Measurement of Top Quark Properties in Single Top Production at CMS

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The Top Quark

• The most massive particle known to date
  – very short lifetime

\[ \tau_t = \frac{1}{\Gamma_t} \sim 0.5 \times 10^{-24} \text{s} < \frac{1}{\Lambda_{QCD}} < \frac{m_t}{\Lambda_{QCD}^2} \sim 3 \times 10^{-21} \text{s} \ll \tau_b \sim 10^{-12} \text{s} \]

→ Top quark decays via the weak interaction before hadronization.

No hadronic bound states
→ bare quark properties are accessible (mass, charge, \( V_{tb} \), spin, polarization, ...)

\( \tau \)
Single Top Production

- Single top quarks are produced through the electroweak interaction.
- First observed in March 2009 by both Tevatron experiments in s+t channel (PRL 103 092002, PRL103 092001) using multivariate techniques.
- All production modes established now by Tevatron and LHC experiments
  - t channel (D0) [PLB 705, 313 (2011)]
  - tW channel (CMS) [PRL 112 231802]
  - s channel (D0 and CDF) [PRL 112 231803]
Single Top Production

- Provides tests of electroweak interactions.
- Sensitive to u/d-PDFs.
- All modes sensitive to Wtb vertex and new physics
  - $W'$, charged Higgs, ... \( \leftrightarrow \) tW- or s-channel.
  - FCNC \( \leftrightarrow \) t-channel
- Background to searches (Higgs, SUSY, ...)

`t-channel`  `tW associated production`  `s-channel`
t-Channel Single Top Production

- Dominant process at the LHC (and the Tevatron).
- Most single top properties measurements from the t-channel.
- Signal signature in lepton+jets final state: 1 isolated lepton, one light (relatively) forward jet, 1 central b-jet, MET.
- Main backgrounds: W+jets, ttbar, QCD multijet

See Mario Merola’s talk for details on t-channel single top production.

arXiv:1403.7366
Testing SM Couplings in Single Top t-Channel

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

\[ \mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu \left( f^L_V P_L + f^R_V P_R \right) t W^-_\mu - \frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu\nu} \partial_\nu W^-_\mu}{M_W} \left( f^L_T P_L + f^R_T P_R \right) t + h.c. \]

Left and right vector operators

Left and right tensor operators

Measure $|V_{tb}|$

arXiv:1403.7366

Measure top and W polarization to test V-A coupling.

CMS-PAS-TOP-13-001
CMS-PAS-TOP-12-020

Look for anomalous couplings in single-top topologies.

CMS-PAS-TOP-12-020, CMS-PAS-TOP-14-007

SM: $f^L_V = V_{tb}$, $f^V_R = f^T_L = f^R_V = 0$ (at tree level)
$|V_{tb}|$ Measurement

$|V_{td}|, |V_{ts}| < |V_{tb}|, Br \approx 1 \rightarrow |f_V^{L}V_{tb}| = \sqrt{\frac{\sigma_{t-ch.}}{\sigma_{theo.}}}$

SM: $f_V^{L} = 1$

BSMs: $f_V \neq 1, \ Br \approx 1$

Cross-section from fit to $|\eta_{j'}|$ of the recoiling light jet where signal is more dominant in the forward region.

$|f_V^{L}V_{tb}| = 0.979 \pm 0.045(\text{exp.}) \pm 0.016(\text{theo.}) @ 7 \text{ TeV}$

$|f_V^{L}V_{tb}| = 0.998 \pm 0.038(\text{exp.}) \pm 0.016(\text{theo.}) @ 7+8 \text{ TeV}$

$f_V^{L} = 1, \ |V_{tb}| \leq 1$

$|V_{tb}| > 0.92 @ 95\% \text{ C.L.}$

arXiv:1403.7366
Summary of $|V_{tb}|$ Measurements

CMS Preliminary

| $|V_{tb}|$ Summary | June 2014 |
|-------------------|-----------|
| CMS tW, 7 TeV, 4.9 fb$^{-1}$, PRL110(2013)02203 |
| $1.010^{+0.160\text{(exp)}}_{-0.130\text{(th)}}^{+0.030\text{(th)}}$ |
| CMS tW, 8 TeV, 12.2 fb$^{-1}$, PRL 112(2014)231802 |
| $1.030 \pm 0.120\text{(exp)} \pm 0.040\text{(th)}$ |
| CMS t-ch., 7 TeV, 1.17/1.56 fb$^{-1}$, JHEP12(2012)035 |
| $1.029 \pm 0.046\text{(exp)} \pm 0.017\text{(th)}$ |
| CMS t-ch., 8 TeV, 19.7 fb$^{-1}$, JHEP06(2014)090 |
| $0.979 \pm 0.045\text{(exp)} \pm 0.016\text{(th)}$ |
| CMS t-ch., 7 and 8 TeV combined, JHEP06(2014)090 |
| $0.998 \pm 0.038\text{(exp)} \pm 0.016\text{(th)}$ |
| CMS $t\bar{t}R_b$, 8 TeV, 19.7 fb$^{-1}$ arXiv:1404.2292 |
| $1.007 \pm 0.016\text{(stat+syst)}$ |

