BSM reach of single top-quark measurements

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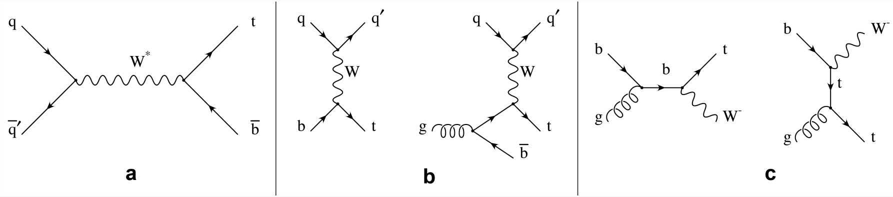
BSM physics in single-top production

Motivation

- We need BSM physics to explain neutrino masses, baryon asymmetry of the universe, DM, hierarchy problem, flavor, etc...
- Due to its high mass, the top-quark is believed to represent a unique portal to new physics
- LHC is a top factory and top quark physics entered the era of precise measurements
- New physics at high energies may manifest itself in the form of effective couplings involving the top-quark (Wtb-vertex, four fermion interactions, etc...)
- BSM physics may be probed in single-top quark production events

Single top s-, t- and tW-channel

Tree level Feynman diagrams

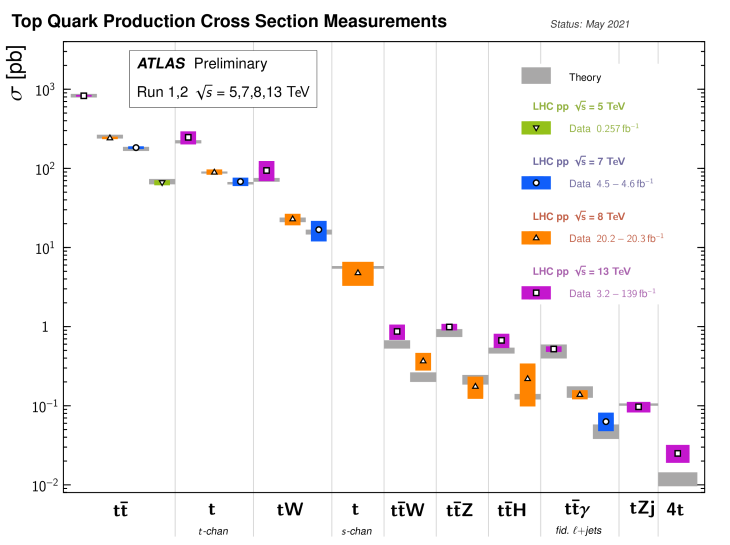


a) s-channel $q_W^2 > (m_t + m_b)^2$

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

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

LHC top factory



Theoretical cross sections

- $\sigma_t(pp \to tj + \bar{t}j) \simeq 136 + 82$ pb @13TeV [Kidonakis 1506.04072] aNNLO QCD
- $\sigma_{tW}(pp \to tW + \bar{t}W) \simeq 70$ pb @13TeV [Kidonakis 1506.04072] aNNLO QCD
- $\sigma_s(pp \to tb + \bar{t}b) \simeq 7 + 4$ pb @13TeV [Kidonakis 1506.04072] aNNLO QCD
- $\sigma(pp \to tZj + \bar{t}Zj) \simeq 900$ fb @13TeV [Pagani *et al* 2006.10086] NLO QCD+EW
- $\sigma(pp \to tHj + \bar{t}Hj) \simeq 80$ fb @13TeV [Kidonakis *et al* 2103.01228] aNNLO QCD

Single-top t-channel is the dominant process

Wtb anomalous couplings

- BSM physics at high energies can affect the top-quark gauge interactions and manifest in the form of effective couplings
- The most general Lorentz-invariant vertex [Li *et al* PRD 43 3759 (1991); Kane *et al.* PRD 45 (1992) 124; Saavedra *et al* 0208171]

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

- In the SM at tree level we have

$$V_L = V_{tb} \simeq 1 \qquad V_R = g_L = g_R = 0$$

- BSM physics can provide additional contributions to $V_{L,R}$ and $g_{L,R}$ [Carlson *et al* 9405277; Atwood *et al* 9605345; Simmons 9612402; Beneke *et al* 0003033; Saavedra 0811.3842; Fabbrichesi, Pinamonti, **AT** 1406.5393; Cao *et al* 1504.03785; Arhrib, Jueid 1606.05270;]

