

## Recent progress in QCD at the LHC

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**Summary.** — Perturbative Quantum Chromodynamics has experienced an impressive progress in the last few years, boosted by the requirements of the LHC experimental program. In this contribution, I briefly review a selection of recent results in QCD and LHC phenomenology, covering progress in parton distribution functions, automation of NLO calculations, merging and matching at NLO, new calculations at NNLO accuracy and their matching to parton showers, and new developments and techniques in jet physics and jet substructure tools.

PACS 12.38.-t – Quantum chromodynamics.

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### 1. – Introduction

With the discovery of the Higgs boson, high-energy physics has entered a completely new era, where its main goals in the following years will be the detailed exploration of the Higgs properties, such as its couplings and branching fractions, as well as the extensive exploration of the energy frontier in the search for new physics beyond the Standard Model. To optimize the scientific output of the LHC, a careful control on the theoretical uncertainties for the various relevant signal and background processes is of paramount importance. At a hadron collider such as the LHC, these uncertainties are dominated by strong interaction physics, perturbative Quantum Chromodynamics (QCD). The progress of perturbative QCD in the last years, boosted by the requirements of LHC data, has been impressive, and it would be difficult to faithfully summarize it even in a full review paper, let alone in this short contribution. Therefore, here I will limit myself to briefly present a necessarily biased selection of various important topics in perturbative QCD of particular relevance for LHC physics, and apologize in advance for any omissions forced by the brevity of this contribution.

The structure of this contribution follows the flow diagram of a typical hadron collision. First I will discuss progress in our understanding of the initial state of hadron collisions, as encoded in the parton distribution functions (PDFs) of the proton. Then I

will move to developments in NLO and NNLO calculational techniques of perturbative matrix elements, and their consistent matching to parton showers to achieve a realistic description of the final state. Finally I will review progress in jet physics and jet substructure.

## 2. – Parton distribution functions

The initial state of hadronic collisions is the domain of the parton distribution functions (PDFs) of the proton (see [1-3] for recent reviews). PDFs are an essential ingredient for LHC phenomenology: they limit the accuracy with which it is possible to extract the Higgs boson couplings from data [4, 5], degrade the reach of searches for massive new BSM particles at the TeV scale [6] and are the dominant systematic uncertainty in the determination of fundamental parameters such as the  $W$  boson mass, that are key ingredients for global consistency tests of the Standard Model [7]. Being non-perturbative objects (although their scale dependence is determined by the perturbative DGLAP evolution equations), they need to be extracted from global fits to hard-scattering data. Various PDF fitting collaborations provide regular updates of their QCD analysis. The most recent PDF sets from these collaboration are ABM12 [8], CT10NNLO [9], HERAPDF1.5 [10], MSTW08 [11] and NNPDF2.3 [12]. A recent benchmarking exercise, comparing the most updated PDF sets between them and with LHC data, has been presented in [13].

A major recent development in PDF fits has been the inclusion of a wide variety of LHC data. While of the various PDF sets discussed above, only NNPDF2.3 and ABM12 already include LHC data, other groups have performed studies of their impact in tailored analysis. LHC observables with PDF sensitivity range from traditional observables, like jet production [14-16] and inclusive electroweak boson production [17, 18], to processes that only at the LHC have become available for PDF fits, like isolated photon production [19],  $W$  production in association with charm quarks [20, 21], top quark pair production [22], low and high mass Drell-Yan production [23, 24] and  $W$  and  $Z$  production in association with jets [25], among others. The data on  $W + c$  production is particularly useful since it provides a clean handle on the strange PDF  $s(x, Q^2)$  [26, 20, 27, 21]. The use of cross-section ratios between different center-of-mass energies also provides useful PDF sensitivity [28], see for instance the ATLAS measurement of the ratio of jet cross-sections between 7 and 2.76 TeV [15]. While some of these PDF studies are being carried by the PDF fitting groups, recently also the ATLAS and CMS collaborations themselves have developed an extensive program of PDF determinations from their own measurements [17, 15, 18]. This has been made possible by the development of the open-source PDF fitting package HERAFITTER<sup>(1)</sup>, which has been used in a variety of PDF-related analysis by ATLAS and CMS.

