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Search for dark matter in events with missing transverse momentum and hadronic jets with the ATLAS experiment at the LHC and HL-LHC

G. Frattari
Dipartimento di Fisica, Sapienza Università di Roma and INFN, Sezione di Roma - Rome, Italy

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Summary. — Several cosmological observations hint at the existence of dark matter, whose particle nature is still unknown. The study of events with a highly energetic jet and large missing transverse momentum in proton-proton collisions at the Large Hadron Collider (LHC) plays an important role in the search for weakly interacting massive particles, which are natural dark matter candidates. The most recent results obtained by the ATLAS experiment using Run-2 data, corresponding to an integrated luminosity of 36 fb^{-1}, are shown, including the projection for the expected discovery potential for the Run-3 and high-luminosity phase of the LHC.

1. – Introduction

Among open questions in physics, the nature of dark matter (DM) is one of the most fascinating and yet far to be solved. Its existence is proven by many experimental observation of the cosmos [1], such as rotational curves of galaxies and unexpectedly strong gravitational lensing. These observations hint at the existence of a kind of matter which seems to interact only gravitationally with ordinary matter. One of the most credited hypotheses implies a particle nature for DM, which could have been produced in high-energy collisions in the early ages of the universe and today appears as a relic. Assuming masses in the range between the GeV and TeV scale, the measured abundance of dark matter in the universe yields to interaction cross-sections with ordinary matter of the scale of the electroweak interaction. This kind of particles are called WIMPs (χ), weakly interacting massive particles.

The searches for WIMPs are categorized as direct, indirect and collider searches. The indirect ones look for the annihilation of pairs of χ particles into Standard Model ones, which could happen in high energy density environments, such as in the nuclei of galaxies. Direct searches try to catch the signal from the scattering of WIMPs with radiation-free targets in underground experiments. The third approach, subject of this talk, are the collider searches: pairs of WIMPs can be produced in high-energy collisions between protons at the LHC. The WIMPs, due to their low interaction cross-section, escape the detection of general-purpose experiments. It is therefore necessary to develop a specific search strategy which exploits the kinematics of the collisions.

2. – Dark matter search with the ATLAS experiment at the Large Hadron Collider

ATLAS [2] is a general-purpose experiment which detects the particles produced in the proton-proton collisions provided by the LHC. During the Run-2 of the machine the centre-of-mass energy was 13 TeV, with a peak instantaneous luminosity of $2 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. The detector is built with a cylindrical symmetry around the beam pipe and at the centre of it the nominal interaction points of the bunch of protons are located. The most inner detector, immersed in an axial magnetic field of 2 T, is made of tracking layers used to identify the interaction point and measure the track momentum by their curvature. The electromagnetic and hadronic sampling calorimeters are used to measure the energy of most of the particles, while muons are detected by means of layers of muon chambers, immersed in a toroidal magnetic field to allow the measurement of muons momentum by their curvature.

The initial state momentum of the protons is only along the axis of the experiment, so the kinematic of the interactions is closed in the transverse plane. This feature is exploited in the search for WIMPs, since in the process $pp \to \chi\chi + X$ only the X part of the final state is detected, leading to a transverse momentum imbalance in the event. In a hadron collider the emission of a gluon from an initial state particle is likely to occur, which boosts the system of the invisible particles and gives rise to a sizeable imbalance of the transverse momentum (p_{T}) in the reconstructed final state. This makes the analysis of events with an energetic jet and large missing transverse momentum a golden channel to seek for WIMPs.

3. – Analysis strategy and results

The signature of the signal is the presence of an excess of events in the missing transverse momentum distribution, indicated as $E_{\mathrm{T}}^{\mathrm{miss}}$. This variable is built as the negative sum of the p_{T} of all the calibrated objects reconstructed in the event. Jets, muons, electrons, photons, plus an additional soft term evaluated from the tracks which are not associated with any of the previous objects and τ leptons (reconstructed as jets) are included in the $E_{\mathrm{T}}^{\mathrm{miss}}$ calculation. This signature can be mimicked by many Standard Model (SM) processes: it could arise in events with multiple jets, which could be misreconstructed and appear as unbalanced events. To build a sample of candidate events enriched in the expected signal, a missing transverse momentum trigger is used, which is fully efficient for $E_{\mathrm{T}}^{\mathrm{miss}} > 150\,\mathrm{GeV}$. Furthermore a threshold of 250 GeV of $E_{\mathrm{T}}^{\mathrm{miss}}$ is set and at least one jet with $p_{\mathrm{T}} > 250\,\mathrm{GeV}$ in the central part of the detector, $|\eta| < 2.4$, is required. Up to three more jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ are allowed, but a cut on the minimum azimuthal distance between any jet and the $E_{\mathrm{T}}^{\mathrm{miss}}$ at 0.4 is applied to minimize the contribution from multi-jet events. Electrons and muons vetoes are applied to reduce the electroweak backgrounds with real $E_{\mathrm{T}}^{\mathrm{miss}}$ (due to neutrinos), like the leptonic decaying W, but also Z+jets processes, with the Z decaying into two leptons.

