LIST OF AVAILABLE PROJECTS FOR THE JAE Intro SOMdM and JAE Intro ICU 2021 at IFCA

The IFCA MdM Unit of Excellence is offering several scholarships for introduction to research and to follow the Master's Degree in Particle Physics and the Cosmos of the Universidad Internacional Menéndez Pelayo (UIMP) and Universidad de Cantabria (UC) in the 2021-2022 course. As part of the scholarship, the student will join one of the international research groups at IFCA carrying out a research project in a topic to be chosen from the list below (a description of each of the projects is given after the table). The student can choose up to three different projects in order of priority. For general enquiries about the scholarships, please send an e-mail to mdmifca-info@ifca.unican.es indicating in the subject "JAE Intro". For specific questions about the proposed projects, please e-mail the corresponding supervisor.

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Characterization of Galactic foregrounds in polarization to unveil the Primordial Background of Gravitational Waves

Supervisor: R. Belén Barreiro (barreiro@ifca.unican.es)

The Cosmic Microwave Background (CMB) is a very weak radiation that reaches us from all the directions of the sky. It was originated shortly after the Big Bang and constitutes the oldest radiation that we can observe in the Universe. It shows tiny differences in temperature from one point to another of the sky, what give us very valuable information about the early universe and how it evolved. CMB radiation is also polarized. In particular, if we were able to detect the so-called B-mode of polarization, this would imply the existence of a Primordial Background of Gravitational Waves, as predicted in inflation. This would constitute a very solid proof of this theory as well as a major discovery in Physics.

During the last two decades, the advance in the knowledge of our Universe has been very large, partially due to the available high-quality CMB data, mainly in intensity. At present, there is a large effort dedicated to the search of the B-mode of polarization with experiments already working or planned. However, CMB observations contain not only this radiation but also a number of astrophysical signals and instrumental noise, that are mixed with the signal of interest and that must be separated from the CMB before deriving any meaningful cosmological conclusion. Therefore, a key point to analyse the CMB data is to develop specific methodology that allows one to separate and characterise the contaminants coming from our Galaxy, in particular the synchrotron and thermal dust emissions.

The student will learn about the CMB field, and would apply advanced statistical tools in order to characterize these emissions. The performance of these techniques will be tested with simulations and/or real CMB data.

Top quark Physics: Top anti-top pair production with additional jets

Supervisor: Javier Brochero (javier.brochero@cern.ch)

The Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC) has a robust program in top quark physics. The LHC, considered a top quark factory, makes possible many precise measurements of the top quark properties. In this proposal, we aim to perform a measurement of the top quark pair production cross section in association with additional jets ($t\bar{t}jj$). We will focus our attention on those $t\bar{t}jj$ events containing leptons and jets in the final state due to their relevance in the recent observation of the $t\bar{t}H$ process and the searches of new physics. We will use the latest ML developments in jets identification and event categorization.

Requirements: C++ programming experience, Python knowledge, ROOT coding basics

Study of signals with 2 leptons in the final state in the CMS detector of the LHC

Supervisor: Alicia Calderón (calderon@ifca.unican.es)

In this proposal, we seek to address whether we can study different signals with 2 leptons, and possibly jets in the final state, using data from the CMS detector of the LHC experiment. Among the different signal we have the production of a pair of W bosons, through a Higgs boson or not.
We will do a special effort on the study of the final decay with 2 leptons and 2 jets in view of understanding the sensitivity to new signal process, such the double Higgs production. It is required to have ROOT, python and C++ knowledge.

<u>Exploring the hot and energetic Universe with Athena</u>

Supervisor: Francisco Carrera (carreraf@ifca.unican.es)

The Athena mission of the European Space Agency (ESA) is a revolutionary space X-ray observatory which will provide essential data to understand many of the great mysteries of Astrophysics in the 2030s.

The Galaxies and AGN group of IFCA participates in that mission by heading the Athena Community Office, developing on board software for one of its instruments (X-IFU) and collaborating in its scientific definition, in particular evaluating its performance to detect and study obscured Active Galactic Nuclei (AGN) at times when the Universe had a fraction of its current age.

The studies for the scientific definition of Athena are performed through realistic simulations of observations by its instruments, using standard tools in X-ray Astronomy, and other tools specific to the mission.

The successful candidate will participate in the group activities, acquiring basic knowledge on Astronomy and X-ray Astronomy, getting familiar with some tools used in those topics (python, xspec, SIXTE), and learning to simulate, analyse and interpret astronomical data.

