NEXT-TO-LEADING ORDER QCD CORRECTIONS TO $t\bar{t}b\bar{b}$ PRODUCTION AT THE LHC*

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In this contribution, we summarize the results from an NLO computation of the production of $t\bar{t}b\bar{b}$ in hadronic collisions. The results are obtained by combining two programs: Helac-1Loop, based on the OPP method and the reduction code CutTools, for the virtual one-loop matrix elements and Helac-Dipoles for the real-emission contributions. Selected numerical results are presented for the LHC.

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1. Introduction

The process $pp \to t\bar{t}b\bar{b}$ represents a very important background reaction to searches at the LHC, in particular to $t\bar{t}H$ production, where the Higgs boson decays into a $b\bar{b}$ pair. A successful analysis of this production channel at the LHC requires the knowledge of direct $t\bar{t}b\bar{b}$ production at NLO in QCD [1]. Moreover, the calculation of NLO QCD corrections to $2 \to 4$ processes at the LHC represents the current technical frontier. The complexity of such calculations triggered the creation of prioritized experimenters wishlists where the $t\bar{t}b\bar{b}$ production ranges among the most wanted candidates [2]. The NLO computation for this process has been completed only very recently in [3] and then confirmed in [4] where we demonstrated the power of our system based on Helac-Phegas[1] [5–7], which has, on its own, already been extensively used and tested in phenomenological studies see *e.g.* [8–11], Helac-1Loop [12], which is not yet publicly available, CutTools[2] [13] and Helac-Dipoles[3] [14] in a realistic computation with six

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[1] http://helac-phegas.web.cern.ch/helac-phegas/

[2] http://www.ugr.es/~pittau/CutTools/

[3] http://helac-phegas.web.cern.ch/helac-phegas/

external legs and massive partons. In the following we briefly summarize the calculation of the virtual and real corrections and present numerical results for the LHC.

2. Virtual corrections

A one-loop n-particle amplitude can be expressed in terms of a basis of known 4-, 3-, 2- and 1-point scalar integrals: boxes, triangles, bubbles and tadpoles. The coefficients depend in general on the dimension of space-time, d, which, upon expansion around $d = 4$, generates a rational function in the invariants (rational term). The concept behind modern methods of evaluation, is the direct determination of the coefficients, without recurring to a Passarino–Veltman reduction.

In our case, the coefficients and one part of the rational term (see [15]) are extracted via the OPP reduction method at the integrand level [16], which is implemented in CutTools. The second part of the rational term coming from the epsilon-dimensional contributions in the numerator is computed with the help of dedicated Feynman rules [17, 18].

The OPP reduction is based on a representation of the numerator of amplitudes, a polynomial in the integration momentum, in a basis of polynomials given by products of the functions in the denominators. Clearly, the cancellation of such terms with the actual denominators will lead to scalar functions with a lower number of denominators. By virtue of the proof provided by the Passarino–Veltman reduction, we will end up with a tower of four-point and lower functions, as mentioned before. The determination of the decomposition in the new basis proceeds recursively, by setting chosen denominators on-shell. This is where the OPP method resembles generalized unitarity [19–25]. For most recent applications see *e.g.* [26–31].

It is important to stress, that working around four dimensions, allows to compute the numerator function in four dimensions. The difference to the complete result is of the order of ϵ, and can, therefore, be determined *a posteriori* in a simplified manner. Since the calculation of the coefficients of the reduction requires the evaluation of the numerator function for a given value of the loop momentum, the corresponding diagrams can be thought as tree level (all momenta are fixed) graphs. To complete the analogy, one needs to chose a propagator and consider it as cut. At this point the original amplitude for an n particle process becomes a tree level amplitude for an $n + 2$ particle process. The advantage is that its value can be obtained by a tree level automate such as Helac. The bookkeeping necessary for a practical implementation is managed by a new software, Helac-1Loop.

To recapitulate, a complete calculation involves three building components: (1) CutTools, for the reduction of integrals with a given numerator to a basis of scalar functions; (2) Helac-1Loop for the evaluation of the numerator functions for given loop momentum (fixed by CutTools); (3) OneLOop[4] [12], a library of scalar functions, which provides the actual numerical values of the integrals. At the end, the 1-loop result is given in the form of real and imaginary parts of the finite term and of the coefficients of the $1/\epsilon$ and $1/\epsilon^2$ poles.

