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Status on measurements of ttH(H→bb) and ttbb at ATLAS + CMS

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Overview of published analyses

	ttbb	ttH with H→bb
ATLAS	2015+16; ℓ+jets, ℓℓ: JHEP04(2019)046	2015-18; ℓ+jets, ℓℓ: JHEP06(2022)097
CMS	2016; ℓ+jets, ℓℓ: JHEP07(2020)125 2016; all-jet: *Phys. Lett. B 803 (2020) 135285* (2016-18; ℓℓ: PUBDB-2021-03289 [PhD thesis by A. Saibel])*	2016+17; all channels: CMS-PAS-HIG-18-030

*not covered in this talk

General overview

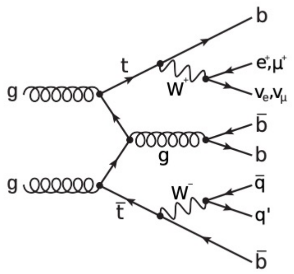
ttbb is difficult to model:

- → multiscale QCD nature (tt mass ~350 GeV and bb mass ~10 GeV) which results in large theoretical uncertainties
- → differences in Monte Carlo modelling (see previous talk)

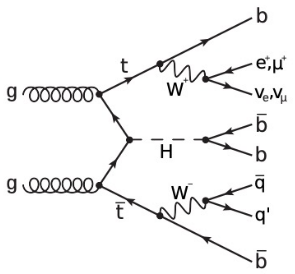
ttH measurements suffer from the large irreducible background ttbb:

- → ttH allows for a top-Higgs Yukawa coupling measurement
- → ttbb modelling uncertainties are a/the limiting factor of sensitivity in ttH

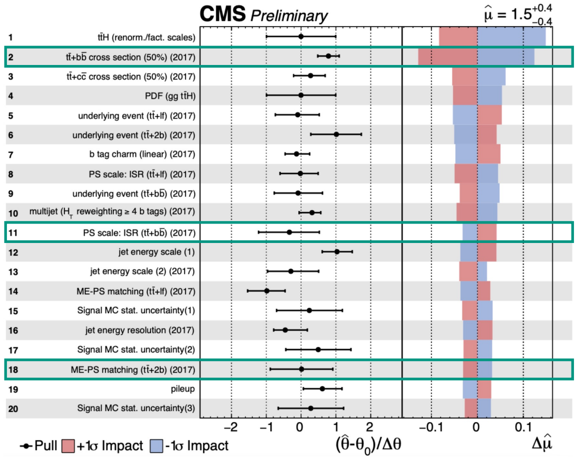
ttbb



ttH



CMS ttH



Post-fit pull of the nuisance parameters ordered by their impact.

CMS ttbb

ttbb at CMS – ℓ+jets and dilepton

2016:
35.9 fb^{-1}

tt+jets (5FS) Powheg+Pythia8 simulation is used as nominal

$$\mu_\text{R} = \mu_\text{F} = \sqrt{m(t) + p_\text{T}(t)}, \qquad h_\text{damp} = 1.58 \cdot m(t)$$

- performed in a fiducial phase space and extrapolated to the full phase space, separately for the lepton+jets and dilepton channels
- Two approaches to identify origin of b jet (if top or additional):
  - ℓℓ: 2 b jets with the largest values of the b tagging discriminant (CSVv2) originate from a top, 3rd and 4th are considered as add. jets
  - ℓ+jets: kinematic fit (χ^2 fit to hypothetical tops and Ws)

Measurements:

- $R_\text{ttbb/ttjj}, \sigma_\text{ttbb}, \sigma_\text{ttjj},$
- σ_ttbb obtained through $\sigma_\text{ttbb} = R_\text{ttbb/ttjj} \cdot \sigma_\text{ttjj}$

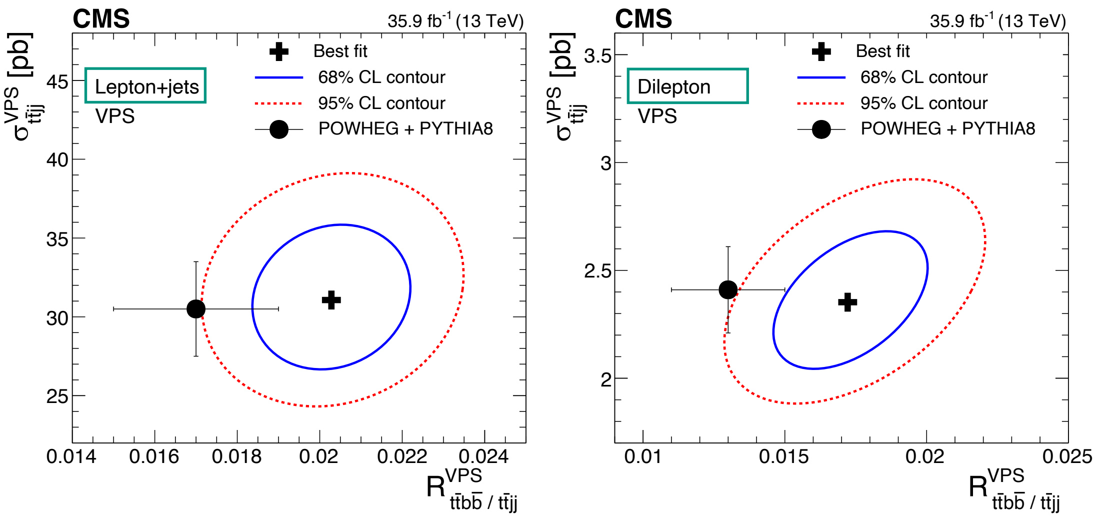
Measurements compared with theoretical predictions of:

- tt+jets (5FS) MG_aMC@NLO + Pythia8 5FS [FxFx]
- tt+jets (5FS) Powheg + HERWIG++

→ $\sigma_\text{ttbb}^{\ell+\text{jets}}$ = 0.040 ± 0.002 ± 0.005 pb

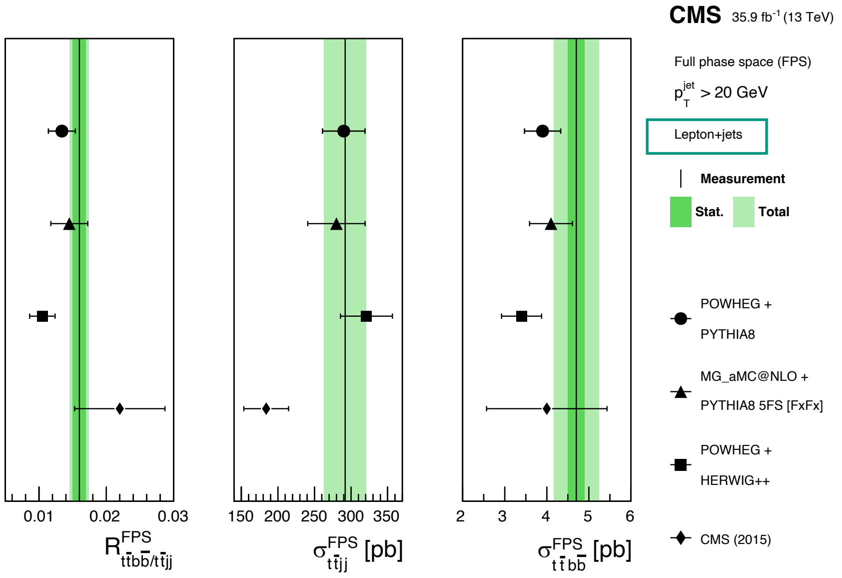
→ $\sigma_\text{ttbb}^\text{dilepton}$ = 0.62 ± 0.03 ± 0.07 pb

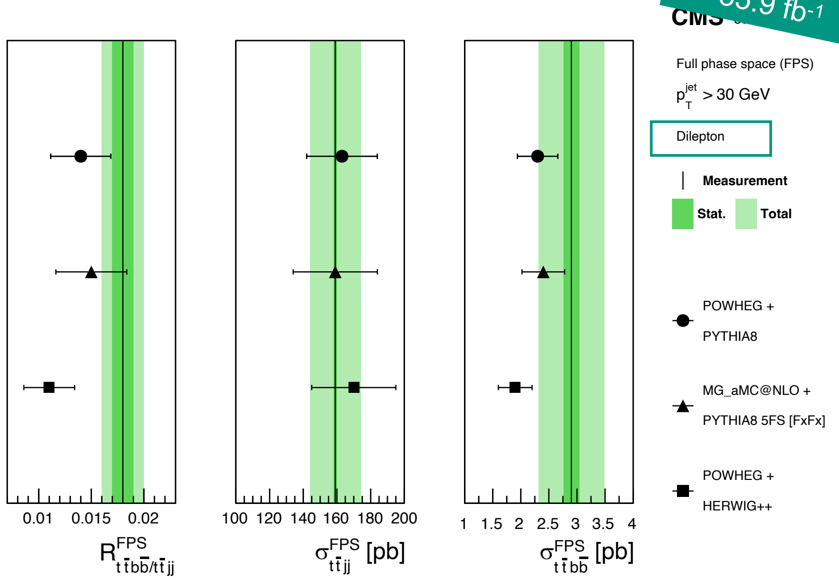
Visible phase space



ttbb at CMS – ℓ+jets and dilepton

2016: 35.9 fb-1





Results:

- $R_{\mathrm{ttbb/ttjj}}, \sigma_{\mathrm{ttbb}}, \sigma_{\mathrm{ttjj}}$ in **agreement** with data for Powheg and MG_aMC@nlo interfaced with Pythia8
- $R_{\mathrm{ttbb/ttjj}}$ (and in consequence) σ_{ttbb} **lower** than measured values for Powheg + HERWIG++
- More precise measurements than before

ttbb at CMS – all jet

2016: $35.9\ fb^{-1}$

Here: all-jet final state of tt system. In LO:
- 4 b jets
- 4 lf jets

Advantages:
- large branching fraction
- complete reconstruction of top quarks

Disadvantages
- large background from multijet production
- difficult to identify jets that originate from top decay

Use of the tt+jets (5FS) Powheg+Pythia8 sample as in ttH analyis, along with the subdivision of tt+B in three sub-categories.

