Published for SISSA by Springer

Received: *September 30, 2017*
Accepted: *January 9, 2018*
Published: *January 22, 2018*

Search for low mass vector resonances decaying into quark-antiquark pairs in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$



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Abstract: A search for narrow vector resonances decaying into quark-antiquark pairs is presented. The analysis is based on data collected in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ with the CMS detector at the LHC, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$. The hypothetical resonance is produced with sufficiently high transverse momentum that its decay products are merged into a single jet with two-prong substructure. A signal would be identified as a peak over a smoothly falling background in the distribution of the invariant mass of the jet, using novel jet substructure techniques. No evidence for such a resonance is observed within the mass range of 50–300 GeV. Upper limits at 95% confidence level are set on the production cross section, and presented in a mass-coupling parameter space. The limits further constrain simplified models of dark matter production involving a mediator interacting between quarks and dark matter particles through a vector or axial-vector current. In the framework of these models, the results are the most sensitive to date, extending for the first time the search region to masses below 100 GeV.

Keywords: Jet substructure, Hadron-Hadron scattering (experiments), Dark matter, Jets

ArXiv ePrint: 1710.00159

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Article funded by SCOAP^3.

https://doi.org/10.1007/JHEP01(2018)097

Contents

1 Introduction 1

2 CMS detector 2

3 Event simulation and selection 3
- 3.1 Simulated samples 3
- 3.2 Event reconstruction and selection 3

4 Background estimate 7

5 Systematic uncertainties 9

6 Results 10

7 Summary 11

A Supplementary materials 15

The CMS collaboration 22

1 Introduction

Many extensions of the standard model (SM) predict the existence of new resonances that couple to quarks (q) [1–11]. The first searches for such particles were reported by the UA1 [12] and UA2 [13, 14] experiments using $\sqrt{s} = 630\,\text{GeV}$ collisions at the CERN Sp$\bar{\text{p}}$S, and were extended to larger values of resonance masses by the CDF [15–19] and D0 [20] experiments using $\sqrt{s} = 1.8$ and $1.96\,\text{TeV}$ collisions at the Fermilab Tevatron. At the CERN LHC, the searches in proton-proton (pp) collisions at $\sqrt{s} = 7$, 8 and $13\,\text{TeV}$ performed by the ATLAS [21–27] and CMS [28–35] Collaborations have mostly focused on the production of heavy particles. For resonance masses below 1 TeV, the sensitivity is limited by high trigger thresholds and by the large expected backgrounds, notably from SM events consisting of jets produced through the strong interaction, referred to here as QCD multijet events.

These difficulties can be avoided by an approach focused on the events where at least one high transverse momentum (p_T) jet from initial-state radiation (ISR) is produced in association with a light resonance decaying into a $\text{q}\bar{\text{q}}$ pair. The ISR requirement provides enough energy in the event to satisfy the trigger, either by the ISR jet or by the resonance itself. The minimum p_T of the resonance considered in this search is sufficiently high that the hadronization products of the daughter quarks merge and are reconstructed as a

JHEP01(2018)097

single, large-radius jet. The only previous search in this topology to place constraints on resonance masses below 300 GeV was by the CMS Collaboration, applying this technique to data collected at the LHC in 2015 [36].

In the current paper, the results of a search for leptophobic vector resonances (Z') decaying to quark-antiquark pairs in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ are reported, using data collected by the CMS detector in 2016, corresponding to an integrated luminosity of $35.9\,\text{fb}^{-1}$. The search is performed by looking for a narrow resonance peak in the continuous jet mass distribution. The analysis exploits a new substructure variable that is decorrelated from the jet mass and p_T and preserves the shape of the jet mass distribution used in the search. The jet is required to have the two-prong substructure expected from the signal. The dominant background from SM QCD multijet production is estimated from a signal-depleted control region created by inverting the substructure requirement. The signal yield is extracted by simultaneously fitting the signal and control regions, while requiring that the ratio of QCD components in each region is described by a smooth two-dimensional function of jet mass and p_T. The W+jets and Z+jets background components are estimated from simulation and the top quark background contribution is obtained from simulation corrected with scale factors derived from a $t\bar{t}$-enriched control sample.

Results are interpreted within the framework of a leptophobic vector resonance model, and are also used to set limits on the existence of generic vector-like resonances decaying into quarks [37]. Limits are also set in the context of a simplified model of dark matter (DM) production at the LHC, in which the mediators couple only to quarks and DM particles [38].

2 CMS detector

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 (HCAL), 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-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events are selected using a two-tiered trigger system [39]. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events of interest in a time interval of less than 4 μs. 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 optimized for fast processing, and further reduces the event rate from around 100 kHz to less than 1 kHz, before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [40].

JHEP01(2018)097

3 Event simulation and selection

3.1 Simulated samples

Simulated samples of the Z′ resonance decaying into a quark-antiquark pair are generated at leading order (LO) with the MadGraph5_aMC@NLO 2.2.3 generator [41] with up to 3 extra jets in matrix element calculations. The dominant SM backgrounds arise from multijet and W/Z + jets processes. These backgrounds are simulated at LO using the MadGraph5_aMC@NLO generator with the MLM matching [42] between jets from matrix element calculations and from parton showers, while the powheg 2.0 [43] generator at next-to-leading order (NLO) precision is used to model the subdominant contribution from pair and single top quark production. All signal and background generators are interfaced with pythia 8.212 [44], with the CUETP8M1 underlying event tune [45], to simulate parton showering and hadronization effects. The generated events are further processed through a Geant4 [46] simulation of the CMS detector. The parton distribution function (PDF) set NNPDF3.0 [47] is used to produce all simulated samples, with the accuracy (LO or NLO) determined by the generator used. For events containing W and Z bosons, we apply higher-order QCD and electroweak (EW) p_{T} dependent corrections to improve the modeling of the p_{T} distribution of W and Z events, following refs. [48–52]. The same NLO QCD corrections that are applied to the W and Z simulation are also applied to the signal simulation. However, since the coupling of the Z′ mediator differs from that of the Z boson, the equivalent Z NLO EW corrections are not applied to the signal model.

3.2 Event reconstruction and selection

The CMS particle-flow (PF) event algorithm [53] reconstructs and identifies individual particles with an optimized combination of information from the various elements of the CMS detector. Each particle candidate is classified as either an electron, a muon, a photon, or a charged or neutral hadron. The energy of photons is obtained directly from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for zero-suppression effects and for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energy. The missing transverse momentum vector is defined as the negative vectorial sum of the transverse momenta of all the particles identified in the event, and its magnitude is referred to as $p_{\mathrm{T}}^{\mathrm{miss}}$.

