Toponium at the LHC

a new frontier in top-quark physics

CEA/Saclay DPhP Seminar, 01/12/2025

Baptiste Ravina (CERN)

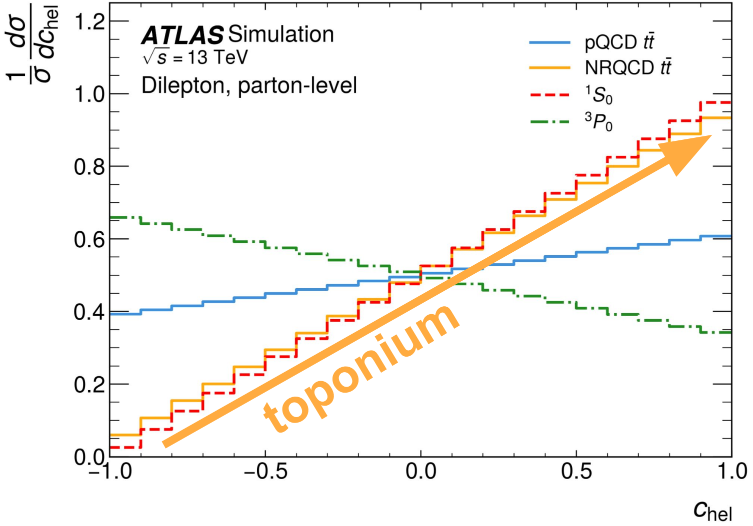
Overview

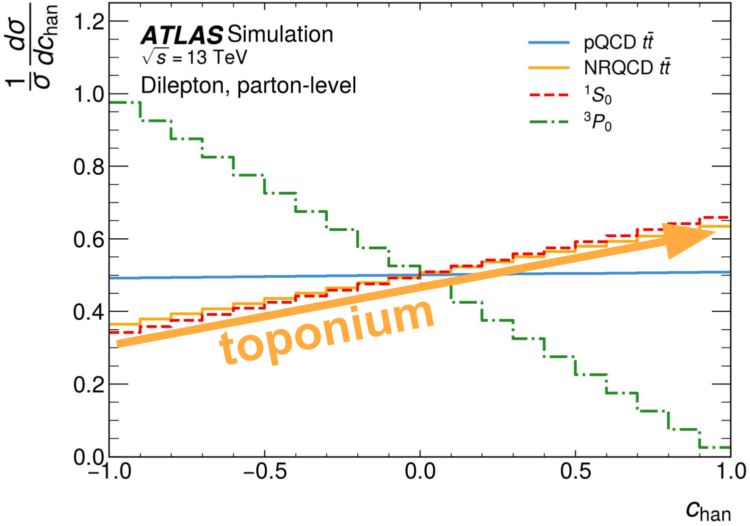
- All the relevant concepts have been introduced Benjamin's talk
  - the LHC is a top quark factory → Run 2 gives us access to **O(100M) $t\bar{t}$ events**
  - the top quark decays fast enough that the full spin information can be reconstructed from the decay products → **access to spin polarisations 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~$2m_t$) 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***

Analysis strategy

- 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 $^3P_0$*



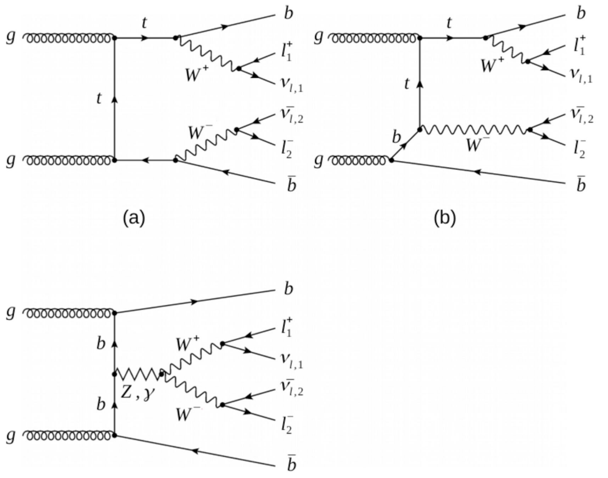


Analysis strategy

- Suppress reducible backgrounds, and use either **state-of-the-art MC modelling** or **data-driven techniques** for the remaining contributions
  - in ee/μμ 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 $t\bar{t}$ 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		
$E_T^{miss} \geq 60$ GeV for OSSF events		—
$\ell^{\pm}\ell'^{\mp}$ $\lvert m_{\ell\ell} - m_Z \rvert \geq 10$ GeV	$e^{\pm}e^{\mp}/\mu^{\pm}\mu^{\mp}$ $\lvert m_{\ell\ell} - m_Z \rvert \leq 10$ GeV	$\ell^{\pm}\ell'^{\pm}$ $\lvert m_{\ell\ell} - m_Z \rvert \geq 10$ GeV

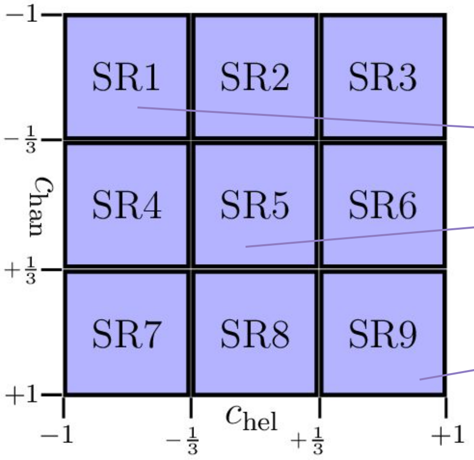


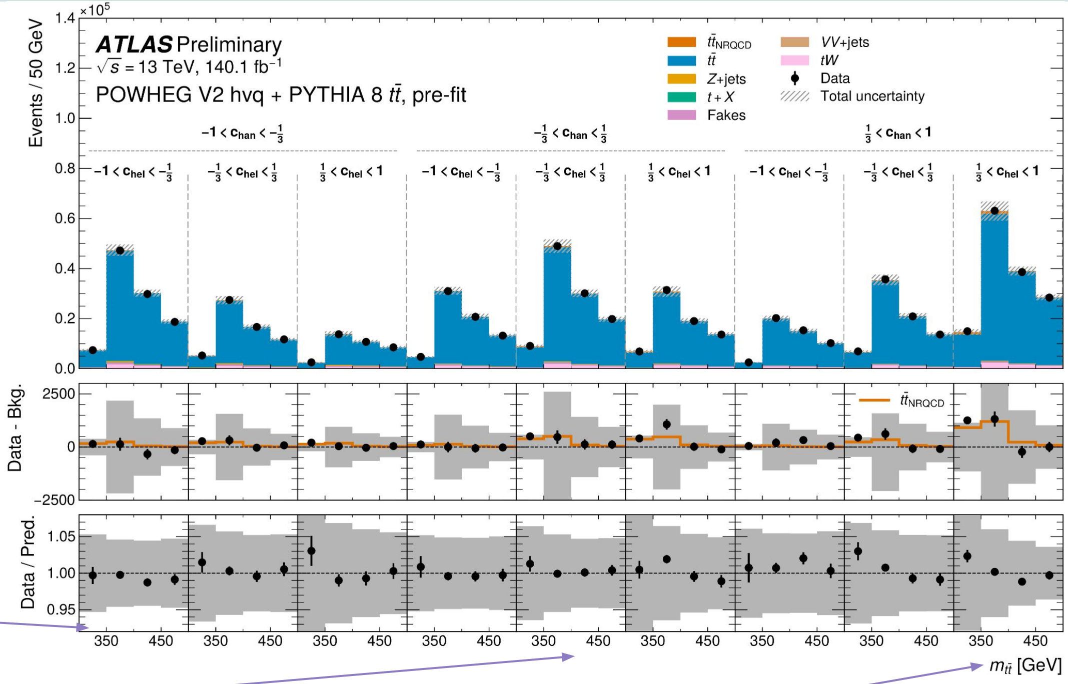
Doubly-, singly-, and non-resonant bbllνν final states

