Highlights of top quark properties measurements at ATLAS

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What makes top quark interesting?

Heaviest fundamental particle in the SM

- Larger mass → Larger coupling to SM Higgs + $m_{\text{top}}$ is a fundamental parameter in SM
- Allows for Self-Consistency Checks of SM Post Higgs Discovery

Short lifetime ($\sim 10^{-25}$s)

- Decays before hadronization – Unique among the quarks!
- Access to Polarization and Spin Correlations

Processes including tops are backgrounds for new physics

- e.g. $H \rightarrow b\bar{b}$
- $H \rightarrow WW$
- + Exotics and SUSY
- Good Understanding → Improvements in Searches

Hints of new/BSM physics

- Exotic Particles Could Decay Preferentially to Top Quarks
Top production and decay

- In $pp$ collisions top production is dominated by QCD production in top and anti-top pairs.
- EW production provides direct access to $Wtb$ vertex.

- In the SM, top decays to $Wb$.
Topics covered in this talk

- Mass
- Spin
- Polarisation

- Lepton, quark

- Polarisation

- Helicity

- Wtb vertex structure

- CP asymmetry

- ttZ, ttW, ttγ production
## Topics covered in this talk

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<td>JHEP 03 (2017) 113</td>
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</tr>
<tr>
<td>CP asymmetries</td>
<td>JHEP 02 (2017) 071</td>
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</table>
Top quark mass

★ Motivations

• EW precision calculations depend on $m_t$
• EW vacuum stability involve $m_t$
• $m_t$ is large $\Rightarrow$ connection with high energy theories
• Unique opportunity to study a (almost) bare quark

★ Methods: Confinement $\Rightarrow$ quark masses are not observables $\Rightarrow$ what is $m_t$?

• **Top decay products invariant mass** $m_{t}^{\text{MC}}$:
  - Direct measurements
    - Choose detector-level observables ($O_i$) which depend on the top quark mass
    - Generate MC with varied $m_{t}^{\text{MC}}$ values
    - From MC, parameterise $O_i(m_{t}^{\text{MC}})$
    - Take value of $m_{t}^{\text{MC}}$ which best describes data

• **theory parameter in the lagrangian** $m_{t}^{\text{pole}}$
  - (in pole mass scheme)

  **Cross section measurements**
  - Take at least a NLO calculation (fix scheme)
  - Obtain (differential also) $\sigma_{t\bar{t}+X}(m_{t}^{\text{pole}})$
  - Compare measured $\sigma_{t\bar{t}+X}^{\text{exp}}$ with theory
  - Choose the value of $m_{t}^{\text{pole}}$ which best match $\sigma_{t\bar{t}+X}^{\text{exp}}$
  - $m_{t}^{\text{pole}}$ well-defined theoretically

★ Topologies

**Newest ATLAS result**

- $t\bar{t}$ all-hadronic
  - 6 jets (2 b-jets)
  - no leptons
  - no $E_T^{\text{miss}}$

- $t\bar{t}$ semileptonic
  - 4 jets (2 b-jets)
  - 1 lepton
  - $E_T^{\text{miss}} > 30$ GeV

- $t\bar{t}$ dileptonic
  - 2 b-jets
  - 2 leptons
  - $E_T^{\text{miss}} > 60$ GeV

**Most precise ATLAS result**

- single-$t$ (t leptonic)
  - 2 jets (1 b-jet)
  - 1 lepton
  - $E_T^{\text{miss}} > 30$ GeV
Top quark mass in the all-hadronic channel

- Largest branching ratio (46%) among the possible top quark decay channels
- Challenging because of the large multijet background
- $m_{\text{top}}$ extracted from a template fit to the distribution of the ratio of three-jet to dijet masses, $R_{3/2} = m_{jjjj}/m_{jj}$ (reduced dependence on the jet energy scale uncertainty)
- The dominant source of systematic uncertainty come from the jet energy scale, hadronisation modelling and the b-jet energy scale.
- with a relative precision of 0.7%, it is about 40% more precise than the previous measurement performed by ATLAS in the all-hadronic channel at 7 TeV.

$$m_{\text{top}} = 173.72 \pm 0.55 \text{ (stat.)} \pm 1.01 \text{ (syst.) GeV}$$
Top quark mass in the dilepton channel

• The analysis uses a template fit to $m_{lb}$

• An unbinned maximum likelihood fit gives the $m_{top}$ value that best describes the data

• Biggest uncertainties come from the jet energy scale and the relative b-to-light-jet energy scale

• The result is the most precise single result in this decay channel to date (40% more precise than the one obtained with 7 TeV data)

