Outline

- Indirect measurement of the top quark pole mass ($m_{\text{pole}}^{\text{top}}$) from lepton differential cross-sections
  - In a well-defined renormalization scheme
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- Overview of direct $m_{\text{top}}$ measurements at 8 TeV in the
  - $t\bar{t} \rightarrow$ all-jets channel,
  - $t\bar{t} \rightarrow$ dilepton channel, and
  - $t$-channel of single-top-quark production

**ATLAS** Preliminary  
$m_{\text{top}}$ summary - May 2017, $L_{\text{int}} = 4.6$ fb$^{-1}$ - 20.3 fb$^{-1}$

- all jets: $E_{\text{T}} = 6.9$ fb$^{-1}$
- single top$^*$: COF0 2014-01  
  - $L_{\text{int}} = 20.3$ fb$^{-1}$
- $t\bar{t}$-jets: ATLAS 2012-010  
  - $L_{\text{int}} = 4.7$ fb$^{-1}$
- dilepton: ATLAS 2013-020  
  - $L_{\text{int}} = 20.2$ fb$^{-1}$
- dilepton: ATLAS 2013-020  
  - $L_{\text{int}} = 20.2$ fb$^{-1}$
- all jets: ATLAS 2017-015  
  - $L_{\text{int}} = 30.2$ fb$^{-1}$

- ATLAS Comb. June 2016: $E_{\text{T}} = 6.9$ fb$^{-1}$
  - $m_{\text{top}}^{\text{pole}}$:
    - $m_{\text{top}} = 172.9 \pm 0.5^{+0.5}_{-0.4}$
    - $m_{\text{top}} = 173.7 \pm 0.3^{+0.3}_{-0.1}$

- ATLAS Comb. ± 1σ
  - stat. uncertainty
  - stat. ± JSF ± bJSF ± syst. uncertainty
  - total uncertainty

$^*$Preliminary, → Input to comb.
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- Overview of direct $m_{\text{top}}$ measurements at 8 TeV in the
  - $t\bar{t} \rightarrow \text{all-jets channel}$,
  - $t\bar{t} \rightarrow \text{dilepton channel}$, and
  - $t$-channel of single-top-quark production

- New measurement of $m_{\text{top}}$ in the
  - $t\bar{t} \rightarrow \text{lepton+jets channel}$ at 8 TeV

- New ATLAS combination of $m_{\text{top}}$

Conclusions and remarks
Example distribution: $p_T^{e\mu}$

- Using $t\bar{t} \rightarrow e\mu + X$ events, measure several lepton/dilepton differential distributions
  
  - $p_T^\ell$, $|\eta^\ell|$, $p_T^{e\mu}$, $m^{e\mu}$, $|y^{e\mu}|$, $\Delta\phi^{e\mu}$, $p_T^e + p_T^\mu$, and $E^e + E^\mu$
**Example distribution: $p_T^{e\mu}$**

- Using $t\bar{t} \rightarrow e\mu + X$ events, measure several lepton/dilepton differential distributions:
  - $p_T^{\ell}$, $|\eta^{\ell}|$, $p_T^{e\mu}$, $m^{e\mu}$, $|y^{e\mu}|$, $\Delta \phi^{e\mu}$, $p_T^{e} + p_T^{\mu}$, and $E^e + E^\mu$

- Both $m_{\text{top}}$ and $m_{\text{top}}^{\text{pole}}$ can be determined using normalized particle-level distributions
Example distribution: $p_T^{e\mu}$

$p_T^{e\mu}$ sensitivity to $m_{\text{top}}$

Fixed-order prediction/data

- Using $t\bar{t} \rightarrow e\mu + X$ events, measure several lepton/dilepton differential distributions
  - $p_T^\ell$, $|\eta^\ell|$, $p_T^{e\mu}$, $m^{e\mu}$, $|y^{e\mu}|$, $\Delta \phi^{e\mu}$, $p_T^e + p_T^\mu$, and $E^e + E^\mu$

- Both $m_{\text{top}}$ and $m_{\text{top}}^{\text{pole}}$ can be determined using normalized particle-level distributions

- The data are described by fixed-order predictions, within uncertainties
$m_{\text{top}}$ results (in a well-defined renormalization scheme) are extracted from the measured distributions by fits to the fixed-order NLO QCD predictions.

