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QCD: Recent theoretical developments and results

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Summary. — I present recent developments and results in theoretical, perturbative QCD.

PACS 12.38.Bx – Perturbative calculations.
PACS 11.15.Bt – General properties of perturbation theory.

1. – Introduction

Calculations at Hadron Colliders at the Next to Leading Order (NLO) or even at the Next-to-next to leading order (NNLO) in QCD are needed mainly for two reasons. Firstly, they are an increasingly important ingredient for computing backgrounds in New Physics searches, that quite often rely on analyses performed in rather narrow corners of the phase-space or tails of distributions, where, on the one hand, not enough statistics is present to extract the background directly from the data and where, on the other hand, radiative corrections are expected to be large. Secondly, (N)NLO calculations should be preferred when measuring (or constraining) fundamental quantities of the Standard Model (SM), such as M_H, M_W, α_S or M_{top}. For example, the recent exclusion limits put by TEVATRON on the Higgs mass [1] have been made possible only thanks to our improved knowledge of 2-loops QCD effects [2].

Both in the case of New Physics searches, where the new produced particles are expected to undergo long chain decays, and in the case of SM measurements, where the hard event is usually accompanied by a rather strong jet activity, multi-leg final states are expected as a typical signature.

For these reasons, the field radiative corrections for multi-particle processes have received a lot of attention, in the last few years, also thanks to new computational techniques [3-5] and to new tools [6-8] that are nowadays at our disposal.

In this contribution, I will review the main results that have been recently obtained in this subject.

TABLE I. – *The original 2007 Les Houches wish list (top) and its 2009 update (bottom).*

$pp \to W + j$	$pp \to t\bar{t} + 2j$	$pp \to V + 3j$
$pp \to H + 2j$	$pp \to VVb\bar{b}$	$pp \to t\bar{t}b\bar{b}$
$pp \to VVV$	$pp \to VV + 2j$	$pp \to b\bar{b}b\bar{b}$

$pp \to t\bar{t}t\bar{t}$	$pp \to 4j$	$pp \to W + 4j$
$pp \to Z + 3j$	$pp \to Wb\bar{b}j$	

2. – NLO processes: the Les Houches wish list(s)

The beginning of the story dates back in 2007, when, in Les Houches, theoreticians and experimentalists agreed upon a list of processes both groups would have liked to know at the NLO accuracy [9]. After 2 years, in occasion of the following Les Houches Workshop [10], thanks to the joint effort of groups using Standard computational techniques and new ideas, the job can be considered almost accomplished, at least at the parton level. The present status can be found in the introduction of [10]. For the reader's reference I present, in table I, the original list and the few entries added in 2009. It has to be pointed out that, even if the processes included in table I that have been (or can be in a very near future) computed look quite impressive, the *perfect* final NLO product, needed from an experimental point of view, would be the matching of NLO parton level processes with shower Monte Carlo simulations. Nice progress in that direction has been achieved by the POWHEG group [11], and examples of actual implementations already exist in practice. Also the pioneering work of organizing together different multiplicity (in the same spirit of the existing algorithms at the tree level, such as MLM matching and CKKW) has been recently undertaken by Nason and Hamilton [12].

3. – NLO tools

It is evident that sophisticated programs are needed to compute multileg processes at NLO. The existing tools can be naturally divided in three categories, as listed in table II, namely codes based on Analytic Formulas, on traditional Feynman Diagram techniques and, finally, on OPP or Generalized Unitarity methods. As usual, most of the programs have been cross checked, to establish their technical agreement. An example of such *tuned* comparisons is reported in table III, for the process $pp \to ttbb$. It is remarkable the fact that the two codes use two completely different techniques. Analogous successful comparisons have been performed by the `GOLEM` group and the team Dittmaier, Kallweit and Uwer on $pp \to ZZ + j + X$ [10].

