PROCEEDINGS OF SCIENCE

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

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A measurement is presented of $t\bar{t}$ production in the invariant-mass region near the pair production threshold, $m_{t\bar{t}} \sim 345$ GeV, in final states with two charged leptons and multiple jets. The measurement is based on 140 fb^{-1} of proton–proton collision data collected at $\sqrt{s} = 13$ TeV with the ATLAS detector. The data are compared to two models of $t\bar{t}$ production: a baseline model including only perturbative QCD (pQCD) predictions for the hard process, and an extended model that, in addition to the pQCD predictions, incorporates Monte Carlo simulations of color-singlet quasi-bound-state formation near the $t\bar{t}$ threshold. An excess of events is observed over the baseline pQCD prediction, with an observed significance of 7.7 standard deviations. This excess is consistent with the formation of colour-singlet, S-wave, quasi-bound $t\bar{t}$ states as predicted by non-relativistic QCD, and corresponds to a measured cross-section of 9.0 ± 1.3 pb.

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1. Introduction

The Large Hadron Collider (LHC) is a top anti-top quark pair ($t\bar{t}$) factory. The cross-section of $t\bar{t}$ during LHC Run 2 at $\sqrt{s}$ = 13 TeV is about 834 pb. The LHC produced 0.83M $t\bar{t}$ events per fb^{-1} data. The top quark has a short life time, and it decays before hadronization. With this enormous dataset, the ATLAS experiment [1] has carried out precision measurements in top quark physics. This note will focus on $t\bar{t}$ production near the threshold region using 140 fb^{-1} full LHC Run 2 proton-proton collisions data.

The cross-section measurement around the $t\bar{t}$ production threshold region is very challenging. The ATLAS Collaboration has previously carried out measurements both of the $pp \to WbWb$ differential cross-section in the dilepton channel [2] and of quantum entanglement [3]. An excess around the $t\bar{t}$ production threshold region has been observed in those two measurements. The results can be found in Figure 1. The $t\bar{t}$ threshold region has received lots of attention in the context of quantum entanglement. There was also a hint from a search done by the CMS Collaboration [4]. Recently, the CMS Collaboration observed an excess in the top quark pair production threshold [5].

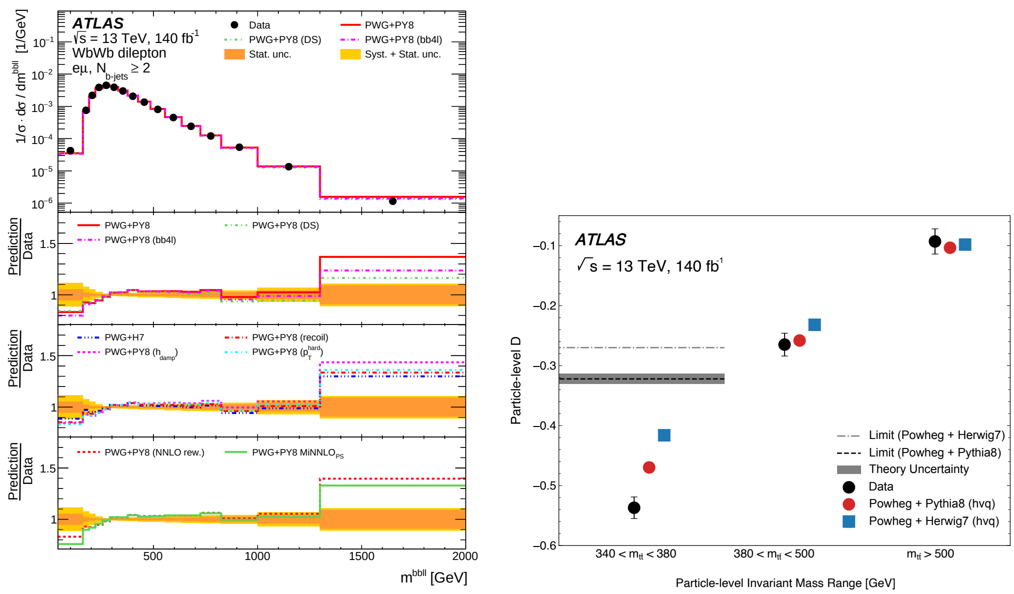

Figure 1: Data excesses around $t\bar{t}$ threshold region from previous measurements by the ATLAS experiment. Left: Relative differential cross-section measurement as a function of the invariant mass of $\ell^+\nu\ell^-\bar{\nu}b\bar{b}$ final states (m^{bbll}) [2]. Right: Particle-level quantum entanglement variable measurement by the ATLAS experiment [3].

