Quantum Chromodynamics and Collider Processes

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Abstract

These lectures notes on quantum chromodynamics aim at reviewing the status of today’s theoretical description of Standard Model processes relevant for Tevatron and Large Hadron Collider analyses, and of the tools that are used in phenomenological studies. A few recent ideas to further refine our abilities to perform technically challenging calculations are also presented.

1 Introduction

Quantum chromodynamics (QCD) is our well-established theory of strong interactions. It is not imaginable to discuss confirming the presence or absence of a Standard Model (SM) Higgs boson, or to discuss the discovery of new physics at the Large Hadron Collider (LHC) without the solid understanding of QCD that we have today. At high energies, QCD is perturbative. This is a key property that allows us to make accurate calculations for collider processes. In this write-up I will focus on the last lectures given at the School, and I will review the status of today’s theoretical description of SM processes relevant for Tevatron and LHC analyses, and of the tools that are used in phenomenological studies. I will also discuss a few recent ideas to further refine our abilities to perform technically challenging calculations. Many phenomenological results have been updated compared to those presented at the lectures in order to take into account the very fast progress in theoretical QCD calculations, as well as in experimental measurements.

I will not, in these lectures, review the material covered in the first two lectures. This is because, besides classic textbooks about QCD at colliders [1–3], there are already several excellent write-ups of lectures that provide students with an introduction to some of the core concepts and methods of QCD that are relevant in the LHC context [4–7]. I hope, nevertheless, that students will find this write-up useful in understanding what is the status of QCD, and what are the main issues that experts in the field face today.

2 Motivation

Today we face many fundamental questions, some of which are driven by experimental data, such as the question about the mechanism of electroweak (EW) symmetry breaking, the nature of dark matter, and the physics associated with the vacuum energy, as well as questions that are driven by theoretical curiosity and ambition, which are in essence propelled by our hope that there is an elegant structure behind what we observe in Nature. Questions of the latter type include why there are three generations, what causes the hierarchy of fermion masses and mixing, and how the strong CP problem is resolved. While questions of the first type do have a definite answer, this is not necessarily the case for the questions of the second type. From this point of view, some of these questions might not even be the right ones to ask. With the start of the LHC, we feel that we are on the verge of big changes, the depth of which we cannot assess yet. Indeed, the LHC marks the start of a long research programme, and experiments at the LHC are expected to revolutionize our understanding of the fundamental forces and matter. The LHC will definitely explore the origin of mass and the associated nature of EW symmetry breaking. In the course of this, it might also shed light on the nature of dark matter and the origin of the matter–antimatter asymmetry. It may also explore the physics that underlies the evolution of the early Universe. While it is clear that the LHC will not answer all the fundamental questions that we have, the questions we ask now will most likely change after the LHC era. It is therefore really a great and unique time to be a particle physicist.
Since the beginning of its run in 2010, the LHC has been remarkably successful. The ATLAS and CMS experiments collected around 45 pb$^{-1}$ in 2010, more than 1 fb$^{-1}$ by the time of summer conferences, and more than 5 fb$^{-1}$ by the end of the year. At the end of the 2011 run, almost every week has set a new record in instantaneous luminosity. With the 2010 and early 2011 data, remarkably, all major SM processes have already been re-established, including single-top and diboson production, challenging measurements (because of the small/large cross-sections/backgrounds) that have been performed at the Tevatron only in recent years. We have now entered new territory in the search for physics “Beyond the Standard Model” (BSM) with sensitivities already well exceeding those of the Large Electron–Positron Collider (LEP) and the Tevatron.

One important question then concerns the role of QCD for LHC measurements and the search for new physics. Understanding how QCD works is essential in order to make accurate predictions for both the signal and background processes. This typically requires complex calculations to higher orders in the perturbative expansion of the coupling constant. Understanding QCD dynamics can, however, also help to reduce backgrounds and sharpen the structure of the signal. This can, for instance, be achieved by designing better observables, by employing appropriate jet algorithms, by using jet substructure, or by exploiting properties of boosted kinematics. Finally, once discovery is made, QCD will be crucial to extract the properties (masses, spins and couplings) of the new states found. Therefore, at the LHC, no matter what physics you do, QCD will be part of your life.

![Fig. 1: The dijet invariant mass distribution for W plus dijet events as measured by the Collider Detector at Fermilab (CDF). (a) The fits for known processes only. (b) By subtraction, the resonant contribution to $m_{jj}$ including WW and WZ production and a hypothesized narrow Gaussian contribution. Figures taken from Ref. [8].](image)

It is interesting first to recall a recent measurement that was the origin of considerable excitement. In April 2011, CDF reported the observation of a peak in the $m_{jj}$ distribution in W + dijet events [8] (see Fig. 1). The first measurement had a 3.2σ significance, and was based on 4.3 fb$^{-1}$. Subsequently, more data (7.3 fb$^{-1}$) have been analysed, leading to a significance of more than 4σ [9]. Since then, a large number of tentative new-physics explanations have appeared on the arXiv, along with a few SM analyses that address the question of whether this effect can be attributed to a mismodelling of one of the SM backgrounds (in particular single top) [10–12]. The excitement was curbed a few months afterwards, when in June, the DZero experiment (D0) announced that it did not confirm the excess seen by CDF [13]. It is as yet unclear as to what the reasons for the discrepancy between the CDF and D0 findings are, if any. However, this example demonstrates that, even in the case where one identifies a mass peak in the tail of a distribution (a scenario that was considered “an easy discovery”), a robust control of SM backgrounds remains mandatory, in particular when the shape of the backgrounds is one of the issues. Currently, we have a number of other recent measurements at collider experiments that report a few-
sigma deviations from the SM predictions. This is, for instance, the case for the top forward–backward asymmetry measured by both CDF [14] and D0 [15], for the dimuon charge asymmetry measured by D0 [16], for $W^+ b$ measured by D0 [17], CP-violation in time-integrated $D^0$ decays [18], and a few more.

The important question then becomes what the tools are at our disposal to make precise predictions, and whether we have the solid control of signal and background processes that is needed in order to claim discoveries. In this write-up I will discuss the status of our theoretical knowledge of the most important SM processes, the tools at our disposal to describe these processes, and the impact of QCD higher orders in view of recent Tevatron/LHC results. Finally, I will discuss a few recent ideas to further improve on the way we perform technically challenging calculations.

