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Search for Dark Matter Particles Produced in Association with a Top Quark Pair at √s =13 TeV

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Search for Dark Matter Particles Produced in Association with a Top Quark Pair at $\sqrt{s} = 13$ TeV

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A search is performed for dark matter particles produced in association with a top quark pair in proton-proton collisions at $\sqrt{s} = 13$ TeV. The data correspond to an integrated luminosity of 35.9 fb^{-1} recorded by the CMS detector at the LHC. No significant excess over the standard model expectation is observed. The results are interpreted using simplified models of dark matter production via spin-0 mediators that couple to dark matter particles and to standard model quarks, providing constraints on the coupling strength between the mediator and the quarks. These are the most stringent collider limits to date for scalar mediators, and the most stringent for pseudoscalar mediators at low masses.

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Astrophysical observations strongly motivate the existence of dark matter [1–4], which may originate from physics beyond the standard model. In a large class of models, dark matter consists of stable, weakly interacting massive particles (χ) [4], which may be pair produced at the CERN LHC via mediators that couple both to dark matter particles and to standard model quarks. The dark matter particles would escape detection, thereby creating a transverse momentum imbalance ($\vec{p}_T^{\text{miss}}$) in the event. Searches at collider experiments can offer insights on the nature of the mediator and provide constraints on dark matter masses of $\mathcal{O}(10\ \text{GeV})$ and below, a region that is difficult to explore both in direct and indirect searches for dark matter. A favored class of models proposes a spin-0 mediator with standard model Higgs-like Yukawa coupling to quarks, which therefore couples preferentially to the top quark [5–9]. Consequently, in this class of models dark matter production in association with a top quark pair ($t\bar{t}$) can offer better search sensitivity compared to other modes such as production in association with a jet [10–14]. At the LHC, the $t\bar{t} + \chi\bar{\chi}$ process is probed through the signature of $t\bar{t}$ accompanied by $\vec{p}_T^{\text{miss}}$ [15,16].

The top quark almost always decays to a W boson and a b quark. The W boson can decay leptonically (to a charged lepton and a neutrino) or hadronically (to a quark pair). The signal regions (SRs) of the search cover three $t\bar{t}$ decay modes: the all-hadronic, lepton + jets (ℓ + jets where $\ell = e, \mu$), and dileptonic (ee, $e\mu$, $\mu\mu$) final states where neither, either, or both of the W bosons decay to leptons, respectively. This Letter presents a search for $t\bar{t} + \chi\bar{\chi}$ in pp collisions at $\sqrt{s} = 13$ TeV with data recorded by the CMS experiment in 2016, corresponding to an integrated luminosity of 35.9 fb^{-1}. The analysis strategy is similar to Ref. [17], but includes additional SRs for the dileptonic mode.

The central feature of the CMS detector is a superconducting solenoid providing a magnetic field of 3.8 T. Within the solenoid volume are the silicon pixel and strip trackers, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. A steel and quartz-fiber Cherenkov forward hadron calorimeter extends the pseudorapidity (η) coverage. The muon system consists of gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A two-tiered trigger system [18] selects events at a rate of about 1 kHz for storage. A detailed description of the CMS detector is provided in Ref. [19].

The event reconstruction is based on the CMS particle-flow algorithm [20], which reconstructs and identifies individual particles using an optimized combination of the detector information. The $\vec{p}_T^{\text{miss}}$ vector is computed as the negative vector sum of the transverse momenta ($\vec{p}_T$) of all the particles in an event. Jets are formed from particles using the anti-k_T algorithm [21,22] with a distance parameter of 0.4. Corrections are applied to calibrate the jet momentum [23] and to remove energy from additional collisions in the same or adjacent bunch crossings (pileup) [24]. Jets in the analysis are required to have $p_T > 30$ GeV and $|\eta| < 2.4$, and to satisfy identification criteria [25] that minimize spurious detector effects. A combined secondary vertex b tagging algorithm [26] is used to identify jets originating from b quarks (b-tagged jets). A multivariate discriminant, the "resolved top tagger" (RTT) [17], based

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on jet properties and kinematic information, is used to identify top quarks that decay into three jets. Electrons and muons are selected using “tight” and “loose” requirements where the former applies more stringent identification criteria than the latter [27]. The tight leptons are used in the selection of specific final states, while loose leptons are used to veto events with extra leptons. The primary pp interaction vertex is taken to be the reconstructed vertex with the highest summed p_T^2 of its associated physics objects. Here, the physics objects are the jets, clustered with the tracks assigned to the vertex as inputs, plus the associated $\vec{p}_T^{\text{miss}}$.

