Run-I Single-top measurements at CMS

Rebeca Gonzalez Suarez
University of Nebraska, Lincoln
Top quarks at the LHC

- At the **LHC**, top quarks are produced mainly in **ttbar pairs**
  - strong interaction
- Alternative mode, at a lower rate: **Single top quark production**
  - electroweak interaction
- Three main single top process:
  - **t-channel**, **tW associated production**, **s-channel**

<table>
<thead>
<tr>
<th>σ [pb]</th>
<th>ttbar</th>
<th>t-channel</th>
<th>tW</th>
<th>s-channel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tevatron (1.96TeV)</td>
<td>7.08</td>
<td>2.08</td>
<td>0.22</td>
<td>1.046</td>
</tr>
<tr>
<td>LHC @ 7TeV</td>
<td>177.31</td>
<td>63.89</td>
<td>15.74</td>
<td>4.29</td>
</tr>
<tr>
<td>LHC @ 8TeV</td>
<td>252.89</td>
<td>84.69</td>
<td>22.2</td>
<td>5.24</td>
</tr>
<tr>
<td>LHC @ 13TeV</td>
<td>831.76</td>
<td>216.99</td>
<td>71.2</td>
<td>10.32</td>
</tr>
</tbody>
</table>
Run-1 of the LHC in tops

Top quarks were observed for the first time at the Tevatron in 1995 via ttbar, in 2009 via single top; but the LHC has been competitive since the start (first single top paper in 2011)

"The LHC is a top quark factory!"
- Every speaker at every talk about top quarks at the LHC

- The Run-1 of the LHC lasted three years:
  - ~5fb\(^{-1}\) of pp collisions at 7TeV
  - ~20fb\(^{-1}\) at 8TeV

CMS then registered
- More than 5M ttbar pairs
- Around 2M of single top quarks (via t-channel)
- Half a million of t\(^{\pm}\)W events
- A bit more than 100K of s-channel events
Step 1

Study the three single top production modes and measure their production cross section
**t-channel**

- **Dominant process** with the highest cross section at the Tevatron and the LHC

  ![Diagram](image)

- **Final state studied:** lepton + jets signature

- **Signal characterized by:**
  - One isolated **muon or electron**
  - Missing transverse energy (**MET**)
  - A central **b jet**
    - light-quark jet from the hard scattering process (often **forward**)
    - Additionally, a second b jet produced in association to the top quark

- **Main backgrounds:** W+jets, ttbar, multijet
t-channel (7TeV)

- At 7 TeV CMS measured the inclusive t-channel cross section
- Using Multivariate methods (BDT, NN) and the shape of the pseudorapidity of the light jet, $|\eta_j|$

Different regions defined (jets, b-tag)
Multijet and W+jets background estimated from data
Statistical, systematic, and theory uncertainties on the same level

September 2012
JHEP 12 (2012) 035
arXiv:1209.4533
7TeV - 1.17 and 1.56 fb$^{-1}$
t-channel (8 TeV)

- At 8 TeV, the measurement was done using the $|\eta_j|$ analysis alone

Similar approach as for 7 TeV, more data-driven (Multijet, $W$+jets, $tt\bar{t}$)

Full luminosity

**Systematic dominated**
main uncertainties:
Signal modeling (≈6%) and JES/JER/MET (≈4%)

March 2014
JHEP 06 (2014) 090

arXiv:1403.7366

8 TeV - 19.7 fb$^{-1}$
**t-channel: results**

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>7TeV</td>
<td>$67.2\pm3.7\text{(stat)}\pm3.0\text{(syst)}\pm3.5\text{(th)}\pm1.5\text{(lumi)} \text{ pb} = 67.2\pm6.1 \text{ pb}$</td>
<td>$63.89\pm2.91-2.52 \text{ (NLO, latest calculation)}$</td>
</tr>
<tr>
<td>8TeV</td>
<td>$83.6\pm2.3 \text{ (stat)} \pm7.4 \text{ (syst)} \text{ pb}$</td>
<td>$84.69\pm3.76 -3.23 \text{ (NLO, latest calculation)}$</td>
</tr>
</tbody>
</table>
t-channel: combination

