Measurement of top quark properties in single top production
Outline

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   - Single top quark production in association with a photon
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Introduction

- Top quark decays before hadronization and its spin information is accessible through angular distributions of its decay products.
- Decays almost exclusively into a $W$ boson and a $b$ quark, and thus provides an effective testing ground for studying the $Wtb$ vertex in a search for new interactions.
- $t$-channel is the dominant single-top production mechanism at the LHC ($\approx 80\%$ of the cross section), all presented analyses consider it as the signal process.
- $t$-channel signature:
W boson helicity

- The polarization of the W bosons from top quark decays is sensitive to non-SM Wtb couplings.
- W boson can be produced with left-handed, longitudinal, or right-handed helicity, 
  \( \Gamma(t \rightarrow Wb) = \Gamma_L + \Gamma_0 + \Gamma_R \) holds for the corresponding partial widths.
- Helicity fractions defined as \( F_i = \frac{\Gamma_i}{\Gamma} \), where \( i = L, 0, \text{ or } R \), with \( \sum F_i = 1 \).
- SM predictions at NNLO are (Czarnecki et al. 2010)
  - \( F_L = 0.311 \pm 0.005 \)
  - \( F_0 = 0.687 \pm 0.005 \)
  - \( F_R = 0.0017 \pm 0.0001 \)
- Experimental results extracted using \( t\bar{t} \) events in good agreement with SM predictions, this is the first measurement with single-top events.
W boson helicity - analysis strategy

- Helicity angle $\cos \theta^*_\ell$ is defined as the angle between the W boson momentum in the top quark rest frame and the momentum of the down-type decay fermion in the rest frame of the W boson.

- Significant contribution from $t\bar{t}$ in final selection, same physics information in the $tWb$ vertex, complementary selection to standard CMS $t\bar{t}$ analysis - included in signal

\[
\rho(\cos \theta^*_\ell) \equiv \frac{1}{\Gamma} \frac{d\Gamma}{d\cos \theta^*_\ell} = \frac{3}{9} (1 - \cos \theta^*_\ell)^2 F_L + \frac{3}{4} \sin^2 \theta^*_\ell F_0 + \frac{3}{8} (1 + \cos \theta^*_\ell)^2 F_R
\]
W boson helicity - Results

- $F_L = 0.298 \pm 0.028^{(stat)} \pm 0.032^{(syst)}$
- $F_0 = 0.720 \pm 0.039^{(stat)} \pm 0.037^{(syst)}$
- $F_R = -0.018 \pm 0.019^{(stat)} \pm 0.011^{(syst)}$
- Compatible results for muon and electron channels separately
W boson helicity - limits for anomalous couplings

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

- Use helicity fractions as input to TOPFIT program to set exclusion limits tWb anomalous tensor couplings
- Assume $V_L = 1$ and $V_R = 0$
- Best fit values are $-0.017$ for $g_L$ and $-0.008$ for $g_R$

![Graph showing exclusion limits for anomalous couplings with CMS data at 19.7 fb$^{-1}$ (8 TeV).](image)
Top-quark polarization - introduction

- In single top-quark production via t-channel, SM predicts that top quarks are produced \( \approx 100\% \) polarized through the V-A coupling structure along the momentum of the spectator quark that recoils against the single top quark.

- New physics models may lead to a depolarization in production or decay by altering the coupling structure.

- \( A_\ell = \frac{1}{2} \cdot P_t \cdot \alpha_\ell = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} \)
  - \( P_t \) - single top-quark polarization along the chosen axis.
  - \( \alpha_X \) - the spin-analyzing power of a decay product X, exactly 1 in the SM for charged leptons.
  - \( N(\uparrow) \) and \( N(\downarrow) \) the number of charged leptons aligned or counter-aligned with the direction of the spectator quark recoiling against the single top quark in the top-quark rest frame.
Top-quark polarization - analysis strategy

- Extract a high-purity sample of t-channel single-top events
- Estimate signal and background components by a fit to data
- Define an angular observable sensitive to the top-quark polarization
- Apply an unfolding technique to infer the parton-level distribution
- Extract the top-quark spin asymmetry from the unfolded distribution
Top-quark polarization - angular distribution

The general form of the angular distribution $\theta^*_X$ of decay product $X = (W, \ell, \nu, b)$ in the top-quark rest frame can be expressed as:

$$\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta^*_X} = \frac{1}{2} (1 + P_t \alpha_X \cos \theta^*_X) = \left( \frac{1}{2} + A_X \cos \theta^*_X \right)$$
Top-quark polarization - results

\[ A_\ell = \frac{N(\cos \theta^*_{\text{unfolded}} > 0) - N(\cos \theta^*_{\text{unfolded}} < 0)}{N(\cos \theta^*_{\text{unfolded}} > 0) + N(\cos \theta^*_{\text{unfolded}} < 0)} \]

\[ A_\ell = 0.41 \pm 0.06 \text{(stat.)} \pm 0.16 \text{(syst.)} \] - combined with BLUE

\[ P_t = 0.82 \pm 0.12 \text{(stat.)} \pm 0.32 \text{(syst.)} \] under assumption \( \alpha_\ell = 100\% \)
**tu(c)γ couplings - Introduction**

