MSc in Theoretical Physics
UAM

Offers for MSc Theses 2025/26
Particle Physics Specialty

(updated 10/09/2025)

On the following pages the possible projects for a MSc thesis are listed. Please note that the MSc thesis is not restricted to be selected from this list; this list simply reflects research interests of potential supervisors. You always have the option to talk to the members and come up with a new project. Note that each project has to be a work worth 12 ECTS which translates to 300 hours (ca. 8 weeks) of work.

The work will primarily be undertaken during (and after) the third trimester, but you are free to start as early as possible.

There will be two calls to present the master thesis: one in end-June/early July and another one in early-Sep.

Title: NLO Effects in EFT Matching

Title: Unimodular gravity

Supervisor(s): enrique alvarez (enrique.alvarez@uam.es)
Abstract (and references):

Unimodular gravity is a slight modification of General Relativity in which the vacuum energy does not source gravity. This partially solves the cosmological constant problem as well as it allows for exponential expansion of the universe without constant energy density.

Recommended subjects: Teoría cuántica de campos, Teoría cuántica de campos avanzada, Gravitacion avanzada

Title: Quantum algorithms as a tool for physical discovery

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

Abstract (and references): 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.

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

Title: Near-criticality of the Higgs system

Supervisor(s): Belen Gavela (belen.gavela@uam.es) and Thomas Steingasser (tstngssr@mit.edu)

Abstract (and references): This work focuses on an emerging alternative to the naturalness criteria to understand why the Higgs particle is so light. The hypothesis that an underlying dynamics forces the parameters of the Higgs potential to take near-critical values leads to strong limits on the possible value of the Higgs mass, and has important experimental (e..g. At future colliders) and cosmological implications.

The present Higgs quest is largely motivated by the so-called ``naturalness´´ issue: the fact that the value of the Higgs mass is ``low´´, i.e. comparable to the electroweak scale, while for a scalar quantum effects from physics at higher energies generically try to push it to high values. A plethora of new physics scenarios tending to this issue is being intensely studied since decades, with no real breakthrough by now and no experimental evidence for new high physics scales. The situation is so perplexing that it has been recently questioned whether the paradigm of naturalness should be applied to this problem at all.

This work will focus on an emerging alternative to naturalness: whether the scalar potential of the visible Universe could seat near a critical point. Intuitively this would be the field-theory equivalent of how sand dunes correspond to self-organized criticality. The near-criticality perspective has already been shown to result in an upper bound for the Higgs mass. In this work it will be explored how simple near-critical potentials induce extremely tight bounds on the Higgs mass, justifying its observed value, and how future accelerators can test Higgs near-criticality.

References:

Higgs near-criticality at future colliders, V. Enguita, B. Gavela and Thomas Steingasser, https://arxiv.org/pdf/2503.03825, to appear in Physical Review D

Higgs criticality and the Metastability Bound, M. Deterring, V. Enguita, B. Gavela,Thomas Steingasser and T. You, https://arxiv.org/pdf/2503.22787, European Strategy for Particle Physics 2026.

Recommended subjects:

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

Title: Hunting the Dark ALP

Supervisor(s): Belen Gavela (belen.gavela@uam.es) and Thomas Steingasser (tstngssr@mit.edu)

Abstract (and references): This work explores a novel arena of axion-like particles (ALPs), which are pseudoGoldstone bosons intensely searched for experimentally, as expected in several solutions to outstanding problems of the Standard Model of Particle Physics. Usually they are assumed to be singlets of the SM and also of the dark sectors of the Universe. There is no reason for the last point to be so, and this work will lift this arbitrary assumption.

The word ALP designs pseudo-Goldstone bosons with derivative plus anomalous couplings, and which have no Standard Model charges (i.e. they are scalar singlets). Their interest is that they are the tell-tale, the signal, of hidden symmetries in Nature expecting discovery. These new symmetries and physics laws are invocated by several very different puzzles and fine-tunings of the Standard Model. ALPs are typically studied using effective field theory (EFT), though, so as to enable results which are independent of any particular high-energy model.

The usual ALP Lagrangian assumes that the ALP is not only a singlet of the SM, but also that it does not carry any charge of the dark sector of the Universe. That is, it assumes that the ALP is a singlet of the possible dark charges of the Universe. There is no reason for it to be so.
The power of EFT allows to consider this possibility without particularizing to any given charge or symmetry group of the dark sector.

In this master thesis the EFT for ALPs which carry some dark charge will be constructed for the first time.

References:

ALP contribution to the strong CP problem, V. Enguita, B. Gavela, B. Grinstein and P.Quilez, https://arxiv.org/abs/2403.12133, accepted for publication in JHEP.
The QCD axion sum rule, B. Gavela, P. Quilez, M. Ramos, https://arxiv.org/pdf/2305.15465, published in JHEP.

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

Title: Top production in pp collisions with ATLAS data

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

Abstract (and references): 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 of 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
ATLAS Collab, JHEP 08 (2024) 182
ATLAS Collab, Phys. Rep. 1116 (2025) 127

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

Title: Isolated photons in pp collisions with ATLAS data

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

Abstract (and references): 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 of 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

Title: 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…
Depending on the specific topic and on the student's performance, the TFM may lead to the publication of a research article.

