Measurement of single top production in pp collisions at 7 TeV with the CMS detector

2011 Europhysics Conference on High-Energy Physics

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On behalf of the CMS collaboration

Based on:
CMS PAS TOP-10-008
Preprint arXiv:1106.3052
The CMS detector

- **Compact design** thanks to 3.8 Tesla superconduction magnet

- **Muon detector**
  For muon identification and momentum reconstruction

- **Inner tracking system** composed of a silicon pixel and a silicon strip detector for charged particle tracks reconstruction

- **Electromagnetic and hadronic**
  calorimeters for electron, photon and jets reconstruction

- **Total Weight**: 12000 t
  **Overall diameter**: 15 m
  **Length**: 21 m
  **Magnetic field**: 3.8 Tesla
The CMS detector: data taking at 7 TeV

2010:
Up to december '10: 
43 pb\(^{-1}\) on tape
peak instant luminosity: 
204.78 μb\(^{-1}\) s\(^{-1}\)

2011
Up to July '11:
> 1 fb\(^{-1}\) on tape
peak instant luminosity:
1.57 nb\(^{-1}\) s\(^{-1}\)

Note: the analysis henceforth described uses the 2010 dataset.
3 single top processes:

Focus on **t-channel**:
- highest cross section
- most favorable s/b ratio

Cross sections(pb)
(top mass =173)

<table>
<thead>
<tr>
<th>Process</th>
<th>Cross Section (pb)</th>
<th>LHC: ( pp ) @7 TeV</th>
<th>Tevatron: ( pp ) @1.96 TeV</th>
<th>LHC: ( pp ) @14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>s-channel</td>
<td>4.59</td>
<td>4.59</td>
<td>1.04</td>
<td>11.9</td>
</tr>
<tr>
<td>tW channel</td>
<td>15.6</td>
<td>15.6</td>
<td>0.22 (arxiv.org/pdf/0909.0037)</td>
<td>83.6</td>
</tr>
<tr>
<td>t channel</td>
<td>63.2</td>
<td>63.2</td>
<td>2.08</td>
<td>243</td>
</tr>
<tr>
<td>( tt )</td>
<td>165</td>
<td>165</td>
<td>7.2</td>
<td>894</td>
</tr>
</tbody>
</table>

NLO, Phys. Rev. D 81, 054028 (2010), N. Kidonakis
NNLO, Phys. Rev. D 82, 054018 (2010), N. Kidonakis
NNLO, Phys. Rev. D 83, 091503(R) (2011), N. Kidonakis
NNLO, arxiv.org/pdf/0909.0037, N. Kidonakis
Main backgrounds ($t \rightarrow bl\nu$ decay mode):

- $tt$ ($\sigma = 165$ pb): same kinematic region as $t$-channel
- $W(\rightarrow l\nu)+\text{jets}$ ($\sigma \sim 31$ nb): different behavior from $W+(u,s,d,g)$ and $W+(c,b)$
- Multijet QCD $\rightarrow l + \text{jets}$: extreme kinematic regions $\rightarrow$ use data driven estimation
Analysis strategy

Baseline selection + QCD background estimation
(lepton, b-jet, light jet, \(M_T\))

(fit to \(M_T\))

Top quark 4-momentum reconstruction

“2D analysis”
Based on template fits for signal extraction

“BDT analysis”
Multivariate analysis using boosted decision trees

Combination of the results
Event selection: physics objects and Particle Flow

- **Particle Flow:**
  Algorithm which uses information from all the sub-detectors to reconstruct leptons, jets, missing energy.

- **JET momentum resolution** greatly benefits of the inclusion of the tracking system.

