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(Getting ready for) precision physics at hadron colliders

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I will review recent progresses in the field of higher-order predictions at hadron colliders, with focus on the LHC. The inclusion of higher order corrections, in particular of those corrections related with QCD, is crucial in order to get accurate and reliable predictions which are needed both to validate the Standard Model of fundamental interaction and to seek for yet unknown particles, but leads to a huge growth of the computational complexity. Recent works have lead to the possibility of computing the first subleading order (Next-to-Leading Order, NLO) corrections in a fully automated manner for any process, hiding all the computational complexity to the user. For what concerns higher orders (next-to-next-to Leading Order, NNLO and beyond), the most relevant processes for LHC physics in the SM have been covered at NNLO in the last few years, with huge efforts from different groups.
References (up to date at the time of the conference) will be given in the talk.

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1. Introduction: why should we care about precision physics?

The Large Hadron Collider (LHC) at CERN is the machine that will help us improve our knowledge of fundamental interactions for the next decade(s). It collides protons accelerated at unprecedented high energies, and collisions are recorded by four experimental apparatus, ATLAS, CMS, ALICE and LHCb. Scientists use these collision to look for confirmations of, or deviations from, the predictions of the Standard Model of fundamental interactions (SM) [1–7], that is the theory which describes our reality at the smallest known scale.
One striking confirmation of the goodness of the SM as a theory is the recent discovery [8, 9] of a candidate for the remnant degree of freedom of the Brout-Englert-Higgs-Kibble-Guralink-Hagen mechanism [10–15], the so-called Higgs boson. Two years after the announcement of the discovery, its properties are being measured with higher accuracy [16–20], and are so-far in excellent agreement with the predictions of the SM.
Despite these facts, scientists have good reasons to expect for new physics coming from extensions of the SM, in particular to explain the existence of Dark Matter and neutrino oscillations, therefore hoping for discoveries of new particles not predicted by the SM.

Discoveries at the LHC can be roughly put into three classes, according to their difficulty and their need of accurate theoretical predictions:

- "easy" discoveries are those where the new particle can be fully reconstructed trough its decay products, showing its existence as a peak over a background in the decay products invariant mass. No theoretical predictions is strictly needed for this kind of discovery. This has been the case for the discovery of the Higgs boson in the di-photon or four-leptons channel.

- Next we have "hard" discoveries, where the new particle cannot be fully reconstruced, but its existence can be probed by other properties of events: typically this means having distributions of some kinematical observable being harder than if the new particle did not exist. In this case theorists have to properly model the shape of these distributions for both signal and background processes. Such distributions can be normalised to data in some control region, i.e. regions where the new particle is supposed not to bring any effect, while the existence of the new particle can be assessed from the signal region which are known to receive large distorsions. This has been, and is the case for the search of invisible Higgs decay, for example in the ZH channel where the E_T^{miss} or $p_T(Z)$ spectra are harder than for the backgound.

- Finally, discoveries classified as "very hard" are those where on top of not being able to reconstruct the new particle, the only way to assess for its existence is to count events, looking for an (often tiny) excess. In this case theoretical predictions for signal and backgrounds cannot be normalised to data, rather they must provide themself a reliable prediction for the expected rates as well as for the kinematics distributions. This has been the case for the discovery of the Higgs boson decaying into $WW^{(*)} \to 2l2\nu$, where the state-of-the-art theoretical predictions have been employed.

From this classification, and since new particles have not shown themselves in an “easy” way, it is apparent that accurate theoretical predictionsi at the LHC range from being desirable to strictly necessary.

