ERC Consolidator Grant 2020
Research Proposal [Part B1]

REALDARK

REAL-time discovery strategies for DARK matter and dark sector signals
at the ATLAS detector with Run-3 LHC data

Principal Investigator	:	Dr. Caterina Doglioni
Host Institution	:	Lund University
Proposal duration in months	:	60

Summary

The Standard Model of Particle Physics (SM) describes the fundamental particles and interactions of ordinary matter. Despite the SM's success in predicting experimental results, it fails to account for the large abundance of dark matter in the Universe. Dark Matter (DM) particles could be created from collisions of SM particles, such as in the Large Hadron Collider, but storage and computing limitations mean that rare processes involving DM may be missed by current data taking methods.

In Realdark, I will consolidate my leadership in DM searches with innovative data-taking techniques that solve this problem for the ATLAS experiment. The technical innovations of Realdark will be disseminated, paving the way to advancements for future experiments.

Under my leadership, the RealDark team will break the traditional paradigm of recording detector data and then analyzing it in separate steps, by deploying data processing in real-time so that far more collision data can be searched for rare processes. We will enable new types of datasets from the upcoming LHC data-taking period and search them for new phenomena, motivated by theories of weakly interacting massive DM particle candidates and particles from a *dark* sector inaccessible to ordinary particles.

The proposed searches will yield either a discovery of dark matter candidates, to be studied in connection with astrophysical observations, or world-leading constraints on the particle nature of dark matter, focusing theoretical efforts and search targets for future experiments.

Section A: Extended synopsis of the proposal

1 Aims and impact of this research project

The first years of data-taking at the Large Hadron Collider (LHC) [1] at CERN yielded the discovery of a new fundamental particle, the Higgs boson [2]. With this and many other notable results, the LHC has confirmed the Standard Model (SM) of particle physics, the theory of fundamental particles and the non-gravitational interactions among them. However, astrophysical observations show the amount of matter described by the SM is exceeded by a factor of five by another kind of matter called Dark Matter (DM) [3].

Many theoretical models explain the abundance of DM in the universe using particles that interact weakly with the SM, called WIMPs. If produced by the LHC, their discovery could complement astrophysical observations and particle experiments searching for direct evidence of DM (see e.g. [4] and references therein), providing a unique opportunity to study its interactions with normal matter. As such, WIMP DM searches have been a flagship of the physics programmes of LHC experiments [4–6].

However, no evidence for WIMPs has yet been found. This motivates a two-prong approach for future DM searches at the LHC. In this Consolidator Grant proposal I will:

- advance the state of the art for WIMP searches by enhancing their sensitivity to rare interactions.
- enable and deliver new searches for DM beyond the WIMP paradigm.

In my Starting Grant (StG), I led the previous generation of state of the art searches for SM-DM interactions [7, 8]. I also collaborated with the DM theory community so that the world-leading LHC constraints resulting from my StG could be placed in the global context of dark matter searches. The resulting theoretical framework [9] has been widely adopted by LHC WIMP searches [5] and by the studies towards the update of the European Strategy of Particle Physics aiming to prioritize future facilities [10].

The discovery of DM and other rare processes mandates continued technical and technological innovation. The LHC collides bunches of protons up to 30 million times per second. Recording and processing all detector data for further analysis is unfeasible: only a small fraction of interesting data can be selected by the experiment's *trigger systems* due to constraints on both processing and storage; the rest is discarded. While this is not a limitation for most of the searches done at the LHC so far, it leads to a loss of sensitivity to large areas of parameter space for DM models.

With a team of two postdocs, two PhD students and a software engineer in RealDark, we [1] will directly address these constraints The solutions developed as part of RealDark will generate secondary impact as they can be used beyond the LHC. The WIMP and non-WIMP searches in this project will be enabled by innovative data-taking techniques at the earliest stage of data selection and processing, increasing the utility of the data recorded by the ATLAS experiment as a whole. These techniques will reduce the data size needed for physics analysis by a factor of 2–200, overcoming storage limitations that would otherwise force ATLAS and other experiments to discard the majority of data crucial to many DM searches.

I am uniquely suited to deliver this ambitious and timely research program. My CV and track record combines both technical and scientific excellence with proven leadership of groups of scientists in the DM and technical communities. With my international collaborators and within my StG, I have prototyped data-taking techniques where selection and processing occurs in near-real-time, from software concept to publication. I coordinate synergistic activities aimed at more efficient software for data selection and analysis that span all of high energy physics and beyond [11]. In addition to authoring a number of publications on LHC searches for DM and new phenomena, I have coordinated ATLAS- and LHC-wide working groups instrumental in the design of DM search strategies, such as the Dark Matter Working Group [12]. I was responsible for summarizing the studies of the sensitivity of future colliders to DM, within the European Strategy update.

The outcomes of this project will transform both data-taking and the global quest to determine the nature of DM. The results from this project, the tools for their interpretation, and the software that enabled them will be disseminated to the broader community to generate impact beyond this proposal. The data-taking techniques in this proposal have many applications beyond it. They will mitigate computing and storage restrictions for the high-luminosity LHC, as well as for experiments where the increase in data collection is not matched by proportional increases in resources [11, 13]. This project delivers as outputs discoveries or constraints that can inform the future direction of DM research, using Open Science tools, for astroparticle and non-collider experiments in the next decade [14, 15].

[1] When the term "we" is used, it refers to myself as PI and to the personnel hired within RealDark.

2 Advancement to the state of the art from this project

The SM does not explain the presence of DM. The lack of a discovery of DM at the LHC and other experiments indicates that, if DM is a particle that interacts with SM particles, its interactions must be very feeble and/or the experimental signals of DM must be subtle. Thus, the enormous data rates of modern particle experiments present a challenge to DM detection. Huge datasets are required to reveal DM signals, but with traditional data-taking methods, it is not possible to record, process and store this data. The majority of the data must be discarded milliseconds after being taken by the experiment's trigger system. Two notable examples of discoveries that are impossible with traditional data-taking methods are:

- Certain rare processes around the electroweak scale, where the decay products of new particles are discarded amongst the vast irreducible backgrounds of SM processes.
- Processes where new particles leave complex non-standard signals in the detector. In these cases, the distinctive features of the signals are too time-consuming to reconstruct in the trigger, due to the limited time budget in which a decision to keep an event must be made. Therefore, these features are not identified and the event is discarded.

