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Search for dark matter particles in proton-proton collisions at $\sqrt{s} = 8\,\text{TeV}$ using the razor variables

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Abstract

A search for dark matter particles directly produced in proton-proton collisions recorded by the CMS experiment at the LHC is presented. The data correspond to an integrated luminosity of $18.8\,\text{fb}^{-1}$, at a center-of-mass energy of 8 TeV. The event selection requires at least two jets and no isolated leptons. The razor variables are used to quantify the transverse momentum balance in the jet momenta. The study is performed separately for events with and without jets originating from b quarks. The observed yields are consistent with the expected backgrounds and, depending on the nature of the production mechanism, dark matter production at the LHC is excluded at 90% confidence level for a mediator mass scale Λ below 1 TeV. The use of razor variables yields results that complement those previously published.

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1 Introduction

The existence of dark matter (DM) in the universe, originally proposed [1] to reconcile observations of the Coma galaxy cluster with the prediction from the virial theorem, is commonly accepted as the explanation of many experimental phenomena in astrophysics and cosmology, such as galaxy rotation curves [2, 3], large structure formation [4–6], and the observed spectrum [7–10] of the cosmic microwave background [11]. A global fit to cosmological data in the ΛCDM model (also known as the standard model of cosmology) [12] suggests that approximately 85% of the mass of the universe is attributable to DM [10]. To accommodate these observations and the dynamics of colliding galaxy clusters [13], it has been hypothesized that DM is made mostly of weakly interacting massive particles (WIMPs), sufficiently massive to be in nonrelativistic motion following their decoupling from the hot particle plasma in the early stages of the expansion of the universe.

While the standard model (SM) of particle physics does not include a viable DM candidate, several models of physics beyond the SM, e.g., supersymmetry (SUSY) [14–18] with R-parity conservation, can accommodate the existence of WIMPs. In these models, pairs of DM particles can be produced in proton-proton (pp) collisions at the CERN LHC. Dark matter particles would not leave a detectable signal in a particle detector. When produced in association with high-energy quarks or gluons, they could provide event topologies with jets and a transverse momentum (p_{T}) imbalance ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$). The magnitude of $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is referred to as missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$). The ATLAS and CMS collaborations have reported searches for events with one high-p_{T} jet and large $E_{\mathrm{T}}^{\mathrm{miss}}$ [19, 20], which are sensitive to such topologies. In this paper, we refer to these studies as monojet searches. Complementary studies of events with high-p_{T} photons [21, 22]; W, Z, or Higgs bosons [23–26]; b jets [27] and top quarks [27–29]; and leptons [30, 31] have also been performed.

This paper describes a search for dark matter particles χ in events with at least two jets of comparable transverse momenta and sizable $E_{\mathrm{T}}^{\mathrm{miss}}$. The search is based on the razor variables M_R and R^2 [32, 33]. Given a dijet event, these variables are computed from the two jet momenta $\vec{p}^{j_1}$ and $\vec{p}^{j_2}$, according to the following definition:

$$
\begin{aligned}
M_R &= \sqrt{(|\vec{p}^{j_1}| + |\vec{p}^{j_2})^2 - (p_z^{j_1} + p_z^{j_2})^2|},\\
\mathrm{R} &= \frac{M_{\mathrm{T}}^R}{M_R},
\end{aligned}
\tag{1}
$$

with

$$
M_{\mathrm{T}}^R = \sqrt{\frac{E_{\mathrm{T}}^{\mathrm{miss}}(p_{\mathrm{T}}^{j_1} + p_{\mathrm{T}}^{j_2}) - \vec{p}_{\mathrm{T}}^{\mathrm{miss}} \cdot (\vec{p}_{\mathrm{T}}^{j_1} + \vec{p}_{\mathrm{T}}^{j_2})}{2}}. \tag{2}
$$

In the context of SUSY, M_R provides an estimate of the underlying mass scale of the event, and quantity M_{T}^R is a transverse observable that includes information about the topology of the event. The variable R^2 is designed to reduce QCD multijet background; it is correlated with the angle between the two jets, where co-linear jets have large R^2 while back-to-back jets have small R^2. These variables have been used to study the production of non-interacting particles in cascade decays of heavier partners, such as squarks and gluinos in SUSY models with R-parity conservation [34, 35]. The sensitivity of these variables to direct DM production was suggested in Ref. [36], where it was pointed out that the dijet event topology provides good discrimination against background processes, with a looser event selection than that applied

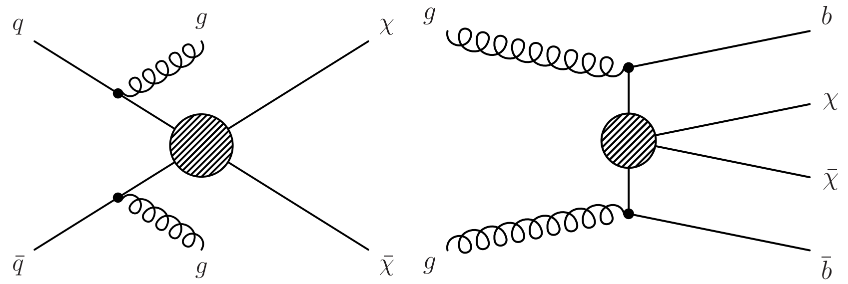

Figure 1: Feynman diagrams for the pair production of DM particles corresponding to an effective field theory using a vector or axial-vector operator (left), and a scalar operator (right).

in the monojet searches. The resulting sensitivity is comparable to that of monojet searches [36, 37]. This strategy also offers the possibility to search for DM particles that couple preferentially to b quarks [38], as proposed to accommodate the observed excess of photons with energies between 1 and 4 GeV in the gamma ray spectrum of the galactic center data collected by the Fermi-LAT gamma-ray space telescope [39]. The results are interpreted using an effective field theory approach and the Feynman diagrams for DM pair production are shown in Fig. 1.

Unlike the SUSY razor searches [33, 35], which focus on events with large values of M_R, this study also considers events with small values of M_R, using R^2 to discriminate between signal and background, in a kinematic region ($R^2 > 0.5$) excluded by the baseline selection of Refs. [33, 35].

A data sample corresponding to an integrated luminosity of 18.8 fb^{-1} of pp collisions at a center-of-mass energy of 8 TeV was collected by the CMS experiment with a trigger based on a loose selection on M_R and R^2. This and other special triggers were operated in 2012 to record events at a rate higher than the CMS computing system could process during data taking. The events from these triggers were stored on tape and their reconstruction was delayed until 2013, to profit from the larger availability of processing resources during the LHC shutdown. These data, referred to as "parked data" [40], enabled the exploration of events with small M_R values, thereby enhancing the sensitivity to direct DM production.

This paper is organized as follows: the CMS detector is briefly described in Section 2. Section 3 describes the data and simulated samples of events used in the analysis. Sections 4 and 5 discuss the event selections and categorization, respectively. The estimation of the background is described in Section 6. The systematic uncertainties are discussed in Section 7, while Section 8 presents the results and the implications for several models of DM production. A summary is given in Section 9.

2 The 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. When combining information from the entire detector, the jet energy resolution amounts typically to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV [41]. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Forward calorimeters extend the pseudorapidity (η) [42] coverage provided by the barrel and endcap detectors. The first level (L1) of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μs. The high-level trigger (HLT) processor farm further decreases the event rate from around 100 kHz to around 400 Hz, before data storage. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the basic kinematic variables, can be found in Ref. [42].

3 Data set and simulated samples

The analysis is performed on events with two jets reconstructed at L1 in the central part of the detector ($|\eta| < 3.0$). The L1 jet triggers are based on the sums of transverse energy in regions $\Delta\eta \times \Delta\phi$ approximately 1.05×1.05 in size [42] (where ϕ is the azimuthal angle in the plane transverse to the LHC beams.). At the HLT, energy deposits in ECAL and HCAL are clustered into jets and the razor variables R^2 and M_R are computed. In the HLT, jets are defined using the FASTJET [43] implementation of the anti-k_T [44] algorithm, with a distance parameter equal to 0.5. Events with at least two jets with $p_T > 64$ GeV are considered. Events are selected with $R^2 > 0.09$ and $R^2 \times M_R > 45$ GeV. This selection rejects the majority of the background, which tends to have low R^2 and low M_R values, while keeping the events in the signal-sensitive regions of the (M_R, R^2) plane. The trigger efficiency, measured using a pre-scaled trigger with very loose thresholds, is shown in Table 1. The requirements described above correspond to the least stringent event selection, given the constraints on the maximum acceptable rate.

Table 1: Measured trigger efficiency for different M_R regions. The selection $R^2 > 0.35$ is applied.