References:
-M.B. Marcos (past Master student), 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.F. 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

Title: 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; arXiv:2410.13799 [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: LHC phenomenology of supersymmetric signals with photon signatures

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

Abstract (and references): Signals with photons at the LHC represent very clean final states whose SM backgrounds can be more easily under control. Various supersymmetric (SUSY) models [1] give rise to experimental signatures with one or more photons that could be searched for at the LHC [2]. The central idea of this project is to contrast the theoretical predictions of these SUSY models, by means of Monte Carlo simulations, with respect to data collected by the LHC ATLAS detector at a center-of-mass energy of 13 TeV. For this purpose, detector-level observables from collider physics [3] will be used to develop dedicated search strategies for each of these SUSY models and their experimental signatures with photons at the LHC, in order to calculate the potential signal significance and/or to estimate the exclusion limits that could be imposed on the SUSY parameter spaces.

[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] G. Aad et al. [ATLAS], JHEP **07** (2023), 021 [arXiv:2206.06012 [hep-ex]].
[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: Cosmology and likelihood data analysis with machine learning

Supervisor(s): Savvas Nesseris (savvas.nesseris@csic.es)

Abstract (and references):
Current and forthcoming surveys are poised to rigorously test the standard cosmological constant and cold dark matter model (ΛCDM) and its underlying principles (e.g. homogeneity and isotropy), as well as possible extensions beyond general relativity (GR), offering unprecedented data quality and volume. In order to test these assumptions, one can perform specific consistency/null tests that require model-independent reconstructions of cosmological parameters and their estimation using minimal assumptions.

In this project, we focus on the Stage IV surveys (DESI, Euclid, SPHEREx) and the Baryon Acoustic Oscillations (BAO) data, coming from galaxy clustering.

The goals of this project are:
Understand and familiarize with the BAO data and the underlying theoretical framework.
Explore the Fisher forecast formalism and learn how to create realistic mock data based on survey specifications.
Use machine learning to place constraints on deviations from homogeneity and isotropy, and perform various consistency tests of the cosmological constant model.

Requisite skills: Python.

References:
Euclid. I. Overview of the Euclid mission, arXiv: 2405.13491
Euclid preparation: VII. Forecast validation for Euclid cosmological probes, A&A 642 (2020) A191, arXiv: 1910.09273
Euclid: Forecast constraints on consistency tests of the ΛCDM model, A&A 660, A67 (2022), arXiv: 2110.11421

Recommended subjects: Advanced Cosmology, Advanced Mathematics

Title: Effects of non-linear electrodynamics to gravity and cosmology

Supervisor(s): Savvas Nesseris
Abstract (and references):

We explore the effects of non-linear electrodynamics (NED) to cosmological observables and the possibility to have non-singular black holes. Specifically, NED can be shown to affect the luminosity distance of far away objects and cause violations of the distance duality relation, an effect that can be constrained from observations with current and future large scale structure surveys [1].
Also, in principle NED can be used to create non-singular black holes, i.e. black holes with no singularity at r=0, albeit many of the solutions suffer from instabilities [2]. In this project, we will explore both possibilities and pursue both cosmological analyses and ones at the strong field regime.

Requisite skills: Python.

References:

[1] “Euclid: Forecast constraints on the cosmic distance duality relation with complementary external probes”, https://arxiv.org/abs/2007.16153
[2] “Instability of nonsingular black holes in nonlinear electrodynamics”, https://arxiv.org/abs/2410.00314

Recommended subjects: Advanced Gravity, Advanced Cosmology, Advanced Mathematics

Title: Testing the singlet/doublet Higgs Nature at LHC

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 appropiate 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 exclussively 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 underling 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)×SU(2)×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 Golstone 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 (mH, mW and mZ , 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 disantangle 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 kV and and k2V 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.

Title: Triple Higgs couplings at the LHC

Supervisor(s): Sven Heinemeyer (Sven.Heinemeyer@cern.ch)
Abstract (and references):

A Higgs boson with a mass of ~125 GeV was discovered at the Large Hadron Collider (LHC, CERN, Geneva) about 12 years ago. Most of its couplings have now been measured at the level of 10-20%. Within theoretical and experimental uncertainties the measurements agree with the predictions of the Standard Model (SM). However, the baryon asymmetry in the universe (BAU) (the fact that there is matter, but no antimatter) cannot be explained within the SM. Extension of the Higgs sector of the SM, however, can yield the measured BAU value during a strong first-order electroweak phase transition (SFOEWPT) in the (very) early universe. Here the triple Higgs couplings (the coupling of three possibly different Higgses) play a crucial role. Such couplings can possibly be measured in the process $pp \rightarrow H_i\ H_j$ (where $H_{i,j}$ are Higgs bosons) at the LHC, or in e+e- $\rightarrow Z\ H_i\ H_j$ at possible future e+e- colliders.

