Observation of a cross-section enhancement near the $t\bar{t}$ production threshold with the ATLAS detector

Haifeng Li

Shandong University

On behalf of the ATLAS Collaboration

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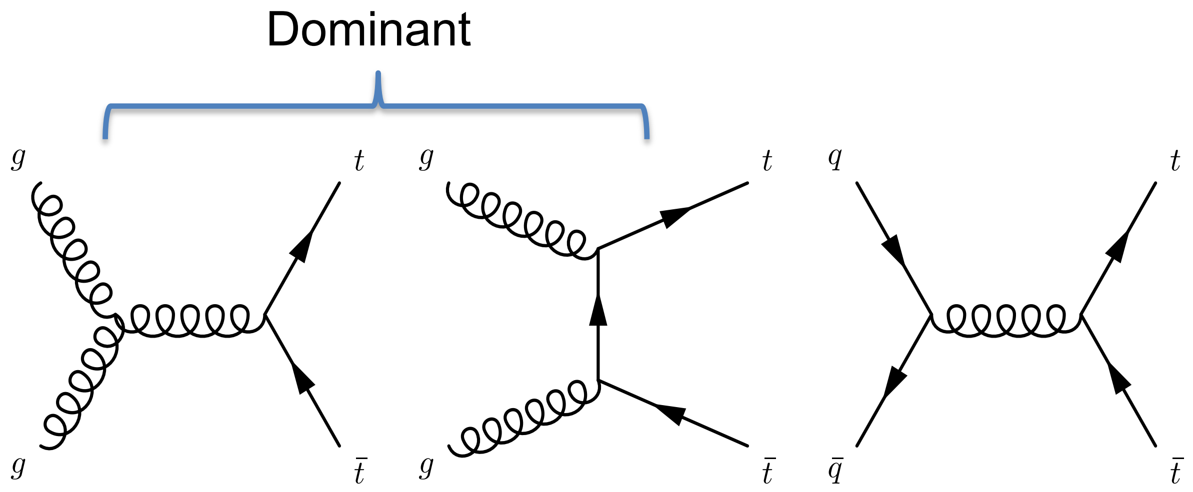
Top Quark Pair Production at LHC

- LHC is a $t\bar{t}$ factory
  - $\sigma_{t\bar{t}} = 834$ pb at LHC Run 2
  - 0.83M $t\bar{t}$ events per fb^{-1}
  - Due to the short life time, can measurement $t\bar{t}$ spin correlations
- With those huge amount of $t\bar{t}$ data, ATLAS has carried out precision measurements in top quark physics

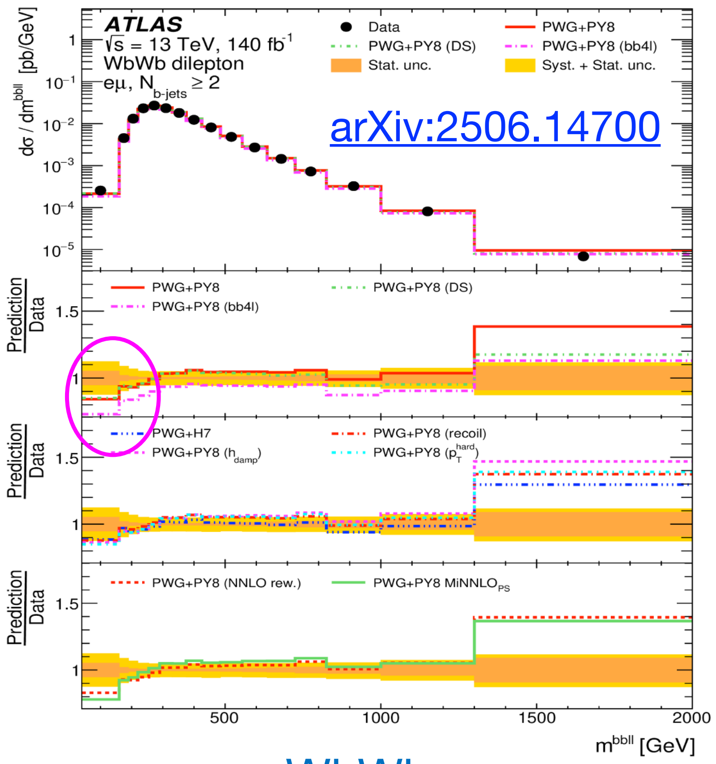


- Thanks to the advanced MC generators and high-order QCD/EW calculations
- In this talk, focus on $t\bar{t}$ production threshold region with 140 fb^{-1} LHC Run 2 pp data

Threshold Region Measurement is Challenging

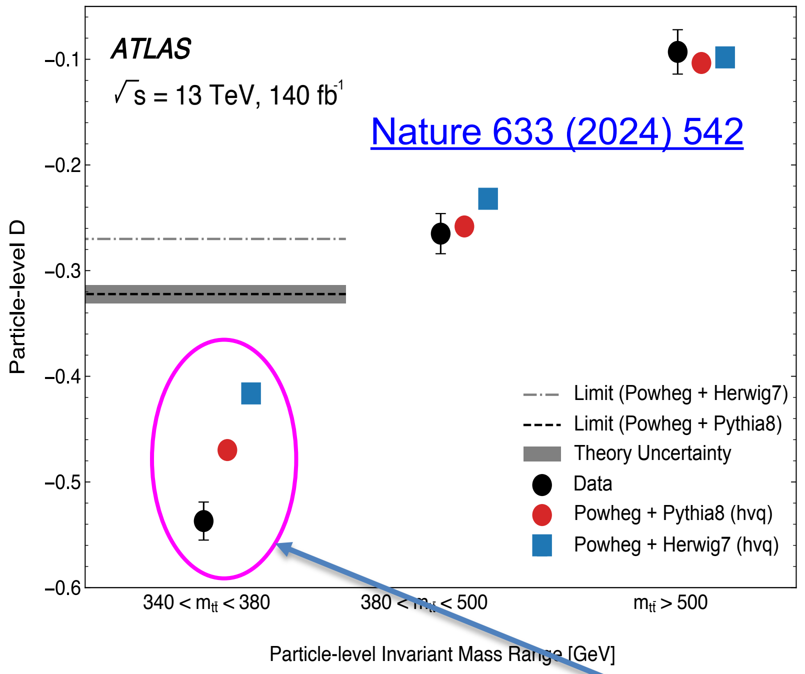
Experimentally very challenging: modelling of $t\bar{t}$ close to threshold region; tiny effect of quasi-bound state

Previous hints



WbWb

First Quantum Entanglement (QE) measurement using $t\bar{t}$ at LHC

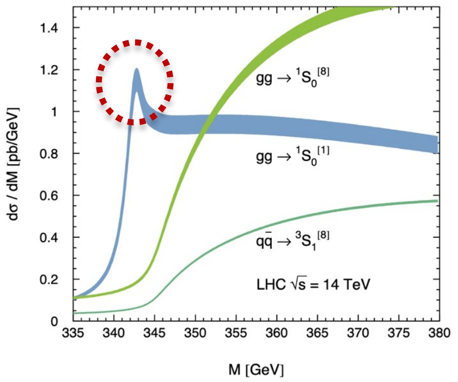


Stronger QE in data than MC.
Missing toponium contributions?