These examples map to two classes of DM models that are able to reproduce the amount of DM measured in the universe (relic density).

The first class of models corresponds to current benchmarks used by most LHC DM searches, a state of the art developed within my StG [4, 9]. In these models, DM is a massive particle that interacts only weakly with SM particles—a WIMP. At collider experiments, WIMPs would only weakly interact with detector material, and so they are sought traditionally by selecting events with a momentum imbalance where one or more particles has escaped detection. WIMPs may be produced from LHC proton-proton collisions through new massive particles mediating the SM-DM interaction. This mediator would decay not only to DM particles but also into ordinary matter through the same mechanism responsible for its production.

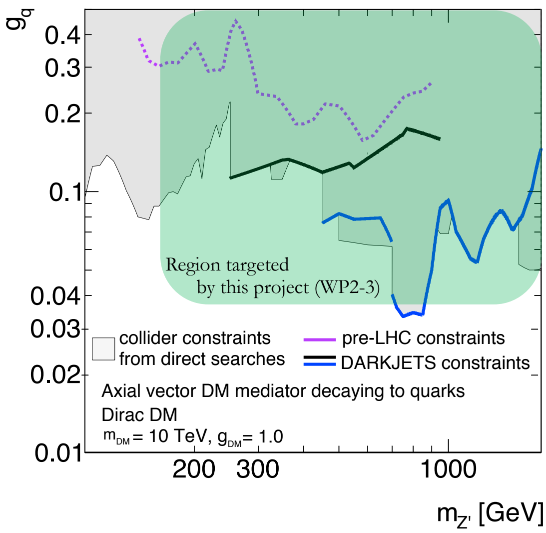

Figure 1: Parameter space for an example WIMP DM mediator model targeted in this project, compared to the state-of-the-art.

In my StG, I delivered new searches for DM mediator decays to two quarks, leading to two sprays of collimated particles (jets) in the detector [7, 8, 16]. Prior to this, potential signals of mediators with masses around the crucial electroweak scale were discarded together with high-rate backgrounds from the strong force (Quantum Chromodynamics, or QCD) to meet storage constraints. The StG search at 450–1000 GeV masses was made possible by applying the Trigger Level Analysis (TLA)[2] technique to jets [7]. In the TLA technique, most of the initial data analysis and calibration is performed in real-time ($< ms$) within the ATLAS software trigger system.This technique records only a small amount of high-level information for further analysis, rather than the entirety of raw detector data. The mediator mass range between 250 and 450 GeV was covered, albeit with less sensitivity, by another new search that my colleagues and I introduced to ATLAS using traditional data taking techniques, as described below [8]. Searches using these techniques with the LHC dataset recorded from 2015 to 2018 (called *Run-2*) have set some of the most stringent constraints to date for DM mediators with masses between 250 GeV and 1 TeV (see Fig. 1).

In this project, my CoG team and I will significantly extend the TLA technique beyond jets, deploying it for photons, electrons and muons for the first time to bring the greater sensitivity of the TLA approach to a larger range of mediator masses as well as to new dark matter models. We will validate these data-taking techniques and the new Run-3 ATLAS trigger system as a whole with physics searches and measurements in early Run-3 LHC data. We will subsequently exploit the full dataset containing TLA photons and jets for more sensitive and lower-mass WIMP mediator searches (see shaded yellow in Fig. 1).

[2] Analogue to the techniques of *Data Scouting* in CMS [17] and *Turbo stream* in LHCb [18]

Motivated by lack of evidence for WIMPs, the second class of models postulates interactions that are much feebler, generally involving lighter mediators. These models [19, 20] predict a multitude of new particles in addition to the DM candidate, mirroring the complexity of the SM and similar to the strong force (*dark QCD*). Unambiguous, generic features of these models are *dark jets*, which, in addition to visible particles, are comprised of invisible particles and low-mass dark matter mediators decaying into low-energy electrons and muons [21]. Existing searches for two-jet signals are not sensitive to dark jets because of the huge backgrounds from QCD processes in the SM (a problem shared by WIMP mediator searches) and because the HLT computing farm is unable to build and identify the characteristic features of dark QCD jets before the events must be discarded. To solve this problem, we will combine for the first time the TLA and the Partial Event Building (PEB) techniques. By augmenting high-level information from the data reduction in the trigger (TLA) with select raw data from detector regions around the dark jets (PEB), we will overcome the previous storage and processing limitations and enable reconstruction of the distinctive signal features at a later processing stage where more resources are available. We will use the dataset recorded with this technique to discover or set stringent constraints on models consistent with the DM relic density but never tested at the LHC.

As a byproduct of performing these searches, the datasets recorded with our techniques will be made available for other searches and measurements in ATLAS, extending the potential for discovery of the entire ATLAS search programme in cases where sensitivity is limited by storage constraints (e.g. low-mass leptonically-decaying DM mediators and dark sector particles [22], axion-like particles [?]) or by HLT computing constraints (e.g. trackless jets [?]).

Absent compelling signals of DM from any particle physics experiment, it is crucial to extract the maximum amount of information from the results obtained in these searches, and combine that information in the broader context of the global search for dark matter. For this reason, I will continue leading the way to define community standards for LHC DM searches, so that any LHC discovery or constraint can be properly considered in synergy with complementary astroparticle, non-collider and cosmological measurements. Building on the success of the Dark Matter Working Group, which under my leadership set the standards for LHC WIMP search targets and for the contextualization of results alongside non-collider experiments, I will lead initiatives that bring together the flourishing experimental and theoretical research communities studying WIMP and non-WIMP DM scenarios [23].