The PF candidates are clustered into jets using the anti-k_{T} algorithm [54, 55]. Jets are clustered with distance parameters of 0.4 and 0.8, and are referred to as AK4 and AK8 jets, respectively. To mitigate the impact of particles arising from additional proton-proton interactions within the same or adjacent bunch crossings (pileup), weights calculated with

JHEP01(2018)097

the pileup-per-particle identification algorithm [56] are applied to each PF candidate prior to jet clustering, based on the likelihood of it coming from the hard-scattering vertex. Further corrections are applied to simulated jet energies as a function of jet η and p_{T} to match the observed detector response [57, 58].

This search focuses on events in which a high-p_{T} jet from a merged $\mathrm{Z}' \to \mathrm{q\bar{q}}$ recoils against another high-p_{T} ISR jet. A combination of several online signatures is required for the trigger selection, all requiring the total hadronic transverse energy in the event (H_{T}) or the jet p_{T} to exceed a certain threshold. In addition, soft radiation remnants are removed with the jet trimming technique [59] before the mass selection, allowing the H_{T} and jet p_{T} trigger thresholds to be reduced, and improving the signal acceptance. To be fully efficient with respect to the trigger requirement, we require at least one AK8 jet with $p_{\mathrm{T}} > 500\,\mathrm{GeV}$ and $|\eta| < 2.5$. Additional quality criteria are applied to the jets in order to remove spurious jet-like features originating from isolated noise patterns in the calorimeters or the tracker. The efficiency of these jet quality requirements for signal events is above 99%. In order to reduce backgrounds from SM EW processes, events are removed if they contain identified and isolated electrons, muons, or taus with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.5$, 2.4, or 2.3, respectively, according to the isolation criteria in [48].

In the subsequent offline analysis, the most energetic jet in the event is assumed to correspond to the $\mathrm{Z}' \to \mathrm{q\bar{q}}$ system, and is reconstructed as a single AK8 jet. The search is performed using the distribution of the jet mass groomed with the soft-drop algorithm (m_{SD}), which is an extension of the modified mass drop tagger [60, 61] that removes soft and wide-angle radiation produced by parton shower activity, pileup interactions, and the underlying event from the jet. Jets are groomed using the parameters $z_{\mathrm{cut}} = 0.1$ and $\beta = 0$. Here, z_{cut} specifies subleading the energy fraction relative to the whole jet at which jet declustering into subjet pairs is stopped. The parameter β adds additional angular requirements on the jet declustering. For $\beta = 0$, these requirements are neglected, and approximately the same fraction of energy is groomed away regardless of the initial jet energy [61]. The soft-drop grooming reduces the jet mass for QCD background jets when large masses arise from soft gluon radiation. In contrast, the jet mass for merged $\mathrm{Z}' \to \mathrm{q\bar{q}}$ and $\mathrm{W/Z} \to \mathrm{q\bar{q}}$ jets comes from the kinematic distributions of the decay, and is largely unchanged by grooming. Figure 1 shows the distributions of m_{SD} for data and simulation, after the jet kinematic selection.

In this paper, the dimensionless scaling variable ρ [60, 62], defined as $\rho = \ln(m_{\mathrm{SD}}^2/p_{\mathrm{T}}^2)$, is used in the characterization of the correlation of jet substructure variables with the jet mass and p_{T}. For QCD jets, the distribution of ρ is approximately invariant under a change of jet p_{T}, in the region where perturbative contributions dominate and scale as $(m_{\mathrm{SD}}/p_{\mathrm{T}})$. This property does not hold in two regimes: in the low mass region below $\rho \approx -6$, where non-perturbative effects are large and scale as $(1/m_{\mathrm{SD}})$ instead, and in the high mass region above $\rho \approx -2$. The departure from ρ invariance in the latter case arises because the cone size of the AK8 jets is insufficient to provide complete containment at high masses. Consequently, only events in the range $-5.5 < \rho < -2.0$ are considered. This requirement is fully efficient for the Z' boson signal and roughly translates to a m_{SD} range from 25 GeV to 185 GeV at $p_{\mathrm{T}} = 500\,\mathrm{GeV}$.

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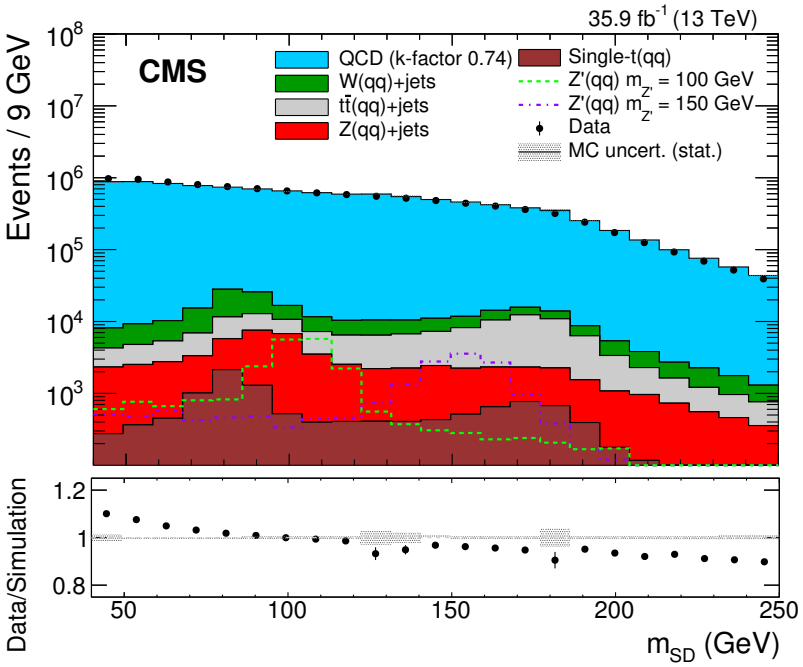


Figure 1. Distributions of data (points) and simulated backgrounds (histograms), of the leading p_{T} jet soft-drop mass after the jet kinematic selection. Dashed lines illustrate the signal contribution for different Z′ boson masses. The multijet processes (QCD) dominate the background component, with subdominant contributions from inclusive SM W, Z, and $\mathrm{t\bar{t}}$ and single top quark processes. The QCD simulation is corrected by an overall factor of 0.74 to match the data yield.

In addition to the jet mass, the observable N_2^1 [63] is used to discriminate the two-prong structure of the jets from the $\mathrm{Z}' \to \mathrm{q\bar{q}}$ decay from the hadronization products of single light quarks or gluons, which are overwhelmingly one-prong. This jet substructure variable is defined from a combination of generalized energy correlation functions ${}_{v}e_{n}$, sensitive to correlations of v pairwise angles among n-jet constituents [63]. In particular, the 2-point (${}_{1}e_{2}$) and 3-point (${}_{2}e_{3}$) correlation functions are defined as:

$$ {}_{1}e_{2} = \sum_{1 \le i < j \le n} z_i z_j \Delta R_{ij} \,, \tag{3.1} $$

$$ {}_{2}e_{3} = \sum_{1 \le i < j < k \le n} z_i z_j z_k \min\{\Delta R_{ij}\Delta R_{ik}, \Delta R_{ij}\Delta R_{jk}, \Delta R_{ik}\Delta R_{jk}\} \,, \tag{3.2} $$

where z_i represents the energy fraction of the constituent i in the jet and ΔR_{ij} is the angular separation between constituents i and j. For a two-prong structure, signal jets have a stronger 2-point correlation than a 3-point correlation. The discriminant variable N_2^1 is then constructed via the ratio:

$$ N_2^1 = \frac{{}_{2}e_{3}}{({}_{1}e_{2})^2} \,. \tag{3.3} $$

The energy correlation functions are computed from the jet constituents after the soft-drop grooming has been applied, thereby reducing their dependence on the jet mass and p_{T} [63].