- **Missing energy resolution** Increases due to Intrinsicly inclusive nature of the Particle Flow algorithm
Event selection

Leptons:

- **Exactly 1 muon(electron)** with $p_T (E_T) > 20(30)$ GeV, $|\eta| < 2.1$ (2.5)

- **relative isolation for the $\mu (e)$:**
  $$\text{RelIso} = (\text{trackIso} + \text{caloIso})/p_T (E_T) < 0.05(0.1)$$
  trackIso and caloIso are the sum of $p_T$ of the tracks and of calorimetric deposits
  In a cone of $\Delta R = \sqrt{\Delta \Phi^2 + \Delta \eta^2} < 0.3$ around the lepton momentum

- **veto extra “loose” $\mu (e)$** with $p_T (E_T) > 10(15)$ GeV and RelIso < 0.2

Only leptonic decays are considered ($t \rightarrow l b \nu$)

Missing energy due to neutrino.
Event selection

Jets

- Jets reconstructed through the anti-kt algorithm with 0.5 cones
- Exactly 2 jets with $p_T > 30$ GeV, $|\eta| < 5$
- Jets overlapping in $\Delta R < 0.1$ with electrons are discarded.
- Veto leptons at $\Delta R < 0.3$ from jets

b-tagging

- Exactly 1 b-tagged jet using an algorithm that measures the impact parameter of tracks associated to the jet
- Exactly 1 b-vetoed jet using the same algorithm, with a looser requirement (2D only)

Jet 1 stems from the light quark $q'$

Jet 2 comes from top quark decay.
A maximum likelihood fit is performed on $M_T$ defined as

$$M_T = \sqrt{2P_{T,\text{lepton}} \cdot \text{MET} (1 - \cos(\varphi_{\text{lepton}} - \varphi_{\text{MET}}))}$$

To determine the amount of QCD after all the cuts.

The shape of the QCD is extracted from an orthogonal control sample obtained inverting the relIso cut.
Selection and QCD fit results

<table>
<thead>
<tr>
<th>Process</th>
<th>2D, $\mu$ channel</th>
<th>2D, $e$ channel</th>
<th>BDT, $\mu$ channel</th>
<th>BDT, $e$ channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>single top, $t$ channel</td>
<td>17.6 ± 0.7 (+)</td>
<td>11.2 ± 0.4 (+)</td>
<td>17.6 ± 0.7 (+)</td>
<td>10.7 ± 0.5 (+)</td>
</tr>
<tr>
<td>single top, $s$ channel</td>
<td>0.9 ± 0.3</td>
<td>0.6 ± 0.2</td>
<td>1.4 ± 0.5</td>
<td>1.0 ± 0.3</td>
</tr>
<tr>
<td>single top, $tW$</td>
<td>3.1 ± 0.9</td>
<td>2.4 ± 0.7</td>
<td>3.8 ± 1.1</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$WW$</td>
<td>0.29 ± 0.09</td>
<td>0.23 ± 0.07</td>
<td>0.32 ± 0.10</td>
<td>0.23 ± 0.07</td>
</tr>
<tr>
<td>$WZ$</td>
<td>0.24 ± 0.07</td>
<td>0.17 ± 0.05</td>
<td>0.33 ± 0.10</td>
<td>1.5 ± 0.4</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.018±0.005</td>
<td>0.011±0.003</td>
<td>0.020±0.006</td>
<td>&lt; 0.1</td>
</tr>
<tr>
<td>$W+$ light partons</td>
<td>18.2 ± 5.5</td>
<td>11.6 ± 2.3</td>
<td>8.4 ± 4.2</td>
<td>7.0 ± 3.5</td>
</tr>
<tr>
<td>$Z + X$</td>
<td>1.7 ± 0.5</td>
<td>1.6 ± 0.3</td>
<td>0.7 ± 0.2</td>
<td>0.05 ± 0.03</td>
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<tr>
<td>QCD</td>
<td>0.6 ± 0.3</td>
<td>2.6$^{+3.4}_{-2.6}$</td>
<td>4.9 ± 2.5</td>
<td>5.3 ± 5.3</td>
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<tr>
<td>$VQQQ$</td>
<td>20.4 ± 10.2</td>
<td>14.1 ± 7.1</td>
<td>17.6 ± 8.8</td>
<td>11.7 ± 5.8</td>
</tr>
<tr>
<td>$Wc$</td>
<td>12.9$^{+12.9}_{-6.5}$</td>
<td>9.4$^{+9.4}_{-4.7}$</td>
<td>9.2$^{+9.2}_{-4.6}$</td>
<td>5.9$^{+5.9}_{-2.9}$</td>
</tr>
<tr>
<td>$tt$</td>
<td>20.3 ± 3.6</td>
<td>15.6 ± 2.8</td>
<td>34.9 ± 4.9</td>
<td>22.9 ± 3.2</td>
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<tr>
<td>Total background</td>
<td>78.6 ± 15.2</td>
<td>58.4 ± 11.0</td>
<td>82.4 ± 13.1</td>
<td>55.9 ± 10.2</td>
</tr>
<tr>
<td>Signal + background</td>
<td>96.2 ± 15.3</td>
<td>69.6 ± 11.0</td>
<td>100.0 ± 13.2</td>
<td>66.6 ± 10.2</td>
</tr>
<tr>
<td>Data</td>
<td>112</td>
<td>72</td>
<td>139</td>
<td>82</td>
</tr>
</tbody>
</table>