The background composition after applying the aforementioned cuts, which define the signal region, is summarised in table I. The $Z(\to \nu\nu) +$ jets process is an irreducible background of the search since it has the same topology of the signal of interest.

TABLE I. – *Expected background composition of the signal region.*

Process	Type of background	Contribution
$Z(\to \nu\nu) + \text{jets}$	irreducible	54%
$W(\to l\nu) + \text{jets}$	reducible	37%
$t\bar{t}$ and single-t production	reducible	3%
$Z(\to ll)$ + jets and diboson production	reducible	3%
Multi-jet and other minor backgrounds	reducible	3%

To constrain the uncertainty on the number of expected background events in the signal region, a multi-control-region (CR) fit is performed. A single normalization factor common to all the V+jet ($V = W, Z$) processes, k_V, and a normalization factor for processes characterised by the presence of top quarks, k_t, are defined and are free parameters of the fit to the control regions. To emulate the kinematics of the $Z(\to \nu\nu)$ process a control region with two muons is defined by the SR cuts, but inverting the μ veto. Moreover, in those events the two muons are treated as an invisible particle, therefore they are not included in the calculation of the $E_{\mathrm{T}}^{\mathrm{miss}}$. This is done in order to be as close as possible to the $Z(\to \nu\nu) + \text{jets}$ process. Given that too few events were available in this CR, two new control regions enriched respectively in $W(\to e\nu) + \text{jets}$ and $W(\to \mu\nu) + \text{jets}$ processes are defined to improve the precision in the knowledge of the total background. Also in this case, if the lepton is treated as an invisible particle, a proxy for the $Z(\to \nu\nu) + \text{jet}$ process is obtained. To constrain the large systematic uncertainty which affects the top processes modelling in the phase space considered, a top CR is introduced with the same definition of the $W(\to \mu\nu)$ one, but requiring at least one b-jet.

A profile likelihood fit is performed to the $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions of the control regions, where theoretical and experimental uncertainties of the MC predictions are taken into account as Gaussian-constrained nuisance parameters fully correlated between the regions. In fig. 1 is reported the data to Monte Carlo comparison in the SR after performing a CR-only fit, showing a good agreement between the SM predictions and the observed data.

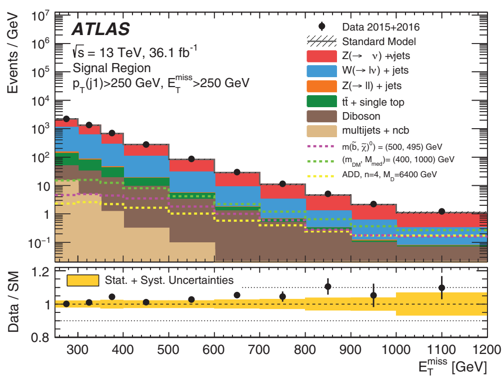

Fig. 1. – Comparison between data and MC simulation for the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in the signal region after performing the control regions fit [3].

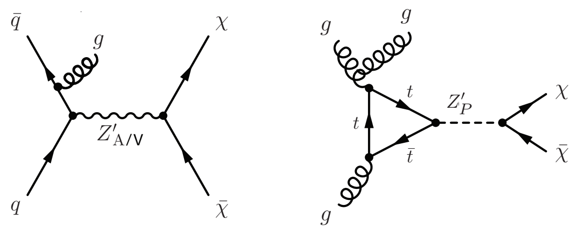

Fig. 2. – Feynman diagrams at the leading order for the signal processes [4].