Single top cross sections

- Parametrization of s-, t- and tW-channel cross sections (K_i k-factor)

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

- Anomalous couplings contribution at LO with $m_b = 0$ [Cao *et al* 1504.03785]

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

with

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

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

Top decay observables

- Helicity ($*$), normal (N) and transverse (T) polarization fractions [Saavedra *et al* 1005.5382]

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

- Anomalous couplings contribution to helicity fractions at LO with $m_b = 0$ [Cao *et al* 1504.03785]

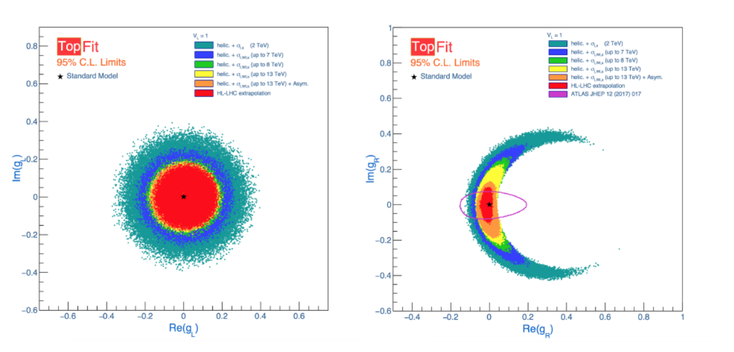
$$\begin{aligned}
F_R^* &= \frac{2x_p}{\frac{m_t^2}{m_W^2}(1+x_0)+2(1+x_m+x_p)} \\
F_L^* &= \frac{2(1+x_m)}{\frac{m_t^2}{m_W^2}(1+x_0)+2(1+x_m+x_p)} \\
F_0^* &= \frac{m_t^2}{m_W^2}\frac{1+x_0}{\frac{m_t^2}{m_W^2}(1+x_0)+2(1+x_m+x_p)}
\end{aligned}$$

- FB asymmetries (P top polarization) [Saavedra *et al* 1005.5382]

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

Current bounds

- 95% CL limits combining helicity fractions, single top production cross section and asymmetries [F. Deliot *et al.* PDR 97 013007 (2018)]



	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]

Expected bounds

- HL-LHC extrrapolation of 95% CL limits combining same observables [F. Deliot *et al.* 1811.02492]

	V_L	V_R	g_L	g_R
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]

- Boosted single top analysis at HL-LHC, HE-LHC and FCC [Saavedra and Mangano 1910.09788]

	14 TeV	27 TeV	100 TeV	100 TeV (1% sys)
$\lvert g_L \rvert$	< 0.087	< 0.05	< 0.046	< 0.03

- Combining angular and energy asymmetries at LHC 13 100 fb^{-1} [Jueid 1805.07763]

$$|g_R| \lesssim 0.01$$

SMEFT and anomalous couplings

- SMEFT formalism to parametrize effects of heavy NP ($\Lambda \gg v, E$)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{c_i}{\Lambda^2} O_i + \ldots$$

- Dim-6 oerators contributing to anomalous couplings

$$O_{\varphi q}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{q}_L \sigma^I \gamma^\mu q_L) \qquad O_{\varphi tb} = i(\tilde{\varphi}^\dagger D_\mu \varphi)(\bar{t}_R \gamma^\mu b_R)$$

$$O_{tW} = \bar{q}_L \sigma^{\mu\nu} \sigma^I t_R \tilde{\varphi} W^I_{\mu\nu} \qquad O_{bW} = \bar{q}_L \sigma^{\mu\nu} \sigma^I b_R \varphi W^I_{\mu\nu}$$

Coupling relations

$$V_L = V_{tb} + c_{\varphi q}^{(3)} \frac{v^2}{\Lambda^2} \qquad V_R = \frac{1}{2} c^*_{\varphi tb} \frac{v^2}{\Lambda^2}$$

$$g_L = \sqrt{2}\, c^*_{bW} \frac{v^2}{\Lambda^2} \qquad g_R = \sqrt{2}\, c_{tW} \frac{v^2}{\Lambda^2}$$

