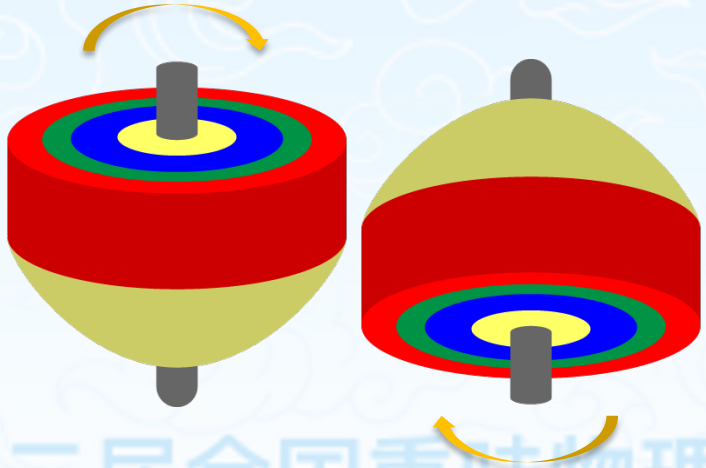
Discovery of Toponium



李海峰

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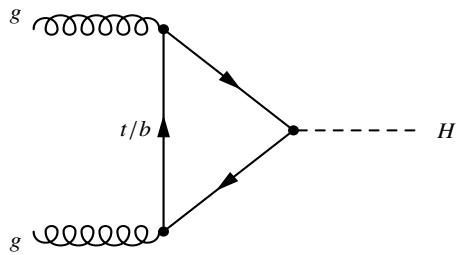
第二十二届全国重味物理与CP破坏研讨会

2025年10月24日-28日，北京大学

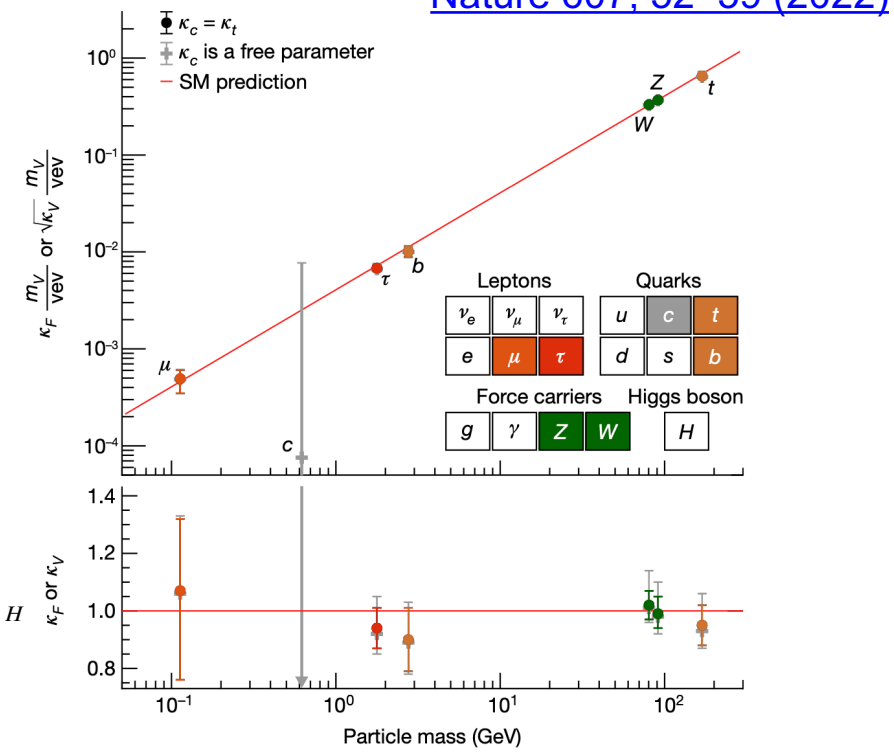
Introduction

- Top quark is very special. Heaviest quark in the SM. Has largest Yukawa coupling to the Higgs field ($y_t \sim 1$)
- Very short life time → decays before forming any real hadron → access to 'bare' quark

$$\underbrace{\frac{1}{m_t}}_{\text{production}\ 10^{-27}\ \text{s}} < \underbrace{\frac{1}{\Gamma_t}}_{\text{lifetime}\ 10^{-25}\ \text{s}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\text{hadronization}\ 10^{-24}\ \text{s}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\text{spin-flip}\ 10^{-21}\ \text{s}}$$



Nature 607, 52–59 (2022)

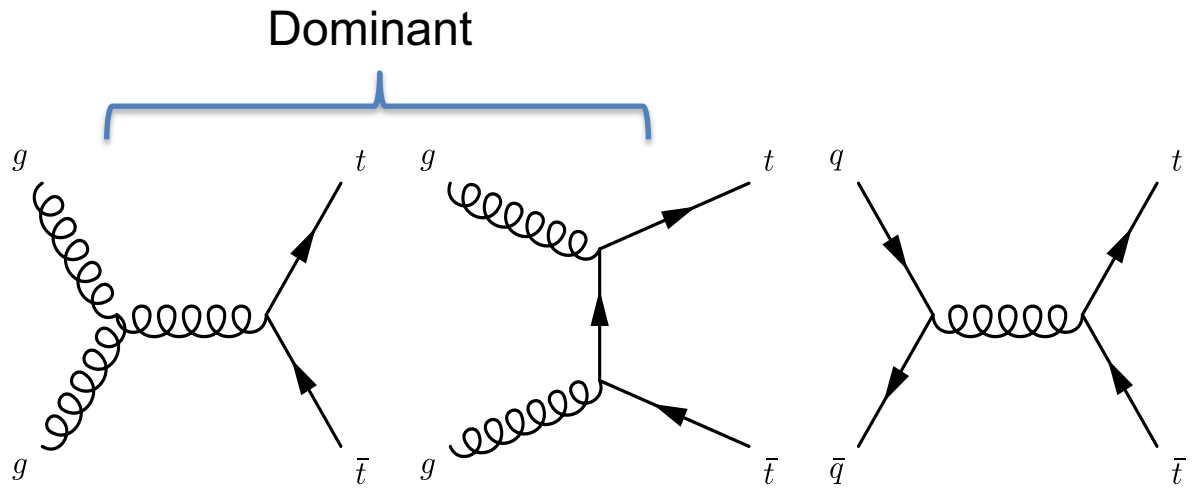


30th anniversary of the top-quark discovery

- Precision measurements of top quark: important for testing the SM and looking for new physics beyond SM

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

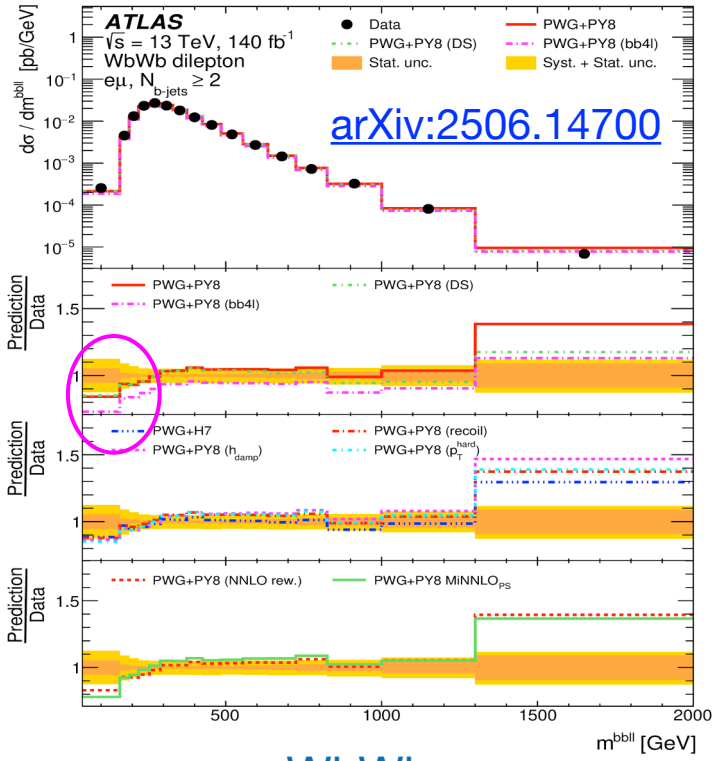


- Thanks to the advanced MC generators and high-order QCD/EW calculations
- In this talk, focus on $t\bar{t}$ production threshold region with 140 fb^{-1} LHC Run 2 pp data

Threshold Region Measurement is Challenging

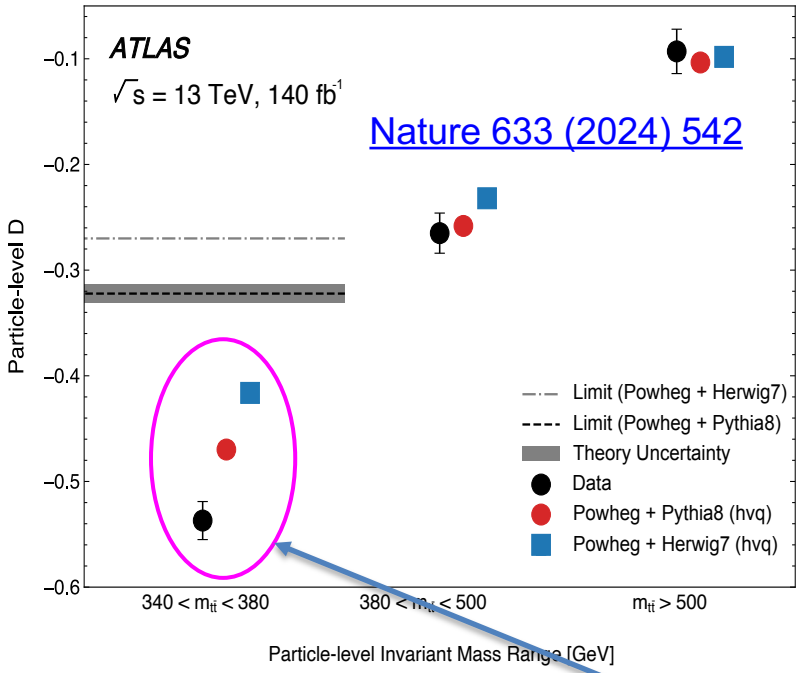
Experimentally very challenging: modelling of $t\bar{t}$ close to threshold region; tiny effect of quasi-bound state

Previous hints



WbWb

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



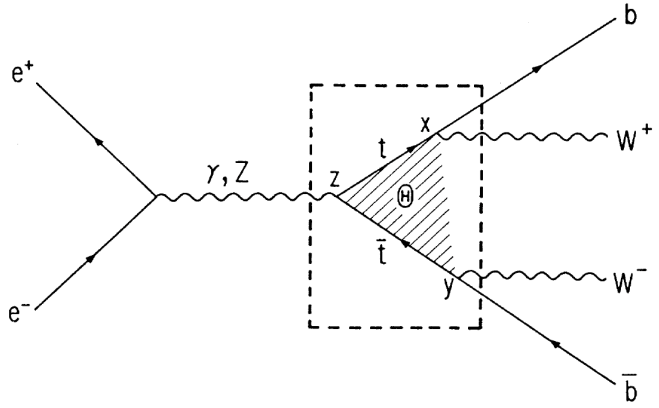
Stronger QE in data than MC.
Missing toponium contributions?