- S/B ratio ~ 1/4, 1/5
- Some differences in the BDT / 2D event yield:
  - Different algorithms used for physics objects reconstruction
  - 2D analysis: partially derives $W$ normalization from orthogonal samples
  - BDT analysis: no second b-veto, extra cuts on $\Delta \Phi > 0.3$
Top quark 4-momentum reconstruction

Reconstructed taking 4 momenta of the lepton and the b-tagged jet and the MET:

1) take \((p_{x,v},p_{y,v})= (MET_x, MET_y)\)

2) costrain the mass of the \(l\nu\) pair \(ln\) to the PDG value of \(M_w\): get 2\(^{nd}\) order equation in \(p_{z,v}\)

3) two real solutions: take the one with lowest \(|p_{z,v}|\)

4) two imaginary solutions: put discriminant to 0. In this case the 1) is not valid anymore, but we can still impose 2.

5) Chose \(p_{x,v},p_{y,v}\) with minimum distance from the MET in the \(p_x/p_y\) plane
2D analysis: $\cos \theta_{lj}^*$ and $\eta_{lj}$

- High discriminating power
- model – independent.

light quark recoiling against much more massive top: non central distribution of $\eta_{lj}$

100 % left (right) polarization of $t(\bar{t})$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta_{lj}^*} = \frac{1}{2} (1 + A \cos \theta_{lj}^*)$$

light jet $l$ ($A=1$)
2D analysis: fit to the 2D templates

**Muon only fit:**

\[ \sigma_\mu = 104.1 \pm 42.3^{+24.8}_{-28.0} \, \text{(stat)} \, pb^{-1} \]

Events = 27.7

**Electron only fit:**

\[ \sigma_\mu = 154.2 \pm 56.0^{+40.6}_{-40.6} \, \text{(stat)} \, pb^{-1} \]

Events = 25.9

Extended Maximum Likelihood fit to the 2D template of \( \cos \theta^* \) and \( |\eta_{lj}| \).

Dice pseudo-experiment to evaluate impact instrumental and theoretical systematics.
BDT analysis:
choice of the variables

- 37 variables combined → 1 discriminator
  with Boosted Decision Trees
- five categories:
  1) Kinematic variables (lepton and jets $p_T, \eta$ etc)
  2) Properties of correlation between objects in 1)
  3) Combination of objects in 1)
  4) Angular properties (e.g.: $\cos \theta_{lj}$)
  5) Overall event properties (total $E_T$, sphericity)
BDT analysis:
validation on data

All variables and BDT output validated in a control region with 0 b-tagged jets

The effect of systematics, like the scaling of the $Q^2$ of the interaction, could be checked on such orthogonal sample

![Histogram](image)
BDT analysis: Signal extraction

Signal was extracted by marginalization of the nuisance parameters using Markov Chain Monte Carlo technique.

Background rates and systematics effects parametrized as nuisance parameters.