Signal regions

ATLAS-CONF-2025-008
RoPP, 88 (2025) 087801

- 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→tt̄ search: enhance sensitivity to A and H bosons in different bins





Background estimation

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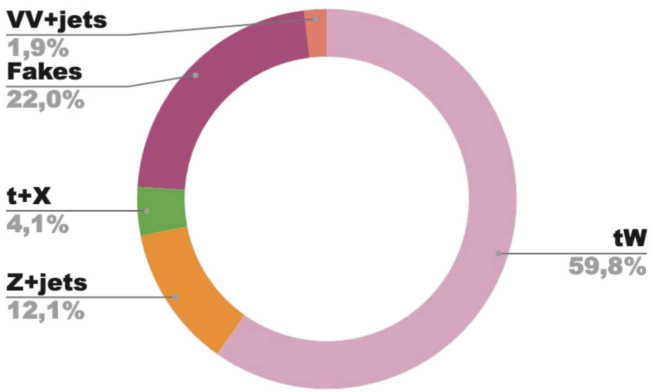
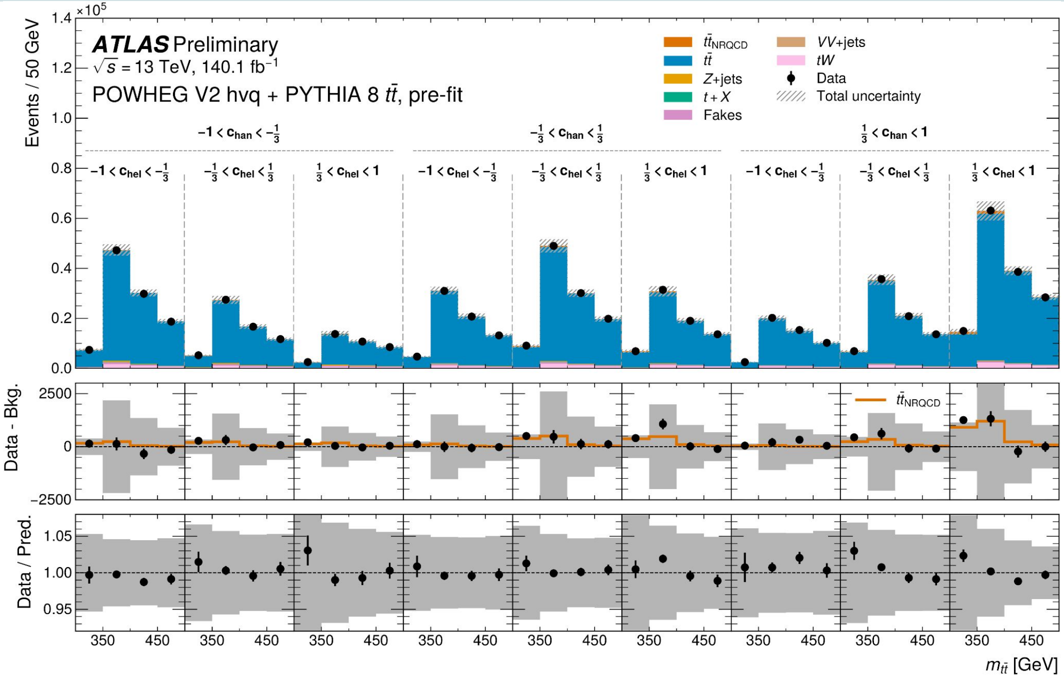
- Expect **~700k $t\bar{t}$ events** and **~40k additional background events**
  - *for only about ~7k signal events!*
- tW is mostly irreducible, taken from MC with detailed set of systematic uncertainties
- t+X and diboson are negligible

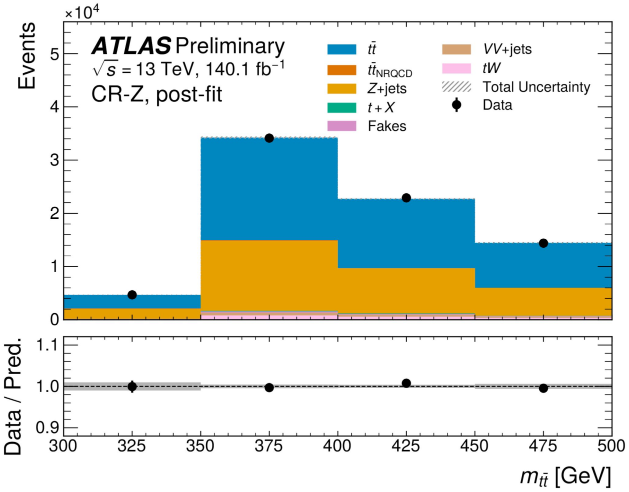


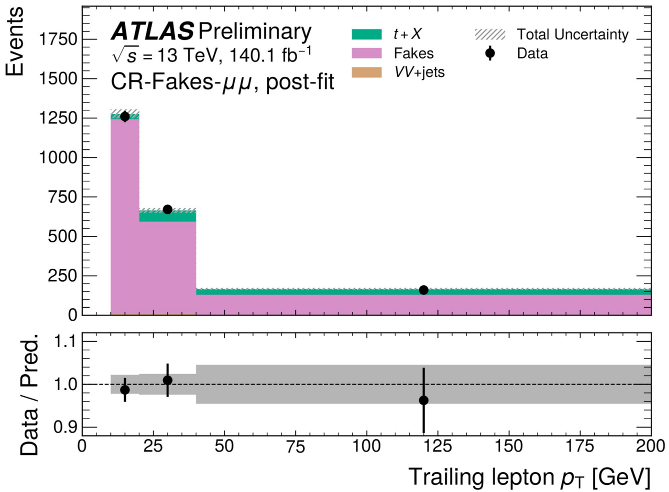


- **CMS:** model contribution of fake leptons directly from MC, use data to normalise Z+jets events
- **ATLAS:** normalise both fake and Z+HF to data, but closer to the SR kinematic space

Background normalisation

- 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/μμ/eμ** 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





Top quark reconstruction

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- Slightly different techniques are used, but both make similar assumptions to constrain the neutrino kinematics [on-shell top quarks and W bosons, and $p_T(\nu\nu)=p_T(miss)$]
- **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**

Modelling of the signal toponium process

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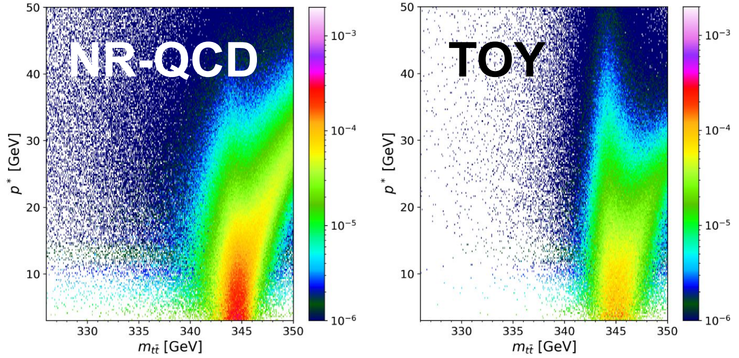
- **ATLAS setup** according to B. Fuks et al. in Eur. Phys. J. C 85 (2025) 157
  - **directly inspired by NR-QCD**: Green's function reweighting + PS matching
  - apply 2D mass/momentum cut to retain validity of NR-QCD calculations
  - claims to accurately represent the LO S-wave colour-singlet contributions
  - MC cross section: 5.60 pb → 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→η→WbWb in MG at LO, use M(η)=343 GeV, Γ(η)=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 → differences in top kinematics
  - this model is also tested by ATLAS



