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QCD CHALLENGES AT PRESENT AND FUTURE COLLIDERS

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Abstract

I give a personal view of three important challenges that QCD practitioners face when dealing with the physics of present and future high-energy colliders. I will discuss in particular the quest for precision in inclusive cross sections, differential distributions, and the role played by hadronisation corrections.

1 Introduction

Despite not having yet provided any striking signal of new physics beyond the Standard Model (SM), the LHC is playing a crucial role in constraining extensions of the SM, hence giving us important clues in understanding the phenomenon of electroweak symmetry breaking. Projections for the high-luminosity phase of the LHC (HL-LHC) indicate the possibility of constraining anomalous Higgs couplings at the percent level 1). In order to establish whether any deviations can be genuinely attributed to new physics, SM theoretical predictions need to be pushed at a comparable level of accuracy. This has fostered an impressive progress in our understanding of strong interactions, in particular the high-order structure of QCD.

At hadron colliders, cross sections can be written as convolutions of parton-distribution functions, which are universal and encode the long-range dynamics of partons (quarks and gluons) in the proton, and process-dependent, short-distance partonic cross sections, that can be computed as perturbative expansions in the strong coupling α_s. The lowest order in α_s is called leading order (LO), next-to-LO (NLO) contributions are suppressed by an extra power of α_s with respect to LO ones, and so on. Fixed-order perturbative contributions are generally calculated from the appropriate Feynman diagrams, taking care that infrared singularities cancel between real and virtual corrections. Such a cancellation can be achieved more easily for inclusive cross sections than for differential distributions. This is why the former, discussed in section 2, enjoy a better accuracy than differential distributions, the topic of section 3. The last section deals with the fact that we measure hadronic, and not partonic cross sections. Given the current level of precision, it is now important to reconsider the modelling of the transition from parton to hadron level.

2 Inclusive cross sections

Perturbative QCD expansions converge quite slowly, hence it is important to reach high orders to have a satisfactory theoretical accuracy. This is particularly true for the Higgs cross section, which starts to show satisfactory convergence starting at NNLO. The new state of the art for inclusive cross sections is an impressive N^{3}LO, in the limit of an infinitely heavy top 2). In fact, only by taking into account N^{3}LO corrections is it possible to push the theoretical accuracy for the Higgs cross section at the percent level. Notably, all integrals for relevant 2 → 1 processes at N^{3}LO are known 2). This gives access to further important total cross sections, such as that for Higgs production through bottom-quark fusion 3), and for the Drell-Yan process, whose calculation is in progress and gives promise to reach sub-percent accuracy. Using a systematic expansion around threshold it is also possible to compute the Higgs rapidity distribution at N^{3}LO 4). Finally, approximating Higgs production in vector-boson fusion (VBF) as the combination of two independent deep-inelastic-scattering (DIS) processes, it has been possible to compute the VBF cross section at N^{3}LO 5). It is known that this approximation breaks down at NNLO due to gluon exchanges between the two DIS lines. These contributions are at the permille level 6), the same size as the N^{3}LO ones 5). The main message here is that the VFB cross section is well under control, and NNLO is sufficient to achieve percent accuracy.

3 Differential distributions

Theoretical control of differential cross sections is particularly important when large invariant masses are probed. In fact, this regime could give access to quantum corrections involving new physics contributions that are inaccessible at low invariant masses. At HL-LHC, data for interesting high-energy regions will reach percent accuracy 1), so it will be crucial to match the same accuracy on the theoretical side.

At fixed-order, percent accuracy can be reached in most cases only through NNLO calculations. There is plenty of evidence that, when they exist, NNLO calculations agree much better with data than the corresponding NLO ones (see e.g. the comparison of theory and experiment for WZ production 7)). In recent years, there has been an explosion of new NNLO results, so that at the moment all relevant SM 2 → 2 processes are known at NNLO. These results have been driven by an impressive progress in the techniques used to perform the cancellation of infrared singularities between real and virtual corrections [8, 9, 10, 11, 12, 13]. In the following, instead of listing all these results, I will focus on a couple of examples of the benefit of having fully differential information on the final state.

The first example is the azimuthal correlation between leptons in top-antitop events. This observable is sensitive to physics beyond the SM. For instance, if the tops were originated from the decay of scalar stops, one would observe a different pattern of spin correlations in top decay. In fact, a fully differential NNLO calculation [14] of this observable in top-antitop production shows a much better agreement with data than the corresponding NLO prediction, with a substantial change in the shape of the distribution with respect to NLO.