Muon:

\[ \sigma_\mu = 89.8 \pm 40.4 \text{ (stat + syst) pb}^{-1} \]

Electron:

\[ \sigma_e = 59.2 \pm 37.8 \text{ (stat + syst) pb}^{-1} \]
Impact of systematics

- Most important sources of uncertainty:
  - b-tagging
  - $Q^2$ scaling
  - JES

- Other notable sources:
  - Different signal generators (LO matched vs NLO)
  - Different hadronization models
  - Different initial and final state radiation scenarios

<table>
<thead>
<tr>
<th>uncertainty</th>
<th>correlation</th>
<th>2D</th>
<th>BDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>statistical only</td>
<td>60</td>
<td>52</td>
<td>39</td>
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<tr>
<td>shared shape/rate uncertainties:</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>ISR/FSR for $t\bar{t}$</td>
<td>100</td>
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<tr>
<td>$Q^2$ for $t\bar{t}$</td>
<td>100</td>
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<tr>
<td>$Q^2$ for $V+\text{jets}$</td>
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<tr>
<td>Jet energy scale</td>
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<td>$b$ tagging efficiency</td>
<td>100</td>
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<tr>
<td>MET (uncl. energy)</td>
<td>100</td>
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</tr>
<tr>
<td>$t\bar{t}$ ($\pm 14%$)</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>single top s ($\pm 30%$)</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>single top $tW$ ($\pm 30%$)</td>
<td>100</td>
<td></td>
<td></td>
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<tr>
<td>$W^{\ell\ell}$ ($\pm 50%$)</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$W_{c}$ ($\pm 100%$)</td>
<td>100</td>
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<td></td>
</tr>
<tr>
<td>$Z$+jets ($\pm 30%$)</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>electron QCD (BDT: $\pm 100%$, 2D: $\pm 130%$)</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>muon QCD (BDT: $\pm 50%$, 2D: $\pm 50%$)</td>
<td>50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>signal model</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BDT-only uncertainties:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>electron efficiency ($\pm 5%$)</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>muon efficiency ($\pm 5%$)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>$V+\text{jets}$ ($\pm 50%$)</td>
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<tr>
<td>2D-only uncertainties:</td>
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<tr>
<td>muon $W$+light ($\pm 30%$)</td>
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<td></td>
</tr>
<tr>
<td>electron $W$+light ($\pm 20%$)</td>
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</tr>
<tr>
<td>$W$+light model uncertainties</td>
<td>0</td>
<td></td>
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</tr>
</tbody>
</table>
Combination: Correlation of the analyses

- Correlation evaluated drawing pseudo-experiments from the overlapping datasets

- Differences in the BDT / 2D:
  - Event selection
  - Data-driven shape and background normalization extraction for 2D

- Most important systematics 100% correlated between 2D-BDT
Combined results and $V_{tb}$ extraction

Measured cross section:

$\sigma = 83.6 \pm 29.8 \ (stat+syst) \pm 3.3 \ (lumi) \ pb$

Standard model prediction:

$\sigma = 64.57 \pm 2.09 \ (scale) + 1.51 \ (pdf) \ pb$

with a significance of $3.7(3.5)$ standard deviations for the 2D (BDT) analysis.

Assuming $|V_{td}|,|V_{ts}| \ll |V_{tb}|$ yields $|V_{tb}| = \sqrt{\frac{\sigma^{exp}}{\sigma^{th}}}$ and:

$|V_{tb}| = 1.14 \pm 0.22 \ (exp) \pm 0.02 \ (th)$

Taking $0 < |V_{tb}| \leq 1$ yields a lower limit at 95% confidence level of $|V_{tb}| > 0.62 \ (0.68)$ for the 2D(BDT) analysis respectively.
Conclusions

In 2010 with $36 \text{ pb}^{-1}$ of data:

- Evidence of single top t-channel
- Cross section measurement consistent with the standard model prediction
- Measurement of $|V_{tb}|$

Higher statistics and rich opportunities for single top studies in 2011:

- t-channel properties like charge asymmetry, differential cross section ...
- Study of other single top channels, FCNC, $W'$ resonances and much more ...

$|V_{tb}| > 0.68$

$\sigma = 83.6 \pm 29.8 \pm 3.3 \text{ pb}$
THANKS!
Backup slides
Physics object reconstruction: b-tagging

- **b jets** stem from decays of long lived B mesons, coming from by b quarks produced in the pp interaction

- **They can be identified** since the vertex of the particles that compose such jet differs from the primary interaction vertex

- **Track Counting algorithms**
  
  Used in the presented analysis counts the 2(3) best tracks associated to the jets and uses as high efficiency(purity) discriminator the the lowest value of the significance of the impact parameter amongst the two(three)

![TC distribution](data-mc comparison)
Physics object reconstruction:
Particle Flow

- **Particle Flow** is the algorithm used to reconstruct physics objects in the presented analysis.

