

On the NNLO QCD corrections to single-top production at the LHC

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We present a fully-differential calculation of the NNLO QCD corrections to the t -channel mechanism for producing single top quarks at the LHC. We work in the structure function approximation, computing QCD corrections to the light- and heavy-quark lines separately and neglecting the dynamical cross-talk between the two. The neglected contribution, which appears at NNLO for the first time, is color-suppressed and is expected to be sub-dominant. Within this approximation, we find that, for the total cross section, NNLO QCD corrections are in the few percent range and, therefore, are comparable to NLO QCD corrections. We also find that the scale independence of the theoretical prediction for single-top production improves significantly once NNLO QCD corrections are included. Furthermore, we show how these results change if a cut on the transverse momentum of the top quark is applied and derive the NNLO QCD prediction for the ratio of single top and single anti-top production cross sections at the 8 TeV LHC.

I. INTRODUCTION

Studies of top quarks produced in hadron collisions are important for understanding many properties of these heavy particles, including their masses, their couplings to electroweak gauge bosons, their Cabbibo-Kobayashi-Maskawa matrix element V_{tb} etc. In many cases, the precision reached in measuring these quantities is already close to a few a percent, thanks to the successful top quark physics programs at the Tevatron and the LHC. Further high-statistics data samples, that will become available during a forthcoming 13 TeV run of the LHC, will remove statistical uncertainties as a limiting factor for these measurements (see e.g. [1]). As the result, theoretical uncertainties related to imprecise knowledge of production cross sections and kinematic distributions will become an important limiting factor in pushing precision measurements forward.

There are two main mechanisms for producing top quarks in hadron collisions. Both at the Tevatron and the LHC, the dominant one occurs due to strong interactions and, through such processes as $q\bar{q} \rightarrow t\bar{t}$ or $gg \rightarrow t\bar{t}$, leads to the production of $t\bar{t}$ pairs. The theoretical description of this production mechanism is very advanced; it includes NLO QCD and electroweak corrections, soft gluon resummations and, since recently, complete NNLO QCD corrections [2–7]. The second mechanism is governed by weak interactions and relies on the flavor changing transitions $W^* \rightarrow tb$, $b \rightarrow tW$ or $W^*b \rightarrow t$ to produce single top (or anti-top) quarks. Although sub-dominant relative to $t\bar{t}$ pair production, this mechanism yields a sizable fraction of top quark events both at the Tevatron and the LHC. Experimental conditions for studying single-top production at the two colliders are however, very different. Indeed, when top quarks decay, they

produce leptons, missing energy and b -jets. Correspondingly, the main background for observing single-top production at a hadron collider is the direct production of W bosons in association with jets in general and with b -jets in particular. The severity of this background and the relative smallness $\mathcal{O}(1 \text{ pb})$ of the single-top production cross section made detailed studies of this process at the Tevatron very difficult. Nevertheless, the CDF and D0 collaborations confirmed the existence of the electroweak production mechanism for top quarks and measured the cross section for this process with, approximately, twenty percent precision [8–11]. Since the single-top production cross section is proportional to the electroweak coupling of a top quark to a W -boson, a $\mathcal{O}(20\%)$ measurement of the production cross section can be interpreted as a $\mathcal{O}(10\%)$ measurement of the CKM matrix element $|V_{tb}|$ or a $\mathcal{O}(20\%)$ measurement of the top quark width.

Experimental conditions improve dramatically at the LHC where the single top quark production cross section is significantly higher, approximately 60 pb at the 8 TeV LHC and 160 pb at the 14 TeV LHC. Given that expected integrated LHC luminosities are in the range of a few hundreds inverse femtobarns, millions of top quarks will be produced at the LHC by virtue of electroweak interactions alone, making high-precision studies of this production mechanism an important part of the experimental program. Indeed, already in the first run of the LHC, ATLAS and CMS collaborations improved significantly on the CDF and D0 results, by measuring the single-top -production cross sections with a ten percent accuracy [12–16]. Similar to what we discussed in the context of the Tevatron, such a measurement can be interpreted as a $\mathcal{O}(5\%)$ measurement of $|V_{tb}|$ and a $\mathcal{O}(10\%)$ measurement of the top quark width. This is the highest experimental precision available for these quantities currently.

It is important to emphasize that there are several experimentally distinguishable ways to produce single top quarks through electroweak interactions. Indeed, writing the primary electroweak tbW -vertex in three different ways, $W^*b \rightarrow t$, $W^* \rightarrow tb$, $b \rightarrow tW$, we obtain dis-

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tinct mechanisms for single top quark production that are usually referred to as the t -channel ($W^*b \rightarrow t$) process, the s -channel process ($W^* \rightarrow tb$) and the tW production ($b \rightarrow Wt$). Among these three mechanisms, the t -channel process has the largest cross section both at the 8 TeV LHC and at the Tevatron contributing, respectively, 82% and 65% to the total cross section σ_t . The s -channel process is 33% of σ_t at the Tevatron and is about 5% at the 8 TeV LHC. The tW production is negligible at the Tevatron and contributes $\mathcal{O}(15\%)$ to σ_t at the 8 TeV LHC. However, since tW production can be distinguished from the other two mechanisms, it is usually treated separately in experimental analyses. Also, we note that for the higher-energy LHC, the t -, s - and tW production channels contribute in similar proportions as for the 8 TeV LHC.