<u>Microwave Photonics-based Synthetized Image Interferometry for the Study of CMB Polarization</u>

Supervisor: Franciso J. Casas (casas@ifca.unican.es)

The measurement of the Cosmic Microwave Background (CMB) polarization is considered a unique tool to study the inflationary process of the universe, in particular by means of the B-mode polarization characterization. In order to reach the instrumental sensitivity required for that, different detection technologies can be used, depending on the frequency range. For frequencies higher than 50 GHz, bolometric technology, such as Transition Edge Sensors (TES) or Kinetic Inductance Detectors (KID) are the most suitable due to their sensitivity and capabilities of fabricating thousands of detectors in a common buffer. However, for frequencies lower than 50 GHz the use of other technologies, such us Microwave-Photonics, results very promising due to their particular capabilities offered to correlate and detect hundreds of wide-band microwave signals.

However, ground-based wide-band observations result nowadays strongly affected by the signals emitted by the increasing number of satellites launched in the frame of communication projects like “Starlink”. For this reason, it is required the implementation of instrumentation with spectral imaging capabilities, in order to filter the signal frequencies that eventually can be contaminated by these communication signals.

The proposed project is oriented towards the study of the capabilities of such technology to implement wide-band (>30%) instrumentation, for the characterization of the CMB polarization, achieving at the same time spectral measurements within its bandwidth of operation. Spectral imaging capabilities of the synthetized image interferometry will be analysed and simulated using a dedicated python code.

Searching for the most distant stars

Supervisor: José M. Diego (jdiego@ifca.unican.es)

Using recent data from the Hubble Space Telescope (BUFFALO project), the student will be searching for extremely magnified stars at cosmological distances. These stars are magnified by factors approx. 1000 due to the gravitational lensing effect. Hence their flux is approx 1000 larger and can be observed directly. The first example of this type of star was Icarus, which was discovered by our team using this technique (https://en.wikipedia.org/wiki/MACS_J1149_Lensed_Star_1), and since we have discovered six more.

As part of the BUFFALO project, we have access to proprietary Hubble data which will be used during this project to search for other stars using a technique based on image difference (looking for fluctuations between images taken in different epochs).
The student will learn the basics of gravitational lensing (bending of space-time by large masses) and get familiarized with techniques such as Fourier filtering or wavelet analysis.

Particle detection with 3D pixels in the CMS experiment

Supervisor: Jordi Duarte (duarte@ifca.unican.es)

The new 3D pixel detection technology is being tested and intensively characterized in order to be used in the innermost layers of Phase-2 Tracker system of CMS detector placed at CERN. The IFCA group, and in particular, the supervisor of this work, are an important part of this effort in the CMS collaboration. The formation and research plan for this work is lying on this field to take advantage of the knowledge and expertise of the group and the supervisor. The student will familiarize him/herself with the 3D pixel technology combining both bibliography study and observational experiments of this devices in the lab, using the usual characterization techniques. The supervisor will introduce those techniques: TCT (Transient Current Technique) to study the detector response emulating the pass of particles through the detector with lasers, and studying the detector response in the same working conditions than in the real experiment (test beam data taking). Both tools have been proven to be very useful from an educational point of view, giving to the student the insights to understand the mechanisms of the semiconductor detectors from the real research work perspective.

The student will learn the basics of those techniques, will perform TCT measurements in the lab, and will analyze real data taken from test beams with the help of the supervisor. This part of the work will allow the student to be exposed into a very important aspect in any Particle Physics research work or project: the development and use of highly specialized software.

The population of Dark Matter spikes in the Universe

Supervisor: Bradley Kavanagh (kavanagh@ifca.unican.es)

Under certain circumstances, dense Dark Matter (DM) spikes may form around black holes (BHs). These spikes can give rise to interesting observational signatures, including bright emission from the annihilation of DM or effects on gravitational waves from BH binaries. These spikes therefore represent a promising way of detecting or constraining Dark Matter, but their abundance and properties in our Universe are poorly understood.

In this project, we will study the growth of DM spikes around black holes. Using existing simulations and models of BH populations, we will determine how many BHs are likely to form spikes and what their expected properties are. In addition, we will examine the evolution and survival of these spikes over the age of the Universe. Finally, we will explore the observational consequences of these unusually dense systems of Dark Matter.

