Why, and how, to Measure the Top Quark Mass?

- Fundamental parameter of the Standard Model
- Largest scale in the Standard Model
- 5 orders of magnitude between up quark and top quark mass
  (not dissimilar to neutrino: electron hierarchy)
- Large effect on the running of the Higgs coupling and stability of the SM vacuum
- Only quark that decays prior to hadronisation
- Probe of QCD and heavy flavour behaviour
Why, and how, to Measure the Top Quark Mass?

Decays can be either fully hadronic, semi-leptonic, or fully leptonic.

**Fully hadronic**
- all top decay products are seen, incl. 1 or 2 b-jets, but, larger QCD effects/background

**Boosted hadronic**
- high pT tops boost decay products into a single (fat) jet
- reduced background (searches), but needs special jet treatment

**semi-leptonic**
- One top decays to b-jet + hadronically decaying W, the other to a b-jet + leptonically decaying W
- Generally most precise, still relies on template fit modelling

**fully-leptonic**
- Both tops decay to b-jet + leptonically decaying W
- Less dependent on jet modelling, but not all decay products can be reconstructed (MET)
Outline

- Will show most recent results from LHC representing overview of these channels
  - di-lepton + b-jets at ATLAS
  - (one) Muon + 4 jets at CMS
  - 3/2 jet ratio in hadronic top decays at ATLAS
  - Boosted top jets at CMS
  - Measurement of mass in single top events

There are a large number of measurements and methods, too many to show them all in this talk.

ATLAS

http://inspirehep.net/record/1094859 - lepton + jets template @ 7 TeV
http://inspirehep.net/record/1261966 - t-tbar mass difference @ 7 TeV
http://inspirehep.net/record/1353391 - lepton + jets and di-lepton @ 7 TeV
http://inspirehep.net/record/1313597 - Fully hadronic @ 7 TeV
http://inspirehep.net/record/1381766 - Pole mass in ttbar + 1 jet
http://inspirehep.net/record/1515025 - Fully hadronic @ 8 TeV (this talk)
http://inspirehep.net/record/1468064 - Di-lepton @ 8 TeV (this talk)

CMS

http://inspirehep.net/record/901829 - lepton + jets @ 7 TeV
http://inspirehep.net/record/1185101 - t-tbar mass difference @ 7 TeV
http://inspirehep.net/record/1185104 - lepton @ 7 TeV
http://inspirehep.net/record/1229333 - di-lepton kinematics @ 7 TeV
http://inspirehep.net/record/1243161 - fully hadronic @ 7 TeV
http://inspirehep.net/record/1241819 - pole mass from cross section @ 7 TeV
http://inspirehep.net/record/1393269 - combination @ 7 & 8 TeV
http://inspirehep.net/record/1430902 - using track jets @ 8 TeV
https://arxiv.org/abs/1701.06228 - single lepton + jets @ 13 TeV (this talk)
https://arxiv.org/abs/1703.02530 - single top events @ 13 TeV (this talk)

Best precision is reached when combining all of them across all experiments
Di-lepton + b-jets with ATLAS

- Electrons, ET > 25 GeV
- Muons, pT > 25 GeV
- Exactly two oppositely charged isolated leptons
- If both leptons same flavour, missing ET > 60 GeV and di-lepton mass outside Z window
- At least two anti-Kt R=0.4 jets with pT > 25 GeV
- At least one of the jets must be b-tagged

Take the lepton-b-jet pairs that minimise the mean mass for the pair in the event

Select events for which the mean l-b-jet pT is above 120 GeV
MC templates produced with Powheg + Pythia 6 (P2011).

