Inclusive and differential cross section measurements of ttbb production in the lepton+jets channel at $\sqrt{s}$ = 13 TeV

Emanuel Pfeffer on behalf of the CMS Collaboration | TOP 2023 Conference, Traverse City, MI, USA

 emanuel.pfeffer@cern.ch

Why ttbb?

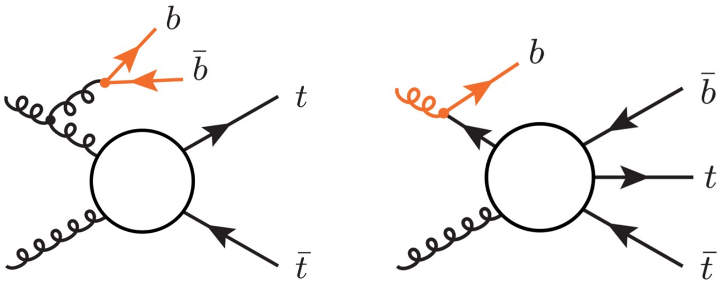
3 key aspects:

- challenging to model due to massive b quark and difference in energy scales of top and b quark
- important test of perturbative QCD calculations
- leading background for searches such as ttH with H→bb and tttt

Differences in ttbb modelling

tt at ME at NLO (5FS)

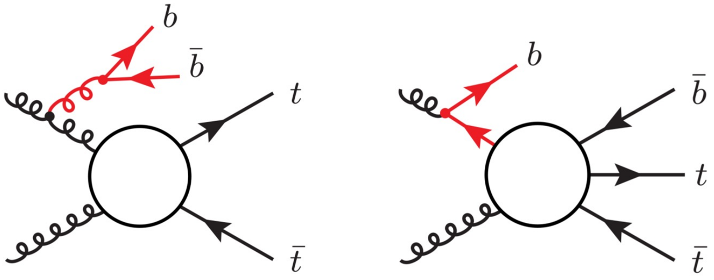
- ttbb described by tt matrix elements at NLO ($m_{\mathrm{b}} = 0$) and g→bb shower splittings
- Residual uncertainties difficult to quantify



➤ Additional b-jets from parton shower

ttbb at ME at NLO (4FS)

- ttbb described by ttbb matrix elements at NLO ($m_{\mathrm{b}} > 0$)
- Theoretically preferred option for ttbb modelling