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

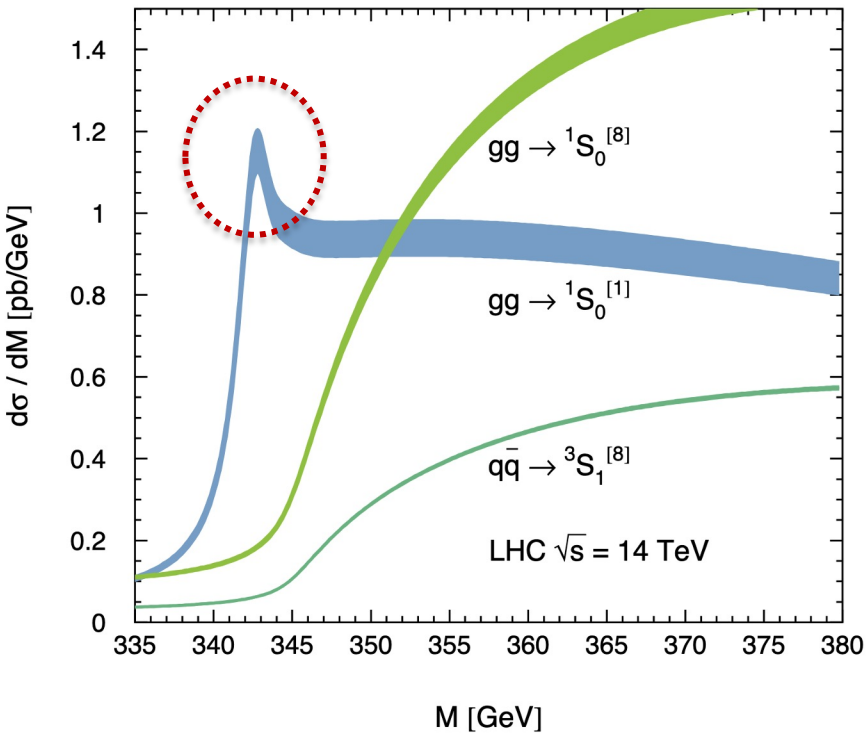
Top quark and $t\bar{t}$ Threshold Region

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)

Phys. Rev. D 47 (1993) 56



EPJC 60 (2009) 375-386



部分理论文章：

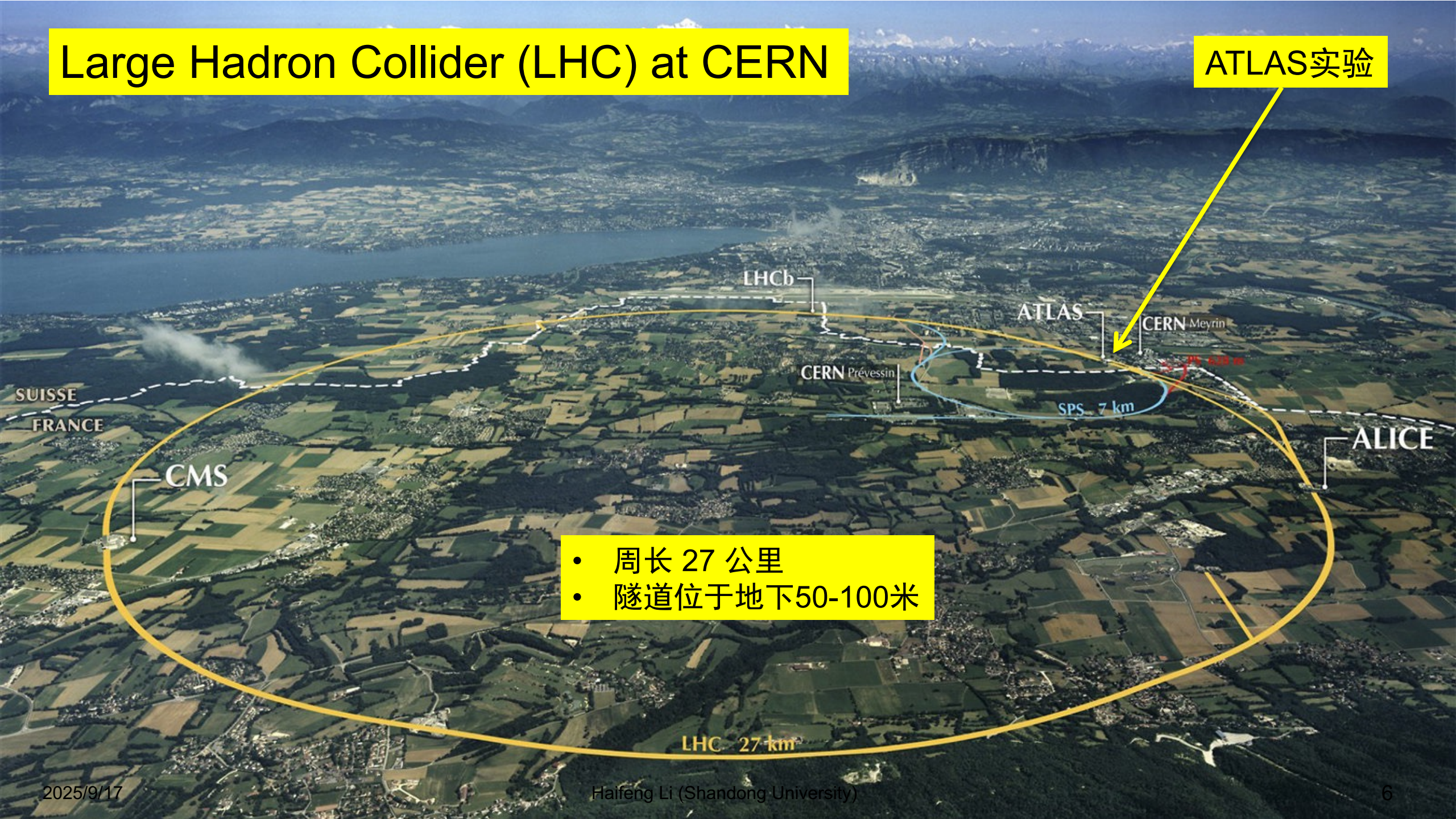
V.S. Fadin and V.A. Khoze, JETP Lett. 46 (1987) 525

Y. Sumino *et al.*, Phys. Rev. D 47 (1993) 56

W.-L. Ju *et al.*, JHEP 06 (2020) 158

Toponium理论详见杨李林老师的报告

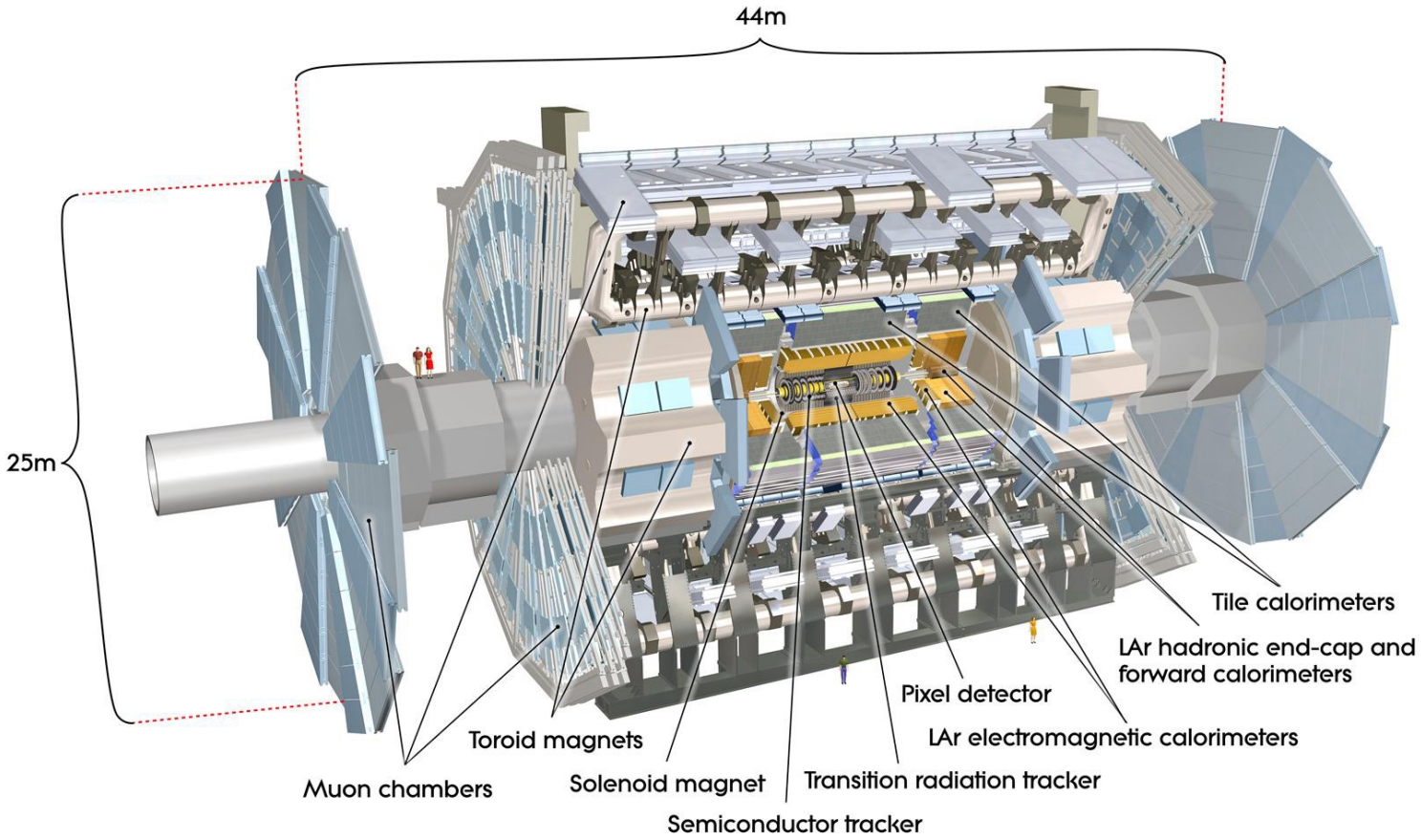
Large Hadron Collider (LHC) at CERN



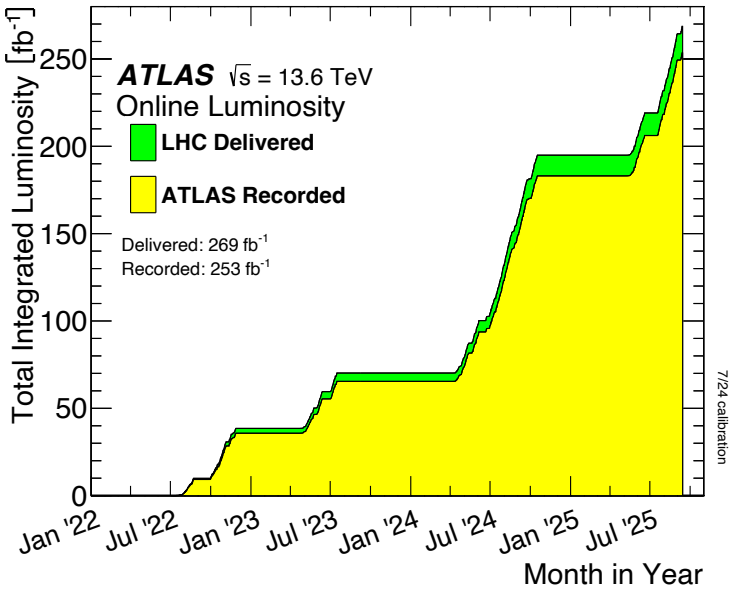
- 周长 27 公里
- 隧道位于地下50-100米

ATLAS (A Toroidal LHC ApparatuS)