(Alpgen + Pythia or Herwig also used for bg, and MC variations use MC@NLO + Herwig)

Signal and bg lepton-b-jet masses fitted with Landau curve -> only free param is $m_t$

Systematic uncertainties are dominated by QCD MC modelling and jet energy scale

<table>
<thead>
<tr>
<th>Source</th>
<th>Approach</th>
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<tbody>
<tr>
<td><strong>Hadronisation</strong></td>
<td>Pythia Vs. Herwig</td>
<td>$0.22 \pm 0.09$ GeV</td>
</tr>
<tr>
<td><strong>Shower &amp; QCD</strong></td>
<td>Matching scale &amp; hdamp variations</td>
<td>$0.23 \pm 0.07$ GeV</td>
</tr>
<tr>
<td><strong>ME</strong></td>
<td>MC@NLO Vs. Powheg</td>
<td>$0.09 \pm 0.15$ GeV</td>
</tr>
<tr>
<td><strong>Jet Energy Scale</strong></td>
<td>25 up/down variations</td>
<td>$0.54 \pm 0.04$ GeV</td>
</tr>
<tr>
<td><strong>B-jet calibration</strong></td>
<td>Additional jet energy uncertainty</td>
<td>$0.3 \pm 0.1$ GeV</td>
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Best fit value is $m_t = 172.99 \pm 0.41$ (stat) $\pm 0.74$ (syst) GeV
Muon + 4 Jets with CMS

https://inspirehep.net/record/1517829

Selection:

- Exactly 1 muon, \( p_T > 25 \) GeV
- At least 4 anti-Kt \( R=0.4 \) jets, \( p_T > 30 \) GeV
- Exactly 2 of the leading 4 jets must be b-tagged
- Combine W-candidate with both b-jets (will give wrong combinations)
- Refine the selection by applying a fit to the 4 jets, muon and missing ET -> reject t candidates where implied \( P(\text{top}) \) is less than 0.2
Muons + 4 Jets with CMS

https://inspirehep.net_RECORD/1517829

"Ideogram" fit method (also used at 7 TeV)

- lepton, 4-jets and MET. Different permutations give different fit masses
- → take the one with lowest $X^2$

JES calibrated in same events using W-mass in fit

Systematic uncertainties are dominated by jet energy calibration and QCD modelling

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<td>Shower matching</td>
<td>Scale variations</td>
<td>0.23 GeV</td>
</tr>
<tr>
<td>Soft QCD</td>
<td>Tune and colour reconnection variations</td>
<td>0.18 GeV, 0.22 GeV</td>
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Reconstructing the top mass from hadronic top decays to 3 jets is susceptible to corrections from both the jet energy scale (detector calibration) and hadronic corrections.

The jets themselves are intrinsically sensitive to QCD modelling - depend on jet R param, out of cone radiation, non-perturbative effects etc.

But, these things affect the W-candidate as well as the top -> there is a significant degree of cancellation in the ratio of the 3-jet top-candidate mass ($M_{jjj}$) to the 2-jet W-candidate mass ($M_{jj}$).
Selection:

- At least 5 jets, \( p_T > 60 \) GeV. Any additional “lead” jets \( p_T > 25 \) GeV
- Jets must be separated by \( \Delta R > 0.6 \)
- Missing ET < 60 GeV (no neutrinos)
- Muon veto (\( p_T > 20 \) GeV) and electron veto (ET > 25 GeV)
- 2 of the lead jets must be b-tagged
- Highest two b-weight jets must satisfy \( \Delta \phi > 1.5 \)
- W-candidate and associated b-jet satisfy \( \Delta \phi > 2 \)

Top candidate combinations selected by minimising

\[
\chi^2 = \frac{(m_{b_1j_1j_2} - m_{b_2j_3j_4})^2}{\sigma^2_{m_{bjj}}} + \frac{(m_{j_1j_2} - m_W)^2}{\sigma^2_{m_W}} + \frac{(m_{j_3j_4} - m_W)^2}{\sigma^2_{m_W}}
\]
Fits to Data

5 Powheg + Pythia samples at mass points 167.5, 170, 172.5, 175 and 177.5 are fitted by a Landau + Novosibirsk curve -> 6 params per curve, but they are linear in generated mass

