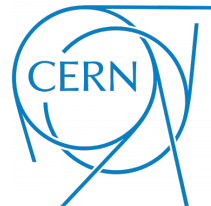


Toponium at the LHC

a new frontier in top-quark physics

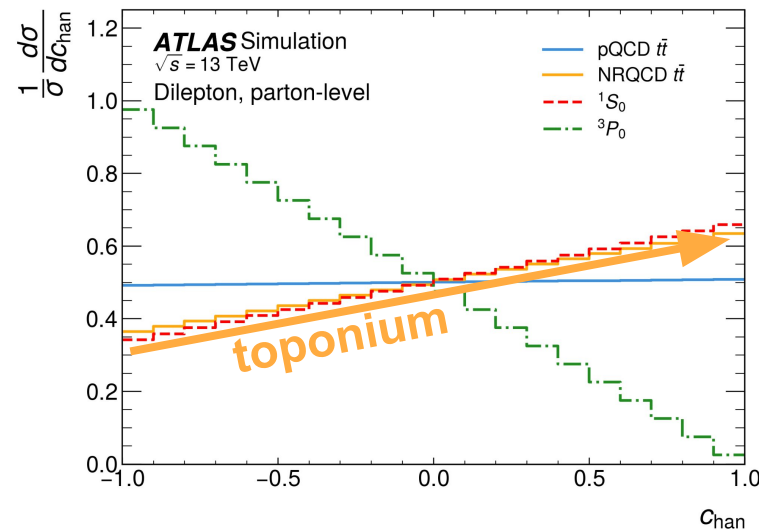
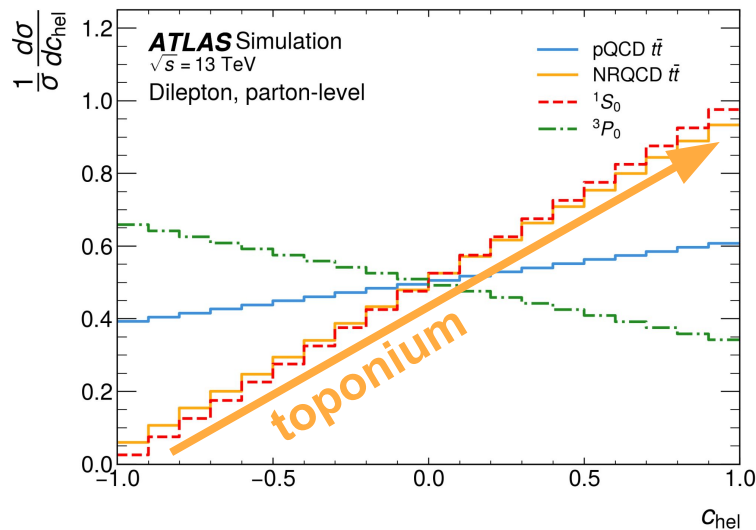
LPNHE Seminar, 24/11/2025

Baptiste Ravina (CERN)



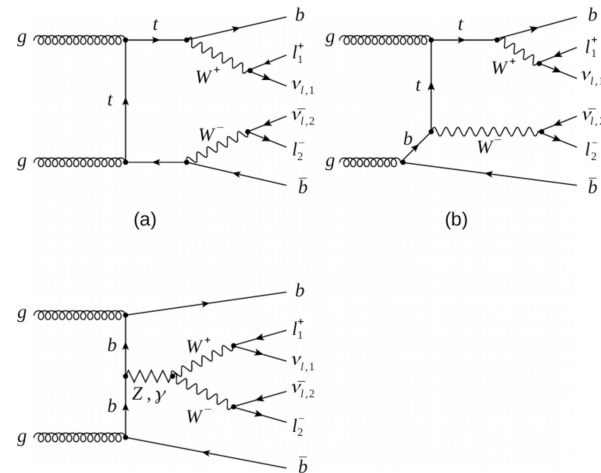
- All the relevant concepts have been introduced Benjamin's talk
 - the LHC is a top quark factory → Run 2 gives us access to **$O(100M)$ $t\bar{t}$ events**
 - the top quark decays fast enough that the full spin information can be reconstructed from the decay products → **access to spin polarisations and correlations**
 - charged leptons are ideal spin analysers → reconstruct the **spin density matrix**
 - **“toponium”** is the quasi-bound state(s), manifesting mostly as a **localised cross section enhancement near threshold ($m \sim 2m_t$) with pseudo-scalar behaviour**
- I will now **focus on the experimental measurements**
 - analysis strategy, signal and background models, treatment of uncertainties
 - **comparing the ATLAS and CMS approaches and their findings**
 - highlighting current limitations and directions for improvements
- Observing toponium before an e^+e^- collider would be an unexpected discovery of “new SM physics” [F. Maltoni] → ***LHC as a precision machine***

- Exploit the **di-leptonic final state**: very **pure $t\bar{t}$ selection**, clean measurement of **high-fidelity spin analysers**, but requires **difficult top reconstruction**
- Reconstruct the tops and **use spin-sensitive observables**
 - c_{hel} : angle between the leptons' directions of flight in their parent top quark's rest frame
→ *maximally sensitive to 1S_0* [this is same distribution we used for quantum entanglement, "D"]
 - c_{han} : same as c_{hel} , but with sign flip along the top direction → *maximally sensitive to 3P_0*



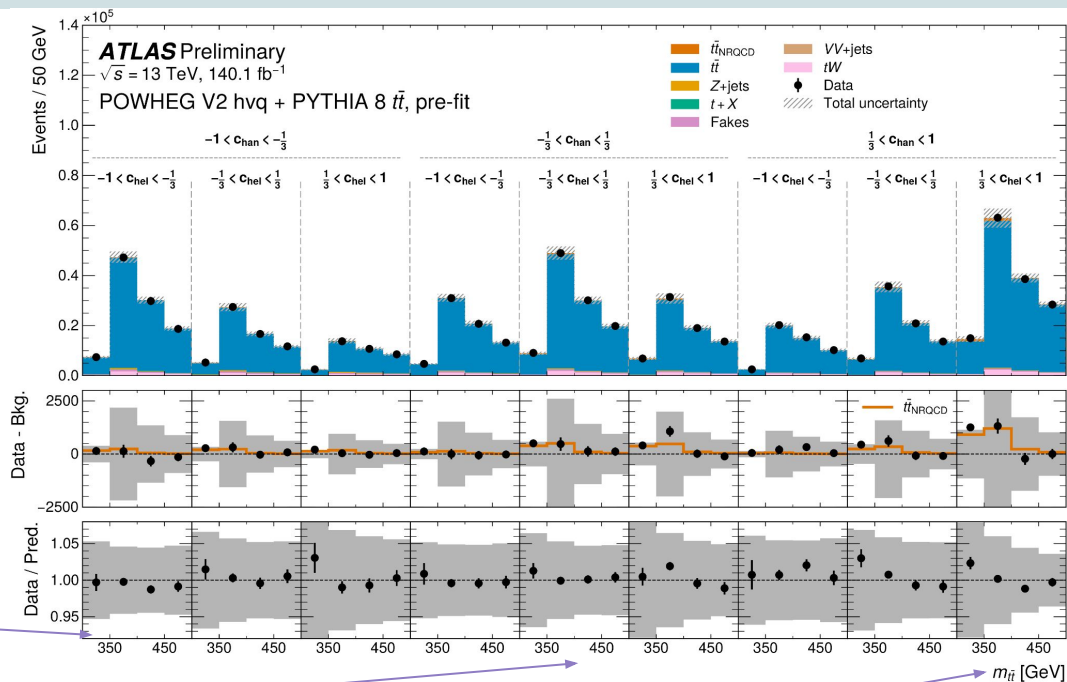
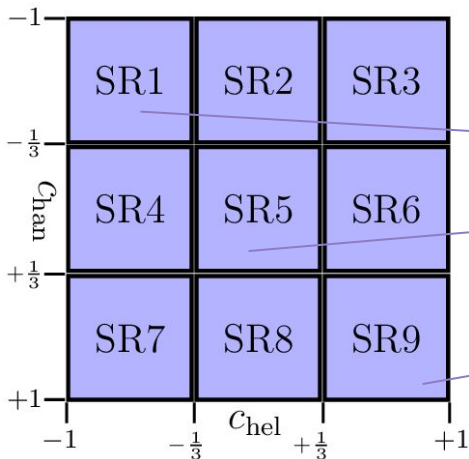
- Suppress reducible backgrounds, and use either **state-of-the-art MC modelling** or **data-driven techniques** for the remaining contributions
 - in ee/ $\mu\mu$ selections, can reject low- m_{ll} events and cut away the Z peak
 - Drell-Yan and fake lepton backgrounds can be obtained from data
 - **interference of tW and tt at NLO QCD** treated with **Diagram Removal (DR)** or **Diagram Subtraction (DS)** approaches, or with **dedicated 2→6 simulation (bb4l)**
- Perform a **profile-likelihood fit at detector-level**
 - using the **3 sensitive observables** $m_{t\bar{t}}$, c_{hel} , and c_{han}

SRs	CR-Z	CR-Fakes
$= 2\ell$ with $p_T(\ell) \geq 10$ GeV ≥ 1 trigger-matched lepton with $p_T \geq 25/27/28$ GeV ≥ 2 jets with $p_T \geq 25$ GeV ≥ 1 b -tagged jet (70% efficiency WP) $m_{\ell\ell} \geq 15$ GeV $m_{t\bar{t}} \leq 500$ GeV		
$E_T^{\text{miss}} \geq 60$ GeV for OSSF events	—	
$\ell^\pm \ell'^\mp$	$e^\pm e^\mp / \mu^\pm \mu^\mp$	$\ell^\pm \ell'^\pm$
$ m_{\ell\ell} - m_Z \geq 10$ GeV	$ m_{\ell\ell} - m_Z \leq 10$ GeV	$ m_{\ell\ell} - m_Z \geq 10$ GeV