In this work the student will analyze a simple extension of the SM that can give rise to a SFOEWPT. The regions in which such a SFOEWPT can occur will be identified. Several di-Higgs production cross sections at the LHC or future e+e- colliders will be evaluated. The sensitivity of the LHC/e+e- collider to experimentally measure these production cross sections, and eventually the triple Higgs couplings will be determined. This will constitute a novel result, since so far no non-SM di-Higgs productions at the LHC have been analyzed.

Depending on the progress of the project, an extension to an experimental determination of triple Higgs couplings via a deep Neural Network analysis is envisaged.
imatter) cannot be explained within the SM. Extension of the Higgs sector of the SM, however, can yield the measured BAU value during a strong first-order electroweak phase transition (SFOEWPT) in the (very) early universe. Here the triple Higgs couplings (the coupling of three possibly different Higgses) play a crucial role. Such couplings can possibly be measured in the process $pp \rightarrow H_i\ H_j$ (where $H_{i,j}$ are Higgs bosons) at the LHC, or in e+e- $\rightarrow Z\ H_i\ H_j$ at possible future e+e- colliders.

In this work the student will analyze a simple extension of the SM that can give rise to a SFOEWPT. The regions in which such a SFOEWPT can occur will be identified. Several di-Higgs production cross sections at the LHC will be evaluated. The sensitivity of the LHC to experimentally measure these production cross sections, and eventually the triple Higgs couplings will be determined. This will constitute a novel result, since so far no non-SM di-Higgs productions at the LHC have been analyzed.

Depending on the progress of the project, an extension to an experimental determination of triple Higgs couplings via a deep Neural Network analysis is envisaged.

References:

https://arxiv.org/abs/2502.03878

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

Recommended tools: Python, MadGrap

Title: Effects of electroweak SMEFT corrections in Higgs decays

Supervisor(s): Ana Cueto (anar.cueto@uam.es), Pier Paolo Giardino (pier.giardino@uam.es)

Abstract (and references): The Standard Model of particle physics had a great success over the last decades being able to describe experimental measurements with high precision. However, there are several open questions that remain to be understood. Some of them are: why is there a large asymmetry between matter and antimatter? What is the origin of dark matter and dark matter? For this reason, it is thought that the Standard Model is just an effective description of the Universe at our energies and that extensions of this theory, that become evident only at very high energies, must exist. In the absence of any clear hints of new physics from the experimental data, the Standard Model Effective Field framework provides a powerful tool to parametrise deviations of measurements from the Standard Model predictions in terms of new physics operators.

Predictions in the SMEFT framework of the Higgs decays have been recently achieved including next-to-leading order electroweak corrections. These predictions allow us to better exploit the sensitivity of Higgs measurements to new physics effects. For this project it is proposed to get familiar with the needs of such calculations, and to study how the presence of the electroweak corrections in the predictions allow to improve the sensitivity to new physics operators using experimental data from the ATLAS Collaboration.

References: https://arxiv.org/abs/2402.05742; https://arxiv.org/abs/2508.14966

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

Title: Dark Matter production in the Early Universe

Supervisor(s): David Cerdeño (davidg.cerdeno@gmail.com)

Abstract (and references):
Dark matter is an abundant, but yet undiscovered new substance in our Universe, only observed through the gravitational effect on visible (ordinary) matter. If interpreted in terms of particle physics, it would correspond to a new type of particle which is not contained in the structure of the otherwise successful Standard Model.

It is not clear how dark matter was formed in the Early Universe, as the conditions under which it co-existed in the hot plasma with the rest of the Standard Model particles depend on some of the unknown properties of this new type of matter. In particular, its interaction strength with the rest of the particles can determine the way it decouples from the thermal plasma.

In this project we will examine different ways to produce dark matter in the Early Universe, paying special attention to the potential role of neutrinos. In particular, if dark matter and neutrinos interact with each other, this has consequences not only on the dark matter abundance today, but also on the various properties of neutrinos.

Recommended subjects:
- Mandatory courses for the specialty "Elementary Particles and Cosmology" (PEC)
- Open Problems in the Standard Model
- Astroparticle Physics

Title: Neutrinos as a window to new physics

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

Abstract (and references): Despite being among the most abundant particles 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 oscillation, 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 phenomenon of neutrino oscillation and why it implies that neutrinos must have mass and 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

Title: Holographic description of AdS vacua with small extra dimensions

Supervisor(s): Fien Apers (fien.apers@gmail.com)

Abstract (and references): The AdS/CFT correspondence is a deep equivalence relating quantum gravity theories in Anti-de Sitter (AdS) vacua to conformal field theories (CFTs) in a holographic way. So far, the only AdS/CFT dual pairs that are well understood involve AdS vacua with large extra dimensions from string theory. The purpose of this project is to explore the potential holographic duals of AdS vacua with small extra dimensions. We will study concrete examples of 3-dimensional AdS vacua that are dual to 2-dimensional CFTs, where many tools and constraints are available. For these examples, we will try to understand basic properties of the CFT dual, such as the central charge and the operator spectrum.

