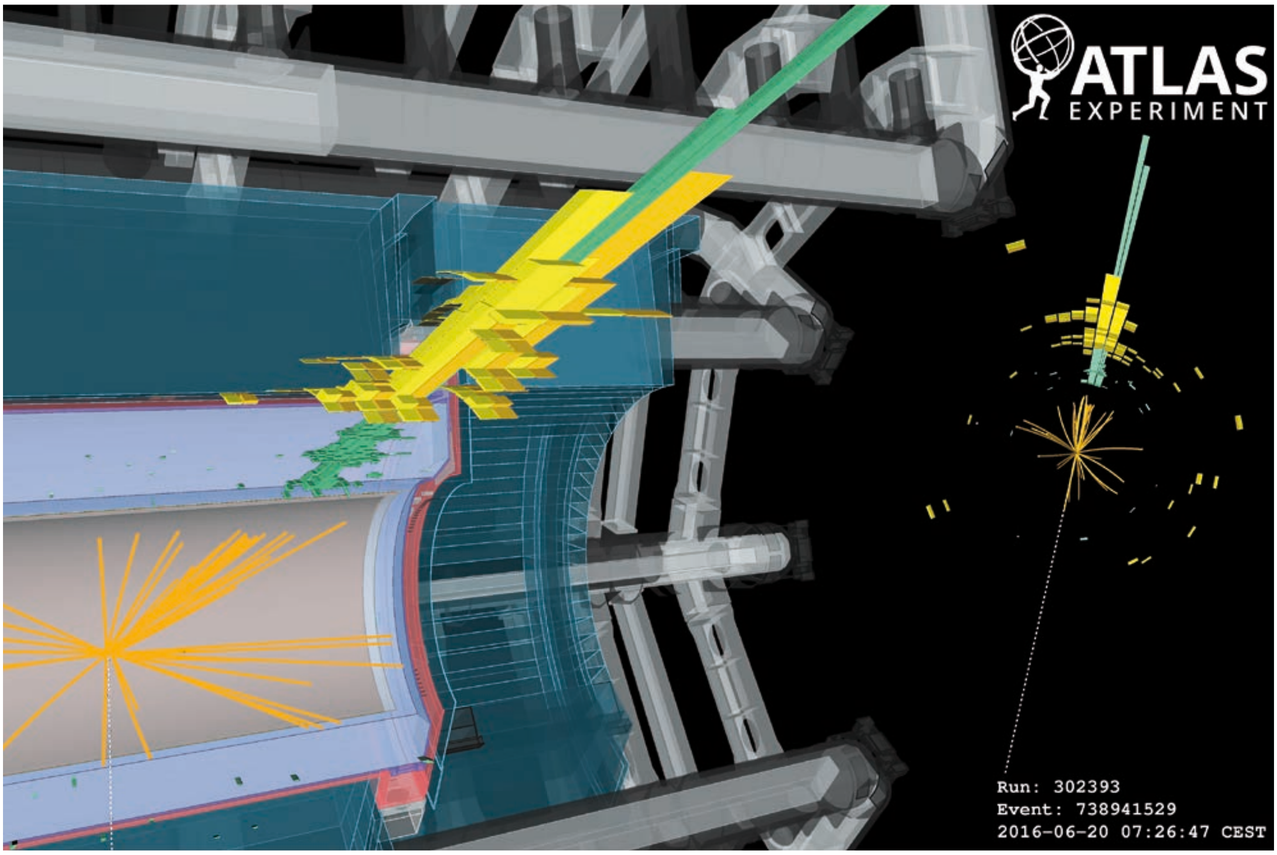


HERTHA-SPONER-PREIS

On top of Dark Matter

How to study Dark Matter from high-energy collisions and what is known so far.

Priscilla Pani

In the last century, high-energy physics has made incredible steps forward towards the comprehension of the nature of our universe, its matter content and interactions. This development culminated with the discovery of a Higgs boson by the Large Hadron Collider experiments completing the last piece of the particle puzzle. Nevertheless, the Standard Model of particle physics cannot explain the existence of Dark Matter yet. Uncovering the identity of this kind of matter is a central and grand challenge for both fundamental physics and astronomy.

