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Dark Matter search at LHC

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Summary. — The results of recent searches for dark matter performed with the first data collected during the CERN LHC Run-2 by the CMS and ATLAS Collaborations, corresponding to $2.1\,\mathrm{fb}^{-1}$ and $3.2\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$, respectively, are presented and categorized according to the event topology characteristics. No excesses are found above the standard model expectations and the results are interpreted in terms of upper limits in the production of dark matter using simplified theory models. The results are also translated into limits on the dark matter-nucleon spin-dependent and spin-independent cross section to compare with the results of direct detection experiments.

1. – Introduction

The presence of dark matter (DM) is one of the most compelling pieces of evidence for physics beyond the description of the standard model (SM). Despite the evidence of its existence, from astrophysical observations, the nature of DM is still unknown. Although there is not yet any evidence for non-gravitational interaction between DM and SM particles many theories currently point to the existence of a stable, neutral, weakly interacting massive particle, that couples to the SM via the presence of a bosonic mediator of either spin-0 or spin-1. Along with the direct and indirect detection experiments, respectively investigating the nuclear recoil potentially caused by the DM scattering off target nucleus, and searching for SM particles arising from the annihilation of DM pairs in dense region of the universe, DM-pairs could be produced in the high energetic inelastic scattering in colliders as the Large Hadron Collider (LHC) at CERN. Searches regarding the latter experimental category are going to be discussed in this review. Since the DM particles themselves are considered weakly-interacting, they do not produce any observable signal in the LHC experiments. The typical experimental technique used to search for DM production at colliders, is the search for a visible SM object X (X = g, light-quark, heavy-quark, γ, Z, W, h) recoiling against the invisible DM-pair, translated in a strong unbalance in transverse momentum in the detector, its magnitude usually referred as missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$. The dominant backgrounds in DM searches at colliders can be mainly attributed to electroweak processes, the largest background consisting of $\mathrm{Z}(\nu\nu) + \mathrm{jets}$ events; the second largest background consists of $\mathrm{W}(\ell\nu) + \mathrm{jets}$ events. The latter is usually suppressed by applying vetoes on events in which a lepton (electron, muon or tau) is identified, but a certain fraction of $\mathrm{W} + \mathrm{jets}$ events, in which the lepton is either out of the detector acceptance or is not identified is anyway retained. The remaining minor sources of background can be attributed to several subdominant processes, including top-quark decays (relevant for the DM + b-jet searches), which are suppressed by applying a veto on events in which a b-jet is identified, semileptonic diboson (WW, WZ, ZZ) decays, and QCD multijet events in which large $E_{\mathrm{T}}^{\mathrm{miss}}$ arises from mismeasurement of jet momentum or from detector noise. LHC Run-1 searches for $\mathrm{X}+E_{\mathrm{T}}^{\mathrm{miss}}$ events, employed contact interaction operators in effective field theories (EFTs) to interpret the results in terms of DM-SM couplings. The EFT is mostly suited in the case the mediator of the interaction between SM and DM particles is very heavy, and the validity of these approaches breaks down at lower masses. To overcome this limitation the ATLAS [2] and CMS [3] communities proposed a new set of simplified models to provide a faithful description of the kinematics of the production of Dirac fermion DM in the considered processes giving direct access to the interaction mediator. The Dark Matter Forum document [1] summarizes the studies carried out and describes the set of benchmark model configurations agreed between the ATLAS and CMS Collaborations. The searches for DM performed by the CMS and ATLAS Collaborations, corresponding to $2.1\,\mathrm{fb}^{-1}$ and $3.2\,\mathrm{fb}^{-1}$ of proton-proton collisions at $\sqrt{s} = 13\,\mathrm{TeV}$ respectively, are discussed in the following sections.