Strategy

- gluon and quark jets are separated using a quark-gluon likelihood (QGL) variable, based on jet substructure observables
- based on the event likelihoods with $N_q = 4$ and $N_g = 0$, as well as $N_q = 0$ and $N_g = 4$, the QGL ratio (QGLR) is defined as

  QGLR = L(4,0)/(L(4,0) + L(0,4)) [1]

Large combinatorial ambiguity[2] in identifying the additional jets
→ "permutation BDT"
1. discard indistinguishable permutations to reduce No. of permutations
2. χ^2 method quantifying the compatibility of the invariant masses of the different jet pairings (t,W) → reduce No. of permutations again
3. train permutation BDT using simulated tt (separate correct parton assignment vs. other, ≥7 jets). Inputs: b tag, kinematic quantities, invariant masses of pairs and triplets of jets, angular openings between jets, p_T.

BDT to separate multijet background from inclusive tt+jets production
→ "classification without labels BDT (CWoLa)" using data
1. relative rates signal and background processes should be different in the two regions
2. distributions of the variables entering CWoLa should be independent of the quantity used to define the two regions
3. CWoLa BDT trained using a sample of data with 7 jets, where two independent regions are defined QGLR is below or above 0.95.
   Inputs: Output value of permuation BDT, kinematic quantities, b tags, …

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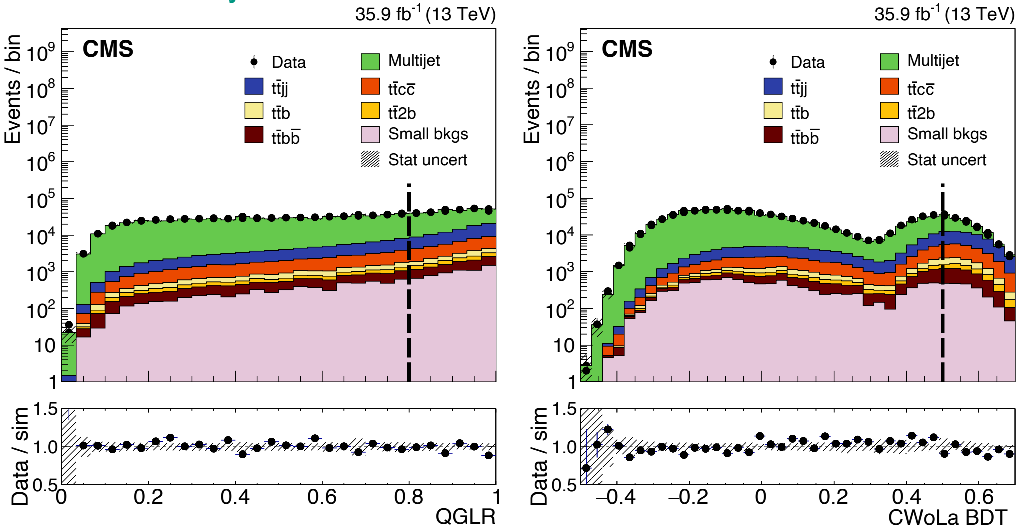
[1] Other lead to reduced discrimination between multijet and tt production

[2] E.g.: 8 jets → 28 ways to select 6 top pair products → 90 ways to match 6 top dec. jets to the 6 partons from top decay chains.

ttbb at CMS – all jet

2016:
35.9 fb^{-1}

Multivariate analysis



Cross section

- extracted from a binned maximum likelihood fit to a two-dimensional distribution constructed using the largest and 2nd-largest b tag value among the additional jets (determined by permutation BDT).
- Signal region to improve purity:
  - CWoLa BDT score > 0.5
  - QGLR score > 0.8.
- Control regions (orthogonal):
  - 3 regions w/ inverted CWoLa and QGLR requirements

$$\rightarrow \sigma_{\mathrm{ttbb}}^{\mathrm{all\ jet,\ VPS}} = 1.6 \pm 0.1^{+0.5}_{-0.4}\ \mathrm{pb}$$

$$\rightarrow \sigma_{\mathrm{ttbb}}^{\mathrm{all\ jet,\ FPS}} = 5.5 \pm 0.3^{+1.6}_{-1.3}\ \mathrm{pb}$$