- An LHC (ATLAS+CMS) combination was made at 8TeV
- It was the first single top combination of the LHC
  - Sept. 2013
  - CMS-PAS-TOP-12-002
**tW associated production**

- Single top process with the second largest cross-section at the LHC

- Final state studied: **dilepton signature**

- Signal events are characterized by:
  - **Two** opposite-sign, isolated **leptons**
  - Missing transverse energy (2 neutrinos in the final state)
  - A jet coming from a **b decay**

- **Backgrounds:** **ttbar (main challenge), DY**
tW (7TeV)

- Impossible to study before the LHC (very low cross section at the Tevatron) → At the LHC is still not easy
- With 7TeV data, CMS reported evidence for the process

September 2012
arXiv:1209.3489

$4.0 \sigma$
7TeV - 4.9fb$^{-1}$
At 8TeV the process was observed with a significance $> 5 \sigma$

7 TeV $\rightarrow$ cut-based, basic BDT
8TeV $\rightarrow$ cut-based, shape-based, more sophisticated BDT

At 8TeV the analysis is already not statistically limited

January 2014
arXiv:1401.2942

6.1$\sigma$
8TeV - 12.2fb$^{-1}$
tW: results

- The main challenge is the ttbar background
  - ttbar with 1 jet outside acceptance or misreconstructed → mimics perfectly the signal
  - not only very similar final states, also their diagrams mix at NLO
  - Main uncertainties come from theory modeling of ttbar
- 2 control regions were established
- Use of variables related ‘loose’ jets

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<tr>
<td>7TeV</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>( \sigma_{tW} = 16 \pm 5 \pm 4 ) pb</td>
<td>( \sigma_{tW} = 15.6 \pm 0.4 \pm 1.1 ) pb</td>
</tr>
<tr>
<td>8TeV</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \sigma_{tW} = 23.4 \pm 5.4 ) pb</td>
<td>( \sigma_{tW} = 22.2 \pm 0.6 \pm 1.4 ) pb</td>
</tr>
</tbody>
</table>
**tW: combination**

### ATLAS+CMS Preliminary TOPLHCWG

Data 2012, $\sqrt{s} = 8$ TeV, $m_t = 172.5$ GeV

<table>
<thead>
<tr>
<th><strong>NLO+NNLL (arXiv:1210.7813)</strong></th>
<th><strong>Stat. uncertainty</strong></th>
<th><strong>Total uncertainty</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>MSTW2008\textsubscript{NNLO}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scale uncertainty</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scale $\otimes$ PDF uncertainty</td>
<td></td>
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$\sigma_{tW} \pm$(stat) $\pm$(syst) $\pm$(lumi)

**ATLAS, $L_{\text{int}} = 20.3$ fb\textsuperscript{-1}**

ATLAS-CONF-2013-100

$27.2 \pm 2.1 \pm 5.9 \pm 1.0$ pb

**CMS, $L_{\text{int}} = 12.2$ fb\textsuperscript{-1}**

PRL 112 (2014) 231802

$23.4 \pm 2.0 \pm 4.6 \pm 0.7$ pb

**LHC combined (July 2015)**

ATLAS-CONF-2014-052, CMS-PAS-TOP-14-009

$25.0 \pm 1.4 \pm 4.4 \pm 0.7$ pb

Effect of LHC beam energy uncertainty: 0.38 pb (not included in the figure)

---

ATLAS+CMS tW combination at 8TeV also performed

September 2014

CMS-PAS-TOP-14-009
s-channel

- Lowest cross-section at the LHC, more important at the Tevatron, where the study of data after the shutdown allowed for the observation of the process
  

- Interesting production mode sensitive to new physics: W’ bosons, charged Higgs bosons

- Very challenging final state: low cross-section, difficult to separate from backgrounds

- Signal signature: lepton + jets
  - A lepton (e, µ) and MET from the decay of a W boson
  - Two jets with high transverse momentum originating from b-quarks

- Main backgrounds: ttbar, W+jets, multijet
s-channel

- CMS has a preliminary result at 8TeV

CMS Preliminary, 19.3 fb⁻¹, Muons, \( \sqrt{s} = 8 \text{ TeV} \)

CMS-PAS-TOP-13-009
(November 2013)
Full lumi, e and \( \mu \)
BDT
Difficult analysis
In Run-2 will be even harder
S/B is a bit better at 7TeV