The second, even more important task of the comparisons, is the assessment of the theoretical accuracy at which a given process is known. In this second type of exercise, each program freely varies a few parameters (such as renormalization and factorization scales). The goodness of the LO prediction (at least in the shape of the distributions) can also be determined that way. In fig. 1 I report, as an example, the result of a comparison of `BlackHat`, `Rocket` and `Sherpa` on $pp \to W + 3$ *jets*. The existence of complete NLO calculations also allows to find the correct interfaces of different approaches, as

TABLE II. – *Some available NLO tools.*

Analytic Formulae
`MCFM` [13]
Feynman Diagrams
`Bredenstein, Denner, Dittmaier, Pozzorini` [14]
`FormCalc/LoopTools/FeynCalc` [15]
`GOLEM` [16]
OPP/Generalized Unitarity
`Helac-NLO/Cuttools` [6, 8]
`BlackHat/Sherpa` [5]
`Rocket` [7]
`C++ implementation of D-dim Unitarity` [17]

in the case of the comparison shown by Schwienhorst, Frederix and Maltoni in [10], where they study how to merge the 4 and 5 flavor schemes in single-top production at TEVATRON.

As a conclusive remark of this section, I would like to point out that the techniques used to obtain the results are getting less and less important. The interest is now going towards commonly accepted interfaces to merge different parts of the NLO calculations. As an example, an accord (worked out in Les Houches '09, mostly by T. Binoth, that left us too soon) to interface Monte Carlo (MC) programs, generating the real radiation, together with programs providing the Virtual One Loop contributions (OLP), can be found in [18]. In fig. 2, I show this accord at work between `BlackHat/Rocket` on the OLP side and MadFKS on the MC side, in the case of $e^+e^- \to jets$ as implemented by Frederix, Maitre and Zanderighi [10].

4. – NNLO calculations and beyond

NNLO calculations are also entering a new era. Full exclusive NNLO calculation can nowadays be produced, allowing a direct comparison with the data. As an example, I show, in fig. 3 the rapidity distribution of an on-shell W^+ boson at TEVATRON, as produced by Catani, Ferrera and Grazzini [19].

TABLE III. – *Example of tuned comparisons between HELAC-NLO* [8] *and the program of* [14].

Process	$\sigma^{\rm LO}_{[14]}$ (fb)	$\sigma^{\rm LO}_{[8]}$ (fb)	$\sigma^{\rm NLO}_{[14]}$ (fb)	$\sigma^{\rm NLO}_{[8]}$ (fb)
$q\bar{q} \to t\bar{t}b\bar{b}$	85.522(26)	85.489(46)	87.698(56)	87.545(91)
$pp \to t\bar{t}b\bar{b}$	1488.8(1.2)	1489.2(0.9)	2638(6)	2642(3)

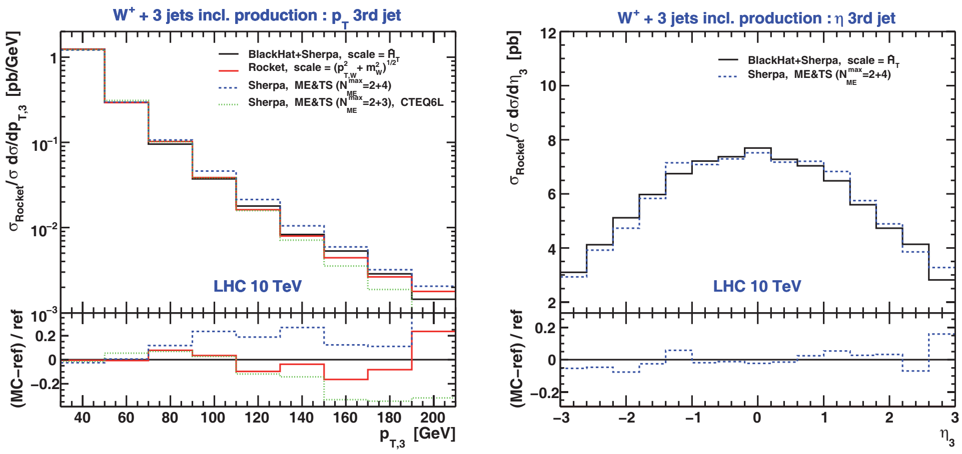

Fig. 1. – Comparisons on $pp \to W + 3\ jets$: p_t and rapidity of the 3rd jet.