2. – Mono-jet

The CMS Collaboration presented a search performed for new physics in events with at least one jet having transverse momentum larger than 100 GeV and $E_{\mathrm{T}}^{\mathrm{miss}}$ greater than 200 GeV, in a dataset recorded by the CMS detector corresponding to $2.1\,\mathrm{fb}^{-1}$ [4]. Events are selected with a trigger that requires $E_{\mathrm{T}}^{\mathrm{miss}}$ larger than 90 GeV; muons are not included in the online $E_{\mathrm{T}}^{\mathrm{miss}}$ evaluation so that the same trigger can also be utilized to select events in the control regions (CR) used for the background prediction. Events with $E_{\mathrm{T}}^{\mathrm{miss}} > 200\,\mathrm{GeV}$ and the leading jet in the event with $p_{\mathrm{T}} > 100\,\mathrm{GeV}$ are selected in the signal region (SR). To reduce the QCD multijet background the minimum azimuthal angle between the direction of the negative vectorial sum of the p_{T} of all reconstructed particles and the first four leading jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ is required to be greater than 0.5. The top-quark background is reduced by applying a veto on events in which a b-jet is present. Finally, events are vetoed if they contain at least one well-identified and isolated electron or muon with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, photon with $p_{\mathrm{T}} > 15\,\mathrm{GeV}$ or tau with $p_{\mathrm{T}} > 18\,\mathrm{GeV}$, to reduce the electroweak backgrounds. The two main irreducible backgrounds, $\mathrm{Z}(\nu\nu)$+jets and $\mathrm{W}(\ell\nu)$+jets, are estimated using five CRs in data consisting of dimuon, dielectron, single muon, single electron, and $\gamma + \mathrm{jets}$ events. The $E_{\mathrm{T}}^{\mathrm{miss}}$ in these CRs is redefined by excluding the leptons or the photon from its computation, defined as the hadronic recoil, to mimic the $E_{\mathrm{T}}^{\mathrm{miss}}$ shape of the backgrounds in the SR. A combined fit of the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the SR and of the hadronic recoil in the CRs is performed in order to constrain the main background contributions. Transfer factors derived from simulation take into account the different branching fractions of the processes evaluated in the SR and CRs, and for the impact of lepton/photon acceptances and efficiencies.

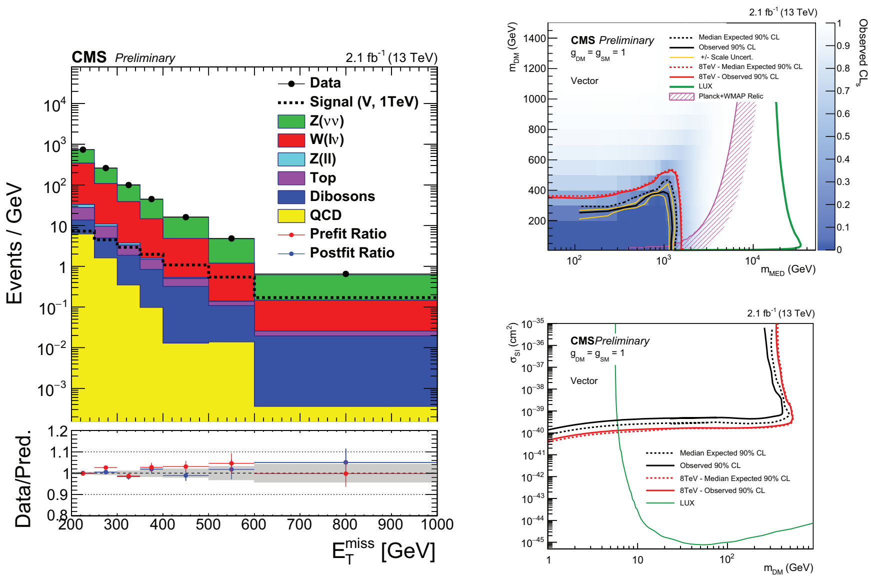

Fig. 1. – Left: Post-fit distribution of $E_{\mathrm{T}}^{\mathrm{miss}}$ expected from SM backgrounds and observed in data in the SR of the CMS mono-jet analysis [4]. Right-top: exclusion contours in the m_{med}-m_{DM} plane assuming a vector-type interaction. The black line shows the 90% CL upper limit on the signal strength assuming the mediator only couples to fermions. The background colors denote the observed exclusion. Right-bottom: 90% CL exclusion contours in the m_{DM}-σ_{SI} plane assuming a vector mediator. The solid green line indicates the most sensitive bound coming from direct detection experiments.