<table>
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\( \sigma_{s\text{-channel}} = 6.2 \pm 5.4 \text{(exp.}) \pm 5.9 \text{(th}) \text{pb} = 6.2 + 8.0 - 5.1 \text{ pb (FC)} \)

\( \sigma_{th\ s\text{-channel}} = 5.55 \pm 0.08 \text{ (scale)} \pm 0.21 \text{(PDF}) \text{ pb (NNLL)} \)

Upper limit of 2.1 (3.1,1.6) times the SM
Run-I Summary

Rebeca Gonzalez Suarez (UNL) DPF2015
Step II

Measure SM properties in single top signatures

The single top production at the LHC is large enough to measure top properties in single top signatures

• Complementary to ttbar
• Another handle to test potential BSM phenomena
• Valuable to get the full picture
Cross-section and $|V_{tb}|$

- From the inclusive production cross section of single top ($t$-channel, $tW$), a value of the CKM matrix element, $|V_{tb}|$, can be extracted.
- Considering $|V_{td}|, |V_{ts}| \ll |V_{tb}|$
- Cross section $\sim |V_{tb}|^2$

$$|V_{tb}| = \sqrt{\frac{\text{measured}}{\text{theory}}}$$

| CMS Preliminary | $|V_{tb}|$ Summary |
|------------------|------------------|
| CMS $tW$, 7 TeV, 4.9 fb$^{-1}$, PRL110 (2013) 02203 | $1.010 \pm 0.160$(exp) $\pm 0.030$(th) $- 0.130$ $- 0.040$ |
| CMS $tW$, 8 TeV, 12.2 fb$^{-1}$, PRL 112 (2014) 231802 | $1.030 \pm 0.120$(exp) $\pm 0.040$(th) |
| CMS $t$-ch., 7 TeV, 1.17/1.56 fb$^{-1}$, JHEP12 (2012) 035 | $1.029 \pm 0.046$(exp) $\pm 0.017$(th) |
| CMS $t$-ch., 8 TeV, 19.7 fb$^{-1}$, JHEP06 (2014) 090 | $0.979 \pm 0.045$(exp) $\pm 0.016$(th) |
| CMS $t$-ch., 7 and 8 TeV combined, JHEP06 (2014) 090 | $0.998 \pm 0.038$(exp) $\pm 0.016$(th) |
| CMS $t\bar{t}R_b$, 8 TeV, 19.7 fb$^{-1}$, PLB 738 (2014) 33 | $1.007 \pm 0.016$(stat+syst) |
**LHC $|V_{tb}|$ summary**

**ATLAS+CMS Preliminary TOPLHCWG**

$|V_{tb}| = \frac{\sigma_{\text{meas.}}}{\sigma_{\text{theo.}}}$ from single top quark production

- $\sigma_{\text{theo.}}$: NLO+NNLL MSTW2008nlo
- $\Delta\sigma_{\text{meas.}}$: Scale @ PDF
- $m_{\text{top}} = 172.5$ GeV

| $|V_{tb}|$ | (meas.) | (theo.) |
|---|---|---|
| 1.02 | ± 0.06 | ± 0.02 |
| 0.97 | ± 0.09 | ± 0.02 |
| 1.020 | ± 0.046 | ± 0.017 |
| 0.979 | ± 0.045 | ± 0.016 |
| 0.998 | ± 0.038 | ± 0.016 |

**t-channel:**

- ATLAS 7 TeV
  - PRD 90 (2014) 112006 (4.59 fb$^{-1}$)
- ATLAS 8 TeV
  - ATLAS-CONF-2014-007 (20.3 fb$^{-1}$)
- CMS 7 TeV
  - JHEP 12 (2012) 035 (1.17 - 1.56 fb$^{-1}$)
- CMS 8 TeV
  - JHEP 06 (2014) 090 (19.7 fb$^{-1}$)
- CMS combined 7+8 TeV
  - JHEP 06 (2014) 090

