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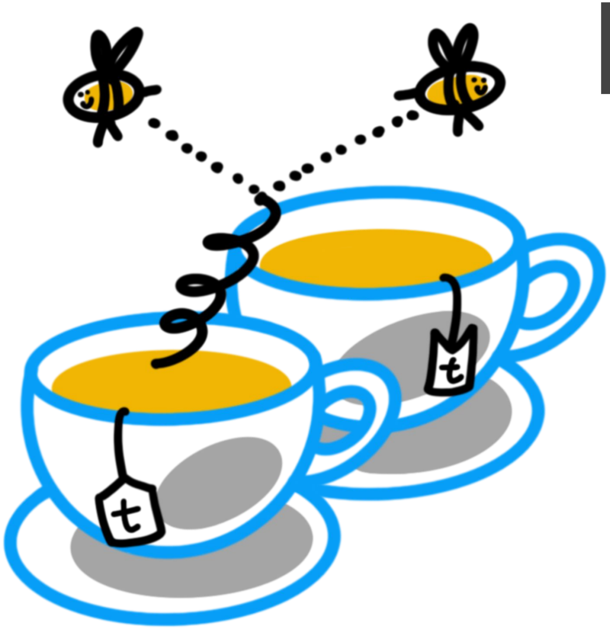
Measurements of $t\bar{t}b\bar{b}$/$t\bar{t}c\bar{c}$ by ATLAS and CMS



TOP2023 Conference
26.09.2023, Traverse City

Jan van der Linden
on behalf of the
ATLAS and CMS
Collaborations

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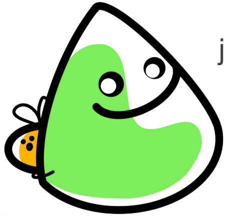


Highlights of today

- **Study of $t\bar{t}b\bar{b}$+$t\bar{t}W$ modeling for $t\bar{t}H$ analyses in ATLAS+CMS**
  - ➢ Available on arXiv: arXiv:2301.11670

- **Inclusive and differential cross section measurement of $t\bar{t}b\bar{b}$ in CMS**
  - ➢ Preliminary publication: PAS-TOP-22-009
  - ➢ Will appear on arXiv in 10h 55min
  - ➢ **Main focus of this talk**

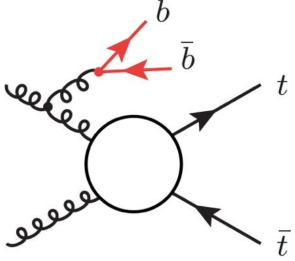
NEW!

See also:
YSF talk by Emanuel Pfeffer
Poster by Juhee Song

- **Inclusive and differential cross section measurement of $t\bar{t}b\bar{b}$ in ATLAS**
  - ➢ Published in JHEP: JHEP 04 (2019) 046

- **Inclusive cross section measurement of $t\bar{t}c\bar{c}$ in CMS**
  - ➢ Published in PLB: PLB 820 (2021) 136565

Why do we care about $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$?



❑ Interesting modeling

- ➢ Large momentum-scale differences between top and bottom/charm quarks
- ➢ Calculations/simulations at ME-level very difficult
- ➢ Interesting probe of perturbative QCD

❑ Important for $t\bar{t}H(b\bar{b})$ and $t\bar{t}t\bar{t}$ measurements

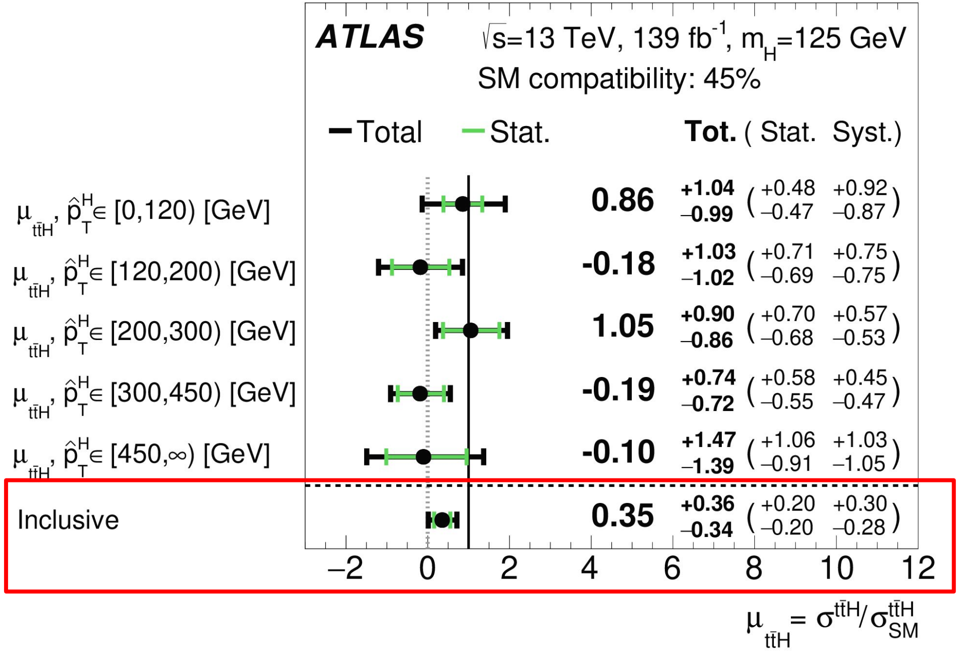
- ➢ $t\bar{t}b\bar{b}$ modeling is by far limiting factor
- ➢ $t\bar{t}b\bar{b}$ often under-predicted in simulations
- ➢ $t\bar{t}c\bar{c}$ will get more important with $t\bar{t}H(c\bar{c})$ measurements!

Uncertainty source	$\Delta\mu_{t\bar{t}H}$ (observed)
Total experimental	$+0.10/-0.10$
jet energy scale and resolution	$+0.08/-0.07$
b tagging	$+0.07/-0.06$
luminosity	$+0.02/-0.02$
Total theory	$+0.16/-0.16$
$t\bar{t}$ + jets background	$+0.15/-0.16$
signal modelling	$+0.06/-0.01$
Size of the simulated event samples	$+0.13/-0.12$
Total systematic	$+0.20/-0.21$
Statistical	$+0.17/-0.16$
background normalisation	$+0.13/-0.13$
$t\bar{t}B$ and $t\bar{t}C$ normalisation	$+0.12/-0.12$
QCD normalisation	$+0.01/-0.01$
Total	$+0.26/-0.26$

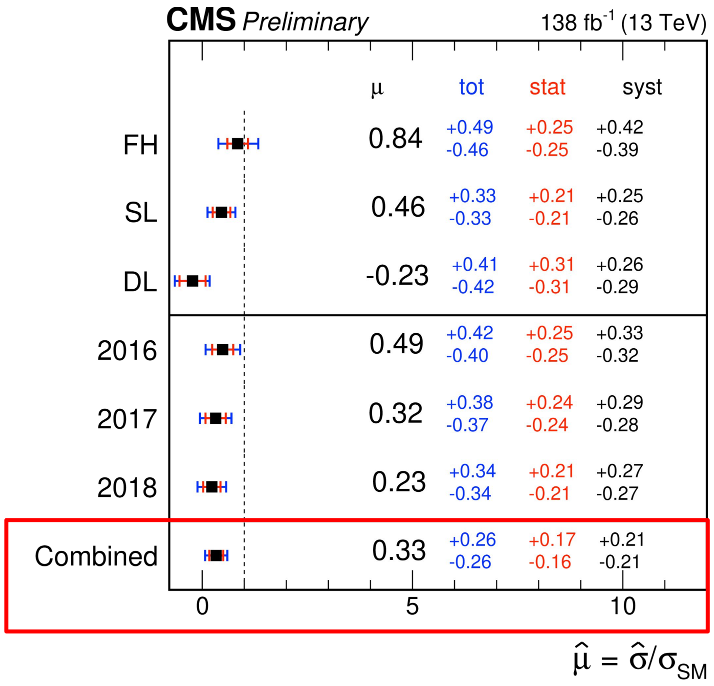
CMS $t\bar{t}H(b\bar{b})$ measurement PAS-HIG-19-011

Why do we care about $t\bar{t}b\bar{b}$ and $t\bar{t}c\bar{c}$?

- ❑ **What do the measurements of $t\bar{t}H(b\bar{b})$ tell us?**
  - ➢ Large under-prediction of $t\bar{t}H$ cross section relative to SM (both ATLAS + CMS)
    - ❑ Both use 4FS $t\bar{t}b\bar{b}$ as nominal background model → Fluctuations coincidental?
  - ➢ More details on $t\bar{t}H(b\bar{b})$ in Lucia's talk later!



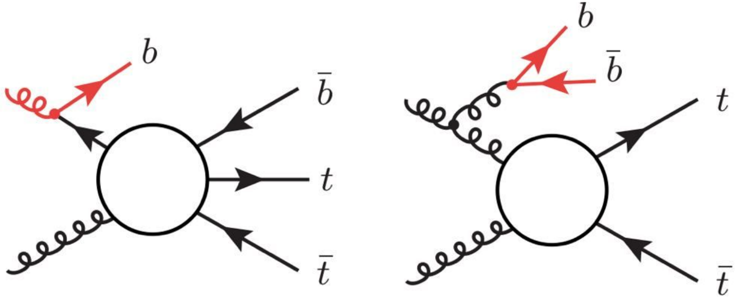
ATLAS $t\bar{t}H(b\bar{b})$ measurement JHEP 06 (2022) 97



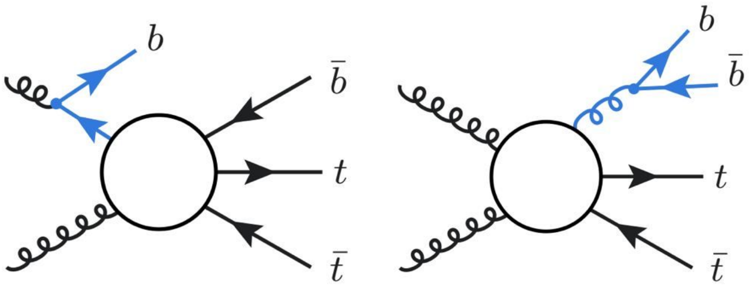
CMS $t\bar{t}H(b\bar{b})$ measurement PAS-HIG-19-011

Different approaches for $t\bar{t}b\bar{b}$ modeling

❑ **$t\bar{t}$@NLO** matrix element:
- ➢ At most one additional b jet from matrix element
- ➢ Remaining b jets from parton shower (PS)
- ➢ Treat b quarks as massless



❑ **$t\bar{t}b\bar{b}$@NLO** matrix element:
- ➢ Difficult to simulate properly
  (large scale difference between top and bottom)
- ➢ Both additional b jets from matrix element (ME)
- ➢ Treat b quarks as massive



➢ **How do these modeling approaches describe the data?**

$t\bar{t}b\bar{b}$ background estimation in ATLAS+CMS

ATLAS+CMS modeling comparisons: arXiv:2301.11670

$t\bar{t}b\bar{b}$ XS differences due to modeling and scale differences (see also next slide)

Nominal $t\bar{t}b\bar{b}$@ME models

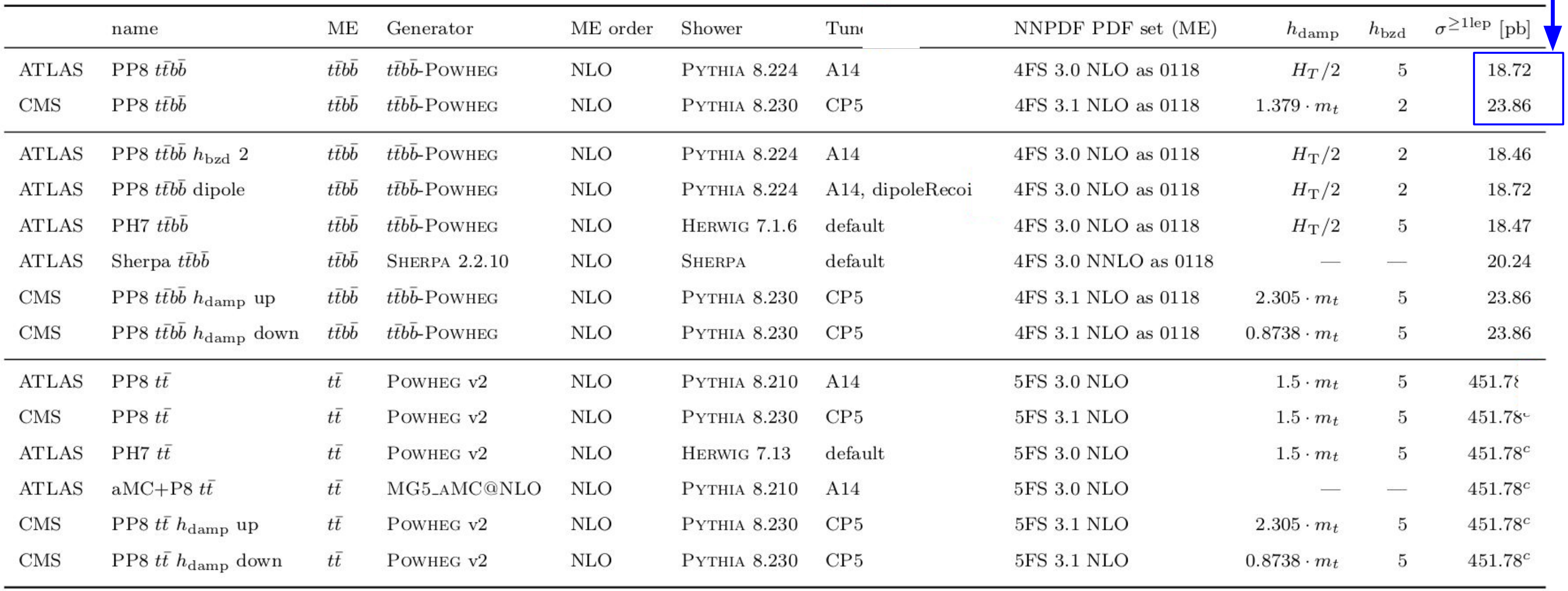
ATLAS $t\bar{t}b\bar{b}$@ME uncertainties

CMS $t\bar{t}b\bar{b}$@ME uncertainties

Nominal $t\bar{t}$@ME models

ATLAS $t\bar{t}$@ME uncertainties

CMS $t\bar{t}$@ME uncertainties



	name	ME	Generator	ME order	Shower	Tun	NNPDF PDF set (ME)	h_{damp}	h_{bzd}	$\sigma^{\geq 1\mathrm{lep}}$ [pb]
ATLAS	PP8 $t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$-POWHEG	NLO	PYTHIA 8.224	A14	4FS 3.0 NLO as 0118	$H_T/2$	5	18.72
CMS	PP8 $t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$-POWHEG	NLO	PYTHIA 8.230	CP5	4FS 3.1 NLO as 0118	$1.379 \cdot m_t$	2	23.86
ATLAS	PP8 $t\bar{t}b\bar{b}$ h_{bzd} 2	$t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$-POWHEG	NLO	PYTHIA 8.224	A14	4FS 3.0 NLO as 0118	$H_T/2$	2	18.46
ATLAS	PP8 $t\bar{t}b\bar{b}$ dipole	$t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$-POWHEG	NLO	PYTHIA 8.224	A14, dipoleRecoi	4FS 3.0 NLO as 0118	$H_T/2$	2	18.72
ATLAS	PH7 $t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$-POWHEG	NLO	HERWIG 7.1.6	default	4FS 3.0 NLO as 0118	$H_T/2$	5	18.47
ATLAS	Sherpa $t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$	SHERPA 2.2.10	NLO	SHERPA	default	4FS 3.0 NNLO as 0118	—	—	20.24
CMS	PP8 $t\bar{t}b\bar{b}$ h_{damp} up	$t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$-POWHEG	NLO	PYTHIA 8.230	CP5	4FS 3.1 NLO as 0118	$2.305 \cdot m_t$	5	23.86
CMS	PP8 $t\bar{t}b\bar{b}$ h_{damp} down	$t\bar{t}b\bar{b}$	$t\bar{t}b\bar{b}$-POWHEG	NLO	PYTHIA 8.230	CP5	4FS 3.1 NLO as 0118	$0.8738 \cdot m_t$	5	23.86
ATLAS	PP8 $t\bar{t}$	$t\bar{t}$	POWHEG v2	NLO	PYTHIA 8.210	A14	5FS 3.0 NLO	$1.5 \cdot m_t$	5	451.78
CMS	PP8 $t\bar{t}$	$t\bar{t}$	POWHEG v2	NLO	PYTHIA 8.230	CP5	5FS 3.1 NLO	$1.5 \cdot m_t$	5	451.78
ATLAS	PH7 $t\bar{t}$	$t\bar{t}$	POWHEG v2	NLO	HERWIG 7.13	default	5FS 3.0 NLO	$1.5 \cdot m_t$	5	451.78^c
ATLAS	aMC+P8 $t\bar{t}$	$t\bar{t}$	MG5_AMC@NLO	NLO	PYTHIA 8.210	A14	5FS 3.0 NLO	—	—	451.78^c
CMS	PP8 $t\bar{t}$ h_{damp} up	$t\bar{t}$	POWHEG v2	NLO	PYTHIA 8.230	CP5	5FS 3.1 NLO	$2.305 \cdot m_t$	5	451.78^c
CMS	PP8 $t\bar{t}$ h_{damp} down	$t\bar{t}$	POWHEG v2	NLO	PYTHIA 8.230	CP5	5FS 3.1 NLO	$0.8738 \cdot m_t$	5	451.78^c

