Heavy quarks and the Higgs: $t\bar{t}b\bar{b}$ with ATLAS

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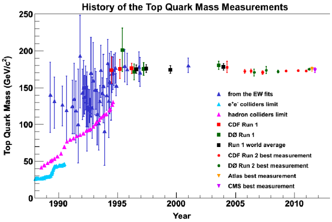
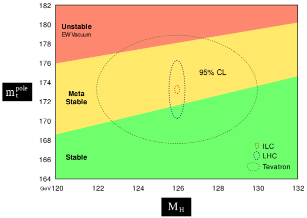
The top quark

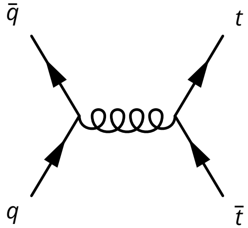
- The top quark is the **heaviest** known fundamental particle
- It has a mass of $\approx$ 173 GeV. **40 times the mass of the next heaviest quark!**
- Similar to that of a **gold atom**.
- Discovered in **1995** at the Tevatron by the CDF and D0 experiments
- “Rediscovered” at the LHC in 2010
- **Unique** amongst the quarks – **decays before hadronisation**
- Yukawa coupling of $\mathcal{O}(1)$. Some special relationship with the Higgs?

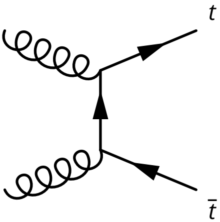




Top quark pair production

- Top quarks produced most often in **pairs**
- At the $\sqrt{s} = 13$ TeV around 90% of $t\bar{t}$ pairs are produced via $gg \rightarrow t\bar{t}$ and the remaining 10% by $q\bar{q} \rightarrow t\bar{t}$
- $\sigma_{t\bar{t}} \approx 830$ pb (NNLO+NNLL QCD) $\rightarrow \approx$ **10 $t\bar{t}$ pairs / s** at a luminosity of $10^{34} \text{cm}^{-2}\ \text{s}^{-1}$





- Large number of tops allows us to make **precise cross-section measurements**
- Many **new physics models** enhance the $t\bar{t}$ cross-section
- Large number of $t\bar{t}$ pairs allows us to measure $\boldsymbol{t\bar{t} + X}$ where X can be $H, W, Z, \gamma, b\bar{b}$ and possibly one day even $t\bar{t}$

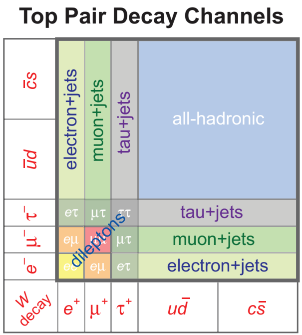
Top quark decay

- The top quark decays nearly 100% of the time to a *b*-quark and a *W*-boson

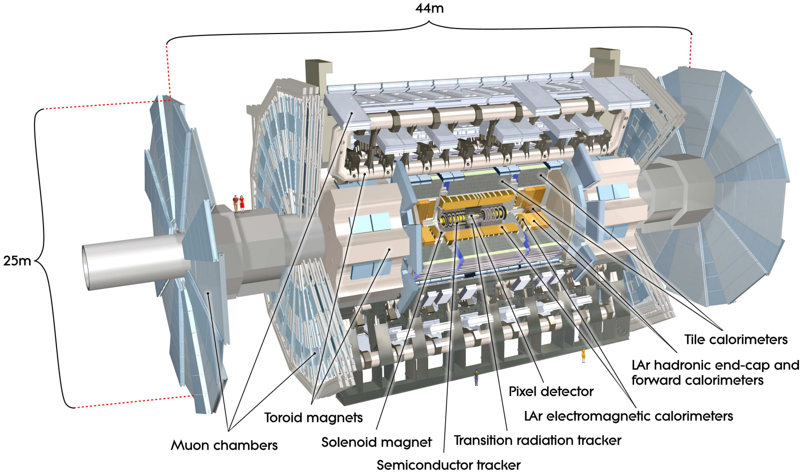
$$t\bar{t} \rightarrow W^+W^-b\bar{b}$$

- $t\bar{t}$ decays are therefore categorised based on how each of the two *W*s decay

