Theoretical perspectives on the heavy ion LHC program

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1 Introduction

One of the most important discoveries at Rhic is a centrality dependent suppression of large transverse momentum hadrons [1, 2]. This phenomenon – although established on the basis of single-inclusive hadrons – is known as 'jet quenching' and is commonly interpreted as being due to radiative energy loss (i.e. QCD bremsstrahlung) of energetic partons in the dense and hot QCD matter produced in ultra-relativistic collisions of heavy nuclei.

2 Analytical approaches

There are several analytical calculations of non-Abelian bremsstrahlung [3, 4, 5, 6, 7, 8]. Despite the different approaches and techniques these calculations have a few things in common. Firstly, they find that the phenomenology is dominated be an interference that can be understood as the non-Abelian analogue of the Landau-Pomerantchuk-Migdal (LPM) effect. Secondly, they operate in a particular kinematical limit, namely the eikonal limit in which the radiating particle's energy is asymptotically large. This has important consequences, for instance in that there is no collisional energy loss. In this limit the action of the medium on the fast parton is characterised by the transport coefficient $\hat{q}$. Finally, all analytical calculations consider the radiation of a single gluon that is then iterated probabilistically. Apart from neglecting possible interferences this does not do justice to the well-known QCD jet evolution. Consequently, these approaches are suitable for describing single inclusive observables, but not for more exclusive observables and jets. An study comparing the different calculations in the same set-up found that they all describe the Rhic hadron suppression data equally well, albeit with very different transport coefficients [9]. A detailed investigation by the TECHQM collaboration concluded that this is due to the fact that the kinematical situation in the experiments is far from the eikonal limit and therefore the models are pushed outside their region of validity [10].

3 Jet Quenching at the LHC

Measurements of the single-inclusive hadron spectra at the LHC have shown a similar amount of suppression as at RHIC, but a different transverse momentum dependence (which is at least partly caused by the different shape of the underlying spectrum) [11, 12]. At the LHC also properties of reconstructed jets in heavy ion collisions are accessible and have been measured. For instance, a large transverse momentum asymmetry was found in di-jet events, while the azimuthal angle between the two jets remains unchanged [13, 15]. The missing momentum is carried by soft particles far away from the jet axis [15]. Furthermore, the intra-jet fragmentation functions are largely unmodified at intermediate and large momentum fractions [16, 17]. All these observations indicate that the jets lose energy and transverse momentum because soft components get transported outside the jet cone while the hard core is not altered. This interpretation is supported by a simple formation time argument [18]: The formation time of medium induced (bremsstrahlung) emissions is given by $\tau_{\text{med}} = \sqrt{2\omega/\hat{q}}$, where ω is the emitted gluon's energy. The angle of the emitted gluon with respect to the radiating parton can be estimated as $\theta_{\text{med}} \approx (2\hat{q})^{1/4}/\omega^{3/4}$, i.e. soft gluons decohere first and at large angles. At the same time the formation time of hard emissions from normal (vacuum) QCD evolution is parametrically of the form $\tau_{\text{vac}} = 2\omega/k_\perp^2$, where $k_\perp$ is the transverse momentum of the radiated gluon. This means that the formation of hard gluons is delayed by a boost factor and thus protected from interactions in the medium.

On the theoretical side technical advances have been made, for instance various calculations have been equipped with more realistic models for the medium. They generally agree at least qualitatively with the hadron suppression data [19, 20, 21, 22], but the conceptual issues have not been resolved. In order to make progress jet-medium interactions need to be formulated in more general non-eikonal kinematics. Then, however, elastic and inelastic interactions cannot be unambiguously separated any more and the ambiguity between the two needs to be resolved. Multi-gluon emissions have to be formulated consistently treating all sources of radiation (vacuum and medium-induced) on equal footing and keeping the interference responsible for the LPM-effect. Also the back-reaction of the jet on the medium has to be understood and modelled. Moreover, in order to obtain credible results all aspects of the calculation need to be controlled and uncertainties quantified.

4 Monte Carlo models

As Monte Carlo codes are widely used in particle physics to simulate complex multi-particle final states, it seems plausible that at least some of these problems can be solved with Monte Carlos. However, one thing to keep in mind is that Monte Carlo models relying on analytical results to simulate medium-induced gluon emissions also inherit the conceptual weaknesses. Still, Monte Carlo techniques can be used to exploit approaches that cannot be treated analytically.

The established Monte Carlo models for jet quenching are HIJING [23], HYDJET++/PYQUEN [24], JEWEL [25], Q-PYTHIA/Q-HERWIG [26, 27], YaJEM [28] and MARTINI [29]. Some of them are based on analytical results while others build on new ideas. They all include some form of jet evolution and produce final states that can in principle be compared to jet measurements. Although the Monte Carlo models typically succeed in reproducing for instance the di-jet asymmetry at least qualitatively, no consistent picture has emerged yet as it is sometimes unclear to what extent all aspects of the modelling are controlled.

5 Conclusions

Jet quenching measurements at the LHC indicate that the hard core of the jets stays intact while soft modes get transported to large angles. This picture supports the interpretation that perturbative, coherent gluon bremsstrahlung is responsible for the observed modification of jets. However, detailed comparisons of theory predictions and data suffer from large systematic theory uncertainties. Therefore, in order to make the most of the LHC data, new developments on the theory side are necessary. Also, with a wealth of jet data new theory tools such as Monte Carlo codes are needed. Monte Carlo models are starting to overcome the limitations of analytical calculations, but most of them still don't provide a controlled and consistent framework.

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