references:

https://arxiv.org/pdf/0712.0689, https://arxiv.org/pdf/1310.4319, https://arxiv.org/pdf/2311.12105, https://arxiv.org/pdf/2202.00682

Title: Spin, Rings & Holograms: Imaging Kerr-AdS Black Holes

Supervisor: Juan F. Pedraza (j.pedraza@csic.es)

Abstract (and references): Can you "photograph" a black hole using only boundary quantum field theory data? Building on the holographic imaging prescriptions of arXiv:1811.12617 and the Einstein-ring construction of arXiv:1906.09113, this TFM will extend the wave-optics imaging map to rotating Kerr-AdS backgrounds, generate images from localized, time-periodic boundary sources, and extract spin-driven signatures, including ring radii, thickness, brightness asymmetry, and possible multi-ring structures. We will benchmark these signatures against results from observational black hole imaging. Although horizon-scale phenomenology is expected to be largely insensitive to asymptotic structure and long-range falloff of bulk fields, we will quantify how AdS boundary conditions affect the images and delineate the scope for reliable comparison with astrophysical data.

Recommended subjects:
- Advanced Quantum Field Theory
- Advanced Gravity
- Advanced Mathematics
- Advanced Cosmology

Title: Emergent lattice gauge theories in Rydberg quantum simulators

Supervisor(s): Daniel González-Cuadra (daniel.gonzalez@ift.csic.es)

Abstract (and references): Simulating the dynamics of lattice gauge theories is a central challenge in theoretical physics, as it is key to understanding fundamental phenomena such as quark confinement, which manifests for instance in out-of-equilibrium heavy-ion collisions. Traditional numerical approaches face severe limitations due to the exponential growth of computational resources required. Quantum computers and quantum simulators provide a promising alternative, as they can efficiently capture the dynamics of large-scale quantum systems using only polynomial space-time resources. Realizing this potential in practice, however, demands a co-design approach in which quantum hardware and algorithms are tailored to the physical problem under study.

In this project, we will investigate how cutting-edge quantum simulators based on Rydberg atom arrays can be employed to simulate the dynamics of U(1) lattice gauge theories. Specifically, we will focus on dual-species Rydberg arrays, which provide a natural encoding of gauge and matter degrees of freedom. Using tensor-network methods, we will benchmark the performance of such simulators in regimes characterized by strong gauge fluctuations driven by plaquette interactions.

Previous research on the topic: https://www.nature.com/articles/s41586-025-09051-6
General information about the group activities: https://www.gonzalez-cuadra.com/research

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

Title: Search for a light charged Higgs boson in the H± → cs channel with the CMS experiment at the CERN LHC.

Supervisor(s): Juan Pablo Fernández Ramos (juanpablo.fernandez@ciemat.es), Jose María Hernández Calama (chema.hernandez.calama@gmail.com)

Abstract: The discovery of the Higgs boson in 2012 by the ATLAS and CMS experiments at the CERN LHC has prompted a wide range of studies aimed at characterizing the nature of this particle. Several extensions of the Standard Model (SM) predict the existence of additional scalar bosons, including two charged Higgs bosons, proposed as solutions to some of the model's limitations, such as the origin of dark matter. In this work, a search for a charged Higgs boson is proposed using data from the CMS experiment. The search targets its production in the decay of a top quark and its subsequent decay into a pair of charm and strange quarks.

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

Title: Precise determination of the strong coupling constant using the ATLAS measurement on event shapes.

Supervisor(s): Javier Llorente Merino(javier.llorentemerino@ciemat.es)
Abstract: This work aims to precisely determine the strong coupling constant, alpha_s, from fits of NNLO predictions [arXiv:2301.01086] to the ATLAS event shape data [arXiv:2007.12600]. From the evaluation of alpha_s in different energy ranges, the dependence of the coupling with the scale will be studied, allowing us to test asymptotic freedom at high energies.

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

Title: Search for physics beyond the Standard Model with the SBND experiment at Fermilab in antineutrino and beam-dump modes

Supervisor(s): Jose Ignacio Crespo Anadón (jcrespo@ciemat.es)

Abstract: Anomalies in short-baseline neutrino experiments and the unknown mechanism of the neutrino mass represent potential hints of the existence of physics beyond the Standard Model. The SBND experiment, a liquid argon neutrino detector located just 110 m downstream from the Booster Neutrino Beam origin at Fermilab (USA) will search for new physics as one of its science goals. SBND started taking data in 2024 in neutrino-beam mode. In this Master Thesis the sensitivity of SBND to physics beyond the Standard Model when running in antineutrino-beam and beam-dump modes will be explored using the advanced Monte Carlo simulation of the experiment.

Bibliografía:

https://arxiv.org/abs/2504.00245

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

Title: Analysis of data from the ProtoDUNE detector at CERN

Supervisor(s): Clara Cuesta Soria (Clara.Cuesta@ciemat.es)

Abstract: The Deep Underground Neutrino Experiment (DUNE) is a next-generation experiment designed to study long-baseline neutrino oscillations, neutrino astrophysics, and beyond-the-standard-model physics. The DUNE far detector will employ liquid argon time projection chambers (LArTPC) on an unprecedented scale, where the photon detection system will be critical for precise timing. This work focuses on analyzing light scintillation data collected at ProtoDUNE at CERN, with the goal of evaluating the performance of the photon detection system and validating its capabilities for future deployment in DUNE.

