

NLO mass effects in $b\bar{b}b\bar{b}$ production at the LHC

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The calculation of NLO QCD corrections to the production cross section of two bottom pairs at the LHC is briefly summarized. We describe the $pp \rightarrow b\bar{b}b\bar{b} + X$ process both in the 4-flavor and 5-flavor scheme and investigate the effect of the finite bottom quark mass. The results for the total cross section and a few differential distributions are presented. They have been obtained with the Nagy-Soper subtraction formalism for real radiation at NLO. A comparison with results based on the traditional Catani-Seymour subtraction is also included.

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1. Introduction

After the discovery of the Higgs boson at the Large Hadron Collider (LHC) by the ATLAS [1] and CMS [2] experiments, a precise determination of its properties is of extreme importance. The determination of the Higgs boson couplings to fermions and gauge bosons as well as the reconstruction of the Higgs potential are among the measurements that are carried out. The $b\bar{b}b\bar{b}$ final state can play an important role in Higgs boson studies at the LHC. For instance, the reconstruction of the Higgs potential requires the measurement of the trilinear Higgs couplings that can be performed in the $pp \rightarrow HH \rightarrow b\bar{b}b\bar{b}$ channel [3–5]. Moreover the $pp \rightarrow b\bar{b}H \rightarrow b\bar{b}b\bar{b}$ production mode where the Higgs boson is radiated off a bottom quark could be used to measure the bottom quark Yukawa coupling [6, 7]. This final state is also of great significance in probing New Physics scenarios, where for example a search for a model-independent s -channel TeV resonance, that decays into a pair of Standard Model (SM) resonances, *e.g.* Z or H , which subsequently decay into four bottom quarks [8], could be performed. Accurate knowledge of the SM background would play a crucial role in devising strategies to look for physics beyond the SM.

In QCD, the $pp \rightarrow b\bar{b}b\bar{b}$ process can be described either in the four flavour scheme (4FS) or in the five flavour scheme (5FS). In the former case bottom quarks appear only in the final state and are massive. They do not enter in the computation of the running of α_s and the evolution of the PDFs. Finite m_b effects enter via power corrections of the type $[(m_b^2/Q^2)]^n$ and logarithms of the type $[\log^n(m_b^2/Q^2)]$ where Q stands for the hard scale of the process. At the LHC, typically $(m_b/Q) \ll 1$ and power corrections are suppressed, while logarithms, both of initial and final state nature, could be large. However, for inclusive observables such as b -jets, logarithms can only originate from nearly collinear initial-state $g \rightarrow b\bar{b}$ splitting. These large logarithms could in principle spoil the convergence of fixed order calculations and a resummation could be required. But up to NLO accuracy those potentially large logarithms, $\log(m_b/Q)$, are replaced by $\log(p_{T,b}^{\min}/Q)$ with $m_b \ll p_{T,b}^{\min} \lesssim Q$ and are less significant numerically. On the other hand, in the 5FS towers of $\log^n(m_b^2/Q^2)$ can be explicitly resummed into the bottom quark PDFs. For consistency with the factorization theorem, one should set m_b to zero in the calculation of the matrix element. Therefore the number of active flavors is $N_F = 5$ and bottom quarks enter in the computation of the running of α_s and evolution of the PDFs. To all orders in perturbation theory those two schemes are identical in describing logarithmic effects. However, the way of ordering in the perturbative expansion is different and at any finite order the results might be different, see *e.g.* [9–11].

NLO calculations for the $pp \rightarrow b\bar{b}b\bar{b} + X$ production in the 5FS with massless bottom quarks have been first performed by the GOLEM collaboration [12, 13]. We have calculated this process using both schemes, 4FS and 5FS, which gave us an opportunity to study the impact of dominant mass contributions [14]. We have also used this process as a testing ground to cross-check our implementation of the newly implemented Nagy-Soper subtraction scheme for both massive and massless cases [15].

In the following we briefly summarize the calculation of the NLO corrections to the $pp \rightarrow b\bar{b}b\bar{b} + X$ process at the LHC in the 4FS and the 5FS. In addition, a comparison with results calculated using the traditional Catani-Seymour subtraction scheme will also be presented.

