First measurement of single top quark production cross-section in association with W boson at 13 TeV with CMS detector

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Measurement of the production cross section for single top quarks in association with W bosons in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS collaboration

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Abstract: A measurement is presented of the associated production of a single top quark and a W boson in proton-proton collisions at $\sqrt{s} = 13$ TeV by the CMS Collaboration at the CERN LHC. The data collected corresponds to an integrated luminosity of 35.9 fb$^{-1}$. The measurement is performed using events with one electron and one muon in the final state along with at least one jet originated from a bottom quark. A multivariate discriminant, exploiting the kinematic properties of the events, is used to separate the signal from the dominant tt background. The measured cross section of $63.1 \pm 1.8_{\text{stat}} \pm 6.4_{\text{syst}} \pm 2.1_{\text{lumi}}$ pb is in agreement with the standard model expectation.

Keywords: Hadron-Hadron scattering (experiments), Top physics

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Outline

➢ Single top quark production at LHC

➢ Introduction & Motivation

➢ Cross section for top quark production at NNLO

➢ tW & tt interference and treatments

➢ Analysis signal & possible backgrounds

➢ Analysis Strategy, Object selection criteria & Status

➢ Results

➢ Summary & Outlook
Single top-quark production at LHC

- t-channel: Dominant process at LHC.

- s-channel: Least dominant process at LHC.

- Associated production of top quark & W boson (tW-channel): 2nd most dominant process at LHC.
Introduction & Motivation

➢ Both analyses are documented on the twiki

➢ Cross-section of Single top-quark production => |V_{tb}| matrix element of CKM matrix\(^1\).

➢ Sensitive to non-SM couplings of Wtb vertex\(^1\).

➢ Background to other searches (e.g. H->WW)

Theoretical (experimental) cross sections (in pb) for top quark production at approximate NNLO.

<table>
<thead>
<tr>
<th>Center of mass Energy</th>
<th>t-Channel (NNLO)</th>
<th>s-Channel (NNLO)</th>
<th>tW-Channel (NNLO)</th>
<th>tt~ (NNLO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (ppBar) 1.96TeV</td>
<td>2.08(^{+0.00}<em>{-0.04})±0.12 (3.04^{+0.54}</em>{-0.49})</td>
<td>1.05(^{+0.00}<em>{-0.01})±0.06 (1.29^{+0.26}</em>{-0.24})</td>
<td>0.22±0.08 (---)</td>
<td>7.164(^{+0.11}_{-0.20})-0.122</td>
</tr>
<tr>
<td>LHC (pp) 7TeV(^{1,3,4})</td>
<td>63.89(^{+1.92}_{-1.25})-2.19 (67.2±6.1)</td>
<td>4.29(^{+0.12}_{-0.1})±0.14 (&lt;26.5)</td>
<td>15.74±0.4(^{+1.1}<em>{-1.14})(^{+16}</em>{-5})</td>
<td>173.60(^{+4.46}_{-5.85})±8.85</td>
</tr>
<tr>
<td>LHC (pp) 8TeV(^{2,3,4})</td>
<td>84.69(^{+2.56}_{-1.68})-2.76 (85±12)</td>
<td>5.24(^{+0.15}_{-0.1})±0.16 (&lt;11.5)</td>
<td>22.37±0.60±1.40 (23.4±5.4)</td>
<td>247.74(^{+6.26}_{-8.45})±11.47</td>
</tr>
<tr>
<td>LHC (pp) 13TeV(^{3,4})</td>
<td>216.99(^{+6.62}_{-4.62})±6.16 (219±1.5±32.9)</td>
<td>10.32(^{+0.29}_{-0.24})±0.27</td>
<td>71.7±1.8±3.4</td>
<td>815.96(^{+19.37}_{-28.61})±34.38 at NNLO+NNLL (772±60±62)</td>
</tr>
</tbody>
</table>

References:

2. Observation of the Associated Production of a Single Top Quark and a W Boson in pp Collisions at 8TeV, PRL 112, 231802 (2014)
3. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SingleTopRefXsec#Single_top_t_channel_cross_sections_at
4. https://twiki.cern.ch/twiki/bin/view/LHCPhysics/TtbarNNLO#Top_quark_pair_cross_sections_at
At LO the two processes are well defined and independent, but $t\bar{t}$ is still the dominant background
- Much larger cross section, and same final state if one b-jet is lost

**Challenge for tW-Channel:** Interference at NLO level with top-quarks ($tt\sim$) pair production for extraction of tW signal.
tW(NLO-interference)
Treatments of tt and tW

- Theoretical difficulty overcome by Diagram Removal (DR) & Diagram Subtraction (DS).

\[ M = M^{(tw)} + M^{(tt\sim)} \]

\[ |M|^2 = |M^{(tw)}|^2 + 2\text{Re}\{M^{(tw)}M^{(tt\sim)*}\} + |M^{(tt\sim)}|^2 \]

- **Diagram Removal (DR):** Removes doubly resonant diagrams in NLO Wt amplitudes.

