Electroweak and Higgs boson production at the LHC

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Abstract. I summarize very briefly the status of theory predictions for the production of electroweak and Higgs bosons at the LHC, highlighting recent developments and issues that have attracted the interest of the theory community. The focus is on inclusive and fixed order differential computations and related developments in parton showers are not discussed at all in this contribution.

1 Introduction

As the first phase of the LHC operation reaches its end, at the beginning of 2013, the particle physics community stands at a fascinating crossroad. On the one hand the extraordinary amount of high quality LHC data scrutinise the Standard Model, challenging the precision of theoretical predictions, without signs of any deviation. On the other hand the community celebrates the discovery [1, 2] of a new bosonic particle with signature and couplings close to what is expected of a Standard Model Higgs boson, with a long and painstaking procedure of disambiguating between various alternatives of electroweak symmetry breaking, lying ahead of us. Theory predictions for processes of the electroweak sector, including it's breaking sector through Higgs' mechanism, are without doubt the key ingredients for success in the years to come. In this proceedings contribution I am reviewing the status of theory predictions for such processes, focusing on the production of one or a pair of electroweak bosons, and the production of a Higgs boson.

2 W and Z boson production

The production of a single electroweak boson is probably the single best predicted hadronic process in perturbation theory. The total cross-section is known, since the early '90s, to NNLO in QCD [3] and to NLO in EW [4–6] expansion, which results to a precision at the few percent level. This is, however, matched by the exquisite precision with which it W and Z production are measured by experiments.

In addition, W and Z production have also been calculated differentially at NNLO by two collaborations [7–9], and the packages FEWZ [10] and DYNNLO[9] are both publicly available and include the decays of the W/Z bosons, also off-shell. FEWZ 2.1[11] also includes electroweak NLO corrections which are small but non-negligible at the per-cent level of accuracy.

As a result crucial observables, like the charge asymmetry of the W boson (or equivalently, the asymmetry of the electron in it's leptonic decay) can be studied reliably and compared with data including a well-motivated theory uncertainty estimate.

A variety of differential observables are used to further constrain parton densities in a fully hadronic environment, and first results are already available from the NNPDF collaboration[12, 13]. This is expected to result in a significant decrease of the theory uncertainties due to parton densities, particularly with respect to valence quarks, that dominate W and Z production.

Stringent tests of theory predictions for differential distributions in very challenging regions of phase space start indicating signs of exhaustion of the perturbative calculation. The case in study is the doubly differential distribution of $Z \to \mu^+\mu^-$, in the invariant mass of the decay products and the rapidity of the dimuon pair. When one looks at the central rapidity bins in the very low invariant mass region (i.e. when Z is severely off-peak) the fixed order and also the parton shower predictions disagree with CMS data[14]. The proper theory description in this region invites a dedicated resummation calculation, similar to what was done recently for the Φ^* and Q_T observables[15]. The appearance of non-perturbative effects might also be of importance here.

3 Diboson production

Diboson production is an omnipresent background to the extremely important *WW* and *ZZ* decay channels in Higgs production, and, moreover, important on its own ground, as a means of accessing the triple gauge boson coupling and measuring any deviations from the Standard Model predictions. Anomalous triple gauge boson couplings could manifest themselves in various BSM scenario, albeit only through loop diagrams. Therefore such contributions are not expected to be large, which, in turn, means that deviations from SM couplings will only be observed if theory predictions are very precise.

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The total cross-section and differential distributions for diboson production are only known to NLO in QCD [16–19] and NLO EW [20, 21]. The fixed order predictions are available through MCFM.

Whether we can trust the very small theory uncertainties that result from the NLO computation is debatable, especially in the case of WW production. In this case the measurement both as a signal and as a background for Higgs production, includes as a necessary ingredient a jet veto that suppresses the otherwise huge top pair production. In the presence of a jet veto, the NLO computation might be unreliable (as was the case in Higgs production itself). Moreover, in such a case the relative contribution of the poorly known (formally NNLO) gluon-gluon initial channel is enhanced due to the gluon densities at LHC. Independently of that, the behaviour of the electroweak corrections that are large ($\sim 50\%$) and negative [22] might be a cause for alarm.

In conclusion, the diboson processes would benefit immensely from a NNLO computation both of the total cross-section and of differential observables. Such a computation is not beyond the limits of current techniques. The diphoton production was recently computed to NNLO [23].

4 Higgs boson production

The discovery of a Higgs boson like resonance, announced in July 2012, has been the most cumbersome discovery in the history of particle physics. By now we have a convincing signal from both CMS and ATLAS[1, 2] in various experimental channels, of a resonance with a mass around 126 GeV, which is fully compatible with electroweak precision tests, and couplings that, to out current imprecise knowledge, are compatible with Standard Model expectations.

The determination of the spin of the new resonance is already under way and the expectation is that, examining differential distributions in the four leptons channel, we can be excluding the spin two hypothesis with 90% CL with the full LHC dataset collected by December 2012. Proposals on how to achieve this can be found at [24, 25].

The measurements of the various couplings to the new boson are a far more difficult but absolutely essential task. In order to succeed the theory community must deliver reduced model dependence of theoretical predictions along with as precise QCD and EW modeling as possible and improved scale and pdf uncertainties.

The fact that the new boson is discovered in the low mass region is certainly a welcomed feature since we can safely separate production from decay and apply the heavy quark effective theory as an excellent approximation, thereby decoupling the role of the top quark from predictions. For the same reason the contributions of all possible BSM resonances to Higgs production, in the dominant gluon fusion channel, can be computed through the corresponding Wilson coefficients, thus retaining the necessary NNLO QCD modeling. The only possible exception to that rule would be the possibility of anomalous light quark Yukawa couplings.