The contributions of the minor backgrounds, mostly due to top-quark and diboson, are estimated from simulation, and the QCD multijet background is instead estimated from a data-driven approach by inverting the angular cut between jet and $E_{\mathrm{T}}^{\mathrm{miss}}$. Figure 1 show the result of the simultaneous fit in all the regions under the background-only hypothesis. The CRs with the larger yields drive the fit, however good agreement is observed in all CRs. Data is found to be in agreement with the SM prediction, and the results are interpreted as exclusion limits as a scan of the DM mass and the mediator mass, and translated in terms of limits on the spin-independent (SI) DM-nucleon scattering cross-section, as shown in fig. 1.

An analogous search has been carried out by the ATLAS Collaboration in events with at least one jet having p_{T} larger than 250 GeV and $E_{\mathrm{T}}^{\mathrm{miss}}$ greater than 250 GeV, in a dataset corresponding to $3.2\,\mathrm{fb}^{-1}$ [5]. A maximum of four jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ are allowed, and the separation in the azimuthal plane of the missing transverse momentum and the each selected jet is required to be greater than 0.4 to reduce the multijet background contribution. A $\mathrm{W}(\mu\nu)+\mathrm{jets}$ CR is used to define normalization factors for both $\mathrm{W}(\mu\nu)+\mathrm{jets}$ and $\mathrm{Z}(\nu\nu)+\mathrm{jets}$ processes, whereas a $\mathrm{W}(e\nu)+\mathrm{jets}$ CR is used to constrain the normalization of the $\mathrm{W}(e\nu)+\mathrm{jets}$ and $\mathrm{W}(\tau\nu)+\mathrm{jets}$ processes, as well as the small $\mathrm{Z}(\tau\tau)+\mathrm{jets}$ contribution. Finally, a $\mathrm{Z}/\gamma*(\mu\mu)+\mathrm{jets}$ CR is used to constrain the $\mathrm{Z}/\gamma*(\mu\mu)+\mathrm{jets}$ contribution. Additional contributions from $\mathrm{Z}/\gamma*(ee)+\mathrm{jets}$, top-quark, and diboson production are determined from simulation, while the multijet background is estimated from data. Simulation-based scale factors are defined for each of the signal selections to estimate the different background contributions in the SRs. A simultaneous likelihood fit to the $\mathrm{W}(\mu\nu)+\mathrm{jets}$, $\mathrm{W}(e\nu)+\mathrm{jets}$, and $\mathrm{Z}/\gamma*(\mu\mu)+\mathrm{jets}$ CRs is performed

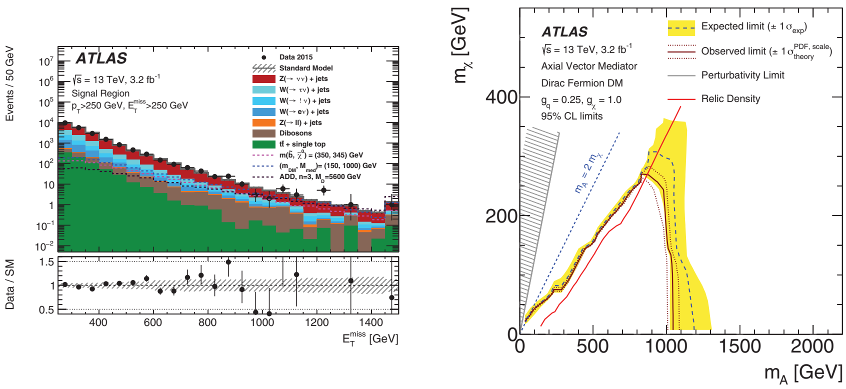

Fig. 2. – Left: Measured distribution of the $E_{\mathrm{T}}^{\mathrm{miss}}$ compared to the SM predictions in the SR of the ATLAS mono-jet analysis [5]. Right: 95% CL exclusion contours in the m_χ-m_{A} parameter plane, where A is an axial-vector mediator. The region excluded due to perturbativity is indicated by the hatched area.

to normalize and constrain the corresponding background estimates in the SRs. Fits are performed separately in 7 inclusive regions, and in 6 exclusive regions in $E_{\mathrm{T}}^{\mathrm{miss}}$. In the latter, normalization factors are considered separately in each exclusive $E_{\mathrm{T}}^{\mathrm{miss}}$ region. Good agreement is observed between data and the SM expected backgrounds, and translated into upper limits for the presence of DM pair-production, assuming the exchange of an axial-vector mediator in the s-channel, as shown in fig. 2.