Theoretical results for single top quark production are available at an ever increasing level of sophistication. These include NLO QCD and electroweak predictions in four- or five-flavor scheme for both stable [17–21] and decaying [22–30] top quarks, resummations [31–34] and fixed order computations matched to parton showers [35–38]. Focusing on NLO QCD corrections, we note that they are small, of the order of a few percent, for the t -channel single-top production. On the other hand, NLO QCD corrections for the s -channel single-top production are large, of the order of fifty percent, both at the Tevatron and the LHC. Corrections to the associated tW production are known to be moderate at both colliders [23].

We note that the smallness of the NLO QCD corrections to the t -channel single-top production cross section is the result of strong cancellations between different sources of such corrections, e.g. different partonic channels. It is unclear if these cancellations are accidental or generic and if the smallness of NLO QCD corrections implies that NNLO QCD corrections are, in fact, even smaller as should be the case for convergent perturbative series. The most obvious reflection of this fact is the strong sensitivity of the NLO QCD prediction for t -channel single-top production to choices of factorization and renormalization scales. In fact, the sensitivity of the NLO QCD corrections to these scales is comparable to the size of corrections themselves. Therefore, if the scale variation is an indication of the size of missing higher-order QCD corrections, it is tempting to conclude that NLO QCD corrections to t -channel single-top production cross section are *accidentally* small and that the natural size of NNLO QCD corrections to this process is at a few percent level. Therefore, we expect that NLO and NNLO QCD corrections to the single-top production cross section are of a similar size. This implies that NNLO QCD corrections to t -channel single-top production cross section must be computed to enable studies of electroweak production of top quarks at the LHC with a percent accuracy.

The goal of this paper is to make the first step towards a high-precision prediction for the single-top pro-

duction at the LHC, by providing fully-differential NNLO QCD corrections to the t -channel single top quark production in the approximation where corrections to light quark $q \rightarrow q'W^*$ and heavy quark $W^*b \rightarrow t$ weak transitions are treated (almost) independently from each other. More precisely, we neglect all dynamical cross-talk between corrections to the light and heavy quark lines, which then depend on each other only through kinematic phase-space constraints. At NLO, this approximation is exact due to color conservation. At NNLO however, the exchange of two (real or virtual) gluons in a color-singlet state between light and heavy quark lines, shown in Fig. 1d, leads to a non-vanishing contribution to the cross section. We expect this contribution to be small since it is suppressed by at least two powers of the number of colors $N_c = 3$ relative to the “factorizable” contributions shown in Fig. 1a-c. Therefore, we neglect the non-factorizable contributions in the rest of the paper.

The paper is organized as follows. In Section II we briefly discuss the technical details of the calculation. In Section III we show some results for NNLO QCD corrections to single-top and single anti-top production at the 8 TeV LHC. We conclude in Section IV.

II. TECHNICAL DETAILS OF THE CALCULATION

Our goal is to compute NNLO QCD corrections to t -channel single top quark production. The top quarks are considered stable. In the approximation where only factorizable corrections are retained, the calculation can be divided into three different parts. We need to compute *i*) NNLO QCD corrections to the weak transition on a heavy quark line $W^*b \rightarrow t$, c.f. Fig.1a; *ii*) NNLO QCD corrections to the weak transition on a light quark line $u \rightarrow W^*d$, c.f. Fig.1b; and *iii*) a product of NLO QCD corrections to weak transitions on both heavy and light quark lines, c.f. Fig.1c. These three contributions are individually infra-red and collinear finite, gauge invariant, and can be considered separately. We now briefly illustrate some of the technical details of our computation, starting from corrections to the heavy quark line.

As a preliminary remark, we note that the computation of NNLO QCD corrections to a process X requires three ingredients: 1) two-loop QCD corrections to X ; 2) one-loop QCD corrections to X +jet and 3) tree-level matrix element for the $X + 2$ jet process. All of the required ingredients to compute NNLO QCD corrections to the $W^*b \rightarrow t$ transition, for arbitrary invariant mass of the W -boson, can be obtained by crossing the two-loop, one-loop and tree amplitudes used by us recently in the computation of NNLO QCD corrections to top quark decay $t \rightarrow W^*b$ [39]. This crossing is straightforward for one- and two-loop virtual amplitudes to the $0 \rightarrow tW\bar{b}$ vertex [40–44] (since they depend on a very small number of kinematic invariants) and for tree-level amplitudes $t \rightarrow bW^*gg$ and $t \rightarrow W^*bq\bar{q}$. The crossing