**Wt production:**

- ATLAS 7 TeV
  - PLB 716 (2012) 142-159 (2.05 fb$^{-1}$)
- CMS 7 TeV
  - PRL 110 (2013) 022003 (4.9 fb$^{-1}$)
- ATLAS 8 TeV
  - ATLAS-CONF-2013-100 (20.3 fb$^{-1}$)
- CMS 8 TeV
  - PRL 112 (2014) 231802 (12.2 fb$^{-1}$)
- LHC combined 8 TeV$^{1,2}$
  - ATLAS-CONF-2014-052, CMS-PAS-TOP-14-009

$^1$ including top-quark mass uncertainty

$^2$ including beam energy uncertainty

Summary plot from TOPLHCWG May 2015
Within the measurement of the \textbf{t-channel} cross-section at 8\,TeV, we measure the \textit{top/anti-top asymmetry}, $R$

Due to the relative proportion of $u$ and $d$ quarks in the proton, more tops than anti-tops are expected to be produced

\begin{align*}
\sigma_{\text{top}} &= 53.8 \pm 1.5{}^{(\text{stat})} \pm 4.4{}^{(\text{syst})} \text{pb} \\
\sigma_{\text{th\,top}} &= 54.87 \pm 2.29 - 1.94 \text{ pb (NLO, latest calculation)} \\
\sigma_{\text{anti-top}} &= 27.6 \pm 1.3{}^{(\text{stat})} \pm 4.4{}^{(\text{syst})} \text{pb} \\
\sigma_{\text{th\,anti-top}} &= 29.74 \pm 1.67 - 1.51 \text{ pb (NLO, latest calculation)}
\end{align*}

$R = 1.95 \pm 0.10{}^{(\text{stat})} \pm 0.19{}^{(\text{syst})}$

\textit{JHEP 06 (2014) 090} \\
\textit{arXiv:1403.7366}
t-channel: differential x-sec

- t-channel **differential cross section** came last September, preliminary
- 8 TeV, full luminosity
- Starting in the same way as the inclusive cross section, the analysis uses a NN to isolate a purer t-channel sample

Events are selected by cutting on an optimal NN discriminant value

September 2014
**CMS-PAS-TOP-14-004**
t-channel: differential x-sec

- Distributions of the $p_T$ and rapidity of the top quarks are then corrected for detector effects (Unfolded) and compared directly with different theoretical predictions:
  - POWHEG+Pythia (solid), aMC@NLO+Pythia (dotted), and CompHEP (dashed)
**t-channel: W-helicity**

- Going further than cross section measurements → measurement of the W-helicity fractions
- Exact same selection and background estimation as the standard t-channel inclusive cross section measurement

$\theta^*$: angle between the W boson in the top rest frame and the lepton in the W rest frame → related to the W-helicity fractions ($F_0, F_L, F_R$)
Using the helicity fractions measured → exclude the tensor terms of the $tWb$ anomalous couplings, $g_L$ and $g_R$.

<table>
<thead>
<tr>
<th>Theory prediction</th>
<th>Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>(NNLO)</td>
<td></td>
</tr>
<tr>
<td>$F_L = 0.311 \pm 0.005$</td>
<td>$F_L = 0.298 \pm 0.028$ (stat) ± 0.032 (syst)</td>
</tr>
<tr>
<td>$F_R = 0.0017 \pm 0.0001$</td>
<td>$F_R = -0.018 \pm 0.019$ (stat) ± 0.011 (syst)</td>
</tr>
<tr>
<td>$F_0 = 0.687 \pm 0.005$</td>
<td>$F_0 = 0.720 \pm 0.039$ (stat) ± 0.037 (syst)</td>
</tr>
</tbody>
</table>

*PRD 81, 111503(R) (2010)*
Single top quarks are highly polarized
- spin aligned with the recoiling light jet
The top quark polarization relates to the spin asymmetry
Which can be extracted from the \( \cos\theta^* \) distribution

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

A BDT is used to get a t-channel enriched sample

August 2013

CMS-PAS-TOP-13-001
t-channel: top polarization

The asymmetry is obtained from the *unfolded* distributions in the \(e\) and \(\mu\) channels separately and combined using BLUE.

\[ A_t = 0.41 \pm 0.06 \text{(stat.)} \pm 0.16 \text{(syst.)} \]  
  
(SM expectation 0.44)

\[ P_t = 0.82 \pm 0.12 \text{(stat.)} \pm 0.32 \text{(syst.)} \]
Step III

Search for FCNC and Anomalous Couplings

Limits on anomalous $Wtb$ couplings can be extracted from SM measurements ($W$-helicity fractions, top polarization)

