Input from LHC Higgs XS WG on $t\bar{t}$+quarks needs

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– LHC Top Working Group Meeting –

Motivation

- built ATLAS-CMS task force of the LHC Higgs Working Group in order to harmonise background theory uncertainties between ATLAS and CMS for the $t\bar{t}H$ legacy papers in Run 2

  $\hookrightarrow$ allow for combination

- created common rivet routine for ATLAS and CMS, allows for easier comparisons
  ▸ github link

- use the same object definition and similar fiducial phase space as the
  ▸ $t\bar{t} + b\bar{b}$ measurements

- today: show MC comparisons for $t\bar{t}$ and $t\bar{t} + b\bar{b}$ between ATLAS and CMS setups

Monte-Carlo generators and settings

Experiment	Process	Generator	ME order	Shower	Tune	PDF set	h_{damp}	Cross section [pb]
ATLAS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	A14 [6]	5FS NNPDF3.0 NLO [7]	$1.5 \cdot m_{\text{top}}$	451.78 [8–13]
ATLAS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	A14 [6]	5FS NNPDF3.0 NLO [7]	$3.0 \cdot m_{\text{top}}$	451.78 [8–13]
CMS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	CP5 [14]	5FS NNPDF3.1 NLO [7]	$1.379 \cdot m_{\text{top}}$	451.78 [8–13]
CMS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	CP5 [14]	5FS NNPDF3.1 NLO [7]	$0.874 \cdot m_{\text{top}}$	451.78 [8–13]
CMS	$t\bar{t}$	Powheg v2 [1–4]	NLO	Pythia 8 [5]	CP5 [14]	5FS NNPDF3.1 NLO [7]	$2.305 \cdot m_{\text{top}}$	451.78 [8–13]
ATLAS	$t\bar{t}+b\bar{b}$	Powheg-Box-Res [15–17]	NLO	Pythia 8 [5]	A14 [6]	4FS NNPDF3.0 NLO as 0118 [7]	$\Sigma_{i=t,\bar{t},b\bar{b}} m_T(i)$	16.89
CMS	$t\bar{t}+b\bar{b}$	Powheg-Box-Res [15–17]	NLO	Pythia 8 [5]	CP5 [14]	4FS NNPDF3.1 NLO as 0118 [7]	$1.379 \cdot m_{\text{top}}$	23.87
ATLAS	$t\bar{t}+b\bar{b}$	Sherpa 2.2.1 [16, 18, 19]	NLO	Sherpa	Sherpa default [20]	4FS NNPDF3.0 NNLO as 0118 [7]	–	14.21
CMS	$t\bar{t}+b\bar{b}$	Sherpa 2.2.4 [16, 18, 19]	NLO	Sherpa	Sherpa default [20]	4FS NNPDF3.0 NNLO as 0118 [7]	–	14.01
ATLAS	$t\bar{t}$	Sherpa 2.2.1 [21, 22]	tt+0,1NLO +2,3,4@LO	Sherpa	Sherpa default	5FS NNPDF3.0 NNLO [7]	–	451.78 [8–13]

- ATLAS and CMS: different tune for Powheg+Pythia 8, both: Sherpa default tunes
- ATLAS Powheg samples: EvtGen for *b*- and *c*-hadron decays
- cross-sections: NNLO calculation for $t\bar{t}$, generator cross-sections for $t\bar{t}+b\bar{b}$
- use events from the lepton+jets and the dilepton channel
- reminder: the $t\bar{t}H$ analysis in ATLAS uses Powheg+Pythia 8 $t\bar{t}+b\bar{b}$ 4FS as nominal, while CMS uses PP8 $t\bar{t}$ 5FS

