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

Tom Neep, CEA-Saclay

Top LHC France, Paris

23/5/2018

Outline

Motivation

Predictions

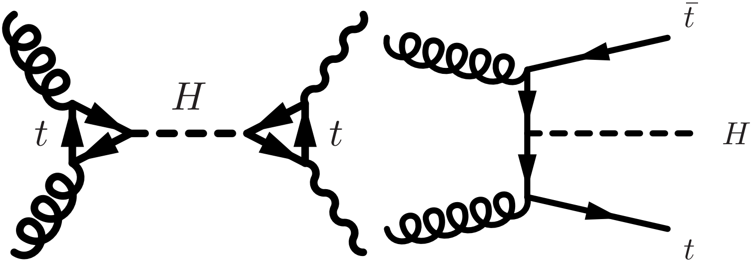
Analysis techniques

Results

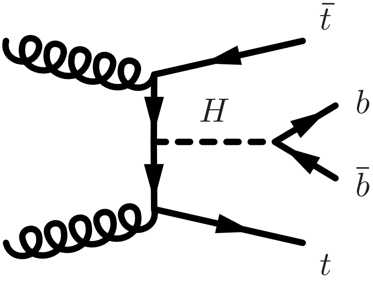
Summary & future prospects

Motivation

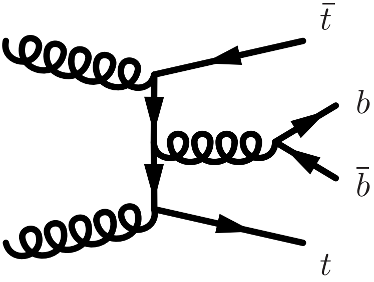
- We want to measure the properties of the Higgs boson- are they consistent with the SM prediction?
- How does the Higgs couple to top quarks?



- 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 Higgs Boson

- 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 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

PRD **97**, 072016

(B)SM searches

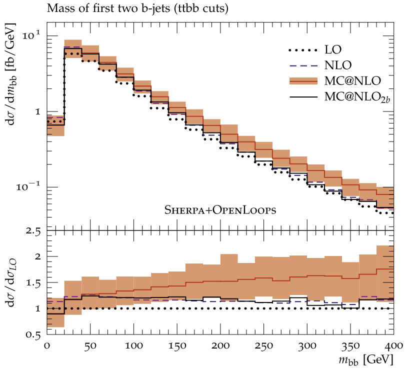
- Aside from $t\bar{t}H$, many other searches would benefit from a better understanding of $t\bar{t}bb$.
- R-parity violating SUSY models can produce a similar signal.
- Four top production is another example of a process with a sizable $t\bar{t}bb$ background.

Predictions

State-of-the-art QCD predictions

- Predicting $t\bar{t}bb$ is very challenging (Massive b-quarks, matching and merging, . . .).
- Uncertainties of these predictions are not small and could benefit from data.
- Some developments in $ttbb$ predictions in the last year.

- The “oldest” of the predictions I will discuss, paper published in 2014.
- NLO $t\bar{t}bb$ production with massive b-quarks using the 4 flavour scheme.

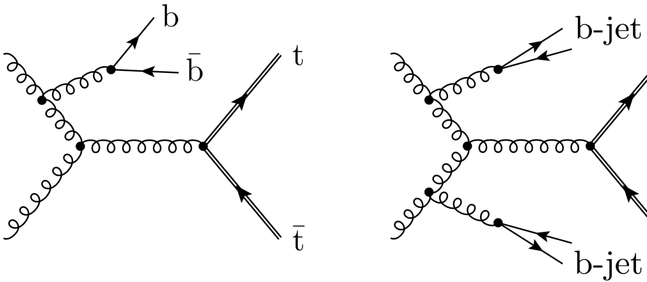


- Cross-section uncertainties vary from 20-40% (depending on fiducial cuts)
- The effect of $g \to b\bar{b}$ splitting in the parton shower is important (MC@NLO vs. MC@NLO$_{2b}$).