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

Title: LiquidO: A Novel Neutrino Detection Technology

Supervisor(s): Diana Navas Nicolás (diana.navas@ciemat.es) and Carmen Palomares Espiga (mc.palomares@ciemat.es)

Abstract: The open questions in neutrino physics require kton-mass detectors with high energy resolution and the ability to identify the particles resulting from the neutrino interaction. Such a detector based on a simple and not very expensive design would be a major breakthrough in the field. LiquidO is a new technology based on opaque liquid scintillator and wavelength shifter fibres capable of identify low-energy neutrinos and determine their interaction point with high precision, overcoming the limitations of the traditional neutrino detection method based on transparent scintillator.

The tasks proposed in this End-of-Master project cover the development of Monte Carlo simulations for the first LiquidO experiment: A 10-ton detector for the monitoring of a nuclear reactor using, for the first time, neutrinos as a direct probe of nuclear fissions. The work is carried out in the context of an international collaboration that includes research institutes and universities from France, UK and Germany.

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

Title: Constraining fundamental physics with cosmology

Supervisor(s): Shahab Joudaki **(** Shahab.Joudaki@ciemat.es)
Abstract: The standard cosmological model includes cold dark matter, dark energy, and massive neutrinos, which together constitute over 95% of the energy content of the Universe. They have a direct impact on the formation of galaxies, the accelerated expansion and ultimate fate of the Universe, and the predominance of matter over antimatter, respectively. Hence, if we are to understand the Universe, we need to fully uncover their physical properties. This includes but is not limited to measuring the density of the dark matter, the equation of state of the dark energy, and the sum and hierarchy of the neutrino masses. To this end, the student will utilize state-of-the-art cosmological datasets to perform a self-consistent combined analysis of the two most powerful probes of the dark Universe: weak gravitational and galaxy clustering. This involves modifying the analysis code to include uncertainties in the modeling, such as how the dark matter is distributed on
nonlinear scales. It subsequently involves performing Markov Chain Monte Carlo runs on supercomputers that will allow for novel constraints on the underlying cosmological model. The student will analyze these constraints and assess possible tensions between different cosmological probes. The project requires the student to have an understanding of Python and Unix.

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
- Advanced Cosmology

Title: Dark Energy and the cosmological model

Supervisor(s): Santiago Avila (santiagoj.avila@ciemat.es) and Anna Porredón (AnnaMaria.Porredon@ciemat.es)

Abstract: The standard model of cosmology, LCDM, postulates that only around 30% of the energy content of the Universe is in the form of matter: ~25% of cold dark matter, and 5% of regular matter. The other 70% of energy, known as dark energy, is responsible for the accelerated expansion of the Universe. Within LCDM, this dark energy takes the form of a cosmological constant, Lambda, equivalent to vacuum energy.

However, recent results by the Dark Energy Survey (DES, arXiv:2401.02929, arXiv:2402.10696, 2503.06712) and the Dark Energy Spectroscopic Instrument (DESI, arXiv:2404.03002, 2503.14738) are finding evidence against this model and favoring a dynamical form of dark energy.

The student will learn how to constrain cosmological models from public data from type Ia supernovae (SN) and Baryonic Acoustic Oscillations (BAO), and will test different alternative models to LCDM.

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
- Advanced Cosmology

Title: Nonlinear Correlation-Based Methods for Template-Free Gravitational Wave Searches in Virgo Data

Supervisor(s): Carlos Delgado (carlos.delgado@ciemat.es)

Abstract: This Master's thesis will be carried out within the CIEMAT Gravitational Waves group, which contributes to the data analysis efforts of the Virgo experiment. The work focuses on the development and evaluation of a statistical method for the detection of gravitational wave signals without relying on matched-filtering templates. The approach is based on nonlinear correlation estimators applied to interferometric data. The method will be tested on real data from the Virgo detector, using confirmed compact binary coalescence (CBC) events as benchmarks to assess sensitivity and detection performance. The study aims to determine the method's potential for identifying unmodeled or poorly modeled transient signals.

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
- Advanced Cosmology

Title: Characterizing the electron flux in high-energy cosmic rays with the HERD space mission

Supervisor(s): Miguel Angel Velasco Frutos (MiguelAngel.Velasco@ciemat.es) and Jorge Casáus Armentano (jorge.casaus@ciemat.es)

Abstract: Precision measurements of cosmic ray fluxes performed with state-of-the-art experiments on space platforms tackle fundamental physics open problems such as the origin and propagation of galactic cosmic rays, the nature of dark matter, and the existence of primordial antimatter.

Current measurements of electrons and positrons with energies below a few TeV show spectral structures that can not be explained by the usual models describing the origin and propagation of cosmic rays in the galaxy.

