Boosted jets and tops at the LHC

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Generic context. Particle physics aims at understanding the fundamental interactions of nature. In this context, CERN's Large Hadron Collider (LHC) plays a key role, as proven by the recent discovery of the Higgs Boson. The LHC now routinely probes energies around and beyond the TeV scale, studying the Standard Model of particle physics and looking for new interactions beyond the Standard Model itself, like a dynamical explanation for Dark Matter.

Jets. Jets are the offsprings of high-energy quarks and gluons (the fundamental particles of strong interactions) which are not observed directly but under the form of a collimated spray of hadrons (pions, kaons,...). They are fundamental objects in collider physics. In order to make high-quality and precise measurements at the LHC it is crucial to reconstruct and understand jets as well as possible. In a sense, an optimal control over the jets means a precise reconstruction of the initial quarks and gluons and therefore an optimal measurement of the fundamental interactions that occurred during the collision.

Boosted jets and substructure. At high energy, a new situation occurs. Consider, for example, a Higgs boson decaying into a (bottom) quark and an anti-quark. If the energy of the Higgs boson is not too large, i.e. below its mass, the two quarks are well separated and each of them is observed as a jet, as expected. When the energy of the Higgs boson increases well beyond its mass, what is called the *boosted* regime, the decay angle between the bottom quarks shrinks to a point where they can be clustered into a single jet i.e. the Higgs boson now appears as a single jet instead of two well-separated ones. A similar situation can happen with electroweak W and Z bosons decaying to a pair of quarks or with a top quark decaying to three quarks. This is conceptually important since it means that objects other than quarks and gluons, i,e, objects which would normally decay in several jets, can now also appear as (single) jets.

To properly reconstruct the fundamental interaction of the collision, one must separate these jets originated by boosted massive particles from the standard quark and gluon jets. This is done by looking inside the jets and exploiting differences in the distribution of their constituents, a field broadly known as *jet substructure*. Over the past few years, several tools have been proposed for this task. They have been tested in numerical simulations, validated (in an experimental context) by the LHC experiments, and are now routinely used in LHC measurements.

A (new) first-principles approach. In order to gain control over jets and their substructure, and to alleviate a series of limitations coming with the use of numerical simulations, we have started to study jet substructure from a first-principles approach, based on Quantum Chromodynamics (QCD), the fundamental theory of strong interactions. Today, some key methods are already under analytic control and, in many situations, this control has led to improvements over the original methods.

The topic of this thesis is to further develop the understanding of jet substructure in general and of boosted top quarks in particular. This includes three main directions of research:

- understand existing substructure techniques from first-principles;
- develop new tools with increased discriminating power and limited sensitivity to poorly-controlled non-perturbative effects;
- provide precision calculations in QCD with reliable theory uncertainties.

In this first-principles approach, several results have already been obtained in the case of electroweak bosons ($H/W/Z$) but very little has been done in the case of the top quark. The latter will therefore be the main focus of the thesis.

Practical details. This thesis topic is closely related to the on-going ANR project `OptimalJets`, meaning that the PhD candidate will be supervised by Matteo Cacciari (LPTHE) and Gregory Soyez (IPhT) and be part of a larger team including also Davide Napoletano (postdoc on the ANR).

Several well-established tasks can be investigated in the context of the thesis. This includes studies (and possible improvements) of existing prong finders (like Y-splitter, trimming, mMDT, SoftDrop,...), and studies (and possible improvements) of existing measures of radiation in jets (like N-subjettiness, Energy-Correlation Functions or their recent variants). Once a good knowledge of these tools is reached, the next goal is to investigate how to optimally combine them into a high-efficiency tool.

Besides the analytic calculations, Monte-Carlo event simulations will be used to gain insight and confidence on the analytic results and to assess the size of the non-perturbative effects.

Impact. With the LHC probing higher and higher energy scales, boosted jets are becoming increasingly common and are relied upon. Boosted jets are now used in a growing number of new physics searches. This thesis topic has thus a broad impact on important aspects of particle physics.

The specific case of top quark-initiated jets is also particularly important, as jet substructure techniques could lead to a definition and a precise measurement of a theoretically well defined "short distance" mass that can in turn be used as an input parameters in calculations like those related to the stability of the vacuum.

Understanding jet substructure in QCD also comes with improvements of our understanding of QCD itself. For example, the PhD student will have to learn all-order resummation techniques in QCD and develop them beyond the current state-of-the-art. A possible direction to investigate during the thesis includes so-called *unsafe but calculable* observables, for which no systematic theory exists to date.

In a broader context, the student working on this topic will acquire a deep expertise in a wide set of tools used in particle physics phenomenology, ranging from important computer packages to advanced analytical techniques in QCD.