Experimental perspectives on *tt*+*X* physics

ATLAS-CMS Monte Carlo Generators Workshop, May 2017

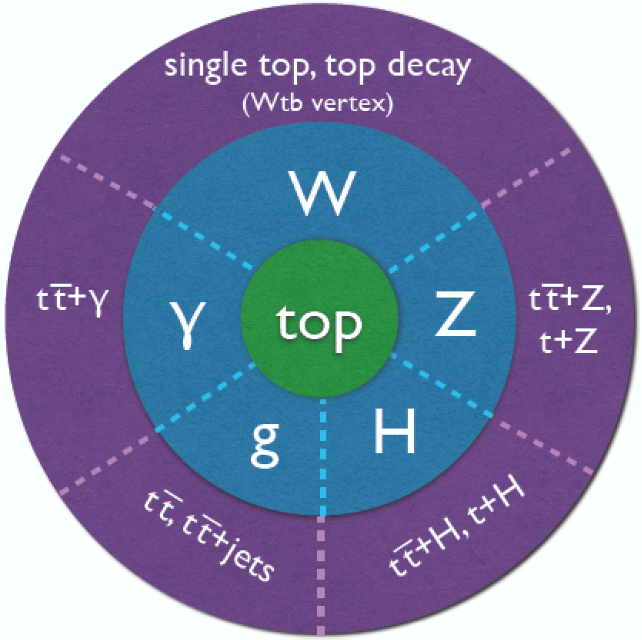
María Moreno Llácer, CERN,
on behalf of ATLAS and CMS collaborations

This talk is based on contributions from several people. Thanks to all of them
in particular TopWG conveners, MC experts and LHCHiggs ttH subgroup coordinators.

High statistics at the LHC: *tt*+bosons (γ, *Z, W* and *H*) becomes available!!
Observation of *tt*+γ/*Z*/*W* processes by both ATLAS and CMS experiments.
Not yet the case for *tt+H* process but getting close…

- Run 1 LHC Higgs combination: *tt+H* significance of 4.4 σ (2.0 σ expected)

Important Standard Model test: new physics modifies the structure of the couplings.



Top + X coupling, how to measure it?

→ Most of these analyses entering regime of results being systematically limited !!

→ Recent developments in theory community and LHCHXSWG (Yellow Report4, arXiv:1610.07922)

- NLO QCD+EW corrections to *tt+H/Z/W*
- NLO QCD corrections to *t+H*
- off-shell effects in *tt+H* production
- beyond NLO QCD: soft resummation

→ Implementation of latest theoretical developments is crucial to reduce uncertainties.

One of the highlights of LHC Run2 ☺, but very challenging for both experimental and theoretical sides.

Searching for the tiniest signals: very challenging

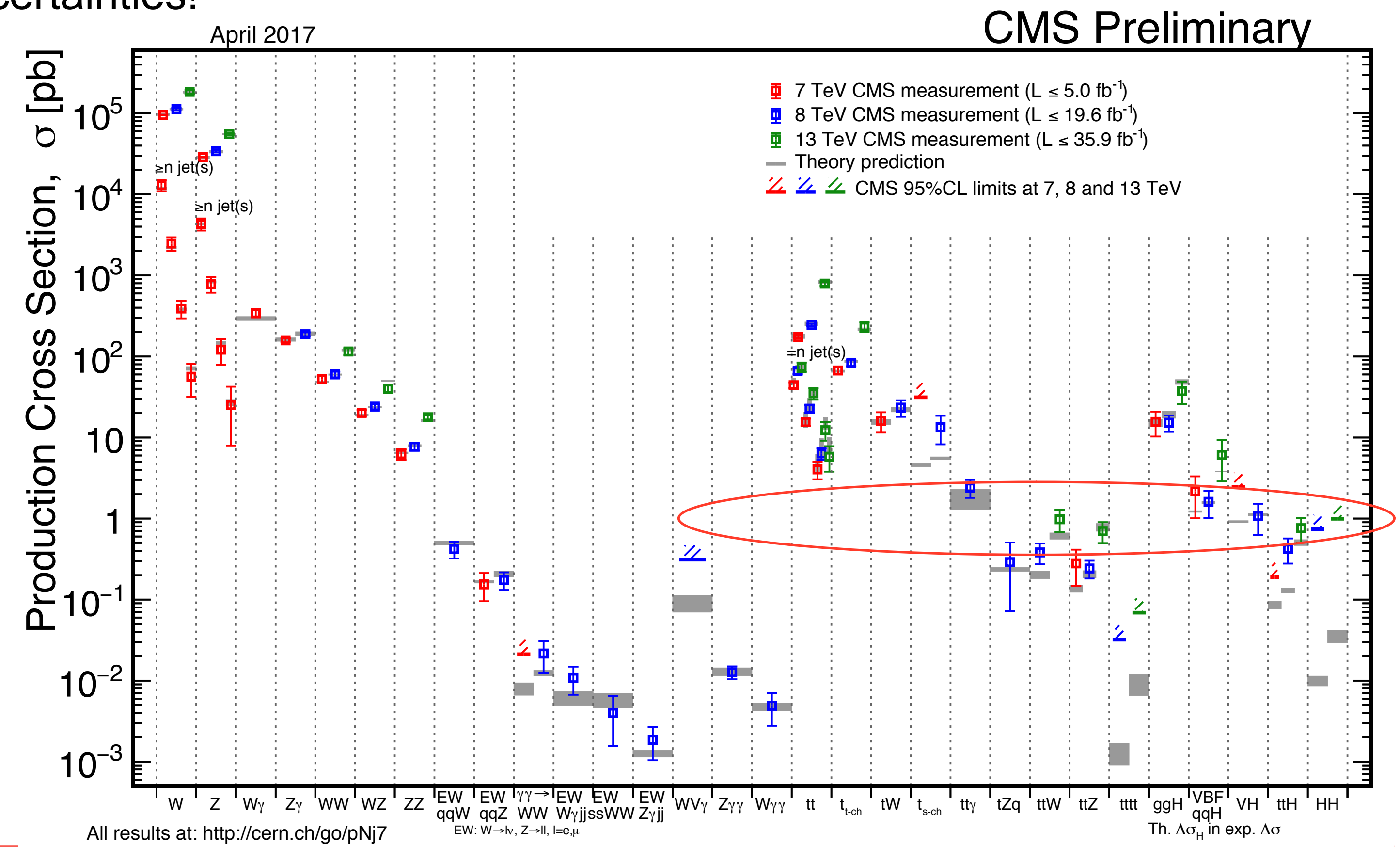
Virtues:

Many possible final states to consider!

Challenges:

- low production cross section
- a priori many handles against backgrounds with large theoretical uncertainties!

σ (pb)	8 TeV	13 TeV	13 / 8
tt+Z	0.206	0.839 (±12%)	3.7
tt+W	0.232	0.601 (±13%)	2.4
tt+H	0.129	0.5085 (±13%)	3.9
tt	~250	~830	3.3



- *tt+H* modelling
- *tt*+heavy flavour modelling
- *tt+Z/W* modelling

covering for each of them:

* summary of currently available measurements
* latest studies in the context of LHCHiggsXS ttH/tH subgroup (from YellowReport4)
* approaches currently followed in the experiments
  → *currently* means in the ongoing measurements
  (sometimes different of what was used in already published results)

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposaltTH
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposalTtbb
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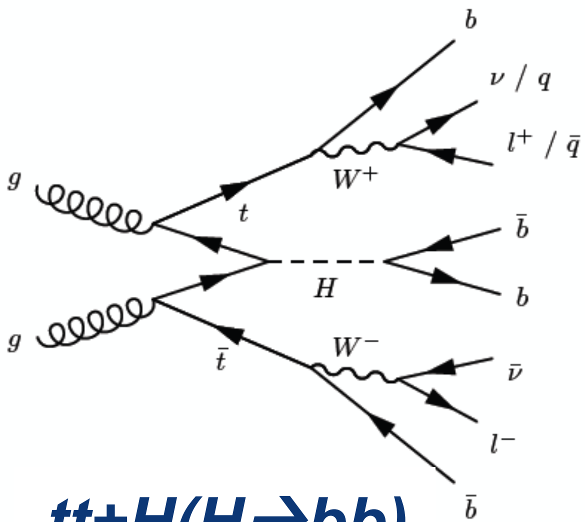
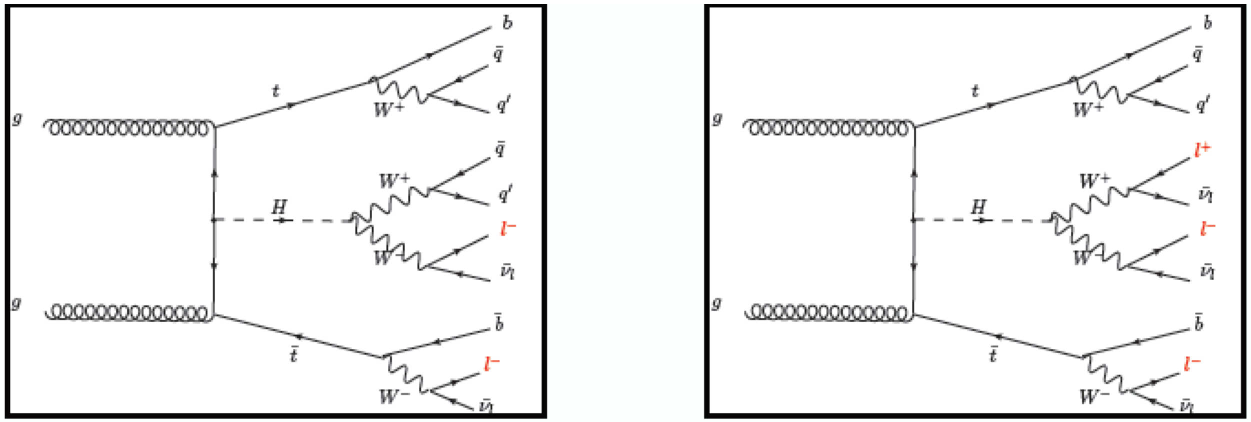
tt+H modelling



tt+H(H→bb)



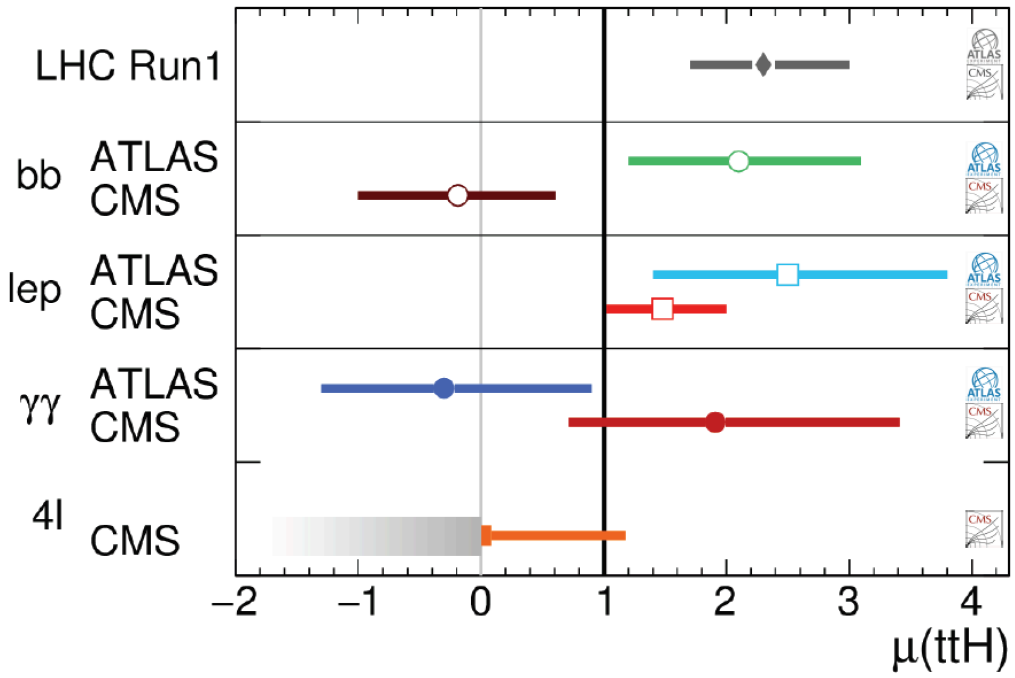
tt+H(H→WW,ττ)

