Measurements of $t\bar{t}$ production with additional heavy-flavour jets

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Outline

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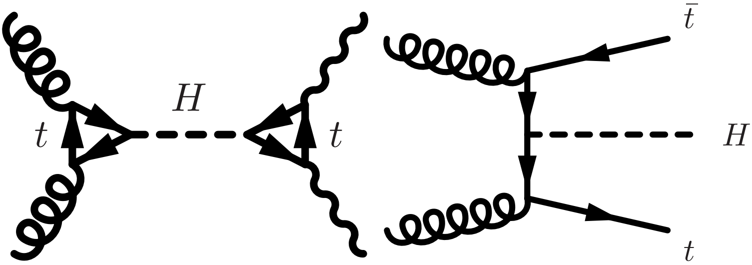
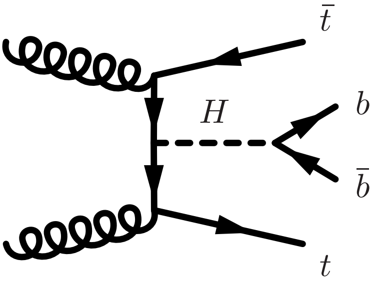
Motivation

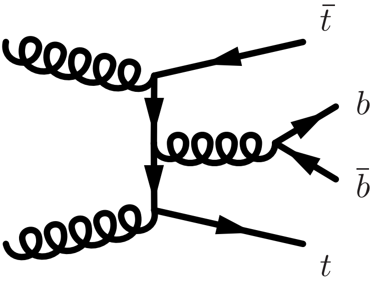
- We want to measure the properties of the Higgs boson- are they consistent with the SM prediction?
- How does the Higgs couple to top quarks?



- As we will hear the $H \to b\bar{b}$ decay channel is one of the channels we want to explore.
- This channel has an irreducible background $t\bar{t}b\bar{b}$.



Signal



Background

- The modelling of the $t\bar{t}b\bar{b}$ background is the leading source of uncertainty in searches for $t\bar{t}H$ (table from ATLAS ICHEP 2016 result).
- Understanding this background is **crucial** for the $t\bar{t}H$ search.

Uncertainty source	$\Delta\mu$	
$t\bar{t}+\geq 1b$ modelling	$+0.53$	-0.53
Jet flavour tagging	$+0.26$	-0.26
$t\bar{t}H$ modelling	$+0.32$	-0.20
Background model statistics	$+0.25$	-0.25
$t\bar{t}+\geq 1c$ modelling	$+0.24$	-0.23
Jet energy scale and resolution	$+0.19$	-0.19
$t\bar{t}$+light modelling	$+0.19$	-0.18
Other background modelling	$+0.18$	-0.18
Jet-vertex association, pileup modelling	$+0.12$	-0.12
Luminosity	$+0.12$	-0.12
$t\bar{t}Z$ modelling	$+0.06$	-0.06
Light lepton (e,μ) ID, isolation, trigger	$+0.05$	-0.05
Total systematic uncertainty	$+0.90$	-0.75
$t\bar{t}+\geq 1b$ normalisation	$+0.34$	-0.34
$t\bar{t}+\geq 1c$ normalisation	$+0.14$	-0.14
Statistical uncertainty	$+0.49$	-0.49
Total uncertainty	$+1.02$	-0.89

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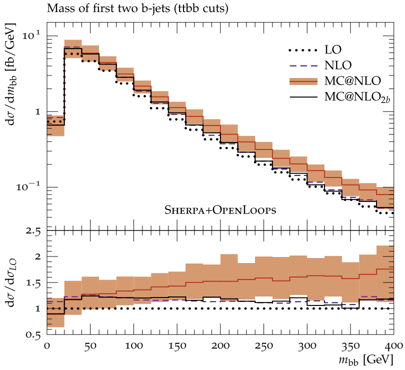
State-of-the-art QCD predictions

- Predicting $t\bar{t}bb$ is very challenging ($2 \to 8$ ME, massive b-quarks, matching and merging, ...).
- Uncertainties of these predictions are not small and could benefit from data.