- 约2900位科学作者
- 1190位博士研究生
- 1304位工程师
- 5940位活跃成员



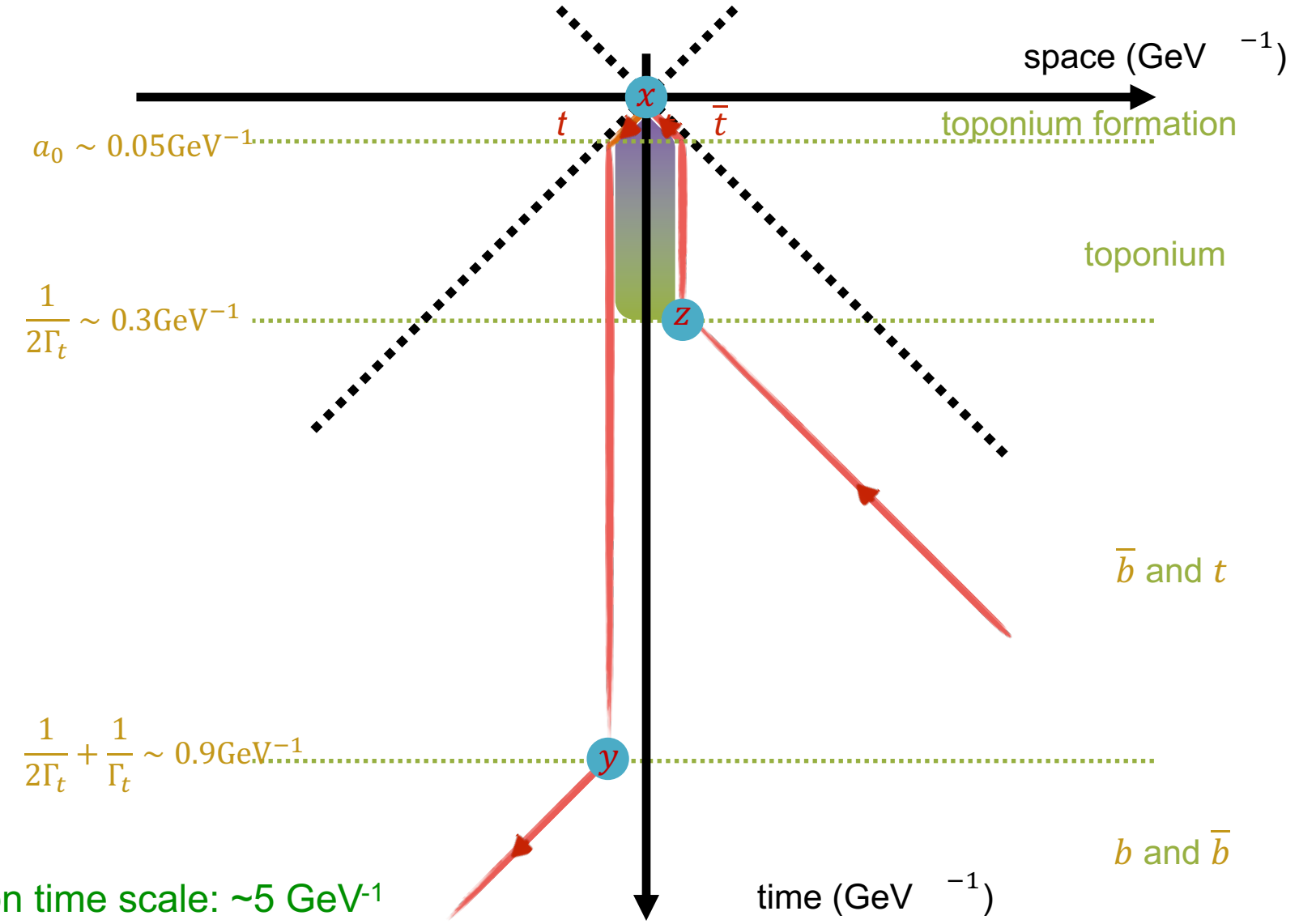
ATLAS already recorded 253 fb^{-1} for Run 3



ATLAS Results

Top-antitop production near threshold

From B. Fuks



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

The toponium Green's function

From B. Fuks

$$K_{abcd}(x,y,z) = \left\langle 0 \left| T\{ t_c(y)\bar{t}_d(z) : \bar{t}_a(x) t_b(x) : \} \right| 0 \right\rangle$$

$$= \frac{(1+\gamma^0)_{ca}}{2} \frac{(1-\gamma^0)_{bd}}{2} \int \mathrm{d}^3 r \left[K_1\left(y; (z^0, \vec{r})\right) K_2(z^0, \vec{r}, \vec{z}; x^0, \vec{x}, \vec{x}) + K_1\left(z; (y^0, \vec{r})\right) K_2(y^0, \vec{y}, \vec{r}; x^0, \vec{x}, \vec{x}) \right]$$

Antitop-decay first

Top-decay first

Non-relativistic spin projection operators

1-particle-state and 2-particle-state propagators

The toponium Green's function

- Solution to the Lippmann-Schwinger equation
  - Fourier transform of the QCD potential
  - S-wave contributions
- To be solved numerically

$$\widetilde{G}(E;p) = \widetilde{G}_0(E;p) + \int \frac{\mathrm{d}^3 q}{(2\pi)^3} \widetilde{V}_{\mathrm{QCD}}(\vec{p}-\vec{q})\, \widetilde{G}(E;q)$$

Free Green's function

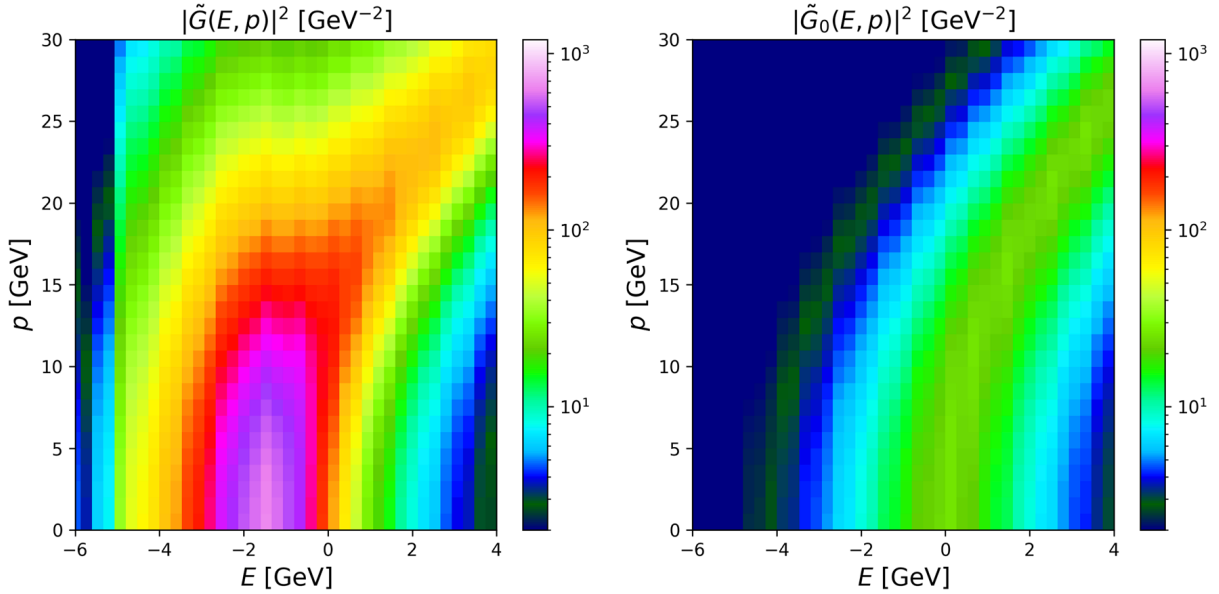
Quasi-bound State from NRQCD

- *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

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

$\tilde{G}$: 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), with approximate spin correlation
  - 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

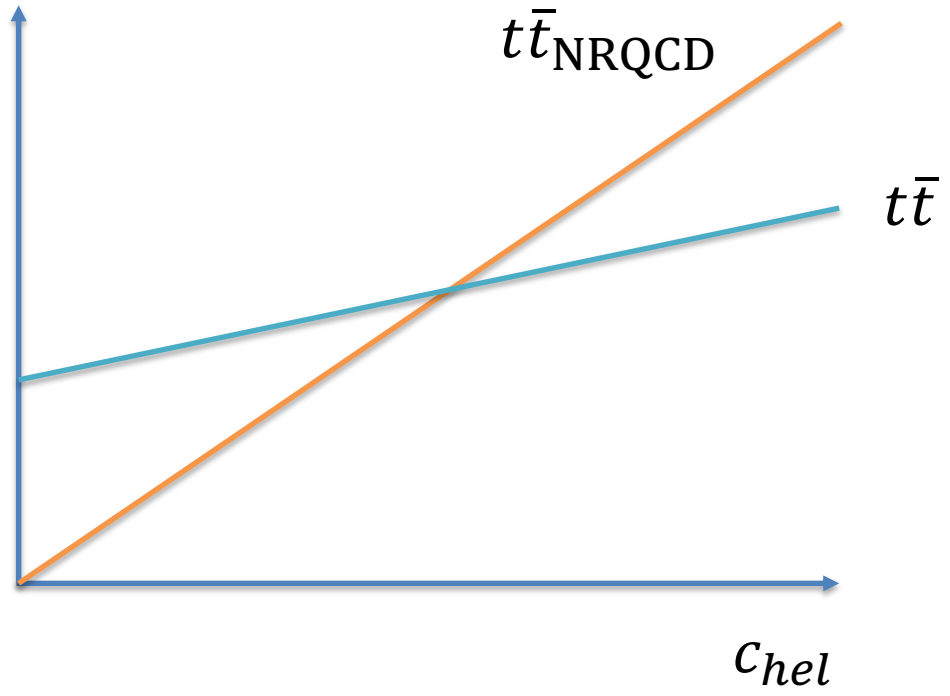
Event Categorization

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

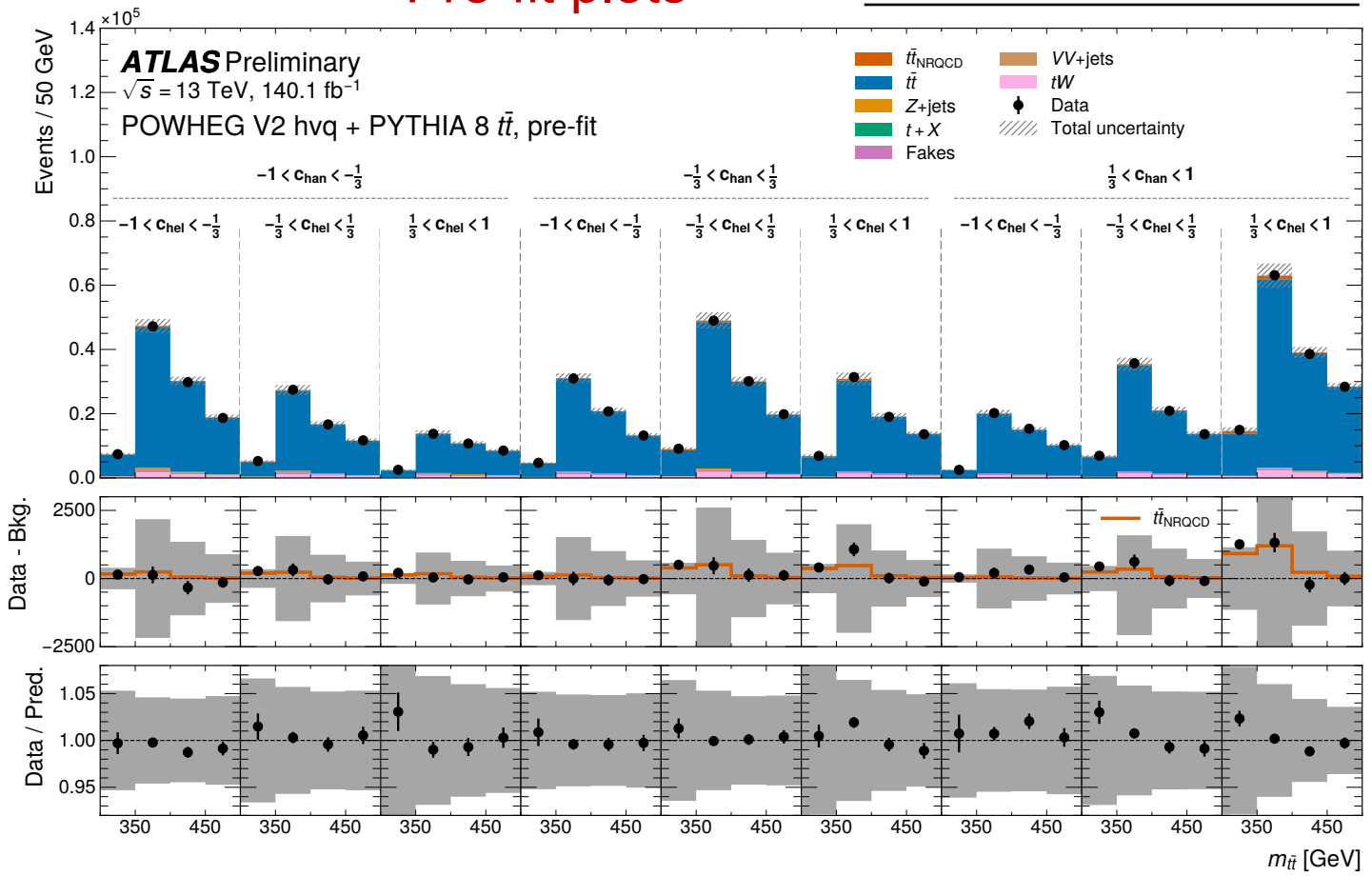
Simultaneous fitting to $m_{t\bar{t}}$ with 13 categories with profile likelihood method

Background Estimations

- $t\bar{t}$: with a free-floating scale factor (SF); tW: estimation from MC
- Z+jets: get some contributions from Z→$\tau\tau$. 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

