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Predictions for single-top cross sections

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Summary. — In this paper we give an overview of the theory status for the predictions of single-top cross sections via the s and t channels.

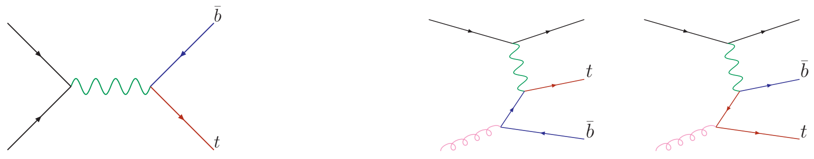
PACS 14.65.Ha – Top quarks.
PACS 12.38.Bx – Perturbative calculations.

1. – Introduction

The measurement of the single-top production cross section plays a significant role in the physics program at the Tevatron, and will also be very important at the LHC. For example, the single top production channel is the only effective way of directly measuring the CKM matrix element $|V_{tb}|$.

At the lowest order in perturbation theory, there are three distinct production mechanisms for single top quarks. All three modes are based on an electroweak process in which a W boson connects the top quark with a bottom quark. The mechanisms are named after the virtuality of the W boson.

- For s-channel single-top production the top quark is produced from a W boson in the s channel [1, 2]. It is produced together with a bottom quark, see fig. 1(a) for the Born-level Feynman diagram.
- In the second channel, t-channel single top production, the top quark is produced from a space-like W boson [3-5]. The W boson converts an incoming bottom quark to a top quark. This bottom quark can either be described as coming directly from the proton, *i.e.* with a PDF, or from an explicit gluon splitting, see fig. 1(b). They are called the 5-flavor and 4-flavor descriptions, respectively.
- The third channel is top production associated with a W boson [6, 7]. In this case, the W boson is produced (almost) on-shell. This mechanism, that plays no significant role at the Tevatron, will not be discussed in more details here. For



(a) (b)

Fig. 1. – Born diagram for s-channel (a) and 4-flavor t-channel (b) single-top production.

a recent discussion of this process at the LHC and it problems in disentangling it from top pair production, see refs. [8, 9].

Although higher orders in perturbation theory trouble the clear Born-level distinction of the three production mechanisms due to interference effects, these contributions are in general color suppressed as well as kinematically disfavored. Therefore, for phenomenologically relevant studies they can safely be neglected.

For all the three channels there has been an intense activity in the last fifteen years to provide more precise predictions at NLO accuracy. Calculations have progressed from evaluations of total rates [10, 11], to differential distributions [12-15], including spin correlations in production and decay [16-19] and finally to the implementation of the three production channels in a fully exclusive Monte Carlo program [20-22]. Recently also the non-factorisable corrections between the production and decay of the top quark were computed for the t-channel process [23], while for the s channel they were known for quite some time already [24]. The complete electroweak corrections in the SM and MSSM have been presented in ref. [25] for the t channel and very recently also for the s channel [26].

2. – s channel

Electroweak top production via an s-channel W-boson exchange is the second largest source for single top quarks at the Tevatron; just after the t-channel mode. The cross section is about 0.8 pb. The large cross section has a relative enhancement over Standard Model (SM) backgrounds due to the domination of valence quarks in the proton–anti-proton collisions at the Tevatron. At the LHC the process is dominated by quarks from the proton sea, which is the reason that the cross section is only about a factor 5 (12) larger for a collision energy of 7 (14) TeV. This makes this channel challenging to detect at the LHC.

From a theoretical point of view this channel is under great control. It is very similar to the Drell-Yan process, and the NLO corrections are small. The (inclusive) theoretical predictions at NLO are given in table I.

The s channel is also of interest for studies of physics beyond the Standard Model (BSM). In the SM the production cross section is directly proportional to $|V_{tb}|^2$ which means that a measurement of the total cross section gives bounds on the CKM matrix element(s). Furthermore, it is sensitive to heavy (charged) New Physics resonances, like a W' or charged Higgs. A resonance could show as a peak in the $t\bar{b}$ invariant mass.