3. – Hadronic mono-V

A search for DM produced in association with a hadronically-decaying W or Z boson has been presented by the ATLAS Collaboration using 3.2 fb^{-1} [6]. The final state probed by this search consists of a boosted, hadronically-decaying W or Z boson recoiling against pair-produced DM particles, manifesting in the detector as a single, large-radius (large-R) jet, high $E_{\mathrm{T}}^{\mathrm{miss}}$, and no leptons. Three jet definitions are employed. “Large-R” jets, with $p_{\mathrm{T}} > 200$ GeV, reconstructed with the anti-k_{T} distance parameter $R = 1.0$, are classified as originating from a Z or W boson using a p_{T}-dependent selection on the jet mass and the jet substructure variable D^2. “Small-R” jets with $R = 0.4$ are used to reduce background events from multi-jet processes. “Track jets”, reconstructed with $R = 0.2$, are finally used to identify events containing b-hadrons. The SR definition requires $E_{\mathrm{T}}^{\mathrm{miss}} > 250$ GeV, at least one large-R and veto on electrons or muons. Three CRs are defined with no significant contribution from signal. Events with exactly two muons are selected in order to define the Z boson CR. Events with one muon and no b-tagged track jets are selected for the W boson CR, and those with one muon and at least one b-tagged track jet for the top-quark CR. In the CRs the hadronic recoil is defined by removing the muon p_{T} from the $E_{\mathrm{T}}^{\mathrm{miss}}$ to mimic the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the SR. A profile-likelihood fit to the $E_{\mathrm{T}}^{\mathrm{miss}}$ in the SR and the hadronic recoil in the CRs is performed to constrain the primary backgrounds and extract the signal strength for the DM production. Besides the signal strength, three overall normalization factors for the W boson, Z boson, and top-quark backgrounds are free parameters in the fit. No deviation from SM predictions are observed, and the results are translated into limits on the signal strength for the vector-mediated DM production, shown in fig. 3.

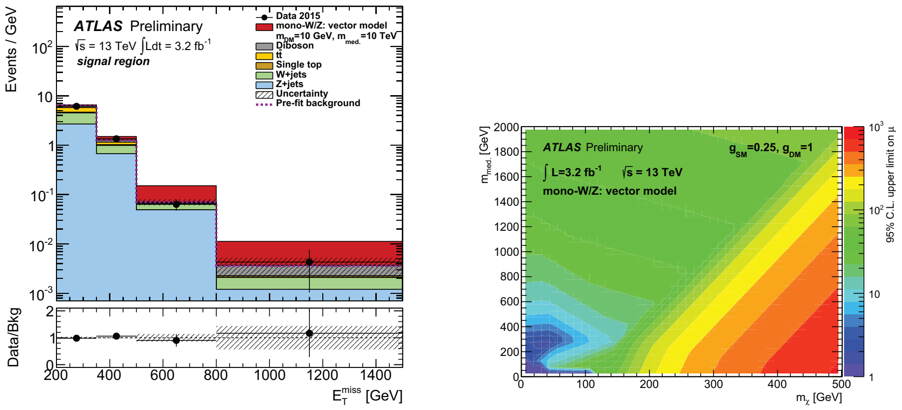

Fig. 3. – Left: The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution of the events in the SR of the ATLAS mono-V analysis [6] after the profile-likelihood fit. The signal expectation for the vector-mediated simplified model with $m_\chi = 10\,\mathrm{GeV}$ and $m_{\mathrm{med}} = 10\,\mathrm{TeV}$ is shown on top of the background. The total background before the fit is shown as a dashed line. Right: Limit at 95% CL on the signal strength, μ, of the vector-mediated simplified model in the plane of the DM particle mass, m_χ, and the mediator mass, m_{med}.

