

MSc in Theoretical Physics UAM

**Offers for MSc Theses 2026/27
Particle Physics Specialty**

(UPDATE 05/10/2026)

Neutrinos as a window to new physics

Supervisor(s): Enrique Fernández (enrique.fernandez@csic.es)

Abstract (and references): Despite being among the most abundant in the Universe, neutrinos are also the most mysterious of the particles discovered so far. The discovery of their masses, through the phenomenon of neutrino oscillations, implies that the Standard Model of particle physics—the reference framework for describing fundamental phenomena—is incomplete and must be extended. This new physics, necessary to explain the origin of neutrino masses, may be connected to other unresolved mysteries.

The objective of this project is to study the evidence for neutrino masses and mixing, as well as possible connections between the neutrino sector and other open questions, such as the nature of dark matter or the origin of the matter-antimatter asymmetry in the Universe, to which we owe our existence.

The work will involve an analytical component to understand the evidence for neutrino masses and why it implies that the Standard Model must be extended. Afterwards, depending on the student's interests, the project can be expanded in different directions. It is interesting to investigate possible connections between extensions of the Standard Model that can explain neutrino masses and other open mysteries such as dark matter or the baryonic asymmetry of the Universe. Another possible interesting project is to predict the phenomenological consequences of these extensions of the Standard Model and compare them with available data to examine their validity and forecast the ability of future experiments to investigate their existence.

Recommended subjects:

- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC)
- Open Problems of the Standard Model
- also useful: Advanced Quantum Field Theory and Astroparticle Physics

Isolated photons in pp collisions with ATLAS data

Supervisor(s): Claudia Glasman (claudia.glasman@uam.es)

Abstract:

The high-energy physics group at UAM participates in the ATLAS experiment at the LHC at CERN (Geneva). The proposed TFM will be carried out with the data from this experiment. The student will learn how to perform an analysis of experimental data using the most up-to-date tools provided for such a task, including ROOT, which is an application for statistical analysis and graphics, distributed by CERN, and which allows an exhaustive statistical analysis of experimental data. In addition, Monte Carlo techniques will be extensively used. All these tools can be classified within the framework of "Big Data" manipulation and will be used to extract the signal of photons in the final state and to compute cross sections, which are sensitive to the parton distribution functions in the proton.

In this project, it is proposed to study the production of final states with an isolated photon in association with jets. Due to the large amount of data available and the excellent performance of the ATLAS detector to identify the different particles in the final state, it is possible to study in great detail the characteristics of isolated photon production and to test the basic interactions in

nature, such as the QCD and electroweak interactions,

Previous knowledge of linux and C++ is advantageous

References:

ATLAS Collab, PLB 780 (2018) 578; e-Print: 1801.00112 [hep-ex]
ATLAS Collab, JHEP 10 (2019) 203; e-Print: 1908.02746 [hep-ex]
ATLAS Collab, JHEP 03 (2020) 179; e-Print: 1912.09866 [hep-ex]
ATLAS Collab, JHEP 07 (2023) 086; e-Print: 2302.00510 [hep-ex]

Recommended subjects:

- Obligatory courses for the specialty "Elementary Particles and Cosmology"
 - Advanced Mathematics
 - Advanced Quantum Field Theory
 - Open Problems in the Standard Model
 - Experimental Particle Physics
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Top production in pp collisions with ATLAS data

Supervisor(s): Claudia Glasman (claudia.glasman@uam.es)

Abstract:

The high-energy physics group at UAM participates in the ATLAS experiment at the LHC at CERN (Geneva). The proposed TFM will be carried out with the data from this experiment. The student will learn how to perform an analysis of experimental data using the most up-to-date tools provided for such a task, including ROOT, which is an application for statistical analysis and graphics, distributed by CERN, and which allows an exhaustive statistical analysis of experimental data. In addition, Monte Carlo techniques will be extensively used. All these tools can be classified within the framework of "Big Data" manipulation and will be used to extract the signal of top quarks in the final state and to compute cross sections, which are sensitive to the parton distribution functions in the proton.

In this project, it is proposed to study the production of final states with a pair of top quarks, which is the heaviest known particle. The production of top-antitop pairs is very high at the LHC, which can be considered as a top factory. In this way, it is possible to study in great detail the characteristics of the top-antitop pair production and to test the basic interactions in nature, such as the QCD and electroweak interactions, due to the large amount of data available and the excellent performance of the ATLAS detector to identify the different particles in the final state.

Previous knowledge of linux and C++ is advantageous

References:

ATLAS Collab, EPJC 79 (2019) 1028; e-Print: 1908.07305 [hep-ex]

ATLAS Collab, JHEP 08 (2024) 182; e-Print: 2406.19701 [hep-ex]

ATLAS Collab, Phys. Rep. 1116 (2025) 127; e-Print: 2404.10674 [hep-ex]

Recommended subjects:

- Obligatory courses for the specialty "Elementary Particles and Cosmology"
 - Advanced Mathematics
 - Advanced Quantum Field Theory
 - Open Problems in the Standard Model
 - Experimental Particle Physics
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Isolated photons in pp collisions with ATLAS data

Supervisor: Claudia Glasman (claudia.glasman@uam.es)

Abstract: The high-energy physics group at UAM participates in the ATLAS experiment at the LHC at CERN (Geneva). The proposed TFM will be carried out with the data from this experiment. The student will learn how to perform an analysis of experimental data using the most up-to-date tools provided for such a task, including ROOT, which is an application for statistical analysis and graphics, distributed by CERN, and which allows an exhaustive statistical analysis of experimental data. In addition, Monte Carlo techniques will be extensively used. All these tools can be classified within the framework of "Big Data" manipulation and will be used to extract the signal of photons in the final state and to compute cross sections, which are sensitive to the parton distribution functions in the proton.

In this project, it is proposed to study the production of final states with an isolated photon in association with jets. Due to the large amount of data available and the excellent performance of the ATLAS detector to identify the different particles in the final state, it is possible to study in great detail the characteristics of isolated photon production and to test the basic interactions in nature, such as the QCD and electroweak interactions,

Previous knowledge of linux and C++ is advantageous

References:

ATLAS Collab, PLB 780 (2018) 578
ATLAS Collab, JHEP 10 (2019) 203
ATLAS Collab, JHEP 03 (2020) 179
ATLAS Collab, JHEP 07 (2023) 086

Recommended subjects:

- Obligatory courses for the specialty "Elementary Particles and Cosmology"
 - Advanced Mathematics
 - Advanced Quantum Field Theory
 - Open Problems in the Standard Model
 - Experimental Particle Physics
-

Quantum algorithms as a tool for physical discovery

Supervisor(s): Álvaro M. Alhambra (alvaro.alhambra@csic.es)

Abstract: In this project we will investigate the possibilities of quantum computers, both present and future, to solve complex physics problems to which we currently do not have access with existing computational methods.

We will investigate quantum algorithms whose target is to approximate physical systems of many interacting quantum particles, including phenomena of non-equilibrium quantum dynamics and quantum statistical physics, such as thermal states. Among the range of algorithms to be studied are both those based on standard Trotter approximations and other modern techniques, such as quantum signal processing.

The project is of a theoretical and mathematical nature, and its purpose is to analyze the computational resources of various algorithms from an analytical perspective, using ideas from both theoretical quantum physics and various fields of mathematics, such as matrix analysis. The ultimate goal is to understand at a fundamental level the complexity of various kinds of complex quantum systems, such as those with strongly coupled electrons, for whose approximation we require quantum computers. Thus, the project is based on ideas from both fundamental physics and complexity theory, and will expose the student to modern research on both complex quantum systems and quantum computation.

References:

-Lin Lin; Dissipative preparation of many-body quantum states: Toward practical quantum advantage. *APL Computational Physics* 1 September 2025; 1 (1): 010901. <https://doi.org/10.1063/5.0283315>

-C. Rouzé, D. Stilck-Franca, and A. M. Alhambra, "Optimal quantum algorithm for gibbs state preparation", *Phys. Rev. Lett.*, vol. 136, p. 060601, Feb 2026 <https://doi.org/10.1103/lhht-svmn>

-J. Sanchez-Segovia, J. T. Schneider, and A. M. Alhambra, "High-temperature partition functions and classical simulatability of long-range quantum systems," *PRX Quantum*, vol. 6, Dec. 2025 (previous MSc project) <https://doi.org/10.1103/cww3-j1vd>

Recommended subjects: Teoría cuántica de campos, Entrelazamiento e información cuánticas

Using the Complexity of the Cosmic Web to constrain our cosmological model.

Supervisor(s): Juan Garcia-Bellido (UAM) juan.garciabellido@uam.es and Santiago Avila (CIEMAT)

Abstract:

Observations from the Large-Scale Structure (LSS) of the Universe (DESI, Euclid, LSST, etc.) are leading the current efforts to better understand the cosmological model of the Universe. Most of the current information is drawn from the 2-point statistics of the density contrast, which is easier to model. However, it is known that the LSS contains a wealth of cosmological information yet to be unravelled.

A recent proposal for an information-theoretic approach to the Cosmic Web (CW) of the Universe allows one to compute the redshift evolution of the Tidal Shannon Entropy of the four different components of the CW (i.e. clusters, filaments, walls and voids) and deduce from there the growth of fluctuations ($f\sigma_8$) and the magnitude of primordial non-gaussianities (f_{NL}) using local (coarsegrained) measurements that are not plagued by observational systematics.

