Top Quark Physics Results from the LHC

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On Behalf of the ATLAS and CMS Collaborations

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LHC as a Top Factory

In Run 2 of the LHC, ~120M $t\bar{t}$ and ~40M single $t$ events were produced.

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots
Top Production and Decay

`t\bar{t}` Production

- ~90% from gluon fusion at $\sqrt{s} = 13$ TeV

`t\bar{t}` Decay

$V_{tb} \sim 1$

ATLAS/CMS comb. JHEP 05 (2019) 088
Differential \( t \bar{t} \) Cross Sections

- Differential \( t \bar{t} \) cross section measurements
  - Provide a good test of perturbative QCD
  - Improve top quark MC modelling
  - Allow extraction of SM parameters (\( m_t \) and \( \alpha_s \))
  - Contribute to gluon PDF constraints

- Single, double, and triple differential cross section measurements have been carried out in dilepton, lepton + jets, and all-hadronic channels
  - [https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults](https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults)
High $p_T$ top production

- Two large-$R$ jets with $p_T > 400$ GeV
- One large-$R$ jet and one small-$R$ jet with a high $p_T$ lepton and $p_T^{\text{miss}} > 50 \ (30) \text{ GeV}$

QCD multi-jets are suppressed using the number of b-tagged subjets, a NN discriminant with jet substructure variables ($\tau_{1,2,3}$) as inputs, and soft-drop mass selection
Cross sections of kinematic variables for both channels are unfolded to the particle and parton level.

- A significant 35% (25%) overestimate of the cross section is observed in the hadronic (lepton+jets) channel.
- Generally good agreement with theory in the normalized distributions.

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CMS-PAS-TOP-18-013
Differential $t\bar{t}$ Cross Sections (ATLAS)

- All-hadronic resolved decay channel
  - At least 6 jets $p_T > 55$ GeV, exactly 2 b-tagged jets, and no leptons
  - A $\chi^2$ discriminant with W-boson mass constraints is used to reconstruct the $t\bar{t}$ system and reject QCD multi-jet background

- The number of b-tagged jets and reconstructed top masses are used in the ABCD method to estimate the multi-jet background

<table>
<thead>
<tr>
<th>Process</th>
<th>Event yield</th>
<th>Fraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ (all-hadronic)</td>
<td>$29,500^{+2,000}_{-2,500}$</td>
<td>68%</td>
</tr>
<tr>
<td>$t\bar{t}$ (non all-hadronic)</td>
<td>$1,490^{+120}_{-120}$</td>
<td>3%</td>
</tr>
<tr>
<td>Multijet background</td>
<td>$1,2600^{+1,900}_{-1,900}$</td>
<td>29%</td>
</tr>
<tr>
<td>Total prediction</td>
<td>$43,500^{+2,800}_{-3,000}$</td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>$44,573$</td>
<td></td>
</tr>
</tbody>
</table>
Differential $t\bar{t}$ Cross Sections (ATLAS)

- Cross sections using kinematic observables not accessible to lepton+jets including those emphasizing additional radiation are unfolded to the particle and parton level.

- MC mismodelling in this and other variables at high jet multiplicities is observed.

- MC describe angular properties more consistently than energy sharing.

- Double differential cross sections highlight differences more than single.

ATLAS-CONF-2020-001
Top Quark Yukawa Coupling (CMS)

- Top quark Yukawa coupling is of interest because it is the largest and also close to 1.
- Higgs boson contributes to the $t\bar{t}$ cross section at order $\alpha_s^2 \alpha_W$ but can produce measurable effects in the shape of kinematic distribution.

\[
Y_t = \frac{g_t}{g_t^{SM}}
\]

- The top quark Yukawa coupling ($Y_t = \frac{g_t}{g_t^{SM}}$) can be indirectly constrained using kinematic distributions of the $t\bar{t}$ system.
Dilepton decay channel
- Exactly two leptons, $\geq 2$ jets, $\geq 2$ b-tagged jets, and selection on $m_{ll}$ and $p_T^{miss}$ in same flavor events to remove DY events
- Two variables are used
  - $M_{b\bar{b}l\bar{l}}$
  - $|y(bl) - y(\bar{b}l)|$
- ML fit is applied to the binned data in the two variables to extract $Y_t$
- Best fit value is $Y_t = 1.16^{+0.24}_{-0.35}$
- Higgs production and decay measurements give $Y_t = 0.98 \pm 0.14$
**t\bar{t}t\bar{t} Production**

- SM prediction for four-top production is $12 \text{ fb} \pm 20\%$ at NLO + EW corrections.

  ![Diagram of t\bar{t}t\bar{t} production](image)

- Enhancements to this cross section are predicted in several BSM models including SUSY and 2HDM.