3 Project organization and description

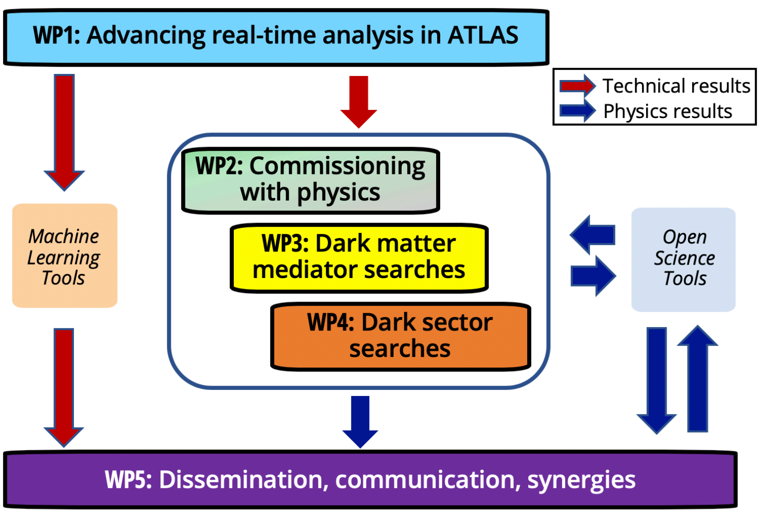

Figure 2: Schema of work packages and expected results.

The project consists of five logically interconnected work packages. The work packages and their interconnections are indicated in Fig. 2. In **WP1**, we will use non-standard data-taking and recording techniques to overcome key technological limitations of searches for a variety of physics phenomena including DM, as well as employ machine learning techniques for compressing data towards further gains in event storage. In **WP2**, we will use early physics data from Run-3 to commission the newly-upgraded ATLAS trigger system and the techniques developed in WP1. In **WP3 and WP4**, we will use the data recorded with the techniques developed and commissioned in WP1 and WP2 to perform world's-best and world's-first searches for dark matter models. In **WP5**, we will interpret and disseminate the results of those searches, including input from LHC measurements and non-collider DM searches using Open Science tools. We will work in synergy with the broader community for optimal contextualization and dissemination of results and tools.

■ WP1: Advancing real-time analysis in ATLAS

As the main technological advancement delivered by this project, we will deploy and commission the two techniques of TLA and Partial Event Building in the Run-3 trigger. As a pioneer of real-time analysis, I have delivered proof-of-concept studies for these techniques in my StG, but they must now be developed and commissioned on a much larger scale via WP1 in order to exploit them for groundbreaking DM searches with the Run-3 dataset.

TLA-recorded events contain only high-level information reconstructed in the trigger. They are considerably smaller than events with full-detector raw data, enabling the recording of a much larger number of events within the same data bandwidth. With my StG team, I have demonstrated the effectiveness of this technique with a published proof-of-concept search for dark matter mediators decaying to jets [7]. Within this project, I intend to expand the technique to photons, electrons and muons, allowing extensive use by ATLAS for a program of searches and measurements.

In the **Partial Event Building** technique, high-level information available to real-time analyses is augmented by a subset of the raw detector information in selected regions of the detector. This combines the data rate enhancements of real-time analysis with the added precision of full offline reconstruction in a user-configurable manner. Subtle features signaling the presence of new phenomena can then be detected *a posteriori*. This project will commission and use this technique in physics searches for the first time in ATLAS.

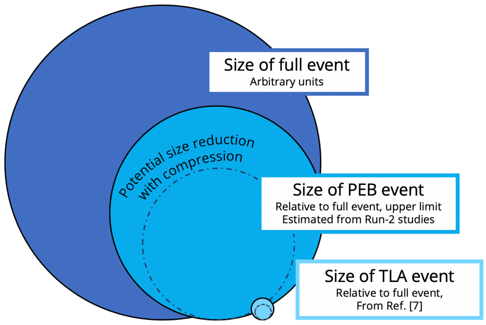

Figure 3: Event sizes for traditional (full) events, and events recorded using TLA and PEB techniques [24].

Both of these techniques reduce data storage requirements with respect to traditional techniques (as shown in Fig. 3), but they can be complemented by **further gains in data compression**. In this project, I will pursue a method for physics-aware data compression using using autoencoder deep neural networks [25, 26]. In preliminary studies, my student and I, in collaboration with other ATLAS ML and computing experts, have shown the potential for an additional compression factor of two for TLA data.This is a forward-looking activity targeting the high-luminosity LHC run in 2026 and experiments beyond the LHC.

■ WP2: Commissioning the Run-3 trigger system with physics

During the two-year shutdown between LHC Run-2 and Run-3, the ATLAS experiment trigger system is undergoing significant upgrades [27], and the trigger and reconstruction software is being rewritten [28]. Thorough commissioning and testing is mandatory, first with simulation and cosmic ray data, and subsequently using early collision data. In WP2, together with my team, I **will test the completely new software trigger framework and its performance using physics quantities**. This work will be documented by physics and technical publications.

We will select events where at least two jets, muons or electrons are detected and reconstructed in real-time within the trigger system, and compare the performance of reconstruction and calibration between trigger-level and traditional data-taking approaches. In addition to technical publications on the new software framework and its commissioning with LHC data, this WP will enable physics publications of the first Run-3 searches for low-mass DM mediators. We will make extensive use of the Open Science tool RECAST [29] to preserve the full analysis workflow, from detector data to final plots, so that we can take advantage of this work for the searches in WP3.

■ WP3: WIMP dark matter mediator searches

In WP3, my team and I will **use the TLA technique to search for decays of WIMP mediators** near the crucial electroweak scale at sensitivities not possible before. This search targets mediators with 150–350 GeV masses, a range close to where the massive mediators of the SM reside. This region is still poorly constrained, as neither traditional searches nor jet-only TLA searches have reached sensitivity to mediators with SM-like couplings (Fig. 1).

We will employ the **dijet+ISR detector signature** that I introduced to ATLAS during Run-2 using traditional data-taking methods, where the mediator is produced in association with an additional jet or photon [8]. This approach yielded the world-leading constraint in the upper mass range of this region. **Performing this search with the TLA method will significantly increase its discovery potential**, allowing for an order of magnitude more signal events to be recorded.

During the 2022-2025 grant period, we will also analyse data in the two-jet signature to search for mediators with masses above 350 GeV with the entire Run-3 dataset. This analysis will capitalize on the end-to-end analysis workflows set up in WP2 to make the analysis more efficient and ensure that the Run-3 results can be combined with the full Run-2 results to constrain a wide set of physics models [30].