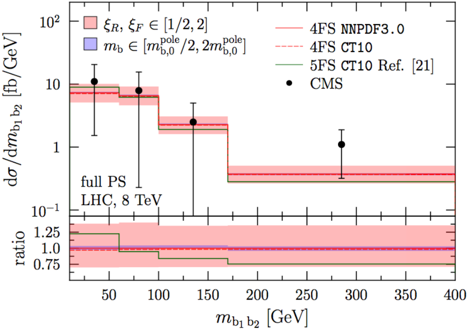
Phys. Lett. B734 (2014) 210

SHERPA (+OPENLOOPS) $t\bar{t}b\bar{b}$

- The contribution of the right diagram to $t\bar{t} + 2b-\mathrm{jets}$ is surprisingly large.
- Parton shower effects still important at NLO.



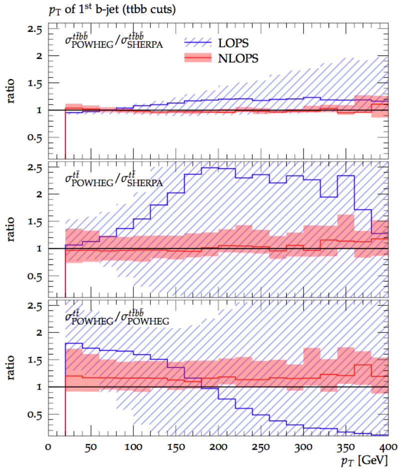
- Last September another paper appeared with NLOPS predictions for $t\bar{t}bb$.
- POWHEL provide predictions in both the 4FS and the 5FS (massless b-quarks).
- Results compared to 8 TeV CMS data.



arXiv:1709.06915

POWHEG-BOX-RES

- In February this year *ttbb* was implemented in the POWHEG-BOX framework.
- The results of this implementation confirm the findings of the SHERPA paper.
- Having the processes implemented in POWHEG-BOX allows the parton shower to be switched between PYTHIA and HERWIG.



▸ arXiv:1802.00426

Summary of predictions

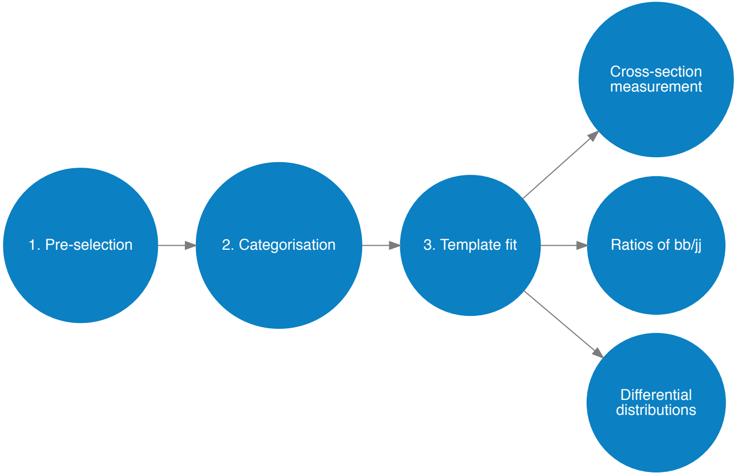
Name	Matching	Shower	Availability	Paper
SHERPA	S-MC@NLO	SHERPA	Public	Phys. Lett. B734 (2014) 210
POWHEL	Powheg	PYTHIA (in paper)	On demand	arXiv:1709.06915
POWHEG	Powheg	PYTHIA/HERWIG	"Soon"	arXiv:1802.00426
MG5_AMC@NLO	MC@NLO	PYTHIA8	Public	

- Several different predictions are now "available".
- So now the job of ATLAS & CMS to provide precise measurements.

Analysis techniques

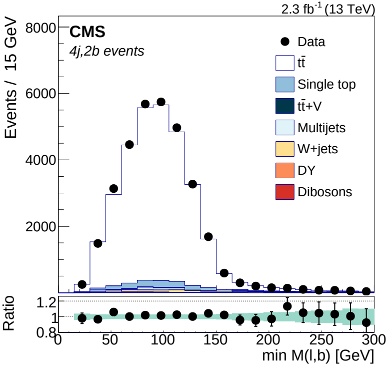
General analysis outline

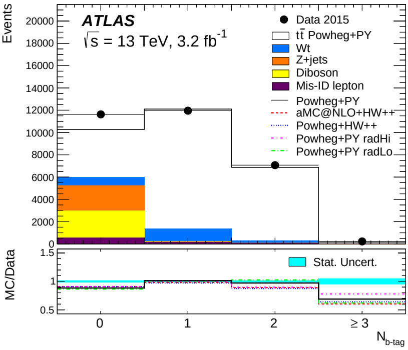
Measurements of $t\bar{t}b\bar{b}$ (and more generally $X + b\bar{b}$) all tend to follow a similar strategy:



Pre-selection

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



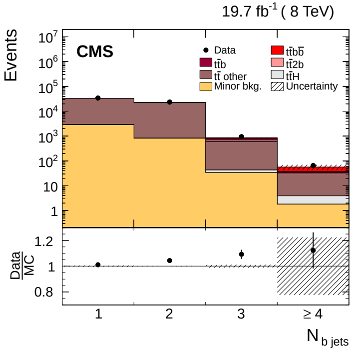


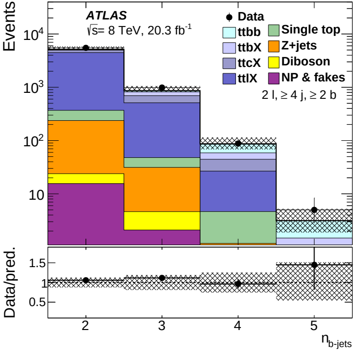
‣ arXiv:1701.06228 [hep-ex]

‣ Phys. Lett. B761 (2016) 136

Categorisation

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



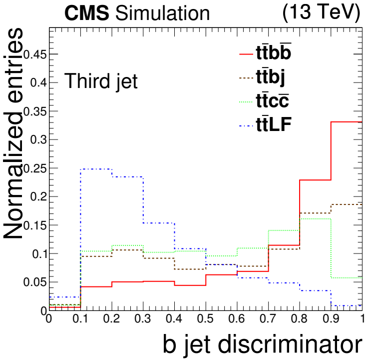


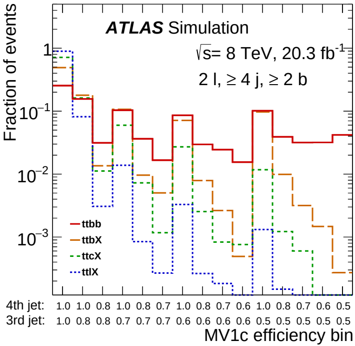
▸ Eur. Phys. J. C 76 (2016) 379

▸ Eur. Phys. J. C76 (2016) 11

Template fit

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



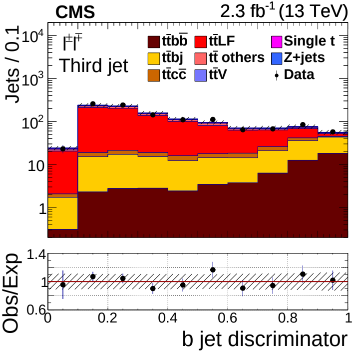


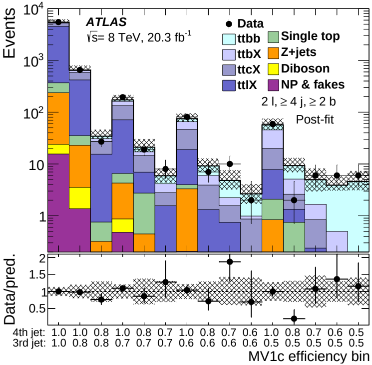
▸ CMS-PAS-TOP-16-010

▸ Eur. Phys. J. C76 (2016) 11

Template fit

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





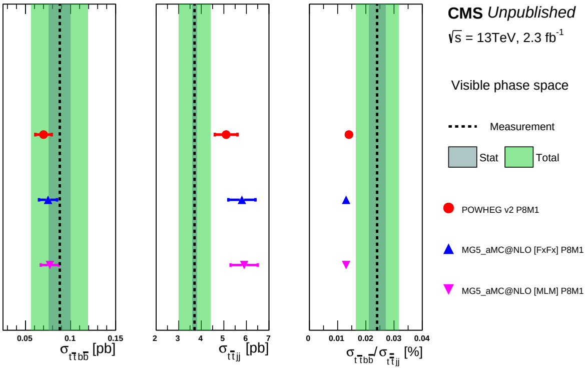
▸ Phys. Lett. B 776 (2018) 355

▸ Eur. Phys. J. C76 (2016) 11

Results

Cross-section

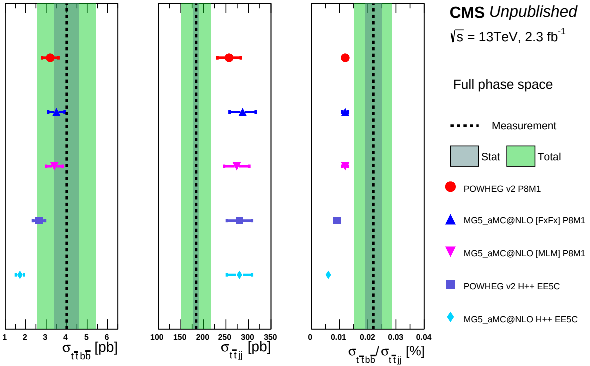
- Cross-sections of $t\bar{t}b\bar{b}$ are typically measured in the visible (fiducial) phase-space by correcting for detector efficiencies.



Phys. Lett. B 776 (2018) 355

Cross-section

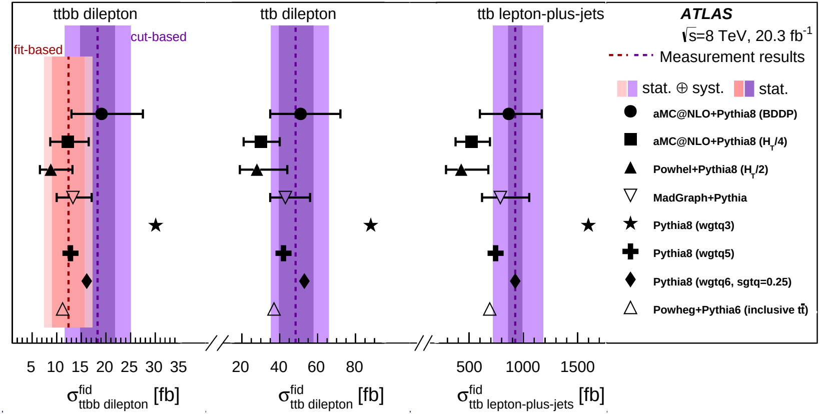