The results can be translated into limits on the number of signal events. The simplified models tested predict the production of fermionic WIMP pairs trough a vector, axial-vector or pseudo-scalar mediator. For the vector and axial-vector cases, the interaction is similar to the one with the Z boson in the SM. The corresponding Feynman diagram is reported in fig. 2(left). For a pseudo-scalar mediator instead a Yukawa coupling is hypothesized, which introduces a top quark loop which suppresses the cross-section. The corresponding Feynman diagram is reported in fig. 2(right).

For the vector and axial-vector mediator models, the coupling between the dark matter mediator and the quarks, g_q, is fixed to 0.25, while the coupling to WIMPs, g_χ, is fixed to 1. For the pseudo-scalar mediator case, both couplings are set to 1. These values are arbitrary and are chosen accordingly to other dark matter searches, so the results depend on this choice. Several signal samples are tested for different values of the mass of the dark matter mediator (m_{med}) and of the WIMPs (m_χ), with the aim to draw an exclusion contour in the (m_{med}, m_χ) plane at 95% of confidence level (CL).

The $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution for the vector and axial-vector mediated interactions is expected to be harder than the SM backgrounds, so an excess in the high $E_{\mathrm{T}}^{\mathrm{miss}}$ regime is expected, while for the pseudo-scalar mediator the behaviour is opposite. The expected $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution is used to extract an upper limit for each tested signal model. The results obtained for an axial vector mediator are reported in fig. 3(left).

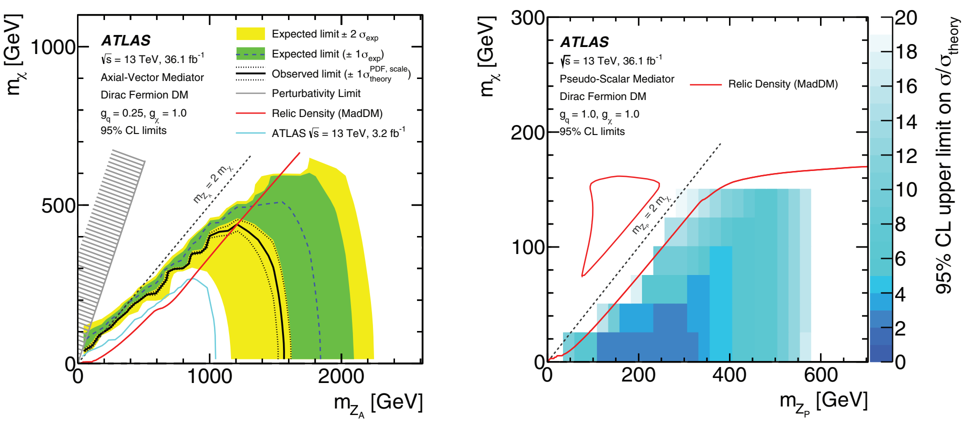

Fig. 3. – Contour plots in the (m_{Z_A}, m_χ) plane (left) and (m_{Z_P}, m_χ) plane (right) [3]. The red line indicates the values of the parameters for which the relic abundance of dark matter obtained equals the one measured today.

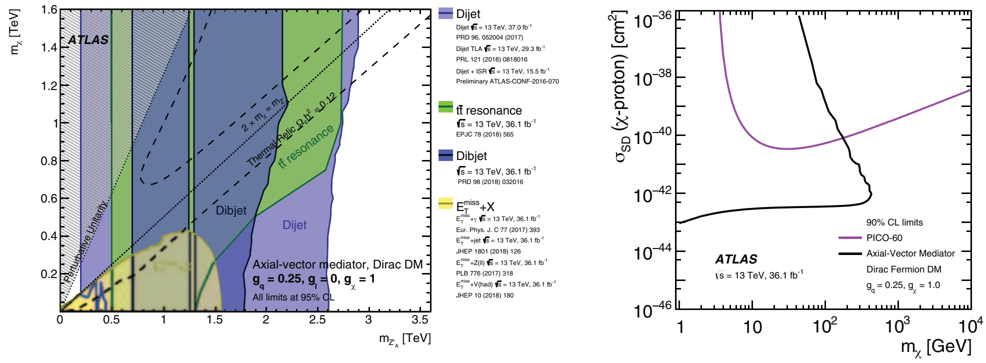

Fig. 4. – Comparison of the mono-jet results for an axial dark matter mediator with other searches in ATLAS [4] and reinterpretation of results in the WIMP mass-interaction cross-section plane [3] at 90% CL. The exclusion contour from the mono-jet search depends on the chosen values of the couplings g_q, g_χ.