■ WP4: Dark sector searches

While the searches in WP3 are powerful probes of WIMPs mediated in ways inspired by the electroweak sector of the SM, they are not sensitive to dark QCD models, or to far lighter, GeV-scale DM mediators mediators whose interaction with the SM is feebler. For this reason, in WP4 my team and I will deploy the **combination of TLA and Partial Event Building** developed in WP1 to target this equally-compelling class of **models yielding new detector signatures**.

WP4 focuses on two new searches.

First, we will search for signals where DM candidates are produced in association with a large number of other dark sector particles. Since these dark sector particles also interact through the SM's strong force, while the DM particles escape detection, this leads to ***semi-visible dark jets*** [20]. We will scan a large part of the parameter space with the unique sensitivity enabled by this dataset, focusing on parameters consistent with relic density of DM [31].

Second, we will builds on the semi-visible jet results and exploit the availability of electrons and muons at the trigger level enabled by WP1, targeting models where low-energy leptons from the decays of a light dark mediator or a dark Higgs boson are also found within dark jets [21, 32], forming ***composite jets***. This dataset will extend the ATLAS sensitivity to low-mass, low-energy and exotic objects overlooked in searches so far, which are restricted to isolated, higher-energy leptons.

■ **WP5: Dissemination, communication, synergies**
WP5 defines frameworks and optimal search regions in the context of the global DM search community, resulting in enhanced conceptualization and dissemination of tools and results. This dedicated WP ensures that the results of the project have a broad research impact that exploits both local synergies and synergies with other communities.

Within WP5, my team and I will **pinpoint the relevant parameter space** to be targeted for the new searches in WP4, and design data-taking parameters and datasets accordingly. This will be done in collaboration with the local Lund theory group, who are authors of the most widely used simulation of the models in WP4 and of the event generation software Pythia [33]. We will use software that enables the use of precision results released by LHC collaborations [34], using them for the first time to constrain dark QCD models.

In WP5, we will ensure that all **physics results from WP2-4 are disseminated** in a way that meets the needs of other communities in terms of reproducibility, usability and complementarity in compliance with the FAIR principles [35]. The successful experience of the Dark Matter Working Group is a stepping stone for a new, ambitious initiative that I co-founded, kicking off in Summer 2020, called iDMEu. This initiative will permit the integration of results from this project within a much broader context that includes non-collider experiments, astrophysics, cosmology and multimessenger astronomy.

An innovative aspect of this project is that its dissemination strategy is not limited to physics results but includes algorithms and tools. As I and many others advocated during the process leading to the update of the European Strategy of Particle Physics [36], challenges related to data acquisition, selection and analysis can be tackled more effectively and efficiently by going beyond a single experiment's boundaries. For this reason, WP5 also includes **sharing analysis workflows within a collaborative Dark Matter virtual environment** that I will co-lead starting from February 2020, envisaged by the European Science Cluster of Astronomy & Particle physics ESFRI research infrastructures. We will also use the ESCAPE Software Repository to **share generic data reduction software and data compression algorithms** with other experiments where a reduced storage footprint is necessary to increase the physics potential within the same computing resources.

4 Timeliness and timeline of the research program

I will lead a research team of two postdoctoral researchers and two graduate students, working on the two lines of physics analysis in this project, and frequently collaborating to share technical tasks and software. An additional software engineer will augment the team during the demanding time of the LHC Run-3 startup. For WP1, the team will be joined by talented Lund University undergraduates that I have a track record of recruiting and training who will work on the forward-looking ML compression activities. The research program spans the entire upcoming Run-3 LHC data-taking period. The 2021-2026 period is the ideal time to advance the state-of-the-art in processing of large datasets and DM searches, as it ensures continued impact through a significant extension of my current successful StG research program that pioneered proof-of-principle real-time searches in ATLAS. The current LHC schedule includes an initial commissioning period where innovations can be deployed and tested via early measurements with Run-3 start-up data, which forms the first part of this project (WP1 and WP2), readying them for the second phase of the project where the LHC will be in production mode. The second (WP3 and WP4) phase of this project will exploit the wealth of LHC data delivered by WP1 and WP2 for novel DM searches, with a dataset that will be much more sensitive to the models sought in this project than the data collected so far. Throughout the timeline of entire project, in WP5 we will share tools and results within the global DM community, to answer one of the most pressing questions of our universe with a discovery or by defining future search directions in which such a discovery will be made.

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Note: The PI is the editor of Refs. [4, 7–9, 36], the initiator of the activities in Refs. [12, 23] and has made significant contributions to Refs. [5, 10, 11, 37]. The PI is the author of all publications by the ATLAS collaboration.

Caterina Doglioni Dr., Date of birth: 27.07.1984 [198407273427], Pronouns: she/her
ORCID ID: https://orcid.org/0000-0002-1509-0390
e-mail: caterina.doglioni@hep.lu.se, website: http://www.hep.lu.se/staff/doglioni/

Brief research statement

Throughout my career, I have been driven by finding out more about the constituents of matter as well as by the challenges related to the "big science" needed to study them (complex instruments, vast amounts of data, an international community working together). I chose to pursue my research at the Large Hadron Collider (LHC), the largest discovery machine ever built by humankind that could produce dark matter (DM) particles in controlled conditions, contributing to the solution of a mystery of our universe. The narrative in this CV outlines the path I took to establish myself as a leading actor for LHC DM searches, with an ambition to pursue these searches using novel data selection techniques essential for discoveries in data-rich research environments.

Education

2003-2008: Undergraduate studies: Universita' di Roma 'Sapienza', Italy.

- Master's Degree, final marks: 110/110 Cum Laude, GPA: 29.7/30.
- Bachelor's Degree, final marks: 110/110 Cum Laude, GPA: 29.2/30.