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- $t\bar{t}bb$ cross-section at 8 TeV predicted to be

$$\sigma_{ttbb} = 600^{+24\%}_{-22\%}\ [\mathrm{fb}]$$

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

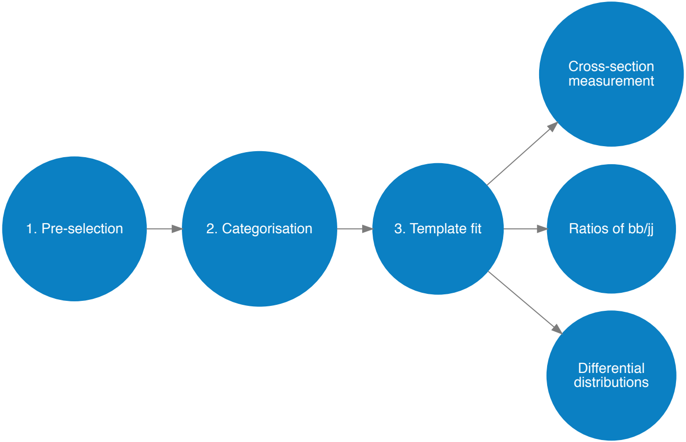
(B)SM searches

- Aside from $t\bar{t}H$, many other searches would benefit from a better understanding of $t\bar{t}bb$.
- R-parity violating SUSY models can produce a similar signal.
- Four top production is another example of a process with a sizable $t\bar{t}bb$ background.

Analysis techniques

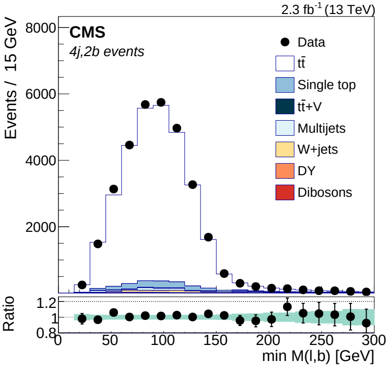
General analysis outline

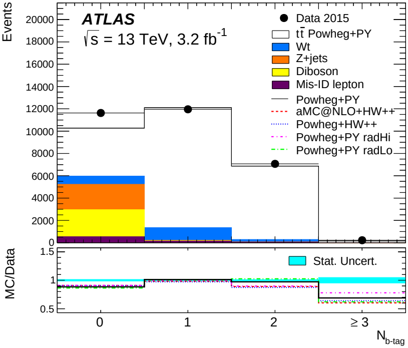
Measurements of $t\bar{t}b\bar{b}$ (and more generally $X + b\bar{b}$) all tend to follow a similar strategy:



Pre-selection

- Selecting a pure sample of $t\bar{t}$ events is the first step.
- This can be achieved using *b*-tagging.





arXiv:1701.06228 [hep-ex]

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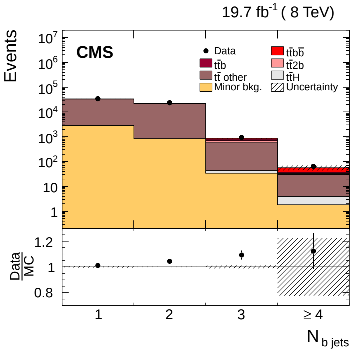
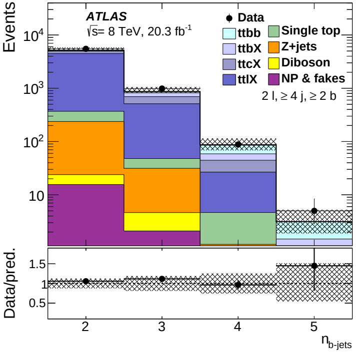
Categorisation

- After selecting $t\bar{t}$ events, they are further categorised based on the flavours of the selected jets.





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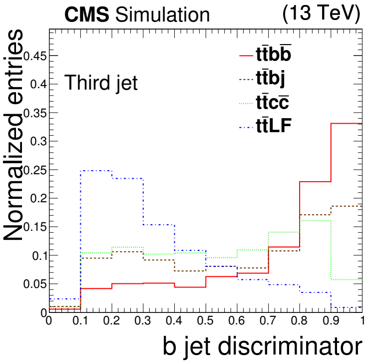
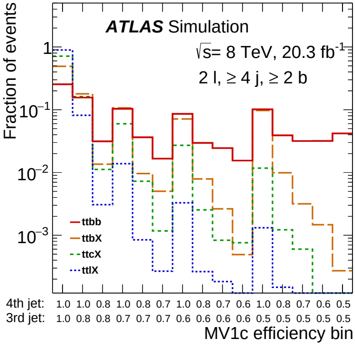
Template fit

- One can then construct templates based on these categories of some variable that distinguishes between them e.g. a *b*-tagging discriminant.