The HERD experiment, to be deployed at the China Space Station (CSS) in 2027, will provide a significant increase in the positron and electron statistics in an extended energy range reaching tens of TeV. This work will be devoted to the study of the HERD sensitivity for the combined electron and positron flux measurement at the highest energies. The precise characterization of the flux will provide key information for studying possible contributions of new high-energy astrophysical sources.

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

Title: Search for Inelastic Boosted Dark Matter (iBDM) with data from the DEAP-3600 experiment

Supervisor(s): Roberto Santorelli (Roberto.Santorelli@ciemat.es)
Abstract: Boosted Dark Matter (BDM) models propose the existence of new particles from the dark sector which, after acquiring a large boost, can produce detectable signals in direct detection experiments. A particularly interesting class of BDM is known as Inelastic Boosted Dark Matter (iBDM), which predicts inelastic scattering processes with target electrons, accompanied by displaced secondary vertices, whose characteristic topology makes them distinguishable from the experimental background. The DEAP-3600 experiment , with more than 3 tonnes of liquid argon, is currently the largest liquid argon detector in operation worldwide, and provides a particularly suitable environment for the search for this type of events. The goal of this Master's thesis is to apply methodologies proposed in recent studies to analyze DEAP-3600 data in search of signals compatible with iBDM, selecting candidate events, defining selection criteria, and evaluating the experimental sensitivity as a function of different model parameters. The work includes the analysis of real data and Monte Carlo simulations, and offers solid training in experimental techniques and astroparticle physics, making it especially valuable for students interested in pursuing a PhD in the field.

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

Title: Detección de Iones con el Observatorio Cherenkov Telescope Array (CTAO) – Prueba de Concepto

Supervisor(s): Igor Oya (Igor.Oya@ciemat.es) y Salvatore Mangano (Salvatore.Mangano@ciemat.es)

Abstract: El origen de los rayos cósmicos (RC) sigue siendo una de las cuestiones fundamentales abiertas en la física de astropartículas. Con energías que abarcan desde unos pocos MeV hasta más de 3×10^20 eV, se cree que los RC se originan en una variedad de entornos astrofísicos, como los restos de supernovas, el agujero negro central de la Galaxia y, en el caso de las energías más altas, fuentes extragalácticas.

Los RC pueden estudiarse mediante instrumentos instalados en el espacio, en globos o ubicados en tierra. A energías superiores a varios cientos de TeV, solo es viable su detección indirecta, mediante técnicas basadas en tierra. Los Telescopios de Imagen por Cherenkov Atmosférico (IACT, por sus siglas en inglés) están diseñados principalmente para estudiar rayos gamma mediante la detección de la luz de Cherenkov producida por las cascadas atmosféricas extensivas (Extensive Air Showers, EASs). Sin embargo, los IACT también ofrecen capacidades prometedoras para el estudio de núcleos cargados (iones) de origen cósmico, lo que representa un enfoque complementario a la detección directa y a los experimentos tradicionales basadoes en la detección de EASs.

El Observatorio Cherenkov Telescope Array (CTAO) es el observatorio terrestre de rayos gamma de nueva generación, diseñado para avanzar significativamente en nuestra comprensión del universo de alta energía. Estará compuesto por dos grandes conjuntos de IACT: uno en el hemisferio norte, en el Observatorio del Roque de los Muchachos (ORM) en La Palma, Islas Canarias, y otro en el hemisferio sur, en el sitio de Paranal, en Chile. En conjunto, estos conjuntos incluirán más de 60 telescopios.

Los RC cargados emiten luz de Cherenkov incluso antes de su primera interacción en la atmósfera. Esta luz, conocida como radiación de Cherenkov directa (DC), permite inferir la naturaleza de la partícula primaria. Los IACT, por tanto, pueden funcionar como detectores tanto de DC como de EAS, lo que permite realizar estudios detallados sobre la composición de los rayos cósmicos.

El objetivo de este TFM es desarrollar, a partir de datos simulados, una prueba de concepto para la detección y caracterización de iones cósmicos mediante el CTAO. Este trabajo se centrará en la técnica DC, analizando las imágenes captadas por las cámaras de los IACT, extrayendo los parámetros clave de dichas imágenes y identificando las características distintivas entre las señales DC y las que se originan a partir de EAS.

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

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

Supervisor(s): Vicente Pesudo (Vicente.Pesudo@ciemat.es)

Abstract: 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 actuan 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 recienemente hemos tenido acceso y los niveles de radón y otras variables ambientales en el LSC.

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

Title: Out of equilibrium physics: temporal entanglement and tensor network methods

Supervisor(s): Esperanza Lopez (esperanza.lopez@csic.es), Luca Tagliacozzo (luca.tagliacozzo@fqa.ub.edu)
Abstract: Recently, new measures of quantum correlations have emerged in the study of out-of-equilibrium quantum systems: the generalized temporal entropies. These quantities extend the concept of entanglement entropy, traditionally used to characterize quantum correlations at equilibrium, into the dynamical regime. Whenever an analytic continuation is possible, generalized temporal entropies coincide with standard entanglement entropies [1]. However, in many physically relevant cases such a continuation cannot be performed, raising fundamental questions about the interpretation and role of temporal entropies.

