Top pair Production Cross section in ATLAS

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On behalf of the ATLAS Collaboration

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The Top Quark

- Top quark is the heaviest known quark in the SM
  - Largest coupling to the Higgs boson
  - Shorter lifetime than hadronization time scale \( \tau < < \Lambda^{-1}_{\text{QCD}} \)

- Why measure the top pair production cross section in the various decay channels:
  - Test of perturbative QCD and of SM description of the top quark decay.
  - Important background in searches for Higgs and BSM physics
  - Might reveal new physics that modifies the production and/or decay of top quarks.
Top quark pair production

Production: \( \sigma_{tt}(\text{LHC}) \sim 160 \text{ pb} \)

cross section LHC = 20 x Tevatron

Total Cross section @ 7TeV

approx. NNLO : 164.6 \( +^{11.4}_{-15.7} \) pb

\((m_t : 172.5 \text{ GeV})\)

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Top decay and event classification

- Top decays even before it can hadronize
  - almost exclusively to $(t \rightarrow bW)$

Event classification follows the W decay channels:

- $\text{Br}(W \rightarrow \text{lepton}) = 1/3$
- $\text{Br}(W \rightarrow \text{quarks}) = 2/3$
Measurement in Atlas with 3pb$^{-1}$

- Measurement of top quark pair production cross section
  - Single lepton and dilepton channel, 3 pb$^{-1}$
  - Observe 46 candidates

\[ \sigma_{t\bar{t}} = 145 \pm 31 \text{(stat.)} +42\text{ (syst.) pb} \]

\[ \frac{\delta \sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} = +36\% -28\% \]

\( \sqrt{s} \) [TeV]

- **ATLAS**: single and dilepton
- **CMS**: dilepton

\[ \sigma_{t\bar{t}} [pb] \]

[Graph showing data points and curves for ATLAS and CMS]
Data samples (Today’s Talk)

- Excellent data taking performance
- Data collected in 2010, 2011 at PP collision @ $\sqrt{s} = 7$ TeV.
- Analyses use 35 pb$^{-1}$ (2010)
  0.5 to 1.08 fb$^{-1}$ (2011)

  - Analyses:
    - Lepton (e, $\mu$) + jets
    - Dilepton (ee, $\mu\mu$, e$\mu$)
  - Combination:
    - Dilepton + Single lepton
  - Dilepton ($\mu+\tau(\rightarrow$ had))
  - All hadronic

ATLAS (2010)
Total Recorded (Delivered) Lumi: 45.0 (48.1) pb$^{-1}$
Lumi uncertainty ~ 3.4%
Cross section Measurements
Object definition and Event Selection

**Electron:**
Isolated EM calo object
Matching to track
\(E_T > 20(25) \text{ GeV}, \ 0 < |\eta| < 2.47\)
Remove: \(1.37 < |\eta| < 1.52\)

**Muon:**
\(P_T > 20 \text{ GeV} \)
\(|\eta| < 2.5\)
Isolated muon track
Tracker & muon spectrometer

**Jet:**
Topological cluster
Anti-K_T (R = 0.4)
\(P_T > 25(20) \text{ GeV} \)
\(|\eta| < 2.5\)

**Trigger:**
Use single lepton (e, \(\mu\)) trigger

**Event cleaning:**
Good Run condition
PV > 4 tracks
Bad jet veto

**B-tagging:**
Based on track distance of closest approach from the collision point (IP) based, and reco. of b-decay Vtx inside jet (SV based)
\(\varepsilon(\text{mis-tag}) = 80\%(10\%) \text{ for IP} \)
\(40\%(0.1\%) \text{ for SV} \)

