Top quark physics in the LHC era

F. Fabbri on behalf of the ATLAS, CMS and LHCb collaborations
Why top-quark physics?

The top has several features that make it a very interesting particle:

- Heaviest particle discovered till now
  \[ m_t \approx 173 \text{ GeV} \]
- Decays before hadronization
  - Give access to the physics of a “free” quark
- Intensively couples to the Higgs boson

The LHC is a top factory and allows:

- Precise measurements of top pairs and single top production
- Observation of rare processes involving top
- Use of the top quark as a “tool” to study the SM
Cross section measurements
Why tt cross-section measurements?

Precise measurements of $t\bar{t}$ production:

- Provide a stringent test of our level of understanding of QCD
- Allow to extract several SM parameters: $\alpha_S$, $m_{\text{top}}$
- Allow to improve the description of parton distribution functions
Inclusive $\sigma(t\bar{t})$ in $l$+jets in ATLAS

- Select events in the l+jets channel:
  - Single e/\(\mu\), $E_T^{\text{miss}}$ and $m_T^W$, at least 4 jets
  - Split in 3 regions based on the number of jets and b-jets
  - Main bkg: W+jets and single top (MC based)
- Profile likelihood fit of three data distributions in three regions
- Extraction of fiducial and inclusive $\sigma$

$$\sigma_{\text{fid}} = 110.7 \pm 0.05 \text{ (stat.)} ^{+4.5}_{-4.3} \text{ (syst.)} \pm 1.9 \text{ (lumi.)} \text{ pb} = 110.7 \pm 4.8 \text{ pb} \ (4.3\%)$$

$$\sigma_{\text{inc}} = 830 \pm 0.4 \text{ (stat.)} \pm 36 \text{ (syst.)} \pm 14 \text{ (lumi.)} \text{ pb} = 830 \pm 38 \text{ pb} (4.6\%)$$

<table>
<thead>
<tr>
<th>Category</th>
<th>$\Delta \sigma_{\text{fid}}$ [%]</th>
<th>$\Delta \sigma_{\text{inc}}$ [%]</th>
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<tbody>
<tr>
<td>Signal modelling</td>
<td></td>
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<tr>
<td>$t\bar{t}$ shower/hadronisation</td>
<td>$\pm 2.8$</td>
<td>$\pm 2.9$</td>
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<td>$t\bar{t}$ scale variations</td>
<td>$\pm 2.2$</td>
<td>$\pm 2.7$</td>
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<td>$h_{\text{damp}}$</td>
<td>$\pm 1.5$</td>
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<td>Background modelling</td>
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<tr>
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<td>Multijet background</td>
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<td>Detector modelling</td>
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<td>Jet reconstruction</td>
<td>$\pm 2.5$</td>
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<td>Luminosity</td>
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<td>$\pm 1.7$</td>
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<tr>
<td>Flavour tagging</td>
<td>$\pm 1.2$</td>
<td>$\pm 1.3$</td>
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<tr>
<td>$E_T^{\text{miss}}$ + pile-up</td>
<td>$\pm 0.3$</td>
<td>$\pm 0.3$</td>
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<td>Muon reconstruction</td>
<td>$\pm 0.6$</td>
<td>$\pm 0.5$</td>
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<td>Electron reconstruction</td>
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<td>$\pm 4.6$</td>
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<tr>
<td>Total uncertainty</td>
<td>$\pm 4.3$</td>
<td>$\pm 4.6$</td>
</tr>
</tbody>
</table>

SM (NNLO):

$$\sigma_{t\bar{t}} = 832_{-29}^{+20} \text{ (scale)} \pm 35 \text{ (PDF + } \alpha_S) \text{ pb} \ (5.4\%)$$
Inclusive $\sigma_{ttjj}$ and $\sigma_{ttbb}$ in CMS

- Extract the $\sigma_{ttjj}$ and $R=\sigma_{ttbb}/\sigma_{ttjj}$ in 2 different channels:
  - Dilepton 2 e/\mu, >= 4 jets, >=2 bjets
    - Extra jets: 3rd and 4th in b-tagging discriminant
  - L+jets: 1e(\mu), >= 6 jets, >=2 bjets
    - Extra jets: leading in b-tagging discriminant among the ones not used to reconstruct the $t\bar{t}$ system.

