DARK MATTER SEARCHES AT THE LARGE HADRON COLLIDER

A.E. Basalaev, Yu.G. Naryshkin

Petersburg Nuclear Physics Institute of National Research Center "Kurchatov Institute", Gatchina, Russian Federation

One of the promising lines of investigation at the Large Hadron Collider (LHC) is a search for dark matter particles. Despite a large body of evidence for dark matter existence, its nature remains unknown. The leading hypothesis is that dark matter consists of weakly interacting massive particles. Collider searches for such particles are most sensitive in the case of spin-dependent interactions, and for the low masses of dark matter particles in the case of spin-independent interactions. The strategies of dark matter searches at the LHC are described, and upper limits on dark matter-nucleon cross-sections based on the experimental data collected in 2015 and 2016 by the ATLAS and CMS collaborations are presented in comparison with the results of other experiments. In conclusion, the perspectives of further searches of dark matter at the LHC are discussed.

Key words: dark matter; LHC; ATLAS; CMS; WIMP; dark matter associative production; mono-*X*

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Introduction

One of the major challenges for the experiments at the Large Hadron Collider located at the European Center for Nuclear Research (CERN, Switzerland) is the search for dark matter particles. Dutch astronomer Jacobus Kapteyn was the first to hypothesize in 1922 that such a substance exists, based on the results of studying rotational velocities of galaxies [1]. The term "dark matter" gained wide circulation after the publication of Fritz Zwicky's works [2].

Some of the current astrophysical observations indicate the existence of dark matter. These include the study of the rotational velocities of galaxies [3], gravitational lensing [4], the structure of the Bullet cluster [5], etc. The theory of primary nucleosynthesis predicts that the distribution of chemical elements in the universe is in good agreement with the observed baryon matter [6]; this implies that the nature of dark matter is non-baryonic. Analysis of the distribution of irregularities in the cosmic microwave background also points to the presence of non-baryonic dark matter [7].

Massive astrophysical compact halo objects (MACHOs) are regarded as potential dark matter formations. Studies of gravitational microlensing [8, 9] exclude the contribution from these objects with masses in the range from $0.6 \cdot 10^{-7}$ to 15 $M_{\odot}$ ($M_{\odot}$ is the mass of the Sun) as possible dark matter formations. According to recent estimates, dark matter comprises about 26.8 % of the total mass-energy of the Universe, while the fraction of baryonic matter does not exceed 5 % [10].

Even though a substantial amount of indirect evidence that dark matter exists has been accumulated, it has not yet proved possible to establish its nature. Attempts to construct modified gravity theories were made to explain this phenomenon but they all faced significant difficulties in interpreting all the available experimental data [11]. To date, the main hypothesis is that dark matter consists of weakly interacting massive particles (WIMPs) [12], which interact with matter only through gravity and some kind of weak interaction.

Dark matter particles appear in some extensions of the Standard Model. For example, the neutralino (Lightest Supersymmetric Particle, LSP) is one of the possible dark matter particles in the minimal supersymmetric extension of the Standard Model [13]. Sterile neutrinos [14] and axions [15] are also considered as candidates for dark matter particles. A detailed review of the particles suitable for the role of dark matter objects can be found in [16].

At the present time, various experiments are under way to find dark matter particles. These are direct, indirect and collider experiments.

The effects of dark matter particles interacting with target nuclei are studied in experiments on direct search for dark matter particles [17 – 19]. A detailed review of direct experiments can be found in [20]. Typically, such studies are performed in laboratories located deep underground (to reduce background radiation), for example, at the Gran Sasso National Laboratory (Italy).

Indirect experiments on searching for dark matter particles study the effects associated with annihilation of dark matter particles and antiparticles, with a particle and an antiparticle of the Standard model (for example, electron-positron or proton-antiproton pairs) forming as a result [21, 22]. The ratio of the number of particles to the number of antiparticles is measured in these experiments as a function of energy. Comparing the measured spectra with the computation results obtained for radiation from known cosmic objects allows to draw conclusions about the existence of dark matter. Another branch of indirect experiments is measuring the gamma radiation flux; if the measured value exceeds the expected one, it indicates the annihilation of particles with antiparticles of dark matter [23].

The third type, collider experiments, are concerned with searching for dark matter particles produced as a result of annihilation of the quarks and antiquarks. The search for such particles is performed by detecting deviations of the experimental spectra from the predictions of the Standard Model.