- NP scale bound [F. Deliot *et al.* PDR 97 013007 (2018)]

$$|g_R| < 0.07, \quad c_{tW} \sim \mathcal{O}(1) \qquad \Rightarrow \qquad \Lambda > 1.1 \quad {\rm TeV}$$

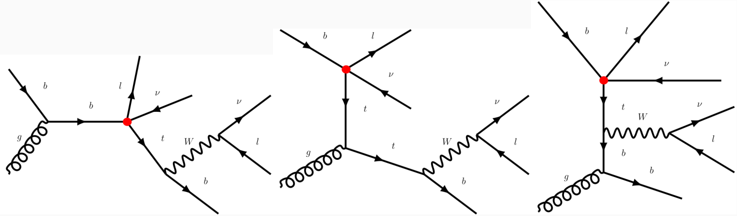
NP in $pp \to tl\nu$: EFT

- Differential distributions in $pp \to tl\nu \to bl\nu l\nu$ used to constrain EFT four fermion operators involving heavy quarks and leptons [Stolarski, **AT** JHEP 08 (2020) 08, 036]

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

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

Representative diagrams

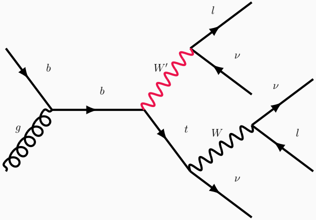


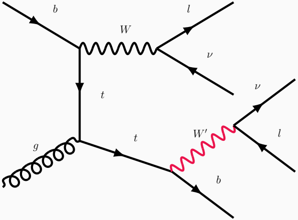
NP in $pp \to tl\nu$: sequential W'

- Differential distributions in $pp \to tl\nu \to bl\nu l\nu$ used to constrain sequential W' model with coupling k_L and mass $M_{W'}$ [Stolarski, **AT**, JHEP 08 (2020) 08, 036]

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

Representative diagrams



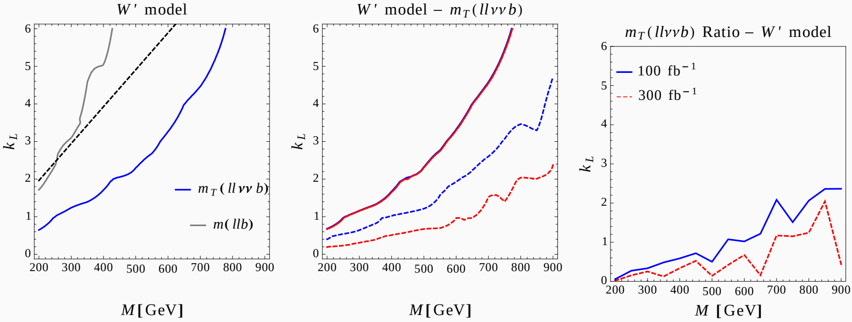


- EFT matching

$$C_2 \equiv \frac{c_{Ql}^{3(1)}}{\Lambda^2} = \pm \frac{g_W^2 k_L^2}{4M_{W'}^2} \qquad\qquad \frac{c_{tl}^{S(1)}}{\Lambda^2} = \frac{c_{tl}^{T(1)}}{\Lambda^2} = 0$$

Current and expected limits

Recasting ATLAS analysis 1712.01602 [Stolarski, **AT**, JHEP 08 (2020) 08, 036]



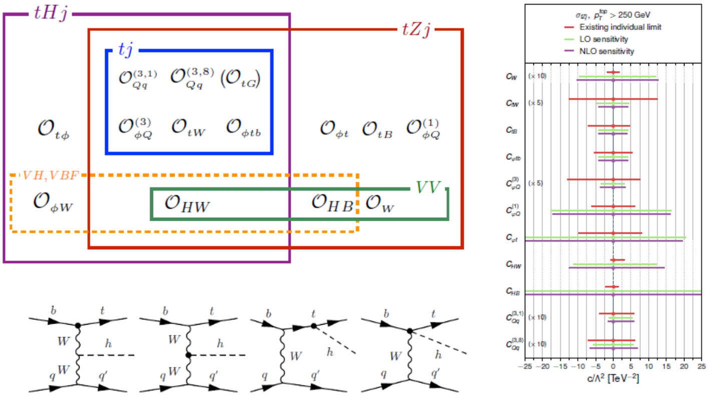
- (left) Current bounds using differential distributions at 36.1 fb^{-1}

$$|C_2| < 10 \text{ TeV}^{-2}$$

- (center) Expected bounds at 300 fb^{-1} (blue) and 3000 fb^{-1} (red)
- (right) Expected bounds using ratios at 100 fb^{-1}and 300 fb^{-1}