➤ Additional b-jets from matrix elements
→ expect larger scale variations

Modelling approaches

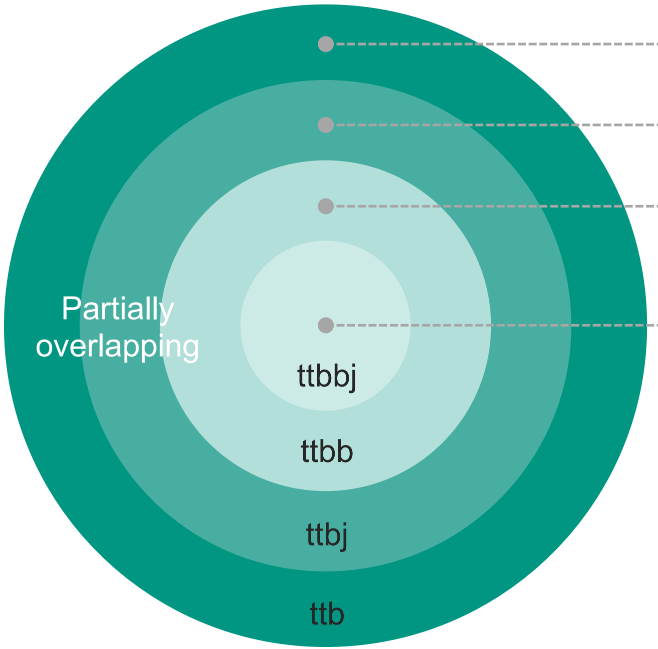
Different ME calculations

Different scale choices in simulations

Generator setup	Process/ME order	Generator/Shower	Tune	PDF set	h_{damp}	Scales
POWHEG+P8 $t\bar{t}$ 5FS	$t\bar{t}$/ NLO	POWHEG v2/ PYTHIA 8.240	CP5	5FS NNPDF3.1 NNLO	$1.379 m_t$	$\mu_F = \mu_R = m_{T,t}$
POWHEG+H7 $t\bar{t}$ 5FS	$t\bar{t}$/ NLO	POWHEG v2/ HERWIG 7.13	CH3	5FS NNPDF3.1 NNLO	$1.379 m_t$	$\mu_F = \mu_R = m_{T,t}$
POWHEG+OL+P8 $t\bar{t}b\bar{b}$ 4FS	$t\bar{t}b\bar{b}$/ NLO	POWHEG-BOX-RES/ PYTHIA 8.240	CP5	4FS NNPDF3.1 NNLO as 0118	$1.379 m_t$	$\mu_R = \frac{1}{2} \prod_{i=t,\bar{t},b,\bar{b}} m_{T,i}^{1/4}$, $\mu_F = H_T/4$
SHERPA+OL $t\bar{t}b\bar{b}$ 4FS	$t\bar{t}b\bar{b}$/ NLO	SHERPA 2.2.4	SHERPA	4FS NNPDF3.0 NNLO as 0118	—	$\mu_R = \prod_{i=t,\bar{t},b,\bar{b}} m_{T,i}^{1/4}$, $\mu_F = H_T/2$
MG5_aMC+P8 $t\bar{t}b\bar{b}$ 4FS	$t\bar{t}b\bar{b}$/ NLO	MADGRAPH5_aMC@NLO v2.4.2/ PYTHIA 8.230	CP5	4FS NNPDF3.1 NNLO as 0118	—	$\mu_F = \mu_R = \sum m_T$
MG5_aMC+P8 $t\bar{t}$+jets FxFx 5FS	$t\bar{t}$+jets FxFx/ NLO [≤2 jets]	MADGRAPH5_aMC@NLO v2.6.1/ PYTHIA 8.240	CP5	5FS NNPDF3.1 NNLO	—	$\mu_F = \mu_R = \sum m_T$, qCut = 40 GeV, qCutME = 20 GeV

Note different pre-factors!

Phase space regions for XS measurement



tt+b jet phase space region definitions

≥5 jets: ≥3 b jets → probing tt events with at least 1 additional b jet

≥6 jets: ≥3 b jets, ≥3 light jets → probing additional light jet radiation

≥6 jets: ≥4 b jets → probing fully resolved ttbb events

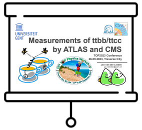
≥7 jets: ≥4 b jets, ≥3 light jets → probing additional light jet radiation

+ exactly one electron or muon in each region.

> Regions targeting distinct aspects of ttbb!