- Perform the measurement in the visible phase space (VPS) and extrapolated to the full phase space (FPS)

- $\sigma_{ttjj}$ and $R=\sigma_{ttbb}/\sigma_{ttjj}$ extracted simultaneously from a profile likelihood fit on 2D discriminant

- Main uncertainties: b-tagging, JES and FSR
Inclusive $\sigma_{ttjj}$ and $\sigma_{ttbb}$ in CMS

- Extract the $\sigma_{ttjj}$ and $R = \sigma_{ttbb}/\sigma_{ttjj}$ in 2 different channels:
  - Dilepton 2 e/\mu, >= 4 jets, >=2 bjets
    - Extra jets: 3rd and 4th in b-tagging discriminant
  - L+jets: 1e(\mu), >= 6 jets, >=2 bjets
    - Extra jets: leading in b-tagging discriminant among the ones not used to reconstruct the tt system.

- Perform the measurement in the visible phase space (VPS) and extrapolated to the full phase space (FPS)

- $\sigma_{ttjj}$ and $R = \sigma_{ttbb}/\sigma_{ttjj}$ extracted simultaneously from a profile likelihood fit on 2D discriminant

- Main uncertainties: b-tagging (light), JES and FSR
Top Measurement in LHCb

- Measurement of forward top production using 1.93 fb⁻¹ @ 13 TeV
- Measurement performed in 2 fiducial region, applying the requirements on top or jets/leptons
- Selection:
  - 1 e and 1 μ in the events, with $p_T > 20$ GeV and $2.0 < |\eta| < 4.5$
  - Complementary region wrt ATLAS and CMS
  - $\Delta R (e/\mu) > 0.1$
  - 1 b-jet $p_T > 20$ GeV and $2.2 < |\eta| < 4.2$
- Background obtained with simulation and data-driven techniques

**Very clean region!**

- Similar systematic and statistical uncertainties
- Dominant systematic uncertainty from b-tagging
Differential $\sigma(\ttbar)$ in all-had in ATLAS

- Select events in the all-hadronic channel: $\geq 6$ jets, 2 b-jets, 0 leptons
  - Fully reconstructed final state
- $\ttbar$ system fully reconstructed by minimizing a $\chi^2$:
  - Constraints on $m^W$ and $\Delta(m^{top})$
- Differential $\sigma$ extracted using a regularized unfolding technique
  - Measurement performed at particle and parton level

- MCs describe angular properties more consistently than energy sharing
- NLO+PS generators struggle to describe $p_T^{t,1}$, $p_T^{tt}$ and double differential distributions
Differential $\sigma(t\bar{t})$ for boosted top in CMS

- Select events in the all-hadronic and l+jets channels:
  - Using 1 or 2 large-R jets ($p_T > 400$ GeV), with soft-drop trimming, identified with top and b-tagging

- Dedicated fit in side-band regions:
  - All-had: to extract QCD normalization and shape, after NN to separate $t\bar{t}$ events from QCD
  - L+jets: to extract background normalization, t (mis)tagging efficiencies

- Unregularized unfolding, $\sigma$ extracted at particle and parton level

- Dominant uncertainties:
  - All-had: JES and b-tagging.
  - L+jets: parton shower, driven by FSR

- Overall normalization difference observed: 56% (all-had) and 25% (l+jets)

- Good agreement on normalized spectra
Rare processes and single top
Why measuring rare processes?

Precise measurement of $t(\bar{t})+X$ production:

- Provide a stringent test also of electroweak processes
- Access to several coupling ($t\gamma, tW, tH$) sensitive to new physics effects
Measurement of tW in CMS

- Differential measurement of normalized $\sigma^{tW}$ in dilepton events:
  - $e$ and $\mu$, 1j1b, veto on “loose” jets to enhance the S/B ratio
- Backgrounds MC estimated and subtracted to the signal
- Differential cross-section extracted with unregularized unfolding
  - $\sigma^{tW}$ measured at particle-level
- Dominant uncertainty: JES/JER

With the current uncertainties all the predictions agree with the data
Measurement of ttZ in ATLAS

Sensitive to the tZ coupling
Collect events with 3 or 4 leptons:
- Split in different signal regions depending on the number of jets and b-jets
- Inclusive cross section evaluated with profile likelihood fit on the yields in the regions
- Include CR to regulate the main backgrounds: WZ+jets in 3l, ZZ+jets in 4l