small backgrounds = ttV, ttH, single top quark, V+jets, diboson

ATLAS ttbb

ttbb measurement ATLAS: all MC samples

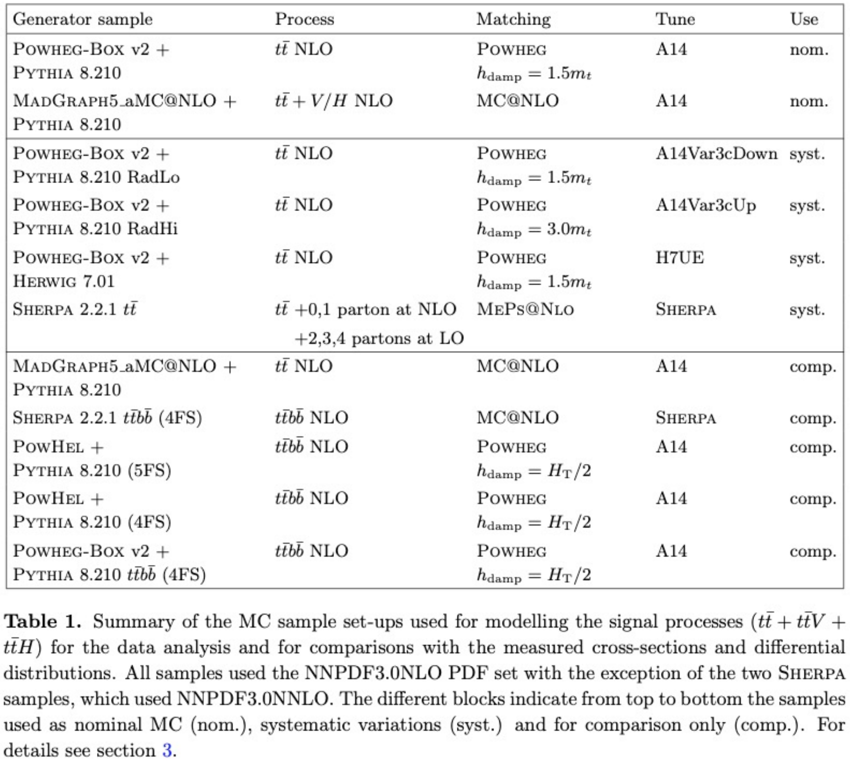
Monte Carlo simulations are used in three ways in this analysis:

- to estimate the signal and background composition of the selected data samples
- to determine correction factors for detector and acceptance effects for unfolding
- to estimate systematic uncertainties

MC nominal

Sys. variations

Comparison only



Generator sample	Process	Matching	Tune	Use
Powheg-Box v2 + Pythia 8.210	$t\bar{t}$ NLO	Powheg $h_{\mathrm{damp}} = 1.5m_t$	A14	nom.
MadGraph5_aMC@NLO + Pythia 8.210	$t\bar{t} + V/H$ NLO	MC@NLO	A14	nom.
Powheg-Box v2 + Pythia 8.210 RadLo	$t\bar{t}$ NLO	Powheg $h_{\mathrm{damp}} = 1.5m_t$	A14Var3cDown	syst.
Powheg-Box v2 + Pythia 8.210 RadHi	$t\bar{t}$ NLO	Powheg $h_{\mathrm{damp}} = 3.0m_t$	A14Var3cUp	syst.
Powheg-Box v2 + Herwig 7.01	$t\bar{t}$ NLO	Powheg $h_{\mathrm{damp}} = 1.5m_t$	H7UE	syst.
Sherpa 2.2.1 $t\bar{t}$	$t\bar{t}$ +0,1 parton at NLO +2,3,4 partons at LO	MEPs@Nlo	Sherpa	syst.
MadGraph5_aMC@NLO + Pythia 8.210	$t\bar{t}$ NLO	MC@NLO	A14	comp.
Sherpa 2.2.1 $t\bar{t}b\bar{b}$ (4FS)	$t\bar{t}b\bar{b}$ NLO	MC@NLO	Sherpa	comp.
PowHel + Pythia 8.210 (5FS)	$t\bar{t}b\bar{b}$ NLO	Powheg $h_{\mathrm{damp}} = H_{\mathrm{T}}/2$	A14	comp.
PowHel + Pythia 8.210 (4FS)	$t\bar{t}b\bar{b}$ NLO	Powheg $h_{\mathrm{damp}} = H_{\mathrm{T}}/2$	A14	comp.
Powheg-Box v2 + Pythia 8.210 $t\bar{t}b\bar{b}$ (4FS)	$t\bar{t}b\bar{b}$ NLO	Powheg $h_{\mathrm{damp}} = H_{\mathrm{T}}/2$	A14	comp.

Table 1. Summary of the MC sample set-ups used for modelling the signal processes ($t\bar{t} + t\bar{t}V + t\bar{t}H$) for the data analysis and for comparisons with the measured cross-sections and differential distributions. All samples used the NNPDF3.0NLO PDF set with the exception of the two Sherpa samples, which used NNPDF3.0NNLO. The different blocks indicate from top to bottom the samples used as nominal MC (nom.), systematic variations (syst.) and for comparison only (comp.). For details see section 3.

ttbb measurement at ATLAS

2015+2016: 36.1 fb^{-1}

tt+jets (5FS) Powheg+Pythia8 simulation is used as nominal

$$\mu_{\mathrm{R}} = \mu_{\mathrm{F}} = \sqrt{m(t) + p_{\mathrm{T}}(t)}, \qquad h_{\mathrm{damp}} = 1.5 \cdot m(t)$$

Among others, four additional predictions were calculated only for comparisons with data based on ttbb ME