3 Perturbative tools

The range of physics analyses that one can do at the LHC is very broad. It includes pure instrumental QCD studies, such as measurements of parton densities and inclusive jet cross-section measurements, precision EW measurements, Higgs searches, direct and indirect BSM searches, B physics, top physics, diffractive studies and forward physics, and heavy-ion physics. Each of these topics includes a vast number of measurements and studies. Yet, there are three things that everybody involved in any of these analyses cannot live without: Monte Carlos (MCs), parton distribution functions (PDFs) and jets.

3.1 Monte Carlos and leading-order matrix elements

The first thing one cannot live without at the LHC are MC generators. Apart from very few exceptions, every analysis at the LHC uses an MC program for the simulation of the signal process, for the backgrounds, for subtracting the underlying event and the non-perturbative contributions, and/or for efficiency studies and modelling of the detector response. The current level of sophistication is such that essentially not a single study relies on Pythia/Herwig alone. It is well understood that in multiparton processes it is important to describe the multiple hard QCD radiation at least using exact matrix elements, employing for instance A1pgen [19], Madgraph [20], or Sherpa [21].

Since experimental studies rely heavily on all these leading-order (LO) tools, there has been continual progress in their development, and the Herwig/Pythia codes that we have today bear little resemblance to their original version of the 1980s. In particular, in Pythia 8.1 [22] (a C++ code), there is a new fully interleaved $p_T$-ordered multiparton interaction (MPI), initial- and final-state evolution (the original mass-ordered evolution is not supported any longer), a richer mix of underlying event processes ($\gamma$, $J/\Psi$, DY), the possibility to select two hard interactions in the same event, an $x$-dependent proton size in the MPI framework, the full hadron–hadron machinery for diffractive systems, several new processes in and beyond the SM, and various other new features. Herwig++ [23] (the current version is 2.5.2) has new next-to-leading-order (NLO) matrix elements, including weak boson pair production, a colour reconnection model, diffractive processes, additional models of BSM physics, and new LO elements for hadron–hadron, lepton–lepton collisions, and photon-initiated processes. Sherpa [21] (version 1.3.1) has improved integration routines in Comix, a simplified kinematics reconstruction algorithm of the parton shower (PS), leading to numerically more stable simulations, HepMC output for NLO events, and various other improvements/bug fixes. Madgraph [20] (version 5) has a completely new diagram generation algorithm, which makes optimal use of model-independent information, has an efficient decay-chain package, and a new library for the colour calculations. Some applications from ALOHA [24], an automatic library of helicity amplitudes for Feynman diagram computations, are also implemented. Altogether, there has been continuous, rapid progress in various directions. So far, it is amazing how well these tools work, once the normalization is fixed using data. A very recent comparison of data with A1pgen for up to six jets (a control region for BSM searches) is shown as an illustration in Fig. 2 [25]. Yet, the devil is often in the detail (i.e. in the $\sim 20$–$30\%$ effects that are opposite to expectations). For instance, in
general, one expects matrix-element-based MCs to work better than pure PSs, but this is not always the case (see e.g. Ref. [26]). Altogether, these LO programs will undergo a real stress test in the coming years.

### 3.2 The next-to-leading-order revolution

Theorists like to advertise NLO computations by using the reduction of scale uncertainties in the predictions as an argument, which is meant to reflect the reduction in the theoretical perturbative uncertainty. However, the strongest argument in support of NLO calculations is their past success in accurately describing LEP and Tevatron data. Because of the importance of NLO corrections, an industrial effort has been devoted in the past years to these computations [27]. Recent revolutionary ideas in the way NLO computations are performed include sewing together tree-level amplitudes to compute loop amplitudes (using on-shell intermediate states, cuts, unitarity ideas, ... ) [28], the OPP algorithm (after Ossola–Papadopoulos–Pittau), an algebraic way to extract coefficients of master integrals by evaluating the amplitudes at specific values of the loop momentum [29], and $D$-dimensional unitarity, a practical numerical tool to evaluate full amplitudes, including the rational part, with unitarity ideas [30]. For a pedagogical review on unitarity methods, see Ref. [31]. These methods have led in the past two to three years to a number of $2 \rightarrow 4$ calculations at hadron colliders. These include $W + 3$ jets [32, 33], $Z + 3$ jets [34], $t\bar{t}b\bar{b}$ [35], $t\bar{t} \rightarrow W^+W^-b\bar{b}$ [36], $W^+W^- + 2$ jets [37], $W^+W^- + 2$ jets [38], $t\bar{t} + 2$ jets [39], four-jet production [40], and a few other ones.

Feynman diagram methods have also been applied successfully to $2 \rightarrow 4$ calculations. This is the case, for instance, for quark-induced $b\bar{b}b\bar{b}$ [41], $t\bar{t}b\bar{b}$ [42], $W^+W^−b\bar{b}$ [43] production, and a number of vector boson fusion (VBF) processes, which are available in the public code $\text{VBFNLO}$ [44]. VBF processes have never been measured at the Tevatron. First measurements of VBF $W$ or $Z$ production at the LHC are therefore of particular interest. They also pave the way to measurements of VBF Higgs production. Note that, only a few years ago, performing this type of calculation with Feynman diagrams was considered an impossible task.

A novel approach to NLO calculations promotes traditional tree algorithms to generators of loop-momentum polynomials that are called open loops [45]. The excellent performance of the method has been demonstrated. Open loops therefore have the potential to address a number of multiparticle processes at hadron colliders. Another recent approach evaluates one-loop QCD amplitudes purely numerically [46]. The algorithm consists of subtraction terms, approximating the soft, collinear and ultraviolet divergences of one-loop amplitudes and a method to deform the integration contour for the loop integration into the complex space. The algorithm is formulated at the amplitude level and does not rely on

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**Fig. 2:** The multiplicity of jets with $p_\mathrm{T} > 55$ GeV for events in a $W$-enriched control region at the LHC (7 TeV). Figure taken from Ref. [25].

**Diagram:**
Fig. 3: The transverse momentum distribution of the leading four jets in $W^{-} + 4$ jet production at the LHC (7 TeV) at LO and NLO. The lower panels show the LO and NLO scale-dependence bands ($\hat{H}'/4 \leq \mu_R = \mu_F \leq \hat{H}'$) normalized to the central NLO prediction ($\mu_R = \mu_F = \hat{H}'/2$). Figure taken from Ref. [48].

Feynman graphs. The power of this method has been demonstrated recently with the calculation of up to seven jets in $e^+e^-$ collisions [47].

