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# Search for Dark Matter Pair Production with CMS

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**On behalf of the CMS collaboration**

Dark matter particles may be produced in pp-collisions at the LHC with their interaction with standard model particles being described by an effective field theory. The pair-produced dark matter cannot be detected directly but rather through radiation of a single jet/photon or the observation of a recoiling W- or Z-boson. The CMS collaboration has performed searches for dark matter using 20 $fb^{-1}$ of pp collision events at sqrt(s)= 8TeV with a single jet and single lepton in the final state. The search strategy and results are described in this paper.

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## 1. The dark matter model

The production of dark matter (DM) at the LHC can be described by an effective field theory (EFT), assuming a contact interaction between Standard Model (SM) particles and DM. Such an approach allows to probe different models, while being specific enough to make predictions. A summary of the models can be found in [1-4]. The characterizing parameters are the scale of the effective interaction $\Lambda = M(\text{Messenger})/\text{sqrt}(g_\chi g_q)$ and the mass of the dark matter candidate $M_\chi$. Different assumptions for the coupling with DM are possible, the most prominent ones being:

- spin-independent vector coupling (V) $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\chi \quad \xi_i\bar{q}_i\gamma_\mu q_i$
- spin-dependent axial-vector coupling (AV) $\frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma^5\chi \quad \xi_i\bar{q}_i\gamma_\mu\gamma^5 q_i$

In pp collisions DM particles may be produced in pairs and cannot directly be detected. They would rather contribute to missing transverse energy (MET) which can also be created by neutrinos or other weakly interacting particles. Therefore, their detection has to be based on additional particles (see Fig.1) - the emission of a single photon or a single jet as initial state radiation or through a recoiling particle, such as a W- or a Z-boson. For the latter, recently the channel W→lν, with l being an electron or muon, has been studied by CMS [5] using the full 2012 pp dataset at sqrt(s)=8 TeV [6] based on the strategy outlined in [4]. The same dataset was used for searches in the monojet final state [7].

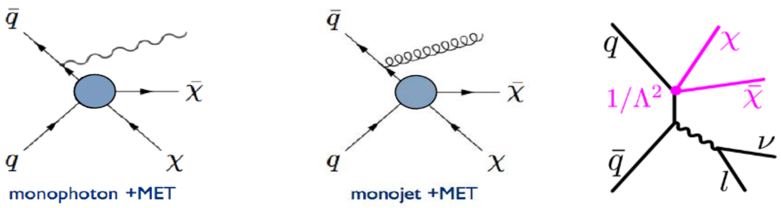


*Fig.1: Feynman Graphs for mono-X plus MET search channels. Radiation of a single photon (left) or a single jet (middle) from initial state. On the right, recoil of a W-boson with a subsequent leptonic decay.*

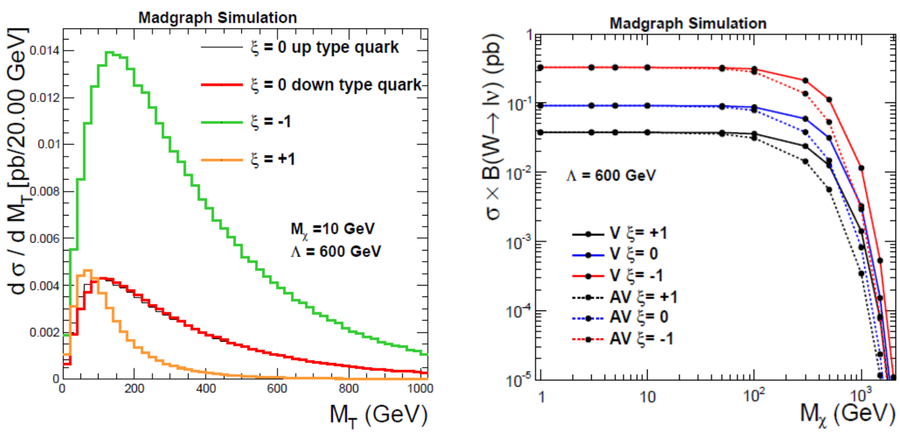


*Fig.2: Left: Signal shapes at generator level for different interference cases, parametrized by ξ=+1,0,-1. Right: production cross sections in leading order from Madgraph for these interference scenarios and the two types (vector and axial-vector like) of couplings.*