ATLAS-CONF-2025-008

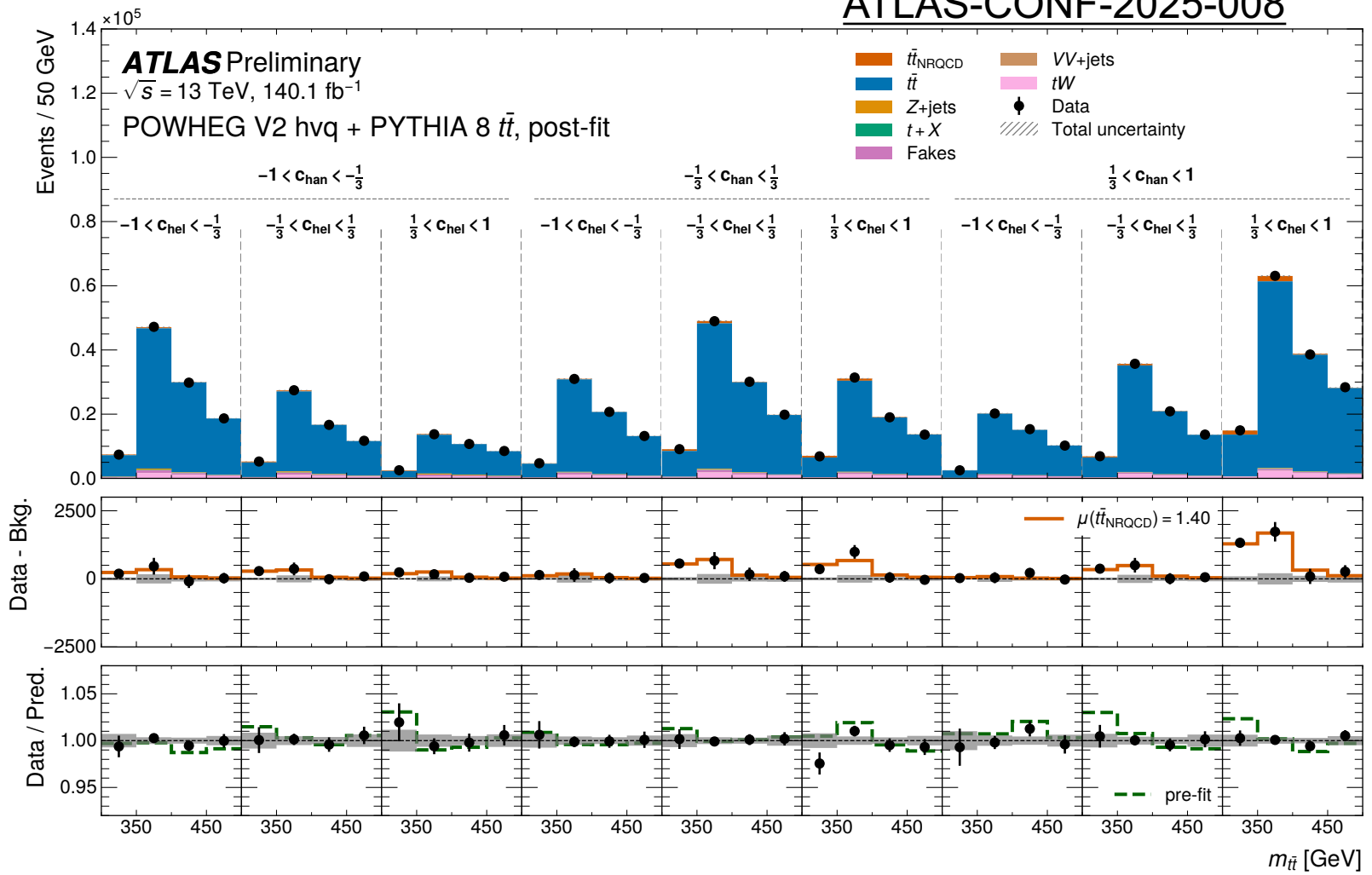


Results: baseline $t\bar{t}$ + quasi-bound state (NRQCD)

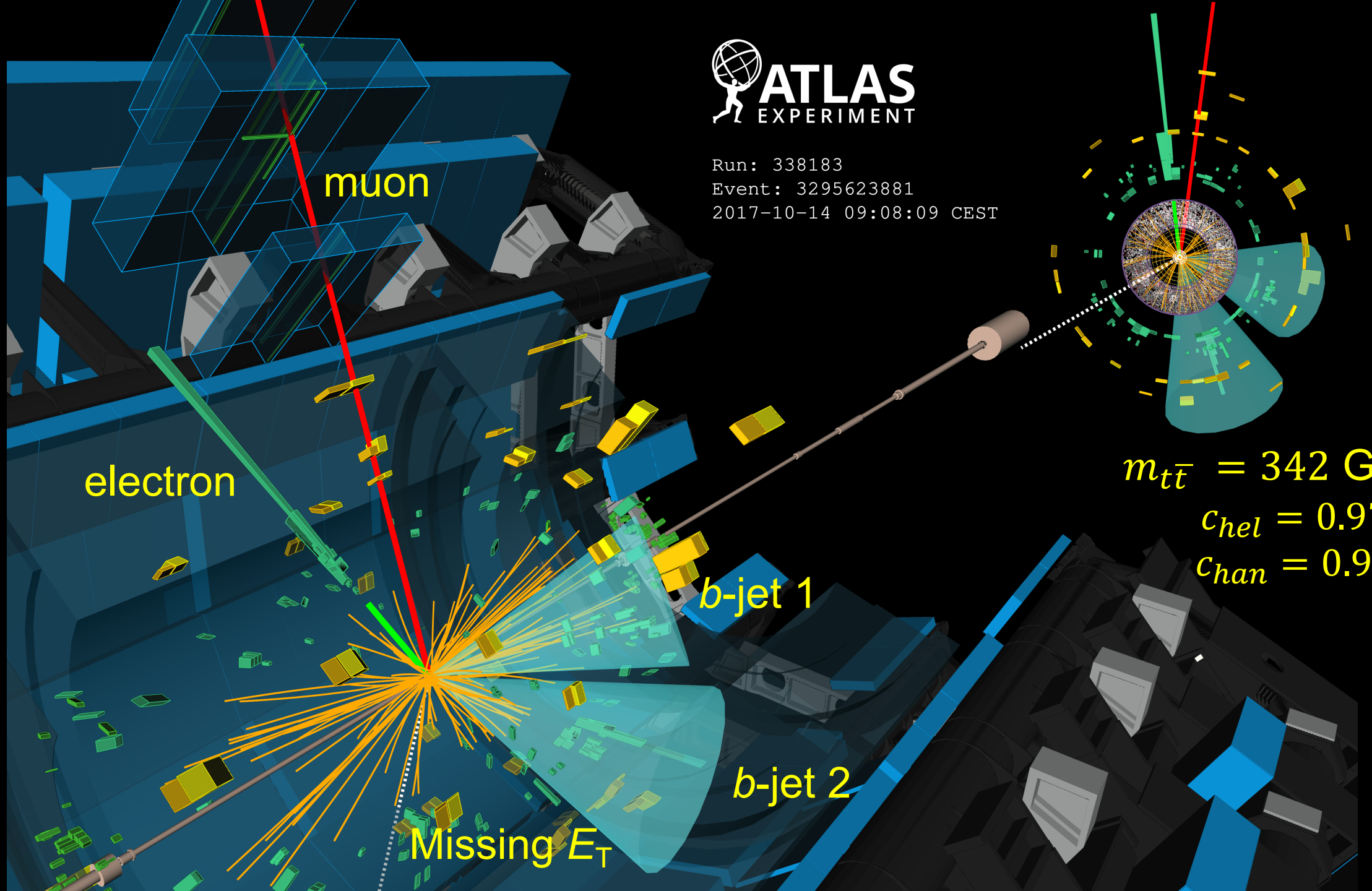
Observed (expected) significance: 7.7σ (5.7σ)

Goodness-of-Fit: 0.93

ATLAS-CONF-2025-008



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

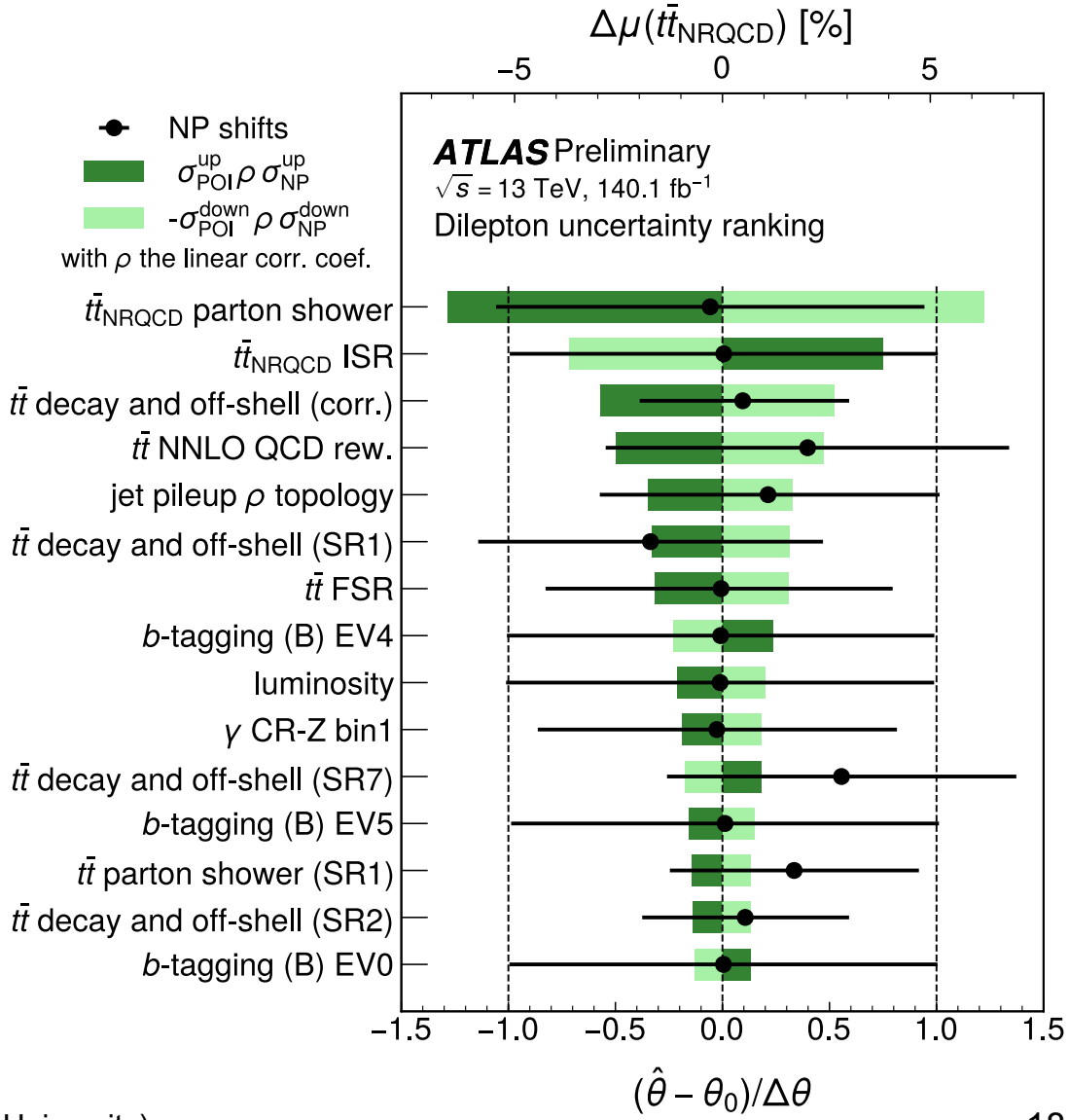

ATLAS
EXPERIMENT
Run: 338183
Event: 3295623881
2017-10-14 09:08:09 CEST
muon
electron
b-jet 1
b-jet 2
Missing E_T
$m_{t\bar{t}} = 342$ GeV
$c_{hel} = 0.97$
$c_{han} = 0.94$