\[ |M^{(tw)}|^2 = |M^{(tw)}|^2 \]

- **Diagram Subtraction (DS):** Implement a subtraction term to locally cancel the tt\sim contribution to modify the NLO Wt cross section.

\[ |M|^2 = |M^{(tw)} + M^{(tt\sim)}|^2 - C^{\text{SUB}} \]

\[ g + g \rightarrow W^- + t + \bar{b} \]

\[ k_1 \quad k_2 \quad k_3 \]

\[ C^{\text{SUB}} = \frac{(m_t \Gamma_t)^2}{((k_1 + k_2)^2 - m_t^2)^2 + (m_t \Gamma_t)^2} |M^{(tt\sim)}(\Phi'_3)|^2 \]

\( \Phi'_3 \): 3-body phase space point obtained by reshuffling \( \Phi_3 \) kinematics to get

\[ (k_1 + k_3)^2 = m_t^2 \]

\[ DR-DS = |M^{(tw)}|^2 - [|M^{(tw)} + M^{(tt\sim)}|^2 - C^{\text{SUB}}] = 2\text{Re}\{M^{(tw)}M^{(tt\sim)*}\} \]

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Top Quark Decays

BR ($t \rightarrow Wb$) ~ 100%

Dilepton channel:
Both W's decay via $W \rightarrow \ell \nu$ ($\ell = e$ or $\mu$; 4%)

Lepton + jet channel:
One W decays via $W \rightarrow \ell \nu$ ($\ell = e$ or $\mu$; 30%)

Full hadronic channel:
Both W's decay via $W \rightarrow $qq (46%)

Channel study consists: $e\mu2\nu b$, $ee2\nu b$, $\mu\mu2\nu b$

➢ In final state we have 2 opposite charge leptons. Leptons include $e, \mu$

➢ Additionally, we have 2 neutrinos, constitute Missing Energy

➢ Also b-jet
Possible Backgrounds

(tt): \(t\bar{t}\rightarrow WWbb\rightarrow 212\nu 2b\) & 1b is not detected.

(Z+jets): Z decays to \(e^+e^-\) or \(\mu^+\mu^-\) & mis-measurement of jet energy causes the missing energy.

(W+jets): W decays leptonically & one of the jets fake as lepton.

(ZZ): One Z decays to \(e^+e^-\) or \(\mu^+\mu^-\) & Second decays hadronically, but mis-measurement of jet energy causes the missing energy.

(WZ): (i) Either W decays hadronically & Z leptonically, but mis-measurement of jet energy causes the missing energy OR (ii) W decays leptonically & Z decays leptonically.

(WW): Both W decays leptonically.

(Non W/Z): Arise from processes with one prompt-lepton (decaying from a W or a Z boson) and one non-prompt lepton that passes the isolation and identification criteria.
Data Samples and triggers

- Analysis is performed over the complete 2016 dataset (35.9 fb\(^{-1}\))
- \textbf{SingleElec, SingleMuon, DoubleElec, DoubleMuon and MuonEG} primary datasets
- Run2016\textbf{B}-Run2016\textbf{H} (03Feb2017 ReReco)
- Using official JSON:
  \texttt{Cert_271036-284044_13TeV_23Sep2016ReReco_Collisions16_JSON.txt}

- Trigger strategy as in \textbf{TOP trigger twiki}

<table>
<thead>
<tr>
<th>Run B-G and MC</th>
<th>Run H</th>
</tr>
</thead>
<tbody>
<tr>
<td>HLT_Mu23_TrkIsoVVL_Ele12_CaloldL_TrackldL_IsoVL_v*</td>
<td>HLT_Mu23_TrkIsoVVL_Ele12_CaloldL_TrackldL_IsoVL_DZ_v*</td>
</tr>
<tr>
<td>HLT_Mu8_TrkIsoVVL_Ele23_CaloldL_TrackldL_IsoVL_v*</td>
<td>HLT_Mu8_TrkIsoVVL_Ele23_CaloldL_TrackldL_IsoVL_DZ_v*</td>
</tr>
<tr>
<td>HLT_Ele27_WPTight_Gsf_v*</td>
<td>HLT_Ele27_WPTight_Gsf_v*</td>
</tr>
<tr>
<td>HLT_IsoTkMu24_v*</td>
<td>HLT_IsoTkMu24_v*</td>
</tr>
<tr>
<td>HLT_IsoMu24_v*</td>
<td>HLT_IsoMu24_v*</td>
</tr>
</tbody>
</table>
MC Datasets

