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Theoretical Progress in QCD

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Abstract

I review very recent new theoretical results in theoretical QCD. In particular, I illustrate developments in the field of higher order calculations, in the techniques for matching fixed order calculations and showers, and in the field of boosted jet algorithms.

Keywords:

1. Introduction

QCD is the established theory of strong interactions. It is weakly coupled at short distances and strongly coupled at large distances. Because of this, perturbation theory is applicable for the computation of observables that are insensitive to long distance dynamics, i.e. to infrared finite observables. There is a large body of tests of Perturbative QCD predictions, as heritage from LEP, Tevatron and HERA physics, with no significant areas of discrepancies between theory and data. Current theoretical developments have thus shifted from QCD tests to predicting and modeling collider processes, in view of the present and future searches for new physics pursued at the Large Hadron Collider (LHC). In fact, all collider processes being studied at the LHC do involve a rather sophisticated use of perturbative QCD. On one hand, accurate cross sections at hadron colliders can only be computed if QCD corrections are included to a certain extent, and in particular instances also when resummation of kinematically enhanced contributions are performed. In some cases, restrictions on the observed final state imposed because of experimental requirements are such that only using a full simulation of the event one can reach a realistic description of the process.

In the last few years, prompted by the perspective of the LHC runs, a remarkable progress has taken place in several areas. Fully automated techniques have been developed for the calculation of Next-to-Leading Order (NLO) cross sections, by several collaborating and competing groups [1]. Techniques for combining fixed order calculations with parton shower generators have appeared, and have been widely applied to collider processes [2]. Intensive work on Next-to-Next-to-Leading Order (NNLO) calculations has been carried out by several groups the past 10 years or more. However, several new NNLO results have appeared since a little more than a year, indicating that a technical breakthrough has taken place recently [3]. A result on a N^3LO calculation of Higgs production near the threshold region has appeared a few months ago, hinting to the possibility of computing the full N^3LO corrections to Higgs production. Considerable progress is under way in the use of resummation techniques for the computation of observables with jet vetoes [5], in the area of jet substructure studies [4], and on Parton Density Functions (PDF's) studies.

In this talk I will review very recent new results that have become available since a little more than a year. I will talk about the recent calculation of the soft-virtual Higgs production at N^3LO, the recent progress in the NNLO calculation, the first shower generators with NNLO accuracy, and the recentl analytical results for jet substructure observables.

2. Gluon fusion threshold Higgs production at N³LO

In ref. [6], a result was presented for the N³LO calculation of the gluon fusion Higgs production cross section in the threshold limit. More specifically, if we write the Higgs partonic cross section as

$$\hat{\sigma}_{ij}(m_{\rm H}^2, \hat{s}) = \frac{\pi C(\mu^2)^2}{8v^2} \sum_{k=0}^{\infty} \left(\frac{\alpha_s}{\pi}\right)^k \eta_{ij}^{(k)}(z) \qquad (1)$$

where $C/4v$ is the effective Hgg coupling, $z = m_{\rm H}^2/\hat{s}$, and $\hat{s}$ represents as usual the partonic four-momentum squared, the new result is

$$\begin{aligned} \eta^{(3)}(z) &= \delta(1-z)\underline{1124.308887}... \\ &+ \left[\frac{1}{1-z}\right]_+ 1466.478272... \\ &- \left[\frac{\log(1-z)}{1-z}\right]_+ 6062.08673... \\ &+ \left[\frac{\log^2(1-z)}{1-z}\right]_+ 7116.015302... \\ &- \left[\frac{\log^3(1-z)}{1-z}\right]_+ 1824.362531... \\ &- \left[\frac{\log^4(1-z)}{1-z}\right]_+ 230 \\ &+ \left[\frac{\log^5(1-z)}{1-z}\right]_+ 216 + O(1) \qquad (2) \end{aligned}$$

valid up to unknown finite corrections (i.e. not involving singularities for $z \to 1$). The numerical coefficients of the distributions are known analytically, and for reasons of space I have reported only their (in some cases approximate) numerical value. The authors of ref. [6] have computed the soft contribution to the coefficient of the δ function term, underlined in the formula. In ref. [6] one can find the references where the remaining contributions were computed. The soft contribution to the $\delta(1-z)$ term is universal, and the result of [6] was immediately extended to the Drell-Yan process in ref. [7] and to generic processes with colourless final states in ref. [8].

Although the result of ref. [6] is far from complete, few attempts have been appeared in the literature that use it to constrain approximate expressions of the full N³LO corrections [9, 10, 11, 12]. In fig. 1 (from ref. [10]) a comparison of different approximation schemes is reported. The large spread among the different approaches can be taken as an indication for the need of a full N³LO result.

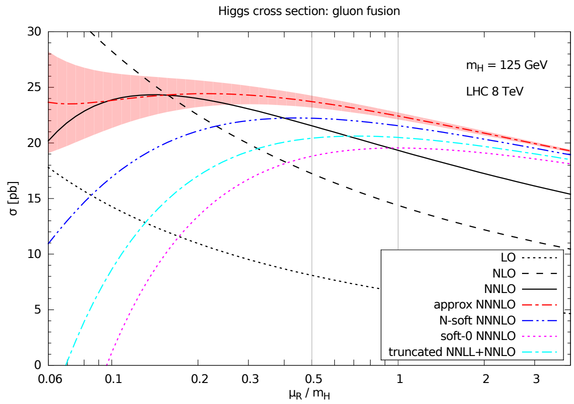

Figure 1: Several approximation to the N³LO total cross section for Higgs production in gluon fusion, as a function of the renormalization scale, making use of the result of ref. [6], taken from ref. [10]. Approx N³LO stands for the result of [10], soft-0 N³LO is from ref. [6], N-soft N³LO is according to ref. [11].

This new N³LO result was made possible thanks to several partial results already available, involving a considerable number of researchers. Thus, the 3-loop virtual contribution to the N³LO Higgs cross section was computed in refs. [13, 14, 15]; certain contributions associated with collinear-ultraviolet counterterms were given in ref. [16, 17, 18, 19]; the two-loop soft current was computed in [20, 21]; the real-virtual contribution was given in [22, 23].

3. Status of NNLO calculations

Next-to-next-to-Leading Order calculations (NNLO) for collider processes have first appeared in 1990 for the Drell-Yan process [24], followed more than ten years later by the NNLO computation of the total Higgs cross section in gluon fusion [25, 26, 27], and of the Higgs differential distributions in [28, 29]. We have witnessed since then a steady increase in the complexity of the processes for which NNLO calculations have become available: 3 jet cross sections in e^+e^- annihilation [30], WH and ZH production [31, 32], $\gamma\gamma$ production [33]. In a little more than a year from now, several new results for complex $2 \to 2$ processes have become available: Higgs production in association with a jet [34], $t\bar{t}$ production [35], a partial result on inclusive jets production [36], $Z/W+\gamma$ production [37], ZZ production [38], W^+W^- production [39] and t-channel single top production [40]. Important results have also been obtained for decay processes [41].

NNLO calculations have been developed thanks to a collaborative effort of several independent research groups, dealing with different aspects of the calculation. On one side, the computation of the double virtual contribution is very demanding. Recent progress with integrals including massive particles [42, 43, 44] have opened the possibility of computing NNLO corrections to pairs of massive vector bosons. In general, it seems that today two loop virtual corrections to generic $2 \to 2$ processes are feasible. A recent groundbreaking technique introduced by Henn [45] is among the developments that have made this possible.

There are several components that make up a NNLO calculation, besides the two loop corrections. One must also supply the square of 1-loop contribution (double virtual), the virtual correction to one real emission (real-virtual) and the two-real-emission contributions. Each contribution contains soft and collinear divergences, that must cancel in the sum. This also constitutes a challenging aspect of NNLO calculations. There are several techniques currently developed for implementing these cancellations. The q_T subtraction method [29] has been used for Higgs production, Drell Yen, $\gamma\gamma$, WH, ZH and ZZ processes. It is particularly useful for processes where the final state is a colour neutral system. The Antenna subtraction method [46] has been used for the computation of $e^+e^- \to 3$ jets and for dijets, and is presently also used in an effort to compute fully differential $t\bar{t}$ production at NNLO [47]. The so called STRIPPER method (Sector Improved Phase sPaCe for real Radiation) [48, 49] has been used for $t\bar{t}$, $H + j$ and t-channel single top production. Another method being developed is described in a sequel of publications (see [50] and references therein).

