LHC PHYSICS: CHALLENGES FOR QCD

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I review the status of the comparisons between a few measurements at hadronic colliders and perturbative QCD predictions, which emphasize the need for improving the current computations. Such improvements will be mandatory for a satisfactory understanding of high-energy collisions at the LHC.

One of the main goals of the LHC will be the search of the Higgs boson, the only piece of the otherwise thoroughly tested Standard Model (SM) of which we miss experimental evidence. Regardless of the existence of the Higgs boson, LHC will likely shed light on the physics Beyond-the-SM (BSM), which should be within reach, as LEP results and solar and atmospheric neutrino data suggest. In this context, the role played by QCD may appear an ancillary one. However, this seems to be quite at odds with the fact that LHC is a hadronic collider, and strong interactions will be responsible for a prominent part of the reactions taking place. On the other hand, one may claim that an accurate knowledge of QCD predictions will not be necessary for the discovery of – say – the Higgs in presence of a striking feature such as a narrow mass peak, which could give the possibility of normalizing the background directly with the data. However, if the discovery is based on a counting experiment, it relies by definition on precise predictions for SM backgrounds, dominated by QCD. These predictions will also prove essential for after-discovery studies, when the properties of the newly-found particles will have to be determined, or in the case of absence of BSM signals, in order to set limits on BSM scenarios.

Having argued that QCD studies are one of the keys for a successful LHC physics program, one question remains: are there still motivations to keep
on working on them? The answer is again yes. The question is legitimate, since the striking success of perturbative QCD in predicting experimental results may lead to think that the current knowledge is sufficient to tackle the problems posed by the LHC. Unfortunately, this is not the case: because of the large energy available, hard reactions will occur in a previously unexplored regime, with peculiar kinematic characteristics, such as the simultaneous presence of many, well-separated hard jets. These new features require to improve QCD predictions, either by increasing the accuracy of the computations, or by considering issues which could have been safely neglected up to now. Although one could give theoretical arguments for the improvements that need to be achieved, it is also instructive to look at those measurements which so far could not be described by perturbative QCD in an entirely satisfactory way, which in fact, rather than hinting to a fundamental problem of QCD, indicate that a deeper understanding is desirable of some aspects of the computation. This is in fact relevant to the problem of QCD predictions for the LHC, since aspects which may be marginal in the current phenomenological picture will be much more important in the future.

Figure 1: $B^+$ data [1] versus theoretical predictions [2].

Let me start with what has been seen historically as a major problem
in QCD, namely single-inclusive $b$ production at hadron colliders: although NLO QCD appears to give a good description of data in terms of shape, the rate is typically underestimated by a factor of 2. Recently, this picture seemed to receive strong support from a CDF measurement [1], where the average of the data/theory ratio for $B^+$ mesons was quoted to be $2.9 \pm 0.2 \pm 0.4$. However, it has been subsequently pointed out [2] that this value is mainly due to an improper treatment of the theoretical prediction, and that the correct result is $1.7 \pm 0.5 \pm 0.5$. This value originates from using the state-of-the-art computation for single-inclusive $b$ $p_T$ spectrum (FONLL [3]), and especially from the observation that the fragmentation function $b \rightarrow B$ as presently determined by using $e^+e^-$ data is not particularly appropriate for the case of hadronic collisions. It is interesting to note that the proper choice of the fragmentation parameters leads to a comparison between theory and data (see fig. 1) which is basically identical to that relevant to $b$-jet transverse energy [4, 5], i.e. to an observable independent of the details of the fragmentation mechanism. Therefore, $b$ production at hadron colliders should not be regarded any longer as a reason of concern; on the other hand, the size of the theoretical uncertainties (solid band in fig. 1) prevents more stringent tests. It is likely that a major source of improvement in this respect would be the computation of the $b$ cross section to NNLO accuracy; a further enhancement of the rate should be expected from small-$x$ [6, 7] and threshold resummations. Finally, let me remind that results for total rates for $b$ production in $ep$, $\gamma p$ and $\gamma\gamma$ collisions are in such a disagreement with NLO QCD predictions, that no viable explanation for this discrepancy has been found in any BSM scenario. It is necessary to note that in many cases the experimental results are extrapolated to the full phase space from a rather narrow visible region. However, it is encouraging that in a few cases the data are also presented without the extrapolation outside the visible region, and in this way they are fully compatible with QCD predictions. This points out that some problem may be hidden in the Monte Carlo (MC) simulation of heavy flavour production, especially in the low $p_T$ region.