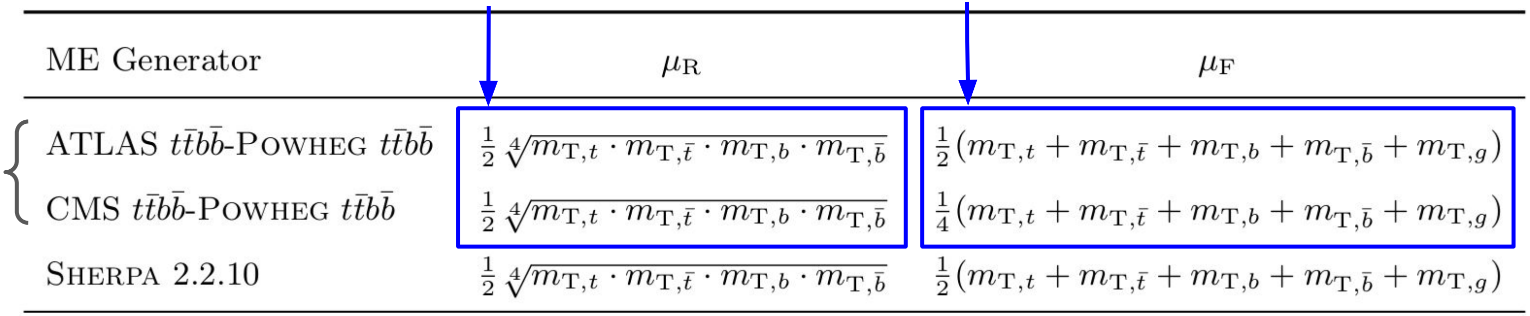
Both: μ_R / μ_F / ISR / FSR / pdf variations
ATLAS: Uncertainties from Sherpa / Herwig / h_{bzd} / h_{damp} variations
CMS: Uncertainties from h_{damp} variations

h_{bzd}: Splitting of finite and singular part of real emissions in POWHEG
h_{damp}: Regulates p_T of first emission in POWHEG PS

$t\bar{t}b\bar{b}$ background estimation in ATLAS+CMS

- **ATLAS+CMS modeling comparisons:** arXiv:2301.11670

Renormalization scales are the same **Factorization scales** differ by factor two



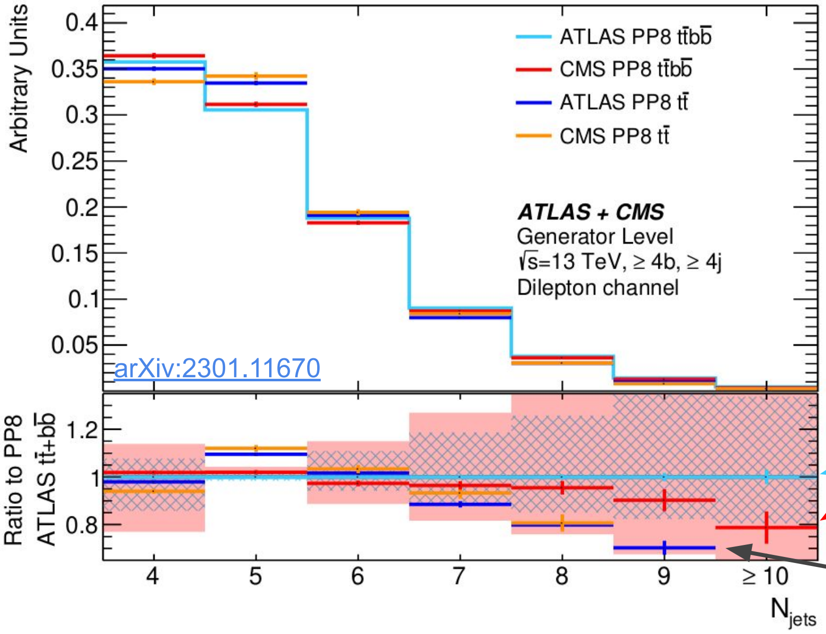
Nominal **$t\bar{t}b\bar{b}$@ME** models

ME Generator	μ_{R}	μ_{F}
ATLAS $t\bar{t}b\bar{b}$-Powheg $t\bar{t}b\bar{b}$	$\frac{1}{2}\sqrt[4]{m_{\mathrm{T},t}\cdot m_{\mathrm{T},\bar{t}}\cdot m_{\mathrm{T},b}\cdot m_{\mathrm{T},\bar{b}}}$	$\frac{1}{2}(m_{\mathrm{T},t}+m_{\mathrm{T},\bar{t}}+m_{\mathrm{T},b}+m_{\mathrm{T},\bar{b}}+m_{\mathrm{T},g})$
CMS $t\bar{t}b\bar{b}$-Powheg $t\bar{t}b\bar{b}$	$\frac{1}{2}\sqrt[4]{m_{\mathrm{T},t}\cdot m_{\mathrm{T},\bar{t}}\cdot m_{\mathrm{T},b}\cdot m_{\mathrm{T},\bar{b}}}$	$\frac{1}{4}(m_{\mathrm{T},t}+m_{\mathrm{T},\bar{t}}+m_{\mathrm{T},b}+m_{\mathrm{T},\bar{b}}+m_{\mathrm{T},g})$
Sherpa 2.2.10	$\frac{1}{2}\sqrt[4]{m_{\mathrm{T},t}\cdot m_{\mathrm{T},\bar{t}}\cdot m_{\mathrm{T},b}\cdot m_{\mathrm{T},\bar{b}}}$	$\frac{1}{2}(m_{\mathrm{T},t}+m_{\mathrm{T},\bar{t}}+m_{\mathrm{T},b}+m_{\mathrm{T},\bar{b}}+m_{\mathrm{T},g})$

- Latest **ATLAS** publication of $t\bar{t}H(b\bar{b})$ (JHEP 06 (2022) 97) uses μ_Rx 2
- Latest **CMS** publication of $t\bar{t}H(b\bar{b})$ (PAS-HIG-19-011) uses the settings from the table
  - ➢ Different scale settings of $t\bar{t}b\bar{b}$ still yield same $t\bar{t}H(b\bar{b})$ result in ATLAS + CMS

$t\bar{t}b\bar{b}$ background estimation in ATLAS+CMS

- **Comparison of $t\bar{t}b\bar{b}$@ME models – including scale and PS uncertainties**
  - ➢ Shaded bands include μ_R/μ_F/ISR/FSR x2/x0.5 variations



arXiv:2301.11670

Effort to homogenize $t\bar{t}$ simulation setups:
Common ATLAS+CMS $t\bar{t}$ effort
e.g. PHYS-2023-016

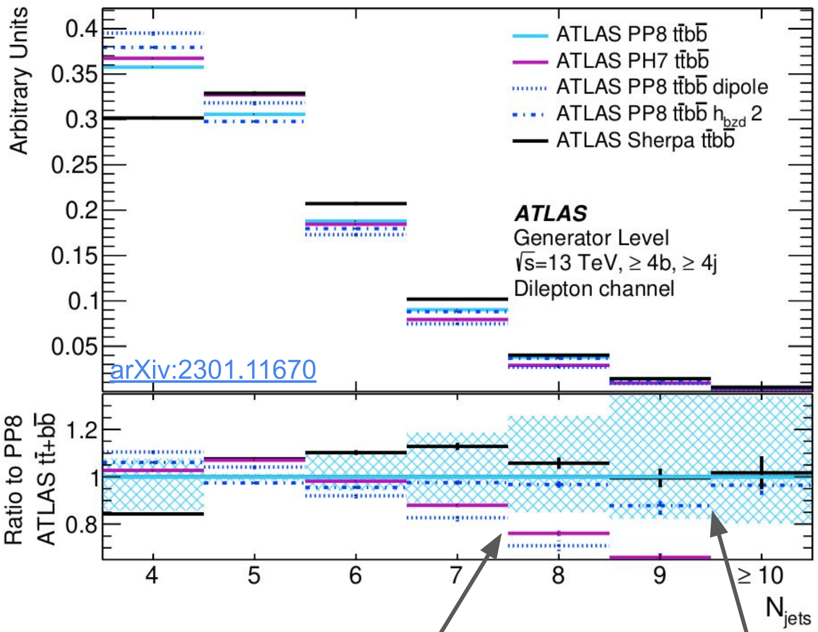
Small differences at large N_{jets} between **ATLAS** and **CMS** $t\bar{t}b\bar{b}$@ME

$t\bar{t}$@ME models show significant differences w.r.t. **$t\bar{t}b\bar{b}$@ME** models

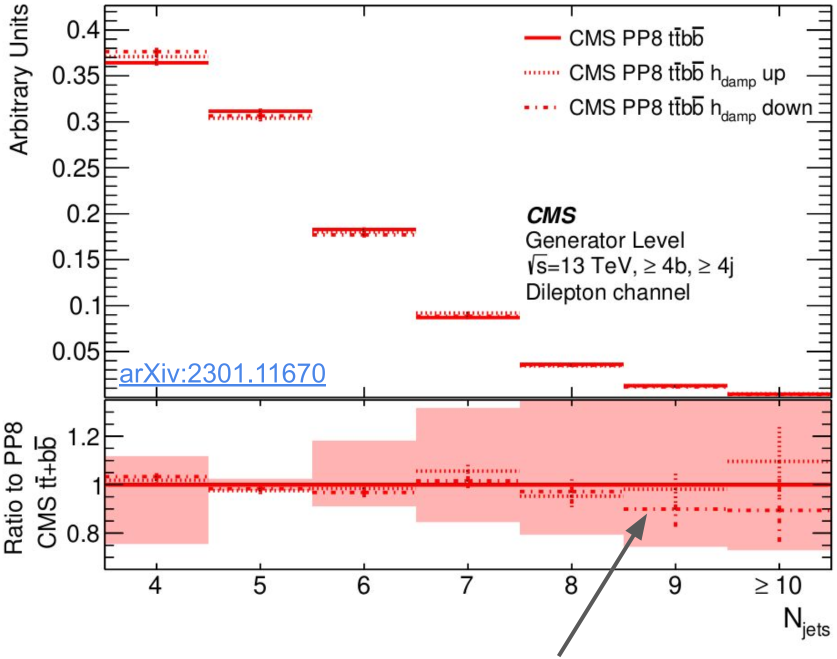
Scale variations dominated by μ_R variation → large shape and rate (30–50%) variations

$t\bar{t}b\bar{b}$ background estimation in ATLAS+CMS

- **Comparison of uncertainties for $t\bar{t}b\bar{b}$@ME models**
  - ➢ Approaches quite different and it seems to be diverging more in Run3



arXiv:2301.11670



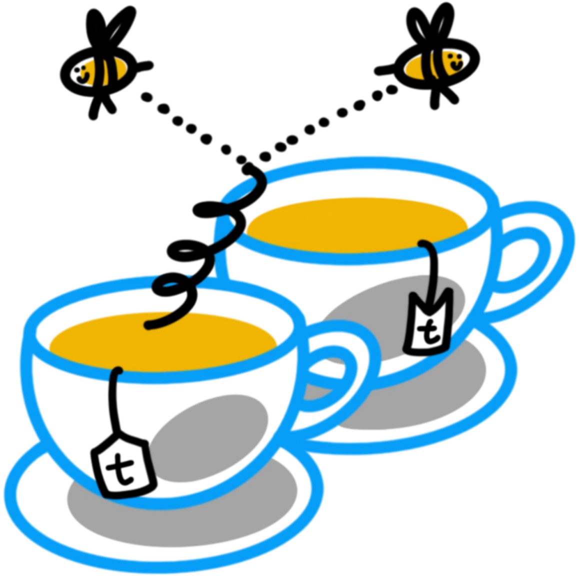
arXiv:2301.11670

Dipole shower variation / Herwig show large differences to nominal model

Smaller difference from Sherpa / h_{bzd} variations

h_{damp} variations small and fluctuating due to limited sample statistics

CMS $t\bar{t}b\bar{b}$ measurement

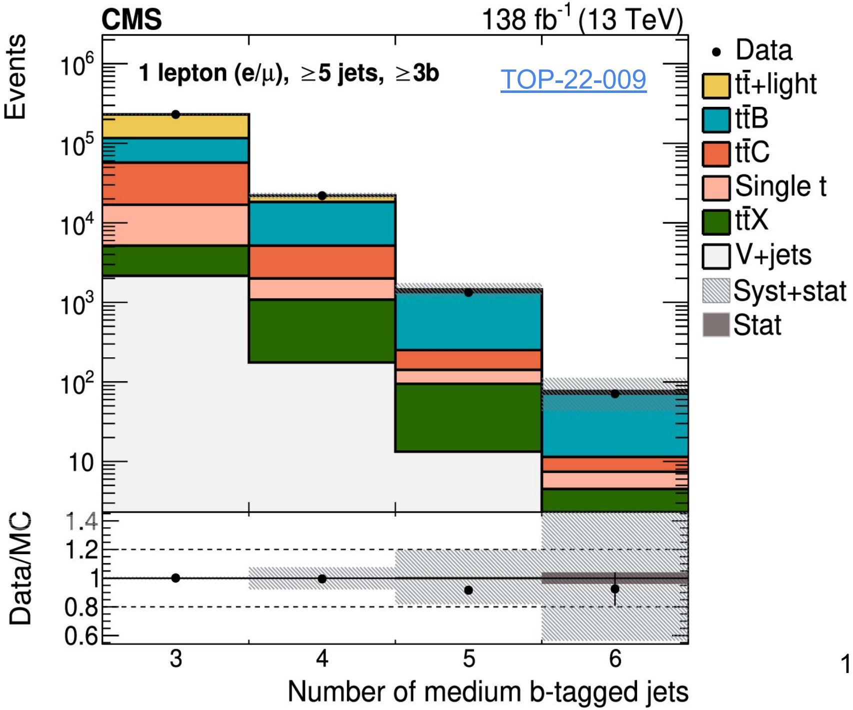


Strategy of CMS $t\bar{t}b\bar{b}$ measurement

- **Basic event selections targeting $t\bar{t}$+b jets and the lepton+jets final state**
  - Exactly **1 e/μ**
  - At least **5 jets** ($p_T > 30$ GeV, $|\eta| < 2.4$)
  - At least **3 b-tagged jets** (deepJet – 75–80% b efficiency / 1% light mistag rate)