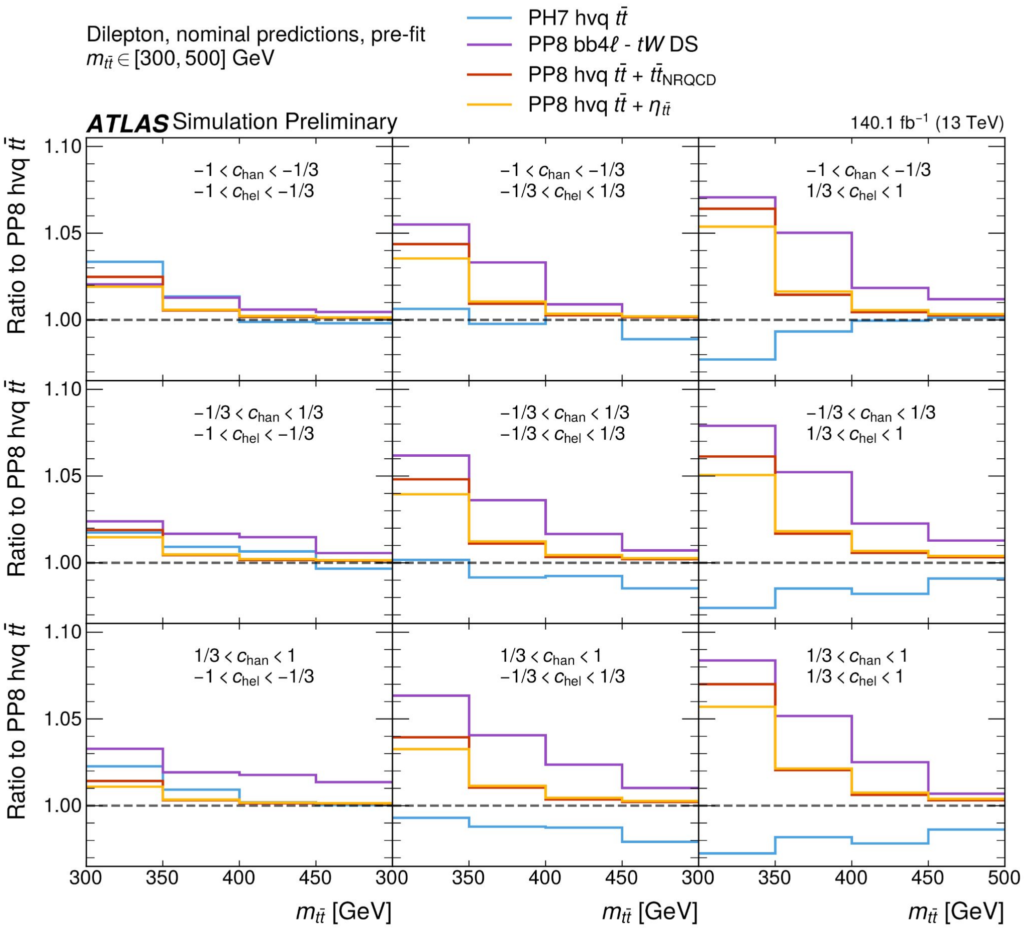
Modelling of the background $t\bar{t}$ process

- **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→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 → can reproduce fixed-order predictions, as well as MiNNLOps

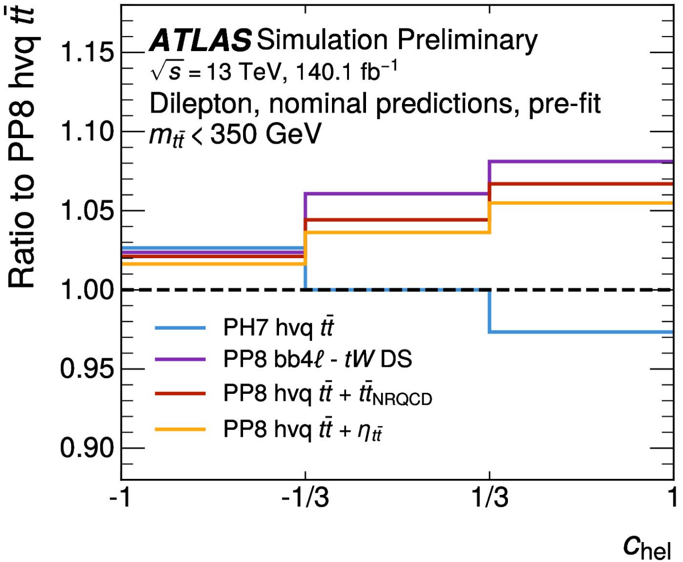
Statistical analysis

- 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 $m_{t\bar{t}}$
- **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*