Threshold region has received a lot of attention recently in the context of quantum entanglement

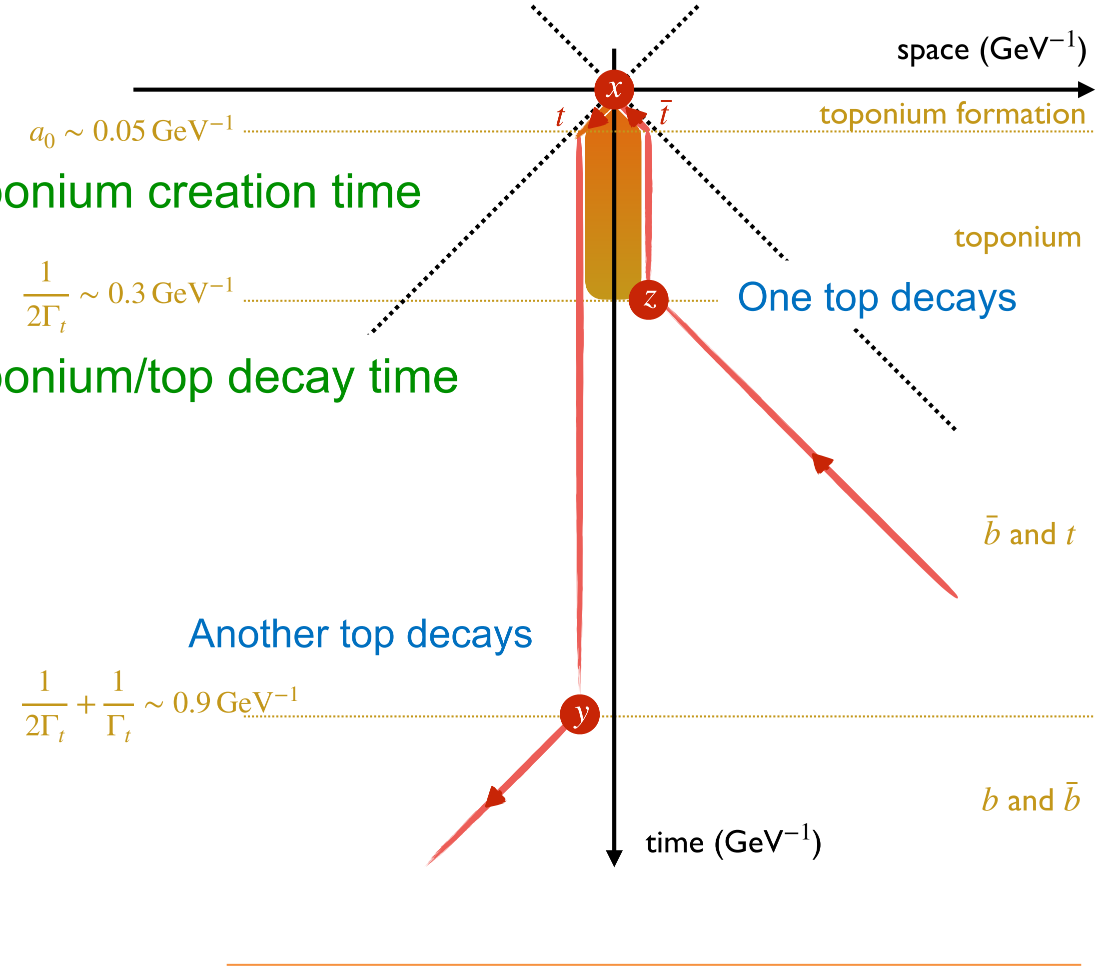
Top quark and $t\bar{t}$ Threshold Region

- Top quark is very special. Heaviest quark in the SM. Has largest Yukawa coupling to the Higgs field
- Very short life time → decays before forming any real hadron
- QCD predicts a quasi-bound state close to the threshold for low momentum top quarks (the prediction was made even before the top quark discovery)



EPJC 60 (2009) 375-386

From B. Fuks



Hadronization time scale: ~5 GeV^{-1}

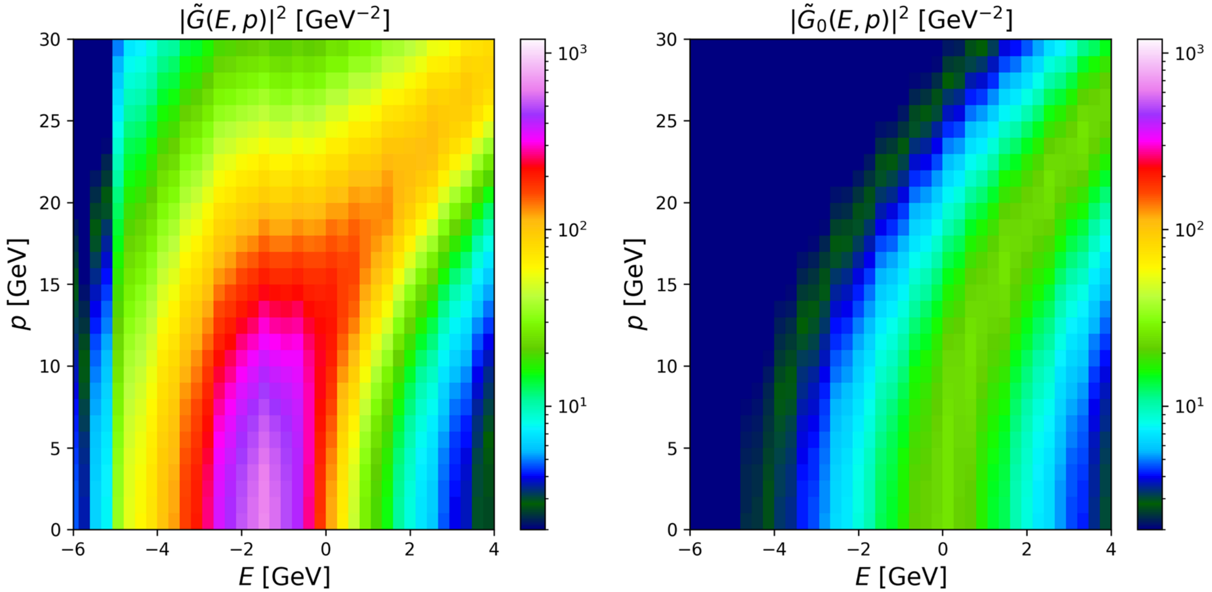
Quasi-bound State from NRQCD

- *S*-wave, color-singlet state with Green's function of non-relativistic (NR) QCD by B. Fuks *et al.*, Eur. Phys. J. C 85 (2025) 157
- Generate $gg \to tt \to b\ell\nu b\ell\nu$ with MG5_aMC. Spin correlations included
- Reweight matrix element with QCD Green's functions

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

$\tilde{G}$: Green's function considering QCD potential

$\tilde{G}_0$: Free Green's function



This model includes NRQCD calculations. More complete w.r.t. previous simplified models (using scalar/pseudoscalar as an effective model)

Background Modelling

Extremely challenging measurement: need precise modelling of the $t\bar{t}$ threshold region

- $t\bar{t}$: main background. Powheg v2 hvq + Pythia8, using narrow-width approximation (NWA). $m_t = 172.5$ GeV
  - 2D reweighting in (cosθ*, M($t\bar{t}$)) to NNLO QCD (from MATRIX) and NLO EW (HATHOR)
  - θ*: angle between the momentum of the top quark in the $t\bar{t}$ center-of-mass frame and the momentum of the $t\bar{t}$ system in the lab. frame
- $t\bar{t}$: alternative MC sample (for syst.), Powheg v2 bb4l + Pythia8
  - Simulate $pp \to b\ell\nu b\ell\nu$ including off-shell, non-resonant contributions, and exact spin correlations at NLO

Event Selections

Target for dilepton channel $tt \rightarrow b\ell\nu b\ell\nu$ SR: Signal Region;   CR: Control Region

SRs	CR-Z	CR-Fakes
$= 2\ell$ with $p_{\mathrm{T}}(\ell) \geq 10$ GeV ≥ 1 trigger-matched lepton with $p_{\mathrm{T}} \geq 25/27/28$ GeV ≥ 2 jets with $p_{\mathrm{T}} \geq 25$ GeV ≥ 1 b-tagged jet (70% efficiency WP) $m_{\ell\ell} \geq 15$ GeV $m_{t\bar{t}} \leq 500$ GeV		
$E_{\mathrm{T}}^{\mathrm{miss}} \geq 60$ 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