CMS-PAS-TOP-16-010

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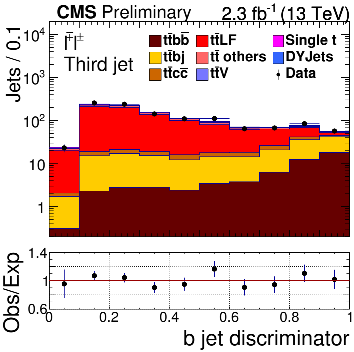
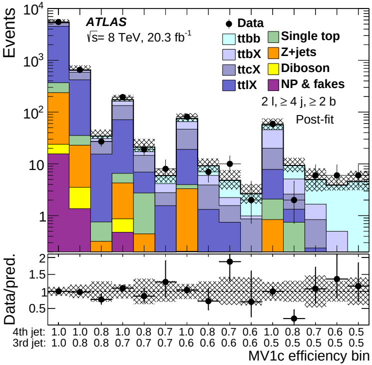
Template fit

- A fit is then performed to data, correcting the components in MC.
- The fit results give us the number of signal events.





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Results

Cross-section

- Cross-sections of $t\bar{t}b\bar{b}$ are typically measured in the visible (fiducial) phase-space by correcting for detector efficiencies.
- CMS has also included the results in the full-phase space[1].

Experiment	$\sqrt{s}$	Ratio to theory[2]	Phase-space	Ref.
CMS	8	1.6 ± 0.9	Visible	Eur. Phys. J. C 76 (2016) 379
CMS	8	1.4 ± 0.7	Full	Eur. Phys. J. C 76 (2016) 379
CMS	13	1.2 ± 0.5	Visible	CMS-PAS-TOP-16-010
CMS	13	1.2 ± 0.5	Full	CMS-PAS-TOP-16-010

[1] Not the full phase space
[2] 8 TeV numbers calculated from appendices.

Visible phase-spaces (8 TeV comparison)

CMS

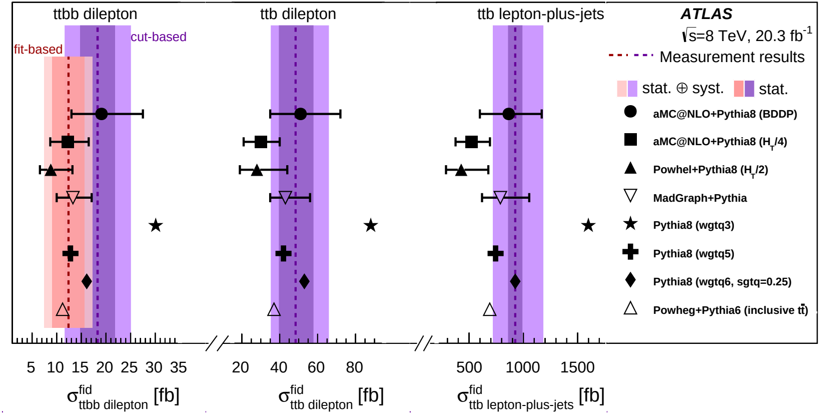
- Leptons: $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.4$,
- *b*-jets arising from top quarks: $p_{\mathrm{T}} > 30$ GeV, $|\eta| < 2.4$,
- Additional jets and *b*-jets: $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.4$.
- anti-k_{T} jets: $R = 0.5$.
- 13 TeV: R=0.4 jets, $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$.

ATLAS

- Leptons: $p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.5$,
- Jets: $p_{\mathrm{T}} > 20$ GeV, $|\eta| < 2.5$,
- anti-k_{T} jets: $R = 0.4$.

Cross-section

- ATLAS doesn't have a 13 TeV measurement yet but at 8 TeV results are also consistent with the theory predictions.