2. HELAC-NLO Framework

Calculations are performed with the help of HELAC-NLO [16], which is based on the tree level HELAC-PHEGAS framework [17–19]. The package consists of HELAC-1LOOP [20] for the computation of the one loop amplitudes, CUTTOOLS [21], which implements the OPP reduction method to decompose loop integrals into scalar integrals [22–25], and ONELOOP [26] for the evaluation of the scalar integrals. The singularities for soft and collinear parton emission are treated using two subtraction schemes as implemented in HELAC-DIPOLES [27], namely Catani-Seymour [28, 29] and Nagy-Soper [15] subtraction schemes. The idea for the latter subtraction scheme has been first introduced by Nagy and Soper in the formulation of an improved parton shower [30] and later on exploited in a series of papers [31–33]. The phase space integration is performed with the help of the Monte Carlo generator KALEU [34], including PARNI [35] for importance sampling. The HELAC-NLO package has already been widely used in the computation of NLO QCD corrections to several processes at the LHC and the Tevatron [36–41].

3. Numerical Results for the LHC

In the following we present predictions for the $b\bar{b}b\bar{b} + X$ process at the LHC with $\sqrt{s} = 14$ TeV. All final-state partons with pseudorapidity $|\eta| < 5$ are recombined into jets with a resolution parameter $R = 0.4$ via the IR-safe anti- k_T jet algorithm [42]. The four b-jets are required to have

$$p_T(b) > 30 \text{ GeV}, \quad |y(b)| < 2.5, \quad \Delta R(b, b) > 0.4, \quad (3.1)$$

where $p_T(b)$ and $y(b)$ are the transverse momentum and rapidity of the b-jet, whereas $\Delta R(b, b)$ is the separation in the plane of rapidity and azimuthal angle between $b\bar{b}$ pairs. The five and four flavor MSTW2008 sets of parton distribution functions (PDFs) are employed [43, 44]. In particular, we take MSTW2008LO PDFs with 1-loop running α_s in LO and MSTW2008NLO PDFs with 2-loop running α_s in NLO. The renormalization and factorization scales are set to a common value

$$\mu_R = \mu_F = H_T = \sum m_T(b), \quad m_T(b) = \sqrt{m_b^2 + p_T^2(b)}. \quad (3.2)$$

For the four flavour scheme we define the bottom quark mass in the on-shell scheme and use $m_b = 4.75$ GeV.

3.1 Comparison between 5FS and 4FS

The cross section predictions in 5FS and 4FS are collected in Table 1. At the central value of the scale both cross sections receive moderate NLO correction of the order of 40%. The scale dependence is indicated by the upper and lower indices. The upper (lower) index represents the change when the scale is shifted towards $\mu = H_T/2$ ($\mu = 2H_T$). Rescaling the common scale from the default value up and down by a factor 2 changes both cross sections at LO by about 60%. Through the inclusion of NLO QCD corrections scale uncertainties are reduced down to about 30%. In Figure 1 a graphical presentation of the scale dependence is given, both at the LO and NLO. We observe a dramatic reduction of the scale uncertainty while going from LO to NLO.

Comparing 4FS with 5FS results, we observe that the bottom mass effects decrease the NLO cross section prediction by 16%. The difference between the massless and the massive calculations

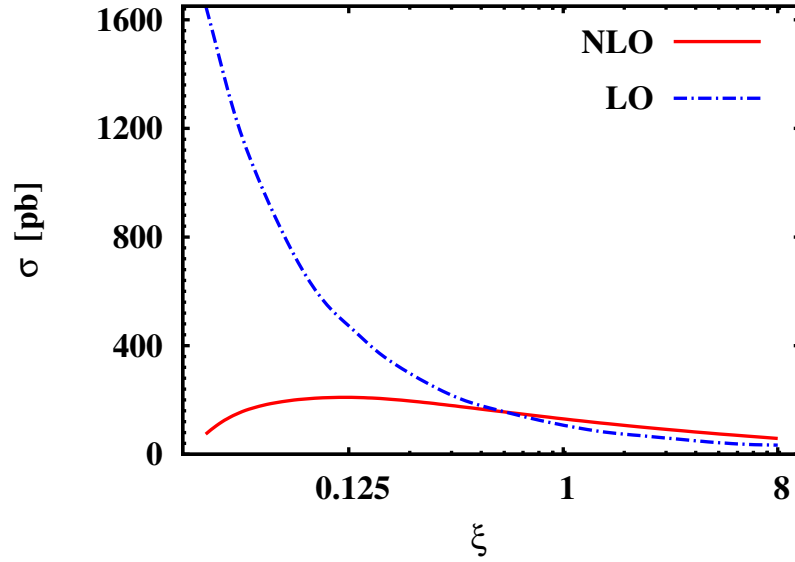


Figure 1: Scale dependence of the 5FS LO and NLO cross sections for $pp \rightarrow b\bar{b}b\bar{b} + X$ at the LHC with $\sqrt{s} = 14$ TeV. The renormalisation and factorisation scales are set to a common value $\mu_R = \mu_F = \xi\mu_0$, where $\mu_0 = H_T$.

