UNIVERSITÀ DEGLI STUDI DI PADOVA

PHYSICS

Course unit English denomination	**Cosmology**
SS	PHYS-05/A Astrofisica, cosmologia e scienza dello spazio
Teacher in charge	Nicola Bartolo Sabino Matarrese
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March – June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	- Standard cosmology: Fundamentals of General Relativity for cosmology; Cosmological models; Friedmann-Robertson-Walker metric - Thermodynamics of the Universe: elements of kinetic theory in the expanding Universe; evolution of the entropy and of the main thermodynamical quantities; photon and neutrino decoupling; relic particles - Inflation: problems of the standard cosmological model; kinematics and dynamics of inflation models; generation of primordial perturbations - Cosmic Microwave Background temperature anisotropies and polarization: main effects and their physical origin, dependence on cosmological parameters, connection to inflationary perturbations, in particular to primordial gravitational waves. - Gravitational Instability: linear evolution of perturbations; Jeans scale; free-streaming, models with dark matter and baryons; cold dark matter, hot dark matter, etc.

	- Statistics of cosmological perturbations: power-spectrum; transfer function; filter functions; higher-order statistics - Non-linear evolution of perturbations: N-body techniques; spherical model; Zel'dovich approximation and adhesion theory. - Dark Energy: observational aspects; models. A LIST OF POSSIBLE ADVANCED TOPICS: - Techniques for computing primordial non-Gaussianity - Open quantum systems in cosmology - Non-linear and general relativistic cosmological perturbations
Learning goals	The "Cosmology" course aims first of all at providing a concise introduction to the current research in this field, both in the direction of Early Universe physics and Inflation and in the context of the late Universe (large-scale structure formation, evolution and statistical analysis) as well as at the phenomenological characterization of dark matter and dark energy. Emphasis will be given to some of the most up-to-date issues nowadays in cosmology. According to the audience, a selected list of advanced topics can be presented, tuned to the interests of the students. During the course students will be encouraged to read at least one or two papers on some topics of particular interest and to report them with a brief interactive discussion with all classmates. At the end of the course, the PhD students will be familiar with the most important concepts of cosmology, and their main implications (in terms of both modeling and observational constraints). The tools the students will acquire will allow them to solve problems related to the specific subject of the course but they will allow the students also to acquire a knowledge to face more general issues, e.g. those which might resemble the same complexity and approximation schemes learned during the course.
Teaching methods	Lectures will be given at the blackboard with the help of some slides. According to the audience, a selected list of advanced topics can be presented, tuned to the interests of the students. During the course students will be encouraged to read at least one or two papers on some topics of particular interest and to report them with a brief interactive discussion with all classmates. Therefore we will also • promote critical reflection in the classroom

	• conduct discussions in working groups in the classroom • use group work in the classroom
Course on transversal, interdisciplinary, transdisciplinary skills	☒ Yes ☐ No
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	Minimal knowledge of general relativity, but not mandatory, the course is self-contained
Examination methods (if applicable)	The students will be asked to prepare a short presentation (30 minutes approximately) with slides, on a topic proposed by the students that should be in connection with what has been explained during the course. The presentation will be based on the reading and study of one or more specific papers.
Suggested readings	- S. Dodelson, 2003. Modern Cosmology, Academic Press. - E.W. Kolb and M.S. Turner, 1990. The Early Universe, Addison-Wesley - A.R. Liddle and D.H. Lyth, 2000. Cosmological Inflation and Large-Scale Structure, Cambridge University Press. - S. Weinberg 2008, Cosmology, Oxford Univ. Press.
Additional information	

Course unit English denomination	**Dark Matter**
SS	PHYS-02/A fisica teorica delle interazioni fondamentali, modelli, metodi matematici e applicazioni
Teacher in charge	Francesco D'Eramo, Marco Peloso Edoardo Vitagliano
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	In the last few decades, there has been growing evidence for the existence of dark matter. This course introduces motivated dark matter paradigms that drive most current theoretical and experimental research activities. The lectures are aimed at Ph.D. students working on theoretical and/or experimental aspects of particle and astroparticle physics. The offer is tailored to meet their needs and their backgrounds. - Mod. A: Concise introduction to hot Big Bang cosmology and the thermal history of the Universe. We will first review the observational evidence for the current particle content of the Universe, including various complementary pieces of evidence for dark matter. Starting from basic knowledge of particle physics and statistical mechanics, it is possible to infer from these observations the behavior and properties of the universe when its age was much younger than just one second. These properties can be well understood only within the framework of cosmic inflation. We will review the simplest realizations of inflation and the reheating process that leads to the formation of a dominant thermal bath from the inflaton