The MSc project will consist of the computation of these new information-theoretic observables with full-sky N-body simulations at several redshifts (snapshots), that are already available, and thus determine the $f\sigma_8$ and f_{NL} parameters with a special control of possible systematics.

Previous knowledge of python is presumed.

References:

Physics Dark Universe (2026); e-Print: [2605.21554](https://arxiv.org/abs/2605.21554) [astro-ph.CO]

Recommended MSc subjects:

- Compulsory courses of the speciality "Elementary Particles and Cosmology"
 - Advanced Mathematics
 - Advanced Cosmology
 - Advanced Gravitation
-

Axions and ALPs model building and phenomenology

Supervisor(s): Luca Merlo (luca.merlo@uam.es)

Abstract (and references):

Axions and Axion-like particles (ALPs) have garnered significant attention in recent years due to their strong theoretical underpinnings beyond the Standard Model of particle physics. Axions, in particular, stand out as one of the most compelling solutions to the Strong CP problem, a longstanding puzzle within the Standard Model. The surge in experimental endeavors to detect these particles underscores their importance, with research efforts expected to continue for decades to come. ALPs, encompassing a broader parameter space compared to traditional Axions, are the focus of investigation, particularly at high-energy colliders. ALPs, that can eventually be considered an effective description of a solution to the Strong CP problem, emerge in a large variety of BSM contexts and have been considered as possible candidates of Dark Matter. This project can be developed in various directions, ranging from formal model building to more numerical analysis, depending on the student's interests and guided by the latest developments in the field. Some examples can be Majorons that deal with the origin of the active neutrino masses, ALPs in beam dump experiments, ALPs in flavour facilities, ALPs in finite temperature field theories...

The TFM may lead to the publication of a research article.

References:

- J. Alda, M. Fuentes Zamoro, L. Merlo, X. Ponce Diaz, and S. Rigolin, "Comprehensive ALP Searches in Meson decays," arXiv: 2507.14970 [hep-ph].
- M.B. Marcos, A. de Giorgi, L. Merlo and J.L. Tastet, "Alps and HNLs at LHC and Muon Colliders: Uncovering New Couplings and Signals," arXiv:2407.14970 [hep-ph].
- A. de Giorgi, M. Fuentes Zamoro and L. Merlo, "Visible GeV ALP from TeV Vector-Like Leptons," arXiv:2402.14059 [hep-ph].
- A. de Giorgi, L. Merlo, X. Ponce Diaz and S. Rigolin, "The Minimal Massive Majoron Seesaw Model," arXiv:2312.13417 [hep-ph].

Recommended subjects:

- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC)
- Advanced Quantum Field Theory
- Open Problems in the Standard Model

Supersymmetry Phenomenology and Machine Learning

Supervisor(s): Ernesto Arganda (ernesto.arganda@uam.es)

Abstract (and references): Supersymmetry (SUSY) still remains a very well-motivated theory [1] as a viable extension of the Standard Model (SM), that provides, among others, the following benefits: a) a solution to the hierarchy problem, b) viable unification of SM gauge couplings, c) a dark-matter (DM) candidate, and d) possible connection with string theory. However, all experimental searches carried out at the LHC by the ATLAS and CMS Collaborations have so far yielded negative results, pushing the SUSY scale to higher and higher energies. The plan of this project consists of the construction of SUSY scenarios, not yet contemplated in the LHC searches such as [2-4], in order to cover new regions of the parameter space through the development of collider search strategies for SUSY and DM particles. At the same time, the optimization of these strategies will be performed by means of the use and development of machine-learning techniques [5], both supervised and unsupervised.

[1] S. P. Martin, Adv. Ser. Direct. High Energy Phys. **21** (2010) 1-153, Adv. Ser. Direct. High Energy Phys. **18** (1998) 1-98 [hep-ph/9709356 [hep-ph]].

[2] H. Baer, V. Barger, X. Tata and K. Zhang, Symmetry **15** (2023) 2, 548 [arXiv:2212.09198 [hep-ph]].

[3] S. Baum, M. Carena, T. Ou, D. Rocha, N. R. Shah, C. E. M. Wagner, JHEP **11** (2023) 037 [arXiv:2303.01523 [hep-ph]].

[4] S. Roy, C. E.M. Wagner, JHEP **04** (2024) 106 [arXiv:2401.08917 [hep-ph]].

[5] E. Arganda *et al.*, Eur. Phys. J. C **82** (2022) 11, 993; PoS **ICHEP2022** (2022) 1226; Eur. Phys. J. C **83** (2023) 12, 1158; Phys. Rev. D **109** (2024) 5, 055032; Eur. Phys. J. Plus **139** (2024) 7, 615; JHEP **07** (2025) 014; Phys. Rev. D **113** (2026) 9, 095013.

Recommended subjects:

- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC)
 - Advanced Quantum Field Theory
 - Open Problems in the Standard Model
 - Experimental Particle Physics
 - Advanced Mathematics
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New Physics Phenomenology at the LHC

Supervisor(s): Ernesto Arganda (ernesto.arganda@uam.es), Ana Cueto (anar.cueto@uam.es)

Abstract (and references): The search for new physics beyond the Standard Model (BSM) [1] is one of the central goals of the LHC, whose ATLAS and CMS experiments have carried out an intensive program [2] since their inception. BSM models typically give rise to distinctive experimental signatures that can be tested at the LHC. The central idea of this project is to contrast the theoretical predictions of different BSM models, by means of Monte Carlo simulations, with respect to data collected by the LHC detectors at its current center-of-mass energies. For this purpose, detector-level observables from collider physics [3] will be used to develop dedicated search strategies for each of these BSM models and their experimental signatures at the LHC, in order to calculate the potential signal significance and/or to estimate the exclusion limits that could be imposed on the BSM parameter spaces.

[1] E. Gardi, N. Glover, A. Robson, "LHC Phenomenology",
<https://link.springer.com/book/10.1007/978-3-319-05362-2>

[2] <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/SearchesPublicResults>;
<https://cms-results-search.web.cern.ch/?-pt=BSM> .

[3] M. D. Schwartz, "TASI Lectures on Collider Physics", arXiv:1709.04533 [hep-ph].

Recommended subjects:

- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC)
- Advanced Quantum Field Theory
- Open Problems in the Standard Model
- Experimental Particle Physics
- Advanced Mathematics

Title: UNIMODULAR COSMOLOGICAL MODELS.

Supervisor(s): enrique alvarez vázquez (enrique.alvarez@uam.es)

Abstract (and references):

In unimodular gravity both flat spacetime (Minkowski) and de Sitter spacetime are solutions of the vacuum equations (no matter). The aim of the project is to build a semi-realistic cosmological model incorporating these characteristics.

Almost everything needed can be found in Pauli's book "Theory of Relativity" (Dover)

Recommended subjects:

Gravitation

Robust cosmology from Machine Learning the Universe

Supervisor(s): Supervisors: Santiago Ávila (CIEMAT), Violeta González Pérez (UAM)
violeta.gonzalez@uam.es

Abstract:

Cosmology is living a golden era thanks to galaxy surveys such as Euclid or DESI. The Large-Scale Structure of the Universe (LSS) contains a wealth of information capable of pinning down the correct cosmological model with high precision. However, standard methods only rely on 2-point statistics (distances among pairs of galaxies), leaving out the majority of information. The SimBIG collaboration uses artificial intelligence to learn the full likelihood of the whole distribution of galaxies in the Universe and infer the cosmological model. However, it relies on certain assumptions of galaxy formation and its relation to the dark matter distribution. The goal of this project is to test the reliability of the SimBIG approach when more complicated (and realistic) galaxy formation scenarios are in place. The student will run the SimBIG cosmological inference on simulated galaxy catalogues from the UNITsim project (led by UAM, <http://www.unitsims.org/>), based on semi-analytical models of galaxy formation. The student will have the chance to work with the international networks of UNITsim and SimBIG.

References:

SimBIG collaboration: <https://arxiv.org/abs/2310.15246>

Recommended subjects:

Advance cosmology, Computational Astrophysics

Gravitational-Wave Data Analysis of Binary Black Hole Mergers

Supervisor(s): Sachiko Kuroyanagi (sachiko.kuroyanagi@csic.es)

Abstract (and references):

The first direct detection of gravitational waves (GWs) by the Advanced LIGO detectors in 2015 opened a new window onto the Universe. This groundbreaking discovery enabled the measurement of tiny distortions in spacetime produced by the merger of two black holes located more than a billion light-years away. Since then, the global network of GW detectors has expanded with the inclusion of Virgo (2017) and KAGRA (2020), leading to the detection of a growing population of compact binary mergers. Future observatories, including the Einstein Telescope (ET) and the space-based Laser Interferometer Space Antenna (LISA), are expected to provide unprecedented sensitivities and significantly enhance our ability to explore the Universe.

The primary objective of this project is to develop skills in GW data analysis, with a particular focus on binary black hole systems. The study of GW observations offers unique opportunities to address fundamental questions in astrophysics and gravity, including the formation and evolution of black holes, the properties of their population, and possible deviations from General Relativity through modifications of GW waveform. In addition, recent observations have enabled precise tests of Hawking's area theorem, demonstrating the potential of GW data to probe fundamental aspects of black hole physics.

