Search for new physics via single-top production at the LHC

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Abstract

We consider single-top production as a probe for new physics effects at the Large Hadron Collider (LHC). We argue that for natural theories a small deviation from the Standard Model tree-level couplings in this reaction can be parameterized by 3 higher dimension operators. Precision measurement of these effective couplings in the single-top events, via studying their interference effects with the SM contributions, can discriminate several new physics models. In particular, combining the production rate of three single-top production modes will provide a severe test of the Little Higgs model with T-parity. We find that at the LHC, a 5% accuracy in the measurement of the single-top cross sections would probe the new physics scale up to about 3 TeV.
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The search for New Physics (NP) beyond the Standard Model (SM) is one of the major goals of the forthcoming Large Hadron Collider (LHC) at CERN. The effects of new physics could be directly observed if their characteristic scale lies below the center mass (CM) energy of the relevant hard processes; otherwise they must be probed through precision measurements of the SM couplings. When the available energy is insufficient to directly produce the heavy excitations underlying the SM, all new physics effects can be parameterized by the coefficients of a series of gauge-invariant operators ($\mathcal{O}_i$) constructed out of the SM fields [1–3]; when the heavy physics decouples, as we will assume, these operators have dimensions $\geqslant 5$ and their coefficients are suppressed by inverse powers of the new physics scale Λ_{NP} (the scale at which the excitations of the underlying theory can be directly probed).[1]

The top quark, because of its heavy mass, is believed to provide a good probe into new physics effects. In particular, processes containing single-top quark are expected to be sensitive to a rich variety of physical effects. For instance, the corresponding production rates can be significantly modified by NP interactions, such as heavy resonances or non-standard flavor-changing vertices [4]. In the SM, single-top quark events can result from the t-channel process ($ub \to dt$), the s-channel process ($u\bar{d} \to t\bar{b}$) and the Wt associate production process ($bg \to tW^-$). Due to their distinct kinematics, each of these three processes can be differentiated and, in principle, measured separately. Recently, the evidence for single-top quark production through weak interactions has been reported by the DØ Collaboration at the Fermilab Tevatron [5]. The soon-to-be-operational LHC offers an excellent opportunity to search for NP via single-top quark production. The LHC will not only observe single-top events but also accurately measure their characteristics. Since each single-top production process will be affected differently by the NP effects, a comparison among them can discriminate NP models.

In this Letter we assume that NP effects in single-top production will not be directly observed at the LHC (e.g. as heavy resonances). Such effects are then described by an effective Lagrangian of the form

$$\mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \frac{1}{\Lambda_{\mathrm{NP}}^2} \sum_i (c_i \mathcal{O}_i + \mathrm{h.c.}) + O\left(\frac{1}{\Lambda_{\mathrm{NP}}^3}\right), \qquad (1)$$

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[1] The dimension 4 operators induced by the NP only renormalize the SM coefficients and are unobservable, though relevant for naturalness arguments.
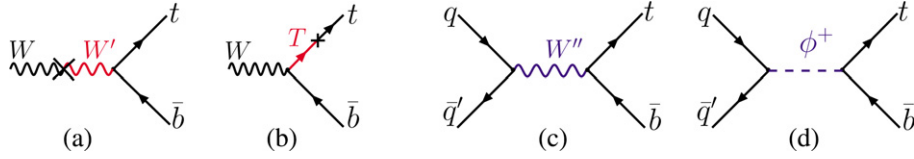
Fig. 1. Examples of new physics that can induce the effective vertices listed in Eqs. (3) and (7). (a) and (b) generate a Wtb vertex through mixing with a heavy W' gauge boson or a heavy T quark (top-quark partner), while (c) and (d) induce effective four-fermion operators through exchanging a heavy W' gauge boson or a heavy charged Higgs boson ϕ^+. Although (a) and (c) are both induced by W', they originate from different new physics effects: the former is related to the gauge boson mixing, while the latter to the W' couplings to quarks.

where c_i's are coefficients that parameterize the non-standard interactions.[2] Because of the excellent agreement between the SM predictions and precision experiments, the allowed deviations from the SM are small, hence, when computing the effects of new operators we can restrict ourselves to the interference terms between $\mathcal{L}_{SM}$ and the operators $\mathcal{O}_i$, i.e. working to first order in the coefficients c_i. Also, since the c_i of loop-generated operators are naturally suppressed by a numerical factor $\sim 1/16\pi^2$, we will only consider tree-level induced operators in this work.

