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Review

QCD and jets at hadron colliders

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ABSTRACT

We review various aspects of jet physics in the context of hadron colliders. We start by discussing the definitions and properties of jets and recent development in this area. We then consider the question of factorization for processes with jets, in particular for cases in which jets are produced in special configurations, like for example in the region of forward rapidities. We review numerous perturbative methods for calculating predictions for jet processes, including the fixed-order calculations as well as various matching and merging techniques. We also discuss the questions related to non-perturbative effects and the role they play in precision jet studies. We describe the status of calculations for processes with jet vetoes and we also elaborate on production of jets in forward direction. Throughout the article, we present selected comparisons between state-of-the-art theoretical predictions and the data from the LHC.

Contents

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1. Introduction

In the era of the Large Hadron Collider (LHC), as in the times of all precedent hadron colliders, jets remain fundamental objects of interest. They manifest themselves in detectors as collimated streams of charged particles in the tracker, or as concentrated energy depositions in the calorimeter.

Jets measured in experiments are build of hadrons, hence, bound states characterized by low energy scales of the order of a GeV or less. However, their existence is a proof of violent phenomena happening at much higher energies, from tens of GeV to half of the total initial energy of the colliding particles. Such highly-energetic phenomena occur only in a tiny fraction of hadron–hadron collisions, but, due to the large centre-of-mass energy and high luminosity, jet processes are extremely common at the LHC.

Because jets form signatures of large momentum transfers at short distances, they belong primarily to the perturbative domain of Quantum Chromodynamics (QCD). Predictions for processes involving jets are therefore computed at the level of partonic degrees of freedom. The relation between jets of hadrons, measured in experiments, and jets of partons, for which theoretical results are obtained, is ambiguous. One source of this ambiguity comes from the parton-to-hadron transitions (hadronization), which are genuinely non-perturbative, and therefore cannot be controlled precisely in theoretical calculations. The other reason is that jets at hadron colliders are always produced in a very busy environment and full theoretical control over the radiation prior to, or following, the hard scattering is practically impossible.

As the ambiguity cannot be removed, continuous efforts have been made over the years to formulate jet definitions that permit for precise studies of short-distance phenomena being at the same time robust with respect to hadronization or incoherent radiation from other parts of the event. Such definitions are currently widely adopted and they allow for a fully controlled comparisons between the theory and experiment. This, in turn, opens innumerable possibilities for the use of jets.

Since they are genuinely QCD objects, jets can, first of all, be employed for tests of Quantum Chromodynamics, and the Standard Model (SM) at large. Many high-precision studies of jets were performed at Tevatron [1–3] and at the LHC [4–9] finding so far no need for extensions of the theoretical descriptions beyond the Standard Model (BSM). Jets are used for studies of various properties of the strong interactions, such as measurements of the strong coupling [10,11], studies of the flavour sector of QCD [12], as well as determination of the parton distribution functions (PDFs) [11]. The modern PDF sets, such as NNPDF3.0 [13], CT14 [14] and MMHT14 [15], profit from a great variety of jet data, including those from the LHC, which are crucial in reduction of the gluon PDF uncertainties at large x. Jet processes are also crucial for such fundamental questions as a validity of factorization between the short- and the long-distance dynamics in QCD [16] as well as the existence of a non-linear domain of the strong interactions [17]. They are also instrumental in reaching out to extreme regions of QCD phase space where theoretical modelling becomes challenging [18].

The importance of jets extends however far beyond the strict domain of physics of the strong interactions, where they are used as representatives of partons participating in a hard process. This is because jets may have origins different than a short-distance interaction between quarks and gluons. They may, for example, also arise from hadronic decays of heavy objects such as the Higgs boson or the vector bosons, which decay into a pair of jets, or the top quark decaying into three jets. Similarly, jets may be produced as decay products of new particles such a hypothetical Z' resonance, which can show up as a peak in the tail of a dijet mass spectrum [19,20], or a variety of SUSY particles, which would readily decay into many-jet final states. Even the dark matter and extra dimensions are looked for in events where a monojet recoils against the missing energy [21,22]. Many other jet processes are used to set limits on new physics [23]. But jets appear not only in the potential signals of BSM phenomena but they also contribute to countless backgrounds to processes within and beyond the Standard Model. Just to give one example for each category: Higgs analyses divide events in samples with different jet multiplicities for more efficient background subtractions [24,25], while gluino production can be mimicked by a $W + 4$ jets process [19,26]. Finally, jets are extensively used in heavy ion physics. The classic example is the study of a dense medium created in collisions of large nuclei, which leads to the asymmetry in dijet events [27].

The above, long, yet still incomplete, list of applications motivates considerable, multi-pronged efforts that are being made to develop better control over jet processes. One direction of research focuses on improvements of our understanding of the properties of jets, as well as the strengths and weaknesses of different jet definitions and jet-related observables.