In fig. 2 I show results from the computation of $Z\gamma$

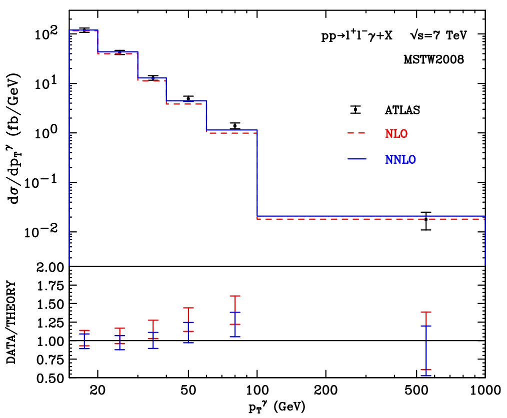

Figure 2: Transverse momentum of the photon in $Z\gamma$ events compared to ATLAS data.

production [37] compared to ATLAS data. We see there a reasonable pattern of NLO and NNLO results, with data slightly favouring the NNLO result. The same authors of ref. [37] are also considering the $W\gamma$ case (in preparation). There NNLO corrections seem to be needed to reach a satisfactory agreement with data, as shown in fig. 3. The ATLAS and CMS experiments have

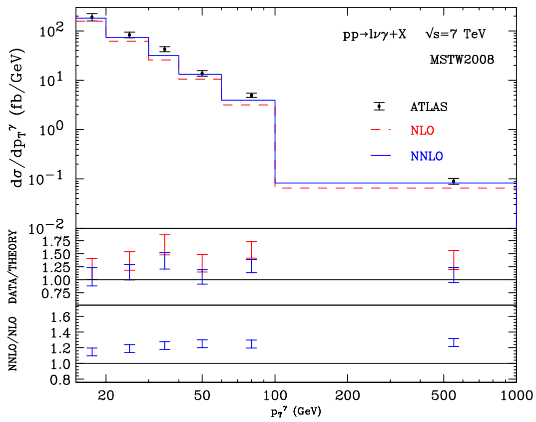

Figure 3: Transverse momentum of the photon in $W\gamma$ events compared to ATLAS data.

claimed an excess in the W^+W^- cross section with respect to Standard Model prediction (see ref. [39] and references therein). In fig. 4 the result of the NNLO

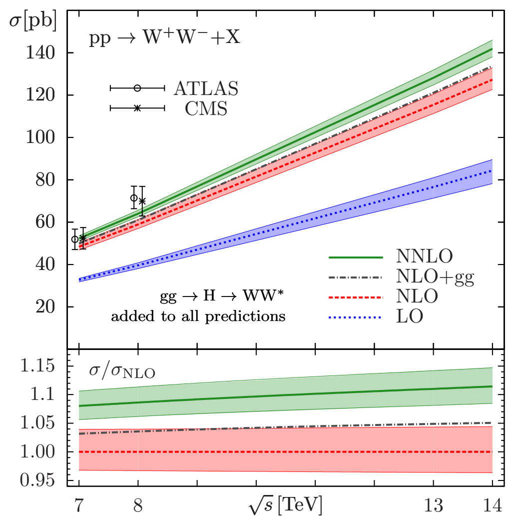

Figure 4: Total cross section for W^+W^- as a function of the CM energy. Comparison of fixed order predictions with ATLAS and CMS data.

calculation of ref. [39] is displayed. There it can be seen that the NNLO calculation is in excellent agreement with 7 TeV data, and that the discrepancy at 8 TeV is largely reduced.[1]

New NNLO results for $t\bar{t}$ production [35] have been used to constrain gluon PDF's [52]. Phenomenological results compared to experimental data are displayed in figs. 5, from ref. [53]. At variance with the $t\bar{t}$ case,