Given that both Feynman diagram and unitarity-based methods allow us to compute $2 \to 4$ processes at NLO in QCD, it might be unclear where the revolution advocated in the heading of the subsection lies. The revolution, I believe, is not yet in the applications that we see today, rather in the prospect for low-cost fully computer-automated NLO calculations even beyond $2 \to 4$ in the near future. Indeed, two $2 \to 5$ processes have already been computed at NLO, namely $W + 4$ jets [48] and $Z + 4$ jets [49]. Figure 3 illustrates in the case of $W^{-} + 4$ jets the typical effect of including NLO corrections: one obtains a considerable reduction of the scale uncertainty, and, for some distributions, a change in shape. As far as the full automation is concerned, let me highlight three interesting approaches. The first one [50] is a method based on Feynman diagrams, which uses the OPP procedure for the virtual calculation, and the FKS (after Frixione–Kunszt–Signer) subtraction of divergences, together with clever and efficient procedures to deal with instabilities. More improvements and refinements are to be expected soon. At present there is no public code; instead, the idea is to provide $N$-tuples. The second approach, HELAC-1L00P [51], is a program that evaluates numerically QCD virtual corrections to scattering amplitudes using the OPP method. The public program is part of the HELAC-NLO framework that allows for a complete evaluation of QCD NLO corrections. GoSam [52] is a third approach, which aims at the full automated calculation of NLO corrections for multiparticle processes. The one-loop amplitudes are generated using Feynman diagrams and are reduced using $D$-dimensional unitarity, a refined Passarino–Veltman style tensor reduction, or a combination of both. GoSam can be used to calculate one-loop corrections to both QCD and electroweak theory, and model files for BSM theories can also be linked. An interface to programs calculating real radiation is included too. The flexibility of GoSam has been demonstrated explicitly by considering various examples.

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1In both cases the leading colour approximation has been used. This approximation is expected to give rise to very small (percentage) corrections only.
Fig. 4: (left) Invariant mass of the pair of the two leading b jets for Wb\bar{b}, Zb\bar{b}, WH (→ ℓνb\bar{b}) and ZH (→ ℓ+ℓ−b\bar{b}) at the LHC (7 TeV), the latter two being rescaled by a factor of 10. Figure taken from Ref. [56]. (right) Invariant mass of the pair of the two hardest jets in W + jet events with CDF/D0 inclusive cuts. Figure taken from Ref. [57].

3.3 Merging next-to-leading-order and parton showers

While NLO predictions provide relatively accurate results for inclusive cross-sections, they do not furnish an exclusive description of the final state that can be compared with actual particles in the detectors, as MC programs do. It is therefore useful to combine the best features of both approaches. Two public frameworks exist for this purpose, namely \texttt{MC@NLO} [53] and \texttt{POWHEG} [54]. These tools are almost 10 years old now, and, since their conception, a long list of processes has been implemented in both frameworks. In particular, recently the \texttt{POWHEG BOX} was released [55], which is a general framework for implementing NLO calculations in shower MC programs according to the \texttt{POWHEG} method. The user only needs to provide a simple set of routines (Born, colour-correlated Born, virtual, real and phase space) that are part of any NLO calculation.

Similarly, \texttt{aMC@NLO} is a novel approach to a complete event generation at NLO. Recently \texttt{aMC@NLO} has been used for the calculation of W/Zb\bar{b} [56] and W + dijet production [57]. Figure 4(left) shows an application to Higgs searches of the W/Zb\bar{b} calculation: the invariant mass of the pair of the two leading b jets, for the processes Wb\bar{b}, Zb\bar{b}, WH and ZH. The figure illustrates a case where signals and irreducible backgrounds are computed with the same accuracy. The process Wb\bar{b} has been implemented shortly before also in the \texttt{POWHEG BOX} [58].

Figure 4(right) illustrates predictions from \texttt{aMC@NLO} for the invariant mass for the dijet system in Wjj (the observable mentioned in the introduction where CDF observed a large deviation from the SM). CDF and D0 estimate the Wjj using a leading-order Monte Carlo (LO + PS) reweighted to the NLO cross-section or to data. With \texttt{aMC@NLO} instead, it is possible to compute directly the Wjj cross-section at the NLO + PS level. It was therefore particularly interesting to check whether there is any shape difference between LO + PS and NLO + PS in the $M_{jj}$ distribution. The study of Ref. [57] shows that there is no sizeable shape difference. Another interesting application of \texttt{aMC@NLO} is the calculation of scalar and pseudo-scalar Higgs production in association with a t\bar{t} pair [59].

A lot of effort has been devoted recently also to the implementation of higher-multiplicity processes in the \texttt{POWHEG BOX} and in \texttt{aMC@NLO}. The first 2 → 4 process that has been implemented in the \texttt{POWHEG BOX} is pp → W+W+ + 2 jets including both the QCD induced part [60] as well as the VBF contributions [61]. This is a relatively simple 2 → 4 process since the cross-section is finite without any cut on the jets. As expected, for inclusive observables, there are only minor differences between pure NLO and \texttt{POWHEG + PS}; but for exclusive observables, depending on the details of the observable definition, there can be important differences. This is shown in Fig. 5 for two different definitions of...
**Fig. 5:** Comparison of NLO and POWHEG + PYTHIA results for the $H_{t,tot}$ distribution in the process $W^+W^+ + 2$ jets at the LHC (7 TeV), when all jets are included in the definition of $H_{t,tot}$ (left panels), and when only the three hardest jets are included (right panels). Figure taken from Ref. [60].

$H_{t,tot} = \sum_j p_{t,j}$, the transverse energy of the event. From the figure it is clear that, if only the three hardest jets are included in the definition of $H_t$, the corrections from the PS are very moderate (right panels), but if all soft jets present in the event are included, then additional radiation from the PS can alter the distribution substantially (left panels). The POWHEG method has been used recently also for the description of other important processes, e.g. for the calculation of $Z$ boson in association with a top–antitop pair at NLO accuracy including PS effects [62].

### 3.4 MENLOPS and LoopSim

**MENLOPS** [63,64] is a method to further improve on NLO + PS predictions with matrix elements involving more partons in the final state. For example, for $W$ production it includes, as in MC@NLO or POWHEG, $W$ production at NLO, the PS, but also $W + 1, 2, 3, \ldots$ jets using exact matrix elements. Roughly speaking, it uses a jet algorithm to define two different regimes, and then corrects the one-jet fraction using exact matrix elements and the two-jet fraction using the NLO $K$-factor. This achieves NLO-quality accuracy for inclusive quantities but an improved sensitivity to hard radiation and multiparton kinematic features.

