Overview

Observation of a pseudoscalar excess at the top quark pair production threshold

THE CMS COLLABORATION

SPRACE Physics Meetings - 02/06/2025

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CMS PAPER TOP-24-007, v22

Extracted from CADi

Paper Chapters

Introduction

- Analysis based on $\mathbf{138\ fb^{-1}}$ **of pp** collisions at $\sqrt{s} = 13$ TeV
  - LHC Run 2 (2016–2018)
- **Top quark**: heaviest known elementary particle, $m_t \sim 172.5$ GeV
- **Unique property**: decays before hadronizing → spin transferred to decay products
- **Nonrelativistic QCD** (NRQCD) predicts possible *enhancements in* $t\bar{t}$ production near threshold due to bound states
- **This work** investigates the existence of a CP-odd pseudoscalar 'toponium' state, denoted η_t
  - A χ_t (CP-even) are also possible
- **Observable:** enhancement in m_{tt} and spin correlation via lepton angles

Introduction

- The “toponium” is a hypothetical **bound state of $t\bar{t}$**
- η_t: ${}^1S_0^{[1]}$ CP-odd (pseudoscalar) state, expected around m_{tt}~343 GeV (where $2m_t$ - binding energy)
- χ_t: ${}^3P_0^{[1]}$ CP-even (scalar) state, suppressed due to velocity factors
- η_t can be formed through **gluon-gluon** initial states;
- Manifests as **event excess** and **spin correlation anomalies**
- ATLAS conclusions (Ref. [23]) are not directly comparable to the ones reported on the paper, nor do they refute or confirm the findings reported.

2 Method

2.1 The CMS detector and event reconstruction

(skip)

2.2 Data and simulated event samples

- Events selected in the dilepton (e/μ) final state with ≥ 2 jets (1 b-tagged minimum)

- They use of kinematic reconstruction to infer $t\bar{t}$ invariant mass (m_{tt}) and lepton angular variables

2 Event selection

- **Final state:** Dilepton ($e^+e^-, \mu^+\mu^-, e\mu$) + ≥ 2 jets
  Key selections:
  - 2 opposite-sign leptons, $p_{\mathrm{t}} > 20$ GeV ($1\ell > 25$ GeV)
  - ≥ 2 jets (1 b-tagged), $p_T^{miss} > 40$ GeV ($ee/\mu\mu$)
  - Z veto: $|m_{\ell\ell} - 91\ \mathrm{GeV}| > 15$ GeV
  - $m_{\ell\ell} > 20$ GeV
- **Kinematic reconstruction:**
  - Kinematic fit assumes two leptonic W decays from tt̄
  - Constrained fit to W and top masses
  - Smearing (100 iterations) recovers resolution and real solutions
  - Reconstructed m_{tt} resolution $\sim 15\%$ near threshold

Signal and Background

- **Signal**: $\eta_t \rightarrow$ WbWb (off-shell tops allowed)
  - Modeled with MADGRAPH5 aMC@NLO (LO), PYTHIA8 (parton shower)
  - Mass: 343 GeV ($m_t \sim$ 172.5 GeV), Width: 2.8 GeV
- **Backgrounds:**
  - Nonresonant $t\bar{t}$: POWHEG v2 + PYTHIA8 (FO pQCD at NNLO+NNLL)
  - Single top (tX): POWHEG and MADGRAPH
  - Drell-Yan: POWHEG + PHOTOS
  - Dibosons: PYTHIA (NNLO/NLO norms)
  - ttV, multijet: negligible or modeled as appropriate
  - Multiple generator setups tested: HERWIG, bb4l, FxFx to verify robustness
- **Theoretical corrections:**
  - Higher-order QCD (NNLO) and EW (NLO) corrections applied
  - PDF set: NNPDF3.1

Statistical Analysis Methodology

Fit Method:

- Binned profile likelihood fit using **COMBINE** tool
- 3D histogram: (m_{tt} , c_{hel}, c_{han})

Uncertainties included as nuisance parameters:

- Experimental: $\boldsymbol{e/\mu}$ **ID, b-tagging, pileup, JEC/JER, trigger**
- Luminosity (±1.6%)
- Theory: PDF, α_s , top mass, μF/μR scales, parton shower/hadronization, ISR/FSR
- Cross-section norm. uncertainties for all backgrounds

Control:

- Postfit deviations of nuisance parameters from their prefit values (**Pulls**) and postfit reduction in uncertainty (**constraints**) evaluated
- Alternative generators (HERWIG, MADGRAPH, POWHEG-res) used for cross-checks

Statistical Analysis Methodology

Purpose: Discriminate between different spin/CP hypotheses

Definitions:

- c_{hel} **:** Scalar product of lepton unit vectors in respective top rest frames
- c_{han} **:** Same as c_{hel} but with one spin axis inverted

Predictions:

State	c_{hel} Slope	c_{han} Slope
η_t (pseudoscalar)	+1	+1/3
χ_t (scalar)	−1/3	−1
SM ($t\bar{t}$ FO pQCD)	~0.3	~0

Analysis uses 3D template fit: $(m_{tt}, c_{hel}, c_{han})$

3 Results

- **Excess observed** near $m_{tt} \approx 343$ GeV with distinctive spin correlations.
- **Best fit cross section:**

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

- Compatible with NRQCD predictions: 6.4 pb estimated
- Significance of excess: $> \mathbf{5\sigma}$
- **No significant χ_t contribution found.**

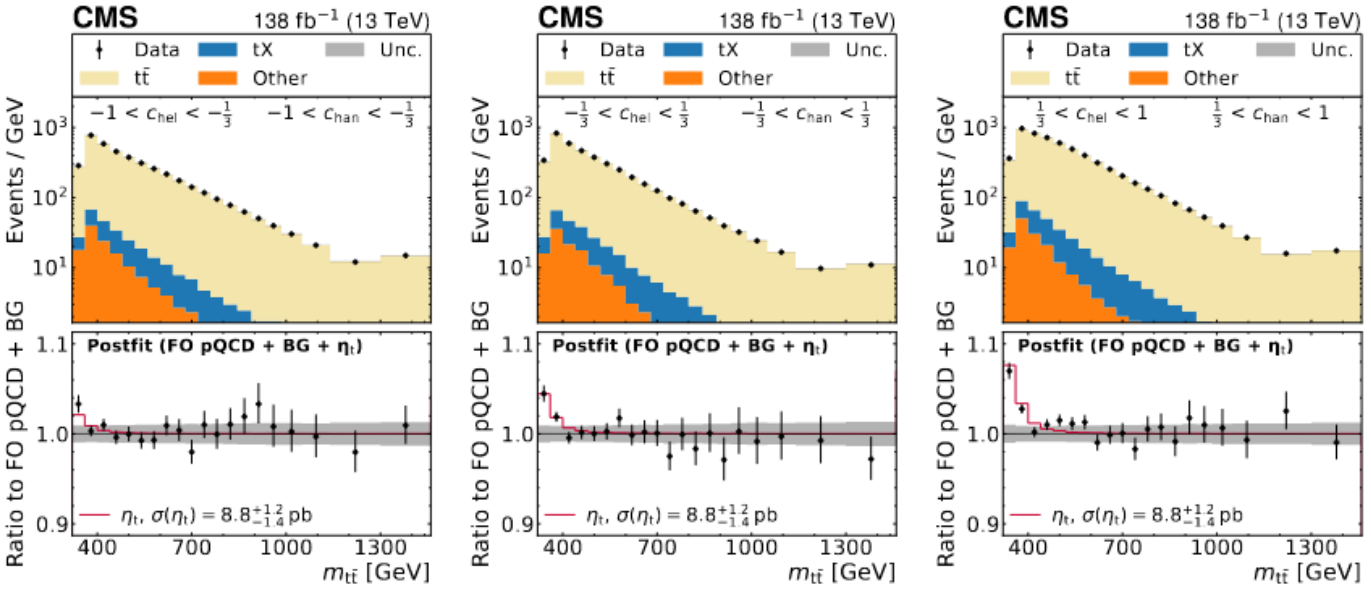

Figure 1: Observed (points with statistical error bars) and predicted (stacked colored histograms) $m_{t\bar{t}}$ distribution in three out of nine (c_{hel}, c_{han}) bins. In the upper panels, the $t\bar{t}$ histogram shows the FO pQCD prediction after the fit to the data that includes the η_t signal model (whose contribution is not drawn), and the shown event rates are divided by the bin width. The lower panels display the ratio of the data to the FO pQCD + background prediction, with η_t signal overlaid at its best fit η_t cross section (red line). The gray band indicates the postfit uncertainty. The first and last $m_{t\bar{t}}$ bins include all events with reconstructed $m_{t\bar{t}}$ below 360 and above 1300 GeV, respectively, and the drawn bin width is used for the normalization in these bins.

