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Search for central exclusive production of top quark pairs in proton-proton collisions at $\sqrt{s} = 13$ TeV with tagged protons

The CMS and TOTEM Collaborations*

Abstract

A search for the central exclusive production of top quark-antiquark pairs ($t\bar{t}$) is performed for the first time using proton-tagged events in proton-proton collisions at the LHC at a centre-of-mass energy of 13 TeV. The data correspond to an integrated luminosity of 29.4 fb^{-1}. The $t\bar{t}$ decay products are reconstructed using the central CMS detector, while forward protons are measured in the CMS-TOTEM precision proton spectrometer. An observed (expected) upper bound on the production cross section of 0.59 (1.14) pb is set at 95% confidence level, for collisions of protons with fractional momentum losses between 2 and 20%.

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*See Appendix A and B for the lists of collaboration members

1 Introduction

Top quarks are copiously produced in proton-proton (pp) collisions at the CERN LHC. At LHC energies, the dominant production mode is via strong interaction processes, resulting in the production of top quark-antiquark pairs ($\mathrm{t\bar{t}}$). The LHC experiments have measured the inclusive $\mathrm{t\bar{t}}$ production cross section at various centre-of-mass energies, using different top quark decay channels [1–19]. Top quarks can also be produced singly in electroweak processes in three different modes known as t channel, s channel, and W-associated production (tW). The ATLAS and CMS Collaborations have observed or reported evidence for single top quark production in all three modes at several centre-of-mass energies [20–23].

A different mechanism can lead to the production of $\mathrm{t\bar{t}}$ pairs in pp scattering via the exchange of colourless particles, such as photons (γ) or pomerons. In this case, one or both protons may remain intact after the interaction, while part of their energy is used to produce the $\mathrm{t\bar{t}}$ pair. The process where the two protons survive the collision, $\mathrm{pp} \to \mathrm{pt\bar{t}p}$, is called central exclusive production. It receives contributions from quantum electrodynamics (QED) and quantum chromodynamics (QCD) diagrams. The diagram with $\gamma\gamma$ fusion, sketched in Fig. 1, is expected to dominate at LHC energies; the pomeron-pomeron fusion, which can be described at the lowest order in perturbation theory as a colour-singlet two-gluon exchange, is negligible in comparison [24, 25].

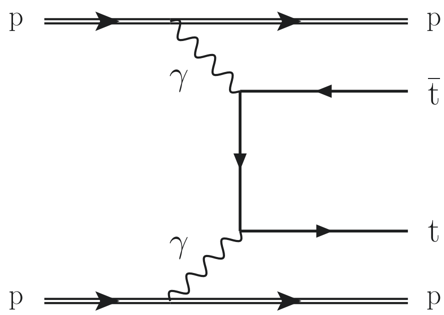

Figure 1: Leading Feynman diagram for $\mathrm{t\bar{t}}$ central exclusive production via $\gamma\gamma$ fusion.

Predictions for central $\mathrm{t\bar{t}}$ exclusive production in the framework of the standard model (SM) are available, including both QED and QCD contributions [26–32]. A critical element, in particular in the case of strong interaction processes, is the evaluation of the so-called proton survival probability. This is the probability that no additional soft interactions between the spectator partons of the colliding protons take place, which can lead to energy loss and/or break up of the interacting protons. For the $\gamma\gamma$ fusion process this value is close to unity, while it is limited to a few percent for the QCD processes. The cross section for the $\mathrm{pp} \to \mathrm{p}\gamma\gamma\mathrm{p} \to \mathrm{pt\bar{t}p}$ process (referred to as $\gamma\gamma \to \mathrm{t\bar{t}}$) amounts to $0.22 \pm 0.05\,\mathrm{fb}$ including next-to-leading-order (NLO) perturbative QCD corrections [32]. While the observation of the central exclusive production of $\mathrm{t\bar{t}}$ pairs is only expected to become possible at the high-luminosity LHC [33], contributions from physics beyond the SM could enhance the production cross section, making it detectable with the data collected so far. In particular, this production mechanism is sensitive to the $\mathrm{t}\gamma$ vertex, which makes it suitable for interpretations in the context of Effective Field Theory [34] or anomalous couplings [28, 35]. This offers complementary information to processes like $\mathrm{t\bar{t}}\gamma$ production, measured by CMS and ATLAS at 13 TeV [36–39]. This process is also sensitive to models that incorporate extra spatial dimensions [40].

This paper reports on a search for central exclusive $\mathrm{t\bar{t}}$ production at the LHC, carried out by reconstructing the top quarks from their decay products in the CMS central detector, and looking for the presence of two forward protons with the CMS-TOTEM precision proton spectrometer

(CT-PPS) [41]. Each top quark decays almost solely to a W boson and a bottom quark. At least one of the two W bosons from top quark decays is reconstructed in the leptonic ($e\nu_e$ or $\mu\nu_\mu$) channel (including $W \rightarrow \tau\nu_\tau$ decays where the tau lepton decays leptonically), while the other W boson is reconstructed either in the leptonic or hadronic decay mode. Throughout the paper, the events where both top quarks decay in the leptonic channel are referred to as dileptonic, while events with one top quark decaying leptonically and the other hadronically are referred to as lepton+jets (ℓ + jets). The two scattered protons are detected by CT-PPS, one on each side of the interaction region. The analysis is based on data collected in 2017.

The paper contains seven sections. Section 2 briefly illustrates the CMS detector, the CT-PPS experimental setup, and the reconstruction of basic objects. Section 3 specifies the data and simulation samples used in the analysis. Section 4 outlines the analysis strategy, and details its various steps. Section 5 is devoted to the treatment of systematic uncertainties. Section 6 describes the statistical analysis and presents the results. The paper is closed with a summary in Section 7.

2 Experimental setup and particle reconstruction

2.1 The CMS detector and the CMS-TOTEM precision proton spectrometer

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionisation chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS central detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [42].