Dominant uncertainty:
- Modelling of tWZ (2.9%)
- ttZ parton shower (3.1%)
Measurement of $ttZ$ in ATLAS

- Differential measurement performed in both channels
  - Combined 3l and 4l for Z observables
- Unregularized unfolding used to measure differential cross-section:
  - At parton and particle level
  - Both Z and $tt$ kinematics
- Dominated by statistical uncertainty
  - Leading detector uncertainties: b-tagging and JES

- Uncertainties on the absolute cross-section range from 20% to 35%
- The difference among predictions are small compared to the data uncertainty
- In most variables measurements generally agree with predictions
Measurement of $tW\gamma$ and $tt\gamma$ in ATLAS

- Dilepton events selected: 1e and 1$\mu$, 1 photon, $\geq 2$jets, $\geq 1$bjets
- All bkg are MC based, main bkg from fake leptons and fake photons
- Measure fiducial (parton level) cross section by profile likelihood fit of scalar sum of transverse momenta “$S_T$”

$$\sigma_{fid} = 39.6^{+2.7}_{-2.3} \text{ fb (syst. dominated) (6.8%)}$$

- Compatible with the theory value: $\sigma_{fid} = 38.5^{+0.56}_{-2.18} \text{ (scale)}^{1.04}_{-1.18} \text{ fb (6.4%)}$
  ○ NLO QCD prediction of $pp \rightarrow WbWb\gamma$ (including not resonant diagrams)
- Dominant uncertainties: signal and bkg modelling, luminosity

- Differential $\sigma$ extracted at parton level
- Measured variables sensitive to $t\gamma$ coupling
  ○ 5 kinematic and event topology variables
- Statistically limited
- NLO theory in good agreement with data
First evidence of $\text{tttt}$ in ATLAS

- Events $2l\text{ SS}/3l$, $\geq 6$ jets and $\geq 2$ b-tag jets, $\text{HT} > 500 \text{ GeV}$
- Dominant bkg is $\text{ttW/Z/H+jets}$, small bkg: non-prompt & mis-identified leptons (fake)
  - Control regions designed to estimate bkg normalizations ($\text{ttW}$ and fake)
  - Bkg shape and $\text{ttZ/(ttH)}$ normalization taken from MC
  - Charge mis-id: data driven rom $Z \rightarrow ee$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$\text{NF}_{\text{ttW}}$</th>
<th>$\text{NF}_{\text{Mat. Conv.}}$</th>
<th>$\text{NF}<em>{\text{Low } m</em>{\gamma^*}}$</th>
<th>$\text{NF}_{\text{HF e}}$</th>
<th>$\text{NF}_{\text{HF } \mu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>$1.6 \pm 0.3$</td>
<td>$1.6 \pm 0.5$</td>
<td>$0.9 \pm 0.4$</td>
<td>$0.8 \pm 0.4$</td>
<td>$1.0 \pm 0.4$</td>
</tr>
</tbody>
</table>

- NF extracted together with the signal in the fit
- All normalization factors compatible with one except $\text{ttW}$
  - Compatible with $\text{ttH}$ multi-lepton result
    - ATLAS-CONF-2019-045
- Uncertainties to cover $\text{ttW}$ mismodelling:
  - Additional jets: 125%(300%) in events with 7(8) jets
  - Additional b-jets: 50% uncertainty on events with $\geq 3$ truth bjets
First evidence of $t\bar{t}t\bar{t}$ in ATLAS

- A BDT discriminant is employed to separate signal from background
  - Includes b-tagging, lepton and jet individual $p_T$ and angular distances
- The $t\bar{t}t\bar{t}$ signal strength is extracted together with the background normalization in a profile likelihood fit
  - BDT score is fitted in the signal region

The observed (expected) significance with respect to a bkg only hypothesis is $\sigma_{t\bar{t}t\bar{t}} = 24 \pm 5 \text{(stat)}^{+5}_{-4} \text{(syst)} \text{ fb} = 24^{+7}_{-6} \text{ fb (29%)}$

SM: $\sigma_{t\bar{t}t\bar{t}} = 12.0 \pm 2.4 \text{ fb (20%)}$

Compatible with the SM at $1.7\sigma$

Dominant uncertainties are:
- statistical uncertainty
- $t\bar{t}W$ modelling

Significance from CMS:
$2.6(2.7)\sigma$ observed (expected)