Simulating the disruption of Dark Matter miniclusters

Supervisor: Bradley Kavanagh (kavanagh@ifca.unican.es)

The axion is a light, scalar particle which is a well-motivated candidate for the Dark Matter in our Universe. Depending on their exact properties, axions may form relatively dense, gravitationally bound structures in the early Universe, known as "miniclusters". These miniclusters may be observable in microlensing surveys, or through the conversion of the axion inside them into radio photons, in the presence of strong magnetic fields. However, encounters with stars may disrupt miniclusters, spoiling our chances of detecting them.

In this project, we will study how axion miniclusters behave when perturbed by stars and how their properties are changed through these interactions. To do this, we will use and adapt existing codes to simulate the dynamics of miniclusters when the wave-like nature of the axion becomes important. With these results, we will explore the implications for the survival of axion miniclusters and for their possible observational signatures.

Use of generative adversarial neural networks to improve the simulation of quark-antiquark top pair events

Supervisor: Pablo Martínez Ruiz del Árbol (parbol@ifca.unican.es)

This project aims at exploring the usage of generative adversarial neural networks (GANN) to produce realistic simulations of quark-antiquark top pair events at the LHC accelerator. The focus of the analysis will be put on the distribution of the MT2 variable. This variable is widely used in searches for the supersymmetric partner of the top quark (stop), because it presents a sharp edge for standard model quark-antiquark top events, while it is unbounded for stops. The GANN will be trained using real data collected by the CMS experiment, targeting to improve the simulation provided by the MADGRAPH generator and the GEANT4 program. It is important to remark that most of the complexity of the searches involving top quarks in the final state, is related to the correction and assignment of the systematic uncertainties to the simulated MT2 distribution. This proposal, directly addresses this problem by trying to produce more realistic simulations using automatic learning from data. The project will require to use standard tools in the market such as Tensorflow and Keras. The results will be presented in the Third-Generation Searches groups of CMS of which I was coordinator in the past. The algorithms will be executed in the computing cluster of the High Energy Physics group at the Institute of Physics of Cantabria.

On a future combination of Planck and LiteBIRD data: gravitational lensing effect

Supervisor: Patricio Vielva (vielva@ifca.unican.es)

The cosmic microwave background (CMB) is, most probably, the observational probe that has provided a larger support to constrain the cosmological standard model. Thanks to it, we know the observable universe is about 13700 million-years-old, its spatial geometry is almost flat, and that its dynamics and evolution are governed by a 5% of ordinary matter, 27% of cold dark matter, and 68% of dark energy (responsible of the current accelerated expansion of the universe). Besides, the CMB has been also supporting some of the predictions made by the cosmic inflation mechanism, which explains several of the cosmological properties of the universe, as well as the origin of the structures nowadays observed in the cosmos. Much of our knowledge about the CMB is due to the ESA Planck mission, which mapped the CMB temperature anisotropies limited only by cosmic variance for scales above a few arcmins. However, this is not yet the case regarding the polarization anisotropies. This intrinsic characteristic of the primordial photons provides complementary information to that offered by temperature anisotropies and, in addition, it permits the detailed exploration of some physical processes, such as, for instance, the reionization of the universe, or the secondary anisotropies. The future JAXA LiteBIRD mission would be able to map the CMB polarization anisotropies, as Planck did for temperature, although for an angular resolution around two times larger.

The main objective of this work would be to study how well we could combine the Planck and LiteBIRD data sets, taking into account important aspects as the level of foregrounds contamination or instrumental properties, in order to test our capability to improve the estimation of an important cosmological probe derived from the CMB measurements: the map of the gravitational lensing effect.

<u>On the inpainting of incomplete CMB sky maps</u>

Supervisor: Patricio Vielva (vielva@ifca.unican.es)

The cosmic microwave background (CMB) is, most probably, the observational probe that has provided a larger support to constrain the cosmological standard model. Thanks to it, we know the observable universe is about 13700 million-years-old, its spatial geometry is almost flat, and that its dynamics and evolution are governed by a 5% of ordinary matter, 27% of cold dark matter, and 68% of dark energy (responsible of the current accelerated expansion of the universe). Besides, the CMB has been also supporting some of the predictions made by the cosmic inflation mechanism, which explains several of the cosmological properties of the universe, as well as the origin of the structures nowadays observed in the cosmos. The CMB is typically obtained after a component separation process on which, the information coded on several frequency observations is used to disentangle the cosmological signal from the contamination due to foreground emissions. However, despite the successful achievements reported by the CMB community, there are certain regions (e.g., the Galactic plane or areas dominated by strong point sources) which must be masked out, since the CMB recovery is very poor. This masking represents a handicap, because it introduces complicated correlations when performing harmonic analyses of the CMB: a very common approach in the field. This is particularly damaging for polarization studies, since, besides the correlations, the mask also introduces leakages between polarization modes.