Main results of the ATLAS & CMS analyses

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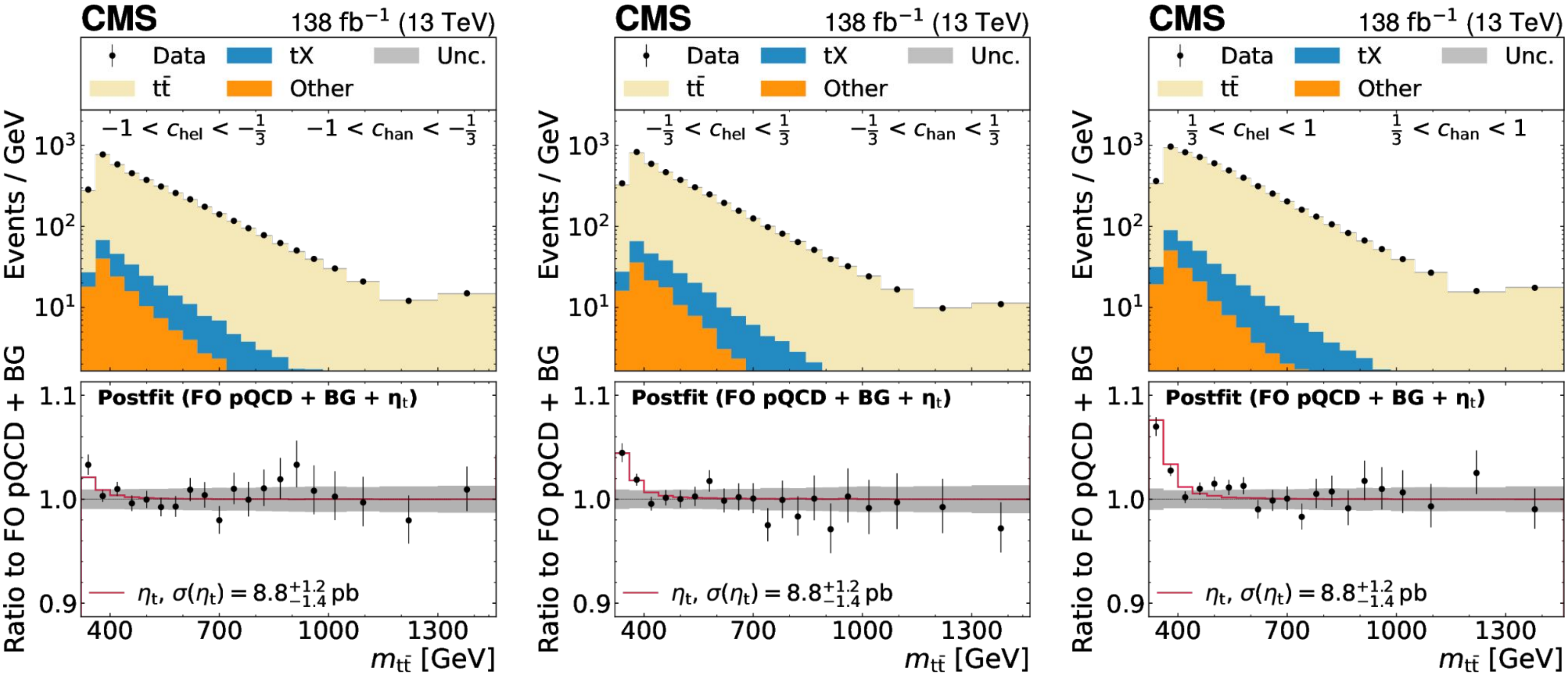
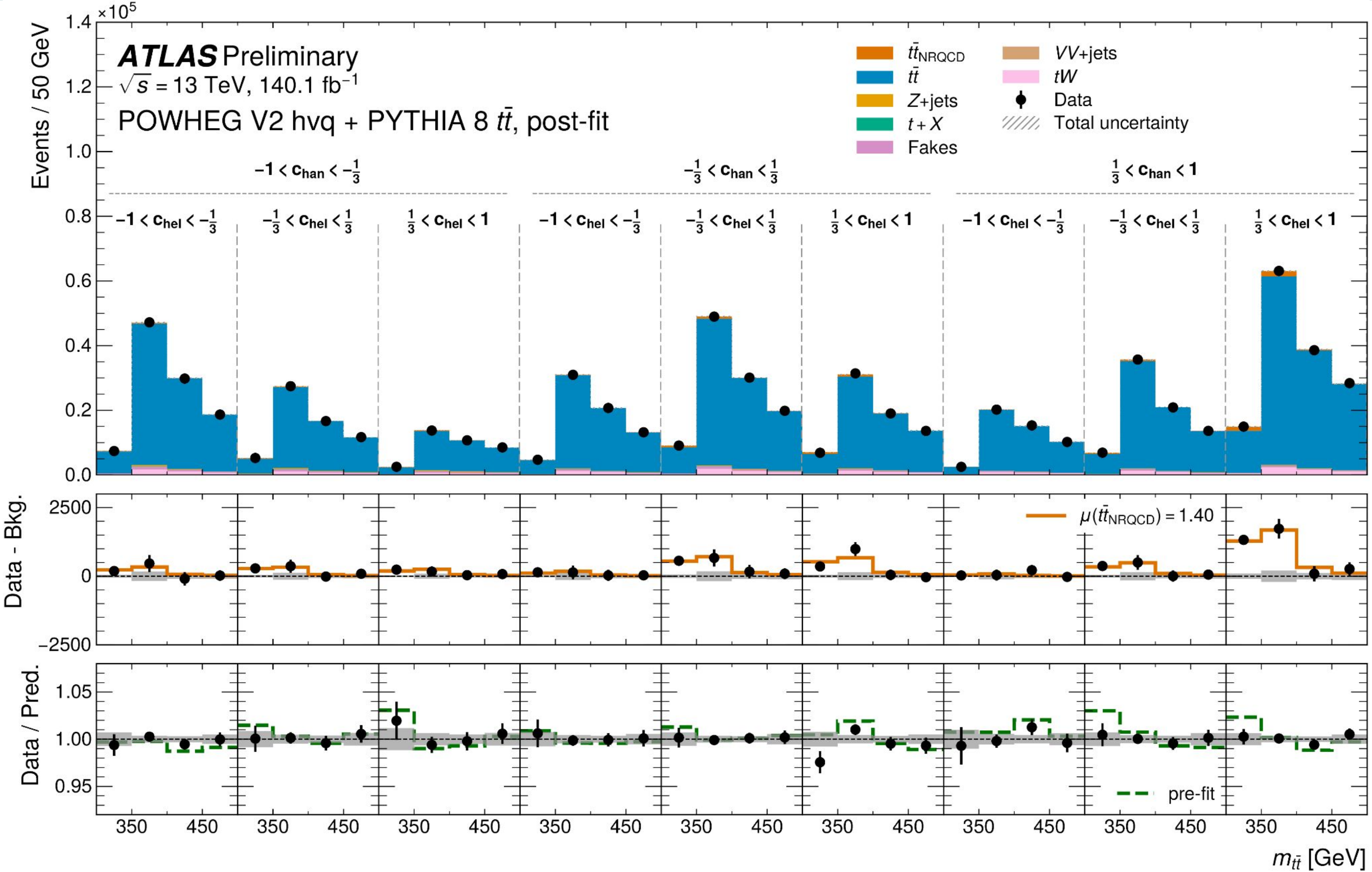


*Clear **excess near threshold**, behaving like **pseudo-scalar toponium***

Main results of the ATLAS & CMS analyses

ATLAS-CONF-2025-008



Main results of the ATLAS & CMS analyses

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- The predicted NRQCD toponium cross section is 6.4pb
- **ATLAS:** 7.7σ obs. (5.7σ exp.), with a GoF of 0.93 [7x10^{-5} for background-only hypothesis]
- **CMS:** >5σ obs.
- **Measured cross sections are compatible with each other and with the NRQCD prediction**, although roughly (40 ± 20)% larger
  - ***Do recall that two different signal models are used!***
- Large impact of tt̄ modelling systematics on both results

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

$$\sigma(\eta_\mathrm{t}) = 8.8 \pm 0.5\,(\mathrm{stat})\,^{+1.1}_{-1.3}\,(\mathrm{syst})\,\mathrm{pb} = 8.8\,^{+1.2}_{-1.4}\,\mathrm{pb}.$$