Functional form of factorisation and renormalisation scales

Sample	Scale ATLAS	Scale CMS
POWHEG +PYTHIA 8 (5FS $t\bar{t}$)	$\mu_{R,F} = \sqrt{m_t^2 + p_{T,t}^2}$	
POWHEG-BOX-RES +PYTHIA 8 (4FS $t\bar{t} + b\bar{b}$)	$\mu_R = \sqrt[4]{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$ $\mu_F = \frac{1}{2}(m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + p_{T,g})$	$\mu_R = \frac{1}{2}\sqrt[4]{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$ $\mu_F = \frac{1}{4}(m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + p_{T,g})$
SHERPA 2.2.4 (4FS $t\bar{t} + b\bar{b}$)		$\mu_R = \sqrt{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$ $\mu_F = \frac{1}{4}(m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + p_{T,g})$
SHERPA 2.2.1 (4FS $t\bar{t} + b\bar{b}$)	$\mu_R = \sqrt[4]{m_{T,t} \cdot m_{T,\bar{t}} \cdot m_{T,b} \cdot m_{T,\bar{b}}}$ $\mu_F = \frac{1}{2}(m_{T,t} + m_{T,\bar{t}} + m_{T,b} + m_{T,\bar{b}} + p_{T,g})$	
SHERPA 2.2.1 (5FS $t\bar{t}$)	$\mu_{R,F} = \sqrt{0.5 \cdot (m_{T,t}^2 + m_{T,\bar{t}}^2)}$ (core scale in CKKW-like scale choice)	-
Scale variation ME	$\mu_{R,F} = 0.5$ and $\mu_{R,F} = 2.0$	
ISR variation (PS, PP8)	Var3c A14 tune[1]	vary α_S^{ISR}, 0.5 and 2.0
FSR variation (PS, PP8)	vary α_S^{FSR}, 0.5 and 2.0	

- use the same scales for Powheg+Pythia 8 $t\bar{t}$ samples
- Powheg-Box-Res: CMS scale is a factor 2 smaller than ATLAS scale
- Sherpa: CMS factorisation scale is a factor 2 smaller than for ATLAS

[1] In Var3c of the A14 tune, $\alpha_S^{\rm ISR}$ is varied between 0.115 and 0.140.

Object definition in the Rivet routine

Object definition and event selection
Leptons (electrons and muons) dressed with photons within $\Delta R < 0.1$
Jets: build from stable final state particles with anti-k_T algorithm with radius $R = 0.4$
Prompt "dressed" leptons and neutrinos are vetoed from jet clustering
b-jets: jets ghost matched to *b*-hadrons with $p_T > 5$ GeV
Overlap removal: remove lepton if $\Delta R(jet, lepton) < 0.4$
Leptons: $\lvert\eta\rvert < 2.5$ and $p_T > 27$ GeV
Jets and *b*-jets: $\lvert\eta\rvert < 2.5$ and $p_T > 25$ GeV
Exactly one charged lepton, ≥ 4 jets, of which ≥ 3 *b*-tagged jets
Two regions: ≥ 3 *b*-jets and ≥ 4 *b*-jets

- defined at stable-particle level to closely match those in ▸ JHEP 04 (2019) 046

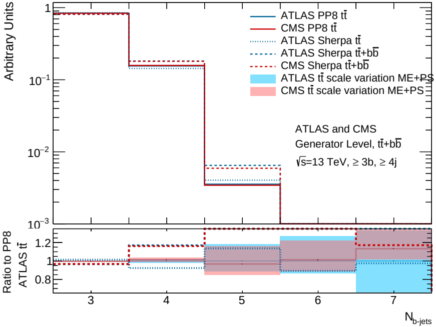
Variables under study

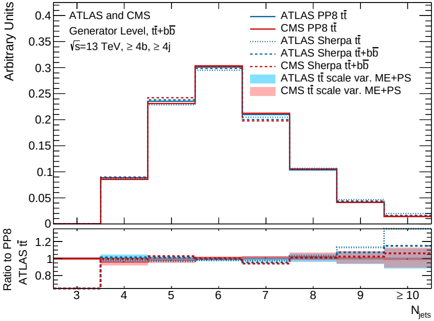
Variable	Description
N_{jets}	Number of jets, as defined in table 3 (including *b*-jets)
N_{b-jets}	Number of *b*-jets
Leading *b*-jet p_T	p_T of *b*-jet with largest p_T in the event
H_T^{jets}	Scalar sum of p_T of all jets in the event
ΔR_{bb}^{avg}	Average over $\Delta R(b,b)$ build from all 2 *b*-jet combinations in the event
$\Delta R_{bb}^{min.\Delta R}$	ΔR of the two *b*-jets in the event which are closest in ΔR
$p_{T,bb}^{max.p_T}$	Transverse momentum of the *bb*-system with the largest scalar sum p_T

All plots in the following:

- normalised either to unity or to the cross-section: NNLO for $t\bar{t}$, generator cross-section for $t\bar{t}+b\bar{b}$
- uncertainty bands: include the ME scale variation and the PS variations
- exception: uncertainty bands for Sherpa $t\bar{t}+b\bar{b}$: have ME scale variations only

