# Vision of education and research

During 2016–2018 the CERN Large Hadron Collider (LHC) provided proton-proton collisions at a record energy of 13 TeV. My research has focused on using data from the LHC to search for signatures of Beyond Standard Model (BSM) physics. BSM physics may allow fundamental issues in the understanding of universe, such as the origin of dark matter, to be solved. Given the lack of an early discovery by inclusive searches in the first years of operation of the LHC, I feel that the best prospects for discovery comes from exploiting general purpose detectors in new and innovative ways and pursuing the construction of new dedicated detectors to search for exotic signatures. To support this aim, I have had a leading role in the construction and data analysis of a prototype millicharged particle (mcp) detector at the LHC (the milliQan prototype), coordinating a search for mcps that provides world-leading constraints. In both building the detector and in data analysis I have taken the opportunity to supervise and guide the work of many graduate and undergraduate students. As a member of the CMS collaboration I have pursued new approaches, undertaking a search that pioneered the use of calorimetry timing to search for long-lived particles (LLPs) at CMS and using my position as one of the two conveners of the LLP group within CMS to encourage new ideas, particularly in the crucial areas of dedicated triggering and reconstruction of long-lived signatures. I believe communication with theorists and experimentalists across the field is critical to keeping a broad view of well-motivated BSM physics and new ideas for discovery at detectors. I have engaged in phenomenological studies throughout my research and am actively involved in coordination efforts for the wider LLP community.

In the coming years the jumps in energies and luminosity that marked the previous running of the LHC will come to an end. While inclusive analyses will continue to play a role in exploring ever larger phase space, new ideas and detectors will be critical to providing the best chance for discovery. In the following paragraphs I describe how the experience gained from my work on CMS and milliQan has prepared me well for the challenge of discovering BSM physics at the LHC.

# Research activities

## The milliQan experiment

In recent years there has been increasing interest in the possibility that astrophysical evidence for dark matter may indicate the existence of not just a single new particle but an entire "dark sector" of particles and interactions with a rich and complex structure. The milliQan experiment was proposed in 2014 as a dedicated scintillator-based detector to search for millicharged particles that can arise in dark sector models.

I became a member of the milliQan collaboration in Sept 2017 and immediately joined the team installing a 1% scale prototype designed to study the feasibility and develop understanding of the experiment. During the first commissioning run, from September 2017 to January 2018, I helped write the framework needed to convert raw PMT waveforms into a format suitable for analysis and took part in monitoring the data from the detector to ensure its smooth operation. This has provided important experience in the rapid analysis and comprehension needed to operate a complex detector in a challenging environment. For example, I found a sudden spike in the trigger rate of the detector and determined the cause as the ramping down of the CMS magnetic field, which had an unexpected impact on PMT performance. This lead to the installation of dedicated magnetic field sensors and additional shielding of the PMTs. As the magnetic field was shown to negatively impact certain PMT species more than others we were also able to learn important lessons for the choice of PMT for the full detector. In addition, I found critical issues in the DAQ logic that caused signal like deposits to fail trigger selection. These could then be fixed early on in the running of the prototype.

In March 2018 I lead the upgrade of the prototype, which built on the experience gained during the first operational run, to expand the size of the active area sensitive to signal deposits and add new components designed to provide active vetos for the signal volume and measure backgrounds. I helped design the upgraded prototype, construct the PMT and scintillator components and supervised both undergraduate and graduate students at UCSB undertaking this work. The upgraded prototype took data for commissioning from March–June 2018 and data suitable for physics analysis was then taken from June until proton-proton collisions stopped in late October 2018. The lessons learnt from the commissing runs of the prototype allowed 86% of the total luminosity delivered by the LHC in this period to be used for physics analysis, corresponding to a data set of 37.5 $fb^{-1}$.

In January 2018 I was tasked with the analysis of data from the milliQan prototype. This involved coordinating the activities of a group of approximately 15 postdocs, graduate students and undergraduates from various institutes in the US, Europe and Asia. The analysis objectives included the calibration of the data from the detector, characterising and measuring backgrounds, and simulating the generation and propagation of signals and backgrounds as well as the response of the detector. I was then able to design a search for millicharged particles using the prototype detector. Despite using sub-optimal PMTs and being only a small fraction of the size of the full milliQan detector, this search achieved world-leading sensitivity to fractionally charged particles and forms a paper submitted to PRD [1].