Impact of systematic uncertainties

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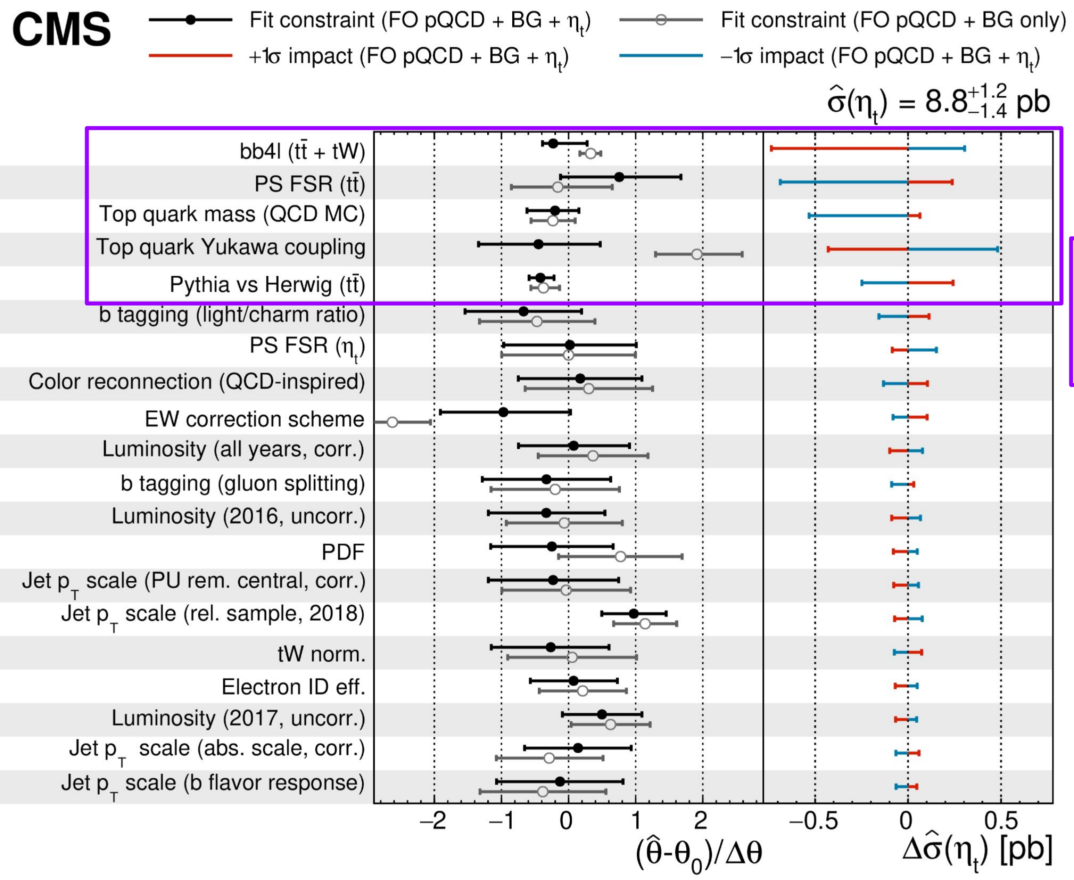
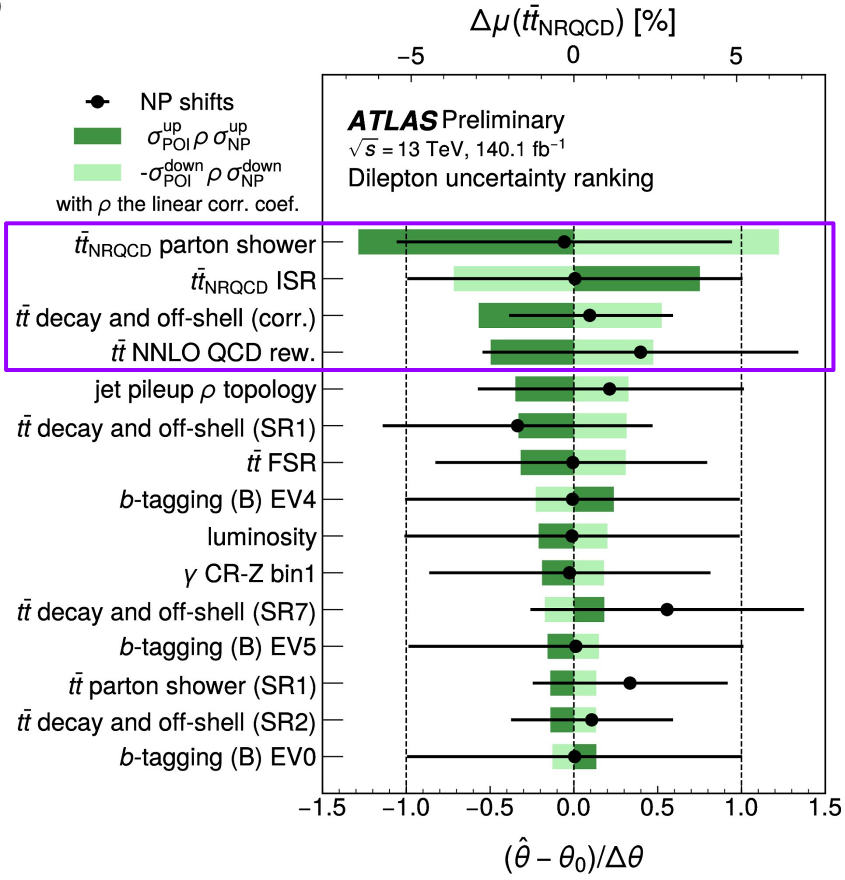
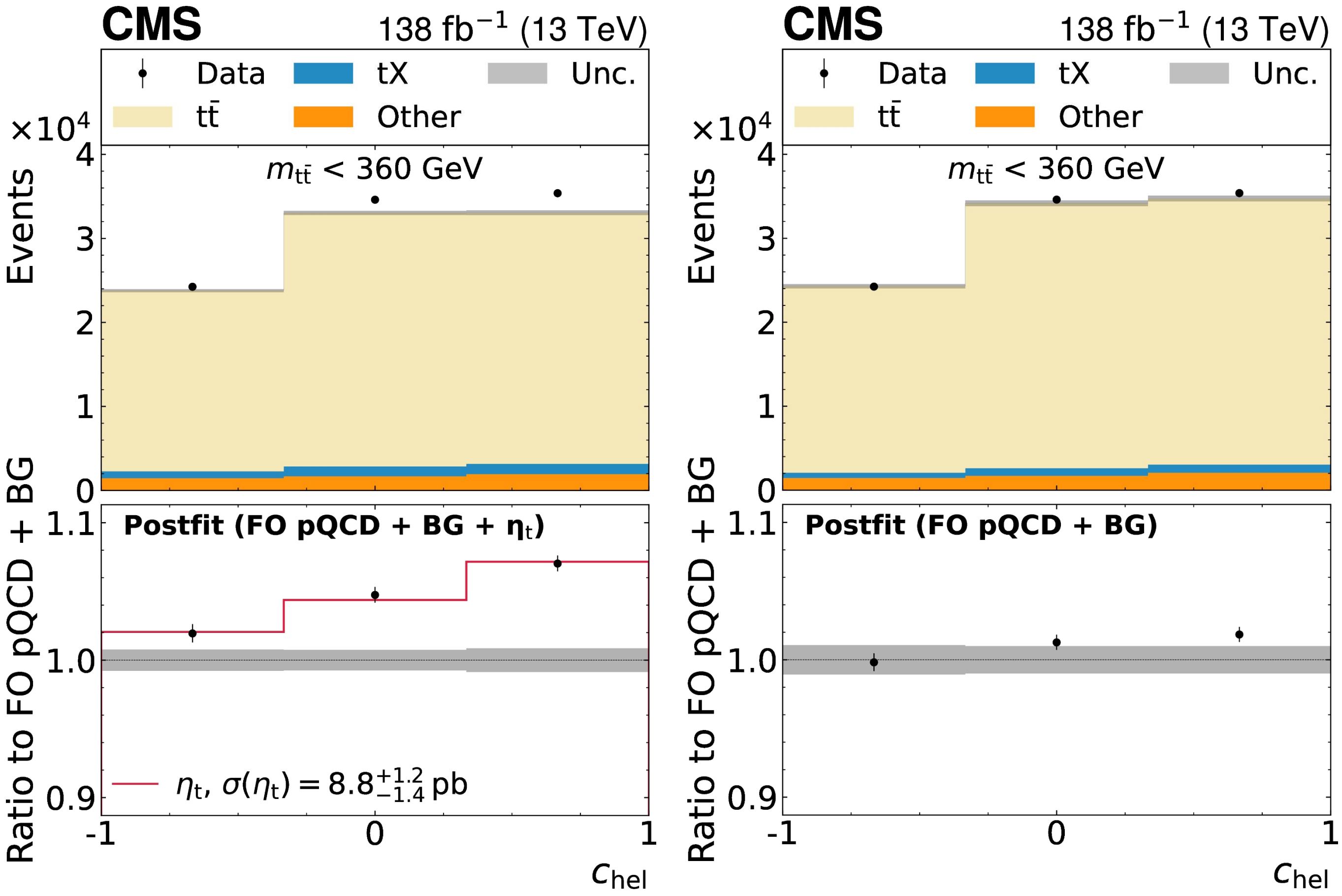




