Measurement of the top quark mass in topologies enhanced with single top-quarks produced in the t-channel at $\sqrt{s} = 8\,\text{TeV}$ using the ATLAS experiment

Hendrik Esch

Technische Universität Dortmund, Lehrstuhl EIV

02.12.2014

Annual Meeting of the Helmholtz Alliance

Bundesministerium für Bildung und Forschung

technische universität dortmund

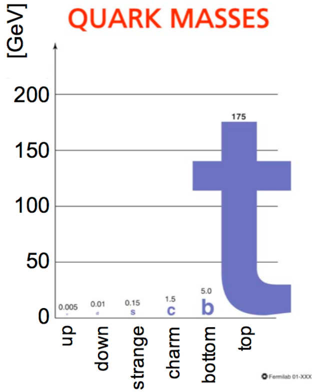
FSP 101 ATLAS

Measurement of the top quark mass in topologies enhanced with single top-quarks produced in the t-channel at $\sqrt{s} = 8\,\text{TeV}$ using the ATLAS experiment

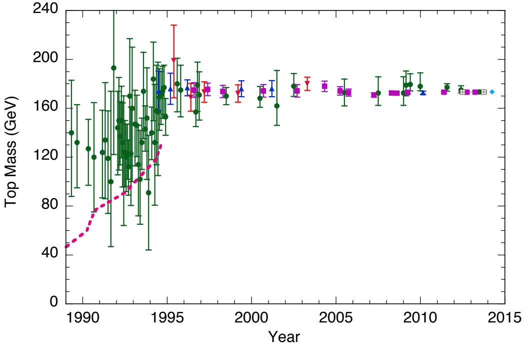
1. The top quark and its mass
2. Basic event selection and neural network based event selection
3. Measurement of the top quark mass

- More details in ATLAS-CONF-2014-055

technische universität dortmund



[1]



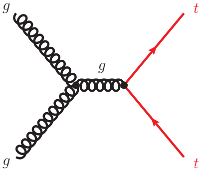
[2]

- The top quark has a much higher mass than all other known elementary particles
- First indirect mass measurements in the early 1990s
- Current world combination from 2014 yields [3]:

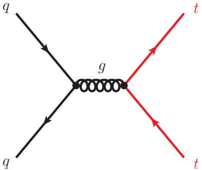
$$m_{\mathrm{top}} = (173.34 \pm 0.27\,(\mathrm{stat.}) \pm 0.71\,(\mathrm{syst.}))\ \mathrm{GeV}$$

[1] http://www-d0.fnal.gov/Run2Physics/top/public/fall06/singletop/plain_english_summary.html
[2] http://lutece.fnal.gov/TTS/ [3] ATLAS-CONF-2014-008, CDF-NOTE-11071, CMS-PAS-TOP-13-014, D0-NOTE-6416

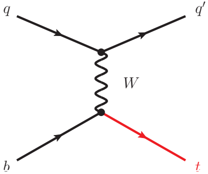
- Discovery in $t\bar{t}$ pair production in 1995 at the Tevatron
- $t\bar{t}$ pair production is always mediated by the strong interaction
- All previous mass measurements performed in $t\bar{t}$ final states

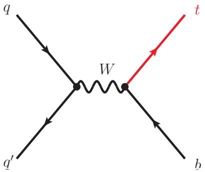


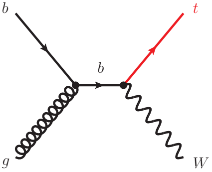
gluon fusion



$q\bar{q}$ annihilation







- First observation of single top quarks in 2009 in *t*+*s*-channel at the Tevatron
- Evidence of associated production with a *W*-boson observed in 2012 at the LHC
- Single top quarks are always produced by the weak interaction