The background measurements and mitigation strategies that I undertook for the search with the milliQan prototype lead to important lessons for the design of the full milliQan detector. In particular, I was able to show that, contrary to the assumption in the original experimental proposal, random overlap of dark rate counts is a subdominant background source compared to the contribution from shower particles generated by cosmic muons in the cavern. To mitigate this I proposed an alteration in the design of the detector from three to four layers. The prototype has also been altered to a four layer configuration and data was collected from January–May 2019 to directly measure background rates. This will be used to provide updated projections in an upcoming paper (expected to be submitted by Autumn 2020).

## Searches with CMS

Over the last few years my main research interests with the CMS experiment have been in searching for signatures of long-lived particles. Such particles can appear in theories with a wide range of motivations, including providing solutions to fundamental problems of cosmology, naturalness considerations, providing a dark matter candidate and allowing non-zero neutrino masses. The discovery of a new LLP would be especially exciting as the non-trivial lifetime provides a unique insight into the fundamental symmetries and hierarchies of scale in the underlying model. Searching for long-lived signatures with a general purpose detector such as CMS is particularly challenging due to the necessity of dedicated reconstruction and triggering, and the prediction and rejection of non-standard backgrounds.

In 2018 I started work on searching for LLPs with CMS, pioneering the use of calorimetry timing to search for LLPs decaying to jets. This analysis was the first carried out at CMS to target hadronic decays beyond the acceptance of the tracking detector and required a detailed understanding of the timing and energy reconstruction performance of the electromagnetic calorimeter. The search also faced highly non-standard backgrounds, such as beam-halo muon deposits, cosmic muon deposits and satellite bunch collisions, which cannot be reliably simulated. I therefore had to design dedicated variables to reject these backgrounds and predict their residual contributions using control regions in data. By also requiring significant missing transverse momentum in the final state the search was able to achieve a low background with only a single displaced object in the final state. This allows a wide sensitivity range in lifetime as well as providing a clear trigger strategy. The analysis achieved world-leading limits for $\mathcal{O}$ TeV long-lived particles decaying to jets with $c\tau_0 > 1$ m. The results were shown publicly at the Moriond Electroweak conference in 2018 and published in PLB in Octover 2019 [4], the first published search from CMS or ATLAS using the full 13 TeV data set provided by the LHC.

While carrying out this search I began engaging with the wider LLP physics community. By attending and presenting at multiple workshops I was able to build connections with experimentalists and theorists working on LLPs and attain a wide view of different search strategies and well motivated theory models. In September 2019 I was appointed as one of two CMS Exotica long-lived subgroup conveners, responsible for leading the LLP efforts within CMS as well as internal review of all CMS long-lived results. Since starting my term, I have actively reviewed four new searches which have been made public to the wider community. I have also made it a priority to increase the connections between different analysts within the CMS long-lived group as well as between analysts and hardware, reconstruction and simulation experts within the CMS collaboration in order to find common solutions to common problems for long-lived analyses and to encourage the adoption of new search strategies. To this end I have presented ideas for new triggers targeting signatures for Run 3 to the long-lived group and trigger experts on multiple occasions, as well as presenting new ideas for using the hadronic calorimeter (HCAL) at the CMS HCAL workshop. These have lead to dedicated studies on new triggers and analysis techniques being actively pursued by multiple groups groups. In addition, with the co-convenor of the CMS EXO long-lived group, I organised the first CMS long-lived workshop in January 2020 with discussions of common issues for LLP searches including triggering, exploiting hardware upgrades, simulation, reconstruction and the use of machine learning for LLPs. The main aim of the workshop was to strengthen dialogue between long-lived analysts, reconstruction, simulation and object experts within CMS, and external theorists and highlight new directions for long-lived particles in future runs of the LHC. The workshop was highly successful with over 100 participants and has been a starting point for multiple ongoing studies. My interest in long-lived physics expands beyond the scope of CMS and milliQan and so in Febuary 2020 I joined the LHC LLP community organising committee and helped to organise the successful LHC LLP workshop in May 2020.

I am expanding my activities in searching for long-lived particles through exploiting new techniques and final states. I have active involvement in the first search for displaced hadronic decays in the CMS muon system, a search using machine learning to look for displaced decays of sterile neutrinos, investigating possible new triggers for the upcoming run of the LHC using new handles from the CMS HCAL, and am investigating the use of timing information in searching for long-lived particles at the HL-LHC.