- Three main channels
  1. All-hadronic
  2. Dilepton
  3. Semi-leptonic
- The $t\bar{t}$ final state can include electrons, muons, taus, neutrinos (not detected) and jets (including *b*-jets).
- We need to make use of the entire ATLAS detector to make measurements!

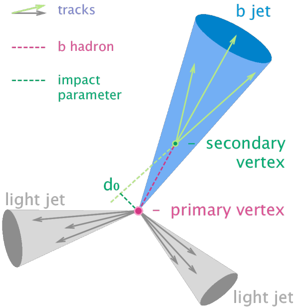


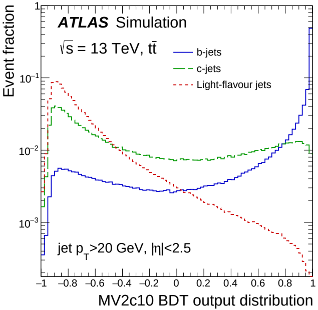
The ATLAS detector



b-tagging

- ***b*-tagging** is crucial for top physics
- Exploit large **impact parameters**, **seconday vertices** and $\boldsymbol{b \to c}$ **decay chains**
- Information is combined using a **Boosted Decision Tree** to identify jets containing b-hadrons





ϵ_b [%]	light-jet mistag	c-jet mistag
60	1550	35
70	380	12
77	135	6
85	35	3

NEW: $t\bar{t}$ cross-section in $e\mu$ events

ATLAS-CONF-2019-041

- The most accurate $t\bar{t}$ cross-section measurements have been made in the $e\mu$ channel
- This is a very clean channel with only small backgrounds
- "Simple" technique, count the number of b-tagged jets

$$N_1 = L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\mathrm{bkg}}$$

$$N_2 = L\sigma_{t\bar{t}}\epsilon_{e\mu}C_b\epsilon_b^2 + N_2^{\mathrm{bkg}}$$

L: Integrated luminosity

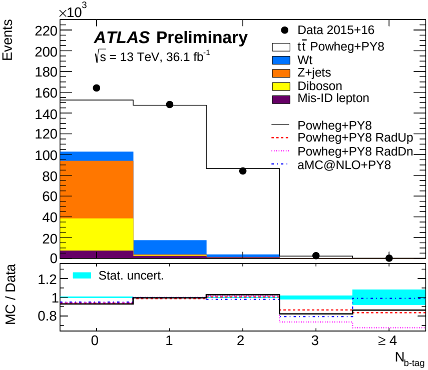
$\sigma_{t\bar{t}}$: $t\bar{t}$ cross-section

$\epsilon_{e\mu}$: Efficiency for event to have one electron and one muon ($\approx 1\%$)

ϵ_b: Efficiency to tag and select a b-jet

C_b: b-tagging correlation ≈ 1

$N_{1,2}^{\mathrm{bkg}}$: Number of background events with 1/2 b-tags



NEW: $t\bar{t}$ cross-section in $e\mu$ events

ATLAS-CONF-2019-041

Uncertainty source (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$
Data statistics	0.44
$t\bar{t}$ mod.	0.97
Lept.	0.59
Jet/b	0.21
Bkg.	0.78
Analysis systematics	1.39
Integrated luminosity	1.90
Beam energy	0.23
Total uncertainty	2.40

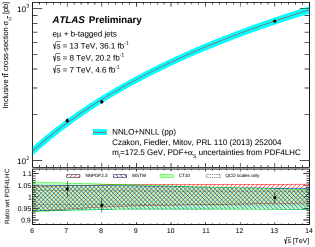
- Uncertainties are statistical, systematic, luminosity and beam energy
- The total uncertainty is dominated by the luminosity uncertainty
- $t\bar{t}$ and background modelling are the next largest