There are two types of tree-level induced effective operators that contribute to single-top production: those modifying the Wtb coupling, which affect all production channels, and the four-fermion interactions that contribute only to the s-channel and t-channel production processes; we will discuss them separately. For example, in Fig. 1, (a) and (b) modify the Wtb vertex through mixing with a heavy W' gauge boson or a heavy T quark (top-quark partner), while (c) and (d) induce effective four-fermion operators through exchanging a heavy W' gauge boson or a heavy charged Higgs boson ϕ^+.

As shown in Refs. [6–8], there are only 2 tree-level generated operators of the first type that can contribute to single-top production:

$$\mathcal{O}_{\phi q}^{(3)} = i\big(\phi^\dagger \tau^I D_\mu \phi\big)\big(\bar{q}_h \gamma^\mu \tau^I q_h\big) + \text{h.c.},$$
$$\mathcal{O}_{\phi\phi} = i\big(\phi^\dagger \epsilon D_\mu \phi\big)\big(\bar{t} \gamma^\mu b\big) + \text{h.c.}, \qquad (2)$$

where ϕ denotes the SM scalar doublet, D_μ the covariant derivative, q_h the left-handed top–bottom $SU(2)$ doublet, and $t(b)$ the corresponding right-handed isosinglets [6]; τ^I denote the usual Pauli matrices, and ϵ the two-dimensional antisymmetric tensor ($\epsilon_{12} = -\epsilon_{21} = 1$) in the weak isospin space. Upon symmetry breaking, the above two operators generate the following contribution to the Wtb coupling:

$$\mathcal{O}_{Wtb} = \frac{g}{\sqrt{2}}\big\{\bar{t}\gamma^\mu(\mathcal{F}_L P_L + \mathcal{F}_R P_R)b W_\mu^+ + \text{h.c.}\big\}, \qquad (3)$$

where $\mathcal{F}_L = C_{\phi q}^{(3)} v^2/\Lambda_{NP}^2$ and $\mathcal{F}_R = C_{\phi\phi} v^2/(2\Lambda_{NP}^2)$, and $v = 246$ GeV is the vacuum expectation value (VEV) of ϕ.

There exists 3 tree-level induced operators of the second type that can contribute to single-top production [6,7]:

$$\mathcal{O}_{qu}^{(1)} = \big(\bar{q}_l t_R\big)\big(\bar{u}_R q_l\big), \qquad (4)$$

$$\mathcal{O}_{qq}^{(1)} = \big(\bar{q}_l^i t_R\big)\big(\bar{q}_l^j b_R\big)\epsilon_{ij}, \qquad (5)$$

$$\mathcal{O}_{qq}^{(3)} = \frac{1}{2}\big(\bar{q}_l \gamma_\mu \tau^I q_l\big)\big(\bar{q}_h \gamma^\mu \tau^I q_h\big), \qquad (6)$$

where q_l and u_R denote either first or second generation left-handed quark isodoublets and right-handed singlets, respectively. The contributions of the first two of these operators, however, will be of order of c_i^2 and can be ignored. This is because the vertices generated by $\mathcal{O}_{qu}^{(1)}$ and $\mathcal{O}_{qq}^{(1)}$ do not interfere with the SM contribution when the bottom quark mass is neglected. Hence we only need to consider the last operator, $\mathcal{O}_{qq}^{(3)}$, from which we extract out the following effective $qq'bt$ vertex:

$$\mathcal{O}_{4f} = \mathcal{G}_{4f}\bigg[\frac{1}{v^2}\big(\bar{Q}'\gamma^\mu P_L Q\big)\big(\bar{b}\gamma_\mu P_L t\big)$$
$$+ \frac{1}{v^2}\big(\bar{Q}\gamma^\mu P_L Q'\big)\big(\bar{t}\gamma_\mu P_L b\big)\bigg], \qquad (7)$$

where $\mathcal{G}_{4f} = C_{qq}^{(3)} v^2/(2\Lambda_{NP}^2)$ and Q, Q' denote light-flavor quarks (u, d, c, s). (We have inserted v^2 to make $\mathcal{G}_{4f}$ dimensionless.) For simplicity, we assume that the coefficients of the four-fermion operators are proportional to the SM Cabibbo–Koboyashi–Maskawa (CKM) matrix, i.e. $C_{ud}^{(3)} = C_{cs}^{(3)} = kC_{us}^{(3)} = -kC_{cd}^{(3)}$ with k being equal to $1/\sin\theta_c$, where θ_c is the Cabibbo angle.[3]