Summary $t\bar{t}+H$ LHC measurements

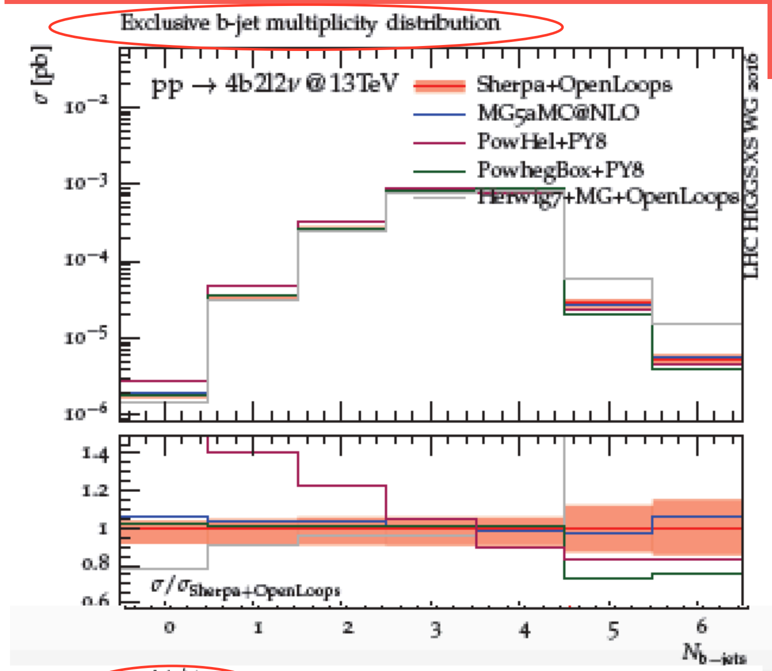
From G. Petrucciani slides at Moriond2017

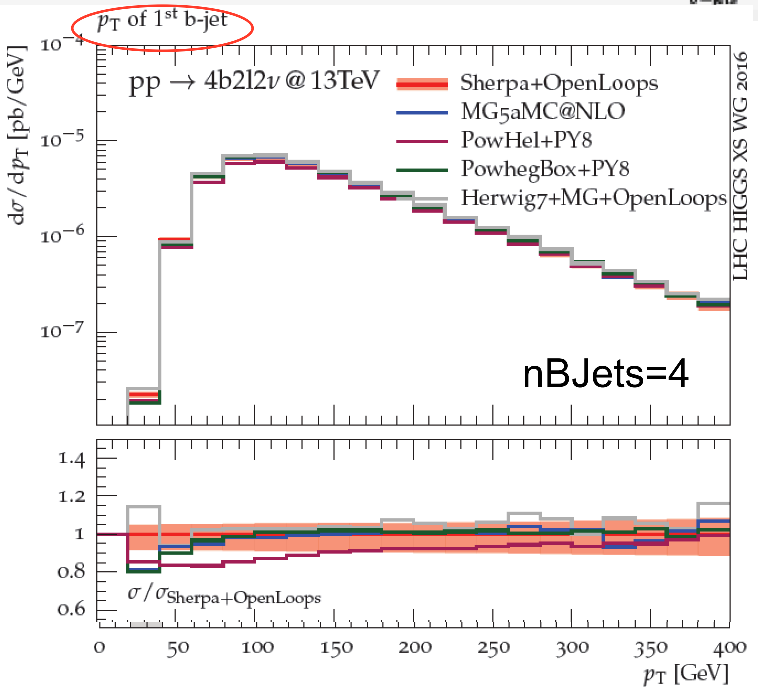
	ATLAS Run 2		CMS Run 2		
bb	2.1	$^{+1.0}_{-0.9}$	−0.2	$^{+0.8}_{-0.8}$	*PAS HIG 16-038*
multilep	2.5	$^{+1.3}_{-1.1}$	1.5	$^{+0.5}_{-0.5}$	*PAS HIG 17-004 (35.9 fb^{-1})*
γγ	−0.3	$^{+1.2}_{-1.0}$	1.9	$^{+1.5}_{-1.2}$	*PAS HIG 16-020*
4ℓ			0.0*	+1.2* −0.0*	*PAS HIG 16-041 (35.9 fb^{-1})*
comb.	1.8 *ATLAS-CONF-2016-068*	$^{+0.7}_{-0.7}$			
Run1 comb. *JHEP 08(2016) 045*	2.3	$^{+1.2}_{-1.0}$			

(*) $-2\Delta\ln L = 1$ interval with $\mu \geq 0$ constraint



tt+H modelling: YR4 studies





Yellow Report4, arXiv:1610.07922

Five NLO QCD+PS setups were compared:
* S- MC@NLO.: Sherpa(NLO)+OpenLoops +Sherpa PS
* MG5_aMC@NLO (fixed NLO)+Pythia8
* PowHel(fixed NLO)+Pythia8
* Powheg(fixed NLO)+Pythia8
* HERWIG7 using OpenLoops+MG5_aMC@NLO+Herwig7

using
5F scheme
$\mu_R=\mu_F=$ $\mu_0 = (E_T(t)E_T(\bar{t})E_T(H))^{1/3}$, where $E_T = \sqrt{M^2 + p_T^2}$
$\mu_Q=H_T/2$ with $H_T = E_T(t) + E_T(\bar{t}) + E_T(H)$
for samples with Sherpa and MG5_aMC@NLO
for Powheg $h = H_T/2$ in the definition of $h_{damp} = h^2/(h^2 + p_T^2)$
PDF set: NLO PDF4LHC15_30
Uncertainty band: scale variations (factor 2 up/down)

Plots for pp→4b2l2v
→ Discrepancies in PowHel for nBjets<4
→ Discrepancies for nBJets>4 mainly of parton-shower origin
→ Kinematic distributions are quite compatible for nBJets=4

tt+H modelling: current approach in the experiments

NLO QCD+PS matched setups used in both experiments.

ATLAS

Nominal: MadGraph5_aMC@NLO* ($\mu_R=\mu_F=H_T/2$, $\mu_Q=\xi\sqrt{\hat{s}}$, NNPDF3.0)+MadSpin+Py8 (A14 tune)

- Showering & hadronization: compared to MG5_aMC@NLO+MadSpin+HWpp (UE-EE5 tune)
- Tune variations: A14 eigentunes for Pythia8
- Scale choice & PDF set: using multiple event weights**

→ Currently also studying (no official samples available yet):

- Powheg+Pythia8 (need to define h_{damp} value)
- Sherpa(NLO)+OpenLoops

CMS

Nominal is different for ttH(bb) and ttH(multilepton, $\gamma\gamma$) to be consistent with main background in each of the channels:

ttH(bb): Powheg+Pythia8 (h_{damp} ~1.58*m_t, CUETP8M2 tune) [as used for tt+jets]

ttH(multilepton, $\gamma\gamma$): MadGraph5_aMC@NLO(NLO)+MadSpin+Pythia8 [as used for tt+W/Z]

- Scale choice & PDF set: using multiple event weights

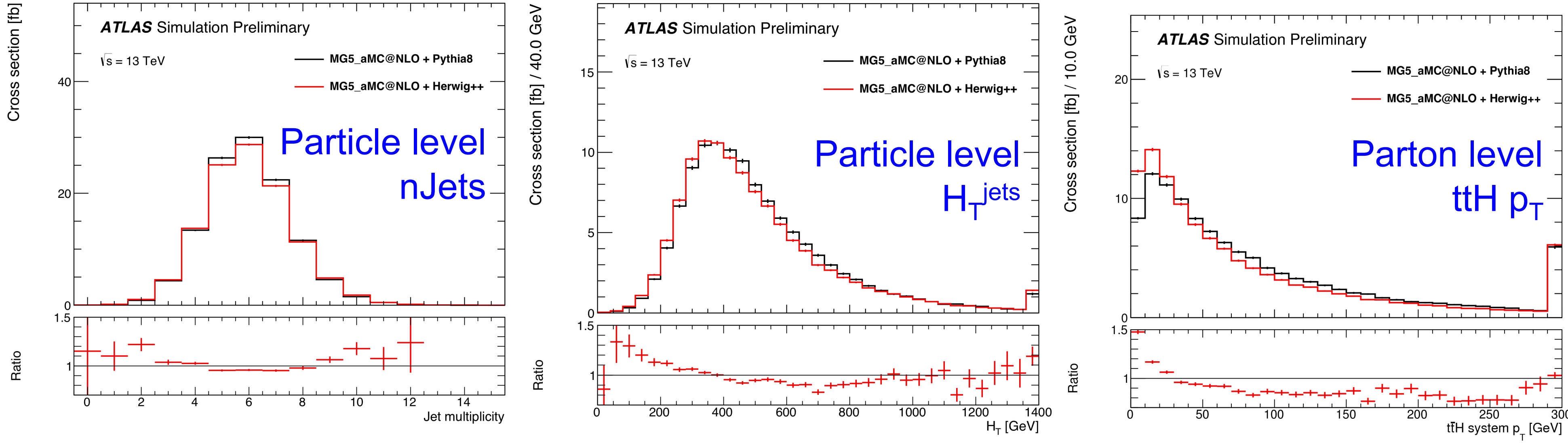
* Caveat of MadGraph5_aMC@NLO (NLO mode): ~25% of events having negative weights.

** Closure between internal and external (LHADPF) RW was tested for MG5_aMC@NLO.

tt+H modelling: studies at particle/parton level (ATLAS)

ATL-PHYS-PUB-2016-005

tt+H (*tt*→lep+jets, *H*→*bb*), Parton shower and hadronisation

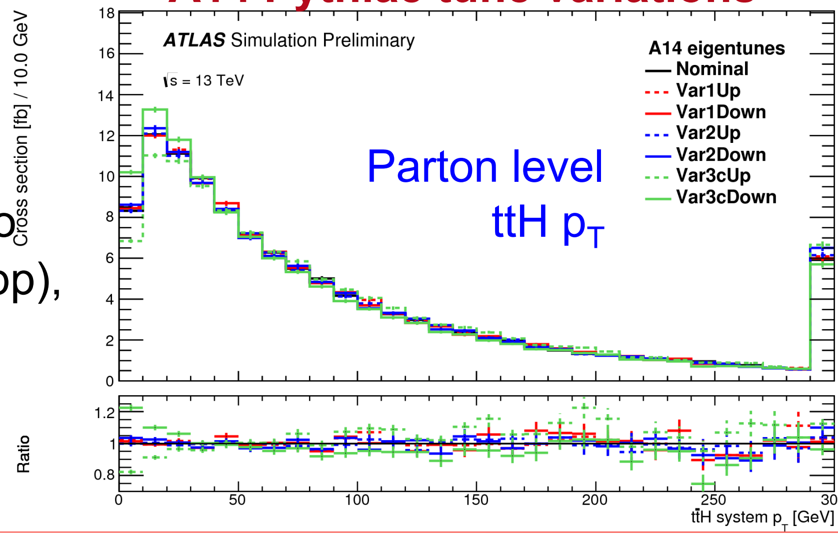


* MG5_aMC@NLO+Pythia8 prediction: slightly more events with six jets (number of expected jets for the selected channel *tt+H* with *tt*→lep+jets, *H*→*bb*).
In addition, jets transverse momenta is harder.

* Visible effects in low region of *tt+H* p_T spectrum due to different showering and hadronisation model (Py8/HWpp), larger than A14 Var3c (ISR) variations.

* Scale choice: main effect from μ_R,
cross-section varies 9%, shape effect <1%

A14 Pythia8 tune variations



Impact of modelling unc. in current *tt+H* searches

ttH(bb)

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

ATLAS-CONF-2016-080

ttH(multilep)

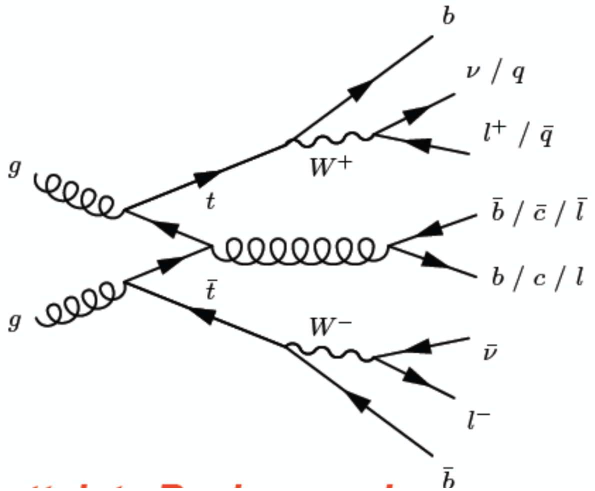
Uncertainty Source	$\Delta\mu$	
Non-prompt leptons and charge misreconstruction	+0.56	−0.64
Jet-vertex association, pileup modeling	+0.48	−0.36
$t\bar{t}W$ modeling	+0.29	−0.31
$t\bar{t}H$ modeling	+0.31	−0.15
Jet energy scale and resolution	+0.22	−0.18
$t\bar{t}Z$ modeling	+0.19	−0.19
Luminosity	+0.19	−0.15
Diboson modeling	+0.15	−0.14
Jet flavor tagging	+0.15	−0.12
Light lepton (e, μ) and τ_{had} ID, isolation, trigger	+0.12	−0.10
Other background modeling	+0.11	−0.11
Total systematic uncertainty	+1.1	−0.9

ATLAS-CONF-2016-058

* *tt+H* modelling includes showering and hadronisation (leading one), scale/PDF choice and tune variations.
* tt+Z/W modelling: MG5_aMC@NLO+Py8 (LOmultilep vs. NLO), scale/PDF choice and tune variations.