M_R region (GeV)	200–300	300–400	400–3500
Trigger efficiency (%)	$91.1\pm^{1.5}_{1.7}$	$90.7\pm^{2.3}_{2.9}$	$94.4\pm^{2.4}_{3.6}$

Monte Carlo (MC) simulated signal and background samples are generated with the leading order matrix element generator MADGRAPH v5.1.3 [45, 46] and the CTEQ6L parton distribution function set [47]. The generation includes the PYTHIA 6.4.26 [48] Z2* tune, which is derived from Z1 tune [49] based on the CTEQ5L set. Parton shower and hadronization effects are included by matching the generated events to PYTHIA, using the MLM matching algorithm [50]. The events are processed with a GEANT4 [51] description of the CMS apparatus to include detector effects. The simulation samples for SM background processes are scaled to the integrated luminosity of the data sample (18.8 fb^{-1}), using calculations of the inclusive production cross sections at the next-to-next-to-leading order (NNLO) in the perturbative QCD expansion [52–54]. The signal processes corresponding to pair production of DM particles are simulated with up to two additional partons with $p_T > 80$ GeV.

4 Event selection

Events are selected with at least one reconstructed interaction vertex within $|z| < 24$ cm. If more than one vertex is found, the one with the highest sum of the associated track momenta squared is used as the interaction point for event reconstruction. Events containing calorimeter noise, or large missing transverse momentum due to beam halo and instrumental effects (such as jets near non-functioning channels in the ECAL) are removed from the analysis [55].

A particle-flow (PF) algorithm [56, 57] is used to reconstruct and identify individual particles with an optimized combination of information from the various elements of the CMS detector. The energy of photons is directly obtained 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 measured by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons (or emissions) spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the associated 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 energies. Contamination of the energy determinations from other pp collisions is mitigated by discarding the charged PF candidates incompatible with originating from the interaction point. Additional energy from neutral particles is subtracted on average when computing lepton (electron or muon) isolation and jet energy. This contribution is estimated as the per-event energy deposit per unit area, in the cone $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$, times the considered jet size or isolation cone area.

Electrons (muons) are required to have $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ and $|\eta| < 2.5$ (2.4). In order to reduce the background from hadrons misidentified as leptons, additional requirements based on the quality of track reconstruction and isolation are applied. Lepton isolation is defined as the scalar p_{T} sum of all PF candidates other than the lepton itself, within a cone of size $\Delta R = 0.3$, and normalized to the lepton p_{T}. A candidate is identified as a lepton if the isolation variable is found to be smaller than 15%. For electrons [58], a characteristic of the shower shape of the energy deposit in the ECAL (the shower width in the η direction) is used to further reduce the contamination from hadrons.

Jets are formed by clustering the PF candidates, using the anti-k_{T} algorithm with distance parameter 0.5. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and is found from simulation to be within 5% to 10% of the generated hadron level jet momentum over the whole p_{T} spectrum and detector acceptance. Jet energy corrections are derived from simulation, and are confirmed with in situ measurements of the energy balance in dijet and photon+jet events. Additional selection criteria are applied to each event to remove spurious jet-like features originating from isolated noise patterns in certain HCAL regions. We select events containing at least two jets with $p_{\mathrm{T}} > 80\,\mathrm{GeV}$ and $|\eta| < 2.4$, for which the corresponding L1 and HLT requirements are maximally efficient. The combined secondary vertex (CSV) b-tagging algorithm [59, 60] is used to identify jets originating from b quarks. The loose and tight working points of the CSV algorithm, with 85% (10%) and 50% (0.1%) identification efficiency (misidentification probability) respectively, are used to assign the selected events to categories based on the number of b-tagged jets, as described below.

In order to compute the razor variables inclusively, the event is forced into a two-jet topology, by forming two *megajets* [34] out of all the reconstructed jets with $p_{\mathrm{T}} > 40\,\mathrm{GeV}$ and $|\eta| < 2.4$. All possible assignments of jets to the megajets are considered, with the requirement that a megajet consist of at least one jet. The sum of the four-momenta of the jets assigned to a megajet defines the megajet four-momentum. When more than two jets are reconstructed, more than one megajet assignment is possible. We select the assignment that minimizes the sum of the invariant masses of the two megajets. In order to reduce the contamination from multijet production, events are rejected if the angle between the two selected megajets in the transverse plane $|\Delta\phi(j_1, j_2)|$ is larger than 2.5 radians. The momenta of the two megajets are used to compute the razor variables, according to Eq. (1, 2). Events are required to have $M_R > 200\,\mathrm{GeV}$ and $R^2 > 0.5$.

Table 2: Definition of the event categories based on the muon multiplicity, the output of the CSV b-tagging algorithm, and the value of M_R. For all the samples, $R^2 > 0.5$ is required.

Sample	b-tagging selection	M_R selection
0μ, 1μ, and 2μ	no CSV loose jet	$200 < M_R \leq 300\,\text{GeV}$ (VL) $300 < M_R \leq 400\,\text{GeV}$ (L) $400 < M_R \leq 600\,\text{GeV}$ (H) $M_R > 600\,\text{GeV}$ (VH)
0μbb	≥ 2 CSV tight jets	$M_R > 200\,\text{GeV}$
0μb	=1 CSV tight jet	
1μb 2μb	≥ 1 CSV tight jets	
$Z(\mu\mu)$b	$\geq$1 CSV loose jets	

5 Event categories

Events are classified according to the muon and b-tagged jet multiplicities. Eight samples are defined, as summarized in Table 2.

The events with no b-tagged jets are divided into three samples: 0μ, 1μ, and 2μ. The 2μ sample includes events with two or more muons with at least one muon pair that has an invariant mass $80 < M_{\mu\mu} \leq 100\,\text{GeV}$. The 1μ sample is composed of the events with exactly one muon. The 0μ sample (events with no muons) is used to search for candidate signal events; the 1μ, 2μ samples are used to predict the background in the 0μ sample.

Similarly, five samples of selected events with b-tagged jets are defined: 0μbb, 0μb, 1μb, 2μb, and $Z(\mu\mu)$b. The 2μb sample contains events with $10 < M_{\mu\mu} < 75\,\text{GeV}$ or $105 < M_{\mu\mu} < 200\,\text{GeV}$, while the $Z(\mu\mu)$b sample includes events with $80 < M_{\mu\mu} \leq 100\,\text{GeV}$. The signal is searched for in the 0μbb and 0μb samples.

Events in the 0μ, 1μ, and 2μ samples are further classified according to their M_R value: (i) *very low* M_R (VL), defined by $200 < M_R \leq 300\,\text{GeV}$; (ii) *low* M_R (L), with $300 < M_R \leq 400\,\text{GeV}$; (iii) *high* M_R (H), with $400 < M_R \leq 600\,\text{GeV}$; and (iv) *very high* M_R (VH), including events with $M_R > 600\,\text{GeV}$. Owing to the smaller sample size, no M_R classification is performed for the events with b-tagged jets. In the H and VH categories, 3% and 35% respectively of the selected events were also selected in the monojet search [61], which used data from the same running period. The overlap in the L and VL categories is negligible, while the overlapping events in the H and VH categories were shown not to have an impact on the final sensitivity. Consequently, the results from this analysis and from the monojet analysis are largely statistically independent.

6 Background estimation

Multijet production is the most abundant source of events with jets and unbalanced p_{T}. Because of measurement uncertainties and the loss of jets falling outside the η acceptance, the reconstruction of multijet events may result in large $E_{\mathrm{T}}^{\text{miss}}$ without the presence of non-interacting particles in the final state. Based on simulated events, this background should be reduced to a negligible level by the event requirements based on the razor variables and $|\Delta\phi(j_1, j_2)|$ (see Section 4). This anticipated background reduction is confirmed in data control regions with looser cuts on the razor variables.

The largest background contribution to the 0μ sample comes from events in which a W or Z boson is produced, in association with jets, and decays to a final state with one or more neutrinos. These background processes are referred to as $\mathrm{W}(\ell\nu)$+jets and $\mathrm{Z}(\nu\overline{\nu})$+jets events. Additional backgrounds arise from events involving the production of top quark pairs, and from events in which a Z boson decays to a pair of charged leptons. These processes are referred to as $\mathrm{t\bar{t}}$ and $\mathrm{Z}(\ell\ell)$+jets, respectively. Using simulated samples, the contribution from other SM processes, such as diboson production, is found to be negligible.

The main background in the 0μb and 0μbb samples comes from $\mathrm{t\bar{t}}$ events. The use of the tight working point of the CSV algorithm reduces the presence of $\mathrm{Z}(\nu\overline{\nu})$+jets and $\mathrm{W}(\ell\nu)$+jets events to 22% and 10%, respectively.

The rest of this section describes the estimation of background in the signal samples using control samples in data and the comparison to the observed yields.

6.1 Background estimation for the 0μ sample

For events without b-tagged jets, the data yields observed in the 1μ sample are used to predict the background from $\mathrm{W}(\ell\nu)$+jets and $\mathrm{Z}(\nu\overline{\nu})$+jets in the 0μ sample. Similarly, the observed yield in the 2μ samples allows the estimation of the contamination from $\mathrm{Z}(\ell\ell)$+jets in the 0μ sample. Each M_R category is binned in R^2. Using the simulated background samples, scaled to the integrated luminosity of the data, the binning in each category is chosen so that there are no bins with zero entries.

