Properties of the Top Quark
Phenomenology 2014

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On behalf of the ATLAS Top Working Group

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Motivation and introduction

The top quark

- **Heaviest** elementary particle at $\approx 173$ GeV. Discovered 1995.
- Lifetime: $\tau = 3 \cdot 10^{-25}$ seconds, decays **without hadronizing**.
- Branching ratio $\text{Br}(t \rightarrow W + b) \approx 1$.

- Top properties enter as important parameters in many BSM theories.
- High precision measurements are important to test SM and BSM.

- LHC acts as a **top factory**, producing $t\bar{t}$ pairs through gluon fusion.
- Final states with $t\bar{t}$, leptons and jets were used for the measurements below.
### Top mass

- Test internal consistency of the SM and BSM theories.
- Constrain masses of undiscovered particles in BSM scenarios.

- **Selection**: lepton+jets from $t\bar{t} \rightarrow b\bar{b}l\nu q_1 \bar{q}_2$.
- $\sqrt{s} = 7$ TeV at 1.04 fb$^{-1}$, 2011 data.
- Measure **invariant mass** of decay products, determine top mass using a template method with a likelihood fit.
- **MC** generated for six different top masses, between 160 and 190 GeV.
- **2d analysis**, optimizing top mass and the JSF simultaneously.

Results

- $m_t = 174.5 \pm 0.6 \pm 2.3$ GeV.
- Statistically as precise as Tevatron combined measurement of $m_t = 173.2 \pm 0.6_{\text{stat}} \pm 0.8_{\text{syst}}$ GeV, larger \textbf{systematic uncertainty}.
- Largest systematic uncertainties: JES and QCD modelling.
Top quark mass: combination

- First combination of LHC (ATLAS+CMS) and Tevatron (CDF+D0) for the top quark mass.
- Final states: $t\bar{t} \rightarrow \text{lepton+jets}$, $t\bar{t} \rightarrow \text{dilepton}$, $t\bar{t} \rightarrow \text{jets}$, $t\bar{t} \rightarrow E_T^{\text{miss}}$.
- Preliminary results: $m_t = 173.34 \pm 0.27_{\text{stat}} \pm 0.71_{\text{syst}}$ GeV.

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**Top properties**

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Mass difference between $t$ and $\bar{t}$

- First ATLAS measurement of $\Delta m = m(t) - m(\bar{t})$.
- By CPT invariance, $\Delta m = 0$, condition for a local field theory.
- Selection: lepton+jets from a $t\bar{t}$ decay.
- 15 samples simulated with $\Delta m : [-15, 15]$ GeV, $\frac{m_t + m_{\bar{t}}}{2} = 172.5$ GeV.
- Results: $\Delta m = 0.67 \pm 0.61_{\text{stat}} \pm 0.41_{\text{syst}}$ GeV, consistent with SM.

Test whether the charge $Q$ of the top quark is $2/3\ e$ (SM) or $-4/3\ e$.

Data taken at $2.05\ fb^{-1}$ and $\sqrt{s} = 7\ TeV$.

Selection: $t\bar{t}$ with a single charged lepton, $t\bar{t} \rightarrow l^\pm \nu jj bb$.

SM top can decay to $l^+$, $b^{-1/3}$, an exotic $T$ to $l^-$, $b^{-1/3}$.

Results: $Q = 0.64 \pm 0.02_{\text{stat}} \pm 0.08_{\text{syst}}\ e$. $Q = -4/3\ e$ excluded at $8\sigma$.

JHEP11(2013)031, arXiv 1307.4568
Top polarization

- CP conservation of the strong force results in negligible longitudinal polarization of $t\bar{t}$ pairs. Small contribution from weak processes.
- Some BSM theories predict enhanced polarization.
- Measure spin state using **angular distributions** of the decay products.
- Data taken at $\sqrt{s} = 7$ TeV, $L = 4.66$ fb$^{-1}$.
- Final states: one or two isolated leptons + jets.