A further recent theoretical development is LoopSim. If one considers the process $W + 1$ jet, the three observables $p_{t,Z}$, $p_{t,j}$ and $H_{t,jets} = \sum_j p_{t,j}$ are identical at LO. However, as illustrated in Fig. 6, at NLO $p_{t,Z}$ has a moderate $K$-factor ($\lesssim 2$), $p_{t,j}$ has a large $K$-factor ($\sim 5$) and $H_{t,jets}$ has a giant $K$-factor ($\sim 50$). The very large $K$-factors in the last two observables are due to the fact that the NLO result is dominated by configurations where there are two hard jets and a soft $W$ (these are enhanced by EW logarithms). Additionally, there is an important enhancement coming from incoming $q\bar{q}$ channels. LoopSim [65] is a procedure that uses a sequential algorithm, close to the Cambridge–Aachen one, to determine the branching history, “loops” over soft particles (i.e. they are removed from the event and the residual event is adjusted), and uses a unitary operator to cancel divergences. In essence, this is a
The top is the most interesting SM quark. Its large mass implies a large Yukawa coupling, which causes the top to be a prominent decay product in many BSM models. LHC data have already been successfully compared to approximate next-to-next-to-leading-order (NNLO) predictions [66, 67]. However, various approximate NNLO predictions, based on a threshold resummation, do not fully agree within quoted uncertainties [68–72]. Significant improvements in the $t\bar{t}$ cross-sections can be expected only upon inclusion of the complete NNLO corrections. A better perturbative control of the top-quark pair production cross-section is also important to further constrain gluon PDFs, to have an accurate extraction of the top mass from the cross-section, and to improve our perturbative control over the $t\bar{t}$ forward–backward asymmetry. In fact, an almost $3\sigma$ deviation from the SM is observed by CDF, which becomes a $4.2\sigma$ effect in the high-mass region, $M_{t\bar{t}} > 450$ GeV [14]. The large inclusive asymmetry has been seen by both CDF and D0 [15], while the rise in the spectrum of the asymmetry is not confirmed by D0. However, one has to bear in mind that $t\bar{t}$ production is a difficult measurement given the presence of neutrinos in the final state, the combinatorics in the reconstruction of the tops, and the limited statistics at the Tevatron. Nevertheless, various suggestions have been made recently to explain the asymmetry in terms of BSM physics, but all proposals face the problem that they have to preserve the good agreement with the symmetric $t\bar{t}$ observables, must respect dijet bounds and/or must evade the stringent limits on like-sign top production. Fervid activity is therefore currently devoted towards a complete NNLO calculation of $t\bar{t}$ production (see Ref. [73] and references therein). Recently, the program Top++ was released that evaluates numerically the total inclusive cross-section for producing top-quark pairs at hadron colliders. It calculates the cross-section at fixed order through approximate NNLO and it includes a soft-gluon resummation in Mellin space at next-to-next-to-leading logarithmic accuracy [74]. The program Hathor [75] also calculates the total cross-section for top-quark pair production in hadronic collisions. It includes approximate next-to-next-to-leading-order perturbative QCD corrections. It also offers the possibility to obtain the cross-section as a function of the running top-quark mass. A direct compari-

![Fig. 6: The LO and NLO distributions for three observables in $Z +$ jet production that are identical at LO: the $Z$ transverse momentum (left), the $p_\perp$ of the hardest jet (middle), and the scalar sum of the transverse momenta of all the jets, $H_{T,jets}$ (right). The bands correspond to the uncertainty from a simultaneous variation of $\mu = \mu_R = \mu_F$ by a factor of 2 around the default $\mu = \sqrt{p^2_{T,j1} + m_Z^2}$. Figure taken from Ref. [65].](image-url)
son between the two programs is, however, not possible, as they use a different subleading terms in the threshold expansion.

Besides the inclusive cross-section, top pair production in association with light jets, heavy partons, photons or heavy vector bosons is also interesting. We know now at NLO $t\bar{t} + 2$ jets [39], $t\bar{t}b\bar{b}$ [35, 42], $t\bar{t}Z$ [76], $t\bar{t} + \gamma$ [77], and $t\bar{t} + 1$ jet including hard jet radiation by the top-quark decay products [78]. The NLO calculations of single top in the $s$ and $t$ channel [79, 80] and in the $Wt$ channel [81, 82] have also been matched to parton showers. For a discussion of recent theoretical progress in single-top physics at hadron colliders, and of aspects of single-top production in BSM scenarios, I refer the reader to Ref. [83].

5 A few theoretical issues in Higgs production

Possibly the most-awaited result during the first year of running of the LHC concerned Higgs searches. Currently, both ATLAS and CMS have reached the expected sensitivity, around or better than the SM cross-section. ATLAS restricted the most likely mass range at 95% confidence level (CL) to the region 115.5–131 GeV. They observe an excess around 124 GeV, with a local significance of $3.6\sigma$, with contributions from the main channels $H \rightarrow \tau\tau$, $H \rightarrow ZZ \rightarrow 4\ell$, $H \rightarrow WW \rightarrow 2\ell 2\nu$. The global significance taking into account the look-elsewhere-effect is $2.3\sigma$. CMS excludes the region 127–600 GeV at 95% CL (while their expected exclusion is 117–543 GeV). They could not exclude the region below 127 GeV since the data have a modest excess of events between 115 and 127 GeV that appear, quite consistently, in five independent channels. The excess is compatible with an SM Higgs hypothesis in the vicinity of 124 GeV or slightly below, but the statistical significance, $2.6\sigma$ local and $1.9\sigma$ global after correcting for the look-elsewhere-effect in the low-mass region, is not large enough to say anything conclusive. For both experiments, what is observed now is consistent either with a background fluctuation or with an SM Higgs boson. More refined analyses and additional data in 2012 will definitely give an answer.

At the LHC, the Higgs is mainly produced via an intermediate top loop in gluon–gluon fusion. The urge to understand the EW symmetry breaking has led in the past years to the computation of the most advanced theoretical predictions for this process. For instance, we now know the main $gg \rightarrow H$ production mechanism including NLO corrections with exact top and bottom quarks in the loop [84], NNLO corrections in the large-$m_t$ limit [85–87], EW corrections [88], mixed QCD–EW corrections [89], and resummation of large logarithms possibly with $N^{3}\text{LO}$ soft effects [90–93]. Furthermore, the most advanced codes [94, 95] allow for fully exclusive decays of the Higgs to $\gamma\gamma$, $W^+W^- \rightarrow e^+\nu e^-\bar{\nu}$ and $ZZ \rightarrow 4\ell$. A similar accuracy has been reached recently also in associated VH production where, because this process is an important one if the Higgs is light, the decay of the Higgs into $b\bar{b}$ has been considered [96]. NLO EW corrections to WH/ZH production including the vector-boson decays are also known [97]. As expected, the EW corrections, which are at the level of 5–10% for total cross-sections, increase with increasing transverse momentum cuts. For instance, for $p_{t,H} > 200$ GeV, which is an interesting range at the LHC, the EW corrections to WH production are of the order of $-15\%$ for $M_H = 120$ GeV.