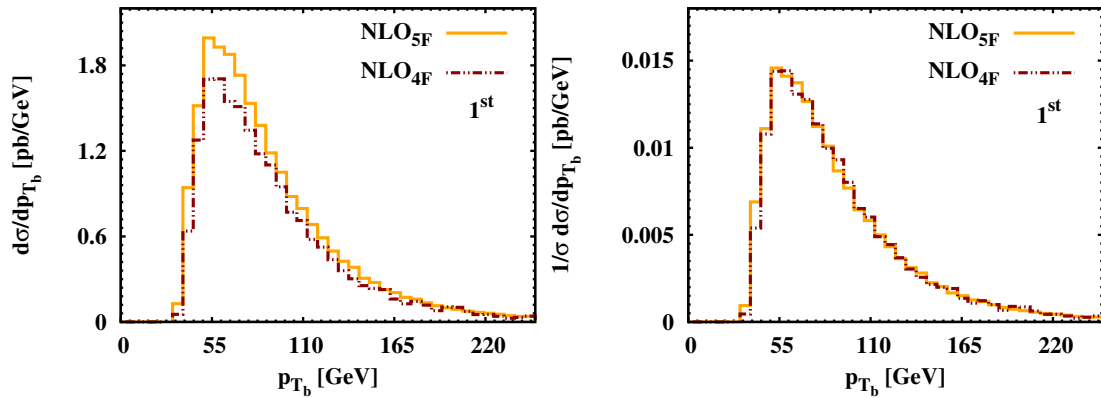


Figure 2: Differential NLO cross section for $pp \rightarrow b\bar{b}b\bar{b} + X$ at the LHC with $\sqrt{s} = 14$ TeV in the 4FS and 5FS as a function of the transverse momentum of the hardest bottom jet. Also shown are the normalised distributions at NLO.

$pp \rightarrow b\bar{b}b\bar{b} + X$	σ_{LO} [pb]	σ_{NLO} [pb]	$K = \sigma_{\text{NLO}}/\sigma_{\text{LO}}$
MSTW2008LO/NLO (5FS)	$99.9^{+58.7(59\%)}_{-34.9(35\%)}$	$136.7^{+38.8(28\%)}_{-30.9(23\%)}$	1.37
MSTW2008LO/NLO (4FS)	$84.5^{+49.7(59\%)}_{-29.6(35\%)}$	$118.3^{+33.3(28\%)}_{-29.0(24\%)}$	1.40

Table 1: 5FS and 4FS LO and NLO cross sections for $pp \rightarrow b\bar{b}b\bar{b} + X$ at the LHC with $\sqrt{s} = 14$ TeV. The theoretical uncertainties and the K -factor are also given.

has two origins. First, we have a genuine bottom mass effect of the order of 10% that depends strongly on the transverse momentum cut and decreases to 1% for $p_T(b)$ higher than 100 GeV. The remaining $\sim 6\%$ variation is due to an interplay of two factors, different pdf sets and different corresponding α_s . The 4FS pdf set does not comprise $g \rightarrow b\bar{b}$ splitting therefore the corresponding gluon flux is much larger than for the 5FS pdf set. On the other hand, the four flavor α_s is smaller than the corresponding value calculated with five active flavors. For the $pp \rightarrow b\bar{b}b\bar{b} + X$ process the difference in α_s dominates, which accounts for a further reduction of the 4FS cross section prediction.

An important input for the experimental analyses and the interpretation of the experimental data are accurate predictions of differential distributions. In Figure 2 the differential distribution in the transverse momentum of the hardest bottom jet, as calculated in the 5FS with massless bottom quarks and in the 4FS with $m_b = 4.75$ GeV is presented. Both, the absolute prediction at NLO, and the predictions normalized to the corresponding 5FS and 4FS NLO inclusive cross sections are shown. The latter plots make it clear that the difference in the shape of the distributions in the 5FS and the 4FS is not significant.