The background expected from W and Z boson production, in each R^2 bin and in each M_R category of the 0μ sample, is computed as

$$n_i^{0\mu} = \left(n_i^{1\mu} - N_i^{\mathrm{t\bar{t}},1\mu} - N_i^{\mathrm{Z}(\ell\ell)\text{+jets},1\mu}\right) \frac{N_i^{\mathrm{W}(\ell\nu)\text{+jets},0\mu} + N_i^{\mathrm{Z}(\nu\overline{\nu})\text{+jets},0\mu}}{N_i^{\mathrm{W}(\ell\nu)\text{+jets},1\mu}} + \left(n_i^{2\mu} - N_i^{\mathrm{t\bar{t}},2\mu}\right) \frac{N_i^{\mathrm{Z}(\ell\ell)\text{+jets},0\mu}}{N_i^{\mathrm{Z}(\ell\ell)\text{+jets},2\mu}}, \tag{3}$$

where $n_i^{k\mu}$ labels the data yield in bin i for the sample with k muons, and $N_i^{X,k\mu}$ indicates the corresponding yield for process X, derived from simulations.

This background estimation method relies on the assumption that the kinematic properties of events in which W and Z bosons are produced are similar.

As a cross-check of the method, the observed yield in the 2μ sample is used to predict the 1μ yield. Simulated event samples are used to estimate the ratio of 1μ to 2μ events in each bin, and the small contribution from $\mathrm{t\bar{t}}$ events. In Table 3, the observed yields in the 1μ sample are compared to the estimate derived from data. The contribution of each process is also given, as predicted directly by simulated samples and therefore not used in the final result. For completeness, the corresponding information for the 2μ sample is given in Table 4.

Figure 2 shows the comparison for the R^2 distributions between the observed yield and the estimated background in the 1μ sample. The observed bin-by-bin difference is taken as a systematic uncertainty, associated with the background estimation method.

The $\mathrm{t\bar{t}}$ background is determined with simulated events, scaled to the NNLO cross section [52–54] and further corrected for an observed deviation from unity in the ratio of yields obtained from data and from simulation, measured in each R^2 bin of the 2μb control sample. The contribution of each process to the 2μb sample, predicted from simulated samples, is given in Table 5. The fraction of $\mathrm{t\bar{t}}$ events in the 2μb control sample is ≈95%. The observed yield is also quoted. Figure 3 shows the comparison of the observed yield and the prediction from simulation, as

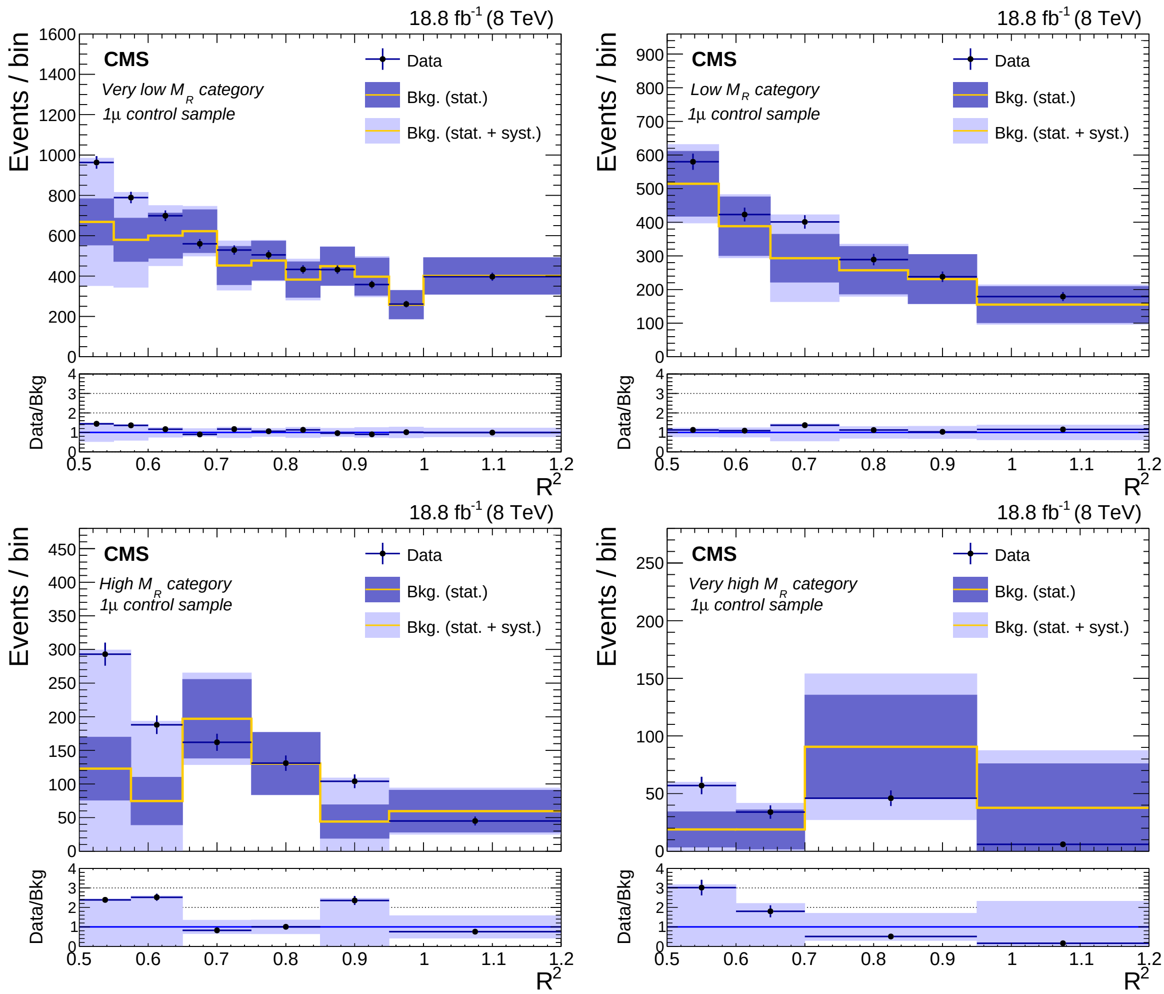

Figure 2: Comparison of observed yields in the 1μ sample and the background estimates from the 2μ sample in the four M_R categories: VL (top left), L (top right), H (bottom left), and VH (bottom right). The bottom panel in each plot shows the ratio between the two distributions. The observed bin-by-bin deviation from unity is taken as a measurement of the uncertainty associated to the background estimation for the 0μ sample. The dark and light bands represent the statistical and the total uncertainties in the estimates, respectively. The horizontal bars indicate the variable bin widths.

Table 3: Comparison of the observed yield for 1μ events in each M_R category and the corresponding background estimates, using the 2μ sample. The uncertainty in the estimates takes into account both the statistical and systematic components. The contribution of each individual background process is also shown, as estimated from simulated samples, as well as the total MC predicted yield.

M_R category	$Z(\nu\overline{\nu})$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	$t\bar{t}$	MC predicted	Estimated	Observed
VL	0.7 ± 0.3	4558 ± 32	133 ± 3	799 ± 9	5491 ± 33	5288 ± 511	5926
L	0.5 ± 0.3	1805 ± 17	44 ± 2	213 ± 4	2063 ± 18	1840 ± 233	2110
H	0.1 ± 0.1	915 ± 11	16 ± 1	66 ± 2	997 ± 11	629 ± 240	923
VH	<0.1	183 ± 5	2.6 ± 0.2	8.5 ± 0.8	194 ± 5	166 ± 93	143

Table 4: Comparison of the observed yield for 2μ events in each M_R category and the corresponding prediction from background simulation. The quoted uncertainty in the prediction reflects the size of the simulated sample. The contribution of each individual background process is also shown, as estimated from simulated samples.

M_R category	$Z(\nu\overline{\nu})$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	$t\bar{t}$	MC predicted	Observed
VL	<0.1	<0.1	214 ± 4	1.9 ± 0.3	215 ± 4	207
L	<0.1	0.4 ± 0.3	88 ± 2	0.5 ± 0.2	89 ± 2	78
H	<0.1	0.1 ± 0.1	48 ± 1	0.1 ± 0.1	48 ± 1	30
VH	<0.1	<0.1	10 ± 1	0.1 ± 0.1	10 ± 1	7

a function of R^2. The uncertainty derived from the data-to-simulation ratio is propagated to the systematic uncertainty in the $t\bar{t}$ prediction in the 0μ search region. This R^2-dependent factor and its uncertainty account for possible systematic errors in the overall normalization, as might arise for instance from a systematic error in the theoretical cross section or in the estimate of the selection acceptance.

The result of the background estimation is given in Table 6, where it is compared to the observed yields in data. The uncertainty in the background estimates takes into account both the statistical and systematic components. The contribution of each process is also given, as predicted directly by simulated samples and therefore not used in the final result.