  - Measure 37 observables independently

  - Four fiducial cross section measurements

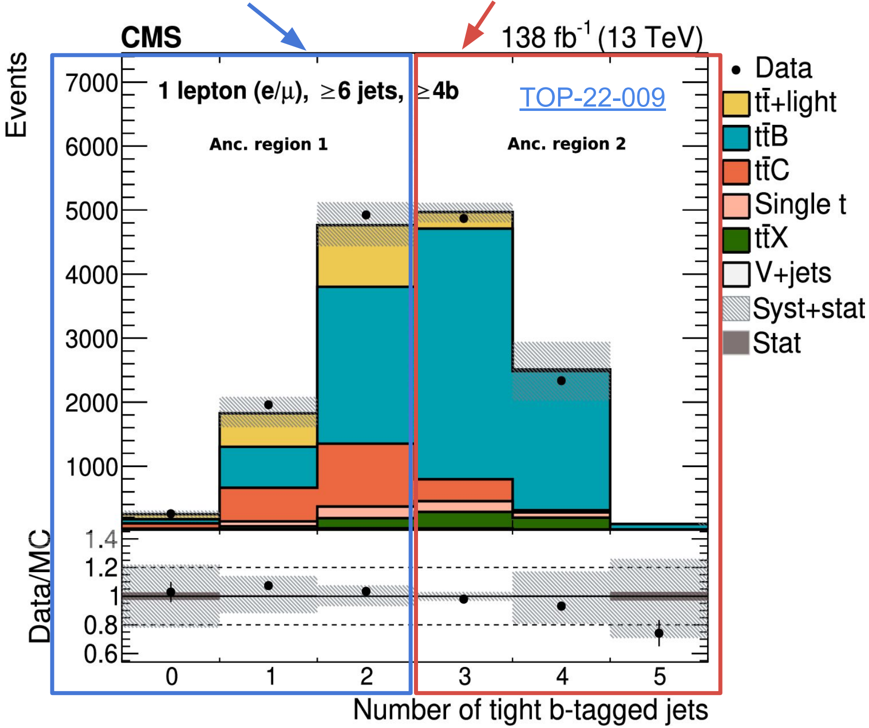


Strategy of CMS $t\bar{t}b\bar{b}$ measurement

- **Separate events in ancillary regions**
  - **Based on b jet multiplicity at tight b tagging WP** (0.1% light jet misidentification rate)
  - Basically in-situ signal and control regions

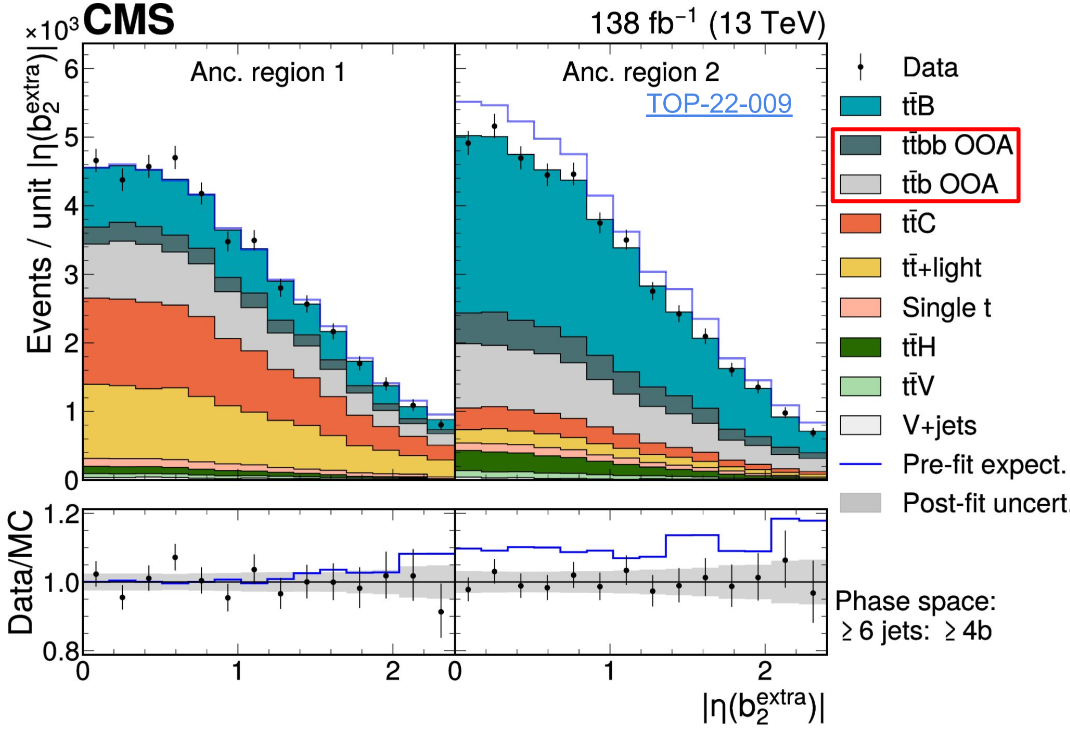
Sufficient control of residual backgrounds

Almost only $t\bar{t}b\bar{b}$



Strategy of CMS $t\bar{t}b\bar{b}$ measurement

- **Each observable independently measured**
  - ➢ Normalized differential cross section
  - ➢ Determine inclusive and normalized differential cross section simultaneously
  - ➢ **Likelihood-based unfolding:** Maximum-likelihood fit to obtain fiducial and differential cross sections
  - ➢ Full profiling of uncertainties



Out-of-acceptance (OOA) processes:

- ➢ Contributions of $t\bar{t}$+b jets not in fid. volume

Fiducial cross section results

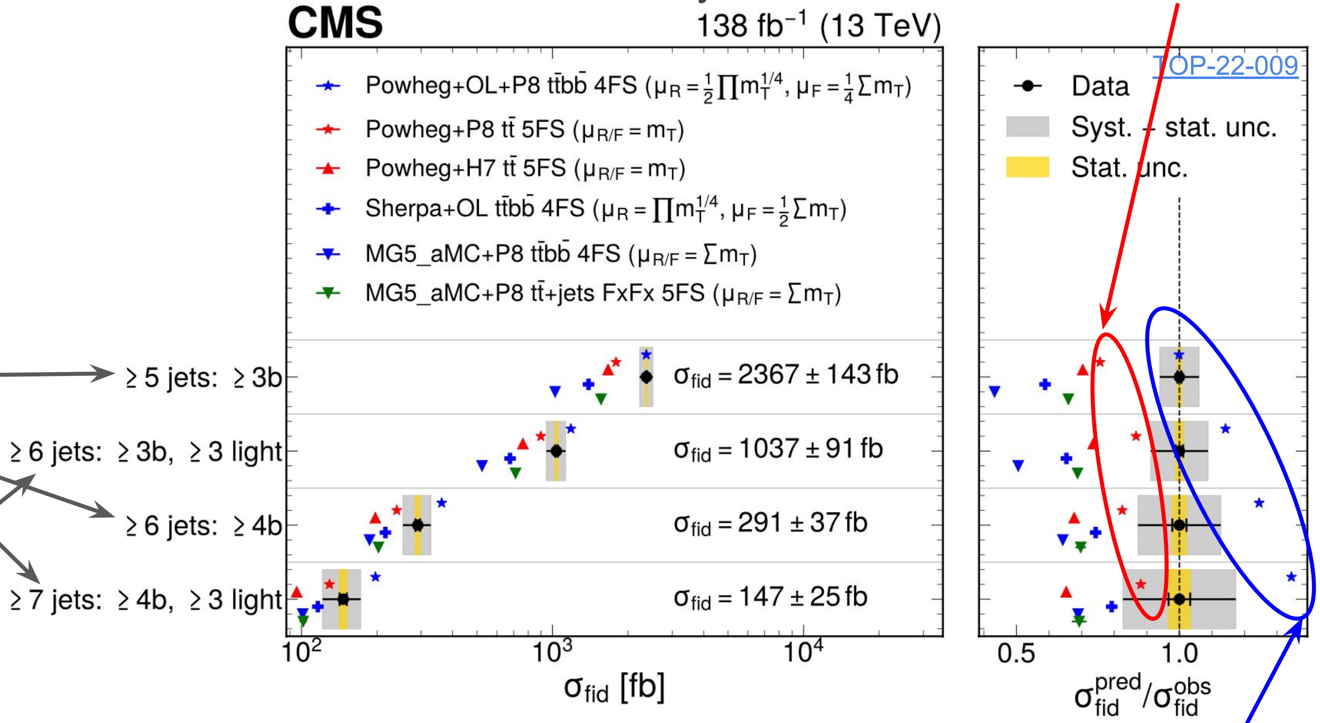
- **Fiducial cross sections measured in four overlapping fiducial regions**
  - ➢ Underpredicted by most models

Previously default CMS model for $t\bar{t}$ and $t\bar{t}b\bar{b}$ ★

Probing $t\bar{t}$ with at least 1 b jet

Probing fully-resolved $t\bar{t}b\bar{b}$

Probing additional jet radiation

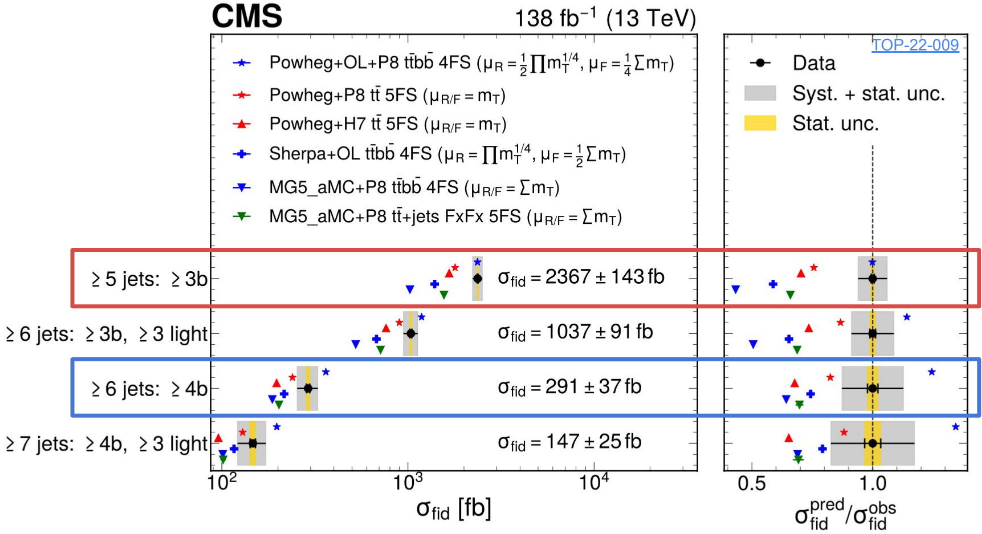


Powheg+Pythia $t\bar{t}b\bar{b}$@ME model: best agreement in 5j3b

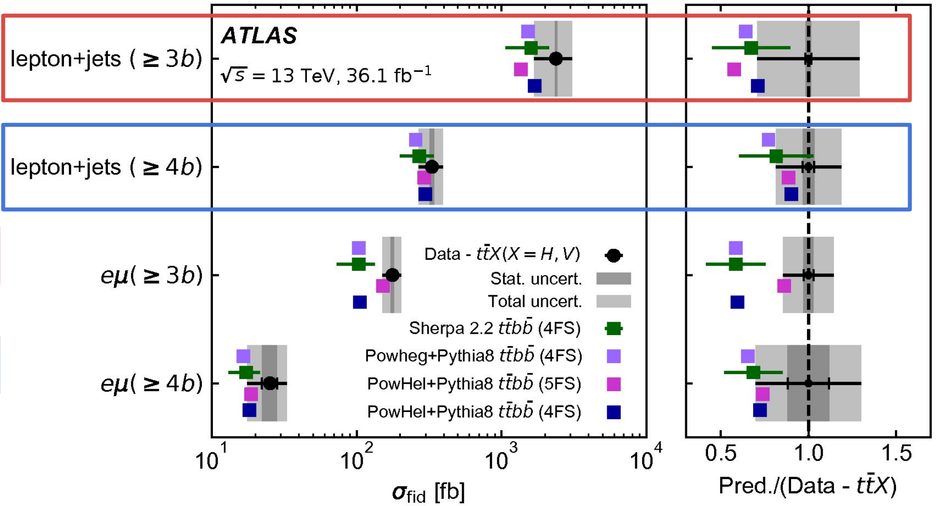
but similar trends as most models when going to more exclusive phase spaces ★

ATLAS + CMS comparison

- **ATLAS tt̄+b jet measurement ([JHEP 04 (2019) 046]) uses similar fid. definitions**
  - **tt̄+≥1b jet / tt̄+≥2b jets**
  - Powheg+Pythia tt̄bb̄ 4FS simulation (★/■):
    - μ_R/μ_F scales x2 in ATLAS publication w.r.t. CMS scales
    - fid. XS too low in ATLAS setup / too high in CMS setup



[JHEP 04 (2019) 046]



Results and limitations of measurements

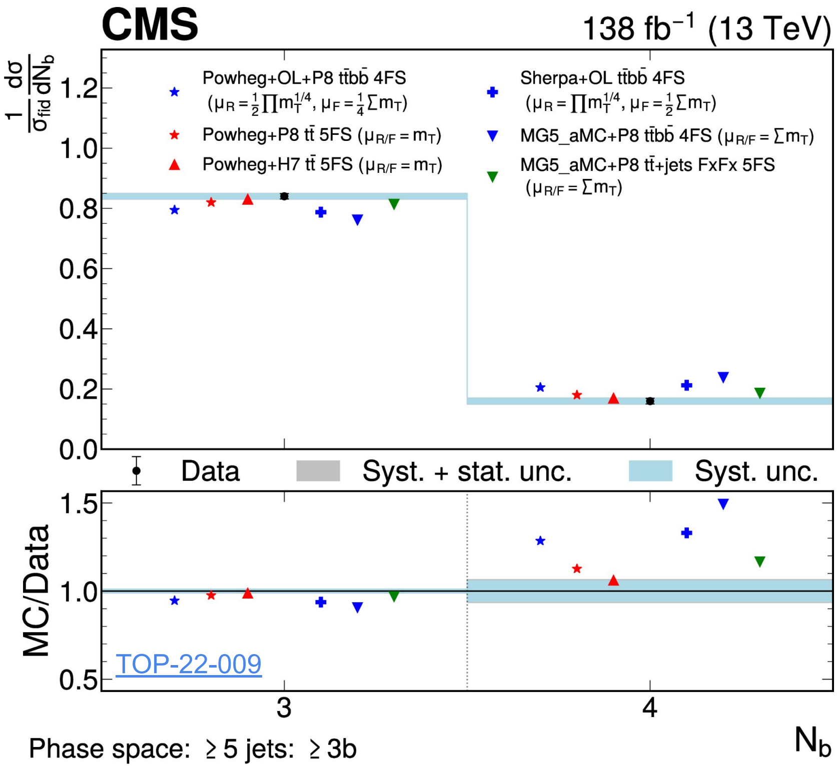
- **Limitations of fiducial cross section measurements:**
  - Precision of **6–17%** in CMS measurement / 13–28% in ATLAS measurement
  - Dominated by signal+background modeling / b-tagging / jet energy calibration

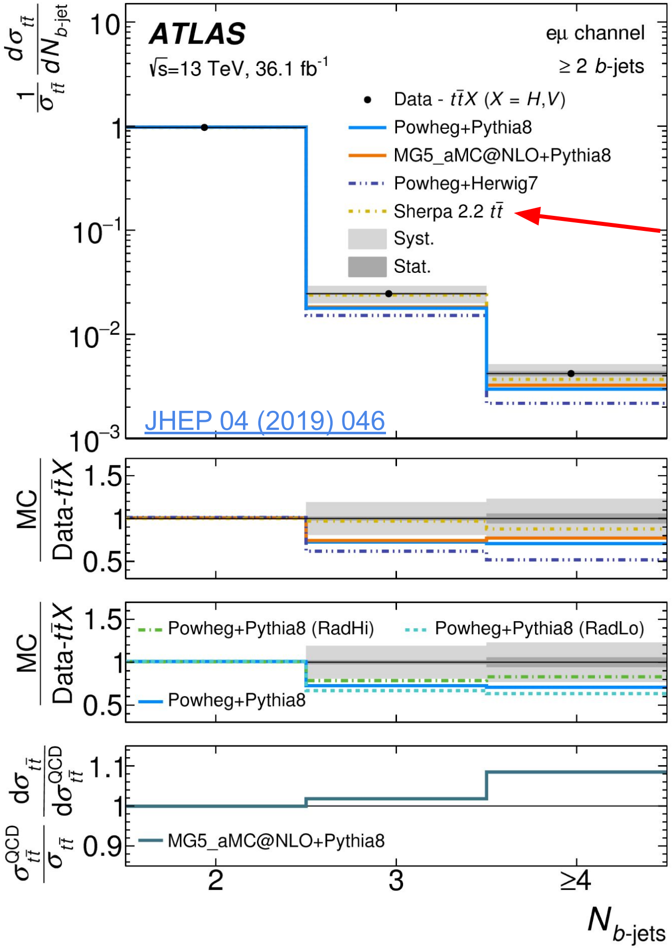
	Uncertainty source	Relative uncertainty (%) 5j3b	6j3b3l	6j4b	7j4b3l
Experimental uncertainties	Integrated luminosity	1.6	1.6	2.0	1.8
	Pileup reweighting	0.2	0.8	0.4	0.5
	Lepton and trigger	1.1	0.9	1.9	1.8
	JES, JER	2.1	1.6	3.5	5.7
	b tagging	4.5	3.9	7.0	9.1
Theory uncertainties	μ_R and μ_F scales	2.8	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 TOP-22-009	6.0	8.8	13	17