This project aims to extract new information from current observations of binary black hole mergers obtained by the LIGO-Virgo-KAGRA (LVK) Collaboration and/or to forecast the scientific capabilities of next-generation observatories such as ET and LISA. The work may also be extended to investigate multi-band GW observations, combining measurements from ground-based and space-based detectors.

To achieve these goals, new data-analysis techniques will be explored and developed, including the application of machine-learning methods. These approaches have the potential to improve detection efficiency, accelerate parameter estimation, and reduce computational costs in GW searches.

Recommended subjects:

- Compulsory courses of the speciality "Elementary Particles and Cosmology"
 - Advanced Cosmology
 - Advanced Gravitation
-

Schema-Based Categorization: Artificial Intelligence, Theoretical Physics and Flexible Cognition

Supervisor(s): Néstor Parga Carballeda (nestor.parga@uam.es) and Marc Pujol Ramón

Abstract (and references):

Artificial Intelligence is increasingly becoming a powerful tool for studying cognition [1]. Neural networks and generative models are not only useful for engineering applications; they also provide theoretical laboratories in which we can ask how cognitive systems build internal models of the world, organize memories, and generalize beyond previous experience [2].

This master's thesis (TFM) will investigate one central question: when does a category become more than a label? In many machine-learning approaches, categorization is treated as a classification problem: an object, stimulus, or situation is assigned to one of several possible classes. However, human and animal categories are richer than this. A concept such as “bird” does not only allow us to classify an animal; it also supports expectations about its likely features, inference about missing information, recognition of atypical cases, and even the generation of plausible new examples (imagination).

The aim of the project is to study categories as generative schemas. In this view, a category is not just a decision boundary, but a structured internal model of the regularities shared by its members. The project will use computational models inspired by modern AI, especially auto-associative memories [3] and latent-variable generative models such as variational autoencoders [4]. These models will be trained on structured feature-based data, for example simplified animal-like categories described by traits such as whether it flies or swims, whether it lays eggs, its typical habitat, locomotion pattern, and possible actions or affordances. The project will ask whether a learned category representation can support operations that go beyond classification: reconstructing incomplete examples, predicting missing features, estimating typicality, detecting atypical members, and generating new possible category members.

The project has a clear theoretical-physics component. Categories will be studied as structured regions in a latent space, where typical and atypical examples correspond to different positions relative to the learned schema. This connects naturally with ideas such as probabilistic inference, collective variables, fluctuations around a learned structure, and energy-landscape descriptions of memory and cognition.

A broader motivation comes from recent theoretical models of memory construction and consolidation, in particular the work of Spens and Burgess, where episodic memories are used to train slower generative models capable of reconstructing and organizing experience [5]. This TFM lies in the interface between theoretical physics, Artificial Intelligence, and computational neuroscience. It combines mathematical modeling, numerical simulation, and the analysis of high-dimensional representations. More broadly, it addresses how flexible cognition may emerge from learned internal models, moving beyond simple classification toward concept formation, memory reconstruction, and generalization.

References

- [1] Parga, N., Serrano-Fernández, L. and Falco-Roget, J. Emergent computations in trained artificial neural networks and real brains. *Journal of Instrumentation* 18, C02060, 2023.
- [2] Bennett, M. S. (2023). *A brief history of intelligence: evolution, AI, and the five breakthroughs that made our brains*. Harper Collins. A good popular science book about intelligence.
- [3] Parga, N. (2025). Premio Nobel de Física 2024. Descubrimientos e inventos fundamentales que impulsan el aprendizaje automático con redes neuronales artificiales. *Revista Española de Física*, 39(1), 47-53.
- [4] Kingma, D. P. and Welling, M. Auto-Encoding Variational Bayes. *International Conference on Learning Representations*, 2014.
- [5] Spens, E. and Burgess, N. A generative model of memory construction and consolidation. *Nature Human Behaviour* 8, 526–543, 2024.

Recommended subjects: Física Estadística

Dopamine, Reinforcement Learning and the Physics of Intelligent Control

Supervisor(s): Néstor Parga Carballada (nestor.parga@uam.es) and Joan Falcó-Roget

Abstract (and references):

A central idea in modern neuroscience and Artificial Intelligence is that intelligence is not only the ability to choose actions, but also the ability to regulate internal states. An intelligent system must decide what to remember, how much effort to invest, when uncertainty matters, and how to allocate limited computational resources.

This MSc thesis (TFM) will study this problem through a theoretical model of dopamine, motivation and working memory. Dopamine is often interpreted as a reward-prediction signal that is used for learning [1], but experimental results suggest that it also reflects motivation and cognitive effort. In particular, in a working-memory task, dopamine activity shows a ramping signal during the delay period, even though no new stimulus or reward is presented [2]. This raises a fundamental question: what is dopamine evaluating during memory maintenance?

The project will approach this question from the perspective of theoretical physics and reinforcement learning (an important machine learning theory, [1]). The main idea is to treat working memory as a noisy dynamical variable that can be stabilized by internal control. Maintaining a precise memory improves future decisions, but it also has a cost. Motivation changes the effective cost of this control. In this framework, a dopamine-like signal may reflect the value of investing resources to preserve information.

The TFM will first study a minimal model with memory degradation, control, cost and future reward. The goal is to test whether a ramping dopamine-like signal can emerge from the dynamics of the system. A more complete version may include motivation, belief updating, contraction bias and actor–critic reinforcement learning.

The project connects naturally with broad questions about the evolution of intelligence [3]. Reinforcement-learning principles may have become useful not only for learning external actions, but also for regulating internal cognitive processes such as memory, attention and effort. From a physics perspective, the project studies intelligence as the control of a noisy dynamical system under resource constraints.

This TFM is suitable for someone interested in theoretical physics, AI and computational neuroscience. The work will involve mathematical modelling, artificial intelligence and the analysis of dynamical systems.

References

- [1] Parga, N., Serrano-Fernández, L. and Falcó-Roget, J. Emergent computations in trained artificial neural networks and real brains. *Journal of Instrumentation* 18, C02060, 2023.
 - [2] Sarno, S., Falcó-Roget, J., Parga, N., et al. Dopaminergic activity during a vibrotactile working-memory task. *Proceedings of the National Academy of Sciences*, 2022.
 - [3] Bennett, M. S. *A Brief History of Intelligence: Evolution, AI, and the Five Breakthroughs That Made Our Brains*. HarperCollins, 2023. A good popular science book about intelligence.
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Neutrino–dark matter interactions and the extragalactic neutrino flux

Supervisor(s): Pedro de la Torre Luque (pedro.delatorre@uam.es), Marina Cermeno (marina.cermeno@upm.es)

Abstract (and references): The nature of dark matter (DM) remains one of the biggest mysteries in physics today. Despite extensive searches, its particle nature and possible interactions with the Standard Model remain unknown. High-energy astrophysical neutrinos provide a unique way of probing such interactions over cosmological distances.

Recent measurements by the IceCube Collaboration indicate that the extragalactic neutrino spectrum is better described by a broken power law than by the single power law traditionally assumed. This newly observed spectral structure provides an interesting opportunity to investigate whether interactions between neutrinos and dark matter could leave observable signatures in the diffuse neutrino flux.

The objective of this project is to study how neutrino–DM interactions modify the extragalactic neutrino flux and to use current IceCube measurements to constrain the strength of these interactions. The student will first investigate neutrino propagation through the cosmological dark-matter distribution and calculate the resulting attenuation of the neutrino flux. The analysis will consider both a model-independent effective-field-theory framework and specific particle-physics models motivated by extensions of the Standard Model. The predicted spectra will then be compared with current observations to derive constraints on the interaction strength.

If time allows, the project can be extended to investigate whether neutrino–DM interactions could themselves produce the spectral curvature or break recently identified by IceCube. This would allow the student to explore whether this feature could provide evidence for new physics beyond the Standard Model and to assess the prospects for future neutrino experiments to probe such interactions.