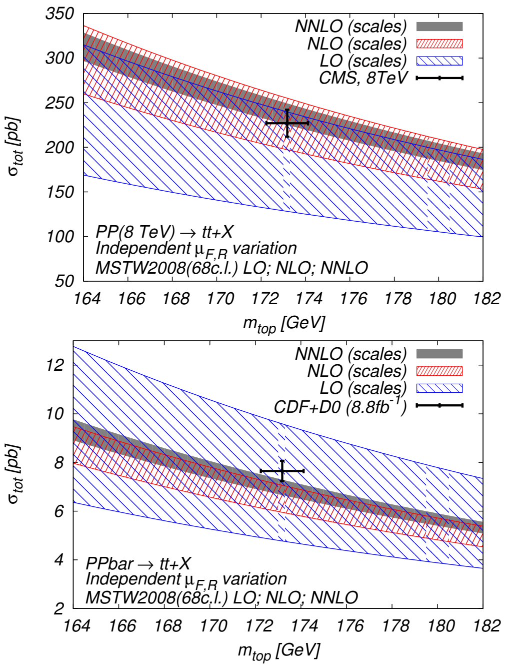

Figure 5: Total cross section for $t\bar{t}$ production compared to experimental data at the LHC and at the Tevatron.

NNLO corrections to t-channel single top production (displayed in fig. 6 from ref. [40]) are very modest in

$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	+2.4%	$54.2^{+0.5}_{-0.2}$	−1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	+4.9%	$48.3^{+0.3}_{-0.02}$	−1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	+9.3%	$36.5^{+0.1}_{+0.1}$	−0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	+13.6%	$25.4^{-0.1}_{+0.2}$	+1.6%

Figure 6: Cross section for single top production as a function of a cut in the top transverse momentum. The error is obtained by varying the factorization and renormalization scale μ, with $\mu = m_t$ (central), $\mu = 2m_t$ (upper) and $\mu = m_t/2$ (lower). The δ columns display the variation of the central value relative to the previous order.

magnitude, and display a considerably small scale dependence.

[1]For a study of extrapolation uncertainties in this measurement arising from jet veto procedures, see ref. [51].

NNLO corrections for jet production are in progress, with the still missing qg component, that is mandatory for LHC physics. However, a pdf study based upon jet data, including the computed NNLO effect has already appeared [54].

4. Fixed Order calculations interfaced to Parton Showers

Parton Shower Monte Carlo (PS) fully simulate hadronic production processes by merging together a QCD component (the Shower itself) and a model for hadron formation. The QCD component is typically given in the collinear approximation. When applied to infrared finite observables, PS generators are accurate only in the collinear and soft regions, failing to predict hard, large angle emissions even at leading order. In ref. [55] a procedure was developed for matching matrix element calculations with PS generators (ME+PS), such that the production of hard, widely separated jets could be improved to LO accuracy, leading to the developments of various ME+PS generators [56].

In the past 10 years, considerable effort has gone in building NLO-improved PS generators (NLO+PS) using the results of NLO calculations. Methods like `MC@NLO` [57] and `POWHEG` [58, 59] allow to interface fixed order NLO calculations to parton shower generators like `PYTHIA` [60, 61] and `HERWIG` [62, 63]. These techniques have seen recently considerable progress, due to the appearance of computer frameworks that automatize some or all aspects of the calculation: the virtual contributions, the implementation of a subtraction framework for the real corrections, and the interface to a PS. In the `MadGraph5_aMC@NLO` framework [64], all aspects of an NLO calculation are automatized, starting from the generation of the LO and NLO matrix element, down to the event generation interfaced to a PS program. The `GoSam` [65], Recola [66] and Open Loops [67] frameworks deal with the automatic generation of general purpose virtual amplitudes. The Black Hat [68] generator provides virtual corrections for selected processes (vector Boson in association with jets) and is capable to deal with fairly high jet multiplicities. In fact it was recently used to compute W production with five associated jets at NLO [69]. The `Sherpa` generator [70] implements a framework for NLO calculations and for NLO+PS generation based upon a variant of the `MC@NLO` method. The so called MatchBox framework [71] implements NLO+PS generators within the `Herwig++` [63] PS generator.

Here I will discuss very recent progress, that have to do with building event generator that reach NNLO accuracy for inclusive quantities. Generators of this sort have been developed now only for Higgs and W/Z production, so, for purpose of illustration, I will discuss them in the framework of Higgs production.