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Properties & mass
Now at LHC is possible to reach great precisions for the property measurements and observe very subtle phenomena.
Measurement of the $Y^t$ in CMS

- Measure the **Yukawa coupling** ($Y^t$) in $t\bar{t}$ production.
  - Exploit the large effect that the radiation of a virtual H boson has on $t\bar{t}$ differential distributions

- $t\bar{t}$ predictions for different values of $y^t$ obtained as event-based multiplicative corrections using HATHOR:
  - Applied to POWHEG predictions

\[
R_{EW}(M_{t\bar{t}}, \Delta y_{t\bar{t}}) = \frac{d^2\sigma_{\text{HATHOR}}}{dM_{t\bar{t}} \ d\Delta y_{t\bar{t}}} / \frac{d^2\sigma_{\text{LO QCD}}}{dM_{t\bar{t}} \ d\Delta y_{t\bar{t}}}
\]

- The comparison with an additive approach is taken as uncertainty
Measurement of the $Y^t$ in CMS

- Events collected in the dilepton channel, $\geq 2$ bjets
- Considering the 2 b-tag with highest score allows to identify the b-jets from the $t\bar{t}$ system 85% of the times
  - Main bkg MC estimated (~2%): Drell-Yan, Single top
- Variables used based on partial system reconstruction: $M(l^+l^-+2$-jets) and $\Delta y_{bl}$
  - $\Delta y_{bl}$ requires the correct matching of b and l
  - Obtained using top and W mass constraints and $\Delta R(b,l)$ info
- $Y^t$ extracted with a profile likelihood fit to the 2D distribution
- Dominant uncertainty: EW corrections, $\mu_F, \mu_R$ variations

$Y_t = 1.16^{+0.24}_{-0.36}$

Compatible with the result in $l+\text{jets}$

$Y_t = 1.07^{+0.34}_{-0.43}$
Measurement of $BR(W\mu)/BR(W\tau)$ in ATLAS

- The universality of lepton coupling to EW gauge boson is a fundamental axiom of the SM: use the $t\bar{t}$ events as $W$ factory to measure
  - LEP $R(\tau/\mu) = BR(W\rightarrow \tau \nu \tau)/BR(W\rightarrow \mu \nu \mu)$ measurement deviates from the SM by $2.7\sigma$
  
  \[
  BR(W \rightarrow \tau \nu \tau \nu \tau)/BR(W\mu \mu \mu) \sim BR(W\rightarrow \tau \nu \tau)/BR(W\rightarrow \mu \nu \mu)
  \]

- Select dilepton events ($e+\mu$ or $\mu\mu$ and $\geq 2$ b-jets) and define the single trigger matched lepton as tag
  - Define probe muons with $p_T > 5$ GeV and use them in the measurement
  - Exploit the difference on impact parameter $|d_0^\mu|$ and $p_T^\mu$ between prompt $\mu$ and $\mu$ coming from $\tau$ to separate them
    - The $|d_0^\mu|$ prediction is corrected using a data-driven method in $Z\rightarrow \mu\mu$ events

\[BR(\tau \rightarrow \mu \nu_\tau \nu_\tau)\text{ is well known}\]
Measurement of $\text{BR}(W_\mu)/\text{BR}(W_\tau)$ in ATLAS

The $R(\tau/\mu)$ is extracted from a profile likelihood fit on the 2D distribution of $|d_{0}^{\mu}|$ and $p_{T}^{\mu}$

- Extracted together with $t\bar{t}+tW$ normalization

\[ R(\tau/\mu) = 0.992 \pm 0.013 \]

- Very good agreement with the SM
- Most precise measurement of this ratio
  - Nearly twice the precision of LEP

<table>
<thead>
<tr>
<th>Source</th>
<th>Impact on $R(\tau/\mu)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prompt $d_{0}^{\mu}$ templates</td>
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</tr>
<tr>
<td>$\mu(\text{prompt})$ and $\mu(\tau/\text{\mu})$ parton shower variations</td>
<td>0.0036</td>
</tr>
<tr>
<td>Muon isolation efficiency</td>
<td>0.0033</td>
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<tr>
<td>Muon identification and reconstruction</td>
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<tr>
<td>$\mu(\text{had.})$ normalisation</td>
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<td>$t\bar{t}$ scale and matching variations</td>
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<td>Top $p_{T}$ spectrum variation</td>
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<td>$\mu(\text{had.})$ parton shower variations</td>
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<td>Monte Carlo statistics</td>
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<td>Pile-up</td>
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<td>$\mu(\tau/\text{\mu})$ and $\mu(\text{had.})$ $d_{0}^{\mu}$ shape</td>
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<td>Other detector systematic uncertainties</td>
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<tr>
<td>Total</td>
<td><strong>0.013</strong></td>
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</table>
tt forward-backward asymmetry in CMS