	decays. We will show how it is possible during reheating to produce dark matter particles that are too weakly coupled to thermalize. - Mod. B: Thermal freeze-out paradigm. First, we will discuss hot dark matter and we will explain why it is not viable. Standard model neutrinos belong to this class, and they can only be a sub component. We will then investigate cold dark matter and review the motivation for weakly interacting massive particles (WIMPs). These particles reach thermal equilibrium with the bath at early times and therefore their couplings to standard model particles are a potential probe to test WIMP models. We will review experimental searches for WIMPs (also known as “Smash it-break it-shake it”) and these include experiments at particle colliders, detection of cosmic rays by Earth- or satellite-based telescopes, and underground experiments searching for elastic scattering. - Mod. C: Feebly interacting particles (FIPs), which are both dark matter candidates and can solve additional open questions in particle physics; the QCD axion as a solution to the strong CP problem is a prominent example. We will describe the “Smash it-break it-shake it” searches in the axion case. Among other probes, we will focus on astrophysical searches for FIPs, their production in stars and transients (supernovae and neutron star mergers), and the observables associated with their production. We will discuss laboratory searches and some of the most promising new ideas in the direct detection of these elusive particles.
Learning goals	This course aims to introduce Ph.D. students to one of the most urgent questions to answer in fundamental physics: the one about the particle identity of dark matter. The target audience includes students working on both theoretical and experimental particle and astroparticle physics. The objectives of this course are to learn the observational evidence for dark matter, particle physics frameworks motivated from the top down, and their experimental tests.
Teaching methods	This course will consist of lecture-based instruction delivered through Blackboard, with students encouraged to actively engage during class
Course on transversal, interdisciplinary, transdisciplinary skills	☐ Yes ☒ No
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	

Examination methods (if applicable)	The exam will be a seminar on a topic chosen by the student during which lecturers will evaluate the comprehension of the topic itself and the entire program of the course.
Suggested readings	
Additional information	

Course unit English denomination	**Elements of X-ray Physics**
SS	PHYS-03/A
Teacher in charge	Peihao Sun Chiara Maurizio Giulio Monaco
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	In this course, we will discuss theoretical and practical aspects of modern X-ray sources and their current use in the study of materials. The course program is divided into three parts: 1. X-ray sources: synchrotron radiation, undulators, coherent sources. 2. X-ray scattering theory: theory of X-ray – matter interaction, diffraction from amorphous materials, diffraction from crystals (kinematic theory and dynamical theory), refraction and reflection. 3. X-ray applications: X-ray optics, imaging (tomography, CDI, ptychography, etc.), XAS, dynamics (IXS, XPCS).
Learning goals	The goal of this course is to acquire a deeper understanding of the physics of X-rays starting from first principles, as well as a basic knowledge of various X-ray measurement techniques, so that the students will be prepared for X-ray experiments at modern synchrotron facilities
Teaching methods	Frontal lectures with exercises.

Course on transversal, interdisciplinary, transdisciplinary skills	☒ Yes ☐ No
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	Knowledge of electrodynamics, optics, special relativity, quantum physics, and solid state physics.
Examination methods (if applicable)	Oral presentation on a topic of the student’s choice relevant to X-ray physics.
Suggested readings	Elements of Modern X-ray Physics (Jens Als-Nielsen & Des McMorrow) X-Ray Diffraction (B. E. Warren) Lecture notes to be distributed in the course
Additional information	

Course unit English denomination	**Introduction to topological phases of matter**
SS	PHYS-04/A
Teacher in charge	Marco Di Liberto
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	INTRODUCTION - Motivation and generalities - Berry phase, spin in a magnetic field, Dirac monopole and gauge freedom, Bloch bands TOPOLOGICAL BAND THEORY - A case study: The Su-Schrieffer-Heeger model. Polarization, Wannier centers, Wilson loop, winding number and edge modes - Chern insulators: Berry curvature, Chern number, Integer quantum Hall effect (QHE), TKNN formula. Examples: Haldane and Qi-Wu-Zhang models. - Time-reversal invariant topological insulators: quantum spin-Hall effect (QSHE) and its Z_2 invariant. Example: the Bernevig-Hughes-Zhang (BHZ) model - Topological insulators in higher dimensions, the Altland-Zirnbauer classification, crystalline topological insulators