To date, some studies have obtained confirmations that dark matter particles might exist. For example, the DAMA experiment [24] studied the scattering of dark matter particles by target nuclei. For this purpose, the spectrum of recoil nuclei was measured for several years. It is assumed that our galaxy is in a cloud of dark matter. Since the Sun moves at a speed of 220 km/s relative to the center of the galaxy, and the Earth, revolving around the Sun at a speed of 30 km/s, moves at different speeds relative to the center of the galaxy in different time periods, the frequency of dark matter particle interactions with the target nuclei is different. As a result of the observations, annual modulations of the signal from scattering of particles by nuclei were found at a level of 9.3 standard deviations, which can be explained by the scattering of dark matter particles by the target nuclei.

Another experiment, AMS-02, involved measuring the energy spectra of cosmic positrons and antiprotons. The data of these measurements differ from the computational results describing the interaction of cosmic rays with the interstellar medium but are in good agreement with the models predicting the existence of dark matter particles with a mass of 1 TeV.

Nevertheless, in order to draw definitive conclusions about the existence of dark matter particles, it is necessary to exclude the contribution of radiation from additional sources such as pulsars. The energy spectrum of positrons in the high-energy region above 1 TeV should be studied for this purpose, which in turn requires more data expected to be obtained by 2025.

This paper presents a review of the studies on the search for dark matter particles (WIMPs) carried out by the ATLAS and CMS collaborations at the Large Hadron Collider in 2015–2016 with the energy of proton-proton interactions $\sqrt{s} = 13$ TeV.

Collider experiments

The first collider searches for dark matter particles were performed at the Tevatron accelerator of the Fermi Laboratory in proton-antiproton interactions in the CDF [25] and DШ [26] experiments with the energy $\sqrt{s} = 1,96$ TeV.

The CDF experiment involved analysis of the data on associative production of dark matter particles and the *t*-quark. As a result, the upper limits established for the cross-section for the production of dark matter particles were 0.5 pb (picobarn) for the masses of dark matter particles in the range of 0 – 150 GeV/c^2.

In the DШ experiment, data were analyzed with the goal of finding a light gauge boson, the so-called 'dark photon' γ_D, which is predicted by the minimal supersymmetric extension of the Standard Model (MSSM). Data analysis did not reveal the dark photon γ_D but helped establish the limits for its production cross-section.

Since the start of experiments at the Large Hadron Collider, the searches for dark matter particles of dark matter have been going in several directions. Collider experiments study the production of dark matter particles as a result of annihilation of quarks and antiquarks, but the dark matter particles themselves are not caught by the detector. In view of this, events producing these particles can only be detected for processes where additional particles are generated. For example, a force-carrying particle is formed in the so-called mono-*X* channel during annihilation of a quark and an antiquark, which then breaks up into dark matter particles. Before the quark and the antiquark annihilate, one of them emits either a photon (γ), a *Z* or *W* boson, or a gluon, which can be registered by the detector. The Feynman diagram for emission of a gluon in the initial state, followed by the formation of a jet, is shown in Fig. 1, *a*.

Associative production of dark matter particles (Fig. 1, *b*) is accompanied with the production of $b\bar{b}$ или $t\bar{t}$ pairs of quarks with subsequent formation of hadronic jets. A Higgs boson can form in the associative production of dark matter particles, instead of a pair of quarks.

Another option is directly searching for a force carrier mediating the interactions between the Standard Model and the dark matter particles, by recording its decay to particles of the Standard Model (Fig. 1, *c*).

So-called model-independent analysis using effective field theory [27] or simplified models [28] is used to interpret the experiments at the LHC. It is assumed that dark matter particles are Dirac fermions.

Effective field theory describes the point interaction of two particles (a quark and an antiquark), with the subsequent production of a dark matter particle and an antiparticle. There are two parameters in this description of the field: the mass of the dark matter particle (antiparticle), and the parameter

$$\Lambda^2 = M^2 / (g_\chi \cdot g_q),$$

where M is the mass of the mediator (force carrier); g_χ and g_q are the coupling constants between the mediator and the dark matter particles and quarks, respectively. This parameter characterizes the strength of the interaction between the Standard Model and the dark matter particles.

This approach is valid only if the mass of the mediator is greater than the momentum transferred, i.e., $M >> Q$. Since collision energy at the Large Hadron Collider has been increased to 13 TeV, this condition is often violated, and effective field theory has very limited applications at present; for this reason, simplified models in which this condition does not have to be fulfilled are used.