4. – Mono-photon

A search for DM in events with an energetic photon and large $E_{\mathrm{T}}^{\mathrm{miss}}$ has been presented by the ATLAS experiment for proton-proton collisions corresponding to an integrated luminosity of $3.2\,\mathrm{fb}^{-1}$ [7]. Events are selected using a trigger requiring at least one photon candidate with $p_{\mathrm{T}} > 120\,\mathrm{GeV}$. For the events to enter the SR, the $E_{\mathrm{T}}^{\mathrm{miss}}$ is required to be larger than 150 GeV and the leading photon in the event must satisfy tight identification requirements and have $p_{\mathrm{T}} > 150\,\mathrm{GeV}$. To increase the signal acceptance and reduce systematic uncertainties related to the modeling of initial-state radiation, one jets is allowed in the event. Events with more than one jets or with one jet close in azimuthal angle with the $E_{\mathrm{T}}^{\mathrm{miss}}$ are rejected. A lepton veto is also applied to reject events arising from W and Z processes. The SM background in the SR is dominated by the $\mathrm{Z}(\nu\nu)\gamma$ process, with secondary contributions from leptonic $\mathrm{W}\gamma$ and $\mathrm{Z}\gamma$ decays. Three CRs are defined to control the normalization of the W, $\mathrm{Z}\gamma$ backgrounds, by inverting the lepton veto of the SR and selecting events with exactly 2 muons, 2 electrons, and 1 muon, respectively. The $\gamma + \mathrm{jets}$ background in the SR, consisting of events where the jet is poorly reconstructed or partially lost, is estimated from a region selected using similar criteria as in the SR by requiring $85 < E_{\mathrm{T}}^{\mathrm{miss}} < 110\,\mathrm{GeV}$. Finally, contributions from processes in which an electron is misidentified as a photon are estimated by scaling yields from a sample of $e + E_{\mathrm{T}}^{\mathrm{miss}}$ events by an electron-to-photon misidentification factor measured with mutually exclusive samples of di-electrons and $\gamma + e$ events in data. Only single-bin SR and CRs are considered in the final fit to data: no shape information within these regions is used. The final number of events observed in data is found to be consistent with the predictions from SM backgrounds sources and the results are therefore interpreted in terms of exclusion limits in simplified DM production models with an axial-vector mediator, shown in fig. 4.

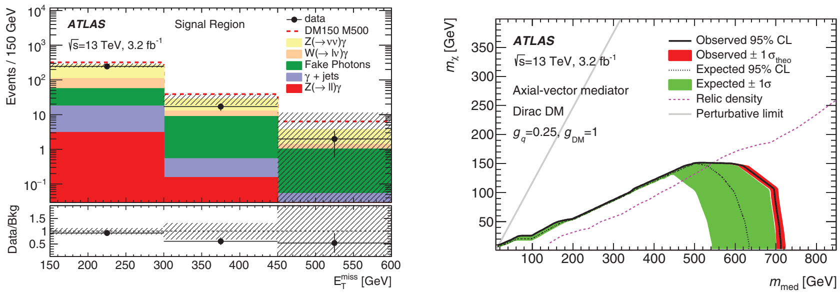

Fig. 4. – Left: Distribution of $E_{\mathrm{T}}^{\mathrm{miss}}$ in the SR of the ATLAS mono-photon analysis [7] for data and for the background predicted from the fit in the CRs. Right: The observed and expected 95% CL exclusion limit for DM production involving an axial-vector operator as a function of the DM mass m_χ and the axial-mediator mass m_{med}.