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

• The result is combined with ATLAS $m_{top}$ measurements in the lepton+jets channel and the dilepton channel @ 7 TeV with a relative precision of 0.4%

  $m_{top} = 172.84 \pm 0.34\text{(stat)} \pm 0.61\text{(syst)}\text{GeV}$
Top quark mass summary

- Main gain in precision of top mass measurements lays in the combination of the results
- Uncertainties are dominated by systematics (JES, b-JES and modelling)
- $m_t^{MC}$ and $m_t^{pole}$ are obtained with different techniques and therefore the results are not directly comparable, specially the uncertainties
Top quark spin observables in $t\bar{t}$ production

- In the SM, top quarks produced in pairs are unpolarised
- The spins of the top and the antitop are correlated and the information is transferred to their decay products, thus affecting their angular distributions.
- Use $t\bar{t}$ dilepton events ($ee, \mu\mu, e\mu$)
- The spin density matrix can be expressed in terms of 15 spin observables using 3 orthogonal spin quantisation axes:
  - 3 polarisation coefficients for the top quark
  - 3 polarisation coefficients for the antitop quark
  - 9 spin correlation coefficients
- Results are provided at parton level in the full phase-space and at stable-particle level in a fiducial phase-space.

Three axes:
- $k$: helicity axis
- $n$: transvers axis
- $r$: orthogonal to $k$ & $n$

$\theta$: angle between the momentum of a decay particle and a quantisation axis
Top quark spin observables in $t\bar{t}$ production

The dominant source of systematic uncertainties comes from the modelling of the signal, which can represent up to 85% of the total uncertainty.

\[
\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta_+^a d \cos \theta_-^b} = \frac{1}{4} \left( 1 + \begin{bmatrix} B_1^a & B_1^b \cos \theta_+^a + B_2^a \cos \theta_-^b \end{bmatrix} \right) C(a,b) \cos \theta_+^a \cos \theta_-^b
\]

- $B$: (anti)top polarisation
- $C$: spin correlations
- (-)+:(anti)top
- $k$: helicity axis
- $n$: transvers axis
- $r$: orthogonal to $k$ & $n$

★ Results at parton level

Highlights of top quark properties measurements at ATLAS
# Wtb vertex

\[ \mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (V_L P_L + V_R P_R) t W^-_\mu - \frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu\nu} q_\nu}{m_W} (g_L P_L + g_R P_R) t W^-_\mu + \text{h.c.} \]

In the SM:
\[
\begin{align*}
V_L & \sim 1 \\
V_R & = g_L = g_R = 0
\end{align*}
\]

Limits set to:
\[
\begin{align*}
\text{Re}(V_R), \text{Re}(g_L), \text{Re}(g_R) \\
\text{Im}(g_R) \\
\text{Re}[g_R/V_L], \text{Im}[g_R/V_L], |V_R/V_L|
\end{align*}
\]

- **W boson polarisation:** top pairs production, lepton+jets
- **W boson spin observables:** t-channel single top production, lepton channel
- **Top quark polarisation:** t-channel single top production, lepton channel
- **Triple-differential angular decay rates:** t-channel single top production, lepton channel
W polarisation in $t\bar{t}$ semileptonic events

$W$ boson helicity fractions can be accessed via angular distribution of polarisation analysers:

- Leptonic decay: charged lepton
- Hadronic decay: down-type quark

The down-type quark is identified using a kinematic likelihood fitter (KLFitter), using the weight of the $b$-jet tagging algorithm.

Template fit of the distribution $\cos\theta^*$ (angle between the analyser and the reversed direction of flight of the $b$-quark from the top quark decay in the $W$ boson rest frame) for the full phase-space:

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\theta^*} = \frac{3}{4} \left(1 - \cos^2\theta^*\right) F_0 + \frac{3}{8} \left(1 - \cos\theta^*\right)^2 F_L + \frac{3}{8} \left(1 + \cos\theta^*\right)^2 F_R$$

**Predictions at NNLO in QCD**

\[
\begin{align*}
F_L &= 0.311 \pm 0.005 \\
F_R &= 0.0017 \pm 0.0001 \\
F_0 &= 0.687 \pm 0.005
\end{align*}
\]

**Hadronic analyser (1 $b$-tag + $\geq 2$-tags)**

\[
\begin{align*}
F_0 &= 0.659 \pm 0.010 \text{ (stat.+bkg. norm.)} \pm 0.052 \text{ (syst.)} \\
F_L &= 0.281 \pm 0.021 \text{ (stat.+bkg. norm.)} \pm 0.063 \text{ (syst.)} \\
F_R &= 0.061 \pm 0.022 \text{ (stat.+bkg. norm.)} \pm 0.101 \text{ (syst.)}
\end{align*}
\]