JHEP01(2018)097

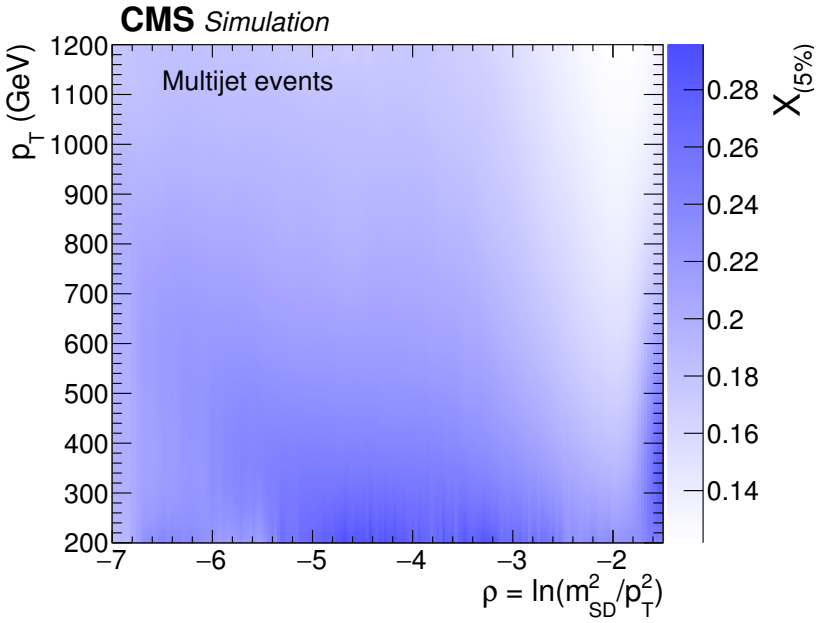


Figure 2. The distribution of $X_{(5\%)}$ used to define the $N_2^{1,\mathrm{DDT}}$ variable, corresponding to the 5% quantile of the N_2^1 distribution in simulated multijet events. The distribution is shown as a function of the jet ρ and p_T and smoothed using a kNN approach [64]. The N_2^1 distribution is mostly insensitive to the jet ρ and p_T in the kinematic phase space considered for this analysis ($-5.5 < \rho < -2.0$). Residual correlations in simulation are corrected by applying a decorrelation procedure that yields the $N_2^{1,\mathrm{DDT}}$ variable.

The N_2^1 observable has excellent performance in discriminating two-prong signal jets from multijet QCD background jets [63]. However, N_2^1 and similar variables are correlated with the jet mass and p_T. A selection based on N_2^1 would distort the jet mass distribution, with the amount of distortion depending on the p_T of the jet. This would make the search for a resonant peak in the jet mass distribution, over a large range of p_T, particularly challenging.

The key feature of our approach is that the application of the substructure requirement preserves the shape of the soft-drop jet mass distribution. Improving on the decorrelation procedure proposed in ref. [62], we apply a DDT (designed decorrelated tagger) transformation of N_2^1 to $N_2^{1,\mathrm{DDT}}$. It is defined as $N_2^{1,\mathrm{DDT}}(\rho, p_\mathrm{T}) \equiv N_2^1(\rho, p_\mathrm{T}) - X_{(5\%)}(\rho, p_\mathrm{T})$, where $X_{(5\%)}$ is derived from the simulated N_2^1 distribution and illustrated in figure 2. We require events to pass the $N_2^{1,\mathrm{DDT}}(\rho, p_\mathrm{T}) < 0$ selection, such that we select a fixed 5% of QCD multijet events independent of ρ and p_T. The distribution of $X_{(5\%)}$ is smoothed using a distance weighted k-nearest neighbor (kNN) approach [64]. The chosen percentile maximizes the sensitivity to the Z′ boson signal.

The distributions of $N_2^{1,\mathrm{DDT}}$ for data and simulation are shown in figure 3 after the jet $p_\mathrm{T} > 500\,\mathrm{GeV}$ requirement. Since there is a visible disagreement between simulation and data, the multijet background is estimated from data, as described in the next section. Additional distributions of kinematic observables for data and simulation are available in appendix A.

JHEP01(2018)097

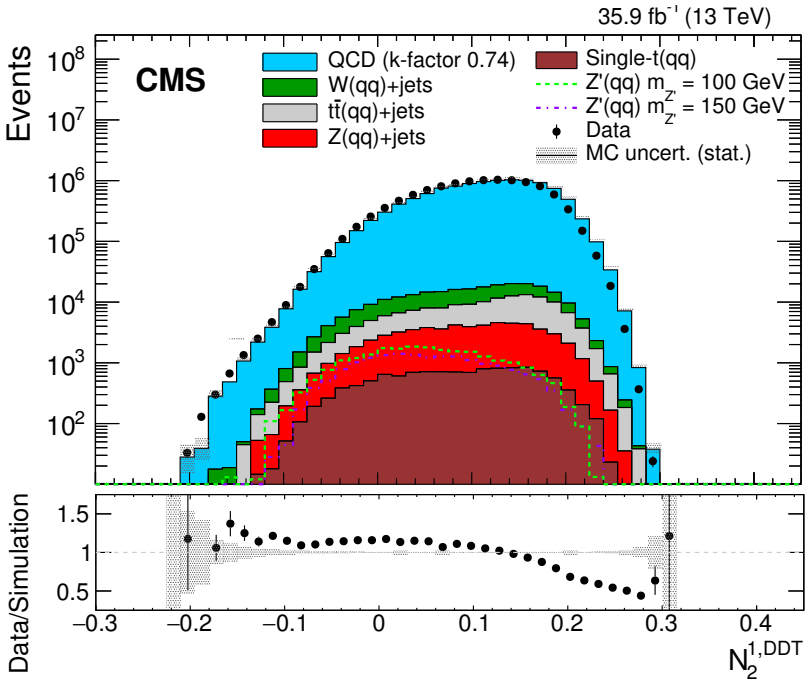


Figure 3. Distributions of data (points) and simulated backgrounds (histograms), of the $N_2^{1,\mathrm{DDT}}$ variable for the leading p_T jet after the kinematic selection. Dashed lines illustrate the signal contribution for different Z′ boson masses. The multijet processes (QCD) dominate the background component, with subdominant contributions from inclusive SM W, Z, and $\mathrm{t\bar{t}}$ and single top quark processes. The QCD simulation is corrected by an overall factor of 0.74 to match the data yield.