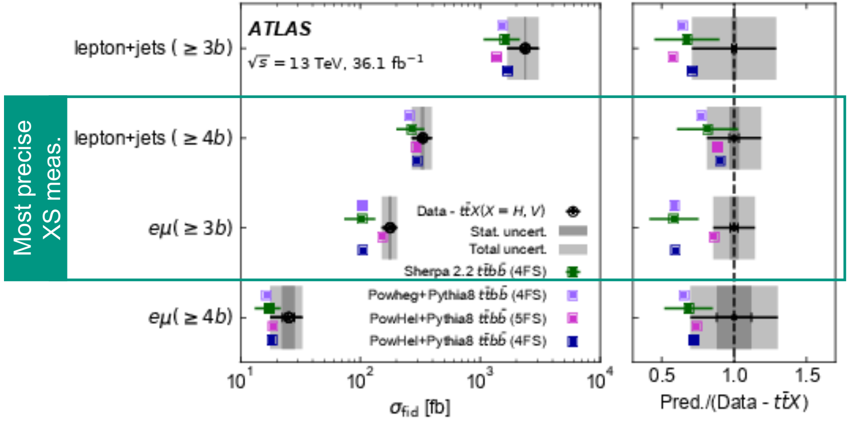
$$\mu_{\mathrm{R}} = \sqrt[4]{m_{\mathrm{T}}(t) \cdot m_{\mathrm{T}}(t) \cdot m_{\mathrm{T}}(b) \cdot m_{\mathrm{T}}(b)}$$
$$\mu_{\mathrm{F}} = \frac{1}{2}\left(m_{\mathrm{T}}(t) + m_{\mathrm{T}}(t) + m_{\mathrm{T}}(b) + m_{\mathrm{T}}(b) + m_{\mathrm{T}}(j)\right)$$

- Sherpa 2.2.1
- PowHel + Pythia 8.210 (5FS)
- PowHel + Pythia 8.210 (4FS)
- Powheg-Box v2 + Pythia 8.210 (4FS)

No distinction between additional b-jets and b-jets that come from the top-quark decays.

Similar to ttH phase space:

- eμ: ≥ 3b and ≥ 4b phase spaces
- ℓ+jets: ≥ 5j, ≥ 3b and ≥ 6j, ≥ 4b phase



Most precise XS meas.

- Measured fiducial cross-sections compared with additional ttbb predictions (central values for PP8, w/ uncert. for Sherpa).
- Uncertainties dominated by systematic uncertainties: tt modelling, b-tagging, and jet energy scale

→ The measured cross-sections, after subtracting estimated contributions from ttH and ttV, are compared with four ttbb predictions and are found to be higher than predicted but compatible within the uncertainties!

ttbb measurement at ATLAS

2015+2016: 36.1 fb^{-1}

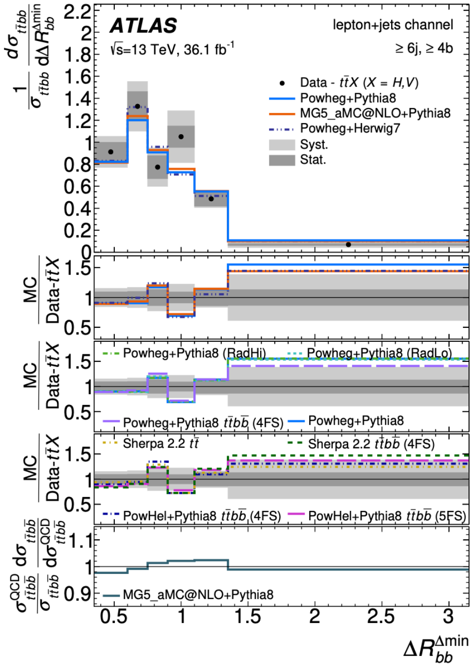
tt+jets (5FS) Powheg+Pythia8 simulation is used as nominal

$$\mu_R = \mu_F = \sqrt{m(t) + p_T(t)},$$
$$h_{damp} = 1.5 \cdot m(t)$$

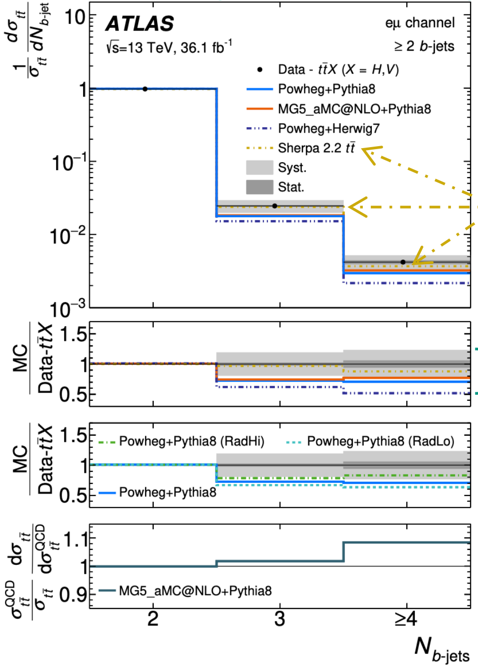
Among others, four additional predictions were calculated only for comparisons with data based on ttbb ME

$$\mu_R = \sqrt[4]{m_T(t) \cdot m_T(t) \cdot m_T(b) \cdot m_T(b)}$$
$$\mu_F = \frac{1}{2}\left(m_T(t) + m_T(t) + m_T(b) + m_T(b) + m_T(j)\right)$$