A combined fit with all distributions (constraining PDF and QCD scale unc.) results in:

$$m_{\text{top}} = 173.2 \pm 0.9 \text{ (stat)} \pm 0.8 \text{ (syst)} \pm 1.2 \text{ (theo)} \text{ GeV} = 173.2 \pm 1.6 \text{ GeV}$$

The theory uncertainty is dominated by QCD scale variations (1.1 GeV).
Direct measurement template methods

The direct measurements of $m_{\text{top}}$ at 8 TeV in ATLAS all use the template method

- Distributions of variables that are sensitive to $m_{\text{top}}$ are fit to analytical functions at several discrete values of the input $m_{\text{top}}$
- These functions are then parameterized as functions of the input $m_{\text{top}}$

Single-top: $m_{lb}$

All-hadronic: $R_{3/2} = \frac{m_{jjj}}{m_{jj}}$

Dilepton: $m_{lb}$
Direct measurement optimization strategies

- Single-top
  - Use a neural network (NN) to better distinguish between signal and background events
  - Choose a cut on the NN output to obtain a $t$-channel purity of 50%

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**ATLAS Preliminary**

2 Jets SR electrons + muons

- DATA
- $t\bar{t}$
- Wt, s-channel
- W+jets
- Z+jets, diboson
- Multijets
- uncertainty

$L_{dt} = 20.3 \text{ fb}^{-1}$
Direct measurement optimization strategies

- Single-top
  - Use a neural network (NN) to better distinguish between signal and background events
  - Choose a cut on the NN output to obtain a \( t \)-channel purity of 50%

- All-hadronic \( \text{arXiv:1702.07546} \)
  - Use the \( R_{3/2} \) distribution as the estimator for \( m_{\text{top}} \) instead of \( m_{jjj} \)
  - More protected from variations in the JES: \( R_{3/2} = \frac{m_{qqb}}{m_{qq}} \propto \frac{\text{JES} \cdot b\text{JES}}{\text{JES}} \)
Direct measurement optimization strategies

- **Single-top**
  - Use a neural network (NN) to better distinguish between signal and background events
  - Choose a cut on the NN output to obtain a $t$-channel purity of 50%

- **All-hadronic**
  - Use the $R_{3/2}$ distribution as the estimator for $m_{\text{top}}$ instead of $m_{jjj}$.
    - More protected from variations in the JES: $R_{3/2} = \frac{m_{qqb}}{m_{qq}} \propto \frac{JES_b \cdot JES}{JES}$

- **Dilepton.**
  - Optimize a cut on $p_{T,lb}$ to minimize the total uncertainty
Direct measurement results in data

Finally, a fit is applied to the observed data to extract $m_{\text{top}}$

**Single-top:** binned max-LH

**All-hadronic:** binned min-$\chi^2$

**Dilepton:** unbinned max-LH

$m_{\text{top}} = 172.2 \pm 0.7\,\text{(stat)} \pm 2.0\,\text{(syst)}\,\text{GeV}$

$m_{\text{top}} = 173.72 \pm 0.55\,\text{(stat)} \pm 1.01\,\text{(syst)}\,\text{GeV}$

$m_{\text{top}} = 172.99 \pm 0.41\,\text{(stat)} \pm 0.74\,\text{(syst)}\,\text{GeV}$
Direct measurement dominant systematic uncertainties ($\Delta m_{\text{top}}$ [GeV])

- **Single-top.**
  - JES (1.5) and $t$-channel hadronisation (0.7)
  - Total uncertainty: $2.1 \text{ GeV}$ (1.2%)
Direct measurement dominant systematic uncertainties ($\Delta m_{\text{top}}$ [GeV])

- **Single-top**
  - JES (1.5) and $t$-channel hadronisation (0.7)
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- **All-hadronic.**
  - JES (0.60), hadronisation (0.64), and bJES (0.34)
  - Total uncertainty: **1.15 GeV** (0.66%)