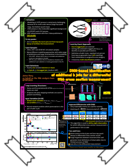
Observables

Observable		5j3b	6j4b	6j3b3l	7j4b3l	
σ_{fid}	Inclusive cross section	✓	✓	✓	✓	XS inclusive
Global observables						Global observables covering various aspects of all jets
N_{jets}	Jet multiplicity	✓	✓			
N_b	b jet multiplicity	✓				
H_T^j	Scalar p_T sum of all jets	✓	✓			
H_T^b	Scalar p_T sum of all b jets	✓	✓			
🔍 H_T^{light}	Scalar p_T sum of all light jets			✓	✓	
Observables related to b jets						Jet kinematics, preferably b jets not from tt ($3^{rd}/4^{th}$ b jet)
$p_T(b_3)$	p_T of third hardest b jet	✓	✓			
$\|\eta(b_3)\|$	$\|\eta\|$ of third hardest b jet	✓	✓			
$p_T(b_4)$	p_T of fourth hardest b jet		✓			
$\|\eta(b_4)\|$	$\|\eta\|$ of fourth hardest b jet		✓			
Observables considering all pairs of b jets (bb)						All b jets
🔍 ΔR_{bb}^{avg}	Average ΔR of all bb pairs		✓			
m_{bb}^{max}	Highest invariant mass among all bb pairs		✓			
Observables related to the pair of b jets closest in ΔR (bb^{extra})						Observables based on closest b jets in ΔR, b^{extra} preferrably b jets not from tt
$p_T(b_1^{extra})$	p_T of leading extra b jet		✓			
$\|\eta(b_1^{extra})\|$	$\|\eta\|$ of leading extra b jet		✓			
$p_T(b_2^{extra})$	p_T of subleading extra b jet		✓			
$\|\eta(b_2^{extra})\|$	$\|\eta\|$ of subleading extra b jet		✓			
🔍 $\Delta R(bb^{extra})$	ΔR of bb^{extra} pair		✓			
$\|\eta(bb^{extra})\|$	$\|\eta\|$ of bb^{extra} pair		✓			
🔍 $m(bb^{extra})$	invariant mass of bb^{extra} pair		✓			
$p_T(bb^{extra})$	p_T of bb^{extra} pair		✓			
Observables related to the pair of b jets not from $t\bar{t}$ decay ($bb^{add.}$)						Observables based on DNN identification targeting b jets not from tt
$p_T(b_1^{add.})$	p_T of leading additional b jet		✓*			
$\|\eta(b_1^{add.})\|$	$\|\eta\|$ of leading additional b jet		✓*			
$p_T(b_2^{add.})$	p_T of subleading additional b jet		✓*			
$\|\eta(b_2^{add.})\|$	$\|\eta\|$ of subleading additional b jet		✓*			
$\Delta R(bb^{add.})$	ΔR of $bb^{add.}$ pair		✓*			
$\|\eta(bb^{add.})\|$	$\|\eta\|$ of $bb^{add.}$ pair		✓*			
$m(bb^{add.})$	invariant mass of $bb^{add.}$ pair		✓*			
$p_T(bb^{add.})$	p_T of $bb^{add.}$ pair		✓*			
Observables related to extra light jets						Extra light jet radiaton
$p_T(lj_1^{extra})$	p_T of leading extra light jet			✓	✓	
$\|\Delta\phi(lj_1^{extra}, b_{soft})\|$	$\Delta\phi$ of leading extra light jet and softest b jet			✓	✓	



Talk by
Jan van der Linden

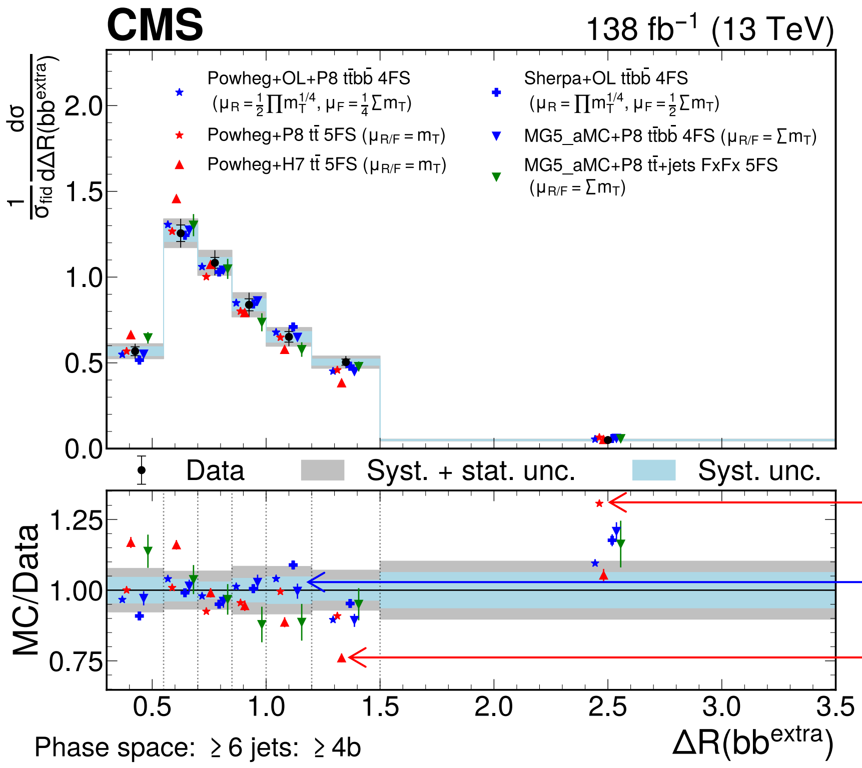
🔍 = covered in this talk



Poster by
Juhee Song

Cherry-picked differential cross section results

Diff. XS results: Probing two closest b jets



Phase space: ≥ 6 jets: ≥ 4b

Target the b jet origin

- Sensitive to b modelling
- Potential preference of additional b jet modelling in PS (tt 5FS) or ME (ttbb 4FS)