The nature of the DM coupling results in interference for the monolepton channel. The coupling to the up- or the down-type quark with their relative coupling strength can be parametrized by the factor $\xi$. The considered values of $\xi$ are 0, +1, -1, following ref. [4], with +1 for destructive and -1 for constructive interference, respectively. The factor $\xi$ could modify either the up or down-type quark couplings, resulting in the same interference behaviour. These configurations are shown in Fig. 2 for $\Lambda$ = 600 GeV. The interference changes the total cross section and steepens the spectrum (Fig.2-left). The different shape of the spectrum has an impact on the sensitivity. While the very high end of the transverse mass spectrum is nearly background free, at lower masses the small signal has to be separated from background. The total production cross section scales with $\xi$ as seen in Fig.2-right.

## 2. Event selection

For the monojet search data from two triggers were used, either MET > 120 GeV or a jet-MET cross trigger with jet transverse momentum ($p_T$) above 80 GeV within $|\eta| < 2.6$ along with MET > 105 GeV. To suppress instrumental and beam-related backgrounds, events are rejected if less than 20% of the energy of the highest $p_T$ jet is carried by charged hadrons or more than 70% of this energy is carried by either neutral hadrons or photons.
The analysis is performed in seven regions of MET (see Fig.3-left). The most energetic jet ( j1) is required to have $p_T$( j1) > 110 GeV and $|\eta| < 2.4$. Events with more than two jets with $p_T$ > 30 GeV and $|\eta| < 4.5$ are rejected. As signal events typically contain jets from initial- or final-state radiation, a second jet ( j2) is allowed, provided $\Delta\phi$( j1, j2) < 2.5 in order to suppress QCD dijet events. The dominant backgrounds after the complete selection has been applied are from $Z(\nu\nu)$ and W+jet events. These are estimated from data samples of $Z(\mu\mu)$ and$W(\mu\nu)$ events.

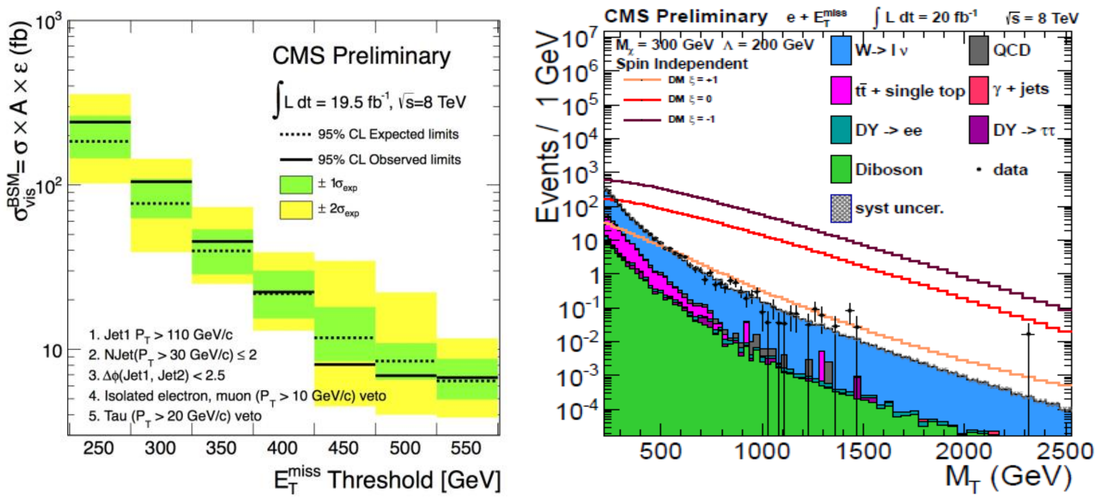


*Fig.3: Left: MET distribution after all selections with the seven search regions in the monojet channel. Right: Transverse mass distribution for one the monolepton search channels (electron+MET).*