It is important to note that the natural values for the coefficients $\mathcal{F}_L$, $\mathcal{F}_R$ and $\mathcal{G}_{4f}$ are of order $(v/\Lambda_{NP})^2$ and that the formalism is applicable whenever the CM energy for the hard process, $\sqrt{\hat{s}}$, is significantly below Λ_{NP}. Taking $\Lambda_{NP} \sim 2$ TeV we find the following estimates:

$$|\mathcal{F}_L|, |\mathcal{F}_R|, |\mathcal{G}_{4f}| < 0.01. \qquad (8)$$

Concerning the right-handed coupling in (3), it is well known that recent data on the decay of $b \to s\gamma$ leads to the constraint $|\mathcal{F}_R| < 0.004$ [9–11], provided that other new-physics effects, such as those produced by a $b\bar{s}t\bar{t}$ 4-fermion interaction,[4] are absent. This constraint will still hold provided we assume (as we will) that no cancellations occur between these two effects; in this case all $\mathcal{F}_R$ effects are negligible. Hence, we will restrict ourselves to the effective vertices containing the couplings $\mathcal{F}_L$ and $\mathcal{G}_{4f}$ and examine their effects in various experimental observables. In our calculation we will take

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[2] Dimension 5 operators involve fermion number violation and are assumed to be associated with a very high energy scale and are not relevant to the processes studied here.

[3] The numerical results presented below do not change noticeably when $C_{us}^{(3)} = C_{cd}^{(3)} = 0$.

[4] This operator can be generated, for example, by exchanging a heavy W' vector boson.
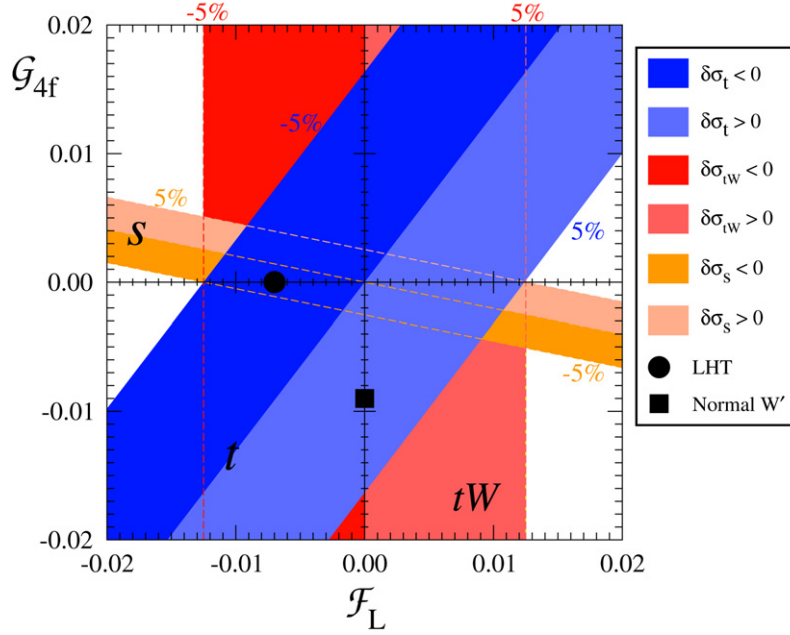
Fig. 2. Regions corresponding to $|\delta\sigma_i| \leqslant 5\%$ for various single-top production processes, in the plane of $\mathcal{F}_L$ and $\mathcal{G}_{4f}$. Predictions for two different models, LHT (circle) and NP with heavy W' (box), are also given. (See the main text for its details.)

all the effective couplings to be real in order to simplify our analysis. We will also assume that the $\nu\ell W$ vertex does not receive significant contributions from physics beyond the SM. Finally, we note that in order to be consistent with the LEP II experimental measurements of the asymmetry observables A_{FB}^b and A_{LR}^b [12], the Wt_Lb_L, $Z\bar{b}_Lb_L$ and $Z\bar{t}_Lt_L$ couplings should be strongly correlated. The operator $\mathcal{O}_{\phi q}^{(3)}$, of Eq. (2), modifies the Wt_Lb_L and $Z\bar{b}_Lb_L$ couplings, at the same order of magnitude as $\mathcal{F}_L$; however, the complete set of effective operators includes $\mathcal{O}_{\phi q}^{(1)} = i(\phi^\dagger D_\mu \phi)(\bar{q}_h\gamma^\mu q_h)$ + h.c. (also tree-level induced [6,7]), which contributes to the $Z\bar{b}_Lb_L$ and $Z\bar{t}_Lt_L$ couplings. To agree with the LEP II data, the contributions from $\mathcal{O}_{\phi q}^{(1)}$ and $\mathcal{O}_{\phi q}^{(3)}$ to the $Z\bar{b}_Lb_L$ coupling must cancel, in which case the $Z\bar{t}_Lt_L$ coupling receives a modification of the same order as $\mathcal{F}_L$, a prediction that can be tested at the LHC and future Linear Colliders by measuring the associated production of Z boson with top quark pairs [13]. In this Letter we will not investigate such effects.