TABLE I. – *Cross sections for s-channel single-top production at NLO. Uncertainties from scale variations are estimated by varying the renormalization and factorization scales independently by a factor 2 around the central scale (which was chosen to be the top quark mass). PDF uncertainties are estimated by using the 44 eigenvectors sets from the CTEQ6.6 PDF set, and the uncertainties on the top quark mass are taken to be 1%, $m_t = 172 \pm 1.7\,\mathrm{GeV}$. The b quark mass has been neglected.*

$\sigma^{\rm NLO}_{\rm s\text{-}ch}(t+\bar{t})$		scale	PDF	m_t	
Tevatron Run II	0.858	$^{+0.023}_{-0.021}$	$^{+0.015}_{-0.016}$	$^{+0.018}_{-0.017}$	pb
LHC (7 TeV)	4.02	$^{+0.12}_{-0.09}$	$^{+0.15}_{-0.16}$	$^{+0.16}_{-0.15}$	pb
LHC (14 TeV)	10.58	$^{+0.34}_{-0.23}$	$^{+0.34}_{-0.34}$	$^{+0.40}_{-0.35}$	pb

3. – t channel

The t-channel single-top production mechanism is the largest of the three both at the Tevatron as well as the LHC, with a cross section of about 2 pb at the Tevatron and 60 (240) pb at the LHC at 7 (14) TeV collision energy. This is only a factor 3-4 smaller than top pair production, which is governed by the strong force. This is mainly due to the sizable gain in phase-space and the t-channel enhancement at high energies due to the space-like W boson. Like the s channel, also these production cross sections are proportional to $|V_{tb}|^2$.

From a BSM point of view of particular interest is the fact that due to the t-channel enhancement and smaller phase space compared to top pair production, the cross section for heavy (4th family) fermion production is relatively large. In fig. 2 the total cross sections of t-channel, s-channel and top pair production are shown as a function of the top quark mass. The dependence on the top quark mass is much milder for the t channel compared to the other two production mechanisms. Furthermore, this channel is of interest in the context of flavor-changing neutral currents related to the coupling with

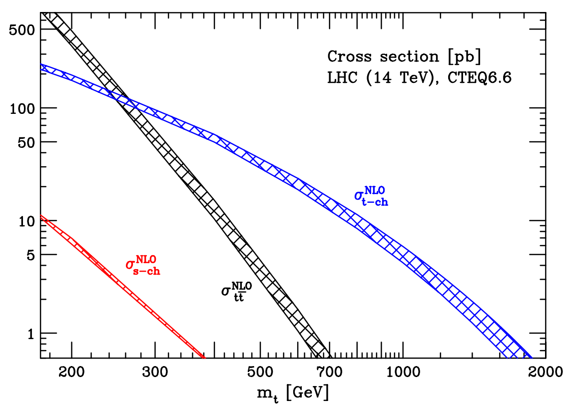


Fig. 2. – NLO cross sections in pb for s- and t-channel single top and top pair production at the LHC (14 TeV) as a function of the top quark mass. These cross sections are identical to cross sections corresponding to a (SM-like) 4th family t' if the CKM matrix element $|V_{t'b}| \simeq 1$.

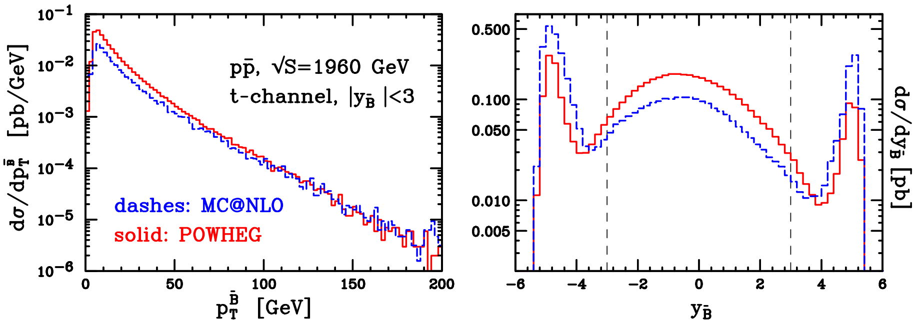


Fig. 3. – Comparisons between POWHEG and MC@NLO results for the hardest b-flavoured hadron transverse momentum (left) and rapidity (right), for t-channel single-top production at the Tevatron. Rapidity cuts are highlighted. Plots taken from ref. [22]. Results in these two plots are for top production, anti-top is similar.

