Top-quark production measurements

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on behalf of the Collaborations

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Top-quark production

Discovered at Tevatron in 1995

LHC is a top quark factory

- \( t\bar{t} \) production: inclusive
- \( t\bar{t} \) production: differential

Single top quark production

- total cross section: \( t-, Wt \) and \( s \)-channel
- differential cross section

Associated production

- \( \gamma, W, Z, b, t \)

In this talk

- highlighting results released in the last year
Uncertainties will then be below the percent level; i.e., the hadronic center-of-mass energy distributions functions (PDF) – up to terms which are suppressed with some power of the scale, e.g. $\alpha_s^2$.

In the following subsections we shall discuss production and decay of the top quark. Production of the top quark is, on the other hand, the main background for considering the top quark to be a signal. Production of top quark pairs is, on the other hand, also an important background to the search for new particles of the SM and/or non-standard Higgs bosons and for signals of supersymmetry. Obviously, the precision of considering the top quark to be a signal requires accurate predictions of both roles the top quark plays at the Tevatron and at the LHC regarding order (NLO) in the QCD coupling, of the problem, e.g. $\sqrt{s} = \tilde{s}$, $\tilde{g} \gg m_t$, $\alpha_s$, $\alpha_t$, $\alpha_b$, $\alpha_c$.

As far as top quark physics is concerned, first measurements were done at the Tevatron during the discovery phase of the LHC millions of production processes during the measurement, statistical observables, statistical systematics dominated.

In the “discovery phase” of the LHC, millions of top quark production processes were measured. Two of the most important processes are the production of top quark pairs via strong interactions and the production and decay of single-top quarks via weak interactions. The $t\bar{t}$ production is, on the other hand, the main background for considering the top quark to be a signal. Production of top quark pairs is, on the other hand, also an important background to the search for new particles of the SM and/or non-standard Higgs bosons and for signals of supersymmetry. Obviously, the precision of considering the top quark to be a signal requires accurate predictions of both roles the top quark plays at the Tevatron and at the LHC regarding order (NLO) in the QCD coupling, of the problem, e.g. $\sqrt{s} = \tilde{s}$, $\tilde{g} \gg m_t$, $\alpha_s$, $\alpha_t$, $\alpha_b$, $\alpha_c$.

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Top-quark decays

Weak decay

- governed by CKM matrix, $\text{BF}(t \rightarrow Wb) \sim 1$
- no FCNC transitions at tree level
- $W \rightarrow \ell \nu, \tau_{\text{had}}\nu$ or $q\bar{q}$

$t\bar{t}$ final states

- all hadronic ($2b, 4q$)
- $\ell$+jets ($2b, 2q, 1\ell, 1\nu$)
- dilepton ($2b, 2\ell, 2\nu$)
- with a $\tau_{\text{had}}$ lepton
- + extra jets
**t\bar{t} production at 1.96 TeV**

### Do inclusive measurement

- **full dataset (9.7 fb\(^{-1}\)), combination**
- **dilepton**
  - b-tag MVA
- **\(\ell\)+jets**
  - b-tag MVA + topological discriminant
  - split in 2, 3, ≥ 4 jets

**Results:**

\[ \sigma_{t\bar{t}} = 7.73 \pm 0.13_{\text{stat}} \pm 0.55_{\text{syst}} \text{ pb} \]

- uncertainty: 7.3%
- largest syst. from hadronisation
**t\bar{t} production at 7 TeV**

New measurement in $t\bar{t}\to \ell\tau_{\text{had}}$

\[
\begin{align*}
\sigma_{t\bar{t}} &= 183 \pm 9_{\text{stat}} \pm 23_{\text{syst}} \pm 3_{\text{lumi}} \text{ pb} \\
\text{also extract BF}(t\to\ell\nu b) \text{ and BF}(t\to q\bar{q}b)
\end{align*}
\]