The fully differential decay of a light Higgs boson to bottom quarks at NNLO in perturbative QCD has been computed recently in Ref. [98]. From a technical point of view, it is interesting to note that this work constitutes the first physical application of a novel method of nonlinear mappings for the treatment of singularities in the radiative processes that contribute to the decay width. The program $iHixs$ [99] has also been released recently. It computes the inclusive Higgs boson cross-section, including QCD corrections through NNLO, EW corrections, mixed QCD–electroweak corrections [89], quark-mass effects through NLO in QCD, and finite width effects for the Higgs boson and the heavy quarks. Furthermore, it allows the evaluation of the cross-section in modified Higgs boson sectors with anomalous Yukawa and EW interactions as appearing in some extensions of the SM [99, 100].

Given the high accuracy with which gluon–gluon fusion has been computed, it is interesting to ask
Fig. 7: Multiplicity of jets with $p_t > 25$ GeV after basic Higgs search cuts. The lower part shows the ratio between the data and the background expectation from MC, with the yellow band indicating the total systematic uncertainty in the normalization (but not the shape) of the various components. The signal is shown for $m_H = 150$ GeV. Figure taken from Ref. [104].

what is the actual theoretical uncertainty on this process. Unfortunately, at present, there is no full consensus on this question. Some more conservative estimates quote errors of the order of 40% [101] (at the Tevatron) and similar uncertainties at the LHC, while other studies suggest that the perturbative uncertainty is considerably smaller. Assigning a correct theoretical error is very important when claiming an exclusion or an excess, and, at a later stage, when making measurements of the Higgs-boson couplings, which is the only way to identify the precise nature of the Higgs boson and EW symmetry breaking. Yet, even for the main Higgs production channel there are still some controversies and subtleties. Most controversies have to do with how different sources of error should be combined; others concern the question of how to assign/interpret the perturbative uncertainties. I will illustrate here just two of these issues.

The soft logarithms appearing in cross-sections can be resummed using an effective theory approach. Performing such a calculation requires an introduction of a matching scale, where the full and effective theory amplitudes must agree. It is well known that choosing a time-like (i.e. complex) matching scale effectively resums $\pi^2$ enhanced terms. In Ref. [102] it is suggested that this procedure improves the convergence of the perturbative expansion significantly, and reduces the uncertainty of the perturbative (NNLO) prediction. This approach is criticized in Ref. [103], with the arguments that $\pi^2$ are just numbers, so that there is no formal limit in which they dominate, and that only one class of $\pi^2$ terms is resummed (those that arise from the gluon form factor), but not all of them. In this context, one has to mention that perturbative QCD is often about pushing approximations beyond their formal limit of validity, and that a given approach should be judged by seeing how well it fares in practice.

The second issue I would like to mention here has to do with a jet veto in Higgs searches. As can be seen from Fig. 7, in Higgs searches one needs to impose a jet veto to suppress the large top background. Higgs production is then studied in zero-, one- and two-jet bins separately in order to maximize the sensitivity. Currently, ATLAS uses $p_{t,\text{veto}} = 25$ GeV, while CMS employs $p_{t,\text{veto}} = 30$ GeV in their Higgs searches.

In Ref. [105] the inclusive, NNLO Higgs production cross-section at the Tevatron is split into
zero-, one-jet exclusive, and two-jet inclusive components:

\[
\frac{d\sigma_{\text{tot}}}{\sigma_{\text{tot}}} = 66.5\%^{+5\%}_{-9\%} (0\text{-jet}) + 28.6\%^{+24\%}_{-22\%} (1\text{-jet}) + 4.9\%^{+78\%}_{-41\%} (\geq 2\text{-jets}) = [-14.3\% + 14.0\%].
\]  

(1)

The errors denote the scale uncertainty that is obtained by varying the renormalization and the factorization scale together around a central value \( m_H = 160 \text{ GeV} \) by a factor of 2. In an NNLO calculation of inclusive Higgs production, only the zero-jet bin is known at NNLO, while the one-jet bin is known at NLO and the two-jet bin is computed at LO only. Therefore, it is not surprising that the relative errors increase with the number of jets. In Ref. [105] one can also find a detailed discussion of why it is not appropriate to use the standard scale variation as an estimate of the perturbative uncertainty for the zero-jet bin cross-section. (Figure 1 of Ref. [106] also shows that for a particular choice of \( p_{t,\text{veto}} \) one obtains a vanishing scale uncertainty band in the zero-jet bin.) The numbers in Eq. (1) were updated by Campbell et al. in Ref. [107] who evaluated the two-jet bin contribution at NLO. The effect of this addition was a slight change in all relative numbers, and, mainly, a decrease in the perturbative uncertainty of the two-jet bin,

\[
\frac{d\sigma_{\text{tot}}}{\sigma_{\text{tot}}} = 60\%^{+5\%}_{-9\%} (0\text{-jet}) + 29\%^{+24\%}_{-23\%} (1\text{-jet}) + 11\%^{+35\%}_{-31\%} (\geq 2\text{-jets}) = [-15.5\% + 13.8\%].
\]  

(2)

From Eq. (2), it is evident that the scale uncertainty is smaller for the exclusive measurement with zero-jets, than the one of the fully inclusive measurement. To explain this feature, Stewart and Tackmann recall that there are two mechanisms at work in the zero-jet cross-section [108]: there is a large \( K \)-factor from perturbative higher orders, as well as large negative logarithms \(-\alpha_s C_A/\pi \ln^2 M_H/p_{t,\text{veto}}\) that become more important the smaller \( p_{t,\text{veto}} \) is. They therefore suggest that the error on the zero-jet bin should be computed taking into account a full correlation between jet bins, i.e. the error from the zero-jet cross-section is computed from the relation \( \sigma_0 = \sigma_{\text{incl}} - \sigma_{\geq 1\text{-jet}} \). One then obtains simply \( \Delta^2 \sigma_0 = \Delta^2 \sigma_{\text{incl}} + \Delta^2 \sigma_{\geq 1\text{-jet}} \). The effect of this is illustrated in Fig. 8. While this procedure is certainly more conservative than a conventional scale variation, it is clear that, to reduce the uncertainty on the jet veto cross-section, a resummation of large logarithms involving the ratio \( p_{t,\text{veto}}/M_H \) is required. Currently, only resummation for quantities related to the jet veto exist, e.g. for \( p_{t,\text{Higgs}} \) [109] or for the beam thrust [110]. Both observables are, however, not the ones used in current Higgs searches. Furthermore, the beam thrust has the drawback that it receives very large non-perturbative corrections, as can be easily seen by running a PS program once at parton and once at hadron level.