Associated single top production

- EFT in tHj and tZj [Degrande *et al.* 1804.07773]



(c) Future, high p_T tZj

Results from hypothetical high p_T measurement of tZj at HL-LHC $\sigma(p_T(t) > 250) \sim 70$ fb

- updated global fit including new meas (see M. Lopez presentation)

Summary and conclusions

- LHC is a top factory allowing to study its properties very precisely
- Single top quark production mechanisms have cross sections directly proportional to the Wtb vertex
- BSM physics may manifests 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 $pp \to tl\nu$
- tHj and tZj used in global fits to constrain operators further (see Marcos Lopez presentation)

Thank you

BACK UP

Anomalous couplings in the SM

- SM corrections to anomalous couplings are extremely small [Jueid *et al.* 1606.05270]

$$g_L = -(1.247 + 0.002747i) \times 10^{-3} \qquad g_R = -(8.6 + 2.05i) \times 10^{-3}$$

$$V_R = (2.911 + 0.9i) \times 10^{-3}$$

- Bounds from $BR(\bar{B} \to X_s \gamma)$ [Grzadkowski *et al.* 0802.1413]

$$-0.15 < g_R < 0.57 \qquad -7 \times 10^{-4} < V_R < 2.5 \times 10^{-3}$$

$$-1.3 \times 10^{-3} < g_L < 4 \times 10^{-4}$$

Anomalous couplings in BSM models

Some references (not exhaustive list):

- Squark and gluino QCD corrections to Wtb vertex [Li *et al.* Phys.Rev.D 48 (1993) 5425-5428]
- EW Chiral Lagrangian with Heavy Higgs [Carlson *et al.* 9405277]

$$V_L = 1 + \frac{G_F}{32\sqrt{2}\pi^2} m_t^2 \log \frac{m_t^2}{m_h^2} \qquad\qquad V_R = 0$$

- Additional gauge boson W' contributions [Tait *et al.* 9710372]
- One loop contribution to the anomalous Wtb couplings in the 2HDM [Jueid *et al.* 1606.05270]

Other top decay observables

- Triple-differential decay rates of polarized top-quarks [Boudreau *et al.* 1304.5639]

$$\frac{1}{N}\frac{dN}{d\Omega d\Omega *}$$

- 95% CL bounds from generalized helicity fractions and phases [ATLAS 1707.05393]

$$\left|\frac{V_R}{V_L}\right| < 0.37$$

FCNC processes

- Top strong FCNC interactions [T. Han *et al.* 9806486; Malkaw and Tait 9511337; Tait and Yuan 0007298]

$$\frac{k_f}{\Lambda} g_s \, \bar{q}\sigma^{\mu\nu} G_{\mu\nu} t + \mathrm{h.c.}$$

- Top weak FCNC [Saavedra *et al.* 9909222]

$$\frac{k_{tqZ}}{\Lambda} e \, \bar{q}\sigma^{\mu\nu} Z_{\mu\nu} t + \mathrm{h.c.} + \ldots$$

- Cross section for $pp \to tZ$ through anomalous t-q-Z couplings $(k_{tuZ} = 0.01)$ [Kidonakis 1712.01144]

$$\sigma(pp \to tZ) \sim 200 \ \mathrm{fb}$$

PRD 97 013007 (2018)

Observables used in the Fit

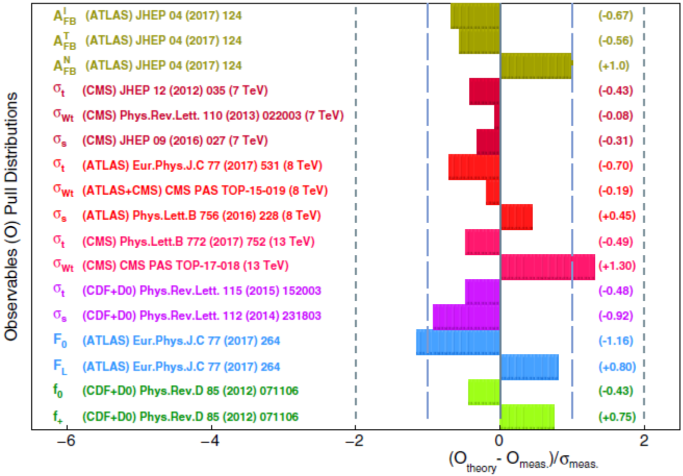


FIG. 1. Relative difference between observable measurements and their most accurate SM predictions.