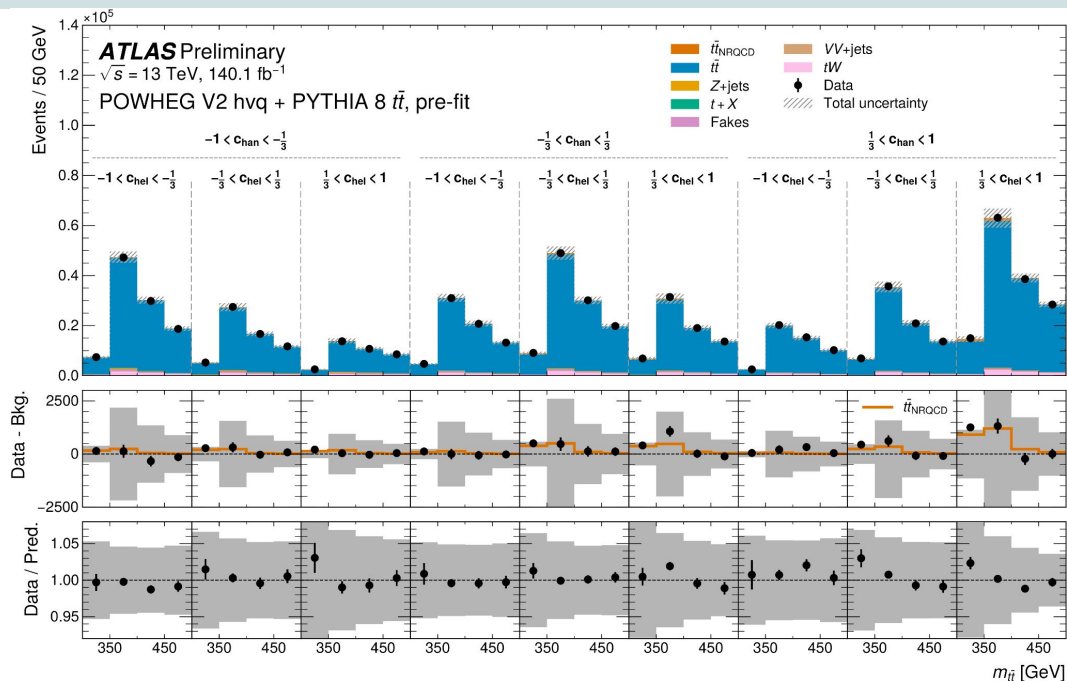
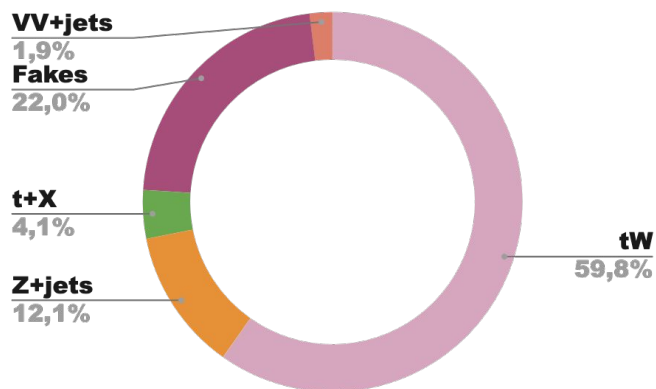
Doubly-, singly-, and non-resonant $bbl\nu\nu$ final states

- Split the event selection according to the reconstructed values of c_{hel} and c_{han}
 - 9 SRs with different S/B ratios
 - idea from the original [CMS BSM A/H \$\rightarrow\$ \$t\bar{t}\$ search](#): enhance sensitivity to A and H bosons in different bins



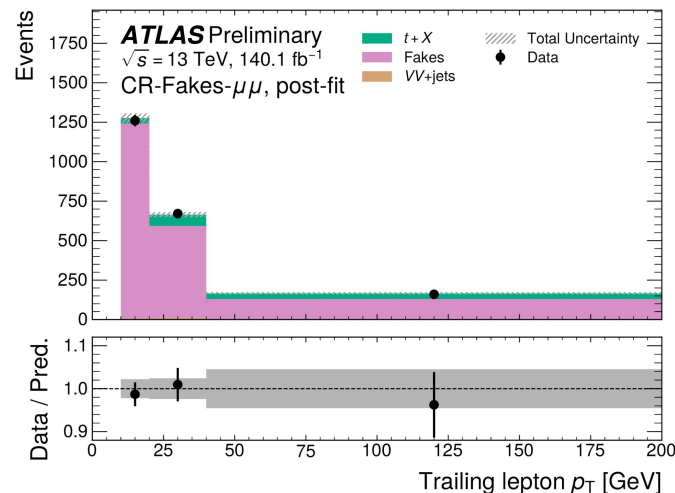
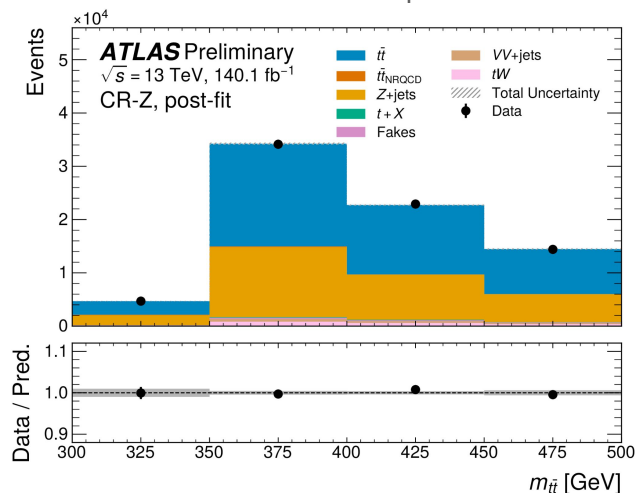
Background estimation

- Expect **~700k $t\bar{t}$ events** and **~40k additional background events**
 - *for only about ~7k signal events!*
- tW is mostly irreducible, taken from MC with detailed set of systematic uncertainties
- $t+X$ and diboson are negligible



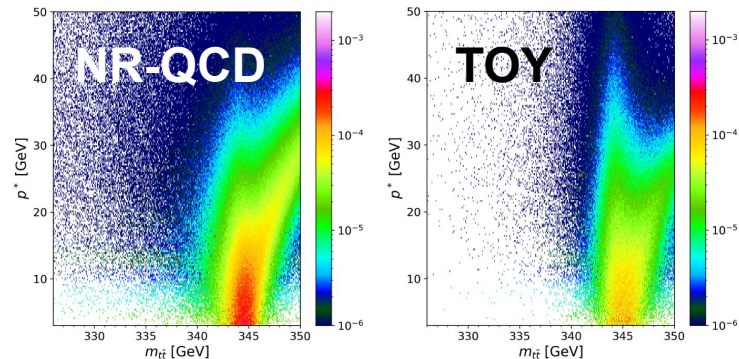
- **CMS:** model contribution of fake leptons directly from MC, **use data to normalise $Z+jets$ events**
- **ATLAS:** **normalise both fake and $Z+HF$ to data**, but closer to the SR kinematic space

- Define a **CR-Z** equivalent to the SR, but **inverting the Z-mass cut**
 - extract the normalisation of Z+b-jets (1 NF), the leading component in the SR
 - still a large contribution of pQCD $t\bar{t}$ in the CR-Z, but no toponium due to high m_{ll} requirement!
- Define **CR-Fakes-ee/ $\mu\mu$ / $e\mu$** equivalent to the SR, but **with same-sign leptons**
 - extract the normalisation of electron and muon fakes from HF decays, and electron fakes from photon conversions (3 NFs)
 - sub-leading lepton p_T provides good enough separation power between types of fakes



- Slightly different techniques are used, but both make similar assumptions to constrain the neutrino kinematics [on-shell top quarks and W bosons, and $p_T(vv)=p_T(\text{miss})$]
- **CMS:**
 - identify the b-quark and anti-b-quark from b-jets in the event and a maximum-likelihood fit to simulated templates of m_{lb} [use a light-jet for events with only one b-tagged jet]
 - solve a set of analytical equations under the above mass and MET assumptions
 - take the solution that yields lowest $m_{t\bar{t}}$ value (unbiased)
 - repeat the solving process over 100 random smearings of the detector-level momenta
 - final solution is a weighted average of all valid solutions within this set
 - resolution of 15% at low $m_{t\bar{t}}$, increasing up to 25% at high $m_{t\bar{t}}$
- **ATLAS:**
 - pick the two highest- p_T b-tagged jets [use a light-jet for events with only one b-tagged jet]
 - for each pairing of b-jet and lepton, solve a similar set of analytical equations
 - repeat the solving process over 100 random smearings of the top and W mass constraints
 - take the solution that yields lowest $m_{t\bar{t}}$ value (unbiased)
 - resolution of 22% at low $m_{t\bar{t}}$, decreasing to about 18% at 500 GeV