- NLO interference terms in \( tt \) production from \( qq \) initial state creates a forward-backward asymmetry.

\[
A_{FB} = \frac{\sigma(c^* > 0) - \sigma(c^* < 0)}{\sigma(c^* > 0) + \sigma(c^* < 0)}
\]

- At NLO this is 6% of \( tt \) production

- Quantity never measured before @LHC, where the charge asymmetry is measured as a proxy

- Use variables sensitive to the difference between \( qq \), \( qg \) and \( gg \) initial state to build templates and separate the \( qq \)

- Extract \( A_{FB} \) and anomalous chromoelectric and chromomagnetic dipole moments
**tt forward-backward asymmetry in CMS**

- Events collected in the l+jets channel in the resolved and boosted topologies.
- Profile likelihood-fit to the 3D template to extract AFB and the anomalous moments separately.

Extracted values consistent with the SM and previous CMS results (from spin correlation).
Search for new physics
Why top-quark physics?

Tool to search for new physics:
- Many BSM models are expected to involve top quarks
  - Possible to perform direct searches for new resonances and FCNC
- Use the precise measurements to set a limit on new operators in an EFT framework
EFT interpretation of $t\bar{t}t\bar{t}$ + leptons in CMS

Considering at the same time the yields from several signals: $t\bar{t}H, t\bar{t}Z(ll), t\bar{t}W(l\nu), tZq, tHq$

- Divide the event collected in regions categorized on jets and b-jets multiplicity and lepton flavour and charge
- Obtained a total of 35 independent regions used to constraint the EFT operators
- Method tested on 2017 dataset only

Investigate 16 EFT operators simultaneously

- Only dimension 6 operators: 4 fermion operators, boson-quark and quark gluon operators included
- Interference among operators and with the SM considered

Signal samples:
- LO simulation ($t\bar{t}l\nu$, $t\bar{t}H$ matched with additional parton)
- EFT included through reweighting in Madgraph
Main uncertainty depends on the Wilson coefficients (WC) extracted:
- Dominant experimental are b-mistag rate and fake-leptons
- Main theoretical:
  - \( \ttbar V \) normalization
  - Matching uncertainty \( \ttbar V/\ttbar H \) and difference with NLO \( \ttbar Zq, \ttbar Hq \)
  - Variation of FSR renormalization and factorization scales

Extraction of the signal obtained with a profile likelihood fit on the regions:
- signal parametrized as a function of the WC
- Fit of individual WC fixing the others at the SM value
- Fit individual WC profiling the others
- The fits can bring to very different constraints, highlighting the relations among EFTs
Conclusions

LHC is a top factory and ATLAS, CMS and LHCb are exploiting the large sample collected maximally:

- Reducing the uncertainties on inclusive measurements
- Performing differential measurements in challenging phase-space and channels and as a function of several variables
  - providing a complete description of the $t\bar{t}$ kinematic and stringent test of QCD and electroweak predictions
- Searching for very rare processes
  - Reaching evidence for $t\bar{t}tt$
  - Measuring with increasing precision $t(\bar{t})+X$ and including differential distributions
- Measuring the top properties and couplings with innovative techniques
  - Use top events to test the fundamental bases of the SM
- Setting constraints to the existence of new physics

Several exciting new measurements have been presented, but stay tuned because more results are coming…

Thanks for your attention!!!!
Backup
Inclusive \( \sigma(t\bar{t}) \) in l+jets in ATLAS

\[
\sigma(3j, \geq 1b) \quad \sigma(4j, \geq 2b) \quad \sigma(5j, \geq 2b)
\]