### Measured

<table>
<thead>
<tr>
<th></th>
<th>SM</th>
<th>LEP (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma_{t\bar{t}}$</td>
<td>178 $\pm$ 3 (stat.) $\pm$ 16 (syst.) $\pm$ 3 (lumi.) pb</td>
<td>177.3 $\pm$ 9.0$^{+4.6}_{-6.0}$ pb</td>
</tr>
<tr>
<td>$B_{\ell}$</td>
<td>66.5 $\pm$ 0.4 (stat.) $\pm$ 1.3 (syst.)</td>
<td>67.51$\pm$0.07</td>
</tr>
<tr>
<td>$B_{\ell}$</td>
<td>13.3 $\pm$ 0.4 (stat.) $\pm$ 0.5 (syst.)</td>
<td>12.72$\pm$0.01</td>
</tr>
<tr>
<td>$B_{\mu}$</td>
<td>13.4 $\pm$ 0.3 (stat.) $\pm$ 0.5 (syst.)</td>
<td>12.72$\pm$0.01</td>
</tr>
<tr>
<td>$B_{\tau}$</td>
<td>7.0 $\pm$ 0.3 (stat.) $\pm$ 0.5 (syst.)</td>
<td>7.05$\pm$0.01</td>
</tr>
</tbody>
</table>

(*) Superseded by results shown below the line

*Effect of LHC beam energy uncertainty: 3.3 pb (not included in the figure)*
Recent measurement in $t\bar{t}\rightarrow\ell+\text{jets}$

- require $\geq 3$ jets, $\geq 1$ $b$-tag
- extract $e+\text{jets}$ and $\mu+\text{jets}$ independently
- template fit to likelihood discriminant with only two variables

**ATLAS+CMS Preliminary $\alpha_{t\bar{t}}$ summary, $\sqrt{s} = 8$ TeV**

- NNLO+NLL (Top++ 2.0), PDF4LHC
- $m_{t\bar{t}} = 172.5$ GeV
- NNLO+NNLL (Top++ 2.0), PDF4LHC
- $m_{t\bar{t}} = 172.5$ GeV
- $\alpha_{t\bar{t}} = 8$ TeV

<table>
<thead>
<tr>
<th>Source</th>
<th>$\sigma_{t\bar{t}}$ [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATLAS, lepton+jets</td>
<td>$260 \pm 1^{+22}_{-23} \pm 8$ pb</td>
</tr>
<tr>
<td>CMS, lepton+jets</td>
<td>$228 \pm 9^{+29}_{-26} \pm 10$ pb</td>
</tr>
<tr>
<td>ATLAS, dilepton $e\mu$</td>
<td>$257 \pm 3 \pm 24 \pm 7$ pb</td>
</tr>
<tr>
<td>CMS, dilepton $e\mu$</td>
<td>$242.4 \pm 1.7 \pm 5.5 \pm 7.5$ pb</td>
</tr>
<tr>
<td>LHC combined $e\mu$ (Sep 2014)</td>
<td>$241.5 \pm 1.4 \pm 5.7 \pm 6.2$ pb</td>
</tr>
</tbody>
</table>

**Effect of LHC beam energy uncertainty:** 4.2 pb (not included in the figure)
**Top quark production**

**Lepton Photon 2015**

**20–Aug–2015**

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**TOPLHCWG combination of best σ_{t\bar{t}} determinations**

- mapping of systematic uncertainties; study effect of correlations

### ATLAS+CMS Preliminary σ_{t\bar{t}} summary, \( \sqrt{s} = 8 \text{ TeV} \)

\[
\begin{align*}
\text{NNLO+NNLL (Top++ 2.0), PDF4LHC} & \\
m_{\text{top}} & = 172.5 \text{ GeV} \\
\end{align*}
\]

\[\sigma_{t\bar{t}} \pm \text{(stat) } \pm \text{(syst) } \pm \text{(lumi)}\]

**LHC combined e\mu (Sep 2014)**

CMS-PAS TOP-14-016, ATLAS-CONF-2014-054, \( L_{\text{tot}} = 5.3 - 20.3 \text{ fb}^{-1} \)

\[\sigma_{t\bar{t}} \pm \text{(stat) } \pm \text{(syst) } \pm \text{(lumi)}\]

**Brochero J. (CMS and ATLAS Collaborations)**

**Inclusive t\bar{t} Cross Section at the LHC**

September 29, 2014 16 / 18

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**Table 1:** Table of uncertainties in the \( t\bar{t} \) cross section used in the BLUE combination. Cross sections and uncertainties are in pb. For the ATLAS measurement, the contribution from pileup effects is already included in the JES and in the Lepton scale and resolution uncertainties. The contribution from Radiation is also included in the latter. For the CMS measurement, the contribution from Jet identification is negligible. The contribution from bJES is already included in the FlavourJES uncertainty.