From the theory point of view, recent developments include the combination of QED corrections together with the QCD ones for the DGLAP evolution in a PDF fit, NNPDF2.3QED set [29], that includes also a determination of the photon PDF  $\gamma(x, Q^2)$  from LHC data. Such PDFs with QED effects are required by consistency for LHC calculations when QED and electroweak effects are taken into account [30]. The LO version of NNPDF2.3QED has been used to produce an updates tune of the PYTHIA8 Monte Carlo, the so-called Monash 2013 Tune [31]. The treatment of heavy quarks in global

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<sup>(1)</sup> <https://wiki-zeuthen.desy.de/HERAFitter>.

PDF fits has also been studied by various groups, showing that the use of a fixed-flavor number scheme as compared to a general-mass variable flavor number one can explain most of the differences between the ABM fits (based on the former) and other PDF sets, that instead employ the latter [32,33]. Also related to heavy quarks, thanks to the use of the running charm mass  $m_c(m_c)$  in DIS structure functions it is now possible [34,35] to determine its value from the HERA combined  $F_2^c$  data with competitive uncertainties. The important issue of the sensitivity of the Higgs cross-section in gluon fusion with respect to the choice of dataset has been investigated by CT in Ref. [36], and by CT together with other groups in the upcoming 2013 Les Houches proceedings. Finally, the possibility of an intrinsic charm component in the proton has been recently revisited by the CT group [37], and important constraints here should be provided by LHC observables such as  $Z + c$ .

### 3. – Automation of NLO calculations, matching and merging

During many years, the needs for NLO calculations were summarized in the so-called Les Houches wish-lists. However, these have become rapidly obsolete with the progress in the automation of NLO calculations by various groups, which makes the calculation of NLO processes essentially a solved problem, and in the latest Les Houches report it has been replaced with NNLO and NLO electroweak wish-lists<sup>(2)</sup>. The key for the automation of NLO calculation has been on the one side, the development of methods for subtraction of soft and collinear singularities in real emission diagrams, such as in the MADFKS [38] and SHERPA [39] programs, and the corresponding progress in the computation of virtual amplitudes, with tools such as GOSAM [40], CUTTOOLS [41], MADLOOP [42], OPENLOOPS [43] and HELAC-NLO [44], just to name a few. Despite this automation, and specially for high final state multiplicities, tailored NLO calculations are still required for efficiency, such as those provided by BLACKHAT [45] and NJET [46]. The state of the art of fixed-order NLO calculations is provided by the recent computation of  $pp \rightarrow W + 5$  jets by the BLACKHAT collaboration [45]. Another related topic that has received attention recently is based around ideas for improved NLO computations, such as in the MINLO approach [47]. The basic idea here is defining an optimal central scale so that it is a good choice all over the phase-space, and not only to compute the total rate or a single distribution. The MINLO approach is specially suited for the matching of fixed-order calculations with parton showers.

In parallel to the automation of NLO calculations, the matching of these to parton showers has also been automated to a good extent. As an illustration, the MADGRAPH5\_AMC@NLO program [48] has recently been made public, which essentially upgrades MADGRAPH5 [49] to the NLO level, including the matching to various parton showers such as PYTHIA8 [50]. Similar features are provided in other frameworks such as POWHEG-BOX [51] and SHERPA [39], which are widely used by the LHC experiments in the analysis of their data.

In order to achieve the best possible description of a realistic final state of LHC collisions, it is required to match samples with different parton level multiplicities. While merging leading-order samples of different multiplicities (matched to parton showers) has been well understood problems for more than a decade, with various prescriptions available, such as CKKW [52] and MLM [53], the extension of this merging procedure

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<sup>(2)</sup> The Les Houches 2013 workshop proceedings, in preparation.