6 Gauge boson production processes

The physics programme involving gauge bosons is particularly rich. The road towards precision measurements and searches starts from the measurement of inclusive \( W \) and \( Z \) cross-sections, which, from a theoretical point of view, are the most precisely known processes at hadron colliders. Beyond measurements of purely inclusive \( W/Z \) production cross-sections, it is possible to study the production of \( W \) or \( Z \) bosons in association with one or more jets, and the ratio of cross-sections. Interesting ratios are, for instance, \( \sigma(V + (n + 1) \text{ jets})/\sigma(V + n \text{ jets}) \), with \( V = W, Z \), that start at \( \mathcal{O}(\alpha_s) \) in the perturbative expansion in the coupling constant, or ratios of \( \sigma(W^{\pm} + n \text{ jets})/\sigma(Z + n \text{ jets}) \), that are of order \( \mathcal{O}(\alpha_s^0) \). In both cases, one expects many experimental and theoretical uncertainties (e.g. those related to the choice of renormalization or factorization scale, or uncertainties in the parton distribution functions) to largely cancel in the ratio. A further extension of simple ratios are asymmetry distributions, for instance, the \( W \) or lepton charge asymmetry. These distributions provide strong constraints on parton distribution functions and are useful probes of new physics. Other interesting observables measure gauge bosons produced in association with heavy quarks (charm or bottom quarks). These processes are particularly interesting because of the discrepancies between theoretical predictions and Tevatron data [17]. However, the perturbative calculation of these processes and of the related theoretical uncertainty is challenging.
Finally, diboson cross-sections are sensitive to any type of new physics that would modify the trilinear gauge couplings, and would give rise to so-called anomalous gauge couplings. These measurements are complementary to the ongoing direct searches for BSM physics, and are able to probe new-physics scales that are not directly accessible.

Figure 9 gives the cross-sections for the main processes involving gauge bosons at the LHC. The figure illustrates that with 1 fb$^{-1}$ ATLAS and CMS could collect $O(10^6)$ and $O(10^5)$ W and Z events per experiment and per lepton channel. One also sees that, including all lepton channels, 1 fb$^{-1}$ of data contain about 100 WW and 10 ZZ events. This means that, even with the data available after a first year of running, a number of interesting analyses could be performed.
6.1 Drell–Yan

The most important gauge boson production process is Drell–Yan. This is the best-known process at the LHC: it has been computed through NNLO in QCD, fully differential in lepton momenta including spin correlations, EW corrections, finite-width effects, and $\gamma^*/Z$ interference. State-of-the-art codes are described in Ref. [112, 113]. Calculations to all orders also exist, for instance, the next-to-next-to-leading-logarithms (NNLL) transverse momentum resummation [114] and soft gluon resummation have been computed [115]. These accurate perturbative calculations have been available for some time, and now that precise LHC data have been compared to those predictions, one cannot but praise the impressive agreement between NNLO theory and experiment (see e.g. Fig. 10 and Ref. [117]). One thing to note is that, in these comparisons of theory with experiment, the dominant error is the theoretical one; however, this is mainly dominated by the luminosity uncertainty (of the order of 4%).

At this level of precision, it is legitimate to start worrying about mixed QCD and EW corrections. QCD + EW interference is formally a higher-order effect, and exact results are not known currently. However, the dominant effects come from emissions in the soft/collinear regions where an approximate factorization holds. It turns out that, in general, mixed corrections are small, $O(0.5\%)$, but they are enhanced in the region of large transverse momenta, where they can reach up to around 5% [118].

6.2 Charge asymmetry

The natural extension of the inclusive cross-section is the $R_W = W^+/W^-$ ratio. One can then study $R_W$ as a function of kinematic variables, e.g. one can look at the charge asymmetry as a function of lepton rapidity $\eta$,

$$A(\eta) = \frac{R_W(\eta) - 1}{R_W(\eta) + 1}.$$  \hspace{1cm} (3)

This measurement is very sensitive to PDFs since, in the ratio, asymmetric properties of PDFs are enhanced, while many uncertainties cancel. Figure 11 shows the relatively good agreement of theoretical predictions that use various PDFs with ATLAS data. It also illustrates how the shape of the theoretical prediction is sensitive to the PDFs chosen. Indeed, ATLAS and CMS measurements of this distribution have already been used by the Neural Network (NN) collaboration to constrain PDFs. In particular, a
Fig. 11: Predictions for the W lepton asymmetry at NLO, obtained with DYNNLO [112] using the CT10 [119], MSTW08 [120] and NNPDF2.1 [121] parton sets, compared to measurements for the muon charge asymmetry from ATLAS [122] (7 TeV). Figure taken from [123].

reduction of uncertainty of the order of 10–30% in the range \( x = [10^{-3}, 10^{-1}] \) was obtained for the valence- and sea-quark distributions. It is interesting to observe that LHCb data at larger rapidities probe larger and smaller values of \( x \) that are currently less constrained. They will therefore soon have a larger impact in PDF determination than ATLAS and CMS have.

6.3 Production of W/Z boson in association with jets

At the LHC, because of the large energy, the production of W and Z bosons in association with jets is very likely. This is illustrated in Fig. 12, which shows the differential distribution for \( H_t \), the total transverse energy of the event, for various jet multiplicities. Since the cross-sections with an additional jet is rescaled in the figure by a factor \( 10^{-1} \) compared to the cross-section with one less jet, it is evident that, at high \( H_t \) (a region of particular interest for various new-physics searches), all jet multiplicities contribute similar amounts.\(^2\) Because of this, it becomes very important to have a good perturbative control of processes involving the production of W/Z bosons together with many jets. The perturbative calculation of processes involving a large number of jets is quite difficult beyond LO. However, as discussed in section 3.2, recent years have seen a revolution in the techniques used for NLO calculations. These novel techniques have allowed, in the past five years, the calculation of a large number of processes involving gauge bosons and jets. In particular, while \( V + 1 \) and \( V + 2 \) jets have been described to NLO in QCD since 1983 [125, 126] and 2002 [127–129], to quote a few examples, we know now at NLO \( VV + 1 \) jet [130, 131, 133, 134], \( W + 3 \) jets [32, 33], \( Z + 3 \) jets [34], \( W^+W^+ \) plus dijets [37] , \( W^+W^- \) plus dijets [38] \( W^+W^-bb \) [36, 43] and \( W + 4 \) jets [48] and \( Z + 4 \) jets [49]. Furthermore, various VBF-induced gauge boson production processes have been computed and are available in the public code VBFNLO [44].