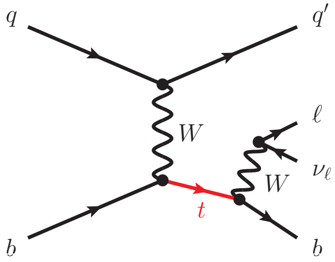
technische universität dortmund

Measuring m_{top} in single-top t-channel topologies

Goal: First measurement of the top quark mass in topologies enhanced with single top-quarks produced in the t-channel

- Event topology is different and has never been studied to measure m_{top}
  - Production via the weak interaction at different typical energy scale
  - Different final state without ambiguities in the jet-parton assignment
  - Complementary sensitivity of systematic uncertainties
- Orthogonal phase-space

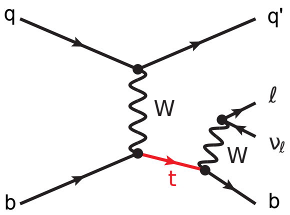
$\rightarrow$ Very good prospects for future combinations



- Electron or muon with $p_T > 25$ GeV and $|\eta| < 2.5$
- Exactly two jets with $p_T > 30$ GeV and $|\eta| < 4.5$
  - $p_T > 35$ GeV (if $2.75 < |\eta^{\text{jet}}| < 3.5$)
- $E_T^{\text{miss}} > 30$ GeV
- $m_T(W) = \sqrt{2 p_T^{\ell} E_T^{\text{miss}} \left[1 - \cos \Delta\varphi(\ell, E_T^{\text{miss}})\right]} > 50$ GeV

Additional cut reducing multijet background

- $p_T^{\ell} > 40\ \text{GeV} \left(1 - \frac{\pi - |\Delta\varphi(\text{jet}_1, \ell)|}{\pi - 1}\right)$
- Reject leptons with low p_T and large opening angle with leading jet (e.g. from dijet production with fake lepton)

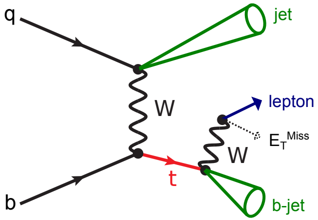


- Signal region:
  - Exactly one jet is tagged by MV1c at $\varepsilon_b^{t\bar{t}} = 50\%$
- Control region enriched with main background (W+jets)
  - Veto against signal region (No jet is tagged by MV1c at $\varepsilon_b^{t\bar{t}} = 50\%$)
  - Exactly one jet is tagged by MV1 at $\varepsilon_b^{t\bar{t}} = 80\%$

- Electron or muon with $p_T > 25$ GeV and $|\eta| < 2.5$
- Exactly two jets with $p_T > 30$ GeV and $|\eta| < 4.5$
  - $p_T > 35$ GeV (if $2.75 < |\eta^{\mathrm{jet}}| < 3.5$)
- $E_T^{\mathrm{miss}} > 30$ GeV
- $m_T(W) = \sqrt{2p_T^{\ell} E_T^{\mathrm{miss}} \left[1 - \cos\Delta\varphi(\ell, E_T^{\mathrm{miss}})\right]} > 50$ GeV

Additional cut reducing multijet background

- $p_T^{\ell} > 40\ \mathrm{GeV} \left(1 - \frac{\pi - |\Delta\varphi(\mathrm{jet}_1, \ell)|}{\pi - 1}\right)$
- Reject leptons with low p_T and large opening angle with leading jet (e.g. from dijet production with fake lepton)



- Signal region:
  - Exactly one jet is tagged by MV1c at $\varepsilon_b^{t\bar{t}} = 50\%$
- Control region enriched with main background (W+jets)
  - Veto against signal region (No jet is tagged by MV1c at $\varepsilon_b^{t\bar{t}} = 50\%$)
  - Exactly one jet is tagged by MV1 at $\varepsilon_b^{t\bar{t}} = 80\%$

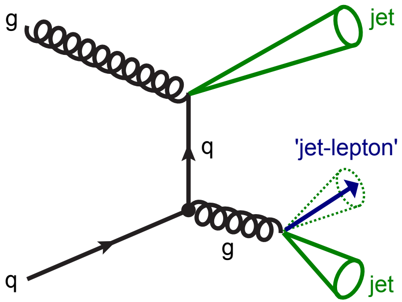
- Two different models to mimic the shape of the multijet background

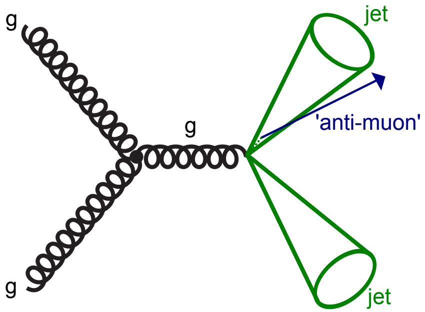
Jet-lepton model

- Requirement of a selected lepton is replaced by a lepton-like jet
- Jet-lepton has to fulfil the same kinematic requirements as a true lepton

Anti-muon model

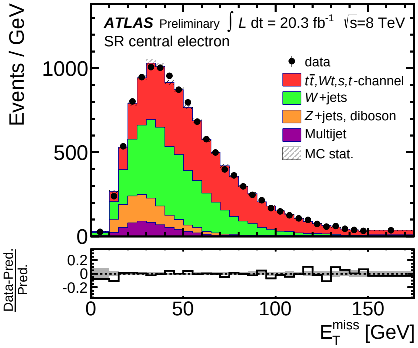
- The anti-muon template is taken from a sample highly enriched with fake muons
- Done by relaxing or inverting some of the muon identification cuts



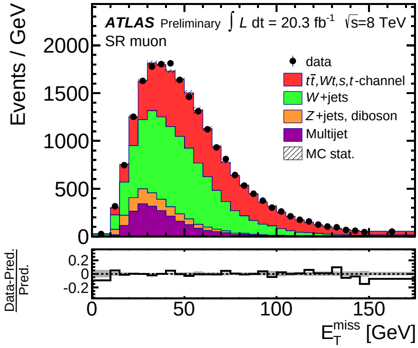


- Both models provide a shape of the multijet background but no normalisation
- Normalisation is estimated using a binned likelihood fit in the full E_T^{miss} distribution in data
  - W+jets, Z+jets, Diboson and top component from simulation fitted with Gaussian constraints
  - Multijet rate is obtained from the fit

[4]

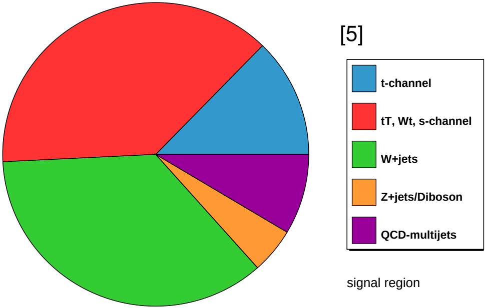


[4]

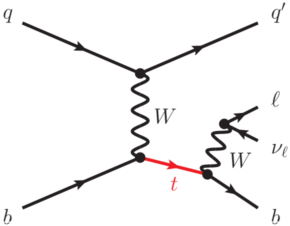


[4] ATLAS-CONF-2014-007

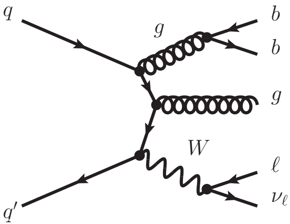
[5]



signal region



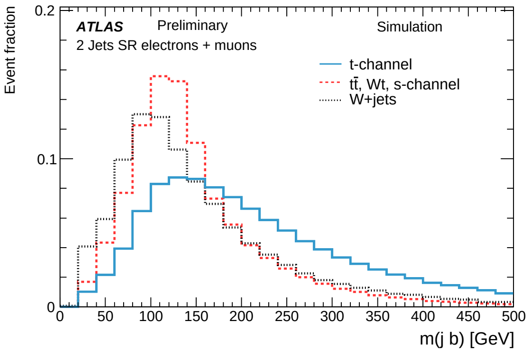
t-channel signal

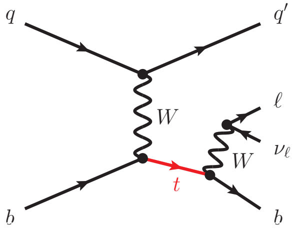


non-reducible background

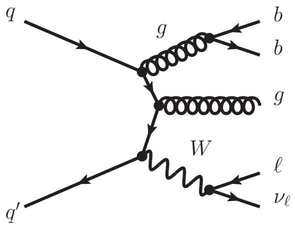
- About 143000 events selected from the full dataset
- Caveat of the basic event selection is a high fraction of non-reducible background

[5] from Table 2 in ATLAS-CONF-2014-007



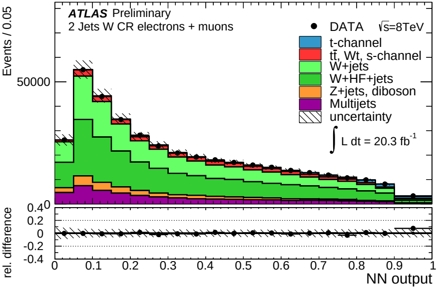


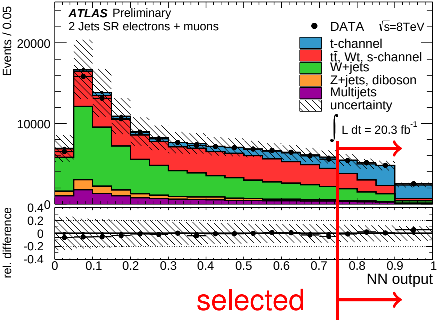
t-channel signal



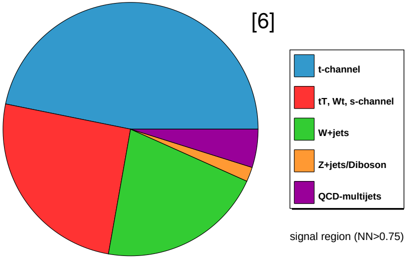
non-reducible background

- *t*-channel process can be fully reconstructed
- Exploit full event topology to distinguish signal from background events
- E.g. invariant mass of the two jets ($m(jb)$)
  $\rightarrow$ from gluon splitting in W+jets

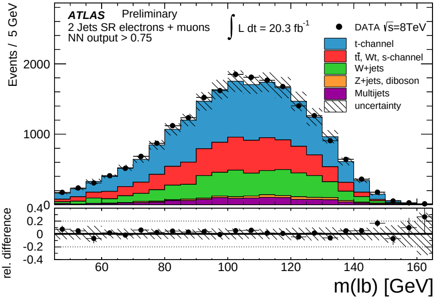


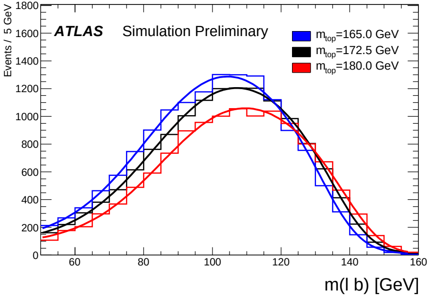


Variable	loss of total correlation (%)
$m(\ell\nu b)$	38
$m(jb)$	31
$m(\ell b)$	18
$\lvert\eta(j)\rvert$	14
$\eta(\ell\nu)$	13
$H_T(\ell, \mathrm{jets}, E_T^{\mathrm{miss}})$	10
E_T^{miss}	7
$m_T(W)$	7
$\cos\theta(\ell, j)_{\ell\nu b,r.f.}$	6
$p_T(W)$	3
$\eta(l\nu b)$	2
$\Delta R(\ell, \ell\nu b)$	1



[6] from Table 2 in ATLAS-CONF-2014-007

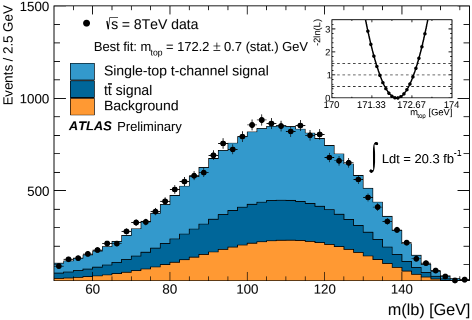




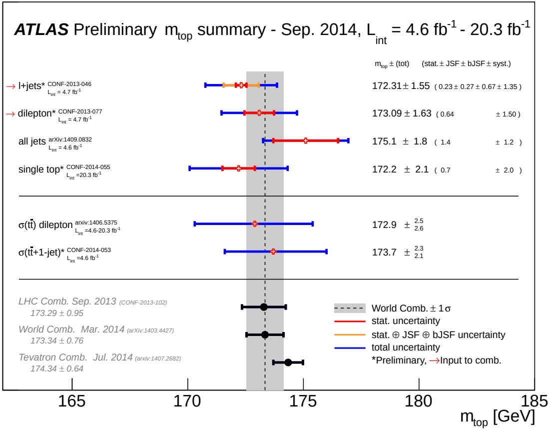
- The invariant mass $m(\ell b)$ of the charged lepton and b-tagged jet is employed as an estimator of the top quark mass using a template method
  - Same technique with the same variable has already been used e.g. in the dileptonic $\mathrm{t\bar{t}}$ decay channel (ATLAS-CONF-2013-077)
- In mass measurement all processes involving top-quarks are treated as signal
- Normalised templates for the signal and background are used in a binned maximum likelihood fit to data with:

$$\mathcal{L} = \prod_{\mathrm{bins}\ i} \mathrm{P}\left(m(\ell b)_i^{\mathrm{data}} | \lambda_i(N, f, s_i(m_{\mathrm{top}}), b_i)\right) \cdot \mathrm{G}\left(f | f_{\mathrm{bkg}}, \sigma_{f_{\mathrm{bkg}}}\right) \quad (1)$$

	Value [GeV]
Measured value	172.2
Statistical uncertainty	0.7
Jet energy scale	1.5
Jet energy resolution	< 0.1
Jet vertex fraction	< 0.1
Flavour tagging efficiency	0.3
Electron uncertainties	0.3
Muon uncertainties	0.1
Missing transverse momentum	0.2
W+jets normalisation	0.4
W+jets shape	0.3
Z+jets/diboson normalisation	0.2
Multijet normalisation	0.2
Multijet shape	0.3
Top normalisation	0.2
t-channel generator	< 0.1
t-channel hadronisation	0.7
t-channel colour reconnection	0.3
t-channel underlying event	< 0.1
$t\bar{t}$, Wt, and s-channel generator	0.2
$t\bar{t}$ hadronisation	< 0.1
$t\bar{t}$ colour reconnection	0.2
$t\bar{t}$ underlying event	0.1
$t\bar{t}$ ISR/FSR	0.2
Proton PDF	< 0.1
Simulation sample statistics	0.3
Total systematic uncertainty	2.0
Total uncertainty	2.1

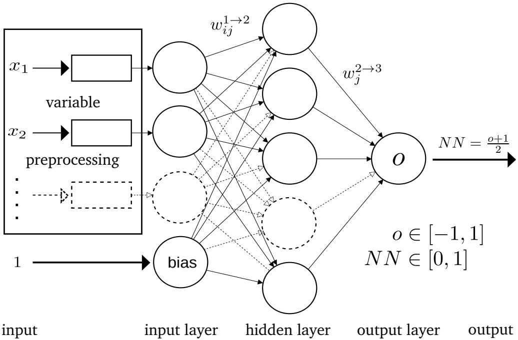


- Measurement is dominated by systematic uncertainties (mainly JES)
- More details about this analysis are given in ATLAS-CONF-2014-055

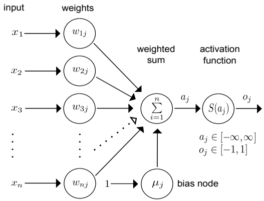


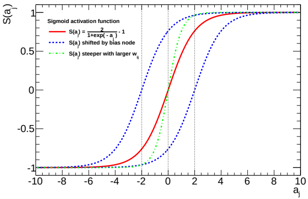
- Result is in good agreement with other ATLAS measurements in different $t\bar{t}$ final states
- The presented analysis is the first top mass mesaurement in this complementary topology $\rightarrow$ Many ideas to further improve the analysis
- The prospects to include this result in future top mass combinations are very good

Backup



- At each node the weighted sum of the input variables is passed through a sigmoid activation function.





- An artificial neural network is inspired by the human brain with neurons and synapses.
- During the training the weights (synapses) between neurons are modified such that the prediction of the network is as close as possible to the true expectation.
- Whole neural network framework and variable preprocessing is implemented in the Neurobayes package.

- The goal of the training procedure is to minimise the difference between the predicted output of the network, $o_K \in [-1, 1]$, and the true target value, $T_K \in [-1, 1]$ for event k.
- This is quantified by the entropy loss function which is defined based on the sum of n events in the training sample

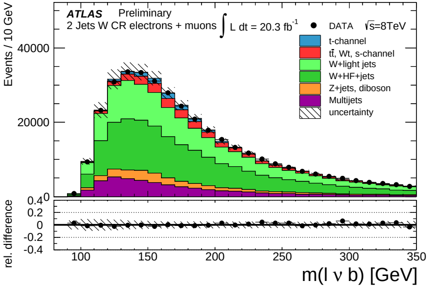
$$E_D = \sum_{k=1}^{n} \log \left[\frac{1}{2} \left(1 + T_K \cdot o_K + \varepsilon \right) \right].$$

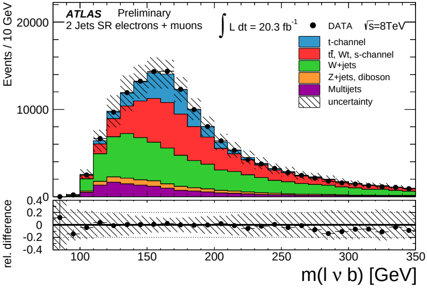
- The network is trained by propagating E_D backwards from output to input layer. The change of the i input weights of neuron j is defined as

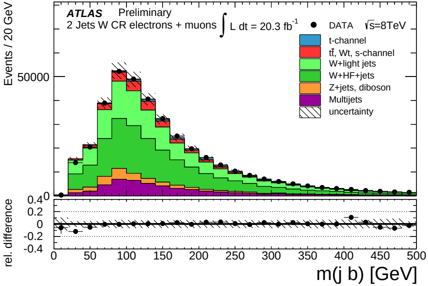
$$\begin{aligned} \Delta w_{ij} &= -\eta \frac{\partial E_D}{\partial w_{ij}} = -\eta \frac{\partial E_D}{\partial o_j} \frac{\partial o_j}{\partial a_j} \frac{\partial a_j}{\partial w_{ij}} \\ &= -\eta \frac{\partial E_D}{\partial o_j} S'(a_j) x_i = -\eta \delta_j x_i. \end{aligned}$$

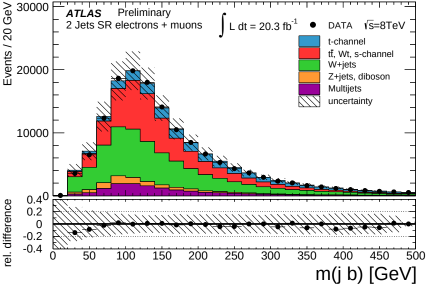
- The error signal δ_j of neuron j depends on the layer

$$\begin{aligned} \delta_j &= S'(a_j) \cdot \frac{\partial E_D}{\partial o_j} = S'(a_j) \cdot \frac{T_j}{1 + T_j o_j + \varepsilon} && \text{(if } j \text{ is output neuron)}, \\ \delta_j &= S'(a_j) \cdot \sum_k \delta_k w_{jk} && \text{(if } j \text{ is hidden neuron)}. \end{aligned}$$


ATLAS Preliminary
2 Jets W CR electrons + muons
$\int$ L dt = 20.3 fb^{-1}
DATA
$\sqrt{s}$=8TeV
t-channel
$t\bar{t}$, Wt, s-channel
W+light jets
W+HF+jets
Z+jets, diboson
Multijets
uncertainty
Events / 10 GeV
rel. difference
m(l ν b) [GeV]


ATLAS Preliminary
2 Jets SR electrons + muons
$\int$ L dt = 20.3 fb^{-1}
DATA
$\sqrt{s}$=8TeV
t-channel
$t\bar{t}$, Wt, s-channel
W+jets
Z+jets, diboson
Multijets
uncertainty
Events / 10 GeV
rel. difference
m(l ν b) [GeV]


ATLAS Preliminary
2 Jets W CR electrons + muons
$\int$ L dt = 20.3 fb^{-1}
DATA
$\sqrt{s}$=8TeV
t-channel
$t\bar{t}$, Wt, s-channel
W+light jets
W+HF+jets
Z+jets, diboson
Multijets
uncertainty
Events / 20 GeV
rel. difference
m(j b) [GeV]


ATLAS Preliminary
2 Jets SR electrons + muons
$\int$ L dt = 20.3 fb^{-1}
DATA
$\sqrt{s}$=8TeV
t-channel
$t\bar{t}$, Wt, s-channel
W+jets
Z+jets, diboson
Multijets
uncertainty
Events / 20 GeV
rel. difference
m(j b) [GeV]

Process	SR	SR ($NN > 0.75$)
t-channel	18100 ± 1800	9100 ± 1300
$t\bar{t}$, *Wt*, *s*-channel	54200 ± 4300	4940 ± 600
W+jets	51000 ± 28000	4090 ± 2200
Z+jets, diboson	6900 ± 1700	360 ± 90
Multijet	12200 ± 6100	950 ± 480
Total expectation	142000 ± 29000	19470 ± 2700
Data	143332	19833

[7]

- About 75% of the obtained sample is from top processes and roughly 50% from single top *t*-channel production.

[7] ATLAS-CONF-2014-055

- JES uncertainty is dominated by η-intercalibration and modelling NP1
- JES uncertainty is the dominant systematic uncertainty of the method

[8]

	Δm_{top} [GeV]
b-jet energy scale	0.4
Modelling1	0.9
Modelling2	< 0.1
Modelling3	0.2
Modelling4	< 0.1
Eta intercalibration (modelling)	0.9
Statistical1	0.1
Statistical2	< 0.1
Statistical3	< 0.1
Eta intercalibration (statistical)	0.2
Detector1	0.4
Detector2	< 0.1
Detector3	< 0.1
Mixed1	< 0.1
Mixed2	< 0.1
Pile-up offset (μ term)	0.2
Pile-up offset (NPV term)	0.2
Pile-up (p_T term)	< 0.1
Pile-up (ρ topology)	0.1
Single particle high p_T	< 0.1
Flavour composition	0.2
Flavour response	< 0.1
Jet energy scale	1.5

[8] ATLAS-CONF-2014-055