Our group has recently shown that temporal entropies admit a natural representation in terms of spatio-temporal tensor networks [2] which provide a powerful language to describe both equilibrium and non-equilibrium quantum processes. In this framework, generalized temporal entropies can be related to the classical computational complexity. This connection opens a novel perspective: temporal entropies not only capture quantum correlations in time, but also quantify the difficulty of simulating dynamical processes with classical resources[4-5]. Finally we managed to show how generalized temporal entropies can be measured in experiments [3].

The goal of this project is to investigate the properties and interpretations of generalized temporal entropies in situations where analytic continuation to equilibrium entanglement entropies is not possible. Specifically we will choose together on which of these open questions we would like to work on:

- Study the scaling of generalized temporal entropies in paradigmatic out-of-equilibrium models (integrable vs. chaotic).
- Explore their connection to classical complexity measures of spatio-temporal tensor network contraction.
- Benchmark numerical simulations (using tensor network methods such as temporal matrix product states or process tensors) against analytical predictions from conformal field theory and integrability.
- Better characterize experimental protocols to measure generalized temporal entropies with current quantum simulators.

Upon mutual satisfaction the student can proceed to a fully funded PhD thesis on the subject.

References:

[1] Spatio-temporal tensor-network approaches to out-of-equilibrium dynamics bridging open and closed systems, S Cerezo-Roquebrún, A Bou-Comas, JT Schneider, E López, Luca

Tagliacozzo, Stefano Carignano, Frontiers in Quantum Science and Technology 4, 1568471, arXiv:2502.20214.
[2] On temporal entropy and the complexity of computing the expectation value of local operators after a quench, S Carignano, CR Marimón, L Tagliacozzo Physical Review Research 6 (3), 033021, arXiv:2307.11649.
[3] Measuring temporal entanglement in experiments as a hallmark for integrability, A Bou-Comas, CR Marimón, JT Schneider, S Carignano, L Tagliacozzo, arXiv:2409.05517.
[4] Loschmidt echo, emerging dual unitarity and scaling of generalized temporal entropies after quenches to the critical point, S Carignano, L Tagliacozzo, arXiv:2405.14706.
[5] Overcoming the entanglement barrier with sampled tensor networks, S Carignano, G Lami, J De Nardis, L Tagliacozzo, arXiv:2505.09714.

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

Title: Cosmic Microwave Background in a finite universe

Supervisor: Yago Ascasibar (yago.ascasibar@uam.es)

Abstract:

As the precision of different tracers of cosmic expansion -most notably, the Cosmic Microwave Background (CMB) radiation, the scale of the Baryon Acoustic Oscillations (BAO), and the Hubble-Lemaître diagram of Type Ia supernovae- has improved beyond a few per cent, several tensions have emerged between the low- and high-redshift probes under the assumption of a spatially flat LCDM cosmology. If all the observational tracers turned out to be correctly calibrated, their results would imply that the so-called standard cosmological model may not be the ultimate description of our universe.

Here we will consider an alternative scenario where three-dimensional space is a finite hypersphere of radius R(t). Our previous results show that this geometry is perfectly compatible with all the available measurements. After acquiring a minimum theoretical background and learning about the main probes of the composition and expansion history of the universe, the student will focus on the evolution of matter and energy in the proposed cosmology and study the main properties of the CMB to test its viability.

References:

https://arxiv.org/abs/1911.02087

https://wiki.cosmos.esa.int/planck-legacy-archive/index.php/Cosmological_Parameters

Recommended subjects: Advanced Cosmology

Title: The origin of cosmic rays

Supervisors: Yago Ascasibar (yago.ascasibar@uam.es), M. Rocamora (U. Innsbruck), M. Wechakama (U. Kasetsart)

Abstract:
Cosmic rays are relativistic particles that propagate through the interstellar and intergalactic medium. While hadrons (protons, antiprotons, and light nuclei) are relatively well understood, the origin of leptons (in particular positrons, both at the central regions of the Milky Way and the Solar neighbourhood) is still a mystery. The favoured candidates are supernova remnants, pulsars, and potentially the annihilation or decay of dark matter particles.
After being introduced to the fundamentals of astroparticle physics, the students will use different numerical codes to model the production and propagation of cosmic rays throughout the Galaxy, as well as the predicted emission at different frequencies. By comparing the results with state-of-the-art observations in the radio, microwave, and/or gamma-ray regime, we will attempt to constrain the main sources of cosmic rays and the relevant propagation parameters (e.g. gas density, radiation and magnetic fields).