- Most general effective Lagrangian up to dimension-six in the vertex of $tu(c)γ$:

$$\mathcal{L}_{\text{eff}} = -eQ_t \sum_{q=u,c} \bar{q} i\sigma^{\mu\nu} q_{\nu} \left( \kappa_{tqγ}^L P_L + \kappa_{tqγ}^R P_R \right) t A_\mu + \text{h.c.}$$

- $\kappa_{tqγ}^{L,R}$ - strength of anomalous couplings

- For simplicity, we assume $\kappa_{tqγ}^L = \kappa_{tqγ}^R = \kappa_{tqγ}$.

- In the SM, the values of $\kappa_{tuγ}$ and $\kappa_{tcγ}$ are zero at tree level.

- Final state of a single top quark and a photon.

- Photon has high $p_T$ because of the recoil against the heavy top quark.
tu(c)γ couplings - Signal Extraction

- Contributions of $Wγ +$ jets and $W+$ jets backgrounds are estimated from data using a template fit method, others from simulation.
- Multivariate classification to optimize the discrimination between SM and possible signal events.
- Trained for $tuγ$ and $tcγ$ separately.
- Signal distributions are scaled to a cross section of 1 pb including the top quark leptonic decay branching ratio.
The experimental upper limits are getting close to the predictions of new physics models.
Anomalous couplings - introduction

Most general, lowest dimension, CP conserving Lagrangian for the Wtb vertex:

\[
\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (f_V^L P_L + f_V^R P_R) t W^- - \frac{g}{\sqrt{2}} \bar{b} i\sigma^{\mu\nu} \partial_\nu W^- \frac{M_W}{(f_T^L P_L + f_T^R P_R)} t + h.c
\]

- \( f_V^L \) (\( f_V^R \)) is left-handed (right-handed) vector coupling, \( f_T^L \) (\( f_T^R \)) tensor couplings
- For SM \( f_V^L = V_{tb} \), \( f_V^R = f_T^L = f_T^R = 0 \)
- We consider two scenarios: \( (f_V^L, f_V^R) \) and \( (f_V^L, f_T^L) \) with other couplings set to zero.
- The kinematics and angular distributions significantly change in the presence of anomalous Wtb couplings, both in the production and in the decay of the top quark
- Train various BNN’s to discriminate between background SM signal and anomalous couplings
- Set limits based on the BNN distributions
Limits on anomalous couplings

One-dimensional constraints on anomalous parameters obtained by fixing one parameter to its SM value and setting the exclusion limit on the other one.

- $(f_L^V, f_R^V)$ scenario - observed (expected)
  - $f_L^V > 0.90 (0.88)$
  - $f_R^V < 0.34 (0.39)$

- $(f_L^V, f_L^T)$ scenario
  - $f_L^V > 0.92 (0.88)$
  - $f_L^T < 0.09 (0.16)$
tug/tcg FCNC anomalous couplings

FCNC tcg and tug interactions can be written in a model-independent form with the following vertex in the effective Lagrangian

\[ \frac{\kappa_{tqg}}{\Lambda} g_s \bar{f} \sigma^{\mu\nu} \frac{\lambda^a}{2} tG_{\mu\nu}^a \]

- \( \Lambda \) scale of new physics \( \mathcal{O}(1 \text{ TeV}) \)
- \( \kappa_{tqg} \) defines the strength of the FCNC interactions in the tug or tcg vertices
- Cross section of the single top quark production through FCNC is proportional to \( (\kappa_{tqg}/\Lambda)^2 \).

- \( \frac{\kappa_{tug}}{\Lambda} < 1.8 \cdot 10^{-2} (1.2 \cdot 10^{-2}) \text{ TeV}^{-1} \)
- \( \frac{\kappa_{tcg}}{\Lambda} < 5.6 \cdot 10^{-2} (3.1 \cdot 10^{-2}) \text{ TeV}^{-1} \)
Conclusions

- First measurement of W boson helicity fractions in single-top
- First measurement of top quark polarization in single-top
- Improved limits for $tu(c)\gamma$ couplings
- Set limits on anomalous Wtb and FCNC couplings
- No deviation from Standard Model observed
- Single top at the LHC is a unique testing ground for top quark properties, complementary to ttbar
References


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