Let me now turn to jet production at the Tevatron. The excess of CDF single-inclusive jet data [8] over NLO predictions at large $p_T$ has been regarded with much interest, being a potential signal of new physics. On the other hand, it has been immediately observed [9] that, by suitably adjusting the gluon density in the proton, one can obtain sets of PDFs (denoted with the “HJ” suffix by CTEQ) which give a decent global fit, and result in predictions for jets compatible with CDF measurements. This proves that QCD has enough flexibility to accommodate the excess, but it is disturbing that the “HJ” family is not the preferred one according to a (unweighted)
global fit procedure. This situation changes when D0 jet data \cite{10} are included in the global fit, since the resulting PDF set turns out to belong to the “HJ” family (although it is not called accordingly). This happens because the Bjorken $x$'s relevant to high-$p_T$ jet production are also relevant to small-$p_T$, large-$\eta$ production, a region probed by D0 (see ref. \cite{11} for a discussion). The comparison between theory and data is now fully satisfactory: the left panel of fig. 2 presents the ratio of the D0 data \cite{10} over theoretical predictions obtained with the PDF set CTEQ6M1 \cite{11}; for reference, the ratios of theoretical predictions obtained with other PDFs are also given; the situation for CDF data is analogous. Although this excludes any evidence of new physics in this channel, the situation may still change. This is shown in the right panel of fig. 2, where the band represents the span of the theoretical predictions due to PDF uncertainties. Thus, single-inclusive jet measurements at the Tevatron clearly stress the importance of precise PDF determinations (which implies the necessity of using data from many complementary processes), and of accurate estimates of the uncertainties affecting the PDFs. It is also worth reminding that there are at least a couple of unpleasant aspects of jet production at colliders. Firstly, by reconstructing jets using a $k_T$-algorithm, D0 \cite{12} finds large discrepancies with QCD predictions, a fact difficult to reconcile with the observation that, at the NLO and for suitable choices of jet-recombination parameters, no major differences can be seen in the single-inclusive $p_T$ distribution of jets reconstructed with the $k_T$ or the cone algorithms. Although more experimental analyses with the $k_T$ algorithm are necessary in order to confirm the result of ref. \cite{12}, it is interesting to observe that hadronization corrections and the underlying event modelling, as simulated by MC’s, affect fairly differently the jets reconstructed with different algorithms. Secondly, the ratio of jet cross sections measured by CDF and D0 at different c.m. energies ($\sqrt{s} = 1.8$ and
0.63 TeV) and fixed $x_T = 2p_T/\sqrt{S}$, is not in agreement with QCD (which can predict this quantity in a fairly accurate manner); besides, CDF and D0 data are also mutually incompatible at low $x_T$. However, the differences are largely within the uncertainties due to neglected power-suppressed effects. In both cases, it appears that the experimental analyses would benefit from a much deeper understanding of the interplay between perturbative and non-perturbative physics, both at the level of MC’s (whose use to estimate the hadronization corrections applied to NLO predictions is rather empiric), and in the context of approaches analogous to that of DMW [13, 14].

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![Figure 3: Comparison between prompt-photon data and QCD predictions](image)