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

ATLAS-CONF-2025-008

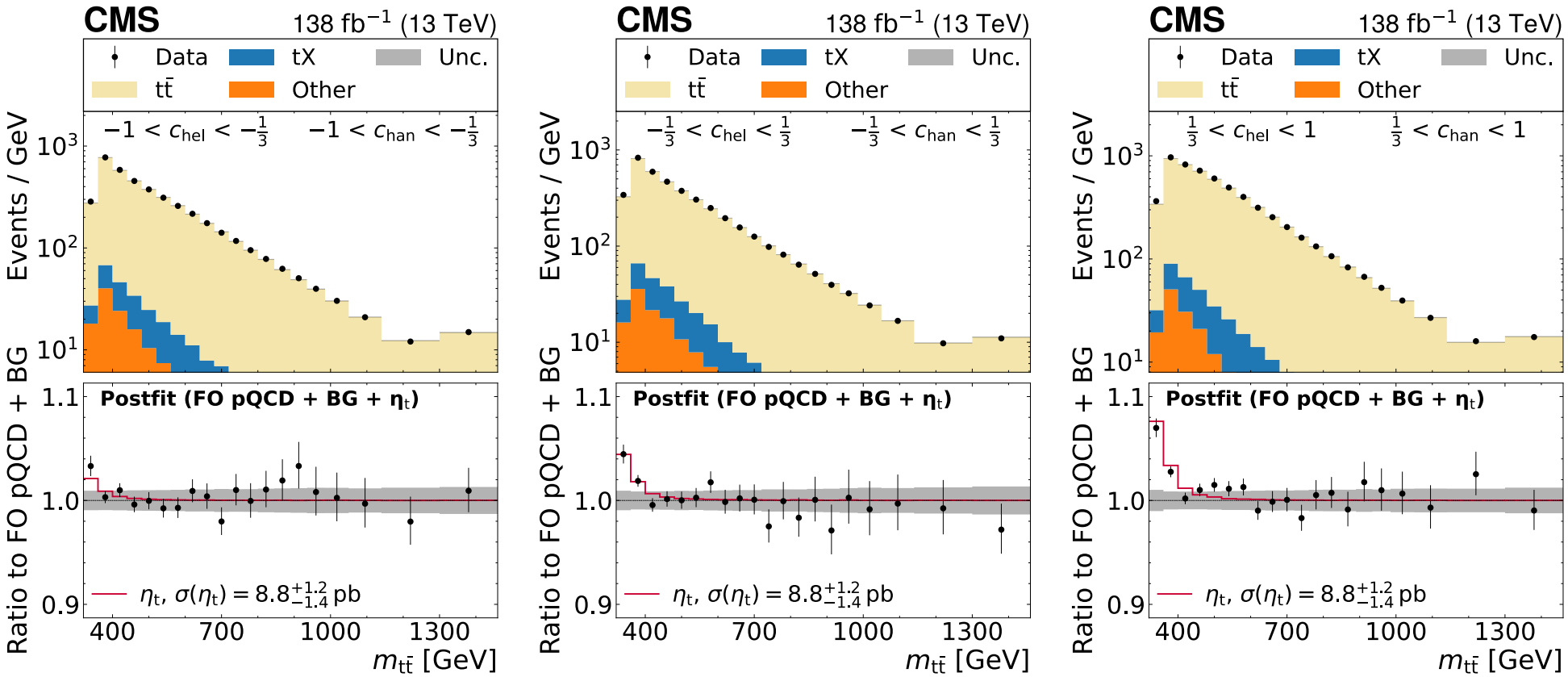


CMS Results

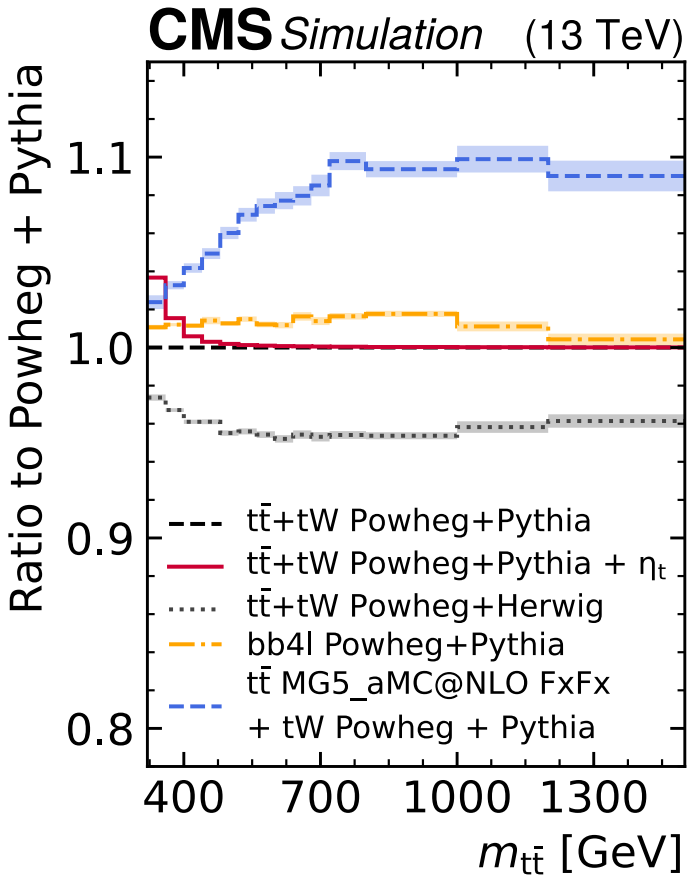
CMS Results

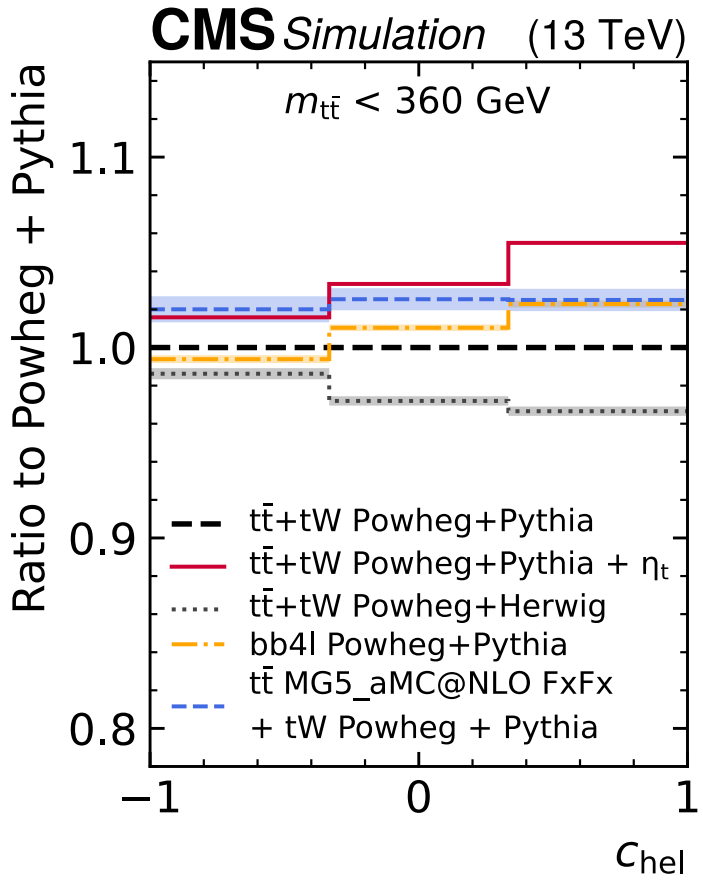
- [arXiv:2503.22382](), [Rep. Prog. Phys. 88 (2025) 087801]()
- Use very similar analysis method compared with ATLAS
- Use toy model for signal

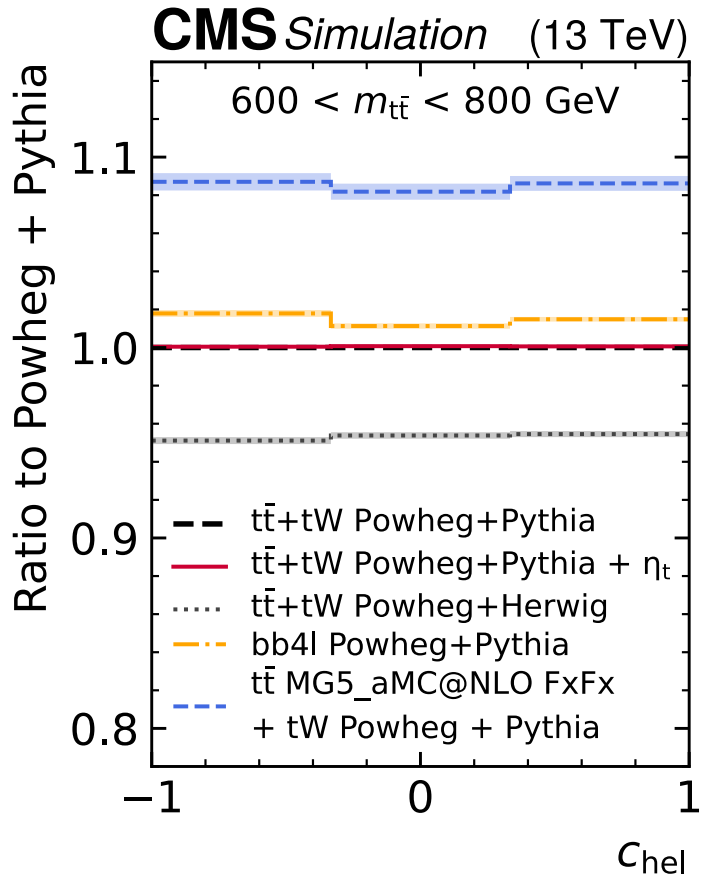
显著度大于5σ



Comparison of different models





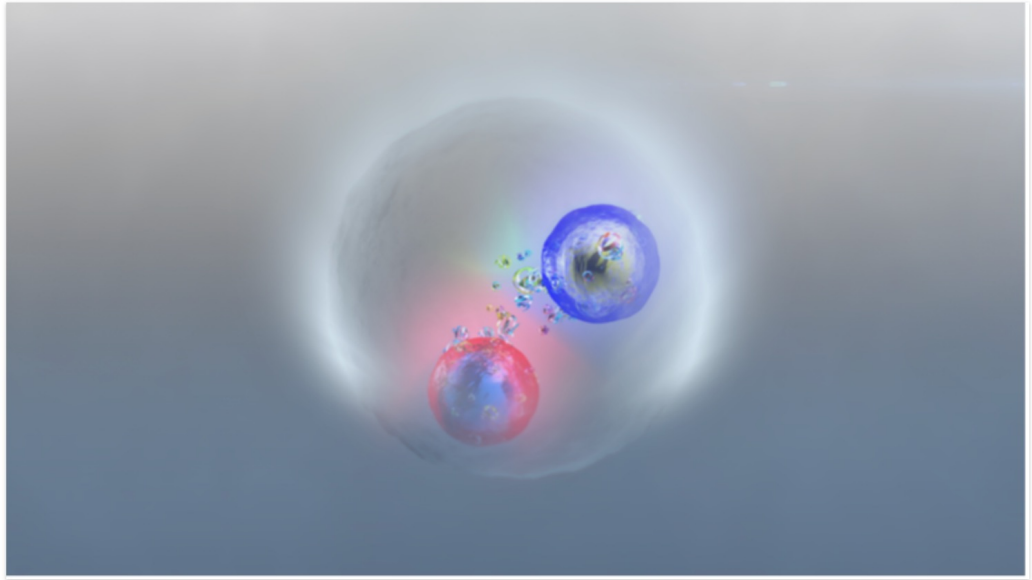


CERN Press Release

Elusive romance of top-quark pairs observed at the LHC

The CMS and ATLAS experiments at CERN's Large Hadron Collider have observed an unforeseen feature in the behaviour of top quarks that suggests that these heaviest of all elementary particles form a fleeting union

8 JULY, 2025



Artist's impression of the short-lived union of a top quark and a top antiquark formed by the exchange of gluons. (Image: D. Dominguez/CERN)

An unforeseen feature in proton-proton collisions previously observed by the CMS experiment at CERN's Large Hadron Collider (LHC) has now been confirmed by its sister experiment ATLAS. The result, reported yesterday at the European Physical Society's High-Energy Physics conference in Marseille, suggests that top quarks – the heaviest and shortest-lived of all the elementary particles – can momentarily pair up with their antimatter counterparts to produce a "quasi-bound-state" called toponium. Further input based on complex theoretical calculations of the strong nuclear force -- called quantum chromodynamics (QCD) -- will enable physicists to understand the true nature of this elusive dance.