The comparison of the data estimates and the observations for each M_R category is shown in Fig. 4, as a function of R^2. For completeness, the expected event distribution is shown for two signal benchmark models, corresponding to the pair production of DM particles of mass 1 GeV in the effective field theory (EFT) approach with vector coupling to u or d quarks. Details on the signal benchmark models are given in Section 8.1.

6.2 Background estimation for the 0μb and 0μbb samples

A technique similar to that described in Section 6.1 is used to determine the expected background for the 0μb and the 0μbb samples.

Table 5: Observed yield and predicted background from simulated samples in the 2μb control sample. The quoted uncertainty in the prediction reflects the size of the simulated sample. The contribution of each individual background process is also shown, as estimated from simulated samples.

Sample	$Z(\nu\overline{\nu})$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	$t\bar{t}$	MC predicted	Observed
2μb	<0.1	0.1 ± 0.1	2.2 ± 0.3	58 ± 2	60 ± 2	60

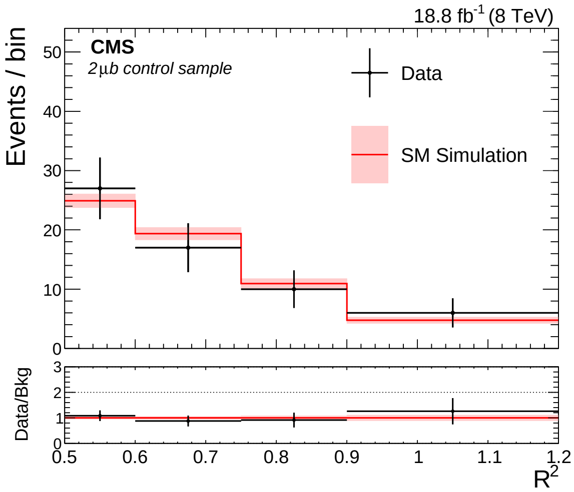

Figure 3: Comparison of the observed yield and the prediction from simulation as a function of R^2 in the 2μb control sample. The uncertainties in the data and the simulated sample are represented by the vertical bars and the shaded bands, respectively. The horizontal bars indicate the variable bin widths.

Table 6: Comparison of the observed yield for 0μ events in each M_R category and the corresponding background estimates, using the 1μ sample. The uncertainty in the estimates takes into account both the statistical and systematic components. The contribution of each individual background process is also shown, as estimated from simulated samples, as well as the total MC predicted yield.

M_R category	$Z(\nu\bar{\nu})$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	$t\bar{t}$	MC predicted	Estimated	Observed
VL	6231 ± 37	4820 ± 33	49 ± 2	555 ± 7	11655 ± 50	12770 ± 900	11623
L	2416 ± 19	1513 ± 16	11 ± 1	104 ± 3	4044 ± 25	4170 ± 270	3785
H	1127 ± 7	625 ± 9	2.9 ± 0.3	24 ± 1	1779 ± 12	1650 ± 690	1559
VH	229 ± 2	103 ± 3	0.2 ± 0.1	3.1 ± 0.5	335 ± 3	240 ± 160	261

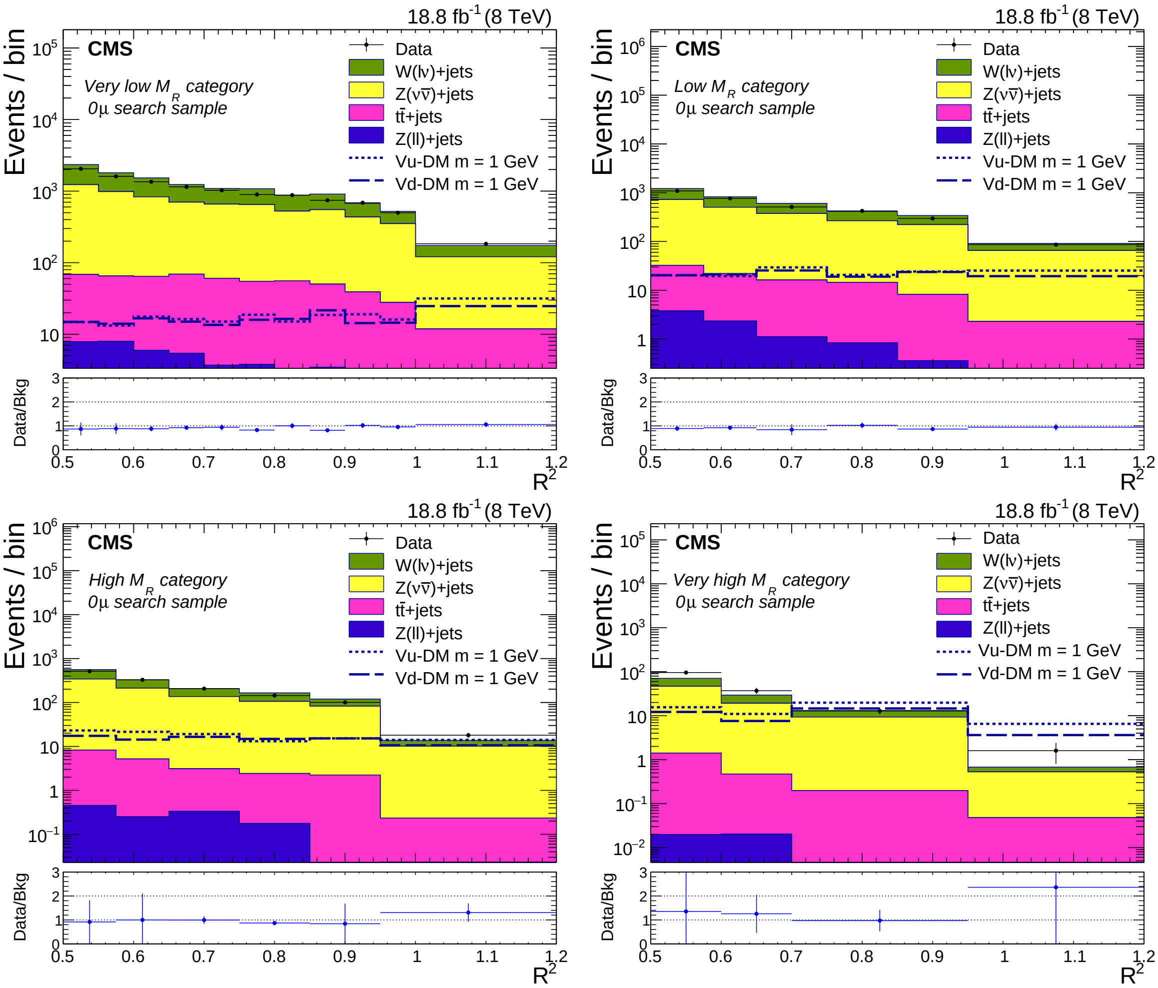

Figure 4: Comparison of the observed yield in the 0μ sample and the background estimates in the four M_R categories: VL (top left), L (top right), H (bottom left), and VH (bottom right). The contribution of individual background processes is shown by the filled histograms. The bottom panels show the ratio between the observed yields and the total background estimate. For reference, the distributions from two benchmark signal models are also shown, corresponding to the pair production of DM particles of mass 1 GeV in the EFT approach with vector coupling to u or d quarks. The horizontal bars indicate the variable bin widths.

Table 7: Comparison of the observed yields in the $Z(\mu\mu)$b and 1μb samples, the corresponding predictions from background simulation, and (for 1μb only) the cross-check background estimate. The contribution of each individual background process is also shown, as estimated from simulated samples.

Sample	$Z(\nu\overline{\nu})$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	$t\bar{t}$	MC predicted	Estimated	Observed
$Z(\mu\mu)$b	<0.1	<0.1	134 ± 3	17 ± 1	151 ± 3	—	175
1μb	0.2 ± 0.1	279 ± 7	11 ± 1	3038 ± 17	3328 ± 18	3410 ± 540	2920

Table 8: Comparison of the observed yield for events in the search samples with b-tagged jets and the corresponding background estimates. The uncertainty in the estimates takes into account both the statistical and systematic components. The contribution of each individual background process is also shown, as estimated from simulated samples, as well as the total MC predicted yield.