Higgs production in gluon fusion is a process of order α_s^2 in the strong coupling constant. NLO corrections to Higgs production are of order α_s^3, and also involve the production of a Higgs in association with a colour parton, i.e. the $H + j$ subprocess. This subprocess starts at order $O(\alpha_s^3)$, so, in this sense it is just a LO process. NNLO corrections to Higgs production are of order $O(\alpha_s^4)$. They thus involves the $H + j$ subprocess at order $O(\alpha_s^4)$, i.e. at NLO order, and the $H + 2j$ subprocess at $O(\alpha_s^4)$, i.e. at leading order. The aim of a NNLO+PS generator is to provide NNLO accuracy for fully inclusive Higgs observables, NLO accuracy for the $H + j$ process and LO accuracy for the $H + 2j$ process.

At an intermediate level, we may ask for a generator that satisfies the last two requirements, but only achieves NLO (i.e. $O(\alpha_s^3)$) accuracy for inclusive Higgs observables, while remaining $O(\alpha_s^4)$ accurate for $H + j$ and $H + 2j$ observables. We will call such generator an `H-HJ` generator, reminding that it has NLO accuracy both for Higgs-inclusive and for Higgs plus one jet inclusive observables. Assuming that we have an `H-HJ` generator, it is easy to build a full NNLO accurate generator just by a simple reweighting procedure. For example, one can reweight the events produced by such generator with the factor

$$\frac{d\sigma^{NNLO}}{dy_{\rm H}} \Big/ \frac{d\sigma^{H-HJ}}{dy_{\rm H}}\ , \qquad (3)$$

where $y_{\rm H}$ is the Higgs rapidity in the generated event. In fact, if the H-HJ generator has the claim accuracy, this reweighting factor is of order $1 + O(\alpha_s^2)$, since all terms of order α_s cancel in the ratio. It thus affects the $H + j$ subprocess, of order $O(\alpha_s^3) + O(\alpha_s^4)$, by terms of order $O(\alpha_s^5)$, thus not spoiling its nominal accuracy.

While reweighting to the NNLO inclusive cross section may be not difficult to achieve, building an H-HJ generator is not so simple. In order to try to achieve this kind of accuracy, one generally tries to build a "merged" generator, i.e. a generator obtained by merging together NLO+PS generators for H and $H + J$ production. The idea here to let the H generator handle the kinematic regions with relatively small hadronic activity, while the $H + J$ ones handles the production of relatively hard jets. In the Higgs case, one may introduce a separation scale Q_0, as shown in fig. 4, and generate two sample of events, one with the H and the other with the HJ generator, retaining only events with the Higgs transverse momentum below (above) Q_0 in the first (second) sample. Events are generated by first choosing one of the two samples with a probability proportional to its integrated cross section, and then picking an event out of the resulting sample. The question is where to choose the Q_0 value. Ideally we would like to choose it as low as possible, in order to have an NLO description of 1-jet emission for most of the jet phase space. However, even if the Sudakov form factor in the H generator is accurate at the NLL level, missing NNLL terms, of order $\alpha_s^2 \times \alpha_s^2 L$, with $L = \log m_{\rm H}/Q_0$, would spoil its NLO accuracy, that requires neglected terms to be of order α_s^4 or higher, as far as the integrated cross section up to the scale Q_0 is concerned. In particular, if the scale Q_0 is chosen near the Sudakov peak, where $\alpha_s L^2 \approx 1$, the neglected terms would be of order $\alpha_s^{3/5}$. Staying above the Sudakov region would already mean to give up an accurate description of jets below 10 GeV in the Higgs case, and of even harder jets in processes with a larger CM energy, like $t\bar{t}$ production. Strictly speaking, the only way out seem to require $\alpha_s L^2 \approx \alpha_s^2$, that is to say $L \approx 1$, i.e. $Q_0 \approx M$. It must also be said that our assumption about the Sudakov form factor being accurate at the NLL level is not often fully satisfied, leading to even worse inaccuracies.

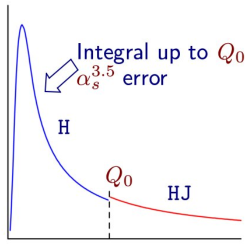

Figure 7: Structure of a merged H-HJ generator. Events with transverse momentum below Q_0 are generated by the H generator, and those above it by the HJ one.

