PROCEEDINGS OF SCIENCE

BSM reach of single top-quark measurements

Alberto Tonero[a,*]

[a] *Ottawa-Carleton, Institute for Physics, Carleton University*
1125 Colonel By Drive, Ottawa, ON, K1S 5B6, Canada

E-mail: alberto.tonero@gmail.com

Overview about the reach of BSM physics using single top production at the LHC.

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*Speaker

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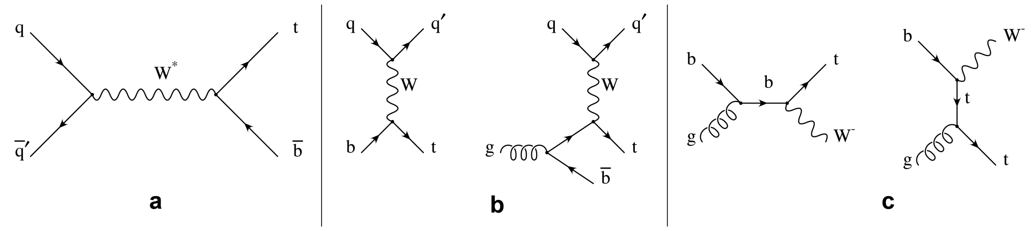

Figure 1: The three main production channels of single top: a) s-channel, b) t-channel and c) tW-channel.

1. Introduction

Despite the numerous successes of the Standard Model (SM), there exist phenomena like Neutrino masses, Baryon Asymmetry of the Universe, Dark Matter, hierarchy problem, flavor, etc... which require the presence of Beyond the Standard Model (BSM) physics in order to be explained. Due to its high mass, the top-quark is believed to represent a unique portal to New Physics (NP). At the Large Hadron Collider (LHC), the physics of the top quark entered the era of precision measurements due to the large number of top particles produced in proton collisions at 13 TeV. Heavy New Physics may manifest itself in the form of effective couplings involving the top-quark (Wtb-vertex, four fermion interactions, etc...) that can be probed in single-top production. There are three main channels for single top production which are characterized by different virtualities of the W-boson: s-, t- and tW-channel. The tree level diagrams for these three production channels are shown in Figure 1. We have:

a) s-channel $q_W^2 > (m_t + m_b)^2$

b) t-channel $q_W^2 < 0$

c) tW-channel $q_W^2 = m_W^2$

The 13 TeV cross sections are [1]: $\sigma_t(pp \to tj + \bar{t}j) \simeq 136 + 82$ pb aNNLO QCD, $\sigma_{tW}(pp \to tW + \bar{t}W) \simeq 70$ pb aNNLO QCD, $\sigma_s(pp \to tb + \bar{t}b) \simeq 7 + 4$ pb @13TeV aNNLO QCD. Single-top t-channel is the dominant process.

2. Wtb anomalous couplings

Heavy BSM physics can affect the top-quark weak gauge interactions and manifest in the form of effective couplings at low energies. The most general Lorentz-invariant vertex is parametrized as [2–4]:

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{m_W}(g_L P_L + g_R P_R)tW_\mu^- + \text{h.c.} \quad (1)$$

In the SM at tree level we have $V_L = V_{tb} \simeq 1$ and $V_R = g_L = g_R = 0$. BSM physics can provide additional contributions to $V_{L,R}$ and $g_{L,R}$ as shown in [5–12].

2.1 Anomalous couplings contributions to observables

Using the effective vertex in eq. (1), it is possible to compute the s-, t- and tW-channel cross sections, which can be parametrized as follows

$$\sigma_i = \sigma_i^{\mathrm{SM}} + K_i \Delta\sigma_i \tag{2}$$

where K_i are the k-factors and $\Delta\sigma_i$ are the LO NP contributions, computed in the limit $m_b = 0$ [11]:

$$\begin{aligned} \Delta\sigma_t &= a_0 x_0 + a_m x_m + a_p x_p + a_5 x_5 \qquad \Delta\sigma_s = b_0 x_0 + b_m x_m + b_p x_p + b_5 x_5 \\ \Delta\sigma_{tW} &= c_0 x_0 + c_m x_m + c_p x_p + c_5 x_5 \end{aligned} \tag{3}$$

with

$$x_0 = |V_L + \frac{m_W}{m_t} g_R|^2 + |V_R + \frac{m_W}{m_t} g_L|^2 - 1 \qquad x_5 = \frac{m_t^2}{m_W^2}\left(|g_L|^2 + |g_R|^2\right) \tag{4}$$

and

$$x_m = |V_L + \frac{m_t}{m_W} g_R|^2 - 1 \qquad x_p = |V_R + \frac{m_t}{m_W} g_L|^2 \tag{5}$$