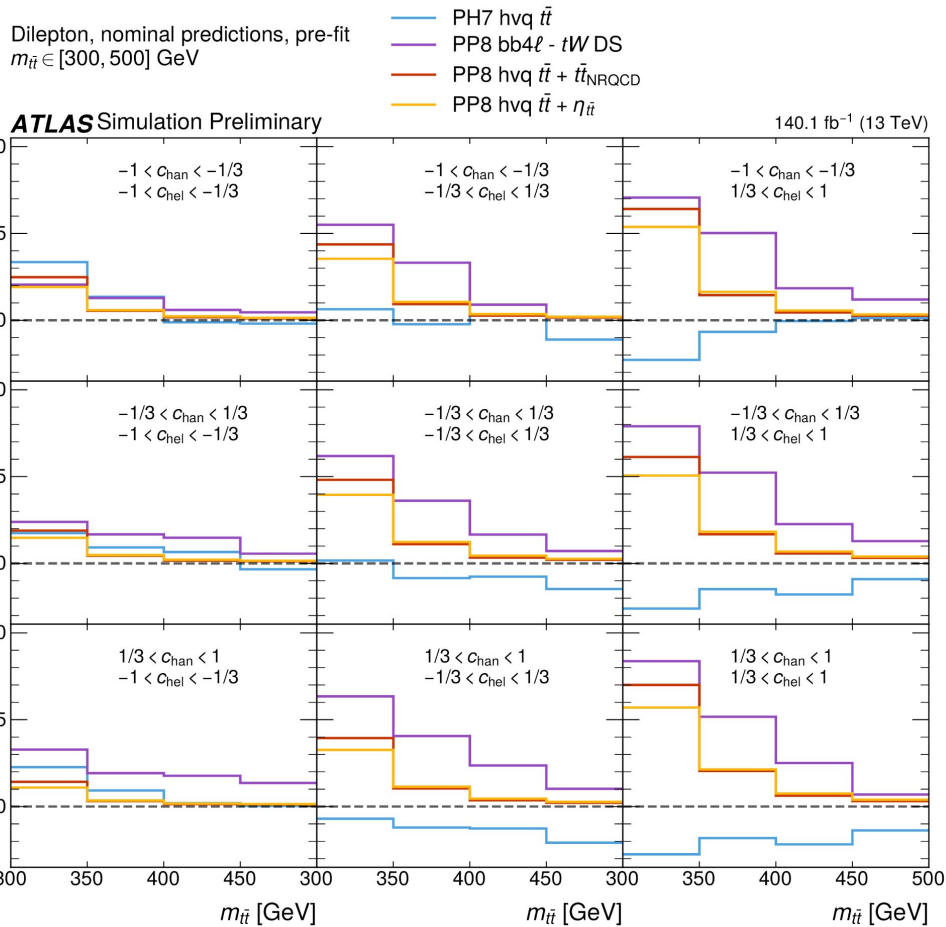
- **ATLAS setup** according to B. Fuks et al. in [Eur. Phys. J. C 85 \(2025\) 157](#)
 - **directly inspired by NR-QCD**: Green's function reweighting + PS matching
 - apply 2D mass/momentum cut to retain validity of NR-QCD calculations
 - claims to accurately represent the LO S-wave colour-singlet contributions
 - MC cross section: 5.60 pb $\rightarrow$ scaled to theory estimate of 6.43 pb, which includes also P-waves and colour-octet contributions
- **CMS setup** according to F. Maltoni et al. in [JHEP 03 \(2024\) 099](#)
 - generate $gg \rightarrow \eta \rightarrow WbWb$ in MG at LO, use $M(\eta)=343$ GeV, $\Gamma(\eta)=2.8$ GeV + tune the couplings to reproduce 1-dimensional NR-QCD results in $m_{t\bar{t}}$
 - **no Green's function reweighting, no mass cuts** $\rightarrow$ differences in top kinematics
 - this model is also tested by ATLAS



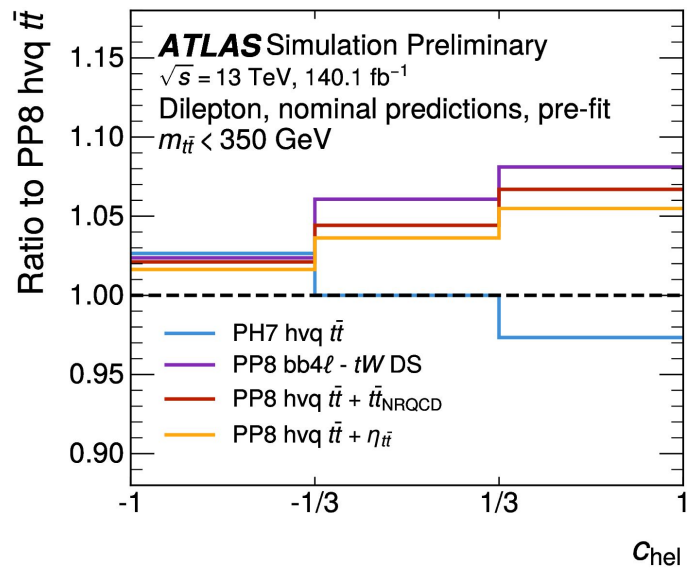
- **Powheg+Pythia8 hvq $t\bar{t}$** (NLO production, LO decay): **nominal setup**
 - well-understood by both ATLAS and CMS, entire set of systematics built around it, standard $t\bar{t}$ sample for Run 2 analyses
 - needs dedicated NNLO QCD and NLO EW reweighting
- **Powheg+Pythia8 bb4l** (NLO $2 \rightarrow 6$ production): **alternative setup**
 - decay is NLO-accurate and off-shell effects are accounted for properly
 - **open questions:** dedicated tuning? different Powheg settings from hvq? **how to reweight to NNLO?** how to normalise inclusively? [[DPA NNLO calculation](#) only very recently became available!]
- **MadGraph5_aMC@NLO FxFx** (NLO+1, 2j production, LO decay): **CMS only**
 - better description of events with higher jet multiplicities
- Kinematic **reweighting to higher order predictions**
 - NNLO QCD with MATRIX, NLO EW with HATHOR
 - 2D reweighting in $(\cos\theta^*, m_{t\bar{t}})$ with associated uncertainties
 - extensive validation $\rightarrow$ can reproduce fixed-order predictions, as well as MiNNLOps

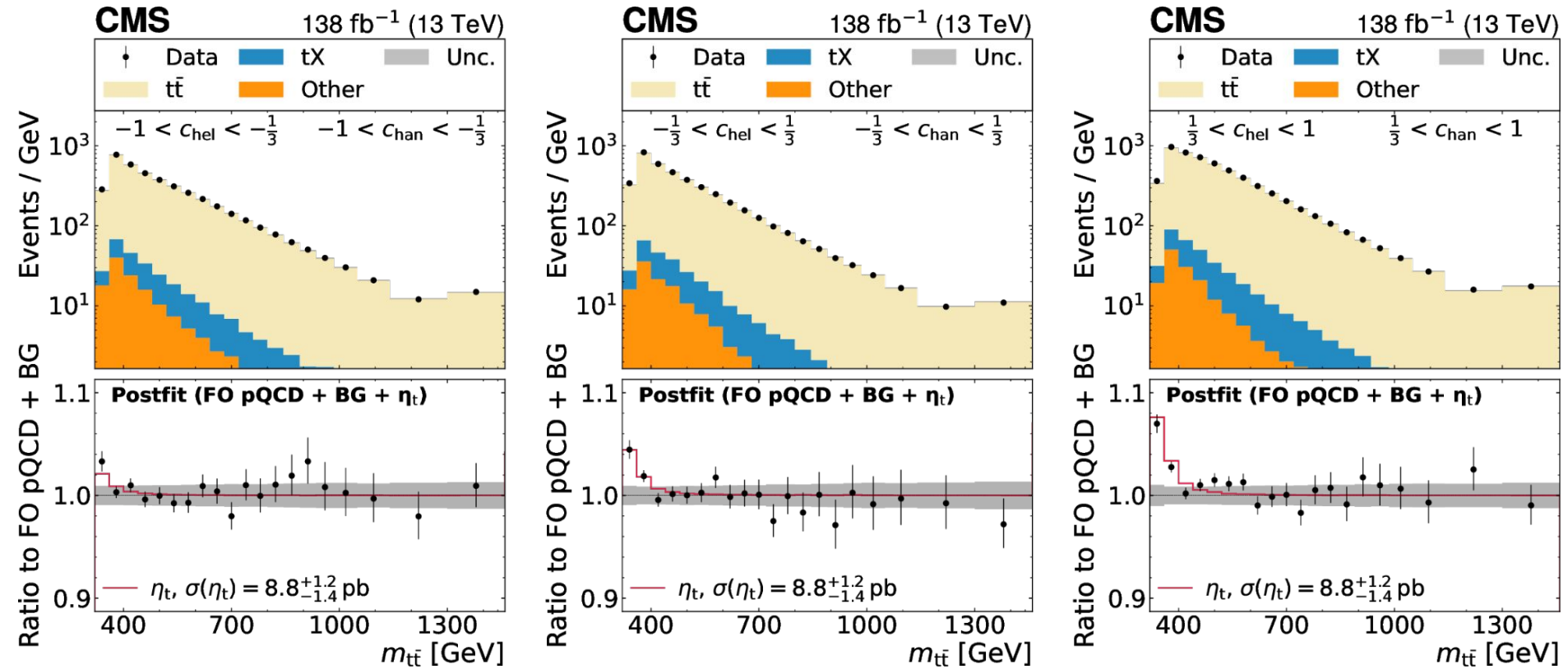
- Perform a **binned detector-level profile-likelihood fit** in the 9 SRs
 - ATLAS also includes the CR-Z and 3 CR-Fakes directly in the likelihood, CMS propagates the normalisation factors for Z+jets from an auxiliary measurement
 - **20 bins of $m_{t\bar{t}}$ per SR for CMS, only 4 bins per SR for ATLAS**
- **Different assumptions can be tested**
 - background-only fit
 - **ATLAS:** check the two different toponium signal models, check also bb4l instead of $t\bar{t}+tW$
 - **CMS:** check pseudo-scalar only vs pseudo-scalar + scalar, check also alternative generators
- **Strong constraints of some $t\bar{t}$ modelling uncertainties are observed – and indeed expected from previous measurements**
 - due to different descriptions of both the $m_{t\bar{t}}$ distribution and spin-sensitive observables in different MC generators [mostly Herwig and bb4l]
 - ATLAS applies a “**partial decorrelation by region**” approach to these problematic uncertainties
 - split the nuisance parameter into 1 fully correlated part (retaining 50% of the effect) and N uncorrelated parts (another 50%) in each region [here $N=9+4=13$]
 - many other approaches were also tested, no effect on the central values, but constraints can be relaxed and goodness-of-fit (GoF) improved