- Signal modelling uncertainties within the first four in ATLAS *tt+H* searches using 13.2 fb^{-1} at 13 TeV.
- Lower in the ranking for CMS results.

tt+heavy flavour (HF) modelling



Available tt+bb cross-section measurements

ATLAS

8 TeV: Eur. Phys. J. C76 (2016) 11

CMS

8 TeV: CMS PAS TOP-13-016, Eur. Phys. J. C76 (2016) 379

13 TeV: CMS PAS TOP-16-010

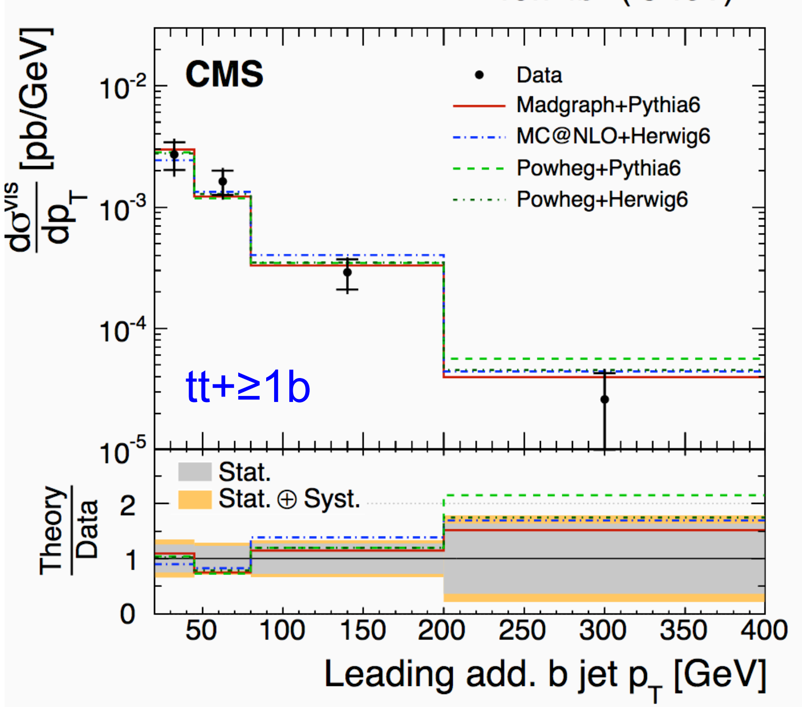
8 TeV: Eur. Phys. J. C76 (2016) 379

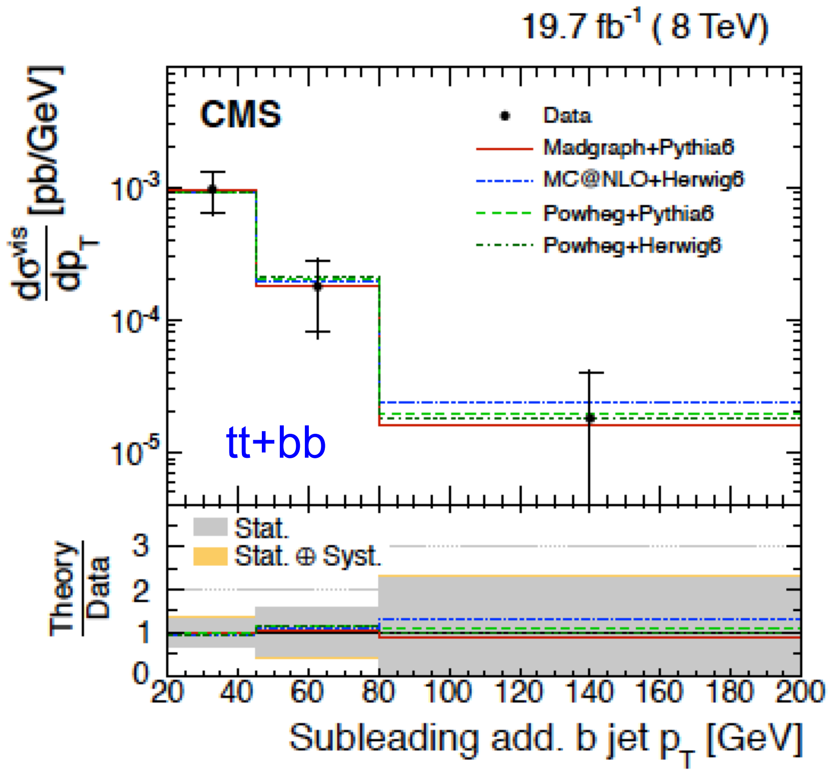
→ *tt+bb* absolute and normalized differential cross-sections measured as a function of the jet multiplicity for different jet transverse momentum thresholds and the kinematic properties of the leading additional jets.

→ First differential *tt+b* and *tt+bb* cross sections as a function of the kinematic properties of the leading additional *b*-jets.

* Data/MC for *tt+b* ~1.3
* Data/MC for *tt+bb* ~1.8
in agreement with other CMS and ATLAS results. Unc. dominated by the stat. unc. (20-100%).

Absolute diff. cross sections





A critical piece in *tt+H* (*H→bb*) searches: *tt*+jets modelling

***ttH* (*H*→bb) signal produces 0-2 leptons and 4-8 jets, 4 of them *b*-jets →** very challenging

Strategy: categorize events according to # jets and b-jets → define control and signal regions with different background composition

tt+jets events classified into several categories (tt+light / c / b), and subcategories, based on the flavour of additional jets and number of hadrons in each of them.

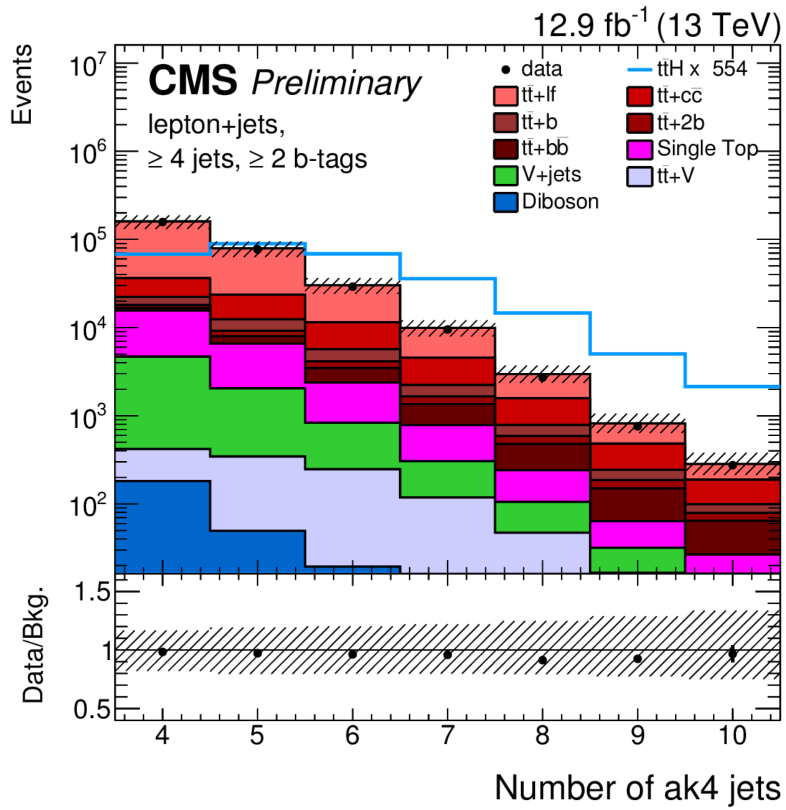
Two distributions crucial to model correctly:

* **ttbar p_T** (mainly affects jet multiplicity): improved thanks to differential measurements with several observables sensitive to different effects (matrix element, radiation, hadronisation)
  → well described with tuned **Powheg+Pythia8** with h_{damp} ~1.5-1.58 m_{top} (nominal)

* **top p_T** (mainly affects jets p_T): largely improved by NNLO computations

→ More details in top modelling and tunning talks (J. Howarth, E. Yazgan and D.Kar)

CMS-PAS-HIG-16-038



THE critical piece in *tt*+*H* (*H*→*bb*) searches: *tt*+HF modelling

The most critical point: *tt*+*bb* irreducible bkg.

- pure QCD process, very complicated and poorly understood: involves several scales and massive quarks
  - ➢ challenging for the MC generator community
  - ➢ implementation of latest theoretical developments crucial
- studies ongoing in both experiments in close collaboration with theorists (LHCHiggs WG)
  - NLO 4F *tt*+*bb* predictions (with massive *b*-quarks in ME) with novel generators
  - comparisons with inclusive 5F *tt*+jets
  - how to merge 4F and 5F samples?
  - heavy flavour classification

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Approach proposed in the LHCHiggs Yellow Report 4

* NLOPS 4F *tt+bb* sample
- can be applied in full phase space (no generation cuts)
- inclusive description of *tt*+≥1*b*-quarks
- includes *gb→ttb* contributions also in the 5F scheme

* Inclusive 5F *tt*+jets sample
- needs to be restricted to *tt*+0 *b*-quarks to avoid double counting (veto events containing *b*-quarks not arising from showered top decays or MPI or UE)

→ Ongoing discussions on possible implementations

↗ **More details in next talk (Laura Reina)**

Comparisons of different *tt+bb* 4F NLO predictions (Sherpa+OpenLoops, MG5_aMC@NLO+Py8 and Powhel+Py8) with theory motivated shower settings for consistent comparisons:

Different NLO+PS methods, showers, and m_b treatments

Tool	Matching	Shower	m_b[GeV]	gencuts
SHERPA2.1+OPENLOOPS	SMC@NLO	Sherpa 2.1	4.75 (4F)	no
MG5_AMC@NLO	MC@NLO	Pythia 8.2	4.75 (4F)	no
POWHEL	Powheg	Pythia 8.2	0 (5F)	$p_{T,b} > 4.75$ GeV $\frac{m_{bb}}{2} > 4.75$ GeV

using 4F scheme

	for MG5_aMC@NLO	for Sherpa
Renormalisation scale μ_R	$\sqrt[4]{m_T(t) * m_T(\bar{t}) * m_T(b) * m_T(\bar{b})}$ (CMMPS)	
Factorisation scale μ_F	$H_T/2$ with $H_T = \sum_{i\epsilon \text{finalstate}} m_T(i)$	
Resummation scale μ_Q (Q_{sh})	$\xi\hat{s}$ with $\xi\epsilon[0.1,0.25]$	$H_T/2$

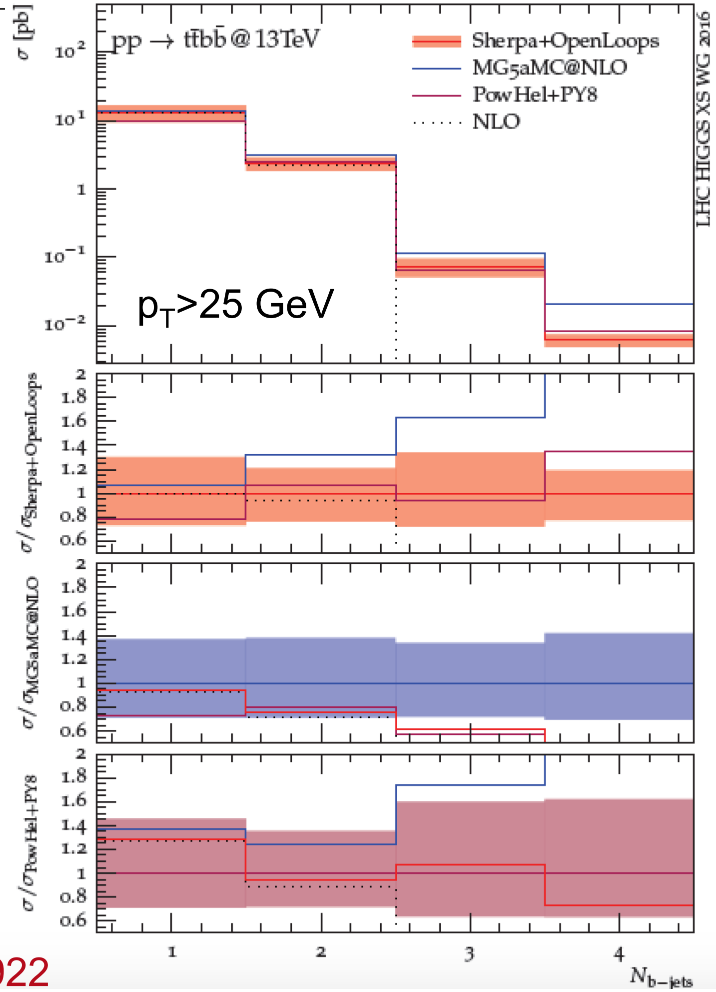
PDF set: NNPDF3.0 4F

Top quarks are not decayed,

hadronisation and UE are swtiched off

- differences of ≥40% for tt+≥2b cross section
- further studies on some of the settings ongoing
  e.g. strong sensitivity to resummation scale (shower starting scale) in MG5_aMC@NLO

 # additional b-jets (inclusive)



Yellow Report4, arXiv:1610.07922

tt+jets (HF) modelling: current approach in the experiments

Common in both experiments: nominal ttbar sample inclusive 5FS Powheg(v2)+Pythia8
slightly different h_{damp} value (1.5, 1.58) and Pythia8 tunes (A14, CUETP8M2) based on Monash

ATLAS

5F tt+jets

- Hard process MC generator: compared to MG5_aMC@NLO+Py8
- Showering & hadronization: compared to Powheg+Herwig7
- ISR/FSR variations: changes in μ_R, μ_F, h_{damp} and A14 tune
- Scale choice & PDF set: using multiple event weights

→Also studying Sherpa(NLO)+OpenLoops

uncorrelated between tt+light/c/b flavours

4F tt+bb

- Nominal: Sherpa(NLO)+OpenLoops only available at particle level → merging with 5F samples not possible → reweighting tt+≥1b events in 5F sample to 4F predictions (see next slides)

(also compared to MG5_aMC@NLO+Py8/HWpp, now repearing studies with updated version for MG5_aMC@NLO with new μ_Q funtional form)

CMS

5F tt+jets

- Hard process MC generator: compared to MG5_aMC@NLO (LOmultileg and NLO mode)+Py8
- Showering & hadronization: Pythia8 with ISR and FSR α_S variations (CUETP8M2 tune)

4F tt+bb: focusing on data-driven validation studies to understand the quality of the predictions. Also studying the stitching procedure 4FS-with-5FS.