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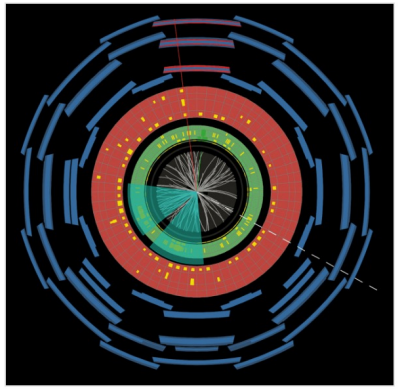
STRONG INTERACTIONS | NEWS

ATLAS confirms top–antitop excess

9 September 2025

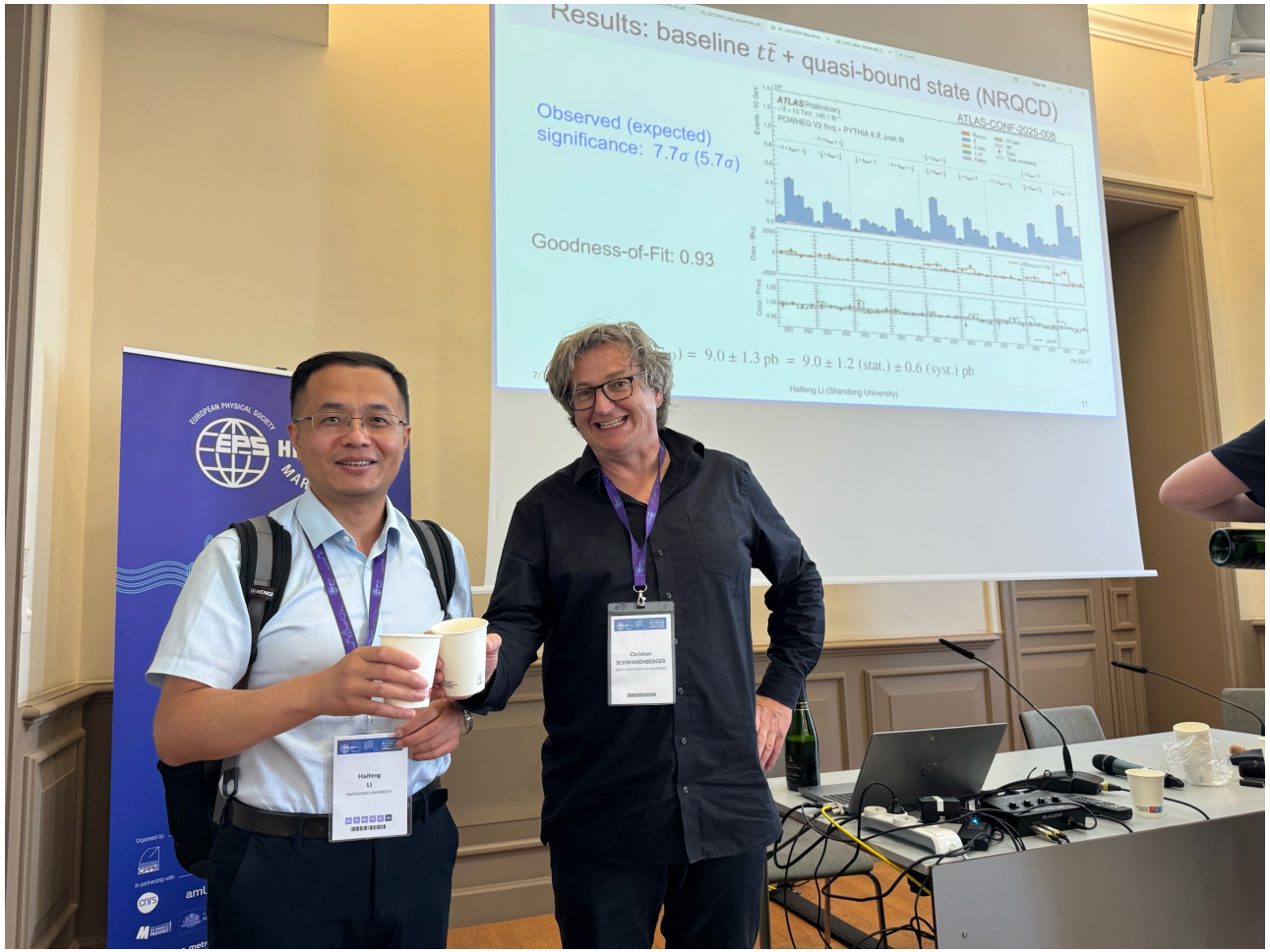


Quasi-bound candidate An event display of an interaction consistent with the formation of toponium in the ATLAS detector. The final state

At the LHC, almost all top–antitop pairs are produced in a smooth invariant-mass spectrum described by perturbative QCD. In March, the CMS collaboration announced the discovery of an additional 1% localised near the energy threshold to produce a top quark and its antiquark (*CERN Courier* May/June 2025 p7). The ATLAS collaboration has now confirmed this observation.

"The measurement was challenging due to the small cross section and the limited

Celebration after toponium talks from ATLAS and CMS during EPS-HEP2025
First report about ATLAS results



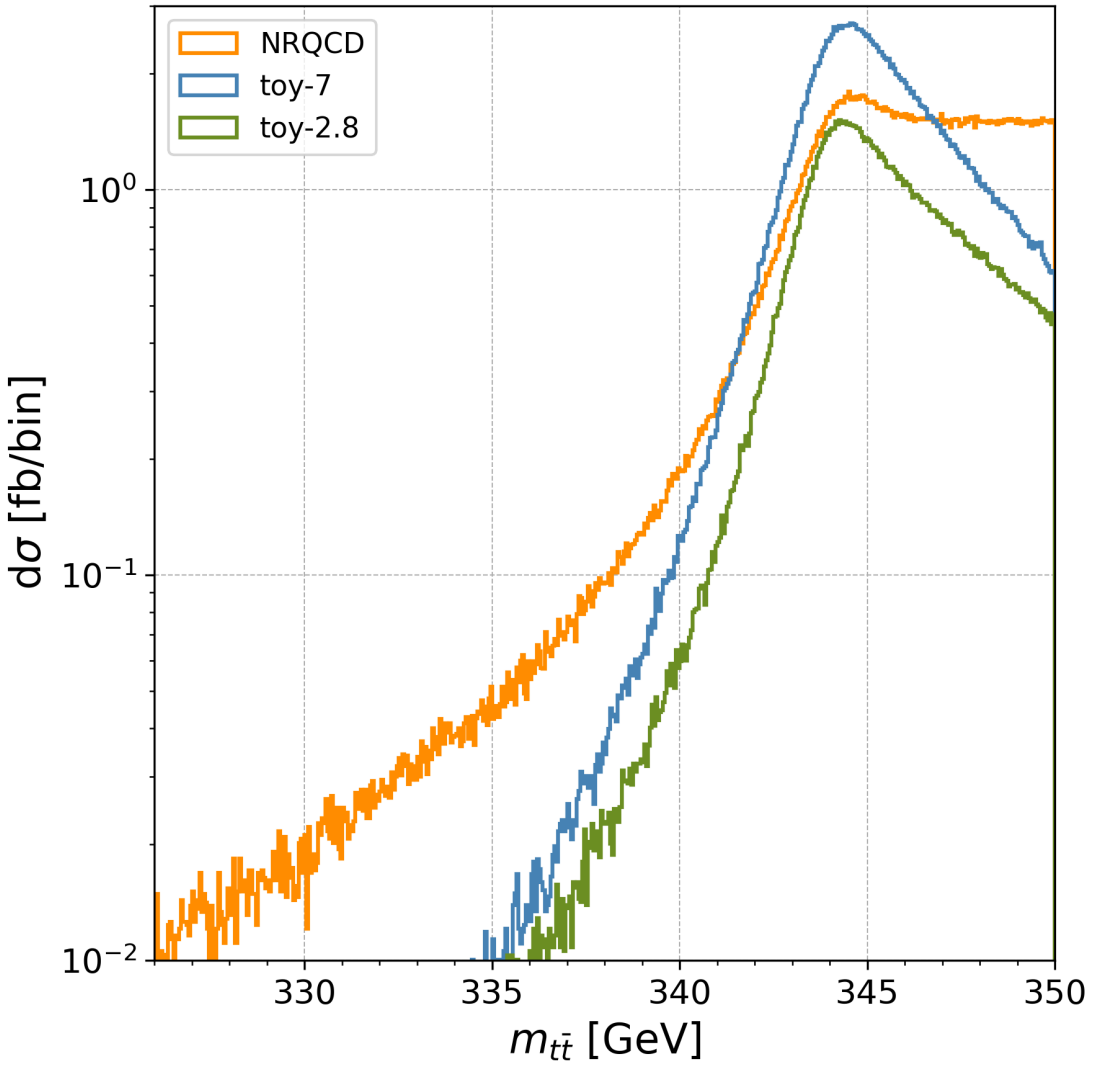
Conclusions

- 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 (Rep. Prog. Phys. 88 (2025) 087801)
- 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

Backup

比较ATLAS和CMS的signal model

LHC Top WG meeting 4-6 June 2025, CERN



ATLAS Event Selections

Target for dilepton channel $tt \to b\ell\nu b\ell\nu$

SR: Signal Region; CR: Control Region

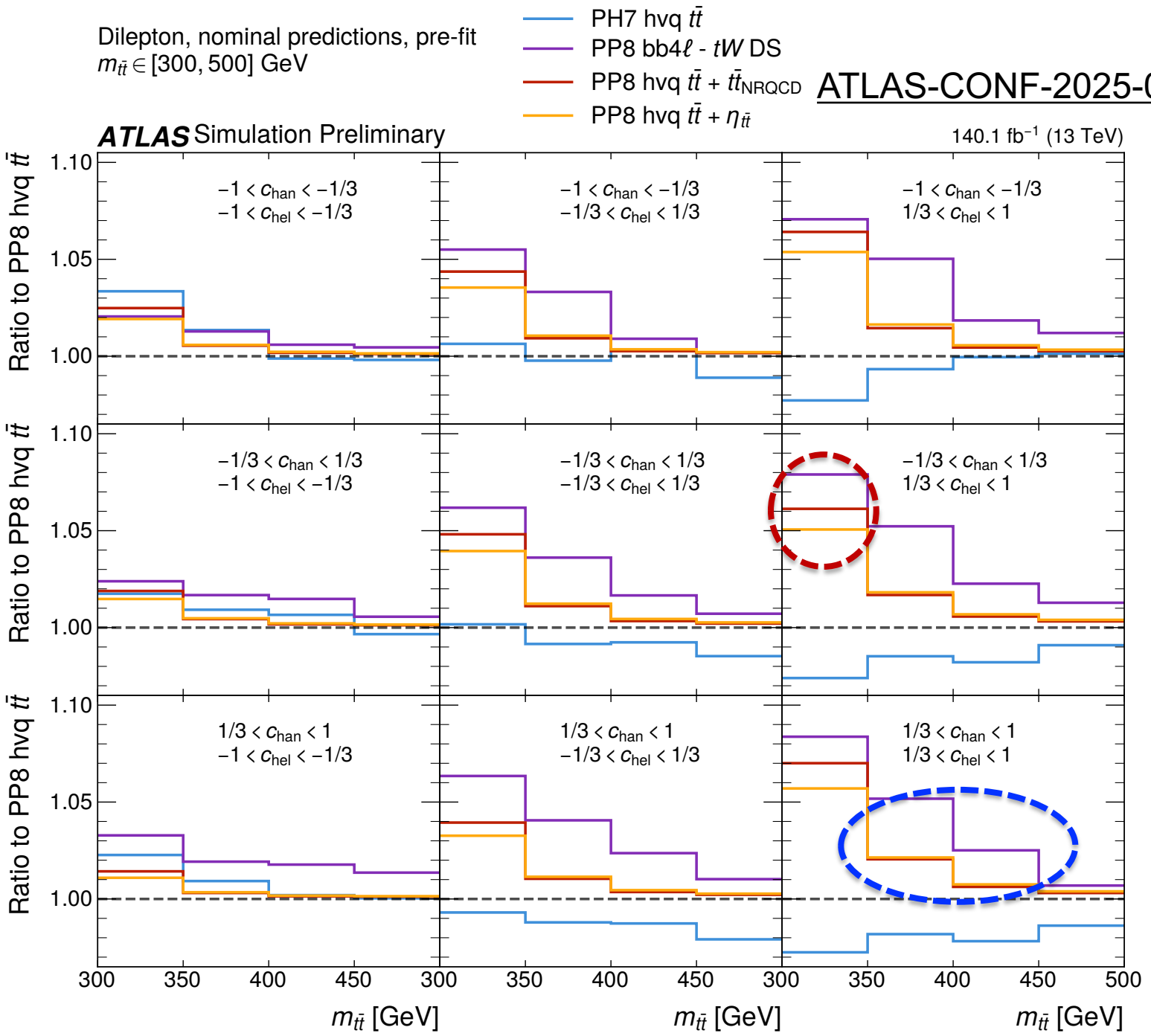
SRs	CR-Z	CR-Fakes
$= 2\ell$ with $p_{\mathrm{T}}(\ell) \geq 10$ GeV ≥ 1 trigger-matched lepton with $p_{\mathrm{T}} \geq 25/27/28$ GeV ≥ 2 jets with $p_{\mathrm{T}} \geq 25$ GeV ≥ 1 b-tagged jet (70% efficiency WP) $m_{\ell\ell} \geq 15$ GeV $m_{t\bar{t}} \leq 500$ GeV		
$E_{\mathrm{T}}^{\mathrm{miss}}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