Findings

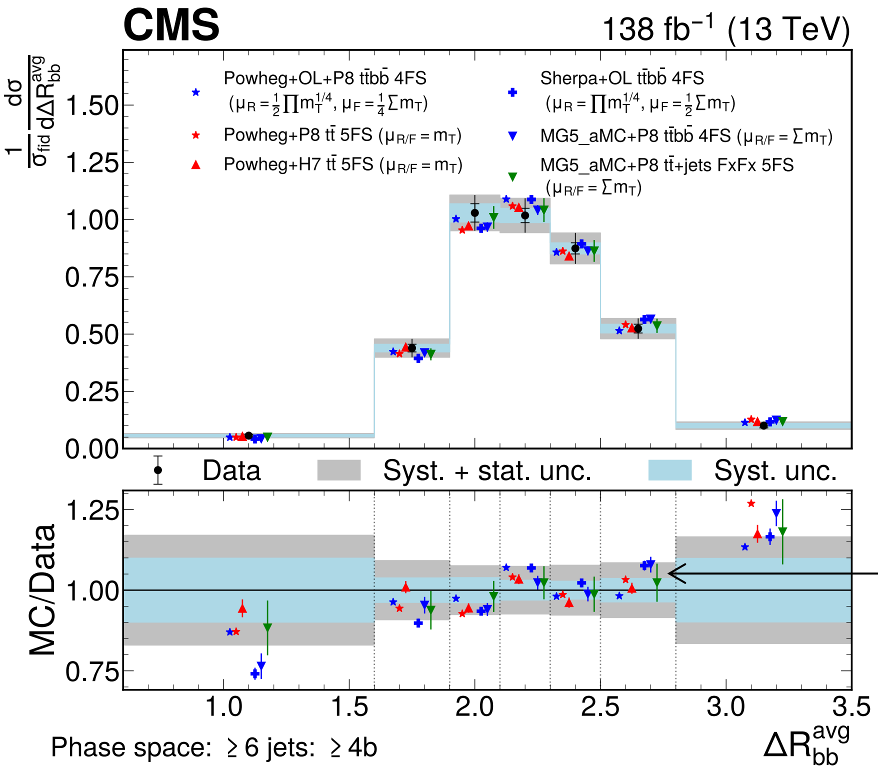
tt (5FS) Pow+P8: prediction of too *large* distances ΔR

ttbb (4FS) simulations: *good* description of ΔR

tt (5FS) Pow+H7: prediction of too *small* distances ΔR

Divergent behavior of tt/ttbb also seen in ATLAS+CMS comparison: arXiv:2301.11670

Diff. XS results: Probing spatial relations



Target the average distance of b jets

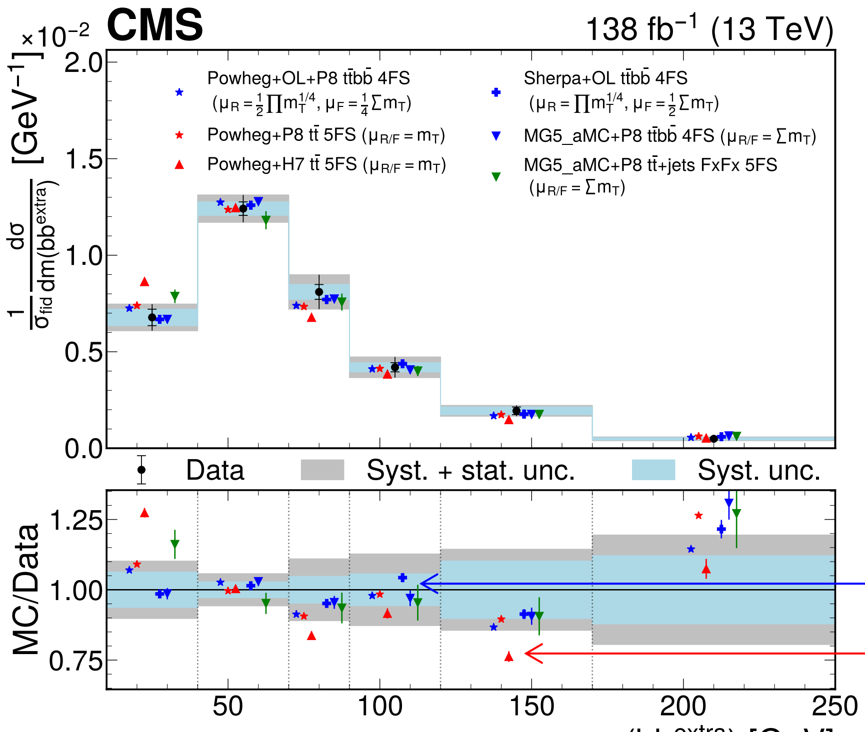
→ very important input feature in ttH with H→bb analyses for discriminator trainings