Key differences in MC predictions

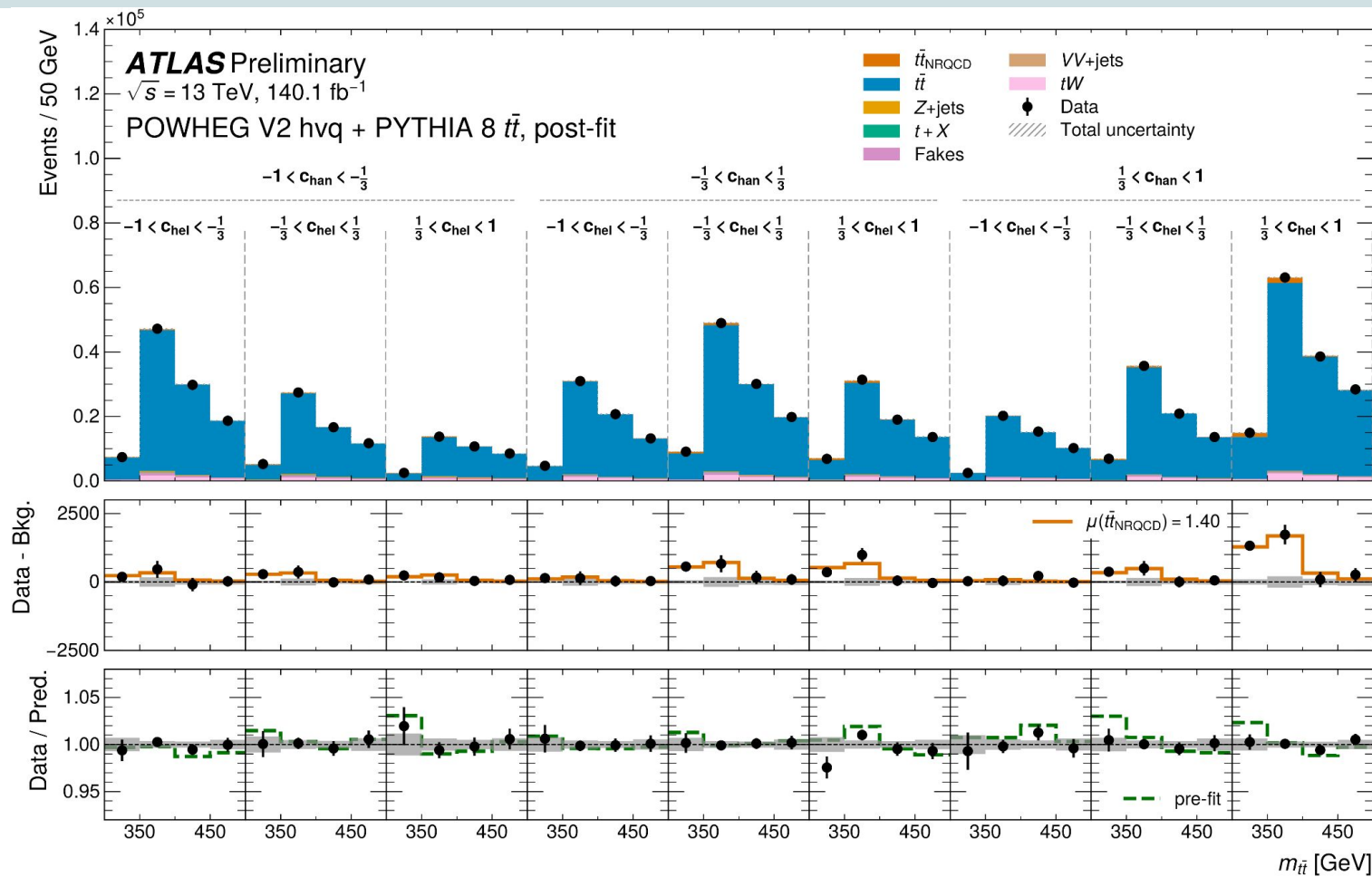


- Slight differences in **toponium** predictions for the first bin of $m_{\bar{t}t}$
- **Herwig** similarly observed to have lower acceptance and opposite slope in c_{hel}
- **bb4l** behaves even more “like toponium”
→ *due to the differences in higher-order reweighting*





Clear excess near threshold, behaving like pseudo-scalar toponium



- The predicted NRQCD toponium cross section is 6.4pb
- **ATLAS:** 7.7σ obs. (5.7σ exp.), with a GoF of 0.93 [7×10^{-5} for background-only hypothesis]
- **CMS:** $>5\sigma$ obs.
- **Measured cross sections are compatible with each other and with the NRQCD prediction**, although roughly $(40 \pm 20)\%$ larger
 - *Do recall that two different signal models are used!*
- Large impact of $t\bar{t}$ modelling systematics on both results



$$\sigma(t\bar{t}_{\text{NR-QCD}}) = 9.0 \pm 1.3 \text{ pb} = 9.0 \pm 1.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}$$



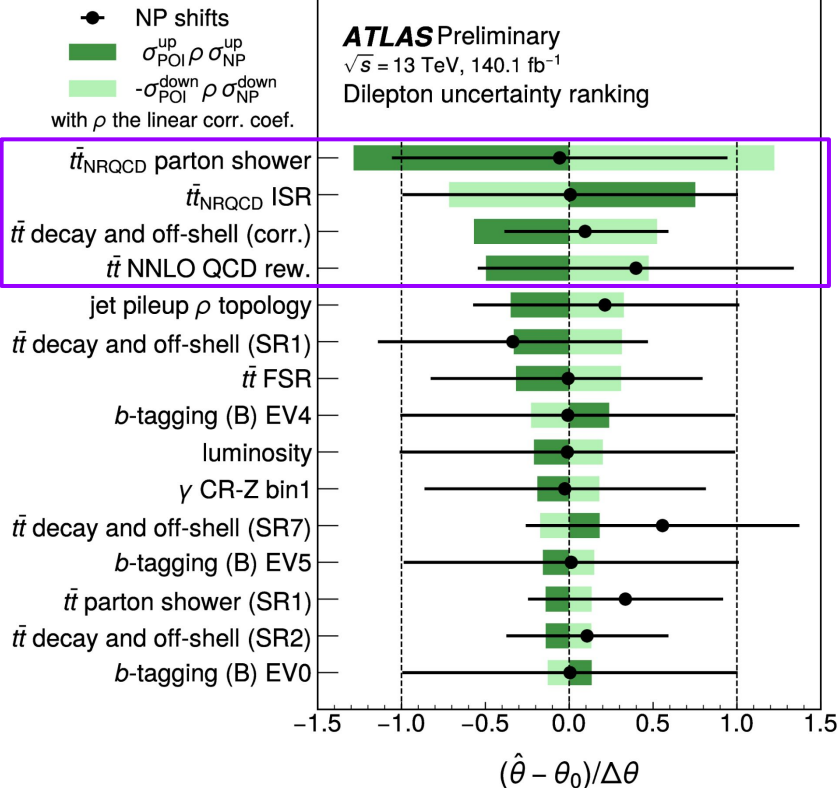
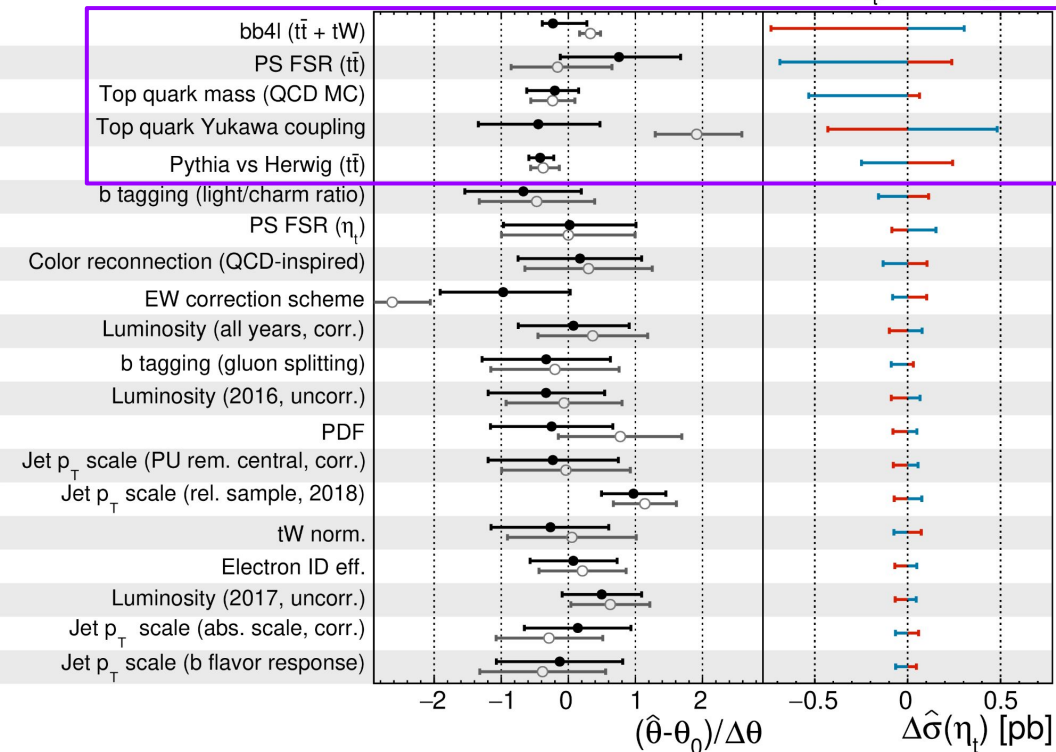
$$\sigma(\eta_t) = 8.8 \pm 0.5 \text{ (stat)}^{+1.1}_{-1.3} \text{ (syst) pb} = 8.8^{+1.2}_{-1.4} \text{ pb.}$$

