TOP QUARK PROPERTIES USING THE ATLAS DETECTOR AT THE LHC

- TOP QUARK MASS
- TOP QUARK PAIR PRODUCTION – SPIN CORRELATIONS AND CHARGE ASYMMETRY

María José Costa - IFIC (UV-CSIC) – on behalf of the ATLAS Collaboration
TOP QUARK MASS

- Measured using different techniques, at 7 and 8 TeV CM E, and in various channels: $t\bar{t}$ (lepton+jets, dilepton, all hadronic), single top $t$-channel.

Direct measurements of $m_{\text{top}}^{\text{MC}}$

Measurements of $m_{\text{top}}^{\text{pole}}$

+ NEW: dilepton @ 8 TeV (arXiv:1606.02179)

Most precise determinations obtained with direct measurements (template method). But the parameter which is being measured in this case is the MC top quark mass.
TOP QUARK MASS - ATLAS 1+Jets @ 7 TeV

- Method: 3D template fit to $m_{\text{top}}^{\text{reco}}$, $m_{W}^{\text{reco}}$ and $R_{lb}^{\text{reco}} \rightarrow m_{\text{top}}$, JSF, bJSF.

$R_{lb}^{\text{reco}}$ sensitive to bJES $\rightarrow$ constrain bJES from data


Use a kinematic fit to the decay hypothesis $\rightarrow m_{\text{top}}^{\text{reco}}$
**TOP QUARK MASS - ATLAS l+jets @ 7 TeV**

<table>
<thead>
<tr>
<th>Results</th>
<th>$m_{\ell^+jets}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Statistics</strong></td>
<td>172.33</td>
</tr>
<tr>
<td><strong>Method</strong></td>
<td>0.75</td>
</tr>
<tr>
<td><strong>Signal Monte Carlo generator</strong></td>
<td>0.11 ± 0.10</td>
</tr>
<tr>
<td><strong>Hadronisation</strong></td>
<td>0.22 ± 0.21</td>
</tr>
<tr>
<td><strong>Initial- and final-state QCD radiation</strong></td>
<td>0.18 ± 0.12</td>
</tr>
<tr>
<td><strong>Underlying event</strong></td>
<td>0.32 ± 0.06</td>
</tr>
<tr>
<td><strong>Colour reconnection</strong></td>
<td>0.15 ± 0.07</td>
</tr>
<tr>
<td><strong>Parton distribution function</strong></td>
<td>0.11 ± 0.07</td>
</tr>
<tr>
<td><strong>Background normalisation</strong></td>
<td>0.25 ± 0.00</td>
</tr>
<tr>
<td><strong>W/Z+jets shape</strong></td>
<td>0.10 ± 0.00</td>
</tr>
<tr>
<td><strong>Fake leptons shape</strong></td>
<td>0.29 ± 0.00</td>
</tr>
<tr>
<td><strong>Jet energy scale</strong></td>
<td>0.05 ± 0.00</td>
</tr>
<tr>
<td><strong>Relative b-to-light-jet energy scale</strong></td>
<td>0.58 ± 0.11</td>
</tr>
<tr>
<td><strong>Jet energy resolution</strong></td>
<td>0.06 ± 0.03</td>
</tr>
<tr>
<td><strong>Jet reconstruction efficiency</strong></td>
<td>0.22 ± 0.11</td>
</tr>
<tr>
<td><strong>Jet vertex fraction</strong></td>
<td>0.12 ± 0.00</td>
</tr>
<tr>
<td><strong>b-tagging</strong></td>
<td>0.01 ± 0.00</td>
</tr>
<tr>
<td><strong>Leptons</strong></td>
<td>0.50 ± 0.00</td>
</tr>
<tr>
<td><strong>$E_T^{miss}$</strong></td>
<td>0.04 ± 0.00</td>
</tr>
<tr>
<td><strong>Pile-up</strong></td>
<td>0.15 ± 0.04</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td>0.02 ± 0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>1.03 ± 0.31</td>
</tr>
</tbody>
</table>

(Dominate uncertainties: b-tagging, JES, stat)
TOP QUARK MASS
ATLAS dilepton @ 7 TeV and 8 TeV

- Background fraction $\leq 2\%$.
- Under-constrained event kinematics.
- Use 1D template method with $m_{lb}$ observable as estimator (exploiting a partial reconstruction).
- 8 TeV analysis: Additional cut on $p_{T,lb} > 120$ GeV $\rightarrow$ significant reduction of JES and modelling.