The explicit formulas for the inclusive cross sections of the three single-top production channels at the LHC are found to be:

$$\sigma_{tW} = \sigma_{tW}^0(1 + 4\mathcal{F}_L), \qquad (9)$$

$$\sigma_s = \sigma_s^0(1 + 4\mathcal{F}_L + 19.69\mathcal{G}_{4f}), \qquad (10)$$

$$\sigma_t = \sigma_t^0(1 + 4\mathcal{F}_L - 3.06\mathcal{G}_{4f}), \qquad (11)$$

while those for the Tevatron Run II are

$$\sigma_{tW} = \sigma_{tW}^0(1 + 4\mathcal{F}_L), \qquad (12)$$

$$\sigma_s = \sigma_s^0(1 + 4\mathcal{F}_L + 13.8\mathcal{G}_{4f}), \qquad (13)$$

$$\sigma_t = \sigma_t^0(1 + 4\mathcal{F}_L - 2.2\mathcal{G}_{4f}), \qquad (14)$$

where σ_i^0, with $i = s, t, tW$ denote the SM cross sections. The $\mathcal{F}_L$ contribution is universal since it is associated with a rescaling of the SM vertex. The four-fermion operators have different effects in the s-channel and t-channel processes, acting constructively or destructively (depending on the sign of $\mathcal{G}_{4f}$) so that one process is always enhanced. The large coefficient in (10) indicates that the s-channel process is better suited for detecting the effects of the operator containing $\mathcal{G}_{4f}$. The contribution of this operator in the top quark decay is negligible because the SM contribution peaks in the region of phase space where $(p_\ell + p_\nu)^2 \simeq M_W^2$, much smaller than Λ_{NP}^2. As expected, the space-like t-channel exchange process is suppressed by the large mass of the new particle, e.g. Z' [4,14]. The measurements can also determine the sign of $\mathcal{G}_{4f}$. For illustration, we show in Fig. 2 the regions in the $\mathcal{F}_L$–$\mathcal{G}_{4f}$ plane where the inclusive cross sections of various single-top production processes deviate from their corresponding SM cross sections, $\delta\sigma_i \equiv (\sigma_i - \sigma_i^0)/\sigma_i^0$, by less than 5% in magnitude, which we take this as a very rough estimate of the systematic experimental uncertainty at the LHC [15]; a realistic determination of this number must await the turning on of the machine. It is worth noting that for the observables under consideration, the NP effects can be comparable to the SM radiative corrections, so we assume that all SM quantities are evaluated up to the one-loop level, but the interference between the SM one-loop and the new physics Born contributions can all be ignored.

Measuring each of the three production processes separately with sufficient accuracy would allow for a complete determination of the $\mathcal{F}_L$ and $\mathcal{G}_{4f}$ coefficients. In Table 1 we summarize the LHC reach study of the single-top production by the ATLAS [16] and CMS [17,18] Collaborations. Both studies clearly demonstrate that LHC has a great potential for discovering all three single-top production processes and precisely

Table 1

Predicted event rates for various single-top production processes by ATLAS and CMS Collaborations, where S_0 and B denote the numbers of the SM signal and background events, respectively. The integrated luminosity ($\mathcal{L}$) is in the unit of fb^{-1}. $\frac{\sqrt{S_0+B}}{S_0}$ denotes the statistical uncertainty

		S_0	B	$\mathcal{L}$	$\frac{S_0}{B}$	$\frac{S_0}{\sqrt{B}}$	$\frac{\sqrt{S_0+B}}{S_0}$
ATLAS	t	3130	925	10	3.38	325.4	2.0%
	s	385	2760	30	0.14	13.4	14.6%
	Wt	12852	133453	30	0.10	44.2	3.0%
CMS	t	2389	1785	10	1.34	179.8	2.7%
	s	273	2045	10	0.13	19.1	17.6%
	Wt	567	1596	10	0.36	44.9	9.2%

measuring their cross sections. In addition, we can derive the consistency sum rule that the results must satisfy. It is

$$\frac{\sigma_s}{\sigma_s^0} + 6.43\frac{\sigma_t}{\sigma_t^0} = 7.43\frac{\sigma_{tW}}{\sigma_{tW}^0}. \qquad (15)$$