	FRACTIONAL QUANTUM HALL EFFECT AND TOPOLOGICAL ORDER - Electrons in a magnetic field in 2D, Landau levels - Conductivity and Hall response - The lattice limit and the Hofstadter model - Interactions, fractional Quantum Hall effect, Laughlin wavefunction - Hole excitations, abelian anyons, composite particles - Topological order, Kitaev's toric code, perspectives for quantum computing
Learning goals	Students will acquire the main concepts regarding topological systems, their characterization and properties that are relevant to appreciate the scientific developments in the last years. They will be able to identify phases and states of matter with different topological features, define and calculate topological invariants starting from the band structure or from the ground state interacting wavefunction. With these abilities and knowledge, the student will have the tools to approach the most recent scientific literature in condensed matter physics, including topological materials, or more in general, those employing topological field theories and appreciate the impact of topology in contemporary physics
Teaching methods	Frontal lessons
Course on transversal, interdisciplinary, transdisciplinary skills	☒ Yes ☐ No
Available for PhD students from other courses	☐ Yes ☒ No
Prerequisites (not mandatory)	Quantum Mechanics, elements of electromagnetism and band theory, elements of many-body theory
Examination methods (if applicable)	Oral exam

Suggested readings	János K. Asbóth, László Oroszlány, András Pályi, A Short Course on Topological Insulators: Band-structure topology and edge states in one and two dimensions, Lecture Notes in Physics, 919 (2016) - A. Bernevig, Topological Insulators and Topological Superconductors, Princeton University Press (2013) - E. Fradkin, Field Theories of Condensed Matter, Cambridge University Press (2013) - D. Tong, Lectures on the Quantum Hall Effect (2016)
Additional information	

Course unit English denomination	**Modern topics in statistical physics**
SS	PHYS-04/A
Teacher in charge	Gianmaria Falasco
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	The course aims to provide an overview of recent developments in the statistical mechanics and thermodynamics of dissipative systems (mainly classical), i.e., open systems weakly coupled to multiple reservoirs (thermal, chemical, etc.). An introduction to the following topics will be provided, with varying emphasis depending on the participants' background: - Review of the mathematical background useful for the description of open systems: Langevin, Fokker-Planck, and Master equations; path integrals and functional methods. - Stochastic thermodynamics: definition of heat, work, entropy along stochastic trajectories; first and second law; time-reversal symmetry breaking and entropy production; fluctuation theorems. - Linear and non-linear response theory; Zubarev-MacLennan formalism for weakly driven systems; (differential) negative response. - A brief overview of the constraints on dissipative processes: information and Landauer's limit; energy transduction. - Large deviations and rare events: equations for generating functions; Donsker-Varadhan and Gartner-Ellis theorems; dynamical phase transitions.

	- Thermodynamic limit and metastability in dissipative systems: spectral theory of the Markov generator; Freidlin-Wentzell quasi-potential; out-of-equilibrium generalization of the Kramers-Arrhenius law.
Learning goals	The course is aimed at acquiring basic knowledge of the dynamics and thermodynamics of systems that are driven and maintained far from thermodynamic equilibrium. Through frequent analogies and comparisons with equilibrium statistical mechanics and thermostatics, the course will provide the foundation for understanding dissipative phenomena such as population inversion, energy transduction, and non-equilibrium phase transitions. Theoretical tools will also be provided to independently analyze multi-scale stochastic models.
Teaching methods	Oral lectures including applications in the form of worked examples of the general theory.
Course on transversal, interdisciplinary, transdisciplinary skills	☐ Yes ☒ No
Available for PhD students from other courses	☐ Yes ☒ No
Prerequisites (not mandatory)	Introductory courses of Statistical Mechanics
Examination methods (if applicable)	Oral
Suggested readings	Instructor's notes, whose link will be shared with the participants. Books: Stochastic Thermodynamics, Peliti Luca, and Simone Pigolotti, Princeton University Press (2021); Kamenev Alex, An Introduction Field theory of non-equilibrium systems, Cambridge University Press (2023).
Additional information	Examples of specific systems analyzed in the lectures are molecular motors, biochemical reaction networks, electronic circuits (such as memories and clocks).