With 36 fb^{-1} of data it is possible to exclude axial vector mediators with mass up to 1.6 TeV for light WIMPs, and χ particles of 400 GeV of mass for a 1.2 TeV dark matter mediator. In the off-mass-shell regime the decrease of the cross-section of the process is such that it is not possible to set a limit. For a vector mediator a similar exclusion contour is obtained. For a pseudo-scalar mediator the results obtained on the several models are reported in fig. 3(right). With the available statistics it is not possible to draw an exclusion contour in the mass-mass plane. This is due to two facts: the loop in the leading order diagram, which suppresses the cross-section of the process, and the fact that the signal significance is higher at low $E_{\mathrm{T}}^{\mathrm{miss}}$, where the signal-to-background ratio is lower. To be able to put a limit on those models, an increase in statistics could not be enough and a reduction of the missing transverse momentum threshold would be necessary.

The search strategy described above falls into the mono-X category, which is complementary to the resonant searches done by the ATLAS experiment. These searches look for a peak in the invariant mass distribution of two jets, or b-jets, seeking for the signal of a dark matter mediator decaying back into two SM quarks. Figure 4(left) shows how the two different kinds of searches are complementary.

The results obtained through the mono-jet search can be translated into a limit in the plane of WIMP mass and spin-dependent interaction cross-section. This expands the exclusion contour obtained through direct dark matter searches, which are limited for low m_χ by the small energies involved in the processes of recoil of target particles. The results are shown in fig. 4(right): the region for $m_\chi < 10$ GeV is covered by the mono-jet search, and extends the exclusion up to 10^{-42} cm^2 of WIMP-proton interaction cross-section. The limits shown are at 90% CL, a typical value reported by the direct searches of WIMPS.

4. – Prospects

Currently the LHC is in a shut down phase, preparing to Run-3 and the high-luminosity phase. The main upgrades of the machine will be the increase in the centre-of-mass energy, from 13 TeV to 14 TeV, and the increase in the instantaneous luminosity,

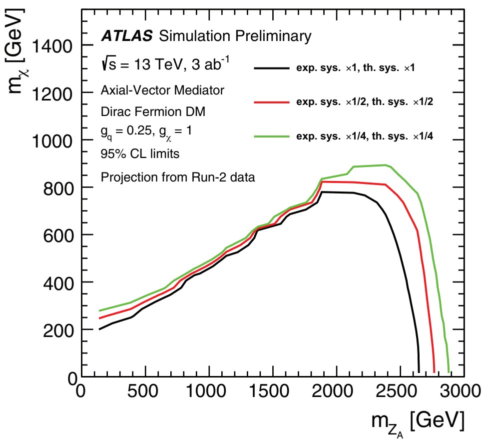

Fig. 5. – Expected exclusion contours for the mono-jet search with 3 ab^{-1} [5] obtained assuming the same level of systematic uncertainties of [3] and reducing at the same time both sources of uncertainty, theoretical and experimental, of a factor 2 and 4.

which will reach peak values up to $7 \cdot 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. This improvement will increase the pile-up, the number of overlapped proton-proton collisions, but will allow to collect more integrated luminosity. For the end of Run-3 the ATLAS experiment foresees $300\,\mathrm{fb}^{-1}$ of available statistics, while a total amount of 3 ab^{-1} is expected at the end of LHC phase-2. The $36\,\mathrm{fb}^{-1}$ mono-jet results have been extrapolated to the expected data amount available in these two scenarios [5]. For this study the model with an axial-vector mediator has been chosen as a benchmark model, and different scenarios regarding the systematic uncertainties affecting the measurement have been explored. To further exploit the shape of the signal in the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution, the binning has been extended up to 1.6 TeV, while in [3] it was limited to 1.2 TeV. In fig. 5 the expected contours for 3 ab^{-1} are shown in the scenarios in which the same performances of the 36 fb^{-1} results are reached (nominal scenario) and for the cases in which the a reduction of a factor 2 (4) of the systematic uncertainties is achieved. The major improvement comes from the reduction of the theoretical uncertainties affecting the prediction of V+jet processes, which is the main background of the analysis. In the nominal scenario the exclusion contour is extended from 1.6 TeV to up to 2.6 TeV for $m_{\chi} = 1\,\mathrm{GeV}$. For an axial-vector mediator with a mass of 2.1 TeV a maximum exclusion on the χ mass is reached, about 800 GeV.

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