In case of $\mathcal{G}_{4f} = 0$, Eq. (15) becomes

$$\frac{\sigma_s}{\sigma_s^0} = \frac{\sigma_t}{\sigma_t^0} = \frac{\sigma_{tW}}{\sigma_{tW}^0}, \qquad (16)$$

while in case of $\mathcal{F}_L = 0$,

$$\frac{\sigma_s}{\sigma_s^0} + 6.43\frac{\sigma_t}{\sigma_t^0} = 0; \qquad (17)$$

these relations can be used to discriminate new physics models, as to be discussed below.

For example, in the Little Higgs model with T-parity (LHT) [19–21], the heavy gauge boson does not mix with the W boson at tree-level, so that $\mathcal{F}_L$ can only be induced through the mixing of the top quark with its even T-parity partner. In this theory $\Lambda_{\mathrm{NP}} = 4\pi f$ and, to first order in an expansion in powers of v^2/f^2, $\mathcal{F}_L = -c_\lambda^4 v^2/(2f^2)$ where $c_\lambda = \lambda_1/\sqrt{\lambda_1^2 + \lambda_2^2}$ ($\lambda_{1,2}$ denote the Yukawa couplings for the top quark and its heavy partner); we also have $\mathcal{G}_{4f} = 0$ so that (16) can be used to restrict the other parameters. For example, taking $c_\lambda = 1/\sqrt{2}$ and $f = 1$ TeV, yields $\mathcal{F}_L = -0.007$ (we note that for this sample model of LHT, the predicted single-top production rates for all three processes are smaller than the corresponding SM rates) and is represented by the circle in Fig. 2. Hence, the above analysis can be used to constrain the LHT parameters if an excess in the single-top production rate is not found [22].

Another example is provided by the NP models that contain one or more heavy, singly-charged vector boson(s) (W'). Here we only consider the simplest case where the W' has the same couplings as the SM W boson. Recent Tevatron data on the search for W' bosons in the $t\bar{b}$ channel requires their mass be larger than 610 GeV [23]. If we assume the W' boson is much heavier and it does not mix with the SM W boson, the effective operator coefficients at the weak scale will correspond to $\mathcal{F}_L = 0$ and $\mathcal{G}_{4f} = -0.009$ when Λ_{NP} is taken to be 1200 GeV. This model can be probed using Eq. (17), and is represented as the square in Fig. 2.

We will now argue that the statistical uncertainties in the measurement of $\mathcal{F}_L$ and $\mathcal{G}_{4f}$ are quite small and the measure-

ments will be dominated by experimental uncertainties. To see this we temporarily ignore other sources of uncertainty and follow the method described in [24]. A reliable estimate of all errors would require a global analysis of both the data and the properties of the detector using the same philosophy as the one followed in Refs. [25,26] for the analysis of the parton distribution functions. In this Letter, however, our main purpose is to outline the methods for probing new physics models via studying the single-top production rates. Hence we will evaluate only the statistical uncertainties and simply assume a 5% experimental systematic uncertainty for all processes studied here. Needless to say that when data becomes available, a more comprehensive analysis has to be carried out.

It follows from (9)–(11) that for each single-top production channel the cross section can be expressed as a product of the SM cross section, denoted as σ^0, and a multiplicative factor depending linearly on the couplings $\mathcal{F}_L$ and $\mathcal{G}_{4f}$:

$$\sigma = \sigma^0(1 + a\mathcal{F}_L + b\mathcal{G}_{4f}). \qquad (18)$$

We can then relate the accuracy of the cross section measurements to the change of the effective couplings by

$$\frac{\Delta\sigma}{\sigma^0} = (a\Delta\mathcal{F}_L + b\Delta\mathcal{G}_{4f}),$$

where $\Delta\sigma$ denotes the statistical uncertainty in the measurement of σ, and $\Delta\mathcal{F}_L$ and $\Delta\mathcal{G}_{4f}$ denote the corresponding quantities for $\mathcal{F}_L$ and $\mathcal{G}_{4f}$, respectively. Let S be the number of expected signal events for an integrated luminosity $\mathcal{L}$ with $S = \sigma\mathcal{L}$, and B the number of background events (mainly from top quark pair production), we then have