### Background from Data

- \( \text{Z} + \text{jets} \) <0.1 1.5 0 0.4
- \( \text{Lepton misidentification} \) 0.8 1.9 0 0.8
- Class subtotal 0.8 2.4 0 0.9

### Background from Simulation

- \( \text{Dibosons} \) 0.3 0.5 1 0.4
- \( \text{Single top quark} \) 2.0 2.3 1 2.1
- Class subtotal 2.0 2.4 1 2.1

### Luminosity

- \( \text{Beam modelling} \) 2.9 5.0 1 3.5
- \( \text{Luminosity determination} \) 6.9 3.6 0 5.1
- Class subtotal 7.5 6.2 0.3 6.2

Total systematic 9.3 13.4 8.4

Total 9.4 13.6 8.5
**tt̄ inclusive production**

- Tevatron combined* 1.96 TeV (L=8.8 fb⁻¹)
- ATLAS dilepton 7 TeV (L=4.6 fb⁻¹)
- CMS dilepton 7 TeV (L=2.3 fb⁻¹)
- ATLAS l+jets* 7 TeV (L=0.7 fb⁻¹)
- CMS l+jets 7 TeV (L=2.3 fb⁻¹)
- ATLAS dilepton 8 TeV (L=20.3 fb⁻¹)
- CMS dilepton 8 TeV (L=5.3 fb⁻¹)
- LHC combined eμ* 8 TeV (L=5.3-20.3 fb⁻¹)
- ATLAS l+jets 8 TeV (L=20.3 fb⁻¹)
- CMS l+jets* 8 TeV (L=2.8 fb⁻¹)

* Preliminary

ATLAS+CMS Preliminary May 2015

TOPLHCWG

Inclusive t̄t cross section [pb]

NNLO+NNLL (pp)
NNLO+NNLL (p̅p)

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004

m_{top} = 172.5 GeV, PDF \oplus \alpha_s uncertainties according to PDF4LHC
LHCb joins the top family

Forward region interesting

- enhanced sensitivity to BSM ($q\bar{q}$ and $qg$ production)
- constrain PDF at large $x \to$ improves background to high-mass particles

LHCb observation

- can identify $W$ bosons and tag $b$- and $c$-jets $\to$ combine to top quark search
- likelihood fit of $N(\mu b)$ and $A(\mu b)$ in fiducial region
- $Wb$-only hypothesis is excluded at 5.4 $\sigma$

$$A(Wq) = \frac{\sigma(W^+ q) - \sigma(W^- q)}{\sigma(W^+ q) + \sigma(W^- q)}$$

$p_T(\mu) > 25$ GeV, $2.0 < \eta(\mu) < 4.5$
$\Delta R(\mu, b) > 0.5$, and $p_T(\mu + b) > 20$ GeV
$50 < p_T(b) < 100$ GeV, $2.2 < \eta(b) < 4.2$

$\sigma(\text{top})[7 \text{ TeV}] = 239 \pm 53 \text{ (stat)} \pm 38 \text{ (syst)}$ fb,
$\sigma(\text{top})[8 \text{ TeV}] = 289 \pm 43 \text{ (stat)} \pm 46 \text{ (syst)}$ fb.
First 13 TeV top quark candidates

$e\mu + 2 \ b\text{-}tags$

$\mu + \geq 4 \ jets$

single top candidate
**Analysis strategy follows Run-1 best measurement**

- select OS $e\mu$, $p_T(\ell') > 25$ GeV, jets (25 GeV), $\geq 1$ $b$-tag, no $E_T^{\text{miss}}$ required