HF definition and treatment of uncertainties

Reconstructed *tt*+jets events are classified into several categories and subcategories, based on the flavour of additional jets (at particle level) and number of hadrons in each of them.

* Only additional particle level jets above a p_T threshold are considered in the classification
* Jets flavour (b, c or light) is determined via a ghost or dR matching to hadrons.
  - For b and c jets, kinematics cuts on the leading hadron to which they are matched being studied.
  - No p_T ratio p_T^{hadron}/p_T^{jet} cut is considered (so far) in the HF classification.

Cuts	ATLAS *	CMS
Reco-level jets	(all events are classified)	≥ two jets with p_T > 30 GeV
Particle level jets	15 GeV	20 GeV
Hadrons	5 GeV, no p_T^{hadron}/p_T^{jet} cut	No cuts
Particle-hadron matching	dR<0.3	Ghost matching

* From ongoing studies, the relative differences among generators in tt+jets fractions seem stable against these cuts

Subcategories

- **"tt+b"**: 1 extra particle jet in the event which is matched to exactly 1 HF hadron
- **"tt+bb"**: 2 particle jets, each of them matched to exactly 1 HF hadron
- **"tt+B/2b"** (ATLAS/CMS): 1 particle jet which is matched to a bb pair (g→bb splitting), i.e to >1 hadron

Treatment of uncertainties

ATLAS: reweighting of kinematics for each subcategory in 5F sample to 4F predictions

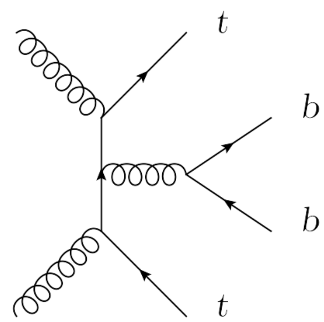
→ treating uncertainties as fully correlated among subcategories

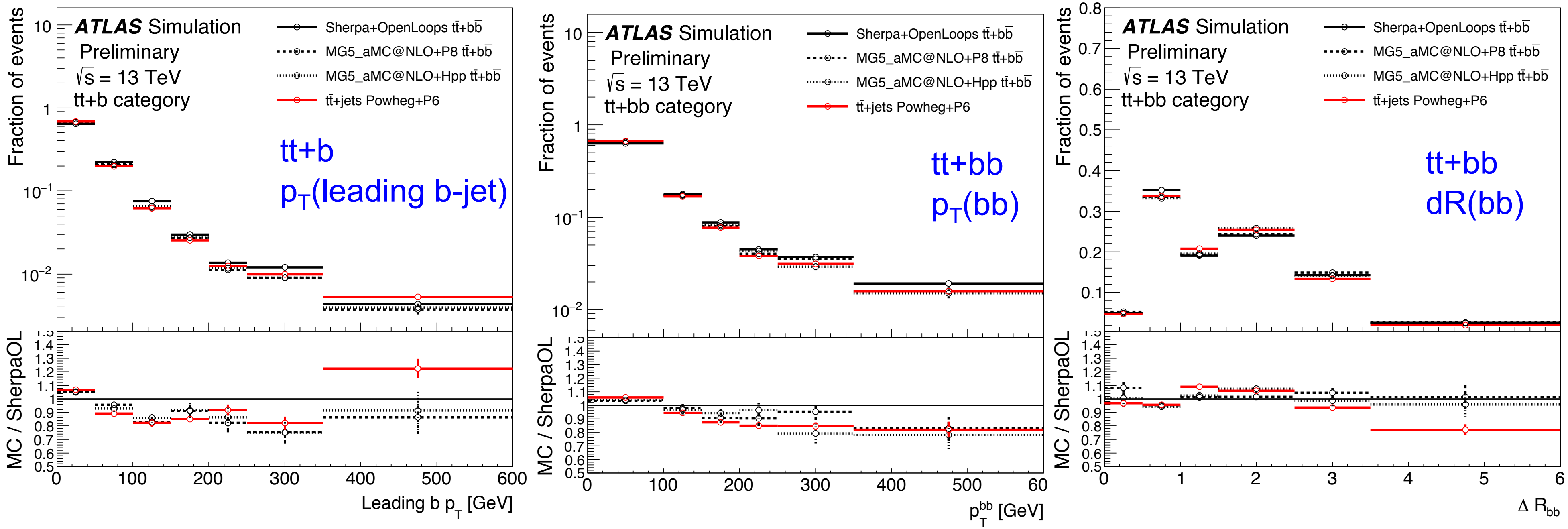
CMS: shapes from 5F predictions → treating uncertainties as fully uncorrelated.

tt+bb 4F samples (ATLAS)

ATL-PHYS-PUB-2016-016

$t\bar{t}b\bar{b}$, $\sqrt{s}$=13 TeV, m_t= 172.5 GeV, m_b= 4.75 GeV			
ME gen.	aMC@NLO + MadSpin	aMC@NLO + MadSpin	Sherpa+OpenLoops -
PS/UE gen.	Herwig++	Pythia8	Sherpa
Renormalisation scale μ_R	$\sqrt[4]{m_T(t) * m_T(\bar{t}) * m_T(b) * m_T(\bar{b})}$		(CMMPS)
Factorisation scale μ_F	$H_T/2$ with $H_T = \sum_{i\epsilon \text{finalstate}} m_T(i)$		
Resummation scale μ_Q (Q_{sh})	$\xi\hat{s}$ with $\xi\epsilon[0.1,0.25]$		$H_T/2$
ME PDF	NNPDF3.0nlo 4F	NNPDF3.0nlo 4F	CT10nlo 4F
PS/UE PDF	CTEQ6L1	NNPDF2.3	
Tune	UE-EE-5	A14	author's tune
Cross-section × BR($t\bar{t} \rightarrow \mu\mu$)[pb]	0.322 ± 0.020	0.320 ± 0.020	0.315 ± 0.020





* Differences (up to 20%) in p_T(leading b-jet) for tt+b category: SherpaOL 4F is harder.

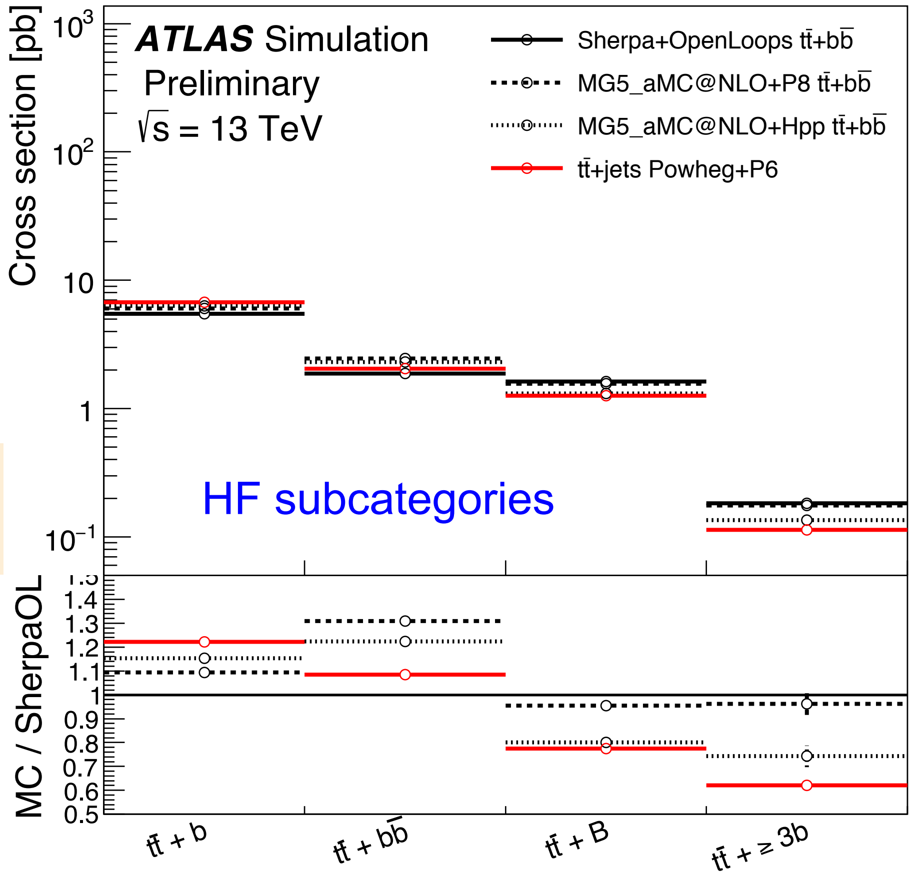
tt+HF modelling: reweighting to 4F Sherpa+OL (ATLAS)

Differences observed in tt+bb kinematics among different 4F predictions and also 5F.
Since no 4F tt+bb sample is available at reconstructed level, tt+≥1b events in nominal tt+jets inclusive 5F sample are reweightied to match 4F tt+bb NLO predictions:

* Correct normalisation of the different subcategories
* Small kinematic corrections in each category

- 2D re-weighting:
  - **top/ttbar pT (SherpaOL)**
- 2D re-weighting:
  - **ΔR(bb)/pT(bb)**
  - **OR: q1 pT/η (for tt+b/B)**

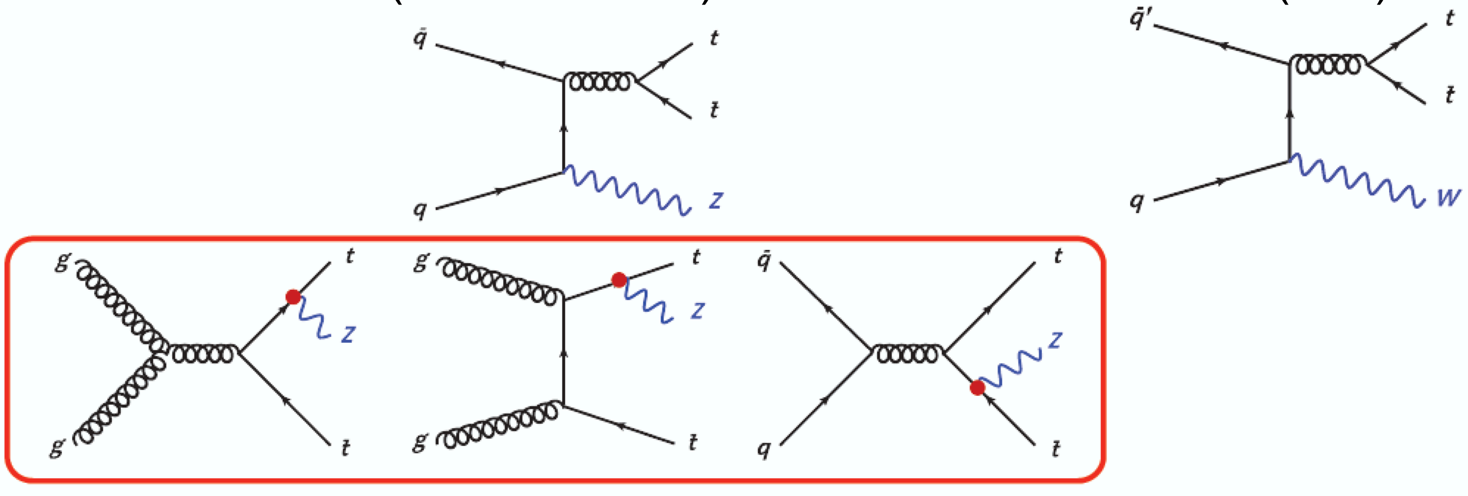
All samples compared predict more events in tt+b/bb categories than SherpaOL 4F.