- Sherpa 2.2.1
- PowHel + Pythia 8.210 (5FS)
- PowHel + Pythia 8.210 (4FS)
- Powheg-Box v2 + Pythia 8.210 (4FS)



underprediction



Sherpa 2.2 tt, which models one additional-parton process at NLO accuracy and up to four additional partons at LO accuracy

$\mu_{R,F}$ scales varied by factors ½; 2 in the ME calculation and PS

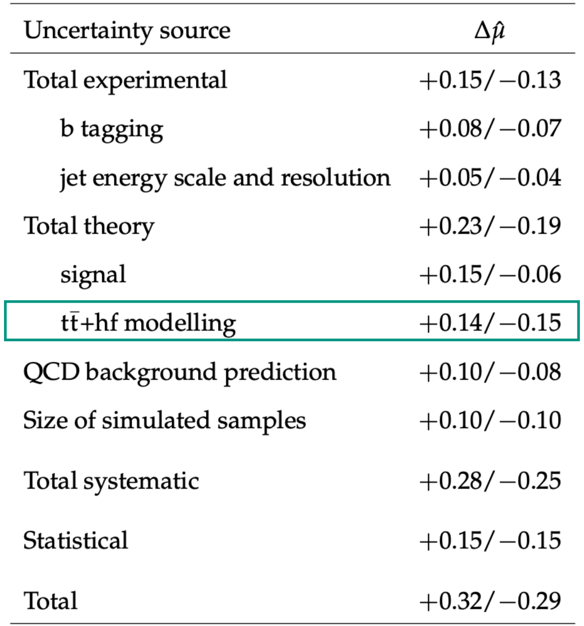
→ All MC predictions that calculate the top-quark pair production matrix element at NLO, but rely on the parton shower for high jet multiplicities, predict too few events with three or four b-jets → b-jet production through parton shower is not accurate.

CMS ttH

ttH at CMS: ttbb uncertainties

2016+2017: 78 fb^{-1}

Contributions of different sources of uncertainties to the result for the combined fit



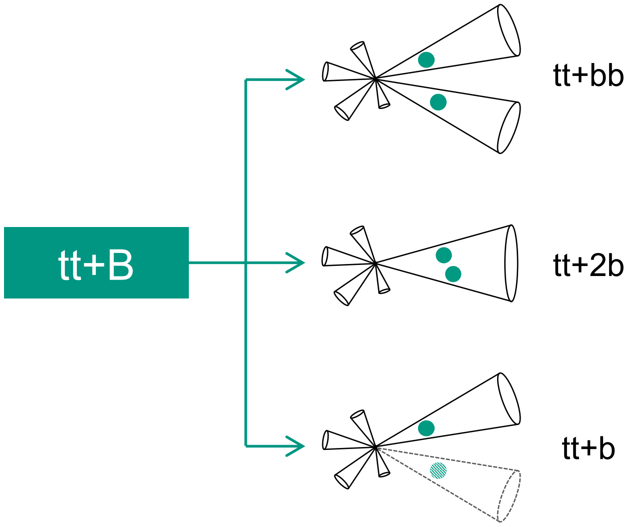
Uncertainty source	$\Delta\hat{\mu}$
Total experimental	+0.15/−0.13
b tagging	+0.08/−0.07
jet energy scale and resolution	+0.05/−0.04
Total theory	+0.23/−0.19
signal	+0.15/−0.06
$t\bar{t}$+hf modelling	+0.14/−0.15
QCD background prediction	+0.10/−0.08
Size of simulated samples	+0.10/−0.10
Total systematic	+0.28/−0.25
Statistical	+0.15/−0.15
Total	+0.32/−0.29

Uncertainties obtained by fixing the listed sources of uncertainties to their post-fit values in the fit and subtracting the obtained result in quadrature from the result of the full fit.

→ The largest contributions originate from theoretical uncertainties, where the **ttbb** modelling uncertainties have a major contribution!

ttH at CMS: modelling of background

- tt+jets (5FS) Powheg+Pythia8 simulation is used for tt+bb, tt+2b, tt+b, tt+cc, or tt+lf.
- Scales: $\mu_\mathrm{R} = \mu_\mathrm{F} = \sqrt{m(t) + p_\mathrm{T}(t)},\ h_\mathrm{damp} = 1.379 \cdot m(t)$



→ each signature is subject to different systematic uncertainties.