Findings

In *all simulations*: prediction of too *large* distances ΔR

Large uncertainties, mostly statistically limited!

Diff. XS results: Probing two closest b jets



Phase space: ≥ 6 jets: ≥ 4b

Target the closest b jets invariant mass

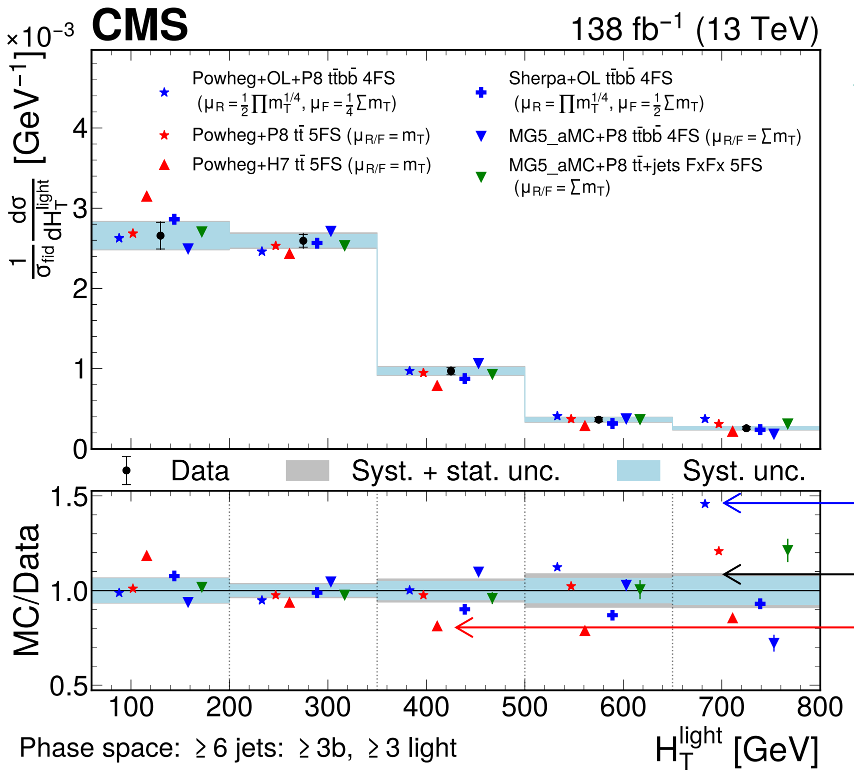
Findings

ttbb (4FS) simulations: *good* description of inv. masses

tt (5FS) Pow+H7: prediction of too *small* inv. masses

Similar behavior for invariant masses as for ΔR of the closest two b jets!