Let me finally deal with the case of $\gamma$ production. One of the reasons of interest in this process is that, through the leading order partonic reaction $qq \rightarrow \gamma q$, it can in principle constrain the gluon density in a rather clean way. This is even more interesting if one observes that the typical range in $x_T(\gamma)$ probed by fixed-target experiments is quite similar to the range in $x_T(jet)$ probed in moderate- and large-$p_T$ jet production at the Tevatron. Unfortunately, as discussed in ref. [15], fixed-target photon data are not mutually compatible. This nowadays prevents the use of these data in global PDF fits. The problem is not peculiar to fixed-target experiments, since the agreement between isolated-photon data at the Tevatron and QCD predictions has always been pretty marginal, as shown in the left panel of fig. 3, where CDF data [16] are compared to NLO QCD results [17]. The situation, partly because of larger statistical errors, improves for D0 [18], as shown in the right panel of fig. 3 (here, ratios of cross sections, rather than cross sections, are presented). It must be stressed that the isolation cuts used by experiments
at colliders are unlikely to be fully equivalent to those applied in theoretical computations. The whole situation is rather inconclusive; if QCD predictions have to be used in the context of analyses involving photons, it is urgent to devise a strategy that allows one to apply the same cuts at the theoretical and experimental levels. For example, in a high-energy environment experiments prefer to define isolated photons with narrow cones; on the other hand, it is known that the isolated-photon cross section at NLO becomes unphysical (being larger than the fully inclusive one) for small isolation cone sizes \[19\]. The computation of yet higher orders, and especially of the all-order resummation of the relevant terms, would be necessary in order to solve this problem.

Although no major problem for QCD emerges from the phenomenological considerations given above, the picture would certainly look firmer (not necessarily better) if we had: a) NNLO results\(^1\); b) resummed results, matched with fixed-order ones\(^1\); c) better determinations of PDFs and their uncertainties; d) better understanding of the interplay between perturbative and non-perturbative physics; e) better models for the underlying event in MC’s. It should be clear that these issues are of primary importance for LHC physics: large numbers of hard jets (and large K-factors), strong impact of the accompanying non-hard events, and many-scale processes will occur plentiful. This is also worrying in view of the fact that MC’s, the ubiquitous tools in experimental analyses, are not reliable when an accurate description of large-angle emission is needed. It seems therefore mandatory to add to the list above: f) better MC simulation of hard emissions.

Items a)–f) are all tough problems, but it is generally believed, thanks to recent developments, that substantial progress will be made before LHC comes into operation. In view of its relevance to experimental collaborations, in the following I’ll concentrate on item f). It is useful to briefly remind how an MC works: for a given process, which at the LO receives contribution from \(2 \rightarrow n_0\) reactions, \((2 + n_0)\)-particle configurations are generated, according to exact tree-level matrix element (ME) computations. The quarks and gluons (partons henceforth) among these primary particles are then allowed to emit more quarks and gluons, which are obtained from a parton shower or dipole cascade approximation to QCD dynamics. To lessen the impact of this approximation on physical observables, one can devise two strategies. The first aims at having \(n_E\) extra hard partons in the final state; thus, in the example given above, the number of final-state hard particles would increase from \(n_0\) to \(n_0 + n_E\). This approach is usually referred to as

\(^1\)For certain processes and observables.
matrix element corrections, since the MC must use the \((2+n_0+n_E)\)-particle ME’s to generate the correct hard kinematics. The second strategy also aims at simulating the production of \(n_0+n_E\) hard particles, but improves the computation of rates as well, to \(N^{n_E} \text{LO}\) accuracy. I’ll generally denote the resulting MC as \(N^{n_E} \text{LOwPS}\).

There are basically two major problems in the implementation of ME corrections. The first problem is that of achieving a fast computation of the ME’s themselves for the largest possible \(n_0+n_E\), and an efficient phase-space generation. A variety of solutions exist nowadays for this problem, implemented in packages which I’ll denote as ME generators. The second problem stems from the fact that multi-parton ME’s are IR divergent. Clearly, in hard-particle configurations IR divergences don’t appear; however, the definition of what hard means is, to a large extent, arbitrary. In practice, hardness is achieved by imposing some cuts on suitable partonic variables, such as \(p_T\)’s and \((\eta, \varphi)\)-distances. I collectively denote these cuts by \(\delta_{\text{sep}}\). One assumes that \(n\) hard partons will result (after the shower) into \(n\) jets; but, with a probability depending on \(\delta_{\text{sep}}\), a given \(n\)-jet event could also result from \(n+m\) hard partons. This means that, when generating events at a fixed \(n_0+n_E\) number of primary particles, physical observables in general depend upon \(\delta_{\text{sep}}\); I refer to this as the \(\delta_{\text{sep}}\)-bias problem. Any solution to the \(\delta_{\text{sep}}\)-bias problem implies a procedure to combine consistently ME’s with different \(n_0+n_E\)’s. It should be stressed that, in presence of a \(\delta_{\text{sep}}\) bias, the interface of an ME generator (which is responsible for producing the hard configurations, i.e. the initial conditions for the shower), and a parton shower code is not, strictly speaking, an event generator, since the events depend somehow on the value of \(\delta_{\text{sep}}\). In practice, the dependence is of the order of 20%, which is acceptable if one considers that, without ME corrections, multi-jet configurations predicted by standard MC’s are completely unreliable. A solution to the \(\delta_{\text{sep}}\)-bias problem has been presented, for \(e^+e^-\) collisions, in ref. [20] (CKKW henceforth), and subsequently extended (without formal proof) to hadronic collisions in ref. [21]. Loosely speaking, CKKW achieve the following: if an \(n\)-jet observable is affected by the \(\delta_{\text{sep}}\) bias in the following way