The project will be carried out within the research activities of the DArk Matter, AStroparticles and COsmology (DAMASCO) group at the UAM Department of Theoretical Physics and the Institute for Theoretical Physics (IFT UAM-CSIC). DAMASCO's research covers indirect searches for dark matter, high-energy neutrino and cosmic-ray astrophysics, numerical cosmological simulations, gamma-ray astronomy, and multi-messenger astrophysics. The group is involved in the Fermi-LAT, CTAO, GRAND, GCOS and DESI collaborations and has an extensive network of collaborations with experts in astroparticle physics and cosmology. Further information about the team and its research activities: [DAMASCO group](#)

Recommended subjects:

- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC)
- Astroparticle Physics
- Open Problems of the Standard Model
- Also useful: Knowledge on Python or Mathematica

References:

- IceCube Collaboration (2025), arXiv:2507.22233
- Argüelles et al. (2017), arXiv:1703.00451

- Zathul et al. (2026), arXiv:2606.00249
 - Xie et al. (2026), arXiv:2604.07824
 - Manzari et al. (2025), arXiv:2508.00725
-

Phenomenology of BSM Higgs with Effective Field Theories (SMEFT and HEFT)

Supervisor(s): Maria Jose Herrero (IFT/UAM) and Roberto Morales (IFLP/CONICET)

Abstract (and references):

Since the discovery of the Higgs boson there has been no clear evidence of new physics beyond the Standard Model (SM) of Particle Physics. In absence of any experimental signal of new fundamental particles, resonances, interactions, nor distortions from SM interactions, the most appropriate tool for studying Beyond Standard Model (BSM) physics is mostly agreed to be provided by the Effective Field Theory (EFT) approach. This Master Thesis will be focused in particular on the EFT approach to describe BSM Higgs physics and will assume that the potential new physics appears exclusively in the bosonic sector, including both the scalar and the gauge boson sectors. The focus will be set on the two most frequently employed EFTs for tests of BSM Higgs physics at colliders: the so-called HEFT (Higgs Effective Field Theory) and the SMEFT (Standard Model Effective Field Theory). The advantage of using EFTs is that they allow for tests of the BSM Higgs physics in a model independent way, i.e without assuming a particular underlying fundamental theory which operates at the ultraviolet (UV) high energy, this being generically called Λ . At low energies compared to Λ , the information of the new Higgs physics is encoded in an effective Lagrangian that is written in terms of a set of effective operators, these being built with the SM fields (here the bosonic fields) and with the unique requirement of being invariant under the SM gauge symmetry, $SU(3) \times SU(2) \times U(1)$. The coefficients in front of these operators (usually called Willson coefficients) are generically unknown and encode the information of the particular underlying fundamental theory. One of the most important differences among the two EFTs is the representation of the Higgs particle respect to the $SU(2)$ group. In the SMEFT the scalar fields (both the Higgs and the would be Goldstone bosons) are assumed to be in a linear representation of the electroweak symmetry group, specifically in a doublet of $SU(2)$, and the criterium to order the SMEFT effective operators is by increasing their canonical dimension. In the HEFT the Higgs boson is a singlet under all symmetries (including $SU(2)$) whereas the would be Goldstone bosons are placed in a non-linear representation of $SU(2)$, usually by an exponential function. The HEFT effective operators are ordered differently, by their chiral dimension which counts the powers of momenta and bosonic masses (m_H , m_W and m_Z , in the present case). The main objective of this proposal of Master Thesis is to explore which kind of phenomenological tests can be done at the colliders, in particular at the LHC, to disentangle the singlet/doublet Nature of the BSM Higgs Physics, by means of the predictions within these two different EFTs. The study of

different patterns expected in multiple Higgs production at LHC by these two EFTs may help in these tests of the singlet/double Higgs Nature.

References:

1) HEFT's appraisal of triple (versus double) Higgs weak boson fusion
By Anisha, D.Domenech, C.Englert, M.J.Herrero and R.A.Morales,
Phys. Rev. D 111, no.5, 055004 (2025)
[arXiv:2407.20706 [hep-ph]].

2) Bosonic multi-Higgs correlations beyond leading order
By Anisha, D.Domenech, C.Englert, M.J.Herrero and R.A.Morales,
Phys. Rev. D 110, no.9, 095016 (2024)
doi:10.1103/PhysRevD.110.095016
[arXiv:2405.05385 [hep-ph]].

3) Exploring correlations between HEFT Higgs couplings k_V and k_{2V} via HH production at e^+e^- colliders.
By J.M.Davila, D. Domenech, M.J.Herrero and R.A.Morales
Eur.Phys.J.C 84 (2024) 5, 503
[arXiv:2312.03877]

4) Double Higgs boson production at TeV e^+e^- colliders with effective field theories: Sensitivity to BSM Higgs couplings
By D.Domenech, M.J. Herrero, R.A. Morales and M.Ramos, doi:10.1103/PhysRevD.106.115027
[arXiv:2208.05452 [hep-ph]]. Phys. Rev.D 106, no.11, 115027 (2022)

Recommended subjects:

- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC). (QFT and SM in particular).
- Advanced Quantum Field Theory
- Open Problems in the Standard Model

Recommended tools:

Effective Field Theories for BSM Higgs Physics. Specifically:
the Bosonic Sector of the HEFT and the SMEFT. Computational Techniques for BSM signals at Colliders. Python, Mathematica, MadGraph.

Novel Strategies for the Validation of Heavy-Flavor Reconstruction and Identification Algorithms in CMS experiment

Supervisor(s): Juan Pablo Fernández Ramos (CIEMAT), Isabel Josa Mutuberría (CIEMAT)
[juanpablo.fernandez@ciemat.es , isabel.josa@ciemat.es]

Abstract (and references): This Master's Thesis focuses on novel validation strategies for CMS heavy-flavor reconstruction and identification algorithms (charm- and bottom-initiated jets) using heavy-quark bound states (J/ψ , Υ and D and B hadrons) . The student will develop analysis tools, study simulated and collision data, and investigate anomalies found during validation. The goal is to improve the reliability of the tools used for precision measurements and searches for new physics.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Open Problems in the Standard Model
 - Experimental Particle Physics
-

Title: A study of the SM Higgs boson in the WW to $2l2\nu$ decay channel at the CMS experiment using Run 3 data

Supervisor(s): Dermot Moran (CIEMAT), Javier Brochero (CIEMAT)
[Dermot.Moran@ciemat.es , javierandres.brochero@ciemat.es]

Abstract (and references): The discovery of the Standard Model (SM) Higgs boson, with a mass close to 125 GeV, by the CERN LHC experiments ATLAS and CMS in 2012 represented a major breakthrough in particle physics. Since then, the Higgs boson has been studied in a number of production and decay channels, including H to WW to $2l2\nu$.

This project will study the Higgs boson signal in the H to WW to $2l2\nu$ channel using CMS Run 3 data, with the aim of measuring its production cross section. The analysis will involve the optimisation of the event selection, the study and estimation of the main SM backgrounds, and the extraction of the Higgs boson signal using kinematic or multivariate discriminating techniques. Control regions will be used to validate the modelling and predictions of the main backgrounds.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - - Advanced Quantum Field Theory
 - Open Problems in the Standard Model
 - Experimental Particle Physics
-

Study of SM processes in dilepton final states with the CMS Detector at 13.6 TeV

Supervisor(s): Javier Brochero (CIEMAT), Dermot Moran (CIEMAT)

[javierandres.brochero@ciemat.es , Dermot.Moran@ciemat.es]

Abstract (and references): CERN is home to the most powerful particle collider ever built, the Large Hadron Collider (LHC). CIEMAT is involved in one of its four main experiments, the Compact Muon Solenoid (CMS). During Run 3 (2022–2026), the LHC has delivered an unprecedented amount of data at a centre-of-mass energy of 13.6 TeV, including a large number of top-quark pair events, allowing increasingly precise measurements of Standard Model (SM) processes.

This project proposes to study the dilepton final state, with the goal of simultaneously measuring the production cross sections of $t\bar{t}$ and another SM process, such as Z +jets or diboson production. In this analysis, the student will become familiar with the main tools and techniques used in experimental particle physics, including the analysis of data, simulated samples, event selection, background estimation, and the treatment of systematic uncertainties. Machine-learning techniques may also be explored to optimize the event selection.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - - Advanced Quantum Field Theory
 - Open Problems in the Standard Model
 - Experimental Particle Physics
-

Búsquedas de nueva física en el experimento CMS del LHC

Supervisor(s): Alberto Escalante del Valle (CIEMAT) [alberto.escalante@ciemat.es]

Abstract (and references): Este Trabajo de Fin de Máster se centrará en la búsqueda de nueva física más allá del Modelo Estándar, con especial atención a la producción y detección de partículas de larga vida (long-lived particles, LLPs) cuyos tiempos de vida dan lugar a desplazamientos macroscópicos antes de su desintegración. Este tipo de partículas aparece de forma genérica en una amplia variedad de escenarios de física más allá del Modelo Estándar, como consecuencia de acoplamientos débiles, escalas de masa jerárquicas o simetrías aproximadamente conservadas, y puede dar lugar a firmas experimentales poco convencionales. En este contexto, el trabajo estudiará y desarrollará estrategias de búsqueda en el experimento CMS del Large Hadron Collider (LHC), centrándose en señales compatibles con modelos de sectores oscuros que producen partículas de larga vida y estados finales de

baja energía, cuyas características dificultan su reconstrucción, identificación y selección mediante las técnicas de análisis convencionales.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Advanced Quantum Field Theory
 - Open Problems in the Standard Model
 - Experimental Particle Physics
-

Search for Dark Matter with the DEAP-3600 Experiment

Supervisor(s): Roberto Santorelli (CIEMAT) [roberto.santorelli@ciemat.es]

Abstract (and references): The nature of dark matter is one of the major open questions in fundamental physics. Although its existence is supported by extensive astrophysical and cosmological evidence, the particles that constitute it and the way they interact with ordinary matter remain unknown.

This Master's thesis project proposes a search for dark matter using data from the DEAP-3600 experiment, a detector containing approximately 3.3 tonnes of liquid argon and located at the SNOLAB underground laboratory in Canada. The study will focus on unconventional signatures that may not have been identified in standard analyses. As a case study, the project will consider Inelastic Boosted Dark Matter (iBDM) models, in which energetic dark-sector particles can produce multiple spatially separated energy deposits within the detector. This distinctive topology provides a promising way to distinguish a potential dark matter signal from the experimental background.