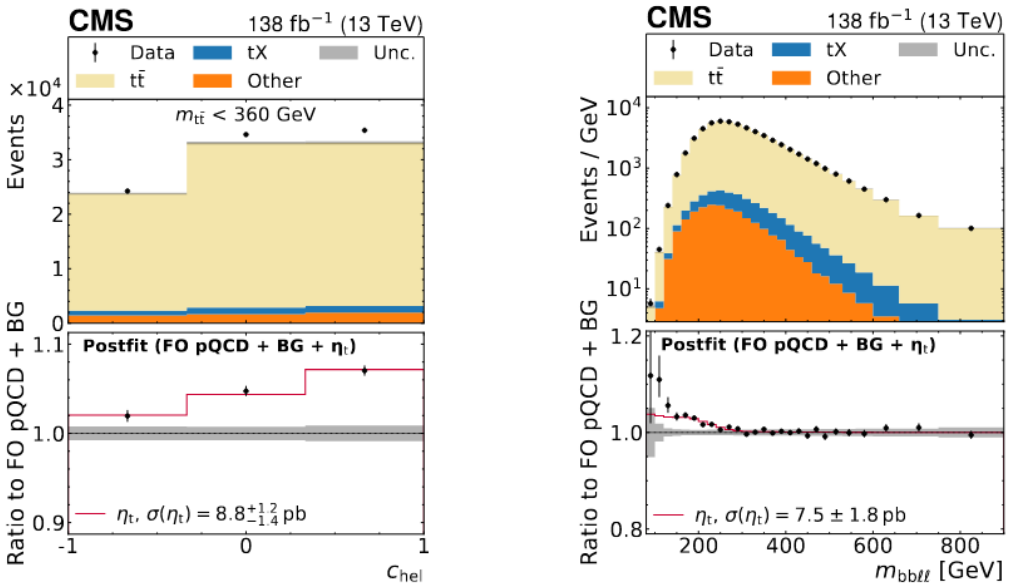

Figure 2: Observed (points with statistical error bars) and predicted (stacked colored histograms) distributions. Left: c_{hel} for $m_{t\bar{t}} < 360$ GeV and integrated over c_{han}, from the nominal fit using $m_{t\bar{t}}$. Right: $m_{bb\ell\ell}$ integrated over c_{hel} and c_{han}, from the alternative fit using $m_{bb\ell\ell}$ instead of $m_{t\bar{t}}$, which is discussed in Section 4.1. In the upper panels, the $t\bar{t}$ histogram shows the FO pQCD prediction after the fit to the data that includes the η_t signal model (whose contribution is not drawn). On the right, the shown event rates are divided by the bin width. The lower panels display the ratio of the data to the FO pQCD + background prediction, with η_t signal overlaid at its best fit η_t cross section (red line). The gray band indicates the postfit uncertainty. The first and last $m_{bb\ell\ell}$ bins include all events with reconstructed $m_{bb\ell\ell}$ below 100 and above 750 GeV, respectively, and the drawn bin width is used for the normalization in these bins.

3 Results

- c_{hel} distribution for $m_{tt} < 360$ GeV shows a steeper slope than SM
- c_{han} further supports **anticorrelated spin hypothesis**
- Data favors η_t over χ_t or SM-only explanations
- Control plot comparison:
  - η_t model aligns well with observed enhancement
  - χ_t model does not improve fit quality