the top quark, which can be enhanced due to larger parton luminosities for charm (and up) quarks compared to bottom quarks.

Compared to the s-channel production channel, the t-channel is theoretically less well understood. In particular, the initial state b quark can be treated in two different ways. In the (commonly-used) five-flavor scheme, it is considered to be part of the proton, with its luminosity described by a PDF set. In this treatment the bottom quark has to be considered massless at leading order. Its mass enters in (some of) the higher-order corrections, in particular when the b quark is not initial state. In general these mass effects are neglected. Also, the mass enters in the starting scale for the evolution of the bottom quark in the PDF set. In the four-flavor scheme the bottom quark mass is taken to be non-zero already at the lowest order and it is unsuitable for a description by a PDF. Indeed, the b quark has to come from an explicit initial state gluon splitting to a $b\bar{b}$ pair. At lowest order this leads to a $2 \to 3$ process, see fig. 1(b). The two descriptions agree when all orders in perturbation theory are included, but there can be sizable differences when the series is truncated at a given order. These differences could arise from the fact that in the 5-flavor description potentially large logarithms of m_b^2/Q^2 are resummed in the PDF, while in the 4-flavor description also the non-logarithmic contributions to the $g \to b\bar{b}$ splitting are taken into account.

When using a LO prediction (in the 5-flavor scheme) together with a parton shower to get a fully exclusive description of the final state, the “spectator” b-quark distributions are not well described. Prescriptions of using matching of the $2 \to 2$ and $2 \to 3$ descriptions of the process have been proposed [27], but are theoretically not very appealing and come with large uncertainties. Even when starting from the NLO description (in the 5-flavor scheme) matched to a parton shower, as is done in MC@NLO [20] and POWHEG [22], it has a not so satisfactory prescription of the spectator bottom quark. In particular when matched to the HERWIG shower, the rapidity distribution shows strange “horns”, see fig. 3, and even when they are cut away (by nominal detector acceptance cuts), the differences in normalization between MC@NLO and POWHEG are sizable. In short, a (N)LO 5-flavor scheme calculation does not describe the spectator b-quark very well.

On the other hand, the NLO corrections to single top production in the 4-flavor scheme have been calculated recently [28, 29]. Because even at LO there is an explicit final state b-quark in the description, calculating the NLO corrections gives for the first time a true NLO prediction for distributions of the spectator b.

