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Review

Towards jetography

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Abstract As the LHC prepares to start taking data, this review is intended to provide a QCD theorist's understanding and views on jet finding at hadron colliders, including recent developments. My hope is that it will serve both as a primer for the newcomer to jets and as a quick reference for those with some experience of the subject. It is devoted to the questions of how one defines jets, how jets relate to partons, and to the emerging subject of how best to use jets at the LHC.

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1 Introduction

It is common to discuss high-energy phenomena involving quantum chromodynamics (QCD) in terms of quarks and gluons. Yet quarks and gluons are never visible in their own right. Almost immediately after being produced, a quark or gluon fragments and hadronises, leading to a collimated spray of energetic hadrons—a jet. Jets are obvious structures when one looks at an event display, and by measuring their energy and direction one can get close to the idea of the original "parton". The concept of a parton is, however, ambiguous: the fact that partons have divergent branching probabilities in perturbative QCD means that one must introduce a prescription for defining what exactly one means by the term. Similarly, jets also need to be defined—this is generally done through a jet definition, a set of rules for how to group particles into jets and how to assign a momentum to the resulting jet. A good jet definition can be applied to experimental measurements, to the output of parton-showering Monte Carlos and to partonic calculations, and the resulting jets provide a common representation of all these different kinds of events.

Jets are used for a wide range of physics analyses. One way of classifying their uses is according to the different possible origins for the partons that give rise to the jets. At hadron colliders (and in photoproduction), one of the best studied jet observables is the inclusive jet spectrum, related to the high-momentum-transfer $2 \to 2$ scattering of partons inside the colliding (anti)protons. In this kind of process the energy of the jet (in the partonic centre-of-mass frame) is closely related to that of the parton in the proton that underwent a hard scattering and the inclusive jet spectrum therefore contains information on the distributions of partons inside the proton (e.g. [1–4]), and also on the strength of their interaction.

Another origin for the partons that lead to jets is that they come from the hadronic decay of a heavy particle, for example a top quark, a Higgs boson, or some other yet-to-be discovered resonance. If, at tree-level, the heavy particle decays to many partons (e.g. through a cascade of decays) then a high multiplicity of corresponding jets may be a sign of the presence of that particle (as used for example in SUSY searches, such as [5]); and the sum of the momenta of the jets (or of the jets, leptons and missing transverse energy information) should have an invariant mass that is close to that of the heavy particle, a feature used for example in measurements of the top-quark mass [6, 7].

Jets may also originate radiatively, for example from the emission of a gluon off some other parton in the event. The rate of production of such jets provides information on the value of strong coupling (for example [8–12]) and is related also to the colour structure of events. One use of this is, for example, to help discriminate between Higgs-boson production through electroweak vector-boson fusion (which radiates less) and through gluon-fusion (which radiates more). Radiative emission of partons is also one of the main backgrounds to multi-jet signals of new physics; consistently predicting such backgrounds involves matching tree-level matrix-element calculations with Monte Carlo parton showers, for which jet definitions provide a powerful way of avoiding double counting, by prescribing which emissions should be the responsibility of the matrix element (those that lead to extra jets) and which ones should come from the parton showers (those that do not) [13, 14].

Though most uses of jets essentially identify a jet as coming from a single parton, one should never forget how ambiguous this association really is, and not just because partons are an ill-defined concept. For example, when a highly boosted W or Z boson decays to two partons, those partons may be so collimated by the boost that they will lead to a single jet, albeit it one with substructure. And QCD radiative corrections also inevitably give substructure to jets. Much as the number of jets and their kinematics can be used to learn about the properties of the event, so can the structure within the jets.

Given the variety of these and other related possible uses of jets, it should not be surprising that there is no single optimal way of defining jets and, over the 30 years that have passed since the first detailed proposal for measuring jets [15], many jet definitions have been developed and used. The ideas behind jet definitions are rather varied. One of the aims of this review (Sect. 2) is to provide an overview of the different kinds of jet definition that exist. Given that the main use of jets in the coming years will be at the Large Hadron Collider at CERN (LHC), the emphasis here and throughout the review will be on hadron-collider jets, though a number of the ideas in jet finding actually have their origins in studies of e^+e^- and ep collisions.

One of the characteristics of the LHC is that its particle multiplicity is expected to be much higher than in preceding colliders. Some part of the increase is due to the LHC's higher energy, but most of it will be a consequence of the multiple minimum-bias interactions (pileup) that will occur in each bunch crossing. High multiplicities pose practical challenges for the computer codes that carry out jet finding, because the computing time that is required usually scales as some power of the multiplicity, N. Until a few years ago, this was often a limiting factor in experimental choices of jet-finding methodology. Recent years' work (described in Sect. 3) has shown how these practical issues can be resolved by exploiting their relation to problems in computational geometry. This makes it easier for LHC's jet-finding choices to be based on physics considerations rather than practical ones.

Given a set of practical jet algorithms, the next question is to establish their similarities and differences. Any jet algorithm will form a jet from a single hard isolated particle. However, different jet definitions may do different things when two hard particles are close by, when a parton radiates a soft gluon, or when the jet is immersed in noise from pileup. Section 4 examines standard and recent results on these issues, for the most important of the current jet algorithms.

Once one has understood how jets behave, the final question that needs to be addressed is that of determining the jet definitions and methods that are optimal for specific physics analysis tasks. One might call this subject "jetography", in analogy with photography, where an understanding of optics, of one's light sensor, and of properties of the subject help guide the choice of focus, aperture and length of exposure. Ultimately, it is neither the photons in photography, nor the jets in jetography that are of interest; rather it is the objects (new particles, PDFs, etc.) that they help you visualise or discover. In the context of the LHC, it is probably fair to say that jetography is still in its infancy, hence the title of the review. Nevertheless some first results have emerged in the past couple of years, notably (as discussed in Sect. 5) with respect to simple dijet mass reconstructions, hadronic decays of boosted heavy particles, and the question of limiting the effect of pileup.

One thing that this review does not do is examine the wide range of uses of jets in LHC and other experiments' analyses, aside from the brief discussion given above. This is a vast subject, and to obtain a full overview probably requires that one consult the main ATLAS and CMS physics analysis programme documents [16, 17] and the "LHC primer" [18], as well as recent work by the Tevatron and HERA, summarised for example in [19, 20]. Other reviews of jets in recent years include [21, 22]. Finally a topic that is barely touched upon here is the nascent field of jet finding in heavy-ion collisions, for which the reader is referred to [23, 24].