In general, the problem of merging several generators for a process with an increasing number of associated jets is referred to as the NLOPS merging problem. In the literature there are several proposal of NLOPS merging techniques, also differing in the way they address the problem discussed in the previous paragraph [72, 73, 74, 75, 76, 77]. In particular, in refs. [72, 73], carried out in the frameworks of the `Sherpa` and `MC@NLO` collaborations respectively, merging is performed using a merging scale, as illustrated previously. In [73], stability under variations of the energy scale is interpreted as an indication of accuracy. In ref. [75], NLO accuracy is adjusted by forcing the inclusive distribution to agree with the NLO one, by subtracting appropriate terms, with a procedure dubbed UNLOPS (standing for "Unitary" NLOPS). In ref. [76] (within the so called GENEVA collaboration) the merging scale is defined in such a way that resummation can be carried out up to the NNLL level. In refs. [78] (the MiNLO method) a method was proposed to improve the accuracy of a generator in such a way that it becomes reliable also after integrating out a radiated parton. In ref. [79] it was also shown that in certain simple cases the MiNLO method applied to generators for a Boson (Higgs, Z or W) plus one jet, can be refined in such a way that it becomes NLO accurate also for inclusive quantities. In ref. [80] a fist NNLOPS accurate generator for Higgs production in gluon fusion was presented, based upon MiNLO and the reweighting formula eq. (3). In fig. 8, from [80], the rapidity distribu-

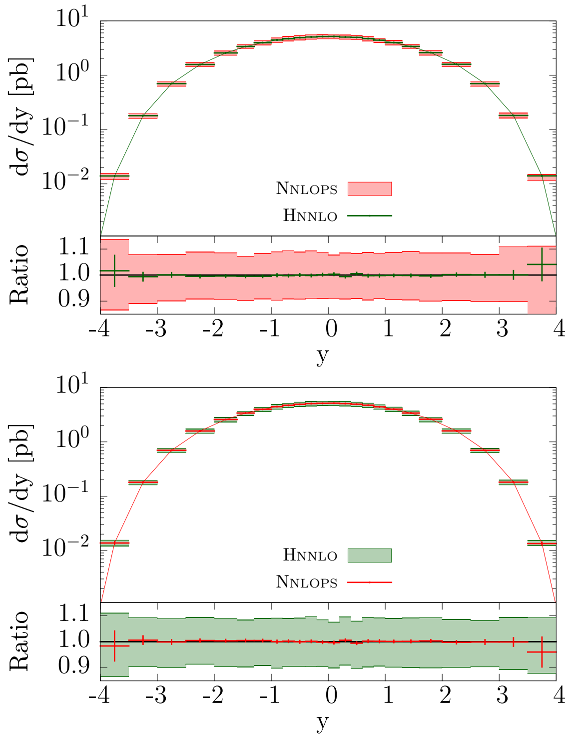

Figure 8: Higgs rapidity distribution from the H-HJ MiNLO generator (upper plot) and from the NNLOPS one (lower plot)

tion of the Higgs boson computed at fixed NNLO order (using the HNNLO program [29, 81]) is compared with the output of the NNLOPS generator. From the figure we can see the reduction in the width of the scale variation band, when going from NLO to NNLO accuracy. Of course, since the NNLOPS was obtained from the H-HJ one by rescaling, this result is expected. In fig. 9 the