Course unit English denomination	**Neutrino Physics**
SS	PHYS-01/A
Teacher in charge	Riccardo Brugnera Stefano Dusini Massimiliano Lattanzi
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	1st part: Direct measurements of neutrino masses - Neutrinos masses – theoretical aspects - Beta decay experiments: general aspects - Past experiments and the KATRIN experiment - Bolometric experiments - Alternative approaches - ν_μ and ν_τ mass determination - Neutrinoless double-beta decay: general aspects - The GERDA/LEGEND experiments - Other important double-beta experiments

	2nd part: Introduction to Neutrino Oscillation - 3 neutrino oscillation formalism - PMNS matrix - Neutrino oscillation in vacuum and matter - Neutrino oscillation experiments with beam, solar, atmospheric and reactor neutrinos - Current and future experimental activity - CP violation - Neutrino Mass Ordering - Sterile Neutrinos 3nd part: Neutrino Cosmology - The Standard Cosmological Model - Cosmological observables: cosmic microwave, background anisotropies, large scale structure, geometrical probes - The cosmic neutrino background - Effects of massive neutrinos on cosmological observables - Cosmological constraints on neutrino masses and on the effective number of neutrinos - Prospects for next-generation experiment
Learning goals	The course aims to give a concise summary of all the main topics of the neutrino physics (from the attempt to measure the neutrino mass and determine its nature to the study of the oscillation phenomenon and what we can learn about our Universe using neutrinos). The spirit of the course is phenomenological/experimental so the goal is to give to the student all the elements to judge critically the experimental program of the neutrino research field
Teaching methods	Frontal lessons with the use of slides
Course on transversal, interdisciplinary,	☐ Yes ☒ No

transdisciplinary skills	
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	
Examination methods (if applicable)	Oral presentation of a topics extracted from the arguments touched during the lessons
Suggested readings	● C. Giunti and C. W. Kim, Fundamentals of Neutrino Physics and Astrophysics, Oxford University Press, 2007. https://galileodiscovery.unipd.it/permalink/39UPD_INST/prmo4k/alma990023993520206046 ● J. Lesgourgues, G. Mangano, G. Miele, S. Pastor, Neutrino Cosmology, Cambridge University Press, 2013 ● S. Navas et al. (Particle Data Group), Phys. Rev. D 110, 030001 (2024): chapters "Neutrino masses, mixing and oscillations" and "Neutrinos in Cosmology"
Additional information	

Course unit English denomination	**Nuclear Astrophysics**
SS	PHYS-01/A
Teacher in charge (if defined)	Antonio Caciolli
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March – June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	Over the course of 24 hours in this comprehensive Ph.D. program, participants will explore the fundamental principles of stellar nucleosynthesis. The course is organized into four distinct segments: 1. Introduction to Nuclear Astrophysics and Nucleosynthesis of Elements (6 hours): Laying the foundation by exploring the fundamental concepts of nuclear astrophysics and the element nucleosynthesis. 2. Cross section extrapolations at Stellar Energies through R-Matrix Calculations (6 hours): a brief theoretical introduction of the R-Matrix approach will be followed by practical exercises, using the 12C+p and 13C+p systems as example. 3. Indirect Methods for Nuclear Astrophysics (6 hours): An introduction of indirect methodologies, highlighted by a practical exercise that employs the Trojan Horse method. 4. Practical Tools (6 hours): Equipping students with essential practical skills, covering topics such as the efficiency of high-purity germanium detectors across a wide energy range (from 500 keV to 10 MeV) and the use of resonance scans as a powerful method to unveil the characteristics of target materials.

Learning goals	Introduce to experimental techniques designed to study stellar processes in terrestrial laboratories. This includes both direct and indirect methodologies, each offering a different perspective on this field of research. Introduce students to practical, hands-on procedures for data analysis at various stages of experimental work. This will encompass critical aspects such as detector efficiency calibration, analysis of target scans, and the design of future experimental setups through simulation exercises. Write experimental proposal, a crucial skill for researchers in nuclear physics experiments.
Teaching methods	Lectures and a dedicated section, spanning approximately 6 hours, will be allocated to the R-Matrix analysis, coupled with practical applications employing the Azure2 code.
Course on transversal, interdisciplinary, transdisciplinary skills	☐ Yes ☒ No
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	
Examination methods (if applicable)	The final evaluation will center in developing and presenting an experiment proposal, either individually or collaboratively.
Suggested readings	
Additional information	