The $t\bar{t}+\chi\bar{\chi}$ signal results in high-p_T jets including b-tagged jets, leptons, and significant $\vec{p}_T^{\text{miss}}$. The background is dominated by $t\bar{t}$ and $V+\text{jets}$ ($V=W$, Z/γ^*) production. The $t\bar{t}$ and single top quark backgrounds are simulated at next-to-leading order (NLO) accuracy in quantum chromodynamics (QCD) using POWHEG v2 and POWHEG v1 [28–31], respectively. Samples of $V+\text{jets}$ and QCD multijet events are simulated at leading order (LO) in QCD using MadGraph5_aMC@NLO v2.2.2 [32] (MadGraph), with up to four additional partons in the matrix element (ME) calculations. The $V+\text{jets}$ samples are corrected with boson p_T-dependent electroweak corrections [33–38] and QCD NLO/LO K factors computed using MadGraph. Samples of $t\bar{t}+V$ and diboson processes (WW, WZ, and ZZ) are generated at NLO using either MadGraph or POWHEG v2. The initial-state partons are modeled with the NNPDF 3.0 [39] parton distribution function (PDF) sets at LO or NLO in QCD to match the ME calculation. Generated events are interfaced with PYTHIA 8.205 [40] for parton showering using the CUETP8M1 tune [41], except for the $t\bar{t}$ simulation which uses the CUETP8M2 tune customized by CMS with an updated strong coupling α_S for initial-state radiation. The simulation of the CMS detector is performed with Geant4 [42]. Corrections derived from data are applied to account for any mismodeling of selection efficiencies in simulation.

The signal is simulated using simplified models of dark matter production [43]. The dominant mechanism is s-channel production of the mediator via gluon fusion, with the mediator then decaying to a pair of dark matter particles. The dark matter particles are assumed to be Dirac fermions, and the mediators are spin-0 particles with scalar (ϕ) or pseudoscalar (a) interactions. The couplings between the mediator and standard model quarks are $g_{qq}=g_q y_q$, where $y_q=\sqrt{2}m_q/v$ are the standard model Yukawa couplings, m_q is the quark mass, and $v=246\ \text{GeV}$ is the Higgs boson field vacuum expectation value. The g_q parameter is assumed to be unity for all quarks. The direct coupling strength of the mediators to dark matter is denoted by g_χ. The model does not take into account possible mixing between ϕ and the standard model Higgs boson [44]. The $t\bar{t}+\chi\bar{\chi}$ signal is generated at LO using MadGraph with up to one additional parton, and the mediator is forced to decay to a pair of dark matter fermions. The mediator width is computed according to partial-width formulas in Ref. [45] and assuming no additional interactions beyond those described here. The relative width of the scalar (pseudoscalar) mediator varies between 4% and 6% (4% and 8%) for masses in the range of 10–500 GeV. The signal is normalized to the cross section computed at NLO in QCD.

Data are collected by triggering on events containing large p_T^{miss} (the magnitude of $\vec{p}_T^{\text{miss}}$) or high-p_T leptons. The triggers for the all-hadronic final state are based on the amount of p_T^{miss} and H_T^{miss} measured with the trigger-level reconstruction. The H_T^{miss} variable is defined as the magnitude of the vector sum of $\vec{p}_T$ over trigger-level jets with $p_T > 20\ \text{GeV}$ and $|\eta| < 5.0$ that pass identification requirements. During the period of data collection, the p_T^{miss} and H_T^{miss} trigger thresholds were increased as the instantaneous luminosity increased, in steps from 90 to 120 GeV. Events in the $\ell+\text{jets}$ final state are obtained using single-lepton triggers that require an electron (muon) with $p_T > 27$ (24) GeV. Events in the dilepton final state are obtained using single-lepton and dilepton (ee, $e\mu$, $\mu\mu$) triggers. The trigger thresholds on the higher- and lower-p_T electrons (muons) are 23 (17) GeV and 12 (8) GeV, respectively, and apply to all pairings of lepton object flavors.

