Single top production and properties at hadron colliders

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on behalf of ATLAS, CDF, CMS and D0 Collaborations
LHCP2016
Lund, Sweden
June 17, 2016
Why study single top?

- **Direct probe of electroweak interactions** (in contrary to ttbar production which is of strong type)

- **Wtb vertex** is involved in all SM single top production mechanism $\rightarrow$ **determination of CKM matrix element** $|V_{tb}|$ from the measured cross sections

- **Probe the PDFs**

- **Test anomalous Wtb couplings** in the production rates of top and antitop quarks

- **Search for FCNC interactions**

More details on single top related results could be found in the talks already given by **Mohsen Naseri, Fabian-Phillipp Tepel, Matthias Komm** and **Peter Uwer**
Single top production

Predicted cross sections depend on PDF, 4FS/5FS, scale choice, top quark mass, etc.

Common efforts within LHCtopWG and Tevatron Top WG to harmonize the comparison to theoretical predictions with Hathor v2.1 (NLO), will proceed at NNLO: Phys. Lett. B 736, 58-63 (2014)

Calculations for Wt are available at NLO+NNLL
Single top at Tevatron

- Final single top combination for $t$ and $s+t$ channels from Tevatron \(^\text{1}\)
- Does not include already reported $s$ channel results \(^\text{2}\)
- Statistically independent combination of $l+jets$ (CDF and D0) and $E_{T\text{miss}}+jets$ (CDF) final states
- Combined MVA based $t$ and $s$ channel discriminants
- Measured cross sections and $|V_{tb}|$ are consistent with SM predictions

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Summary on single top at Tevatron

Tevatron Run II single top quark summary

Measurement
s-channel:
CDF [25] 1.36 \pm 0.37
D0 [22] 1.10 \pm 0.33
Tevatron [26] 1.29 \pm 0.26

t-channel:
CDF [21] 1.65 \pm 0.38
D0 [22] 3.07 \pm 0.54
Tevatron [this Letter] 2.25 \pm 0.29

s+t:
CDF [21] 3.02 \pm 0.49
D0 [22] 4.11 \pm 0.60
Tevatron [this Letter] 3.30 \pm 0.52

Cross section [pb]

Theory (NLO+NNLL) [9,12] \(m_t = 172.5\) GeV

References:
t channel at CMS

- Measurement with full 2015 data (2.3 fb\(^{-1}\))\(^{1}\) following the first t channel measurement at 13 TeV (42 pb\(^{-1}\))\(^{2}\) at CMS
- Measured in muon+jets channel
- Event categorization according to the number of jets and b tagged jets
- Signal extracted through binned likelihood fit to a Neural Net discriminant

\[ |f_{LV}V_{tb}| = 1.02 \pm 0.07 \text{(exp.)} \pm 0.02 \text{(theo.)} \]

\[ \sigma_{t\text{-ch.}} = 227.8 \pm 9.1 \text{ (stat.)} \pm 14.0 \text{ (exp.)}^{+28.7}_{-27.7} \text{ (theo.)} \pm 6.2 \text{ (lumi.)} \text{ pb} = 227.8^{+33.7}_{-33.0} \text{ pb} \]
First separate top-quark and top-antiquark t channel measurement at 13 TeV

Measurement is done in muon+jets channel

Event categorization according to the number of jets and b tagged jets

Signal extracted through a binned likelihood fit to a Neural Net discriminant

\[
\sigma(tq) = 133 \pm 6 \text{ (stat.)} \pm 24 \text{ (syst.)} \pm 7 \text{ (lumi.)} \text{ pb}
\]

\[
\sigma(\bar{t}q) = 96 \pm 5 \text{ (stat.)} \pm 23 \text{ (syst.)} \pm 5 \text{ (lumi.)} \text{ pb}
\]

\[
\sigma(tq + \bar{t}q) = 229 \pm 48 \text{ pb} \quad 21\%
\]

\[
|f_{LV} \cdot V_{tb}| = 1.03 \pm 0.02 \text{ (stat.)} \pm 0.11 \text{ (syst.)} \pm 0.02 \text{ (theor.)} \pm 0.03 \text{ (lumi.)}
\]

\[
= 1.03 \pm 0.11 \quad 11\%
\]

|V_{tb}| > 0.75 \@95\% CL \quad (f_{LV} = 1, V_L = V_{tb})

**t channel at CMS**

- **First t channel differential cross section measurement at 13 TeV**
- Analysis is done in **muon+jets** events
- Signal is extracted with binned maximum likelihood fit to **BDT** discriminator ($m_T(W) > 50$ GeV) and to $m_T(W)$ in the signal and background control regions
- Unfolded cross section is measured as a function of the **top quark $p_T$ and rapidity**

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[1] CMS-PAS-TOP-16-004
Evidence for s channel at 8 TeV

Previous ATLAS result based on the same dataset using BDT gave 1.3\sigma observed significance

Analysis in lepton+jets channels

Matrix element (ME) method to define discriminant (contributes up to \( \approx 50\% \) improvement with respect to BDT analysis)

Another \( \approx 50\% \) of improvement comes from the latest calibrations, optimized event selection and simulated samples

Signal extracted from simultaneous binned maximum-likelihood fit to ME discriminant and lepton charge in signal and control regions

Observed significance is 3.2\sigma (3.9\sigma expected)

\(|V_{tb}| > 0.5 @95\% \text{ CL}

(f_{LV} = 1, V_L = V_{tb})

\[\sigma_s = 4.8 \pm 0.8(\text{stat.})^{+1.6}_{-1.3}(\text{syst.}) \text{ pb}\]
Combined fit of 7 TeV (muon channel) and 8 TeV (electron and muon channels) data results.

Categorization of events by the number of b tagged jets.

Signal extracted through a binned maximum-likelihood fit to a signal vs background BDT discriminant.

\[
\sigma_s = 7.1 \pm 8.1 \text{(stat + syst) pb}, \text{ muon channel, 7 TeV;}
\]
\[
\sigma_s = 11.7 \pm 7.5 \text{(stat + syst) pb}, \text{ muon channel, 8 TeV;}
\]
\[
\sigma_s = 16.8 \pm 9.1 \text{(stat + syst) pb}, \text{ electron channel, 8 TeV;}
\]
\[
\sigma_s = 13.4 \pm 7.3 \text{(stat + syst) pb}, \text{ combined, 8 TeV.}
\]

Observed significance is \(2.5\sigma\) (\(1.1\sigma\) expected).

**Wt channel at CMS**

- **First observation** of Wt production channel at 8 TeV
- Analysis of events with **two oppositely charged leptons**
- Signal extracted from a simultaneous binned likelihood fit to BDT discriminant over the signal and background control regions

\[
|f_{LV}V_{tb}| = 1.03 \pm 0.12\text{ (exp.)} + 0.04\text{ (th.)} \quad 13\%
\]

\[
|V_{tb}| > 0.78 \text{ @95\% CL (} f_{LV} = 1, V_L = V_{tb})
\]

\[
\sigma(\text{Wt}) = 23.4 \pm 5.4 \text{ pb} \quad 23\%
\]

**Observed significance is** 6.1σ (5.4σ expected)

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Wt channel at ATLAS

- **Observation** of Wt production channel at 8 TeV
- Two oppositely charged leptons are considered
- Signal extracted via profile likelihood fit over the signal and background control regions
- **First fiducial cross section** (Wt+ttbar) measured for two selected leptons with $p_T > 25$ GeV, $|\eta| < 2.5$, one b jet with $p_T > 20$ GeV, $|\eta| < 2.5$ and $E_T^{miss} > 20$ GeV

\[
\sigma(Wt) = 23.0 \pm 1.3\text{(stat.)}^{+3.2}_{-3.5}\text{(syst.)} \pm 1.1\text{(lumi.) \, pb}
\]

\[
\sigma_{\text{fiducial}} = 0.85 \pm 0.01\text{(stat.)}^{+0.06}_{-0.07}\text{(syst.)} \pm 0.03\text{(lumi.) \, pb}
\]

\[
|f_{LV}V_{tb}| = 1.01 \pm 0.10 \quad 17%
\]

**Observed significance is** $7.7\sigma \, (6.9\sigma \text{ expected})$

\[
|V_{tb}| > 0.80 \, @95\% \, CL \, (f_{LV} = 1, V_L = V_{tb})
\]

New LHC combination for Wt production cross sections at 8 TeV

Results are combined using the best linear unbiased estimator (BLUE) method

Combination results in an improved precision of 16% (ATLAS - 17%, CMS - 23%)

The dominant uncertainties are due to theory modeling (ISR/FSR, Scale, Parton shower, etc.)

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
<th>Uncertainty (pb)</th>
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<td>Data statistics</td>
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<td>Simulation statistics</td>
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<td>Luminosity</td>
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<td>Background normalization</td>
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<td>Jets</td>
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<tr>
<td>Detector modelling</td>
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<tr>
<td>Total systematics (excl. lumi)</td>
<td>14.4</td>
<td>3.3</td>
</tr>
<tr>
<td>Total systematics (incl. lumi)</td>
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<td>3.4</td>
</tr>
<tr>
<td>Total uncertainty</td>
<td>15.6</td>
<td>3.6</td>
</tr>
</tbody>
</table>

$\sigma_{Wt} = 23.1 \pm 1.1 \text{ (stat.)} \pm 3.3 \text{ (syst.)} \pm 0.8 \text{ (lumi.)} \text{ pb} = 23.1 \pm 3.6 \text{ pb}$

$|f_{LV}V_{tb}| = 1.02 \pm 0.09$
Summary on single top production at LHC

Inclusive cross-section [pb]

- **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) 1.02 ± 0.04 ± 0.017
  - CMS 13 TeV (CMS-PAS-TOP-16-003) 2.3 fb⁻¹
  - ATLAS 13 TeV (ATLAS-CONF-2015-079) 3.2 fb⁻¹

- **Wt:**
  - ATLAS 7 TeV (PLB 716 (2012) 142) 4.95 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

- **s-channel:**
  - ATLAS 8 TeV (PLB 756 (2016) 228) 20.3 fb⁻¹

- **NP:**
  - NNLO + NNNLL MSTW2008nlo, NNPDF2.3nlo

Scale uncertainty:
- ATLAS-CONF-2011-118 95% C.L.
- CMS-PAS-TOP-15-019 95% C.L.
- arXiv:1603.02555 95% C.L.

PDF uncertainty:
- ATLAS-CONF-2016-023, CMS-PAS-TOP-15-019

68% confidence interval:
- For the ATLAS 7 TeV t-channel result, the 68% confidence interval is 1.02 ± 0.06 ± 0.02.
Single top production cross section is proportional to the size of Wtb interaction

Provides the direct measurement of $|V_{tb}|$ and allows one to probe anomalous Wtb couplings: vector ($V_R$) and tensor ($g_L, g_R$)

Top quarks are polarized in the single top production ($P \approx 0.9$)

Look for differences in kinematical and angular distributions in the presence of anomalous couplings

In SM: $V_L = V_{tb} \approx 1$ with $V_R, g_L$ and $g_R$ vanishing at LO
First measurement of top quark spin asymmetry (sensitive to top quark polarization) in high purity $t$ channel

Probe the coupling structure via spin asymmetry

Analysis in muon+jets events

Spin projection is measured along the direction of the recoiling spectator quark momentum

\[ A_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)} \]

\[ A_\mu(t + \bar{t}) = 0.26 \pm 0.03 \text{ (stat)} \pm 0.10 \text{ (syst)} = 0.26 \pm 0.11 \]

Results are consistent with SM ($A_\mu^{SM} = 0.44$), p-value = 4.6%
- Perform a **normalized double differential angular measurement** in $\theta^*$ and $\phi^*$ in single top events.
- The triple differential decay rate of the top quark is expressed in the form of parametrized spherical harmonics.

Two-dimensional limits at 95% CL correlation = 0.11

$$\text{Re} \left( \frac{g_R}{V_L} \right) \in [-0.36, 0.10]$$

$$\text{Im} \left( \frac{g_R}{V_L} \right) \in [-0.17, 0.23]$$

Flavour-changing neutral current (FCNC) is forbidden in SM at tree level by the Glashow-Iliopoulos-Maiani (GIM) mechanism.

- Only possible at higher orders via loops induced processes → highly suppressed
- FCNC decays could be enhanced in various BSM
Summary on FCNC searches

**Latest results:**
- $t \rightarrow \gamma q$ (*CMS* Collaboration, *JHEP* 04 (2016) 035): the only existing analysis to probe this coupling
Single top production provides unique environment to test the SM and to search for new physics by probing anomalous couplings.

Several new single top results are available from LHC Run 2 experiments: \textit{t channel inclusive and differential cross sections}.

All results show \textit{good agreement with SM} predictions.

Looking forward to more data, more results and only \textit{good} surprises.

\textbf{Top quark public results:} ATLAS, CMS, CDF, D0.
Backup slides
Top quark has special powers

- Top quark is the **heaviest** elementary particle known.
- An excellent candidate to study **EW symmetry breaking mechanism** and **fermion mass hierarchy** due to its large Yukawa coupling ($y_t \approx 1$).
- Almost exclusively decays to **W boson** and **b quark**.
- The **short lifetime** ($\tau \approx 4 \times 10^{-25}$ s) of a top quark makes it decay before any hadronization occurs to produce bound states.

**Distinctive experimental signature**

- The **new physics** could manifest itself in observed anomalies of the top quark production and decays.
Top quark discovered at Fermilab
Observation of inclusive single top production at Tevatron
Rediscovered $t$ channel at LHC
Observation of $Wt$ production at LHC
Observation of $s$ channel at Tevatron

Tools
Measurement of top quark mass in t channel (purity ≈ 75%)\(^1\)

**Muon+jets** channel is considered

Mass extracted from the reconstructed top quark mass through an extended unbanned maximum likelihood fit

Signal parametrization is done with Crystal Ball function

Total uncertainty on the measurement is driven by several sources (JES, signal modelling, fit calibration, etc.)

\[
m_t = 172.60 \pm 0.77 \text{ (stat)} +0.97\text{ (syst)} \text{ GeV}
\]

Top quark mass in single top at ATLAS

- Measurement of top quark mass in t channel (purity ≈ 70%)
- Neural network to reduce the background (ttbar not included in the training)
- Invariant mass of charged lepton and b jet as an estimator for top quark mass
- Template method to determine the mass via likelihood fit
- Main systematic uncertainties: JES, signal modelling, background normalization, etc.

\[ m_{\text{top}} = 172.2 \pm 0.7 \text{(stat.)} \pm 2.0 \text{(syst.) GeV} \]
Summary on top quark mass measurements

**CMS Preliminary**

**b hadron lifetime**
TOP-12-030 (2013)
173.50 ± 1.50 ± 2.91 GeV

**Kinematic endpoints**
EPJC 73 (2013) 2494
173.90 ± 0.90 +1.70 -2.10 GeV

**b-jet energy peak**
172.29 ± 1.17 ± 2.66 GeV

**Lepton+J/Ψ**
TOP-15-014 (2016)
173.50 ± 3.00 ± 0.90 GeV

**Lepton+SecVtx**
173.68 ± 0.20 +1.58 -0.97 GeV

**Dilepton kinematics**
TOP-16-002 (2016)
171.70 ± 1.10 +2.68 -3.09 GeV

**Single top**
TOP-15-001 (2016)
172.60 ± 0.77 +0.97 -0.93 GeV

**ATLAS Preliminary m_{top} summary** - Mar. 2015, L_{int} = 4.6 fb^{-1} - 20.3 fb^{-1}

- **all jets**
  - arXiv:1403.0022
  - 175.1 ± 1.8 ± 1.2

- **single top**
  - arXiv:1503.05427
  - 172.2 ± 2.1 ± 2.0

- **dilepton**
  - arXiv:1503.05427
  - 173.79 ± 1.41 ± 1.30

- **σ(t+1-jet)**
  - arXiv:1404.0203
  - 173.7 ± 2.9 ± 2.1

- **σ(t) dilepton**
  - arXiv:1403.0427
  - 172.9 ± 2.5 ± 2.6

**World Comb. Mar. 2015**
- 172.99 ± 0.91
- 172.3 ± 0.79
- 173.34 ± 0.64

**CMS 7+8 TeV (2015)**
arXiv:1509.04044
172.44 ± 0.13 ± 0.47 GeV

**World combination**
ATLAS, CDF, CMS, D0
173.34 ± 0.27 ± 0.71 GeV

(value ± stat. ± syst.)

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Kirill Skovpen - LHCP2016
## Summary on top quark mass measurements

### ATLAS+CMS Preliminary LHCtop WG

<table>
<thead>
<tr>
<th>Source</th>
<th>m$_{\text{top}}$ (stat$\pm$syst)</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Comb. Mar 2014, [7]</td>
<td>m$_{\text{top}}$ = 173.34 ± 0.76 (0.36 ± 0.67) GeV</td>
<td></td>
</tr>
<tr>
<td>ATLAS, l+jets (*)</td>
<td>172.31 ± 1.55 (0.75 ± 1.35) GeV</td>
<td>7 TeV [1]</td>
</tr>
<tr>
<td>ATLAS, dilepton (*)</td>
<td>173.09 ± 1.63 (0.64 ± 1.50) GeV</td>
<td>7 TeV [2]</td>
</tr>
<tr>
<td>CMS, l+jets</td>
<td>173.49 ± 1.06 (0.43 ± 0.97) GeV</td>
<td>7 TeV [3]</td>
</tr>
<tr>
<td>CMS, dilepton</td>
<td>172.50 ± 1.52 (0.43 ± 1.46) GeV</td>
<td>7 TeV [4]</td>
</tr>
<tr>
<td>CMS, all jets</td>
<td>173.49 ± 1.41 (0.69 ± 1.23) GeV</td>
<td>7 TeV [5]</td>
</tr>
<tr>
<td>LHC comb. (Sep 2013)</td>
<td>173.29 ± 0.95 (0.35 ± 0.88) GeV</td>
<td>7 TeV [6]</td>
</tr>
<tr>
<td>World comb. (Mar 2014)</td>
<td>173.34 ± 0.76 (0.36 ± 0.67) GeV</td>
<td>1.96-7 TeV [7]</td>
</tr>
</tbody>
</table>

(*) Superseded by results shown below the line

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### ATLAS comb. (Mar 2015) | l+jets, di.l. | 172.99 ± 0.91 (0.48 ± 0.78) GeV | 7 TeV [8] |

### CMS comb. (Sep 2015) | 172.44 ± 0.48 (0.13 ± 0.47) GeV | 7+8 TeV [11] |

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[10] CMS PAS TOP-14-022
## Single top event generation

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Generator</th>
<th>Order</th>
</tr>
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<tbody>
<tr>
<td>CDF</td>
<td>POWHEG-BOX</td>
<td>NLO</td>
</tr>
<tr>
<td>DO</td>
<td>SINGLETOP</td>
<td>NLO</td>
</tr>
<tr>
<td>ATLAS</td>
<td>POWHEG-BOX, MG5.aMC@NLO</td>
<td>NLO</td>
</tr>
<tr>
<td>CMS</td>
<td>MG5.aMC@NLO, POWHEG-BOX</td>
<td>NLO</td>
</tr>
</tbody>
</table>
Observation of **s channel** at Tevatron