Course unit English denomination	**Phenomenology of Particle Physics - Effective Field Theories and Amplitudes**
SS	PHYS-02/A Fisica Teorica, Modelli E Metodi Matematici
Teacher in charge	Matteo Fael Pierpaolo Mastrolia
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	Module: Effective Field Theory Effective Field Theories (EFTs) form the foundation of modern particle physics, providing a versatile framework to describe a broad spectrum of phenomena and calculate experimentally measurable quantities. This course covers the essential principles behind the emergence of EFTs and their consistent application in research. Special focus will be given to widely used EFTs in collider physics and their role in the search for new physics beyond the Standard Model. The course is designed for students specializing in theoretical physics, but also those involved in the CMS and Belle II experiments can benefit from it, offering a bridge between theoretical concepts and experimental exploration at the frontiers of high-energy physics. Module: Amplitudes Scattering Amplitudes and related cross sections represent the interface between Quantum Field Theory and experimental verification, and constitute the ideal “theoretical laboratory” for the study of fundamental

	interactions through the direct production of real particles or the indirect determination of their virtual effects. At the same time, Scattering Amplitudes offer an interesting window on the understanding of the formal properties of gauge theories, effective field theories (EFT) and gravity. In this course, students will familiarize with modern computational techniques for Feynman integrals, based on integration by parts identities, differential equations as well as with on-shell methods and techniques based on the spinor-helicity formalism, generalized unitarity, and integrand decomposition, reaching out to the basics concepts of intersection theory. The lectures cover applications of Feynman calculus and Scattering Amplitudes in Particle Physics and in Gravitational Waves Physics, within the General Relativity-EFT diagrammatic approach. Students' competence and abilities are finally enhanced through the participation in interdisciplinary projects that may combine Theoretical Physics, Mathematics and Computer Science.
Learning goals	The students will develop the following abilities: 1) Understand the emergence of an EFT: separation of scales, degrees of freedom, symmetries and power counting. 2) Implement an EFT as a consistent quantum field theory. 3) Model effects of new physics above the EW scale within the framework of the SM EFT. 4) Describe low-energy dynamics of hadrons containing a heavy quark using EFTs. 5) Apply the spinor-helicity formalism, on-shell and generalised unitarity; 6) Study the algebraic properties of Feynman integrals; 7) Derive and solve systems differential equations for Feynman integrals; 8) Describe higher-order effects in scattering events.
Teaching methods	Lectures are delivered at the blackboard with the aid of slides.
Course on transversal, interdisciplinary, transdisciplinary skills	☐ Yes ☒ No
Available for PhD students from other courses	☐ Yes ☒ No

Prerequisites (not mandatory)	Quantum Field Theory
Examination methods (if applicable)	Oral presentation on a topic relevant to the course or short-term research project
Suggested readings	- A. Manohar, “Introduction to Effective Field Theories,” hep-ph/1804.05863 - S. Badger, J. Henn, J. C. Plefka and S. Zoia, “Scattering Amplitudes in Quantum Field Theory,'' Lect. Notes Phys. 1021 (2024), hep-th/2306.05976
Additional information	

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PHYSICS

Course unit English denomination	**Quantum tools for future scientific research**
SS	PHYS-04/A
Teacher in charge	Simone Montangero
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	Module I Quantum and classical computing Quantum advantage Elements of superconducting, photonic and Rydberg quantum hardware Module II Elementary tensor operations Tensor network ansatz Tensor network operators Tensor network algorithms; ground state search, time evolution Module III Presentation of selected topics in flipped classroom mode

Learning goals	Learning the concepts of quantum computation and simulations, quantum advantage and the main hardware supports developed to achieve them. Acquiring knowledge of the current available methodologies and concepts developed in quantum information theory and their potential applications to different research areas, such as condensed matter physics and high energy physics. Acquiring knowledge on tensor network methods. Learning to present advanced topics in the field, being able to transmit knowledge and make connections among different fields
Teaching methods	Frontal lessons, case studies, flipped classroom
Course on transversal, interdisciplinary, transdisciplinary skills	☐ Yes ☒ No
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	Quantum Mechanics Examination methods
Examination methods (if applicable)	Oral exam – presentation on selected topic
Suggested readings	
Additional information	

Course unit English denomination	**Renormalization group techniques for equilibrium and nonequilibrium statistical mechanics**
SS	PHYS-04/A
Teacher in charge	Amos Maritan
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	This course delves into the theoretical and practical aspects of the Renormalization Group (RG), highlighting its pivotal role in understanding emergent phenomena at large spatiotemporal scales. The main topics covered include: - Motivations and fundamental concepts of RG: Emergent phenomena at large scales and the need for scaling laws to describe both infinite and finite systems. The theoretical framework underpinning RG, with particular emphasis on the Kadanoff-Wilson approach. - RG in equilibrium statistical mechanics: Applications to the Ising model and field theories, focusing on phase transitions and correlation functions. - RG in non-equilibrium statistical mechanics:

	Analysis of dynamic phenomena via the Langevin equation and interface growth equations.
Learning goals	By the end of the course, participants will be able to: 1. **Identify the key ingredients** underlying emergent phenomena at large spatiotemporal scales. 2. **Construct minimal models** that incorporate these key ingredients. Apply RG techniques in both real space and momentum space to analyze complex physical problems
Teaching methods	Lectures
Course on transversal, interdisciplinary, transdisciplinary skills	☒ Yes ☐ No
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	
Examination methods (if applicable)	Oral exam and project
Suggested readings	P. Kopietz, L. Bartosch, and F.Schütz. *Introduction to the functional renormalization group*. Vol. 798. Springer Science & Business Media, 2010. U. C. Täuber, *Critical Dynamics: A Field Theory Approach to Equilibrium and Non-Equilibrium Scaling Behavior*, Cambridge University Press, Cambridge. Course notes and various scientific papers
Additional information	

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PHYSICS

Course unit English denomination	**Scientific Computing for Physics Students**
SS	PHYS-01/A, PHYS-02/A, PHYS-03/A, PHYS-04/A, PHYS-05/A, PHYS-05/B, PHYS-06/A
Teacher in charge	Alessandro Renzi
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	The course provides skills in using tools for developing scientific software for physics, covering development environments, programming languages, algorithms, data structures, parallel and GPU computing, FFTs, Monte Carlo techniques, machine learning, and code optimization. Languages covered include C, C++, Fortran, Python, Julia and Mathematica.
Learning goals	Acquire knowledge and abilities in using scientific languages, managing Linux environments, implementing numerical algorithms and data structures, following software development best practices, and utilizing high-performance computing techniques.
Teaching methods	Lectures, hands-on coding exercises, case studies, group work
Course on transversal, interdisciplinary, transdisciplinary skills	☐ Yes ☒ No
Available for PhD students from other courses	☒ Yes ☐ No

Prerequisites (not mandatory)	Basic knowledge of programming and numerical computing
Examination methods (if applicable)	Final coding project with weekly handouts
Suggested readings	Suggestions for books or websites for scientific computing related to the course modules will be provided during the lectures.
Additional information	Course designed for theorists and experimentalists.

Course unit English denomination	**Standard Model and Flavour Physics**
SS	PHYS-01/A, PHYS-02/A
Teacher in charge	Gabriele Simi Mia Tosi Alessandro Gaz Patrizia Azzi
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	1) Precision Electroweak Physics (8h) This part of the course will cover: - Measurement at the Z pole (LEP 1 and SLD): Z mass and width, eff, branching fractions - Asymmetries: forward-backward, left-right, polarization - W mass (and width) at Lep II, Tevatron and LHC - Top mass (Tevatron and LHC): methods and issues - Higgs discovery and measurements of its properties: mass, width, spin, coupling - Global Electroweak Fits

	2) CKM Matrix and New Physics (7h) This part of the course will cover: - The CKM mechanism CP violation, the role of B meson oscillations - The measurement of B and D mesons mixing - How to measure CKM Angles (β, γ), - How to measure CKM Sides Vub and Vcb, LFU violation - Rare B decays as constraints on new physics and search for dark matter at colliders 3) Advanced Topics (5h) This part of the course will cover: - Experimental techniques to perform amplitude analysis of resonant decays - Time dependent amplitude analyses - How to search for exotic (multiquark) states - CP violation in kaons and rare K decays 4) Future Colliders (4h) This part of the course will be devoted to the possible post-LHC physics program, which includes e+e- colliders, high energy hadron colliders (including heavy ion collisions), electron-hadron/ion colliders, muon-muon colliders. The students will see the relevant physical measurements that can be performed at the different machines, considering the various types of colliding particles (protons, electrons, muons, ions, etc.) and the different energy ranges, such as those of the current designs under discussion. The course will discuss the various physics challenges and the final performances of each type of machine. Some details on the detectors will be provided
Learning goals	In the first part of the course, the student will learn how to perform precision electroweak measurements at the energy frontier how to use them to perform the global electroweak fit (Z,W,H,t). The main EW measurements will be described, highlighting the experimental strategies and challenges. The most recent results in terms of EW measurements will be discussed.