<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>$\Delta m_{\text{top}}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monte Carlo generator</td>
<td>$0.18 \pm 0.21$</td>
</tr>
<tr>
<td>Hadronisation modelling</td>
<td>$0.64 \pm 0.15$</td>
</tr>
<tr>
<td>Parton distribution functions</td>
<td>$0.04 \pm 0.00$</td>
</tr>
<tr>
<td>Initial/final-state radiation</td>
<td>$0.10 \pm 0.28$</td>
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<tr>
<td>Underlying event</td>
<td>$0.13 \pm 0.16$</td>
</tr>
<tr>
<td>Colour reconnection</td>
<td>$0.12 \pm 0.16$</td>
</tr>
<tr>
<td>Bias in template method</td>
<td>$0.06$</td>
</tr>
<tr>
<td>Signal and bkgd parameterisation</td>
<td>$0.09$</td>
</tr>
<tr>
<td>Non all-hadronic $t\bar{t}$ contribution</td>
<td>$0.06$</td>
</tr>
<tr>
<td>ABCD method vs. ABCDEF method</td>
<td>$0.16$</td>
</tr>
<tr>
<td>Trigger efficiency</td>
<td>$0.08 \pm 0.01$</td>
</tr>
<tr>
<td>Lepton/$E_T^{\text{miss}}$ calibration</td>
<td>$0.02 \pm 0.01$</td>
</tr>
<tr>
<td>Overall flavour-tagging</td>
<td>$0.10 \pm 0.00$</td>
</tr>
<tr>
<td>Jet energy scale (JES)</td>
<td>$0.60 \pm 0.05$</td>
</tr>
<tr>
<td>b-jet energy scale (bJES)</td>
<td>$0.34 \pm 0.02$</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>$0.10 \pm 0.04$</td>
</tr>
<tr>
<td>Jet vertex fraction</td>
<td>$0.03 \pm 0.01$</td>
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<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td><strong>1.01</strong></td>
</tr>
<tr>
<td><strong>Total statistical uncertainty</strong></td>
<td><strong>0.55</strong></td>
</tr>
<tr>
<td><strong>Total uncertainty</strong></td>
<td><strong>1.15</strong></td>
</tr>
</tbody>
</table>
Direct measurement dominant systematic uncertainties ($\Delta m_{\text{top}}$ [GeV])

- **Single-top**
  - JES (1.5) and $t$-channel hadronisation (0.7)
  - Total uncertainty: **2.1 GeV** (1.2%)

- **All-hadronic**
  - JES (0.60), hadronisation (0.64), and bJES (0.34)
  - Total uncertainty: **1.15 GeV** (0.66%)

- **Dilepton.**
  - JES (0.54), relative $b$-to-light JES (0.30), hadronisation (0.22), and ISR/FSR (0.23)
  - Total uncertainty: **0.84 GeV** (0.49%)
Direct measurement dominant systematic uncertainties ($\Delta m_{\text{top}}$ [GeV])

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  - JES (1.5) and $t$-channel hadronisation (0.7)
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New results

Measurement of $m_{\text{top}}$ in the lepton+jets channel at 8 TeV and a combination with previous ATLAS measurements

TIME FOR SOMETHING NEW!
Use the 3-D template method developed in the 7 TeV lepton+jets analysis

- Templates constructed from distributions of $m_{\text{top}}^{\text{reco}}$, $m_{W}^{\text{reco}}$, and $R_{bq}^{\text{reco}}$

$$R_{bq}^{\text{reco}} = \frac{p_{T}^{b_{\text{had}}} + p_{T}^{b_{\text{lep}}}}{p_{T}^{q_1} + p_{T}^{q_2}}, \text{ where } q_1 \text{ and } q_2 \text{ are the light jets assigned to the } W \text{ boson}$$

A 3D unbinned maximum likelihood fit of these templates is applied to the observed data to extract the measured $m_{\text{top}}$, JSF, and bJSF

The simultaneous measurement of $m_{\text{top}}$ with a jet energy scale factor (JSF) and a relative $b$-to-light-jet energy scale factor (bJSF) reduces the sizeable JES and bJES uncertainties in $m_{\text{top}}$
Require **one** high-$p_T$ electron or muon along with **at least four** high-$p_T$ central jets
- Exactly **two** of these jets must be **$b$-tagged**

Use a kinematic likelihood fitter (KLFitter) for jet-parton assignment and to obtain $m_{\text{reco}}^{\text{top}}$