<table>
<thead>
<tr>
<th>SR1</th>
<th>SR2</th>
<th>SR3</th>
</tr>
</thead>
<tbody>
<tr>
<td>(t\bar{t})</td>
<td>3630000 ± 210000</td>
<td>990000 ± 90000</td>
</tr>
<tr>
<td>W+jets</td>
<td>350000 ± 160000</td>
<td>24000 ± 10000</td>
</tr>
<tr>
<td>Single top</td>
<td>255000 ± 31000</td>
<td>52000 ± 7000</td>
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<tr>
<td>Z+jets &amp; diboson</td>
<td>80000 ± 40000</td>
<td>8000 ± 4000</td>
</tr>
<tr>
<td>(t\bar{t}X)</td>
<td>15600 ± 2100</td>
<td>2110 ± 290</td>
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<tr>
<td>Multijet</td>
<td>210000 ± 80000</td>
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<tr>
<td>Total prediction</td>
<td>4540000 ± 310000</td>
<td>1110000 ± 100000</td>
</tr>
<tr>
<td>Data</td>
<td>4540 886</td>
<td>1 100 558</td>
</tr>
</tbody>
</table>
Differential $\sigma(\bar{t}t)$ in all-had in ATLAS

\[
\chi^2 = \frac{(m_{b_1j_1j_2} - m_{b_2j_3j_4})^2}{\sigma_t^2} + \frac{(m_{j_1j_2} - m_W)^2}{\sigma_W^2} + \frac{(m_{j_3j_4} - m_W)^2}{\sigma_W^2}
\]

\[
D(X) = \frac{B_1(X) \cdot C(X)}{A_1(X)},
\]

\[
D'(X) = \frac{B_0(X) \cdot C(X)}{A_0(X)}
\]

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [%]</th>
</tr>
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<tr>
<td></td>
<td>Particle level</td>
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<tr>
<td>PS/hadronisation</td>
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<td>Multi-jet syst.</td>
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<tr>
<td>JES/JER</td>
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<td>ISR, PDF</td>
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<td>ME generator</td>
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<td>Flavour tagging</td>
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<td>Luminosity</td>
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<tr>
<td>Multi-jet stat.</td>
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<td>MC signal stat.</td>
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<td>Stat. unc.</td>
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<tr>
<td>Stat.+syst. unc.</td>
<td>14</td>
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</table>
Differential $\sigma(t\bar{t})$ for boosted top in CMS
Differential $\sigma(\bar{t}t)$ for boosted top in CMS

Particle level
- Data
- Total unc.
- Powheg+Pythia8
- aMC@NLO+Pythia8
- Powheg+Herwig++

Higgs boson production and decay in the single-top quark channel at the LHC

Observables
- $|y|$ distribution
- M_{tt} distribution

Data compared to SM predictions

Uncertainties
- Experimental
- Theoretical

35.9 fb\(^{-1}\) (13 TeV)
Measurement of $ttZ$ in ATLAS

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>$\Delta\sigma_{ttZ}/\sigma_{ttZ}$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ttZ$ parton shower</td>
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<td>$tWZ$ modelling</td>
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</tr>
<tr>
<td>$b$-tagging</td>
<td>2.9</td>
</tr>
<tr>
<td>$WZ/ZZ +$ jets modelling</td>
<td>2.8</td>
</tr>
<tr>
<td>$tZq$ modelling</td>
<td>2.6</td>
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<tr>
<td>Lepton</td>
<td>2.3</td>
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<tr>
<td>Luminosity</td>
<td>2.2</td>
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<tr>
<td>Jets + $E_T^{\text{miss}}$</td>
<td>2.1</td>
</tr>
<tr>
<td>Non-prompt/fake leptons</td>
<td>2.1</td>
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<tr>
<td>$ttZ$ A14 tune</td>
<td>1.6</td>
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<tr>
<td>$ttZ$ $\mu_f$, $\mu_T$ scales</td>
<td>0.9</td>
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<tr>
<td>Other backgrounds</td>
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<tr>
<td>Pile-up</td>
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<tr>
<td>$ttZ$ PDF</td>
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<tr>
<td>Total systematics</td>
<td>8.4</td>
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<td>Data statistics</td>
<td>5.2</td>
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<tr>
<td>Total</td>
<td>9.9</td>
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</tbody>
</table>
Evidence of tttt in SSML channel in ATLAS

Pre-fit impact on $\mu$:
- $\theta = \bar{\theta} + \Delta \theta$
- $\theta = \bar{\theta} - \Delta \theta$

Post-fit impact on $\mu$:
- $\theta = \bar{\theta} + \Delta \theta$
- $\theta = \bar{\theta} - \Delta \theta$