**Count number of $e\mu$ events with**

- exactly one ($N_1$) and exactly two ($N_2$) $b$-tagged jets
- extract $\sigma_{t\bar{t}}$ and prob. to $b$-tag $q$ from $t \rightarrow Wq$ ($\varepsilon_b$)

\[
N_1 = L \sigma_{t\bar{t}} \epsilon_{e\mu} 2\varepsilon_b (1 - C_b \varepsilon_b) + N_1^{\text{bkg}}
\]

\[
N_2 = L \sigma_{t\bar{t}} \epsilon_{e\mu} C_b \varepsilon_b^2 + N_2^{\text{bkg}}
\]

- $\varepsilon_b = 0.527 \pm 0.026_{\text{stat}} \pm 0.006_{\text{syst}}$
  - in good agreement with simulation (0.543), includes jet acceptance
$t\bar{t}$ production at 13 TeV

Analysis strategy focussing on simplicity

- also use very clean $e\mu$ channel $p_T(\ell)>20$ GeV,
- $\geq 2$ jets (30 GeV)
- dilepton trigger, no b-tagging, no $H_T$ required
- extract $\sigma_{t\bar{t}}$ by counting events

<table>
<thead>
<tr>
<th>Source</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drell–Yan</td>
<td>$6.4 \pm 1.2$</td>
</tr>
<tr>
<td>Non-W/Z leptons</td>
<td>$8.5 \pm 4.3$</td>
</tr>
<tr>
<td>Single top quark</td>
<td>$10.6 \pm 3.4$</td>
</tr>
<tr>
<td>$VV$ ($V = W$ or $Z$)</td>
<td>$2.6 \pm 0.9$</td>
</tr>
<tr>
<td>Total background</td>
<td>$28.1 \pm 5.7$</td>
</tr>
<tr>
<td>$t\bar{t}$ dilepton signal</td>
<td>$206.7 \pm 16.0$</td>
</tr>
<tr>
<td>Data</td>
<td>220</td>
</tr>
</tbody>
</table>
**tt̅ production at 13 TeV**

**ATLAS and CMS analyses presented already on Monday**

**Comparing uncertainties**

- **luminosity uncertainty** is dominating (9%, 12%)
  - will be reduced with dedicated scans this month

- **tt̅ modeling**
  - tt̅ hadronisation (4.5%, 1.8%)
  - tt̅ NLO modeling, ISR/FSR radiation & PDF (2.9%, 2.4%)

- **detector-related**
  - lepton triggers (1.3%, 5.0%)
  - electron ID and isolation (4.2%), muon ID and isolation (1.6%); lepton efficiency (4.3%)
  - lepton mis-ID (1.3%, 1.0%)
  - jet energy scale (0.3%, 2.6%)

- **statistical uncertainty**
  - ATLAS analysed 78 pb⁻¹ (6.0%), CMS 42 pb⁻¹ (7.7%)

**Resulting in**

- \( \sigma_{tt̅} = 825 \pm 49_{\text{stat}} \pm 60_{\text{syst}} \pm 83_{\text{lumi}} \text{ pb} \), \( \Delta \sigma_{tt̅}/\sigma_{tt̅} = 14\% \) (ATLAS)
- \( \sigma_{tt̅} = 772 \pm 60_{\text{stat}} \pm 62_{\text{syst}} \pm 93_{\text{lumi}} \text{ pb} \), \( \Delta \sigma_{tt̅}/\sigma_{tt̅} = 16\% \) (CMS)
ATLAS summary plot

- **ATLAS dilepton** \( \sqrt{s} = 13 \, \text{TeV}, \, L = 78 \, \text{pb}^{-1} \)
- **ATLAS dilepton** \( \sqrt{s} = 8 \, \text{TeV}, \, L = 20.3 \, \text{fb}^{-1} \)
- **ATLAS dilepton** \( \sqrt{s} = 7 \, \text{TeV}, \, L = 4.6 \, \text{fb}^{-1} \)
- **Tevatron combined** \( \sqrt{s} = 1.96 \, \text{TeV}, \, L = 8.8 \, \text{fb}^{-1} \)

* Preliminary

\[ m_{\text{top}} = 172.5 \, \text{GeV}, \, \text{PDF} \oplus \alpha_s \text{ uncertainties according to PDF4LHC} \]
CMS summary plot