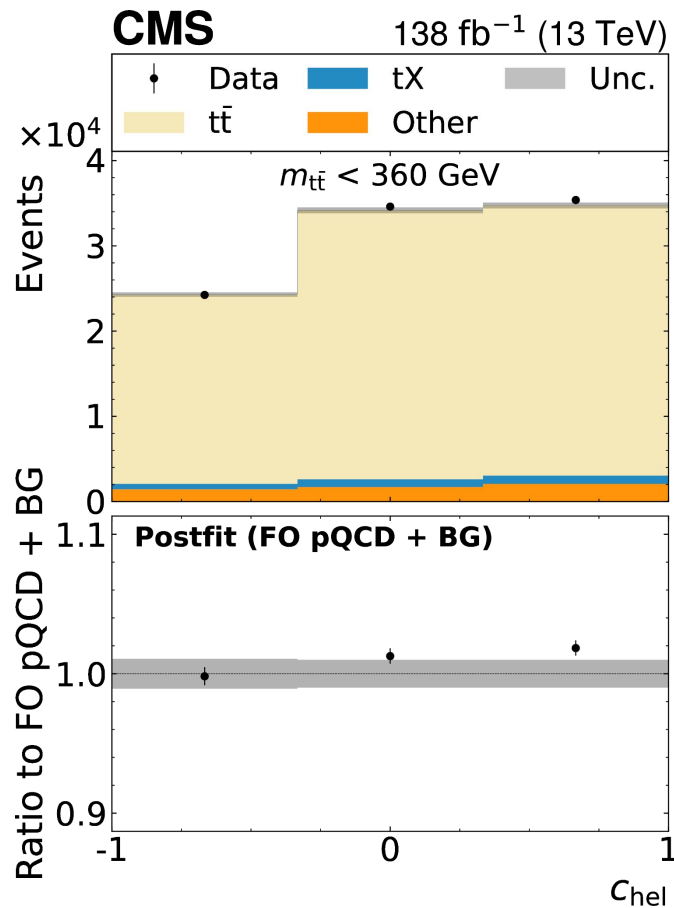
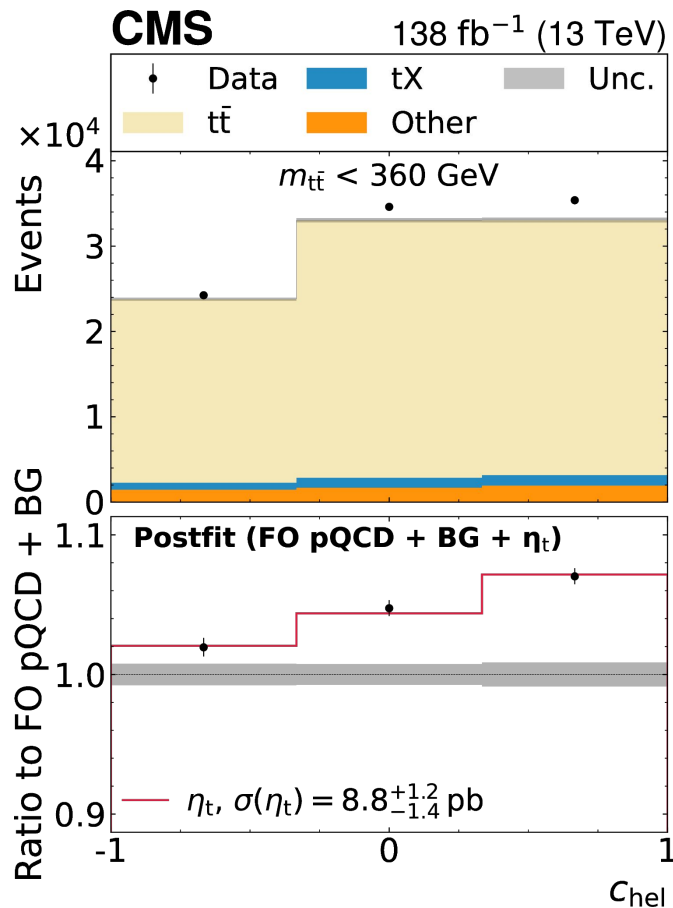
Impact of systematic uncertainties

CMS

- Fit constraint (FO pQCD + BG + η_t)
- Fit constraint (FO pQCD + BG only)
- +1 σ impact (FO pQCD + BG + η_t)
- 1 σ impact (FO pQCD + BG + η_t)

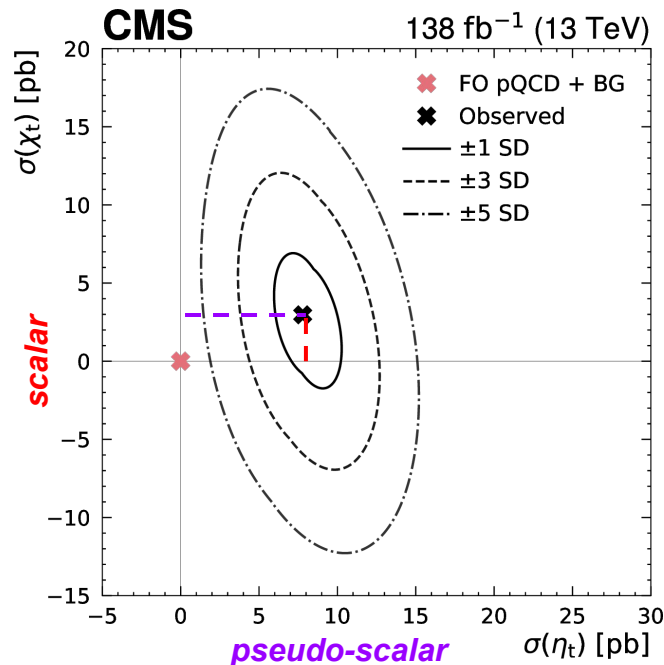
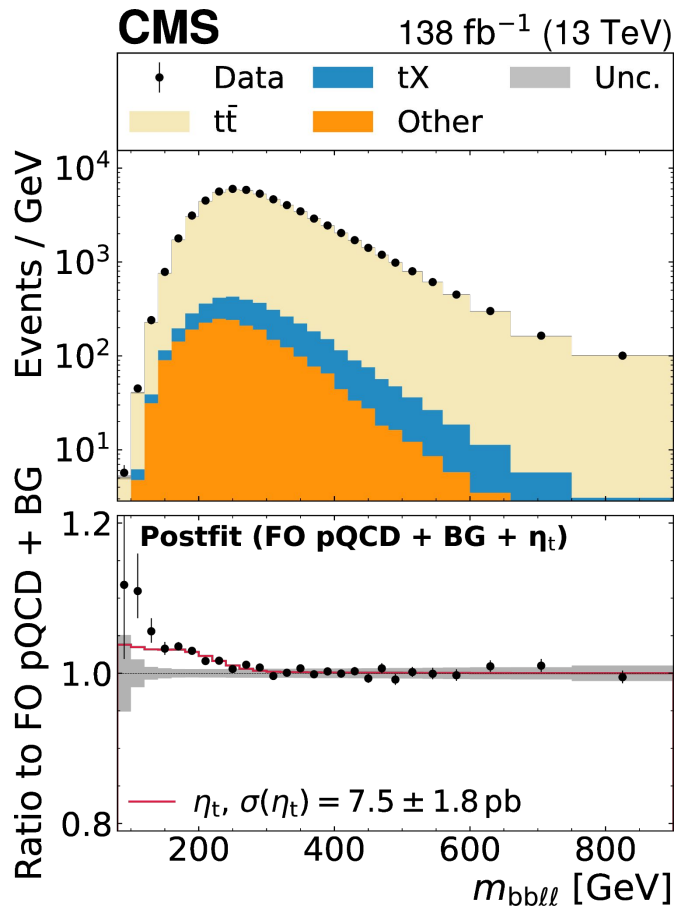
$$\hat{\sigma}(\eta_t) = 8.8^{+1.2}_{-1.4} \text{ pb}$$





- **Residual slope clearly visible** in the fit **without any toponium** template
- **Large unphysical pulls** of many uncertainties
- **Significantly degraded GoF** for ATLAS

$\Rightarrow$ toponium-like signal is needed to explain the data!



