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The Higgs boson at high p_T: Finite top-mass improved results

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We present a calculation of $H+j$ at NLO partially including the effect of a finite top-mass. Where possible we include the complete dependence on m_t, this includes the leading order amplitude, infrared poles and the $H+2j$ amplitude for the real radiation. The remaining finite piece of the virtual correction is considered in an asymptotic expansion in m_t.

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1. Introduction

One of the prior goals of the LHC has been fulfilled: finding the scalar boson intimately connected to electroweak symmetry breaking and assessing its compatibility with the Standard Model Higgs boson [1, 2]. Using inclusive and semi-inclusive measurements and predictions, the Standard Model compatibility has been validated to a level of 15-20% within Run I. Analyses based on LHC's Run II will shift toward less inclusive observables to focus on the most promising kinematical regions. New physics will be thoroughly searched for through modified Standard Model couplings, effective field theories, simplified models or UV-complete models [3].

Studying the Higgs boson at large transverse momentum is one of the most promising regions to quantify new physics: At hadron colliders the Higgs boson is predominantly produced through gluon fusion [4], where the coupling of the Higgs boson to the partonic gluons is mediated by a massive top-quark. Analyzing this coupling through an effective field theory leads to one operator of dimension 5, describing a point-like coupling to gluons, the so called heavy top limit (HTL) when matched to the Standard Model. At partonic energies that are small compared to the top-quark mass m_t, the HTL is an excellent description of the Standard Model. A fact that has been used to simplify higher order inclusive calculations, and lead for example to the total inclusive N^{3}LO Higgs production cross section through gluon fusion [5]. Unfortunately this induces a degeneracy between potential heavy new physics which has been integrated out, and maps to the same operator, and the Standard Model.

To lift this degeneracy, which prevents disentangling new physics from Standard Model predictions, Higgs bosons produced at large transverse momenta can be considered [6, 7, 8, 9, 10, 11, 12, 13, 14] or through a direct test of the top-Yukawa coupling in subleading production processes like $t\bar{t}H$. High transverse momenta lead to a resolution of the Higgs gluon coupling, which invalidates the use of the point-like approximation for high precision predictions. Only at leading order in Higgs+jet production is the full top-quark mass dependence known [15, 16]. For the next-to-leading order cross section, mass effects have been estimated through an asymptotic expansion [17, 18], limiting the effect of a finite m_t to a few percent up to $p_T \simeq m_t$. NNLO corrections have only been performed in the HTL and are sizable [19, 20, 21, 22]. To reach this separation, a full NLO calculation including the full top-mass dependence is mandatory though, as well as using the NNLO corrections. For future TeV colliders [3] the issue of gluon fusion predictions with a finite top-quark mass will clearly be even more severe. Recently a leading-log high-energy resummation technique, exact in m_t, has been applied to the Higgs p_T distribution [23, 24]. This corrects the badly failing HTL approximation for high energies.

First differential measurements of the Higgs boson performed by CMS and ATLAS [25, 26, 27, 28, 29, 30, 31, 32] for Run I data are available. To continue the improvement program of Standard Model predictions, we compute all parts of $H+$jet production through gluon fusion at NLO with full top-mass dependence except for the two loop integrals contributing to the virtual corrections. These are computed in an asymptotic expansion in the top-quark mass. A similar recent study has been performed, which uses the complete virtual correction in the heavy top limit reweighted by the m_t-exact born cross section [33]. We show that using our improved result the dependence of the asymptotic expansion, compared to previous results [17, 18] is considerably reduced.

2. Calculation

We have calculated a H+jet production at NLO accuracy which is fully differential, and implemented it as a Monte-Carlo code in MCFM [34]. It is, up to the virtual corrections, exact in the top-quark mass. The virtual corrections are considered in an asymptotic expansion in $1/m_t$.

For this calculation the major necessary pieces were computed as follows:

- m_t-exact born amplitudes to calculate the LO piece and the necessary Catani-Seymour subtractions were taken from ref. [35, 36], see also [37, 16].
- m_t-exact real emission amplitudes were calculated in Mathematica[1] using unitarity methods: In particular, box and triangle coefficients, as well as the rational pieces, were calculated with D-dimensional generalized unitarity [39]. Bubbles were computed using Stokes' Theorem spinor integration [40]. The amplitudes were checked using an in-house implementation of the D-dimensional unitarity method [41].
- The asymptotic expansion [42, 43] of the two-loop virtual corrections has been performed with the setup exp/q2e [44, 45, 46]: The massive one- and two-loop tadpoles are computed with MATAD [46], massless one-loop integrals are reduced to scalar master integrals with Reduze [47]. The assembly relies on FORM [48].

We combine the exact top-mass dependent real emission with the virtual corrections in the asymptotic expansion. The code is based on the Catani-Seymour dipole subtraction [49], where the insertion operator to provide a finite virtual correction is constructed from the asymptotically expanded born cross section. Full top-mass dependent born dipole subtraction terms are used to make the real emission finite.