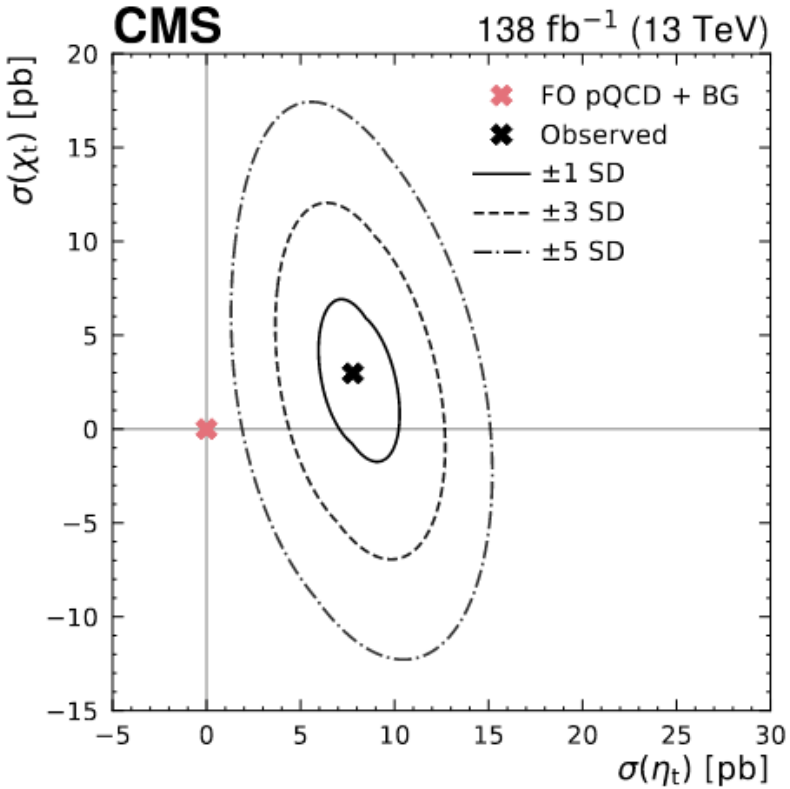

Figure 3: Best fit value (cross) and allowed regions at one (solid line), three (dashed line), and five (dotted-dashed line) SDs for the cross section of η_t and χ_t production, as observed in data (black). The FO pQCD + background expectation of zero η_t and χ_t contributions is denoted by a pink star. Negative cross section values refer to a reduction of the $t\bar{t}$ production cross sections with respect to the FO pQCD + background prediction around the threshold.

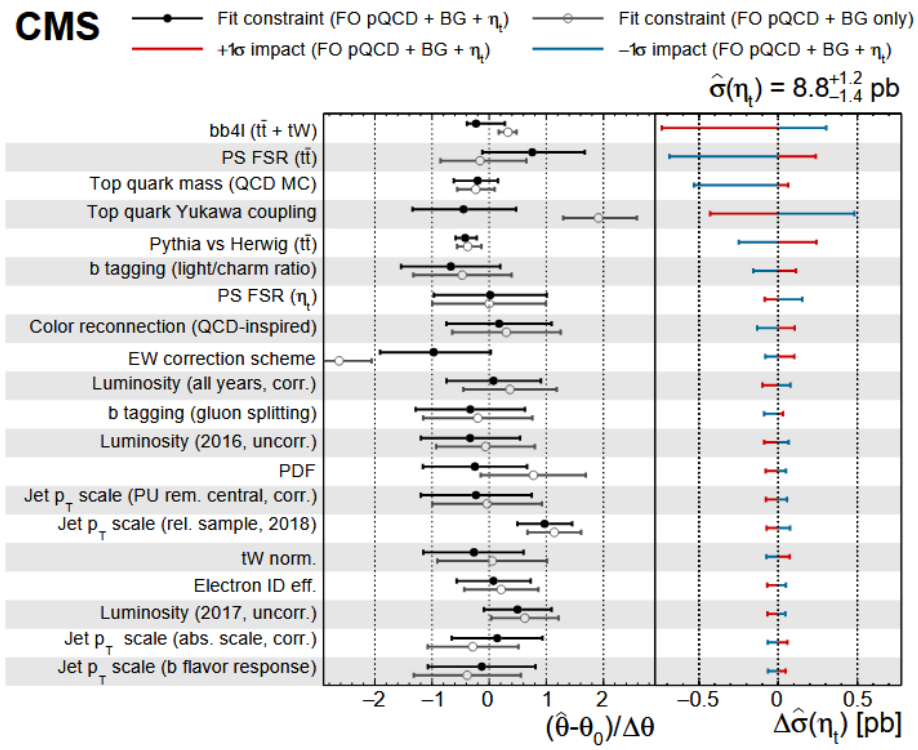

Figure 5: For the nuisance parameters listed in the left column, the pulls $(\hat{\theta} - \theta_0)/\Delta\theta$ (middle column), where $\hat{\theta}$ and θ_0 are the postfit and prefit values of the nuisance parameters and $\Delta\theta$ is the prefit uncertainty, are shown for the FO pQCD + background + η_t (black filled circles) and FO pQCD + background (gray empty circles) fit, as well as the impacts $\Delta\hat{\sigma}(\eta_t)$ (right column) for the FO pQCD + background + η_t fit. The impact $\Delta\hat{\sigma}(\eta_t)$ for a nuisance parameter θ is calculated by varying θ by ± 1 SD and evaluating the shift in $\sigma(\eta_t)$. The nuisance parameters are ordered by the maximum of their ± 1 SD impacts in the FO pQCD + background + η_t fit.

4 Discussion - Tests

- **Test 1**: Replace m_{tt} with $m_{bb\ell\ell}$
  - Any assumption on the value of m_t and is less model-dependent
    $\rightarrow \sigma(\eta_t) = 7.5 \pm 1.8\, pb$

- **Test 2:** Jet p_T scale shifted $\pm 1\sigma$ in pseudo-data
  $\rightarrow$ Negligible effect on η_t cross section

Table 1: Results for $\sigma(\eta_t)$ obtained with different simulated event samples for the FO pQCD $t\bar{t}$(+tW) prediction. Nuisance parameters encoding the difference between different generators are not included in these results. The nominal result, i.e., POWHEG v2 hvq + PYTHIA including these nuisance parameters, is shown for comparison.