The nature and properties of Dark Matter are largely unknown: proposed candidates span tens of orders of magnitude in mass, ranging from elementary particles infinitesimally lighter than electrons to massive primordial black holes [1]. One of the most compelling candidates is a new class of subatomic particles: weakly interacting massive particles (WIMPs). WIMPs represent the current paradigm for searches for Dark Matter particles. They are up to a hundred times heavier than protons and only interact weakly with ordinary particles. Presumably, they were produced in the early universe.

To understand Dark Matter is a multi-disciplinary effort involving different and complementary experimental techniques. Direct searches rely on the distribution of Dark Matter in the Milky Way exposing the Earth to a constant high flux of Dark Matter particles. Direct detection experiments aim to detect their elastic scattering off nuclei in specialised low background detectors. Indirect searches are based on the annihilations or decays of Dark Matter particles in astrophysical systems. Various ground and space-based specialised instruments monitor the frequency of such events. Collisions in high-energy particle accelerators like the Large Hadron Collider (LHC) might create particles which were present in the early universe. Therefore, Dark

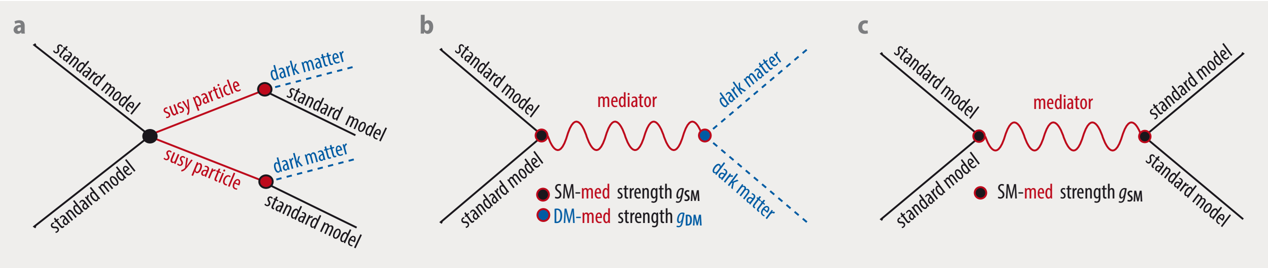


Fig. 1 Feynman diagrams of typical events occuring in the searches for Dark Matter particles: including supersymmetric particles (a) and based on a mediator model decaying into Dark Matter (b) and ordinary particles (c).

Matter particles could be produced and studied in a controlled laboratory environment.

These methods probe the characteristics of Dark Matter by exploiting different interactions between the particles of the Standard Model (SM) and Dark Matter (DM):

SM + DM → SM + DM	direct detection
DM + DM → SM + SM	indirect detection
SM + SM → DM + DM	collider searches

In case of a discovery, confirmation by all approaches will be mandatory to fully establish whether the new particle possesses all appropriate properties and interactions to be the final solution.

How to detect the invisible

If Dark Matter particles interact non-gravitationally with ordinary matter, they could be produced in the collisions of particle accelerators. To date, the LHC is the particle collider operating at the highest energy. Situated at CERN in Geneva, Switzerland, it has been taking data since 2009. Two machine runs took place from 2010 to 2012 (Run-1) and from 2015 to 2018 (Run-2), respectively. During Run-2, protons collided with a centre-of-mass energy of 13 TeV. At four interaction points through the LHC circumference, the general-purpose experiments ATLAS and CMS as well as the specialised experiments LHCb and ALICE collected the products of these collisions. The experimental programmes of ATLAS and CMS include a large variety of searches for Dark Matter candidates and their interactions.

Dark Matter particles would only be produced in pairs and pass through the detector without leaving any signal due to their extremely weak interaction cross section with ordinary matter. These “invisible” signatures are only detectable using momentum conservation. Collider experiments search for events where Dark Matter is produced in association with particles of the Standard Model. The proton momenta in the plane perpendicular to the beam axis add up to zero before the proton-proton collision. Due to momentum conservation, it remains zero afterwards as well. Therefore, Dark Matter and ordinary particles will be produced back-to-back in this plane. However, only the ordinary particles will be detected resulting in a characteristic momentum-imbalanced or missing energy signature as a clean fingerprint for Dark Matter.

To determine the production mechanism of Dark Matter, theoretical assumptions describe the interaction between particles of the Standard Model and Dark Matter. Thus, the results of a collider search depend on this theoretical model. However, despite being theoretically inspired, these searches are still experimentally designed to be as model-independent as possible.