Using additional selection requirements, two all-hadronic, one $\ell+\text{jets}$, and four dilepton SRs are defined. Several control regions (CRs) enriched in standard model processes are used to improve the simulation-based background estimates for the all-hadronic and $\ell+\text{jets}$ SRs. There are no event overlaps among the regions. Together, the SRs and CRs associated with the individual $t\bar{t}+\chi\bar{\chi}$ final states are referred to as “channels.” All three $t\bar{t}+\chi\bar{\chi}$ channels are used in a simultaneous maximum-likelihood fit of p_T^{miss} distributions to extract a potential dark matter signal. In the fit, the CRs constrain the contributions of $t\bar{t}$, $W+\text{jets}$, and $Z+\text{jets}$ processes within each channel via freely floating normalization parameters for each p_T^{miss} bin.

The all-hadronic SRs require $p_T^{\text{miss}} > 200\ \text{GeV}$, and four or more jets, of which at least one must be b tagged. Any event with a loose lepton of $p_T > 10\ \text{GeV}$ is vetoed. The dominant background consists of $t\bar{t}$ decays to $\ell+\text{jets}$, referred to as $t\bar{t}(1\ell)$, where the lepton is not identified as loose and therefore not vetoed, and the neutrino is the source of $\vec{p}_T^{\text{miss}}$. The RTT is employed to define a category of events with two tagged hadronic top quark decays (2RTT), which suppresses the $t\bar{t}(1\ell)$ background, and a category with less than two top quark tags (0,1RTT) and at least two b-tagged jets. The RTT variable is essentially independent of p_T^{miss}; therefore, any bias on the p_T^{miss} shape from requiring top tags is negligible. Spurious p_T^{miss} can arise in multijet events as a result of jet energy mismeasurement. In such cases, the reconstructed $\vec{p}_T^{\text{miss}}$ tends to align with a jet. The multijet background is suppressed by requiring the smallest azimuthal angle between the $\vec{p}_T^{\,\text{miss}}$ and each jet in the event, $\Delta_j \equiv \min \Delta\phi(\vec{p}_T^{\,\text{j}}, \vec{p}_T^{\,\text{miss}})$, to be greater than 0.4 (1.0) radians in the 2RTT (0,1RTT) category. The Δ_j requirement also reduces the $t\bar{t}(1\ell)$ background, for which $\vec{p}_T^{\,\text{miss}}$ can align with a bottom jet.

The CRs targeting the $t\bar{t}(1\ell)$ background, one for each category, are defined by selecting events with exactly one tight lepton with $p_T > 30$ GeV, and by requiring the transverse mass, m_T, given in terms of $\vec{p}_T^{\,\text{miss}}$ and the lepton momentum ($\vec{p}_T^{\,\ell}$) by the following expression:

$$m_T = \sqrt{2 p_T^{\ell} p_T^{\text{miss}} [1 - \cos \Delta\phi(\vec{p}_T^{\,\ell}, \vec{p}_T^{\,\text{miss}})]}, \qquad (1)$$

to be less than 160 GeV, in order to avoid overlaps with the SR of the $\ell +$ jets channel. For ideal measurements, the m_T quantity is bounded above by the W boson mass for $t\bar{t}(1\ell)$ and for $W(\ell\nu) +$ jets where the W boson is produced on shell.

There are also significant background contributions from $Z(\nu\bar{\nu}) +$ jets, and from $W(\ell\nu) +$ jets where the lepton is not identified. The CRs enriched in both $W +$ jets and $Z +$ jets are formed by modifying the SR selections to require no b-tagged jets. Additionally, dedicated $W +$ jets CRs are defined by requiring a tight lepton with $p_T > 30$ GeV and $m_T < 160$ GeV. A CR enriched in $Z +$ jets is defined by selecting two tight, oppositely charged, and same-flavor leptons, with the dilepton invariant mass between 60 and 120 GeV. This CR is not subdivided into categories based on the number of top quark tags because the event yield with two tags is negligible. The p_T^{miss} calculation does not consider the two leptons in order to emulate the $Z(\nu\bar{\nu}) +$ jets process.