FO pQCD generator setup	$\sigma(\eta_t)$ [pb]
POWHEG v2 hvq + PYTHIA	8.7 ± 1.1
POWHEG v2 hvq + HERWIG	8.6 ± 1.1
MADGRAPH5_aMC@NLO FxFx + PYTHIA	9.8 ± 1.3
POWHEG vRES bb4l + PYTHIA	6.6 ± 1.4
Nominal result	$8.8\,^{+1.2}_{-1.4}$

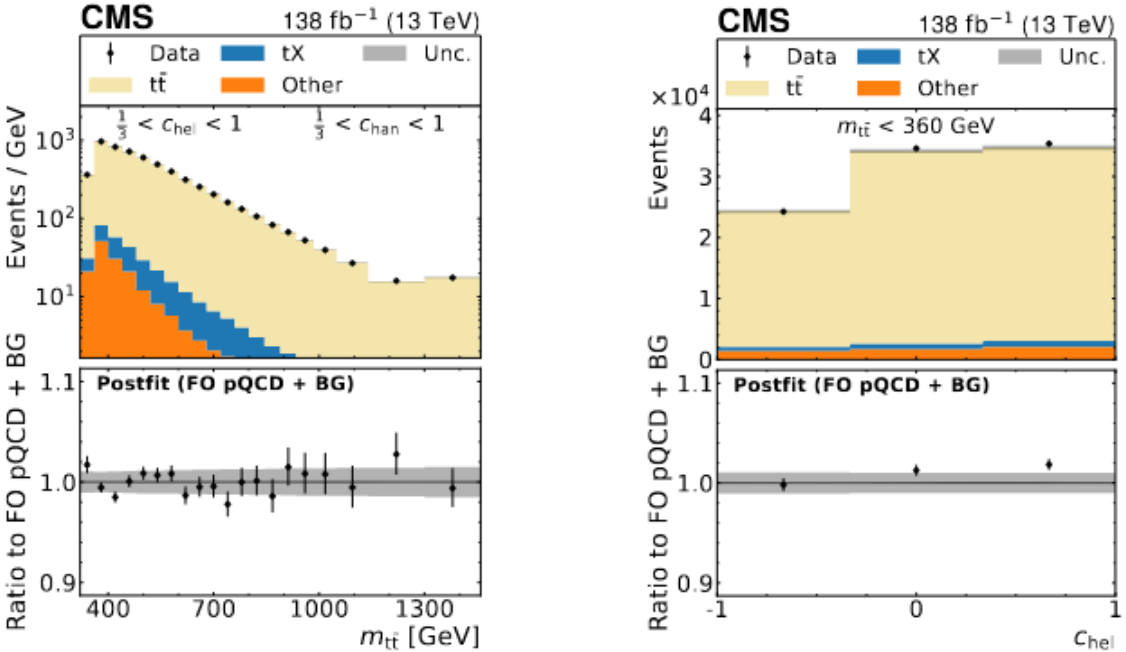

Figure 4: Observed (points with statistical error bars) and predicted (stacked colored histograms) $m_{t\bar{t}}$ distribution in the (c_{hel}, c_{han}) bin with the highest expected η_t contribution (left) and c_{hel} distribution for $m_{t\bar{t}} < 360$ GeV and integrated over c_{han} (right). In the upper panels, the histograms account only for the FO pQCD + background prediction, and are shown after the background-only fit to the data. On the left, the shown event rates are divided by the bin width. The lower panels display the ratio of the data to the FO pQCD + background prediction. The gray band indicates the postfit uncertainty. The binning is the same as in Figs. 1 and 2 (left).

Interpretation

- Results compatible with **NRQCD toponium formation** (η_t state)
- Confirms earlier mild hints in previous analysis with 2016 dataset
- Strongest direct evidence yet for QCD binding effects at $t\bar{t}$ threshold

- **Alternative explanations:**
  - BSM pseudo-scalar states (e.g. in 2HDMs) not ruled out
  - Companion paper (Ref. [20]) explores generic scalar/pseudoscalar resonance search

5 Summary

- First observation ($> 5\sigma$) of a **pseudoscalar excess in $t\bar{t}$ threshold region**
- Kinematic + angular evidence supports $\boldsymbol{\eta}_{\mathrm{t}}$ production
- Compatible with **NRQCD** expectations
- They reinforce top quark as a unique probe of fundamental interactions
- They suggest theoretical refinements in NRQCD modeling;
- And to extend searches to broader m_{tt} ranges