In the monolepton channel, candidate events with at least one high transverse momentum lepton are selected using single-muon (with offline $p_T$>45 GeV) and single-electron (with offline $p_T$>100 GeV) triggers. The lepton reconstruction is optimized for high $p_T$ [8]. The main observable is the transverse mass ($M_T$) of the lepton-MET spectrum, calculated as $M_T = \sqrt{2 \cdot p_T \cdot MET \cdot (1 - \cos \Delta\phi_{l,\nu})}$ where $\Delta\phi_{l,\nu}$ is the azimuthal opening angle between the charged lepton's transverse momentum and MET. The main background is W→lν (see Fig.3) which is used with a $M_T$-binned k-factor for higher order QCD and electroweak corrections. Other backgrounds are Z/DY, ttbar, multi-jet QCD and di-boson processes, all are derived from simulation using NLO cross sections (except QCD). In order to suppress backgrounds, events exhibiting a back-to-back kinematics are selected, requiring the ratio of lepton $p_T$ and MET to be in the range $0.4<p_T/MET<2$ and the angle between both to be $>0.8\pi$. The resulting $M_T$ distribution for the example of the electron channel is shown in Fig.3.

## 3. Excluded cross sections and translation into DM-nucleon plane

No significant excess was observed in data and limits on the production are set. For the monojet channel, the limit of potential new physics ($\sigma_{BSM}$) is shown on the left of Fig.3 for the seven search bins in MET. For the monolepton channel the limits are shown in Fig.4, separately for the two couplings (V, AV) and the three cases of interference ($\xi$ = +1,0,-1). Following a similiar behaviour of the production cross sections (see Fig.2), limits are nearly independent on the coupling and depend on $M_\chi$ only for approximately $M_\chi$>100 GeV. Since the absolute cross section scales with $\xi$, the monolepton limits in Fig.4 scale accordingly. All monolepton limits are a combination of the e+MET and μ+MET channels.

The effective theory is valid for heavy mediator masses, up to values of $\Lambda < 2\, M_\chi$ [2]. The monojet analysis also considered the case in which the mediator is light enough to be accessible to the LHC, see [7] for details.

Since direct detection experiments measure the potential recoil of DM on nuclei, their limits are given in the DM-nucleon plane. To compare their results to LHC searches, the latter have to be transformed into that plane, as a function of Λ and $M_\chi$. The excluded pp cross sections are translated into a limit on the parameter Λ (see following table) and subsequently a nucleon-DM limit is derived.

To translate the vector operator limits into the DM-nucleon spin-independent plane, a coefficient ($f_q^N$) relating the nucleon and the quark content is introduced. For the axial-vector operator into the spin-dependent plane the sum of quark helicities ($\Delta_q^N$) is introduced. Along with the lambda value summarized the following table, the following two equations are used [8] with μ being the reduced mass of the nucleon:

| Channel | Lambda limit for $M_\chi$ < 100 GeV |
|---|---|
| l+MET $\xi$ = +1 | 300 GeV |
| l+MET $\xi$ = 0 | 700 GeV |
| l+MET $\xi$ = -1 | 1000 GeV |
| Jet + MET | 900 GeV |

*Spin independent*

$$\sigma_{SI} = \sum_q \frac{\mu^2}{\pi \Lambda^4} \cdot \left(f_q^N\right)^2$$

*Spin dependent*

$$\sigma_{SD} = \sum_q \frac{3\mu^2}{\pi \Lambda^4} \cdot \left(\Delta_q^N\right)^2$$