Besides discoveries, which may or may not appear, accurate theoretical predictions play a crucial role in the extraction of SM parameters, like couplings or particle masses. One quite instructive example is contained in Ref. [21], where the extraction of the top-quark mass m_t is discussed. Quite recently, ATLAS and CMS, together with the Tevatron experimets CDF and D0, have published a combination of the top-mass measurement with sub-GeV accuracy [22]. The authors of Ref. [21] propose a method for the extraction of m_t in di-leptonic top decays using only lepton-based observables, in order to be less sensitive to low energy effects, such as hadronization and color-reconnection. When they study the systematics of their method, they consider theoretical simulations with different perturbative accuracy (LO, NLO) as well as with different description of the final state (parton-level, hadron-level, with or without including spin-correlations in the decay of top quarks). They show how using such different theoretical setups leads to extracted values of the top mass which often are not compatible within the error of the fit among themselves and with the “true” value. Therefore the usage of poor theoretical predictions to extract SM parameters can bias in a serious way their value.

Having justified the need of accurate theoretical predictions, I will now turn to describe how to obtain theoretically accurate predictions and the most recent results.

2. Precision physics: how-to in a nutshell

In order to compute the cross-section for the production of a final state X at a hadron collider with center of mass energy $\sqrt{s}$, the factorization theorem is used [23], where the hadron-level cross-section $\sigma_{pp\to X}$ is written as a convolution of non-perturbative and process-independent parton distribution functions (PDFs) f_i and the perturbative, process-dependent parton-level cross-section $\hat{\sigma}_{ab\to X}$:

$$\sigma_{pp\to X}(s) = \sum_{ab} \int dx_1\, dx_2\, d\Phi\, f_a(x_1,\mu_F) f_b(x_2,\mu_F) \hat{\sigma}_{ab\to X}(\hat{s} = x_1 x_2 s, \mu_F, \mu_R)\,. \tag{2.1}$$

PDFs represent the probability of extracting parton a with momentum fraction x from a proton probed at a scale μ_F. As said, they are non-perturbative objects, i.e. they have to be extracted by data. In what follows I will not speak about how to determine accurately PDFs, the interested reader can find more in Refs. [24–27].

The partonic cross-section can instead be computed in perturbation theory up to a given order. One expands the cross-section in some coupling (at hadron colliders strong interactions dominate, therefore the expansion is typically done in the strong coupling α_s), obtaining the series

$$\hat{\sigma}_{ab\to X} = \sigma^0_{ab\to X}\left(1 + \frac{\alpha_s}{2\pi}\Delta_1 + \left(\frac{\alpha_s}{2\pi}\right)^2 \Delta_2 + \dots\right), \tag{2.2}$$

where $\sigma^0_{ab\to X}$ is called the Leading Order (LO) or Born contribution to the cross-section, Δ_1 is the Next-to-Leading Order (NLO) correction, Δ_2 is the Next-to-Next-to-Leading Order (NNLO)

correction and so on. From a technical point of view, the complexity increases exponentially with the perturbative order and with the number of external particles. Diagrams with up to k loops have to be computed at N^{k}LO, which feature Infra-Red (IR) divergences that have to be canceled by the corresponding real-emission processes: for example, at LO one just has to consider tree level diagrams for the process $ab \to X$, at NLO one has also diagrams with one loop and tree-level diagrams with an extra light parton in the final state, at NNLO one has diagrams with two loops, with one loop and one extra parton and at tree-level with two extra partons and so on.
The effort due to the conceptual complexity of higher order computations is paid off by having a more reliable prediction, with smaller theoretical uncertainties and which needs less fine-tuning to fit to experimental data.

3. Where do we stand with precision physics?

The LHC physics project has greatly pushed the development of techniques to tackle higher-order computations. The computation of NLO corrections is fully automatized, general techniques are being developed for NNLO corrections leading to the possibility to tackle $2 \to 2$ processes, and even the first NNNLO computations have appeared in the literature. I will give more details and relevant references in what follows.

3.1 NNNLO

No hadroproduction process is currently known at full NNNLO accuracy. However, there are on-going works by several group to reach NNNLO accuracy for some $2 \to 1$ processes of key importance at the LHC, such as Drell-Yan and Higgs production in gluon-fusion. An accurate prediction for the former is crucial in order to lower the error on the extracted value of the W boson mass, while the latter is a process which is affected by large corrections in QCD. The approaches are mostly based on the resummation of threshold logarithms [28], possibly improved with matching to the high energy limit of the cross-section [29,30]. The exact computation of $gg \to H$ at NNNLO is being tackled by another group, and partial results are available [31–33].

