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New predictions for single top production at hadron colliders

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Summary. — We present the next-to-leading order calculation for single-top production at hadron colliders. Our approach is novel in the fact that the calculation has been performed starting from the $2 \to 3$ Born process, $qg \to q'tb$, keeping the b-quark massive. A first comparison with the predictions based on the $2 \to 2$ Born process, using the b distribution function, is shown. Finally, we present, for the first time, the NLO prediction for the differential distributions of the spectator b both at the Tevatron and at the LHC.

PACS `13.85.-t` – Hadron-induced high- and super-high-energy interactions.
PACS `14.65.Ha` – Top quarks.
PACS `14.70.Fm` – W bosons.

1. – Introduction

The electroweak production of a single top quark at hadron colliders is an interesting process to study for at least two reasons: first, at the Tevatron [1, 2] it allows for a further test of the Standard Model (SM) weak current where the top is involved and, second, the accurate knowledge of the total cross-sections as well as of the distributions is mandatory as single-top is an important background to Higgs boson as well as new physics beyond the Standard Model scenario. In the SM there are three channels to produce a single top [3-5]: the s-channel, the t-channel and the Wt associated production. Their total cross-sections, at Next to Leading Order (NLO) in the strong coupling constant, are reported in table I. Many previous NLO single top results can be found in refs. [6-15]. In table I we included the cross-section for the production of a $t\bar{t}$ pair. One can see that the single top cross-section is between 1/2 and 1/3 of the $t\bar{t}$ cross-section both at the Tevatron and the LHC. This is because the smallness of the weak coupling, with respect to the strong coupling, is partially compensated by the larger phase space available in the production of one top quark only. Nevertheless, in spite of the hundreds of $t\bar{t}$ pairs reconstructed at the Tevatron so far, the way to extract the single top signal is still a source of intense activity, due to large backgrounds mainly from $t\bar{t}$ and W plus jets events [16]. The t-channel and Wt processes are usually represented with a b quark

Table I. – *Next-to-leading order cross-sections for single top production channels and for $t\bar{t}$ production both at the Tevatron and at the LHC.*

Process	$p\bar{p}$ $\sqrt{s} = 1.96\,\mathrm{TeV}$	pp $\sqrt{s} = 14\,\mathrm{TeV}$
s-channel	0.872 pb	10.4 pb
t-channel	1.92 pb	245 pb
tW	0.143 pb	68.7 pb
$t\bar{t}$	6.7 pb	870 pb

in the initial state. This correspond to the standard approach to study the single top cross-section and other processes, based on the fact that the main contribution to this process comes from a gluon splitting into a $b\bar{b}$ pair in the collinear limit. The logarithm of the transverse b quark momentum can be resummed by defining a b parton distribution function (pdf) and including it in the evolution equations (5-flavour scheme). This approach is simpler than assuming explicitly the gluon splitting and has the advantage to finally produce a resummed result for the total cross-section that is expected to be more precise with respect to a gluon-initiated calculation. From now on we will call "resummed" the NLO result obtained starting from the 2 to 2 Born t-channel process using the b-pdf and "not resummed" the one obtained from the 2 to 3 Born diagrams of fig. 1. There are two main reasons to perform a full NLO calculation starting with a gluon in the initial state, as represented in fig. 1: first, in the resummed approach the b-pdf is calculated, so that the theoretical uncertainty on the derived results is hard to compute and could have been underestimated in the past. This can be supported from the fact that there have been quite significant changes in the b distributions both in the MRST and CTEQ sets [17, 18]. Second, from the experimental point of view, tagging the second b quark is only possible in the not-resummed approach.

2. – Calculation and results

In ref. [19] we presented the NLO calculation for the non resummed process. All the calculations have been done in the helicity formalism so that the top spin information is retained. The real corrections have been evaluated with FORM [20] and checked with MadGraph/MadEvent [21]. We treated the divergences using the subtraction method in the formulation given in refs. [22, 23] and checked the counterterm with an independent code (MadDipole [24]). The virtual contributions have been computed adopting an anticommuting γ_5 and adding finite counterterms to restore the Ward identity, violated by ultraviolet divergent triangle diagrams. We also checked gauge invariance, $m_b \leftrightarrow m_t$ and CP symmetry. The most interesting check we made on the whole calculation comes from

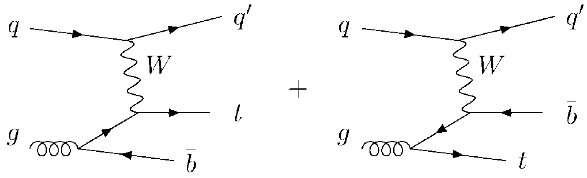

Fig. 1. – Leading order graphs for $qg \to q'tb$.