Theoretical toolbox

Searches for Dark Matter at colliders aim to detect and identify the elusive particles using a data analysis technique designed for the specific theoretical framework in use. In order to extract information about the nature of Dark Matter particles from a non-discovery, this theoretical framework also serves as a tool for the interpretation of the results. Conventionally, exclusion limits on selected benchmark models are used to compare the results with the ones of direct and indirect searches. To date, most of the collider searches belong to two broad categories of models. Supersymmetry is based on a generalisation of space-time transformation

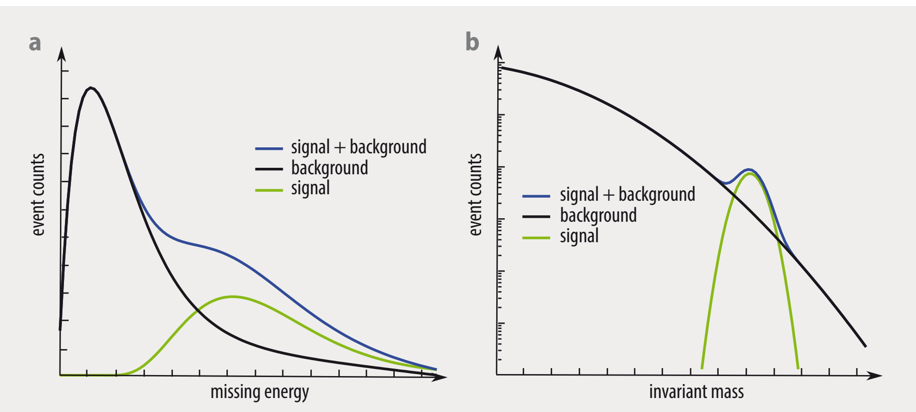


Fig. 2 The ratio of signal and background differs significantly between missing energy searches (a) and new resonance searches (b).

[2]. This model links fermions and bosons and predicts a zoo of new particles each being the supersymmetric partner of one of the known particles. In contrast, only one new particle provides the interaction in mediator-based models being the only link between the dark sector and the ordinary matter [3].

Due to their inherent theoretical complexity, both categories of models are benchmarked in terms of simplified models. This ansatz reduces the number of free parameters to a minimum of one Dark Matter candidate, one additional new particle or force and, possibly, one or two interaction couplings. This allows focussing on the different experimental fingerprints of the model rather than struggling with its complexity of parameters. In addition, it offers the scientific community a generic reinterpretation language to present and compare experimental results.

The main experimental difference stems from the nature and properties of the additional new particles producing the Dark Matter candidate (**Fig. 1**). In supersymmetry, the new particles are either fermions, both electrically charged or neutral ones, or bosons, most of them being coloured like quarks. They are always produced in pairs and each of them decays into one Dark Matter and one Standard Model particle. Conversely, in mediator-based models, the mediator is a charge-neutral state that can assume various spin properties and decays either in a pair of Dark Matter particles or in a pair of ordinary particles. Therefore, looking for new resonances with properties consistent with the ones of mediators is an important component of collider searches.

Given the plethora of different experimental fingerprints considered, the experimental programmes of ATLAS and CMS both include 20 to 30 "mini experiments" on Dark Matter. New theoretical ideas can inspire to perform additional searches with an extremely fast turn-around time for a new mini experiment. However, it is impossible to design the ultimate model-independent collider search: the infinite space of the possible models and parameters – despite being more and more constrained each year – will never be completely explored unless a Dark Matter candidate is finally found.

Experimental toolbox

Within these theoretical frameworks, colliders provide not only access to Dark Matter particles but also allow searching and investigating the particles which mediate the interaction. Therefore, the searches can be experimentally divided into two broad categories: missing energy searches and new resonance searches.