	In the second part, the student will learn how to describe the flavor sector of the SM in terms of the CKM matrix, how to build the unitarity triangle, and how to measure its angles and sides. Furthermore, the student will learn how to use the B meson rare decays as a tool to search for new physics at the intensity frontier. Finally, the student will learn the main techniques for searching for dark matter at colliders. In the third part of the course, the student will learn some advanced topics relevant to modern particle physics, including how to use the amplitude analysis method to search for exotic states and to measure CP violation. The student will also learn how to use advanced tools such as the b- and charm flavor taggers. An overview of CP violation in the kaon system will also be given. In the fourth part of the course, students will learn to use the fundamental concepts learned throughout the course (physical observables, phenomenology, measurement methods, systematic evaluation...) to critically understand the differences of the various machines proposed for the future and which physics can be performed better on which machine. The goal is to understand the advantages and limitations of different choices of machines for various physics benchmarks that we want to achieve: precision electroweak measurements, properties of the Higgs boson, including the measurement of self-coupling, direct searches for new physics
Teaching methods	The course is organized into four sets of lectures, where different topics are treated and described. Several publications from the most important peer-reviewed journals are presented or suggested for further studies
Course on transversal, interdisciplinary, transdisciplinary skills	☐ Yes ☒ No
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	Sub-nuclear physics course, basic principles of theoretical physics
Examination methods (if applicable)	The exam will consist of an oral presentation on an experimental topic among those covered or suggested during the course.
Suggested readings	Slides and the most relevant publications
Additional information	

Course unit English denomination	**Statistical methods for physics analysis**
SS	PHYS-01/A, PHYS-02/A, PHYS-03/A, PHYS-04/A, PHYS-05/A, PHYS-05/B, PHYS-06/A
Teacher in charge	Denis Bastieri, Tommaso Dorigo Luca Stanco
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	The course aims at providing students with a basic understanding of fundamental issues in statistics of relevance for practical data analysis, and a knowledge of the main techniques for statistical inference in experimental science. General Introduction: - Random variables, probability density functions, the Central Limit theorem, cumulative function, properties of estimators, examples and applications. - Methods of minimum squares and maximum likelihood, covariance matrix. Applications and examples. - Error propagation: some examples and practical applications.

- Probability theory, Kolmogorov axioms, theorem of Bayes, practical applications.

- Lemma of Neyman-Pearson. Probability ordering.

- Interval estimation, confidence intervals, hypothesis testing and p-values, goodness of fit and practical applications. Construction of the power-curve. Coverage for the confidence intervals from maximum likelihood.

- The problem of the measurement of 0 or very few events. The method of Feldman-Cousins.

- Technicalities in the generation of random numbers. Simulations of several functional relations.

- Processes of Markov. Sketch of Markov chain. The process of Filtering and Smoothing. The Kalman filter.

Statistics in HEP:

- Evaluation of p-values for counting experiments, with and without nuisances.

- Definition and computation of significance for a signal.

- Correspondence between p-value and significance in case of non-Gaussian nuisances.

- Look-elsewhere effect and approximate methods for its estimation.

- The CLS method and its application to the search for signals.

- Profile likelihood and statistical tests.

- Application to the search for the Higgs boson at LHC.

- Asymptotic methods for the evaluation of sensitivity with the profile likelihood.

Statistics in Astrophysics:

- Applications of statistical inference and test of models: Z-score and T-score

- Coefficient of correlation and related test. Bootstrapping.

- Non-parametric tests: Spearman’s rank.

- Kolmogorov-Smirnov: test and related applications, test of Cramér-von Mises

	- Test of isotropy: monolope, dipole and quadrupole, statistics of Rayleigh, Watson and Bingham. - Correction of Bonferroni or trial factors. - Test of Anderson-Darling. - Statistics of Cash (Poisson) - Application of maximum likelihood: the catalogue. - Errors of type I and type II: screening and testing, technicalities, sensitivity and power of testing. - Data analysis: correlation, auto-correlation, function of angular correlation at 2 points, and applications. - Analysis of images: linear filters and applications, the Gaussian filter
Learning goals	Enable students to appropriately choose the statistical method for different use cases in data analysis tasks; teach students the importance of reasoning on the sampling distribution of their data, and on its effects on inference; stress the importance of error analysis and uncertainty quantification; make them better scientists by distributing information on what are sound analysis practices and what are incorrect or faulty techniques
Teaching methods	Frontal lectures; open discussion of software solutions; homework exercises; stimulating students to critically assess topics in open discussion
Course on transversal, interdisciplinary, transdisciplinary skills	☒ Yes ☐ No
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	
Examination methods (if applicable)	Discussion of a topic of interest of the candidate, chosen from the course; or of aspects of the statistical analysis relevant for the research carried out by the candidate