The anomalous couplings contribute also to helicity ($*$), normal (N) and transverse (T) polarization fractions [13] which are defined as:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\theta_l^x} = \frac{3}{8}(1+\cos\theta_l^x)^2 F_R^x + \frac{3}{8}(1-\cos\theta_l^x)^2 F_L^x + \frac{3}{4}\sin^2\theta_l^x F_0^x \tag{6}$$

At LO, in the limit $m_b = 0$, the expressions for F_i^* can be found here [11]. Other powerful observables to probe anomalous couplings are Forward-Backward Asymmetries (P top polarization) [13] constructed in terms of polarization fractions

$$A_{\mathrm{FB}} = \frac{3}{4}\left[F_R^* - F_L^*\right] \qquad A_{\mathrm{FB}}^{N,T} = \frac{3}{4}P\left[F_R^{N,T} - F_L^{N,T}\right] \tag{7}$$

2.2 Current and expected bounds

95% CL limits on anomalous couplings obtained by combining helicity fractions, single top production cross section and A_{FB} asymmetries can be found in [14, 15]. Those limits are summarized in Table 1 where ImV_L is set to be 0.

	V_L	V_R	g_L	g_R
Re	[0.85,1.08]	[-0.35,0.39]	[-0.23,0.22]	[-0.07,0.07]
Im	–	[-0.37,0.39]	[-0.22,0.23]	[-0.20,0.15]
Re	1	[-0.28,0.32]	[-0.17,0.19]	[-0.05,0.02]
Im	–	[-0.30,0.30]	[-0.19,0.18]	[-0.11,0.10]

Table 1: The first two lines show 95% CL limits on anomalous couplings allowing all couplings to vary simultaneously, these limits are extracted from collected data at LHC and Tevatron [14]. The bottom two lines show limits where ReV_L is kept fixed to 1 and include the extrapolated results from the HL-LHC (3000 fb^{-1}) [15].

3. Constraining NP with $pp \to tl\nu$

Differential distributions in $pp \to tl\nu \to bl\nu l\nu$ [16] can be used to constrain EFT four fermion operators involving heavy quarks and leptons

$$\frac{c^{3(1)}_{Ql_i}}{\Lambda^2}(\bar{l}_{iL}\gamma^\mu\sigma^I l_{iL})(\bar{Q}_L\gamma_\mu\sigma_I Q_L) \qquad \frac{c^{S(1)}_{tl_i}}{\Lambda^2}(\bar{l}_{iL}e_{iR})\epsilon(\bar{Q}_L t_R) + \text{h.c.}$$

$$\frac{c^{T(1)}_{tl_i}}{\Lambda^2}(\bar{l}_{iL}\sigma^{\mu\nu}e_{iR})\epsilon(\bar{Q}_L\sigma_{\mu\nu}t_R) + \text{h.c.} \tag{8}$$

A sequential W' model with coupling k_L and mass $M_{W'}$

$$\mathcal{L} = -\frac{g_W}{\sqrt{2}}k_L\bar{\nu}_L\gamma^\mu e_L W'_\mu - \frac{g_W}{\sqrt{2}}k_L\bar{t}_L\gamma^\mu b_L W'_\mu + \text{h.c.} \tag{9}$$

can be matched to the EFT operators as follows:

$$C_2 \equiv \frac{c^{3(1)}_{Ql}}{\Lambda^2} = \pm\frac{g_W^2 k_L^2}{4M^2_{W'}} \qquad \frac{c^{S(1)}_{tl}}{\Lambda^2} = \frac{c^{T(1)}_{tl}}{\Lambda^2} = 0 \tag{10}$$

Current and expected bounds on the sequential W' model with comparison are obtained in [17]

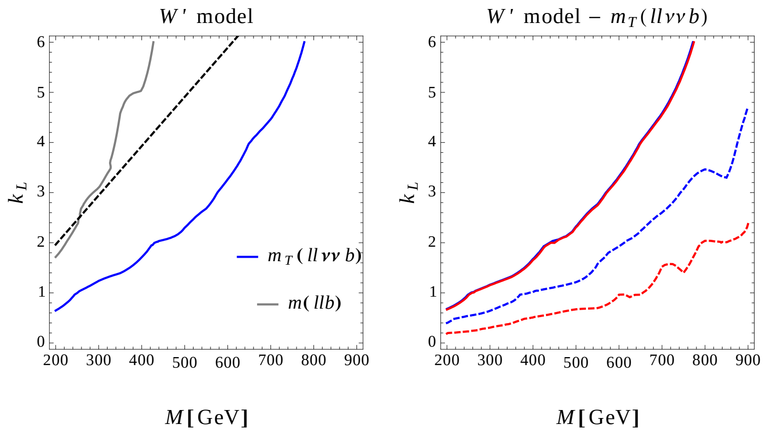

Figure 2: Left: current bounds using differential distributions at 36.1 fb^{-1}. Right: expected bounds at 300 fb^{-1} (blue) and 3000 fb^{-1} (red).