The work will combine the analysis of real data with Monte Carlo simulations to characterize the expected signal, search for compatible events, and evaluate the sensitivity of DEAP-3600 to different dark matter scenarios.

The project provides training in particle physics and astroparticle physics, data analysis, simulation, and low-background experimental techniques. It is particularly suitable for students interested in pursuing a PhD in the field.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Open Problems in the Standard Model
 - Experimental Particle Physics
-

Correlación del nivel de radón en el Laboratorio Subterráneo de Canfranc con datos de estaciones meteorológicas colindantes usando técnicas de inteligencia artificial.

Supervisor(s): Vicente Pesudo Fortes (CIEMAT) [Vicente.Pesudo@ciemat.es]

Abstract (and references): El nivel de radón en laboratorios subterráneos impone limitaciones en la sensibilidad que los experimentos allí emplazados tienen a eventos raros. Estos niveles tienen patrones de estacionalidad y así como otras variaciones de menor periodo cuya explicación se supone correlacionada con la meteorología exterior. Esta causalidad, sin embargo, no ha sido establecida. Los cientos de metros de roca actúan como un filtro mitigando y retrasando el impacto y estudios anteriores no tenían acceso a nuevos datos meteorológicos recolectados en las montañas cercanas al LSC. El/la estudiante usará diferentes técnicas de machine learning (redes neuronales, random forest, boosted decision trees y otras) para correlacionar los datos en superficie a los que recién hemos tenido acceso y los niveles de radón y otras variables ambientales en el LSC.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Open Problems in the Standard Model
 - Experimental Particle Physics
-

Sensitivity studies of lepton-flavour-violating processes at future colliders

Supervisor(s): Cristina Martín Pérez (CIEMAT), María Cepeda Hermida (CIEMAT)

[Cristina.Martin@ciemat.es , maria.cepeda@cern.ch]

Abstract (and references): This Master's Thesis aims to study the sensitivity of the Future Circular Collider in its electron-positron phase (FCC-ee) to lepton flavour violating (LFV) decays of the Higgs and Z bosons, such as $H/Z \rightarrow e \mu$, $H/Z \rightarrow e \tau$ y $H/Z \rightarrow \mu \tau$. These processes are practically forbidden in the Standard Model but are predicted to occur at observable rates in several scenarios of new physics. The student will analyze simulated signal and background samples, develop event selection and optimisation strategies to maximize the sensitivity of the analysis, and estimate the FCC-ee potential for discovery and exclusion. The project will provide training in Monte Carlo simulations, event reconstruction, statistical analysis and modern analysis tools used in high-energy physics, offering a comprehensive introduction to experimental physics at future colliders.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Advanced Quantum Field Theory
 - Open Problems in the Standard Model
 - Experimental Particle Physics
-

Assembly and validation of the photodetectors for the Deep Underground Neutrino Experiment (DUNE)

Supervisor(s): Clara Cuesta Soria (CIEMAT)

[clara.cuesta@ciemat.es]

Abstract (and references): The Deep Underground Neutrino Experiment (DUNE) requires a highly efficient light detection system for the reconstruction of neutrino interactions in liquid argon. This Master's Thesis focuses on the mass assembly and validation of the photodetectors, known as X-ARAPUCAs, at the CIEMAT cryogenics laboratory. First, the X-ARAPUCAs will be assembled. These devices are capable of collecting the ultraviolet light produced by interactions in liquid argon, shifting it to the visible range, and guiding it towards silicon photomultipliers (SiPMs), where it is ultimately detected, all within a highly reflective module. The validation, carried out in liquid nitrogen, will allow the correct operation of each photodetector to be individually verified and relevant response parameters, such as the gain, to be determined through the analysis of the data collected in the laboratory. The photodetectors will subsequently be installed in the DUNE experiment, located at the Sanford Underground Research Facility (SURF), in South Dakota, USA.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Experimental Particle Physics
-

Machine-learning reconstruction of neutrino interactions using scintillation light in the SBND experiment

Supervisor(s): José Ignacio Crespo Anadón (CIEMAT)

[jcrespo@ciemat.es]

Abstract (and references): The SBND experiment is a liquid argon time projection chamber (LArTPC) detector located just 110 m from the source of the BNB neutrino beam at Fermilab (United States) taking data since 2024. SBND's physics program encompasses searches for

sterile neutrinos and other physics beyond the Standard Model, precision measurements of neutrino-nucleus interactions, and the development of LArTPC technology. Featuring the most advanced light-detection system of its kind, SBND can reconstruct interactions with centimeter-level spatial precision and nanosecond-level timing precision. This work will explore the use of neural networks with state-of-the-art architectures to improve scintillation light reconstruction, enhancing the experiment's sensitivity to new physics.

Bibliography:

SBND Collaboration. Scintillation light in SBND: simulation, reconstruction, and expected performance of the photon detection system. Eur. Phys. J. C 84, 1046 (2024). <https://doi.org/10.1140/epjc/s10052-024-13306-3>

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Experimental Particle Physics
 - Open Problems in the Standard Model
-

LiquidO: Una nueva tecnología para la Detección de Neutrinos

Supervisor(s): Diana Navas Nicolás (CIEMAT), Carmen Palomares Espiga (CIEMAT)

[diana.navas@ciemat.es , mc.palomares@ciemat.es]

Abstract (and references): Las incógnitas abiertas en física de neutrinos exigen enormes detectores ($> \text{kton}$), con gran resolución energética y que sean capaces de distinguir las partículas resultantes de la interacción del neutrino. Un detector con estas características basado en un diseño simple y no muy costoso supondría un avance enorme para este campo. LiquidO es una nueva tecnología basada en el uso de líquido centellador opaco y fibras centelladoras que es capaz de identificar neutrinos de baja energía, distinguir neutrinos de anti-neutrinos y conocer su punto de interacción con gran precisión, resolviendo las limitaciones del método tradicional de detección (centellador transparente).

El trabajo propuesto se integra en el primer experimento que se está llevando a cabo con la tecnología LiquidO: un detector de 10 toneladas que tiene como objetivo principal monitorizar un reactor nuclear usando por primera vez los anti-neutrinos generados en las reacciones de fisión.

Consiste en el análisis de datos de un prototipo de ~60 litros, donde se probarán los diferentes componentes, y del análisis de datos simulados del detector final. El trabajo tiene lugar en el entorno de una colaboración internacional en la que participan institutos de investigación y universidades de Francia, Gran Bretaña, Portugal y Alemania.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
- Experimental Particle Physics
- Open Problems in the Standard Model

Study of the performance of the HERD space mission for the measurement of high-energy cosmic-ray electrons

Supervisor(s): Miguel Angel Velasco Frutos (CIEMAT), Jorge Casaus Armentano (CIEMAT)
[MiguelAngel.Velasco@ciemat.es , Jorge.Casaus@ciemat.es]

Abstract (and references): Precision measurements of cosmic-ray fluxes performed by experiments on space-based platforms allows to address fundamental questions such as their origin and propagation, the nature of dark matter, and the possible existence of primordial antimatter.

Current observations of electron and positron fluxes cover an energy range from a few hundred MeV up to a few TeV. These measurements reveal features that cannot be fully explained by conventional models of the origin and transport of cosmic rays in the Galaxy.

The HERD experiment, which is scheduled to be installed on the Chinese Space Station (CSS) in 2029, will significantly increase the available statistics of electrons and positrons and extend existing measurements to energies of tens of TeV. To achieve these goals, HERD will be equipped with several specialized subdetectors capable of accurately determining the properties of the incoming particles. Among them, the electromagnetic calorimeter will play an essential role, as it will provide a precise measurement of the particle energy and an efficient electron and positron discrimination from the dominant proton background. This work will study the response and performance of the calorimeter in order to assess its capability to fulfill the scientific objectives of the mission.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Experimental Particle Physics
 - Open Problems in the Standard Model
 - Astroparticle Physics
-

Búsquedas de ondas gravitacionales en datos de Virgo usando métodos basados en correlaciones no lineales.

Supervisor(s): Carlos Delgado Méndez (CIEMAT), Pablo García Abia (CIEMAT)

[carlos.delgado@ciemat.es , pablo.garcia@ciemat.es]

Abstract (and references): Este TFM se llevará a cabo en el grupo de Ondas Gravitacionales del CIEMAT, cuyos miembros contribuyen al análisis de datos tomados por el experimento VIRGO.

El trabajo se centra en el desarrollo y caracterización de un método estadístico para la detección de ondas gravitacionales sin basarse en plantillas de filtros coincidentes. El método se basa en estimadores de correlaciones no lineales aplicados a datos de interferometría. Se probará usando datos reales provenientes del detector VIRGO, con sucesos confirmados de Compact Binary Coalescence (CBC) para determinar las capacidades de detección y su sensibilidad. Este estudio tiene como objetivo determinar el potencial del método para identificar señales transitorias pobremente (o no) modeladas.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Experimental Particle Physics
 - Open Problems in the Standard Model
 - Cosmology and Gravitation
-

Measurement of Baryon Acoustic Oscillations from the DES MagLim sample

Supervisor(s): Anna Porredon (CIEMAT), Santiago Ávila (CIEMAT)

[annamaria.porredon@ciemat.es SantiagoJ.Avila@ciemat.es]

Abstract (and references): Baryon Acoustic Oscillations (BAO) provide one of the most robust standard rulers in observational cosmology, enabling precise measurements of the expansion history of the Universe and offering stringent constraints on cosmological models. In particular, they can help discern whether dark energy is a cosmological constant or is dynamical. While spectroscopic galaxy surveys have traditionally delivered the most accurate BAO measurements, the growing volume and depth of modern photometric surveys present an opportunity to extend these analyses to significantly larger galaxy samples. The Dark Energy Survey (DES) has produced high-precision BAO measurements using a galaxy sample specifically optimized for this measurement [1, 2].