Simplified models consider a dark matter particle (and an antiparticle), as well as the mediator of the interactions between the Stan-

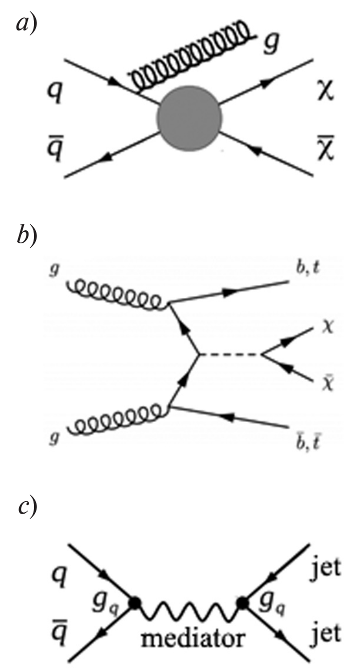


Fig. 1. Feynman diagrams for production of dark matter particles at the Large Hadron Collider: mono-X channel *a*, associative birth *b*, search for a mediator+ particle *c*

dard Model and the dark matter particles. The masses of the dark matter particles m_χ and of the mediator m_η are given as parameters. The lifetime Γ (the decay width) of the mediator and its coupling constants with the Standard Model and dark matter particles (g_q and g_χ) are also used as parameters. Thus, the simplified model involves five parameters.

Data analysis is performed in the so-called signal region where the contribution of signal events is the greatest compared to the background. This region is selected based on the procedure for optimizing the selection of useful events. Both signal and background events obtained by the Monte Carlo simulations are used for optimization. The contribution of background processes, including the processes of the Standard Model, can be estimated by different methods based both on Monte Carlo simulations and on experimental data. Methods for estimating the background via the experimental data are used when Monte Carlo simulation cannot yield reliable estimates because the event generator is insufficiently accurate in describing the process and there are additional uncertainties related both to the description of the experimental setup and the response function of the detector. Such estimates typically have large systematic uncertainties. The MadGraph event generator is used to simulate the production of dark matter particles [29]. Different types of mediators are considered in simplified models: vector, axial-vector, scalar and pseudo+scalar, with different sets of coupling constants and in a wide range of particle masses [30]. Criteria of statistical significance are used for the final choice of the signal region, i.e., the one with the maximum contribution of signal events. The measured spectra are compared with the spectra of background processes in this region.

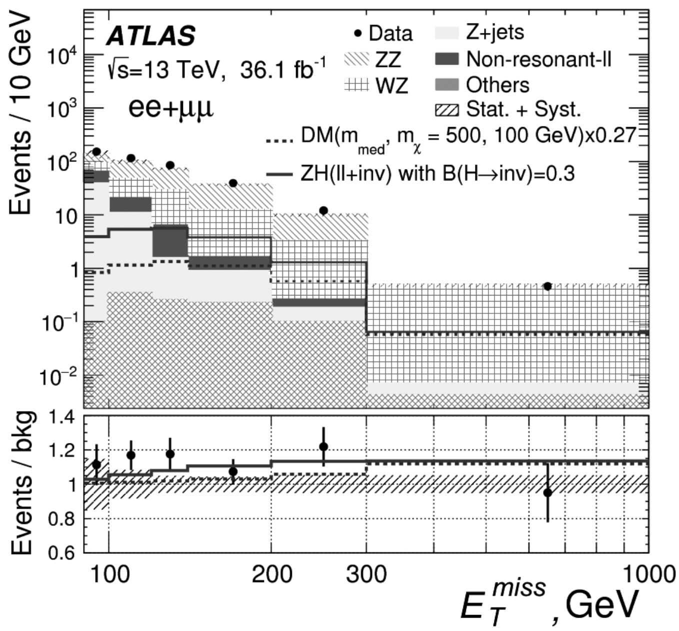
Searches in the mono-*X* channel

As stated above, an additional $Z(W)$ boson, a photon or a jet is detected in the mono-X during the search for dark matter particles [31 – 33]. For example, a Z boson is produced in the mono-Z process; it can be detected by its decay to an electron and a positron, a muon and an anti-muon, or a quark-antiquark pair with the formation of two jets. The main background process in this case is the production of two Z bosons (ZZ), one of them decaying to detectable particles (electrons, muons or hadrons), and the second into neutrinos. It is impossible to separate the signal and background processes of the production of a Z boson pair by means of kinematic variables. The contribution of this process in the signal region was estimated by Monte Carlo simulation. The contribution of the second largest process that is the simultaneous production of a W and a Z boson was estimated by a method based on using experimental data. The contribution from other background processes is much less than those mentioned above and was estimated using other methods based on experimental data.