The CT-PPS detector is an array of movable, near-beam devices, called Roman Pots (RPs), enclosing tracking or timing detectors, and installed along the LHC beam line at about 210 m from the CMS interaction point (IP), on both sides, in LHC sectors 45 ("arm 0") and 56 ("arm 1"). A sketch of the system layout for one arm is shown in Fig. 2. During normal data taking, detectors are inserted horizontally, their edges approaching the beam as close as 2–3 mm from its nominal orbit, in order to reconstruct the flight path of protons coming from the IP. As insufficient information was available from the timing detectors in 2017, only data from the tracking stations are used in this analysis. In the 2017 configuration, one tracking station per side was equipped with silicon strip detectors [43] and one with silicon pixel detectors [44], at a distance of about 213 ("210 far") and 220 m ("220 far") from the IP, respectively. They can provide up to five and up to six measured points per track, respectively. Each strip tracker allows the recon-

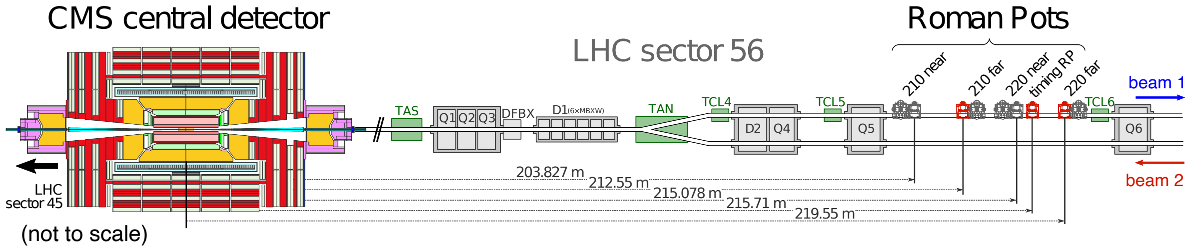

Figure 2: A schematic layout of one arm of CT-PPS along the LHC beam line. The RPs shown in red are those used by CT-PPS.

struction of at most one proton track per event; if hits compatible with more than one track are reconstructed in at least one strip tracker, the event is discarded, to avoid ambiguities arising from wrong combinations of orthogonal strips. Each pixel tracker allows the reconstruction of multiple tracks per event, up to 10.

2.2 Particle reconstruction

In CMS, object reconstruction is based on the particle-flow algorithm [45], which aims at reconstructing and identifying each individual particle in an event, with an optimised combination of information from the various detector elements.

The electron momentum is estimated by combining the energy measurement in the ECAL, including all bremsstrahlung photons spatially compatible with originating from the electron track, with the momentum measurement in the tracker. The transverse momentum (p_{T}) resolution ranges from 1.7 to 4.5% for electrons with $p_{\mathrm{T}} \approx 45\,\mathrm{GeV}$ from $\mathrm{Z} \to \mathrm{e}^{+}\mathrm{e}^{-}$ decays [46].

The muon energy is obtained from the curvature of the corresponding track. Matching muons to tracks measured in the silicon tracker results in a relative p_{T} resolution of 1% in the barrel and 3% in the endcaps [47], for muons with p_{T} up to 100 GeV.

The primary vertex (PV) is selected using tracking information only: vertices with at least four tracks and a longitudinal distance of less than 24 cm from the centre of the detector are selected. From these candidates, the PV is taken as the one with largest scalar sum of associated particle p_{T}, as described in Section 9.4.1 of Ref. [48].

Jets are clustered from reconstructed particles using the anti-k_{T} algorithm [49, 50] with a distance parameter of 0.4. The jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be, on average, within 5–10% of the true momentum over the whole p_{T} spectrum and detector acceptance. To mitigate effects from additional pp interactions within the same or nearby bunch crossings ("pileup"), tracks identified to be originating from pileup vertices are discarded, and an offset correction is applied to correct for remaining contributions [51, 52]. Jet energy corrections are derived from simulation studies so that the average measured energy of jets becomes identical to that of particle-level jets. In-situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to determine any residual differences between the jet energy scale in data and in simulation, and appropriate corrections are applied [53]. The jet energy resolution amounts typically to 15–20% at 30 GeV, 10% at 100 GeV, and 5% at 1 TeV.

The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is computed as the negative vector sum of the p_{T} of all the particle-flow candidates in an event, and its magnitude is denoted as $p_{\mathrm{T}}^{\text{miss}}$ [54]. The vector $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event.

Intact protons emerging from interaction vertices at small angles are detected by CT-PPS, either with a single RP station (pixels or strips), or the combination of the information from two stations in the same arm (multi-RP reconstruction). The latter features superior resolution, thanks to the lever arm between the two stations, while it suffers from lower efficiency because of the double-track requirement. In this analysis, only multi-RP proton candidates are used. The proton reconstruction efficiency is evaluated as the product of three different contributions. The first one is the efficiency of the strip detectors, locally degrading in time because of radiation damage. The second contribution is the multi-RP reconstruction efficiency, which combines the acceptance of protons propagating between the near and far stations, the pixel detector efficiency (similarly affected by radiation damage), and the efficiency of the reconstruction algorithm. Values for the combination of these two effects are provided, as functions of the position of the track in the transverse plane, for each of two subsets of the 2017 data-taking period. Finally, the efficiency of the single-track requirement in the strips mentioned in Section 2.1 is taken into account by applying scaling factors, derived globally per arm, for each of five data-taking periods ("eras"). This is the most significant contribution to proton reconstruction efficiency, with values below 50% for the periods with the highest instantaneous luminosity.

The proton kinematics is characterised by the fractional momentum loss, defined as $\xi = (|\vec{p}_\mathrm{i}| - |\vec{p}_\mathrm{o}|)/|\vec{p}_\mathrm{i}|$, where $\vec{p}_\mathrm{i}$ and $\vec{p}_\mathrm{o}$ are the momenta of the incoming and outgoing protons, respectively. The value of ξ is derived from the measured slopes and intercepts of the outgoing proton along with detailed knowledge of the LHC magnetic field. Dedicated alignment and calibration procedures are in place for different fills and LHC optics setup [55]. The detector acceptance as a function of ξ is determined by the geometry of the detectors and the LHC collimators, and also depends on the specific LHC settings: in 2017, detectable protons had, generally, ξ values in the range $0.02 < \xi < 0.18$ [55].

3 Data and simulation samples

This analysis uses data collected in 2017 considering only runs where all CT-PPS strip and pixel detectors were operational, which corresponds to an integrated luminosity of 29.4 fb^{-1} [56, 57]. The beam crossing angle at the IP, α_X, defined here as the angle between the LHC axis and one of the beams, was set at different values, with most data being recorded at $\alpha_\mathrm{X} = 120$, 130, 140, or 150 μrad. The remaining data are not included in this analysis.