OSSF: opposite-sign, same-flavor

CRs are for correcting Z+jets and Fakes normalization in fit

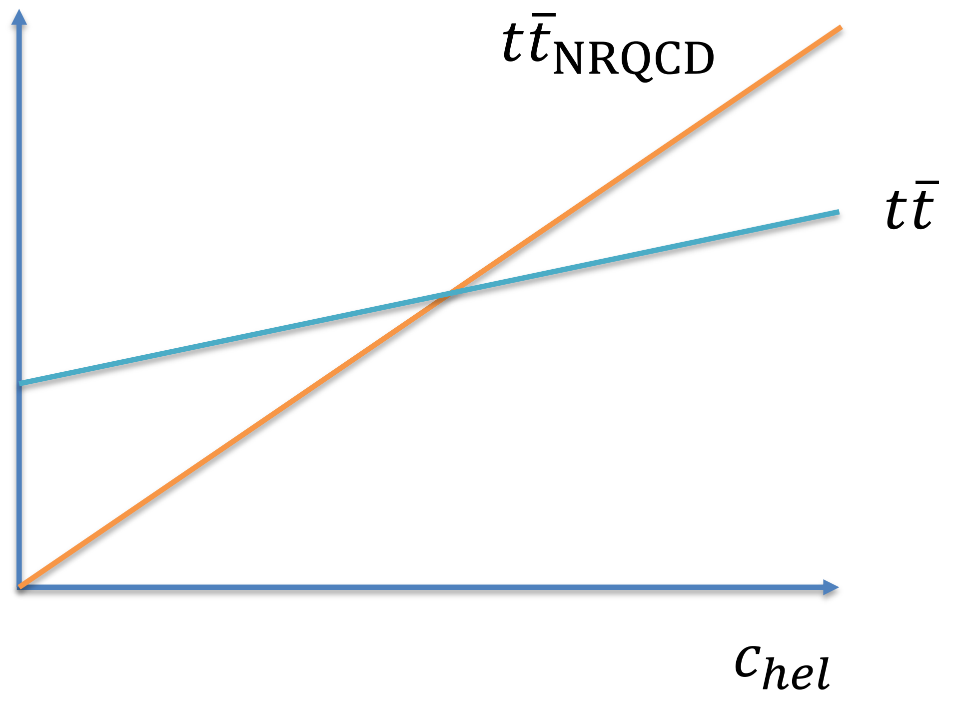
Event Categorization

SR events are categorized into 9 regions based on two observables: c_{hel} and c_{han}

$$c_{hel} = \vec{\ell}_{+} \cdot \vec{\ell}_{-} \, ,$$

where the $\vec{\ell}_{\pm}$ are the lepton directions in $t\bar{t}$ center-of-mass frame, and then in turn boosted into t and $\bar{t}$ frames. This distribution has a maximum slope for a spin-singlet state

c_{han}: flip the $\vec{\ell}$ in t direction. This distribution has a maximum slope for a spin-triplet state



c_{hel} is useful to separate pseudoscalar from other contributions

Event Categorization and Fitting

	$-1 < c_{hel} < -\frac{1}{3}$	$-\frac{1}{3} < c_{hel} < \frac{1}{3}$	$\frac{1}{3} < c_{hel} < 1$
$-1 < c_{han} < -\frac{1}{3}$	SR1	SR2	SR3
$-\frac{1}{3} < c_{han} < \frac{1}{3}$	SR4	SR5	SR6
$\frac{1}{3} < c_{han} < 1$	SR7	SR8	SR9

CR-Fakes ee	CR-Fakes $e\mu$	CR-Fakes $\mu\mu$		CR-Z

Simultaneous fitting to $m_{t\bar{t}}$ with 13 categories with profile likelihood method

Background Estimations

- $t\bar{t}$: with a free-floating scale factor (SF); tW: estimation from MC
- Z+jets: get some contributions from Z$\rightarrow\tau\tau$. Use the CR-Z to normalize the Z+b process
- fake / non-prompt leptons: Fakes represent 1.5% of SR yields. Data-driven estimation with 3 CR-Fakes

Pre-fit plots

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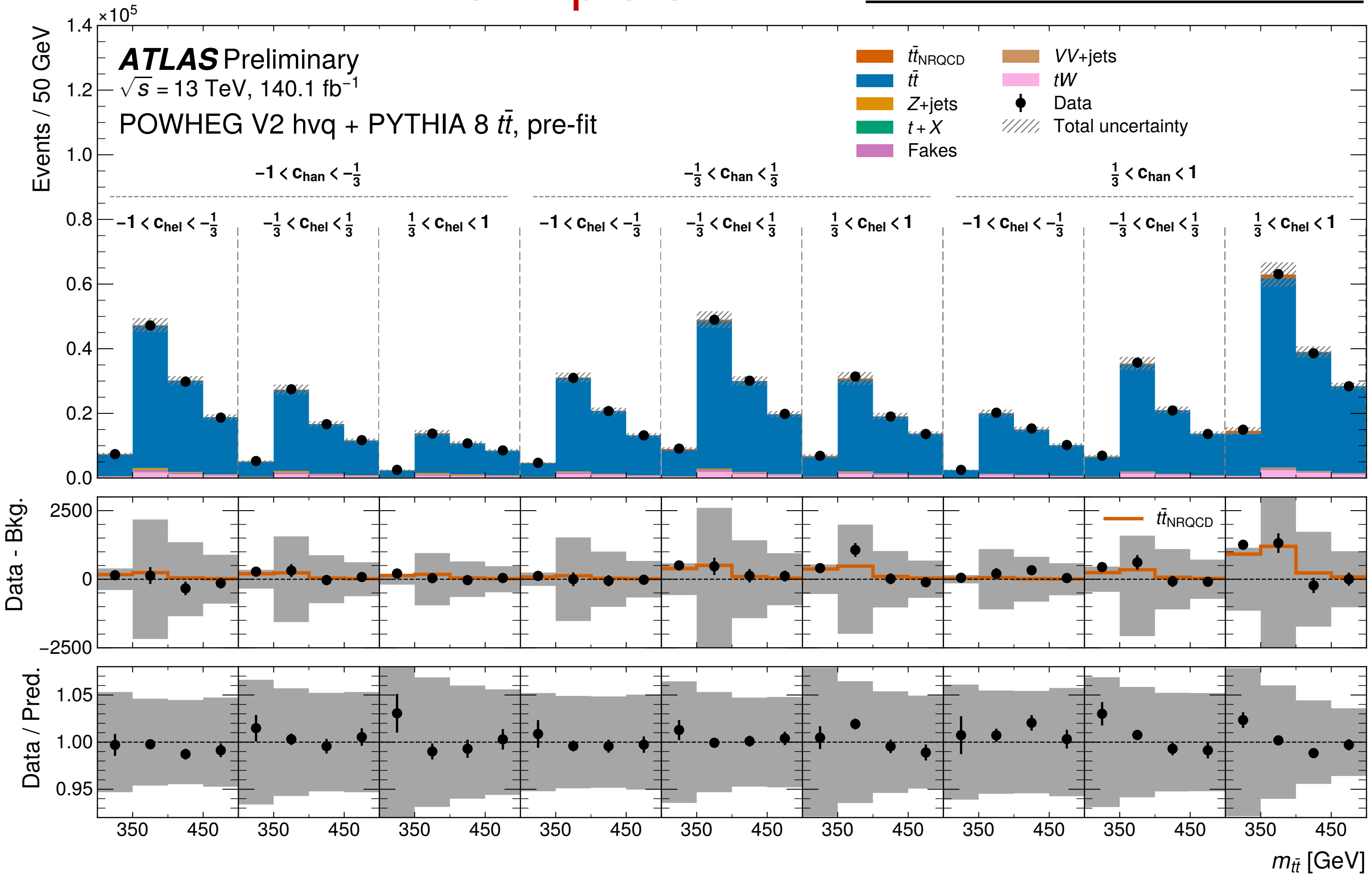

Results: baseline $t\bar{t}$ + quasi-bound state (NRQCD)