5. – Heavy flavor

The CMS Collaboration carried out a measurement of DM produced in association to heavy flavor (HF) quarks, where both bottom and top quarks are considered, using a dataset of 2.1 fb^{-1} [8]. Events are selected by $E_{\mathrm{T}}^{\mathrm{miss}}$ triggers with 90 GeV threshold, and required to have an offline $E_{\mathrm{T}}^{\mathrm{miss}} > 200$ GeV. To reduce electroweak backgrounds events a lepton veto is applied, and to minimize the multijet contribution all the jets selected in the event are required to be well separated from the $E_{\mathrm{T}}^{\mathrm{miss}}$. Two exclusive categories are defined in the SR, based on the number of b-tagged jets in the event. The first category, requiring one b-jet with $p_{\mathrm{T}} > 50$ GeV and allowing for an additional (non-b) jet of $p_{\mathrm{T}} > 30$ GeV, is mainly populated by DM + $\mathrm{b\bar{b}}$ signal; a second category requires instead two b-jets and allows for a third (non-b) jet, and is introduced to recover part of the efficiency of the DM production in association to top quarks. In addition to the SM background processes $\mathrm{Z}(\nu\nu)$ + jets and $\mathrm{W}(\ell\nu)$ + jets, this analysis is also sensitive to the $\mathrm{t\bar{t}}$ production enhanced by the b-tagging requirements. The normalizations of

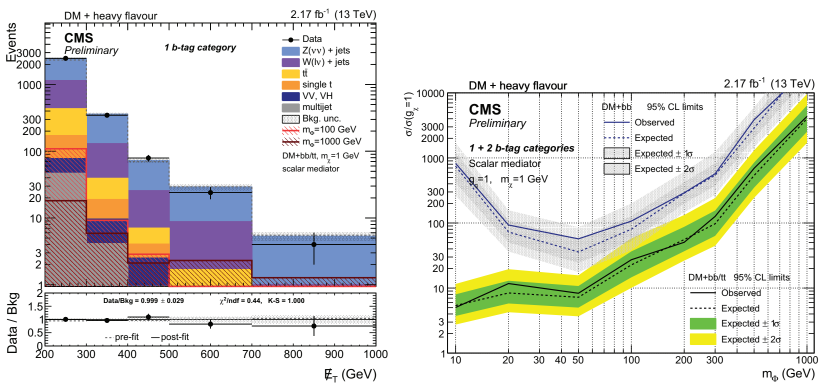

Fig. 5. – Left: Observed and expected events in single b-tag SR category of the CMS DM+heavy flavor analysis [8]. Right: Observed and expected exclusion limits with 1σ-, 2σ- uncertainty bands for the combination of the two categories as a function of the mass of a scalar mediator. The DM candidate is assumed to have a mass equal to 1 GeV.

the $Z(\nu\nu)$ + jets, $W(\ell\nu)$ + jets, and top-quark production processes are extracted from 10 CRs defined with isolated leptons. Double-electron and double-muon categories are used to extract the normalization of the $Z(\nu\nu)$ + jets background, whereas the top-quark normalization is extracted in an almost pure leptonic $t\bar{t}$ selection accepting events with two opposite sign, different flavor isolated leptons. To obtain the normalization of the $W(\ell\nu)$ + jets process, two single-lepton (e, μ) categories are defined, where also the semileptonic $t\bar{t}$ background contribution is not negligible. Minor contributions from other SM backgrounds are estimated from the appropriate simulated samples. The signal strength is finally extracted through a combined fit to the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the SR and the 10 single-bin CRs. The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution after the fit procedure is performed, shown in fig. 5 for the single b-jet category, is found in agreement with the SM predictions. The results are then translated into limits on the signal strength for the scalar- and pseudo-scalar mediated DM production in association with heavy flavor quarks.

6. – Conclusions

Searches for evidence for DM production in proton-proton collisions collected during the first LHC Run-2 phases at the ATLAS and CMS Collaborations at CERN have been reported. The ATLAS and CMS DM searches covered a wide range of final states all involving topologies with large $E_{\mathrm{T}}^{\mathrm{miss}}$ and additional objects as jets, photons, hadronic-decaying vector bosons, and heavy flavor quarks. The observed data are found in excellent agreement with the SM expectations and the results are interpreted in terms of the DM production cross section using simplified models. The results are also translated in terms of upper limits on the DM-nucleon cross section, to compare with direct detection experiments, resulting in the strongest experimental bounds on the low DM mass regions.

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