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

- 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



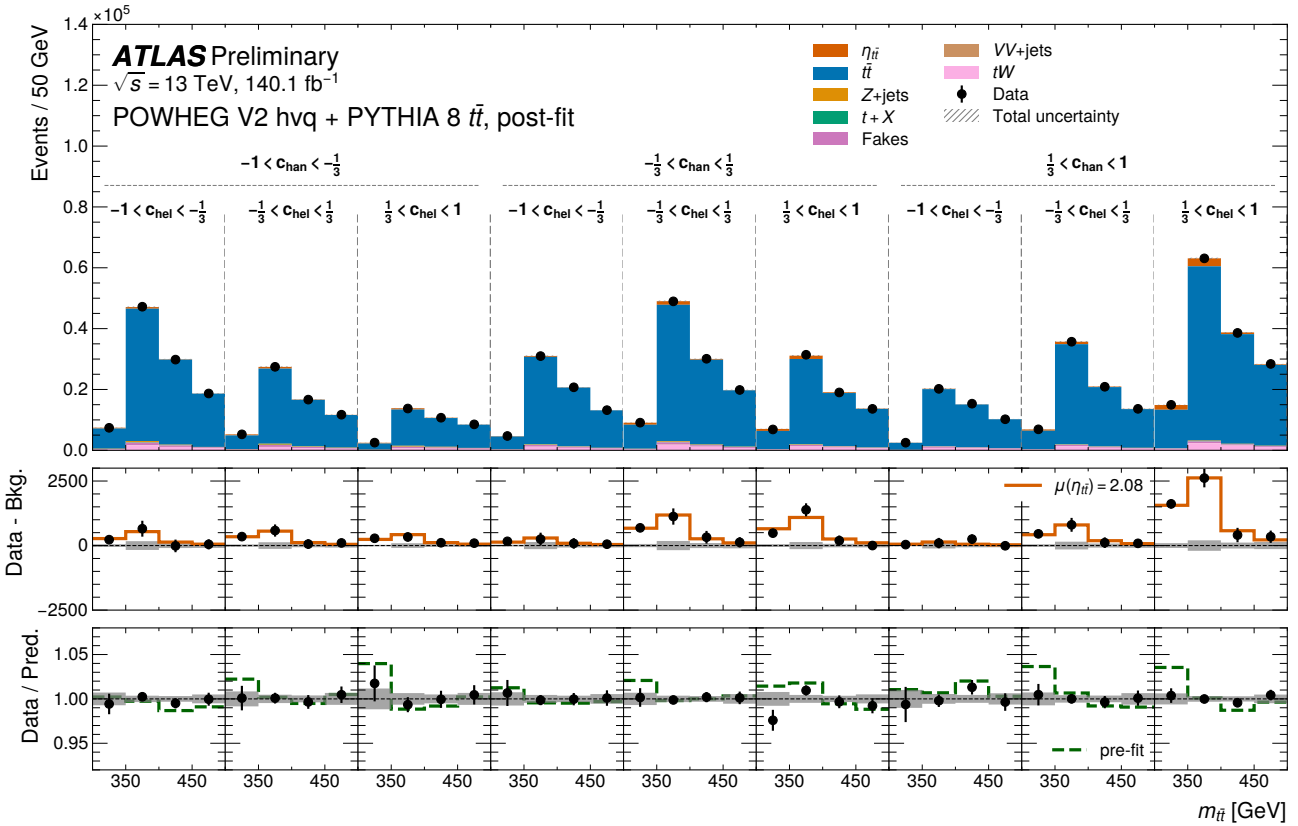
Simplified model for $t\bar{t}$ quasi-bound states

- A pseudo-scalar spin-singlet resonance or as a combination of scalar and pseudo-scalar resonances. Mostly pseudo-scalar ${}^1S^{[1]}$ 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

Alternative fit: Powheg hvq + simplified model of toponium

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

Goodness-of-Fit: 0.95



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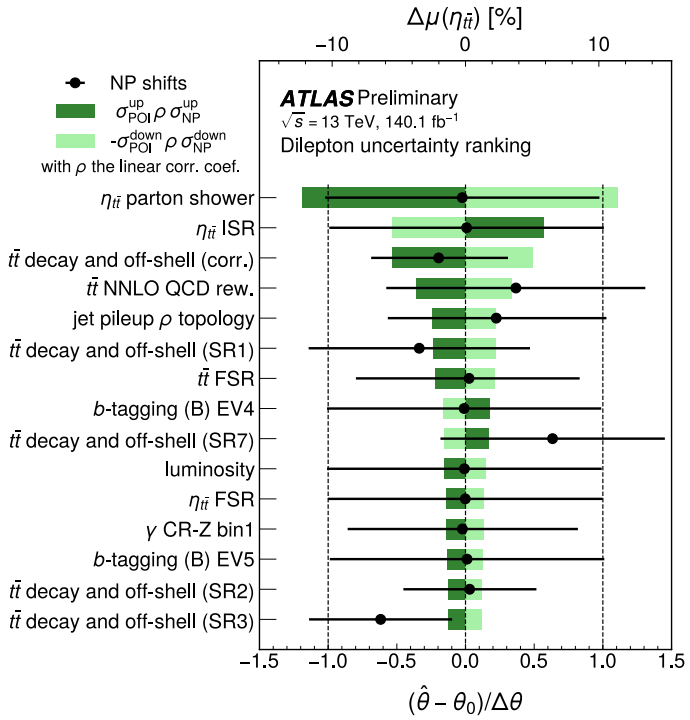
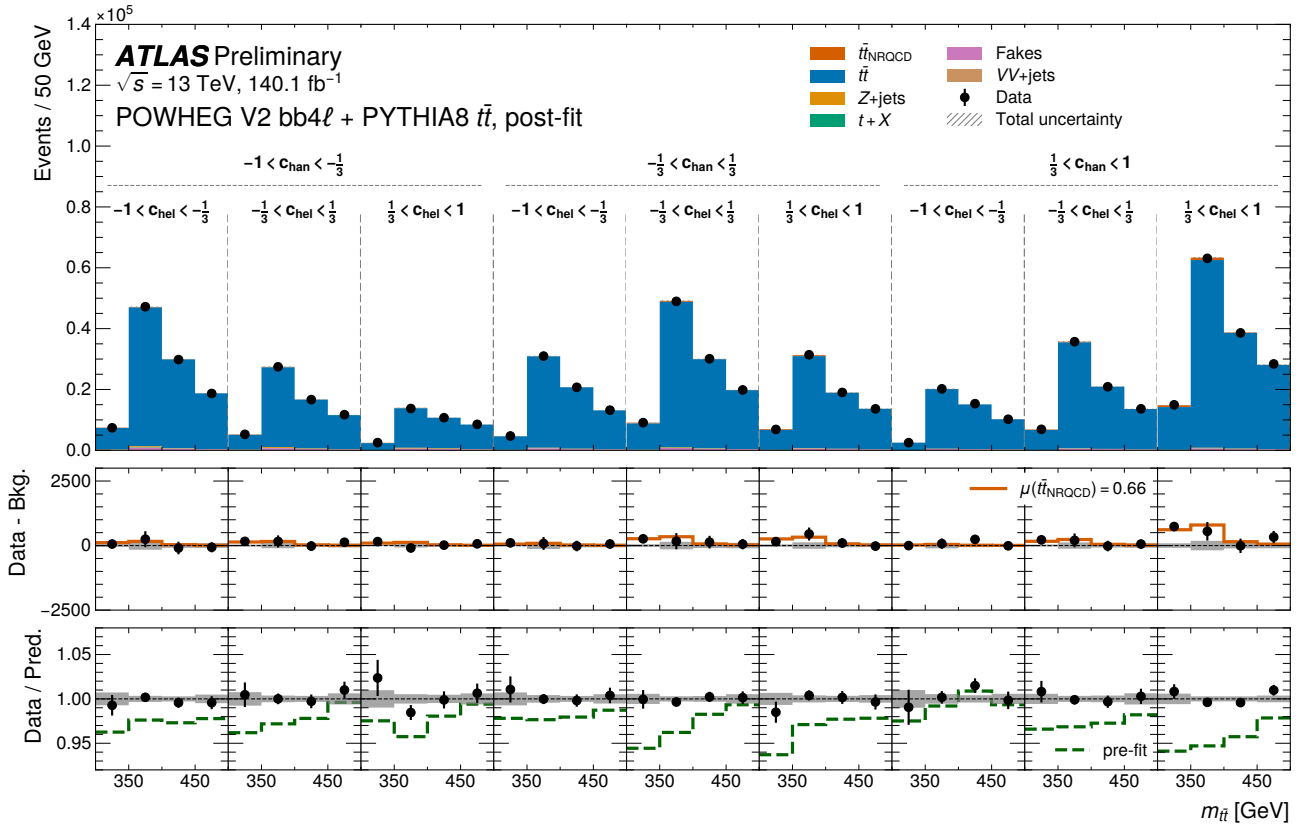


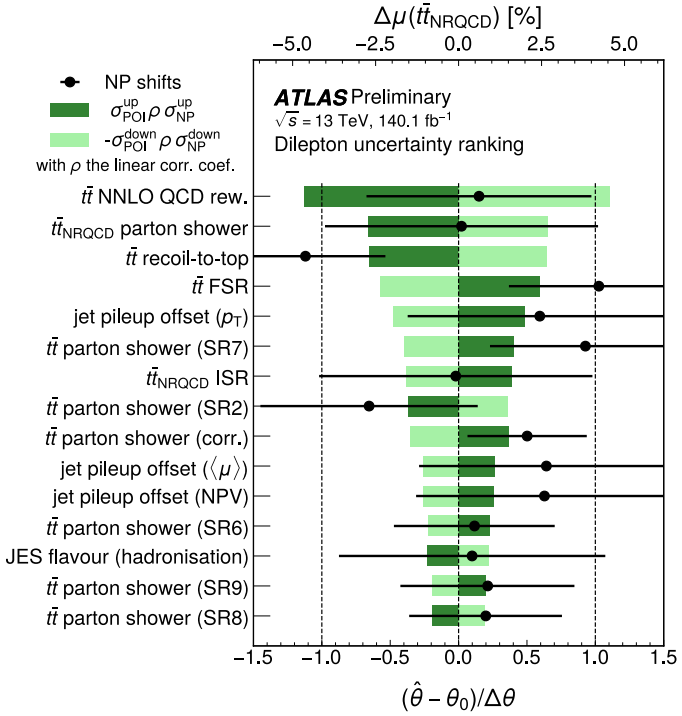
Alternative fit: Powheg bb4l + quasi-bound state (NRQCD)