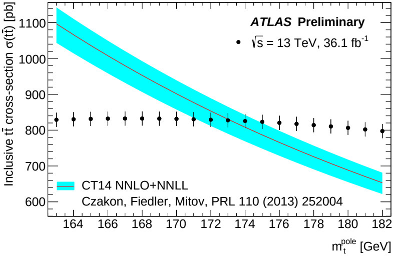
NEW: $t\bar{t}$ cross-section in $e\mu$ events

ATLAS-CONF-2019-041

Result: $\sigma_{t\bar{t}} = 826.4 \pm 3.6 \pm 11.5 \pm 15.7 \pm 1.9$ pb (2.4%)

- Analysis has now been performed at 7, 8 and 13 TeV
- All results are consistent with the SM (NNLO+NNLL QCD) prediction
- The measurement is more precise than the prediction!





Some Birmingham involvement!

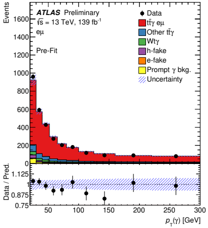
EB chair: Miriam Watson

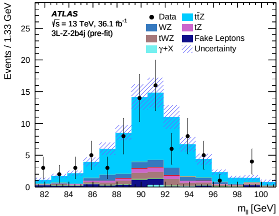
Top cross-section convener: TN

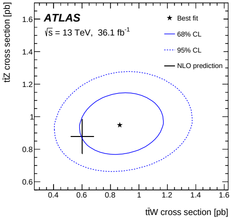
$$m_t^{\text{pole}} = 173.1 \pm 1.0(\text{exp.})^{+1.8}_{-2.1}(\text{theory}) \text{ GeV}$$

$t\bar{t} + X$

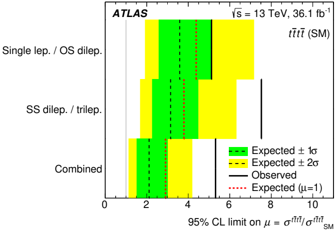
- ATLAS has also measured $t\bar{t}$ production in association other particles





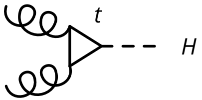


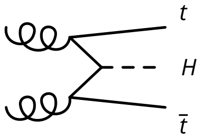
- $t\bar{t} + \gamma$ and $t\bar{t} + Z$ give very clean signals
- Can start to measure differential distributions
- $t\bar{t}W$ more challenging
- Searches for $t\bar{t}t\bar{t}$ ongoing, but will likely need more data for evidence

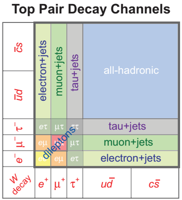


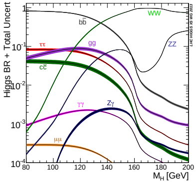
The Higgs and the top

- It is important that we make the most of the LHC and study the Higgs as comprehensively as possible
- The top Yukawa coupling can be probed through loops but also directly in Higgs production in association with top quarks ($t\bar{t}H$)



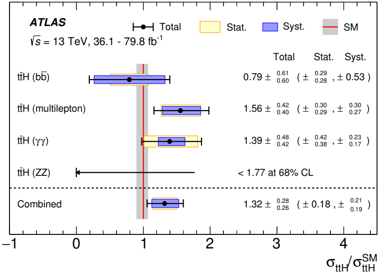


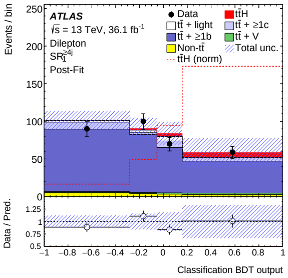




- The $t\bar{t}H$ process can decay to a large number of different final states. The more we measure the better!
- $H \to b\bar{b}$ is the dominant decay – can we measure $t\bar{t}H(H \to b\bar{b})$?

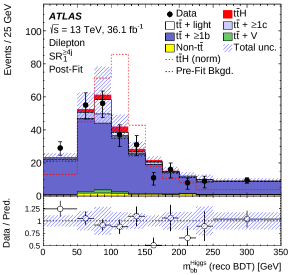
- ATLAS observed $t\bar{t}H$ production last year
- Sensitivity comes mainly from the $H \to \gamma\gamma$ and **multilepton** channels ($H \to \tau\tau$ and $H \to WW^*$)
- $H \to b\bar{b}$ not competitive, despite large branching ratio
- The sensitivity of the $t\bar{t}H(b\bar{b})$ channel is limited by systematic uncertainties on the QCD $t\bar{t}b\bar{b}$ background





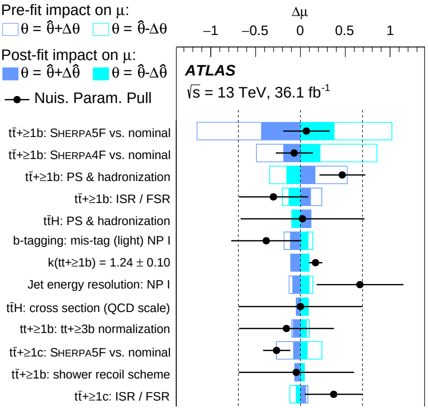
- Measuring $t\bar{t}H(bb)$ is extremely challenging
- Final state with four b-jets – need to determine which jets are from $H \to b\bar{b}$ and which are from $t \to Wb$
- Use MVA techniques to reconstruct the system and to separate signal from background

- Background is completely dominated by $t\bar{t}b(\bar{b})$



$t\bar{t}H(b\bar{b})$ uncertainties

Phys. Rev. D 97 (2018) 072016



- $k(t\bar{t}+\geq 1b)$ is a normalization parameter
- Measure 1.24 ± 0.10 (uncertainty statistical)

- The four uncertainties with the largest impact on the limit are all $t\bar{t}b$ related
- A better understanding of $t\bar{t}b\bar{b}$ crucial for this channel to be useful

CMS uncertainties

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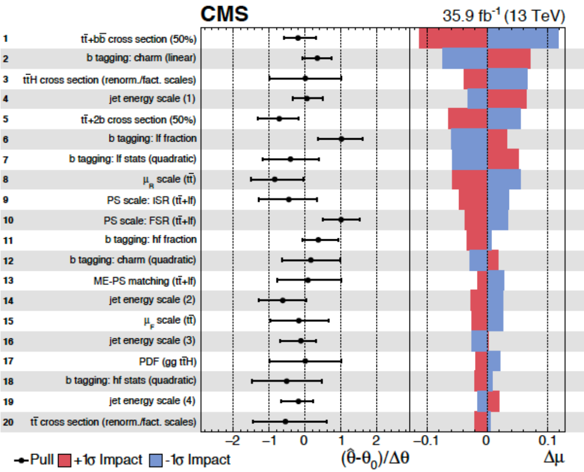


CMS result: $\mu = 0.72 \pm 0.24 \pm 0.38$ ATLAS result: $\mu = 0.79 \pm 0.29 \pm 0.53$

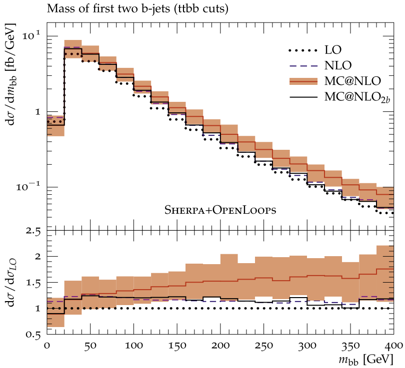
$t\bar{t}b\bar{b}$ predictions

- Clearly, an improved understanding of $t\bar{t}b\bar{b}$ is need for searches/measurements of $t\bar{t}H(b\bar{b})$
- Many other searches have large $t\bar{t}b\bar{b}$ backgrounds (SUSY, four top production . . .)

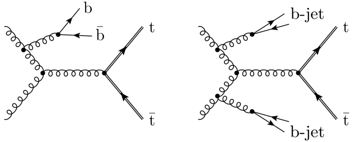
- Predicting $t\bar{t}b\bar{b}$ is challenging
- Massive b-quarks in the matrix element, large scale differences (m_t versus m_b)
- NLO predictions of $t\bar{t}b\bar{b}$ started to arrive about five years ago
- Some surprising results . . .

$t\bar{t}b\bar{b}$ predictions

- NLO $t\bar{t}b\bar{b}$ production with massive b-quarks in the matrix element using the four flavour scheme



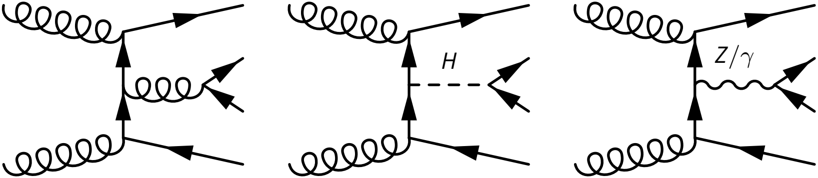
- The effect of $g \to b\bar{b}$ splitting in the parton shower is important (MC@NLO vs. MC@NLO$_{2b}$)
- The contribution of the right diagram below is surprisingly large



- Parton shower effects still important at NLO
- Cross-section uncertainties range from 20-40% (depending on fiducial cuts)

Measuring $t\bar{t}b\bar{b}$

- Experimental input is required to move our understanding of $t\bar{t}b\bar{b}$ forward
- ATLAS has performed a measurement of $t\bar{t}$ with additional heavy-flavour jets at 13 TeV, using data collected in 2015 & 2016
- Fiducial cross-sections measured
- We **DO NOT** attempt to identify which *b*-jets are from the top quarks and which are considered "additional"
- The measurement therefore includes "QCD" $t\bar{t}b\bar{b}$, $t\bar{t}H$ and $t\bar{t}Z$



Analysis outline

1. Select an inclusive (≥ 2 *b*-jets) sample of $t\bar{t}$ events
2. Categorise simulated $t\bar{t}$ events based on the "flavours" of the jets in the event. Use these to create templates from $t\bar{t}$ simulation
3. Fit the templates to data in a discriminating variable
4. From the results of this fit, measure inclusive and differential fiducial cross-sections

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The analysis is performed in two channels

- ℓ+jets
- $e\mu$

Analysis selection

- Both channels require the ATLAS detector to be fully operational
- A primary vertex with at least two tracks
- Single electron/muon triggers with $p_{\mathrm{T}} > 20(26)$ GeV for muons and $p_{\mathrm{T}} > 24(26)$ GeV for electrons in 2015 (2016)

ℓ+jets

- 1 $\ell(e/\mu)$ with $p_{\mathrm{T}} > 27$ GeV
- ≥ 5 jets with $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
- ≥ 2 tagged at the 60% *b*-tagging efficiency WP

$e\mu$

- 1 e and 1 μ with $p_{\mathrm{T}} > 27$ GeV
- $Q^{e} \cdot Q^{\mu} = -1$
- ≥ 2 jets with $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$
- ≥ 2 jets tagged at the 77% *b*-tagging efficiency WP

Number of *b*-tags after pre-selection

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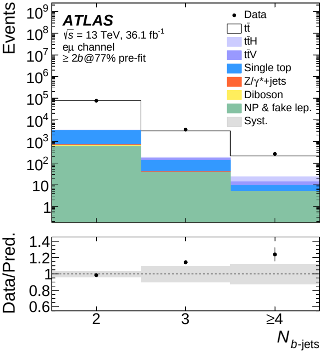

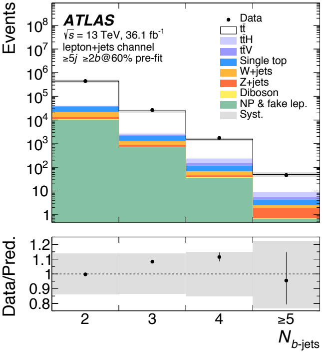

- After pre-selection there is a slope in the data / MC ratio in the number of *b*-jets distribution
- The number of events with ≥ 3 *b*-jets is under-estimated
- We want to identify the cause of this. Is it due to modelling or an experimental effect (flavour tagging?)?

Leading b-jet p_{T}

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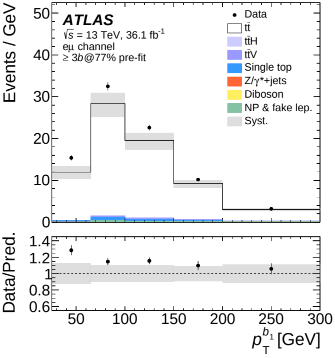
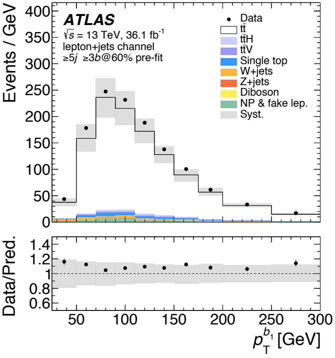
- We can also look at jet variables
- Here we can clearly see the ”purity” of the sample we are dealing with
- Non-$t\bar{t}$ backgrounds are small contributions in both channels





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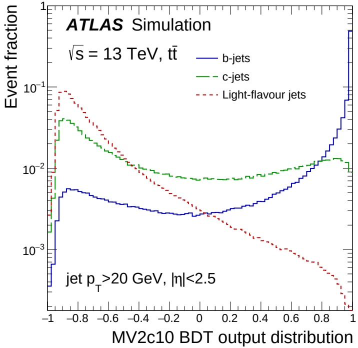
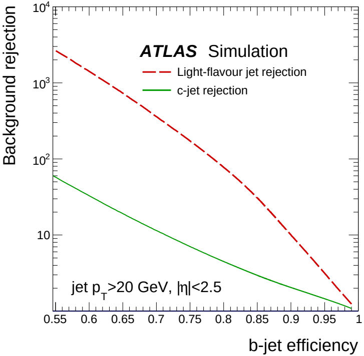
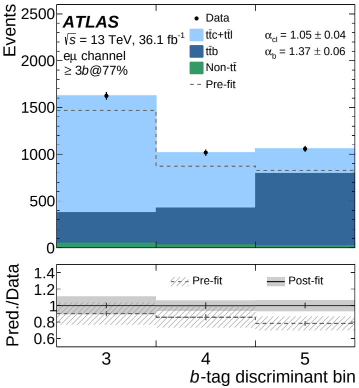
- To discriminate between the various cases, we use the output of the *b*-tagging variable
- The output of the *b*-tagging algorithm is split into five bins, each of which is calibrated
- The tightest *b*-tagging working point (5) is 60% efficiency and has a light(*c*)-jet rejection rate of $\approx 1550(35)$





- In the $e\mu$ channel the fit is performed using the b-tagging discriminant of the jet with the third largest value of D_{MV2}
- $t\bar{t}c$ and $t\bar{t}l$ templates are combined
- A systematic uncertainty is included by varying the normalisation of the $t\bar{t}c$ template by $\pm 40\%$ before combining with the $t\bar{t}l$ template
- The best fit value scales the $t\bar{t}b$ template by ≈ 1.4