To simulate the signal and background processes, different Monte Carlo (MC) event generators are used. For all processes, the response of the central CMS detector is simulated using the GEANT4 package [58], tuned on data.

A $\gamma\gamma \to \mathrm{t\bar{t}}$ signal sample is produced at leading order using FPMC [59] as the matrix element generator, with the equivalent photon approximation for the photon flux [60] and a rapidity gap survival probability of 0.9. Events are generated for $0.02 < \xi < 0.20$. Top quark decays are simulated with MADSPIN [61], selecting dilepton and $\ell +$jets decays. The outgoing protons are propagated through the beamline from the IP to the RPs. The response of the CT-PPS detector is simulated using a fast forward-proton simulation that includes beam-divergence and vertex smearing at the IP as well as the beam crossing angle dependence [55]. The aperture limitations for a given crossing angle are included in the simulation, and hits in the detectors are generated taking into account sensor acceptance and resolution. The simulated hits are then used to reconstruct proton tracks by means of the standard CT-PPS reconstruction algorithms.

Backgrounds arise from a variety of hard processes in combination with two uncorrelated protons from pileup interactions within the CT-PPS acceptance. The dominant hard-process background is inclusive $\mathrm{t\bar{t}}$ production. A smaller contribution comes from single top quark production in the tW channel and, for the $\ell +$jets channel, from QCD multijet events; additionally, depending on the $\mathrm{t\bar{t}}$ decay channel, there are small but non-negligible contributions from V +jets, VV$'$, where V and V$'$ are either a W or a Z boson, and Drell–Yan events.

The inclusive $\mathrm{t\bar{t}}$ sample is simulated at NLO precision using the POWHEG (v2.0) [62–64] event generator. The inclusive $\mathrm{t\bar{t}}$ production cross section is scaled before the fit to the best available theoretical prediction at next-to-next-to-leading-order (NNLO) in QCD, amounting to 832 pb [65]. For all background sources containing top quarks, the p_T spectra of top quarks in simulated samples are reweighted according to predictions at NNLO QCD accuracy [66]. For both signal and background event generation, a top quark mass of 172.5 GeV is assumed.

For all processes, the parton showering and hadronisation are simulated using PYTHIA 8.2 [67] with the CP5 underlying event tune [68]. The NNPDF3.1 [69] NNLO parton distribution functions (PDFs) are used.

No simulated sample is used to evaluate the contribution of the QCD multijet background. Instead, a purely data-driven method is applied, as described in Section 4.3.

4 Analysis strategy

The analysis is conducted independently for the events in the dilepton decay channel and for those in the $\ell +$jets decay channel. The resulting distributions from the two channels are used as input to a common maximum likelihood fit, and a combined result is extracted.

4.1 Event selection

Events of interest are selected by CMS using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz [70]. The second level, known as the high-level trigger (HLT), consists of a farm of processors running a version of the full event reconstruction software optimised for fast processing, and reduces the event rate to around 1 kHz before data storage [71].

In the dilepton analysis, events are selected using a combination of single-lepton and dilepton triggers that identify leptons within $|\eta| < 2.5$. The single-lepton HLT selection requires the presence of an isolated electron (muon) reconstructed with $p_{\mathrm{T}} > 35$ (27) GeV. Alternatively, a 24 GeV requirement is applied for muons within $|\eta| < 2.1$. The dilepton HLT selection requires the presence of two isolated electrons with $p_{\mathrm{T}} > 23$ and 12 GeV, two isolated muons with $p_{\mathrm{T}} >$ 17 and 8 GeV, one isolated electron with $p_{\mathrm{T}} > 23$ GeV and one isolated muon with $p_{\mathrm{T}} > 8$ GeV, or one isolated muon with $p_{\mathrm{T}} > 23$ GeV and one isolated electron with $p_{\mathrm{T}} > 12$ GeV.

In the $\ell +$jets analysis, events are selected using a combination of single-lepton and jet triggers. The single-lepton HLT selection requires the presence of a single isolated electron (muon) with $p_{\mathrm{T}} > 35$ (27) GeV, reconstructed within $|\eta| < 2.5$. The remaining selections require the presence of a single electron with $p_{\mathrm{T}} > 28$ GeV and a sum of the p_{T} of the jets greater than 150 GeV, or the presence of a single electron with $p_{\mathrm{T}} > 30$ GeV and at least one jet with $p_{\mathrm{T}} > 35$ GeV; in both cases, the electron must be reconstructed within $|\eta| < 2.1$.

Offline, the reconstructed lepton with highest p_{T} must have $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.1$ (2.4) for electrons (muons); in the dilepton analysis, the lepton with the second highest value of p_{T} must have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.4$. Additionally, the charged leptons are required to satisfy specific quality criteria. A set of scale factors is applied to simulated events as a function of the lepton p_{T} and η to account for differences observed in the lepton trigger, reconstruction, and identification efficiency between data and simulation.

Reconstructed jets are required to have $p_{\mathrm{T}} > 30$ (25) GeV in the dilepton ($\ell +$jets) channel, and $|\eta| < 2.4$. Moreover, the angular distance $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ between a jet and a lepton must be greater than 0.4, where ϕ is the azimuthal angle in radians.

Jets originating from the hadronisation of b quarks are identified with the DEEPCSV algorithm [72] as b-tagged jets. The "medium" working point is used, corresponding to a typical efficiency of about 70% for correctly identified b quark jets, with a misidentification probability of 12 (1)% for c quark (gluon or light quark) jets. Scale factors are applied to the simulated events as a function of the jet p_{T} and η to account for the differences observed in the b jet identification efficiency between data and simulation.

The final selection in the dilepton channel requires the presence of at least two oppositely charged leptons; at least one of them is required to have $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ and $|\eta| < 2.1$. The two leptons with the highest p_{T} are required to have opposite charge, and the dilepton system they form is required to have an invariant mass $m_{\ell\ell} > 20\,\mathrm{GeV}$. For the events with two reconstructed leptons of the same flavour, $m_{\ell\ell}$ is required to be outside a 30 GeV window around the Z boson mass peak: $(m_{\ell\ell} < 76\,\mathrm{GeV}) \cup (m_{\ell\ell} > 106\,\mathrm{GeV})$. Events are categorised according to the final-state charged leptons as ee, eμ, or $\mu\mu$. Only events with at least two b-tagged jets are retained. In the $\ell +$jets channel, the final selection requires the presence of exactly one lepton (electron or muon), at least two jets passing the b tagging selection criteria, and at least two jets failing the b tagging selection criteria.