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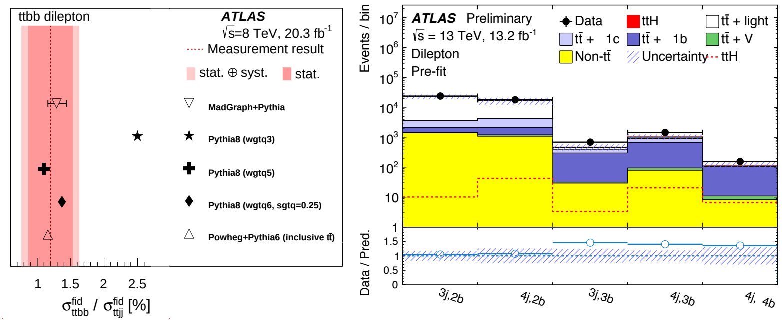
Ratios

- Another thing that has been done is look at the ratio of $t\bar{t}bb/t\bar{t}jj$ to try and cancel some systematics.
- CMS results suggest more $t\bar{t}bb$ than the MC.

$\sqrt{s}$ [TeV]	Measured	Theory	Ref.
8	0.022 ± 0.006	0.011 ± 0.003	Phys. Lett. B 746 (2015) 132
13	0.022 ± 0.007	0.012 ± 0.001	CMS-PAS-TOP-16-010

Ratios

- ATLAS 8 TeV results consistent with theory.
- At 13 TeV $t\bar{t}H$ studies suggest not enough $t\bar{t}bb$.



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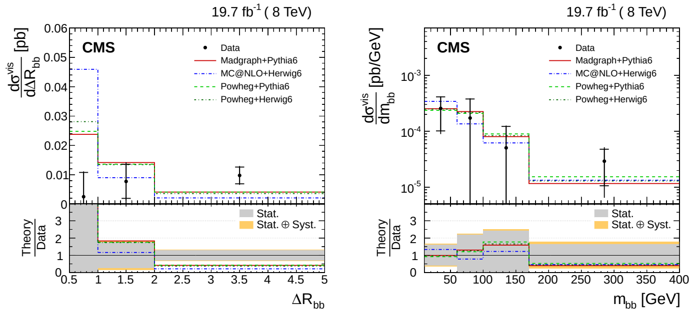
Differential cross-sections

- Measuring differential cross-sections should allow for better discriminating power between different models of $t\bar{t}$ + HF.
- CMS has already produced some unfolded measurements at 8 TeV.
- The additional *b*-jets are identified using a BDT.



Systematics

- $t\bar{t}$ modelling systematics are important for both ATLAS & CMS and need to be better understood (10−20%).
- b-tagging ($> 10\%$) and JES ($\approx 10\%$) are the leading detector uncertainties.
- b-tagging and modelling uncertainties remain large even in the ratio measurements.
- The total uncertainty on the $t\bar{t}bb$ cross-section is around 35% in both experiments which is still larger than the theory uncertainties of $20 - 25\%$ that I mentioned earlier.

Summary & future prospects

Summary & future prospects

- We need to understand $t\bar{t}$ + HF production better to help the ongoing searches for $t\bar{t}H$ and BSM physics.
- Both ATLAS & CMS have over $30\mathrm{fb}^{-1}$ of 13 TeV data to analyse!
- State-of-the-art theory predictions are ready and now need us to provide measurements to compare with.
- Systematic uncertainties will be challenging (*b*-tagging, JES, modelling). . .
- . . . but theory uncertainties on the predictions are still reasonably large and so we can hopefully supply useful data.
- Measuring $t\bar{t}cc$ is another challenging and related measurement to think about going forwards!

Backup

Selecting b-jets (not) from top quarks with a BDT

- CMS uses a BDT to identify jets (not) from top quarks.
- Twelve variables used as input for a BDT trained on ttH events (to avoid overtraining).
- Difference in b-jet charges, angles between b-jets and leptons, properties of the $b\ell$ combinations (mass, p_{T}), differences in mass between $bb\ell\ell$ system and bb system etc. . .
- Correctly selects the additional b-jets $\approx$ 40% of the time in $t\bar{t}bb$ events.