ℓ+jets channel

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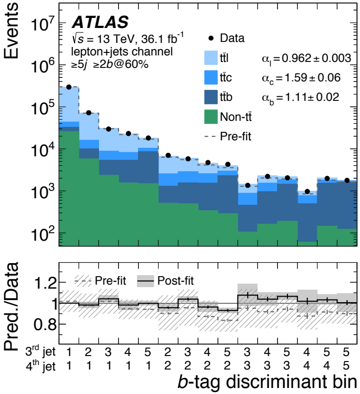
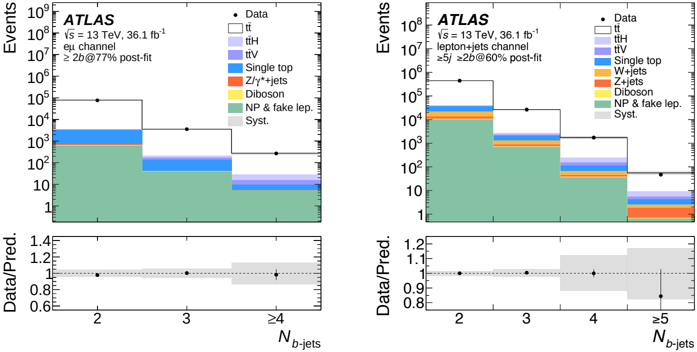


- In the ℓ+jets channel there are always at least four jets and so the fit is performed using the *b*-tagging discriminants of the two jets with the third and fourth largest values of D_{MV2}
- 2D fit flattened to 1D in the figure
- $t\bar{t}c$ and $t\bar{t}l$ templates are treated separately
- The best fit value scales the $t\bar{t}b$ template by $\approx$ 1.1
- Can see that the final bin in the distribution, which is equivalent to four very tight *b*-tags, is very pure in $t\bar{t}b$ events

Applying the correction factors



- We can apply these correction factors back to our poorly modelled distributions
- There is a clear improvement in the agreement between the data and the prediction

Applying the correction factors

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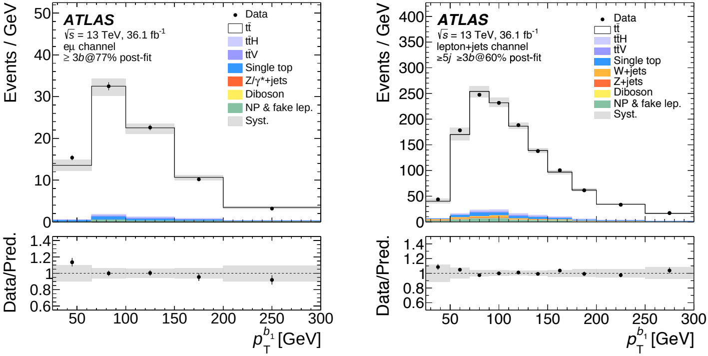

- We can apply these correction factors back to our poorly modelled distributions
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$t\bar{t}b$ fiducial cross-sections

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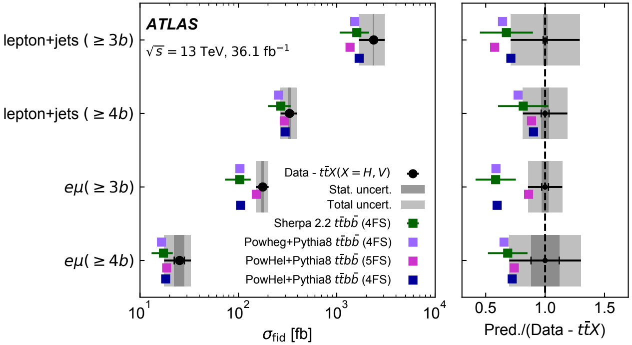