(see Sergio Jindariani’s talk for $|V_{tb}|$ measurement from ttbar)
Anomalous couplings in the t-channel

- Separate Bayesian Neural Networks (using up to 25 variables)
  - Suppress QCD
  - Discriminate signal and backgrounds.
  - Search for anomalous Wtb couplings
  - (Search for FCNC interactions – see the talk by Mojtaba Mohammadi Najafabadi)

Two scenarios to look for anomalous couplings:

- CMS-PAS-TOP-14-007

- gbar

- QCD BNN

- SM BNN

- ttbar

- 4jets with 2 btags

- Wjets

- no btagged jets

- → control regions
Anomalous couplings in the t-channel

BNNs to distinguish SM $|f_V^L|$ and anomalous Wtb couplings $|f_V^R|$ and $|f_T^L|$.

95% C.L.

$|f_V^L| > 0.90 (0.88)$

$|f_V^R| < 0.34 (0.39)$

$|f_T^L| > 0.92 (0.88)$

$|f_T^L| < 0.09 (0.16)$

The dominant uncertainty: PDFs
Top Polarization

- Single tops are produced left-handed polarized in SM (V-A coupling)
  - BSM particles or interactions can modify the top polarization to be < 100%.
- Signal and background are extracted by a boosted decision tree (BDT) fit to the data.
- Unfolding to parton-level.

\[
\frac{d\Gamma}{d\cos\theta_X} = \frac{\Gamma}{2} \left(1 + P_\alpha \alpha_X \cos\theta_X\right) \equiv \Gamma \left(\frac{1}{2} + A_X \cos\theta_X\right)
\]

\[\theta_X \rightarrow \text{between } l^+ \text{ and untagged jet in the top frame.}\]
Top Polarization

CMS preliminary $\sqrt{s} = 8$ TeV, $L = 20$ fb$^{-1}$

$A = 0.42 \pm 0.07$ (stat.) $\pm 0.15$ (syst.)

$A_\ell = 0.41 \pm 0.06_{\text{stat.}} \pm 0.16_{\text{sys.}}$

Forward/backward asymmetry of charged leptons w.r.t. untagged jet in the top frame:

$$A_\ell \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

$P_t = 0.82 \pm 0.12_{\text{stat.}} \pm 0.32_{\text{sys.}}$

(spin analyzing power of charged lepton, $\alpha_l = 1$)

- Measurement dominated by the uncertainties in jet energy scale, renormalization and factorization scales, top mass and background estimation.
- In agreement with the SM V-A coupling (100% polarization).
W-helicity

- W polarization from top quark decay → sensitive to anomalous Wtb couplings.

\[ \frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8} \left( 1 - \cos\theta^* \right)^2 F_L + \frac{3}{8} \left( 1 + \cos\theta^* \right)^2 F_R + \frac{3}{4} \left( \sin\theta^* \right)^2 F_0 \]

Helicity fractions:

\[ F_X \equiv \frac{\Gamma_X}{\Gamma}, \quad F_L + F_R + F_0 = 1 \]

=0 at tree level neglecting m_b

θ*: angle between the p(d-type fermion) in W rest-frame and p(W) in top rest-frame.

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NNLO QCD

- \( F_0 = 0.687(5) \)
- \( F_L = 0.311(5) \)
- \( F_R = 0.0017(1) \) with \( m_b = 4.8 \text{ GeV} \)
- \( m_t = 172.8(1.3) \text{ GeV} \)

Czarnecti et al., PRD 81, 111503 (2010)
W Helicity in Single Top Topologies

- First measurement of the W-helicity fractions using single-top events (μ+jets final state).
- Helicities obtained from likelihoods with reweighted signals.
  - including all processes involving the top quark (t-,s-,tW-channels, and ttbar semileptonic and dileptonic final states)
  - Helicity fractions and W+jets contribution simultaneously extracted.
W Helicity in Single Top Topologies

7+8 TeV combined results

\[ F_L = 0.293 \pm 0.069 \text{(stat.)} \pm 0.030 \text{(syst.)} \]
\[ F_0 = 0.713 \pm 0.114 \text{(stat.)} \pm 0.023 \text{(syst.)} \]
\[ F_R = -0.006 \pm 0.057 \text{(stat.)} \pm 0.027 \text{(syst.)} \]

Right handed fraction obtained using

\[ F_R = 1 - F_0 - F_L \]

- Dominant systematic uncertainties
  - MET uncertainty from the fluctuations in un-clustered energy, JES/JER
  - \( Q^2 \) and simulation; W+jet shape

Results consistent with the SM (NNLO QCD) and measurements in the ttbar channel.

Eliminated by single top cross-section measurements.

Exclusion limits on tensor couplings
Conclusions

- Top quark properties from single top quark measurements
  - $|V_{tb}|$, anomalous couplings, top polarization, $W$ helicity
- Measurements of top quark properties in single top production at CMS are providing thorough tests of the standard model.
- So far, all top quark properties measurements show good agreement with the standard model predictions.

All public CMS top quark results at: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsTOP