Recent Top Quark Production Results

*Harvest of LHC Run I and first measurements at 13 TeV*

Jeannine Wagner-Kuhr

MPP colloquium, Munich, November 3rd 2015
Outline

- Introduction
- Recent results on top quark pair production
- Recent results on single top quark production
Top Quark

- By far the heaviest quark
  - it decays before it can hadronize
  - investigation of a bare quark

- Large coupling to the Higgs boson
  - top plays an important role in the SM

Open questions of SM:
- Dark matter and dark energy
- Matter antimatter asymmetry
- Unification of forces

Expect SM to be a low-energy approximation of a more general theory

Top quark plays an important role in many BSM models
LHC Accelerator

LHC:
Run I started in spring 2010
2010 and 2011: $\sqrt{s} = 7$ TeV
2012: $\sqrt{s} = 8$ TeV
Run II started in spring 2015
with $\sqrt{s} = 13$ TeV

<table>
<thead>
<tr>
<th></th>
<th>LHC Run I</th>
<th>LHC Run II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delivered luminosity</td>
<td>$\sim 23$ fb$^{-1}$</td>
<td>$\sim 2.6$ fb$^{-1}$</td>
</tr>
<tr>
<td>Max. inst. luminosity</td>
<td>$\sim 7.7 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$</td>
<td>$\sim 4.6 \cdot 10^{33}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Luminosity on tape</td>
<td>$\sim 22$ fb$^{-1}$</td>
<td>$\sim 2.4$ fb$^{-1}$</td>
</tr>
<tr>
<td>Luminosity used in analyses</td>
<td>$\sim 20$ fb$^{-1}$</td>
<td>$\sim 0.4$ fb$^{-1}$</td>
</tr>
</tbody>
</table>

2012 data taking period October 2015
Detectors

**CMS**
- Length: 22 m
- Height: 15 m
- Weight: 14 kt
- B-field: 3.8 T (solenoid)

- Excellent momentum and vertex resolution (~200 m² silicon sensors)
- Good EM calorimeter resolution

**ATLAS**
- Length: 46 m
- Height: 25 m
- Weight: 7 kt
- B-field: 4T (toroidal)

- Very good momentum resolution
- Excellent hadron cal. resolution
Hadron Collider

Highest energies achievable with hadron colliders

Hadron collisions = collisions of “broadband” parton beams

Longitudinal momentum fractions $x_i$ unknown $\rightarrow$ partonic center of mass energy unknown

Consequence: use only Lorentz invariant transverse quantities, e.g. transverse momentum $p_T = \sqrt{p_x^2 + p_y^2} = p \sin \theta$

Instead of polar angle use pseudorapidity $\eta = -\ln \left( \tan \frac{\theta}{2} \right)$ or Lorentz invariant rapidity $y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right)$
Top quark production rate

LHC: ~ 5,000,000 top pairs (2012, 8 TeV, about 20 fb⁻¹)

LHC is a top quark factory!

2012 data taking period
Top quark pair production

- Top quark pair production via strong interaction (dominant process)
- Electroweak production of single top quarks (factor 2-3 smaller than pair prod.)

Cross section

<table>
<thead>
<tr>
<th></th>
<th>Tevatron</th>
<th>LHC 7 TeV</th>
<th>LHC 8 TeV</th>
<th>LHC 14 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross section</td>
<td>7.2 pb</td>
<td>172 pb</td>
<td>246 pb</td>
<td>954 pb</td>
</tr>
<tr>
<td>Gluon fusion</td>
<td>~15%</td>
<td>~80%</td>
<td>≥80%</td>
<td>~90%</td>
</tr>
</tbody>
</table>

NNLO+NNLL: PRL 110, 252004 (2013)
Single top quark production

- Electroweak production mode of top quarks
- t-channel most abundant production mode for single top quarks
- Direct measurement of $|V_{tb}|^2$

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</thead>
<tbody>
<tr>
<td></td>
<td>$\sqrt{s}=1.96$ TeV</td>
<td>$\sqrt{s}=7$ TeV</td>
<td>$\sqrt{s}=8$ TeV</td>
<td>$\sqrt{s}=14$ TeV</td>
</tr>
<tr>
<td>s-channel</td>
<td>1.0</td>
<td>5</td>
<td>6</td>
<td>12</td>
</tr>
<tr>
<td>t-channel</td>
<td>2.1</td>
<td>66</td>
<td>87</td>
<td>243</td>
</tr>
<tr>
<td>Wt</td>
<td>0.26 (*)</td>
<td>16</td>
<td>22</td>
<td>84</td>
</tr>
</tbody>
</table>

Approximate NNLO (based on threshold resummation at NNLL accuracy): PRD 83, 091503 (2011); PRD 81, 054028 (2010); PRD 82, 054018 (2010); arXiv:1210.7813

*) Approximate NNLO (based on threshold resummation at NLL accuracy): PRD 74, 114012 (2006)
Top Quark Decay Channels

**SM:**
- $t \rightarrow b\, W \approx 100\%$
- $W \rightarrow e/\mu/\tau\, \nu \approx 10\%$
- $W \rightarrow \text{hadronisch} \approx 70\%$

**$t$- and $s$-channel single top:**
- Decay of 1 $W$-boson
- Most analyses use the “leptonic” decays $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ (~20%)

**$\bar{t}t$ and $Wt$:**
- Decay channels classified according to the decay of the two $W$-bosons
- Most $\bar{t}t$ properties analyses use the “lepton+jets” channel
- Most $Wt$ analyses use the dilepton channel

**$\bar{t}t$: “lepton+jets”-channel:**
- $(e+jets\ and\ \mu+jets)$
- Moderate background
- Relative high branching ratio (~30%)
Survey of top quark

**1995:** Discovery of the top quark by both Tevatron experiments CDF and D0

Since then the top quark has been studied widely ...

**Production:**
- Production rate of different processes (*strong and EW*)
- Differential distributions
- New production mechanisms

**Intrinsic properties:**
- Top quark mass → constraints on Higgs mass
- Charge
- Lifetime

**Decay:**
- Decay channels *(SM and new)*
- Couplings
Outline

- Introduction

- **Recent results on top quark pair production:**
  - Top quark pair cross section
  - Charge asymmetry
  - Search for resonant production
  - $t\bar{t}V$ cross section

- **Recent results on single top quark production**
Top pair event signatures

**Dilepton**

- **BR:** $\approx 5\%$
- **BG:** few
- Mainly $Z$+jets

**Lepton+Jets**

- **BR:** $\approx 30\%$
- **BG:** moderate
- Mainly $W$+jets

**All Hadronic**

- **BR:** $\approx 44\%$
- **BG:** huge
- Mainly multijets
Recent top quark pair cross section measurement in the $e\mu$ channel from CMS

- Select events with opposite charged $e\mu$ pairs and categorize events in 12 classes according to $N_{b\text{-jets}} = 0,1,2$ and $N_{\text{add. jets}} = 0,1,2,3$ ($\text{add. jets: non b-jets}$)
- Perform binned likelihood fit to event number ($N_{\text{add. Jets}} = 0$) and to $p_T$ of the least energetic add. jet ($N_{\text{add. Jets}} > 0$) in these 12 classes
- Constrain systematic uncertainties insitu with likelihood fit

Result:

$$\sigma_{\ttt} = 174.5 \pm 2.1 \text{ (stat)} \pm 4.5^{+4.0}_{-4.0} \text{ (syst)} \pm 3.8 \text{ (lumi)} \text{ pb} \quad \text{at } \sqrt{s} = 7 \text{ TeV}$$

$$\sigma_{\ttt} = 245.6 \pm 1.3 \text{ (stat)} \pm 6.6^{+6.6}_{-5.5} \text{ (syst)} \pm 6.5 \text{ (lumi)} \text{ pb} \quad \text{at } \sqrt{s} = 8 \text{ TeV}$$

Relative uncertainty: $< 4\%$; good agreement with SM theory prediction
Summary of LHC Run I $t\bar{t}$ cross section measurements

**7TeV**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Process</th>
<th>$\sigma_{t\bar{t}}$ (pb)</th>
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</tr>
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<tbody>
<tr>
<td>ATLAS</td>
<td>$t\bar{t}$+jets</td>
<td>$179 \pm 4 \pm 7$</td>
<td>$173 \pm 6 \pm 10$</td>
<td>$167 \pm 3 \pm 7$</td>
<td>$164 \pm 12 \pm 1$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dilepton (+)</td>
<td>$170 \pm 4 \pm 8$</td>
<td>$170 \pm 4 \pm 8$</td>
<td>$149 \pm 24 \pm 9$</td>
<td>$136 \pm 4 \pm 8$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>all jets (*)</td>
<td>$166 \pm 2 \pm 8$</td>
<td>$173 \pm 2 \pm 8$</td>
<td>$166 \pm 2 \pm 8$</td>
<td>$173 \pm 2 \pm 8$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$t\bar{t}$+jets</td>
<td>$165 \pm 2 \pm 3$</td>
<td>$162 \pm 2 \pm 3$</td>
<td>$181 \pm 2 \pm 3$</td>
<td>$194 \pm 18 \pm 46$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dilepton $e\mu$, b-tag</td>
<td>$162 \pm 2 \pm 3$</td>
<td>$181 \pm 2 \pm 3$</td>
<td>$194 \pm 18 \pm 46$</td>
<td>$168 \pm 12 \pm 7$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dilepton $e\mu$, $N_{\text{mis}}$</td>
<td>$162 \pm 2 \pm 3$</td>
<td>$181 \pm 2 \pm 3$</td>
<td>$194 \pm 18 \pm 46$</td>
<td>$168 \pm 12 \pm 7$</td>
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<td>$194 \pm 18 \pm 46$</td>
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<tr>
<td>ATLAS</td>
<td>all jets</td>
<td>$168 \pm 12 \pm 7$</td>
<td>$183 \pm 9 \pm 3$</td>
<td>$158 \pm 2 \pm 4$</td>
<td>$152 \pm 12 \pm 3$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$t\bar{t}$+jets</td>
<td>$165 \pm 2 \pm 3$</td>
<td>$162 \pm 2 \pm 3$</td>
<td>$181 \pm 2 \pm 3$</td>
<td>$194 \pm 18 \pm 46$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dilepton $e\mu$</td>
<td>$174.5 \pm 21.2$</td>
<td>$174.5 \pm 21.2$</td>
<td>$174.5 \pm 21.2$</td>
<td>$174.5 \pm 21.2$</td>
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<tr>
<td>ATLAS</td>
<td>$t\bar{t}$+jets</td>
<td>$143 \pm 14 \pm 22$</td>
<td>$152 \pm 12 \pm 3$</td>
<td>$152 \pm 12 \pm 3$</td>
<td>$152 \pm 12 \pm 3$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>all jets</td>
<td>$158 \pm 2 \pm 4$</td>
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**8TeV**

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<th>$\sigma_{t\bar{t}}$ (pb)</th>
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<tbody>
<tr>
<td>ATLAS</td>
<td>$t\bar{t}$+jets</td>
<td>$260 \pm 1 \pm 22$</td>
<td>$228 \pm 9 \pm 10$</td>
<td>$257 \pm 3 \pm 24$</td>
<td>$257 \pm 3 \pm 24$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>dilepton $e\mu$</td>
<td>$242.4 \pm 1.7 \pm 5.5$</td>
<td>$239.0 \pm 2.1 \pm 11.3$</td>
<td>$245.6 \pm 1.3 \pm 6.6$</td>
<td>$245.6 \pm 1.3 \pm 6.6$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$t\bar{t}$+jets</td>
<td>$241.5 \pm 1.4 \pm 5.7$</td>
<td>$241.5 \pm 1.4 \pm 5.7$</td>
<td>$241.5 \pm 1.4 \pm 5.7$</td>
<td>$241.5 \pm 1.4 \pm 5.7$</td>
</tr>
<tr>
<td>ATLAS</td>
<td>all jets</td>
<td>$275.6 \pm 6.1 \pm 37.8$</td>
<td>$275.6 \pm 6.1 \pm 37.8$</td>
<td>$275.6 \pm 6.1 \pm 37.8$</td>
<td>$275.6 \pm 6.1 \pm 37.8$</td>
</tr>
</tbody>
</table>

Measurements in different channels are in good with each other and with SM pred. Relative uncertainty of most precise measurements ($e\mu$) < 4%
Counting experiment using opposite sign eμ pairs with 1 or 2 b-tags

First measurements are in good agreement with SM prediction

Rel. uncertainty of most precise measurement: <14%
tt cross section - summary

Total top pair cross section in good agreement with SM theory prediction

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004
m_{top} = 172.5 GeV, PDF \oplus \alpha_s uncertainties according to PDF4LHC
Charge Asymmetry in Top Quark Pair Production

**SM:** Small asymmetry caused by higher order interference effect, which occurs for asymmetric initial states only (qq, qg)

- Small asymmetry caused by higher order interference effect, which occurs for asymmetric initial states only (qq, qg).

**pp - Tevatron**
- t (anti-t) are preferentially produced in q (anti-q) direction
- q (anti-q) mostly from proton (antiproton)
- → forward-backward asymmetry $A_{FB}$

**pp - LHC**
- average quark momentum fraction $x_q > x_{anti-q}$
- → central-peripheral asymmetry $A_C$
SM Predictions for the Charge Asymmetry

\[ A_{FB} \approx 8\% \quad (2007, \text{NLO calc. with estimated EW cor.}) \]
\[ A_{FB} \approx 9\% \quad (2011, \text{NLO calc. with full EW cor.}) \]
\[ A_{FB} \approx 10\% \quad (2014, \text{NNLO calc. with full NLO EW cor.}) \]

**Sensitive variables:** rapidity in lab or in \( t\bar{t} \)-frame

\[ \text{Asym. in } t\bar{t}\text{-frame} > \text{Asym in lab-frame} \]

**\( t\bar{t} \)-frame:** \( \Delta Y = y_t - y_{\text{anti-}t} = 2y^t_t \)

**\( pp \) – Tevatron:**

Sensitivity in lab:
\[ |y_t| - |y_{\text{anti-}t}| \]

Sensitivity in \( t\bar{t} \)-frame:
\[ A_{C} \approx 1.2\% \quad (2012, \text{NLO calc. with full EW cor.}) \]

**\( pp \) – LHC:**

Sensitivity in lab:
\[ |y_t| - |y_{\text{anti-}t}| \]

Sensitivity in \( t\bar{t} \)-frame:
\[ \Delta Y = y_t - y_{\text{anti-}t} = 2y^t_t \]
In 2008, first measurements indicated a larger inclusive $A_{FB}$ than predicted.

In 2011, both Tevatron experiments measure a larger inclusive $A_{FB}$ than predicted by SM.

Leptonic asymmetry measured by D0 in the L+J channel is also larger than the SM prediction (3.3σ compared to MC@NLO).

CDF measured a large asymmetry for $M_{tt}>450\text{GeV}$, but D0 not (3.4σ compared to MC@NLO).

Observed deviation generated large number of theoretical BSM explanations.

### Table

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Lower Limit</th>
<th>Asymmetry</th>
<th>Uncertainty</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDF LJ</td>
<td>$0.158 \pm 0.074$</td>
<td>$(5.3 \text{ fb}^{-1})$</td>
<td>$(0.072 \pm 0.017)$</td>
<td></td>
</tr>
<tr>
<td>CDF DIL*</td>
<td>$0.420 \pm 0.158$</td>
<td>$(5.1 \text{ fb}^{-1})$</td>
<td>$(0.150 \pm 0.050)$</td>
<td></td>
</tr>
<tr>
<td>CDF combined*</td>
<td>$0.201 \pm 0.067$</td>
<td>$(5.1 \text{ fb}^{-1})$</td>
<td>$(0.065 \pm 0.018)$</td>
<td></td>
</tr>
<tr>
<td>D0 LJ**</td>
<td>$0.196 \pm 0.060$</td>
<td>$(5.1 \text{ fb}^{-1})$</td>
<td>$0.016$</td>
<td>$0.020$</td>
</tr>
</tbody>
</table>

**References**
- N. Kidonakis, PRD64:011504 (2011)
Measurement of $A_C$ in lepton+jets channel

- Select events with 1 isolated central $e/\mu$, $\geq 4$ jets whereof at least one jet is $b$-tagged
- Reconstruction of $t\bar{t}$ kinematic; lepton charge determines the charge of semileptonically decaying t-quark:
  \[ \Delta |y| = |y_t| - |y_{\text{anti-}t}| = Q_l \cdot (|y_{\text{lep}}| - |y_{\text{had}}|) \]
- Perform unfolding to account for biases due to event selection and non-perfect reconstruction

Result: $A_C = 0.0010 \pm 0.0077$ (CMS)

$A_C = 0.009 \pm 0.005$ (ATLAS)

Measurements are in good agreement with SM prediction.
Differential $A_C$ – Investigation of different aspects of $A_C$

Study extra hard radiation
(increased neg. contribution of $A_C$)

$\slash \! \! \! q q$ induced $\bar{t}t$ events increase with velocity $\beta$

**ArXiv:1507.03119**

$\sqrt{s} = 8$ TeV, $20.3 \text{ fb}^{-1}$

NP could result in an $A_C$ increasing with inv. mass

**ArXiv:1509.02358**

Differential $A_C$ measurements at the LHC are in good agreement with SM predictions

In particular there is no indication that there is a strong rise of $A_C$ with the inv. mass (as seen by CDF)
Inclusive charge asymmetry using the template method

- Fit symmetric and asymmetric $t\bar{t}$ templates to sensitive variable $\Upsilon_{tt} = \tanh(\Delta|y|)$

- Use fitted relative magnitude of sym. and asym. components to determine the asymmetry

New template method (TM) assumes SM-like distributions for sym. and asym. components

TM results in a larger model dependence but the statistical uncertainty is substantially smaller than in the standard method (unfolding)

Measured inclusive and differential $A^y_c$ are well consistent with SM prediction but there is still room for new physics contributions
Overview of Asymmetry measurements at the LHC

### 7TeV

<table>
<thead>
<tr>
<th>ATLAS+CMS Preliminary</th>
<th>LHCtopWG</th>
<th>$\sqrt{s}$ = 7 TeV</th>
<th>Sept 2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>tt asymmetry</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS $t\bar{t}$+jets</td>
<td>$A_c = 0.006 \pm 0.010 \pm 0.005$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS $t\bar{t}$+jets</td>
<td>$A_c = 0.004 \pm 0.010 \pm 0.011$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS+CMS $t\bar{t}$+jets</td>
<td>$A_c = 0.005 \pm 0.007 \pm 0.006$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preliminary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS dilepton</td>
<td>$A_c = 0.021 \pm 0.025 \pm 0.017$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS dilepton</td>
<td>$A_c = -0.010 \pm 0.017 \pm 0.008$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theory (NLO+EW)</td>
<td>$A_c = 0.0123 \pm 0.0005$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| lepton asymmetry       |          |                     |           |
| ATLAS dilepton         | $A_c = 0.024 \pm 0.015 \pm 0.009$ |
| CMS dilepton           | $A_c = 0.009 \pm 0.010 \pm 0.006$ |
| Theory (NLO+EW)        | $A_c = 0.0070 \pm 0.0003$ |

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<tr>
<td>ATLAS $t\bar{t}$+jets</td>
<td>$A_c = 0.009 \pm 0.004 \pm 0.005$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS $t\bar{t}$+jets template</td>
<td>$A_c = 0.003 \pm 0.003 \pm 0.003$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS $t\bar{t}$+jets</td>
<td>$A_c = 0.001 \pm 0.007 \pm 0.004$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Theory (NLO+EW)</td>
<td>$A_c = 0.0111 \pm 0.0004$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| All $t\bar{t}$ asymmetry and lepton asymmetry measurements are consistent with each other and with the SM prediction |
| There is no indication for new physics from the $A_c$ measurements at the LHC |
State of the Charge Asymmetry in 2015

- **Theory**: SM prediction increased (full EW contribution, NNLO QCD pred.)

- **LHC**: All $A_C$ measurements and leptonic asym. are consistent with the SM prediction

- **Tevatron**: Latest $A_{FB}$ measurements and leptonic asym. (not shown, larger unc.) are larger but consistent with the SM prediction

Charge asymmetry puzzle seems to be solved, but full NNLO QCD calculations and full EW corrections are important for $tt$ modeling
Search for resonances decaying to $t\bar{t}$

No indication for heavy resonances at the Tevatron (sub-TeV range)

With the LHC the TeV range can be explored for the first time

In many models with NP occur heavy resonances decaying preferentially to $t\bar{t}$

No indication for heavy resonances at the Tevatron (sub-TeV range)

With the LHC the TeV range can be explored for the first time
The larger the invariant top pair mass $M_{t\bar{t}}$, the more boosted the top quarks and the smaller the angles between the decay products.

**Leptonic side:**
Lepton close to b-jet or in b-jet (lepton not isolated)

**Hadronic side:**
Jets overlap → reconstruction of 1 or 2 jets instead of 3 (jet with substructure)
Search for resonant $t\bar{t}$ production at the LHC – latest result (I)

High mass analyses:

- Separate analyses for high and low inv. $t\bar{t}$ mass regions
- Event selections in the high inv. $t\bar{t}$ mass region designed to cope with the boosted topology:
  - **all-had**: Require 2 jets that are identified as top-jets (via substructure in merged fat jets) and categorize events according to the number of b-tags
  - **lepton+jets**: Require $\geq 2$ jets and one non-isolated l, categorize events according to the number of top-tags and b-tags

$\mu$+jets, 1 t tag

$\mu$+jets, 0 t tag, 1 b tag

$\mu$+jets, 0 t tag, 2 b tags

ArXiv:1506.03062, submitted to PRD
Search for resonant $\bar{t}t$ production at the LHC – latest result (II)

Use reconstructed inv. mass of $\bar{t}t$ for statistical inference

No indication for heavy resonances decaying to top quark pairs

Most stringent limits on topcolor narrow and 10% wide $Z'$ and KK gluon excitation: 2.4 TeV, 2.9 TeV, 2.8 TeV at 95% CL

Search from ATLAS in the l+jets channel (JHEP08 (2015), 148) results in similar exclusion limits as l+jets analysis from CMS

Top pair events with $M_{\bar{t}t} > 1$TeV/c² observed but no indication for heavy resonances decaying to $\bar{t}t$

LHC Run II will allow to explore multi-TeV range
13TeV data – Boosted $\bar{t}t$ candidate (all-hadronic)

CMS Experiment at LHC, CERN
Data recorded: Sun Jul 12 07:25:11 2015 CEST
Run/Event: 251562 / 111132974
Lumi section: 122
Orbit/Crossing: 31722792 / 2253

Subjet 1, et = 275 GeV
  eta = 2.08
  phi = 1.94

Subjet 2, et = 49 GeV
  eta = 1.64
  phi = 1.64

Subjet 3, et = 203 GeV
  eta = 2.37
  phi = 1.48

Subjet 4, et = 133 GeV
  eta = -0.47
  phi = -1.56

Subjet 5, et = 402 GeV
  eta = -0.86
  phi = -1.44

Subjet 6, et = 73 GeV
  eta = -0.18
  phi = -1.30

Top jet candidate 1
  pt = 488 GeV
  eta = 2.22
  phi = 1.74
  mass = 176 GeV

Top jet candidate 2,
  pt = 613 GeV
  eta = -0.70
  phi = -1.46
  mass = 177 GeV
### ttV – Decay Channels

<table>
<thead>
<tr>
<th>Process</th>
<th>$t\bar{t}$ decay</th>
<th>Boson decay</th>
<th>Channel</th>
<th>$Z \rightarrow \ell^+\ell^-$</th>
<th>jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ttW^\pm$</td>
<td>lepton+jets</td>
<td>$\ell^\pm\nu$</td>
<td>OS dilepton</td>
<td>no</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>dilepton</td>
<td>$q\bar{q}$</td>
<td>OS dilepton</td>
<td>no</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>lepton+jets</td>
<td>$\ell^\pm\nu$</td>
<td>SS dilepton</td>
<td>no</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>dilepton</td>
<td>$\ell^\pm\nu$</td>
<td>Trilepton</td>
<td>no</td>
<td>2</td>
</tr>
<tr>
<td>$ttZ$</td>
<td>dilepton</td>
<td>$q\bar{q}$</td>
<td>OS dilepton</td>
<td>no</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>all-hadronic</td>
<td>$\ell^+\ell^-$</td>
<td>OS dilepton</td>
<td>yes</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>lepton+jets</td>
<td>$\ell^+\ell^-$</td>
<td>Trilepton</td>
<td>yes</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>dilepton</td>
<td>$\ell^+\ell^-$</td>
<td>Tetralepton</td>
<td>yes</td>
<td>2</td>
</tr>
</tbody>
</table>

- **Most sensitive channels**
- OS: opposite sign leptons
- SS: same sign leptons

### Signal

- OS dilepton: $ttZ$
- SS dilepton: $ttW$ (ATLAS only)
- Trileptons: $ttZ$
- Tetraleptons: $ttZ$

### Dominant background

- OS dilepton: $tt, Z$+jets
- SS dilepton: $tt$
- Trileptons: $tt$ with non-prompt lepton, WZ
- Tetraleptons: $tt$ with non-prompt lepton, WZ, ZZ
Measurement of the $t\bar{t}V$ cross sections at ATLAS

*ArXiv:1509.05276*

**ATLAS**

$\sqrt{s} = 8$ TeV, 20.3 fb$^{-1}$

- **CR**
- **2LOS**
- **2LSS**
- **3L**
- **4L**

**OS**: opposite sign leptons  
**SS**: same sign leptons

- Use of 15 SR and 5 CR
- Perform a fit to the event numbers in all 20 categories
- In case of the dilepton (2L) categories also shape information is used
Measurement of the $t\bar{t}V$ cross sections at CMS

- Use of 5 SR with subcategories ($N_{jets}$, lepton-type)
- Some backgrounds (non-prompt, charge mis. id.) determined from data CR
- Reconstruction of $t\bar{t}$-system
- $t\bar{t}$ rec. and kin. event variables used in BDT
- Extract cross sections from fit to BDT outputs
Observation of the $\tilde{t}\tilde{t}V$ process at the LHC

Rare SM processes $ttV$ have been observed and measured cross sections are consistent with SM prediction.
Outline

- Introduction
- Overview of the current status in top quark physics
- Recent results on top quark pair production
  - Recent results on single top quark production:
    - t-channel
    - Wt production
    - s-channel
Single top event signature

Distinct event signature

Very similar event signature as top pairs

Backgrounds:
- W+jets
- Top pairs: lepton+jets
dilepton
- Diboson
- Z+jets

Jeannine Wagner-Kuhr
MPP colloquium, Munich, 3.11. 2015
First single top t-channel cross section measurements at 13TeV

- Consider leptonic decay of W-boson
- Require 1 e/µ, 2 jets (up to |η|<5), whereof one is b-tagged, minimum transverse mass of W to reduce QCD background and a rec. top quark mass $m_{t\nu b}$ compatible with the top mass
- Validate W+jets backgrounds in side band regions of $m_{t\nu b}$
- Perform simultaneous fit to $|\eta_{j'}|$ in the SR and in an $t\bar{t}$ enriched region (3Jets, 2 b-tags)

Measured cross section at 13 TeV: $\sigma = (274 \pm 116)$ pb

SM prediction: $\sigma \approx 217$ pb (NLO 5FS, HARTHOR)

First single top t-channel events seen at 13TeV, measured cross section is consistent with SM prediction
Overview of single top t-channel measurements at Run I

Measured single top t-channel cross sections at 7 and 8TeV are in good agreement with SM prediction

Jeannine Wagner-Kuhr

MPP colloquium, Munich, 3.11. 2015
Measurement of the Wt cross section

Consider dilepton channels: ee, µµ, eµ

SR: opposite sign lepton pair, 1 b-tagged jet, missing transverse energy

Use of BDTs to separate Wt and tt

Perform simultaneous fit to BDT outputs in SR and in two tt enriched regions (2 jets, 1 or 2 b-tags)

Systematic uncertainties are constrained insitu via nuisance parameters

Measured Wt cross section at 8 TeV: \( \sigma = (23.0^{+3.6}_{-3.9}) \) pb

SM prediction: \( \sigma \approx 22 \) pb (NLO + NNLL)

Measured Wt cross section is in good agreement with SM prediction, relative uncertainty of measurement is about 16%
Search for single top s-channel with the ME method

Idea of ME method: Compute event probability for signal and background hypotheses

\[
P(x | H_{\text{proc}}) = \frac{1}{\sigma} \int d^m \sigma(y) dq_1 dq_2 f(q_1) f(q_2) W(x | y)
\]

\(X\): reconstructed final state

\(H_{\text{proc}}\): Process of Hypothesis

- Use full kinematic information of events, integrate over unknown or poorly measured quantities
- Calculate probability densities for signal (s-channel with 2 or 3 partons) and backgrounds (t-channel 4FS, \(\bar{t}t\), W+qq, W+qc, W+bb)
- Discriminant (prob. for an event with rec. final state \(x\) being a signal event):

\[
P(S | x) = \frac{\sum_i \alpha_{S_i} P(x | S_i)}{\sum_i \alpha_{S_i} P(x | S_i) + \sum_j \alpha_{B_j} P(x | B_j)}
\]

\(\alpha_{S_i}, \alpha_{B_j}\): Expected fractions of signal/background process events after selection
Evidence for single top s-channel

- Select events with one e or µ, exactly two jets which are b-tagged, MET, veto events with an add. loosely rec. e or µ
- Validate t̄t and W+jets in control regions
- Perform a fit to the ME discriminant P(S|X) in the SR and to the charge of the lepton in the W+jets CR
- Constrain syst. unc. insitu

Observed significance: \(3.2\sigma\) (exp. significance: 3.9\(\sigma\))

Measured cross section: \(4.8^{+2.5}_{-2.2}\) pb \((\text{SM: } \sigma \approx 5.6\text{ pb (NLO + NNLL)})\)

There is evidence for single top s-channel production at the LHC
Status of single top quark production cross sections in 2015

Measured single top quark cross sections are in good agreement with SM prediction.
Extraction of the CKM matrix element $|V_{tb}|$