- Using these correction factors we can measure $t\bar{t} + b$-jet fiducial cross-sections
- Data here refers to the measured cross-section
- The $t\bar{t}H$ and $t\bar{t}Z$ components are subtracted from the results to allow for easy comparison with QCD $t\bar{t}b\bar{b}$ predictions
- Measured fiducial cross-sections generally **larger** than $t\bar{t}b\bar{b}$ predictions by $\approx 1\sigma$
- **Confirms** what had been seen in related analyses ($t\bar{t}e\mu$, $t\bar{t}H$)
- Uncertainties range from 13 – 28 %

Uncertainties

Source	Fiducial cross-section phase space			
	$e\mu$		$\ell + \text{jets}$	
	$\geq 3b$ unc. [%]	$\geq 4b$ unc. [%]	$\geq 5j, \geq 3b$ unc. [%]	$\geq 6j, \geq 4b$ unc. [%]
Data statistics	2.7	9.0	1.7	3.0
Detector+background total syst.	8.5	14	18	12
$t\bar{t}$ modelling total syst.	10	20	21	12
Total	13	26	28	17

- Largest uncertainties due to b-tagging (mistagging light and c-jets) and $t\bar{t}$ modelling
- Improving these areas important to understand $t\bar{t} + b$-jets in more detail

Differential measurements

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- In addition, several differential measurements are made
- Use 3 b-jets in the $e\mu$ channel and 4 b-jets in the ℓ+jets channel
- “Simple” variables are chosen
- $N_{\mathrm{b-jets}}$ in the $e\mu$ channel
- The b-jet p_{T}s

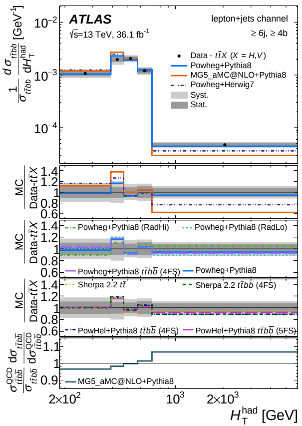
$$p_{\mathrm{T}}^{b,1}, p_{\mathrm{T}}^{b,2}, p_{\mathrm{T}}^{b,3}, p_{\mathrm{T}}^{b,4}$$

- The scalar sum of jet p_{T} and lepton p_{T} (used in $t\bar{t}H(b\bar{b})$ MVAs)

$$H_{\mathrm{T}}^{\mathrm{jets}} = \sum_{i \in \mathrm{jets}} p_{\mathrm{T}}^{i}, \quad H_{\mathrm{T}} = H_{\mathrm{T}}^{\mathrm{jets}} + p_{\mathrm{T}}^{\ell}$$

- Properties of the bb system (both the leading two b-jets and the closest two b-jets)

$$p_{\mathrm{T}}^{bb}, m_{bb}, \Delta R_{bb}$$



- The shapes of distributions are generally reasonably described

Summary and outlook for $t\bar{t}b\bar{b}$

- $t\bar{t} + b$-jets measured by ATLAS in two channels
- $t\bar{t} + b$-jet cross-sections measured to be larger than what is predicted
- **Results confirm** what has been **hinted** at in other analyses
- **No major shape differences** seen in distributions

- We have **four times more data** on disk than has been analysed
- As with other $t\bar{t}$ measurements, the very clean $e\mu$ channel will become the most useful channel
- We need to understand **which variables** in the $t\bar{t}H(b\bar{b})$ MVA cause large modelling uncertainties!
- Attempt to assign jets from top decays in next measurement?
- **MC improvements** are on the way!

The view from the top

- The top quark may be a window to new physics
- Testing how it interacts with other particles, particularly the Higgs, is important
- The latest $t\bar{t}$ measurements from ATLAS are a challenge to theorists!
- The future (and present) of top cross-section measurements is **differential** and **associated**!!