2008-2011: D. Phil. Degree (16/12/2011), University of Oxford, Merton College, UK.
Thesis title: Measurement of the inclusive jet cross section with the ATLAS detector at the LHC.
Supervisor: Prof. Amanda Cooper-Sarkar.
During my PhD, fully funded by external grants from UK, Italy and Sweden (see this Guardian article), I have become an expert in the identification, reconstruction and performance of the most common physics signature produced at the LHC: jets of particles originating from the constituents of the collided protons. My PhD thesis provides the first-ever estimate of the uncertainty on jet energy measurements in ATLAS, nominated as an outstanding contribution by the University of Oxford, published in the Springer Theses series *and described in one of the 20 most cited LHC papers.*

Postdoctoral experience (Previous positions)

2011-2015: Senior research and teaching assistant (Maître-assistante), University of Geneva, CH
At the start of my post-doc I used my PhD knowledge to perform the first search for new particles decaying into two jets with early 2012 LHC data, probing the highest possible energy scales. In 2012 I was appointed co-convener of the Jets and Dark Matter group (70 members) to the publication of papers on searches for new physics with jets. My own research focused on DM and highlighted an unexplored region out of the reach of traditional data taking techniques. In 2014, I was appointed by ATLAS and CMS management to co-lead the Dark Matter Forum and in 2015 the LHC Dark Matter Working Group (~300 members) to disseminate recommendations on the search targets and interpretation of LHC DM searches. These years leading international groups of physicists while working hands-on on cutting-edge physics analysis were instrumental for the DARKJETS ERC StG research program to begin the exploration of low-mass DM mediators that is significantly extended with the REALDARK CoG research program.

Current positions

2019-present: Senior University Lecturer (Lektor), Lund University. Reader (docent) since 30/08/2017.
2015-2019: Associate Senior University Lecturer (Biträdande lektor), Lund University.
As an associate professor at Lund University, I work with a post-doctoral researcher and two PhD students supported by the DARKJETS ERC StG. We deployed a real-time analysis technique called "Trigger-Level Analysis" (TLA) for the first time in the ATLAS experiment and applied it to dark matter searches, leading to the strongest constraints to date on DM mediator models. We disseminated our results through peer-reviewed papers that I edited, contributions at international conferences, press releases[1] and outreach events. TLA has also been added to the current issue of The Swedish Guide for Big Science and I continue being involved in synergistic activities (see below) as real-time analysis goes beyond the ATLAS experiment. The ongoing success of my Starting Grant, and the strong constraints set on WIMPs, motivated me to apply for this Consolidator grant proposal for further breakthroughs in analysis techniques and DM searches.

Fellowships and awards

2003-2008: Full scholarship at the Collegio Universitario Lamaro Pozzani**,** funded by the IT National Federation of Holders of the Order of Merit for Labour, hosting < 15 selected Italian students/year. Winner of INFN scholarship for physics graduates in particle physics (ranked 1st in Italy).

Supervision of postdoctoral fellows, graduate and undergraduate students

Main supervisor of: **two postdocs** (William Kalderon 2016-09/2019, currently postdoctoral fellow at Brookhaven National Lab, Jannik Geisen 09/2019-now), **2 PhDs** (Eric Corrigan 2016-now, Eva Hansen 2016-now), **a Licentiate, 7 Master's, 8 Bachelor's students** (Lund University, supervised theses can be found on my website) who are now mostly pursuing PhDs in experimental or theoretical physics, 13 CERN summer students (Lund/Geneva). **Co-supervisor of 5 PhD students** (Lund/Geneva).

[1]For a press release about DARKJETS and its team, see this link.. For an interview in Italian see this link.

Teaching, mentoring, and course development activities

2015-: *Lund University.* Course responsible for Particle Physics, Cosmology and Accelerators, Bachelor's degree at the Natural Sciences faculty. Co-teacher of various courses, including graduate-level course on Jupyter notebooks and Master's level course using ATLAS Open Data (described in the Proceedings of LHCP2018)
2019-: Steering group member for the COMPUTE research school in the LU Science/Engineering/Medicine Faculties, responsible for alumni network.

Organization of selected scientific meetings of relevance for this proposal

2020: Co-organizer of the particle/astroparticle sessions at the Nordic Physics Days in Uppsala.
2020: Main organizer of the HEP Software Foundation / WLCG workshop in Lund (expected 250 participants)
2019: Overall programme committee chair of 23rd international conference on Computing for High Energy Physics (CHEP), Australia (500 pp)
2018: Main organizer of the Swedish particle physics community conference (Partikeldagarna) in Lund (80 pp)
2016: Scientific organizer committee of the Dark Matter workshop during KAW foundation's 100th anniversary symposium "Big Questions in Astrophysics" (36 pp)
2015, 2017: Chair of the "Dark Matter" and "Higgs and Beyond the Standard Model physics" sessions at the European Physical Society Conferences, Austria and Italy
2014-: Member of the local organizing committee for the Large Hadron Collider Physics Conference in Lund (350 participants). Chair of the Beyond the Standard Model and QCD session at the 3rd, 4th and 6 th editions of the LHCP conference (US, Sweden, Italy).
2014-: Session chair and organizer of DM@LHC conferences in Netherlands, UK and Germany (100 pp)
2014: Local organizer and responsible for logistics (350 participants) of Future Circular Colliders Kick-off meeting, Switzerland.

Membership of scientific societies

2020-: Chair of the Swedish Particle Physics and Astrophysics Board, Swedish Physical Society
2017-: Elected member of the Swedish Particle Physics and Astrophysics Board.

Grant review assignments:

Remote expert reviewer for ERC Grants.
Panel member for the annual merit-review and comparative-based research program for the U.S. Department of Energy, Washington, D.C. (USA).
Evaluator for the Merit Reviews of the Israel Science Foundation (ISF)

Journal review assignments

Since 2016	Reviewer for the European Journal of High Energy Physics (JHEP)
Since 2018	Reviewer for the European Journal of Physics C (EPJC)

Most recent synergistic and outreach activities:

2019: Organizing committee of 2-week Institute Pascal workshop on Real-time analysis, in Paris
2018-: Invited with other 15 Lund junior faculty to the LMK Foundation Idea Forum. Led to the funding of the interdisciplinary Pufendorf Institute Advanced Study Group on Real-time analysis with the faculties of Physics, Social Sciences, Law, Engineering, whose activities can be found here.
2018-: Convenor of HEP Software Foundation (HSF) Trigger and Reconstruction working group.
2020-: Overall co-coordinator of the HSF, with the aim of increasing cross-talk with astroparticle experiments.
2019-: Co-spokesperson and co-coordinator of the Lund-Hamburg Helmholtz International Research Graduate school HELIOS, on intelligent instrumentation for present and future physics facilities (see Funding ID).
2016-: Lund University responsible for the IPPOG Masterclasses in Particle Physics. In 2018 I started hosting the Masterclasses for the UN International Day of Women and Girls in Science, (open to all genders). LU Press release.