Figure 13 shows the transverse momentum distribution for the four \( p_t \) ordered jets in \( Z + 4 \) jets production. The middle row illustrates the typical reduction of the dependence of the cross-section on renormalization and factorization scale at NLO, compared to LO. However, it is also evident that, while for some distributions (e.g. \( p_{t_{j4}} \)) the ratio of LO/NLO is flat, in other cases the shape of the NLO

\(^2\)Of course, this statement depends on the precise definition of the jets, in particular on their \( p_t \) cut.
distribution is different from the LO one, so that LO/NLO has a non-flat slope. It is also interesting to look at the ratio of $Z/W^+$ and $Z/W^-$ displayed in the lower row. The agreement of LO and NLO predictions for these ratios illustrates the excellent perturbative control that one can achieve at NLO on these ratios. Furthermore, the fact the $Z/W^+$ is flat, while $Z/W^-$ rises with $p_t$ can be attributed to the fact that both $W^+$ and $Z$ production are dominated by the $u$ quark distribution, while $W^-$ is mainly produced from $d$ quarks in the protons. Therefore the $Z/W^-$ ratio displays the slope of the $u/d$ quark distributions as a function of the jet transverse momenta.

6.4 Diboson production and anomalous couplings

The $ZZ$, $WW$ and $WZ$ diboson production processes have been implemented recently in the POWHEG BOX. The calculation includes $\gamma^{\ast}/Z$ interference, single resonant contributions, interference effects for identical fermions and, for $WW$ and $WZ$, the effect of anomalous couplings. The gluon–gluon fusion contribution, that is formally NNLO, but is important when Higgs search cuts are applied, is available from the $gg2WW$ and $gg2ZZ$ generators [135–137], and, recently, also from the program MCFM [138].

A pure NLO calculation, as implemented earlier in MCFM [139, 140], reveals that for these processes the conventional scale variation of the LO result is very modest but underestimates completely the size of the NLO corrections. For example, for $pp \rightarrow W^+W^- \rightarrow e^+\nu_e\mu^-\nu_\mu$ production at the 7 TeV LHC without any cuts, the LO cross-section using NNPDF2.1 [121] is $375.2^{+1.6}_{-3.8}$ fb, while the NLO cross-section is $499.8^{+12}_{-10}$ fb [141]. Here the error denotes the scale uncertainty. Similar results (with smaller
cross-sections) are obtained for the other processes. The reason for the large NLO corrections (not caught by the LO scale variation) is that new partonic channels open up at NLO. It is therefore clear that only an NLO calculation can provide a reliable estimate of the cross-section and of its error. These diboson production processes are particularly interesting since they are important backgrounds to Higgs searches. Furthermore, they are sensitive to new physics at high scales through the measurement of anomalous trilinear gauge couplings (ATGCs). Indeed, while the LHC does probe new physics at the TeV scale directly, ATGCs indirectly probe physics in the multi-TeV range, since they arise when high-energy degrees of freedom are integrated out. Both the Tevatron [142–144] and LEP [145] were able to place quite stringent bounds on ATGCs. However, since their effects are enhanced at high energies, one expects even better bounds from the LHC. Indeed, CMS already presented bounds on the anomalous couplings appearing in an effective Lagrangian with the parametrization of Ref. [146] without form factors [147].

Following Refs. [146, 148, 149], one can parametrize the most general terms for the WWV vertex (V = γ, Z) in a Lagrangian that conserves C and P as

$$\mathcal{L}_{\text{eff}} = ig_{WWV} \left[ g_1^V (W_{\mu\nu}W^{\mu\nu}V^\nu - W_{\mu\nu}W^\nu V^{\mu\nu}) + \kappa^V W_{\mu\nu}W^\nu V^{\mu\nu} + \frac{\lambda^V}{M_W^2} W_{\mu\nu}W^{\mu\nu}V^{\rho\nu} \right],$$  \hspace{1cm} (4)

where $W_{\mu\nu} = \partial_{\mu}W_{\nu} - \partial_{\nu}W_{\mu}$, $g_{WWZ} = -e \cot \theta_W$ and $g_{WW\gamma} = -e$. In the SM, $g_1^V = \kappa_1^V = 1$, and $\lambda^V = 0$. Any departure from these values ($\Delta g_1^V = g_1^V - 1$, etc.) would be a sign of new physics. In the \textsc{Powheg} generator, all six parameters can be set independently.

In the presence of anomalous couplings, the effective Lagrangian of Eq. (4) gives rise to interactions that violate unitarity at high energy. Thus, in order to achieve a more realistic parametrization, the couplings are multiplied by form factors that embody the effects arising from integrating out the new

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Fig. 13: Transverse momentum distributions of the leading four jets in Z + 4 jet production at the LHC (7 TeV). Figure taken from Ref. [49].
Fig. 14: The integrated cross-section for $W^+W^-$ production at the LHC (7 TeV) as a function of the cut on the transverse momentum of the leading lepton. Figure taken from Ref. [141].

degrees of freedom. The precise details of the form factors therefore depend on the particular model considered. Paralleling the discussion of Ref. [150], in the POWHEG BOX it is assumed that all anomalous couplings $\Delta g$ are modified as

$$\Delta g \rightarrow \frac{\Delta g}{(1 + M_{VV}^2/\Lambda^2)^2} ,$$

where $M_{VV}$ is the invariant mass of the vector boson pair and $\Lambda$ is the scale of new physics.

Figure 14 sets the anomalous coupling to the maximum deviation from the SM allowed by LEP bounds and displays the sensitivity of the transverse momentum of the leading jet in $W^+W^-$ events to anomalous couplings, for the case of a form factor $\Lambda = 2$ TeV, $\Lambda = 5$ TeV, and no form factor ($\Lambda = \infty$). The plot illustrates the great potential of the LHC to improve on existing bounds (even more so when the machine will run at yet higher energy).

For the production of four charged leptons, a similar NLO study (again including all off-shell, spin-correlation, virtual-photon-exchange and interference effects) can be performed with the aMC@NLO generator [151]. The parton showering can be done either with HERWIG and (for the first time in this context) with Pythia 6. The $O(\alpha_s^2)$ contribution of the $gg$ channel is also included directly here, as obtained from MadLoop [50]. In the study of Ref. [151] several key distributions together with the corresponding theoretical uncertainties are presented. A further theoretical improvement is that scale and PDF uncertainties are computed at essentially no extra CPU time using reweighting techniques.