4 Background estimate

The search is performed by looking for a resonance in the soft-drop mass distribution over background contributions dominated by QCD multijet events and smaller contributions from $\mathrm{W(q'\bar{q})}$+jets, $\mathrm{Z(q\bar{q})}$+jets, and top quark background processes.

To model the background contribution from pair and single top quark production we utilize simulation with data-driven corrections based on a dedicated control region. This region has the same kinematic requirements as the signal region but with the muon veto inverted. The muon is selected using dedicated muon triggers and is required to have $p_\mathrm{T} > 100\,\mathrm{GeV}$ and $|\eta| < 2.1$ and to be in the opposite hemisphere to the selected AK8 jet. To enrich the $\mathrm{t\bar{t}}$ contribution and reduce the multijet contamination, at least one AK4 jet with $p_\mathrm{T} > 50\,\mathrm{GeV}$ is required to pass the b-tagging medium selection based on the combined secondary vertices version-2 algorithm [65], which identifies AK4 jets that originate from the hadronization of b quarks. Separate scale factors correct the overall top quark background normalization and the $N_2^{1,\mathrm{DDT}}$ efficiency for mistagging jets from top quark decays. These scale factors are $\mathrm{SF}^{\mathrm{t\bar{t}}}_{\mathrm{norm}} = 0.75 \pm 0.10$ and $\mathrm{SF}^{\mathrm{t}}_{\mathrm{mistag}} = 0.83 \pm 0.03$, respectively.

Subdominant backgrounds arising from resonant SM processes (W/Z+ jets) are estimated from simulations that include corrections to the shape and normalization from higher order NLO QCD and EW calculations. Additional data-to-simulation corrections

JHEP01(2018)097

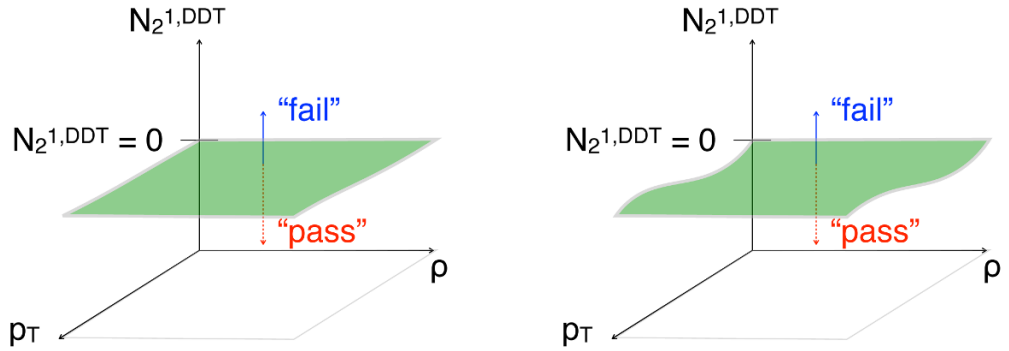


Figure 4. A schematic of the background estimation method. The pass-to-fail ratio, $R_{\mathrm{p/f}}(\rho(m_{\mathrm{SD}}, p_{\mathrm{T}}))$, is defined from the events passing and failing the $N_2^{1,\mathrm{DDT}}$ selection. The variable $N_2^{1,\mathrm{DDT}}$ is constructed so that, for simulated multijet events, $R_{\mathrm{p/f}}$ is constant (left). To account for residual differences between data and simulation, $R_{\mathrm{p/f}}$ is extracted by performing a two-dimensional fit to data in (ρ, p_{T}) space (right).

for the jet mass shapes and $N_2^{1,\mathrm{DDT}}$ tagging efficiencies are applied to the simulation. These corrections are evaluated from a $\mathrm{t\bar{t}}$ control region rich in merged hadronic W bosons, as further explained below.

We estimate the main QCD multijet event background by taking advantage of the decorrelation of $N_2^{1,\mathrm{DDT}}$ from ρ and p_{T}. The fraction of events passing the $N_2^{1,\mathrm{DDT}}$ selection is, by construction, a constant 5% in simulated multijet events. The decorrelation ensures that the events passing and failing the selection have the same shape of the QCD jet mass distribution, and their ratio, the "pass-to-fail ratio" $R_{\mathrm{p/f}}$, is constant for simulated multijet events. The prediction of events passing the selection can then be expressed as:

$$n_{\mathrm{pass}}^{\mathrm{QCD}}(m_{\mathrm{SD}}, p_{\mathrm{T}}) = R_{\mathrm{p/f}}(\rho(m_{\mathrm{SD}}, p_{\mathrm{T}}), p_{\mathrm{T}})\, n_{\mathrm{fail}}^{\mathrm{QCD}}(m_{\mathrm{SD}}, p_{\mathrm{T}})\,, \tag{4.1}$$

where $n_{\mathrm{pass}}^{\mathrm{QCD}}$ and $n_{\mathrm{fail}}^{\mathrm{QCD}}$ are the number of passing and failing events in a given m_{SD}, p_{T} bin. This procedure is illustrated schematically in figure 4. Since the distribution of ρ is expected to be invariant under a change of p_{T}, $R_{\mathrm{p/f}}$ is parametrized as a function of ρ, which is in turn expressed as a function of m_{SD} and p_{T}.

Owing to residual differences between data and simulation, the correction $R_{\mathrm{p/f}}(\rho, p_{\mathrm{T}})$ is allowed to deviate from a constant. The deviation is modeled by expanding $R_{\mathrm{p/f}}(\rho, p_{\mathrm{T}})$ into a polynomial series in orders of ρ and p_{T}:

$$\begin{aligned} R_{\mathrm{p/f}}(\rho, p_{\mathrm{T}}) = \epsilon_{\mathrm{QCD}}(1 &+ a_{01}p_{\mathrm{T}} + a_{02}p_{\mathrm{T}}^2 + \cdots \\ &+ (a_{10} + a_{11}p_{\mathrm{T}} + a_{12}p_{\mathrm{T}}^2 + \cdots)\rho \\ &+ (a_{20} + a_{21}p_{\mathrm{T}} + a_{22}p_{\mathrm{T}}^2 + \cdots)\rho^2 + \cdots). \end{aligned} \tag{4.2}$$

The coefficients ϵ_{QCD} and $a_{k\ell}$ have no external constraints but are determined from a simultaneous fit to the data events passing and failing the substructure requirement, together with the signal yield. The number of required coefficients in the fit is determined with a Fisher F-test on data [66] by iteratively adding polynomial orders. The optimum

JHEP01(2018)097

choice is found to be of fourth order in ρ and third order in p_{T}. The fact that $R_{\mathrm{p/f}}$ varies slowly across the m_{SD}–p_{T} domain is essential, since it allows one to estimate the background under a narrow signal resonance based on the events across the whole jet mass range.