- $m_{\text{reco}}^{\text{top}}$ reconstructed within the KLFitter
- $m_{\text{reco}}^{W}$ and $R_{\text{reco}}^{bq}$ use the chosen jet permutation from KLFitter, but the original jet momentum 4-vectors
  - in order to retain the maximum sensitivity to JES and bJES
Idea:
- Remove wrongly/unmatched events, expected to have larger systematic uncertainties

Method:
- Train a BDT algorithm to distinguish these events from correctly matched events
- Make a cut on the BDT output ($r_{\text{BDT}}$)

- 13 variables are used as inputs to the BDT
- The two with by far the greatest separation power are
  - the KLFitter likelihood of the best permutation
  - the angular separation of the two untagged jets from the hadronically decaying $W$ boson ($\Delta R(q, q)$)
The BDT is trained on $t\bar{t}$ signal MC

- Good separation of the event categories

A scan of the cut on $r_{\text{BDT}}$ around the crossing point of 0 is performed

- Run complete analysis for each point in the scan to compare the total uncertainty in $m_{\text{top}}$

A cut of $r_{\text{BDT}} \geq -0.05$ results in the smallest total uncertainty
After applying the $r_{\text{BDT}}$ cut, the background fraction is only 1%.

Single-top-quark production is included in signal:
  - resulting in a background independent of $m_{\text{top}}$

Distributions of fit variables agree well with data within uncertainties:
  - MC simulation is normalised to the data and only shape uncertainties remain in the band.
Simulated distributions of $m_{\text{top}}^{\text{reco}}$, $m_{W}^{\text{reco}}$, and $R_{bq}^{\text{reco}}$ are fit to analytical functions which are parameterised as functions of the input $m_{\text{top}}$, JSF, and bJSF depending on sensitivity:

- $m_{\text{top}}^{\text{reco}}$ ($m_{\text{top}}$, JSF, bJSF) strong to all three
- $m_{W}^{\text{reco}}$ (JSF) strong to JSF, negligible to $m_{\text{top}}$ and bJSF
- $R_{bq}^{\text{reco}}$ ($m_{\text{top}}$, JSF, bJSF) strong to bJSF, weak to $m_{\text{top}}$ and JSF
The 3D unbinned maximum likelihood fit to the data results in:

\[ m_{\text{top}} = 172.08 \pm 0.39 \text{(stat)} \text{ GeV} \quad \text{JSF} = 1.005 \pm 0.001 \text{(stat)} \quad \text{bJSF} = 1.008 \pm 0.005 \text{(stat)} \]

Including systematic uncertainties, the result is:

\[ m_{\text{top}} = 172.08 \pm 0.39 \text{(stat)} \pm 0.82 \text{(syst)} \text{ GeV} = 172.08 \pm 0.91 \text{ GeV} \]
Dominant sources of uncertainty
- JES (0.54 GeV) and $b$-tagging (0.38 GeV)

Total uncertainty reduced with BDT sel.
- 19% improvement over no BDT at 8 TeV
- Reduces theory modelling uncertainties
- Also improves resolution in $m_{\text{top}}$ as seen by the scaling of the stat. unc.
  - With no improvement in resolution:
    \[
    \sigma_{\text{BDT}}^{\text{stat}} = \sigma_{\text{std}}^{\text{stat}} \sqrt{N_{\text{std}}/N_{\text{BDT}}} = 0.60
    \]
    as compared to 0.39
- Altogether, a 29% improvement over the 7 TeV lepton+jets measurement

Given the new result, an updated ATLAS combination is performed
Combination: correlations of pairs of estimators

-lepton+jets (8 TeV) vs. dilepton (8 TeV)

-lepton+jets (8 TeV) vs. lepton+jets (7 TeV)

- Pairwise $\Delta m_{\text{top}}$ when simultaneously varying a pair of measurements for each syst. unc.
- The correlations of the estimators for each uncertainty component are evaluated
- The combination is performed using the BLUE method

ATLAS Preliminary
Combined value (left) and uncertainty (right) in the combination of the two 8 TeV measurements as a function of their total correlation (blue line)

- The red and gray lines indicate the pair of input values (left) and uncertainties (right)
- The uncertainty in the combined \(m_{\text{top}}\) strongly depends on the total correlation
This combination results in a precision of 0.29%:

\[ m_{\text{top}} = 172.51 \pm 0.27\text{(stat)} \pm 0.42\text{(syst)} \text{ GeV} = 172.51 \pm 0.50 \text{ GeV} \]