Missing energy searches rely on the precise measurement of the properties of ordinary particles in each event in order to infer the momentum of the Dark Matter particles. Obviously, these analyses are designed to look at a phase space enriched as much as possible in signal and depleted as much as possible in background (**Fig. 2a**). Naturally, all "invisible" particles – including neutrinos – contribute to the missing energy signature. Therefore, one of the important features of each analysis is to estimate the background stemming from particles which mimic Dark Matter. This is achieved using a semi-data driven technique: it exploits Monte Carlo-based simulations of all processes known in the Standard Model. The prediction is calibrated using carefully designed analysis regions. These regions should only contain or, at least, be enriched in the most important backgrounds. To reduce uncertainties, a very close location to the signal phase-space is desirable. All semi-data driven estimates are validated in dedicated phase-space regions which usually verify the reliability of the extrapolation.

New resonance searches use a different approach. If the interaction with an ordinary particle produces the mediator, it can decay back into final states which do not contain any Dark Matter. Therefore, the data analysis aims to detect a resonance: a Gaussian-shaped distribution situated on top of a smoothly decreasing background in the invariant mass distribution constructed from the four-momentum of two ordinary particles (**Fig. 2b**). These searches experimentally estimate the background in a data-driven way from the sideband(s) of the signal distribution.

Both types of searches target experimental signatures with a large variety of ordinary particles in the final states: jets originating from light quarks or gluons; so-called b jets

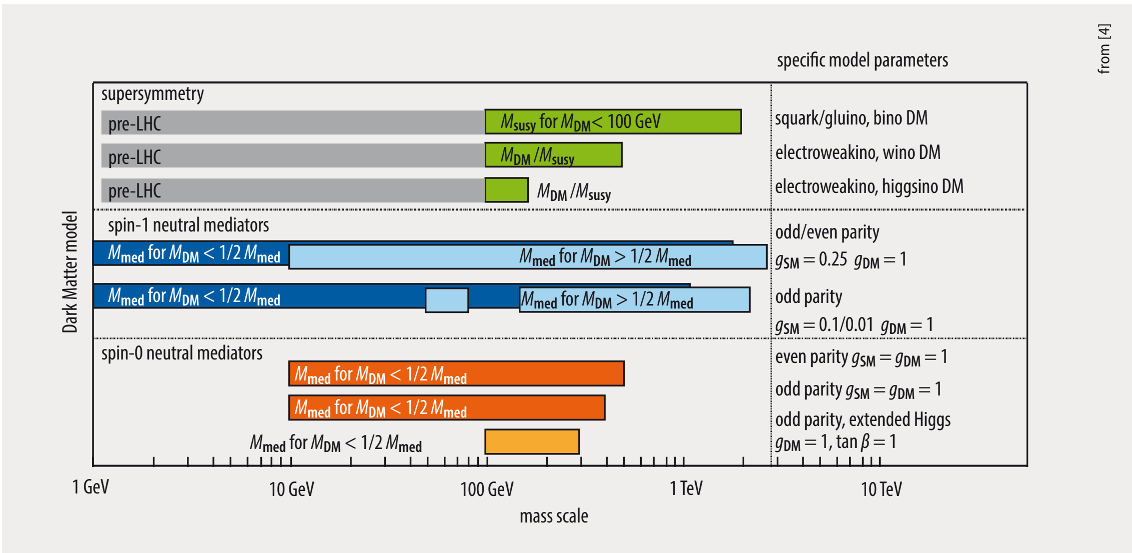
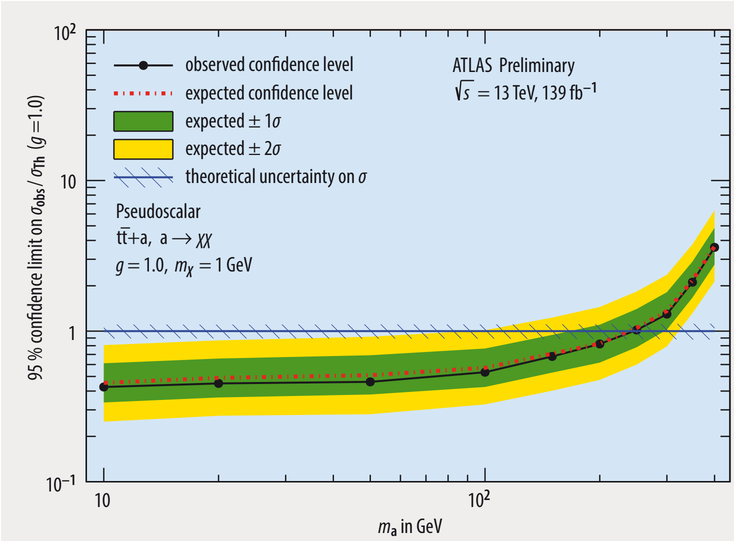