5 Systematic uncertainties

Uncertainties in the multijet background arise from the fit parameter uncertainties in the pass-to-fail ratio fit described in eq. (4.2). The uncertainties in the top quark background normalization (10%) and $N_2^{1,\mathrm{DDT}}$ mistag (2%) scale factors are propagated to the signal extraction through the fit.

The systematic effects for the shapes and normalization of the W, Z backgrounds, and signal components are strongly correlated since they are affected by similar systematic mismeasurements. We constrain the jet mass scale, the jet mass resolution, and the $N_2^{1,\mathrm{DDT}}$ selection efficiency using a sample of merged W boson jets in semileptonic $\mathrm{t\bar{t}}$ events in data. In this region, events are required to have an energetic muon with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$, $p_{\mathrm{T}}^{\mathrm{miss}} > 80\,\mathrm{GeV}$, a high-$p_{\mathrm{T}}$ AK8 jet with $p_{\mathrm{T}} > 200\,\mathrm{GeV}$, and a b-tagged AK4 jet separated from the AK8 jet by $\Delta R > 0.8$. Using the same $N_2^{1,\mathrm{DDT}}$ requirement described above, we define samples with events that pass and fail the selection for merged W boson jets in data and simulation, shown in figure 5. A simultaneous fit to the two samples is performed in order to extract the selection efficiency of a merged W jet in simulation and in data. We measure the data-to-simulation scale factor for the $N_2^{1,\mathrm{DDT}}$ selection to be 0.88 ± 0.10. The mass scale between data and simulation is found to be 1.10 ± 0.05. The jet mass resolution data-to-simulation scale factor is measured to be 1.14 ± 0.06. These scale factors determine the initial distributions of the jet mass for the W, Z boson, and signal and they are further constrained in the fit to data because of the presence of the W and Z resonances in the jet mass distribution. To account for potential deviations due to missing higher-order corrections to the simulated boson p_{T} distributions, uncertainties are assumed in the W and Z boson yields that are p_{T}-dependent. An additional systematic uncertainty is included to account for potential differences between the W and Z boson higher-order corrections. Finally, uncertainties associated to the jet energy resolution [57], trigger efficiency, lepton veto efficiency, and the integrated luminosity determination [67] are also applied to the W, Z boson, and Z′ boson signal yields. A quantitative summary of the systematic effects considered is listed in table 1.

To validate the robustness of the fit, we perform a goodness-of-fit test and bias tests using pseudo-experiments and injecting a simulated signal, for different values of Z′ boson mass. No significant bias is observed. As a further test of fit robustness, we split the region failing the $N_2^{1,DDT}$ selection into two smaller regions mimicking the passing and failing regions in the signal extraction fit. The mimicked passing-like region corresponds to a background efficiency of 60–65% and the mimicked failing-like region corresponds to an efficiency of 65–100%. We repeat our background estimation procedure on this selection as if the 60–65% efficiency region were the passing region. We find negligible biases in the fitted signal strength.

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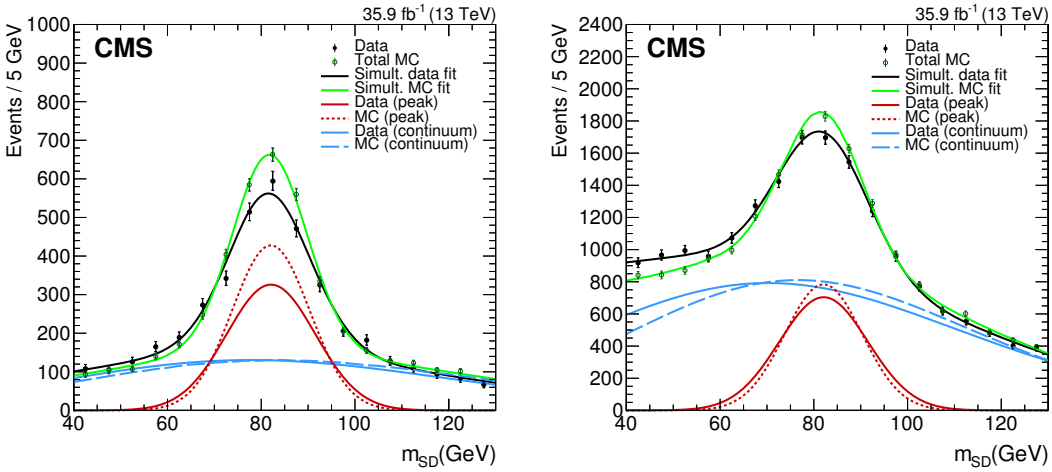


Figure 5. Soft-drop jet mass distributions that pass (left) and fail (right) the $N_2^{1,\mathrm{DDT}}$ selection in the semileptonic $\mathrm{t\bar{t}}$ sample. Results of fits to data and simulation are shown.

Systematic source	Multijet	Z′	W/Z	$\mathrm{t\bar{t}}$
Lepton veto efficiency	—	0.5%	0.5%	—
Jet mass scale†	—	0.5%	0.5%	—
Jet mass scale (p_{T} dependence) $^{\dagger\triangle}$	—	0.5–2%	0.5–2%	—
Trigger efficiency	—	2%	2%	—
Top quark mistag rate	—	—	—	2%
Integrated luminosity	—	2.5%	2.5%	—
Multijet fit parameters	1–3%	—	—	—
$N_2^{1,\mathrm{DDT}}$ selection efficiency	—	9%	9%	—
Top quark background normalization	—	—	—	10%
Jet energy resolution†	—	10%	10%	—
NLO QCD corrections	—	10%	10%	—
NLO EW corrections$^{\triangle}$	—	—	15–35%	—
NLO EW W/Z decorrelation	—	—	5–15%	—

Table 1. Summary of the systematic uncertainties for signal and background processes and their relative size. The symbol $^{\triangle}$ denotes uncertainties decorrelated per p_{T} bin in the 500–1000 GeV range. The symbol † denotes a shape uncertainty in the peaking SM W and Z boson backgrounds and Z′ boson signal shape. A long dash (—) indicates that the uncertainty does not apply.

6 Results

We combine the estimates of the various SM background processes and search for a potential signal from a Z′ resonance in the mass range from 50 to 300 GeV. A binned maximum likelihood fit to the observed shape of the soft-drop jet mass distribution is performed simultaneously in the passing and failing regions of five p_{T} ranges whose boundaries are: 500, 600, 700, 800, 900 and 1000 GeV. The number of observed events is consistent with the predicted background from SM processes. Figure 6 shows the soft-drop jet mass distribution for data and measured background contributions in the different p_{T} ranges for a

JHEP01(2018)097

Z' mass of 135 GeV; the W and Z boson contributions are clearly visible in the data. The m_{SD} distribution for data in the combined p_T ranges is available in appendix A.