**Leptonic analyser ($\geq 2$-tags)**

\[
\begin{align*}
F_0 &= 0.709 \pm 0.012 \text{ (stat.+bkg. norm.)} \pm 0.015 \text{ (syst.)} \\
F_L &= 0.299 \pm 0.008 \text{ (stat.+bkg. norm.)} \pm 0.013 \text{ (syst.)} \\
F_R &= -0.008 \pm 0.006 \text{ (stat.+bkg. norm.)} \pm 0.012 \text{ (syst.)}
\end{align*}
\]
W polarisation in $t\bar{t}$ semileptonic events

Limits on the anomalous couplings are set assuming these to be real, corresponding to the CP-conserving case.

- $V_L$ is fixed to the SM prediction of one.
- Only one anomalous coupling is allowed to vary at a time, while the rest of them are fixed to their SM predictions.

<table>
<thead>
<tr>
<th>Coupling</th>
<th>95% CL interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_R$</td>
<td>$[-0.24, 0.31]$</td>
</tr>
<tr>
<td>$g_L$</td>
<td>$[-0.14, 0.11]$</td>
</tr>
<tr>
<td>$g_R$</td>
<td>$[-0.02, 0.06], [0.74, 0.78]$</td>
</tr>
</tbody>
</table>

Main uncertainty sources:

- Leptonic analyser: jet energy scale and resolution and MC template statistics
- Hadronic analyser: b-tagging uncertainty, jet energy resolution and ttbar modelling
Wtb vertex at production and decay in t-channel events

★ **Wtb vertex at production:** the information about the top polarisation can be measured from asymmetries in the angular distributions of the decay products reconstructed in the top quark rest frame.

★ **Wtb vertex at decay:** the spin density matrix elements for the W boson helicity components 0, ±1 resulting from the decay of polarised top-quarks can be parameterised in terms of expected values of six independent W spin observables which are sensitive to anomalous Wtb couplings. These can be extracted from asymmetries in the angular distributions of the charged lepton reconstructed in the W boson rest frame.

<table>
<thead>
<tr>
<th>Asymmetry</th>
<th>Angular observable</th>
<th>Polarisation observable</th>
<th>SM prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_{FB}^\ell$</td>
<td>$\cos \theta_\ell^*$</td>
<td>$\frac{3}{8} P (F_R + F_L)$</td>
<td>-0.10</td>
</tr>
<tr>
<td>$A_{FB}^{W}$</td>
<td>$\cos \theta_W \cos \theta_\ell^*$</td>
<td>$\frac{3}{8} P (F_R + F_L)$</td>
<td>-0.10</td>
</tr>
<tr>
<td>$A_{FB}^T$</td>
<td>$\cos \theta_\ell^*$</td>
<td>$\frac{3}{4} &lt;S_3&gt;$</td>
<td>-0.23</td>
</tr>
<tr>
<td>$A_{EC}$</td>
<td>$\cos \theta_\ell^*$</td>
<td>$\frac{3}{4} \sqrt{2} &lt;T_0&gt;$</td>
<td>-0.20</td>
</tr>
<tr>
<td>$A_{FB}^N$</td>
<td>$\cos \theta_\ell^N$</td>
<td>$-\frac{3}{4} &lt;S_2&gt;$</td>
<td>0</td>
</tr>
<tr>
<td>$A_{FB}^T$</td>
<td>$\cos \theta_\ell^T$</td>
<td>$\frac{3}{4} &lt;S_1&gt;$</td>
<td>0.34</td>
</tr>
<tr>
<td>$A_{FB}^{N,\phi}$</td>
<td>$\cos \theta_\ell^* \cos \phi_N^*$</td>
<td>$\frac{2}{\pi} &lt;A_2&gt;$</td>
<td>0</td>
</tr>
<tr>
<td>$A_{FB}^{T,\phi}$</td>
<td>$\cos \theta_\ell^* \cos \phi_T^*$</td>
<td>$-\frac{2}{\pi} &lt;A_1&gt;$</td>
<td>-0.14</td>
</tr>
</tbody>
</table>
W boson spin observables and top polarisation related observables obtained via the measurement of asymmetries assuming SM couplings in the unfolding procedure: **consistency check of the SM**.