References:
https://arxiv.org/abs/2403.03303
https://github.com/cosmicrays/DRAGON2-Beta_version
https://github.com/cosmicrays/hermes

Recommended subjects: Astroparticle Physics

Title: Probing the Electroweak phase transition in Higgs boson decays

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

Abstract (and references):
The breaking of the electroweak (EW) symmetry in the early Universe, known as the EW phase transition, 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 particles coupled to the Higgs field should exist to yield the measured BAU during a first-order EW phase transition (FEWPT). If these new particles are light, the 125 GeV Higgs boson discovered at the LHC could decay into them. Such exotic decay would add to the measured Higgs boson decays predicted by the SM. Then, searches for new – exotic – Higgs boson decays at the LHC play a crucial role in probing a FEWPT. The experimental LHC programme to search for exotic Higgs boson decays in various final states (with leptons, quarks and/or photons) is well-developed, yet their connection with the EW phase transition properties has been only scratched so far.

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 a simple and well-motivated extension of the SM. Then, he/she will investigate the connection between a FEWPT and the possible existence of exotic Higgs decays, finding the FEWPT parameter regions that could be discovered by ongoing and future LHC searches.

Depending on the student's performance, the TFM may lead to the publication of a research article, and also help the LHC experimental ATLAS and CMS Collaborations in sharpening their exotic Higgs boson decay search programme.

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)
- J. Kozaczuk, M. Ramsey-Musolf, J. Shelton, Exotic Higgs boson decays and the electroweak phase transition (https://arxiv.org/abs/1911.10210)
- Marcela Carena et al, Probing the Electroweak Phase Transition with Exotic Higgs Decays, (https://arxiv.org/abs/2203.08206)
- A. Escalante, Dark scalar reinterpretation of searches for Higgs boson decays into long-lived particles at the LHC, https://arxiv.org/abs/2509.02564

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

Title: NLO Effects in EFT Matching

Supervisor(s): Pier Paolo Giardino (pier.giardino@uam.es)
Abstract (and references): EFTs are a powerful tool that let us describe low-energy phenomena without needing the full details of the high-energy theory. By systematically expanding in powers of energy over the cutoff scale, EFTs capture the relevant physics with controlled approximations, while keeping calculations manageable. However, to ensure that the EFT faithfully reflects possible UV completions, it is crucial to match its parameters to those of the underlying theory: this guarantees that predictions are consistent across energy scales, avoids double counting, and allows one to correctly interpret experimental measurements in terms of fundamental physics.
The purpose of this project is to investigate NLO effects in the matching between the SMEFT and specific UV-complete extensions of the Standard Model. Particular emphasis will be placed on analyzing how different computational schemes—such as choices of input parameters, renormalization prescriptions, and treatments of gamma5 —influence the matching procedure and its phenomenological implications.
References: https://arxiv.org/abs/2212.04510; https://arxiv.org/pdf/2503.07724; https://arxiv.org/abs/2504.00112

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

Supervisor(s): Néstor Parga Carballeda - Joan Falcó Roget

Abstract (and references): Artificial intelligence (AI) is transforming the way we investigate and understand the world. Among the most influential tools are reinforcement learning algorithms, which allow a machine to learn from experience through trial and error, in a way analogous to how an animal or a person learns [1].

A prominent example is Proximal Policy Optimization (PPO) [2], a state-of-the-art algorithm that has recently begun to be applied in brain studies [3]. These works show how AI can help us unravel the mechanisms of learning and decision-making in the brain, while experimental observations inspire new improvements in AI algorithms.

This master's thesis aims to contribute to this "two-way journey" between AI and the brain. The goal is to explore how algorithms such as PPO and related approaches can be applied to problems of modeling learning and decision-making in the brain. In doing so, the project seeks to advance in two directions: on the one hand, achieving more realistic models of brain function; on the other, developing AI systems that learn more efficiently and in ways closer to biological learning.

Some recent works of the computational neuroscience group in this field can be found in the references [4–7].

[1] Bennett, M. S. (2023). *A brief history of intelligence: evolution, AI, and the five breakthroughs that made our brains*. HarperCollins.

[2] Schulman, J., Wolski, F., Dhariwal, P., Radford, A., & Klimov, O. (2017). Proximal policy optimization algorithms. arXiv:1707.06347. An article with nearly 30,000 citations.

[3] Fascianelli, V., Battista, A., Stefanini, F., Tsujimoto, S., Genovesio, A., & Fusi, S. (2024). Neural representational geometries reflect behavioral differences in monkeys and recurrent neural networks. Nature Communications, 15(1), 6479.

[4] Parga, N., Serrano-Fernández, L., & Falco-Roget, J. (2023). Emergent computations in trained artificial neural networks and real brains. *Journal of Instrumentation*, 18(02), C02060

[5] Carnevale, F., de Lafuente, V., Romo, R., Barak, O., & Parga, N. (2015). Dynamic control of response criterion in premotor cortex during perceptual detection under temporal uncertainty. *Neuron*, 86(4), 1067-1077

[6] Serrano-Fernandez, L., Beiran, M., & Parga, N. (2024). Emergent perceptual biases from state-space geometry in spiking recurrent neural networks trained to discriminate time intervals. *Cell Reports, 43(7).*

[7] Serrano-Fernández, L., Beirán, M., Romo, R., & Parga, N. (2024). Representation of a perceptual bias in the prefrontal cortex. *Proceedings of the National Academy of Sciences*, *121*(50), e2312831121.

Recommended subjects: Advanced Mathematics