The above procedure provides the bare 1-loop amplitude. Renormalization is performed as usual, by evaluating tree level diagrams with counterterms. For our process, we chose to renormalize the coupling in the $\overline{\mathrm{MS}}$ scheme, but the mass in the on-shell scheme (wave function renormalization is done in the on-shell scheme as it must be). Notice, that also this part is performed in four dimensions. This means, that the whole procedure is equivalent to the 't Hooft–Veltman version of dimensional regularization [32].

Let us emphasise that all parts are calculated fully numerically in a completely automatic manner.

3. Real corrections

The singularities from soft or collinear gluon emission are isolated via dipole subtraction for NLO QCD calculations [33] using the formulation for massive quarks [34] and for arbitrary polarizations [14]. After combining virtual and real corrections, singularities connected to collinear configurations in the final state as well as soft divergencies in the initial and final states cancel for collinear-safe observables automatically after applying a jet algorithm. Singularities connected to collinear initial-state splittings are removed via factorization by PDF redefinitions. We do not use finite dipoles regularizing the quasi-collinear divergence induced by both top quarks moving in the same direction. Due to the large top quark mass, they are not needed to improve the numerical convergence.

Calculations are performed with the help of the Helac-Dipoles software, which is a complete and publicly available automatic implementation of Catani–Seymour dipole subtraction and consists of phase space integration of subtracted real radiation and integrated dipoles in both massless and massive cases. Let us stress at this point, that a phase space restriction on the contribution of the dipoles as originally proposed in [35, 36] is also implemented. All results presented in the next section have been obtained with $\alpha_{\max} = 0.01$ parameter. The phase-space integration is performed with the multichannel Monte Carlo generator Phegas [6] and optimized via Parni[5] [37].

[4] The package includes all divergent and finite scalar integrals, with massless and massive propagators, and with the UV as well as the IR divergencies dealt with within dimensional regularization. It can be obtained from`http://annapurna.ifj.edu.pl/~hameren/`

[5] `http://annapurna.ifj.edu.pl/~hameren/`

4. Numerical results

We present predictions for $pp \to t\bar{t}b\bar{b} + X$ at $\sqrt{s} = 14$ TeV. For the top-quark mass we take $m_t = 172.6$ GeV, while all other QCD partons, including b quarks, are treated as massless. Final states involving collinear gluons and b-quarks are recombined into collinear-safe jets by means of the $k_{\rm T}$-algorithm [38–40]. Specifically we require two b-quark jets with separation $\sqrt{\Delta\phi^2 + \Delta y^2} > D = 0.8$ in the rapidity azimuthal-angle plane. Motivated by the search for a $t\bar{t}H(H \to b\bar{b})$ signal at the LHC [1], we impose the following additional cuts on the transverse momenta and rapidity of the b-quark jets: $p_{\rm T} > 20$ GeV, $|y| < 2.5$. The outgoing (anti)top quarks are neither affected by the jet algorithm nor by phase-space cuts. We use CTEQ6 PDFs [41, 42]. Most precisely we use the CTEQ6M parton distributions at NLO, and the CTEQ6L1 set at LO. The suppressed contribution from b quarks in the initial state has been neglected.

We start with a presentation of the total cross-section at the central value of the scale, $\mu_{\rm R} = \mu_{\rm F} = m_t$ at LO and NLO. At the central scale, the full pp cross-section receives a very large NLO correction of the order of 77%, which is mainly due to the gluonic initial states. The full LO and NLO cross-sections are given by $\sigma_{\rm LO} = 1489.2$ fb and $\sigma_{\rm NLO} = 2636$ fb, respectively. Varying the scale up and down by a factor 2 in a uniform way changes the cross-section by 70% in the LO case, while in the NLO case we have obtained a variation of the order 33%.

Subsequently, in Fig. 1 we show the result for the scale dependence graphically.

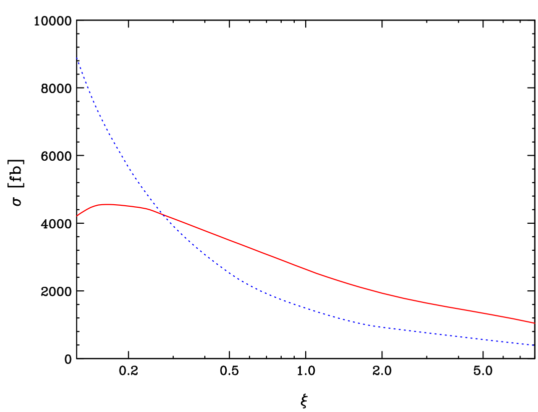

Fig. 1. Scale dependence of the total cross-section for $pp \to t\bar{t}b\bar{b} + X$ at the LHC with $\mu_{\rm R} = \mu_{\rm F} = \xi m_t$. The blue dashed curve corresponds to the leading order, whereas the red solid one to the next-to-leading order result.