Events in the $\ell +$ jets SR are selected by requiring $p_T^{\text{miss}} > 160$ GeV, exactly one tight lepton with $p_T > 30$ GeV, and three or more jets, of which at least one is b tagged. Events must not contain additional loose leptons with $p_T > 10$ GeV. A selection of $m_T > 160$ GeV is imposed to reduce the $t\bar{t}(1\ell)$ and $W +$ jets backgrounds. Following these selections, the remaining background events primarily consist of dileptonic $t\bar{t}$ decays, referred to as $t\bar{t}(2\ell)$ events, where one of the leptons is not identified. This background is suppressed by requiring that the m_{T2}^{W} quantity [46] be larger than 200 GeV, and for the two highest p_T jets in the event that $\Delta_{j_{1,2}} \equiv \min \Delta\phi(\vec{p}_T^{\,\text{j}_{1,2}}, \vec{p}_T^{\,\text{miss}}) > 1.2$. The m_{T2}^{W} variable corresponds to the minimum mass of a particle consistent with being pair-produced and decaying to a bottom quark and a W boson, where both W bosons decay leptonically but one of the two leptons is not detected. The key characteristic of m_{T2}^{W} is that for ideal measurements the distribution for $t\bar{t}(2\ell)$ events is bounded above by the top quark mass.

The CR targeting the $t\bar{t}(2\ell)$ background is defined by requiring an additional tight lepton of $p_T > 30$ GeV with respect to the SR selection and removing the selections on m_T, m_{T2}^{W}, and $\Delta_{j_{1,2}}$. To reduce the signal contamination and avoid overlap with the dileptonic SRs, the $m_{T2}^{\ell\ell}$ variable [47–49] is required to be less than 110 GeV. The $m_{T2}^{\ell\ell}$ variable is essentially the minimum m_T of a pair-produced particle that decays to a lepton and a neutrino. The $m_{T2}^{\ell\ell}$ distribution for $t\bar{t}(2\ell)$ events is bounded above by the W boson mass for ideal measurements. A $W +$ jets CR for the $\ell +$ jets channel is defined by requiring no b-tagged jets and removing the selections on m_{T2}^{W} and $\Delta_{\text{j}_{1,2}}$.

Events in the dilepton SRs are selected by requiring exactly two oppositely charged tight leptons with higher (lower) $p_T > 25$ (15) GeV, two or more jets with at least one b-tagged jet, and $p_T^{\text{miss}} > 50$ GeV. The dilepton mass is required to be greater than 20 GeV, and for the dielectron and dimuon events, to be at least 15 GeV away from the Z boson pole mass (m_Z) [50]. Separate categories are considered for events with same- and different-flavor lepton pairs, and for events with $m_{T2}^{\ell\ell}$ greater or less than 110 GeV. Additionally, events with $m_{T2}^{\ell\ell} < 110$ GeV must not pass the selection for the $t\bar{t}(2\ell)$ CR of the $\ell +$ jets search channel. The SRs with large $m_{T2}^{\ell\ell}$ have significantly higher signal purity.

The estimates for the backgrounds from Drell-Yan production and from jets misidentified as leptons are performed using dedicated sideband regions not included in the fit. A p_T^{miss}-dependent correction to the Drell-Yan simulation in the same-flavor SRs is obtained by comparing data and simulation yields within 15 GeV of m_Z. The misidentified leptons background is estimated using data events with pairs consisting of one tight lepton plus a "nontight" lepton-like object passing a less stringent selection. The number of such combinations is scaled by misidentification rates, which are measured in a jet-enriched sample.

The dark matter signal, which would be observed as an excess of events compared to the predicted background at high p_T^{miss}, is extracted via a simultaneous maximum-likelihood fit to the binned p_T^{miss} distributions of the signal and backgrounds, based on simulation with the exception of the misidentified leptons background, in the SRs and associated CRs. The fit is performed using the RooStats statistical package [51]. The template shapes and normalization are allowed to vary in the fit, constrained by the priors of the systematic uncertainties, parametrized as nuisance parameters.

The common sources of uncertainty are correlated across SRs and CRs and across channels. The sources of normalization uncertainty include the integrated luminosity (2.5%) [52], b tagging efficiency (1%–5%) [26], lepton efficiency (1.5%–2.2%) [27], and pileup simulation (0.8%–1.9%), where the range of values indicates variations across different physics processes. The common sources of shape uncertainty include p_T^{miss} trigger efficiency, jet energy scale and resolution [25], PDF [39], uncertainty on the K factors for $V+\text{jets}$, uncertainty from missing higher order QCD corrections for each simulated physics process, and the uncertainty in the modeling of top quark p_T in $t\bar{t}$ simulation [53]. The jet energy scale uncertainties have the largest impact on the $\ell+\text{jets}$ and dilepton channels, while in the all-hadronic channel the top quark p_T modeling and p_T^{miss} trigger uncertainties are more important.

Within the all-hadronic and $\ell+\text{jets}$ search channels, additional nuisance parameters scale the yields of the $t\bar{t}$, $W+\text{jets}$, and $Z+\text{jets}$ backgrounds independently in each p_T^{miss} bin across the SRs and CRs of a given channel. For example, in each bin of p_T^{miss} a single parameter is associated with the contribution of the $W+\text{jets}$ process in the all-hadronic SRs and CRs, while another set of parameters distinct from those of the all-hadronic channel, is associated with the $W+\text{jets}$ background in the $\ell+\text{jets}$ SRs and CRs. These nuisance parameters allow the data in the CRs to constrain the estimates of the dominant background processes in the corresponding SRs. Signal yields in all the SRs and CRs are scaled simultaneously by the signal strength parameter (μ), defined as the ratio of the measured signal cross section to the theoretical cross section, $\mu=\sigma/\sigma_{\text{th}}$.

The fit is performed across all search channels and no significant excess is observed. Figure 1 shows the p_T^{miss} distributions for three of the seven SRs, obtained after the background-only fit assuming the absence of any signal. Upper limits are set on the $t\bar{t}+\chi\bar{\chi}$ production cross section using a modified frequentist approach (CL_s) with a test statistic based on the profile likelihood in the asymptotic approximation [54–56]. For each signal hypothesis, 95% confidence level (C.L.) upper limits on μ are determined. The all-hadronic channel provides the best sensitivity. The dileptonic channel is competitive with the all-hadronic channel for scalar mediator masses less than about 50 GeV, where the signal has a soft p_T^{miss} spectrum, but is typically the least sensitive channel in other regions of the parameter space.

The limits are shown as a function of $m_{a/\phi}$ and m_χ in Fig. 2. The contours enclose the region where the upper limit on μ is less than 1. Because of the narrow width of the mediator, the signal cross section drops rapidly across the $m_{a/\phi}=2m_\chi$ line, marking the boundary between the on-shell to the off-shell region. Therefore, the exclusion contour runs close to the $m_{a/\phi}=2m_\chi$ line but does not cross it. The observed (expected) upper limits on μ exclude scalar and pseudoscalar masses of 160 (240) and 220 (320) GeV, respectively, at 95% C.L. The observed exclusion is weaker than the expected because of tension in the fit between CRs and SRs of the all-hadronic channel, although the difference is not significant as the observed result lies only just outside the 68% probability interval.