The main goal of this TFM is to measure the BAO signal using the DES MagLim sample [3], which was instead optimized for the joint analysis of galaxy clustering and weak lensing. The resulting BAO measurements will be compared with other works in the literature and with the Cosmic Microwave Background observations. This work will contribute to understanding the trade-offs between sample optimization and scientific versatility. The results will help assess the potential of unified photometric galaxy samples for future cosmological analyses and inform strategies for upcoming large-scale imaging surveys like Euclid and the Rubin Observatory Legacy Survey of Space and Time.

Bibliography:

- [1] J. Mena-Fernández et al., Dark Energy Survey: Galaxy sample for the baryonic acoustic oscillation measurement from the final dataset (2024)
- [2] DES Collaboration, Dark Energy Survey: A 2.1% measurement of the angular baryonic acoustic oscillation scale at redshift $z_{\text{eff}}=0.85$ from the final dataset (2024)
- [3] Porredon et al., Dark Energy Survey Year 3 results: Optimizing the lens sample in a combined galaxy clustering and galaxy-galaxy lensing analysis (2021)

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Open Problems in the Standard Model
 - Advanced Cosmology
-

Discovering the Laws of the Universe with Symbolic Regression

Supervisor(s): Shahab Joudaki (CIEMAT), H. Desmond (U. Portsmouth, UK)

[shahab.joudaki@ciemat.es]

Abstract (and references): Symbolic regression (SR) is a machine learning technique that aims to discover the physical equations governing scientific data. Unlike many standard machine learning techniques, it does not provide black-box predictions, but instead produces interpretable mathematical expressions. As a result, while already a mature field in computer science, it is now gaining traction in astrophysics (e.g. arXiv:2202.02306, 2211.11461, 2410.14623). This project aims to develop, adapt and apply SR methodology to current open problems in astrophysics and cosmology. Depending on the student's interest, this may involve methodological improvements to existing SR methods, synergizing distinct approaches, applying existing SR methods to learn the physical laws generating astrophysical data, and/or developing symbolic emulators to expedite cosmological inference. A concrete first target may be to integrate SR-based emulators for the cosmological matter power spectrum into the likelihood functions used in state-of-the-art cosmological surveys and characterize the improvements they afford over traditional methods.

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"

- Open Problems in the Standard Model
 - Advanced Cosmology
-

Probing scalar-field dark energy with DESI Baryon Acoustic Oscillations and ShapeFit measurements

Supervisor(s): Carlos García García (CIEMAT), Eusebio Sánchez Alvaro (CIEMAT)

[carlos.garcia2@ciemat.es , eusebio.sanchez@ciemat.es]

Abstract (and references): DESI has found evidence, at the $\sim 4\sigma$ level, that dark energy may not be described by a cosmological constant, but could instead evolve with time. One of the simplest ways of producing dynamical dark energy is through a cosmologically evolving scalar field. Recent studies have shown that, under this hypothesis, the data favour models more complex than a minimally coupled canonical scalar field, requiring either a non-minimal coupling to curvature or a non-standard kinetic term. However, these models can modify the effective strength of gravity and therefore affect the formation of cosmological structure.

In this Master's project, the student will use DESI measurements of Baryon Acoustic Oscillations and the galaxy power spectrum to simultaneously study the expansion history and the growth of structure in the Universe. This type of analysis has recently been performed using eBOSS data, finding no significant tensions, and this project will update those results using the latest DESI DR1 data (or DESI DR2, if available).

The project will require developing the infrastructure needed to use ShapeFit parameters in dynamical dark energy models. ShapeFit compresses the information contained in the galaxy power spectrum into a small number of observables that characterise its geometry, growth, and shape. In particular, a method will be implemented to extract the smooth component of the power spectrum without assuming a Λ CDM form, thereby allowing ShapeFit measurements to be consistently interpreted in scalar-field and modified-gravity models. Finally, cosmological and scalar-field parameters will be inferred and the resulting constraints compared with those previously obtained using eBOSS data.

References:

- Scalar-field dark energy: arXiv:2607.07777 (and references therein)
- DESI DR2 results: arXiv:2503.14738
- DESI DR1 Full Shape and ShapeFit: arXiv:2411.12021 (and references therein)

Recommended subjects:

- Obligatory courses for the speciality "Elementary Particles and Cosmology"
 - Open Problems in the Standard Model
 - Advanced Cosmology
-

The Standard Model Effective Field Theory: Foundations and Applications

Supervisor(s): Pier Paolo Giardino (pier.giardino@uam.es)

Abstract (and references): Despite the remarkable success of the Standard Model of particle physics, compelling evidence indicates that it cannot be the ultimate description of Nature. The absence of direct discoveries of new particles at the LHC has made Effective Field Theory one of the central theoretical frameworks for searching for new physics through precision measurements.

The first objective of this project is to introduce the Standard Model Effective Field Theory (SMEFT) and understand how new heavy or light degrees of freedom can modify the interactions of known particles. The work will involve an analytical component to study the construction of effective operators, their symmetry properties, and their phenomenological interpretation in Higgs and electroweak physics.

Afterwards, the project can develop in different directions depending on the student's interests. Possible topics include the study of Higgs and electroweak observables at the LHC and future colliders, the matching of explicit dark matter models onto SMEFT, effective theories containing new light particles such as light dark matter or axion-like particles, or the role of effective operators in scenarios of electroweak baryogenesis and the matter-antimatter asymmetry of the Universe. The TFM combines theoretical methods with phenomenological applications and may naturally evolve toward a research project depending on the student's interests and progress.

References:

- C. P. Burgess, "Introduction to Effective Field Theory," arXiv:hep-th/0701053 [hep-th]
- B. Grzadkowski, M. Iskrzynski, M. Misiak and J. Rosiek, "Dimension-Six Terms in the Standard Model Lagrangian," arXiv:1008.4884 [hep-ph]
- L. Bellafronte, S. Dawson, C. Del Pio, M. Forsslund and P. P. Giardino, "Higgs decays at NLO in the SMEFT," arXiv:2601.09599 [hep-ph]
- G. Isidori, F. Wilsch and D. Wyler, "The standard model effective field theory at work," arXiv:2303.16922 [hep-ph]

Recommended subjects:

- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC)
 - Advanced Quantum Field Theory
 - Open Problems in the Standard Model
 - Advanced Mathematics
-

Observational forecasts and cosmological constraints of non-linear electrodynamics

Supervisor(s):

Savvas Nesseris (savvas.nesseris@csic.es) & Ziad Sakr (ziad.sakr@ift.csic.es)

Abstract:

Current and future cosmological surveys, such as Euclid, LSST (Rubin), and SphereX, will measure the expansion history and the growth of cosmic structure with unprecedented precision, providing powerful opportunities to test extensions of the standard cosmological model and fundamental physics. Non-linear modifications of electromagnetism can affect the propagation of photons over cosmological distances and consequently modify the relation between theoretical cosmological quantities and their observational determination. Such effects may therefore be constrained through a combination of complementary cosmological probes.

In this project, we will investigate the observational prospects for constraining cosmological effects arising from non-linear electrodynamics. Starting from a phenomenological description of the modifications to electromagnetic propagation, we will study their impact on observables associated with the Cosmic Microwave Background, Baryon Acoustic Oscillations and large-scale structure, and Type Ia supernovae. Fisher-matrix and other similar statistical techniques will be used to forecast the sensitivity of current and forthcoming surveys to the relevant parameters and to identify possible degeneracies with standard cosmological parameters. Particular attention will be given to the complementarity between different probes and to determining which future observations are most capable of testing departures from standard Maxwell electrodynamics.

References:

- [1] Martinelli et al., <https://arxiv.org/abs/2007.16153>
- [2] Vacher et al., <https://arxiv.org/abs/2207.03258>
- [3] Minazzoli et al., <https://arxiv.org/abs/1404.4266>
- [4] Aizpuru et al., <https://arxiv.org/abs/2106.00428>

Recommended subjects:

- Obligatory courses for the specialty "Elementary Particles and Cosmology"
 - Advanced Mathematics
 - Advanced Cosmology
 - Advanced Gravitation
-

Theoretical aspects of the effects of non-linear electrodynamics in cosmology

Supervisor(s):

Savvas Nesseris (savvas.nesseris@csic.es)

Abstract:

Non-linear electrodynamics provides a well-motivated extension of standard Maxwell theory in which the electromagnetic Lagrangian is allowed to depend non-linearly on the electromagnetic field invariants. Such theories arise in a variety of contexts, including effective field theories and models inspired by high-energy physics, and can lead to modifications of the propagation and evolution of electromagnetic fields in an expanding Universe. These effects may in turn leave characteristic signatures in cosmological observables, making it important to understand their theoretical foundations and their behaviour in different physical regimes.