Both the dilepton and the $\ell +$jets analysis require one multi-RP proton track to be reconstructed in each arm.

The overall efficiency of the selection, including detector acceptance, is about 2% for the dilepton channel and 0.8% for the $\ell +$jets channel.

4.2 Top quark pair reconstruction

Full reconstruction of the $\mathrm{t\bar{t}}$ pair can be used to relate its kinematics to that of the forward protons. In central exclusive production, the momentum transfer at the interaction vertex is typically quite small, implying very small values (below 1 GeV) for the transverse momentum of the outgoing protons and, consequently, of the central system. Moreover, the invariant mass and the rapidity of the central system X are related to the momentum loss of the protons by the expressions:

$$m_{\mathrm{X}} = \sqrt{s\xi_1\xi_2}, \tag{1}$$

$$y_{\mathrm{X}} = \frac{1}{2}\ln\frac{\xi_1}{\xi_2}, \tag{2}$$

where $\sqrt{s}$ is the centre-of-mass energy and ξ_1, ξ_2 are the fractional momentum losses of the outgoing protons in the positive and negative z direction, respectively. The reconstruction of a $\mathrm{t\bar{t}}$ candidate through its decay chain is carried out independently for the dilepton and $\ell +$jets channels, in order to take advantage of their different kinematic properties. In the dilepton channel, the $\mathrm{t\bar{t}}$ system is reconstructed by means of an analytic method and the resulting $\mathrm{t\bar{t}}$ observables are used as input to the multivariate discriminant described in Section 4.5, together with the kinematic observables of the tagged protons. In the $\ell +$jets channel, the kinematics matching between the $\mathrm{t\bar{t}}$ system and the tagged protons is explicitly used as a constraint in a global kinematic fit.

In the dilepton analysis, the two charged leptons and the two b-tagged jets with the highest p_{T} are selected. The association of the leptons with the jets relies on a kinematic reconstruction algorithm [73] that also estimates the kinematics of the top quark and antiquark. The missing transverse momentum is assumed to originate solely from the two neutrinos in the decay, and the W boson and top quark masses, m_{W} and m_{t}, are constrained to their known values [74]. Multiple replicas of the energy-momentum conservation equations are generated, with particle momenta varied according to their resolution and the width of the W boson. For each of them, the solution with the smallest value of the $\mathrm{t\bar{t}}$ invariant mass ($m_{\mathrm{t\bar{t}}}$) is chosen, and a weight is assigned based on the spectrum of the generator-level invariant mass of the lepton and b quark jet system. The weights are then used to obtain weighted averages of the kinematic observables of the top quark and antiquark. The combination of leptons and jets which yields the highest sum of weights is chosen as the best combination. This algorithm finds a physical solution in about 90% of the events passing the previous selection, both for data and for simulation. For simulated $\mathrm{t\bar{t}}$ events, the correct association of lepton and b jet is achieved in 70% of the cases. The events for which no physical solution is found are not removed, but a fixed, unphysical value is assigned to their $\mathrm{t\bar{t}}$ observables.

In the ℓ + jets analysis, only the b-tagged jets and the non-b-tagged (denoted 'light-flavour') jets with the highest p_{T} values are considered: up to four of each type are selected. Top quark candidates with the W boson decaying leptonically are reconstructed from combinations of a b-tagged jet, the selected lepton, and a neutrino candidate. The neutrino candidate is initially reconstructed from the missing transverse momentum, with the longitudinal component assigned by imposing the constraint $m_{\ell\nu} = m_{\mathrm{W}}$. In cases where the two solutions of the resulting quadratic equation are real, the one closest to the longitudinal momentum of the lepton is chosen. Top quark candidates with the W boson decaying hadronically are reconstructed from combinations of a b-tagged and two light-flavour jets. The choice of the two b quark jets to be used for top quark and antiquark reconstruction, and of their association with the other objects, is based on the invariant mass of the reconstructed t and $\mathrm{\bar{t}}$ candidates, $m_{\mathrm{t}}^{\mathrm{reco}}$ and $m_{\mathrm{\bar{t}}}^{\mathrm{reco}}$. The combination that yields the lowest value of $|m_{\mathrm{t}}^{\mathrm{reco}} - m_{\mathrm{t}}^{\mathrm{ref}}| + |m_{\mathrm{\bar{t}}}^{\mathrm{reco}} - m_{\mathrm{t}}^{\mathrm{ref}}|$ is selected, where $m_{\mathrm{t}}^{\mathrm{ref}}$ is chosen to be 173.1 GeV, from direct measurements [74]. Using this procedure, b quark jets are found to be correctly assigned in 75% of all cases. The kinematic observables of all reconstructed objects are further corrected by means of a kinematic fit. The momentum components of the lepton, the four jets, and the neutrino, as well as the fractional momentum loss of the forward protons, are used as inputs to the fit and allowed to float, constrained by Gaussian probability distribution functions centred on their measured values and with the widths equal to the measurement uncertainties. The longitudinal component of the neutrino momentum is left free to float in the fit. The W boson mass (m_{W}) and m_{t} are constrained to their known values, and the total p_{T} of the $\mathrm{t\bar{t}}$ system is set to zero. Finally, $m_{\mathrm{t\bar{t}}}$ and the fractional momentum loss of the protons are required to satisfy Eq. (1), where X is the $\mathrm{t\bar{t}}$ pair.

Figure 3 shows the $m_{\mathrm{t\bar{t}}}$ resolution achieved for the dilepton and ℓ + jets channels. The poorer resolution obtained for the dilepton mode, for which the width of the Gaussian core of the distribution is $\simeq$15%, is understood from the presence of two neutrinos in the final state. For the ℓ + jets case, the resolution is shown before ($\simeq$7.5%) and after ($\simeq$5%) applying the kinematic fitter.

4.3 Background from multijet events

For the ℓ + jets analysis, the background originating from QCD multijet events has been evaluated with a data-driven approach. The method is based on the observation that the leptons selected in such events are generally not produced promptly in the primary interaction, but are rather real leptons from semileptonic decays of hadrons, or other objects incorrectly identified as leptons.