The main objective of this work would be to study and characterise the performance of different inpainting techniques that try to fill-in the masked gaps in the sky with random signals, which are statistically coherent with the rest of the sky. As a test bench, we will use simulations of the future JAXA LiteBIRD missions.

<u>Radiation Tolerance of Depleted Monolithic Active Pixel Sensors using TPA-TCT technique</u>

Supervisor: Iván Vila (vila@ifca.unican.es)

Depleted Monolithic Active Pixel Sensors (DMAPS) are one emerging technology that will enable the next decade particle physics experiments. The development of a DMAPS based on a high resistivity substrate allowing the creation of a fully depleted detection volume will be studied. The detector is based on the multiple-well structure — the standard option in any modern CMOS technology. A p-type silicon substrate contains a deep n-well that acts as the signal collecting electrode. The deep n-well contains the entire pixel electronics, both PMOS (implemented directly inside the n-well) and NMOS transistors (placed inside a p-well that itself is embedded inside the n-well). By applying a reverse bias voltage to the n-well with respect to the substrate, a depletion area is created. After the passage of a charged particle through the bulk, the charge carriers created by ionization in the depleted region drift along the electric field lines towards the electrode.

The DMAPS concept overcomes the inherent limitations of charge collection by diffusion in the standard (non-depleted) MAPS design boosting its radiation tolerance. In this proposal we will characterize the radiation tolerance of several DMAPs prototypes manufactured in the context of the RD50 collaboration and irradiated with neutrons. This characterization will be carried out with using the non-linear optics TPA-TCT method developed by the IFCA instrumentation and CERN solid state detector groups. A dedicated study on the radiation-induced acceptor removal mechanisms and comparison with the current theoretical model will be also carried out.

CCD Test Chamber setup for DAMIC-M/LSC

Supervisor: Rocío Vilar (vilar@ifca.unican.es)

Understanding the nature of the Dark Matter (DM) is one of the most important topics in modern physics now a day. Many efforts are dedicated to it in the astrophysics and particle physics communities, with a whole variety of experiments that exploits the interaction of DM with matter.

One of them is DAMIC-M (DArk Matter In CCDs at Modane), based on skippers Charge Coupled Devices (CCDs) that allows to reach a readout noise well below the single electron resolutions. This performance makes these devices to get a unique sensitivity for sub-GeV dark matter candidates search. DAMIC-M will start in 3 years and will be located in the underground laboratory of Modane, France. IFCA participate in the experiment since the very beginning.

This project proposed to participate in the commissioning stage of the test chamber setup of the DAMIC-M at IFCA to study in detail the skipper CCDs sensors use in the experiment. The setup will be started from scratch mounting all the different components to get the first signal and images. This would be the main part of the project.

Once the setup is working and we understand the images and signals obtained, specific measurement for the experiment will be done. One of the main issues for these CCDs is the understanding of the Dark Current, which actually is the one of the limiting factors in the sensitivity. Measurement of the Dark Current of the CCDs under different conditions and assumptions will be study.

To analysis this data GEANT4 simulations of the setup including the geometry and materials will be develop by the student. Also the analysis of the images taken will use a DQM software already prepare but it maybe need some tuning for this specific setup.

Searches for long-lived particles at CMS

Supervisor: Jesús Vizán (vizan@ifca.unican.es)

Since the observation of a Higgs boson with a mass around 125 GeV during the Run 1 of the LHC many of its properties have been studied in detail and a large number of searches for new particles have been carried out without finding significant deviations from the Standard Model (SM) predictions. However, several theoretical considerations, like the problems for the SM to explain the observed mass of the Higgs boson in the presence of quantum corrections (hierarchy problem), motivate searching for physics beyond the SM (BSM) with the data from the Run 2 of the LHC, and also in the future Run 3 and during the High- Luminosity LHC period.

In this project, we consider the possibility that the lack of evidence for Beyond the Standard Model processes at the LHC is due to the fact that new physics phenomena manifest themselves via rare signatures due to the presence of new long-lived particles, a well-motivated possibility from the theoretical point of view. Concretely, this work will consider decays to electrons or muons of long-lived particles with mean decay lengths in the range of 5 – 500 mm approximately. This work is based on an ongoing analysis at Compact Muon Solenoid experiment, being the goal of this project to explore possible analysis improvements, such as the optimization of selection criteria either generally or for specific models.