Fig. 2, *a* shows the measured spectrum of the missing transverse energy E_T^{miss} for the mono-Z process after the final selection of events in the signal region, obtained for the integral luminosity of 36.1 (fb)$^{-1}$ in the ATLAS experiment. Events with $E_T^{miss} > 90$ GeV were considered to reduce the background contribution from the production of Z bosons with jets. As can be seen from Fig. 2, the experimental spectra are in good agreement with the estimates of background events within statistical and systematic errors. The dashed line indicates the result of signal simulation for a dark matter particle with a mass m_χ = 100 GeV and a mediator with a mass m_{med} = 500 GeV, scaled with a coefficient of 0.27. Fig. 2, *b* shows the restrictions on the mass of a dark matter particle as a function of the mediator mass during the decay of the Z boson to a pair of electrons or muons, obtained in the ATLAS experiment by analyzing the data for the axial-vector model of the mediator and the coupling constants equal to g_q = 2.5 and g_χ = 1.0. The range of particle masses falling inside the solid line was excluded [31]. Similar results were obtained in the CMS experiment [34]. The search for dark matter in mono-X processes with the emission of W or Z bosons in the initial state with decay to hadrons is discussed in [35].

Associative production of dark matter particles

Associative production means that one or two particles are additionally produced along with dark matter particles. For example, the *a*)



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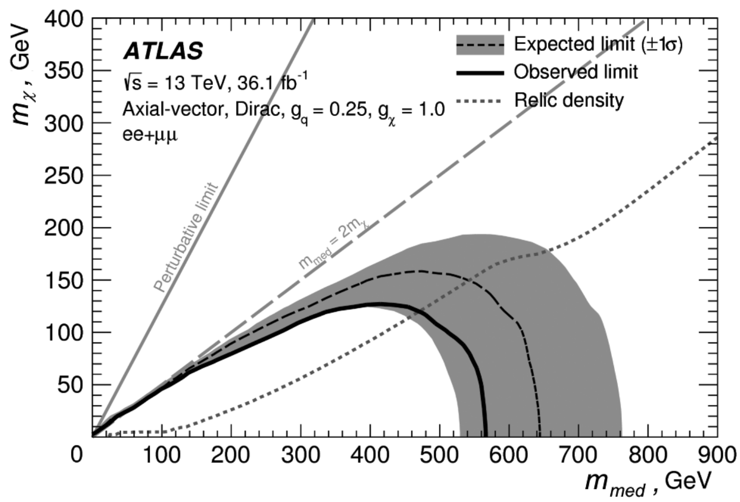


Fig. 2. Results of the search for dark matter particles of the mono-*Z* process (the ATLAS experiment, $\sqrt{s}$ = 13 TeV): *a* are the distributions over the missing transverse energy E_T^{miss} for the combined *ee* and μμ channels; *b* are the expected and observed limits for the masses of the mediator and the dark matter particle.

the black dots in (*a*) indicate the data, histograms show the results of the estimation of various background processes, diagonal hatching indicates the full systematic error, the dotted line indicates the simulation results of the signal events for m_c = 100 GeV and m_{med} = 500 GeV

production of a scalar or pseudo-scalar mediator that decays to dark matter particles is accompanied by the production of $b\bar{b}$ or $t\bar{t}$ quark pairs, with subsequent jet hadronization (see Fig. 1, *b*). In this case, the presence of two *b* or *t* quark jets is a mandatory condition for selecting signal events. The main background processes are the following:

the production of a *Z* boson and two jets, followed by the decay of the *Z* boson to two neutrinos;

processes with the production of $b\bar{b}$ and $t\bar{t}$ quark pairs.

