text{ MeV}$, consistent with the expected temperature at which QCD matter transfers from partonic to hadronic degrees of freedom. To obtain a fair agreement with the measured nuclear modification factor at RHIC, JEWEL+PYTHIA requires an initial temperature of $T_i = 350 \text{ MeV}$ at initial proper time $\tau_i = 0.8 \text{ fm}$, see Fig. 2. This is remarkably consistent with the input parameters in fluid dynamic simulations of heavy ion collisions. We note that at high $p_\perp$, where the Monte Carlo results are reliable, they reproduce both the factor $\sim 5$ suppression and the approximately flat $p_\perp$-dependence seen in the data. Varying the Debye mass by $\pm 10\%$ has a significant effect on the overall suppression, indicated by the grey band, but hardly affects the shape. Other sources of uncertainties like pdf-uncertainties, choice of initial time $\tau_i$ etc. can be expected to be smaller and will be discussed elsewhere.

The charged hadron multiplicities measured in heavy ion collisions constrain the initial entropy density of the system, $s_i \tau_i \propto dN/dy$, $s_i \propto \epsilon_i/T_i \propto T_i^3$ and therefore allow to relate the initial temperatures at RHIC and at the LHC,

$$T_i^{\text{LHC}} = T_i^{\text{RHIC}} \left( \frac{T_i^{\text{RHIC}}}{T_i^{\text{LHC}}} \frac{dN/dy|_{\text{LHC}}}{dN/dy|_{\text{RHIC}}} \right)^{1/3}. \quad (5)$$

The observation of a factor 2.2 increase in the event multiplicity from RHIC to LHC is therefore consistent with an initial temperature $T_i = 530 \text{ MeV}$ at $\tau_i = 0.5 \text{ fm}$ at the LHC. There is some freedom in initializing the fluid dynamic evolution at the LHC at a different initial time $\tau_i$, but this is numerically unimportant. At early times the parton shower is dominated by emissions at rather high scales initiated by the initial hard scattering, and this high virtuality protects the partons from medium-induced emissions and makes them insensitive to the medium at early times. Thus, the medium at the LHC is specified in terms of parameters fixed in Fig. 2. As seen from Fig. 3, the calculation of JEWEL+PYTHIA then leads without any additional adjustments to a very good agreement with preliminary data of the nuclear modification factor at the LHC.

To understand the characteristically different $p_\perp$-dependencies of $R_{AA}$ at RHIC and at the LHC, we have performed control simulations in which a LHC-like distribution of hard processes is fragmented in a RHIC-like medium, and vice versa (data not shown). This showed that the significant change in the slope of $R_{AA}(p_\perp)$ from RHIC to the LHC can be attributed fully to the $\sqrt{s}$-dependence of the distribution of initial hard processes. We therefore conclude that a purely perturbative dynamics of parton energy loss supplemented by an arguably simple model of the medium whose characterisation matches physical expectations, can account for the main features of the measured nuclear modification factors, including the strength of the suppression pattern,
and its $\sqrt{s}$ - and $p_\perp$-dependence.

At very large $p_\perp$ the nuclear modification factor continues to rise above unity. This is a purely kinematical effect that becomes visible at very large $p_\perp$, where the energy loss starts to vanish. The elastic scattering of energetic partons converts longitudinal momentum into transverse momentum and thus effectively makes the $p_\perp$-spectrum harder. While this is a generic effect its size and the turn-on point to some degree depend on the medium model, as they are sensitive to the amount of scattering centres encountered in the forward direction.

In this publication we have presented a novel description of jet quenching dynamics entirely based on standard perturbative technology also used in the simulation of proton–proton collisions, and implemented it into the Monte Carlo generator JEWEL. In contrast to other similar attempts, we do not only overcome certain limitations imposed by the eikonal limit [29], but we also resolve the dichotomy in the description of in-medium and vacuum radiation, basing all emissions on the same parton shower. We reinterpret induced radiation as regular, although infra-red-regulated, 2 → 2 parton scatterings, supplemented with our parton shower. This of course makes any distinction of elastic and inelastic scattering obsolete. We hinted at various ways of how our model can systematically be improved, using a well–understood perturbative language. This framework is flexible enough to accommodate observables such as correlations, or jets, which reach far beyond the very inclusive ones studied here. For the fairly successful simulation of the nuclear modification factor at RHIC and LHC we used a simple Bjorken model. Taking the description of this inclusive data as a proof of principle, we reserve further and more detailed investigations to future work.

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