Fig. 3 The coloured bands indicate the excluded range of masses based on a supersymmetry model (green), spin-1 (blue) and spin-0 (yellow) neutral mediators, respectively. Specific model parameters like coupling strengths and particle properties are indicated (right). Some mass ranges were already excluded before the LHC experiments (grey), others are still unexplored (white).

from [5]



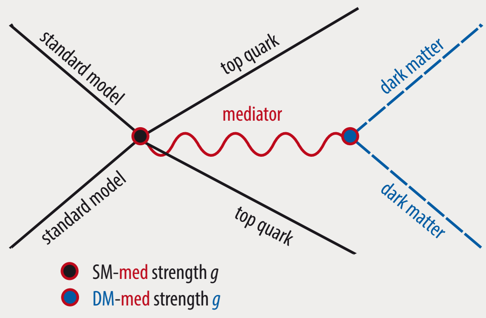


Fig. 4 A recent result from the ATLAS experiment excluded a broad range of masses for mediator particles ($\sigma_{obs}/\sigma_{theo} < 1$) with properties similar to the Higgs boson. For values above 1, the search does not possess sensitivity.

originating from bottom quarks; one or two top quarks; gauge bosons, i.e., the Z, W or Higgs boson; electrons; muons; photons. These objects originate in association with Dark Matter particles and in the decay chains of supersymmetric particles or mediators, respectively.

State of affairs at the Large Hadron Collider

To date, the ATLAS and CMS experiments have performed over 50 analyses targeting mediator-based searches with Dark Matter particles, mediator-based resonance searches, and supersymmetry Dark Matter searches [4]. All results are based on data of Run-2. None of them finds a significant excess in the data over the expected background from Standard Model particles. Therefore, each of them served as basis to extract exclusion limits for Dark Matter models with selected parameter assumptions (**Fig. 3**). Since additional data will provide further constraints, the complete set of experimental results based on the full datasets of the ATLAS and CMS collaborations are eagerly looked forward to.

Currently, charge-neutral Dark Matter mediators with spin 0 represent a particularly interesting category of models. These mediators are closely related to the Higgs boson regarding their properties and behaviour and/or extend the Higgs sector. Similarly to the Higgs boson, these mediators interact strongest with the heaviest particles. Therefore, a possible fingerprint contains enhanced interactions to top and bottom quarks while more conventional signatures with light quarks and/or photons are suppressed. Hence, finding such mediators is experimentally very challenging; especially, as the mass and parameter space for such models is consistently limited (**Fig. 4**). Experimentally, these searches rely on the understanding of complex final states, e.g., the simultaneous production of Dark Matter and two top quarks. Another approach is the search for rare final states being very similar in topology to quite common processes of the Standard Model, e.g., the production of Dark Matter and two bottom quarks at the same time with an irreducible background stemming from $Z(\nu\nu) + bb$.

The detection of such mediators is also challenging for theoretical reasons. The final states – such as resonances produced by pairs of top quarks from spin-0 particles – exhibit strong interference patterns with processes of the Standard Model sharing the same final state. The full ATLAS dataset of Run-2 limits the mass and coupling strength of a pseudo-scalar mediator (**Fig. 3**). Previous searches for this model excluded mediator masses between 15 and 30 GeV. The new result extends this mass range to values between 10 and 200 GeV and increases the sensitivity to smaller coupling strengths by a factor of 2 for the excluded masses. Recently, it was pointed out in literature that final states with a single top quark – associated to a forward jet or an additional W boson – represent novel and unexplored signatures for these spin-0 mediators and possess a great potential for their discovery [6].

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The Author

Priscilla Pani has obtained her PhD at the University of Amsterdam, Netherlands, in 2014 with highest honors after receiving a master degree in physics at Sapienza Rome University, Italy, in 2010 with highest honors. Starting with her PhD studies, she has worked with data from the ATLAS experiment. She focuses on experimentally complex signatures involving heavy quarks and has contributed to new ideas for Dark Matter searches. She is currently leading the Dark Matter subgroup in the ATLAS collaboration as well as the corresponding group of the LHC Physics Centre at CERN (LPCC).

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