**Missing \(E_T\):**
Vector Sum of Calo Energy deposits
Corrected for Identified objects
Cross section Measurements

(1 Lepton + jets)
Lepton + Jets: Analysis Strategy

- Measurement strategy (multivariate):
  - exploits the difference in kinematic distributions of signal and background events.
- Projective Likelihood (LH) is used:
  - to separate signal from bkg (both analysis with and without b-tag)
- Discriminant constructed from multiple variables
- MC signal and background models these variables for building LH discriminant
- Fit the likelihood discriminant distribution in data by sum of two “templates”, signal and bkg, and get the $\mathcal{N}_{\text{sig}}$

$$D_i = \frac{L^i_s}{L^i_s + L^i_b}$$

$$L^i_{s(b)} = \prod_{k=1}^{N_{\text{var}}} \mathbf{p}_{s(b)}(X^i_k)$$

For each event $\textbf{i}$ we calculate the $D_i$

Assume that the variable $(X^i_k)$ are uncorrelated

$$\sigma_{t\bar{t}} = \frac{\mathcal{N}_{\text{sig}}}{\int L \mathbf{d}t \times \epsilon_{\text{sig}}}$$
Lepton + Jets: Background Estimate

**Backgrounds:**

- **W+jets backgrounds**
  - Shape is determined by MC
  - Normalization from fit
- **Small Bkgd (Z+jets, diboson, single top)**
  - Shape from MC
  - Normalization from NLO calculation
- **QCD multijet (Fake lepton)**
  - Due to mis-ID of lepton, not well modeled in simulation
  - Used (for example) matrix method for μ channel

\[
N_{\text{loose}} = N_{\text{fake, } \mu} + N_{\text{real, } \mu} \\
N_{\text{tight}} = \varepsilon_{\text{tight}} N_{\text{fake, } \mu} + \varepsilon_{\text{tight}} N_{\text{real, } \mu}
\]
Lepton + Jets: Analysis (No Btag)

- **Variables chosen:**
  - Lepton $\eta$: ttbar more central
  - Aplanarity: ttbar more isotropic
  - Transformed to $e^{-8xA}$ for uniformity

- **Lepton $P_T$:** Leading jet

- **$H_{T,3p}$:** Ratio of transverse to longitudinal activity. ttbar is more transverse
Fit To The Data (No BTag)

- Cross-section is extracted from a fit of projective likelihood discriminant reconstructed with the chosen set variables:
  - Combined cross-section: 3-jet, 4-jet(exclusive), 5-jet(inclusive):
    \[ \sigma_{t\bar{t}} = 179 \pm 3.9\text{(stat.)} \pm 9.0\text{(syst.)} \pm 6.6\text{(lumi.) pb} \]
    \[ \frac{\delta \sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} = 6.6\% \]

Independent of b-tagging, avoids the related systematics uncertainty at price of higher s/b

- Most syst. are part of the LH fit as Gaussian nuisance par
  - reduction in JES/I-FSR (20-70% of initial value)
- Stat. uncertainty (0.5 %)
- Syst uncertainty (5.0 %)
- gen (3.0%), Lep.SF(2.0%)
- Lumi uncertainty (3.7%)
Lepton + Jets: Analysis (With Btag)

- Cross section is extracted from a fit of projective likelihood (split in 6 channels: 3, 4, ≥ 5 jet e, µ)
- Lepton η, exp(-8xA), exp(-4xHT,3p); mean of b-tag weight of 2 jets with highest b-tag weight.
- Profile LH fit extracts:
  - 16 normalization parameters including \( \sigma_{\text{tt}} \)
  - Systematic uncertainties: 11%
    - HF fraction in W+jets (7%)
    - B-tagging Calibration (7%)

\[ \sigma_{\text{tt}} = 186 \pm 10(\text{stat.})^{+21}_{-20}(\text{syst.}) \pm 6(\text{lumi.}) \text{ pb} \]

\[ \frac{\delta \sigma_{\text{tt}}}{\sigma_{\text{tt}}} = 13\% \]
Cross section Measurements
(2 Leptons)
Using 0.70 fb$^{-1}$
2 lepton Analysis Strategy