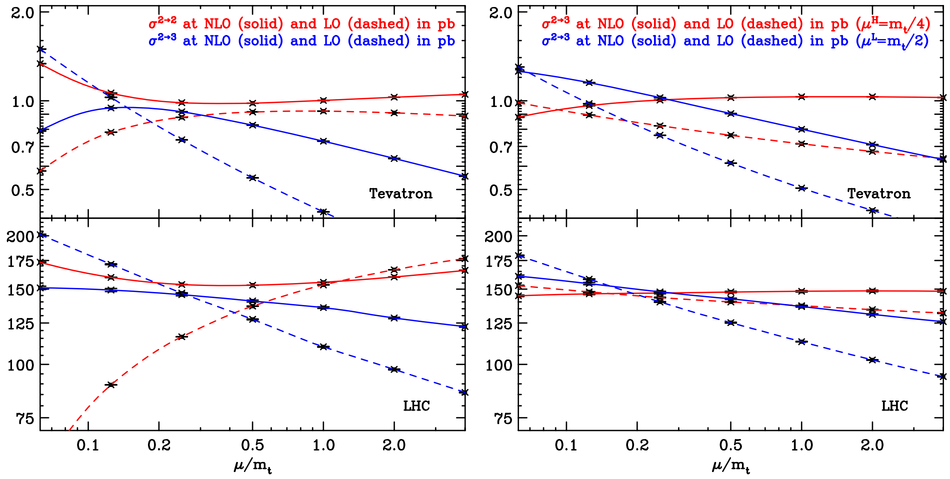


Fig. 4. – (Colour on-line) Left plots: scale dependence of the 5-flavor (red) and 4-flavor (blue) calculations at the LO (dashed) and NLO (solid) for a common renormalization and factorization scale for the Tevatron (upper plot) and 14 TeV LHC (lower plot). Right plots: scale dependence of the 4-flavor calculation with independent variation of the scales for the heavy (blue) and light (red) quark lines (keeping the other fixed to its central value). Renormalization and factorization scales are kept equal. Upper plot is for the Tevatron and lower for the LHC (14 TeV). Results in these plots are for top production, anti-top is similar.

For a consistent description in the 4-flavor scheme, also the running of α_S and the PDF sets should be strictly 4 flavor. The most recent([1]) publicly available 4-flavor PDF set is from 2004 [30] and out-dated. Another description, which is correct up to NLO, is to use a 5-flavor set and compensate by using the description of ref. [31]. The latter solution is used for the results in this talk using the CTEQ6.6 PDF set [32].

In the left plot fig. 4 the dependence of the LO and NLO calculations on a common renormalization and factorization scale is shown for the Tevatron and LHC (14 TeV). In both schemes the dependence is greatly reduced when going from LO to NLO. In particular the NLO predictions in the 5-flavor scheme are very stable and hardly show any residual dependence. The 4-flavor prescription is not much worse, even though there is an extra power of α_S at the same order in perturbation theory. The preferred scale (*i.e.*, where the NLO corrections are small, and the NLO shows only a small scale dependence) for the $2 \to 3$ process is significantly smaller than m_t, as expected from the fact that the renormalization scale should be of the same order as the (maximum) p_T of the spectator b quark. Due to a (near-)factorization of the corrections to the light and heavy quark lines in the 5-flavor calculation, as described in ref. [28], the scales of the light and heavy quark lines can be varied independently. As can be seen in the right plot of fig. 4 this independent variation of the scales confirms that the scale of the heavy quark line, *i.e.* with the gluon splitting, is preferentially smaller than m_t, while for the light quark line a larger scale looks better. We chose here the same central scales as in refs. [28, 29], that is $m_t/4$ for the heavy and $m_t/2$ for the light quark line.

In table II the inclusive NLO predictions for t-channel production of single-top quarks are given for both the 5-flavor ($2 \to 2$) and 4-flavor ($2 \to 3$) schemes. From the inclusive

([1]) Only very recently the ABKM group produced a new set of PDFs in the 4-flavor scheme.

TABLE II. – *Cross sections for t-channel single-top production at NLO in the 5-flavor* ($2 \to 2$) *and 4-flavor* ($2 \to 3$) *schemes. Uncertainties from scale variations are estimated by varying the renormalization and factorization scales independently by a factor 2 around their central value* (m_t *in the 5-flavor and* $m_t/2$ *for the light quark line and* $m_t/4$ *for the heavy quark line in the 4-flavor calculations). PDF uncertainties are estimated by using the 44 eigenvectors sets from the CTEQ6.6 PDF set, the uncertainties on the top quark mass are taken to be 1%,* $m_t = 172 \pm 1.7\,\text{GeV}$*, and the uncertainty from the bottom quark mass has been estimated by assuming an uncertainty on the b quark mass of* $m_b = 4.5 \pm 0.2\,\text{GeV}$.