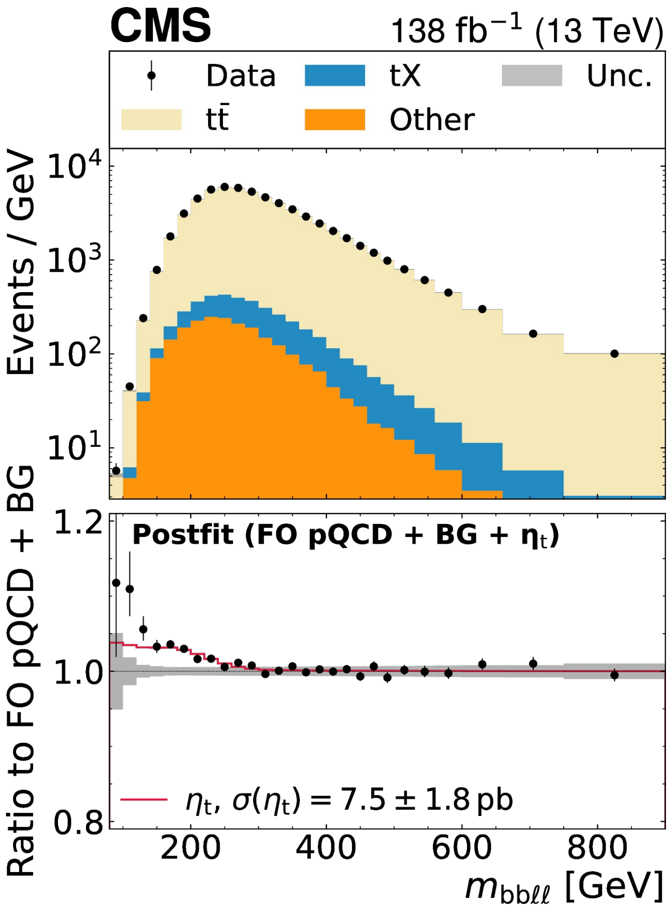
Further checks: background-only fits

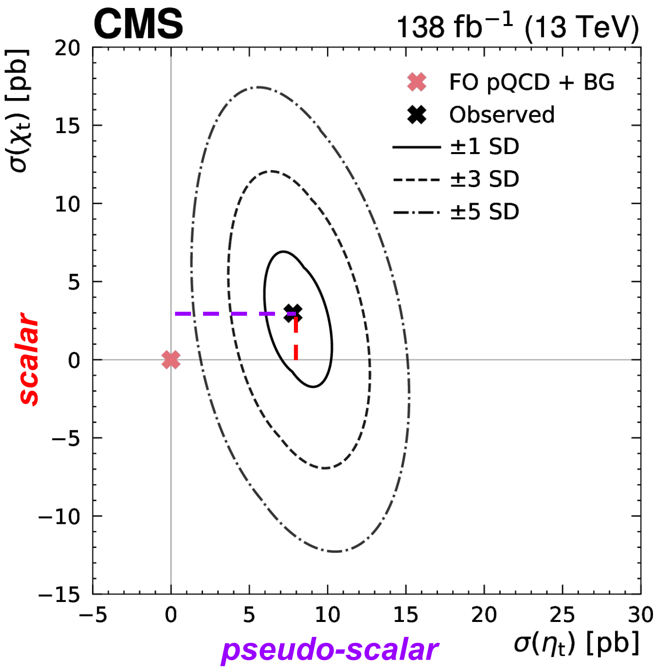


- **Residual slope clearly visible** in the fit **without any toponium** template
- **Large unphysical pulls** of many uncertainties
- **Significantly degraded GoF** for ATLAS

⇒ toponium-like signal is needed to explain the data!

Further checks: alternative templates





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

Further checks: alternative models

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- 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 → **~2σ 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 → *follow-up ATLAS paper to adopt new recommendations from theorists*

Conclusions

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- **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.

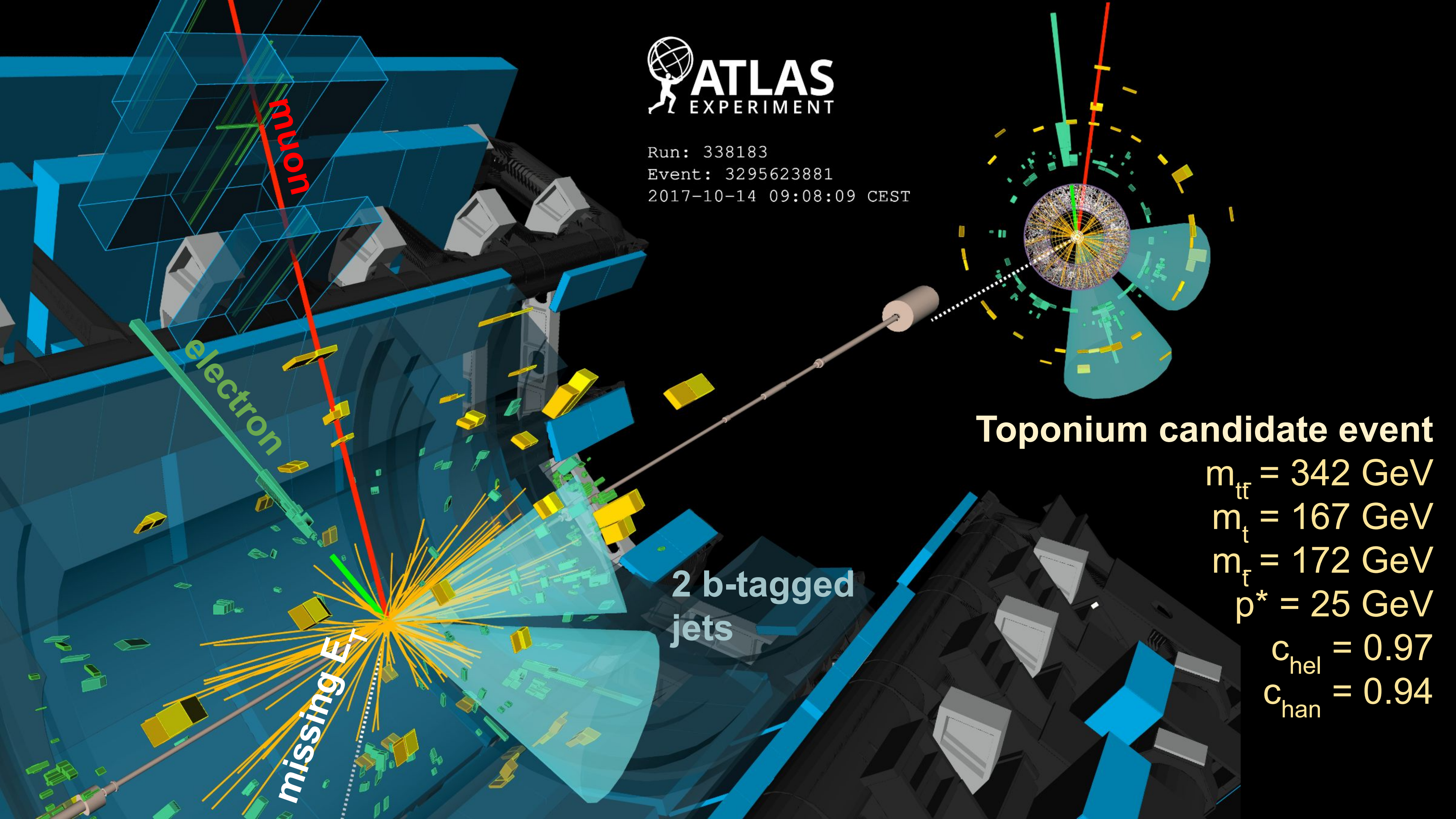
- Both ATLAS and CMS **observe a significant excess** seemingly compatible with **toponium formation**
  - **many checks have been performed:** different selection cuts, observables, signal and background models, splitting datasets by year and by lepton flavour, etc. → robust!
  - **future improvements** to come from better top reconstruction [m_{tt} 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