- **Each physics object** is reconstructed using information from all sub-detectors of CMS.

- **Muons** have the cleanest signature and are identified first: they pass through the muon detector of CMS and can be discriminated from other particles.

- **Electrons** are identified after muons through their releases in the Electromagnetic calorimeter in association to a track and through tight quality cuts.

- **Jets** are reconstructed with the anti-kt algorithm taking information from all the sub-detectors. Jets are required not to overlap with the already identified muons and electrons and pass through quality cuts.

- **Missing energy** in PF can be measured taking into account all information from sub-detectors in a coherent way.
Single top t-channel: backgrounds

Main processes reproducing the same event topology:

- $\bar{t}t$ (cross section: 165 pb):
  - $\bar{t}t \rightarrow bl\nu bqq'$: two of the jets not passing the transverse momentum or quality cuts.
  - $\bar{t}t \rightarrow bl\nu bl\nu$: the second lepton is outside the detector acceptance/not identified.

  **Remarks:** one top has same decay chain as single top.

- $W+$jets (cross section 31314 pb with MCFM):
  - $W +$ light partons $(u,d,s$ quarks,gluon) $\rightarrow l\nu+$ jets, one of the jets reproduces the behavior of a b-jet.
  - $W +$ heavy partons $(c,b$ quarks) $\rightarrow l\nu+$ jets.

  **Remarks:** $W+$ light partons and $W+$ heavy partons have different behavior, high cross section with respect to single top.

- **Multijet QCD** $\rightarrow l +$ jets

  **Remarks:** high cross section with respect to single top, signal region in the tail of Monte Carlo distributions $\rightarrow$ data driven methods to keep it under control
### Systematics sources and effects

<table>
<thead>
<tr>
<th>Type</th>
<th>Source</th>
<th>Affects</th>
<th>Correlation 2D-BDT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Theoretical and modeling</strong></td>
<td>Q2 of the interaction, $t\bar{t}$ and Wjets</td>
<td>Background event selection, distributions</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Initial/Final state radiation, $t\bar{t}$</td>
<td>Event selection, distributions</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Background processes ($t\bar{t}$, W+jets, etc) rate</td>
<td>Background normalizations, overall variables distributions, Signal extraction</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Signal model</td>
<td>Signal event selection and distribution, signal extraction</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Instrumental</strong></td>
<td>Jet energy scale</td>
<td>Event selection, distributions</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>b-tagging</td>
<td>Event selection, distributions</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Unclustered missing energy</td>
<td>Event selection, distributions</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td>Lepton efficiencies</td>
<td>Event selection, distributions</td>
<td>100%</td>
</tr>
<tr>
<td><strong>Analysis specific</strong></td>
<td>Data driven procedures (e.g.: QCD estimation)</td>
<td>Signal extraction</td>
<td>Uncorrelated or conservative 50%</td>
</tr>
</tbody>
</table>

- Most of the systematics are shared by both analyses and 100% correlated

- Most of them are 100% correlated between $\mu$ and e channels.
Physics object reconstruction: Particle Flow performances

- **PF Jets** matching efficiency (MC)

**PF Jets** data-mc comparison → on minimum bias data

← Transverse missing energy relative resolution
Single top t-channel physics

Focus on **t-channel**:  
- highest cross section  
- most favorable s/b ratio  

Physics of **t-channel**:  
- $\sigma_{(t\text{-channel})}$ related to CKM element Vtb  
- asymmetry in the production of $t\bar{t}$  
- sensitive to $W'$  
- study of Flavour Changing Neutral Currents
A maximum likelihood fit is performed on $M_T$ defined as

$$M_T = \sqrt{2 \cdot P_{T,\text{lepton}} \cdot \text{MET} \left(1 - \cos(\varphi_{\text{lepton}} - \varphi_{\text{MET}})\right)}$$

To determine the amount of QCD after all the cuts.

The cut on $M_T$ after optimizing the figure of merit:

$$W/\sqrt{(W + Q + k^2 Q^2)}$$