<table>
<thead>
<tr>
<th>CMS 2LSS/3L</th>
<th>CMS 2LSS/3L, 1L/2LOS</th>
<th>ATLAS 2LSS/3L, 1L/2LOS</th>
</tr>
</thead>
<tbody>
<tr>
<td>137 fb$^{-1}$</td>
<td>36 fb$^{-1}$</td>
<td>36 fb$^{-1}$</td>
</tr>
<tr>
<td>2.6$\sigma$</td>
<td>1.4$\sigma$</td>
<td>2.1$\sigma$</td>
</tr>
</tbody>
</table>
**t̅tt̅̅ött̅ atoproduction in 2LSS/3L (CMS)**

- **2LSS/3L channel baseline selection**
  - 2 same sign or at least 3 leptons
  - $\geq 2$ jets, $\geq 2$ b-jets, $H_T \geq 300$ GeV, $p_T^{miss} > 50$ GeV

- **Two analyses – cut based and BDT classifier based**
  - 19 variables including $n_j, n_b, n_l, H_T, p_T^{miss}$
  - 17 SR and 1 CR for $t\bar{t}Z$

- **Profile likelihood fit gives**
  - $\sigma(t\bar{t}t\bar{t}) = 12.6^{+5.8}_{-5.2}$ fb
  - Also used to constrain the Yukawa coupling of the top to Higgs
  
  $Y_t = \left| \frac{g_t}{g_t^{SM}} \right| < 1.7$ @ 95%CL
$t\bar{t}t\bar{t}$ Production in 2LSS/3L (ATLAS)

- **2LSS/3L channel selects**
  - 2 same sign or at least 3 leptons
  - $\geq 6$ jets, $\geq 2$ b-jets, $H_T(\text{leptons+jets}) \geq 500$ GeV

- Signal is separated from background using a BDT with 12 observables including a continuous b-tagging discriminant

- Subsequent profile likelihood fit to the BDT distribution and variables in 4 CR’s
  - $t\bar{t}Z + jets, t\bar{t}H + jets, t\bar{t}W + jets$ (70%)
  - Charge mis-id, fake/non-prompt leptons (25%)

- Main systematic errors include $t\bar{t}W$ modelling and signal renormalization / factorization scales
\[ \sigma(t\bar{t}t\bar{t}) = 24 \pm 5(\text{stat}) \pm 5(\text{syst}) \text{ fb} \]

- The observed (expected) \(4.3\sigma\ (2.4\sigma)\) significance provides evidence for four-top production.
Single Top Production

- Single top production can be used to test SM predictions at higher orders and constrain BSM models.

\[t - channel\]

\[s - channel\]

\[Wt - channel\]
Single Top Cross Section

- Note the relative contributions of $t$, $tW$, and $s$ channels
- [Link to CERN TWiki page](https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots)
Opposite sign $e^\pm \mu^{\mp}$ dileptons are used with one b-tagged jet and without additional loose jets.

Good agreement with various MC predictions is observed.
tZq Production (ATLAS and CMS)

- Probes tZ and WWZ couplings
- Event selection includes 3 high $p_T$ leptons, 1 b-tagged jet, and one or two additional jets

\[
\sigma(SM) = 102^{+5}_{-2} \text{ fb} \text{ @ NLO}
\]

- NN (ATLAS) or BDT (CMS) for signal/background discrimination

$\sigma = 97 \pm 13 \text{ (stat)} \pm 7 \text{ (syst)} \text{ fb}$

arXiv:2002.07546

$\sigma = 111 \pm 13 \text{ (stat)}^{+11}_{-9} \text{ (syst)} \text{ fb}$

PRL 122 (2019) 132003
CKM Elements $|V_{tb}|$, $|V_{ts}|$, $|V_{td}|$ (CMS)

Focuses on t-channel production and decay

\[
|V_{tb}|^2 \quad |V_{tb}|^2 \\
|V_{tb}|^2 \quad |V_{tb}|^2
\]

\[
|V_{tb}|^2 \quad |V_{tb}|^2 \\
|V_{tb}|^2 \quad |V_{tb}|^2
\]
CKM Elements $|V_{tb}|, |V_{ts}|, |V_{td}|$ (CMS)

- Event selection uses one high $p_T$, isolated lepton, 2 or 3 high $p_T (> 40$ GeV) jets of which 1 or 2 are b-tagged

- CKM elements can be extracted directly from measurement of the single top production cross section and branching ratios