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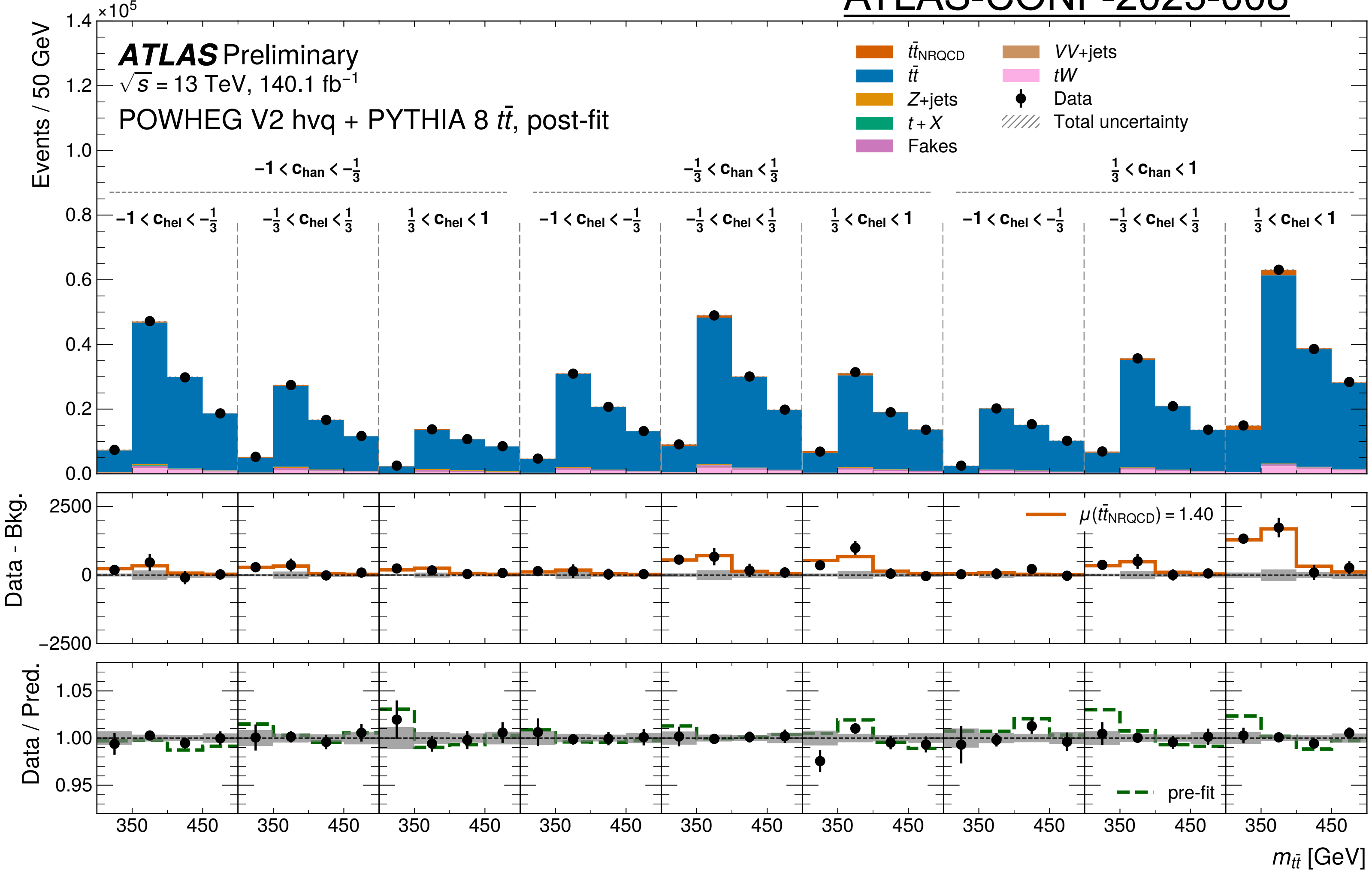
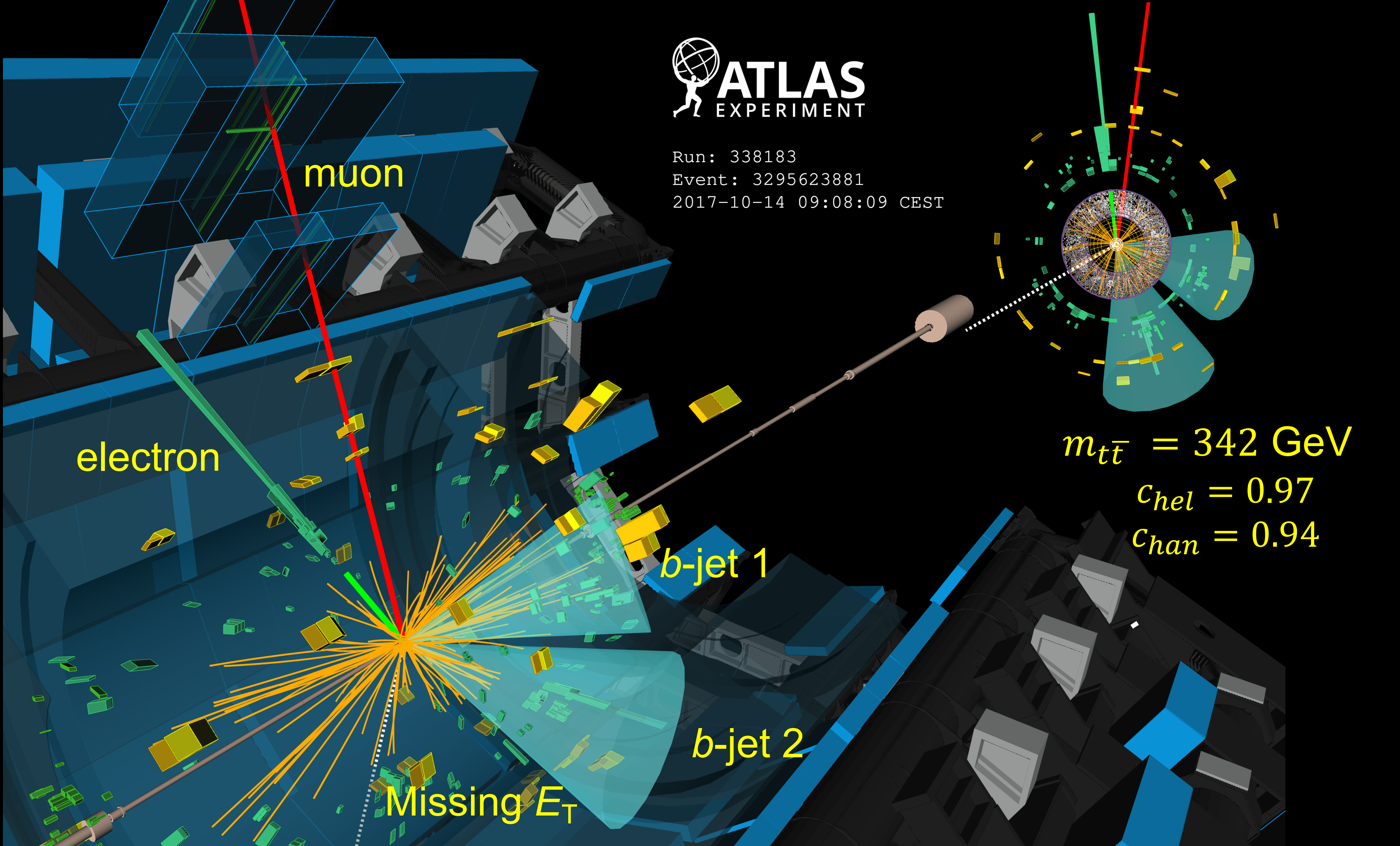
Observed (expected) significance: 7.7σ (5.7σ)

Goodness-of-Fit: 0.93



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



ATLAS
EXPERIMENT
Run: 338183
Event: 3295623881
2017-10-14 09:08:09 CEST
muon
electron
b-jet 1
b-jet 2
Missing E_T
$m_{t\bar{t}} = 342$ GeV
$c_{hel} = 0.97$
$c_{han} = 0.94$

Impacts of Systematics

- Quasi-bound state modelling: Parton shower [Herwig7]
- $t\bar{t}$ decay and off-shell [comparison to bb4l]
- NNLO QCD rew.: NNLO QCD scale variations

- No strong pulls or constraints
- Largest effects from toponium modelling and off-shell effect modelling