Source	Fiducial cross-section phase space $e\mu$		lepton + jets	
	$\geq 3b$ unc. [%]	$\geq 4b$ unc. [%]	$\geq 5j, \geq 3b$ unc. [%]	$\geq 6j, \geq 4b$ unc. [%]
Data statistics	2.7	9.0	1.7	3.0
Luminosity	2.1	2.1	2.3	2.3
Jet	2.6	4.3	3.6	7.2
b-tagging	4.5	5.2	17	8.6
Lepton	0.9	0.8	0.8	0.9
Pile-up	2.1	3.5	1.6	1.3
$t\bar{t}c$ fit variation	5.9	11	-	-
Non-$t\bar{t}$ bkg	0.8	2.0	1.7	1.8
Detector+background total syst.	8.5	14	18	12
Parton shower	9.0	6.5	12	6.3
Generator	0.2	18	16	8.7
ISR/FSR	4.0	3.9	6.2	2.9
PDF	0.6	0.4	0.3	0.1
$t\bar{t}V/t\bar{t}H$	0.7	1.4	2.2	0.3
MC sample statistics	1.8	5.3	1.2	4.3
$t\bar{t}$ modelling total syst.	10	20	21	12
Total syst.	13	24	28	17
Total JHEP 04 (2019) 046	13	26	28	17

Differential measurement: b jet multiplicity

- **ATLAS+CMS:** b jet multiplicity not well modelled



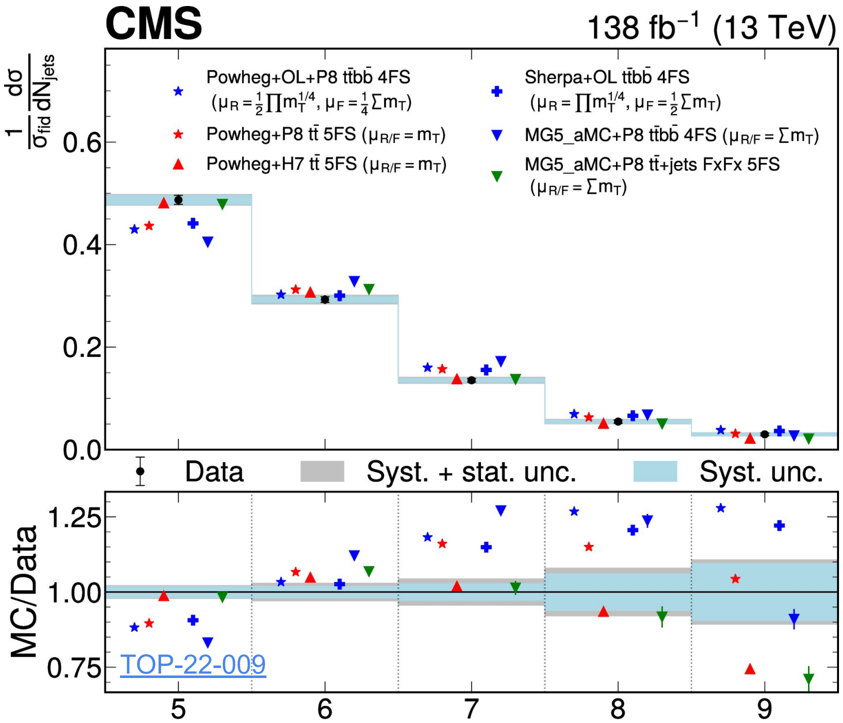


Sherpa yields good prediction

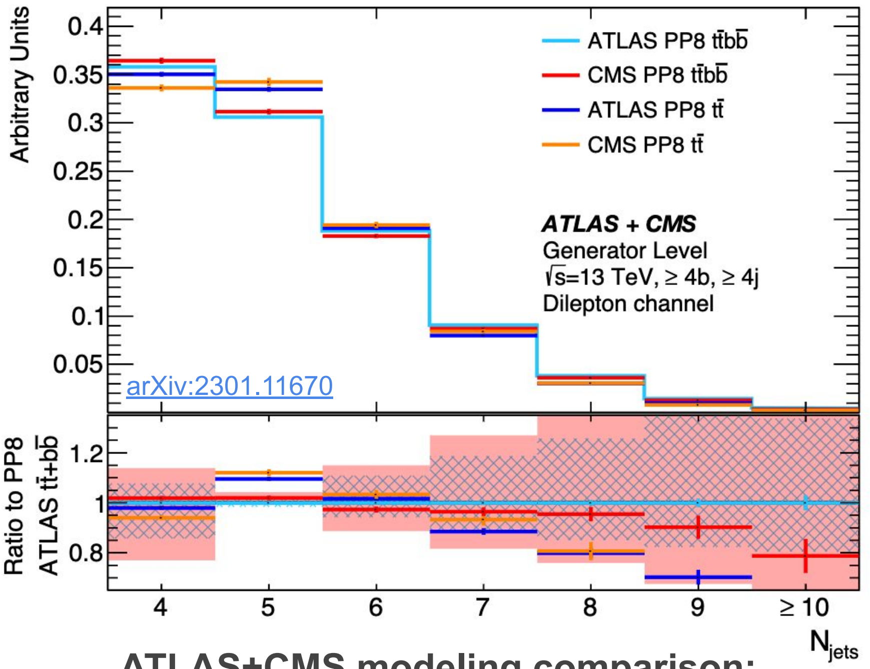
$t\bar{t}$@ME simulations do better than $t\bar{t}b\bar{b}$@ME simulations

Differential measurement: jet multiplicity

- **CMS:** not well described by any of the tested generator setups



Phase space: ≥ 5 jets: ≥ 3b

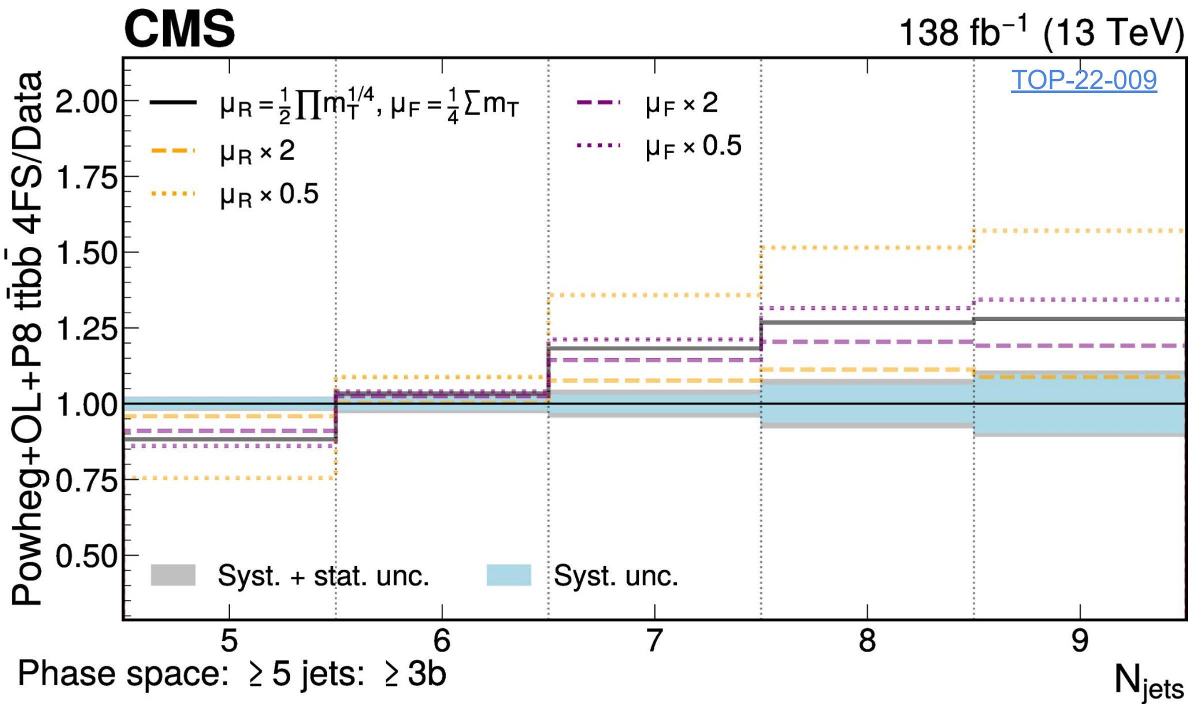


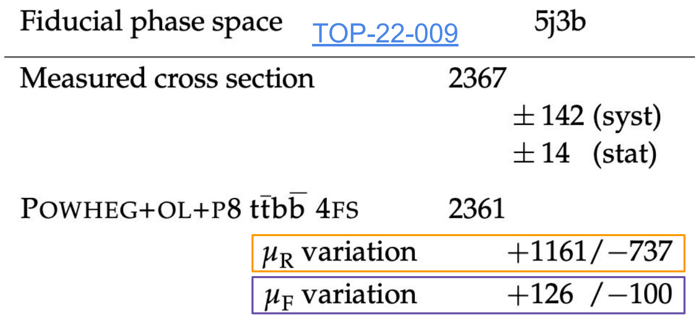
ATLAS+CMS modeling comparison:
← All would fail test against data

$t\bar{t}b\bar{b}$@ME simulations with their settings predict way too many jets

Differential measurement: jet multiplicity

- **QCD scale variations improve N_{jets} description for Powheg+Pythia $t\bar{t}b\bar{b}$ 4FS simulation**
  - ➢ Increased scales seem favorable for differential distribution
  - ➢ Increased scales at the same time reduce fiducial cross section compatibility





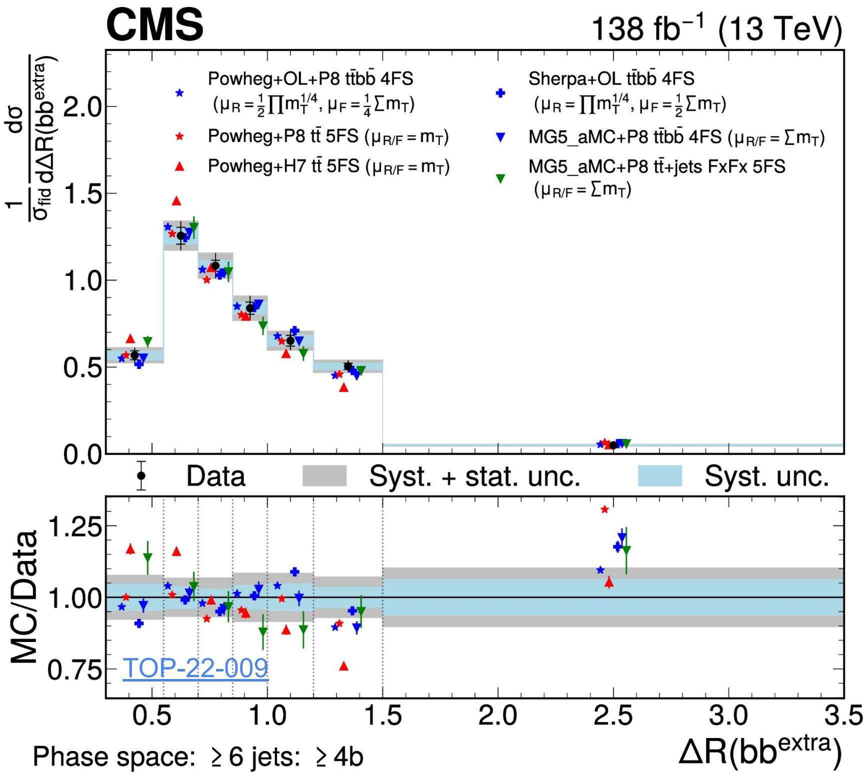
Fiducial phase space TOP-22-009	5j3b
Measured cross section	2367 ± 142 (syst) ± 14 (stat)
POWHEG+OL+P8 $t\bar{t}b\bar{b}$ 4FS	2361
μ_R variation	+1161/−737
μ_F variation	+126 / −100

Decreasing scales

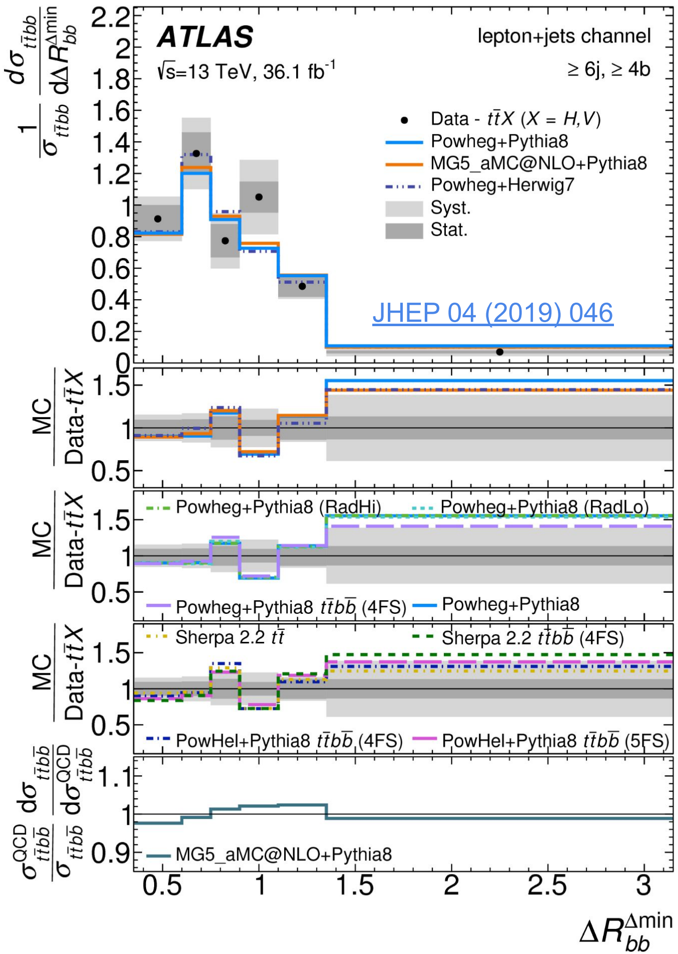
Increasing scales

Differential measurement: min dR(bb)

- $t\bar{t}b\bar{b}$@ME describes min dR(bb) quite well



TOP-22-009



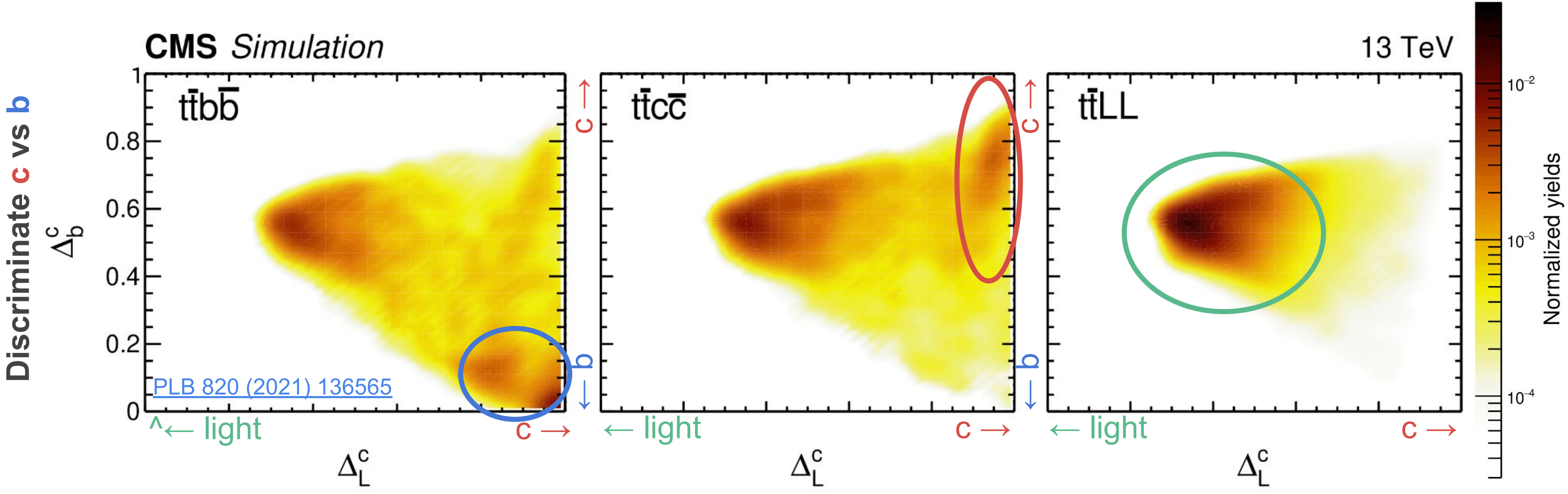
JHEP 04 (2019) 046

→ more on this observable in Emanuel's talk!