Major collaborations (current/planned):

Within the LHC research environment, I have many close links with my international. This list contains the most relevant current and planned collaborations on the topics of this research proposal. The experts external to ATLAS who have agreed to collaborate on these topics are underlined.
Tancredi Carli (CERN, Switzerland): jet performance and jet triggers.
Graeme Stewart (CERN, Switzerland): trigger and data analysis, head of the HEP Software Foundation.
Vladimir Gligorov (LPNHE and Univ. Sorbonne, France): interdisciplinary implications of real-time analysis
Antonio Boveia (Ohio State University, USA), David Strom (University of Oregon, USA), Monica Dunford (Heidelberg University, Germany): trigger and WIMP DM searches.
Deepak Kar (University of Wits, South Africa), Marie-Hélène Genest (LPSC Grenoble): dark sector searches
Stefan Prestel (Lund University, Sweden): interleaved QCD and dark photon showers (Pythia author)
Felix Kahlhoefer. Michael Krämer (RTWH Aachen), Tilman Plehn (Heidelberg U.): dark sector searches
Torsten Akesson (Lund University, Sweden): non-WIMP DM searches, Lund University

Funding ID

Ongoing external funding

Project title	Funding source	Amounts Euro (SEK)	Period	Role of the PI	Relation to current proposal
DARKJETS: Discovery strategies for DM and new phenomena in hadronic signatures with the ATLAS detector at the LHC	European Research Council	1270000	2016-2021	Sole PI	Proof-of-principle results for WP1-3, see below of this document for how this Consolidator Grant is a significant step beyond this Starting Grant (StV). In the first 3.5 years, my StG team (1 postdoc, 2 PhDs) and I have published 6 ATLAS papers, 6 whitepapers (4 peer-reviewed) and 2 review papers. 3 more publications are expected before the conclusion of this project in February 2021.

This Consolidator grant is a **significant extension of the successful research program that was enabled by my Starting Grant, expanded in ambition and experimental coverage**.

The research program in the Consolidator Grant is much more ambitious than the ERC program, extending the success of the TLA proof-of-principle technique that was novel for the ATLAS experiment to other fundamental particles and use cases. The data recorded with one of these extensions (TLA with photons) will be used in a search that I pioneered at the LHC, extending the world-best constraints to a discovery potential many orders of magnitude better. This research program and its work on data compression will also make TLA become a standard analysis technique that can be used by other members of the collaboration, allowing for more sensitive searches that are currently limited by trigger constraints and providing a solution to future challenges. Its use in combination with the Partial Event Building technique is completely new, and it will be used to search for a more complex search target with respect to the targets of my Starting Grant, moving from WIMP searches to well-motivated non-WIMP dark sector searches that have captured the interest of part of the theoretical community of DM experts.

The achievements of the Dark Matter Forum and Dark Matter Working Group in focusing the LHC DM community around a prioritized set of benchmark models and a way to present results in the context of direct and indirect searches for DM will be the stepping stone of a new initiative that includes the work already done and brings it into an even broader context that includes non-collider experiments, astrophysics, cosmology and multimessenger astronomy.

Such an ambitious research and dissemination program is only possible with the addition of five members to the Lund University team, defining my profile as research-oriented PI with a small amount of focused teaching (see justification for VR grant below for further information of the funding of my position). Thanks to a Consolidator grant, I will have time to work with and supervise two postdoctoral researchers, one postdoctoral researcher with software expertise, and two students that will be trained as part of this proposal,

This Consolidator grant extend the use of real-time analysis to more sensitive DM searches with broad theoretical motivations, and enables my research group and the ATLAS DM search community as a whole to make a major contribution to the global DM landscape. **This grant would establish me further as a leader in my field and responsible for a research program with physics and technical implications beyond high energy physics.** It would also be the stepping stone for me to apply for early **promotion to full professor**.

Project title	Funding source	Amounts Euro (SEK)	Period	Role of the PI	Relation to current proposal
Real-time Strategies and Precision Searches for Dark Sector Particles	VR (Swedish Research Council), Project Grant	423020 (4400000)	2019-2024	Sole PI	Covering PI's salary and salary of PhD student. The PhD student will be spending 30% of their time physics topics that are different but complementary to this proposal. In 2020- early 2021, the student will analyze TLA data from Run-2. From early 2021 to mid-2022, the student will develop machine learning algorithms for dark sector models that are complementary models targeted with respect to this proposal (prompt dark jets rather than composite and semi-visible jets) using a dataset collected using traditional data taking techniques. Since this position is part of HELIOS (hardware-oriented DESY/Hamburg/Lund Helmholtz graduate school), the majority of the work of the

					PhD student in 2021-2024 will be on the hardware for the ATLAS experiment upgrade and on the LDMX experiment, for work not directly related to this proposal.

It should be noted that **the financing of the non-teaching employment of Swedish researchers and a large fraction of PhD student funding comes from national funding agencies rather than from the internal budget of the employing university**. Researchers from EU countries who are dependent on grants from a national funding agency should not be penalized with respect to others where the employment of the researcher is fully financed from the internal budget of the University.

It is only the combination of this current funding and the Consolidator Grant that will allow me to maintain a **strong research-oriented profile,** and lead a group that continues the very successful research line on dark matter enabled by novel data analysis techniques in ATLAS. This work so far has been recognized with high-profile responsibilities in both computing/data analysis and dark matter communities for me and my postdocs and students.

This combination also enables me to participate in a time-limited but still significant extent to **ATLAS upgrades and to a new promising experiment, the LDMX experiment,** given the synergies with this proposal in terms of dark matter searches for models with new particles coupling to photons and electrons. While the searches in this proposal search for light dark matter mediators decaying to electrons within hadronic jets, the LDMX experiment searches for the invisible decays of these mediators. **Participating in two complementary experiments offers the perfect scenario to verify discoveries and employ constraints to direct promising future search programs.**

Time sharing in my role as a PI of both grants has been built in the time plan of this proposal done with a professional Gantt chart software (OmniPlan), with an involvement in LDMX that grows to 20% in 2023 as foreseen in the VR project plan, maintaining a 70% involvement in the Consolidator grant in the first two years and lowering to 50% in the last three years enabling me to apply for additional funding and apply for full professorship.