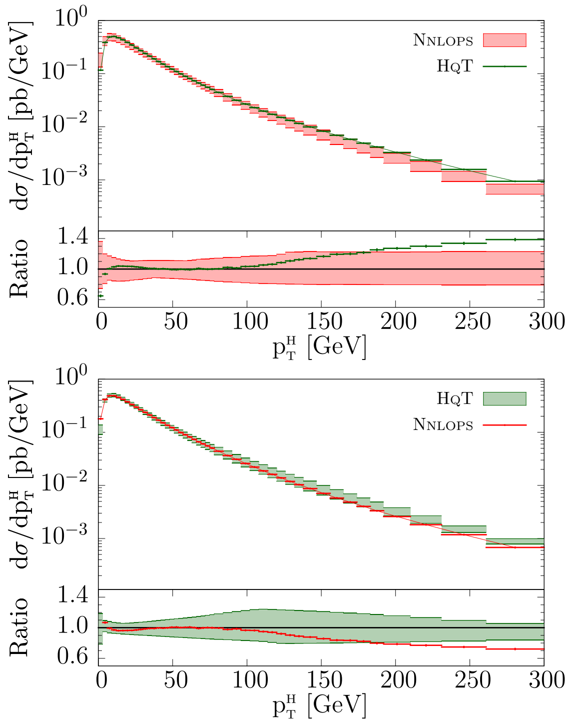

Figure 9: NNLOPS compared with HqT for the transverse momentum spectrum of the Higgs boson. In the upper (lower) plot the error band of NNLOPS (HqT) is shown.

NNLOPS result is compared with HqT [82, 83], a program dedicated to the computation of the Higgs transverse momentum spectrum at NNLO+NNLL accuracy. We see good agreement for moderate p_T. At large p_T values the two result differ (in spite of the fact that they become formally equivalent in this regime) due to the very different scale choice made in HqT,that chooses $m_{\rm H}/2$, with respect to NNLOPS, that chooses the transverse mass (i.e. $p_T^2 + m_{\rm H}^2$) of the Higgs.

Further work has appeared in recent literature about NNLOPS generators. The same method discussed above was also applied recently to the Drell-Yan process [84]. In refs. [85, 86] NNLOPS generators were built for the Drell Yan process and for Higgs production respectively. The method used there is called UN^{2}LOPS (for "unitary" NNLOPS), and uses an extension of the unitarization technique of ref. [75]. Fig. 10, from ref. [86], display the Higgs transverse momentum computed with this method. The method adjusts the cross section in the low p_T region, below the shower scale, in order to preserve NNLO accuracy. The visible feature in the first bin of the plot seems to be due to this procedure.

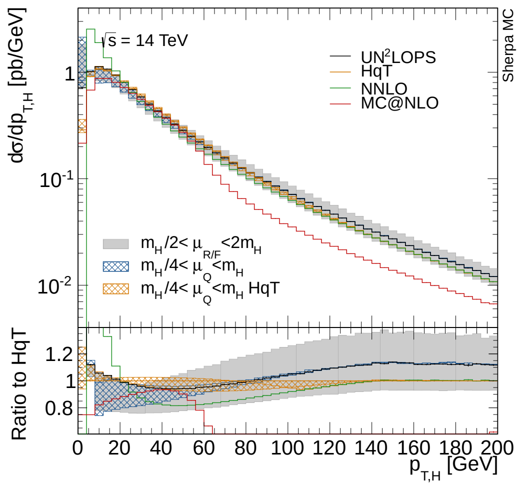

Figure 10: UN^{2}LOPS compared with HqT for the transverse momentum spectrum of the Higgs boson.

In ref. [87], a general strategy for NNLOPS generators based upon the GENEVA framework was outlined. No complete application of this method to physical processes has been published, although preliminary results on the Drell-Yan process have been shown to conferences [88].

5. Boosted jets

In high energy collisions, highly boosted, massive particles decaying into hadrons will be reconstructed as jets. Jet substructure analysis may be used to distinguish them from ordinary QCD jets. Pioneering work on this subject has appeared in 1993 [89]. In more recent time, after the publication of ref. [90], this field has become a very active research direction, with its own dedicated conference [91].