- Fit to m_{bbl} instead of m_{tt} is **less precise** but still returns **compatible cross section**
- Fit to both **scalar** and **pseudo-scalar** components **prefers the pseudo-scalar** hypothesis to $>5\sigma$

- Various combinations of toponium and pQCD $t\bar{t}$ models have been checked by **ATLAS** and **CMS**
- The extracted toponium cross sections (in pb) are reported below

Models	Powheg hvq + Pythia 8	Powheg hvq + Herwig 7	aMC@NLO FxFx + Pythia 8	Powheg bb4l + Pythia 8
NRQCD [Fuks et al.]	9.0 ± 1.3	—	—	4.2 ± 1.0
η_t [Maltoni et al.]	8.8 ± 1.3 13.4 ± 1.9	8.6 ± 1.1	9.8 ± 1.3	6.6 ± 1.4

- **All models point to an excess compatible with toponium formation**, with **two caveats**
 - ATLAS sees slightly different results between the two toponium models, likely due to the differences in top kinematics affecting the reconstruction $\rightarrow$ **$\sim 2\sigma$ tension with CMS if both use the same model**
 - **the results obtained with bb4l are weaker**: still need to study and validate this model [tuning?], but kinematic reweighting to higher-order already identified as a current limitation $\rightarrow$ *follow-up ATLAS paper to adopt new recommendations from theorists*

- **Extremely challenging measurement:** need precise models of the threshold region and toponium signal, understanding of NLO EW and NNLO QCD corrections to production, NLO and off-shell effects in decay, etc.
- Both ATLAS and CMS **observe a significant excess** seemingly compatible with **toponium formation**
 - **many checks have been performed:** different selection cuts, observables, signal and background models, splitting datasets by year and by lepton flavour, etc. → robust!
 - **future improvements** to come from better top reconstruction [$m_{t\bar{t}}$ resolution] and modelling, enabling also a possible observation in the lepton+jets channel
 - alternative fit results with **bb4l raise some important questions** that warrant further studies



$$\sigma(t\bar{t}_{\text{NR-QCD}}) = 9.0 \pm 1.3 \text{ pb} = 9.0 \pm 1.2 \text{ (stat.)} \pm 0.6 \text{ (syst.)}$$



$$\sigma(\eta_t) = 8.8 \pm 0.5 \text{ (stat)} {}^{+1.1}_{-1.3} \text{ (syst) pb} = 8.8 {}^{+1.2}_{-1.4} \text{ pb.}$$



Run: 338183

Event: 3295623881

2017-10-14 09:08:09 CEST

Toponium candidate event

$$m_{t\bar{t}} = 342 \text{ GeV}$$

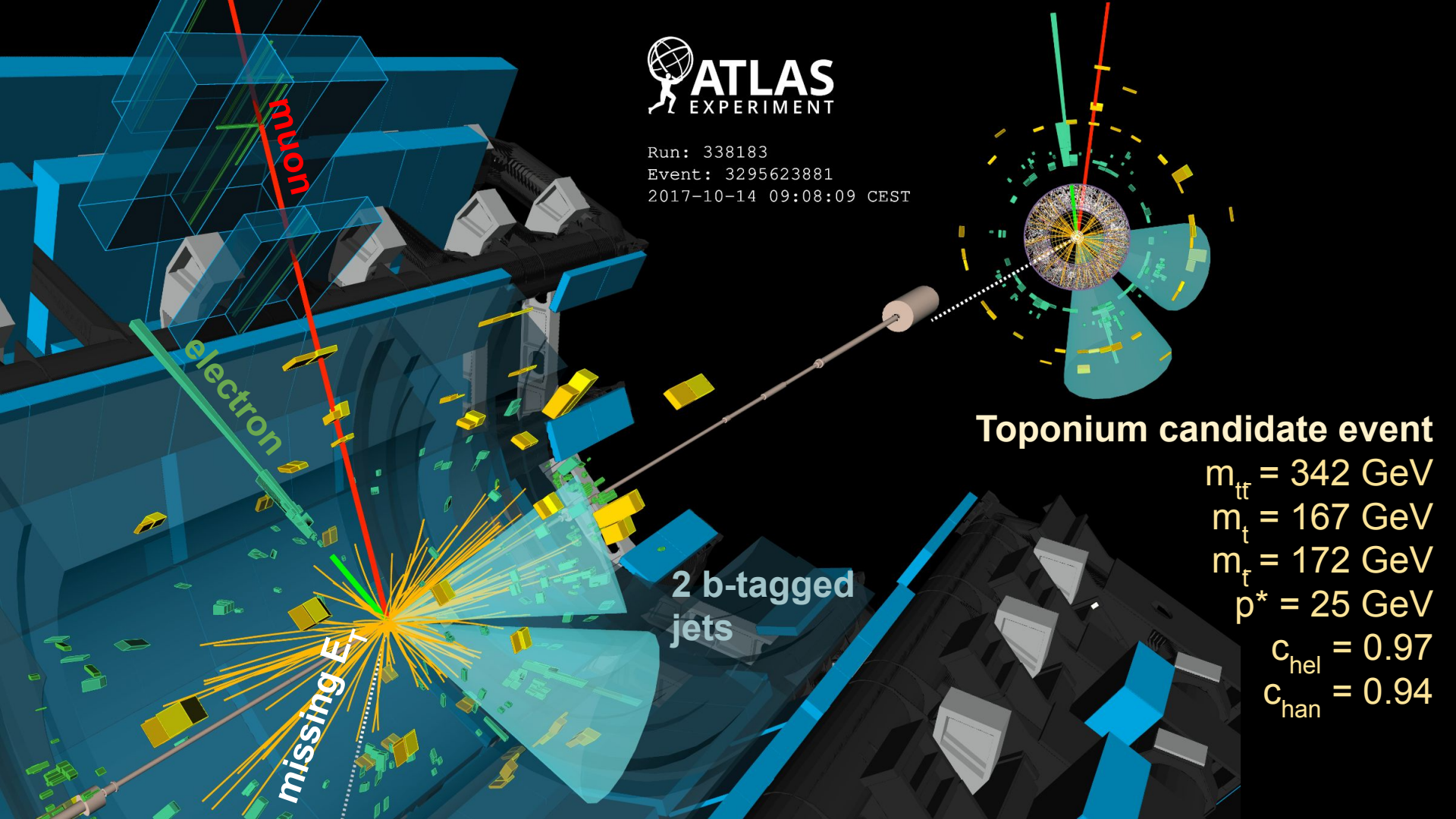
$$m_t = 167 \text{ GeV}$$

$$m_{\bar{t}} = 172 \text{ GeV}$$

$$p^* = 25 \text{ GeV}$$

$$C_{\text{hel}} = 0.97$$

$$C_{\text{han}} = 0.94$$



BACKUP

What is toponium?

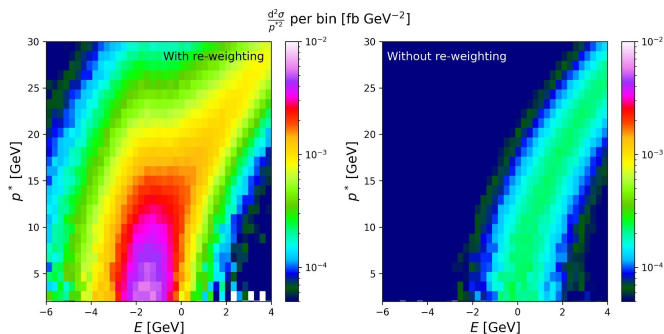
23

- Standard Model predicts a **quasi-bound** state below the $t\bar{t}$ threshold
 - “*toponia*” were not expected to be visible at the LHC!
 - Coulomb potential with gluon and soft-gluon emissions between the tops $\sim (\alpha_s/\beta)^n$
 - can be computed in potential non-relativistic QCD (**NR-QCD**) at next-to-leading power in β
- It behaves dominantly like a **pseudoscalar** [important for spin correlations!] but crucially is **NOT an s-channel resonance** [no destructive interference terms!]

Simulating toponium formation signals at the LHC

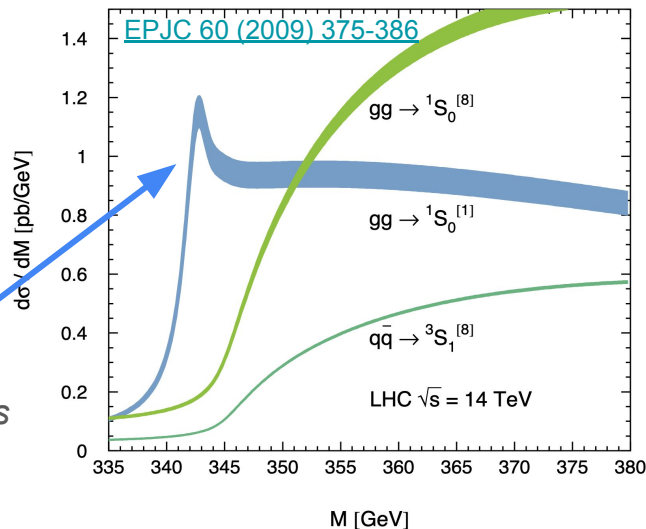
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Published: 07 February 2025
Volume 85, article number 157, (2025) [Cite this article](#)