The results are interpreted in terms of 95% confidence level (CL) upper limits on the production cross section. Upper limits are computed using the modified frequentist approach for confidence levels (CL_s); taking the profile likelihood as the test statistic [68, 69] in the asymptotic approximation [70]. They are shown as a function of the resonance mass in figure 7 (left), where they are compared to cross sections for a model of a leptophobic Z' resonance with quark coupling $g_{q'}$ value of either 0.17 or 0.08 that are close to our current sensitivity. Systematic uncertainties are treated as nuisance parameters, which are modeled with log-normal priors and profiled over in the limit calculations. The maximum local observed p-value corresponds to 2.9 standard deviations from the background-only expectation at a Z' boson mass of 115 GeV, and the global significance, calculated over the probed mass range [71], corresponds to approximately 2.2 standard deviations.

Upper limits on the signal cross section are translated into the coupling $g_{q'}$ as a function of Z' boson mass, related to the Z' coupling convention of ref. [37] by $g_{q'} = g_B/6$. Coupling values above the solid curves are excluded. In figure 7 (right), we show previous results from UA2, CDF, ATLAS and CMS experiments. Indirect constraints from the hadronic Z boson partial width measurement and limits from the UA2 and CDF experiments are interpreted from [37].

The results of this analysis can be used to constrain simplified models of DM. Figure 8 shows the excluded values at 95% CL of mediator mass (m_{Med}) as a function of the dark matter particle mass (m_{DM}) for vector mediators, in simplified models that assume a leptophobic mediator that couples only to quarks and DM particles [38, 73]. Limits are shown for a choice of universal quark coupling $g_q = 0.25$ and a DM coupling $g_{DM} = 1.0$. The difference in limits between axial-vector and vector mediator couplings is small and thus only constraints for the latter coupling scenario are shown. The excluded range of mediator mass (red) is between 50 and 300 GeV. The upper bound decreases to 240 GeV when $m_{Med} > 2m_{DM}$, because the branching fraction (BR) to $q\bar{q}$ decreases as the BR to DM becomes kinematically favorable. If $m_{Med} < 2m_{DM}$, the mediator cannot decay to DM particles and the dijet cross section from the mediator model becomes identical to that in the leptophobic Z' model, meaning that the limits on the mediator mass in figure 8 are identical to the limits on the Z' mass with a coupling $g_{q'} = g_q = 0.25$. For axial-vector mediators, the excluded values of mediator mass are expected to be identical to the excluded values in figure 8 when $m_{DM} > m_{Med}/2$ or $m_{DM} = 0$, with differences only expected in the transition region $m_{Med} \simeq 2m_{DM}$. Additional limits (blue) in figure 8 come from traditional dijet searches [35].

7 Summary

A search for a vector resonance (Z') decaying into a quark-antiquark pair and reconstructed as a single jet has been presented, using a data set comprising proton-proton collisions at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb^{-1}. Novel substructure techniques are employed to identify a jet containing a Z' boson candidate over a smoothly

JHEP01(2018)097

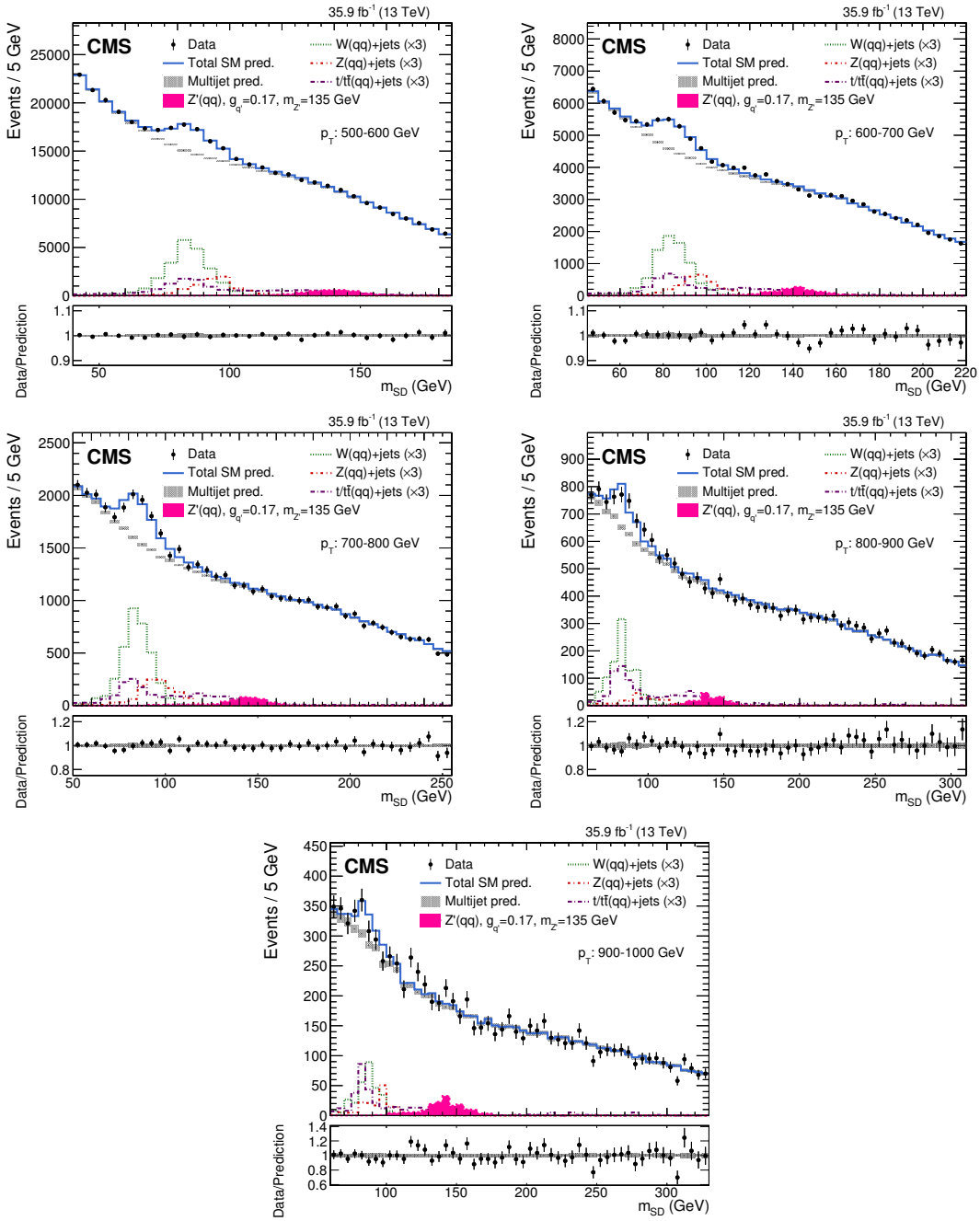


Figure 6. Soft-drop jet mass distribution for the different p_T ranges of the fit from 500 to 1000 GeV. Data are shown as black points. The multijet background prediction, including uncertainties, is shown by the shaded bands. Contributions from the W and Z boson, and top quark background processes are shown, scaled up by a factor of 3 for clarity. A hypothetical Z′ boson signal at a mass of 135 GeV is also indicated. In the bottom panel, the ratio of the data to the background prediction, including uncertainties, is shown. The scale on the x-axis differs for each p_T range due to the kinematic selection on ρ.