2. Prediction of quasi-bound state at top quark anti-top quark threshold region

Quantum chromodynamics (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 [6–8]. At the LHC, the dominant non-relativistic QCD (NRQCD) contribution to the $t\bar{t}$ production threshold region is the production of S-wave, color-singlet $t\bar{t}$ pairs via gluon fusion ($gg \to t\bar{t}$). In the present

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analysis, NRQCD effects close to the production threshold, referred to as toponium, are modeled following the approach described in Ref. [9].

The procedure is to generate $gg \to t\bar{t} \to b\ell\nu b\ell\nu$ events using MadGraph [10] and Pythia [11]. Then the events are reweighted using QCD Green's function described in Ref. [9].

3. Background modeling

This measurement is extremely challenging because the $t\bar{t}$ production threshold region needs to be modeled precisely. The regular $t\bar{t}$ process (without toponium) is the dominant background for this measurement. The baseline modeling for the $t\bar{t}$ process uses Powheg v2 `hvq` [12–16], which employs the narrow-width approximation for top-quark decays. The $t\bar{t}$ sample is reweighted to next-to-next-to-leading order (NNLO) QCD and next-to-leading order (NLO) electroweak (EW) with a 2-dimensional reweighting in ($\cos\theta^*$ and $m_{t\bar{t}}$). The Matrix programme [17] is used to obtain the predictions at NNLO QCD, while Hathor [18–21] is used to obtain the EW predictions at NLO. θ^* is the 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 laboratory frame.

An alternative $t\bar{t}$ sample is generated with Powheg vres `bb4l` model[22–24]. This model includes off-shell and non-resonant contributions as well as exact spin correlations at NLO accuracy and simulates the inclusive production of $b\bar{b}\ell^+\ell^-\nu\bar{\nu}$ final states. This sample is used to estimate systematic uncertainties.

4. Event selection and fit

Events are categorized into nine signal regions (SRs), three control regions (CRs) for fake lepton estimation, and one CR for Z+jets normalization. The splitting of the signal region is based on two observables: c_{hel} and c_{han}. c_{hel} is defined as the cosine of the angle between the two leptons,

$$c_{\text{hel}} = \frac{\vec{\ell}_+ \cdot \vec{\ell}_-}{|\vec{\ell}_+||\vec{\ell}_-|}, \tag{1}$$

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_{hel} is useful to separate pseudoscalar from other contributions. A sketch of the c_{hel} distribution can be found in Figure 2. The observable c_{han} is the cosine of the same angle, with a sign-flip in the component parallel to the top direction [25]. This distribution has a maximum slope for a spin-triplet state.

A simultaneous profile-likelihood fit to the $t\bar{t}$ invariant mass ($m_{t\bar{t}}$) in 13 categories is performed to extract the signal strength. In the fit, the normalization of the $t\bar{t}$ process uses a free-floating scale factor, which is determined from data. The single top quark tW process is estimated from Monte Carlo (MC) samples. The Z+jets process is estimated from Z CR. The contributions from fake and non-prompt leptons are estimated from the three fake CRs.

5. Results

An excess of events is observed compared to the background-only model (without toponium process), with an observed significance of 7.7σ. The expected significance with toponium model

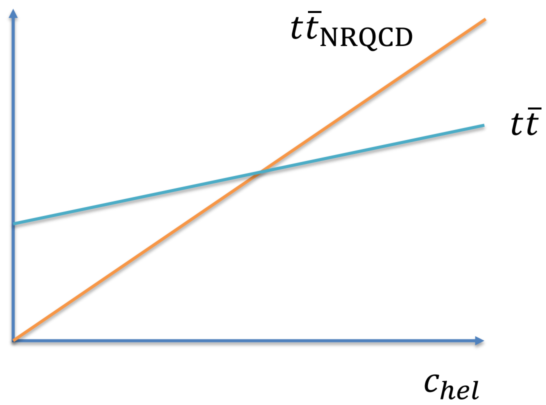

Figure 2: Sketch of $c_{\rm hel}$ distributions from $t\bar{t}$ and $t\bar{t}_{\rm NRQCD}$.