Samples of events enriched with nonprompt leptons are created by imposing looser selection criteria on the lepton. A "tight-to-loose" ratio is defined as the ratio of the number of nonprompt lepton events satisfying the tight (nominal) selection to the number of those only passing the loose selection. It is evaluated in a data sample mostly populated by multijet events

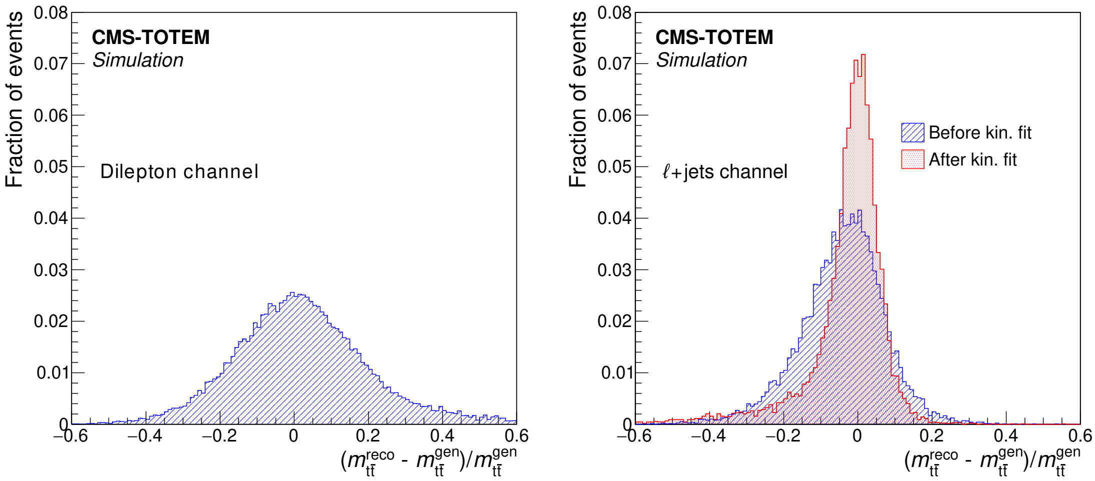

Figure 3: Normalised distribution of the relative resolution of the reconstructed $m_{t\bar{t}}$ in simulated signal events, for the dilepton (left) and $\ell +$jets (right) analyses. The resolution is shown only for events where the reconstruction is successful. For the $\ell +$jets decay mode, the hatched blue and the dotted red histograms represent the distribution before and after applying the kinematic fit, respectively.

("control region", or CR) and then used to estimate the number of nonprompt lepton events passing the nominal $\ell +$jets selection ("signal region", or SR) described in Section 4.1.

The CR is defined by the same selection criteria as the SR, except for the requirement that no jet pass the b tagging selection, and that $p_T^{miss} < 20\,\text{GeV}$. Contributions from background sources other than multijet events are subtracted using the simulated samples. Values of the tight-to-loose ratio are calculated as a function of the lepton p_T separately for the two lepton flavours, and then applied to data in the SR, after all simulated contributions from prompt-lepton background sources have been subtracted.

This method can be used to obtain the distribution of any kinematic variable for the nonprompt lepton component, as well as of the multivariate discriminant used for signal extraction described in Section 4.5. For the latter, the resulting shape is observed to be consistent, within statistical uncertainties, with that from the dominant inclusive $t\bar{t}$ background. Since the inclusive $t\bar{t}$ normalisation is a free parameter in the final fit described in Section 6, separately for the dilepton and the $\ell +$jets channels, and the contribution of the nonprompt lepton component is estimated to be much smaller (about 13%), an independent QCD multijet background contribution is not included in the final fit.

4.4 Signal and background models

The presence of multiple proton interactions within the same LHC bunch crossing results in the superposition of objects from different PVs both in the central CMS apparatus and in CT-PPS. The probability to have at least one proton in the acceptance of a given arm of CT-PPS, for any bunch crossing, ranges from 40 to 70% depending on the LHC optics settings and instantaneous luminosity. However, while the pileup activity in the central detector can be modelled with adequate accuracy, no simulation has been validated so far for protons from uncorrelated diffractive events, where the pp interaction is mediated by strongly interacting colour-singlet exchange. As a consequence, in the MC samples, background events contain no forward protons, while signal events contain exactly two forward protons on opposite sides (though not necessarily within the acceptance).

The presence of pileup protons, uncorrelated with the event reconstructed in the central detector, has two effects:

- a background event may be selected because exactly one random proton per arm has been reconstructed in CT-PPS;
- a signal event may be rejected because of the multiple proton reconstruction inefficiency, or it may be wrongly reconstructed because a background proton is selected instead of the signal one that went undetected as a result of detector inefficiency or limited acceptance.

In order to correctly take these effects into account, a pool of forward proton pairs reconstructed in the collision data is collected to be used as a sample of pileup protons, from events subject to the same requirements of the nominal selection (including one reconstructed proton in each CT-PPS arm) except for those on b-tagged jets. Moreover, the proton reconstruction efficiency as a function of ξ and the probability of having zero (not including multitrack inefficiency) or one proton reconstructed in each arm are taken from dedicated studies on collision data [55]. Because the detector and beam conditions varied significantly throughout the data taking, both the forward proton pools and the efficiency/probability values are considered separately for each of the five eras and, except for the reconstruction efficiency, for four values of the beam crossing angle α_X at the IP (120, 130, 140, and 150 μrad).

For each simulated event, a pair of protons is selected from the pool according to the relative normalisation of the (era, α_X) samples. Then, the following procedure is applied:

- for background events, the proton pair is added and a weight corresponding to the probability of reconstructing one proton in each arm is assigned;
- for signal events, the number of reconstructed protons is first determined according to the detector acceptance and a random correction based on the reconstruction efficiency. If only one of the original protons is left, the other is replaced with one from the pool, and an appropriate weight is assigned to the event, according to the probability of ending up with exactly one proton. Events in which neither forward proton is reconstructed are treated as background events, as described above.