ATLAS EXPERIMENT

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

CMS

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


ATLAS
EXPERIMENT
Run: 338183
Event: 3295623881
2017-10-14 09:08:09 CEST
muon
electron
missing E_T
2 b-tagged
jets
Toponium candidate event
$m_{t\bar{t}}$ = 342 GeV
m_t = 167 GeV
$m_{\bar{t}}$ = 172 GeV
p^* = 25 GeV
c_{hel} = 0.97
c_{han} = 0.94

BACKUP

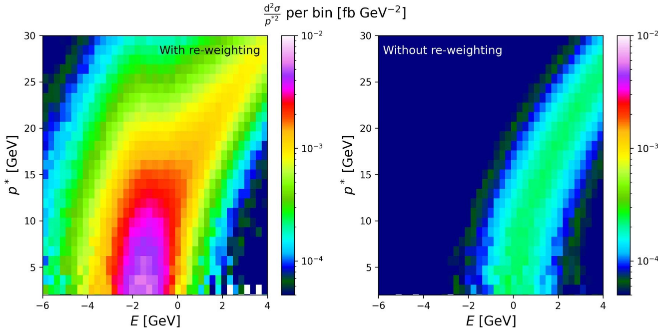
What is toponium?

- 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 ~ $(\alpha_S/\beta)^n$
  - 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

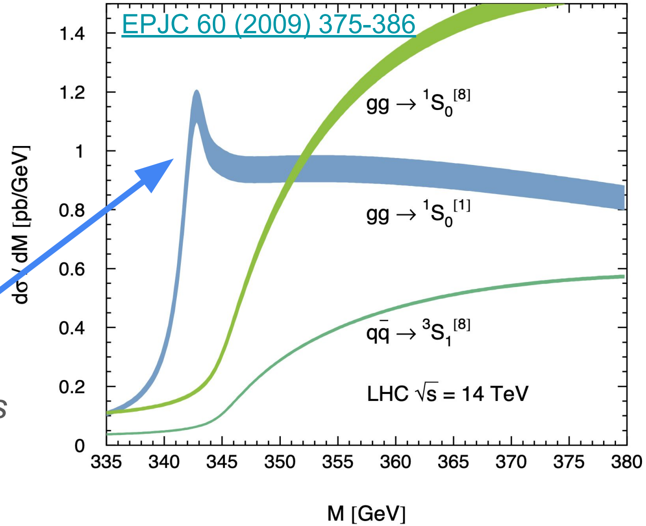
Regular Article – Theoretical Physics | Theoretical Physics | Open access
Published: 07 February 2025
Volume 85, article number 157, (2025) Cite this article

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



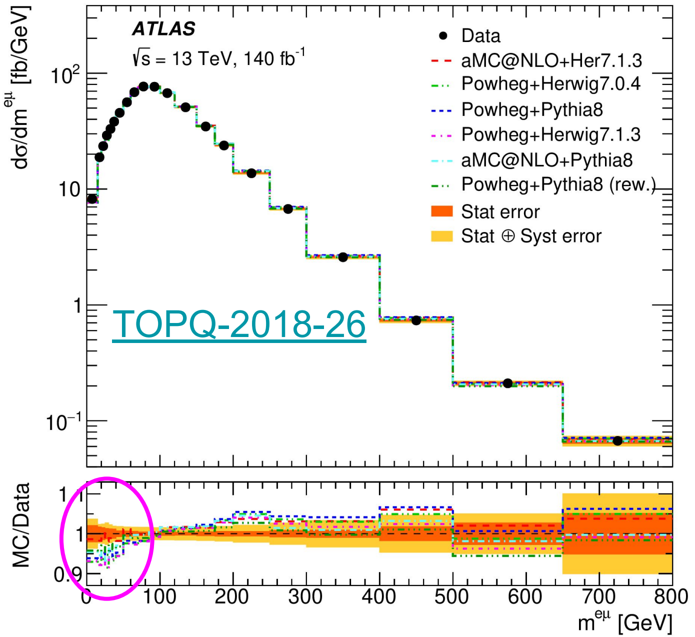
$$|\mathcal{M}|^2 \quad \rightarrow \quad |\mathcal{M}|^2 \left| \frac{\widetilde{G}(E;p^*)}{\widetilde{G}_0(E;p^*)} \right|^2$$

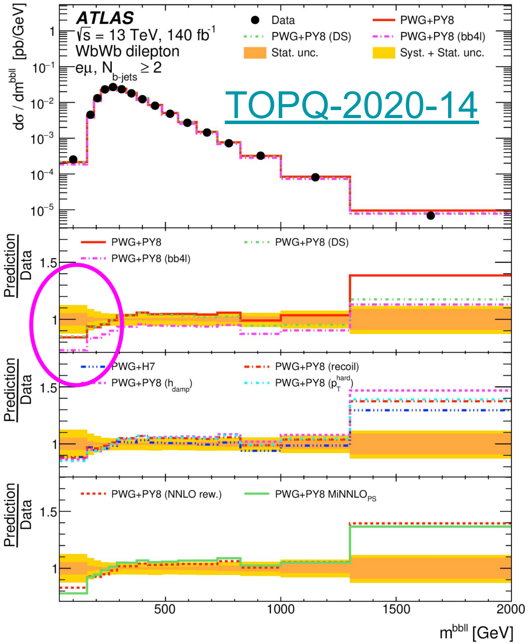
modelling full S-wave contributions

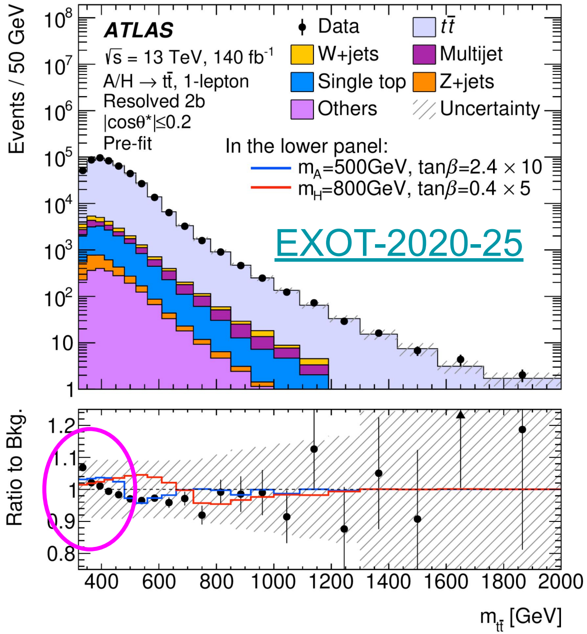


Previous hints: differential cross sections & BSM searches

- 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

From the recent paper by Jonas Lindert et al.: arXiv:2507.11410

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

10278 ± 55 (MC/extrapolation) ± 152 (NWA) fb = **10278 ± 162 fb**

The branching ratio they use is **BR(W→lν)=10.8598%**

Therefore the inclusive cross section is: **871.5 ± 13.7 pb**

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

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

The total HO cross section is: 913.2 ± 30 (scales) ± 21 (PDF) ± 23 (m_{top}) pb = **913.2 ± 43.4 pb**

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

or: **0.954 ± 0.030** [assuming full correlation]

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

Background estimation (ATLAS)