<table>
<thead>
<tr>
<th>Category</th>
<th>Enriched in</th>
<th>Cross section $\times$ branching fraction</th>
<th>Feynman diagram</th>
</tr>
</thead>
<tbody>
<tr>
<td>2j1t</td>
<td>$ST_{b,b}$</td>
<td>$\sigma_{t,ch,b} B(t \rightarrow Wb)$</td>
<td>1a</td>
</tr>
<tr>
<td>3j1t</td>
<td>$ST_{b,q}$, $ST_{q,b}$</td>
<td>$\sigma_{t-ch,b} B(t \rightarrow Wq), \sigma_{t-ch,q} B(t \rightarrow Wb)$</td>
<td>1b, 1c, 1d</td>
</tr>
<tr>
<td>3j2t</td>
<td>$ST_{b,b}$</td>
<td>$\sigma_{t-ch,b} B(t \rightarrow Wb)$</td>
<td>1a</td>
</tr>
</tbody>
</table>

- BDT’s are used as the discriminating variables between single top and background processes
A two step ML fit is employed

- Using the $m_T^W$ distribution for the 2j1t and 3j1t samples to extract the QCD multijet contribution
- Using the BDT discriminators for the 3 samples

Results at 95% CL

$|V_{tb}| > 0.970$
$|V_{td}|^2 + |V_{ts}|^2 < 0.057$

- No theoretical assumptions for $|V_{td}|$ and $|V_{ts}|$
- Improves $|V_{tb}|$ over previous ATLAS/CMS combination
Conclusions

The results presented today clearly show we are in an era of precision top physics at the LHC

Highlights shown

- Wide variety of single and double differential cross section measurements in $t\bar{t}$ and single $t$ production
- New measurement and evidence for the $t\bar{t}t\bar{t}$ production cross section
- Measurement of the CKM matrix elements involving top in a model independent way
Control regions are used to provide normalizations from fits to data for photon conversion, leptons from heavy flavor, and \( t\bar{t}W + jets \)

<table>
<thead>
<tr>
<th>Region</th>
<th>Channel</th>
<th>( N_j )</th>
<th>( N_b )</th>
<th>Other requirements</th>
<th>Fitted variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRttbarCO2l</td>
<td>( e^+e^- | e^\pm\mu^\pm )</td>
<td>4 ( \leq N_j &lt; 6 )</td>
<td>1 ( \geq 1 )</td>
<td>( M_{ee}@CV \in [0, 0.1 \text{ GeV}] ) ( 200 &lt; H_T &lt; 500 \text{ GeV} )</td>
<td>( M_{ee}@PV )</td>
</tr>
<tr>
<td>CR1b3Le</td>
<td>( eee | e\mu )</td>
<td>-</td>
<td>1 ( = 1 )</td>
<td>( 100 &lt; H_T &lt; 250 \text{ GeV} )</td>
<td>counting</td>
</tr>
<tr>
<td>CR1b3Lm</td>
<td>( e\mu | \mu\mu )</td>
<td>-</td>
<td>1 ( = 1 )</td>
<td>( 100 &lt; H_T &lt; 250 \text{ GeV} )</td>
<td>counting</td>
</tr>
<tr>
<td>CRttW2l</td>
<td>( e^\pm\mu^\pm | \mu^\pm\mu^\pm )</td>
<td>( \geq 4 )</td>
<td>2 ( \geq 2 )</td>
<td>( M_{ee}@CV \notin [0, 0.1 \text{ GeV}],</td>
<td>\eta(e)</td>
</tr>
</tbody>
</table>
FCNC are heavily suppressed at higher orders in the SM but BSM models can increase the BR manifold

One relatively recent search is \( t \rightarrow \gamma u \) and \( t \rightarrow \gamma c \)
FCNC $t \rightarrow \gamma u/c$ (ATLAS)

- Selected events require exactly one electron or muon, exactly one b-tagged jet, and $E_T^{miss} > 30$ GeV
- Signal and background are distinguished using a NN for both $tuy\gamma$ and $tc\gamma\gamma$ and both LH and RH couplings
- Primary background are mis-identified photons (fakes) in $t\bar{t}$ production and $W/Z + \gamma$ events
- No significant FCNC contribution is observed
FCNC Results (ATLAS and CMS)

In some channels, beginning to challenge BSM predictions

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCTopWGSummaryPlots
V-A structure and masses predict the polarization fractions of the W

- At NNLO, $F_0 = 0.687, F_L = 0.311, F_R = 0.0017$

Experimentally, the polarization fractions can be measured using

$$\frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{3}{4} (1 - \cos^2 \theta^*) F_0 + \frac{3}{8} (1 - \cos \theta^*)^2 F_L + \frac{3}{8} (1 + \cos \theta^*)^2 F_R.$$
W Boson Polarization (ATLAS and CMS)