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

Goodness-of-Fit: 0.54



ATLAS-CONF-2025-008



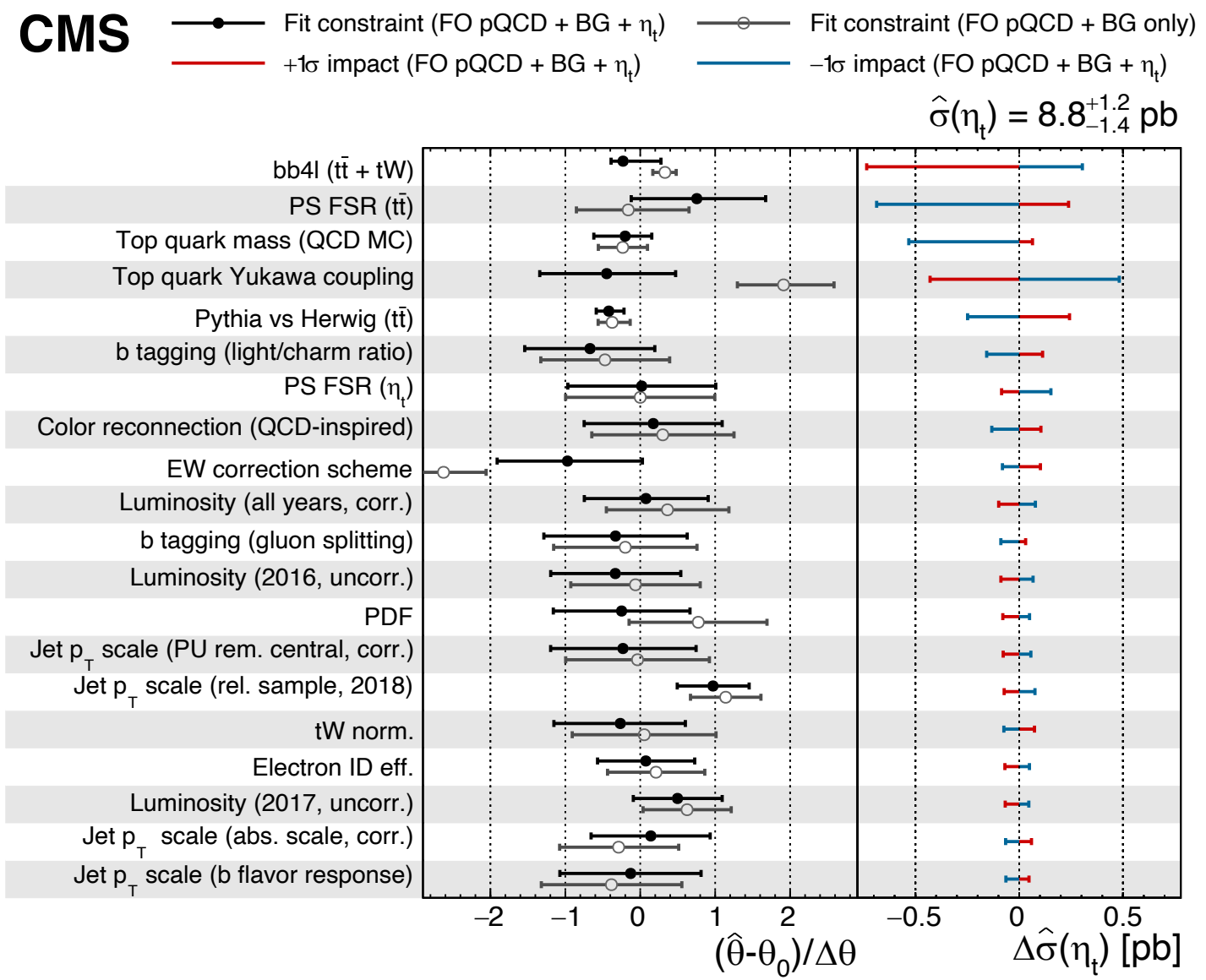
Reconstruction of the $t\bar{t}$ System

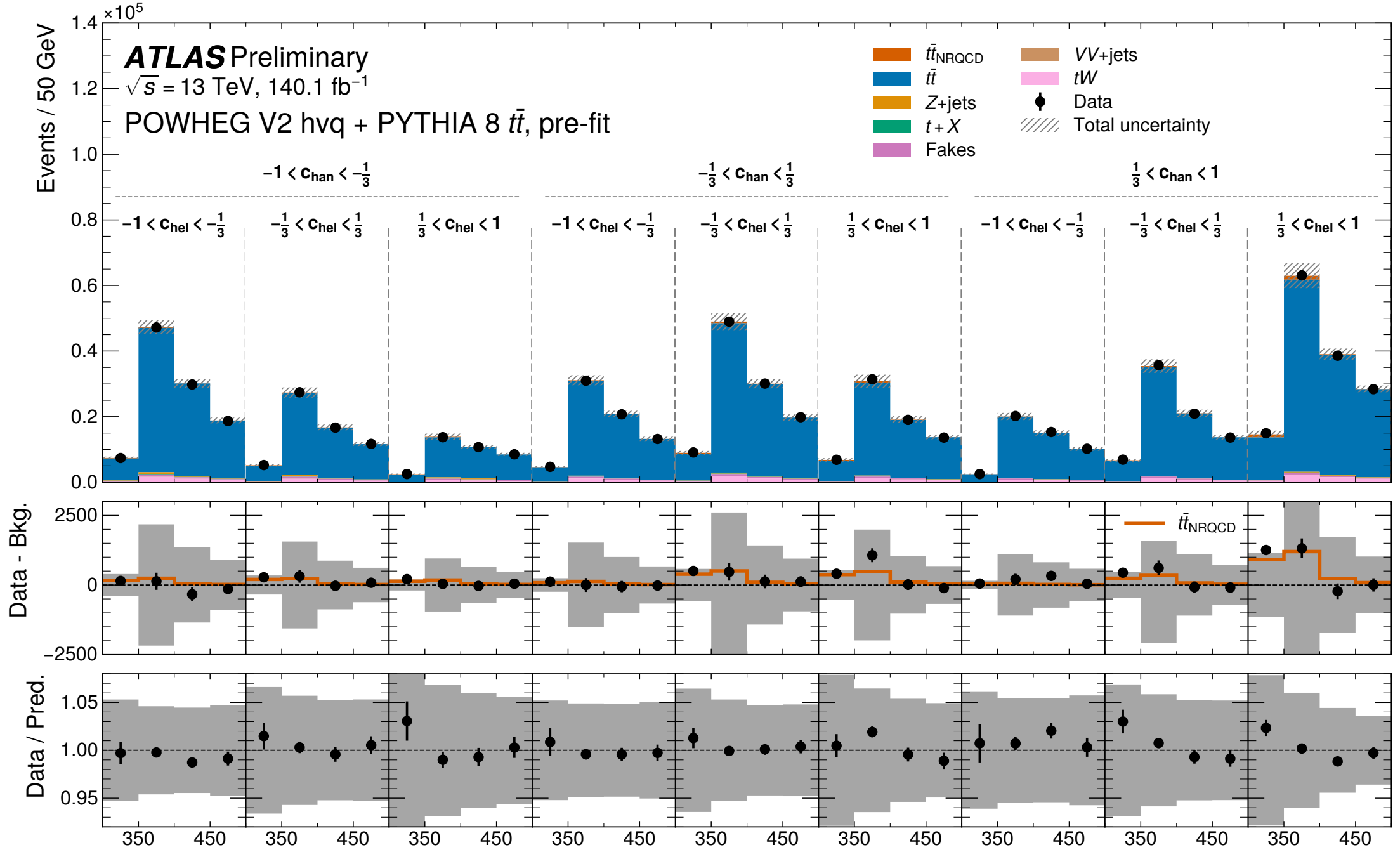
- Ellipse Method [NIM A 736 (2014) 169]: geometric/analytic approach that imposes W and top mass constraints
- The two b-tagged jets associated with the decays of the top and antitop quark are chosen from all selected hadronic jets. If more than two of them are b-tagged, the two leading b-tagged jets 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

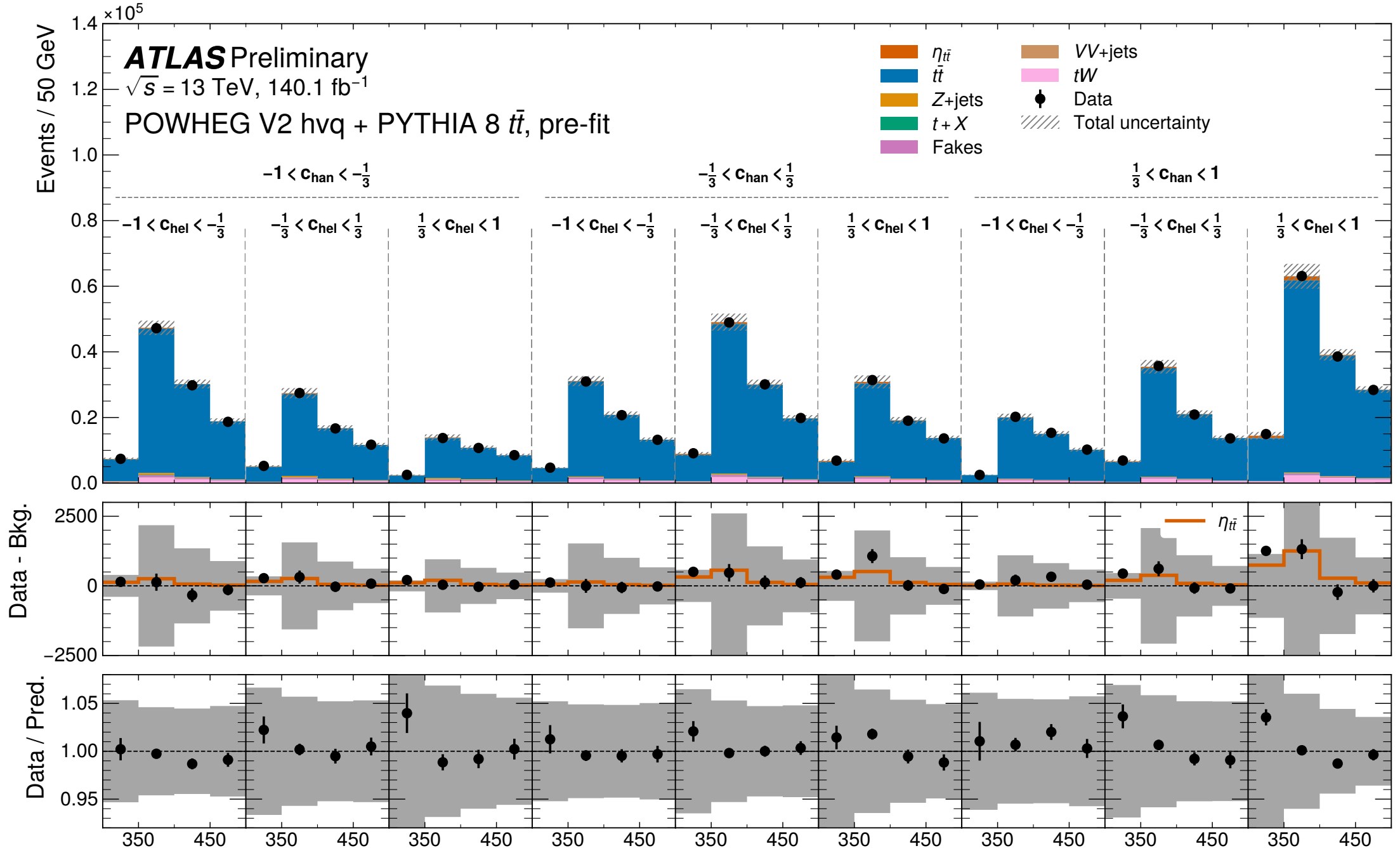
ATLAS Systematics

- **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

CMS Systematics




ATLAS Preliminary
√s = 13 TeV, 140.1 fb⁻¹
POWHEG V2 hvq + PYTHIA 8 tt̄, pre-fit
tt̄NRQCD
tt̄
Z+jets
t + X
Fakes
VV+jets
tW
Data
Total uncertainty
−1 < c_han < −1/3
−1/3 < c_han < 1/3
1/3 < c_han < 1
Events / 50 GeV
Data - Bkg.
Data / Pred.
m_tt̄ [GeV]


ATLAS Preliminary
√s = 13 TeV, 140.1 fb⁻¹
POWHEG V2 hvq + PYTHIA 8 tt̄, pre-fit
ηtt̄
tt̄
Z+jets
t + X
Fakes
VV+jets
tW
Data
Total uncertainty
−1 < c_han < −1/3
−1/3 < c_han < 1/3
1/3 < c_han < 1
−1 < c_hel < −1/3
−1/3 < c_hel < 1/3
1/3 < c_hel < 1
Events / 50 GeV
×10^5
Data - Bkg.
Data / Pred.
mtt̄ [GeV]