- Tevatron combined* 1.96 TeV (L=8.8 fb⁻¹)
- CMS dilepton 7 TeV (L=2.3 fb⁻¹)
- CMS l+jets 7 TeV (L=2.3 fb⁻¹)
- CMS dilepton 8 TeV (L=5.3 fb⁻¹)
- CMS l+jets* 8 TeV (L=2.8 fb⁻¹)
- LHC combined e⁺μ⁺ 8 TeV (L=5.3-20.3 fb⁻¹)
- CMS e⁺μ⁺ 13 TeV (L=42 pb⁻¹)

* Preliminary

Inclusive $t\bar{t}$ cross section [pb]

CMS Preliminary

** Cross section uncertainties according to PDF4LHC

$\alpha_s^{\oplus} = 172.5$ GeV, PDF $\oplus \alpha_s$ uncertainties according to PDF4LHC

Czakon, Fiedler, Mitov, PRL 110 (2013) 252004

$M_{top} = 172.5$ GeV, PDF $\oplus \alpha_s$ uncertainties according to PDF4LHC

$\sqrt{s}$ [TeV]
Why?

- detailed test of pQCD
- constrain PDF and some MC parameters
- background for Higgs, rare processes and many BSM searches

General analysis strategy

- tight event selection → pure $t\bar{t}$ sample
- $t\bar{t}$ system / top quark kinematic reconstruction
- background subtraction
- corrections: detector acceptance, resolution → unfolding
- compare to theory predictions at parton or particle level

Object Reconstruction

Top Kinematic Reconstruction

Theory Comparison

\[
\frac{1}{\sigma} \frac{d\sigma_i}{dX} = \frac{1}{\sigma} \text{unfold}(s_i^X - b_i^X) \Delta_i^X \cdot \int \mathcal{L} dt
\]
**$t\bar{t}$ differential: 8 TeV results**

Many observables studied in $t\bar{t}$ ($\ell$+jets, dil.)

- directly measured quantities of decay products
  - kinematics of leptons, b-jets in fiducial phase space
  - compared with MC simulations
- reconstructed quantities (top and $t\bar{t}$ system) unfolded at parton level
  - determined in full phase space
  - compared with MC and calculations

$p_T(t)$ measured to be softer than expectation
$t\bar{t}$ differential: particle level top

Use well-defined top definition at particle level\(^1\)

- fully fiducial, differential measurement
- top-quark proxy constructed from stable particles/detector-level observables

Cut based analysis in $\ell+\text{jets}$ channel

- data generally well described by models
- discrepancy at low $m_{t\bar{t}}$ observed
- main uncertainties: $b$-tagging, JES and JER

\(^1\)TOPLHCWG recommendations at https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ParticleLevelTopDefinitions
**tt differential: boosted**

For $p_T(t) > 300$ GeV enter boosted regime
- merging of jets, dedicated reconstruction, single large-R jet

Fiducial, particle and parton level differential measurements
- main uncertainty: large-R jet energy scale (signal modeling)

Measured $\sigma$ lower than predictions
- discrepancy increases with $p_T(t)$
- compared with several generators
**tt differential: boosted**

**Measure inclusive \( \sigma_{tt} \) for \( p_T(t) > 400 \) GeV**
- \( \sigma_{tt} \) (particle-level) = \( 1.28 \pm 0.09^{\text{stat+syst}} \pm 0.10^{\text{PDF}} \pm 0.09^{Q^2} \pm 0.03^{\text{lumi}} \) pb
- \( \sigma_{tt} \) (parton-level) = \( 1.44 \pm 0.10^{\text{stat+syst}} \pm 0.13^{\text{PDF}} \pm 0.15^{Q^2} \pm 0.04^{\text{lumi}} \) pb

Powheg MC predicts 1.49 pb (particle), 1.67 pb (parton level)

**Differential measurements in \( p_T(t) \)**
- normalised, shape comparison only

Generators predict harder distribution than measured
Single top at Tevatron

CDF and D0 combination of $\sigma_{t+s}$ vs $\sigma_t$

- following previous combinations, s-channel (observed at 6.3 $\sigma$)