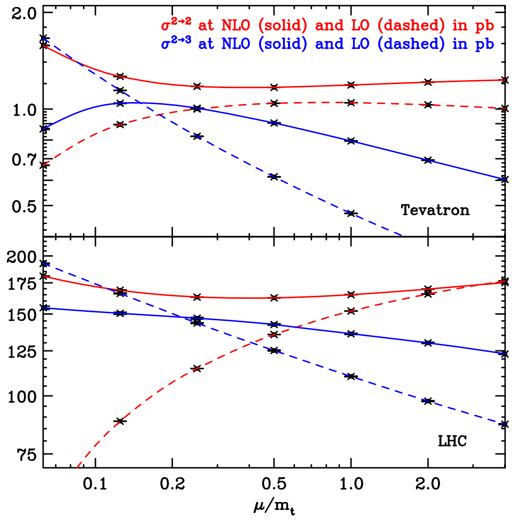

Fig. 2. – Variation of the total cross-section at NLO with respect to the renormalization and factorization scales for both the resummed and the not resummed calculation.

crossing the W virtuality and setting $m_t = m_b$. In this way, we reproduced, with excellent agreement, the result for $e^+e^- \to b\bar{b}g$ at NLO of ref. [25]. All the calculations have been implemented in the general purpose partonic Monte Carlo program MCFM [26].

In fig. 2 we present the scale dependence of the total cross-section, for the resummed and not resummed case. In table II we compare the results for the total cross-section. We argue that the effect of the resummation is limited and that the two calculations are compatible both at the Tevatron and the LHC. The distributions for the top quark and the light jet can be found in ref. [19] and are very similar for the two calculations. For the spectator b-jet we present the distributions in fig. 3. In the $2 \to 2$ calculation, the spectator b appears at NLO so that the accuracy evaluating its distributions is comparable to the one obtainable at LO within the $2 \to 3$ calculation. This has an impact when, for example, the acceptance of the signal, as a function of the p_T of the spectator b, is estimated. Starting from the resummed result this acceptance is the ratio of a LO quantity over a NLO one. In the non-resummed calculation, it is the ratio of two genuine NLO quantities, so that the scale dependency is very mild. As an example,

Table II. – *Next-to-leading order t-channel total cross-sections. The central values are calculated with $\mu_L = m_t/2$, $\mu_H = m_t/4$ with, μ_L, μ_H the factorization scale for the massless and massive quark line, respectively, using the CTEQ6.6 pdf set. The first error refers to the scale dependence, the second to the pdf uncertainty.*

Born process	TeV $t(=\bar{t})$ (LO) NLO	LHC t (LO) NLO	LHC $\bar{t}$ (LO) NLO
$2 \to 2$	$(0.92)\ 1.00^{+0.03\ +0.10}_{-0.02\ -0.08}$	$(153)\ 156^{+4\ +3}_{-4\ -4}$	$(89)\ 93^{+3\ +2}_{-2\ -2}$
$2 \to 3$	$(0.68)\ 0.94^{+0.07\ +0.08}_{-0.11\ -0.07}$	$(143)\ 146^{+4\ +3}_{-7\ -3}$	$(81)\ 86^{+4\ +2}_{-3\ -2}$

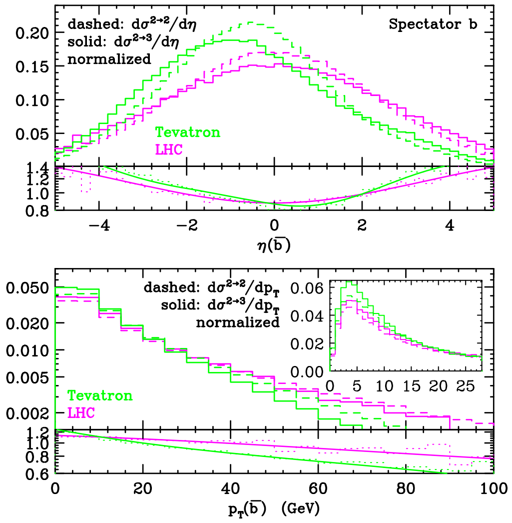

Fig. 3. – Rapidity (η) and p_T distributions of the spectator $\bar{b}$ quark for the 2 → 3 and 2 → 2 calculations.

in fig. 4 we show the mentioned scale dependence for the acceptance of a second b with $p_T > 20\,\text{GeV}$ and $|\eta| < 2.5$ at the Tevatron and LHC energy. We conclude with a list of the possible extensions of our work: understanding the impact of our results on the single top analysis at Tevatron, include the top decay, study the implications for other processes with a heavy quark in the initial state, include the present result in a Monte Carlo program with showering and hadronization. Finally, we plan to apply our calculation to the prediction of the weak production of fermions of a fourth family.

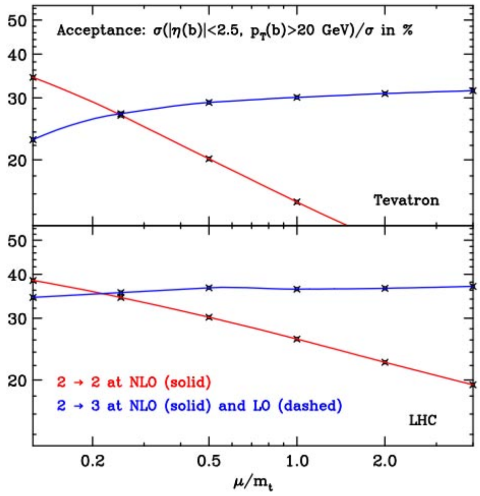

Fig. 4. – Signal acceptance for the second b with $|\eta| < 2.5$ and $p_T > 20\,\text{GeV}$ at the Tevatron, as a function of the factorization scale.

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