$\sigma^{\text{NLO}}_{\text{t-ch}}(t+\bar{t})$	$2 \to 2$ (pb)					$2 \to 3$ (pb)				
		scale	PDF	m_t	m_b		scale	PDF	m_t	m_b
Tevatron Run II	1.96	$^{+0.05}_{-0.01}$	$^{+0.20}_{-0.16}$	$^{+0.06}_{-0.06}$	$^{+0.05}_{-0.05}$	1.87	$^{+0.16}_{-0.21}$	$^{+0.18}_{-0.15}$	$^{+0.06}_{-0.06}$	$^{+0.04}_{-0.04}$
LHC (7 TeV)	62.6	$^{+1.1}_{-0.5}$	$^{+1.4}_{-1.6}$	$^{+1.1}_{-1.1}$	$^{+1.1}_{-1.1}$	59.4	$^{+2.1}_{-3.4}$	$^{+1.4}_{-1.4}$	$^{+1.0}_{-1.0}$	$^{+1.3}_{-1.2}$
LHC (14 TeV)	244	$^{+5}_{-4}$	$^{+5}_{-6}$	$^{+3}_{-3}$	$^{+4}_{-4}$	234	$^{+7}_{-9}$	$^{+5}_{-5}$	$^{+3}_{-3}$	$^{+4}_{-4}$

cross sections the agreement between the 4- and 5-flavor calculations is remarkably good, in particular for the Tevatron. Also at the LHC the difference is (almost) within the scale uncertainties. After the scale dependence, the largest theoretical uncertainties are coming from the PDF, which has been estimated by running the 44 eigenvector sets of the CTEQ6.6 PDF set. The uncertainties on the total cross section coming from the top quark mass and the bottom quark mass are similar in size. For the $2 \to 2$ the latter uncertainty has been estimated by changing the starting scale of the b-quark evolution

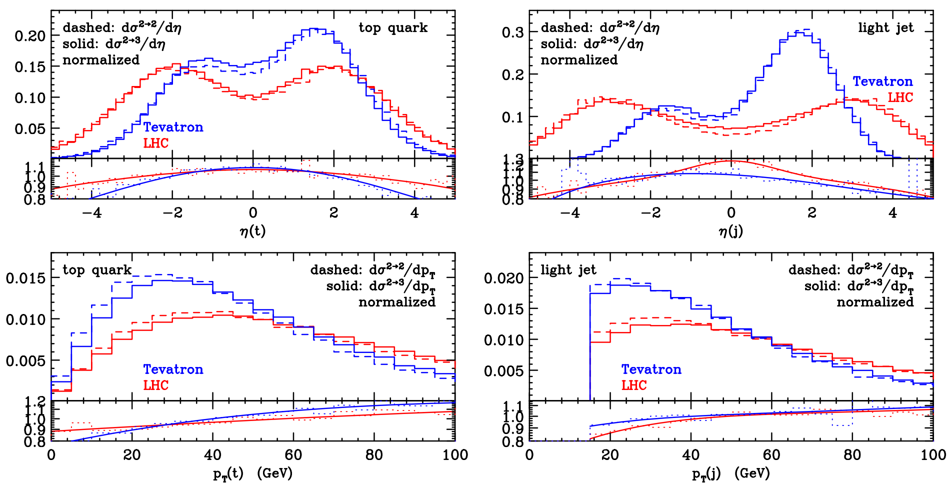


Fig. 5. – (Colour on-line) Comparisons between (normalized) distributions at NLO in the 5-flavor (dashed) and 4-flavor (solid) schemes at the Tevatron (blue) and 14 TeV LHC (red). Upper plots show the pseudo-rapidities, lower plots the transverse momenta of the top (left plots) and light jet (right plots). For plotting the jet, the k_T jet algorithm was used with a pseudo-cone size of 0.7 and $p_T > 15\,\text{GeV}$. The lower insets of the plots show the ratio of the 4-flavor over the 5-flavor predictions. Results in these plots are for top production, anti-top is similar.