2016+2017:
78 fb^{-1}

Shape and rate systematics:

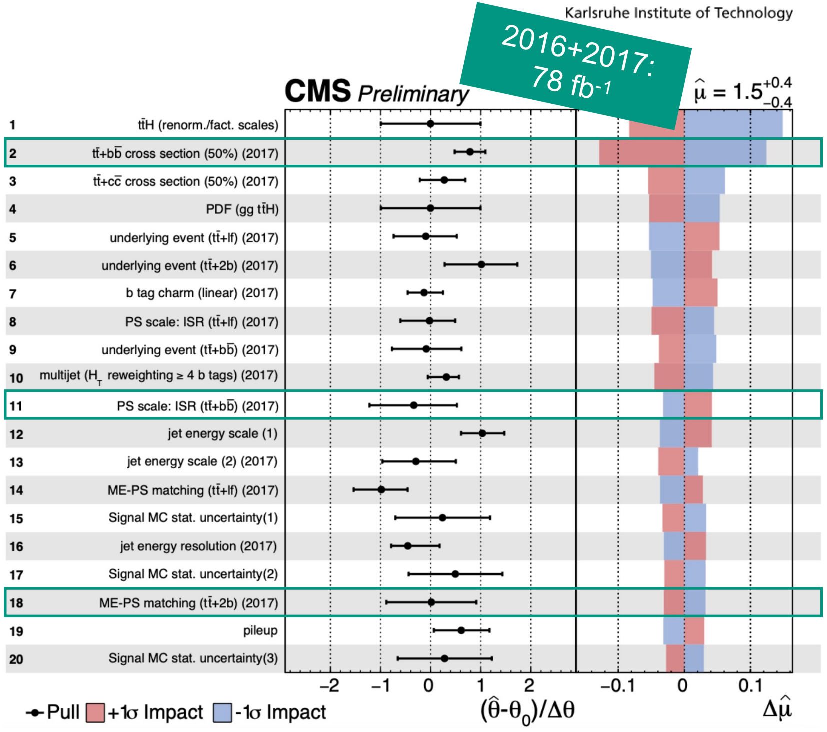
	Source	Type	Remarks
XS	Renorm./fact. scales	rate	Scale uncertainty of NNLO tt prediction
	tt+hf cross sections	rate	Additional 50% rate uncertainty of tt+hf predictions
PDF	PDF shape variations	shape	Based on the NNPDF variations, same for ttH and additional jet flavours
ME	μ_R scale	shape	Renormalisation scale uncertainty of the tt ME generator (POWHEG), same for additional jet flavours
	μ_F scale	shape	Factorisation scale uncertainty of the tt ME generator (POWHEG), same for additional jet flavours
	ME-PS matching	rate	NLO ME to PS matching, *hdamp*, inde- pendent for additional jet flavours
PS	PS scale: ISR	shape	Initial state radiation uncertainty of the PS (for tt events), independent for additional jet flavours
	PS scale: FSR	shape	Final state radiation uncertainty of the PS (for tt events), independent for additional jet flavours

ttH at CMS: pulls

Post-fit pulls of the nuisance parameters reveal:

- ttbb cross section ranked very prominently (#2)
- ttbb initial state radiation (ISR) uncertainty of the PS (#11) as well as NLO ME to PS matching (hdamp) (#18) pulls observed

→ ttbb cross section pulled up: consistent with larger XS favoured by data!



2016+2017: 78 fb^{-1}

Post-fit pull of the nuisance parameters included in the fit to the 2017 data as well as their impact on the signal strength μ, ordered by their impact.

ATLAS ttH

ttH at ATLAS: background modelling

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2015-2018:
139 fb^{-1}

- tt+jets (5FS) Powheg+Pythia8 simulation is used for tt+≥1c and tt+lf.
  - $\mu_R = \mu_F = \sqrt{m(t) + p_T(t)},\ h_{damp} = 1.5 \cdot m(t)$
- tt+bb (4FS) Powheg+Pythia8 is used for tt+≥1b
  - $\mu_R = \sqrt[4]{m_T(t) \cdot m_T(\bar{t}) \cdot m_T(b) \cdot m_T(\bar{b})}$
  - $\mu_F = \frac{1}{2}\left(m_T(t) + m_T(\bar{t}) + m_T(b) + m_T(\bar{b}) + m_T(j)\right)$
  - $h_{damp} = \frac{1}{2}\left(m_T(t) + m_T(\bar{t}) + m_T(b) + m_T(\bar{b})\right)$

→ fraction of tt+≥1b events in the selected phase-space is reweighted to match the fraction in the nominal sample

Systematic uncertainties:

Systematic uncertainties related to varying the amount of ISR and FSR, PS NLO matching procedure comparing the nominal prediction with alternative samples.
For tt+≥1b: Comparisons are made using predictions in which additional b-quarks were generated at leading-log precision from gluon splitting.
→ Checked with ttbb Sherpa 2.2.1 sample

Systematics overview:

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	±6%		$t\bar{t}$ + light
$t\bar{t} + \geq 1b$ normalisation	Free-floating		$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1c$ normalisation	±100%		$t\bar{t} + \geq 1c$
NLO matching	MADGRAPH5_AMC@NLO + PYTHIA 8 vs POWHEG BOX + PYTHIA 8		All
PS & hadronisation	POWHEG BOX + HERWIG 7 vs POWHEG BOX + PYTHIA 8		All
ISR	Varying α_s^{ISR} (PS), μ_r & μ_f (ME)	in POWHEG BOX RES + PYTHIA 8	$t\bar{t} + \geq 1b$
		in POWHEG BOX + PYTHIA 8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
FSR	Varying α_s^{FSR} (PS)	in POWHEG BOX RES + PYTHIA 8	$t\bar{t} + \geq 1b$
		in POWHEG BOX + PYTHIA 8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
$t\bar{t} + \geq 1b$ fractions	POWHEG BOX + HERWIG 7 vs POWHEG BOX + PYTHIA 8		$t\bar{t} + 1b$, $t\bar{t} + \geq 2b$
p_T^{bb} shape	Shape mismodelling measured from data		$t\bar{t} + \geq 1b$

5FS → 4FS

4FS

- tt+lf: uncertainty of 6% is assumed for the inclusive tt production XS predicted at NNLO+NNLL (incl. effects from varying $\mu_{R,F}$, PDFs, α_s, m_t)
- tt+≥1c: uncertainty of 100% is assumed
- tt+≥1b: normalisation is allowed to float freely in the signal extraction fit

ttH at ATLAS: uncertainties

ttbb background modelling has the highest impact on uncertainties!

2015-2018: 139 fb^{-1}

ttbb

Uncertainty source	$\Delta\mu$	
Process modelling		
$t\bar{t}H$ modelling	$+0.13$	-0.05
$t\bar{t}+\geq 1b$ modelling		
$t\bar{t}+\geq 1b$ NLO matching	$+0.21$	-0.20
$t\bar{t}+\geq 1b$ fractions	$+0.12$	-0.12
$t\bar{t}+\geq 1b$ FSR	$+0.10$	-0.11
$t\bar{t}+\geq 1b$ PS & hadronisation	$+0.09$	-0.08
$t\bar{t}+\geq 1b$ p_{T}^{bb} shape	$+0.04$	-0.04
$t\bar{t}+\geq 1b$ ISR	$+0.04$	-0.04
$t\bar{t}+\geq 1c$ modelling	$+0.03$	-0.04
$t\bar{t}+$ light modelling	$+0.03$	-0.03
tW modelling	$+0.08$	-0.07
Background-model statistical uncertainty	$+0.04$	-0.05
…		
Total systematic uncertainty	$+0.30$	-0.28
$t\bar{t}+\geq 1b$ normalisation	$+0.04$	-0.07
Total statistical uncertainty	$+0.20$	-0.20
Total uncertainty	$+0.36$	-0.34

ttH at ATLAS: pulls

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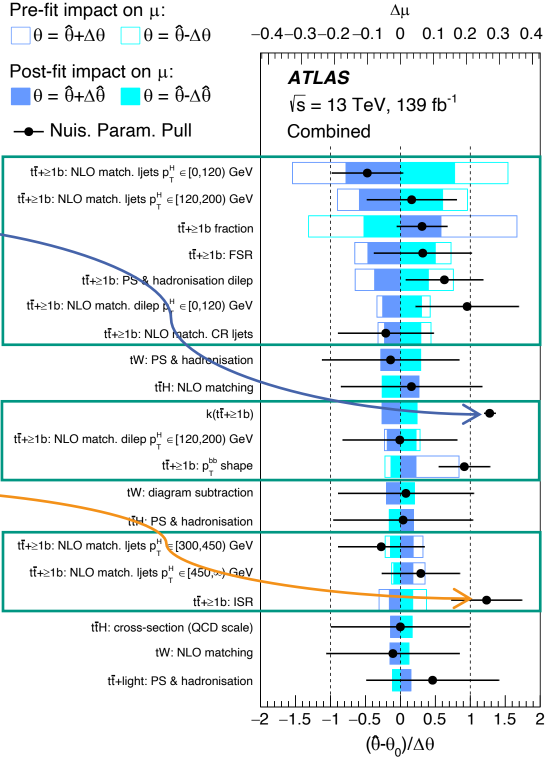
2015-2018:
139 fb^{-1}

Normalization factor determined to be 1.28±0.08:
→ larger ttbb XS favored by data!

tt+≥1b: large ISR pull



→ **Measurement** uncertainty is **dominated** by **systematic** uncertainties, despite significant improvement rel. to previous measurement[1], esp. regarding theoretical knowledge of ttbb, which still **drives the sensitivity**!

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[1] Phys. Rev. D 97, 072016: 2015+16, 36.1 fb^{-1}

Summary / Outlook

ttH analyses

- so far mainly use of tt+jets (5FS) simulations in ttH with H→bb analyses
  - however, ATLAS additionally used ttbb (4FS) simulations
- significant differences in the description for ttbb in various simulations, often underprediction of XS
- ttbb is the most important influence on sensitivity for ttH with H→bb analyses

ttbb analyses

- inclusive and differential measurements so far without data from 2017 and 2018 Significant differences → Run II measurements with more statistics to be expected from both experiments?
- partial inclusion and comparison of dedicated ttbb simulations

→ Modelling of ttbb background so far relied on NLO tt + parton shower simulations.
Latest measurements started to use more accurate NLO ttbb matrix element simulations.