- Combination of **l+jets** (CDF and D0) and **$E_T^{\text{miss}} + \text{jets}$** (CDF) channels
- **W+jets** backgrounds normalized to data
- Observed with $S = 6.3\sigma$ (expected $5.1\sigma$)
- Probability to observe an excess in the absence of signal is $1.8 \times 10^{-10}$

![Graph showing s-channel single top quark observation](image)

$$p(\sigma_s) = \int L(\sigma_s, \{\theta\} | \text{data}) \pi(\sigma_s) \Pi(\{\theta\}) d\{\theta\}$$

### t channel measurement (uncertainties)

<table>
<thead>
<tr>
<th>Source</th>
<th>ATLAS</th>
<th>CMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data statistics</td>
<td>± 4.6 ± 5.0</td>
<td>± 4.6 ± 5.0</td>
</tr>
<tr>
<td>MC statistics</td>
<td>± 6.3 ± 6.5</td>
<td>± 4.0% ± 4.7%</td>
</tr>
<tr>
<td>Multijet normalisation</td>
<td>± 0.8 ± 2.4</td>
<td>± 5.5% ± 5.7%</td>
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<tr>
<td>Other background normalisation</td>
<td>± 1.4 ± 0.5</td>
<td>± 2.8% ± 3.4%</td>
</tr>
<tr>
<td>Muon uncertainties</td>
<td>± 1.6 ± 1.6</td>
<td>± 2.0% ± 4.0%</td>
</tr>
<tr>
<td>JES</td>
<td>± 5.5 ± 1.6</td>
<td>± 6.2/±6.2%</td>
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<tr>
<td>Jet energy resolution</td>
<td>± 4.3 ± 3.1</td>
<td>± 5.5% ± 9.2%</td>
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<tr>
<td>$E_T^{miss}$ modelling</td>
<td>± 4.2 ± 4.5</td>
<td>± 6.7/±6.7%</td>
</tr>
<tr>
<td>b-tagging efficiency</td>
<td>± 7.1 ± 7.5</td>
<td>± 6.1/±6.9%</td>
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<tr>
<td>c-tagging efficiency</td>
<td>&lt; 0.5 &lt; 0.5</td>
<td>± 3.9% ± 6.9%</td>
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<tr>
<td>Light-jet tagging efficiency</td>
<td>&lt; 0.5 &lt; 0.5</td>
<td>± 1.1/±0.4%</td>
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<tr>
<td>Pile-up reweighting</td>
<td>± 1.2 ± 3.2</td>
<td>± 5.9% ± 4.2%</td>
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<tr>
<td>W+jets modelling</td>
<td>± 2.3 ± 1.0</td>
<td>± 1.1/±0.4%</td>
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<tr>
<td>$t\bar{t}$, $Wt$ and s-channel generator</td>
<td>&lt; 0.5 &lt; 0.5</td>
<td>± 5.9% ± 4.2%</td>
</tr>
<tr>
<td>$t\bar{t}$, $Wt$ and s-channel NLO matching</td>
<td>± 2.7 ± 2.7</td>
<td>± 1.1/±0.4%</td>
</tr>
<tr>
<td>$t\bar{t}$, $Wt$ and s-channel scale</td>
<td>± 2.6 ± 0.9</td>
<td>± 3.9% ± 6.9%</td>
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<tr>
<td>t-channel scale</td>
<td>± 5.9 ± 7.7</td>
<td>± 1.1/±0.4%</td>
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<tr>
<td>t-channel generator</td>
<td>± 11.0 ± 15.0</td>
<td>± 5.9% ± 4.2%</td>
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<tr>
<td>PDF</td>
<td>&lt; 0.5 &lt; 0.5</td>
<td>± 1.1/±0.4%</td>
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<tr>
<td>Luminosity</td>
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<tr>
<td>Total systematic uncertainty</td>
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<td>Total uncertainty</td>
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<td>± 19.0 ± 25.0</td>
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<table>
<thead>
<tr>
<th>Uncertainty source</th>
<th>ATLAS</th>
<th>CMS</th>
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<tbody>
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<td>Uncertainty of the fit (stat. + prof. unc.)</td>
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<td>± 7.4%</td>
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<td>Statistical uncertainty</td>
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<tr>
<td>Profiled uncertainties</td>
<td>± 5.5%</td>
<td>± 5.7%</td>
</tr>
<tr>
<td>MC statistics</td>
<td>± 2.8%</td>
<td>± 3.4%</td>
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<tr>
<td>Pileup</td>
<td>-0.2/±0.1%</td>
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<td>Experimental uncertainty</td>
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<tr>
<td>Signal modeling</td>
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### Uncertainty source (CMS)