- CMS has also included the results in the full phase-space.
- Not really any differences with respect to the visible phase-space.



▸ Phys. Lett. B 776 (2018) 355

Cross-section

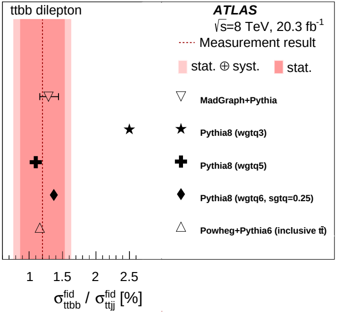
- ATLAS doesn't have a 13 TeV measurement yet but at 8 TeV results are also consistent with the theory predictions.



Eur. Phys. J. C76 (2016) 11

Ratios

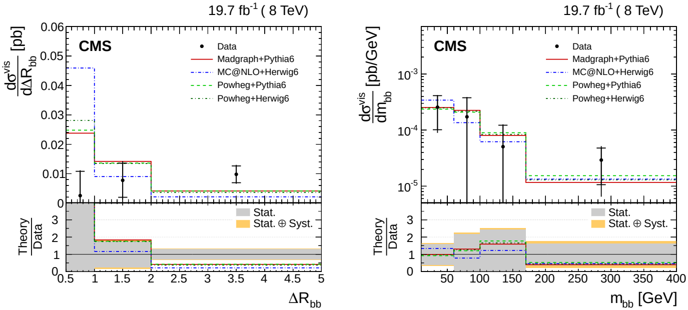
- ATLAS 8 TeV results consistent with theory.



Eur. Phys. J. C76 (2016) 11

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.



Eur. Phys. J. C 76 (2016) 379

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.
- Starting to become competitive with the theory uncertainties of 20-40%.

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.
- Only one Run 2 results so far from the LHC on $t\bar{t}bb$ production using only 2.3 fb^{-1} of data.
- Many new MC predictions to be tested.
- Systematic uncertainties will be challenging (*b*-tagging, JES, modelling)...
- ...but even with the latest calculations 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.