Diff. XS results: Probing additional light jets



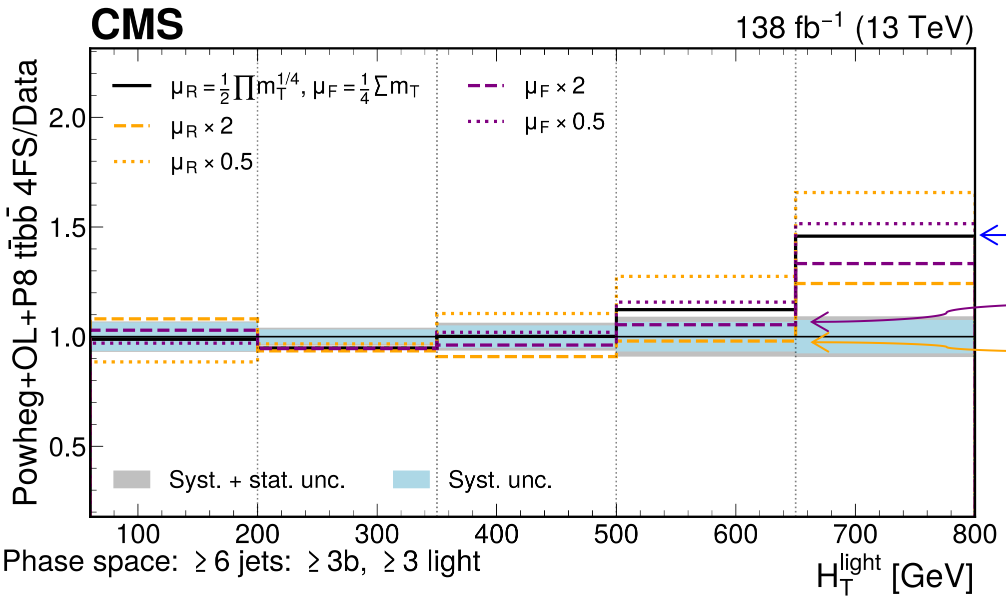
Target jet p_T of light jets through H_T

Findings

- ttbb (4FS) Powheg+Pythia8: p_T of light jets too high
- Other simulations: decent modelling of light jets
- tt (5FS) Powheg+Herwig7: very soft light jets

Mis-modelling visible!

Diff. XS results: Probing additional light jets



How could the mis-modelling be improved?

Nominal line of ttbb (4FS) Powheg+Pythia8 simulation from previous slide

Factorization scale multiplied by a factor of 2

Renormalization scale multiplied by a factor of 2

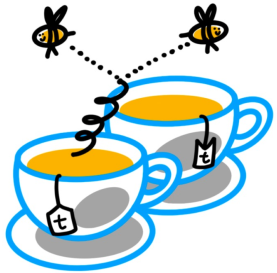
Not necessarily a problem of the generator, but doubling μ_R and μ_F tend to describe light jet p_T better!

Summary

Measurements of cross sections of ttbb production in the lepton+jets channel at $\sqrt{s}$ = 13 TeV with 138 fb^{-1}:

- ✓ Results compared to the predictions of several event generators and settings
- ✓ None of them simultaneously describe all measured distributions in various phase space regions
- ✓ ≥6 jets: ≥4 b jets: predictions compatible with the data within larger experimental uncertainties
- ✓ Other phase spaces: mis-modelling in predictions visible

- ✓ Rivet routine available to test generators!



ttbb measurement

Measurement helps tune and refine theoretical predictions and better assess theoretical uncertainties estimated from various ttbb event generators.

Measurement available at https://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-22-009

Backup

Sources of uncertainty

	Uncertainty source	Relative uncertainty (%) 5j3b	6j3b3l	6j4b	7j4b3l
Exp.	Integrated luminosity	1.6	1.6	2.0	1.8
	Pileup reweighting	0.2	0.8	0.4	0.5
	Lepton and trigger	1.1	0.9	1.9	1.8
	JES, JER	2.1	1.6	3.5	5.7
	b tagging	4.5	3.9	7.0	9.1
Theory	μ_R and μ_F scales	2.8	6.8	8.2	12
	Top quark p_T modelling	0.3	1.0	0.6	1.3
	PDF	0.2	0.7	1.0	1.9
	PS scales	2.8	2.7	2.4	1.5
	ME-PS matching (h_{damp})	0.4	0.9	1.3	2.8
	Underlying event	0.4	$<$0.1	0.4	0.4
	Colour reconnection	1.1	1.5	1.9	4.5
	b quark fragmentation	0.3	0.4	0.4	0.4
	Inclusive $t\bar{t}C$ cross section	0.5	0.3	1.9	2.6
	MC statistical	0.8	1.6	2.4	2.8
	Total systematic uncertainty	6.0	8.7	13	17
	Statistical uncertainty	0.6	1.2	2.2	3.3
	Total uncertainty	6.0	8.8	13	17