In this project, we will investigate the theoretical and mathematical consequences of non-linear electrodynamics in a cosmological background. Particular emphasis will be placed on deriving the modified field equations and studying the propagation of electromagnetic waves using analytical approximation schemes, as well as exploring extensions in which the Lagrangian depends on both electromagnetic invariants, i.e. $F_{\mu\nu}F^{\mu\nu}$ and $F_{\mu\nu}\tilde{F}^{\mu\nu}$, including both the usual field strength tensor $F_{\mu\nu}$, and also its dual $\tilde{F}_{\mu\nu}$. Different classes of non-linear electrodynamics models and their cosmological implications will be analysed, complemented where appropriate by numerical studies of the resulting evolution equations. The project will combine analytical calculations with numerical exploration in order to identify the main physical effects and assess the regimes in which departures from standard electromagnetism could become relevant.

References:

- [1] Misner, Thorne, Wheeler, Gravitation, section 22.5.
- [2] de Felice & Tsujikawa, <https://arxiv.org/abs/2410.00314>
- [3] Vacher et al., <https://arxiv.org/abs/2207.03258>
- [4] Uzan, <https://arxiv.org/abs/2410.07281>
- [5] Sotiriou et al, <https://arxiv.org/abs/0805.1249>
- [6] Minazzoli et al., <https://arxiv.org/abs/1404.4266>

Recommended subjects:

- Obligatory courses for the specialty "Elementary Particles and Cosmology"
 - Advanced Mathematics
 - Advanced Cosmology
 - Advanced Gravitation
-

Probing Exotic Corners of Holography with Branes

Supervisor: Fien Apers (fien.apers@uam.es)

Abstract: Holography is a remarkable connection between theories of quantum gravity in spacetimes with anti-de Sitter (AdS) asymptotics and a special class of highly symmetric quantum field theories called conformal field theories (CFTs). This connection arises naturally in string theory, where many holographic examples can be understood by studying stacks of D-branes, extended objects that live in the higher-dimensional spacetime of string theory. Looking at the geometry produced by these branes in different limits provides one of the standard ways of arriving at the AdS/CFT correspondence.

In this thesis, we will explore new D-brane configurations that may lead to less familiar holographic setups. The project will start with the basic ideas of string theory, D-branes, and holography, and then move on to studying specific ten-dimensional geometries using techniques from general relativity. The goal is to understand how these brane configurations behave and what kind of holographic physics they may describe. A good background in general relativity will be useful, while the necessary string theory and holography will be introduced as part of the project.

Interpretable cosmological emulators via symbolic regression

Supervisor(s):

Savvas Nesseris (savvas.nesseris@csic.es) & Ziad Sakr (ziad.sakr@ift.csic.es)

Abstract:

Cosmology has entered a precision era with current surveys, like Euclid, DESI, and LSST (Rubin) producing exquisite measurements. However, in order to analyze this data we need to perform computationally expensive theoretical calculations and to explore high-dimensional likelihoods using Markov chain Monte Carlo (MCMC) analyses. As the data is becoming bigger and bigger, the quest to analyse the data in a timely fashion is becoming more difficult, with MCMC runs typically taking at least a week nowadays, even for simple models. One way to speed up the aforementioned analyses is to use emulators, i.e. tools that efficiently mimic the

parts of the pipeline causing the bottlenecks without sacrificing the overall accuracy of the analysis.

However, it is much preferable if the emulator is not only fast and accurate, but also interpretable so that it provides insights into the underlying physics of the problem. One way to achieve this is via symbolic regression which in general can produce simple and analytic expressions accurately capturing the features of the underlying training data. Yet, the output has to be simple enough to be readily usable and not lose its original purpose to be interpretable.

In this project we explore new methods aiming to reduce the high number of variables that appear in other common approaches and we apply our methodology to emulate several large scale structure observables within the standard cosmological constant model (Λ CDM) first, to then extend it to beyond- Λ CDM models such as models with dynamical dark energy, massive neutrinos and modified gravity, while keeping the increase of degrees of freedom comparable to the ones added from the considered extensions. This will enhance the resulting emulators from their usual intermediate speeding role, to serve in the final crucial step of drawing conclusions from the analysis.

References:

- [1] Aizpuru et al., <https://arxiv.org/abs/2106.00428>
- [2] Ferreira et al., <https://arxiv.org/abs/2606.07745>
- [3] Orjuela et al., <https://arxiv.org/abs/2307.03643>
- [4] Orjuela et al., <https://arxiv.org/abs/2407.16640>

Recommended subjects:

- Obligatory courses for the specialty "Elementary Particles and Cosmology"
 - Advanced Mathematics
 - Advanced Cosmology
-

Probing the Electroweak phase transition via Dimensional Reduction at Finite Temperature

Supervisor(s): Jose Miguel No (josemiguel.no@uam.es), Thomas Biekötter (thomas.biekotter@csic.es)

Abstract: The breaking of the electroweak symmetry in the early Universe, known as the EW phase transition (EWPT), is a key moment in the very first stages of the evolution of the Universe. It could have given rise to the primordial matter/antimatter asymmetry – the *baryon asymmetry of the Universe* (BAU) –, whose origin is at present a mystery. Yet, the Standard

Model (SM) is not sufficient for this purpose, and new, beyond the SM (BSM) particles coupled to the Higgs field should exist to yield the measured BAU during a first-order EWPT. The accurate study of the EWPT in such BSM setups demands the use of advanced finite-temperature QFT techniques. In this respect, the use of 3D effective field theories (EFTs) at finite temperature resulting from Dimensional Reduction (DR) of the corresponding 4D theory at finite temperature has been shown to provide a systematic perturbative approach in finite-temperature QFT, yet its use in phenomenological studies of the EWPT is very much under-developed in the literature.

The student will learn the quantum field theory techniques – effective potential & finite-temperature corrections – needed to investigate the evolution of the Higgs field in the early Universe, and will use them to study the properties of the EWPT (in 4D) in a simple and well-motivated extension of the SM, with the addition of a real singlet scalar – *SM + Singlet* – . Then, he/she will investigate the DR of the 4D finite-temperature theory of the *SM + Singlet* model into a 3D EFT – both analytically and with the help of the numerical package DRAlgo – to build a reliable framework for the study of the EWPT in this model. Depending on the student's performance, the TFM may lead to the publication of a research article.

References:

- M. Quiros, Finite Temperature Field Theory and Phase Transitions, <https://arxiv.org/abs/hep-ph/9901312>
- D. Alonso, The Higgs boson and the early Universe (TFM, IFT, 2021)
- D. García Tejada, Probing the Electroweak phase transition in a light singlet extension of the SM (TFM, IFT, 2026)
- Espinosa et al, Strong Electroweak Phase Transitions in the Standard Model with a Singlet, <https://arxiv.org/abs/1107.5441>
- Ekstedt et al, DRalgo: a package for effective field theory approach for thermal phase transitions, <https://arxiv.org/abs/2205.08815>

Recommended subjects:

- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC)
- Advanced Quantum Field Theory
- Open Problems in the Standard Model

Machine learning quasinormal modes

Supervisor(s): Karl Landsteiner (karl.landsteiner@csic.es)

Abstract (and references): Quasinormal modes are damped oscillations that arise as the eigenmodes of black holes. They play an important role in gravitational wave astronomy and are supposed to describe the late stage of a black hole merger. A few modes have been identified in the gravitational wave event GW250114 [1]. Quasinormal modes do show, however, a marked spectral instability. The potential the gravitational waves have to traverse before they reach the detector is therefore likely to have an impact on the observed quasinormal frequencies and damping rates. In the masters thesis we will employ machine learning techniques to explore the question how this spectral instability can be exploited in order to reconstruct this gravitational potential from the knowledge of the quasinormal frequencies.

[1] "Black Hole Spectroscopy and Tests of General Relativity with GW250114"
LIGO Scientific Collaboration, Virgo Collaboration, and KAGRA Collaboration
Physical Review Letters 136, 041403.

Recommended subjects:

Advanced Mathematics (MAV)- 32559

Gravitation (GRA) - 32880

Detecting Dark Matter Self Interactions with Gravitational Waves

Supervisor(s): Juan Urrutia (j.urrutiape@gmail.com), Miguel Zumalacárregui (miguel.zumalacarregui@csic.es)

Abstract (and references):

Gravitational waves travelling across the universe pass through dark matter, and along the way they diffract on halos far too small to have ever been observed. This leaves a faint stochastic imprint on the signal, and we have recently worked out how LISA could look for it: the effect is dominated by halos between 1 and 10^4 solar masses, dark matter halos that do not contain stars and have not been detected yet. This project asks what that imprint looks like if dark matter interacts with itself. Self-interactions first flatten the centre of a halo and then, later on, drive it into a runaway gravothermal collapse that makes the centre far denser.

What makes the mass range interesting is that these are the coldest bound systems in the universe, with internal velocities of a few tens of metres per second. That is precisely where self-interaction cross sections are expected to be largest, and it is three orders of magnitude below anything current observations can reach. You would begin by reproducing the cold dark matter baseline and then implement how self-interacting halos evolve, and finally forecast what LISA or other future detector could actually measure. Happy to discuss it in person if you are curious.