8 TeV: arXiv:1606.02179
TOP QUARK MASS
ATLAS dilepton @ 7 TeV and 8 TeV

Best precision achieved @ 8 TeV: Rel. total uncertainty 0.5% (dominant uncertainties: JES, bJES, signal modelling).

<table>
<thead>
<tr>
<th></th>
<th>7 TeV</th>
<th>8 TeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{\text{top}}^{\text{dil}}$ [GeV]</td>
<td>173.79 ± 0.54 (stat) ± 1.30 (syst) GeV</td>
<td>172.99 ± 0.41 (stat) ± 0.74 (syst) GeV</td>
</tr>
</tbody>
</table>

8 TeV $m_{\text{top}} = 172.99 \pm 0.41$ (stat) ± 0.74 (syst) GeV

7 TeV $m_{\text{top}}^{\text{dil}} = 173.79 \pm 0.54$ (stat) ± 1.30 (syst) GeV.
The 3 measurements combined using the BLUE method taking correlations into account.

\[ m_{\text{top}} = 172.84 \pm 0.34 \text{ (stat)} \pm 0.61 \text{ (syst)} \text{ GeV} \]

(Rel. total uncertainty: 0.4%)

Dominant uncertainties: JES, stat, bJES, Hadronisation)
TOP QUARK MASS

Alternative Techniques

- Measure an observable that can be theoretically calculated using a well defined top mass scheme (e.g. pole mass).

\[ m_t^{MC} = m_t^{MSR}(R = 1 \text{ GeV}) + \Delta_t^{MC}(R = 1 \text{ GeV}) \]
\[ \Delta_t^{MC}(1 \text{ GeV}) \sim \mathcal{O}(1 \text{ GeV}). \]

- Observables used:
  - Top quark pair cross section (predictions at NNLO+NNLL).
  - Normalised $t\bar{t}+1$-jet differential cross section as a function of the inverse of the invariant mass of the $t\bar{t}+1$-jet system (predictions at NLO+PS) (better sensitivity).

\[ m_t^{pole} = 172.9^{+2.5}_{-2.6} \text{ GeV} \]
TOP SPIN CORRELATIONS IN TOP PAIRS

- The top spin information is transferred to the decay products without dilution.

\[
\text{top lifetime} < \frac{\text{QCD timescale}}{\text{spin-flip timescale}} \ll 10^{-21} \text{s}
\]

- Negligible polarisation in SM QCD top pair production, but spins of the top and anti-top are correlated.

- The amount of spin correlation is sensitive to the production mechanism (many BSM scenarios predict different spin correlations).

- Latest measurements performed with lepton angular distributions in dilepton events:
  - Indirect measurement: \( \Delta \Phi_{ll} \) (best probe in laboratory frame)
  - Direct measurement: \( \cos \theta_1 \cos \theta_2 \) (in the top rest frame)

\[
\frac{1}{N} \frac{d^2 N}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} \left( 1 + B_1 \cos \theta_1 + B_2 \cos \theta_2 - C_{\text{helicity}} \cos \theta_1 \cdot \cos \theta_2 \right)
\]

\[
C_{\text{helicity}} = -A_{\text{helicity}} \alpha_1 \alpha_2 \quad A_{\text{helicity}} = \frac{N_{\text{like}} - N_{\text{unlike}}}{N_{\text{like}} + N_{\text{unlike}}}
\]

\[
A_{\text{helicity}}^{\text{SM}} = 0.318 \pm 0.005
\]
TOP SPIN CORRELATIONS @ 8 TeV, dilepton

- Quantify spin correlation strength as fraction \( f_{SM} \) of SM expectation.
- Template fit using MC with and without spin correlations.
- Search for stop quark production
  - squarks have spin 0 \( \rightarrow \) daughter top quarks look similar to uncorrelated ttbar events.
  - But only 1/6 of ttbar cross section for \( m_{stop} = m_{top} \).
  - Exclusion of \( m_{top} < m_{stop} < 191 \) GeV @ 95%CL (assuming 100% BR stop \( \rightarrow \) top +LSP).

\[
\begin{align*}
  f_{SM} &= 1.20 \pm 0.05 \text{ (stat)} \pm 0.13 \text{ (syst)} \\
  A_{\text{helicity}} &= 0.38 \pm 0.04
\end{align*}
\]

(in agreement with SM predictions)
TOP SPIN CORRELATIONS @ 7 TeV, dilepton

- Distribution of $\cos \theta_1 \cos \theta_2$ is reconstructed using a "topology reconstruction method".
- Unfolded to parton level using an Iterative Bayesian Method.