- adding s- and t-channel discriminants

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• following previous combinations, s-channel (observed at 6.3 $\sigma$)

- adding s- and t-channel discriminants
Single top at LHC

\[ |V_{tb}|_{\text{CMS 7+8 TeV}} = 1.00 \pm 0.04 \]
\[ |V_{tb}|_{\text{LHC 8 TeV}} = 1.06 \pm 0.11 \]

in good agreement with \[ |V_{tb}|_{\text{global SM fit}} = 0.99914 \pm 0.00005 \] (Chin. Phys. C38 (2014))
**t-channel differential at 8 TeV**

**Measurement of single top t-channel firmly established**
- inclusive and fiducial cross-section at 7 and 8 TeV
- large dataset allows for differential measurements (7 TeV)
- helps validate theory predictions and MC generators at NLO

**Differential cross-section vs $p_T$ and $|y|$ of top quark at 8 TeV**
- employ NN discriminator with variables like $\eta$(jet) or $m_{\ell vb}$
- cut on NN to enhance signal
- unfolded distributions show good agreement with generators
s-channel search

Very low rate in pp collisions
- expect $\sigma(s\text{-channel}) = 5.61 \pm 0.22$ pb

Analysis
- $|\Delta\phi(t,b)|$ is the most discriminating variable
- use BDT to increase sensitivity
- ML fit to extract signal cross-section

Result
- $\sigma(s\text{-channel}) = 5.0 \pm 4.3$ pb
- $< 14.6$ pb @ 95% C.L.
- significance 1.3 $\sigma$ (1.4 $\sigma$ expect.)

Uncertainties
- $E_{T}^{\text{miss}}$, JES, statistical
Wt channel

LHC measurements

- exploit dilepton signature + 1 or 2 jets
- use BDT for S/B separation
- Powheg+Pythia generator with DR scheme

All dilepton channels
- partial dataset: 22% uncertainty
- full dataset: 23% uncertainty

Combination: 19% uncertainty dominated by ME/PS matching and scales
Observation in 7 TeV data

- sensitive to $t\gamma$ coupling and to anomalous $t^* \rightarrow t\gamma$

**Fiducial cross section measurement at particle level**

- with generator cuts $p_T(\gamma) > 20$ GeV and $\Delta R(\gamma, \ell) > 0.7$
- template fit to photon isolation variable in $\ell$+jets+$\gamma$ channel
- suppress misidentified $\gamma$ from $Z \rightarrow ee$: $|m_{e\gamma} - m_Z| > 5$ GeV

- jet energy scale and $b$-tagging efficiency are main systematics

**Null hypothesis excluded at 5.3 $\sigma$**
**Couplings of top quark to Z are largely unexplored**

- can probe EWSB
- $t\bar{t}W$ and $t\bar{t}Z$ backgrounds to new physics searches and $t\bar{t}H$

**Four signal regions: $2\ell$ OS, $2\ell$ SS, $3\ell$, $4\ell$**

- extract $t\bar{t}W$ and $t\bar{t}Z$ simultaneously in a binned profile likelihood fit
- increase sensitivity by splitting channels according to
  - number of jets and $b$-jets
  - relative lepton flavour ($Z$ or not-$Z$ like), $m_{\ell\ell}$
  - $E_T^{miss}$ or $H_T$

- profile likelihood technique, statistical uncertainty dominates
\( t\bar{t}+Z \) and \( t\bar{t}+W \) fit to data

- additionally attempt full (partial) \( t\bar{t}W/Z \) reconstruction
  - match reconstructed objects to \( W, Z, t\bar{t} \)
  - combine into linear discriminant
  - choose best permutation

- combine information into BDT → using kinematic quantities
$t\bar{t}+Z$ and $t\bar{t}+W$ results

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

**ATLAS Preliminary**
- ATLAS Best Fit
- ATLAS 68% CL
- ATLAS 95% CL
- NLO calculation

**CMS Preliminary**
- SM
- best fit

$2\ell$OS
- Expected: 0.4
- Observed: 0.1

$2\ell$SS
- Expected: 2.8
- Observed: 5.0

$3\ell$
- Expected: 1.4
- Observed: 1.0

$4\ell$
- Expected: -
- Observed: -

Combined
- Expected: 3.2
- Observed: 5.0

$\rightarrow$ associated $t\bar{t}+W$ and $t\bar{t}+Z$ production established
\(t\bar{t}+Z\) event display