Compare nominal generator setups ATLAS vs. CMS

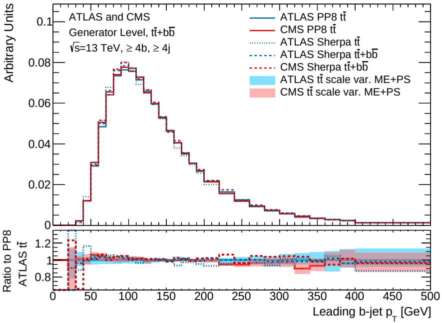




- Sherpa $t\bar{t} + b\bar{b}$ samples show higher number of b-jets than $t\bar{t}$ samples
- $t\bar{t}$ samples have very good agreement between ATLAS and CMS

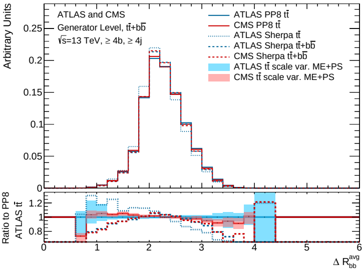
  $\hookrightarrow$ for nominal distributions as well as size of scale variation effects

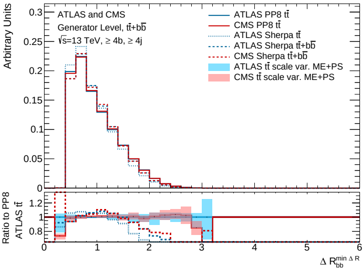
Compare nominal generator setups ATLAS vs. CMS

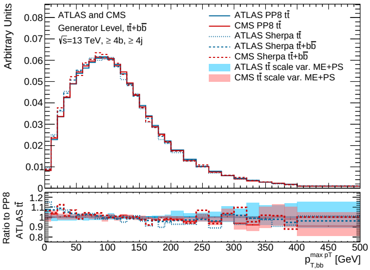


- also here: very good agreement between all $t\bar{t}$ generators for leading b-jet p_T
- a little slope between $t\bar{t}$ and $t\bar{t}+b\bar{b}$ generator setups for H_T^{jets}

Compare nominal generator setups ATLAS vs. CMS

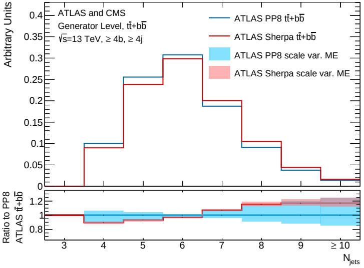


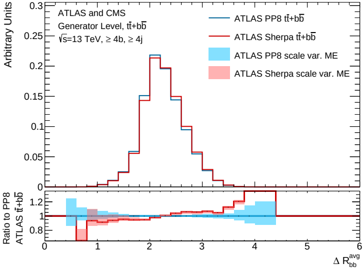


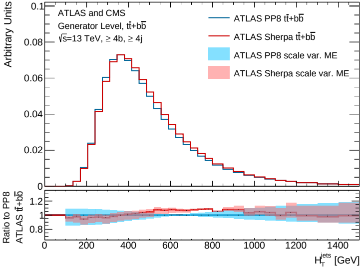


- also here: very good agreement between ATLAS and CMS for PP8
- large differences between PP8 and Sherpa in ΔR_{bb}
- difference caused by $\Delta R_{bb}^{\mathrm{min}\Delta\mathrm{R}}$, which is expected to be dominated by *b*-quarks from gluon splitting
- no difference observed for ΔR_{bb}^{maxpT} will be shown in upcoming document

Comparison Powheg-Box-Res vs. Sherpa $t\bar{t} + b\bar{b}$ 4FS (ATLAS)

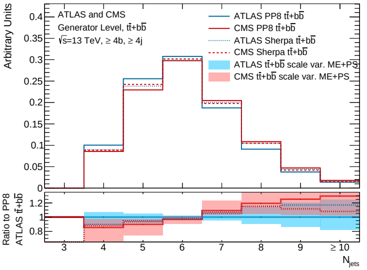


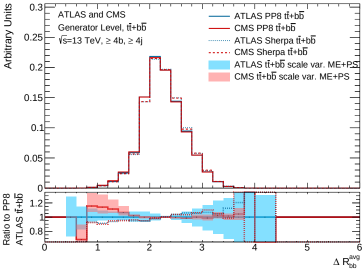


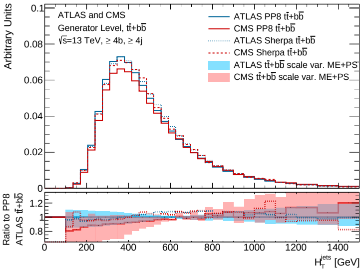


- use same scale choice for the two samples
- disagreement between nominal Powheg and Sherpa samples
- Why are scale variations so different?