Fig. 3 shows the upper limits for the cross-

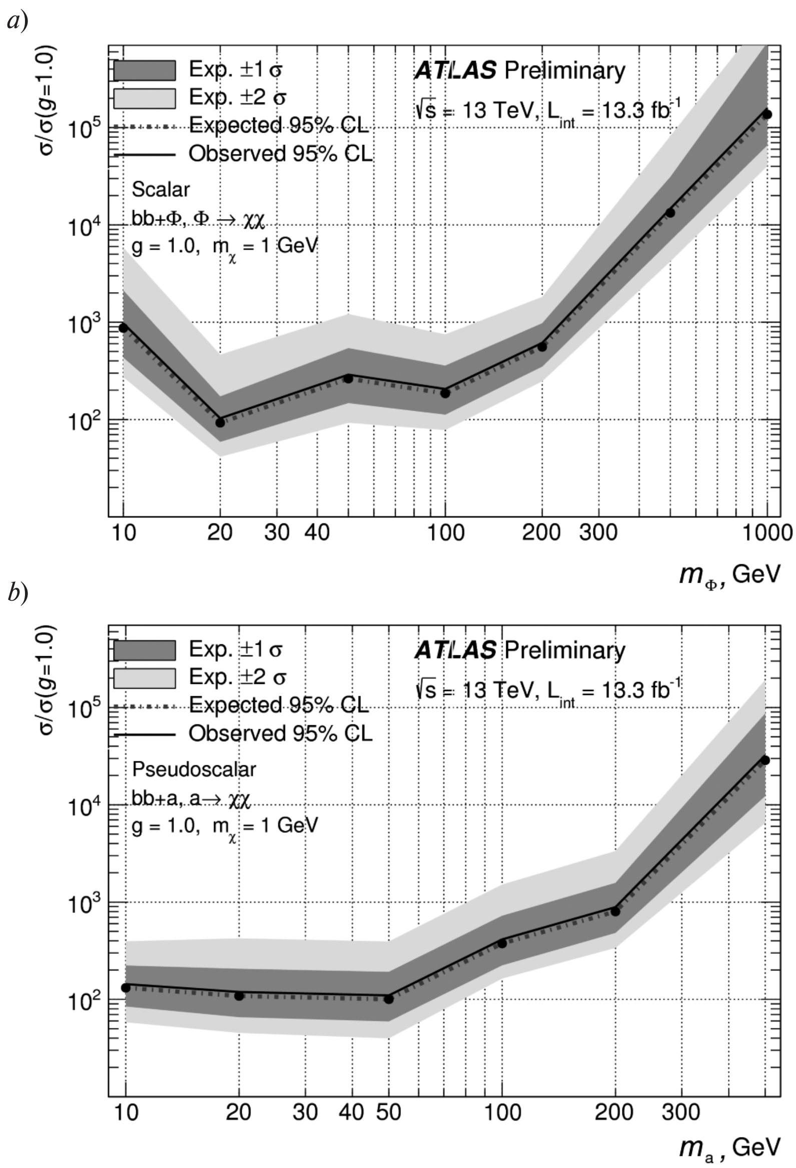


Fig. 3. The expected and observed limits (confidence interval 95 %) for the cross-sections of the production of dark matter particles, depending on the mediator mass, for the cases of scalar (*a*) and pseudoscalar (*b*) mediators.
The computations were performed for the mass of a dark matter particle equal to 1 GeV; $g_q = g_\chi = 1.0$. The data of 2015 – 2016 were analyzed; the integrated luminosity was 13.3 (fb)$^{-1}$ for an energy in the center-of-mass system $\sqrt{s} = 13$ TeV [36]

section of the production of dark matter particles in the mass range from 10 GeV to 1 TeV, obtained in the ATLAS experiment [36], for the case of a scalar mediator with masses in the range of 10 – 1000 GeV and for a pseudoscalar interaction carrier with masses in the range of 10 – 400 GeV, depending on the mass of the dark matter particle, with the coupling constant $g_q = 1$. The results were obtained by analysis of the 2015 – 2016 data at an integrated luminosity of 36.1 (fb)$^{-1}$.

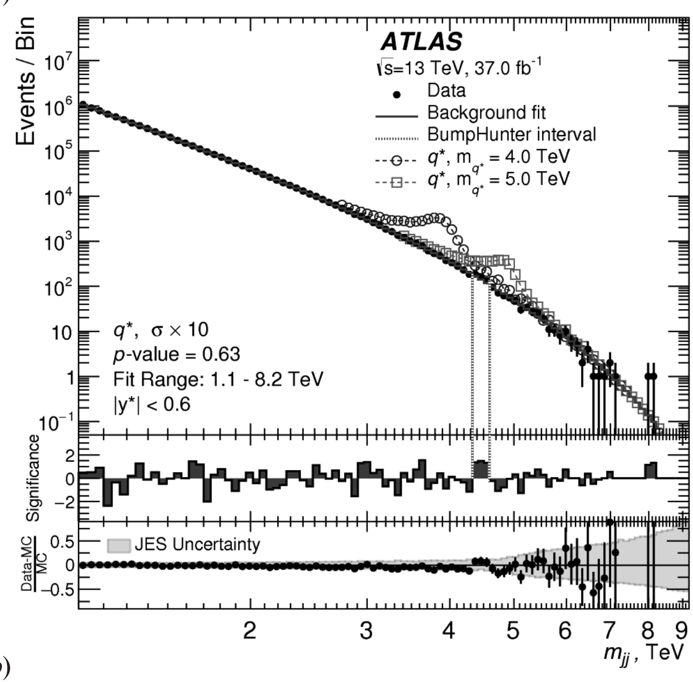
Other options of associative production of dark matter particles are also explored. For example, some extensions of the Standard Model predict the production of a heavy vector boson *Z'*, with subsequent decay to dark matter particles [37], or into two Higgs bosons: a light neutral *h* and a CP-odd pseudo-scalar neutral

A^0 followed by the decay of A^0 to dark matter particles, $A^0 \to \chi\bar{\chi}$ [38]. Dark matter particles can also be produced in the decay of a heavy CP-even neutral Higgs boson H [38].

