


Editorial

Higher Order Radiative Corrections in QCD

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The spectacular physics results collected during the first two runs of the Large Hadron Collider (LHC) present compelling evidence that the Standard Model of Particle Physics describes nature with a very high degree of accuracy. The discovery of the Higgs boson particle in 2012 was only the start of a wide program aimed at characterizing the properties of this new particle and confirm its position into the Standard Model (SM). Many precision measurements have been performed since then in the sectors of strong and electroweak interactions, heavy quarks, and flavor physics, all confirming the validity of the SM at the smallest scales tested in the laboratory.

However, despite its spectacular success, the SM leaves several important questions unanswered. For example it does not explain why there are three families of quarks and leptons, or why particle masses are distributed according to the observed hierarchy, or yet what is the origin of particle quantum numbers. Furthermore, it does not provide any viable dark matter candidate with all the required properties deduced from cosmological observations. Not to mention that it does not incorporate gravity. These and other issues have fostered speculations that the SM could be an effective theory valid up to some energy scale Λ_{SM} and should be extended by some fundamental underlying theory which describes phenomena at higher-energy scales $\Lambda > \Lambda_{SM}$ (possibly up to the Planck scale). One of the most widely explored candidates for this role is Supersymmetry, which solves several problems beyond the Standard Model (BSM) and predicts several new heavy states in the spectrum of the elementary particles.

The LHC is designed to allow scientists to probe different BSM scenarios up to the TeV scale. Despite the cautious optimism expressed by a part of the high energy physics community at the beginning of the LHC era, no spectacular signature of BSM physics has been observed to date. As lower bounds for searches of new heavy states have increased over the years, the attention has been increasingly turned on precision studies. The latter rely on the idea that new physics is too heavy to be directly produced at the LHC, thus only small deviations from the SM can be effectively observed. As of today, there are two intriguing hints of new physics that enforce this approach: the first is the observation of sustained tensions in semileptonic charged and neutral-current B decays at LHC; the second is the recent announcement of a 4.2σ discrepancy by the Muon g-2 experiment at Fermilab.

Whichever direct or indirect approach is adopted for BSM searches, achieving an excellent theoretical control over SM backgrounds is the fundamental prerequisite. This represents a real challenge for a hadron collider such as the LHC, as strongly interacting particles are ubiquitous players in this context. Precise computations of cross sections involving hadrons demand a particularly detailed understanding of perturbation theory in Quantum Chromodynamics (QCD). The QCD factorization theorem sets the general framework for the modeling of hadronic collisions. The calculation of the scattering cross section is separated into two main aspects: (i) a process-dependent, perturbatively calculable part describing the process at hard scales, and (ii) a universal, nonperturbative part which accounts for physical effects occurring at soft scales.



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Matrix elements for the partonic hard scattering represent the core of the perturbative part of the calculation. The use of perturbation theory is justified by the relative weakness of the interactions among particles, as quantified by the couplings of the electroweak and strong interactions (α_{EW}, α_S). A salient feature of these couplings is that they acquire a dependence on the characteristic energy scale of the process after renormalization. All physical predictions thus exhibit an unphysical scale dependence order by order in perturbation theory, which provides an important source of theoretical uncertainty. This effect is most pronounced in the case of the largest of the couplings, α_S , thus QCD corrections are the most sensitive. The only way to reduce the scale dependence problem is by adding higher-order terms in the perturbative expansion, which is not a trivial task. In fact, developing techniques for the efficient computation of higher-order corrections is one of the core problems of modern research. As of today, next-to-next-to-leading order (NNLO) in perturbation theory is the precision frontier for the majority of QCD processes. Given that NNLO QCD corrections and NLO electroweak (EW) corrections are formally comparable in size ($\alpha_S^2 \sim \alpha_{EW}$), and exploiting the complete automation of NLO calculations, combined QCD+EW studies are also becoming a standard for many physics analyses at the LHC.

Beside matrix element calculations, there is a number of other aspects where QCD, both perturbative and nonperturbative, plays a prominent role. Parton distribution functions (PDF) are fundamental ingredients to all predictions at hadron colliders and set another relevant source of theoretical uncertainty for the cross sections. QCD parton shower and hadronization help to connect the hard scattering with soft processes and provide a bridge between the parton- and the particle-level description of the underlying event. As such, they are necessary ingredients for a realistic description of hadronic final states. In particular, the precise modeling of hadronic jets and the study of jet substructures can give important insights to improve jet-tagging algorithms and signal/background discrimination in multijet analyses at the LHC. Not to mention effects from multiple interactions in hadron–hadron collisions, which are described by QCD through models of multi-parton interactions and minimum bias.

From all these considerations, it should be clear that developing precision phenomenology for the LHC requires synergy between different areas of expertise; multi-loop Feynman integral calculations, general subtraction schemes for the treatment of infrared singularities, formal developments in QFT, and accurate simulations of predictions for BSM benchmarks are all very specialized topics, and it is difficult to imagine real advancements in the precision frontier without an intense collaboration among specialists in each field. The coordination of networking necessary to this effort can largely benefit from the resources of dedicated funding schemes. One of the initiatives which supported this effort was the COST Action PARTICLEFACE—“Unraveling new physics at the LHC through the precision frontier”. The Action aimed to foster new collaborations and progress in the broad field of precision physics at colliders, with special focus on innovative algorithms and methods in QFT and computer algebra, as well as on precision phenomenology at LHC and future colliders. The goal was to pave the road to theoretical predictions of the highest possible precision in view of accurate comparisons with experimental data.

The range of contributions is broad and highly specialized. Hence, a Special Issue of review articles, as well as original contributions, that collects the state of the art about these topics with emphasis on comprehensiveness and methodical detail is timely and can be highly beneficial to foster further progress. The purpose of this Special Issue is to provide an overview as broad as possible of recent advancements in the precision frontier at high-energy colliders. Although the main emphasis is on QCD, large space is also given to other important topics relating to the physics of the Standard Model and beyond. This edition brings together several contributions from the COST Action PARTICLEFACE and thus should be also considered a report of the activities of the various Working Groups.

The main activities of the COST Action 16201: “Unraveling new physics at the LHC through the precision frontier” were structured into five Working Groups:

- WG1: “Innovative Quantum Field Theory” with the goal of developing innovative cutting edge algorithms to push the precision frontier forward, aiding the development of computational tools, computer algebra implementations, and proof-of-concept computations [1–4].
- WG2: “Precision Phenomenology” to provide precise theoretical predictions for LHC in the high-energy run to push the frontiers regarding precision and sensitivity; to compute cross sections for Higgs boson production (single and multiple Higgs boson production), EW gauge bosons, heavy-quark, multi-jet, and ultra-rare processes in differential kinematics [5–7].
- WG3: “Future Colliders” to assess the discovery potential of future high energy colliders based on the experimental results from the high-energy run of the LHC combined with progress in theoretical research [8,9].
- WG4: “Networking and Training” for efficient coordination of the Action activities, transparent administration, and reliable reporting.
- WG5: “Inclusiveness, Gender, Open Innovation and Outreach”, aiming at the implementation of the Action policies, communication of the Action results to the wider public; attraction of public awareness to fundamental research in particle physics.

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