Project title	Funding source	Amounts Euro (SEK)	Period	Role of the PI	Relation to current proposal
INSIGHTS	MSCA ITN (ETN)	3.02 MEUR	2017-2021	Co-PI and second supervisor of an Early Stage Researcher (was initially main Lund PI, but brought in a second Lund researcher to share responsibilities so I could concentrate on real-time analysis and DM searches)	None, since this proposal focuses in statistics in physics and society. Synergies with this proposal can be found in the statistical tools for the physics analyses.

Project title	Funding source	Amounts Euro (SEK)	Period	Role of the PI	Relation to current proposal
Light Dark Matter	Knut and Alice Wallenberg Foundation	2.6 MEUR (26 MSEK)	2019-2024	Co-PI (but not funded through this grant)	None, since this proposal only funds the LDMX experiment. Synergies with this proposal can be found in different DM search strategies, see VR Project Grant above

Project title	Funding source	Amounts Euro (SEK)	Period	Role of the PI	Relation to current proposal
HELIOS: graduate school on intelligent instrumentation for present and future facilities (25 graduate students)	Helmholtz, U. Hamburg, Lund University (in-kind), City of Hamburg	7.9 MEUR	2021-2027	Deputy spokesperson and co-organizer (team of 5 PIs). VR grant student is one of the 25 “in-kind” students, working on ATLAS tracker upgrade with DESY researchers.	None, since this graduate school mostly focuses on instrumentation (hardware). Synergies with this grant can be found from the trigger and data acquisition side.

On-going and submitted grant applications

Project title	Funding source	Amounts Euro	Period	Role of the PI	Relation to current proposal
Synergies between machine learning, real-time analysis and hybrid architectures for efficient event processing and decision making (SMARTHEP)	MSCA ITN (ETN)	3.2 MEUR	2016-2021	Coordinator	LHC-wide and industrial applications of real-time analysis techniques, not covered in this proposal but synergistic to it.

Previous external funding

Project title	Funding source	Amounts Euro (SEK)	Period	Role	Relation to current proposal
Searches for DM and New Phenomena with the ATLAS detector at the Large Hadron Collider and beyond.	VR (Swedish Research Council)	230760 (2400000)	2015-2018	Sole PI	None

10 most relevant publications

ATLAS Collaboration papers: Due to the large nature of experimental collaborations in particle physics, each publication relies on the results of a very large number of individual researchers and technicians. For this reason, the author list of each of the public documents by the ATLAS experiment includes all members of the collaboration, in alphabetical order. My full bibliometric information (Inspire-HEP) can be found at this link. The following list of ATLAS papers has been selected based on their relevance to this research proposal, and my contribution is described below.

1) **(2018) Search for low-mass dijet resonances using trigger-level jets with the ATLAS detector in pp collisions at sqrt(s)=13 TeV.** G. Aad *et al.* [ATLAS Collaboration]. Phys. Rev. Lett. 121, 081801 (2018), arXiv:1804.03496. *This paper describes the first search using the Trigger Level Analysis technique in ATLAS with the full 2016 LHC dataset, and the world-leading constraints on Dark Matter mediator particles decaying into dijets. I was one of three editors of this paper and one of the main analysers, together with the Lund postdoctoral researcher who is now the analysis contact for the full Run-2 search.* Journal impact factor (2018): 9.227; citations: 61[1].

2) **(2018) Search for low-mass resonances decaying into two jets and produced in association with a photon using pp collisions at sqrt(s) =13 TeV with the ATLAS detector.** G. Aad *et al.* [ATLAS Collaboration]. Phys.Lett. B795 (2019) 56-75, arXiv:1901.10917. *This paper describes the first search using the dijet+ISR signature at the ATLAS detector, extending TLA constraints for DM mediators to lower masses. I introduced this search to ATLAS and I was one of three editors of this paper and my student was one of the main analyzers and responsible for the DM interpretation and summary plots.* Journal impact factor (2018): 4.162; citations: 17.

3) **(2017) Performance of the ATLAS Trigger System in 2015.** G. Aad *et al.* [ATLAS Collaboration]. Eur. Phys. J. C 77 (2017) 317, arXiv:1611.09661. *The performance of the ATLAS trigger system is described in this paper, including the performance and commissioning of the Trigger Level Analysis. I made the relevant plots for this paper together with a student.* Journal impact factor: 4.843; citations: 452.

4) **(2016) Search for new phenomena in the dijet mass and angular distribution from pp collisions at sqrt(s) = 13 TeV with the ATLAS detector.** G. Aad *et al.* [ATLAS Collaboration]. Phys. Let. B754 (2016) 302-322 arXiv:1512.01530 *is the first search publication for the LHC, for the 13 TeV run, setting the strongest constraint at the time on high-mass dijet resonances. I have contributed to many aspects of the analysis, especially on the performance of the highest energy jets used for this search, and supervised the Lund PhD student who was the contact person for this analysis.* Journal impact factor: 4.162; citations: 192;

5) **(2013) Jet energy measurement with the ATLAS detector in proton-proton collisions at sqrt(s)=7 TeV.** G. Aad *et al.* [ATLAS Collaboration]. Eur. Phys. J. C **73**, 2304 (2013). *This paper documents the calibration and performance of hadronic jets in the ATLAS detector for the full 2010 LHC dataset, and established many of the techniques that have been used since. This was my thesis topic, and I have been the leading author or the analysis and public notes that appear in sections 8-9.* Journal impact factor: 4.843; citations: 1046.