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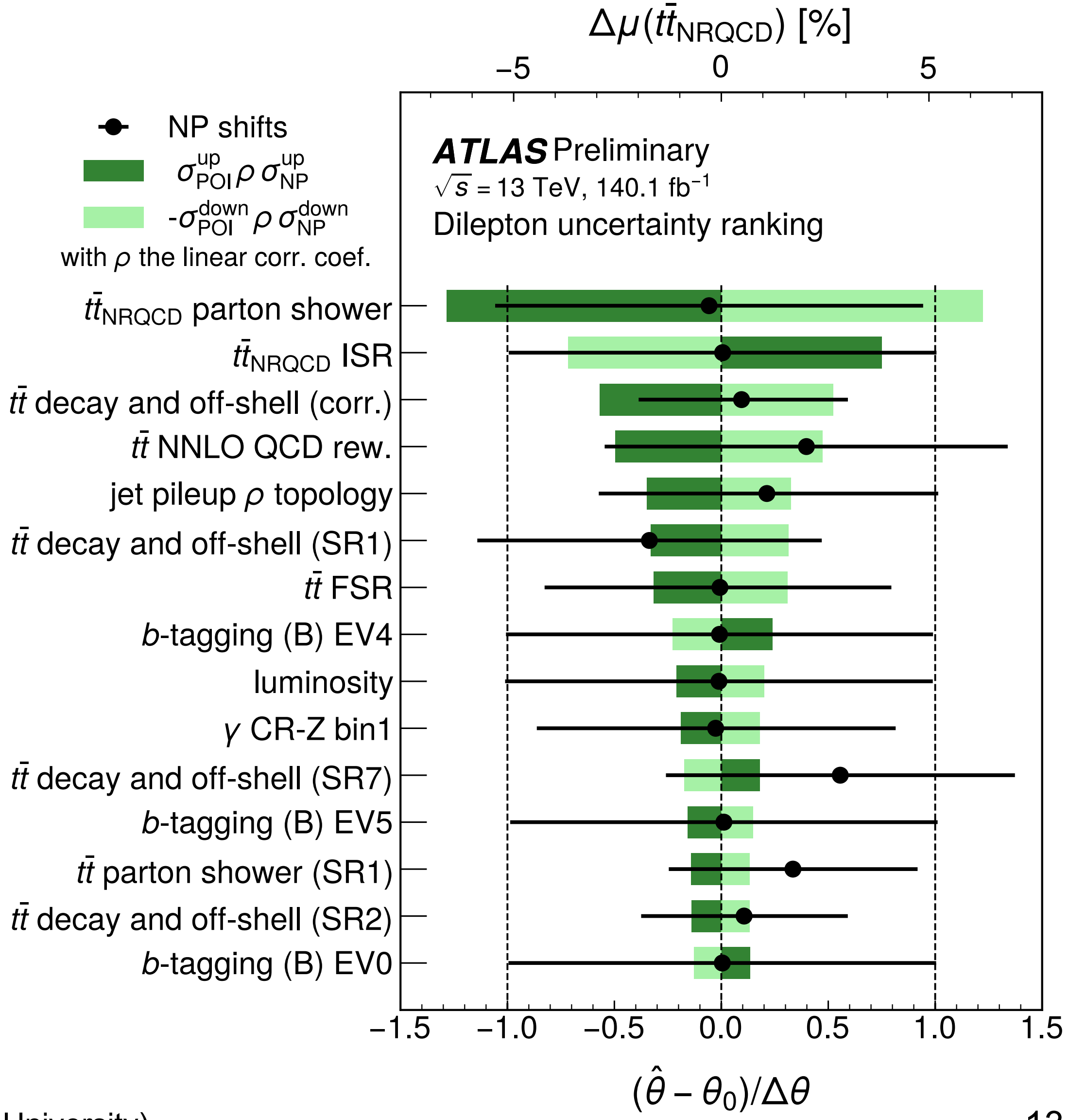

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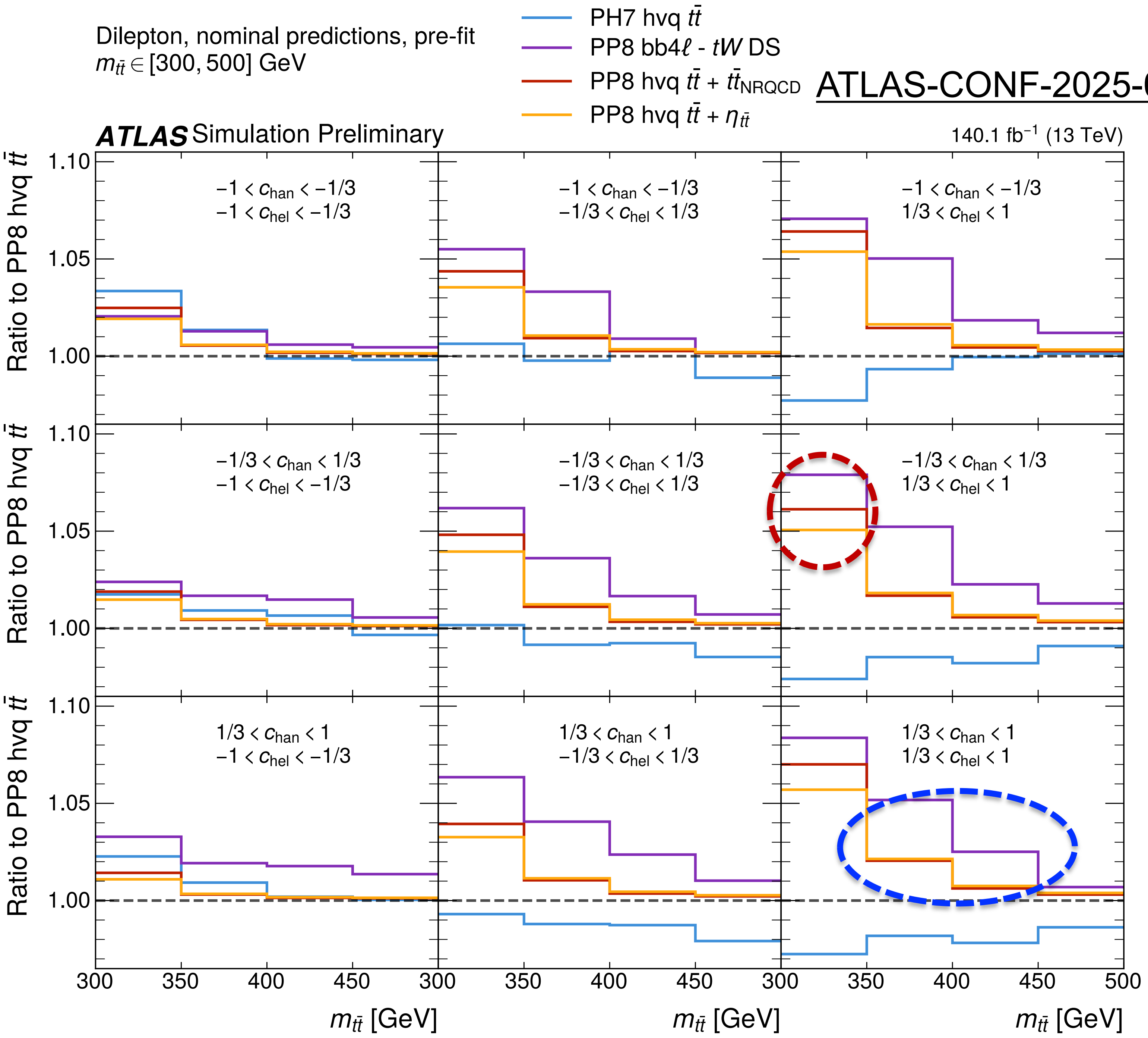
Category	Impact
$t\bar{t}_{\text{NRQCD}}$ modelling	5.3%
$t\bar{t}$ modelling	3.5%
Jet energy scale (pileup)	1.3%
b-tagging	1.2%
Instrumental (other)	0.9%
Limited MC statistics	0.7%
Jet energy scale (flavour)	0.5%
Background normalisations	0.4%
tW modelling	0.4%
Jet energy scale (η inter-calibration)	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%

Ratios of the pre-fit distributions for $t\bar{t}$ MC models vs. baseline Powheg hvq



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- Low $m_{t\bar{t}}$ region: bb4l is more similar to hvq+toponium than hvq only
- High $m_{t\bar{t}}$ region: bb4l differs from hvq+toponium model

Conclusions

- An excess of events is observed over the NNLO perturbative QCD prediction, with **7.7σ observed (5.7σ expected)** near the $t\bar{t}$ production threshold by ATLAS with LHC Run 2 data. [ATLAS-CONF-2025-008], [ATLAS Physics Briefing]
- This excess is consistent with **color-singlet, S-wave, quasi-bound $t\bar{t}$ states** predicted by NRQCD with cross-section of 9.0 ± 1.3 pb
- A more complete model from NRQCD calculation is used in this analysis. Important advantage compared with recent CMS results (arXiv:2503.22382)
- This results show the strength of the LHC as a precision machine
- **Observation of toponium** opens a new field to study NRQCD with top quarks
- More work to characterize this excess and to better quantify the impact of off-shell top-quark decays

Top quark and anti top quark "shake their hands" before they decay

Backup

Simplified model for $t\bar{t}$ quasi-bound states

- A pseudo-scalar spin-singlet resonance or as a combination of scalar and pseudo-scalar resonances. Mostly pseudo-scalar ${}^{1}S^{[1]}$ configuration
- The contributions from states with higher total angular momentum J and color-octet states are expected to be sub-dominant and are neglected in this model
- In contrast, the main $t\bar{t}$ quasi-bound-state model used in this study includes the full set of S-wave color-singlet contributions, incorporating both bound state and scattering-state effects