Sample	$Z(\nu\overline{\nu})$+jets	$W(\ell\nu)$+jets	$Z(\ell\ell)$+jets	$t\bar{t}$	MC predicted	Estimated	Observed
0μbb	44 ± 3	14 ± 2	0.2 ± 0.1	204 ± 4	262 ± 5	271 ± 37	247
0μb	417 ± 8	216 ± 7	2.4 ± 0.4	1480 ± 12	2115 ± 16	2230 ± 280	2282

The background from $t\bar{t}$ events for each R^2 bin in the 0μb sample, $n(t\bar{t})_i^{0\mu b}$, is computed as:

$$n(t\bar{t})_i^{0\mu b} = \left(n(t\bar{t})_i^{2\mu b} - N_i^{Z(\ell\ell)\text{+jets},2\mu b} - N_i^{W(\ell\nu)\text{+jets},2\mu b}\right)\frac{N(t\bar{t})_i^{0\mu b}}{N(t\bar{t})_i^{2\mu b}} \tag{4}$$

where $n(t\bar{t})_i^{2\mu b}$ is the observed yield in the ith R^2 bin for the 2μb sample, while $N(t\bar{t})_i^{0\mu b}$ and $N(t\bar{t})_i^{2\mu b}$ are, respectively, the corresponding $t\bar{t}$ yields in the ith R^2 bin for the 0μb and 2μb samples derived from the simulated $t\bar{t}$ sample. Similarly, the $t\bar{t}$ background in the 0μbb sample is derived from Eq. (4), replacing $N(t\bar{t})_i^{0\mu b}$ with $N(t\bar{t})_i^{0\mu bb}$, the $t\bar{t}$ background yield in the ith bin of the 0μbb sample, predicted from the simulated $t\bar{t}$ events. The data yield in the 2μb sample is corrected to account for the small contamination from Z+jets and W+jets, predicted with the simulated yields $N_i^{Z(\ell\ell)\text{+jets},2\mu b}$ and $N_i^{W(\ell\nu)\text{+jets},2\mu b}$, respectively.

The background contribution from $W(\ell\nu)$+jets and $Z(\nu\overline{\nu})$+jets events is predicted using the $Z(\mu\mu)$b sample, having a Z+jets purity $\approx$89% (see Table 7). The observed yield in the $Z(\mu\mu)$b sample is shown in the left plot of Fig. 5, as a function of R^2. This contribution, scaled by the ratio of the predicted V+jets background in the signal region to that in the control sample, obtained from simulation, provides an estimate for each R^2 bin. In Table 7 and in the left plot of Fig. 5, discrepancies between the observation and the prediction could be larger than the quoted uncertainty, since the latter accounts only for the statistical uncertainty of the simulated sample.

As a cross-check of the method, the same procedure is applied to derive the expected yield in the 1μb control sample (see the right plot of Fig. 5), using as input the same 2μb and $Z(\mu\mu)$b control samples.

The estimated background in the 0μb and 0μbb samples is given in Table 8 and shown in Fig. 6, where it is compared to the observed yields in data. The uncertainty in the estimates takes into account both the statistical and systematic components.

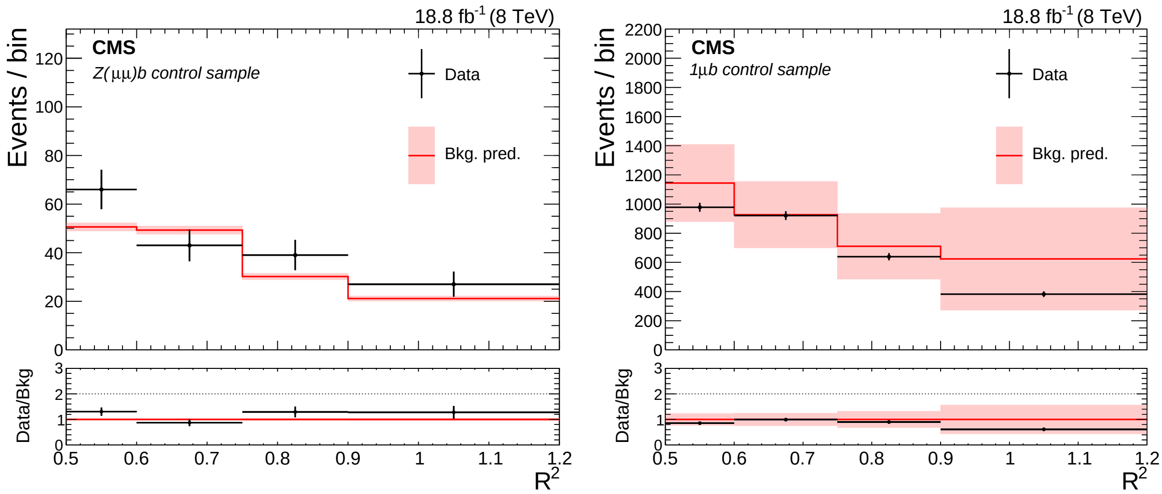

Figure 5: Comparison of the observed yield and the prediction from simulation in the $Z(\mu\mu)$b control sample (left) and of the observed yield in the 1μb control sample and the background estimates from the 2μb and $Z(\mu\mu)$b control samples (right), shown as a function of R^2. The bottom panel of each figure shows the ratio between the data and the estimates. The shaded bands represent the statistical uncertainty in the left plot, and the total uncertainty in the right plot. The horizontal bars indicate the variable bin widths.

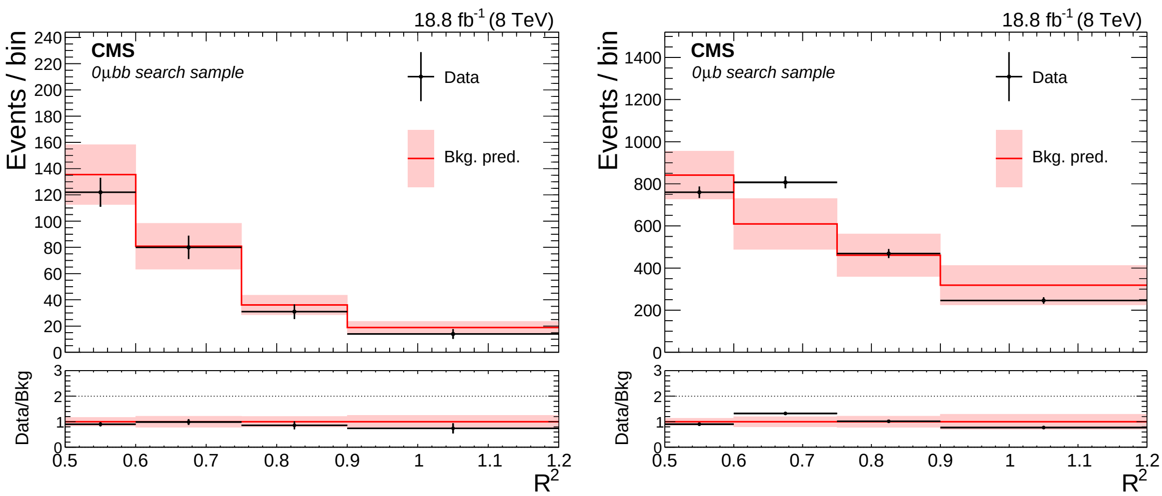

Figure 6: Comparison of observed event yields and background estimates as a function of R^2, for the 0μbb (left) and 0μb (right) samples. The shaded bands represent the total uncertainty in the estimate. The horizontal bars indicate the variable bin widths.

Table 9: Systematic uncertainties associated with the description of the DM signal. The values indicated represent the typical size. The dependence of these systematic uncertainties on the R^2 and M_R values is taken into account in the determination of the results.

Effect	Uncertainty
Jet energy scale	3–6%
Luminosity	2.6%
Parton distribution functions	3–6%
Initial-state radiation	8–15%

7 Systematic uncertainties

For each R^2 bin in each M_R category, the difference between the observed and estimated yields in the crosscheck analysis (see Section 6) is taken as the estimate of the uncertainty associated with the method. The uncertainty is found to be $\approx$20–40%, depending on the considered bin in the (M_R, R^2) plane.

For the 0μ analysis, differences between the kinematic properties of W+jets and Z+jets events are additional sources of systematic uncertainty. These differences arise from the choice of the PDF set, jet energy scale corrections, b tagging efficiency corrections, and trigger efficiency. These effects largely cancel when taking the ratio of the two processes, and the resulting uncertainty is found to be smaller than one fifth of the total uncertainty. The quoted uncertainty is an upper estimate of the total systematic uncertainty.

For the 0μb and 0μbb samples, both the signal and control samples are dominated by $t\bar{t}$ events. The cancellation of the systematic uncertainties is even stronger in this case, since it does not involve different processes, and different PDFs. The remaining uncertainty is dominated by the contribution arising from the small size of the control sample.

Systematic uncertainties in the signal simulation originate from the choice of the PDF set, the jet energy scale correction, the modeling of the initial-state radiation in the event generator, and the uncertainty in the integrated luminosity. The luminosity uncertainty changes the signal normalization while the other uncertainties also modify the signal shape. These effects are taken into account by propagating these uncertainties into the M_R category and the R^2 bin. These uncertainties are considered to be fully correlated across M_R categories and R^2 bins. Typical values for the individual contributions are given in Table 9. The total uncertainty in the signal yield is obtained by propagating the individual effects into the M_R and R^2 variables and comparing the bin-by-bin variations with respect to the central value of the prediction based on simulation. In the particular case of the uncertainties due to the choice of the PDF set we have followed the PDF4LHC [62–64] prescription, using the CTEQ-6.6[65] and MRST-2006-NNLO [66] PDF sets.

8 Results and interpretation

In Figs. 4 and 6 the estimated backgrounds are compared to the observed yield in each M_R region, for events without and with b-tagged jets, respectively. The background estimates agree with the observed yields, within the uncertainties. This result is interpreted in terms of exclusion limits for several models of DM production.