JHEP01(2018)097

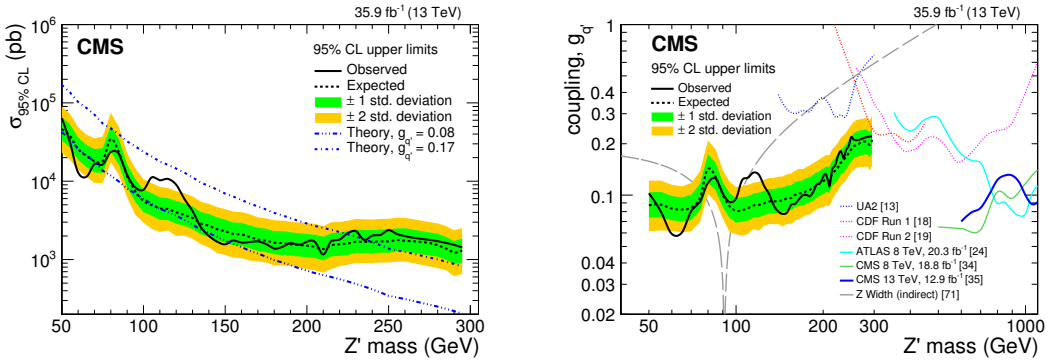


Figure 7. The 95% CL upper limits on the Z′ boson production cross section compared to theoretical cross sections (left) and on the quark coupling $g_{q'}$ as a function of resonance mass for a leptophobic Z′ resonance that only couples to quarks (right). The observed limits (solid), expected limits (dashed) and their variation at the 1 and 2 standard deviation levels (shaded bands) are shown. Limits from other relevant searches and an indirect constraint on a potential Z′ signal from the SM Z boson width [72] are also shown.

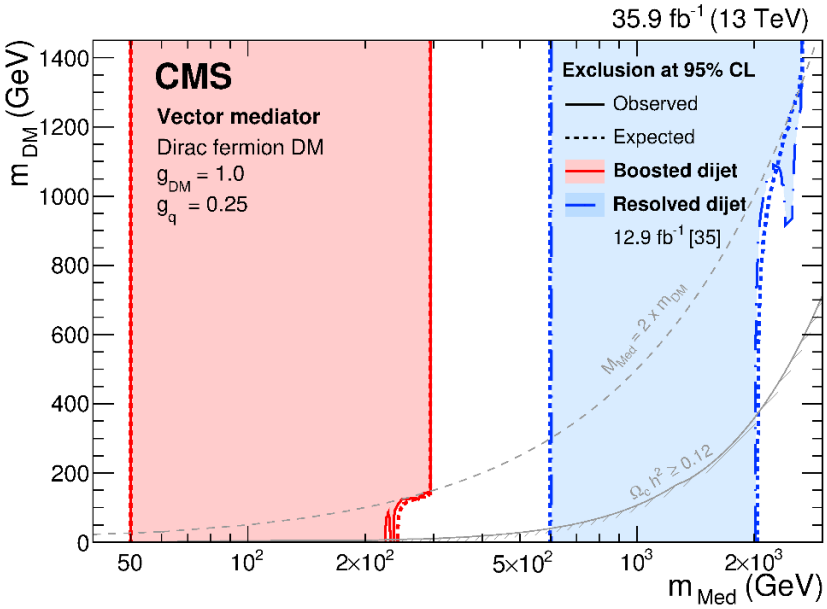


Figure 8. The 95% CL observed (solid red) and expected (dashed red) excluded regions in the plane of dark matter particle mass (m_{DM}) vs. mediator mass (m_{Med}), for vector mediators. A branching fraction of 100% is assumed for a leptophobic vector mediator decaying to dijets. The exclusion is computed for a quark coupling choice $g_q = 0.25$ and for a dark matter coupling $g_{\mathrm{DM}} = 1$. The excluded regions from the dijet resolved analysis (blue dot dashed lines) using early 2016 data [35] are also shown. Results are compared to constraints from the cosmological relic density of DM (light gray) determined from astrophysical measurements [74, 75] and MadDM version 2.0.6 [76, 77] as described in ref. [78].

JHEP01(2018)097

falling soft-drop jet mass distribution in data. No significant excess above the SM prediction is observed, and 95% confidence level upper limits are set on the Z' boson coupling to quarks, $g_{q'}$, as a function of the Z' boson mass. Coupling values of $g_{q'} > 0.25$ are excluded over the Z' mass range from 50 to 300 GeV, with strong constraints for masses less than 200 GeV. The results obtained for masses from 50 to 100 GeV represent the first direct limits to be published in this range. Limits are set on a simplified model of dark matter mediators that only couple to quarks and dark matter particles, excluding vector mediators with masses between 50 and 300 GeV, and using a universal quark coupling $g_q = 0.25$ and a dark matter coupling $g_{DM} = 1.0$.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centres and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR and RAEP (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI and FEDER (Spain); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

Individuals have received support from the Marie-Curie programme and the European Research Council and Horizon 2020 Grant, contract No. 675440 (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS programme of the Foundation for Polish Science, cofinanced from European Union, Regional Development Fund, the Mobility Plus programme of the Ministry of Science and Higher Education, the National Science Center (Poland), contracts Harmonia 2014/14/M/ST2/00428, Opus 2014/13/B/ST2/02543, 2014/15/B/ST2/03998,

JHEP01(2018)097

and 2015/19/B/ST2/02861, Sonata-bis 2012/07/E/ST2/01406; the National Priorities Research Program by Qatar National Research Fund; the Programa Severo Ochoa del Principado de Asturias; the Thalis and Aristeia programmes cofinanced by EU-ESF and the Greek NSRF; the Rachadapisek Sompot Fund for Postdoctoral Fellowship, Chulalongkorn University and the Chulalongkorn Academic into Its 2nd Century Project Advancement Project (Thailand); the Welch Foundation, contract C-1845; and the Weston Havens Foundation (U.S.A.).