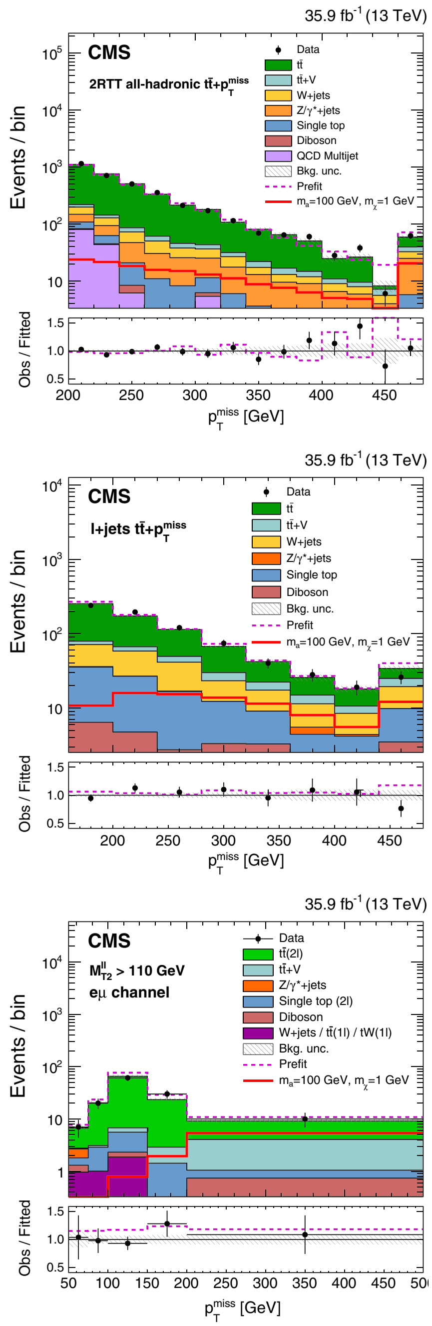

FIG. 1. Selected p_T^{miss} distributions in SRs: 2RTT SR for the all-hadronic (top), the $\ell+\text{jets}$ (middle), and the different-flavor, $m_{T2}^{\ell\ell}>110$ GeV SR in the dileptonic channel (bottom). The solid red line shows the expectation for a signal with $m_a=100$ GeV and $m_\chi=1$ GeV. The last bin contains the overflow events. The lower panel shows the ratio of the observed to the fitted distribution (points), and the ratio of the background expectation before the fit to the fitted distribution (dashed magenta line). The vertical bars indicate the statistical uncertainty on the data. The horizontal bars on the rightmost plot indicate the bin width. The uncertainty bands in both panels include the statistical and systematic uncertainties on the total background.

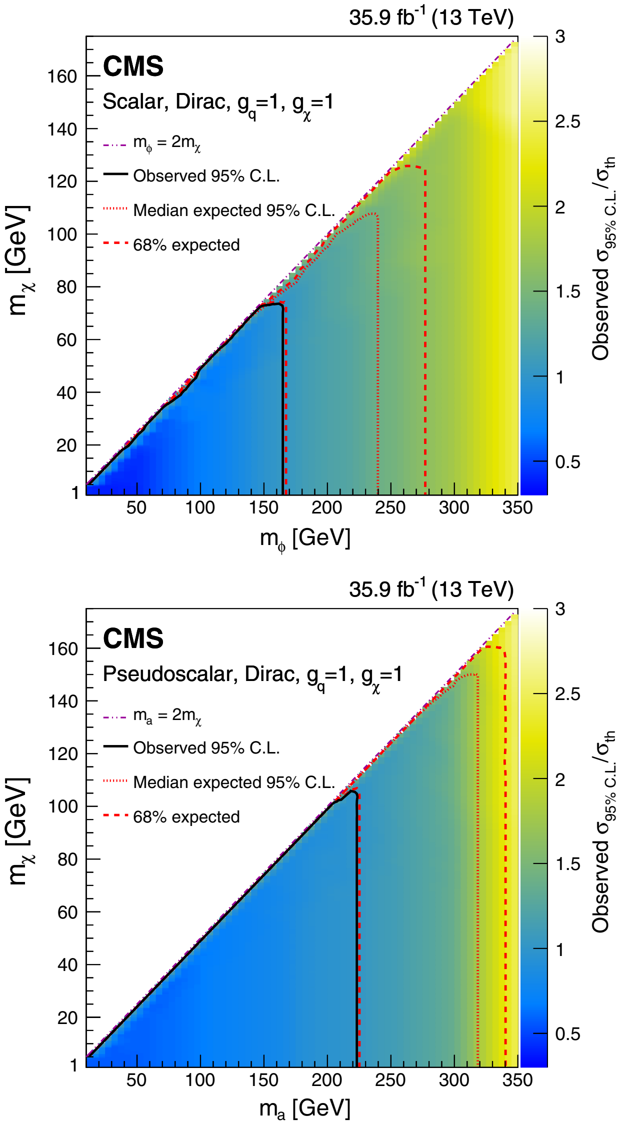

FIG. 2. The exclusion limits at 95% C.L. on the signal strength $\mu = \sigma/\sigma_{\mathrm{th}}$ computed as a function of the mediator and dark matter mass, assuming a scalar (top) and pseudoscalar (bottom) mediator. The mediator couplings are assumed to be $g_q = g_\chi = 1$. The dashed magenta lines represent the 68% probability interval around the expected limit. The observed limit contour is almost coincident with the boundary of the 68% probability interval.

This arises because the *a priori* estimation of the background exceeds the number of events observed in the CRs, while the estimate is in better agreement with data in the SRs. Consequently, the signal + background fit, in contrast to the background-only fit, reduces this tension between CRs and SRs by accommodating for some signal, which contributes primarily to the SRs.