Benjamin Fuks , Kaoru Hagiwara, Kai Ma & Ya-Juan Zheng

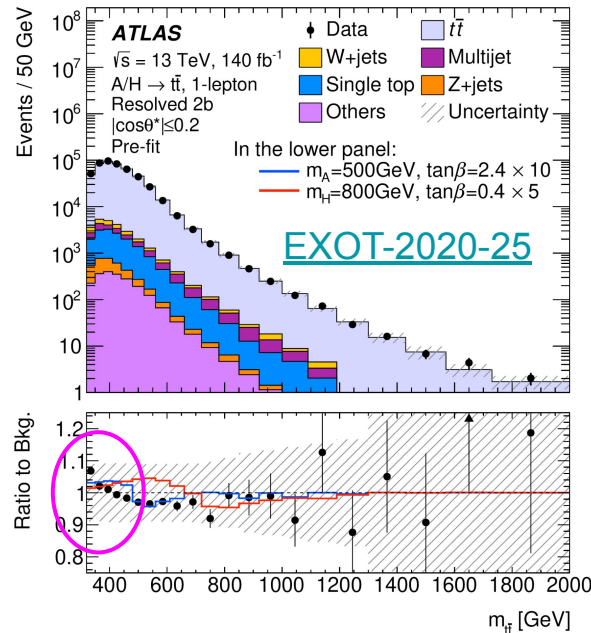
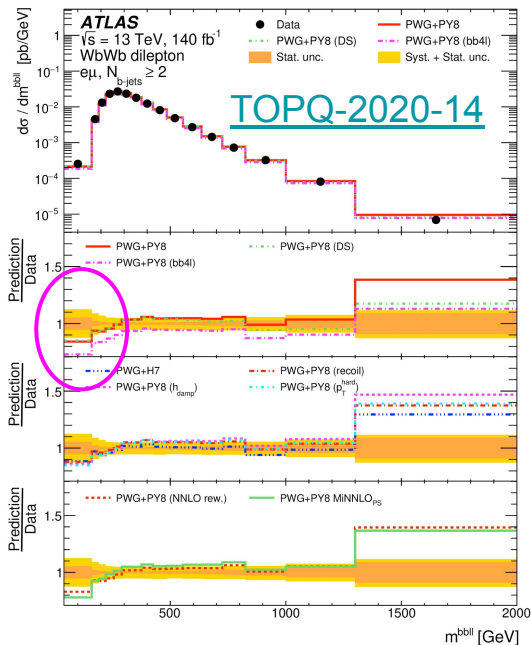
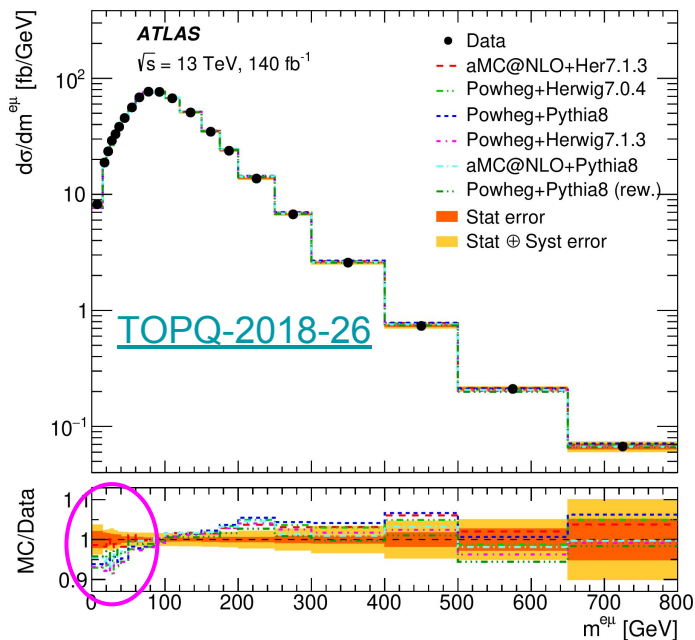


$$|\mathcal{M}|^2 \rightarrow |\mathcal{M}|^2 \left| \frac{\tilde{G}(E; p^*)}{\tilde{G}_0(E; p^*)} \right|^2$$

modelling full S-wave contributions



- **Slight excess** in data near production threshold
 - the inclusive toponium cross section is roughly 0.6% that of inclusive $t\bar{t}$ at 13 TeV
 - we don't have the resolution to see it directly in $m_{t\bar{t}}$
 - **need to use spin-sensitive observables** to leverage the pseudoscalar component



Normalisation of bb4l: HO $t\bar{t}$ + HO tW vs DPA NNLO

25

From the recent paper by Jonas Lindert et al.: [arXiv:2507.11410](https://arxiv.org/abs/2507.11410)

The **DPA NNLO cross section** for bb4l dilepton is:

$$10278 \pm 55 \text{ (MC/extrapolation)} \pm 152 \text{ (NWA) fb} = \mathbf{10278 \pm 162 \text{ fb}}$$

The branching ratio they use is **BR($W \rightarrow l\nu$)=10.8598%**

Therefore the inclusive cross section is: **871.5 $\pm$ 13.7 pb**

The HO $t\bar{t}$ cross section is: $833.9 \pm 30 \text{ (scales)} \pm 21 \text{ (PDF)} \pm 23 \text{ (} m_{\text{top}} \text{)} \text{ pb}$

The HO tW cross section is: $79.3 \pm 1.9 \text{ (scales)} \pm 2.2 \text{ (PDF)} \pm 1.2 \text{ (} m_{\text{top}} \text{)} \text{ pb}$

The total HO cross section is: $913.2 \pm 30 \text{ (scales)} \pm 21 \text{ (PDF)} \pm 23 \text{ (} m_{\text{top}} \text{)} \text{ pb} = \mathbf{913.2 \pm 43.4 \text{ pb}}$

Therefore the **ratio DPA/sum(HO)** is: **0.954 $\pm$ 0.048** [assuming no correlation]

or: **0.954 $\pm$ 0.030** [assuming full correlation]

Quote from Jonas Lindert: “proper comparison would require careful alignment of all input parameters”

	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9		CR-Z	CR-Fakes- $e\mu$	CR-Fakes- ee	CR-Fakes- $\mu\mu$
$t\bar{t}$	97000 $\pm$ 4000	55600 $\pm$ 3100	31500 $\pm$ 2100	65100 $\pm$ 3200	100000 $\pm$ 5000	65000 $\pm$ 4000	44500 $\pm$ 2500	72000 $\pm$ 4000	135000 $\pm$ 7000	$t\bar{t}$	43500 $\pm$ 2000	460 $\pm$ 230	220 $\pm$ 110	—
tW	3650 $\pm$ 240	2430 $\pm$ 180	1620 $\pm$ 140	2590 $\pm$ 180	4060 $\pm$ 280	2930 $\pm$ 240	1870 $\pm$ 160	2840 $\pm$ 190	5400 $\pm$ 400	tW	1830 $\pm$ 130	—	—	—
$t\bar{t} + tW$ (bb41)	102000 $\pm$ 5000	59600 $\pm$ 3100	34000 $\pm$ 2100	68900 $\pm$ 3300	108000 $\pm$ 5000	70000 $\pm$ 4000	47100 $\pm$ 2600	77000 $\pm$ 4000	147000 $\pm$ 6000	$t\bar{t} + tW$ (bb41)	46000 $\pm$ 2000	480 $\pm$ 240	240 $\pm$ 120	< 0.1
$t\bar{t}_{\text{NRQCD}}$	476 $\pm$ 26	489 $\pm$ 27	374 $\pm$ 20	255 $\pm$ 13	1030 $\pm$ 50	990 $\pm$ 40	121 $\pm$ 6	685 $\pm$ 31	2430 $\pm$ 90	$t\bar{t}_{\text{NRQCD}}$	204 $\pm$ 12	—	—	—
$\eta t\bar{t}$	476 $\pm$ 21	503 $\pm$ 24	392 $\pm$ 20	264 $\pm$ 11	1060 $\pm$ 40	990 $\pm$ 40	128 $\pm$ 6	704 $\pm$ 28	2380 $\pm$ 90	$\eta t\bar{t}$	237 $\pm$ 11	< 0.1	< 0.1	< 0.1
Z+jets	990 $\pm$ 140	880 $\pm$ 130	870 $\pm$ 110	490 $\pm$ 80	680 $\pm$ 90	520 $\pm$ 90	230 $\pm$ 50	350 $\pm$ 50	540 $\pm$ 90	Z+jets	33000 $\pm$ 6000	—	—	—
$t + X$	320 $\pm$ 100	180 $\pm$ 50	105 $\pm$ 32	200 $\pm$ 60	280 $\pm$ 80	170 $\pm$ 50	140 $\pm$ 40	190 $\pm$ 60	310 $\pm$ 90	$t + X$	330 $\pm$ 100	370 $\pm$ 110	109 $\pm$ 33	160 $\pm$ 50
Fakes	1480 $\pm$ 50	1200 $\pm$ 40	1020 $\pm$ 40	1090 $\pm$ 40	1430 $\pm$ 60	996 $\pm$ 34	803 $\pm$ 27	950 $\pm$ 60	1127 $\pm$ 33	Fakes	484 $\pm$ 23	4890 $\pm$ 130	1640 $\pm$ 70	1650 $\pm$ 60
VV+jets	120 $\pm$ 40	104 $\pm$ 32	92 $\pm$ 29	79 $\pm$ 25	120 $\pm$ 40	104 $\pm$ 32	54 $\pm$ 17	80 $\pm$ 25	140 $\pm$ 40	VV+jets	1100 $\pm$ 350	110 $\pm$ 60	30 $\pm$ 15	30 $\pm$ 15
Total	104000 $\pm$ 5000	60900 $\pm$ 3300	35600 $\pm$ 2200	69800 $\pm$ 3400	108000 $\pm$ 5000	71000 $\pm$ 4000	47800 $\pm$ 2600	77000 $\pm$ 4000	145000 $\pm$ 7000	Total	80000 $\pm$ 7000	5830 $\pm$ 340	2000 $\pm$ 160	1840 $\pm$ 80
Total (bb41)	106000 $\pm$ 5000	62500 $\pm$ 3200	36500 $\pm$ 2200	71100 $\pm$ 3400	111000 $\pm$ 5000	73000 $\pm$ 4000	48400 $\pm$ 2600	79000 $\pm$ 4000	152000 $\pm$ 6000	Total (bb41)	81000 $\pm$ 7000	5850 $\pm$ 350	2020 $\pm$ 170	1840 $\pm$ 80
Data	103095	61071	35514	69602	107995	70917	48258	77123	145030	Data	76127	6120	2013	2091

Largest background: single-top tW production (4%) → detailed systematic model

Smaller backgrounds: Z+jets (0.8%) and fake leptons (1.5%) → decent pre-fit description from MC templates, normalisation to data in CRs.