\[
\sigma_n \sim \alpha_s^{n-2} \sum_k a_k \alpha_s^k \log^{2k} \delta_{\text{sep}},
\]

by applying the CKKW prescription one gets

\[
\alpha_s^{n-2} (\delta_{\text{sep}}^a + \sum_k b_k \alpha_s^k \log^{2k-2} \delta_{\text{sep}}).
\]
The implementation of CKKW in popular event generators for hadronic collisions is under way, and it will have reached a mature and well-tested stage when LHC will come into operation.

The implementation of an $N^{nE}$LOwPS can be seen as an upgrade of ME corrections: not only one wants to describe the kinematics of $n_0 + n_E$ hard particles correctly, but the information on $N^{nE}$LO rates must also be included. First attempts at solving this problem have only recently become available, and only for the case $n_E = 1$. The striking feature of an NLOwPS is the computation of loop diagrams (which are necessary in order to compute total rates to NLO accuracy); this in general implies the presence of negative weights. This is a new feature in MC’s, which however doesn’t spoil their probabilistic nature. In fact, in NLOwPS the distributions of positive and negative weights are separately finite, at variance with what happens in NLO computations; thus, each of them can be unweighted and evolved separately, since no cancellation between large numbers is involved in this procedure. On the other hand, the contribution of loop diagrams implies that the $\delta_{\text{sep}}$-bias problem which affects ME corrections is simply not present. At the moment, the following codes implement different prescriptions for NLOwPS in hadronic collisions: Φ-veto [22], MC@NLO [23, 24], GRACELLsub [25]. Φ-veto is based on the slicing method, and features $Z^*$ and $W^*$ production; it is affected by double counting according to the definition of ref. [23], but numerically this problem seems to be of minor importance; it is interfaced with Herwig and Pythia. MC@NLO is based on the subtraction method, and features $W^+W^-$, $ZZ$, $WZ$, $t\bar{t}$, SM Higgs, $Z$, $W$, and $\gamma$ production; it is interfaced with Herwig. GRACELLsub is based on the slicing method and on the fully-numerical computation of the matrix elements; it features Drell-Yan production, and is not affected by double counting only if the parton shower of ref. [25] is adopted (i.e., other showering codes cannot be used at the moment). The field of NLOwPS, still behind that of ME corrections, is rapidly evolving, and more ideas will appear in the future; soon, more processes will be implemented, and a thorough comparison between the various approaches will have to be made.

In summary, a lot of interesting developments are currently occurring in QCD, which will provide a solid benchmark for LHC studies. It will be vital for experimental collaborations to exploit these results, both by using new MC tools (with ME corrections and NLOwPS) in the course of their analyses, and by considering the most precise theoretical results available, at fixed-order (NNLO) or in resummed computations (with NLL or NNLL accuracy). In the coming years, it will also be crucial to learn from the experience of HERA and the Tevatron, which will hopefully provide the
necessary data to determine PDFs at an unprecedented level of accuracy, and to test the various models for underlying events.

It’s a pleasure to thank the organizers for an interesting meeting; as a phenomenologist, I think it is beneficial for both theoretical and experimental communities to have frequent (elastic) interactions.

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