8.1 Limits on dark matter production from the 0μ sample

The result is interpreted in the context of a low-energy effective field theory, in which the production of DM particles is mediated by six or seven dimension operators [67, 68]. This choice allows the results be compared with those of previous analyses [19, 20], and shows that a similar sensitivity is achieved.

Operators of dimension six and seven are generated assuming the existence of a heavy particle, mediating the interaction between the DM and SM fields. To describe DM production as a local interaction, the propagator of the heavy mediator is expanded through an operator product expansion. The nature of the mediator determines the nature of the effective interaction. Two benchmark scenarios are considered in this study, axial-vector (AV), and vector (V) interactions [69], described by the following operators:

$$\hat{\mathcal{O}}_{\mathrm{AV}} = \frac{1}{\Lambda^2}\left(\bar{\chi}\gamma^{\mu}\gamma_5\chi\right)\left(\bar{q}\gamma_{\mu}\gamma_5 q\right) \; ; \qquad \hat{\mathcal{O}}_{\mathrm{V}} = \frac{1}{\Lambda^2}\left(\bar{\chi}\gamma^{\mu}\chi\right)\left(\bar{q}\gamma_{\mu}q\right). \tag{5}$$

Here γ_μ and γ_5 are the Dirac matrices, χ is the DM field, and q is an SM quark field. The DM particle is assumed to be a Dirac fermion where both operators will contribute in the low-energy theory, while in the case of a Majorana DM particle the vector coupling $\hat{\mathcal{O}}_V$ will vanish in the low-energy theory. Below the cutoff energy scale Λ, DM production is described as a contact interaction between two quarks and two DM particles. In the case of s-channel production through a heavy mediator, the energy scale Λ is identified with M/g_{eff}, where M is the mediator mass and $g_{\mathrm{eff}} = \sqrt{g_q g_\chi}$ is an effective coupling, determined by the coupling of the mediator to quark and DM fields, g_q and g_χ, respectively.

The results in Tables 13-16 in the Appendix are used to obtain an upper limit at 90% confidence level (CL) on the DM production cross section, σ^i_{UL} (where the superscript denotes the coupling to an up or down quark). The limits are obtained using the LHC $\mathrm{CL_s}$ procedure [70, 71] and a global likelihood determined by combining the likelihoods of the different search categories. Each systematic uncertainty (see Section 7) is incorporated in the likelihood with a dedicated nuisance parameter, whose value is not known a priori but rather must be estimated from the data.

Subsequently, the cross section (σ^i_{UL}) limit is translated into a lower limit Λ_{LL} on the cutoff scale, through the relation:

$$\Lambda_{\mathrm{LL}} = \Lambda_{\mathrm{GEN}}\left(\frac{\sigma_{\mathrm{GEN}}}{\sigma_{\mathrm{UL}}}\right)^{\frac{1}{4}}. \tag{6}$$

Here Λ_{GEN} and σ_{GEN} are the cutoff energy scale and cross section of the simulated sample, respectively. The derived values of Λ_{LL} as a function of the DM mass, shown in Fig. 7, are comparable to those derived for the CMS monojet search [61]. The analysis has been repeated removing the events also selected by the monojet search. The reduction in background yields due to this additional requirement compensates for the reduction in signal efficiency, resulting in a negligible difference in the exclusion limit on Λ.

The EFT framework provides a benchmark scenario to compare the sensitivity of this analysis with that of previous searches for similar signatures. However, the validity of an EFT approach is limited at the LHC because a fraction of events under study are generated at a $\sqrt{\hat{s}}$ comparable to the cutoff scale Λ [68, 72–74]. For theories to be perturbative, g_{eff} is typically required to be smaller than 4π, and this condition is unlikely to be satisfied for the entire region of phase space probed by the collider searches. In addition, the range of values for the couplings being probed within the EFT may be unrealistically large. Following the study presented in Refs. [75–77],

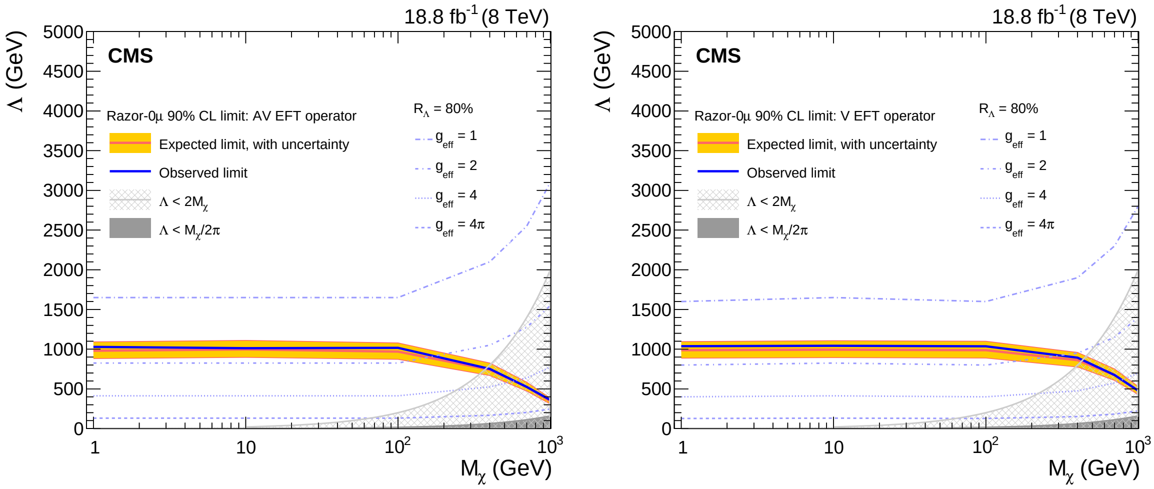

Figure 7: Lower limit at 90% CL on the cutoff scale Λ as a function of the DM mass M_χ in the case of axial-vector (left) and vector (right) currents. The validity of the EFT is quantified by $R_\Lambda = 80\%$ contours, corresponding to different values of the effective coupling g_{eff}. For completeness, regions forbidden by the EFT validity condition $\Lambda > 2M_\chi/g_{\text{eff}}$ are shown for two choices of the effective coupling: $g_{\text{eff}} = 1$ (light gray) and $g_{\text{eff}} = 4\pi$ (dark gray).

we quantify this effect through two EFT validity measures. The first is a minimal kinematic constraint on Λ obtained by requiring $Q_{\text{tr}} < g_{\text{eff}}\Lambda$ and $Q_{\text{tr}} > 2M_\chi$, where Q_{tr} is the momentum transferred from the mediator to the DM particle pair, which yields $\Lambda > 2M_\chi/g_{\text{eff}}$. The second is more stringent and uses the quantity:

$$R_\Lambda = \frac{\int \mathrm{d}R^2 \int \mathrm{d}M_R \left.\dfrac{\mathrm{d}^2\sigma}{\mathrm{d}R^2\mathrm{d}M_R}\right|_{Q_{\text{tr}}<g_{\text{eff}}\Lambda}}{\int \mathrm{d}R^2 \int \mathrm{d}M_R \dfrac{\mathrm{d}^2\sigma}{\mathrm{d}R^2\mathrm{d}M_R}}. \tag{7}$$

Values of R_Λ close to unity indicate a regime in which the assumptions of the EFT approximation hold, while a deviation from unity quantifies the fraction of events for which the EFT approximation is still valid. We consider the case of s-channel production, and we compute R_Λ as a function of the effective coupling g_{eff} in the range $0 < g_{\text{eff}} \leq 4\pi$. The contours corresponding to $R_\Lambda = 80\%$ for different values of g_{eff} are shown in Fig. 7. For values of $g_{\text{eff}} \gtrsim 2$, the limit set by the analysis lies above the $R_\Lambda = 80\%$ contour.

The exclusion limits on Λ for the axial-vector and vector operators are transformed into upper limits on the spin-dependent ($\sigma^{\text{SD}}_{N\chi}$) [78–84] and spin-independent ($\sigma^{\text{SI}}_{N\chi}$) [80, 81, 85–90] DM-nucleon scattering cross section, respectively; using the following expressions [69]:

$$\sigma^{\text{SD}}_{N\chi} = 0.33\frac{\mu^2}{\pi\Lambda^4_{\text{LL}}}, \tag{8}$$

$$\sigma^{\text{SI}}_{N\chi} = 9\frac{\mu^2}{\pi\Lambda^4_{\text{LL}}}, \tag{9}$$

where

$$\mu = \frac{M_\chi M_{\text{p}}}{M_\chi + M_{\text{p}}}, \tag{10}$$

Table 10: The 90% CL limits on DM production in the case of axial-vector couplings. Here, σ^{u}_{UL} and σ^{d}_{UL} are the observed upper limits on the production cross section for u and d quarks, respectively; Λ_{LL} is the observed cutoff energy scale lower limit; and $\sigma_{N\chi}$ is the observed DM-nucleon scattering cross section upper limit.