3.2 NNLO

In the recent years, NNLO techniques have grown more and more mature. If, on the one hand, completely general techniques both for subtraction of IR singularities and for the reduction of two-loops diagrams to some basis of master integrals are not known yet, on the other hand progress has been impressive in the recent years, at the point that $2 \to 2$ processes are being feasible. Among the recent NNLO results we have not only processes with colorless particles in the final state, such as Higgs-vector boson associated production [34], diphoton production [35], Higgs pair [36] and vector boson pair production [37], but also processes with colored particles, for which the subtraction of IR singularities is more involved: Higgs plus one jet [38], dijet production [39] and top-pair production [40]. Each of these processes is a crucial milestone by itself, and requires skills, a huge effort and dedication.

3.3 NLO

While at NNLO no general techniques exists yet, the situation is different for NLO. Indeed completely general techniques for the subtraction of IR singularities, such as the FKS [41] and dipole [42] subtraction schemes are available, and for what concerns the reduction and evaluation of one-loop diagrams, the problem was conceptually solved already by Passarino and Veltman [43] in the late seventies. It is only in the last decade, however, that the method of Passarino and Veltman has been made capable of tackling complex processes with high-multiplicity final states. Indeed, Passarino and Veltman proved that any one loop amplitude can be written in term of a linear combination of a basis of known master integrals, of which the coefficients can be determined by solving a system of equation. Until the last decade, where efficient numerical techniques have been developed, the system of equation had to be solved analytically, and the growth in complexity of the coefficients hampered the possibility of doing NLO computations with many (≥ 3) final-state particles. These techniques fall into three main classes: tensor reduction [44,45], generalized unitarity [46–48] and integrand reduction [49–51]. The impact of these new techniques is such that nowadays the computation of NLO cross-sections is not a problem any longer, as it can be carried out *automatically* with publicly-available codes, such as MadGraph5_aMC@NLO [52], of which the author is one core developer. Such automated tools hide all the complexity of a NLO computation from the user, and are therefore suitable to be used by non-experts, in particular directly by the experimental collaborations.

3.4 From partons to real world

The last part of my review will be devoted in how to perform a not only accurate, but also *realistic* simulation, where by realistic I mean a simulation in which the final state is described as we see it in reality. With this I mean that detectors do not see quark and gluons, but rather hadrons. Parton-Shower MonteCarlos (PSMCs) are typically used to evolve the final state partons of the perturbative computation to a more realistic hadronic final state. They typically work by generating extra QCD emissions in the soft-collinear approximation, starting from a momentum scale of the order of the typical scales of the process down to lower scales, until the confinement scale of QCD is reached. At this point, a non-perturbative hadronization model maps the partons into hadrons, generating an hadronic final state.

While it is trivial to apply PSMCs to events at the LO, it is not when higher orders are taken into account. The reason is that both the perturbative calculation and the shower generate extra emissions, and care has to be paid in order not to double-count such emissions. At NLO this problem has been solved, and two method exists that match NLO computation and PSMC: MC@NLO [53] and Powheg [54].

The goodness of NLO+PS predictions is such that at present such predictions play the role of state-of-the art prediction for differential observables.

People are now trying to understand how to macth PSMC with NNLO computations. NNLO+PS predictions are so far available only for $2 \to 1$ processes, where the effects of the shower can be accounted for simply via reweighting [55, 56], although more general techniques are also being explored [57,58].

4. Conclusions

Accurate predictions have played an important role for the LHC physics program, and will play an even more important role at the next RunII. In this talk I have explained what physicists in the HEP community mean by accurate predictions, and presented the latest developments in the inclusion of higher order corrections.

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