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<tr>
<th>Uncertainty source</th>
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### s channel measurement (uncertainties)

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Total 34
Wt combination at LHC (uncertainties)

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</tr>
<tr>
<td>b-tagging</td>
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<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Pileup</td>
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<td>0.9%</td>
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<tr>
<td>Total</td>
<td>16.8%</td>
<td>21.7%</td>
<td>0.40</td>
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</table>
ttbar production at LHC

\[
\frac{\sigma_{\bar{t}t}(13\text{TeV})}{\sigma_{\bar{t}t}(8\text{TeV})} \approx 3.2
\quad \frac{\sigma_s(13\text{TeV})}{\sigma_s(8\text{TeV})} \approx 2
\quad \frac{\sigma_t(13\text{TeV})}{\sigma_t(8\text{TeV})} \approx 2.5
\quad \frac{\sigma_{Wt}(13\text{TeV})}{\sigma_{Wt}(8\text{TeV})} \approx 3.2
\]
W boson helicity

- W helicity - projection of W’s spin on its momentum
- Helicity fractions: $F_{L,R,0} = \frac{\Gamma_{L,R,0}}{\Gamma(t\rightarrow Wb)}$, $\sum F_i = 1$
- Helicity is sensitive to the real part of Wtb anomalous couplings

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

@NNLO
$F_0 = 0.687 \pm 0.005$
$F_L = 0.311 \pm 0.005$
$F_R = 0.0017 \pm 0.0001$

**W boson helicity in t channel at CMS**

- **First measurement** of W boson helicity in **single top quark event topology**
- Single top statistics accompanied by ttbar events also used to extract helicity fractions
- $F_0$, $F_L$ and W+jets fraction are free parameters in the fit

Best fit gives $\text{Re}(g_L) = -0.017$, $\text{Re}(g_R) = -0.008$

Measured helicity fractions are consistent with SM

---

Forward-backward asymmetry

- Measure forward-backward asymmetry in the normal direction \( A_{FB}^N \) in **single top** events \( \to \) probe complex phase of \( g_R \)

- **In ttbar:**
  - Top quarks are only slightly polarized due to EW corrections \( \to \) no \( A_{FB} \) asymmetry

- **In single top:**
  - Top quark is highly polarized \( (P \approx 0.9) \)
  - Two new reference directions: \( N \) and \( T \)

- A presence of FB asymmetry would be a sign of **CP violation** in top quark decays

\[
A_{FB}^N \equiv \frac{N_{evt}(\cos\theta^N > 0) - N_{evt}(\cos\theta^N < 0)}{N_{evt}(\cos\theta^N > 0) + N_{evt}(\cos\theta^N < 0)}
\]
**A_{FB} in single top at ATLAS**

- Measure $A_{FB}$ asymmetry in lepton+jets events
- Asymmetry extracted with unfolding the $\cos\theta_N$ distribution
- $g_R$ assumed to be purely imaginary