Dominant uncertainties: Unfolding method, signal modelling, jets

$A_{\text{helicity}} = 0.315 \pm 0.061(\text{stat.}) \pm 0.049(\text{syst.})$

(in agreement with SM predictions)
**CHARGE ASYMMETRY**

- At LO tops and anti-tops are symmetric.
- At higher orders: interference of diagrams connects the direction of top and initial quark and direction of anti-top and initial anti-quark.

Only in $\bar{q}q$ initial state (not for the dominant $gg$ fusion).
- Relatively a small effect in the SM. $A_C: 1\%$ $A_{||}: 0.6\%$
- Can be enhanced in BSM scenarios (axigluons, $Z'$ bosons, KK gluons).

**Measured Observables**

$$A_{\bar{t}t}^C = \frac{N(|y| > 0) - N(|y| < 0)}{N(|y| > 0) + N(|y| < 0)}$$

$\Delta|y| = |y_t| - |y_{\bar{t}}|$. NLO QCD: $0.0111 \pm 0.0004$

In dilepton channel:

$$A_{\ell\ell}^C = \frac{N(|\eta| > 0) - N(|\eta| < 0)}{N(|\eta| > 0) + N(|\eta| < 0)}$$

$\Delta|\eta| = |\eta^+| - |\eta^-|$. NLO QCD: $0.0064 \pm 0.0003$

Measurements of inclusive and differential observables in full and fiducial phase space available.
CHARGE ASYMMETRY MEASUREMENTS

- Measurements performed in $l$+jets (including also boosted top specific analysis) and dilepton channels.
- Different methods to reconstruct the ttbar kinematics (e.g. likelihood fit in $l$+jets, specific technique to deal with boosted top decays in $l$+jets boosted, KIN method in dilepton).
- A Bayesian unfolding used to correct to parton level (the likelihood is extended with nuisance parameter terms to take systematics into account).
CHARGE ASYMMETRY @ 8 TeV l+jets

- Inclusive and differential measurements as a function of invariant mass, $p_T$ and longitudinal boost $\beta_z$ of the ttbar system provided.

$A_C = 0.009 \pm 0.005$ (stat.+syst.)

- Precision dominated by statistical uncertainty (dominant systematic uncertainties signal modelling and uncertainties affecting W+jets).
- All compatible with SM predictions.
- Limits set on the parameters (i.e. mass and couplings) of BSM models.
CHARGE ASYMMETRY @ 8 TeV l+jets
BOOSTED TOP QUARKS

- Measurement in events where top quark pairs are produced with large invariant mass (> 750 GeV).
- Used reconstruction techniques designed to deal with collimated decay topology of boosted tops.
- Hadronic top reconstructed as a single large-R jet and tagged using jet substructure variables.
- This kinematic regime has a higher sensitivity for the SM asymmetry and BSM models that introduce massive new states.

Measurements compatible with SM. Precision limited by statistics.

\[ m_{t\bar{t}} > 750 \text{GeV}, \ -2 < \Delta y \bar{t} < 2, \quad A_C = (4.2 \pm 3.2)\% \]
CHARGE ASYMMETRY @ 8 TeV dilepton

- $A_c$ and $A_{ll}$ inclusive and differential measurements provided in fiducial and full phase space.
- Inclusive measurements also compared with BSM compatible with Tevatron results.

Measurements compatible with SM. Precision limited by statistics (dominant systematics being signal modelling and kinematic reconstruction).
CONCLUSIONS

- Run-1 legacy measurements available for top quark mass and angular distributions in top pair events sensitive to spin correlations and charge asymmetry effects.
- Allow for stringent test of the SM, being also sensitive to new physics.
- Top quark mass:
  - Best precision achieved using the standard “template” method to determine the MC top quark mass with 0.4% precision.
  - Direct pole top quark mass determinations reaching 1.3% precision.
- Spin correlations and charge asymmetry measurements all compatible with SM predictions, allowing to set limits on BSM scenarios.
- Statistical uncertainties still important in top quark mass and charge asymmetry measurements.