	$-1 < c_{hel} < -\frac{1}{3}$	$-\frac{1}{3} < c_{hel} < \frac{1}{3}$	$\frac{1}{3} < c_{hel} < 1$
$-1 < c_{han} < -\frac{1}{3}$	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

Figure 3: Summary of 13 categories used in the fitting.

is 5.7σ. The cross-section for the $t\bar{t}$ quasi-bound-state contribution extracted from the fit with free-floating signal normalization $\mu(t\bar{t}_{\rm NRQCD})$ is

$$\sigma(t\bar{t}_{\rm NRQCD}) = 9.0 \pm 1.3 \text{ pb} = 9.0 \pm 1.2 \text{ (stat.)} \pm 0.6 \text{ (syst.) pb}. \quad (2)$$

The expected cross-section of the toponium from analytical calculation is 6.43 pb [26]. Post-fit distribution for $m_{t\bar{t}}$ can be found in Figure 4. The results reported here are further discussed in Ref. [27].

The dominant systematics affecting the results are parton shower modeling uncertainty for toponium signal process, the top quark width effect, and the high-order QCD reweighting. A summary plot of the impacts of the 15 most important nuisance parameters can be found in Figure 5.

6. Conclusions

A measurement of $t\bar{t}$ production near the kinematic threshold was conducted in events with exactly two leptons, using 140 fb^{-1} of $\sqrt{s}$ = 13 TeV LHC pp collision data collected with the ATLAS

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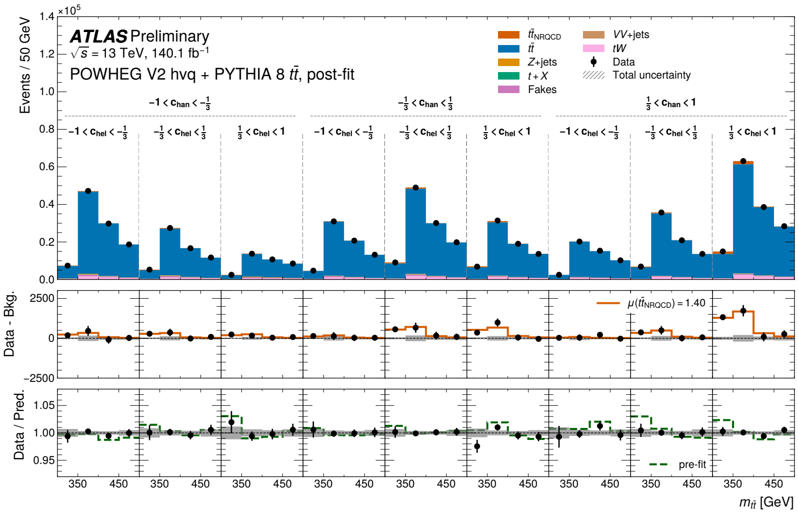

Figure 4: Post-fit distributions of $m_{t\bar{t}}$ in the nine SRs [27].

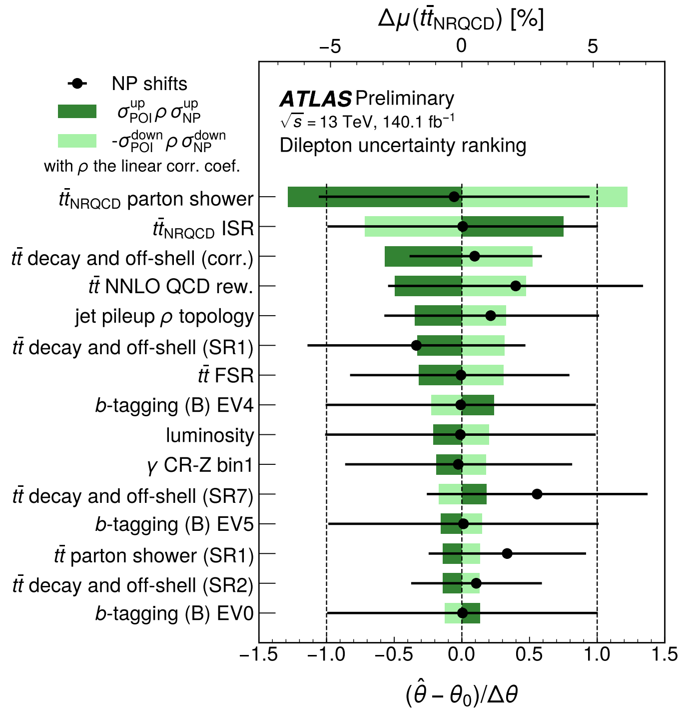

Figure 5: Ranking of the 15 most impactful nuisance parameters [27].

detector. An excess of events is observed over the baseline perturbative QCD prediction, with an observed significance of 7.7 standard deviations. This excess is consistent with the formation of color-singlet, S-wave, quasi-bound $t\bar{t}$ states as predicted by non-relativistic QCD, and corresponds to an observed cross-section of 9.0 ± 1.3 pb.

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