4. Conclusion

LHC is a top factory which allows to study top-quark properties very precisely. Single top is a great probe of NP because its production mechanisms have cross sections directly proportional to the Wtb vertex. Heavy BSM physics may manifest at low energy by modifying the Wtb vertex. Current measurements constrain Wtb anomalous couplings at the 0.1 level, future sensitivity may reach 0.01 level. EFT limits imply $\Lambda \gtrsim 1$ TeV. Less constrained SMEFT operators may be probed in differential measurements of the full final state $pp \to tl\nu$.

References

[1] N. Kidonakis, PoS **DIS2015**, 170 (2015) doi:10.22323/1.247.0170 [arXiv:1506.04072 [hep-ph]].

[2] C. S. Li, R. J. Oakes and T. C. Yuan, Phys. Rev. D **43**, 3759-3762 (1991) doi:10.1103/PhysRevD.43.3759

[3] G. L. Kane, G. A. Ladinsky and C. P. Yuan, Phys. Rev. D **45**, 124-141 (1992) doi:10.1103/PhysRevD.45.124

[4] F. del Aguila and J. A. Aguilar-Saavedra, Phys. Rev. D **67**, 014009 (2003) doi:10.1103/PhysRevD.67.014009

[5] D. O. Carlson, E. Malkawi and C. P. Yuan, Phys. Lett. B **337**, 145-151 (1994) doi:10.1016/0370-2693(94)91459-1

[6] D. Atwood, S. Bar-Shalom, G. Eilam and A. Soni, Phys. Rev. D **54**, 5412-5416 (1996) doi:10.1103/PhysRevD.54.5412 [arXiv:hep-ph/9605345 [hep-ph]].

[7] E. H. Simmons, Phys. Rev. D **55**, 5494-5500 (1997) doi:10.1103/PhysRevD.55.5494 [arXiv:hep-ph/9612402 [hep-ph]].

[8] M. Beneke, I. Efthymiopoulos, M. L. Mangano, J. Womersley, A. Ahmadov, G. Azuelos, U. Baur, A. Belyaev, E. L. Berger and W. Bernreuther, *et al.* [arXiv:hep-ph/0003033 [hep-ph]].

[9] J. A. Aguilar-Saavedra, Nucl. Phys. B **812**, 181-204 (2009) doi:10.1016/j.nuclphysb.2008.12.012 [arXiv:0811.3842 [hep-ph]].

[10] M. Fabbrichesi, M. Pinamonti and A. Tonero, Eur. Phys. J. C **74**, no.12, 3193 (2014) doi:10.1140/epjc/s10052-014-3193-8 [arXiv:1406.5393 [hep-ph]].

[11] Q. H. Cao, B. Yan, J. H. Yu and C. Zhang, Chin. Phys. C **41**, no.6, 063101 (2017) doi:10.1088/1674-1137/41/6/063101 [arXiv:1504.03785 [hep-ph]].

[12] A. Arhrib and A. Jueid, JHEP **08**, 082 (2016) doi:10.1007/JHEP08(2016)082 [arXiv:1606.05270 [hep-ph]].

[13] J. A. Aguilar-Saavedra and J. Bernabeu, Nucl. Phys. B **840**, 349-378 (2010) doi:10.1016/j.nuclphysb.2010.07.012 [arXiv:1005.5382 [hep-ph]].

[14] F. Déliot, R. Faria, M. C. N. Fiolhais, P. Lagarelhos, A. Onofre, C. M. Pease and A. Vasconcelos, Phys. Rev. D **97**, no.1, 013007 (2018) doi:10.1103/PhysRevD.97.013007 [arXiv:1711.04847 [hep-ph]].

[15] F. Déliot, M. C. N. Fiolhais and A. Onofre, Mod. Phys. Lett. A **34**, no.18, 1950142 (2019) doi:10.1142/S0217732319501426

[16] M. Aaboud *et al.* [ATLAS], Eur. Phys. J. C **78**, no.3, 186 (2018) doi:10.1140/epjc/s10052-018-5649-8 [arXiv:1712.01602 [hep-ex]].

[17] D. Stolarski and A. Tonero, JHEP **08**, no.08, 036 (2020) doi:10.1007/JHEP08(2020)036 [arXiv:2004.07856 [hep-ph]].