→ Further studies currently ongoing.
Also with updated MC generators versionns.

tt+Z/W modelling

$t\bar{t}Z$ (ISR and FSR) $t\bar{t}W$ (ISR)



Available tt+Z/W cross-section measurements

ATLAS

8 TeV: JHEP 11 (2015) 172

13 TeV: Eur. Phys. J. C77 (2017) 40 (3.2 fb^{-1})

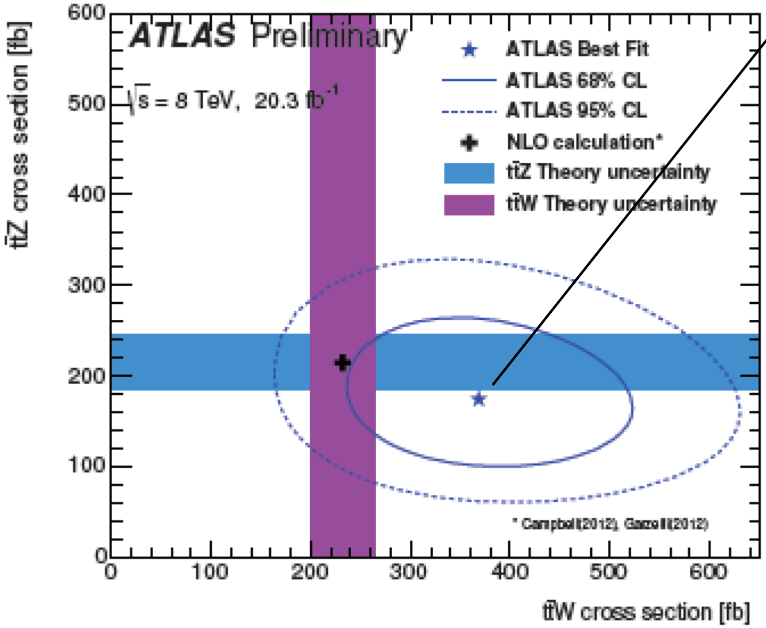
CMS

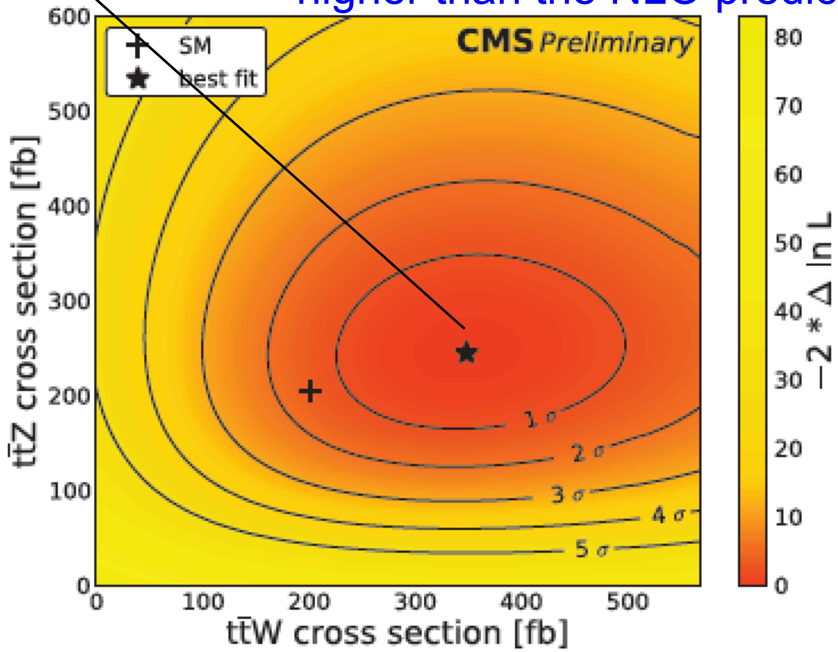
8 TeV: JHEP 01 (2016) 096

13 TeV: CMS PAS TOP-16-017 (12.9 fb^{-1})

8 TeV

Experiments tend to measure these processes higher than the NLO predictions.





JHEP 11 (2015) 172

ΔttZ = 33%

ΔttW = 26%

JHEP 01 (2016) 096

ΔttZ = 27%

ΔttW = 31%

→ Stat. unc. dominates. Main syst. unc. source: bkg. modelling.

13 TeV

Eur. Phys. J. C77 (2017) 40

ΔttZ = 33%

ΔttW = 53%

3.2 fb^{-1}

CMS PAS TOP-16-017

ΔttZ = +30% -27%

ΔttW = +32% -29%

12.9 fb^{-1}

Stat. unc.~syst. unc

LHCHiggs Yellow Report 4: *tt+Z* and *tt+W* cross-sections

Recent developments in theory community and LHCHXSWG:

* NLO QCD+EW corrections to *tt+H/Z/W*

Table 40: Inclusive $t\bar{t}V$ cross sections at NLO QCD and NLO QCD+EW accuracy for $\sqrt{s} = 13$ TeV. NLO QCD+EW results represent the best predictions and should be used in experimental analyses. Scale, PDF, and α_s uncertainties are quoted in per cent. Absolute statistical uncertainties are indicated in parenthesis. We also quote the NLO QCD+EW $t\bar{t}W^- + t\bar{t}W^+$ combined cross sections where correlation effects have been consistently included in the estimate of the corresponding uncertainties. Collider energy and cross sections are in TeV and femtobarn, respectively.

Process	$\sqrt{s}$	$\sigma^{\text{NLO}}_{\text{QCD}}$	$\sigma^{\text{NLO}}_{\text{QCD+EW}}$	K_{QCD}	$\delta_{\text{EW}}[\%]$	Scale[%]		PDF[%]		$\alpha_S[\%]$	
$t\bar{t}Z$	13	841.3(1.6)	839.3(1.6)	1.39	−0.2	+9.6%	− 11.3%	+2.8%	− 2.8%	+2.8%	− 2.8%
$t\bar{t}W^+$	13	412.0(0.32)	397.6(0.32)	1.49	−3.5	+12.7%	− 11.4%	+2.0%	− 2.0%	+2.6%	− 2.6%
$t\bar{t}W^-$	13	208.6(0.16)	203.2(0.16)	1.51	−2.6	+13.3%	− 11.7%	+2.1%	− 2.1%	+2.9%	− 2.9%
$t\bar{t}W^- + t\bar{t}W^+$	13	620.6(0.36)	600.8(0.36)	1.50	−3.2	+12.9%	− 11.5%	+2.0%	− 2.0%	+2.7%	− 2.7%

- Values for fixed scale $\mu = m_t + m_V/2$ (replacing by a dynamic scale $\mu = H_T/2$ shifts cross-sections by -7%, within unc. quoted)
- For ttW production QCD+EW corrections as well as the NLO scale uncertainties are slightly more pronounced than for ttZ.
- Scale variations range from 10 to 13% and represent the dominant source of uncertainty.

* Experiments are using these cross-section values to normalise their samples, but currently available MC simulated do not include EW corrections.
* tt+Z values include on-shell contribution only, but experiments include off-shell *tt*$\gamma^* \rightarrow ll$ and thus some approximations are made to derive a K-factor for *tt+ll*.

* Comparison of NLO QCD predictions for differential distributions (MadGraph5_aMC@NLO, PowHel, Sherpa+OpenLoops): similar shapes

LHCHiggs Yellow Report 4: *tt*+*Z* and *tt*+*W* cross-sections

Recent developments in theory community and LHCHXSWG:

* NLO QCD+EW corrections to *tt*+*H/Z/W*

Table 40: Inclusive $t\bar{t}V$ cross sections at NLO QCD and NLO QCD+EW accuracy for $\sqrt{s} = 13$ TeV. NLO QCD+EW results represent the best predictions and should be used in experimental analyses. Scale, PDF, and α_s uncertainties are quoted in per cent. Absolute statistical uncertainties are indicated in parenthesis. We also quote the NLO QCD+EW $t\bar{t}W^- + t\bar{t}W^+$ combined cross sections where correlation effects have been consis[illegible] included in the estimate of the corresponding uncertainties. Collider energy and cross sections [illegible] femtobarn, respectively.

Process	$\sqrt{s}$	$\sigma^{\text{NLO}}_{\text{QCD}}$	$\sigma^{\text{NLO}}_{\text{QCD+EW}}$	K_{QCD}	$\delta_{\text{EW}}[\%]$	[illegible]		PDF[%]		$\alpha_S[\%]$	
$t\bar{t}Z$	13	841.3(1.6)	839.3(1.6)	[illegible]	[illegible]	+9.6%	−11.3%	+2.8%	−2.8%	+2.8%	−2.8%
$t\bar{t}W^+$	13	412.0(0.32)	[illegible]	[illegible]	−3.5	+12.7%	−11.4%	+2.0%	−2.0%	+2.6%	−2.6%
$t\bar{t}W^-$	13	[illegible]	[illegible]	1.51	−2.6	+13.3%	−11.7%	+2.1%	−2.1%	+2.9%	−2.9%
$t\bar{t}W^- + t\bar{t}W^+$	13	[illegible]	600.8(0.36)	1.50	−3.2	+12.9%	−11.5%	+2.0%	−2.0%	+2.7%	−2.7%

NEW!! Recent NLO+NNLL cross sections for ttV (arXiv::1702.00800)

- Values for fixed scale $\mu = m_t + m_V/2$ (replacing by a dynamic scale $\mu = H_T/2$ shifts cross-sections by -7%, within unc. quoted)
- For ttW production QCD+EW corrections as well as the NLO scale uncertainties are slightly more pronounced than for ttZ.
- Scale variations range from 10 to 13% and represent the dominant source of uncertainty.

* Experiments are using these cross-section values to normalise their samples, but currently available MC simulated do not include EW corrections.
* tt+Z values include on-shell contribution only, but experiments include off-shell $tt\gamma^* \rightarrow ll$ and thus some approximations are made to derive a K-factor for *tt*+*ll*.

* Comparison of NLO QCD predictions for differential distributions (MadGraph5_aMC@NLO, PowHel, Sherpa+Openloops): similar shapes

tt+Z/W modelling: current approach in the experiments

ATLAS: *tt+ll, tt+Z(→qq), tt+Z(→νν), tt+W*

tt+ll (includes off-shell *ttγ*→ll* production with m_{ll}>5 GeV for OSSF matrix element leptons)

Nominal: MadGraph5_aMC@NLO($\mu_R=\mu_F=H_T/2$, $\mu_Q=\xi\sqrt{\hat{s}}$, NNPDF3.0)+MadSpin+Py8 (A14 tune)

- Alternative MC generator: vs. Sherpa LOmultileg or MG5_aMC@NLO LOmultileg (N_p<=2)
- Tune variations: A14 eigentunes for Pythia8
- Scale choice & PDF set: using multiple event weights

→ Should we include m_{ll}<5 GeV ?
→ Planning to generate NLO Sherpa samples.
→ Is it possible to simulate tt+Z/W with Powheg+Pythia8 ?

CMS: *tt+ll, tt+Z(→qq), tt+Z(→νν), tt+W*

tt+ll (includes off-shell *ttγ*→ll* production with m_{ll}>10 GeV for OSSF matrix element leptons)

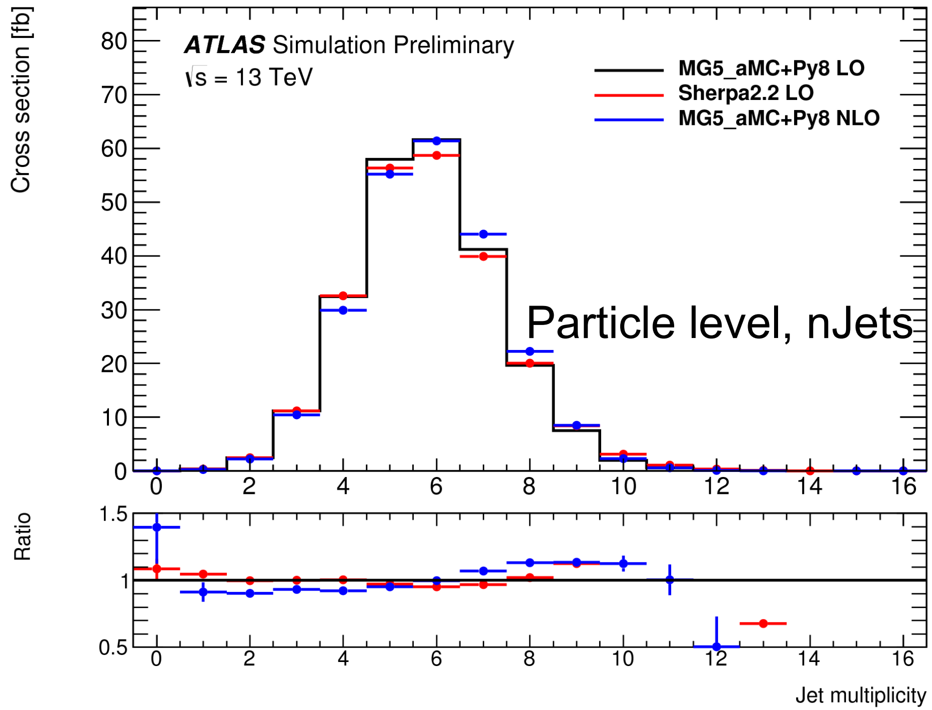
Nominal: MadGraph5_aMC@NLO (LOmultileg_MLMmatching, NNPDF3.0)+MadSpin+Pythia8