Comparison Powheg-Box-Res vs. Sherpa $t\bar{t}+b\bar{b}$ 4FS (ATLAS+CMS)

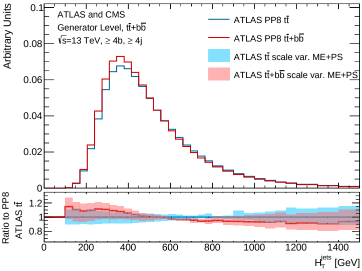


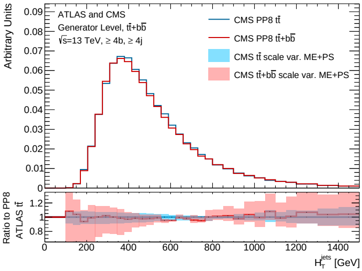


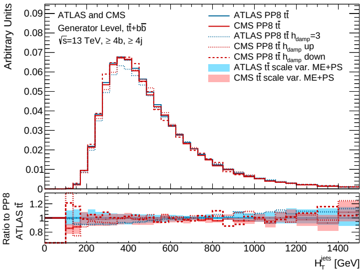


- CMS and ATLAS samples similar for Sherpa
- see differences in nominal and scale variations for Powheg+Pythia 8 ATLAS+CMS samples
- CMS samples and ATLAS Sherpa samples look similar, but deviate from ATLAS PP8

Comparison ATLAS/CMS: $t\bar{t}$, $t\bar{t}+b\bar{b}$ and h_{damp} variations

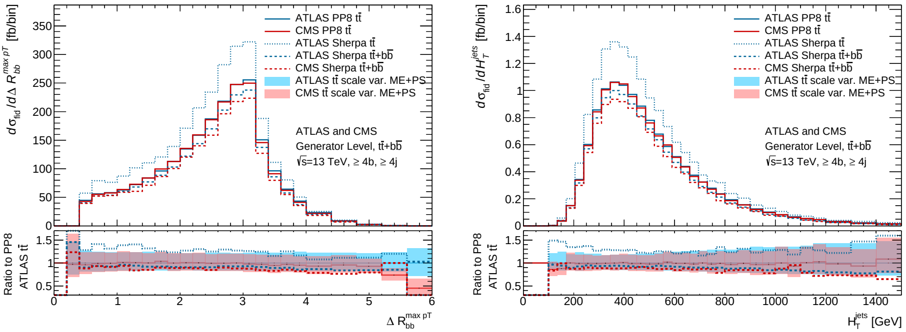






- ATLAS: slope in H_T^{jets}, slightly larger scale variations for $t\bar{t}+b\bar{b}$
- CMS: good agreement for nominal, but scale variations a lot larger for $t\bar{t}+b\bar{b}$

Fiducial distributions



- Sherpa $t\bar{t} + b\bar{b}$ samples are very similar for both distributions

  $\hookrightarrow$ much better agreement than for other ΔR definitions

- larger offset for Sherpa $t\bar{t}$ distributions, and small slope

Summary and Conclusion

- have first studies to compare ATLAS/CMS generator setups
- surprisingly good agreement between PP8 $t\bar{t}$ samples
- see differences between ATLAS/CMS PP8 $t\bar{t}+b\bar{b}$
  $\hookrightarrow$ CMS uses scale which is a factor 2 lower than ATLAS
  $\hookrightarrow$ cross-section in ATLAS too low, lower scale neccessary
- CMS has larger scale variations for PP8 $t\bar{t}+b\bar{b}$
- do not understand difference in scale variations between Sherpa and PP8
- precision data with differential distributions of $t\bar{t}+b\bar{b}$ unfolded to particle level are needed to constrain the models

➔ working on a note with additional observables and generator setups

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