One of the most important examples of a 2 → 2 process with jets in the final state is Higgs production with an additional jet. There, the tail of the transverse momentum distribution of the Higgs is sensitive to physics beyond the SM [15, 16, 17]. At LO, this process needs already a loop of quarks, with the top quark playing the dominant contribution. An NLO calculation requires the evaluation of two-loop diagrams with an internal mass, which have been computed only very recently using semi-numerical methods [18]. The most remarkable finding of this calculation is that the K-factor NLO/LO is about 2, of the same size as that of the Higgs total cross section, and basically independent of the Higgs transverse momentum.

For Higgs characterisations, it is also crucial to compute NNLO corrections to 2 → 3 processes, especially to Higgs production in association with a top-antitop pair, which gives direct access to the top Yukawa coupling. Here progress is needed in the evaluation of the corresponding two-loop amplitudes. In this respect, we mention the first analytic calculation of a 2 → 3 two-loop amplitude, the full-colour five-gluon all-plus helicity amplitude [19]. Also, the recent calculation of NNLO corrections to three-photon production at the LHC [20] constitutes the first NNLO QCD calculation of a 2 → 3 process.

A general problem of fixed-order calculations for processes characterised by two disparate scales is the occurrence of large logarithms L of the ratio of the two scales. This happens for instance whenever we impose a jet-veto in the production of a heavy object (e.g. Higgs decaying to WW) to suppress some large irreducible background (e.g. top-antitop). These large logarithms need to be resummed at all orders to obtain meaningful predictions. For most observables, such resummation consists in a reorganisation of the perturbative series in the region $\alpha_s L \sim 1$. The leading logarithms (LL) build up an exponential function $\exp\left[L g_1(\alpha_s L)\right]$, next-to-LL (NLL) factorise in a function of $\alpha_s L$, next-to-NLL (NNLL) contributions, for $\alpha_s L$ fixed, are suppressed by a power of α_s with respect to NLL ones, and so on.

Jet-veto resummations have reached a remarkable accuracy (NNLL for the production of a colour singlet [21]). Predictions are now fully differential in the decay products of the colour singlet (e.g. a Higgs or a vector boson) with a jet-veto, and we now have an implementation of such NNLL jet-veto resummations in soft-collinear effective theory (SCET) in MADGRAPH (MADGRAPH_MC@NLO_SCET [22]), and in QCD in MCFM

(MCFM-RE [23]).

The highest resummation accuracy (N^3LL) has been reached for the transverse momentum distribution of a colour singlet, both in QCD with the RadISH formalism [24], and in SCET [25]. Notably, RadISH is able to provide a double differential distribution in the transverse momentum of the colour singlet and the leading accompanying jet, being simultaneously fully differential in the decay products of the colour singlet [26].

4 Hadronisation

In view of the precision of present and future calculations, precise measurements of α_s start to play a role. Until very recently, the determination of α_s from jet observables in e^+e^- annihilation was mainly affected by perturbative QCD uncertainties [27]. The precision of current calculations [28, 29, 30] is such that the dominant uncertainty is due to poorly understood hadronisation effects. These are either determined with Monte Carlo event generators [30], or with analytic models of the leading hadronisation corrections [28, 29]. Note that hadronisation corrections, suppressed by inverse powers of the e^+e^- centre-of-mass energy, become smaller with increasing energy. Therefore, at future e^+e^- colliders, different Monte Carlo hadronisation models might have less impact on the determination of α_s than perturbative QCD uncertainties. Also, considering only leading hadronisation corrections might be appropriate. This might foster improvements in analytic models of hadronisation, for instance their extension to a larger set of observables. Also, hadronisation effects in three-jet events at future e^+e^- colliders will be of the same order as in two-jet events at LEP1 [31]. This will give the opportunity to perform further non-trivial tests of the features of leading hadronisation corrections.

5 Conclusions

To conclude, present and future colliders offer many exciting possibilities to reinforce our understanding of QCD dynamics. The precision of experimental data, especially at the HL-LHC, pushes theory at least to NNLO accuracy, and requires fully differential predictions, both fixed-order and resummed. Future e^+e^- colliders give promise to provide better determinations of the strong coupling due to smaller hadronisation corrections. This in turn might positively affect the accuracy of theoretical predictions for the LHC. We hope that all these improvements will help give access to hints of new physics that could explain the unsolved puzzles of the SM.

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