NP in $pp \to tl\nu$: distributions

We use the following normalized differential distribution as defined in the ATLAS analysis 1712.01602

- the energy of the system of the two leptons and the b-jet, $E(llb)$;
- the mass of the two leptons and the b-jet, $m(llb)$;
- the transverse mass of the leptons, the b-jet and the neutrinos, defined to be

$$m_T(ll\nu\nu b) = \sqrt{\left(\sum_{i=l_1,l_2,b} p_{T_i} + p_{T_{\text{miss}}}\right)^2 - \left(\sum_{i=l_1,l_2,b} \overrightarrow{p_{T_i}} + \overrightarrow{p}_{T_{\text{miss}}}\right)^2}$$

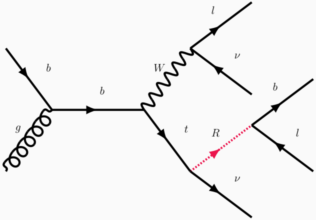
where $p_{T_i} = |\overrightarrow{p_{T_i}}|$ and $\overrightarrow{p}_{T_{\text{miss}}}$ is the missing transverse momentum.

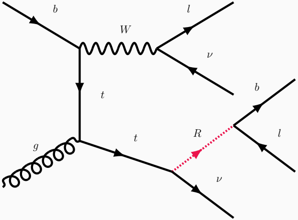
NP in $pp \to tl\nu$: scalar leptoquark model

- Differential distributions in $pp \to tl\nu \to bl\nu l\nu$ used to constrain scalar leptoquark model $R \sim (3, 2, 7/6)$ with coupling g and mass M_R [Stolarski, **AT**, JHEP 08 (2020) 08, 036]

$$\mathcal{L}_Y = g\bar{e}_R R^{a*} Q^a_L - g\bar{t}_R R^a \epsilon_{ab} l^b_L + \text{h.c.}$$

Representative diagrams



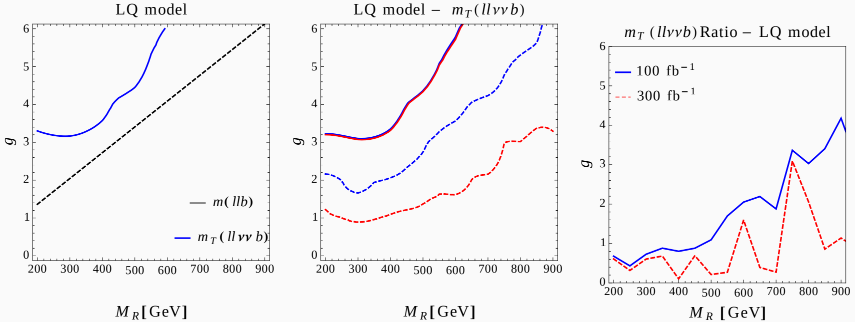


- EFT matching

$$C_1 \equiv \frac{c^{T(1)}_{tl}}{\Lambda^2} = \frac{c^{S(1)}_{tl}}{4\Lambda^2} = \pm\frac{g^2}{8M_R^2} \qquad \frac{c^{3(1)}_{Ql}}{\Lambda^2} = 0$$

Current and expected limits

Recasting ATLAS analysis 1712.01602 [Stolarski, **AT**, JHEP 08 (2020) 08, 036]



- (left) Current bounds using differential distributions at 36.1 fb^{-1}

$$|C_1| < 5\ \mathrm{TeV}^{-2}$$

- (center) Expected bounds at 300 fb^{-1} (blue) and 3000 fb^{-1} (red)
- (right) Expected bounds using ratios at 100 fb^{-1}and 300 fb^{-1}