Search for the mediator

The mediator of the interaction between the Standard Model and the dark matter particles can also decay to Standard Model particles, for example, quarks with the formation of jets in the final state. Notably, direct searches for the mediator are possible only in collider experiments. There are different models for the interaction mediator, for example, a heavy

a)



b)

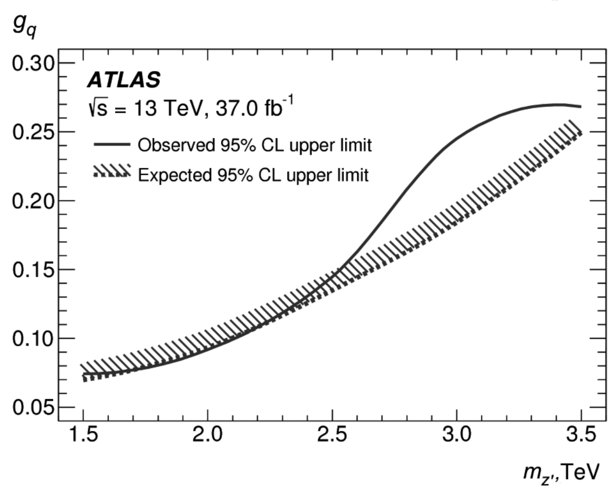


Fig. 4. Results of the studies on the direct search for a dark matter mediator (the ATLAS experiment for two-jet events): a are the spectra for invariant mass for the data, the background and the signal events; b are the obtained limits (confidence interval 95 %) for the constant g_q depending on the mass of the intermediate particle (the model of the Z' mediator is described in [41])

The bottom part of Fig. 4, *a* shows a comparison of the experiment with Monte Carlo simulation results; the solid bar is the systematic error vector leptophobic boson Z', which has either a small coupling constant with leptons [39], scalar or pseudo-scalar particles, or a colored scalar mediator [40]. Fig. 4, *a* shows the distribution over the invariant mass m_{jj} for two jets, obtained in the ATLAS experiment [41]. The circles in the figure indicate the results of simulation of signal events for mediators with masses of 4 and 5 GeV. The solid curve indicates the result of approximating the background distribution. It can be seen from the figure that the data are in good agreement with the predictions of the Standard Model for the region considered.

The obtained limits for the value of the coupling constant between the mediator and the Standard model particles depending on the mediator mass $m_{Z'}$ are shown in Fig. 4, *b*. The cross-section for a fixed mass increases with increasing g_q, and thus the range of values on the left and above the curve is excluded.