M_{χ} (GeV)	σ^{u}_{UL}(pb)	σ^{d}_{UL}(pb)	Λ_{LL} (GeV)	$\sigma_{N\chi}$ (cm^2)
1	0.39	0.45	1029	8.5×10^{-42}
10	0.43	0.45	1012	2.9×10^{-41}
100	0.30	0.37	1017	3.3×10^{-41}
400	0.25	0.26	752	1.1×10^{-40}
700	0.21	0.26	524	4.7×10^{-40}
1000	0.17	0.22	360	2.1×10^{-39}

Table 11: The 90% CL limits on DM production in the case of vector couplings. Here, σ^{u}_{UL} and σ^{d}_{UL} are the observed upper limits on the production cross section for u and d quarks, respectively; Λ_{LL} is the observed cutoff energy scale lower limit; and $\sigma_{N\chi}$ is the observed DM-nucleon scattering cross section upper limit.

M_{χ} (GeV)	σ^{u}_{UL}(pb)	σ^{d}_{UL}(pb)	Λ_{LL} (GeV)	$\sigma_{N\chi}$ (cm^2)
1	0.41	0.38	1038	2.3×10^{-40}
10	0.36	0.45	1043	6.9×10^{-40}
100	0.33	0.44	1036	8.3×10^{-40}
400	0.23	0.35	893	1.5×10^{-39}
700	0.22	0.27	674	4.7×10^{-39}
1000	0.22	0.27	477	1.8×10^{-38}

with M_{p} and M_{χ} indicating the proton and DM masses, respectively. The numerical values of the derived limits are given in Tables 10 and 11. The bound on $\sigma_{N\chi}$ as a function of M_{χ} is shown in Fig. 8 for spin-dependent and spin-independent DM-nucleon scattering.

In order to compare our results with those from direct detection experiments, the experimental bounds in [78–81, 85–88] are translated into bounds on Λ. This comparison is shown in Fig. 9. This translation is well defined since the momentum transfer in most direct detection experiments is low compared to the values of Λ being probed, and thus the EFT approximations in question are mostly valid.

8.2 Limits on dark matter production from the 0μb and 0μbb samples

The results from the 0μb and 0μbb samples are interpreted in an EFT scenario, following a methodology similar to that of Section 8.1. In this case, a heavy scalar mediator is considered [91], generating an operator:

$$\hat{\mathcal{O}}_S = \frac{M_q}{\Lambda^3}\bar{\chi}\chi\bar{q}q. \tag{11}$$

The dependence on the mass, induced by the scalar nature of the mediator, implies a stronger coupling to third-generation quarks, enhancing the sensitivity of the 0μb and 0μbb samples to this scenario. Unlike the case of V and AV operators, the production cross section for this process is proportional to $1/\Lambda^6$. The value of Λ_{LL} is then derived as

$$\Lambda_{\mathrm{LL}} = \Lambda_{\mathrm{GEN}} \left(\frac{\sigma_{\mathrm{GEN}}}{\sigma_{\mathrm{UL}}}\right)^{\frac{1}{6}}. \tag{12}$$

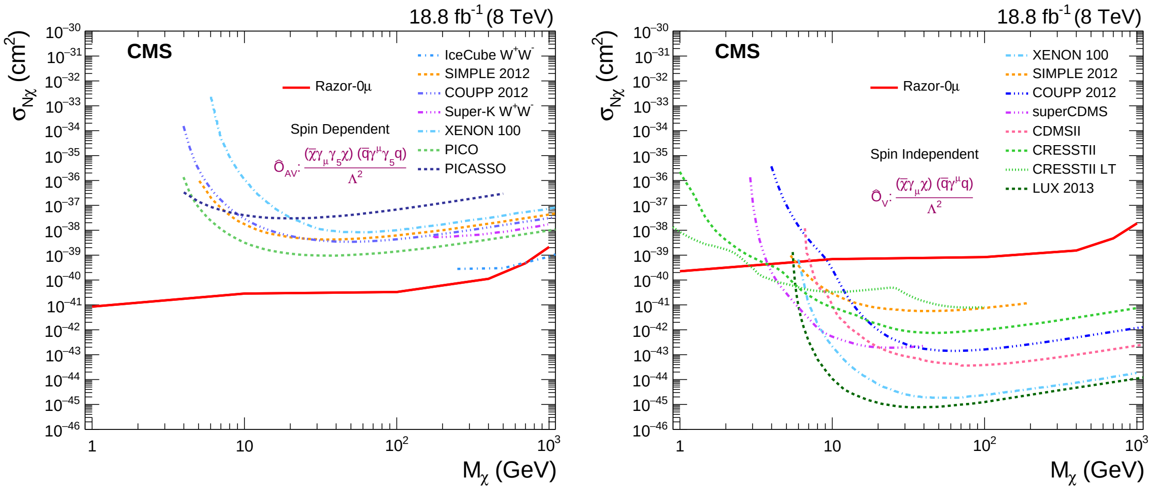

Figure 8: Upper limit at 90% CL on the DM-nucleon scattering cross section $\sigma_{N\chi}$ as a function of the DM mass M_χ in the case of spin-dependent axial-vector (left) and spin-independent vector (right) currents. A selection of representative direct detection experimental bounds are also shown.

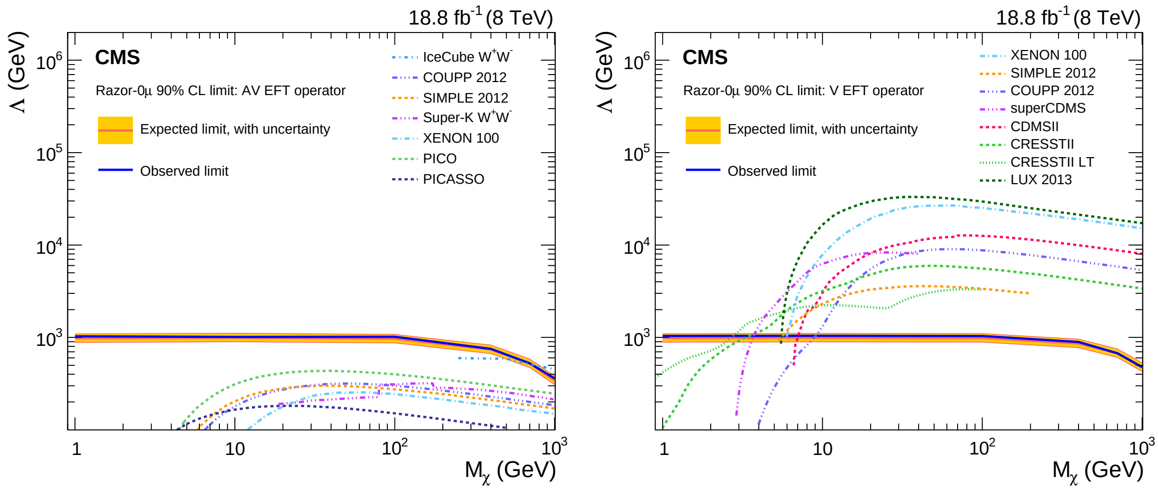

Figure 9: Lower limit at 90% CL on the cutoff scale Λ as a function of the DM mass M_χ in the case of axial-vector (left) and vector (right) currents. A selection of direct detection experimental bounds are also shown.

Table 12: The 90% CL limits on DM production in the case of scalar couplings. Here, $\sigma_{\mathrm{UL}}^{\mathrm{obs}}$ is the observed upper limit on the production cross section, $\Lambda_{\mathrm{LL}}^{\mathrm{obs}}$ and $\Lambda_{\mathrm{LL}}^{\mathrm{exp}}$ are the observed and expected cutoff energy scale lower limit, respectively.

M_χ (GeV)	$\sigma_{\mathrm{UL}}^{\mathrm{obs}}$(pb)	$\Lambda_{\mathrm{LL}}^{\mathrm{obs}}$ (GeV)	$\Lambda_{\mathrm{LL}}^{\mathrm{exp}}$ (GeV)
0.1	5.4	43.0	48.2
1	3.8	45.3	49.9
10	6.3	43.2	48.4
100	0.8	53.7	55.1
200	0.7	47.2	48.3
300	2.8	32.5	35.8
400	2.8	28.3	30.8
1000	1.7	13.2	13.8