In order to match the pileup conditions for simulated events to those in the collision data, a further reweighting procedure is applied to simulated events, based on the number of reconstructed interaction vertices. The normalised distribution of this number for a given simulated sample, $P^{\mathrm{MC}}(n_{\mathrm{vtx}})$, and that for the data in each of the 20 (era, α_X) regions, $P^{\mathrm{data}}(n_{\mathrm{vtx}} \mid \mathrm{era}, \alpha_X)$, are determined. A weight $w_{\mathrm{PU}} = P^{\mathrm{data}}(n_{\mathrm{vtx}} \mid \mathrm{era}, \alpha_X) / P^{\mathrm{MC}}(n_{\mathrm{vtx}})$ is assigned depending on the sampled region.

To assess the validity of the background model obtained from this procedure, the distributions of various event variables in data and simulated samples are compared, and very good agreement is observed. Figure 4 shows the overall distribution of ξ in each arm of CT-PPS for the $\ell +$jets decay mode.

4.5 Multivariate analysis

In order to enhance the signal content of the selected samples, information from variables showing discriminating power against background sources is efficiently exploited by means of multivariate analysis techniques. For both the dilepton and the $\ell +$jets channels, a boosted decision tree (BDT) algorithm [75] is used, implemented with the TMVA toolkit [76]. The train-

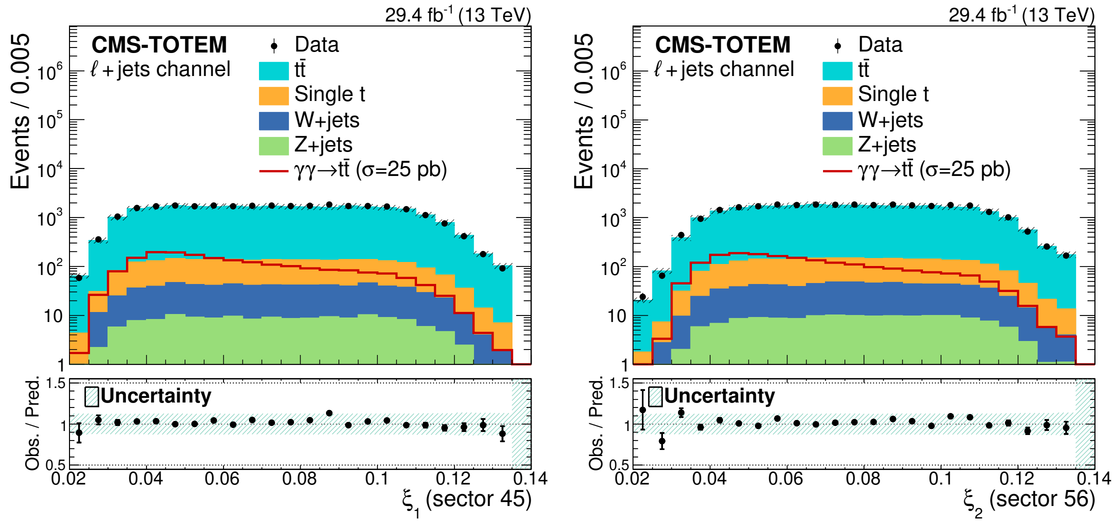

Figure 4: Distribution of ξ in data and background simulated samples after pileup proton mixing and pileup reweighting, in the $\ell + $jets channel. Protons in CT-PPS arm 0 (left) and arm 1 (right), as defined in the text. The solid histograms show the expected background contributions, while the red open histograms show the expected signal shapes, normalised to a cross section of 25 pb, approximately 10^5 larger than the SM cross section prediction from Ref. [32]; points with statistical error bars represent collision data. The lower panels show the data-to-prediction ratios; the hatched bands represent the relative uncertainty in the predictions.

ing samples consist of simulated signal events with both protons reconstructed, and simulated inclusive $t\bar{t}$ production events, by far the largest source of background, with two pileup protons added from collision data, as described in the previous section. Because of the different objects in the two final states and their related kinematics, the choice of the discriminating variables is different for the two decay modes. For each decay mode, a large set of variables was initially tested, and then reduced to a smaller set through optimisation, where the most performant and uncorrelated variables were selected.

For the dilepton decay mode, the following 15 kinematic variables are used: the mass and the rapidity of the central system reconstructed both from the $t\bar{t}$ decay products and from proton kinematics (Eqs. (1) and (2)); p_T^{miss}; the invariant mass and the angular distance ΔR of the two leptons; $|\Delta\phi|$ of the two selected b-tagged jets; the rapidity of the system formed by the two b quark jets and the two leptons, and the sum of the absolute values of their individual rapidities; the rapidity of the system formed by all other reconstructed jets, and the sum of the absolute values of their individual rapidities; the squared energy sum for all objects used for the $t\bar{t}$ reconstruction; the minimum absolute value of the rapidity difference for any two systems formed by a lepton and a b-tagged jet; and the number of light-flavour jets.

For the $\ell + $jets decay mode, the following 10 kinematic variables are used: the number of light-flavour jets and of b-tagged jets; the sum of the invariant mass of all jets; the total energy of all light-flavour jets; the mean ΔR for all pairs of light-flavour jets; the total energy of all extra jets (not used for $t\bar{t}$ reconstruction); the lepton momentum and a variable quantifying its isolation from other particles in the event; $m_{t\bar{t}}$; the difference in central system rapidity reconstructed from the $t\bar{t}$ and the pp systems (Eq. (2)); and the χ^2 of the kinematic fit.

The distributions of some of the kinematic variables of interest are shown in Fig. 5 for the two decay modes.