Category	Impact
$t\bar{t}_{\text{NRQCD}}$ modelling	5.3%
$t\bar{t}$ modelling	3.5%
Jet energy scale (pileup)	1.3%
b -tagging	1.2%
Instrumental (other)	0.9%
Limited MC statistics	0.7%
Jet energy scale (flavour)	0.5%
Background normalisations	0.4%
tW modelling	0.4%
Jet energy scale (η inter-calibration)	0.4%
Jet energy scale (other)	0.3%
Jet energy resolution	0.3%
Leptons	0.2%
Total syst. uncertainties	6.8%
Total stat. uncertainties	13%

Parameter	Setting
POWHEG-BOX-RES version	bb4l-beta
PDF (ME)	NNPDF30_NLO
h_{damp}	258.75
Γ_t [GeV]	1.32733
Matching factor between 4FS ME and 5FS PDF	$Q_R = m_b$
ptsqmin	1.44
Inverse-width-correction	yes
Resonance history	$t\bar{t}, tW^-\bar{b}, tW^+b$
PYTHIA version	8.312
PS tune	A14
PDF (PS)	NNPDF2.3LO
POWHEG:veto	1
POWHEG:vetoCount	3
POWHEG:pThard	0
POWHEG:pTemt	0
POWHEG:emitted	0
POWHEG:pTdef	2
POWHEG:nFinal	-1
POWHEG:MPIveto	1
POWHEG:QEDveto	1
POWHEG:bb4l:FSREmission:veto	1
POWHEG:bb4l:vetoQED	0
POWHEG:bb4l:FSREmission:vetoDipoleFrame	0
POWHEG:bb4l:pTpythiaVeto	0
POWHEG:bb4l:ScaleResonance:veto	0
POWHEG:bb4l:pTminVeto	1.2
SpaceShower:pTmaxMatch	2
TimeShower:pTmaxMatch	2
TimeShower:recoilStrategyRF	3 (recoil-to-top)

Selection requirement	ATLAS	CMS
Leptons	Exactly 2 $p_T \geq 25/27/28, 10 \text{ GeV}$	Exactly 2 $p_T \geq 25, 20 \text{ GeV}$
Jets	At least 2 $p_T \geq 25 \text{ GeV}$	At least 2 $p_T \geq 30 \text{ GeV}$
b-tagged jets	At least 1 (70% efficiency)	At least 1 (77% efficiency)
Range of reconstructed $m_{t\bar{t}}$	300 to 500 GeV <i>no overflow above!</i>	300 to ~1400 GeV <i>with overflow above</i>
Only for OSSF $ee/\mu\mu$		
Dilepton invariant mass	$m_{ll} \geq 15 \text{ GeV}$ $ m_{ll}-m_Z \geq 10 \text{ GeV}$	$m_{ll} \geq 20 \text{ GeV}$ $ m_{ll}-m_Z \geq 15 \text{ GeV}$
Missing ET	$\text{MET} \geq 60 \text{ GeV}$	$\text{MET} \geq 40 \text{ GeV}$

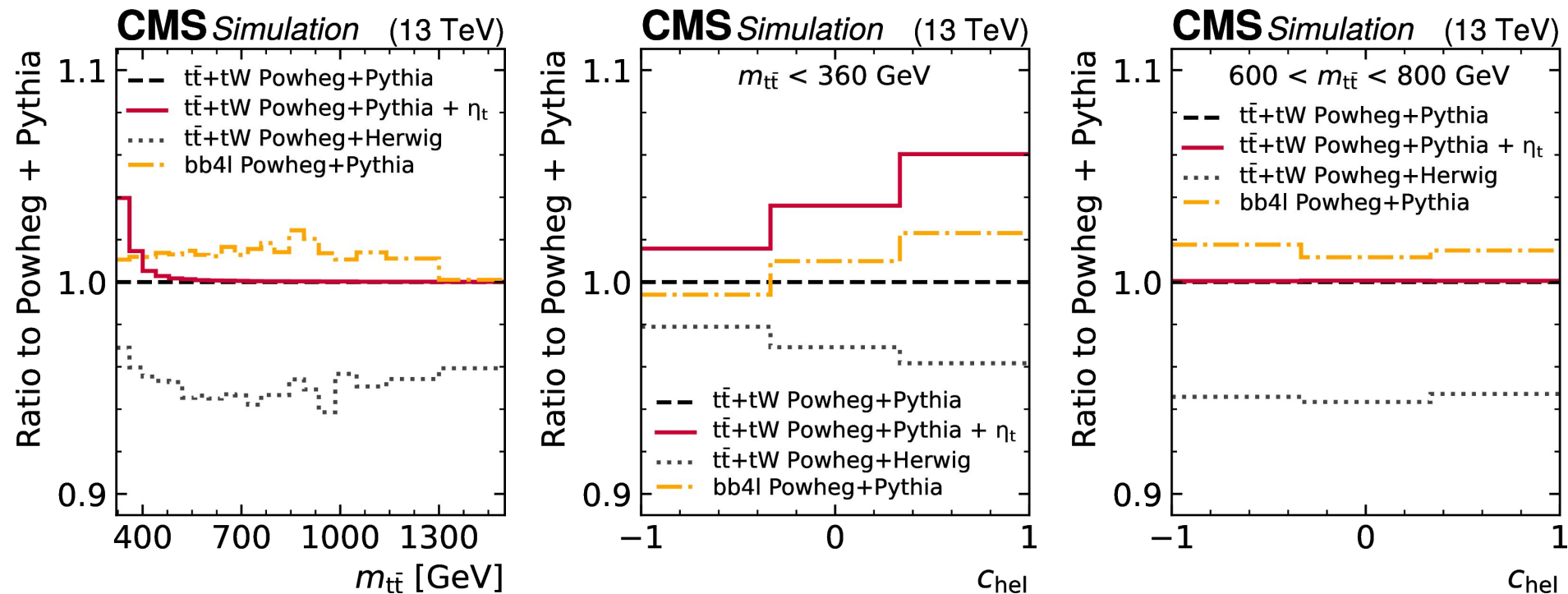
Type	ATLAS	CMS
Experimental	electrons, muons, jets, b-tagging, MET, pileup, luminosity	
Minor backgrounds	normalisation unc. only	normalisation unc. μ_R/μ_F and ISR/FSR for Drell-Yan
Fake background	normalised in data shape variations	shape variations only
tW background	aNNLO normalisation with 4% unc. parton shower [Herwig 7.2], matching [pThard, hdamp], interference scheme [DR/DS], top mass [± 0.5 GeV]	aNNLO normalisation with 15% unc. μ_R/μ_F and ISR/FSR
Signal toponium modelling	μ_R/μ_F , PDF + α_s PS [Herwig 7.2] and ISR/FSR obtained from particle-level reweighting	μ_F [μ_R irrelevant because of contact interaction] top mass [± 1 GeV], corr. with pQCD $t\bar{t}$ ISR/FSR PDF found to be negligible

Systematic uncertainties: $t\bar{t}$ modelling

Type	ATLAS	CMS
Scales & PDF	— PDF + α_s [PDF4LHC15]	μ_R/μ_F [NLO QCD] PDF + α_s [NNPDF3.1], with PCA
Higher-order reweighting	NNLO QCD: scales NLO EW: additive vs multiplicative schemes [top Yukawa variation tested, irrelevant]	— NLO EW: additive vs multiplicative schemes, and $\pm 11\%$ variation of top Yukawa
Top quark mass	± 0.5 GeV	± 1 GeV
Top quark decay and off-shell effects	compare hvq+tW DS and bb4l [bb4l is reweighted independently to HO]	compare hvq+tW DR and bb4l [bb4l is reweighted like hvq to HO]
Parton shower and hadronisation	Powheg+Herwig 7.2	Powheg+Herwig 7.2
ME/PS matching (Powheg)	hdamp = $1.5m_t \rightarrow 2m_t$ pThard = $0 \rightarrow 1$	hdamp = $1.58m_t + 0.66m_t - 0.59m_t$ —

Type	ATLAS	CMS
Initial state radiation (Pythia) Final state radiation (Pythia)	Var3c variation of the A14 tune (α_s) μ_R variation in the PS	μ_R variation in the PS μ_R variation in the PS
Recoil scheme (Pythia)	recoil-to-colour $\rightarrow$ recoil-to-top	—
Colour reconnection (Pythia)	maximum of CR1 [QCD-based] and CR2 [gluon-move] compared to CR0 [MPI-based] [CR2-based unc. found negligible]	CR1 and CR 2 compared to CR0, and CR0 + EarlyResonanceDecay compared to CR0 [CR2-based unc. found negligible]
Underlying event (Pythia)	Var1 variation of the A14 tune	variations of the CP5 tune

Key differences in MC predictions



- **Toponium** localised near threshold, with strong positive slope in c_{hel}
- **Herwig** predicts fewer $t\bar{t}$ events overall, with negative slope in c_{hel} near threshold → *should be constrained but without affecting the extracted signal*
- **bb4l** predicts more events overall, and positive slope in c_{hel} near threshold → *should be constrained and decrease the extracted signal*