Two of the asymmetries, $A_{FB}^N$ (which has the highest sensitivity to $\text{Im } g_R$) and $A_{FB}^l$, have been used to extract **limits** on this coupling. For this computation, the rest of the couplings were assumed to have SM values.

$$\text{Im } g_R \in [-0.18, 0.06] \text{ at the } 95\% \text{ CL}$$

The dominant sources of systematic uncertainties are the modelling of the t-channel and $t\bar{t}$ processes, and the jet reconstructions and energy scale.
Wtb vertex: three angle analysis

★ Complete description of the full space of anomalous couplings governing the Wtb vertex plus de top-quark polarisation by using the normalised triple-differential \((\theta, \theta^*, \Phi^*)\) decay rate of top quarks.

\[
e(\theta, \theta^*, \phi^*; P) = \frac{1}{N} \frac{d^3 N}{d(\cos \theta)d\Omega^*} = \frac{1}{8\pi} \left\{ \frac{3}{4} \left| A_{1, \frac{1}{2}} \right|^2 (1 + P \cos \theta) (1 + \cos \theta^*)^2 \right. \\
+ \frac{3}{4} \left| A_{-1, -\frac{1}{2}} \right|^2 (1 - P \cos \theta) (1 - \cos \theta^*)^2 \\
+ \frac{9}{2} \left( \left| A_{0, \frac{1}{2}} \right|^2 (1 - P \cos \theta) + \left| A_{0, -\frac{1}{2}} \right|^2 (1 + P \cos \theta) \right) \sin^2 \theta^* \\
- \frac{3 \sqrt{2}}{2} P \sin \theta \sin \theta^* (1 + \cos \theta^*) \text{Re} \left[ e^{i\phi^*} A_{1, \frac{1}{2}} A_{0, \frac{1}{2}}^* \right] \\
- \frac{3 \sqrt{2}}{2} P \sin \theta \sin \theta^* (1 - \cos \theta^*) \text{Re} \left[ e^{-i\phi^*} A_{-1, -\frac{1}{2}} A_{0, -\frac{1}{2}}^* \right] \right\} = \sum_{k=0}^{2} \sum_{l=0}^{2} \sum_{m=-l}^{l} a_{k,l,m} M_{k,l}^m (\theta, \theta^*, \phi^*)
\]

★ Only nine of the coefficients \(A_{k,l,m}\) are nonzero and can be parameterised by three amplitude fractions and and two phases:

- 3 observable amplitude fractions: \(f_1, f_{1+}, f_{0+}\)
- 1 observable phase: \(\delta^-\)
- 1 likely unobservable phase: \(\delta^+\)
- 1 observable nuisance parameter: \(P\)

★ Detector effects are deconvolved from data by measuring differential rates using Fourier techniques

★ All amplitudes and phases (and couplings) + \(P\) are determined simultaneously and include all correlations
Wtb vertex: three angle analysis

- Global fit: Likelihood function with all correlations (covariance matrix)
  - Distributions are obtained from numerical calculations of the likelihood function

- Interpretation in terms of anomalous couplings by propagating the statistical and systematic uncertainties
  - Limits are placed simultaneously on the possible complex values of the ratio of the anomalous couplings
  - No assumptions on values of the other anomalous couplings
CP asymmetry in $t\bar{t}$ dileptonic events

- CP asymmetries in heavy-flavour mixing and decay from $b$-hadrons from top quark decays.

- Measurement of same- and opposite-sign charge asymmetries from the probabilities for an initial (anti)$b$-quark to decay via either a positively or negatively charged muon.

- Measurement of CP asymmetries which relate to $B_q - \overline{B}_q$ mixing and direct CP-violating $b$- and $c$-decays.

- Asymmetries unfolded to a well-defined fiducial region.

\[
A_{\text{ss}}^{\ell} = \frac{P(b \to \ell^+) - P(\bar{b} \to \ell^-)}{P(b \to \ell^+) + P(\bar{b} \to \ell^-)} \\
A_{\overline{\text{ss}}}^{\ell} = \frac{P(b \to \ell^-) - P(\bar{b} \to \ell^+)}{P(b \to \ell^-) + P(\bar{b} \to \ell^+)} \\
A_{\text{mix}}^{b\ell} = \frac{\Gamma(b \to \bar{b} \to \ell^+X) - \Gamma(\bar{b} \to b \to \ell^-X)}{\Gamma(b \to \bar{b} \to \ell^+X) + \Gamma(\bar{b} \to b \to \ell^-X)}, \\
A_{\text{mix}}^{b\ell} = \frac{\Gamma(b \to \bar{b} \to \ell^-X) - \Gamma(\bar{b} \to b \to \ell^+X)}{\Gamma(b \to \bar{b} \to \ell^-X) + \Gamma(\bar{b} \to b \to \ell^+X)}, \\
A_{\text{dir}}^{b\ell} = \frac{\Gamma(b \to \ell^-X) - \Gamma(\bar{b} \to \ell^+X)}{\Gamma(b \to \ell^-X) + \Gamma(\bar{b} \to \ell^+X)}, \\
A_{\text{dir}}^{c\ell} = \frac{\Gamma(c \to \ell^-X_L) - \Gamma(c \to \ell^+X_L)}{\Gamma(c \to \ell^-X_L) + \Gamma(c \to \ell^+X_L)}, \\
A_{\text{dir}}^{b\ell} = \frac{\Gamma(b \to cX_L) - \Gamma(\bar{b} \to \ell^+X_L)}{\Gamma(b \to cX_L) + \Gamma(\bar{b} \to \ell^+X_L)},
\]
CP asymmetry in $t\bar{t}$ dileptonic events