CMS $t\bar{t}c\bar{c}$ measurement

First measurement of $t\bar{t}c\bar{c}$ production by CMS

- **Need to differentiate b, c and light jets to access $t\bar{t}c\bar{c}$**
  - More difficult than $t\bar{t}b\bar{b}$
  - use DNN + charm jet tagging to separate $t\bar{t}c\bar{c}$/$b\bar{b}$/etc classes



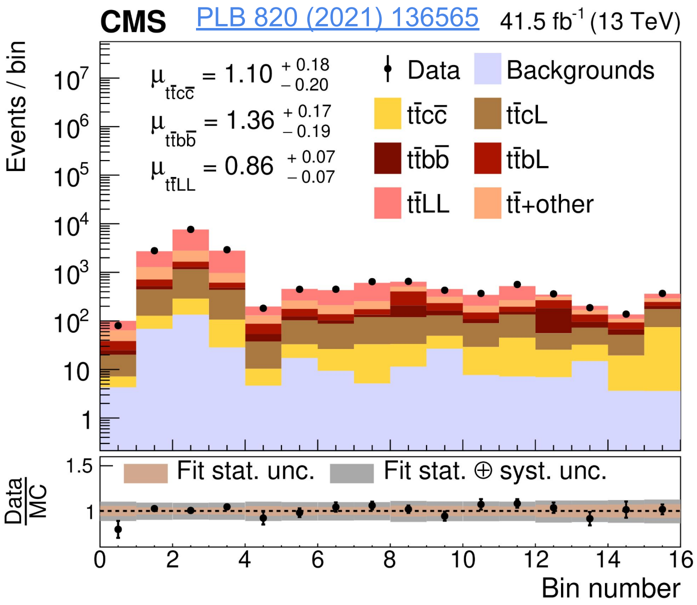
PLB 820 (2021) 136565

Discriminate c vs light

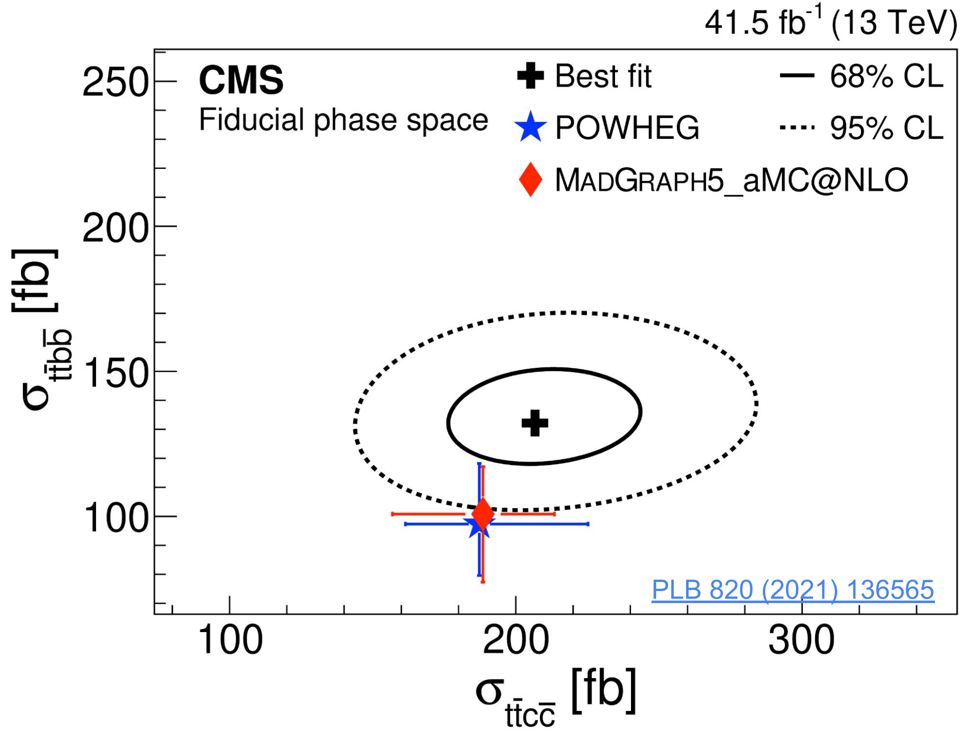
First measurement of $t\bar{t}c\bar{c}$ production by CMS

- Measure $t\bar{t}b\bar{b}$, $t\bar{t}c\bar{c}$, $t\bar{t}$+light at the same time (and also their ratios)

2D distributions from last slide unrolled for fit



13.7% precision on ttcc cross section!



$t\bar{t}c\bar{c}$ fairly well described by simulation
$t\bar{t}b\bar{b}$ underpredicted by simulation

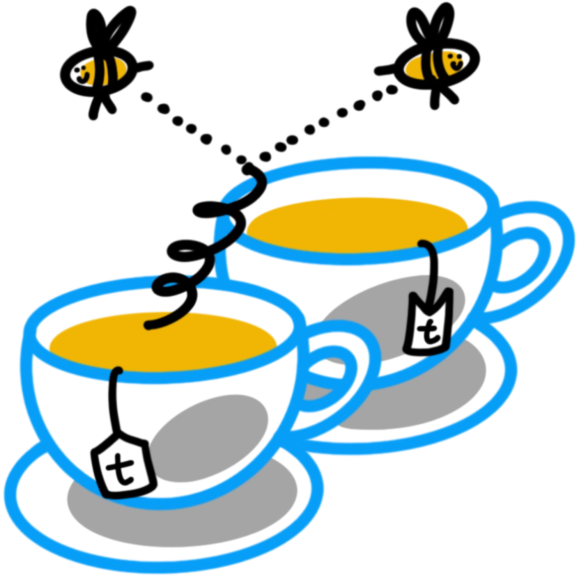
Summary

- **Differential $t\bar{t}b\bar{b}$ measurements by CMS+ATLAS**
  - 6–17% (13–28%) uncertainty achieved by CMS (ATLAS)
  - CMS improved precision w.r.t. previous measurements
  - In total 37 (24) observables measured by CMS (ATLAS)!
  - Valuable input for modeling updates

More CMS $t\bar{t}b\bar{b}$ results of [TOP-22-009](TOP-22-009):
YSF talk by Emanuel Pfeffer
Poster by Juhee Song

- **Modeling comparisons ATLAS+CMS**
  - Small differences in $t\bar{t}b\bar{b}$@ME setups
  - Large difference between $t\bar{t}b\bar{b}$@ME/$t\bar{t}$@ME
  - Modeling and uncertainty recommendations to be reviewed

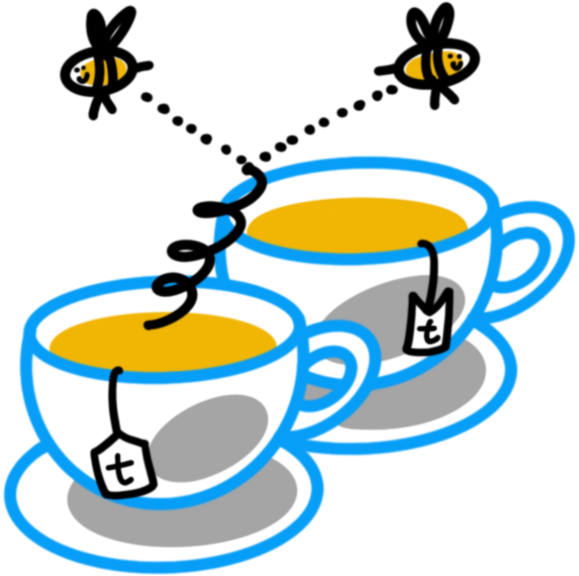
- **$t\bar{t}c\bar{c}$ measurement by CMS**
  - First time accessing $t\bar{t}c\bar{c}$ – 13.7% precision
  - Interesting for future $t\bar{t}H(c\bar{c})$ measurements



Backup

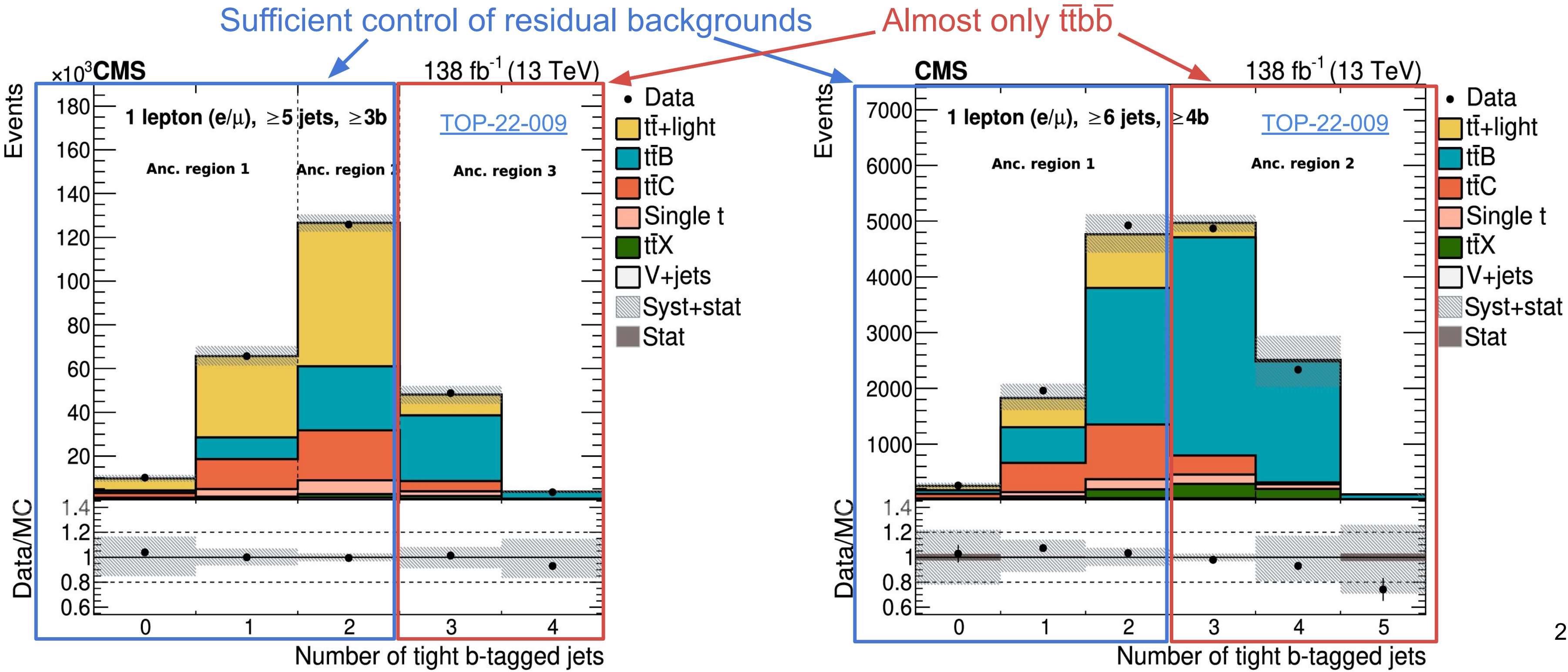

16th Top Physics Workshop
Traverse City, MI, USA – 24th to 29th September 2023
Traverse City Michigan USA
16th Top 2023

CMS $t\bar{t}b\bar{b}$ measurement



Strategy of CMS $t\bar{t}b\bar{b}$ measurement

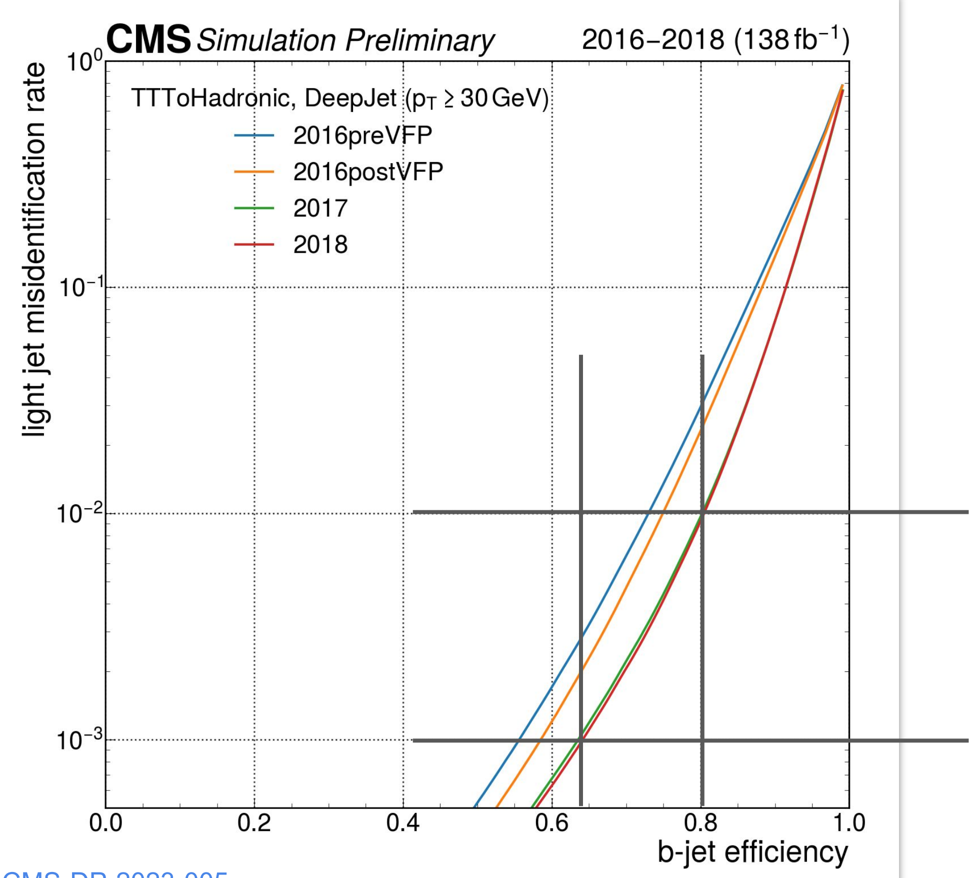
- **Separate events in ancillary regions**
  - **Based on b jet multiplicity at tight b tagging WP** (0.1% light jet misidentification rate)
  - Basically in-situ signal and control regions



Sufficient control of residual backgrounds

Almost only $t\bar{t}b\bar{b}$

b tagging performance



CMS-DP-2023-005

Medium WP:

1% light jet misID

80% b jet efficiency

High selection efficiency for $t\bar{t}b\bar{b}$, but also large contribution from backgrounds (e.g. $t\bar{t}$+light, $t\bar{t}$C)

Tight WP:

0.1% light jet misID

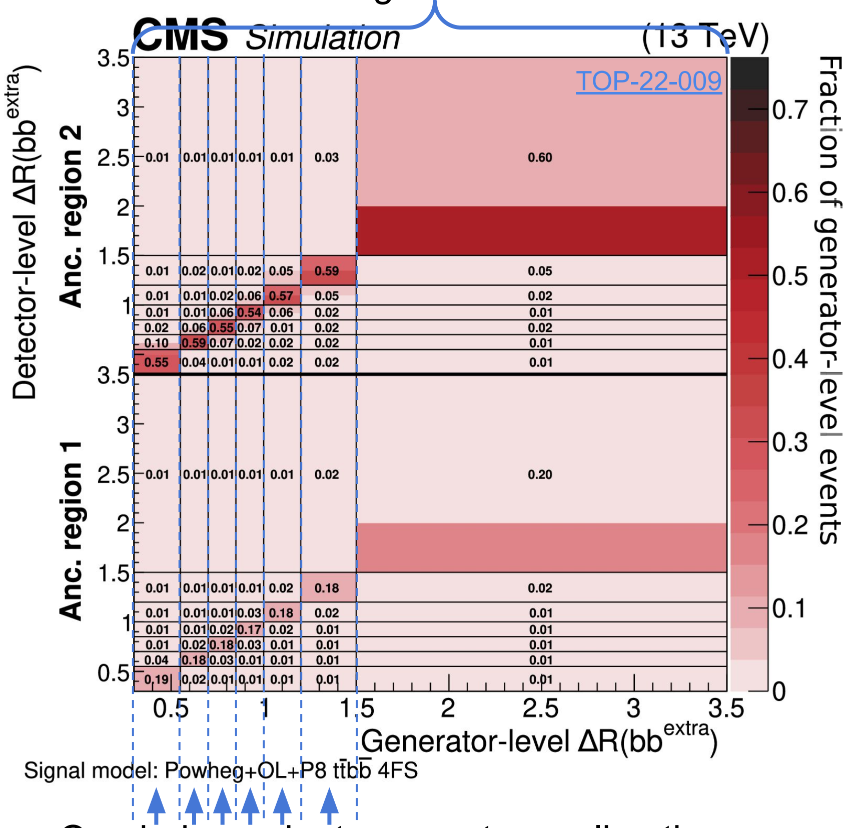
65% b jet efficiency

Good selection efficiency for $t\bar{t}b\bar{b}$, almost no more background contributions (except for irreducible $t\bar{t}$X($b\bar{b}$))

Strategy of CMS $t\bar{t}b\bar{b}$ measurement

- **Each observable independently measured**
  - ➢ Normalized differential cross section
  - ➢ Free parameters for fid. XS and fractions of events in generator-level bins
  - ➢ Good correspondence between detector and generator level
  - ➢ Maximum-likelihood fit to obtain fiducial and differential cross sections
  - ➢ Full profiling of uncertainties

One parameter scaling the full signal contribution



Signal model: Powheg+OL+P8 $t\bar{t}b\bar{b}$ 4FS

One independent parameter scaling the fraction of events in each generator-level bin

Strategy of CMS $t\bar{t}b\bar{b}$ measurement

- **Robust systematic model**
  - Important modeling uncertainties decorrelated between signal and backgrounds
    (μ_R / μ_F / ISR / FSR / h_{damp})
  - Rate-changing effects of modeling uncertainties removed for signal processes
    (d.o.f.s of cross sections)
  - Out-of-acceptance $t\bar{t}b\bar{b}$ modeling uncertainties correlated to signal in 6j4b/7j4b3l
    (similarity to signal process)
  - Many correlation schemes / alternatives tested during CMS-internal review
    - Results very robust against changes

	Source	Corr. (period)	Corr. (process)
Experimental	Integrated luminosity	∼	✓
	Pileup	✓	✓
	Trigger efficiency	×	✓
	L1 prefiring	✓	✓
	Electron selection efficiency	✓	✓
	Muon selection efficiency	✓	✓
	Jet energy scale	∼	✓
	Jet energy resolution	×	✓
	b tagging efficiency	∼	✓
Theoretical	μ_F and μ_R scales	✓	∼
	Top p_T modelling	✓	✓
	PDF choice	✓	✓
	PS modelling: ISR & FSR scale	✓	×
	Colour reconnection	✓	✓
	ME-PS matching (h_{damp})	✓	∼
	Underlying-event tune	✓	✓
	b fragmentation	✓	✓
	$t\bar{t}C$ normalization	✓	—

Fiducial signal definition + observables

- ❑ **Generator-level phase space definitions**
  - ➢ Mimic event-level selections:
    - ❑ Exactly 1 e/μ
    - ❑ At least 5 jets (p_T > 25 GeV)
    - ❑ At least 3 b jets (Ghost Hadron clustering)
  - ➢ **No reference to MC history of jets i.e. origin of b jets is unknown (purely particle-level)**
  - ➢ Four fiducial phase space regions:
    - ❑ **5j3b:** $t\bar{t}$ + at least one b jet
    - ❑ **6j4b:** $t\bar{t}$ + at least two b jets
    - ❑ **6j3b3l:** additional light jets in 5j3b
    - ❑ **7j4b3l:** additional light jets in 6j4b

	Observable	5j3b	6j4b	6j3b3l	7j4b3l
σ_{fid}	Inclusive cross section	✓	✓	✓	✓
Global observables					
N_{jets}	Jet multiplicity	✓	✓		
N_{b}	b jet multiplicity	✓			
H_{T}^{j}	Scalar sum of jet p_{T}	✓	✓		
H_{T}^{b}	Scalar sum of b jet p_{T}	✓	✓		
$H_{\text{T}}^{\text{light}}$	Scalar sum of light jet p_{T}			✓	✓
Observables related to b jets					
$p_{\text{T}}(\text{b}_3)$	p_{T} of third hardest b jet	✓	✓		
$\lvert\eta(\text{b}_3)\rvert$	$\lvert\eta\rvert$ of third hardest b jet	✓	✓		
$p_{\text{T}}(\text{b}_4)$	p_{T} of fourth hardest b jet		✓		
$\lvert\eta(\text{b}_4)\rvert$	$\lvert\eta\rvert$ of fourth hardest b jet		✓		
Observables considering all pairs of b jets (bb)					
$\Delta\text{R}_{\text{bb}}^{\text{avg}}$	Average ΔR of all bb pairs		✓		
$\text{m}_{\text{bb}}^{\text{max}}$	Highest invariant mass among all bb pairs		✓		
Observables related to the pair of b jets closest in ΔR (bb^{extra})					
$p_{\text{T}}(\text{b}_1^{\text{extra}})$	p_{T} of leading extra b jet		✓		
$\lvert\eta(\text{b}_1^{\text{extra}})\rvert$	$\lvert\eta\rvert$ of leading extra b jet		✓		
$p_{\text{T}}(\text{b}_2^{\text{extra}})$	p_{T} of subleading extra b jet		✓		
$\lvert\eta(\text{b}_2^{\text{extra}})\rvert$	$\lvert\eta\rvert$ of subleading extra b jet		✓		
$\Delta\text{R}(\text{bb}^{\text{extra}})$	ΔR of bb^{extra} pair		✓		
$\lvert\eta\rvert(\text{bb}^{\text{extra}})$	$\lvert\eta\rvert$ of bb^{extra} pair		✓		
$\text{m}(\text{bb}^{\text{extra}})$	invariant mass of bb^{extra} pair		✓		
$p_{\text{T}}(\text{bb}^{\text{extra}})$	p_{T} of bb^{extra} pair		✓		
Observables related to the pair of b jets not from $t\bar{t}$ decay ($\text{bb}^{\text{add.}}$)					
$p_{\text{T}}(\text{b}_1^{\text{add.}})$	p_{T} of leading additional b jet		✓*		
$\lvert\eta(\text{b}_1^{\text{add.}})\rvert$	$\lvert\eta\rvert$ of leading additional b jet		✓*		
$p_{\text{T}}(\text{b}_2^{\text{add.}})$	p_{T} of subleading additional b jet		✓*		
$\lvert\eta(\text{b}_2^{\text{add.}})\rvert$	$\lvert\eta\rvert$ of subleading additional b jet		✓*		
$\Delta\text{R}(\text{bb}^{\text{add.}})$	ΔR of $\text{bb}^{\text{add.}}$ pair		✓*		
$\lvert\eta\rvert(\text{bb}^{\text{add.}})$	$\lvert\eta\rvert$ of $\text{bb}^{\text{add.}}$ pair		✓*		
$\text{m}(\text{bb}^{\text{add.}})$	invariant mass of $\text{bb}^{\text{add.}}$ pair		✓*		
$p_{\text{T}}(\text{bb}^{\text{add.}})$	p_{T} of $\text{bb}^{\text{add.}}$ pair		✓*		
Observables related to extra light jets					
$p_{\text{T}}(\text{lj}_1^{\text{extra}})$	p_{T} of leading extra light jet			✓	✓
$\lvert\Delta\phi(\text{lj}_1^{\text{extra}}, \text{b}_{\text{soft}})\rvert$	$\Delta\phi$ of leading extra light jet and softest b jet			✓	✓

Comparing measurement to predictions

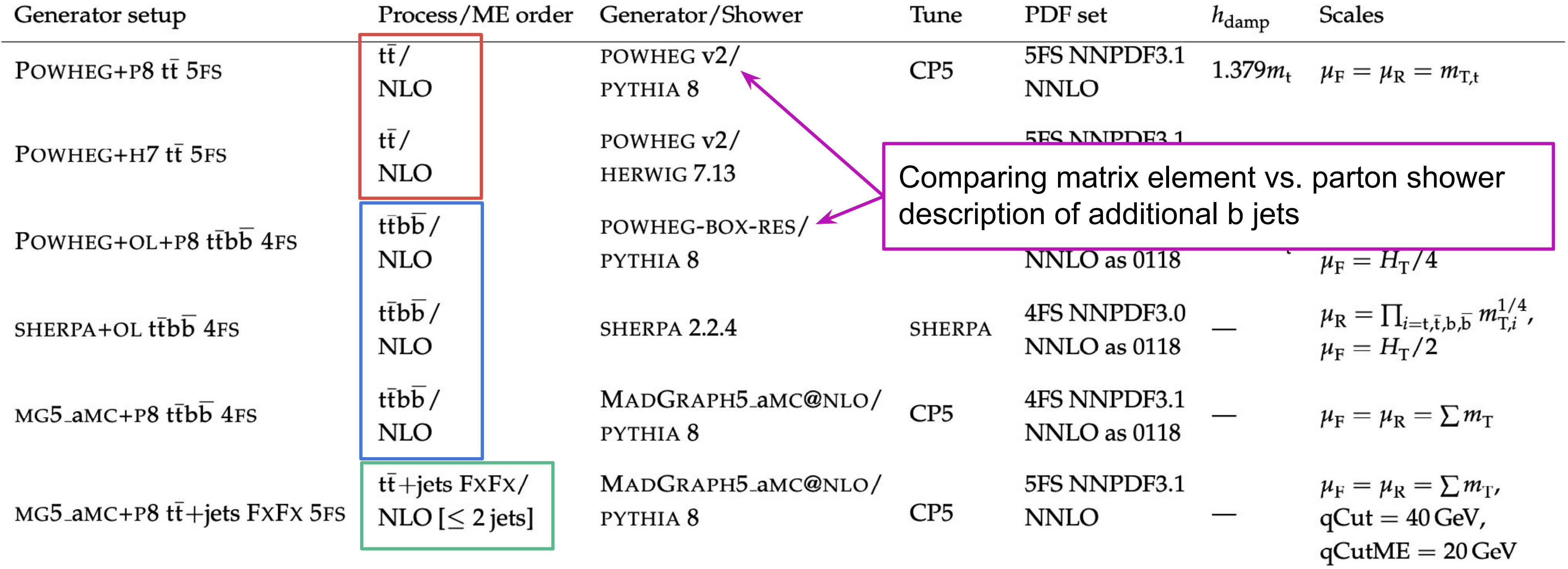
- **Test some possible predictions of $t\bar{t}b\bar{b}$ against the measurements**

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	CP5	5FS NNPDF3.1	$1.379m_{\mathrm{t}}$	$\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = m_{\mathrm{T,t}}$
POWHEG+H7 $t\bar{t}$ 5FS	$t\bar{t}$/ NLO	POWHEG v2/ HERWIG 7.13	CH3	5FS NNPDF3.1 NNLO	$1.379m_{\mathrm{t}}$	$\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = m_{\mathrm{T,t}}$
POWHEG+OL+P8 $t\bar{t}b\bar{b}$ 4FS	$t\bar{t}b\bar{b}$/ NLO	POWHEG-BOX-RES/ PYTHIA 8	CP5	4FS NNPDF3.1 NNLO as 0118	$1.379m_{\mathrm{t}}$	$\mu_{\mathrm{R}} = \frac{1}{2}\prod_{i=\mathrm{t,\bar{t},b,\bar{b}}} m_{\mathrm{T},i}^{1/4}$, $\mu_{\mathrm{F}} = H_{\mathrm{T}}/4$
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	—	$\mu_{\mathrm{R}} = \prod_{i=\mathrm{t,\bar{t},b,\bar{b}}} m_{\mathrm{T},i}^{1/4}$, $\mu_{\mathrm{F}} = H_{\mathrm{T}}/2$
MG5_aMC+P8 $t\bar{t}b\bar{b}$ 4FS	$t\bar{t}b\bar{b}$/ NLO	MADGRAPH5_aMC@NLO/ PYTHIA 8	CP5	4FS NNPDF3.1 NNLO as 0118	—	$\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \sum m_{\mathrm{T}}$
MG5_aMC+P8 $t\bar{t}$+jets FxFx 5FS	$t\bar{t}$+jets FxFx/ NLO [$\leq$ 2 jets]	MADGRAPH5_aMC@NLO/ PYTHIA 8	CP5	5FS NNPDF3.1 NNLO	—	$\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \sum m_{\mathrm{T}}$, qCut = 40 GeV, qCutME = 20 GeV

Comparing different parton showers

Comparing measurement to predictions

- Test some possible predictions of $t\bar{t}b\bar{b}$ against the measurements



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	CP5	5FS NNPDF3.1 NNLO	$1.379 m_{\mathrm{t}}$	$\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = m_{\mathrm{T,t}}$
POWHEG+H7 $t\bar{t}$ 5FS	$t\bar{t}$/ NLO	POWHEG v2/ HERWIG 7.13		5FS NNPDF3.1		
POWHEG+OL+P8 $t\bar{t}b\bar{b}$ 4FS	$t\bar{t}b\bar{b}$/ NLO	POWHEG-BOX-RES/ PYTHIA 8		NNLO as 0118		$\mu_{\mathrm{F}} = H_{\mathrm{T}}/4$
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	—	$\mu_{\mathrm{R}} = \prod_{i=\mathrm{t},\bar{\mathrm{t}},\mathrm{b},\bar{\mathrm{b}}} m_{\mathrm{T},i}^{1/4}$, $\mu_{\mathrm{F}} = H_{\mathrm{T}}/2$
MG5_aMC+P8 $t\bar{t}b\bar{b}$ 4FS	$t\bar{t}b\bar{b}$/ NLO	MADGRAPH5_aMC@NLO/ PYTHIA 8	CP5	4FS NNPDF3.1 NNLO as 0118	—	$\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \sum m_{\mathrm{T}}$
MG5_aMC+P8 $t\bar{t}$+jets FxFx 5FS	$t\bar{t}$+jets FxFx/ NLO [≤ 2 jets]	MADGRAPH5_aMC@NLO/ PYTHIA 8	CP5	5FS NNPDF3.1 NNLO	—	$\mu_{\mathrm{F}} = \mu_{\mathrm{R}} = \sum m_{\mathrm{T}}$, qCut = 40 GeV, qCutME = 20 GeV

Comparing matrix element vs. parton shower description of additional b jets

Comparing measurement to predictions

❑ **Test some possible predictions of $t\bar{t}b\bar{b}$ against the measurements**

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	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	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				
MG5_aMC+P8 $t\bar{t}b\bar{b}$ 4FS	$t\bar{t}b\bar{b}$/ NLO	MADGRAPH5_aMC@NLO/ PYTHIA 8	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 [$\leq$ 2 jets]	MADGRAPH5_aMC@NLO/ PYTHIA 8	CP5	5FS NNPDF3.1 NNLO	—	$\mu_F = \mu_R = \sum m_T$, qCut = 40 GeV, qCutME = 20 GeV