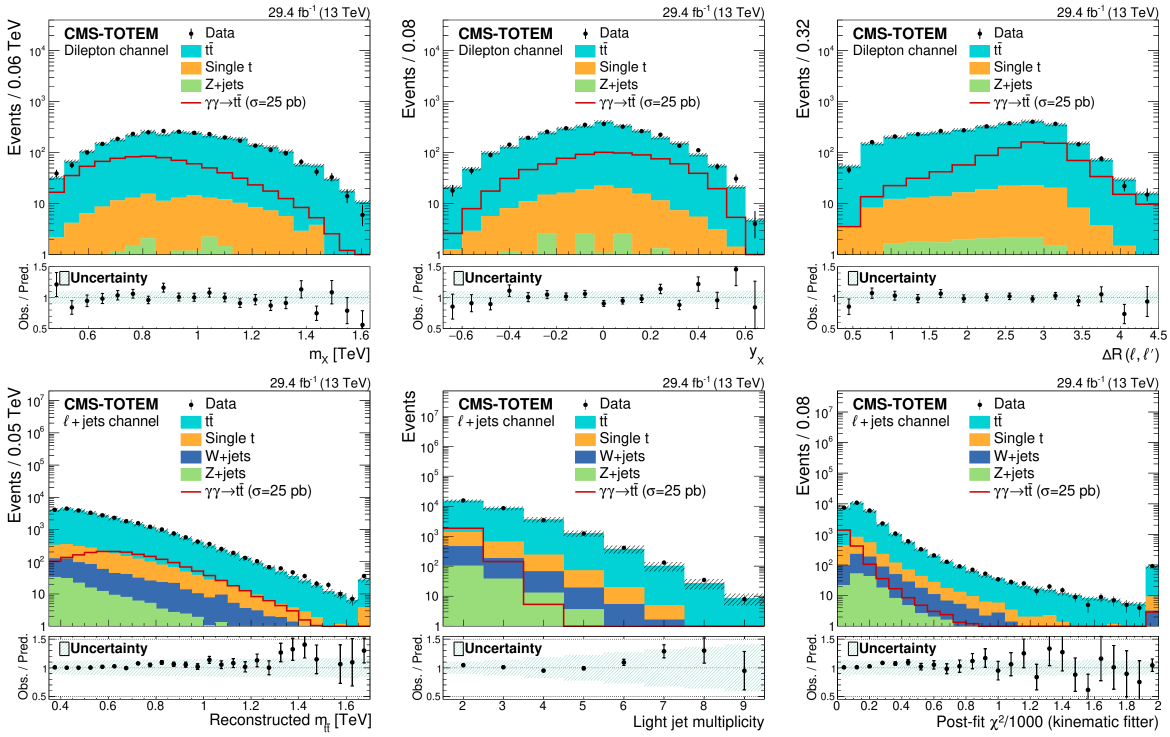

Figure 5: Distribution of a selection of the kinematic variables of interest for the dilepton (upper) and ℓ + jets (lower) analysis. The solid histograms show the expected background contributions, while the red open histograms show the expected signal shapes, normalised to a cross section of 25 pb, approximately 10^5 larger than the SM cross section prediction from Ref. [32]; points with statistical error bars represent collision data. The lower panels show the data-to-prediction ratios; the hatched bands represent the uncertainty in the predictions. The leftmost and rightmost bin in each histogram includes accepted events outside the histogram range.

5 Systematic uncertainties

Several sources of systematic uncertainty affect the normalisation of the signal and background yields, as well as the shape of the BDT output used as the final discriminant. For each of them, the impact on the final result is assessed by varying appropriately the parameters involved, and repeating the analysis. When the variations imply a change in the BDT shape, a smoothing procedure (using the '353QH' algorithm described in Ref. [77]) is applied to the associated template used in the fitting procedure described in Section 6. Modified BDT shapes are compared to the nominal one using a Kolmogorov–Smirnov-inspired test: if the test result (calculated as described in Section 6.2.2 of Ref. [78]) is larger than 0.95 for both the upwards and downwards variation, the corresponding systematic uncertainty is only included as an overall normalisation effect; otherwise, the shape uncertainty is included as a nuisance parameter and profiled in the likelihood fit.

The sources of systematic uncertainty can be subdivided into experimental and theoretical components.

Experimental uncertainties The measured integrated luminosity that is used to normalise the MC predictions has an associated systematic uncertainty of 2.3% [56, 57]. Several uncertainties arise from the reconstruction and identification of various objects. For leptons, b quark jets, and forward protons, efficiency correction scale factors are varied within their uncertainties, which affect both the shape and normalisation of the final discriminant. The uncertainty in the jet energy has an effect on the reconstruction of the kinematic variables used to calculate the discriminants: the corresponding uncertainty is evaluated by rescaling the p_T- and η-dependent scale factors of the reconstructed jet energy [53] and jet energy resolution. The variation in four-momentum for each selected jet is propagated to $\vec{p}_T^{miss}$ and the b tagging scale factors. Uncertainties in the efficiency corrections for the lepton trigger are estimated as functions of the lepton p_T and η from control samples in data; for electrons (muons) they are within 3% (below 1%), except for $p_T < 35\,GeV$, where they range up to 8 (3)%. In the pileup proton mixing procedure described in Section 4.4, the normalisation of the simulated data samples is performed according to the pileup proton probability measured in real data with no requirement on the b quark jet multiplicity. A possible bias of the proton tag probability arising from the different b quark jet selection is estimated by measuring the proton tag probability again after requiring $N_{b\ jet} \geq 1$: the difference in the predicted tagged proton probability is taken as the corresponding systematic uncertainty. For the signal sample, the simulation of forward protons is tuned to reproduce the expected bias and resolution in ξ reconstruction assuming perfect knowledge of the detector alignment and LHC optics. The effect of uncertainties in this assumption is estimated by shifting, in each event, the reconstructed ξ values according to the "systematics" contribution described in Ref. [55].

Theoretical uncertainties The uncertainties related to the choice of the factorisation and renormalisation scales at the matrix element level are estimated by performing 6 variations of the scales by factors 2 and 0.5 [79]. For PDF modeling, two effects are considered: a variation of the strong coupling constant α_S, and the root-mean-square of the variations from a collection of PDF error eigenvectors sets, as described in the PDF4LHC Collaboration recommendations [80]. The uncertainty associated to parton shower emission in initial and final state is evaluated by varying the renormalisation scale for QCD emissions by factors of 2 and 0.5. The normalisation of the inclusive $t\bar{t}$ background is free to vary around its nominal values for the $\ell +$jets and the dilepton channels separately, while single top quark and other backgrounds normalisation uncertainties are taken to be 5% [81] and 30% [82–84], respectively. Finally, the effect of the finite size of the simulated samples used for the analysis is taken into account with the Beeston–Barlow method [85].

6 Results

A profile maximum-likelihood fit is performed to the distributions of BDT discriminants for the two decay modes. While the sensitivity with the current data does not allow to obtain evidence for central exclusive $t\bar{t}$ production, an upper limit for its cross section can be derived. The limits are computed based on an asymptotic approximation of the distributions of the test statistics, which in turn is based on the profile likelihood ratio, under given hypotheses for the signal and the background [86–88]. The sources of systematic uncertainty described in Section 5 are included in the fit as nuisance parameters.