A Supplementary materials

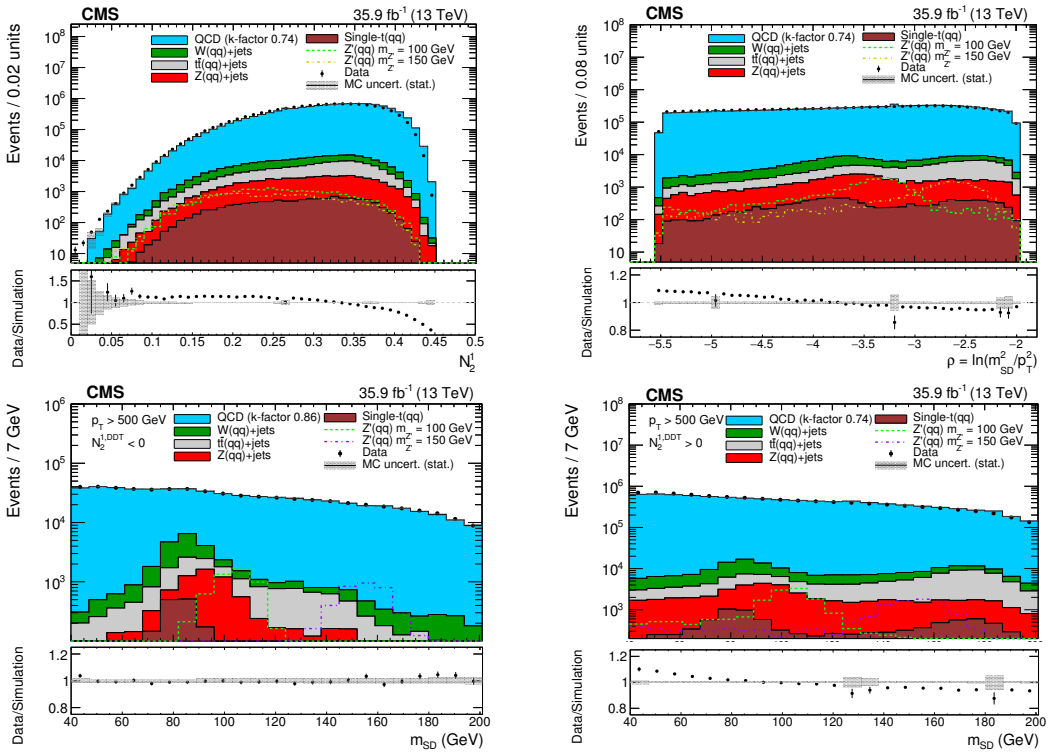


Figure 9. Distributions of data (points) and simulated backgrounds (histograms) of the leading p_T jet N_2^1 (top left) and ρ (top right) observables, after the kinematic selection. The soft-drop jet mass distributions for the passing (bottom left) and failing (bottom right) region, defined by the $N_2^{1,DDT}$ selection, are also shown. The decorrelation ensures that the shape of the multijet mass distribution in both regions is unaffected by the $N_2^{1,DDT}$ selection for different p_T ranges. Dashed lines illustrate the signal contribution for different Z′ boson masses. The multijet processes (QCD) dominate the background component, with subdominant contributions from inclusive SM W, Z, and $t\bar{t}$ and single top quark processes. The QCD simulation is scaled by an overall factor of 0.74 to match the data yield. Residual differences between data and simulation demonstrate the need for a background estimation method based on control samples in data.

JHEP01(2018)097

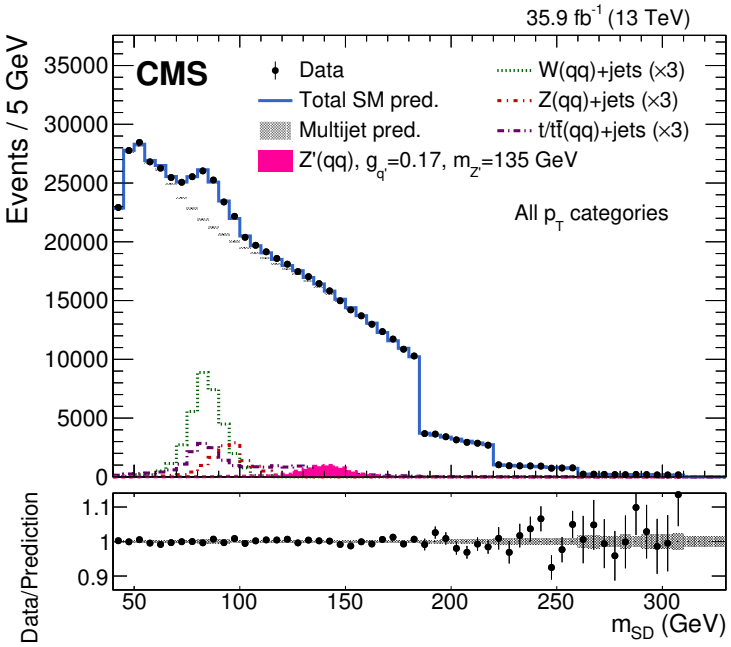


Figure 10. Soft-drop jet mass distribution for the passing region and combined p_{T} categories. The multijet background prediction in the passing region is obtained using the failing region and the pass-fail ratio $R_{\mathrm{p/f}}(m_{\mathrm{SD}}, p_{\mathrm{T}})$. Data are shown as black points. The multijet background prediction, including uncertainties, is shown by the shaded bands. Contributions from the W and Z boson, and top quark background processes are shown, scaled up by a factor of 3 for clarity. A hypothetical Z′ boson signal at a mass of 135 GeV is also indicated. The features at 45, 185, 220 and 255 GeV in the m_{SD} distribution are due to the kinematic selection on ρ, which affects each p_{T} category differently. In the bottom panel, the ratio of the data to the background prediction, including uncertainties, is shown.

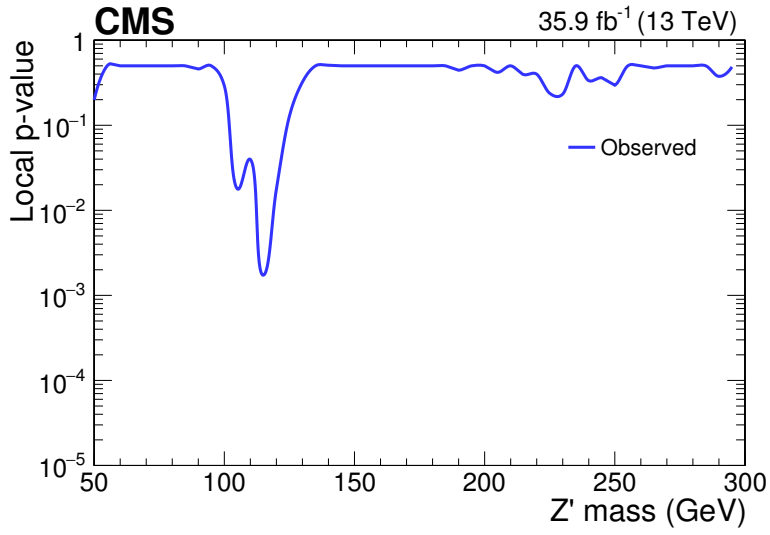


Figure 11. The observed p-value, obtained from the fit to data, as a function of the Z′ boson mass. The maximum local observed p-value, at 115 GeV, is 1.72×10^{-3} and corresponds to 2.9 standard deviations from the background-only expectation, and the global p-value, calculated over the probed mass range, corresponds to 0.0138 and 2.2 standard deviations.

JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097

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JHEP01(2018)097