- a 41% improvement w.r.t. the most precise single input measurement
- a 29% improvement w.r.t. the previous ATLAS combination
Conclusions and remarks

- An indirect measurement of $m_{\text{top}}^{\text{pole}}$ has been made using lepton differential cross-sections.
- Direct measurements of $m_{\text{top}}$ have been made using the 8 TeV ATLAS data in all $t\bar{t}$ decay channels as well as in the $t$-channel of single-top-quark production.
- **New** 8 TeV measurement of $m_{\text{top}}$ in the $t\bar{t} \rightarrow \text{lepton+jets}$ channel:
  \[ m_{\text{top}}^{1+\text{jets}} = 172.08 \pm 0.91 \text{ GeV} \]
- **New** ATLAS combination of $m_{\text{top}}$:
  \[ m_{\text{top}}^{\text{comb}} = 172.51 \pm 0.50 \text{ GeV (0.29\%)} \]
  - The two LHC combinations of $m_{\text{top}}$ are consistent and have comparable precision.
- Take-away messages from 8 TeV:
  - Trade statistical for systematic precision to achieve a reduced total uncertainty.
  - Keep the combination in mind and **minimize the correlation** between individual measurements whenever possible.
- Looking forward to $m_{\text{top}}$ results from 13 TeV data!
<table>
<thead>
<tr>
<th>Separation</th>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>31%</td>
<td>$\ln L$</td>
<td>Logarithm of the likelihood of best permutation</td>
</tr>
<tr>
<td>13%</td>
<td>$\Delta R(q, q)$</td>
<td>$\Delta R$ of the two untagged jets from the hadronically decaying $W$ boson</td>
</tr>
<tr>
<td>5.0%</td>
<td>$p_T(W_{\text{had}})$</td>
<td>$p_T$ of hadronically decaying $W$ boson</td>
</tr>
<tr>
<td>4.3%</td>
<td>$p_{T,\text{had}}$</td>
<td>$p_T$ of hadronically decaying top quark</td>
</tr>
<tr>
<td>4.2%</td>
<td>$P_{E\text{vt}}$</td>
<td>Event probability of best permutation</td>
</tr>
<tr>
<td>2.0%</td>
<td>$p_T(t\bar{t})$</td>
<td>$p_T$ of reconstructed $t\bar{t}$ system</td>
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<tr>
<td>1.7%</td>
<td>$p_{T,\text{lep}}$</td>
<td>$p_T$ of leptonically decaying top quark</td>
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<tr>
<td>1.2%</td>
<td>$m_T^W$</td>
<td>Transverse mass of leptonically decaying $W$ boson</td>
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<td>0.3%</td>
<td>$p_T(W_{\text{lep}})$</td>
<td>$p_T$ of leptonically decaying $W$ boson</td>
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<td>0.3%</td>
<td>$N_{\text{jets}}$</td>
<td>Number of jets</td>
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<tr>
<td>0.2%</td>
<td>$\Delta R(b, b)$</td>
<td>$\Delta R$ of reconstructed $b$-tagged jets</td>
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<tr>
<td>0.2%</td>
<td>$E_T^{\text{miss}}$</td>
<td>Missing transverse momentum</td>
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<tr>
<td>0.1%</td>
<td>$p_T,\ell$</td>
<td>$p_T$ of lepton</td>
</tr>
</tbody>
</table>
8 TeV lepton+jets: data/MC agreement in BDT output

\[ \text{BDT} \]

\[ r = 0.6 - 0.4 - 0.2 - 0 \]

\[ 0.2 0.4 \]

\[ \text{Data/MC} \]

\[ 0.8 1 1.2 \]

\[ \text{Events / 02} \]

\[ 1000 2000 3000 4000 5000 6000 7000 \]

\[ = 8 \text{ TeV}, 20.2 \text{ fb}^{-1} \]

\[ \text{ATLAS Preliminary} \]

\[ \sqrt{s} = 8 \text{ TeV}, 20.2 \text{ fb}^{-1} \]

\[ \text{Top mass in ATLAS} \]

\[ \text{Braga, Portugal} \]

\[ 19 \text{ September 2017} \]