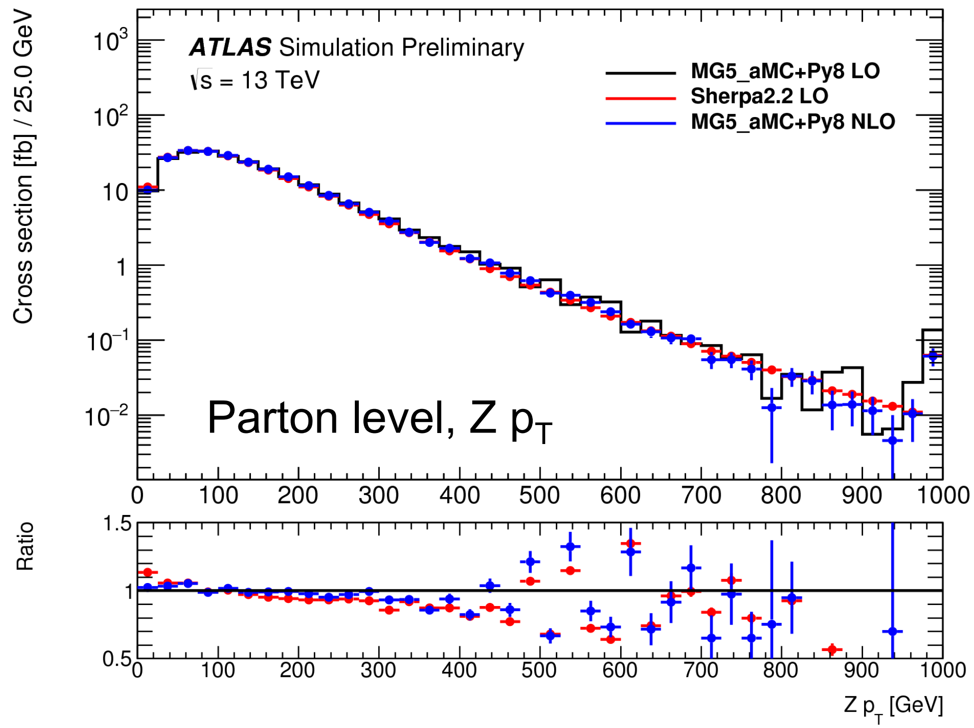
- Alternative MC generator:
  ttZ: MadGraph5_aMC@NLO NLOmode vs. LOmultileg_MLMmatching
  ttZ: MadGraph5_aMC@NLO NLOmode vs. LOmultileg_MLMmatching
- Scale choice & PDF set: using multiple event weights

tt+Z(→qq) modelling studies at particle/parton level

tt+Z (tt→lep+jets, Z→qq)
MC generator comparison

MG5_aMC@NO+Py8 (LOmultileg, up to 2 partons)
Sherpa2.2 (LOmultileg, up to 2 partons)
MadGraph5_aMC@NLO (NLO mode)+Py8 [current nominal]





Higher jet multiplicity for NLO prediction.

Sherpa sample predicts slightly softer Z boson p_T.

ATL-PHYS-PUB-2016-005

→ *tt+Z* and *tt+W* cross section measurements dominated by theoretical bkg. unc. (WZ) and instrumental background (fake leptons).

Other samples: tt+photon, tZq, tWZ, tHq, tWH

- tt+photon:
  MG5_aMC@NLO+Py8 (LO mode),
  including photons radiated from the top quarks as well as from their decay products
  (Note: MadSpin was NOT used since it does NOT include photon radiation in top decay products)
  ATLAS cuts at generation level: $p_T(\gamma)$>15 GeV, dR(lep, γ)>0.2 and dR(jet, γ)>0.2
  CMS cuts at generation level: $p_T(\gamma)$>13 GeV, dR(lep, γ)>0.3 and dR(jet, γ)>0.3

- tZq
  ATLAS: MG5_aMC@NLO (LO mode)+Py6, CTEQ6L1, Perugia2012, 4 FS → moving to NLO & Py8
  CMS: MG5_aMC@NLO (NLO mode)+Py8, 4 FS

- tWZ
  ATLAS: MG5_aMC@NLO (NLO mode)+Py8, A14, 5FS, with DR1 and DR2 strategies
  (28% discrepancies) to remove interference with ttZ [arXiv: 1607.05862, ATL-PHYS-PUB-2016-020]
  CMS: MG5_aMC@NLO (LO mode)+Py8, 5FS

$$|\mathcal{M}_{\rm tot}|^2 = \underbrace{\overbrace{|\mathcal{M}_{\rm sr}|^2}^{\rm DR1} + 2Re(\mathcal{M}_{\rm sr}\cdot\mathcal{M}_{\rm dr})}_{\rm DR2} + |\mathcal{M}_{\rm dr}|^2$$

- tHq
  ATLAS: MG5_aMC@NLO+Py8 (LO mode), 4 FS [samples with Herwig++ also available]
  CMS: MG5_aMC@NLO+Py8(LO mode), 4 FS

- tWH
  ATLAS: MG5_aMC@NLO (NLO mode)+HWpp, A14, 5 FS, interference with ttH removed with DR1
  CMS: MG5_aMC@NLO+Py8(LO mode)+Py8, 5FS

Top quark couplings: Effective Field Theories (EFT)

The effects of new physics at a scale Λ can be described by an effective Lagrangian

$$\mathcal{L}_{SM}^{(6)} = \mathcal{L}_{SM}^{(4)} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \ldots$$

Interference SM-BSM

Pure BSM term

$$\sigma = \sigma_{SM} + \sum_i \frac{C_i}{(\Lambda/1\mathrm{TeV})^2}\sigma_i^{(1)} + \sum_{i\leq j} \frac{C_i C_j}{(\Lambda/1\mathrm{TeV})^4}\sigma_{ij}^{(2)}$$

Dimension 6 operators relevant for top quark physics.

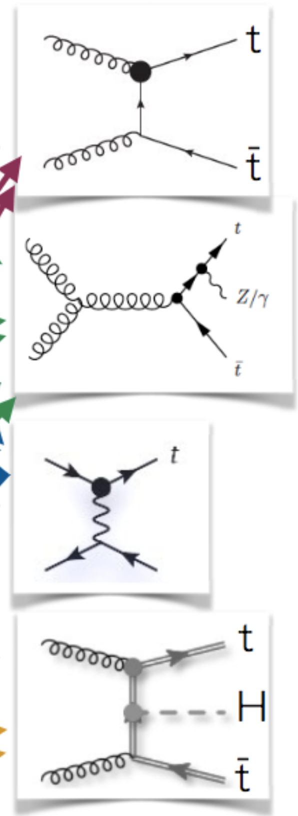
modify vector and axial coupling of top to EW gauge bosons

O_{tB}, O_{tW}: EW dipole operator
O_{tG}: chromomagnetic dipole operator

$$O_{\varphi Q}^{(3)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}^I_\mu \varphi\right)\left(\bar{Q}\gamma^\mu\tau^I Q\right)$$
$$O_{\varphi Q}^{(1)} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{Q}\gamma^\mu Q\right)$$
$$O_{\varphi t} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{t}\gamma^\mu t\right)$$
$$O_{\varphi b} = i\tfrac{1}{2}y_t^2 \left(\varphi^\dagger \overleftrightarrow{D}_\mu \varphi\right)\left(\bar{b}\gamma^\mu b\right)$$
$$O_{tW} = y_t g_w (\bar{Q}\sigma^{\mu\nu}\tau^I t)\tilde{\varphi}W^I_{\mu\nu}$$
$$O_{bW} = y_b g_w (\bar{Q}\sigma^{\mu\nu}\tau^I b)\varphi W^I_{\mu\nu}$$
$$O_{tB} = y_t g_Y (\bar{Q}\sigma^{\mu\nu} t)\tilde{\varphi}B_{\mu\nu}$$
$$O_{tG} = y_t g_s (\bar{Q}\sigma^{\mu\nu}T^A t)\tilde{\varphi}G^A_{\mu\nu}$$
$$O_{t\varphi} = (\varphi^\dagger\varphi)(\bar{Q}t\tilde{\varphi})$$
$$O_{\varphi tb} = i(\varphi^\dagger D_\mu \varphi)(\bar{t}\gamma^\mu b)$$

$$O_G = g_s f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$$
$$O_{\varphi G} = g_s^2 \left(\varphi^\dagger\varphi\right) G^A_{\mu\nu}G^{A\mu\nu}$$

4-fermion ops



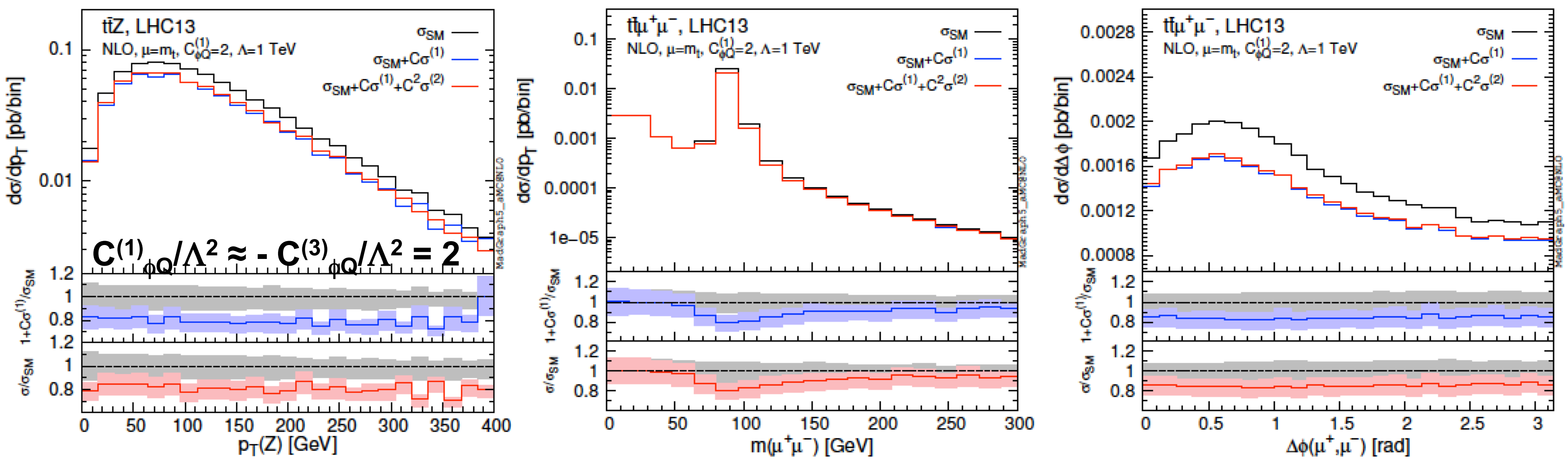
Ongoing activities related to EFT or κ_t samples

ttZ/W EFT interpretations

* CMS ttV 8 TeV paper: parametrisation of the cross-sections in terms of $C_{1,V}$ and $C_{1,A}$, no dedicated MC samples with different values of $C_{1,V}$ and $C_{1,A}$ couplings.

* For Run2: both experiments are generating samples with the EFT NLO QCD model implemented in MG5_aMC@NLO (+Py8 or HW). arXiv: 1601.08193
Coefficients are assumed to be real. Assume only one coefficient is non-zero at the time.

Effect of EFT coefficients in some tt+ll observables



ttH/tH samples with different κ_t values in both experiments.

Outlook

The program of *tt+X* production at the LHC is well underway:

- entering regime of results being systematically limited (bkg. and signal modelling)
  → one of the main focus of the LHCHiggs *ttH/tH* XS subgroup
- implementation of the latest theoretical developments is crucial to reduce unc.
- will continue comparing with data to further tune and improve the MC generators

Main critical points for current measurements:

* 4F *tt+bb* NLO: need to investigate large differences among MC generators, but this is a extremely expensive process (CPU time) → sharing common LHEfiles ?
* how to merge 4F *tt+bb* and 5F *tt*+jets samples ?
* *tt+H* modelling (showering& hadronisation) starting to appear in the ranking list

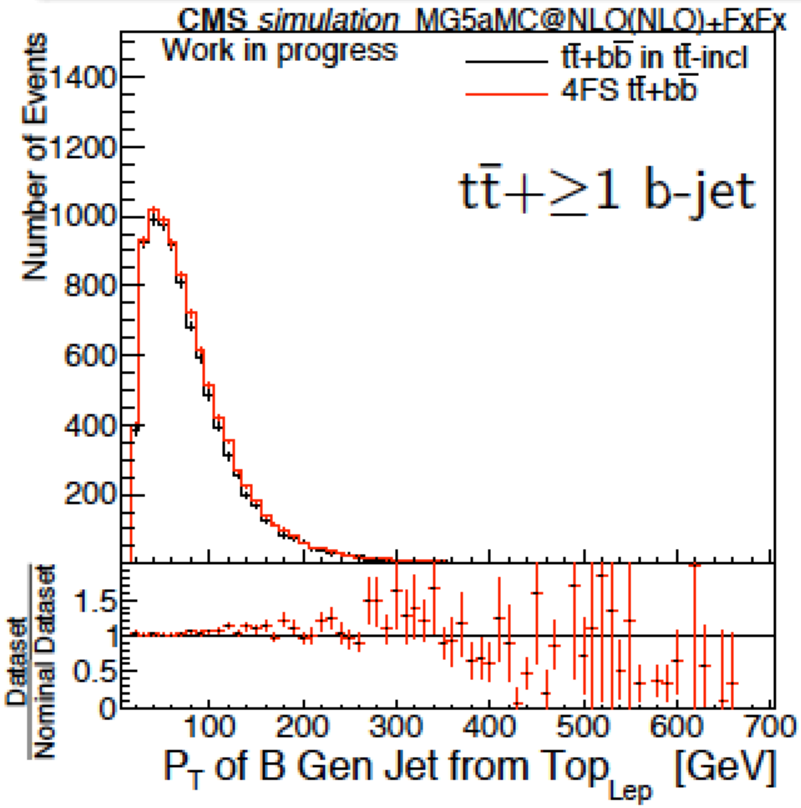
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposalttH
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposalTtbb
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/ProposalttV