4.1 Gluon Fusion

The total cross-section for Higgs production via gluon fusion is already known for more that a decade at NNLO in QCD (in the HQET approximation) [26–28] in the HQET approximation. The exact NLO corrections, retaining the mass dependence of the top and bottom quarks, as well as the top-bottom interference effects are also known inclusively [29–31] and differentially [32], and provide corrections at the 10% level. Non-fixed-order improvements include resummation of soft gluon logarithmic contributions up to NNLL [33] and the soft plus-distribution terms at NNNLO [34]. Renormalization-group-improved predictions for Higgs production in the SCET framework are also available [35, 36], resulting in significantly smaller estimates of the total theory uncertainty. These calculations indicate that the effects of the higher order corrections are moderate and therefore enhance our confidence that the NNLO prediction with its assigned uncertainty correctly models gluon fusion production. The validity of the HQET approximation has been extensively checked by directly evaluating sub-leading terms in the $1/m_t$ expansion [37–42] and found to be an excellent approximation at the mass range around 126 GeV.

Electroweak corrections at the NLO (two-loop) level have also been calculated [43–47] and contribute at the 5% level in the mass range where the new boson is found. Mixed QCD-EW corrections [48] and NLO EW corrections to $H + j$ [49–51] contribute only at the per mille level to the total cross-section, but they become more prominent in differential distributions where their effect can rise to 5%.

The theoretical description of the gluon fusion production channel is currently satisfactory. The inclusive cross section is modelled by various publicly available programs [51–54] and published results for LHC at 8 TeV are in relatively good agreement with each other [55, 56]. It should be noted, however, that the central value of the inclusive cross-section (and hence the position of the uncertainty interval estimated) at 8 TeV depends on the choice of renormalisation and factorisation scales, contrary to what happens at 7 TeV. This leads to a difference of $\sim 5\%$ between the results of [55, 56], which, although within the range of the theoretical scale uncertainty ($\sim 9\%$), is rather disturbing and should be further examined. The Higgs Cross Section Working Group has recommended the result of [56] to the LHC experiments, and that is what was used at the discovery papers of July 2012 [1, 2].

At the differential level, two independent NNLO computations have been completed [57–59], and transverse momentum resummation up to NNLL accuracy has been achieved [60, 61]. These have been used extensively by the experimental collaborations to verify differential distributions produced by parton shower Monte-Carlo programs, and to estimate reliably theoretical uncertainties on the acceptances in the presence of experimental cuts. Recently there has been an extensive debate concerning the acceptance in the presence of a jet veto in Higgs production with the Higgs boson decaying to a pair of Ws (where the jet veto is necessary to suppress the top background). In such

a set-up the jet veto is severely suppressing all hard real emissions, and the introduction of a new scale (the veto value) casted some doubts on whether the fixed order prediction underestimates the uncertainty. This motivated a resummation of the corresponding logarithmic contributions to NNLL accuracy both in the SCET [62] and in the traditional resummation framework [63], providing a better understanding of efficiencies in the presence of jet vetoes.

In order to achieve the target accuracy of 5% for the total theory uncertainty in the inclusive cross-section for Higgs production via gluon fusion, deemed necessary for the precise measurement of Higgs couplings, the theory community has to proceed one order higher in the perturbative expansion. The first steps for such a monumental calculation have been taken recently by the computation of the NNLO partonic cross-section to order ϵ [65] and of the necessary NNLO master integrals to one order higher in ϵ than previously available, and to all ϵ-orders in the soft limit [64].

4.2 Vector boson fusion

The production of a Higgs boson through vector boson fusion is a process for which theoretical predictions are pretty accurate. The (DIS-like) NNLO QCD corrections to the process have been evaluated in recent years [66, 67] which, in combination with the already known NLO EW corrections [68, 69] reduce the scale uncertainty to the entirely acceptable $\tilde{2}$% level. The challenging issue in this channel, from the theory perspective, is the overlap with $H + 2j$ production via gluon fusion, known at NLO in QCD [70, 71], which can be considered a signal or a background depending on whether a particular analysis aims to discover the Higgs boson or to measure it's coupling with the weak vector bosons.

4.3 Associated production

The production of a Higgs boson in association with a vector boson, although prominent at Tevatron, is more troublesome at the LHC due to the large corresponding backgrounds. This difficulty can be overcome if the analysis focuses on events with a boosted Higgs boson [72]. The process is very similar to Drell-Yan production, with a subsequent emission of a Higgs boson from the final state vector boson, and is known at NNLO in QCD [73, 74] and NLO EW [75], while recently the differential NNLO computation in the case of WH production was completed [76]. As a result, the theory scale uncertainty for associated production is at or below the 2% level.

5 Conclusions

The Large Hadron Collider is at the end of it's first run, and it has already delivered an extraordinary wealth of data. Its success culminated in the celebrated discovery of a new particle, very similar to what is expected of the Standard Model Higgs boson. In the exciting period that lies ahead

the particle physics community will face the challenge of precision physics at the LHC. Electroweak processes are at the center of this program, and advances in their understanding will involve computations that take us one order further in their perturbative expansion. These cumbersome undertakings, that will challenge both our theoretical tools and our computational capabilities, are, however, prerequisites for a advancing our knowledge of physics at the TeV scale.

I have briefly reported here on the state of our knowledge regarding electroweak processes at the LHC, focusing on computations of mostly inclusive cross-sections and the precision they currently achieve.

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