More Information for Fitting

- Profile likelihood fitting to $m_{t\bar{t}}$
- Control regions: use the 3 CR-Fakes to extract scale factors (SF) for heavy-flavor and photon-conversion electron fakes, and heavy-flavor muon fakes; use the CR-Z to normalize the Z+b process
- Signal regions: use the 9 SRs to extract a SF for regular $t\bar{t}$ and signal strength for quasi-bound state $t\bar{t}$
- Nuisance parameters (NPs) correlation scheme for constraint ones: In the case of NPs that are strongly constrained to less than 50% of their prior uncertainty, the original systematic variation is treated as partially (50%) correlated between SRs and CRs

Alternative fit: Powheg hvq + simplified model of toponium

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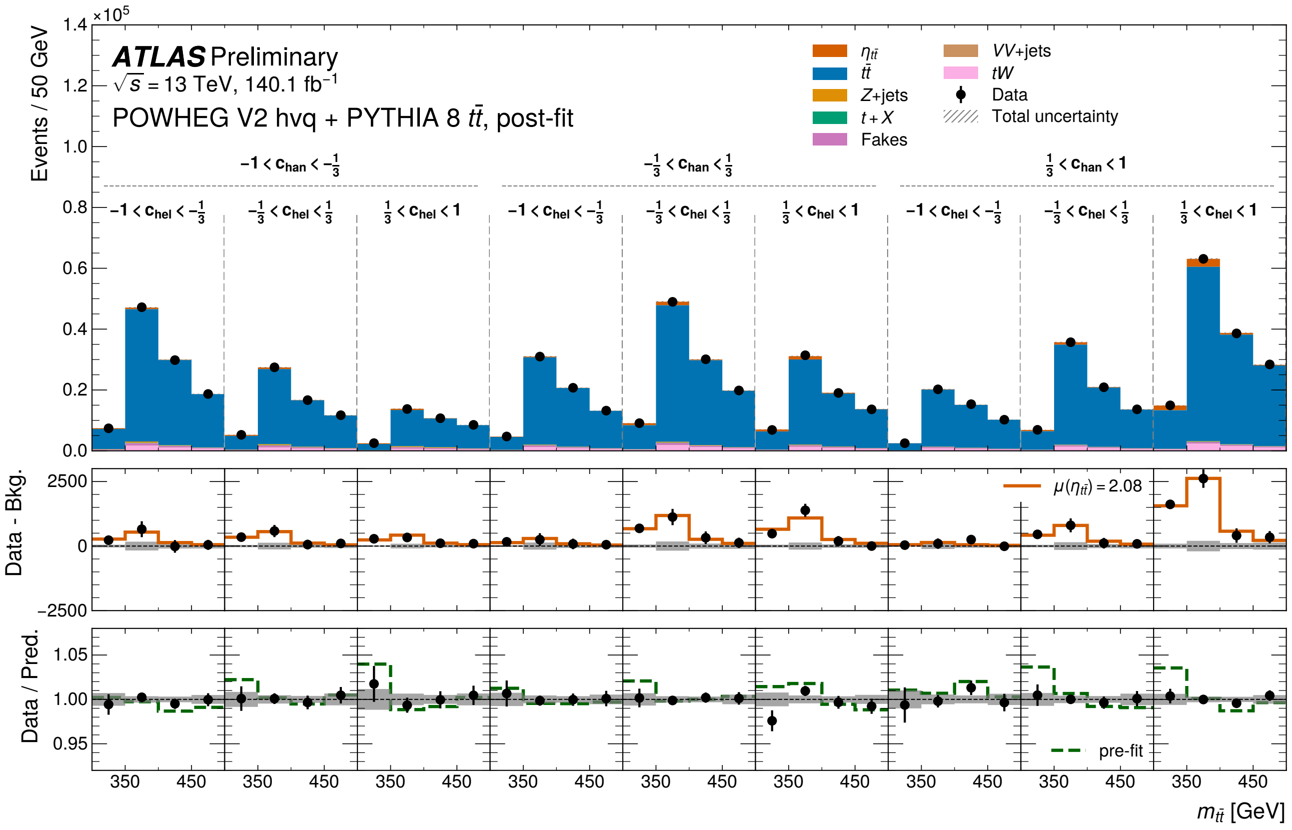
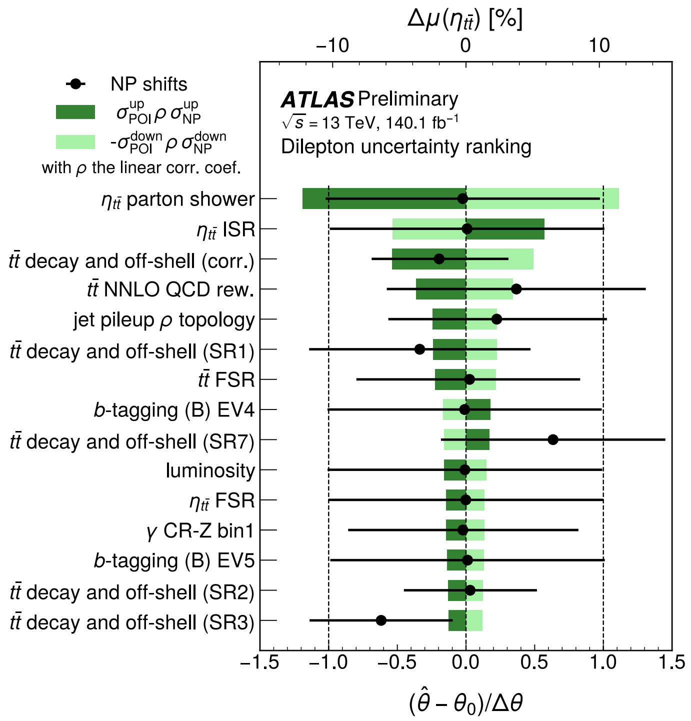
Observed (expected) significance of 7.8σ (4.0σ)

Goodness-of-Fit: 0.95





Alternative fit: Powheg bb4l + quasi-bound state (NRQCD)