In the next step the differential distributions are depicted together with their dynamical K-factors. Invariant mass and rapidity of the two-b-jet system are presented in Fig. 2 and in Fig. 3, respectively. Clearly, the distributions show the same large corrections, which turn out to be relatively constant.

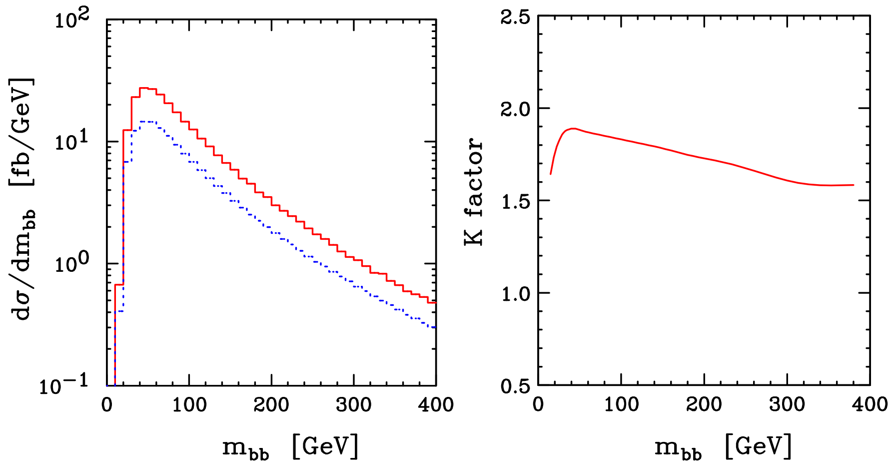

Fig. 2. Left panel: distribution of the invariant mass $m_{b\bar{b}}$ of the $b\bar{b}$ pair for $pp \to t\bar{t}b\bar{b} + X$ at the LHC at LO (blue dashed line) and NLO (red solid line). Right panel: ratio of the NLO and LO distributions.

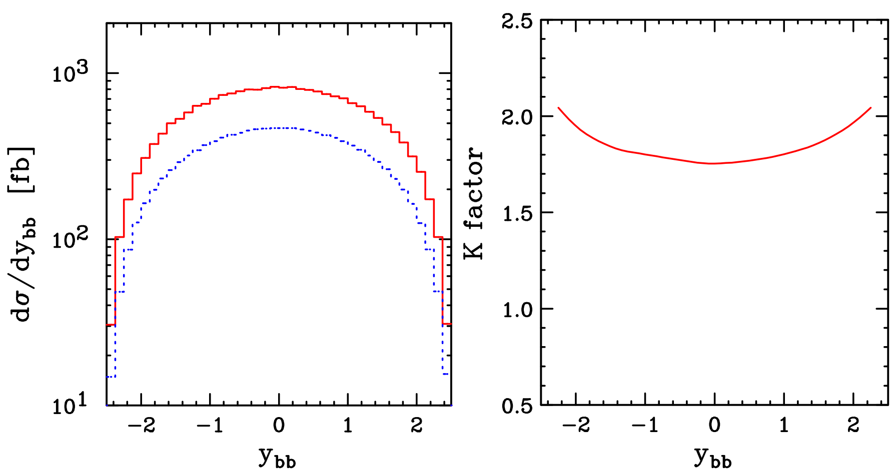

Fig. 3. Left panel: distribution in the rapidity $y_{b\bar{b}}$ of the $b\bar{b}$ pair for $pp \to t\bar{t}b\bar{b} + X$ at the LHC at LO (blue dashed line) and NLO (red solid line). Right panel: ratio of the NLO and LO distributions.

This large scale variation and the size of the corrections themselves, imply that if a meaningful analysis were required in the present setup, additional cuts on extra jets must be introduced in order to reduce the NLO corrections.

5. Summary

A brief summary of the calculations of NLO QCD corrections to the $pp \to t\bar{t}b\bar{b}+X$ process at the LHC has been presented. The QCD corrections to the integrated cross-sections are found to be very large, changing the leading-order results by about 77%. The distributions show the same large corrections. Moreover, the shapes of some kinematical distributions change appreciably compared to leading order. The residual scale uncertainties of the NLO predictions are at the 33% level.

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