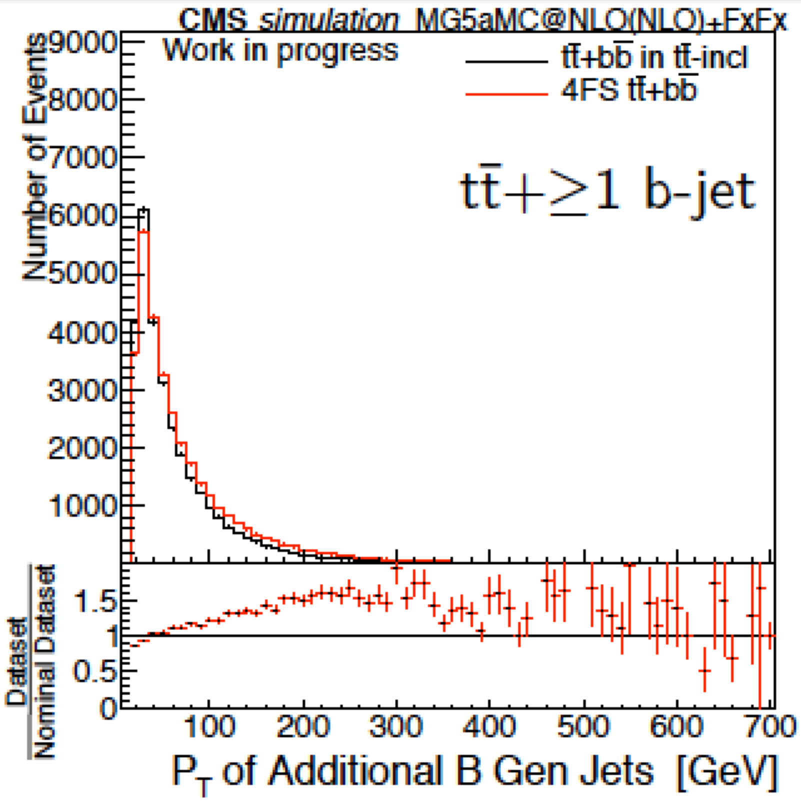
THANKS FOR YOUR ATTENTION

BACK-UP

Comparisons *tt+bb* 4F and tt+jets NLOmultileg 5F (CMS)

- Comparison between MG5aMC@NLO+Pythia8 (FxFx merged) 5FNS $t\bar{t}$+0/1/2 jets and 4FNS $t\bar{t}+b\bar{b}$
- Require 1 b-gen-jet not from Top decay in $p_T \geq 20.0\text{GeV}$, $|\eta| < 2.4$
- b-gen-jets defined through jet-flavour-clustering (ghost hadrons)





Tune variations: A14 eigentunes (ATLAS)

ATL-PHYS-PUB-2014-021

Param	+ variation	− variation
VAR1: MPI+CR (UE activity and incl jet shapes)		
`BeamRemnants:reconnectRange`	1.73	1.69
`MultipartonInteractions:alphaSvalue`	0.131	0.121
VAR2: ISR/FSR (jet shapes and substructure)		
`SpaceShower:pT0Ref`	1.60	1.50
`SpaceShower:pTdampFudge`	1.04	1.08
`TimeShower:alphaSvalue`	0.139	0.111
VAR3a: ISR/FSR ($t\bar{t}$ gap)		
`MultipartonInteractions:alphaSvalue`	0.125	0.127
`SpaceShower:pT0Ref`	1.67	1.51
`SpaceShower:pTdampFudge`	1.36	0.93
`SpaceShower:pTmaxFudge`	0.98	0.88
`TimeShower:alphaSvalue`	0.136	0.124
VAR3b: ISR/FSR (jet 3/2 ratio)		
`SpaceShower:alphaSvalue`	0.129	0.126
`SpaceShower:pTdampFudge`	1.04	1.07
`SpaceShower:pTmaxFudge`	1.00	0.83
`TimeShower:alphaSvalue`	0.114	0.138
VAR3c: ISR ($t\bar{t}$ gap, dijet decorrelation and Z-boson p_T)		
`SpaceShower:alphaSvalue`	0.140	0.115

Table 4: Parameters for five pairs of eigentunes, with distributions most sensitive to that variation indicated.

* Var1 for UE (MPI)
* Var2 for jet substructure (FSR)
* Three different Var3 cover jet production (ISR) but are analysis and physics process dependent

>Current recommendation is to use all five variation pairs
>Can be reduced to three pairs by picking one from 3a/3b/3c

- Five sets: one set for UE/MPI and four for ISR/FSR (one mostly for jet shape substructure type observables, and rest three for extra jets).

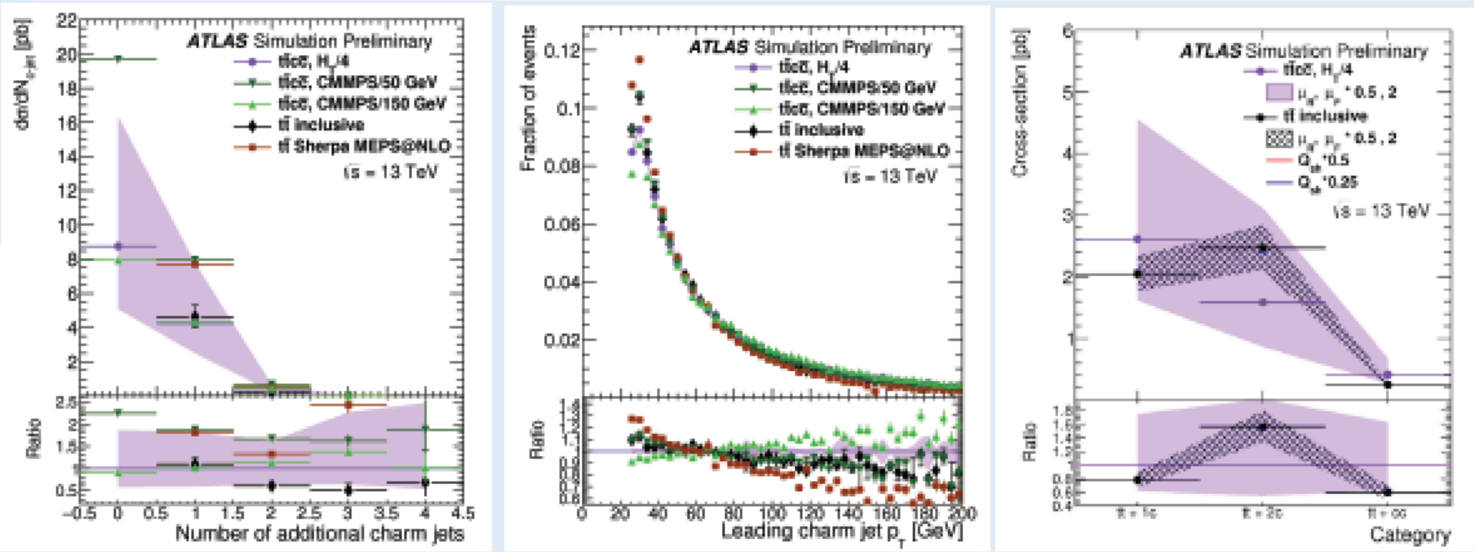
tt+cc 3F samples (ATLAS)

Also experimentally challenging since it is very hard to isolate charm jets from *b*- or light jets.

<u>MC samples</u>

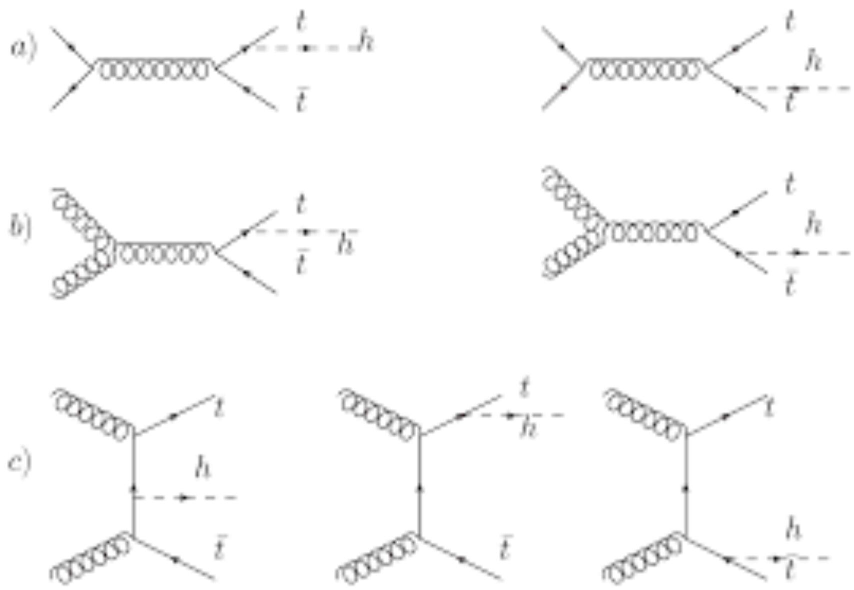
For the first time, NLO *tt+cc* 3FS samples have been generated in ATLAS using MG5_aMC@NLO+Herwig++ with diff. scale choices and compared to inclusive 5F *tt* samples.

$t\bar{t}+c\bar{c}$, $\sqrt{s}$=13 TeV, m$_t$= 172.5 GeV, m$_b$= 4.95 GeV, m$_c$= 1.55 GeV			
ME generator	MadGraph5_aMC@NLO + MadSpin		
PS/UE generator	Herwig++		
Renormalisation μ_R and factorisation scale μ_F	$\max(\mu_{\mathrm{CMMPS}}, \mu^{\mathrm{lower\ bound}}_{\mathrm{fixed}})$ with $\mu_{\mathrm{CMMPS}} = \sqrt[4]{\prod_i m_{\mathrm{T}}(i)}$ and $\mu^{\mathrm{lower\ bound}}_{\mathrm{fixed}} = 50$ GeV	$\mu^{\mathrm{lower\ bound}}_{\mathrm{fixed}} = 150$ GeV	$H_T/4$, $H_T = \sum_i m_{\mathrm{T}}(i)$
Resummation scale μ_Q (Q_{sh})	$f_Q\sqrt{\hat{s}}$ with $f_Q \epsilon [0.1,1.0]$		
ME PDF	CT10 3F		
PS/UE PDF	CTEQ6L1		
Tune	UE-EE-5		
XS (stat. unc.) ± scale unc. [pb]	$135.6(0.3)^{+112\%}_{-47\%}$	$60.50(0.11)^{+84\%}_{-42\%}$	$65.44(0.11)^{+84\%}_{-42\%}$

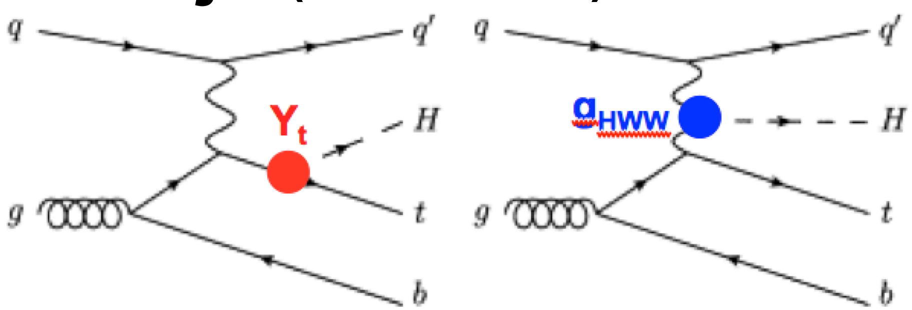


ATL-PHYS-PUB-2016-011

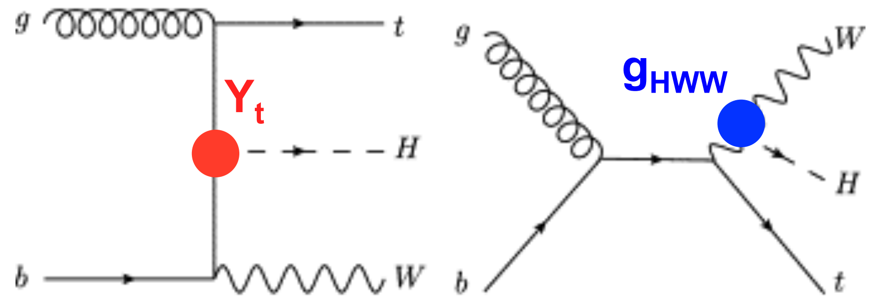
ttH (5F scheme)



tHjb (4F scheme)



tWH (5F scheme, DR)