$$a\Delta\mathcal{F}_L + b\Delta\mathcal{G}_{4f}$$
$$\simeq \frac{\sqrt{S_0+B}}{S_0}\left[1 + \frac{S_0}{2(S_0+B)}(a\mathcal{F}_L + b\mathcal{G}_{4f})\right] \qquad (19)$$
$$\equiv A, \qquad (20)$$

where $S_0 = \mathcal{L}\sigma^0$. The last approximation holds when $(a\mathcal{F}_L + b\mathcal{G}_{4f}) \ll 1$ for all three single-top processes, so that the limits on $\Delta\mathcal{F}_L$, $\Delta\mathcal{G}_{4f}$ will depend only weakly on the values of $\mathcal{F}_L$ and $\mathcal{G}_{4f}$. In this study, we consider one non-zero parameter at a time, so that $\Delta\mathcal{F}_L = A/a$ when $\Delta\mathcal{G}_{4f} = 0$, and $\Delta\mathcal{G}_{4f} = A/|b|$ when $\Delta\mathcal{F}_L = 0$. The total statistical error after combining the three channels in quadrature is

$$\frac{1}{\Delta g} = \sqrt{\sum_{i=s,t,Wt}\frac{1}{(\Delta g_i)^2}}, \qquad (21)$$

where g denotes $\mathcal{F}_L$ or $\mathcal{G}_{4f}$. Due to their different experimental setup, ATLAS and CMS have different sensitivities to the three channels. In Fig. 3 we plot the statistical accuracy on measuring $\mathcal{F}_L$ and $\mathcal{G}_{4f}$ at the ATLAS for $\mathcal{L} = 30$ fb^{-1}.[5] We find that this sensitivity can be quite high: for instance, if $\mathcal{F}_L = \mathcal{G}_{4f} = 0$, $\Delta\mathcal{F}_L \simeq 0.0015$, which corresponds to a 0.2% accuracy in the measurement of the relevant SM couplings. As stated above,

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[5] Here, we naively scale the signal and background event rates listed in Table 1 to those corresponding to $\mathcal{L} = 30$ fb^{-1} by the $\sqrt{\mathcal{L}}$ rule.
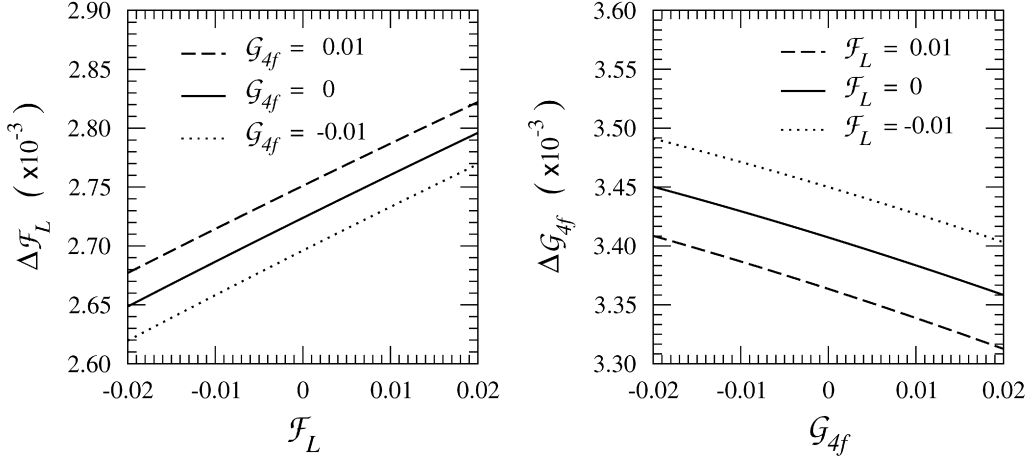
Fig. 3. The expected statistical accuracy on measuring $\mathcal{F}_L$ and $\mathcal{G}_{4f}$ at the ATLAS with an integrated luminosity of 30 fb^{-1} at the LHC.

Table 2
The uncertainties $\Delta\mathcal{F}_L$ and $\Delta\mathcal{G}_{4f}$ for $\mathcal{F}_L = \mathcal{G}_{4f} = 0$ with $\mathcal{L} = 30$ fb^{-1}. Here, only statistical uncertainty is considered

	ATLAS		CMS	
	$\Delta\mathcal{F}_L$	$\Delta\mathcal{G}_{4f}$	$\Delta\mathcal{F}_L$	$\Delta\mathcal{G}_{4f}$
t-channel	0.0029	0.0038	0.0039	0.0051
s-channel	0.0364	0.0074	0.0254	0.0052
tW-channel	0.0074		0.0118	

these statistical uncertainties are much smaller than our rough estimate of the experimental systematic errors.