![Graphs showing CP asymmetry]

<table>
<thead>
<tr>
<th>Data (10^{-2})</th>
<th>MC (10^{-2})</th>
<th>Existing limits (2\sigma) (10^{-2})</th>
<th>SM prediction (10^{-2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A^{ss}$</td>
<td>$-0.7 \pm 0.8$</td>
<td>$0.05 \pm 0.23$</td>
<td>$&lt; 10^{-2}$</td>
</tr>
<tr>
<td>$A^{os}$</td>
<td>$0.4 \pm 0.5$</td>
<td>$-0.03 \pm 0.13$</td>
<td>$&lt; 10^{-2}$</td>
</tr>
<tr>
<td>$A^{b}_{\text{mix}}$</td>
<td>$-2.5 \pm 2.8$</td>
<td>$0.2 \pm 0.7$</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>$A^{b}_{\text{dir}}$</td>
<td>$0.5 \pm 0.5$</td>
<td>$-0.03 \pm 0.14$</td>
<td>$&lt; 1.2$</td>
</tr>
<tr>
<td>$A^{c}_{\text{dir}}$</td>
<td>$1.0 \pm 1.0$</td>
<td>$-0.06 \pm 0.25$</td>
<td>$&lt; 6.0$</td>
</tr>
<tr>
<td>$A^{b}_{\text{dir}}$</td>
<td>$-1.0 \pm 1.1$</td>
<td>$0.07 \pm 0.29$</td>
<td>-</td>
</tr>
</tbody>
</table>

The main contribution to systematic uncertainties come from the modelling of additional radiation and PDF uncertainties, the jet energy scale and the lepton energy resolution.
**t\bar{t}V production in multilepton final states**

- Large datasets give access to rate t\bar{t}+W and t\bar{t}+Z processes
  - t\bar{t}Z: information about neutral-current coupling to the top quark.
  - Sensitive to the presence of BSM physics (vector-like quarks, strongly coupled Higgs boson, technicolor)
- \( \sigma_{ttW} \) and \( \sigma_{ttZ} \) are fitted simultaneously in nine signal regions and two control regions
  - Definition based on the number, charge and flavour of leptons and on the number of jets and b-jets.

\[
\begin{align*}
\sigma_{ttW} &= 1.5 \pm 0.8 \text{ pb} \\
\sigma_{ttZ} &= 0.9 \pm 0.3 \text{ pb}
\end{align*}
\]

(SM: 0.5 ± 12%)

\[
\begin{align*}
\sigma_{ttW} &= 1.5 \pm 0.8 \text{ pb} \\
\sigma_{ttZ} &= 0.9 \pm 0.3 \text{ pb}
\end{align*}
\]

(SM: 0.5 ± 12%)
$\bar{t}t\gamma$ production in multilepton final states

- Probe the $t\gamma$ electroweak coupling
- Fiducial cross section of top-quark pair events in association with a photon
- Differential cross sections wrt. photon $p_T$ and $\eta$ are measured.
- Measurement based on the minimisation of a profile likelihood ratio, using the photon track isolation as the discriminating variable.
- The dominant source of systematic uncertainty come from the hadron-fake template and the template describing electrons misidentified as photons

$$\sigma_{\text{fid}}^{\text{sl}} = 139 \pm 7(\text{stat}) \pm 17(\text{syst}) \text{fb}$$

$$\sigma(\text{NLO prediction}) = 151 \pm 24 \text{fb}$$

Highlights of top quark properties measurements at ATLAS
Conclusion

★ The top quark provides a potential window to new physics.

★ Its properties are studied with great precision at ATLAS experiment

★ Most of the precision measurements with Run1 data @ 8TeV are finished

★ All top quark properties are consistent with SM with current precision

★ Main sources of uncertainties come from jet and b-jet energy scale and the modelling of the ttbar processes

★ Starting to look at Run2 data @ 13TeV with larger statistics