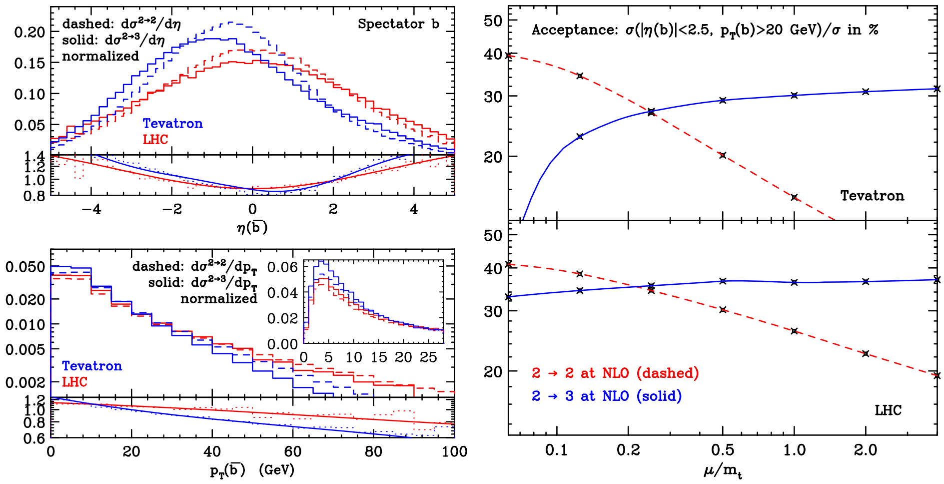


Fig. 6. – (Colour on-line) Left plots: comparisons between (normalized) distributions at NLO in the 5-flavor (dashed) and 4-flavor (solid) schemes at the Tevatron (blue) and 14 TeV LHC (red). Upper plot shows the pseudo-rapidity, the lower plot the transverse momentum of the spectator b quark. The lower insets of the plots show the ratio of the 4-flavor over the 5-flavor predictions and the inset in the upper right corner of the lower plot is a zoom of the low transverse momentum region. Right plot: the acceptance as a function of a common renormalization and factorization scale. Dashed lines for the predictions in the 5-flavor scheme and in solid lines for the 4-flavor scheme. Upper plot for the Tevatron and lower plot for the LHC (14 TeV). Results in these plots are for top production, anti-top is similar.

in the PDF. As can be seen in fig. 5, also the descriptions of the top quark and the light jet are in good agreement with differences of the order of 10% in the regions where the cross section is large.

Given that the agreement between the 5- and 4-flavor calculations is so good, we can argue that the logarithms related to the b quark (that are resummed in the PDF) are not of great importance. It seems that a NLO calculation in the 4-flavor scheme, that includes the first logarithms, describes also the process quite well. We can therefore be confident that the NLO in the 4-flavor scheme describes the spectator b quark well, see fig. 6 (left plots). The differences in shape with the NLO 5-flavor predictions, which are equal to the LO 4-flavor, are not dramatic. Note that these plots have been normalized and the y-axes are in arbitrary units. When looking at absolute (non-normalized) predictions, by for example considering the acceptance, larger differences are visible, see fig. 6 (right plot), where we have defined the acceptance as the ratio between the cross section with a hard and central spectator b quark ($|\eta(b)| < 2.5$ and $p_T(b) > 20\,\mathrm{GeV}$) over the total inclusive cross section. Indeed, the right plots of fig. 6 show a large uncertainty for the description in the 5-flavor scheme and only a very mild scale dependence in the 4-flavor scheme.

4. – Conclusions

With recent developments, both the s- and the t single-top production channels are now in good theoretical control. In particular for the s-channel process, the fully exclusive NLO calculations as implemented in MC@NLO and POWHEG are considered to be in excellent shape. For the t channel the situation is slightly more complicated due to the presence of an initial state b quark in the 5-flavor scheme which leads to a non-satisfactory description of the spectator b. The recent calculation of the NLO corrections to t-channel single-top production in the 4-flavor scheme, which describes the spectator b for the first time at NLO, sheds light on the large uncertainties related to the spectator b-quark distributions. However, this calculation is only available at parton level and a final solution would be to match this calculation to a parton shower *à la* MC@NLO or POWHEG.

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