As is well known, NNLO predictions help in improving the scale dependence of the computed observables and allow to determize a K factor with respect to the leading-order result. A nice example of such a study, in the presence of a jet-veto, is presented in fig. 4 for $pp \to WW \to ee\nu\nu$ at NNLO in QCD (by Dissertori and Stökli in [10]).

I conclude by mentioning a recent result beyond NNLO obtained by Gardi and Magnea in [20] (see also Becker and Neubert in [21]). They proved that the structure of infrared and collinear divergences in massless gauge theories, for amplitudes with any number of colored partons, and to all orders in the $1/N_c$ expansion, is significantly simpler than previously expected and fulfills a simple dipole structure, with possible corrections that are tightly constrained.

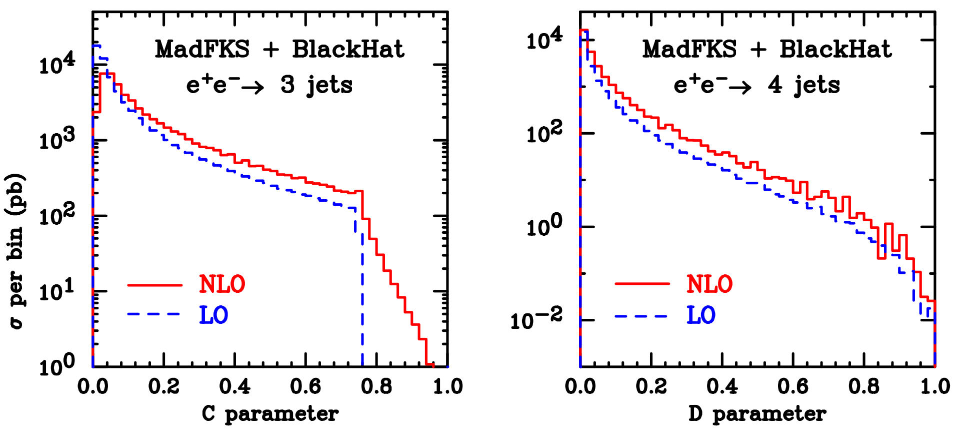

Fig. 2. – Results on $e^+e^- \to jets$ using the Binoth Les Houches accord.

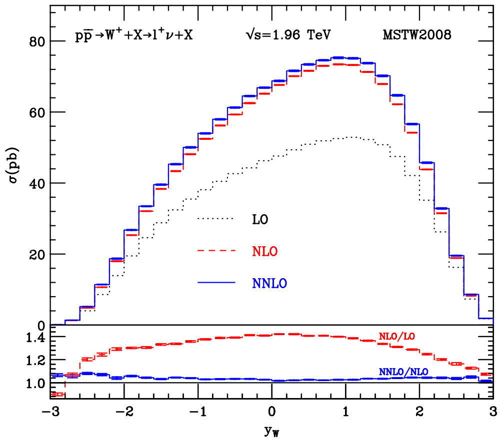

Fig. 3. – The rapidity distribution of an on-shell W^+ boson at TEVATRON.

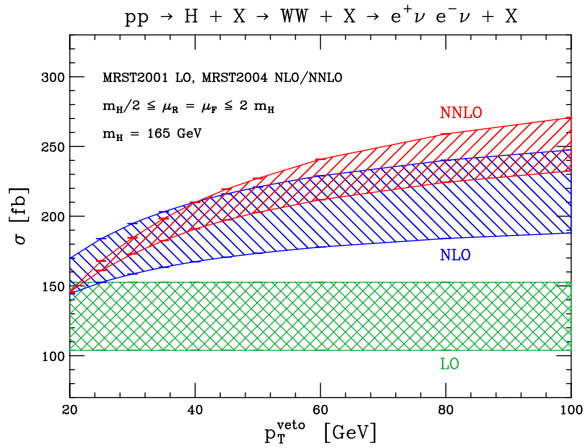

Fig. 4. – $pp \to H \to WW \to ee\nu\nu$ at the LHC.

5. – Conclusions

I have presented recent progresses in our theoretical understanding of perturbative QCD at NLO, NNLO and beyond. The tools at our disposal to deal with the data are refined enough to cope with the complexity of the LHC and TEVATRON measurements.

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