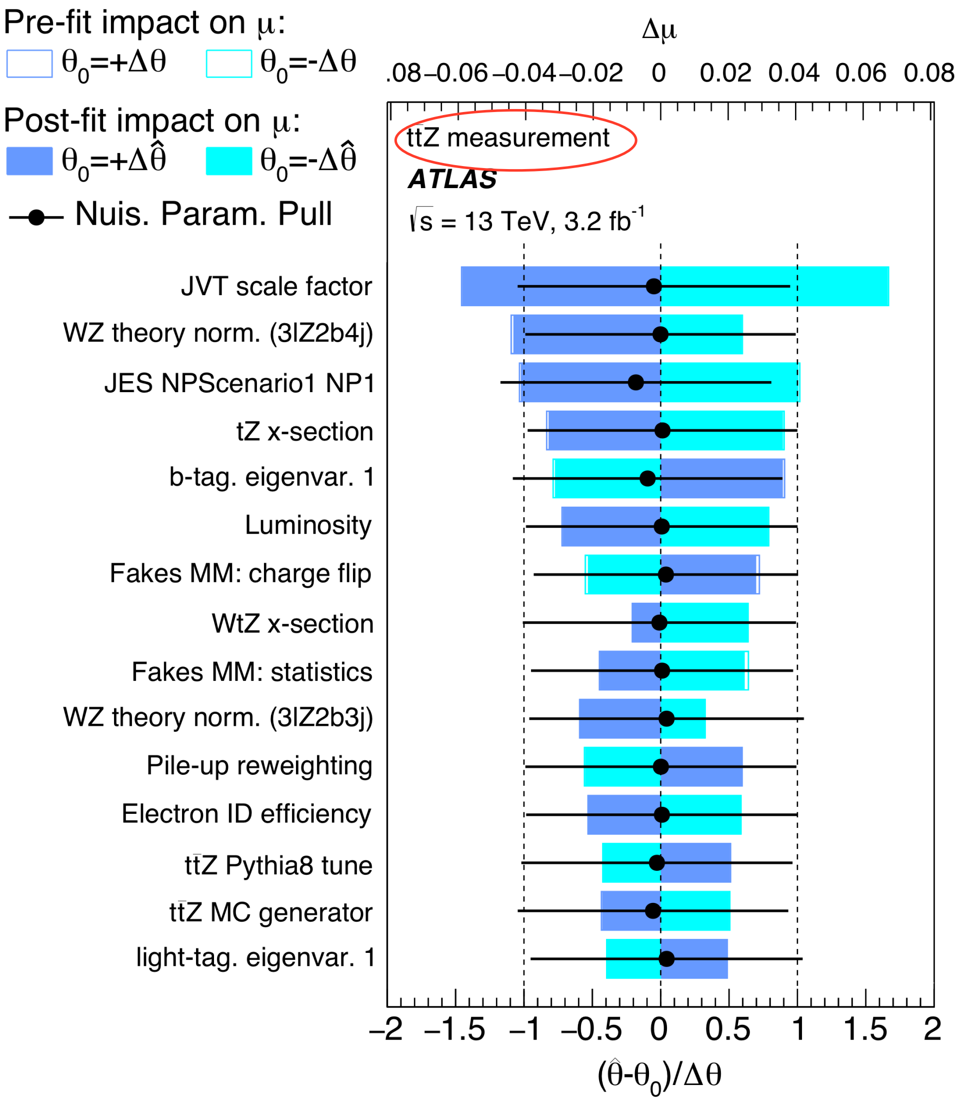


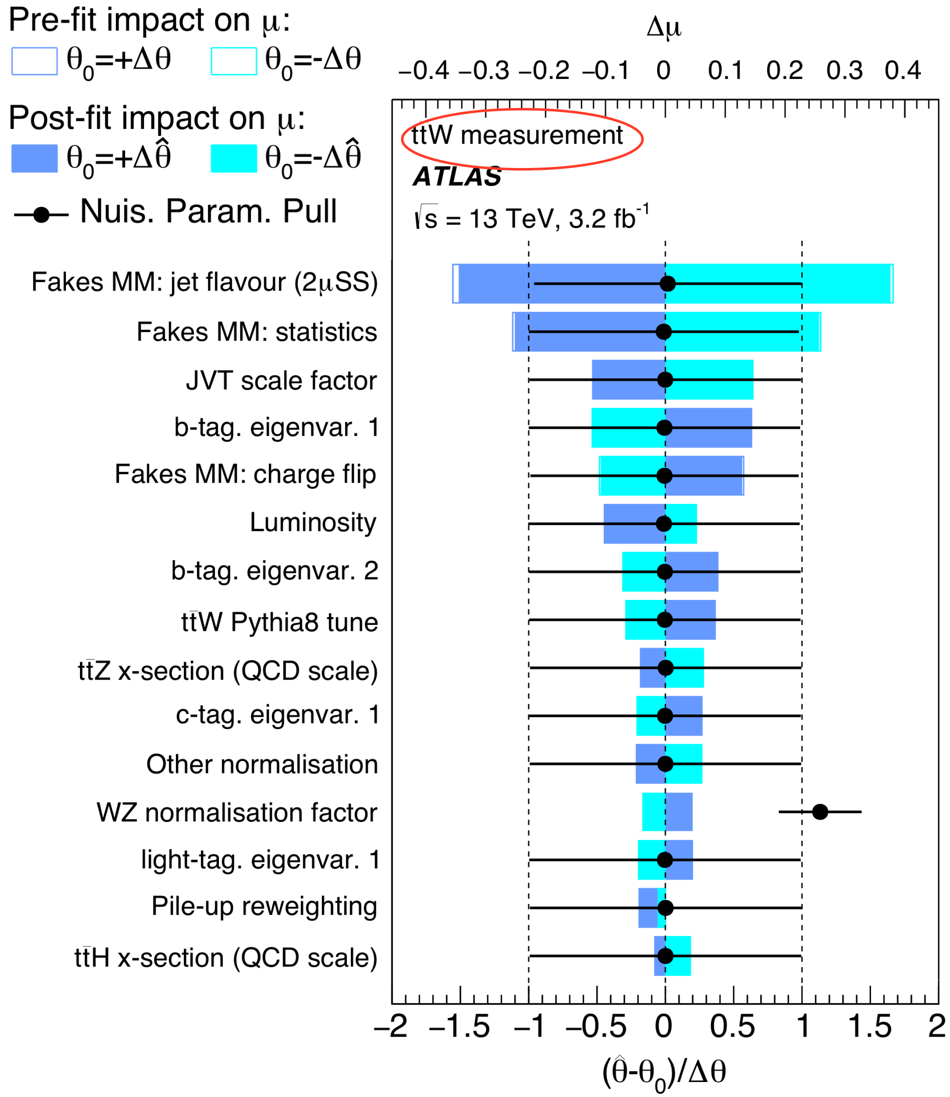
→ For ttH, tWH, tHjb and other SM production modes, NLO normalisation from YellowReport4

ATLAS *tt+H(bb)*: tt modelling uncertainties

Systematic source	How evaluated	$t\bar{t}$ categories
$t\bar{t}$ cross-section	$\pm 6\%$	All, correlated
NLO generator (*residual*)	Powheg-Box + Herwig++ vs. MG5_aMC + Herwig++	All, uncorrelated
Radiation (*residual*)	Variations of μ_{R}, μ_{F}, and *hdamp*	All, uncorrelated
PS & hadronisation (*residual*)	Powheg-Box + Pythia 6 vs. Powheg-Box + Herwig++	All, uncorrelated
NNLO top & $t\bar{t}$ p_{T}	Maximum variation from any NLO prediction	$t\bar{t}+\geq 1c$, $t\bar{t}$ +light, uncorr.
$t\bar{t}+b\bar{b}$ NLO generator *reweighting*	SherpaOL vs. MG5_aMC + Pythia8	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PS & hadronis. *reweighting*	MG5_aMC + Pythia8 vs. MG5_aMC + Herwig++	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ renorm. scale *reweighting*	Up or down a by factor of two	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ resumm. scale *reweighting*	Vary μ_{Q} from $H_{\mathrm{T}}/2$ to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ global scales *reweighting*	Set μ_{Q}, μ_{R}, and μ_{F} to μ_{CMMPS}	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ shower recoil *reweighting*	Alternative model scheme	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ PDF *reweighting*	CT10 vs. MSTW or NNPDF	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ MPI	Up or down by 50%	$t\bar{t}+\geq 1b$
$t\bar{t}+b\bar{b}$ FSR	Radiation variation samples	$t\bar{t}+\geq 1b$
$t\bar{t}+c\bar{c}$ ME calculation	MG5_aMC + Herwig++ inclusive vs. ME prediction	$t\bar{t}+\geq 1c$

ATLAS *tt+V* 2015 analysis: systematic uncertainties

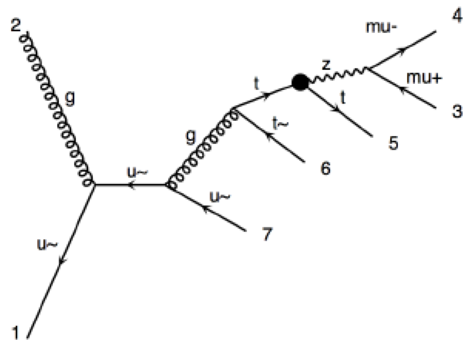




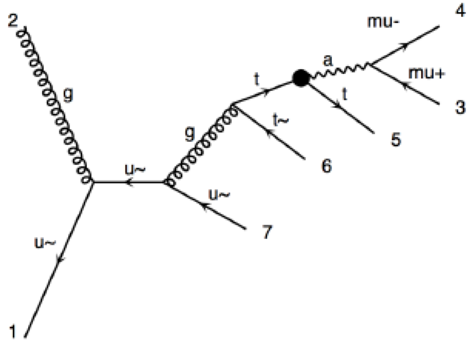
One has to pay attention to which operators contribute each process:

Process	O_{tG}	O_{tB}	O_{tW}	$O^{(3)}_{\varphi Q}$	$O^{(1)}_{\varphi Q}$	$O_{\varphi t}$	$O_{t\varphi}$	O_{4f}	O_G	$O_{\varphi G}$
$t \to bW \to bl^+\nu$	N		L	L				L		
$pp \to t\bar{q}$	N		L	L				L		
$pp \to tW$	L		L	L				N	N	N
$pp \to t\bar{t}$	L						N	L	L	L
$pp \to t\bar{t}\gamma$	L	L	L				N	L	L	L
$pp \to t\bar{t}Z$	L	L	L	L	L	L	N	L	L	L
$pp \to t\bar{t}h$	L						L	L	L	L
$gg \to H, H \to \gamma\gamma$	N						N			L

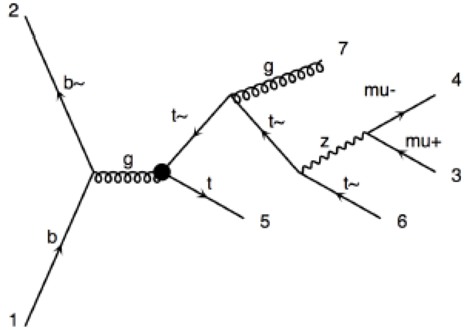
- $\mathcal{O}_{\phi t}, \mathcal{O}_{\phi Q^3}, \mathcal{O}_{\phi Q^1}$ - $t\bar{t}Z$ vertex
- $\mathcal{O}_{tW}, \mathcal{O}_{tB}$ - $t\bar{t}Z$ and $t\bar{t}\gamma$ vertices
- $\mathcal{O}_{tG}$ - $t\bar{t}g$ vertex



$\mathcal{O}_{\phi t}, \mathcal{O}_{\phi Q^3}, \mathcal{O}_{tW}, \mathcal{O}_{tB}$



$\mathcal{O}_{tW}, \mathcal{O}_{tB}$



$\mathcal{O}_{tG}$

Process	σ(8TeV)	σ(13TeV)	σ(13TeV)/σ(8TeV)
ttZ	0.206 pb	0.760 pb	3.7
tZ (t+s ch.)	0.236 pb	t-ch: 0.7 pb t-ch:0.4(LO)/0.5657(NLO) s-ch: 0.010(LO)/0.015(NLO) pb	
tWZ	~0.03 pb	0.156 pb	4.7
ttW	0.203-0.232pb	0.566 pb	2.8
ttH	0.129 pb	0.5085 pb	3.9
tH (t+s ch.)	0.0187+0.0012=0.02 pb or 0.0138 pb	0.063 pb (includes s-ch?) or 0.0743 pb	~3
tWH	0.005 pb	0.025 pb	~5
ttbar	~250 pb	~830 pb	3.3
single top	87+5.7+22.0=114.7 pb	218+11.2+70.4=299.6 pb	2.6
ZZ (mZ>60GeV)	8.8 pb	15.8 pb	1.8
WW	66.1	117.5	1.8
WZ	27.5	51.3	1.9
Z(→ℓ+ℓ−)+jets	~1120 pb	~1906 pb	1.7
W(→ℓ±ν)+jets	~12000 pb	~20000 pb	1.7

Increase in the cross sections

Increase of expected cross section in Run 2 → more tt+X events in Run2 !!!!!