- Nuis. Param. Pull

**ATLAS**

$t\bar{t}t$ cross section
$tW$ syst $\geq$ 8jets
$tW$ renorm./fact. scale
$ttt$ modelling (shower)
$b$-tagging $MV2c10$ light b
$tW$ + 1 truth b
$ttt$ cross section
Luminosity
JES pileup rhoToplogy
JES effectiveNP modelling1
JES flavor composition signal
$b$-tagging $MV2c10$ C0
$t\bar{t}b$ + 1 truth b
tW syst 7jets
$t\bar{t}b$ + 2 truth b
JES pileup offsetNPV
$tW$ + 2 truth b
t$Z$ modelling (generator)
t$t$ b light fake cross section
Jet vertex tagger efficiency

**ATLAS**

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$

- Observed
- Expected
- SM $\sigma_{_{NLO}}$(tttt)
- Scale uncertainty
Measurement of the $y^t$ in CMS

![Graph showing measurement of $y^t$ in CMS](image)

- Events / Bin
- Data
- $t\bar{t}$
- Single $t$
- Drell-Yan
- Total unc.

CMS Preliminary

137 fb$^{-1}$ (13 TeV)

![Relative Uncertainty (y^t)](image)

CMS

Simulation

Preliminary

Weak Corrections

- $t\bar{t}$ ($Y_t = 1$)
- $t\bar{t}$ ($Y_t = 2$)
- $t\bar{t}$ ($Y_t = 0$)
- Single $t$
- Drell-Yan

<table>
<thead>
<tr>
<th>M_{b\bar{t}} range [GeV]</th>
<th>Events / Bin</th>
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<tr>
<td>Data</td>
<td>Pred.</td>
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<tr>
<td>M_{b\bar{t}}</td>
<td>Relative Uncertainty (y^t)</td>
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<td>M_{b\bar{t}} Range [GeV]</td>
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</table>
Measurement of the $y^t$ in CMS
Measurement of $t\bar{t}W\gamma$ and $tty$ in ATLAS

Pre-fit impact on $\mu$:
- $\theta = \bar{\theta} + \Delta\theta$
- $\theta = \bar{\theta} - \Delta\theta$

Post-fit impact on $\mu$:
- $\bar{\theta} = \bar{\theta} + \Delta\bar{\theta}$
- $\theta = \bar{\theta} - \Delta\theta$

Nuis. Param. Pull

$\bar{t}\bar{\gamma}$ PS model (rate)
$\bar{t}\bar{\gamma}$ ISR (rate)
luminosity
prompt $\gamma$ normalisation
photon efficiency isolation
$h$-flakes normalisation
pile-up
photon identification
electron identification
JES pile-up correction (1)
$t\bar{t}W\gamma$ PS model
b-tagging: light-flavour (1)
jet vertex tagging
JES in-situ calibration (1)
$\bar{t}\bar{\gamma}$ PDF

$\sqrt{s} = 13$ TeV, 139 fb$^{-1}$
W polarization in ATLAS and CMS

- Combination of the W boson polarization in top quark decays, on Run1 (8 TeV, 20 fb⁻¹) data.
  - W boson polarization determined by the V-A structure of the tWb vertex
  \[
  \frac{1}{\Gamma} \frac{d\Gamma}{d \cos \theta^*} = \frac{3}{4} (1 - \cos^2 \theta^*) F_0 + \frac{3}{8} (1 - \cos \theta^*)^2 F_L + \frac{3}{8} (1 + \cos \theta^*)^2 F_R
  \]

- Combination of the polarization fractions from 4 measurements

- Improvement > 20% wrt the most precise measurement
- Measurement used to set limits on the anomalous coupling in the tWb vertex

<table>
<thead>
<tr>
<th>Coupling</th>
<th>ATLAS</th>
<th>CMS</th>
<th>ATLAS+CMS combination</th>
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<tbody>
<tr>
<td>Re((V_R))</td>
<td>([-0.17, 0.25])</td>
<td>([-0.12, 0.16])</td>
<td>([-0.11, 0.16])</td>
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<tr>
<td>Re((g_L))</td>
<td>([-0.11, 0.08])</td>
<td>([-0.09, 0.06])</td>
<td>([-0.08, 0.05])</td>
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<tr>
<td>Re((g_R))</td>
<td>([-0.03, 0.06])</td>
<td>([-0.06, 0.01])</td>
<td>([-0.04, 0.02])</td>
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