- Cross section estimated by counting No. of signal events
  - Exactly two opposite sign high $p_T$ central leptons ($ee$, $e\mu$, $\mu\mu$)
  - $\geq 2$ central high $p_T$ jets ; High $E_T^{miss} > 30$ GeV ($ee$, $\mu\mu$) or Transverse activity ($H_T = \Sigma |p_T|$) ; Veto on Z-like mass events ($ee$, $\mu\mu$)
  - If $\geq 1$ b-tag, relax $E_T^{miss}$

- Backgrounds:
  1. $Z^*/\gamma (\rightarrow ee/\mu\mu)$ + jets backgrounds
     - Estimated w/data & assisted with MC
  2. Fake from QCD, $W$+jets (using Data driven methods)
     - For QCD: Matrix method – same as in case of 1-lepton analysis.
  3. Other SM backgrounds
     - Single top, 2-boson, $Z^*/\gamma (\rightarrow \tau \tau)$ + jets backgrounds
       (normalized using the theoretical cross section)
\( \sigma_{tt} \) Measurement in 2-Lepton

- Cross section is extracted simply by counting experiment
  - Data well modeled by MC
  - Profile LH method to combine channels.

\[ \int L \, dt = 0.70 \, \text{fb}^{-1} \]

\[ \sigma_{tt} = 171 \pm 6 \text{(stat.)} +16^{+14}_{-14} \text{(syst.)} \pm 8 \text{(lumi.) pb} \]

\[ \frac{\delta \sigma_{tt}}{\sigma_{tt}} = 10\% \]
Cross section is extracted simply by counting experiment.

**Additional b-tagging**: improves S/B but systematics is large.

**Measurement in 2-Lepton**

Systematic Uncertainty: 10%
- b-tag Calibration: 5%

\[ \sigma_{t\bar{t}} = 177 \pm 6 \text{(stat.)} +_{17}^{-14} \text{(syst.)} +_{8}^{-7} \text{(lumi.) pb} \]

\[ \frac{\delta \sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} = 10.1\% \]
Complementary and consistent results are obtained from similar analysis with and w/o b-tag information

✓ Also consistent with theoretical prediction (164.6^{+11.4}_{-15.7} \text{ pb})

\[
\int L dt = 35 \text{ pb}^{-1} \text{ (L+jets, 2010)}
\]
\[
\int L dt = 0.70 \text{ fb}^{-1} \text{ (dilepton, 2011)}
\]

- L+jets w/ b-tagging: $186 \pm 10^{+21}_{-20} \pm 6$
- Dilepton w/o b-tagging: $171 \pm 6^{+16}_{-14} \pm 8$
- Combination: $176 \pm 5^{+13}_{-10} \pm 7$

\[
\sigma_{\text{tt}} = 176 \pm 5(\text{stat.})^{+13}_{-10}(\text{syst.}) \pm 7(\text{lumi.}) \text{ pb}
\]
\[ \sigma_{\bar{t}t} \text{ Combination (l+jets + dilepton)} \]

- Combine single lepton and di-lepton channels

\[ \sigma_{\bar{t}t} = 176\pm5\text{(stat.)}^{+13}_{-10}\text{(syst.)}\pm7\text{(lumi.) pb} \]

- $\delta\sigma_{\bar{t}t}/\sigma_{\bar{t}t} = 8.3\%$

- Stat. uncertainty (3 %)
- Systematic uncertainty (7.4 %)
- Luminosity uncertainty (4 %)

Good agreement with SM prediction

$164.6^{+11.4}_{-15.7}$ pb

\[ \delta\sigma_{\bar{t}t}/\sigma_{\bar{t}t} = 9.6\% \]
Cross section Measurements

(2 Leptons - $\mu^+ \tau$)

All Hadronic
Measurement in 2-Lepton ($\mu^+ \tau$)

- Important to check universality + sensitivity to $t \rightarrow H^\pm b \rightarrow \tau \nu b$
  - One high $p_T \mu$ and no identified $e$,
  - $\geq 2$ jet ($\geq 1$ b-jets) no overlap with $\tau$
  - $E_T^{\text{miss}} > 30$ GeV & $H_T > 200$ GeV