**Extract $|V_{tb}|$ from measured single top quark cross sections**

$\sigma \sim V_{tb}^2$

Assuming $|V_{td}|, |V_{ts}| << |V_{tb}|$:

$$|f_{LV} V_{tb}| = \sqrt{\frac{\sigma_{single\ top}}{\sigma_{theory}}}$$

$f_{LV}$: possible anomalous form factor

(SM: $f_{LV}=1$)

Relative uncertainty of $|V_{tb}|$ determination from $t$-channel single top production at the 5% level

$|V_{tb}| = 1$

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**ATLAS+CMS Preliminary**

| $|V_{tb}|$ extraction from single top quark production |
| --- |
| $\sigma_{theo}$: NLO+NNLL MSTW2008mfnlo |
| PRD 61 (2005) 054028 |
| NLO+NNLL MSTW2008mfnlo |
| PRD 61 (2005) 054028 |

$\Delta \sigma_{total}$: scale @ PDF

$m_{top} = 172.5 \text{ GeV}$

|$f_{LV} V_{tb}| \pm (\text{meas.}) \pm (\text{theo.})$

### t-channel:

- **ATLAS 7 TeV**
  - PRD 90 (2014) 110006 (4.59 fb$^{-1}$)
- **ATLAS 8 TeV**
  - ATLAS+CONF-2014-007 (20.3 fb$^{-1}$)
- **CMS 7 TeV**
  - JHEP 12 (2012) 025 (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:

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

### s-channel:

- **ATLAS 8 TeV**
  - paper in preparation (20.3 fb$^{-1}$)
- **ATLAS+CONF-2015-047 (20.3 fb$^{-1}$)**

Relative uncertainty of $|V_{tb}|$ determination from $t$-channel single top production at the 5% level
Conclusion

Recent results from top quark production at the LHC

◆ Harvest from Run I:
  - Measured $t\bar{t}$ and single top $\sigma$ are in good agreement with SM pred.
  - Inclusive $\sigma$ of $t\bar{t}$, single top t-channel, $Wt$ measured with a precision of below 4%, below 10% and of about 16%
  - Puzzle of large asymmetries at the Tevatron seems to be solved but full NNLO QCD calc. and full EW corrections are important for $t\bar{t}$ modeling
  - Observed $t\bar{t}$ events in $M_{tt}=1-3$ TeV range, no indication for resonant prod.
  - Observed $ttV$ production, consistent with SM
  - Evidence for s-channel single top quark production

◆ First Measurements/studies at 13TeV:
  - $t\bar{t}$ cross section measured with a rel. unc. of <14%, first t-channel single top events seen at 13TeV
  - Have seen nice $t\bar{t}$ events which are highly boosted

◆ Looking forward to more detailed studies at 13 TeV
Back-Up Slides
Charge asymmetry in new physics models

- $Z'$: Flavor violating $Z'$ exchanged in t-channel in $uu \rightarrow tt$ and with right-handed $Z'tu$ couplings
- $W'$: $W'$ boson with right-handed couplings exchanged in t-channel in $dd \rightarrow tt$
- $\Omega^4$: Color-sextet scalar with right-handed flavor violating $tu$-couplings and exchanged in u-channel
- $\omega^4$: Color triplet with flavor violating $tu$-couplings, right-handed, exchanged in u-channel in $uu \rightarrow tt$
- $G_\mu$: Axigluon, color octet vector with axial couplings

LHC charge asymmetry measurement provides complementary information

J. Aguilar-Saavedra, M. Perez-Victoria, arXiv:1105.4606
t-channel: Signal and background modeling

Monte-Carlo:
- Single top processes: POWHEG+Pythia
- \( \bar{t}t \)+jets, W+jets, Z+jets: MadGraph+Pythia
- Diboson (WW, WZ, ZZ): Pythia

Data-driven multijet QCD modeling:
- Template obtained from loose lepton selection
- Normalization determined from fit to \( M_{T,W} (\mu) \) and MET(e), respectively

Data-driven W+jets modeling (\( |\eta_j|\)-analysis):
- W+jets yield and \( |\eta_j|\)-template is extracted from data in \( m_{\ell\nu b} \) sideband (SB)
- Non-W+jets backgrounds are subtracted

Data-driven top pair modeling (\( |\eta_j|\)-analysis at 8TeV):
- \( |\eta_j|\)-template is obtained using the 3-jets 2-tags data sample
- Normalization is taken from the simulation