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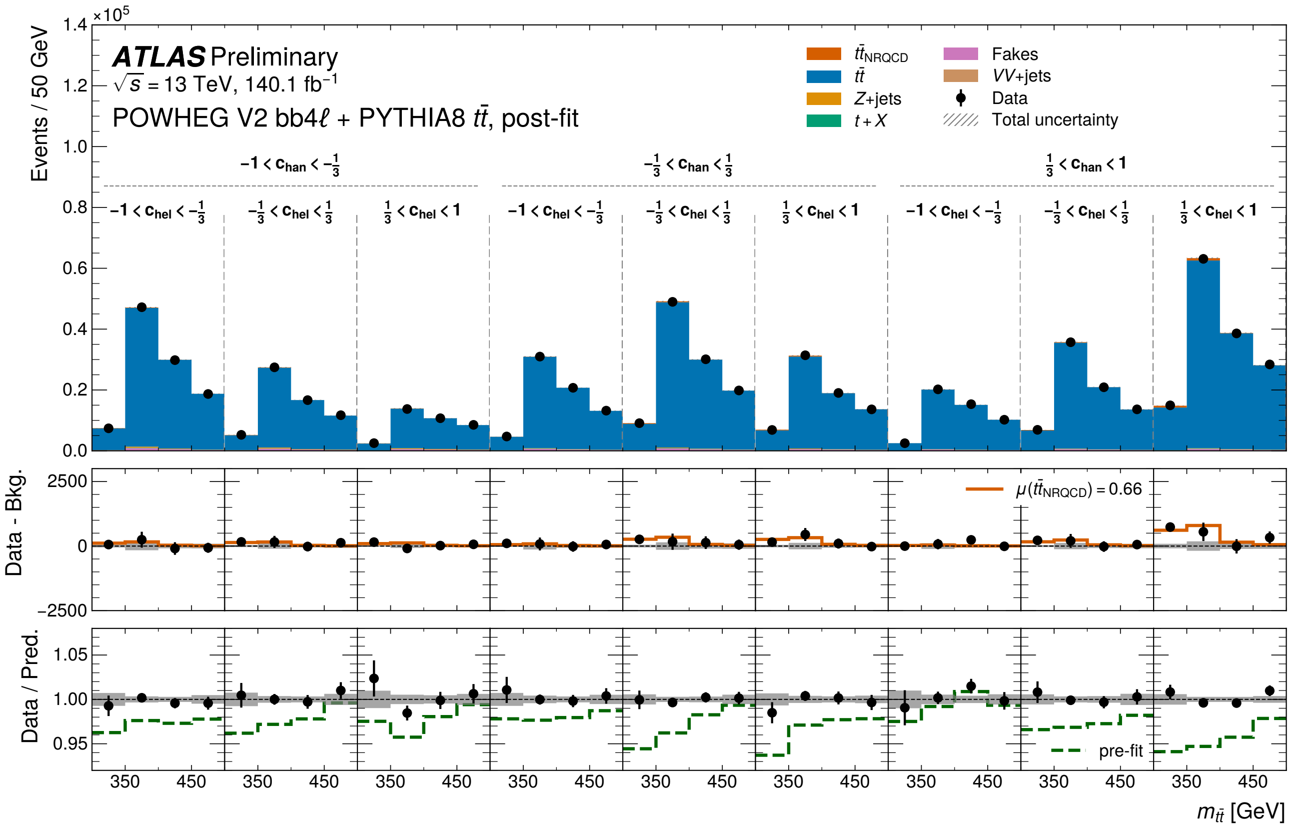
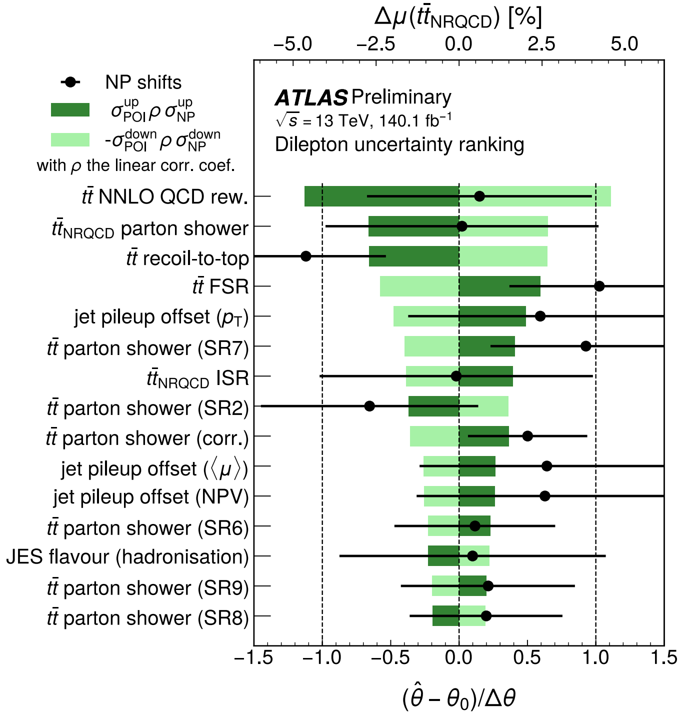
Observed (expected) significance of 4.3σ (6.3σ)

Goodness-of-Fit: 0.54





Reconstruction of the $t\bar{t}$ System

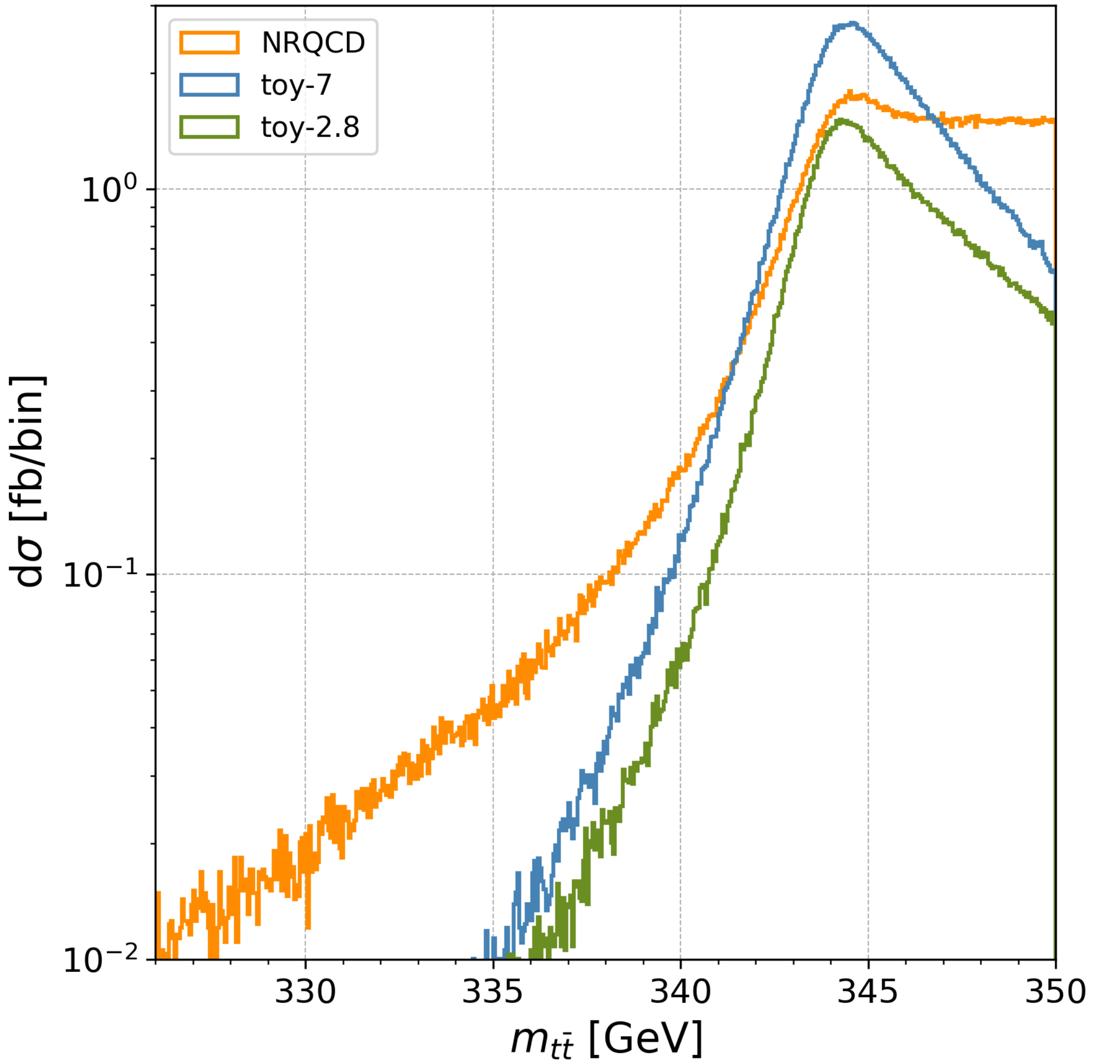
- Ellipse Method [NIM A 736 (2014) 169]: geometric/analytic approach that imposes W and top mass constraints
- The two b-tagged jets associated with the decays of the top and antitop quark are chosen from all selected hadronic jets. If more than two of them are b-tagged, the two leading b-tagged jets are selected. If there is only one b-tagged jet, the highest-pT jet among the remaining untagged ones is selected.
- The Ellipse Method provides a solution for about 95% of $t\bar{t}$ dilepton events