7 Parton distribution functions and $\alpha_s$

PDFs are the second thing one cannot live without, if one works on LHC physics. Huge effort is devoted today to understanding differences and improving the theoretical and statistical treatment of PDFs. This activity is reflected in new PDF sets being released by various groups [152]. The main focus of all groups is now directed towards NNLO PDF sets, an improvement in the treatment of heavy quarks, an introduction of flexible parametrization, a more dynamic tolerance and, of course, the inclusion of more data in the fits. Discussions are ongoing that try to clarify whether discrepancies between different PDFs are due to the inclusion of different datasets. For instance, there is no full consensus on what impact the Tevatron jet data has on gluon distributions at the LHC.

Figure 15 shows the uncertainty on three LHC benchmark processes ($Z$, $W^+$ and $t\bar{t}$, from left to right) coming from the use of different PDFs or a different value of $\alpha_s$, at NLO and at NNLO. The differ-
Fig. 15: The total cross-sections for $Z$, $W^+$ and $t\bar{t}$ (left to right) at the LHC (7 TeV) for NNPDF2.1 with $\alpha_s(M_Z) = 0.119$ (NLO and NNLO), $\alpha_s(M_Z) = 0.120$ (NLO) and $\alpha_s(M_Z) = 0.114$, 0.117 (NNLO), for MSTW08 with $\alpha_s(M_Z) = 0.1202$ (NLO) and $\alpha_s(M_Z) = 0.1171$ (NNLO), and for ABKM09 with $\alpha_s(M_Z) = 0.1135 \pm 0.0014$ (NNLO). The uncertainties shown correspond to 1\sigma. The band corresponds to the combination of CMS and ATLAS measurements. Figure taken from Ref. [121].

ences are due to the inclusion of different data in the fits, different methodology (e.g. the parametrization), different treatment of heavy quarks and different default value of the coupling constant. In particular, it is remarkable how much benchmark processes depend on the value of $\alpha_s$. The preliminary 2011 average value of $\alpha_s$ is $\alpha_s = 0.1183 \pm 0.0010$ [153]. It is interesting to note that the value barely changed compared to the 2009 number ($\alpha_s = 0.1184 \pm 0.0007$) [154], but that the uncertainty on it increased. This is due to the inclusion of new data in the fits, which tend to move the average value in opposite directions. An open issue today, in the combination of the various measurements to produce a world average for $\alpha_s$, is the treatment of outliers that have very small errors. This is the case for the extraction of $\alpha_s$ from thrust computed at N^3LL including power corrections using SCET [155], for the number obtained from $\tau$ decays in [156], and for the hadronic event shapes in $e^+e^−$ collisions at OPAL using NNLO + NLLA theoretical predictions [157], just to quote the most important cases.

New processes added to the world average since 2009 include inclusive jets at the Tevatron [158], the $e^+e^−$ three-jet rate that is known to NNLO [159], and $e^+e^− \rightarrow 5$ jets, which is now known at NLO [160]. The use of the Tevatron jet data in this context is particularly interesting. While the error on $\alpha_s$ from this extraction is not particularly small, this measurement and the sensitivity of benchmark processes on the value of $\alpha_s$ shown in Fig. 15 raises the question of whether it is possible to make competitive measurements of $\alpha_s$ at the LHC. The extraction of the value of the coupling constant at hadron colliders must take into account that PDFs themselves do depend on $\alpha_s$. A viable possibility then is to consider appropriate ratios, e.g. $[W/(\mathbb{Z} + (n + 1) \text{ jets})]/[\mathbb{Z}/(W + n \text{ jets})]$. 

8 Jet algorithms

Jet algorithms are the third thing you cannot live without, if you work on LHC physics. For a long time, infrared-unsafe algorithms were used at the Tevatron, with several “patches” introduced to minimize the effect of the infrared-unsafety. At the LHC, both ATLAS and CMS have adopted as default the anti-$k_t$ algorithm [161]. Given that this algorithm was proposed only three years ago, it shows how flexible experimentalists are today in adopting new, successful ideas.\footnote{A minor downside to this is that ATLAS and CMS use a different radius – the choices for ATLAS are 0.4 and 0.6, while for CMS they are 0.5 and 0.7.} Using this algorithm both collaborations have already explored scales up to 4 TeV and could place constraints on various BSM models, in particular those models that would give rise to a resonance in the $M_{jj}$ distribution (such as massive coloured bosons, black holes, . . . ).

Other infrared-safe algorithms like the Cambridge–Aachen or SISCone are in use as well. These are particularly useful for studies that exploit the fact that, when a massive boosted object decays, it gives rise to a “fat jet” with a non-trivial jet substructure. Looking at the internal structure of these
jets using jet grooming techniques like filtering, pruning or trimming has a huge potential for making discoveries “easier” [162, 163]. These techniques have a big gain in sensitivity over traditional methods, but one might lose many events when imposing strict kinematic cuts and requiring a boosted regime. The potential of these studies has been demonstrated in several examples [162, 163]. However, sophisticated jet studies are still a young field, and as of now there are no precise rules on how to make discoveries easier. What is impressive is that even these very new techniques are already being used at the LHC. Figure 16 shows, for instance, the single hadronic jet mass in \( W + \text{jets} \) events in a boosted regime, an observable relevant for \( WH (\rightarrow bb) \). In Fig. 16 the \( Z \) peak coming from \( WZ (\rightarrow bb) \) is evident. These very first results therefore seem very promising in finding a possible peak due to Higgs production.

9 Conclusions

The physics programme at the LHC is very rich: it spans from most precise measurements, e.g. in the case of Drell–Yan, to searches with highest reach for new physics, either direct searches or indirect ones (e.g. through the potential presence of anomalous couplings). This experimental programme at the LHC is supplemented by robust theoretical predictions that include NLO QCD corrections, mixed NLO-QCD + EW corrections, NNLO and resummation of logarithmically enhanced contributions. Furthermore, different calculations are merged using clever matching procedures that catch the best features of different calculations. From the theoretical community, there has been a clear and successful effort to produce predictions and public codes that have the flexibility required for today’s sophisticated experimental analysis (e.g. including parton shower, decays with spin correlations, massive quark effects, etc.).

Impressive results have already come out of the LHC, but this is certainly only the tip of the iceberg. After just one year of running at the LHC, some measurements, e.g. in processes involving \( W/Z \) production, start to be dominated by theoretical and parton density errors. It will therefore be a real challenge for theorists to keep up with the high experimental precision.
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