- Background
  - Data-driven dominant $tt$ & $W$+jets (enriched low $N_{\text{jet}}$),
  - QCD (non-iso mu sample normalized to low $E_T^{\text{miss}}$)
  - $\sigma_{tt} = N_{\mu^+\tau}/A^* x Lumi$ , $N_{\mu^+\tau}$ from LH fit of difference of BDT in OS & SS samples

- $\sigma_{tt} = 142 \pm 21\text{(stat.)} +^{20}_{-16}\text{(syst.)} \pm 5\text{(lumi.)} \text{pb}$

BDT $\tau_h$ identification:
- Narrow jet cone,
- $N_{\text{trk}}: \text{BDT}_j$ score
- $N_{\text{trk}} = 1(\tau_1)$, $N_{\text{trk}} > 1(\tau_3)$, charge $\neq 0$
- Sample split in OS and SS

$\delta \sigma_{tt}/\sigma_{tt} = 21\%$

1.08 fb$^{-1}$ ATLAS Preliminary

Fit for $\tau_1$
Selection

- ≥ 4 jet trigger, good jets
- ≥ 6 high $p_T$ jets, ≥ 2 b-tag jets
- 4 jets with $p_T > 60$ GeV, rest > 50 GeV
- No e/μ, $H_T > 300$ GeV

Reconstruct with Kin. $\chi^2$ fit

Background

- Data-driven QCD background:
  - control samples >=6 jets with data driven b-tag prob.
- $\sigma_{tt} = \frac{N_{tt}}{A} * \text{Lumi}$,
  - $N_{tt}$ from $\chi^2$ fit to Top mass

95% CL upper limit $\sigma_{tt} < 100$ pb
Summary and Outlook

- The era of top physics at the LHC:
  - Cross section measured in ATLAS within 8.2% uncertainty with LHC pp collisions at $\sqrt{s} = 7$ TeV by combining results.
  - Competitive measurements are emerging (176 pb with 8.2% precision)
    - Compatible with theory error: $164.6 \pm 11.4/\pm 15.7$ pb
- Top pair production differential cross section and $\text{ttbar} + \text{jets}$: important background for processes BSM is in progress.
- Anticipate $\sim 5$ fb$^{-1}$ by the end of year ($>3.0$ fb$^{-1}$ already on tape)
  - 2011: the year of top measurements at LHC and may be discoveries!!

More Results are available at the top public result page.
Thank You
\( Z^*/\gamma(\rightarrow ee/\mu\mu) + \text{jet background} \)

- Count the \( Z^*/\gamma \) contribution in sideband region
  Where fraction of \( Z^*/\gamma \) is about 90%
- Extrapolate it to signal region

\[
N_{Z^*/\gamma + \text{jets}} = \frac{\text{MC}_{Z^*/\gamma + \text{jets}}(\text{SR})}{\text{MC}_{Z^*/\gamma + \text{jets}}(\text{CR})} \times (\text{Data(\text{CR})} - \text{MC}_{\text{other}}(\text{CR}))
\]

**Definition of control region (CR):**
- Inside Z mass window \( 81 \text{ GeV} < |M_{ll}| < 101 \text{ GeV} \)
- High MET region; MET > 30 GeV
- High jet multiplicity events \( \geq 2 \text{jets} \)
## SYETEMATICS (dilepton NO BTAG)

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<th>Uncertainty Source</th>
<th>$ee$</th>
<th>$\mu\mu$</th>
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<td>$\Delta \sigma/\sigma [%]$</td>
<td>$\Delta \sigma/\sigma [%]$</td>
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\[
\sigma_{tt} = 171 \pm 6 \text{(stat.)}^{+16}_{-14} \text{(syst.)}^{\pm 8 \text{(lumi.)}} \text{ pb}
\]

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\frac{\delta \sigma_{tt}}{\sigma_{tt}} = 10\%
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