→ Dedicated analyses searching for deviations from the SM are also in place in single top signatures
FCNC \( tZ \)

7 TeV

Three-lepton signature

Simulated samples with different scenarios

BDT (gut, gct, Zut, Zct)

No excess → Limits on couplings and branching fractions

<table>
<thead>
<tr>
<th>couplings</th>
<th>Expected</th>
<th>Observed</th>
<th>( B(t \rightarrow gq/Zq) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \kappa_{gut}/\Lambda )</td>
<td>0.096</td>
<td>0.096</td>
<td>0.56 %</td>
</tr>
<tr>
<td>( \kappa_{gct}/\Lambda )</td>
<td>0.427</td>
<td>0.354</td>
<td>7.12 %</td>
</tr>
<tr>
<td>( \kappa_{Zut}/\Lambda )</td>
<td>0.492</td>
<td>0.451</td>
<td>0.51 %</td>
</tr>
<tr>
<td>( \kappa_{Zct}/\Lambda )</td>
<td>2.701</td>
<td>2.267</td>
<td>11.40 %</td>
</tr>
</tbody>
</table>
FCNC $t\gamma$

- $tq\gamma$, single top produced in association with a photon
  - Enhancement on $t \rightarrow u(c)\gamma$ BR due to FCNC
  - 8 TeV, $\mu$ only
  - Samples with anomalous $t\gamma$, $t\gamma$ couplings
  - Dedicated BDTs
  - No excess
  - Limits on couplings and branching fractions

May 2014
CMS-PAS-TOP-14-003

<table>
<thead>
<tr>
<th>Coupling</th>
<th>Exp. limit (LO)</th>
<th>Obs. limit (LO)</th>
<th>Exp. limit (NLO)</th>
<th>Obs. limit (NLO)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{t\gamma} \times Br(W \rightarrow l\nu_l)$</td>
<td>0.0404 pb</td>
<td>0.0234 pb</td>
<td>0.0408 pb</td>
<td>0.0217 pb</td>
</tr>
<tr>
<td>$\sigma_{t\gamma} \times Br(W \rightarrow l\nu_l)$</td>
<td>0.0411 pb</td>
<td>0.0281 pb</td>
<td>0.0410 pb</td>
<td>0.0279 pb</td>
</tr>
<tr>
<td>$\kappa_{t\gamma}$</td>
<td>0.0367</td>
<td>0.0279</td>
<td>0.0315</td>
<td>0.0229</td>
</tr>
<tr>
<td>$\kappa_{t\gamma}$</td>
<td>0.113</td>
<td>0.094</td>
<td>0.0790</td>
<td>0.0652</td>
</tr>
<tr>
<td>$Br(t \rightarrow u\gamma)$</td>
<td>0.0279%</td>
<td>0.0161%</td>
<td>0.0205%</td>
<td>0.0108%</td>
</tr>
<tr>
<td>$Br(t \rightarrow c\gamma)$</td>
<td>0.261%</td>
<td>0.182%</td>
<td>0.193%</td>
<td>0.132%</td>
</tr>
</tbody>
</table>
FCNC and AC in t-channel

- **FCNC and anomalous couplings in t-channel**
- 7TeV, μ
- Anomalous operators in the Wtb vertex and tcg/tug FCNC couplings
- NN to separate different scenarios considered Vs SM
- No excess → Limits on couplings and branching fractions

May 2014

CMS-PAS-TOP-14-007
Summary

- Single top signatures were largely unknown until recently
- In the last 5 years we have made very good progress
  → the LHC is very powerful for top, and single top in particular

- In CMS we have studied the three main production modes
- We have used single top quarks produced via $t$-channel for measurements:
  - $W$-helicity fractions, top polarization, $|V_{tb}|$...
- We have explored conventional and rare single top production modes to look for BSM physics: **FCNC and Anomalous Couplings**
  - Also (not in this talk): single top+Higgs (see Ken Bloom’s talk on Thursday!), monotops (DM)

- **Run-2 will be the time to fully explore single top signatures, in particular to look for physics beyond the standard model**
Stay tuned!

Single top candidate event (t-channel, $\mu$)