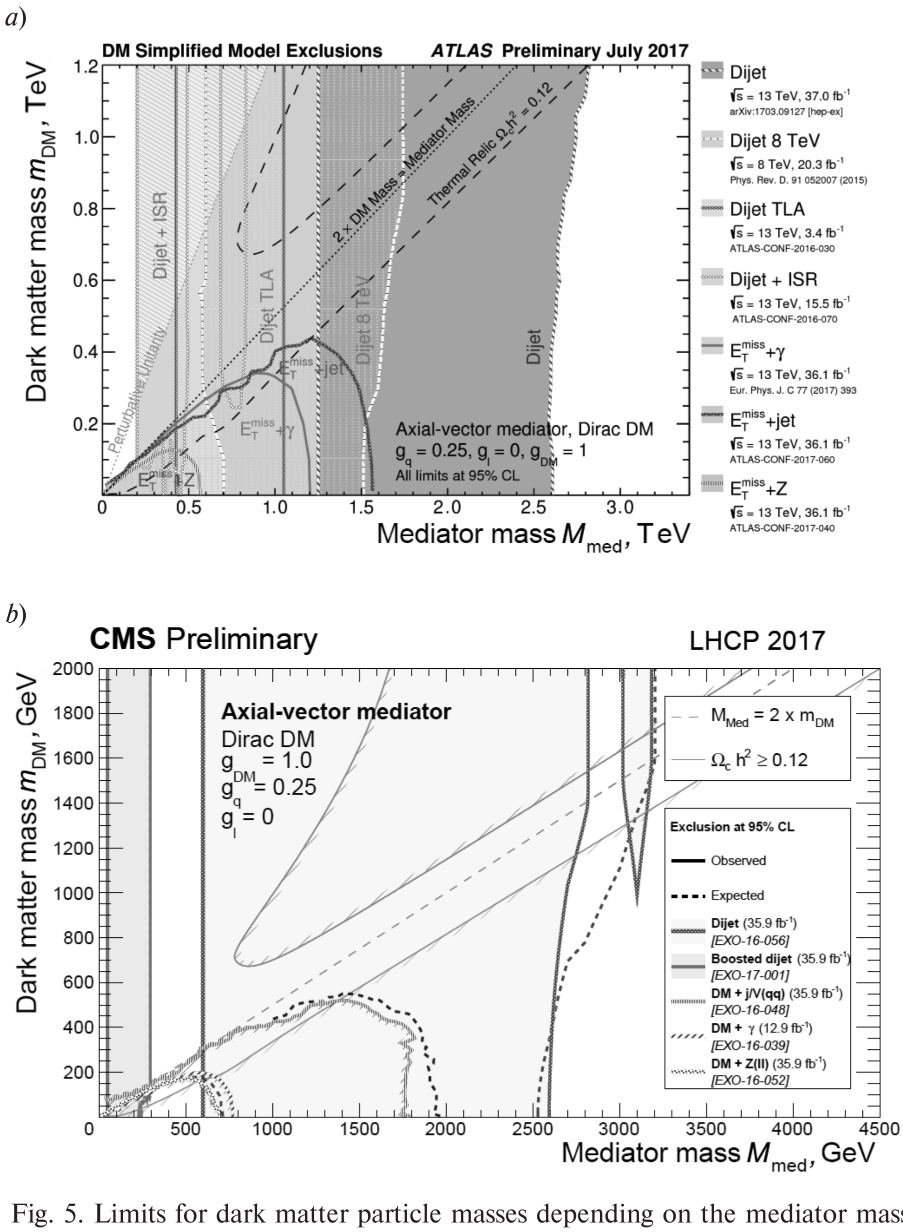


Fig. 5. Limits for dark matter particle masses depending on the mediator mass, obtained in the ATLAS (*a*) and CMS (*b*) experiments.
The coupling constants between the mediator and dark matter particles g_χ = 1.00 and between the mediator and quarks g_q = 0.25 were used in the computations (the same for all types of quarks and for the axial-vector mediator)

The results of collider experiments and discussion

The limits for the masses of dark matter particles and the axial-vector mediator obtained in the ATLAS and CMS experiments for the mono-X processes, the associative production of dark matter particles and the searches for the mediator particle are shown in Fig. 5 with the coupling constant between the mediator and the Standard model particles $g_q = 0.25$ and between the mediator and the dark matter particles $g_\chi = 1.00$. It follows from the data given that the strongest restrictions on the mediator mass are obtained in analysis of