The sensitivity to each single-top production channel for $\mathcal{F}_L = \mathcal{G}_{4f} = 0$ is presented in Table 2 for both the ATLAS and CMS Collaborations. As explained above, the numerical results will not change much for non-zero $\mathcal{F}_L$ and $\mathcal{G}_{4f}$. The t-channel process provides the best measurement of $\mathcal{F}_L$ both at ATLAS and CMS in the sense that it has the smallest statistical uncertainty. For the measurement of $\mathcal{G}_{4f}$, contrary to the common belief, the reaches of the t- and s-channel processes are comparable, because the large coefficient of $\mathcal{G}_{4f}$ in the s-channel process in Eq. (10) compensates the larger uncertainty.

From the precision measurement of single-top events, one can also derive conservative bounds on the new physics scales. Expressing the deviations from the SM contributions, $\delta\sigma_i = (\sigma_i - \sigma_i^0)/\sigma_i^0$, in terms of parameters which are more directly related to the heavy physics, Eqs. (9)–(11) become

$$\delta\sigma_{tW} = 0.12 C_{\phi q}^{(3)} \left(\frac{1\text{ TeV}}{\Lambda_{\text{NP}}} \right)^2, \tag{22}$$

$$\delta\sigma_s = 0.12 C_{\phi q}^{(3)} \left(\frac{1\text{ TeV}}{\Lambda_{\text{NP}}} \right)^2 + 0.60 C_{qq}^{(1,3)} \left(\frac{1\text{ TeV}}{\Lambda_{\text{NP}}} \right)^2, \tag{23}$$

$$\delta\sigma_t = 0.12 C_{\phi q}^{(3)} \left(\frac{1\text{ TeV}}{\Lambda_{\text{NP}}} \right)^2 - 0.09 C_{qq}^{(1,3)} \left(\frac{1\text{ TeV}}{\Lambda_{\text{NP}}} \right)^2. \tag{24}$$

Though we expect $C_i = O(1)$, their precise values are unknown. Measurements such as the ones described above can be used to obtain the ratios of these coefficients, but the value of Λ_{NP} cannot be obtained separately. After including the theoretical, statistical, experimental systematic, and machine lumi-

nosity uncertainties, the single-top processes are expected to be measured to a 5% accuracy [15]. If we require $|\delta\sigma| \leqslant 5\%$, then we obtain the following realistic bounds

$$\left| C_{\phi q}^{(3)} \right| \left(\frac{1\text{ TeV}}{\Lambda_{\text{NP}}} \right)^2 < 0.42, \qquad \left| C_{qq}^{(3)} \right| \left(\frac{1\text{ TeV}}{\Lambda_{\text{NP}}} \right)^2 < 0.14. \tag{25}$$

Assuming $C_i \simeq 1$ these imply

$$\Lambda_{\text{NP}} > 2.8 \text{ TeV}. \tag{26}$$

It is worth noting that the average characteristic energy of the hard processes is always significantly below 500 GeV, for the effective parton luminosity drops as the invariant mass of the hard scattering process increases. Thus, the above results indicate that single-top production provides a promising process which can probe new physics effects up to ~ 6 times the CM energy scale of the hard scattering process.

In the t-channel process the single-top quark is produced via the $ub \to dt$ process with the subsequent decay of top quark $t \to bW^+(\to b\ell^+\nu)$. Aside from the charged lepton and missing transverse energy, the final state will contain two jets: one b-tagged jet and one non-b-tagged light quark jet; the latter will be predominately in the forward direction and can be used to suppress the copious SM backgrounds (such as those produced by $Wb\bar{b}$ and $t\bar{t}$ events). In the s-channel process, the single-top quark is produced via the $u\bar{d} \to t\bar{b}$ process with the subsequent top decay; its collider signature consists of two b-tagged jets, one charged lepton, and missing transverse energy. The transverse momentum (p_T) of the bottom quark from top quark decay peaks at about $m_t/3$ and it is insensitive to the $\mathcal{G}_{4f}$ coupling. In contrast, the p_T distribution of the $\bar{b}$ or q, produced in association with the t quark is shifted toward the large p_T region by the $\mathcal{G}_{4f}$ contribution; a similar shift occurs in the invariant mass distributions of $(t, \bar{b})$ system. The spectator jet is also shifted toward the central (for $\mathcal{G}_{4f} > 0$) or forward (for $\mathcal{G}_{4f} < 0$) regions. These effects are illustrated in Fig. 4.[6]