3.2 Comparison between Catani-Seymour and Nagy-Soper subtraction scheme

The calculations have been performed with two different subtraction schemes: the standard Catani-Seymour dipole subtraction, and a new scheme based on the splitting functions and momentum mappings of an improved parton shower by Nagy and Soper. The comparison between the two schemes for the inclusive 5FS and 4FS cross sections is presented in Table 2. Cross sections obtained using both subtraction schemes are in agreement. They provide a validation of our implementation of the new subtraction scheme into HELAC-DIPOLES for the case of massive and massless fermions and allow for a non-trivial internal cross check of the calculation. The results

$pp \rightarrow b\bar{b}b\bar{b} + X$	$\sigma_{\text{NLO}}^{\text{CS}}$ [pb]	$\sigma_{\text{NLO}}^{\text{NS}}$ [pb]
MSTW2008NLO (5FS)	136.7 ± 0.3	137.6 ± 0.5
MSTW2008NLO (4FS)	118.3 ± 0.5	118.0 ± 0.5

Table 2: 5FS and 4FS NLO cross sections for $pp \rightarrow b\bar{b}b\bar{b} + X$ at the LHC with $\sqrt{s} = 14$ TeV. Results are shown for two different subtraction schemes, the Catani-Seymour (CS) dipole subtraction and the new Nagy-Soper (NS) scheme. The numerical error from the Monte Carlo integration is also included.

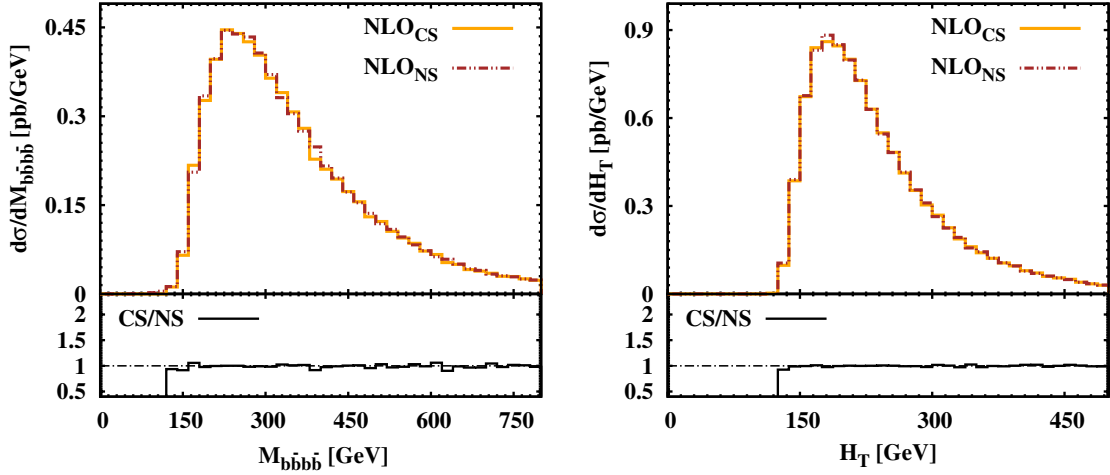


Figure 3: Differential cross section for $pp \rightarrow b\bar{b}b\bar{b} + X$ at the LHC with $\sqrt{s} = 14$ TeV in the 5FS as a function of the $b\bar{b}b\bar{b}$ invariant mass (left panel) and the total transverse energy (right panel). Results are shown for two different subtraction schemes, the Catani-Seymour (CS) dipole subtraction and the new Nagy-Soper (NS) scheme. The lower panels show the ratio of the results within the two schemes.

have also been compared at the differential level. Differential cross sections in the 5FS as a function of the total transverse energy, H_T , and the invariant mass of the four bottom system, $M_{b\bar{b}b\bar{b}}$, are depicted in Figure 3. Again we observe full agreement between the predictions calculated with the two schemes.

4. Summary and Outlook

We report on the next-to-leading order calculation for the production of four bottom quarks at the LHC at the centre-of-mass energy of $\sqrt{s} = 14$ TeV. The higher order corrections significantly reduce the scale dependence, with a residual theoretical uncertainty of about 30% at NLO. The impact of the bottom quark mass is moderate for the cross section normalization and negligible for the shape of distributions. As a completely technical detail, results for inclusive and differential cross-sections have been shown for two subtraction schemes for treating real radiation corrections: Catani-Seymour and Nagy-Soper. They provide a validation of our implementation of the second scheme for massive and massless fermions within HELAC-DIPOLES.

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