The four measurements and the combination of measurements using BLUE

\[ F_0 = 0.693 \pm 0.009 \text{ (stat+bkg)} \pm 0.011 \text{ (syst)} \]
\[ F_L = 0.315 \pm 0.006 \text{ (stat+bkg)} \pm 0.009 \text{ (syst)} \]

The results can be used to set limits on BSM contributions to the $tWb$ vertex

- Limits on possible L- and R-handed tensor couplings
- Limits on Wilson coefficients giving the strength of operators in top quark EFT

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS+CMS combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{\phi\phi}$</td>
<td>$[-5.64, 7.68]$</td>
<td>$[-3.84, 4.92]$</td>
<td>$[-3.48, 5.16]$</td>
</tr>
<tr>
<td>$C_{tW}$</td>
<td>$[-1.30, 0.96]$</td>
<td>$[-1.06, 0.72]$</td>
<td>$[-0.96, 0.67]$</td>
</tr>
<tr>
<td>$C_{tW}$</td>
<td>$[-0.34, 0.67]$</td>
<td>$[-0.62, 0.19]$</td>
<td>$[-0.48, 0.29]$</td>
</tr>
</tbody>
</table>

ML fit is applied to the binned data (shown on left) to extract $Y_t$

- Best fit value is $Y_t = 1.16^{+0.24}_{-0.35}$
  - Higgs global fit gives $Y_t = 0.98 \pm 0.14$
  - $t\bar{t}t\bar{t}t\bar{t}$: $Y_t < 1.7$ (95% CL)

Dashed lines indicate $|\Delta y|_{bl}$ bins

CMS-PAS-TOP-19-008
Differential cross sections in the Wt-channel have also been measured

- Opposite sign $e^\pm \mu^\mp$ dileptons are used with 1 b-tagged jet and without additional loose jets
- Several different kinematic variables are compared against predictions including leading lepton $p_T$, jet $p_T$, $\Delta\phi(e^\pm, \mu^\mp)$, $p_Z(e^\pm, \mu^\mp, j)$, $m(e^\pm, \mu^\mp, j)$ and $m_T(e^\pm, \mu^\mp, j, p_T^{miss})$
- Backgrounds are subtracted bin by bin and unfolded using a response matrix parameterizing bin migration to produce the differential cross sections
Good agreement with POWHEG DR, POWHEG DS, and MadGraph5_aMC@NLO is observed.
Differential cross sections in the Wt channel were previously measured by ATLAS also

- Signal selection uses two opposite sign dileptons and exactly one jet that is b-tagged along with $m_{ll}$, $E_T^{miss}$ selections

- A BDT technique was used to separate Wt signal from the dominant $t\bar{t}$ background
  - Input variables are derived from the two lepton and b-tagged jet four momenta and $E_T^{miss}$
An iterative Bayesian technique is used for unfolding.

The dominant uncertainties are limited data statistics and $Wt$ and $t\bar{t}$ modelling.

Good agreement with various MC models is observed.
tZq Production (ATLAS)

- Probes tZ and WWZ couplings
- Event selection includes 3 high $p_T$ leptons, 1 b-tagged jet, and one or two additional jets
- Signal and background discrimination is achieved using a NN
  - Kinematic variables of leptons, jets, and b-jet
  - Top quark mass ($l, E_T^{miss}, b$)
  - Z boson kinematics

arXiv:2002.07546

2j1b signal region
tZq Production (ATLAS)

- Cross section is extracted from a binned ML fit performed on the NN output in 2 SRs and variables in the 6 CRs

- Largest uncertainties are
  - Statistics (12%)
  - Prompt lepton modelling and norm. (3%)
  - Lepton reconstruction and calibration (2%)
  - Jet and $E_T^{miss}$ calibration (2%)

$$\sigma = 97 \pm 13 \text{ (stat)} \pm 7 \text{ (syst)} \text{ fb}$$

$$\sigma(SM) = 102^{+5}_{-2} \text{ fb @ NLO}$$

arXiv:2002.07546
tZq Production (CMS)

- CMS previously observed this cross section with a significance > 5\(\sigma\)
- Event selection was 3 high \(p_T\) leptons, 1 b-tagged jet and at least one additional jet
- BDT’s were used to discriminate between prompt and non-prompt leptons
Cross section results from a ML fit performed on the BDT output in 3 SRs and normalizations from 2 CRs enriched with WZ and ZZ background.

Largest uncertainties are:
- Statistics (12%)
- Non-prompt lepton normalization (4%)
- Lepton selection (3%)
- Jet energy scale (3%)

\[ \sigma = 111 \pm 13^{+11}_{-9} \ (stat) \ (syst) \ fb \]
Opposite sign $e^\pm \mu^\mp$ dileptons are used with one b-tagged jet and without additional loose jets.

Good agreement with various MC predictions is observed.