Dark Matter Forum / Working Group papers: The Dark Matter Working Group (DMWG, link to mandate) regularly publishes the results of the work of the LHC Dark Matter community in terms of search targets and presentation of results. As one of the working group leaders from 2014-2018 I have been among the 2-5 editors for the four publications, published on Physics of the Dark Universe. Two are highlighted below:

6) **(2015) "Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum".** A. Abercrombie et al. Phys. Dark Univ. 26 (2019) 100371 arXiv:1507.00966**.** *This document is the final report of the ATLAS-CMS Dark Matter Forum, a forum organized by the ATLAS and CMS collaborations with the participation of theory. It contains DM signal benchmarks early LHC Run-2 searches and studies of their parameter space, and a repository of generator implementation as supplementary material. I have been one of the five organizers and main editors of this paper.* Journal impact factor: 5.660; citations: 380;

7) **(2016) Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter.** A. Albert et al. Phys.Dark Univ. (2019) 100365 arXiv:1603.04156. *This document contains the DMWG recommendations used by all DM searches for these models, on how to show results of LHC searches together with non-collider searches using the models from Ref. 6), followed by a companion document on how to convey the complementarity of visible/invisible mediator LHC searches. I am the contact editor and author of this document.* Journal impact factor: 5.660; citations: 251.

Invited review papers and summaries: As an internationally recognised expert in the field, I have been invited to write review articles on the subject area of this proposal. I have also contributed to the European Strategy update, which defines the next 10 years of Europe-wide and international research in HEP, as one of the scientific secretaries of both the Dark Matter and Beyond the Standard Model Physics Planning Groups with work included in the summary Physics Briefing Book submitted to the European Strategy Group (arXiv:1910.11775).

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[1] In High Energy Physics, the number of citations is not as relevant as in other fields, but it is still an indication for the impact on the field and on further papers of the same experiments. For this reason self-citations are not removed.

8) **(2017) "Search for dark matter at colliders".** Oliver Buchmueller, Caterina Doglioni and Lian-Tao Wang. Published as a Nature Physics Progress Article, Nature Physics **13**, 217–223 (2017), arxiv:1912.12739. *This article reviews the state of dark matter theory and searches at the Large Hadron Collider, concentrating on the weakly interactive massive particle (WIMP) scenario. I am one of the three authors who have been invited by the journal for a special issue of Nature Physics and Nature Astronomy, focused on dark matter.* Journal impact factor: 20.113, citations: 12, bibliometric information

9) **(2018) "Dark Matter Searches at colliders".** Antonio Boveia, Caterina Doglioni. Ann.Rev.Nucl.Part.Sci. 68 (2018) 429-459, arXiv:1810.12238. *This is an invited review of dark matter searches at colliders. This is a much broader and longer review than Ref. 8) above, targeting a broad range of audiences (from PhD students to experts in the field), describing the state of the art of collider searches for dark matter, their connections to other experiments and an outlook for the future.* Journal impact factor: 7.7, citations: 29.

High Energy Physics (HEP) Software Foundation whitepaper: As a member of the HEP Software Foundation, I authored its initial whitepaper and its supporting documentation as input to the strategy for trigger and reconstruction for high energy physics for the next decade. Since 2018, I have been selected as convenor of the Trigger and Reconstruction Working Group of the HEP Software Foundation.

10) **(2017) "A roadmap for HEP software and computing R&D for the 2020s"**, A. Alves Jr et al. [HEP Software Foundation]. Comput. Softw. Big Sci. 3 (2019) no.1, 7, arXiv:1712.06982**.** *This whitepaper delineates the R&D activities needed to prepare for the upgrades of the experimental programme of HEP in the coming decades. I have contributed to the main document and chapter on trigger and event reconstruction in terms of real-time analysis. This whitepaper has been the stepping stone for the NSF-funded IRIS-HEP Institute for Research and Innovation in Software in High Energy Physics (http://iris-hep.org).* Journal impact factor: N/A (new), citations: 46

Technology and software

ATLAS Software: All ATLAS trigger and reconstruction software is Open Source (CC-BY4). I was the author of the core code that has made Trigger Level Analysis possible in ATLAS (entry point to the Run-2 code at this link), and I made significant contributions to a number of software frameworks for final data analysis.

Dark Matter Working Group repository: As Dark Matter Working Group convener, I ensured that most software products are accessible and versioned by creating a public GitHub community and repository where each software product is indexed on Zenodo (e.g. the relic density curves for the models considered, to be added to presented results).

Recent press and communication material

2019: ATLAS Feature on Dark Matter co-authored with D. Tovey, being prepared as a Scholarpedia article to appear in 2020 with CMS co-authors.
2019: Dark Matter Day interview for the online newsletter of the National Institute of Astrophysics (in Italian)
2019: Vision on astroparticle, particle and nuclear physics synergies, CERN EP Newsletter, ECFA Newsletter
2018: Article on CERN Courier: Trigger level searches for low-mass dijet resonances,

Invitations to seminars, lectures and conferences

2012-present: Teacher and Lund University contact at the International Hadron Collider Summer School, Goettingen. Topics: ROOT, QCD and jets. Promotional video (2016).
2019: Invited lecturer for the CERN/Fermilab Summer School (advanced international graduate school). Topic: Beyond the Standard Model physics. Slides & recordings.
2016-: Invited talks on DM and Beyond the Standard Model (BSM) searches at the LHC at a number of conferences and workshop. Most recent and relevant, with slide links

- *Dark Matter searches at accelerators*, Next Frontiers in Dark Matter, Galileo Galilei Institute (2019, Italy)
- *Connections between DM and long-lived particle (LLP) signatures*, LLP Workshop (2019, Belgium)
- *Dark matter at future hadron colliders*, Dark Matter @ LHC (2019, US);
- *Experimental DM at colliders* (+ panel discussions), Open Symposium, European Strategy Update (2019, Spain);
- *Synergies between astroparticle, particle and nuclear physics*, EPS-HEP (2019, Belgium)
- *Dark Matter*, APPEC-NuPECC-ECFA JENAS workshop (2019, France)
- *Real-time analysis*, HEP Software Foundation workshop before the CHEP conference (2019, Australia)
- *Real-time decisions at LHC experiments*, Real-time Decision-Making program, Simons Institute (2017, US)

2019: DESY Colloquium on "Making the most of the data" (DESY Hamburg and DESY Zeuthen)
2014-: Invited seminars on DM, BSM, trigger and jets in universities and labs in Sweden, France, Germany, UK, US (full list on website).

Prizes

2018: Sten Von Friesens Pris, Royal Physiographic Society in Lund, *for the advancement of measurement methods in particle physics and for the ambition of strongly linking particle physics and other disciplines*
2009: Perkins prize for Best performance for 1st year PhD student in Oxford particle physics.