Systematics are (surprise!) dominated by QCD modelling and jet energy scale. Main ones are

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<td>0.34 GeV</td>
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$173.72 \pm 0.55 \text{ (statistical)} \pm 1.01 \text{ (systematic)} \text{ GeV}$
1. The result is polynomial to determine the minimum, and the uncertainty is determined by a change in and certainties. The latter are calculated by changing up and down by factors of two the scales matrix, which includes the statistical, experimental systematic, modelling, and theoretical uncertainties. The numerical values of the measured particle-level cross sections are given in Table 3, together with the predictions of M\(^{\text{AD}}\) through the full covariance matrix of the measurement, which is given in Appendix A. The data are well described by the simulation, showing that the overall theoretical predictions are obtained from M\(^{\text{AD}}\).

When appropriate calculations become available, can be used to extract the top mass in a theoretically well defined way -

- lepton + jets channel, one muon or electron with p\(T\) > 45 GeV and |\(\eta\)| < 2.1
- Exactly one additional jet, p\(T\) > 150 GeV. Second jet and lepton must satisfy \(\Delta r < 1.2\)
- Largest uncertainties are statistical. More data will allow a better unfolding (more finely binned, more correlations)
- Modelling of ttbar production also affects the unfolding and contributes to the uncertainty.

Unfolded R=1.2 CA jets, p\(T\) > 400 GeV, |\(\eta\)| < 2.5

170.8 ± 6 (stat) ± 2.8 (syst) ± 4.6 (MC) ± 4 (theory) GeV
Single top is produced at LHC via electroweak exchange.

Interesting because

- Different production means different QCD background to ttbar pair production -> different colour topology could help constrain QCD uncertainty
- Theoretical grey area (difference between ttbar and t + highly off-shell t = W + b)

Event selection:

- 1 isolated muon with pT > 26 GeV (no additional muons above 10 GeV or electron above 20 GeV)
- Two AKt R=0.5 jets, pT > 40 GeV. Exactly one b-tag (selects t-channel W EW exchange above)
- Missing transverse pT > 50 GeV
- Transverse mass of the W (μ + pTMiss) > 50 GeV

After final selection requires light jet |η| > 2.5 and muon charge is positive
Top Mass in Single Top Events with CMS

https://inspirehep.net/record/1516412

Fit $\mu_\text{vb}$ mass with crystal ball function

Needs calibration of fitted mean Vs. generated mass - 5 MC samples

Largest uncertainties are jet calibration, background fit and fit calibration

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<td>Up / down jet energy scale variations</td>
<td>+0.68 / -0.61 GeV</td>
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<td>0.39 GeV</td>
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BG is dominated by t\bar{t}bar and W+jets (MadGraph + Pythia 6). BG normalisation is varied up and down by 1 $\sigma$, and the BG fit params are also varied by the same. BG scale variations add 0.18 (fact + renorm) and 0.3 (shower matching) GeV

$172.95 \pm 0.77$ (stat) + 0.97 / -0.93 (syst) GeV
Combinations are a bit old and will need to be re-done once the full set of 8 and 13 TeV results are available.

Most recent ATLAS combination: $172.84 \pm 0.7$ GeV (June 2016)

Most recent CMS combination: $172.44 \pm 0.13 \pm 0.47$ GeV (Sept 2015)
The most recent world combination (incl. Tevatron) is 173.34 ± 0.76 GeV (March 2014). Only includes 7 TeV LHC results -> to be updated!
Have shown recent results representing the range of LHC top mass measurements

Di-lepton channel at ATLAS and muon + 4 jets at CMS
- Channels with the best experimental precision

Hadronic channel at ATLAS
- 3/2 ratio reduces QCD and jet uncertainties

Single top at CMS
- Complementary channel with different QCD dependence

Boosted fat top jets at CMS
- Demonstration of feasibility, opportunity for well defined theory and QCD constraints