Using QCDLoop [50, 51] for the scalar master integrals, all parts are assembled in the MCFM framework. For singular regions in the real emission we dynamically switch between double and quad precision.

Our input parameters are $\sqrt{s} = 14\,\text{TeV}$ for the center of mass energy, $m_H = 125\,\text{GeV}$ for the Higgs boson mass, $m_t = 173.5\,\text{GeV}$ for the on-shell top-quark mass, and $\mu_R = \mu_F = \sqrt{m_H^2 + p_{Tx,H}^2}$ for a common renormalization and factorization scale. We use CT14 NLO PDFs [52].

3. Results

Previous studies mainly used the asymptotic expansion in $1/m_t$ to assess the validity of the commonly used, and at best rescaled, heavy top limit results [17, 18]. The goal of our upcoming study

[1] We made frequent use of the spinor helicity library S@M [38].

[53] is to go beyond an assessment, and provide improved predictions that take into account a finite top-quark mass as much as possible. By using asymptotic expansions in the remaining two-loop virtual corrections, which are the only pieces left unknown in the full theory, we show that the dependence on the asymptotic expansion decreases significantly. Our preliminary results here are a step toward this goal: they use the fully asymptotically expanded virtual corrections, where both parts parts of the interference, born piece and two-loop part, are expanded. Our fully improved virtual corrections [53] will consist of the exact born piece interfered with the expanded two-loop part, thus further reducing the dependence on the asymptotic series.

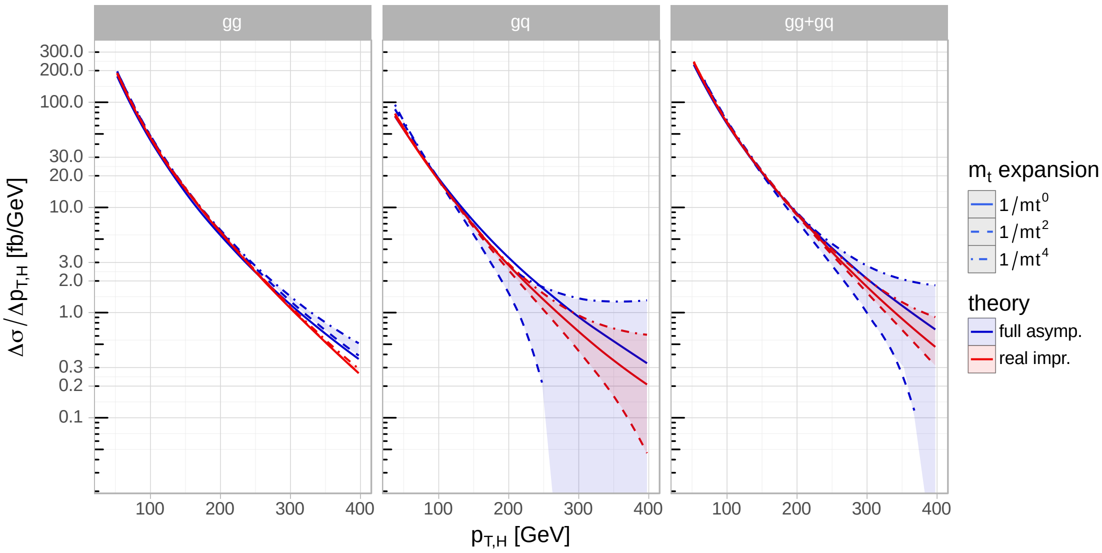

Figure 1: NLO Higgs inclusive p_T spectrum in different orders of the asymptotic expansion, where for "theory = full asymp." the asymptotic expansion is used in all parts, and for "theory = real impr." only the virtual part is in the asymptotic expansion. To guide the eye in the reduction on the dependence of the asymptotic expansion, a shading has been applied. The spectrum is split by initial state channels, containing either two gluons or a quark/antiquark and a gluon, or the sum. The channels with two initial state quarks, which only start contributing at NLO through the real emission are left out; see text.

In Figure 1 the NLO Higgs p_T spectrum is shown in different orders of the asymptotic expansion. No (jet) cuts are applied beyond $p_{T,H} > 30\,\text{GeV}$, so the cross section is Higgs inclusive. Because the asymptotic expansion for the gluon-gluon initiated partonic channel converges better than the gluon-quark one, for academic interest, we perform the unphysical split by these partonic channels and include the sum. The channel with two initial state quarks/antiquarks is left out here, since it only begins to contribute at NLO through the real emission, and is only a minor contribution, while the asymptotic expansion also rapidly diverges, even at low energies. Figure 1 only shows the dependence on the asymptotic expansion, and in our implementation this channel is of course included with the full m_t dependence [53].

Comparing the full asymptotic expansion with our exact real emission improved result, we find a significant decrease in the dependence on the asymptotic expansion. More detailed phenomenological studies are in preparation [53].

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