- Monte Carlo samples of $tW$ and $t\bar{t}$ used in the analysis

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\sigma$ [pb]</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>/TT_TuneCUETP8M2T4.13TeV-powheg-pythia8</td>
<td>831.8</td>
<td>77,229,341</td>
</tr>
<tr>
<td>/TT_TuneCUETP8M2T4.13TeV-powheg-pythia8 (.backup)</td>
<td>831.8</td>
<td>78,006,311</td>
</tr>
<tr>
<td>/TTTo2L2Nu_TuneCUETP8M2_ttHtranche3.13TeV-powheg-pythia8</td>
<td>831.8</td>
<td>79,092,400</td>
</tr>
<tr>
<td>/STtW_top_5f.inclusiveDecays.13TeV-powheg-pythia8_TuneCUETP8M1 (.ext1-v1)</td>
<td>35.85</td>
<td>6,952,830</td>
</tr>
<tr>
<td>/STtW_antitop_5f.inclusiveDecays.13TeV-powheg-pythia8_TuneCUETP8M1 (.ext1-v1)</td>
<td>35.85</td>
<td>6,933,094</td>
</tr>
<tr>
<td>/STtW_top_5f.NoFullyHadronicDecays.13TeV-powheg_TuneCUETP8M1</td>
<td>19.467</td>
<td>5,372,991</td>
</tr>
<tr>
<td>/STtW_top_5f.NoFullyHadronicDecays.13TeV-powheg_TuneCUETP8M1 (.ext1-v1)</td>
<td>19.467</td>
<td>3,256,650</td>
</tr>
<tr>
<td>/STtW_top_5f.NoFullyHadronicDecays.13TeV-powheg_TuneCUETP8M1 (.ext2-v2)</td>
<td>19.467</td>
<td>2,715,978</td>
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<tr>
<td>/STtW_antitop_5f.NoFullyHadronicDecays.13TeV-powheg_TuneCUETP8M1</td>
<td>19.467</td>
<td>5,425,134</td>
</tr>
<tr>
<td>/STtW_antitop_5f.NoFullyHadronicDecays.13TeV-powheg_TuneCUETP8M1 (.ext1-v1)</td>
<td>19.467</td>
<td>3,256,407</td>
</tr>
<tr>
<td>/STtW_antitop_5f.NoFullyHadronicDecays.13TeV-powheg_TuneCUETP8M1 (.ext2-v1)</td>
<td>19.467</td>
<td>2,726,603</td>
</tr>
</tbody>
</table>

- Dileptonic ($t\bar{t}$) and “not fully hadronic” ($tW$) samples are used for BDT training, inclusive for background estimation and signal extraction.
- Other backgrounds
  - **DY**: M50 and M10to50 amcatnloFXFX-pythia8
  - **W+jets**: madgraphMLM
  - **ttV**: amcatnloFXFX-pythia8
  - **VV**: pythia8
Di-lepton(eµ) Analysis Strategy

- HLT (Logical OR between single & double lepton triggers)
- At least two well identified, isolated leptons.
- Leptons must be with opposite charge (signal)
- \(m_{ll} > 20 \text{ GeV}\) (Suppress low mass Resonances)

Signal region: 1jet 1b-tag, 2jet 1b-tag, 2jet 2b-tag

Distinguish signal (tW) from background (tt) :
- Multivariate technique (MVA) => Boosted decision tree (BDT).
- Simultaneous Likelihood fit over the different regions to BDT discriminant to separate signal tW and dominant tt background.
Selection Criteria-I ✓

Event should have at least one Tight Electron and one Tight muon

➢ Electrons
   ✶ Cut based identification with Tight working points electronID
   ✶ $P_T > 20\text{GeV}, |\eta| < 2.4$
   ✶ Gap veto: $1.4442 < |\eta_{sc}| < 1.566$

➢ Muons
   ✶ Tight ID MuonID
   ✶ $P_T > 20\text{GeV}, |\eta| < 2.4$

Leading Lepton’s $P_T > 25\text{GeV}$

➢ Jets
   ✶ L1Fastjet, L2, L3 JECs for MCs.
   ✶ MC’s+L2L3Residual JECs for real data.
   ✶ $P_T > 30\text{GeV}, |\eta| < 2.4$
   ✶ Loose ID JetID
   ✶ CSVv2M=0.8484 bTaggingLink
   ✶ jet-lepton cleaning $dR < 0.4$

➢ Met
   ✶ Used Type-I Corrected MET.
   ✶ Recommended Filters applied.
Data-MC comparison for several lepton kinematic variables at pre-selection level
Signal strength extracted using a maximum likelihood fit to the shape of 1j1tBDT, 2j1tBDT, 2j2t sub-leading jet’s $p_T$
Summary & Outlook

• $tW$ production cross-section paper has been published in JHEP (Cadi-line: TOP-17-018).

• Signal extraction and cross-sections are measured to be:

$$\mu = 0.88 \pm 0.02(\text{stat.}) \pm 0.09(\text{syst.}) \pm 0.03(\text{lumi.}) \text{pb}$$
$$\sigma_{tW} = 63.1 \pm 1.8(\text{stat.}) \pm 6.4(\text{syst.}) \pm 2.1(\text{lumi.}) \text{pb}$$
$$\sigma_{tW}(\text{NNLO}) = 71.7 \pm 1.8(\text{scale}) \pm 3.4(\text{PDF}) \text{pb}$$

Main uncertainties: JES, lepton identification, $tt$ modeling
THANK YOU