My interest in BSM physics extends beyond long-lived signatures during During my PhD (from 2013 – 2017) I worked on the $\alpha_{\mathrm{T}}$ analysis searching for BSM phyiscs in a final state containing jets and missing transverse momentum. The record energy reached for Run 2 of the LHC provided an excellent possibility of discovery in the first months of operation. Taking advantage of this opportunity required rapid and reliable analysis of this dataset. I held a pivotal role in ensuring the results from the $\alpha_{\mathrm{T}}$ analysis were among the first to be shown publicly with 2.3 $fb^{-1}$ of data at CERN in November 2015 and with 12.9 $fb^{-1}$ [3] of data at ICHEP16, for which I gave the successful approval talk. Despite being targeted at prompt signatures this latter search also included an interpretation of long-lived supersymmetry models. My key involvement in these analyses allowed me to gain important experience in quickly and robustly understanding and then analysing data to search for BSM physics.

## Phenomenology

As part of the MasterCode collaboration from 2012 – 2018 I developed a framework for deriving constraints from direct searches for BSM physics on GUT scale models of SUSY. This required the comprehension, implementation and validation of several searches from both the CMS and ATLAS experiments. Using this framework, I worked to show that through combining several inclusive analyses targeting different final states the sensitivity of the limit to the non-coloured sector of the SUSY spectra can be approximately removed. These ‘universal limits’ can be used to greatly reduce the time taken to sample a GUT model parameter space. Through this work, I also gained experience with event generation (PYTHIA) as well as fast detector simulation (DELPHES) [5].

In addition to my work for the mastercode collaboration I have worked on studies of the discovery potential for SUSY at future colliders and how metastable supersymmetric taus (staus), predicted in certain SUSY models to provide the observed dark matter relic density, may be discovered by experiments at the LHC [2]. This work on metastable staus was one of the first considerations of long-lived decays to taus, which is rapidly gaining in interest within the community.

My phenomenology experience has been very useful in understanding the kinds of models that are well motivated theoretically and evade current experimental limits and may be targeted in the future. I have also gained an appreciation of the information which is needed to reliably reinterpret an analysis and so which should be released in CMS publications.

In 2017, I worked with a collaborator in CMS to make a proposal for additional material to be released by CMS analyses to allow their searches to be easily reinterpreted by those outside the collaboration. This work built on my experience with the statistical framework for $\alpha_T$ as well as being informed by my work with the MasterCode collaboration. The predictions and covariances between analysis bins may be used to define a simplified likelihood to allow reinterpretation for any search. A recommendation to release this information for all analyses will be made in the SUSY and Exotica groups. This work formed the basis of a paper which looked more generally at improving the reinterpretation of likelihoods.

## Research Plans

My extensive experience in

- rapid data comprehension and analysis
- designing new search techniques and optimising sensitivity for BSM physics signatures
- building, designing and analysing data from a new dedicated experiment
- phenomenology and coordination within the long-lived community

will allow me to take a leading and pivotal role in searches for BSM physics and new experiments. As inclusive searches have failed to uncover any evidence for BSM physics, I believe the best opportunity for discovery will come from novel techniques and dedicated experiments to exploit the data produced by continued LHC operation at 13 TeV. I would like to continue searching for signatures of BSM physics using CMS data from collisions at the LHC and pursue the construction of a full scale milliQan detector.

The supervision of students both at UCSB and other institutes has formed an integral part of my work on milliQan and my recent analysis activities. I hope to continue to support the uniquely important training and development that such activities can provide. The ability to make vital contributions to projects at the forefront of physics research is vital in enouraging students to become the next generation of scientists.

Over the last three years as a Postdoctoral researcher working on CMS and milliQan I have seized the opportunity to take leading roles within both collaborations and within the wider long-lived particle community. I am eager to build on my experience to play a pivotal role in searches for BSM physics as the LHC moves into a new and exciting phase. The position at VUB provides the perfect opportunity to strengthen my activities within the milliQan collaboration and make VUB a European centre for research and development of the full milliQan detector.

## Five most important publications


[1] A. Ball et al. Search for millicharged particles in proton-proton collisions at $\sqrt{s} = 13$ TeV, 2020. Submitted to Phys. Rev. D.

[2] M. Citron et al. End of the CMSSM coannihilation strip is nigh. *Phys. Rev. D*, 2013.

[3] CMS Collaboration. Search for natural and split supersymmetry in proton-proton collisions at $\sqrt{s} = 13$ TeV in final states with jets and missing transverse momentum. *JHEP*, 2018.

[4] CMS Collaboration. Search for long-lived particles using nonprompt jets and missing transverse momentum with proton-proton collisions at $\sqrt{s} = 13$ TeV. *Phys. Lett. B*, 2019.

[5] K. J. de Vries et al. The pMSSM10 after LHC Run 1. *Eur. Phys. J. C*, 2015.