The impact of a given systematic uncertainty on the upper limit is defined as the relative difference between the nominal limit and the limit extracted by including all other systematic uncertainties but excluding the uncertainty in question. For the final result, uncertainties whose impact on the upper limit is less than 0.1% are not included.

In the dilepton analysis, a simultaneous fit is performed to each of the final-state lepton combinations ee, eμ, and $\mu\mu$, integrating over era and α_X. For the $\ell +$ jets analysis, the simultaneous fit is performed on each of the 20 samples defined by (η, α_X), combining the two lepton flavours. These choices are the result of an optimisation based on a compromise between the expected sensitivity and the statistical uncertainty.

The expected and observed distributions of the BDT variable for the dilepton and ℓ + jets decay modes are shown in Fig. 6, where all signal regions are combined.

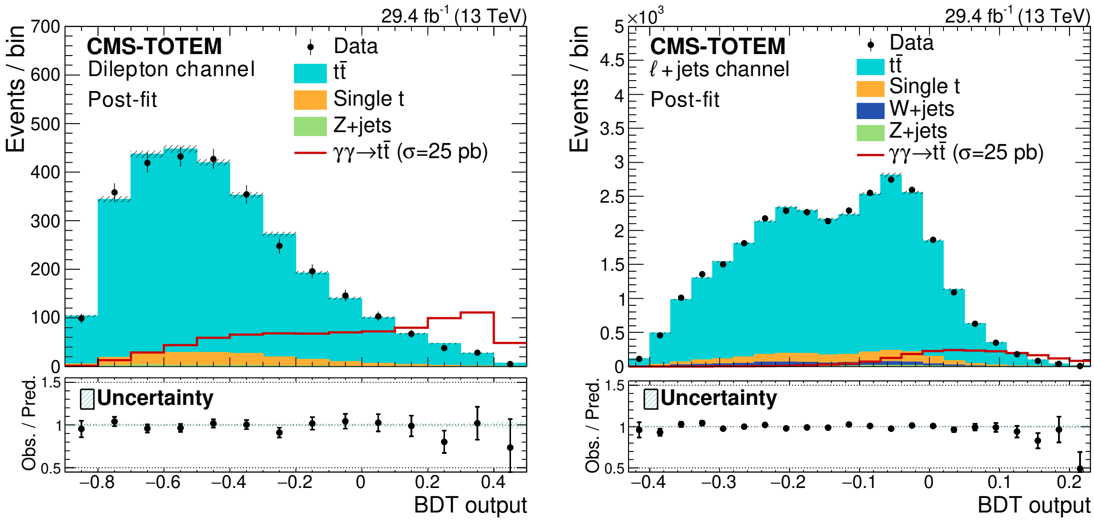

Figure 6: Distribution of the BDT output in the signal region for simulated events after the fit, and for data. Left: dilepton channel; right: ℓ + jets channel. The different ranges of the two BDT output distributions are a consequence of the different architectures of the algorithms. The solid histograms show the expected background contributions, while the red open histograms show the expected signal shapes, normalised to a cross section of 25 pb, approximately 10^5 larger than the SM cross section prediction from Ref. [32]; points with statistical error bars represent collision data. For both reconstruction modes, all signal regions are combined. The lower panels show the data-to-prediction ratios; the hatched bands represent the relative uncertainty in the predictions.

In the dilepton decay mode, the fit yields an observed (expected) 95% confidence level upper limit on exclusive central production of $t\bar{t}$ pairs of 1.71 (2.02) pb; in the ℓ + jets mode, an upper limit of 0.78 (1.54) pb is obtained. The two modes are then considered jointly in a combined fit, where each source of systematic uncertainty is treated as fully correlated between the two channels. The observed (expected) limit resulting from the combined fit is 0.59 (1.14) pb.

The results of the fit are shown in Fig. 7, for the separate decay channels, as well as for the combination. The value of the extracted limit depends mostly on the statistical precision; the increase due to inclusion of the systematic uncertainties is about 10%. The most important contributions from systematic uncertainties are those related to background normalisation, final-state radiation modelling, jet energy corrections and resolution, as well as proton reconstruction with CT-PPS.

7 Summary

A search is reported for the central exclusive production of top quark-antiquark pairs in proton-proton interactions, $pp \to pt\bar{t}p$, for the first time using tagged intact protons, reconstructed by the CMS-TOTEM precision proton spectrometer. The $t\bar{t}$ pairs are reconstructed by the CMS detector either in the dilepton or the lepton+jets decay modes. The search is conducted both separately for the two modes, and in a combined fit. With a data sample of proton-proton collisions at a centre-of-mass energy of 13 TeV corresponding to an integrated luminosity of

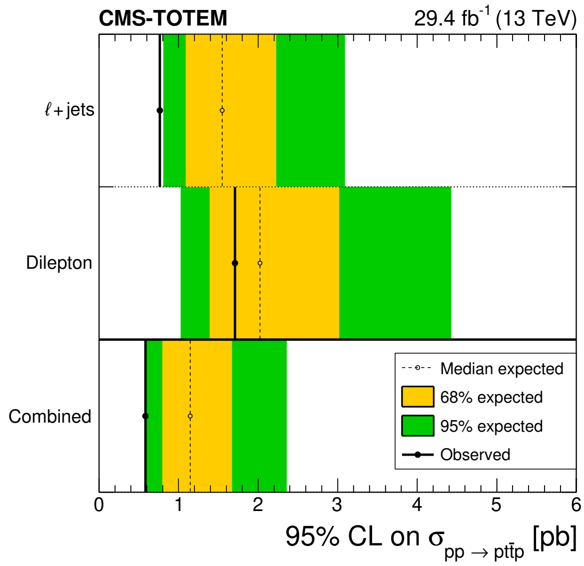

Figure 7: Expected and observed 95% confidence level (CL) upper limits for the cross section of $\mathrm{pp} \to \mathrm{pt\bar{t}p}$, for the dilepton and $\ell+$jets channels separately and combined. The green and yellow bands show the 68 and 95% intervals, respectively, for the expected upper limit.

$29.4\,\mathrm{fb}^{-1}$, results consistent with predictions from the standard model are obtained. An upper limit of 0.59 pb at 95% confidence level (compared to an expected limit of 1.14 pb) is set on the central exclusive production of $\mathrm{t\bar{t}}$ pairs, with fractional momentum loss of the intact protons in the range $0.02 < \xi < 0.20$.

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