ATLAS-CONF-2025-008

	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9
$t\bar{t}$	97000 ± 4000	55600 ± 3100	31500 ± 2100	65100 ± 3200	100000 ± 5000	65000 ± 4000	44500 ± 2500	72000 ± 4000	135000 ± 7000
tW	3650 ± 240	2430 ± 180	1620 ± 140	2590 ± 180	4060 ± 280	2930 ± 240	1870 ± 160	2840 ± 190	5400 ± 400
$t\bar{t}+tW$ (bb41)	102000 ± 5000	59600 ± 3100	34000 ± 2100	68900 ± 3300	108000 ± 5000	70000 ± 4000	47100 ± 2600	77000 ± 4000	147000 ± 6000
$t\bar{t}_{\mathrm{NRQCD}}$	476 ± 26	489 ± 27	374 ± 20	255 ± 13	1030 ± 50	990 ± 40	121 ± 6	685 ± 31	2430 ± 90
$\eta_{t\bar{t}}$	476 ± 21	503 ± 24	392 ± 20	264 ± 11	1060 ± 40	990 ± 40	128 ± 6	704 ± 28	2380 ± 90
Z+jets	990 ± 140	880 ± 130	870 ± 110	490 ± 80	680 ± 90	520 ± 90	230 ± 50	350 ± 50	540 ± 90
$t+X$	320 ± 100	180 ± 50	105 ± 32	200 ± 60	280 ± 80	170 ± 50	140 ± 40	190 ± 60	310 ± 90
Fakes	1480 ± 50	1200 ± 40	1020 ± 40	1090 ± 40	1430 ± 60	996 ± 34	803 ± 27	950 ± 60	1127 ± 33
VV+jets	120 ± 40	104 ± 32	92 ± 29	79 ± 25	120 ± 40	104 ± 32	54 ± 17	80 ± 25	140 ± 40
Total	104000 ± 5000	60900 ± 3300	35600 ± 2200	69800 ± 3400	108000 ± 5000	71000 ± 4000	47800 ± 2600	77000 ± 4000	145000 ± 7000
Total (bb41)	106000 ± 5000	62500 ± 3200	36500 ± 2200	71100 ± 3400	111000 ± 5000	73000 ± 4000	48400 ± 2600	79000 ± 4000	152000 ± 6000
Data	103095	61071	35514	69602	107995	70917	48258	77123	145030

	CR-Z	CR-Fakes-$e\mu$	CR-Fakes-ee	CR-Fakes-$\mu\mu$
$t\bar{t}$	43500 ± 2000	460 ± 230	220 ± 110	—
tW	1830 ± 130	—	—	—
$t\bar{t}+tW$ (bb41)	46000 ± 2000	480 ± 240	240 ± 120	< 0.1
$t\bar{t}_{\mathrm{NRQCD}}$	204 ± 12	—	—	—
$\eta_{t\bar{t}}$	237 ± 11	< 0.1	< 0.1	< 0.1
Z+jets	33000 ± 6000	—	—	—
$t+X$	330 ± 100	370 ± 110	109 ± 33	160 ± 50
Fakes	484 ± 23	4890 ± 130	1640 ± 70	1650 ± 60
VV+jets	1100 ± 350	110 ± 60	30 ± 15	30 ± 15
Total	80000 ± 7000	5830 ± 340	2000 ± 160	1840 ± 80
Total (bb41)	81000 ± 7000	5850 ± 350	2020 ± 170	1840 ± 80
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.

Uncertainty breakdown (ATLAS)

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Category	Impact
$t\bar{t}_{\mathrm{NRQCD}}$ 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%

bb4l settings (ATLAS)

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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)

Event selection

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Selection requirement	**ATLAS**	**CMS**
Leptons	Exactly 2 $p_T \geq$ 25/27/28, 10 GeV	Exactly 2 $p_T \geq$ 25, 20 GeV
Jets	At least 2 $p_T \geq$ 25 GeV	At least 2 $p_T \geq$ 30 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 *no overflow above!*	300 to ~1400 GeV *with overflow above*
Only for OSSF ee/μμ		
Dilepton invariant mass	$m_{ll} \geq$ 15 GeV $\lvert m_{ll}-m_Z \rvert \geq$ 10 GeV	$m_{ll} \geq$ 20 GeV $\lvert m_{ll}-m_Z \rvert \geq$ 15 GeV
Missing ET	MET ≥ 60 GeV	MET ≥ 40 GeV

Systematic uncertainties

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 ±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 = $1.58m_t$ $+0.66m_t$ $-0.59m_t$ —

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

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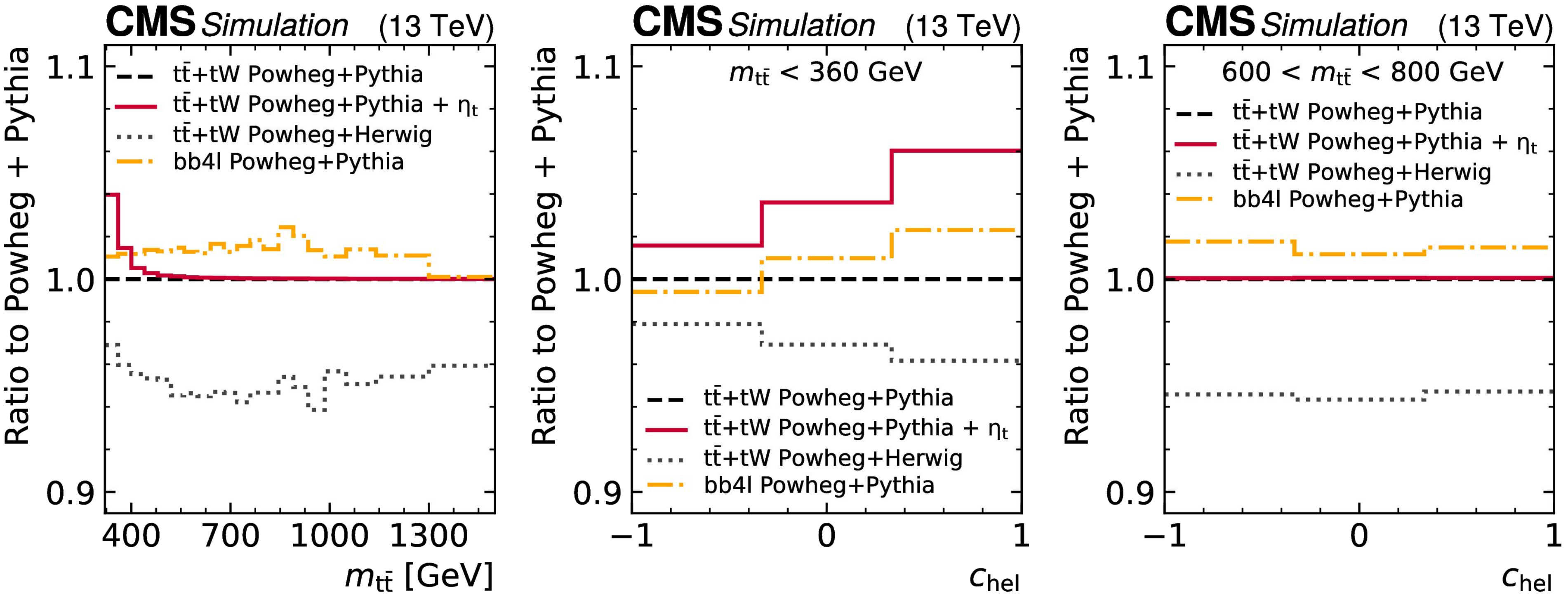
Type	ATLAS	CMS
Initial state radiation (Pythia) Final state radiation (Pythia)	Var3c variation of the A14 tune (α_S) μ_R variation in the PS	μ_R variation in the PS μ_R variation in the PS
Recoil scheme (Pythia)	recoil-to-colour → recoil-to-top	—
Colour reconnection (Pythia)	maximum of CR1 [QCD-based] 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*