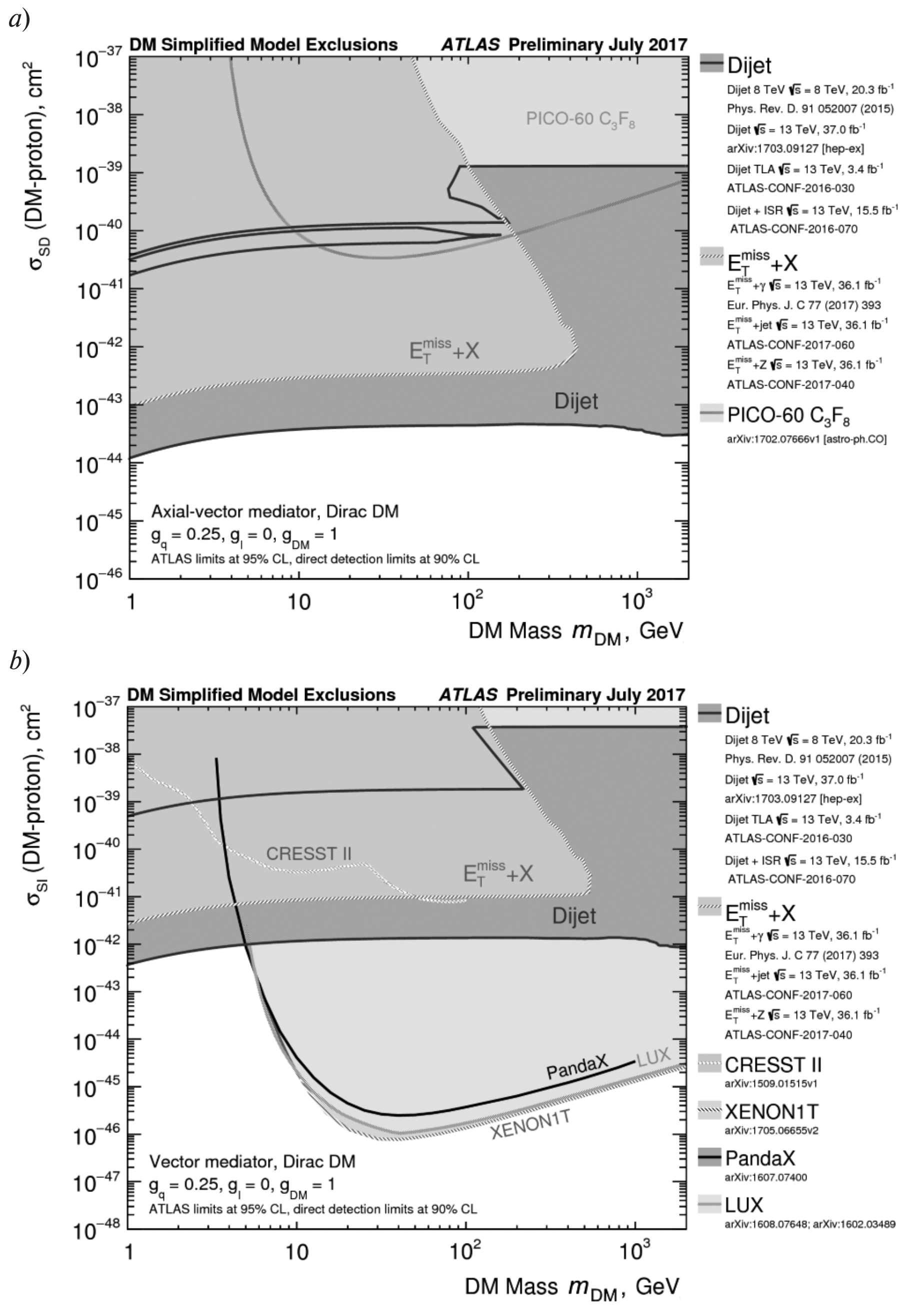


Fig. 6. Comparison of the results obtained in the ATLAS experiment with the results of direct measurements for spin-dependent (*a*) and spin-independent (*b*) cross-sections. Comparison with the experiments of the PICO (*a*) and CRESST, XENON1T, LUX and PandaX (*b*) experiments

two-jet events.

Fig. 6 shows the comparison of the results obtained at the LHC in the ATLAS experiment with the results of direct search experiments. Both spin-dependent and spin-independent interactions have been compared. The figure shows the upper limits for the cross-sections of the interaction of dark matter particles as a function of their mass, obtained in the ATLAS experiment by analysis of two-jet events: [41 – 44] and in the mono-*X* channel [31 – 33], including a comparison with the results of direct search experiments: CRESST [45], XENON1T [46], PICO [47], LUX [48] and PandaX [49]. It follows from Fig. 6 that collider experiments are more sensitive than direct searches for dark matter particles (PICO, LUX) in case of spin-dependent interactions. The results of direct search experiments with spin-dependent interactions (PandaX) are more sensitive for dark matter particle masses above 6 GeV.

Conclusion

To date, numerous studies have been conducted to search for dark matter particles in different channels in the ATLAS and CMS experiments at the Large Hadron Collider. Model-independent analysis was used to interpret the results, with different hypotheses for the mediator (vector, axial-vector, scalar and pseudoscalar). A wide range of possible masses from 10 GeV to 1 TeV was analyzed for both dark matter particles and the mediator. No deviations from the predictions of the Standard Model were discovered, with upper limits found for the cross-sections for the production of dark matter particles and for the masses of dark matter particles, depending on the force carrier mass. The obtained limits for the cross-sections were compared with the results of direct search experiments for spin-dependent and spin-independent interactions: CRESST, XENON1T, PICO, LUX, and PandaX. The upper limits established for the cross-sections of the production of dark matter particles in experiments at the Large Hadron Collider for the case of spin-dependent interaction turned out to be lower than for direct measurement experiments; in other words, the experiments at the collider were more sensitive. At the same time, the experiments conducted at the Large Hadron Collider for spin-independent cross sections make it possible to analyze the range of masses of dark matter particles less than 6 GeV, and this option is not available in direct measurements.

It is expected that a data corresponding to an integrated luminosity of about 120 $(\mathrm{fb})^{-1}$ will be accumulated during the second period of data collection at the Large Hadron Collider. That is 4 times higher than the current integral luminosity used for the results presented. It is proposed to use, among other models, an extension of the Standard Model including an additional doublet of the Higgs bosons, the 2HDM model, to interpret the data [50]. In addition to the limits for the cross-sections depending on the mass of dark matter particles and the mediator, it is proposed to establish limits for the model parameters, for example, the ratio of the vacuum means of two Higgs fields $\mathrm{tg}\beta$ and the mixing angle α.

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THE AUTHORS

BASALAEV Artyom E.
Petersburg Nuclear Physics Institute of National Research Center "Kurchatov Institute"
Orlova Roscha, Gatchina,
188300, Leningrad Oblast, Russian Federation
artem.basalaev@cern.ch

NARYSHKIN Yuriy G.
Petersburg Nuclear Physics Institute of National Research Center "Kurchatov Institute"
Orlova Roscha, Gatchina, 188300, Leningrad Oblast, Russian Federation
yury.naryshkin@cern.ch