The limits on μ are also expressed in terms of the mediator coupling strength to quarks in Fig. 3. These results are obtained by fixing $m_\chi = 1$ GeV and $g_\chi = 1$, and then finding the value of g_q that corresponds to the upper limit on the cross section. This procedure is valid because the kinematic properties of the signal do not vary appreciably with g_q. The width-to-mass ratio is around 4% for the g_q and $m_{a/\phi}$ values considered.

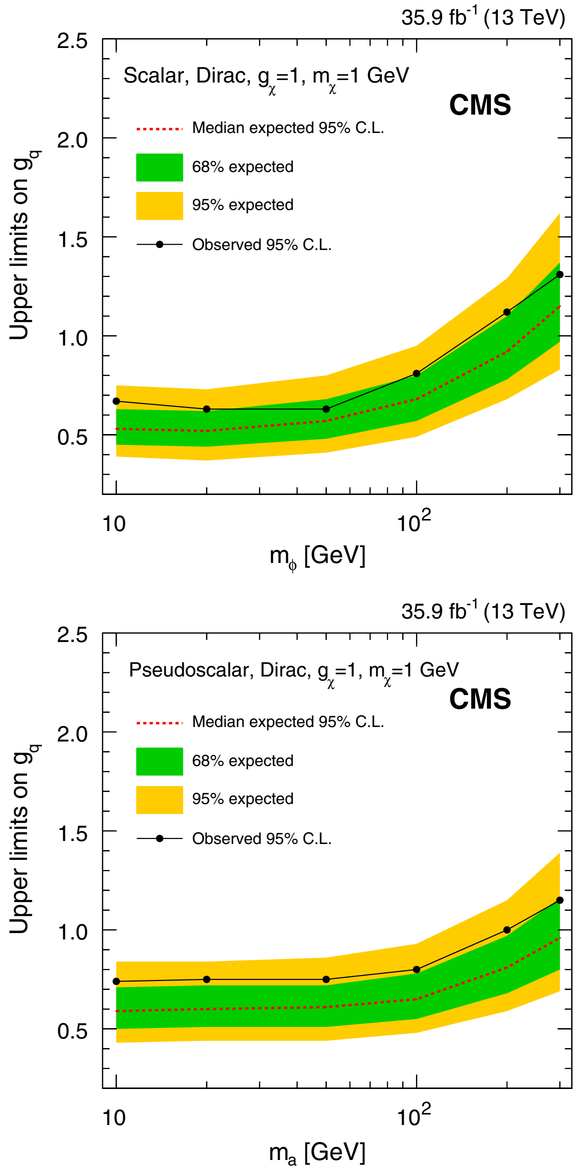

FIG. 3. The 95% observed and median expected C.L. upper limits on the coupling strength of the mediator to the standard model quarks under the assumption that $g_\chi = 1$. A dark matter particle with a mass of 1 GeV is assumed. The green and yellow bands indicate respectively the 68% and 95% probability intervals around the expected limit. The interpretations for a scalar (top) and a pseudoscalar (bottom) mediator are shown.

In summary, a comprehensive search for dark matter particles produced in association with a top quark pair yields no significant excess over the predicted background. The results presented in this Letter provide 30%–60% better cross section limits compared to earlier searches targeting the same signature [57–59]. The analysis offers stronger constraints than direct and indirect experiments for dark matter masses of $\mathcal{O}$ (10 GeV) and below. Over much of the parameter space, the $t\bar{t}+\chi\bar{\chi}$ signature has better sensitivity for spin-0 mediators than dark matter production in association with a jet [14]—previously considered to be the most sensitive signature. For the pseudoscalar model, the $t\bar{t}+\chi\bar{\chi}$ signature provides the most stringent cross section constraints for mediator masses of around 200 GeV and below. The observed (expected) limits exclude a pseudoscalar mediator with mass below 220 (320) GeV under the $g_q = g_\chi = 1$ benchmark scenario. The $t\bar{t}+\chi\bar{\chi}$ signature provides the best sensitivity for the scalar mediator model and is currently the only collider signature that is sufficiently sensitive to exclude regions of parameter space with these values of the couplings. The observed exclusion of a mediator with mass below 160 GeV (240 GeV expected) provides the most stringent constraint to date on this model.

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