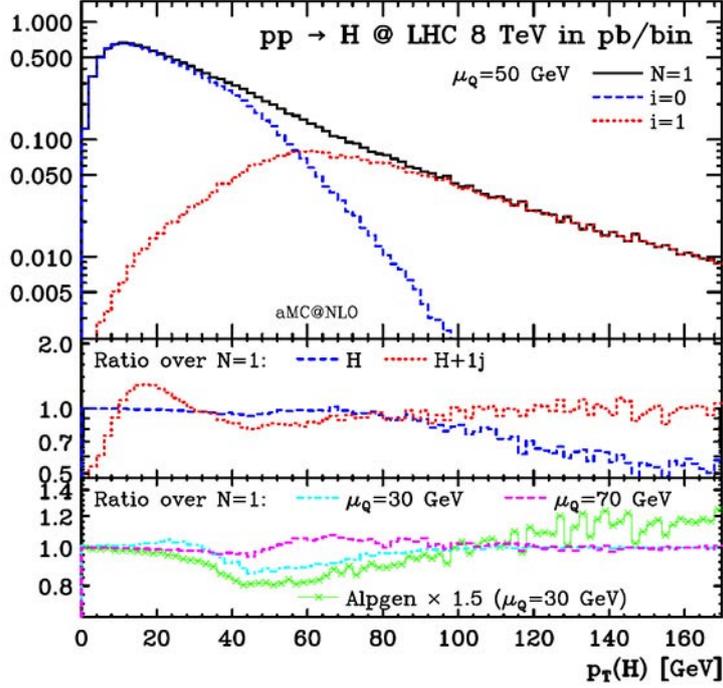


Fig. 1. – Illustration of the NLO merging procedure as implemented in the FxFx approach in Higgs plus jet production, from ref. [54].

at NLO was much more challenging. Recently, several approaches has been proposed for this combination of matching and merging, including FxFx [54], MEPS@NLO [55] and UNLOPS [56]. These tools are important in that they allow to carry out LHC phenomenology at the NLO level for all exclusive processes of relevance. As an illustration of the advantages of NLO merging, in fig. 1 I show the results of the NLO merging procedure in the FxFx approach for Higgs production in gluon fusion in association with one extra jet, from ref. [54].

At the level of precision that QCD calculations are achieving, it is becoming more pressing to also include electroweak corrections to a variety of LHC processes. Since purely weak corrections are enhanced by double logarithms of the type  $\alpha_W \log^2 s/M_W^2$ , the effect of these corrections becomes more important at the upcoming 13 TeV run of the LHC. A comprehensive summary of the status of NLO weak calculations at hadron colliders has been presented in ref. [57] in the context of the Snowmass studies. With a similar motivation, the possibility of including weak corrections in the parton shower [58], as well as in the evolution of parton distributions [59], is also being studied.

#### 4. – The NNLO revolution

While NLO is the first order for which theory uncertainties in QCD calculations are at the 10–20% level, NNLO corrections are essential to get down to the percent level and match the experimental accuracy of many LHC observables. Until recently, only few QCD processes were available at NNLO in a fully differential way, and these were restricted

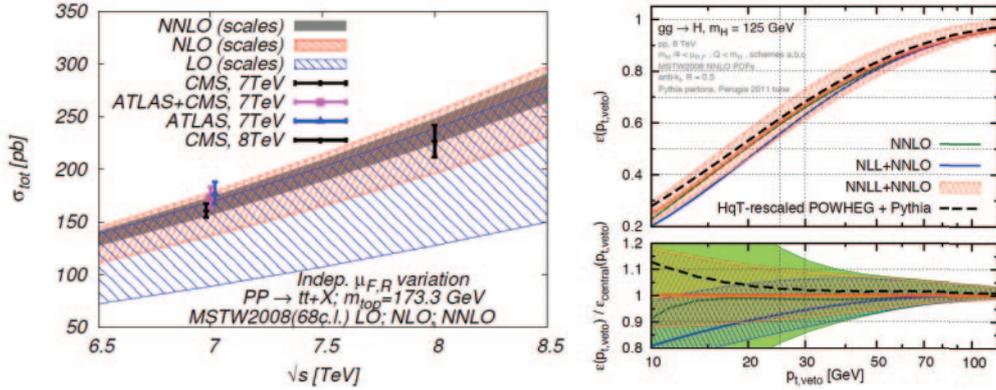


Fig. 2. – Left plot: the NNLO calculation of  $\sigma(t\bar{t})$  as a function of the collider center-of-mass energy. Right plot: resummed calculation for the jet veto efficiency  $gg \rightarrow H$ , from [67].

to processes with either colorless initial or final state: for hadron-hadron collisions, these included Higgs production in gluon fusion, inclusive vector boson production and di-photon production.