First experimental limit on $\text{Im}(g_R)$ of $[-0.20, 0.30]$ at 95% CL

\[ A_{FB}^N = 0.031 \pm 0.065 \text{ (stat.)} +^{0.029}_{-0.031} \text{ (syst.)} \]

Flavour-changing neutral current (FCNC) → process where a fermion changes its flavour with preserving its charge

FCNC amplitudes are forbidden at tree level by the Glashow-Iliopoulos-Maiani (GIM) mechanism [Phys. Rev. D2 (1970) 1285] in SM

FCNC is only possible in SM at higher orders via loops induced processes → highly suppressed

FCNC decays could be enhanced in various BSM

### FCNC in BSM

<table>
<thead>
<tr>
<th></th>
<th>2HDM</th>
<th>MSSM</th>
<th>RS</th>
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<td>$10^{-7} - 10^{-6}$</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>$\text{BR}(t \rightarrow c\gamma)$</td>
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<td>$10^{-9} - 10^{-8}$</td>
<td>$10^{-9}$</td>
</tr>
<tr>
<td>$\text{BR}(t \rightarrow cH)$</td>
<td>$10^{-5} - 10^{-3}$</td>
<td>$10^{-9} - 10^{-5}$</td>
<td>$10^{-4}$</td>
</tr>
</tbody>
</table>


$\text{BR}(t \rightarrow uX) \approx \text{BR}(t \rightarrow cX) \left| \frac{V_{ub}}{V_{cb}} \right|^2$

K. Agashe et al., arXiv:1311.2028
Search for single top FCNC at ATLAS

- Search for flavor changing neutral currents (FCNC) in single top events
- Event topology is a top quark leptonic decay
- Main background is W+jets
- Most stringent limits to date on FCNC $t \rightarrow gq$ BR

BR($t \rightarrow gu$) < 0.0040% (obs) 0.0035% (exp)
BR($t \rightarrow gc$) < 0.017% (obs) 0.015% (exp)

Search for top+gamma FCNC at CMS

- Search for FCNC in single top+γ events
- Main background is W(γ) +jets
- The only existing analysis to search for t→γq decays

Wγ+jets and W+jets measured from data using cos(W,γ) template fit

FCNC NLO corrections are sizable (k≈1.375 @ 50GeV)

Limits @NLO

- \( \kappa_{uγ}/\Lambda < 0.025 \text{ TeV}^{-1} \)
- \( \kappa_{cγ}/\Lambda < 0.091 \text{ TeV}^{-1} \)
- \( \text{BR}(t\rightarrow γu) < 0.01 \% \text{ (obs)} \)
  \( 0.02 \% \text{ (exp)} \)
- \( \text{BR}(t\rightarrow γc) < 0.17 \% \text{ (obs)} \)
  \( 0.20 \% \text{ (exp)} \)

Search for top+Z FCNC at CMS

- Search for FCNC in single top+Z events in trilepton channel
- Main background is WZ +jets, fake leptons

\[
\frac{\Gamma(Zu)}{\Lambda} < 0.45 \text{ TeV}^{-1} \\
\frac{\Gamma(Zc)}{\Lambda} < 2.27 \text{ TeV}^{-1} \\
\frac{\Gamma(ug)}{\Lambda} < 0.10 \text{ TeV}^{-1} \\
\frac{\Gamma(gc)}{\Lambda} < 0.35 \text{ TeV}^{-1}
\]

BR(\(t \rightarrow Zu\)) < 0.51 % (obs) \\
0.61 % (exp)

BR(\(t \rightarrow Zc\)) < 0.11 % (obs) \\
0.16 % (exp)

BR(\(t \rightarrow gu\)) < 0.56 % (obs) \\
0.56 % (exp)

BR(\(t \rightarrow gc\)) < 0.71 % (obs) \\
1.03 % (exp)

[1] CMS-PAS-TOP-12-021
Summary on FCNC searches (references)

- **HERA:**

- **LEP:**

- **TEVATRON:**

- **CMS:**

- **ATLAS:**