Comparing different matrix element generators

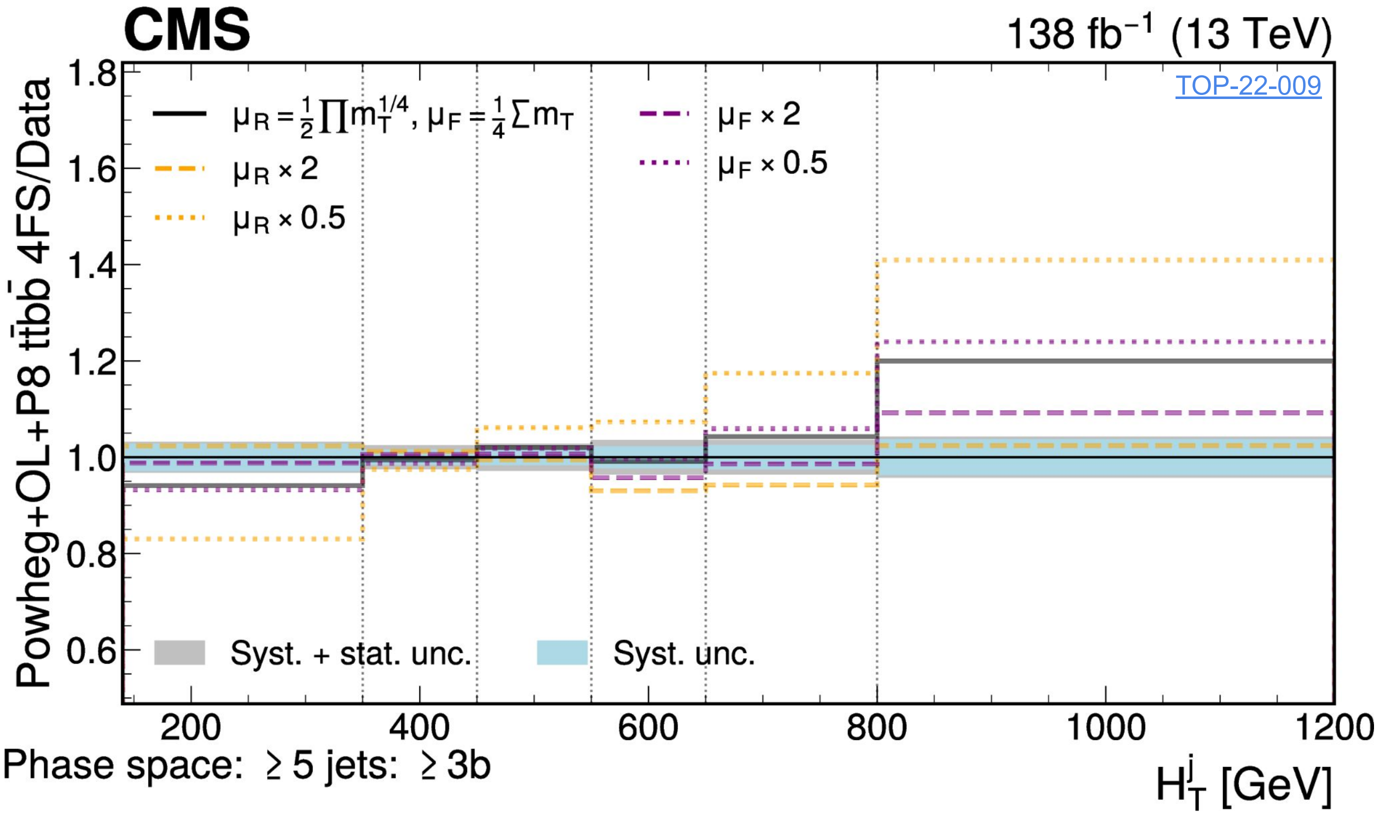
Fiducial cross section values

Fiducial phase space	5j3b	6j3b3l	6j4b	7j4b3l
Measured cross section	2367 ± 142 (syst) ± 14 (stat)	1037 ± 90 (syst) ± 12 (stat)	291 ± 36 (syst) ± 6 (stat)	147 ± 24 (syst) ± 5 (stat)
POWHEG+OL+P8 $t\bar{t}b\bar{b}$ 4FS	2361	1183	361	197
μ_R variation	+1161/−737	+826/−433	+183/−113	+121/−67
μ_F variation	+126 /−100	+97 /−78	+23 /−18	+16 /−13
POWHEG+P8 $t\bar{t}$ 5FS	1791	899	240	129
POWHEG+H7 $t\bar{t}$ 5FS	1665	762	197	95
SHERPA+OL $t\bar{t}b\bar{b}$ 4FS	1391	677	216	116
MG5_aMC+P8 $t\bar{t}b\bar{b}$ 4FS	1024	524	187	101
MG5_aMC+P8 $t\bar{t}$+jets FxFx 5FS	1560	712	203	101

TOP-22-009

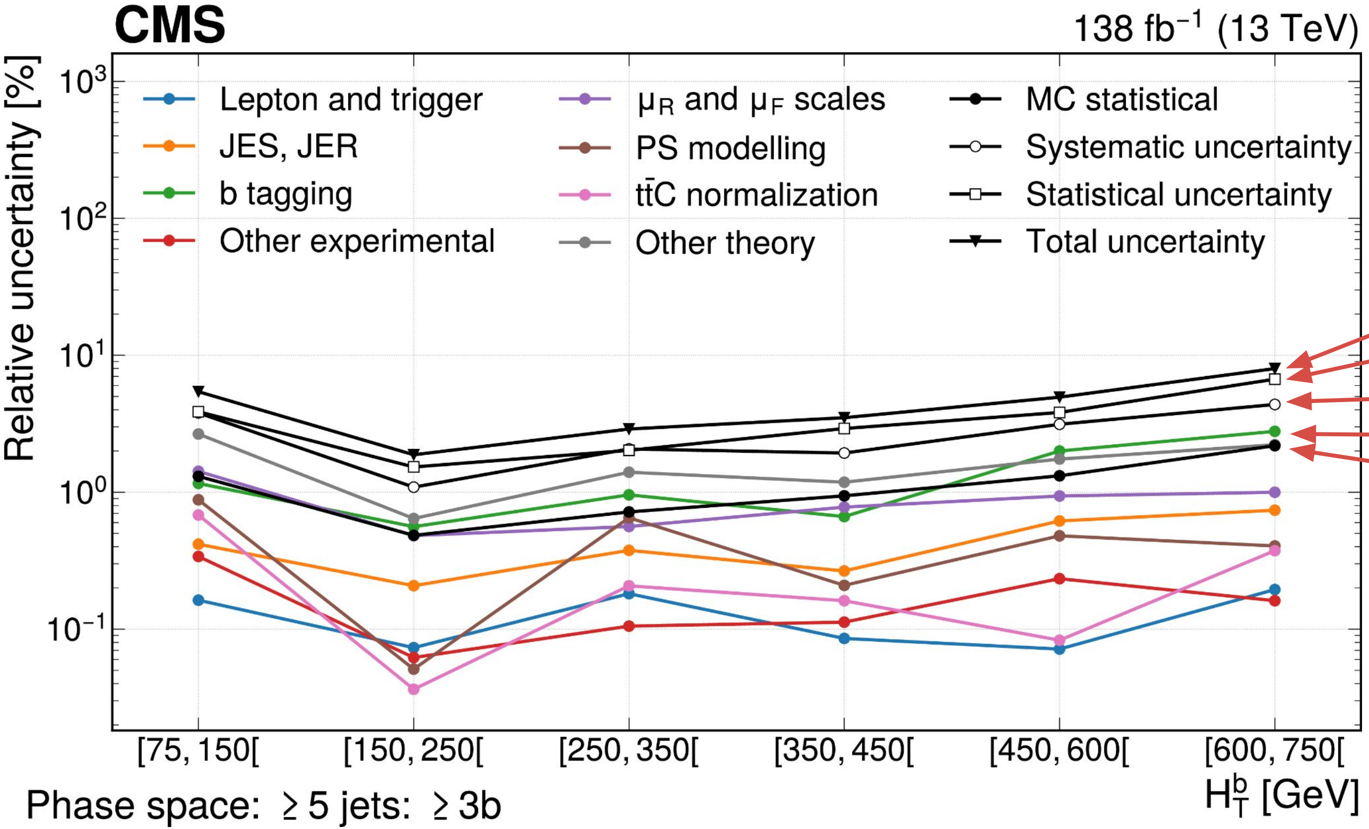
Differential measurement: H_T of jets

- QCD scale variations improve H_T description for **Powheg+Pythia $t\bar{t}b\bar{b}$ 4FS** simulation
  - Increased scales favorable!

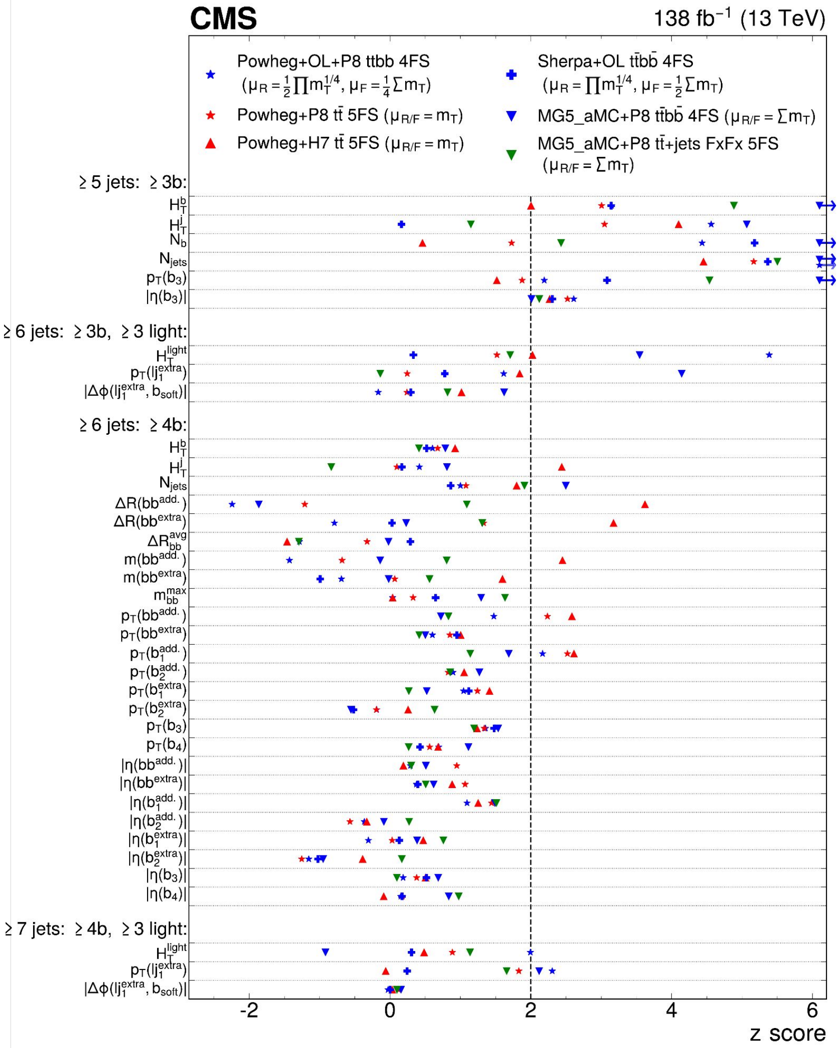


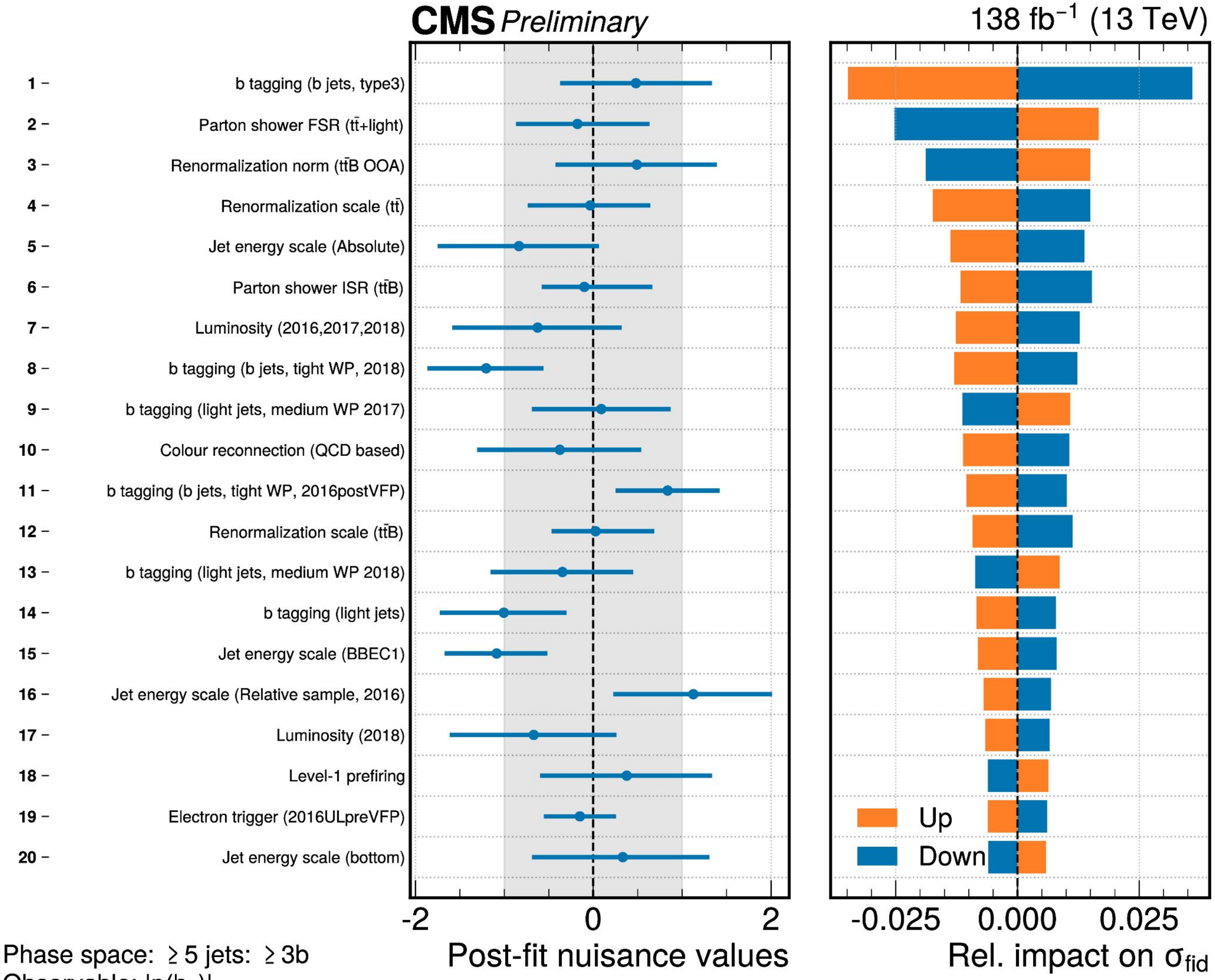
Results and limitations

- **Limitations of normalized differential cross sections:**
  - mostly statistically limited due to cancellation of systematics in normalized diff. XSs



Total uncertainty
Data statistics
Systematic uncertainties
b tagging
MC statistics


CMS
138 fb^{-1} (13 TeV)
Powheg+OL+P8 ttbb 4FS ($\mu_R = \frac{1}{2}\prod m_T^{1/4}$, $\mu_F = \frac{1}{4}\sum m_T$)
Powheg+P8 $t\bar{t}$ 5FS ($\mu_{R/F} = m_T$)
Powheg+H7 $t\bar{t}$ 5FS ($\mu_{R/F} = m_T$)
Sherpa+OL $t\bar{t}b\bar{b}$ 4FS ($\mu_R = \prod m_T^{1/4}$, $\mu_F = \frac{1}{2}\sum m_T$)
MG5_aMC+P8 $t\bar{t}b\bar{b}$ 4FS ($\mu_{R/F} = \sum m_T$)
MG5_aMC+P8 $t\bar{t}$+jets FxFx 5FS ($\mu_{R/F} = \sum m_T$)
≥ 5 jets: ≥ 3b:
H_T^b
H_T^j
N_b
N_{jets}
$p_T(b_3)$
$|\eta(b_3)|$
≥ 6 jets: ≥ 3b, ≥ 3 light:
H_T^{light}
$p_T(lj_1^{extra})$
$|\Delta\phi(lj_1^{extra}, b_{soft})|$
≥ 6 jets: ≥ 4b:
H_T^b
H_T^j
N_{jets}
$\Delta R(bb^{add.})$
$\Delta R(bb^{extra})$
ΔR_{bb}^{avg}
$m(bb^{add.})$
$m(bb^{extra})$
m_{bb}^{max}
$p_T(bb^{add.})$
$p_T(bb^{extra})$
$p_T(b_1^{add.})$
$p_T(b_2^{add.})$
$p_T(b_1^{extra})$
$p_T(b_2^{extra})$
$p_T(b_3)$
$p_T(b_4)$
$|\eta(bb^{add.})|$
$|\eta(bb^{extra})|$
$|\eta(b_1^{add.})|$
$|\eta(b_2^{add.})|$
$|\eta(b_1^{extra})|$
$|\eta(b_2^{extra})|$
$|\eta(b_3)|$
$|\eta(b_4)|$
≥ 7 jets: ≥ 4b, ≥ 3 light:
H_T^{light}
$p_T(lj_1^{extra})$
$|\Delta\phi(lj_1^{extra}, b_{soft})|$
-2
0
2
4
6
z score