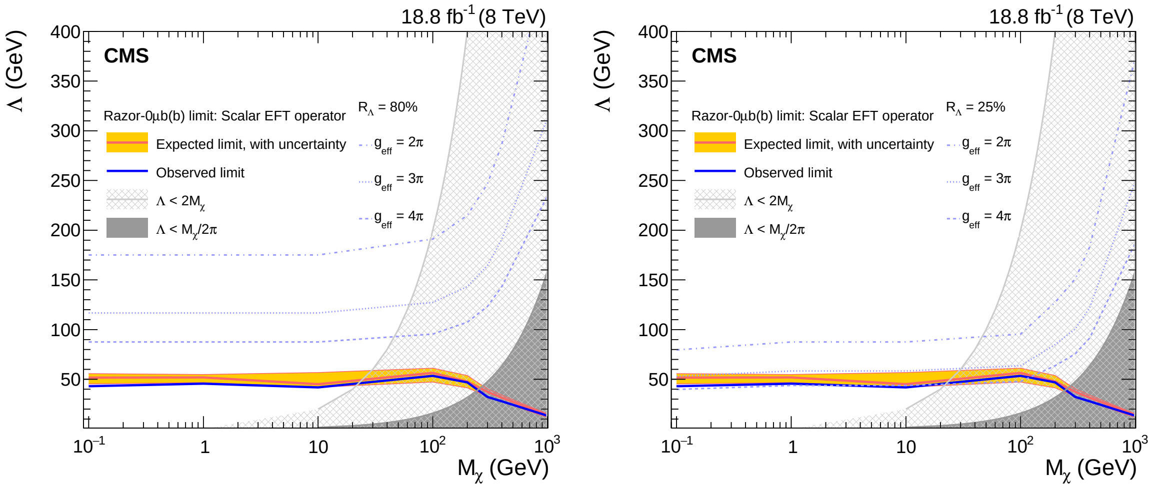

Figure 10: Lower limit at 90% CL on the cutoff scale Λ for the scalar operator $\hat{\mathcal{O}}_S$ as a function of the DM mass M_χ. The validity of the EFT is quantified by $R_\Lambda = 80\%$ (left) and $R_\Lambda = 25\%$ (right) contours, corresponding to different values of the effective coupling g_{eff}. For completeness, regions forbidden by the EFT validity condition $\Lambda > 2M_\chi/g_{\mathrm{eff}}$ are shown for two choices of the effective coupling: $g_{\mathrm{eff}} = 1$ (light gray) and $g_{\mathrm{eff}} = 4\pi$ (dark gray).

Given the results of Table 8 we proceed to set limits at 90% CL on the cutoff scale (see Table 12) using the LHC CL$_\mathrm{s}$ procedure. To quantify the validity of the EFT we follow the discussion in Section 8.1, considering an interaction mediated by an s-channel produced particle. The operator of Eq. (11) is suppressed by an additional factor m_b/Λ with respect to the operators in Eq. (5). As a result, for a given value of the coupling g_{eff}, smaller values of Λ are probed in this case. The observed limit stays below the contours derived for $R_\Lambda = 80\%$, even when the coupling is fixed to the largest value considered, $g_{\mathrm{eff}} = 4\pi$, as shown in the left plot of Fig. 10. For the same choice of coupling, the derived limit on Λ would correspond to $R_\Lambda \approx 25\%$, as shown in the right plot of Fig. 10. Only for $g_{\mathrm{eff}} > 4\pi$ does the observed limit correspond to values of $R_\Lambda > 80\%$. This requirement implies a UV completion of the EFT beyond the perturbative regime. For this reason, this result is not interpreted in terms of an exclusion limit on $\sigma_{N\chi}$.

9 Summary

A search for dark matter has been performed studying proton-proton collisions collected with the CMS detector at the LHC at a center-of-mass energy of 8 TeV. The data correspond to an integrated luminosity of 18.8 fb^{-1}, collected with a dedicated high-rate trigger in 2012, made possible by the creation of parked data, and processed during the LHC shutdown in 2013.

Events with at least two jets are analyzed by studying the distribution in the (M_R, R^2) plane, in an event topology complementary to that of monojet searches. Events with one or two muons are used in conjunction with simulated samples, to predict the expected background from standard model processes, mainly Z+jets and W+jets. The analysis is performed on events both with and without b-tagged jets, originating from the hadronization of a bottom quark, where in the latter case the dominant background comes from $\mathrm{t\bar{t}}$.

No significant excess is observed. The results are presented as exclusion limits on dark matter production at 90% confidence level for models based on effective operators and for different assumptions on the interaction between the dark matter particles and the colliding partons. Dark matter production at the LHC is excluded for a mediator mass scale Λ below 1 TeV in the case of a vector or axial vector operator. While the sensitivity achieved is similar to those of previously published searches, this analysis complements those results since the use of razor variables provides more inclusive selection criteria and since the exploitation of parked data allows events with small values of M_R to be included.

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Appendix

A Background estimation and observed yield

In this section, we provide the background estimate and the observed yield for each bin of the (M_R, R^2) plane.

Tables 13-16 show the expected and observed yields in each R^2 bin of each M_R category for the 0μ sample. Tables 17 and 18 show the corresponding values for the 0μb and the 0μbb samples, respectively.

Table 13: Background estimates and observed yield for each R^2 bin in the VL M_R category.

R^2 range	0.5–0.55	0.55–0.6	0.6–0.65	0.65–0.7
Observed	2049	1607	1352	1147
Estimated	2350 ± 720	1810 ± 450	1530 ± 180	1240 ± 110
R^2 range	0.7–0.75	0.75–0.8	0.8–0.85	0.85–0.9
Observed	1026	896	880	744
Estimated	1090 ± 140	1081 ± 76	876 ± 97	909 ± 63
R^2 range	0.9–0.95	0.95–1.0	1.0–2.5	
Observed	688	499	735	
Estimated	674 ± 67	521 ± 43	694 ± 62	

Table 14: Background estimates and observed yield for each R^2 bin in the L M_R category.

R^2 range	0.5–0.575	0.575–0.65	0.65–0.75
Observed	1088	765	682
Estimated	1220 ± 120	828 ± 65	810 ± 210
R^2 range	0.75–0.85	0.85–0.95	0.95–2.5
Observed	565	395	290
Estimated	551 ± 59	454 ± 32	304 ± 43

Table 15: Background estimates and observed yield for each R^2 bin in the H M_R category.

R^2 range	0.5–0.575	0.575–0.65	0.65–0.75
Observed	513	328	279
Estimated	560 ± 550	330 ± 360	275 ± 41
R^2 range	0.75–0.85	0.85–0.95	0.95–2.5
Observed	203	151	85
Estimated	242 ± 18	171 ± 173	74 ± 17

Table 16: Background estimates and observed yield for each R^2 bin in the VH M_R category.

R^2 range	0.5–0.6	0.6–0.7	0.7–0.95	0.95–2.5
Observed	117	58	75	11
Estimated	100 ± 150	59 ± 36	75 ± 30	9 ± 7

Table 17: Background estimates and observed yield for each bin in the 0μb signal region.

R^2 range	0.5–0.6	0.6–0.75	0.75–0.9	0.9–2.5
Observed	760	807	469	246
Estimated	850 ± 170	620 ± 120	470 ± 110	320 ± 160

Table 18: Background estimates and observed yield for each bin in the 0μbb signal region.

R^2 range	0.5–0.6	0.6–0.75	0.75–0.9	0.9–2.5
Observed	122	80	31	14
Estimated	135 ± 30	81 ± 18	36 ± 8	19 ± 9

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35: Also at Warsaw University of Technology, Institute of Electronic Systems, Warsaw, Poland
36: Also at Institute for Nuclear Research, Moscow, Russia
37: Now at National Research Nuclear University 'Moscow Engineering Physics Institute' (MEPhI), Moscow, Russia
38: Also at St. Petersburg State Polytechnical University, St. Petersburg, Russia
39: Also at California Institute of Technology, Pasadena, USA
40: Also at Faculty of Physics, University of Belgrade, Belgrade, Serbia
41: Also at INFN Sezione di Roma; Università di Roma, Roma, Italy
42: Also at National Technical University of Athens, Athens, Greece
43: Also at Scuola Normale e Sezione dell'INFN, Pisa, Italy
44: Also at National and Kapodistrian University of Athens, Athens, Greece
45: Also at Institute for Theoretical and Experimental Physics, Moscow, Russia
46: Also at Albert Einstein Center for Fundamental Physics, Bern, Switzerland
47: Also at Gaziosmanpasa University, Tokat, Turkey
48: Also at Adiyaman University, Adiyaman, Turkey
49: Also at Mersin University, Mersin, Turkey
50: Also at Cag University, Mersin, Turkey
51: Also at Piri Reis University, Istanbul, Turkey
52: Also at Ozyegin University, Istanbul, Turkey
53: Also at Izmir Institute of Technology, Izmir, Turkey
54: Also at Marmara University, Istanbul, Turkey

55: Also at Kafkas University, Kars, Turkey
56: Also at Istanbul Bilgi University, Istanbul, Turkey
57: Also at Yildiz Technical University, Istanbul, Turkey
58: Also at Hacettepe University, Ankara, Turkey
59: Also at Rutherford Appleton Laboratory, Didcot, United Kingdom
60: Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom
61: Also at Instituto de Astrofísica de Canarias, La Laguna, Spain
62: Also at Utah Valley University, Orem, USA
63: Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia
64: Also at Facoltà Ingegneria, Università di Roma, Roma, Italy
65: Also at Argonne National Laboratory, Argonne, USA
66: Also at Erzincan University, Erzincan, Turkey
67: Also at Mimar Sinan University, Istanbul, Istanbul, Turkey
68: Also at Texas A&M University at Qatar, Doha, Qatar
69: Also at Kyungpook National University, Daegu, Korea