**\(t\bar{t}Z\) candidate**

- 4 leptons: \(\mu^− e^+ e^− e^±\)
- \(m(e_2e_3) = 94\) GeV
- 2 jets \(p_T > 50\) GeV
- both \(b\)-tagged
- \(E_T^{\text{miss}} = 57\) GeV
**Interest**

- irreducible background to $t\bar{t}H(\rightarrow b\bar{b})$
- test of NLO QCD calculation

**Measurements in dilepton and $\ell$+jets channels**

- fit to combined information of $b$-jet discriminator of jets beyond 2 $b$-tags
- several categories in $\ell$+jets
- jet flavour at gen. level defined by
  - leading quark flavour (parton) or presence of B hadron (particle)

---

Footnotes:

$\sigma_{t\bar{t}b\bar{b}}(\text{NLO}) = (1.09^{+0.43}_{-0.14})\%$

$\sigma_{t\bar{t}b\bar{b}}(\text{dil.}) = (2.2 \pm 0.3_{\text{stat.}} \pm 0.5_{\text{syst.}})\%$

$\sigma_{t\bar{t}b\bar{b}}(\ell + \text{jets, parton}) = (1.17 \pm 0.40)\%$

$\sigma_{t\bar{t}b\bar{b}}(\ell + \text{jets, particle}) = (1.51 \pm 0.49)\%$
**Detailed $t\bar{t}b(b)$ study**
- cut-based and fit-based analyses for $t\bar{t}+bb$ in dil. channel
- fiducial measurements of $t\bar{t}+b$ in $\ell+jets$ and dil. channels
- ratio $t\bar{t}bb/t\bar{t}jj$ determined to be $R = (1.30 \pm 0.33_{\text{stat}} \pm 0.28_{\text{syst}})\%$

**Additionally checked**
- subtract $t\bar{t}V/H$ and compare to QCD-only predictions
- compare with different $g \to b\bar{b}$ splitting models

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**Measurement results**

$\frac{\sigma_{t\bar{t}bb}}{\sigma_{t\bar{t}jj}}_{\text{(NLO)}} = (1.09^{+0.43}_{-0.14})\%$

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$t\bar{t}+t\bar{t}$

**At 8 TeV** $\sigma_{t\bar{t}t\bar{t}} \sim 1$ fb

- main background is $t\bar{t}$+jets

**Searches**

- Dedicated CMS $\ell + \geq 6$ jets, $\geq 2$ $b$-tags, large $H_T$
- Two ATLAS searches targeting several exotic final states
  - $\ell$+jets and same-sign 2$\ell$

**Strategies**

- use BDT classifier with top content, event activity and $b$-jet content

**Limits at 95% C.L. in fb**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Channel</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS</td>
<td>$\ell$+jets</td>
<td>32 ± 17</td>
<td>32</td>
</tr>
<tr>
<td>ATLAS</td>
<td>same sign 2$\ell$</td>
<td>27</td>
<td>70</td>
</tr>
<tr>
<td>ATLAS</td>
<td>$\ell$+jets</td>
<td>32</td>
<td>23</td>
</tr>
</tbody>
</table>
Summary

Top quark production studies provide stringent tests of pQCD

$t\bar{t}$ production
- inclusive cross-section measured with 4% accuracy, first 13 TeV analysis
- differential: resolved vs. boosted, parton vs. particle level, central vs. forward
- $t\bar{t}$ modelling important for Higgs and searches
- ✔ SM predictions in general in good agreement with data

Single top production
- $t$-channel large enough to investigate properties
- $Wt$ channel observed (LHC) and $s$-channel observed (Tevatron)
- ✔ again SM holds remarkably well

Associated production
- $t\bar{t}$+heavy flavour important for $tH$ coupling
- first look at $t\gamma$ and $t\Z$ couplings → important for Run-2