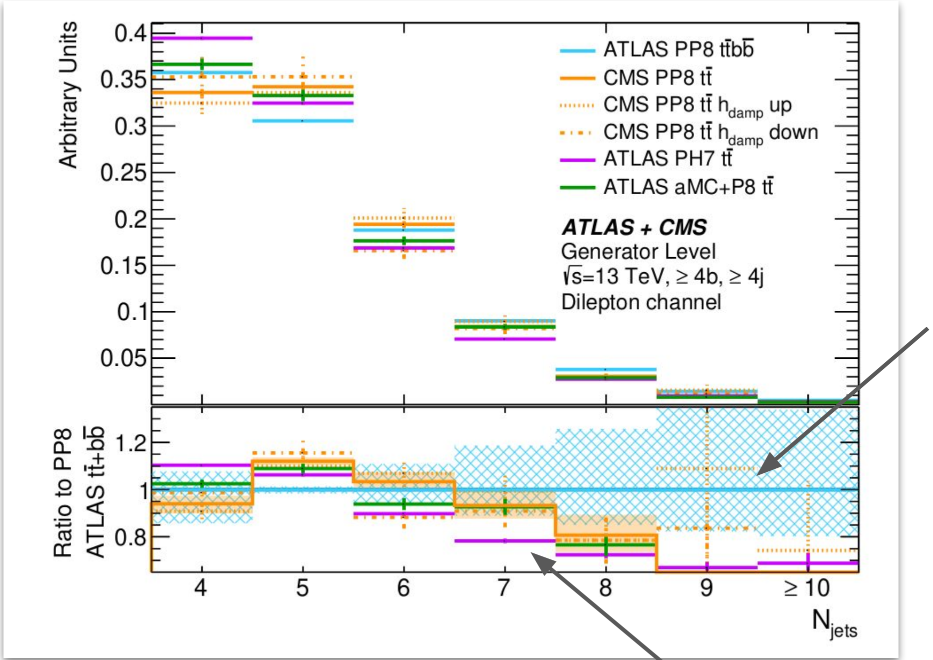


Phase space: ≥ 5 jets: ≥ 3b
Observable: $|\eta(b_3)|$

CMS+ATLAS comparisons

Modeling comparisons ATLAS+CMS

❑ Comparison of uncertainties for $t\bar{t}$@ME models

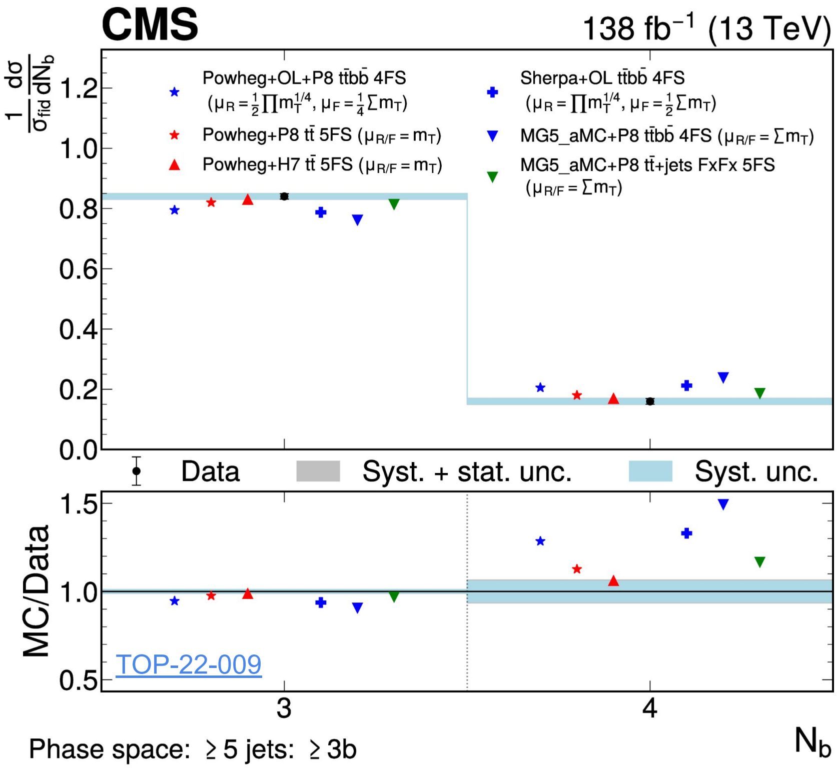


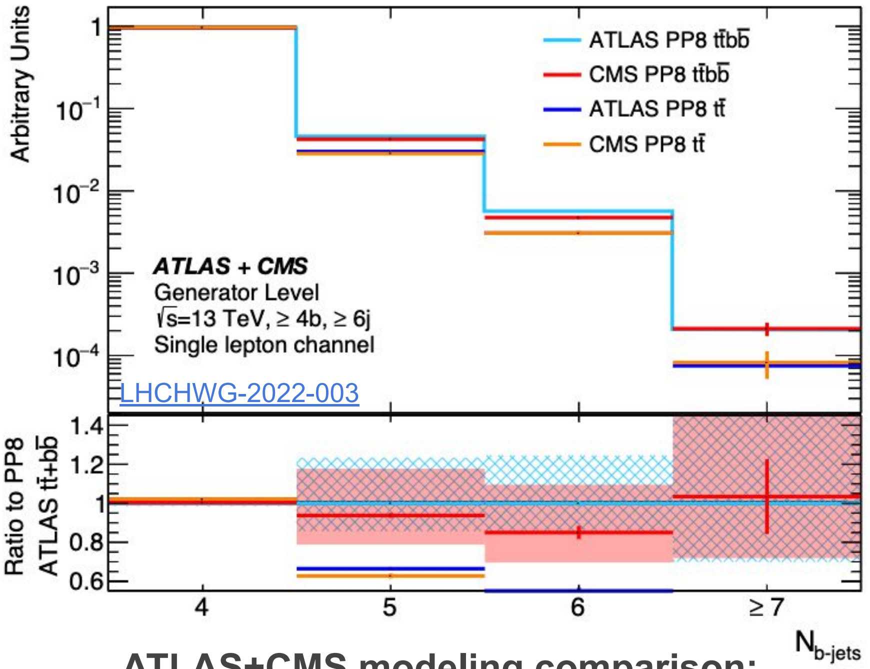
h_{damp} variations small and fluctuating due to limited sample statistics

Herwig / amC variations more significant

Differential measurement: b jet multiplicity

- **ATLAS+CMS:** b jet multiplicity not well modelled



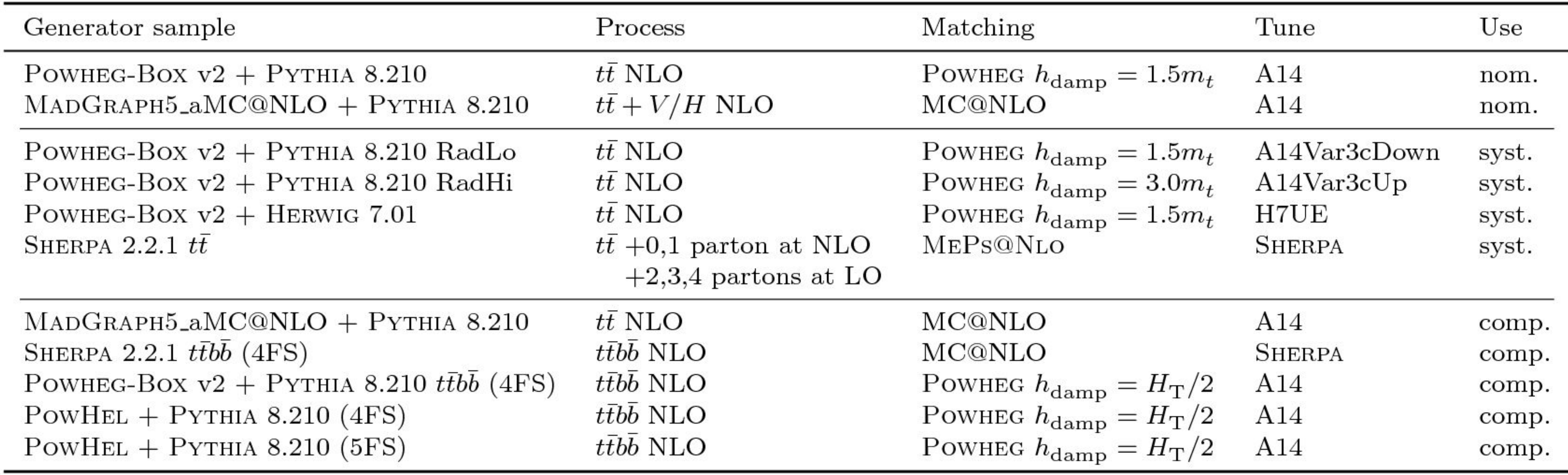


ATLAS+CMS modeling comparison:
$t\bar{t}$ and $t\bar{t}b\bar{b}$ predictions different

$t\bar{t}$-inclusive simulations do better than $t\bar{t}b\bar{b}$ simulations

ATLAS $t\bar{t}b\bar{b}$ measurement

ATLAS generator set$\bar{t}$ings in $t\bar{t}b\bar{b}$ measurement

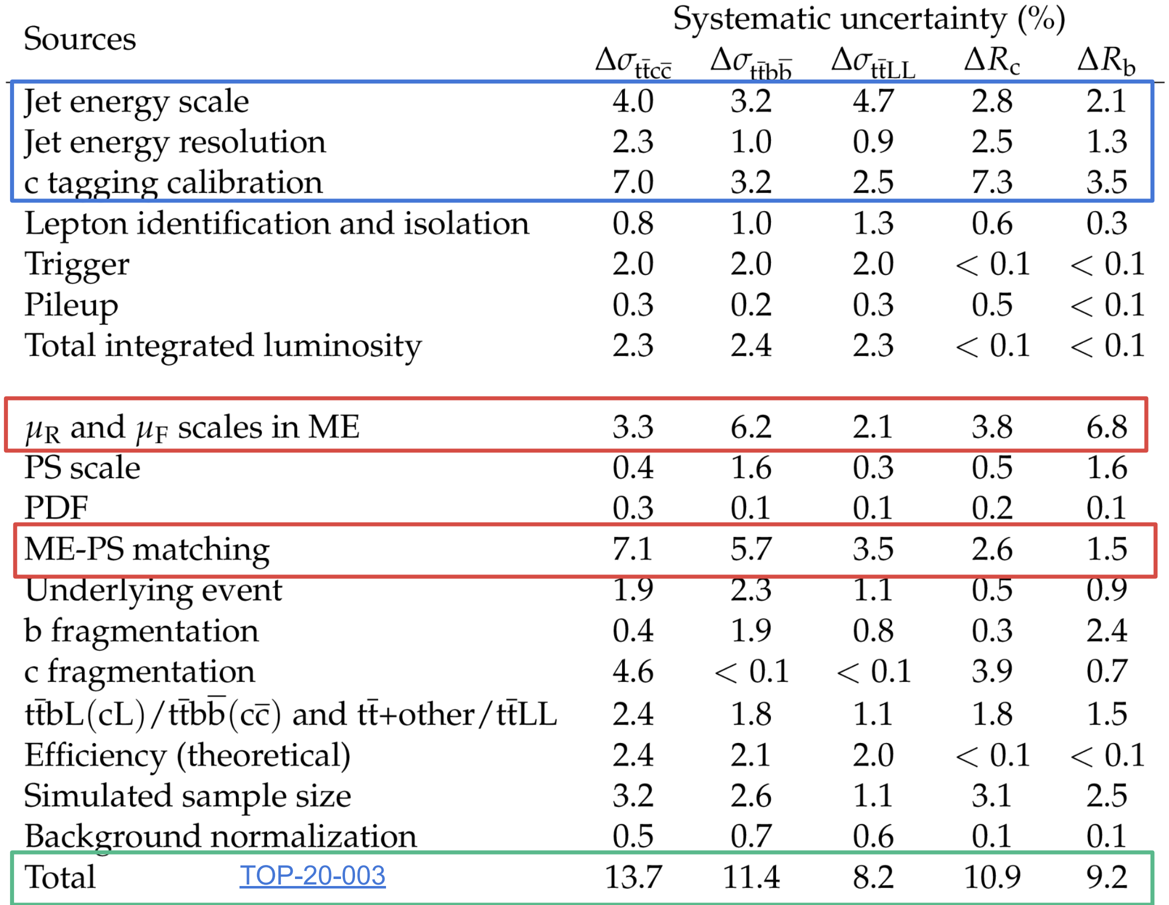


Generator sample	Process	Matching	Tune	Use
Powheg-Box v2 + Pythia 8.210	$t\bar{t}$ NLO	Powheg $h_{\text{damp}} = 1.5m_t$	A14	nom.
MadGraph5_aMC@NLO + Pythia 8.210	$t\bar{t} + V/H$ NLO	MC@NLO	A14	nom.
Powheg-Box v2 + Pythia 8.210 RadLo	$t\bar{t}$ NLO	Powheg $h_{\text{damp}} = 1.5m_t$	A14Var3cDown	syst.
Powheg-Box v2 + Pythia 8.210 RadHi	$t\bar{t}$ NLO	Powheg $h_{\text{damp}} = 3.0m_t$	A14Var3cUp	syst.
Powheg-Box v2 + Herwig 7.01	$t\bar{t}$ NLO	Powheg $h_{\text{damp}} = 1.5m_t$	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.
Powheg-Box v2 + Pythia 8.210 $t\bar{t}b\bar{b}$ (4FS)	$t\bar{t}b\bar{b}$ NLO	Powheg $h_{\text{damp}} = H_{\text{T}}/2$	A14	comp.
PowHel + Pythia 8.210 (4FS)	$t\bar{t}b\bar{b}$ NLO	Powheg $h_{\text{damp}} = H_{\text{T}}/2$	A14	comp.
PowHel + Pythia 8.210 (5FS)	$t\bar{t}b\bar{b}$ NLO	Powheg $h_{\text{damp}} = H_{\text{T}}/2$	A14	comp.

CMS $t\bar{t}c\bar{c}$ measurement

First measurement of $t\bar{t}c\bar{c}$ production by CMS

- 11.4% precision for $t\bar{t}b\bar{b}$ / 13.7% precision for $t\bar{t}c\bar{c}$



Sources	Systematic uncertainty (%)				
	$\Delta\sigma_{t\bar{t}c\bar{c}}$	$\Delta\sigma_{t\bar{t}b\bar{b}}$	$\Delta\sigma_{t\bar{t}LL}$	ΔR_c	ΔR_b
Jet energy scale	4.0	3.2	4.7	2.8	2.1
Jet energy resolution	2.3	1.0	0.9	2.5	1.3
c tagging calibration	7.0	3.2	2.5	7.3	3.5
Lepton identification and isolation	0.8	1.0	1.3	0.6	0.3
Trigger	2.0	2.0	2.0	< 0.1	< 0.1
Pileup	0.3	0.2	0.3	0.5	< 0.1
Total integrated luminosity	2.3	2.4	2.3	< 0.1	< 0.1
μ_R and μ_F scales in ME	3.3	6.2	2.1	3.8	6.8
PS scale	0.4	1.6	0.3	0.5	1.6
PDF	0.3	0.1	0.1	0.2	0.1
ME-PS matching	7.1	5.7	3.5	2.6	1.5
Underlying event	1.9	2.3	1.1	0.5	0.9
b fragmentation	0.4	1.9	0.8	0.3	2.4
c fragmentation	4.6	< 0.1	< 0.1	3.9	0.7
$t\bar{t}bL(cL)/t\bar{t}b\bar{b}(c\bar{c})$ and $t\bar{t}$+other/$t\bar{t}LL$	2.4	1.8	1.1	1.8	1.5
Efficiency (theoretical)	2.4	2.1	2.0	< 0.1	< 0.1
Simulated sample size	3.2	2.6	1.1	3.1	2.5
Background normalization	0.5	0.7	0.6	0.1	0.1
Total TOP-20-003	13.7	11.4	8.2	10.9	9.2

Experimental limitations from jet energy calibration / c tagging calibration

Theory limitations from QCD scales and ME-PS matching