The single-top production differential cross sections have been calculated recently to NLO by various groups [27–35];

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[6] $\mathcal{F}_L$ only produces a change in the overall normalization of the cross section.
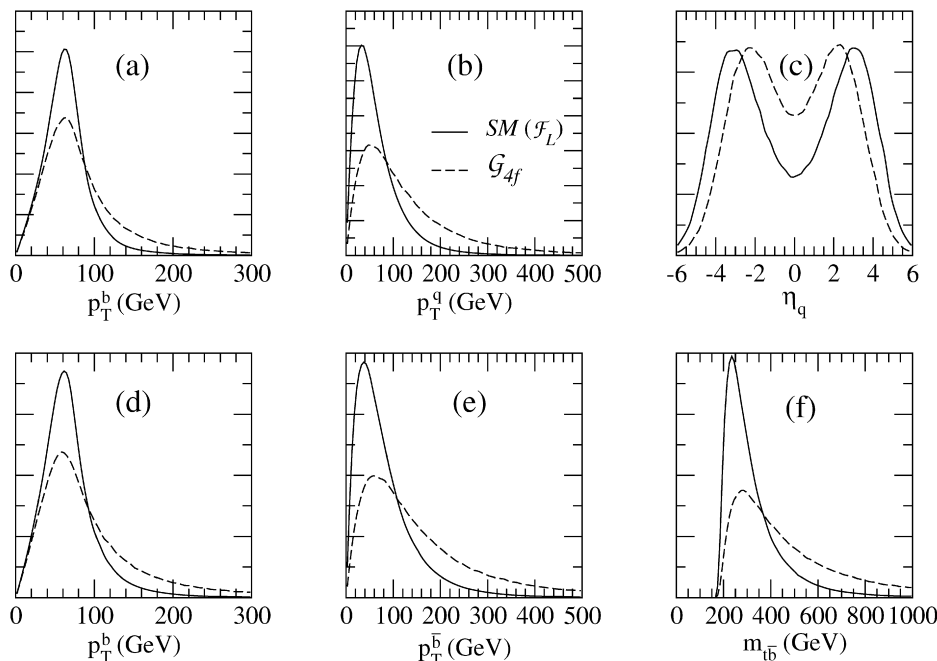
Fig. 4. Normalized distributions of p_T^b, p_T^q and η_q of the *t*-channel process for $\mathcal{G}_{4f} = -0.01$ (first row) and of p_T^b, $p_T^{\bar{b}}$ and $m_{t\bar{b}}$ of the *s*-channel process for $\mathcal{G}_{4f} = 0.01$ (second row) at the LHC. p_T^z and η_z denote the transverse momentum and rapidity of particle *z*; m_X denotes the invariant mass of the set of particles *X*.

so the theoretical uncertainty in the SM predictions for the various kinematical distributions is small. Extracting $\mathcal{G}_{4f}$ from the corresponding event distribution measurements will be limited mainly by experimental statistics and systematic uncertainties, and is not expected to largely improve the sensitivity obtained from the total cross-section measurements.

In summary, we have considered the single-top production at the LHC as a probe for new physics effects. Assuming that the NP effects in single-top production cannot be directly observed as resonance enhancement signal, we argued that for natural theories the small deviations from the SM tree-level couplings in this reaction can be parameterized by 3 couplings. One of these ($\mathcal{F}_R$) is strongly constrained by the low-energy data (assuming no cancellations), while another ($\mathcal{F}_L$) affects only the overall normalization of the single-top cross sections. The four-fermion coupling $\mathcal{G}_{4f}$ affects both the total cross section and the kinematical distributions in the *s*- and *t*-channel processes, acting constructively or destructively, depending on its sign. Accurate measurement of all three production channels can determine $\mathcal{F}_L$ and $\mathcal{G}_{4f}$ to within a few percent (statistical) accuracy for an integrated luminosity of 30 fb^{-1}. The *s*-channel is expected to be better suited for detecting $\mathcal{G}_{4f}$ but suffers from larger statistical and experimental uncertainties than the *t*-channel process. Our study shows that the uncertainties of measuring $\mathcal{G}_{4f}$ in the *s*- and *t*-channel are comparable. Assuming the single-top production can be measured with 5% accuracy, one can probe the new physics scale ~ 3 TeV in the single-top production at the LHC.

Acknowledgements

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