However, the development of new calculational techniques, such as Antenna Subtraction [60] and Sector-Improved decomposition [61,62], lead in 2013 to a breakthrough in NNLO QCD calculations, and in particular for the first time it has become possible to compute NNLO corrections for processes with both colored initial and final states. These landmark NNLO results include the fully differential distributions for the gluon-gluon initial state in dijet production [63] and for Higgs production in association with one jet [64], as well as the total cross-section for top quark pair production [65], where in this latter case the differential distributions should follow soon. These results are an important milestone towards a new level of precision for LHC phenomenology, for instance allowing to include consistently for the first time jet and top pair production data into global NNLO fits, and using the NNLO  $H + j$  calculation to reduce the theoretical uncertainties in the determination of Higgs couplings. As an illustration of the reduction in theory uncertainties in NNLO calculations, in fig. 2, taken from [66], I show the predictions for the  $t\bar{t}$  cross-section as a function of the collider center-of-mass energy.

Thanks to the improvement in calculational techniques discussed above, more NNLO results are expected in the near future. At this point, the ultimate accuracy frontier for the QCD description of LHC processes would be the matching of these NNLO calculations with parton showers, in order to achieve the most precise theory description of exclusive LHC final states. This challenging problem has already seen encouraging progress with different approaches aiming to establish NNLO+PS as the next frontier of QCD calculations. Two of these approaches are the one of the GENEVA group, based on soft-collinear effective theory [68], and the other is based on generalizing the MINLO approach to higher orders [69].

## 5. – Jet physics and jet substructure

Jets are ubiquitous in hadronic collisions [70], an essential tool for virtually all LHC analysis, from SM measurements and Higgs physics to BSM searches. The current

paradigm for jet reconstruction at the LHC is based on the use of the anti- $k_T$  algorithm [71] with jet radius  $R$  in a range between 0.4 and 0.7. Virtually all relevant jet algorithms and jet reconstruction tools, from the most basic to the more advanced, are available through the FASTJET framework [72], either part of the core code or as part of the FASTJET CONTRIB project<sup>(3)</sup>.

Recently, substantial effort has been devoted to the understanding of the theoretical uncertainties that arise in perturbative calculations which involve the presence of jet vetoes. This is particularly important for Higgs analysis where events are classified in bins of different jet multiplicity, with the motivation to disentangle the different production channels, such as gluon-fusion from vector-boson-fusion. In this context, various resummed calculations have been proposed [67, 73, 74], which allow to reduce perturbative uncertainties in the jet veto efficiencies, both for the  $H + 0$  jet and the  $H + 1$  jet processes. As an illustration, in fig. 2 I show the results for the resummed calculation for the jet veto efficiency in  $gg \rightarrow H$ , taken from ref. [67].

Another area that has witnessed intense activity recently is that of jet substructure. In the decays of boosted resonances, either SM particles like  $W$  or top quarks [75], the Higgs boson [76], or for heavy new particles present in many BSM scenarios, the decay prongs are often collimated into a single jet, and jet substructure techniques can be used to discriminate these *fat* jets with respect to the standard QCD jets. With this motivation, a variety of jet substructure tools has been proposed to sharpen interesting signals and at the same time tame the overwhelming QCD backgrounds. Detailed reviews of the developments in this area can be found in the proceedings of the BOOST series of workshops [77, 78]. A related interesting issue is the matching of the resolved and boosted regime into a unified analysis strategy, see ref. [79] for a proposal to address this problem.

However, I should emphasize that it is crucial to avoid using blindly these tools. Indeed, it is essential to back them not only with Monte Carlo studies but also with analytical calculations, such as the recent studies of ref. [80]. Thanks to these analytical insights, further-improved jet taggers and groomers can be obtained, and their results trusted with higher confidence. In addition, in parallel with theoretical and computational developments, the validation of the various substructure tools on real LHC data is an essential prerequisite before they can be safely applied to searches of new physics in boosted final states.

## 6. – Outlook

It should be clear from the above discussion that the recent progress in perturbative QCD has been impressive, and that even better results are being prepared for the years to come. These include parton distributions based only on collider data and including NNLO QCD and NLO electroweak corrections, the maturity of the NLO merging approaches, a wider range of NNLO calculations and their matching to parton showers, and the quantitative improvement of jet substructure taggers and groomers, among many others. All these developments will lead to a new generation of precision for our study of LHC processes and the exploration of the laws of Nature at the energy frontier.

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<sup>(3)</sup> <http://fastjet.hepforge.org/contrib/>

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