[1] Choi, Urrutia & Zumalacárregui, arXiv:2607.11887 — the stochastic diffraction method.

[2] Adhikari et al., Rev. Mod. Phys. 97, 045004 (2025), arXiv:2207.10638 — review of SIDM.

Recommended MSc subjects:

- Compulsory courses of the speciality "Elementary Particles and Cosmology"
- Advanced Cosmology

Fast Inference for Gravitationally Lensed Gravitational Waves with Machine Learning

Supervisor(s): Xikai Shan (xikai.shan@aei.mpg.de), Miguel Zumalacárregui (miguel.zumalacarregui@csic.es)

Abstract (and references):

Gravitational waves (GWs) that pass near a compact object on their propagation, and the signal arrives with a pattern of frequency-dependent fringes that encodes the mass of the lens. Finding these signatures in the LIGO-Virgo-KAGRA catalogue is a direct probe of compact dark matter. However, the standard Bayesian analysis costs hundreds of CPU hours per event and per lens model, so only a handful of events have been examined in detail. Neural posterior estimation

(DINGO) removes that bottleneck: a network trained once on simulated signals returns the posterior of a new event in seconds. Importance sampling then corrects for inaccuracies of the network and provides Bayesian evidence.

Lensing makes the problem much harder for the network. Our first lensed networks recover the right posteriors, but with a very low sampling efficiency. We have traced the loss to how the fringes (e.g. interference) are represented: the compressed input that DINGO builds for the network grows by a factor of 3 to 30 once the lens is included (depending on the lens-mass range), so most of the lensing information is discarded before the network sees it. Fortunately the structure being lost is simple in physical terms. In the geometric-optics limit a lensed signal is just two copies of the same chirp separated by a time delay, which points to representations that make the fringes cheap to learn.

You would begin by training a standard DINGO network and reproducing our lensed results, then implement and compare fringe-aware representations, and finally run the network on real events from the GW catalogue to search for lensing signatures. The project combines GW physics, wave optics and modern machine learning, and the resulting network would enable the first systematic microlensing search over thousands of events.

References:

- [1] Dax et al., Phys. Rev. Lett. 127, 241103 (2021), arXiv:2106.12594. DINGO: neural posterior estimation for GWs.
- [2] Dax et al., Phys. Rev. Lett. 130, 171403 (2023), arXiv:2210.05686. Importance sampling makes the results exact.
- [3] Caldarola, Goyal, Gupte, Green & Zumalacárregui, Phys. Rev. D 113, 104073 (2026), arXiv:2511.08486. Our first lensed DINGO network.
- [4] Villarrubia-Rojo, Savastano, Zumalacárregui et al., arXiv:2409.04606. GLoW, the wave-optics lensing code used to simulate the signals.
- [5] Takahashi & Nakamura, Astrophys. J. 595, 1039 (2003), astro-ph/0305055. Wave-optics lensing of GWs.

Recommended MSc subjects:

- Compulsory courses of the speciality "Elementary Particles and Cosmology"
 - Advanced Cosmology
-

Gravitational-Wave Lensing by Ultracompact Minihalos

Supervisor(s): Han-Gil Choi (hgchoi1w@gmail.com), Miguel Zumalacárregui (miguel.zumalacarregui@csic.es)

Abstract (and references):

Ultracompact minihalos (UCMHs) are compact dark-matter structures that may form from enhanced primordial fluctuations in the early Universe. Their abundance and internal structure can therefore carry information about fundamental physics on otherwise inaccessible small scales. Gravitational waves offer a new way to search for such objects: through diffraction, their lensing signals can probe the spatial structure of a compact lens and potentially distinguish an extended UCMH from a point-like primordial black hole (PBH).

This project provides an opportunity to explore the connections between fundamental cosmology, dark-matter physics, and gravitational-wave astronomy. The work will cover the cosmological origin of UCMHs and the wave-optics methods used to calculate their gravitational-lensing signatures. The main goal is to determine when UCMH diffraction patterns can be distinguished from those of PBH lenses. If time permits, the comparison can be extended to conventional NFW dark-matter halos.

References:

- [1] Bringmann, Croon & Sevilano Muñoz, Phys. Rev. Lett. 137, 061002 (2026), arXiv:2506.20704
- Constraints on UCMH
- [2] Cheung, Ng, Zumalacárregui & Berti, Phys. Rev. D 109, 124020 (2024), arXiv:2403.13876
- Wave optics of various lens objects
- [3] Choi, Jung, Lu & Takhistov, Phys. Rev. Lett. 133, 101002 (2024), arXiv:2311.17829
- Distinction of lens object by diffraction

Recommended MSc subjects:

- Astroparticle Physics,
 - Advanced Cosmology
-

Exploring New Neutrino Physics with Dark Matter Detectors

Supervisor(s): Patrick Foldenauer (IFT) [patrick.foldenauer@csic.es]

Abstract (and references):

Dark matter direct detection experiments are designed to observe the tiny energy deposits produced when hypothetical dark matter particles scatter inside an ultra-low-background detector. Their sensitivity has now improved to the point where leading experiments (such as XENONnT, LZ and PandaX-4T) have observed the scattering of neutrinos from the Sun. Although these neutrinos constitute an important background to dark matter searches, they also demonstrate that direct detection experiments can operate as neutrino observatories beyond searches for dark matter.

The objective of this project is to investigate which additional neutrino sources beyond the Sun could become accessible to future multi-tonne detectors such as XLZD and PandaX-xT, and how these signals could be used to test new neutrino interactions. The project will first assess the potential of additional neutrino sources within the Standard Model and determine whether their normalisation or broad spectral features can be reconstructed. Building on this baseline, the student will investigate how representative interactions beyond the Standard Model modify the predicted signal and derive the sensitivity of future experiments to their parameters. The analysis will use the open-source Python package SnuDD (<https://github.com/SNuDD/SNuDD>) to calculate neutrino-induced recoil spectra, together with realistic detector responses, backgrounds and statistical uncertainties. The student will then perform statistical forecasts to determine the exposures required for detection and compare Standard Model and new physics predictions. SnuDD already combines neutrino propagation, scattering and detector effects for solar neutrinos, providing a validated computational foundation that can be extended to additional sources in this thesis.

The project will provide training in neutrino and astroparticle physics, numerical modelling, scientific software and statistical inference. It will contribute to the emerging use of dark matter detectors as precision probes of neutrino physics.

References:

1. J. L. Newstead, R. F. Lang and L. E. Strigari, "Atmospheric neutrinos in next-generation xenon and argon dark matter experiments," *Physical Review D* **104**, 115022 (2021).

<https://arxiv.org/abs/2002.08566>

This is a good starting point for the project, covering expected neutrino signals, detector requirements and future xenon and argon sensitivities.

2. D. W. P. Amaral, D. Cerdeño, A. Cheek, V. Costa and P. Foldenauer, "SNuDD: Solar Neutrinos for Direct Detection," arXiv:2607.22817 [hep-ph] (2026).

<https://arxiv.org/abs/2607.22817>

This paper introduces the SNUDD package and its treatment of neutrino propagation, nuclear and electron scattering, detector effects and new neutrino interactions.

3. E. Aprile et al. [XENON Collaboration], "First Indication of Solar 8B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT," *Physical Review Letters* **133**, 191002 (2024).

<https://arxiv.org/abs/2408.02877>

This paper reports the first measurement of solar-neutrino-induced nuclear recoils with XENONnT and provides the experimental motivation for using dark-matter detectors as neutrino observatories.

4. Z. Bo et al. [PandaX Collaboration], "First Indication of Solar 8B Neutrino Flux through Coherent Elastic Neutrino-Nucleus Scattering in PandaX-4T," *Physical Review Letters* **133**, 191001 (2024).

<https://arxiv.org/abs/2407.10892>

This provides a complementary measurement of solar-neutrino nuclear recoils in a liquid-xenon detector.

5. J. Aalbers et al. [XLZD Collaboration], "The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics," *European Physical Journal C* **85**, 1192 (2025).

<https://arxiv.org/abs/2410.17137>

This describes the planned XLZD detector, its expected performance and its broader programme in dark-matter and neutrino physics.

Recommended subjects:

- Compulsory courses of the speciality "Elementary Particles and Cosmology"
- Open Problems of the Standard Model
- Astroparticle Physics

- Helpful: prior experience with Python

Explorando la mecánica cuántica en la frontera de la energía

Supervisor(s): J.A. Aguilar Saavedra, J. A. Casas (j.alberto.casas@gmail.com)

Abstract (and references):

La mecánica cuántica es uno de los pilares fundamentales de la física moderna. Aún así, hay determinados aspectos que no han sido aún entendidos, entre los cuales están el concepto de medida y la transición del mundo cuántico al mundo macroscópico clásico. Los experimentos en colisionadores de alta energía ofrecen nuevas posibilidades tanto cuantitativas como cualitativas para poner a prueba la validez de la mecánica cuántica en la frontera de la energía.

En este trabajo de fin de máster se pretende introducir al estudiante a los conceptos cuánticos fundamentales como entrelazamiento, “steering”, no-localidad, contextualidad, y aplicarlos en un cálculo de un proceso de interés para la fenomenología en el gran colisionador de hadrones (LHC).

Recommended subjects:

Se recomienda cursar la asignatura de Entrelazamiento Cuántico e Información