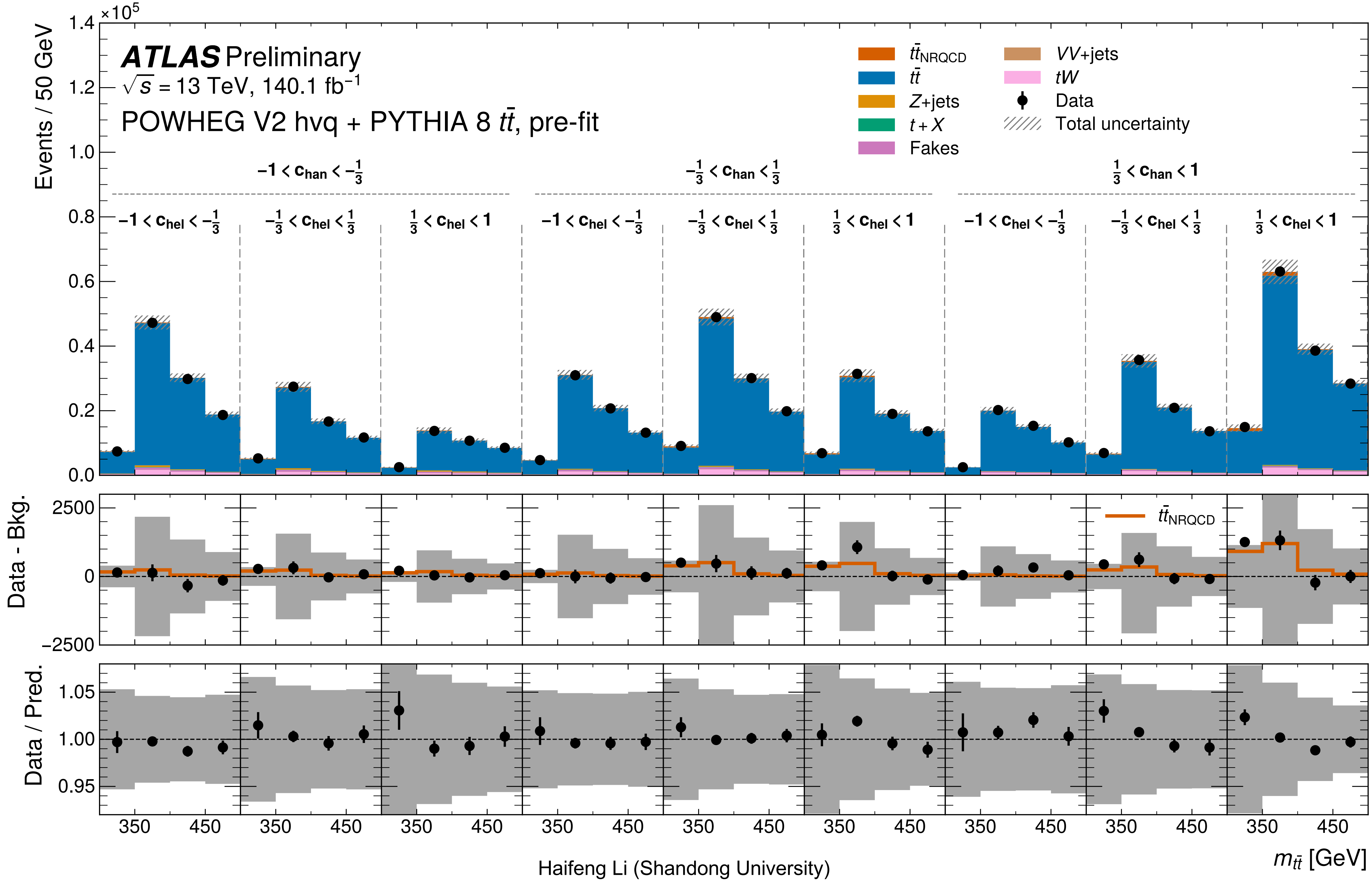
Systematics

- **Experimental systematics**: Electron, muon, jet, b-jet tagging, Missing E_T, pileup, and luminosity
- **$t\bar{t}$ modelling**: Parton shower [Herwig7], decay and off-shell [comparison to bb4l], matching [$p_{\mathrm{T}}^{\mathrm{hard}}, h_{\mathrm{damp}}$], recoil-to-top, underlying event [A14 Var1], color reconnection [CR0 vs CR1/CR2 models], top mass [$\pm$0.5 GeV], ISR/FSR, PDF4LHC15, NNLO QCD scale variations, NLO EW scheme
- **tW modelling**: Parton shower [Herwig7], matching [$p_{\mathrm{T}}^{\mathrm{hard}}, h_{\mathrm{damp}}$], interference scheme [DR/DS], top mass [$\pm$0.5 GeV]
- **Background normalizations**: 4% tW, 20% $t\bar{t}$+b, 40% $t\bar{t}$+c, 50% top+X, 50% Z+c/light, 50% diboson
- **Quasi-bound state modelling**: μ_r/μ_f variations, PDF4LHC21, parton shower [Herwig7], ISR/FSR

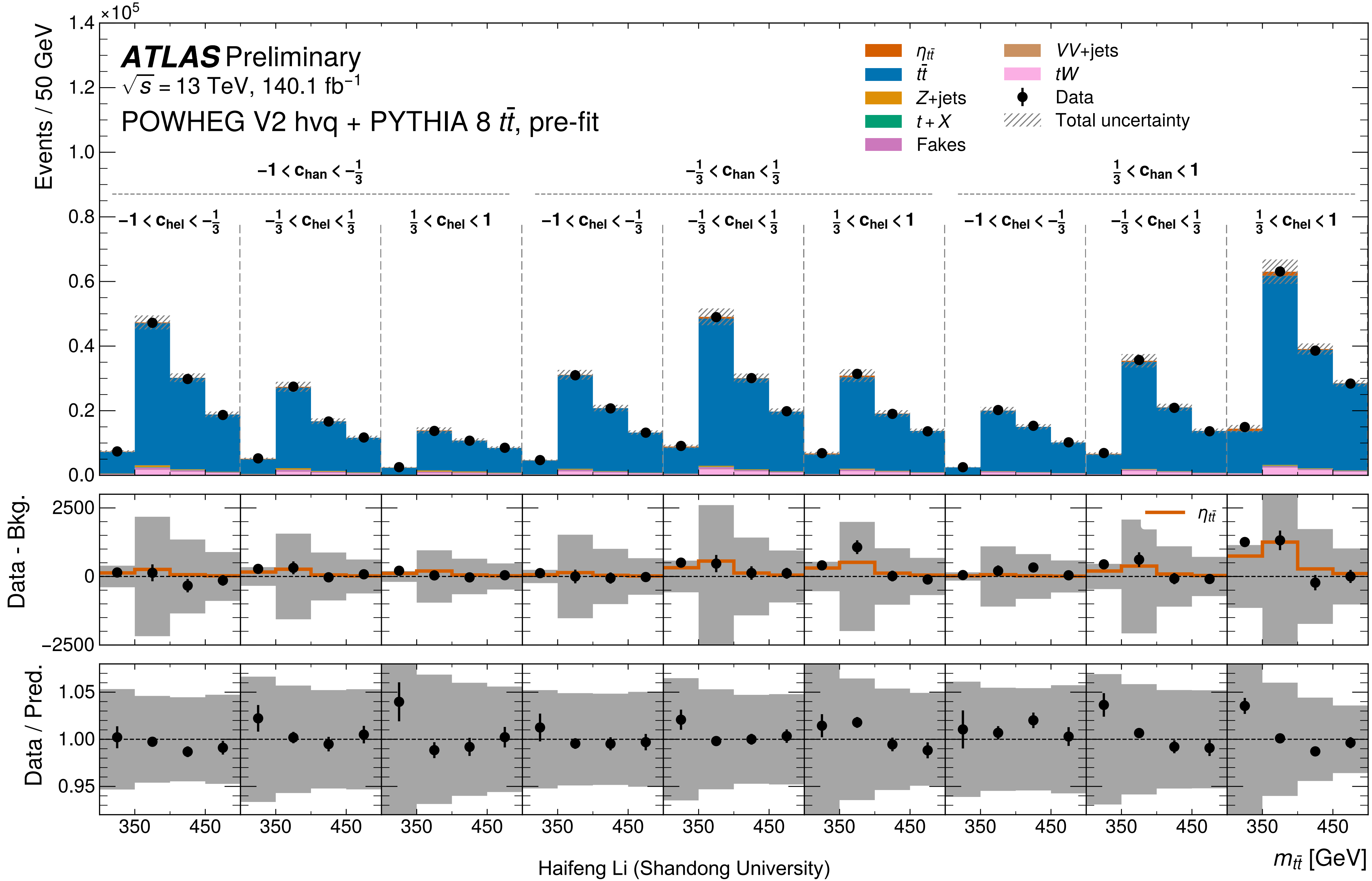
From Benjamin Fuks

LHC Top WG meeting 4-6 June 2025, CERN





ATLAS Preliminary
$\sqrt{s}$ = 13 TeV, 140.1 fb^{-1}
POWHEG V2 hvq + PYTHIA 8 $t\bar{t}$, pre-fit
$t\bar{t}_{NRQCD}$
$t\bar{t}$
Z+jets
$t+X$
Fakes
VV+jets
tW
Data
Total uncertainty
$-1 < c_{han} < -\frac{1}{3}$
$-\frac{1}{3} < c_{han} < \frac{1}{3}$
$\frac{1}{3} < c_{han} < 1$
$-1 < c_{hel} < -\frac{1}{3}$
$-\frac{1}{3} < c_{hel} < \frac{1}{3}$
$\frac{1}{3} < c_{hel} < 1$
Events / 50 GeV
×10^5
Data - Bkg.
Data / Pred.
$m_{t\bar{t}}$ [GeV]



Haifeng Li (Shandong University)