Top polarization (2)

- Measure $\alpha_1 P$: leptonic spin analyzing power $\times$ top polarization.
  \[ \frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_1 d\cos \theta_2} = \frac{1}{4} (1 + \alpha_1 P_1 \cos \theta_1 + \alpha_2 P_2 \cos \theta_2 - C \cos \theta_1 \cos \theta_2) \]
  
- Two measurements under the hypotheses: polarization caused by CP conserving or maximally CP violating processes.
  \[ \alpha_1 P_{\text{CP\,cons}} = -0.035 \pm 0.014 \pm 0.037, \; \alpha_1 P_{\text{CP\,viol}} = 0.020 \pm 0.016^{+0.013}_{-0.017}. \]
  
- Agreement with SM prediction: top polarization compatible with zero.

\[ \int \mathcal{L} \, dt = 4.7 \text{ fb}^{-1} \]

$\sqrt{s} = 7$ TeV

\begin{align*}
\text{ATLAS single lepton} & \quad \text{Data} \quad \text{Fit} \quad \text{Bkgd.} \\
\text{cos} \theta(\ell^+) & \quad \text{cos} \theta(\ell^-) \\
\text{Events/0.1} & \quad \text{Events/0.1}
\end{align*}

\[ aP = 0 \quad aP = +0.3 \quad aP = -0.3 \]
The spin correlation in $t\bar{t}$ pairs is measured.
Measurement at $L = 2.1 \text{ fb}^{-1}$, $\sqrt{s} = 7 \text{ TeV}$.
Selection: 2 leptons, 2 jets and missing $E_T$, targeting $t\bar{t} \rightarrow W^+ W^- b\bar{b} \rightarrow l^+ \nu l^- \bar{\nu} b\bar{b}$.

At low invariant mass, $t\bar{t}$ is produced from gluons with like helicity
Predicted spin correlation in $t\bar{t}$ pairs.
Spin correlation:

\[ A = \frac{N_{\uparrow\uparrow, \downarrow\downarrow} - N_{\uparrow\downarrow, \downarrow\uparrow}}{N_{\text{tot}}} \]

Two hypotheses: \( A_{SM}, A = 0 \).

BSM process that could reduce spin correlation: \( t \to H^+ b \).

\( A \) is extracted from angular distribution \( \Delta \phi \) of lepton pairs using fits to templates.

Correlation measure \( f \), with \( f = 1 \) being the SM prediction.

**Results**

\[ f_{SM} = 1.30 \pm 0.14_{\text{stat}}, A_{\text{helicity}} = 0.40^{+0.09}_{-0.08}. \]

Results are compatible with SM \( A_{SM}^{\text{helicity}} = 0.31 \).

0 spin correlation hypothesis excluded at 5.1\( \sigma \).
Motivation: test QCD. Probe BSM processes with anomalous vector or axial-vector couplings.

SM asymmetry sources: interference of gluon emission state at NLO in $q\bar{q}g \rightarrow t\bar{t}g$ + interference of tree and box diagrams.

Shown in pseudorapidity $\eta$ distribution of $t\bar{t}$.

The measurement

Data taken at $\sqrt{s} = 7$ TeV, $L = 4.7 \text{ fb}^{-1}$.

Selection: 1 lepton, $\geq 4$ jets, one b-tag and large missing transverse momentum.

JHEP02(2014)107, arXiv 1311.6724
• SM prediction at the LHC: $A_{C_{SM}} = 0.0123 \pm 0.0005$.

• Results: $A_C = 0.006 \pm 0.010$, consistent with the SM prediction.

• Combination of ATLAS+CMS. Preliminary results: $0.005 \pm 0.007 \pm 0.006$, in agreement with the SM.
Conclusions

- Top properties have been measured at ATLAS in $\sqrt{s} = 7$ TeV data.
- Measurements of the top mass, charge and polarization were presented as well as spin correlation in $t\bar{t}$ pairs the charge asymmetry and the mass difference between $t$ and $\bar{t}$.
- No inconsistencies with the SM were found.
- Several BSM scenarios excluded, such as $Q = -4/3e$ and 0 spin correlation in $t\bar{t}$ pairs.
- The Standard Model prevails.