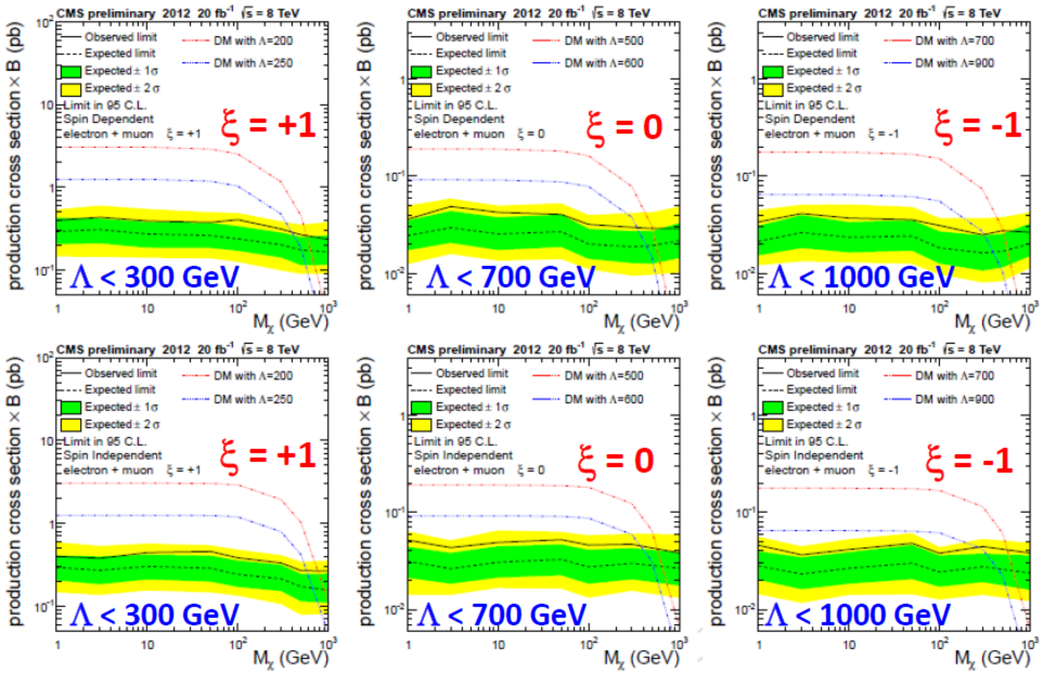


*Fig.4: Excluded cross sections in the monolepton channel, for vector (upper row) and axial-vector (lower row) couplings for the three cases of $\zeta$=+1,0,-1.*

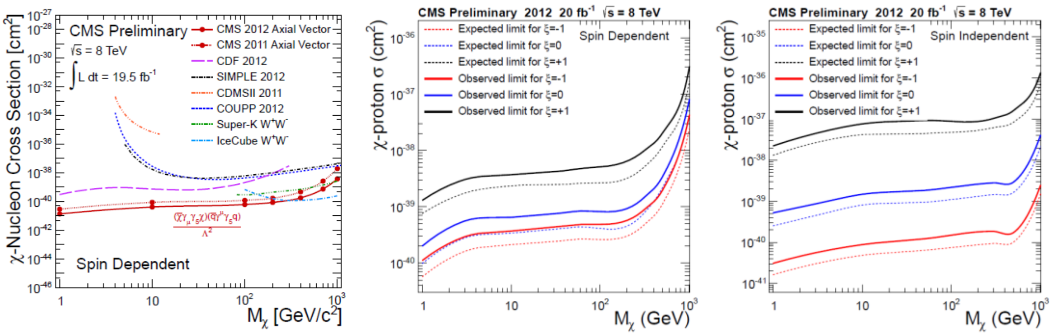


*Fig.5: Resulting DM-nucleon limits. On the left, the monojet channel showing the limit in comparison to some direct detection experiments. Limits from the monolepton channel for the three interference cases for spind dependent (middle) and spin independent (right).*

The resulting limits are shown in Fig.5. Masses $M_\chi$<10 GeV are only accessible by the LHC. As seen in Fig.2 for the monolepton channel (similar for the monojet channel), the DM production cross section steeply decreases for DM masses above ~500 GeV due to the limited phase space necessary to produce a pair of DM particles plus a real W-boson. Therefore the sensitivity drops for high masses (or high Λ).

## 4. Summary

Complementary to direct searches, DM may be pair-produced in pp collisions at the LHC. Searches have been performed by CMS in the final states with a single jet + MET and single lepton (e, μ) + MET using the full 2012 dataset. No excess in data was found and exclusion limits on the pp production cross section for different scenarios in terms of couplings and interference are placed. They have been transformed into the DM-nucleon plane to be compared to direct detection experiments. Very low DM masses (<10 GeV) are only accessible by the LHC.

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