In order to distinguish QCD jets from decay of heavy objects, one can consider several handles. In essence, QCD jets tend to be asymmetric (soft emissions are favoured). Furthermore they are surrounded by more activity with respect to the decay of colour neutral objects, since colour coherence inhibits large angle soft emissions. Several techniques have been put forward to select out QCD jets, using jet substructure: mass-drop, pruning and trimming techniques, N subjettiness, template overlap, energy correlation functions, shower deconstruction, planar flow and several others [91]. The performance of a jet tagger is generally accessed using shower Monte Carlo generators. At times, this may be hard to do with all required parameter combinations and for the whole range of kinematics and jet definitions. In a recent paper [92], a first analytic, resummed calculation of the tagging rate of commonly used jet substructure tools was presented. This result provide valuable insight into the performance of these tools, and sets new standards for future studies in this field. Here I will just illustrate one example from ref. [92], the Mass Drop Tagger (MDT). It is defined starting with jets reconstructed according to the Cambridge-Aachen algorithm, a recursive algorithm that recombines pairs of (pseudo)particles that have the smallest distance in the η,ϕ plane. Given a reconstructed jet j of mass m, one looks at the previous clustering step, with the jet broken into two subjets j_1, j_2 with masses $m_1 > m_2$. If there is a significant mass drop, $m_1 < \mu m$, with $\mu \approx 3/4$, and the splitting is not too asymmetric $y = \mathrm{m}in(p^2_{t,1}, p^2_{t,2})\Delta R^2_{12}/m^2_j > y_{\rm cut}$, the jet is tagged. Otherwise, j is redefined to be equal to j_1, j_2 is discarded, and the procedure is repeated. The authors of [92] have modified this definition, introducing the modified MDT (mMDT), that differs in the last step of the algorithm, where instead of j_1 (the jet with the largest mass), it is the jet with the largest $p_t^2 + m^2$ that replaces j. This makes little difference in the performance of the algorithm, while making it more solid and easier to treat analytically. In order to give an idea on how well the analytic result matches the result of a full Shower simulation, I show in fig. 11, (from ref. [92]) the performance of the mMDT computed with a shower Monte Carlo and with the analytic formula. As can be seen, the analytic result captures both qualitatively and quantitatively the features of the simulation.

Studies on new jet tagger algorithms, using this novel analytic understanding, have already appeared in the literature [93].

6. Conclusions

The field of theoretical QCD is very active at the moment, mainly driven by the demanding requirements of LHC physics. The accuracy of QCD calculation is being improved to an unprecedented level. In the present report I have briefly illustrated highlights of very new theoretical progress that has taken place in perturbative QCD in the past year. A first glimpse to a N^{3}LO calculation has appeared in the literature, showing that it may be possible in the near future to compute the Higgs cross section at the N^{3}LO level. A number of new impressive results in NNLO calculations have appeared in a little more than a year, showing that NNLO results

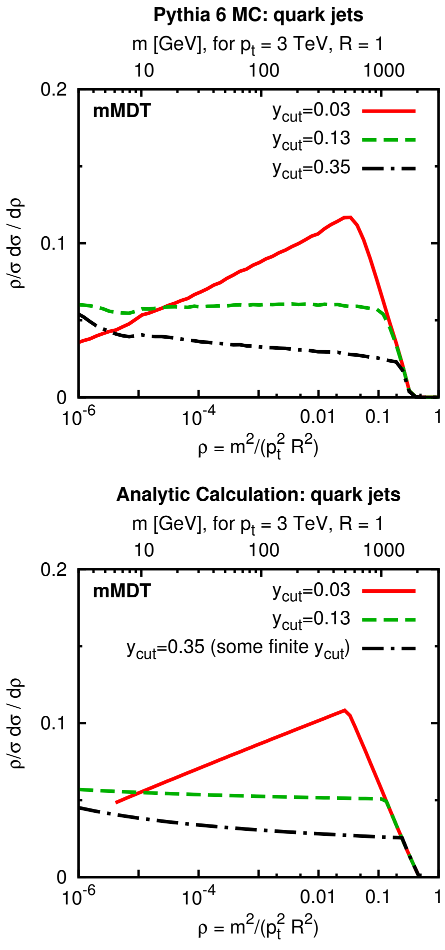

Figure 11: Performance of the mMDT as computed with PYTHIA6 (upper plot) and as given by the analytic result of ref. [92]. The μ parameter is fixed to 0.67 (its precise value has no impact on the result, unless it is taken parametrically small).

may soon become accessible for all $2 \to 2$ LHC processes. Algorithms for achieving NNLO accuracy in fixed order calculations matched to shower generators have begun to appear, now limited to simple processes, such as Higgs and W/Z production. Application of QCD resummation techniques to jet algorithms used to tag hadronic decay of heavy particles (aimed at the study of Higgs production channels and of new physics searches) have appeared in the literature, allowing for an analytic control of the features of jet taggers, thus contributing a promising new approach to this very active research field.

Acknowledgments

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