Suggested readings	Lecture notes, slides shown during lectures, software provided by the instructors; book by Glen D. Cowan “Statistical Data Analysis”, Oxford Science Publications 1997
Additional information	It is advisable to download and install the ROOT program from root.cern.ch to carry out exercises proposed during the course

Course unit English denomination	**String theory, supersymmetry and supergravity**
SS	PHYS-02/A
Teacher in charge	Fabio Apruzzi Gianluca Inverso
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	String theory is a theory of quantum gravity which is currently the best candidate for a UV completion of the presently tested models of the fundamental interactions. It can be used to answer questions sensitive to the Planck scale; it provides a set of lower energy effective field theories which are relevant for phenomenology, putting constraints on models of cosmology and particle physics beyond the standard model. It has produced several ground-breaking results: the microscopic description of the Bekenstein-Hawking entropy of black holes, the AdS/CFT correspondence (that is, the holographic description of strongly coupled quantum field theories), the discovery of large families of non-perturbative “dualities" between apparently unrelated quantum theories, and many others. The aim of this course is to explain the basic principles of string theory, supersymmetry and supergravity, and to discuss their applications. The program, which can be adapted to the background of the students, consists in an introduction to perturbative string theory, the formalism of supersymmetric gauge theories and supergravity, superstring effective actions, D-branes and dualities, holography and phenomenological applications.
Learning goals	The aim of this course is to develop an understanding of the basic principles of string theory, supersymmetry and supergravity, and their applications. Students will acquire the tools to perform supersymmetry

	calculations, in the construction of string theory effective actions, understand the basics of flux compactifications, the relation between brane systems and gauge theories, and the study of non-perturbative effects and dualities within these frameworks.
Teaching methods	Lectures
Course on transversal, interdisciplinary, transdisciplinary skills	☐ Yes ☒ No
Available for PhD students from other courses	☐ Yes ☒ No
Prerequisites (not mandatory)	General Relativity, Quantum Field Theory
Examination methods (if applicable)	Presentation on a topic relevant to the course and to the student's research project
Suggested readings	Polchinsky "String Theory"; Green–Schwarz–Witten "Superstring Theory"; Freedman–Van Proeyen "Supergravity", Dall'Agata–Zagermann "Supergravity, From First Principles to Modern Applications"
Additional information	

Course unit English denomination	**Structured light: from principles to modern applications**
SS	PHYS-03/A
Teacher in charge	Gianluca Ruffato Filippo Romanato
Teaching Hours	24
Number of ECTS credits allocated	3
Course period	March - June 2026
Course delivery method	☒ In presence ☐ Remotely ☐ Blended
Language of instruction	English
Mandatory attendance	☒ Yes (50% minimum of presence) ☐ No
Course unit contents	The course covers the following topics: - Recap of wave optics and electromagnetism. - Fourier optics: description of the propagation of a light beam in the paraxial regime. - Orbital angular momentum of light: families of optical vortices and their properties. - Polarization and combination with spatially structured light: vector beams. - Refractive, diffractive optical elements, and metasurfaces: physical principles, design methods, and realization. - Spatial modes in multimode optical fibers and their applications in classical and quantum regimes. - Methods for generating, measuring, and controlling the orbital angular momentum of a light beam. - Design and fabrication of optics for the generation of structured light.

	- Nanostructuring of matter to achieve nano-optical effects. - Basics of nanofabrication for nanostructured optical devices. - Design and fabrication of metalenses and diffractive optics. - Optical characterization and applications of metalenses and diffractive optics. - Applications of light with innovative devices, such as quantum computers and trapping, optical computers, metaguides, and quantum optics.
Learning goals	At the end of the course, the student will be able to: - describe the propagation of an optical beam in free space or in an optical fiber - describe the effect of an optical element on the propagation of a light beam - design standard optical elements (refractive or diffractive) and metasurfaces to perform specific optical operations - understand the physical mechanisms underlying optical devices used in the field of information and communication technologies, particularly for encoding and transmitting information on the spatial modes of light, both in the classical and quantum regimes - apply concepts of modeling, simulation, and computation to the design of nanostructured optical devices - understand and describe the correlations between the nanostructuring of matter and the effects on nanostructured light - understand and describe processes and protocols for nanofabrication.
Teaching methods	Lessons in presence and analysis of case studies
Course on transversal, interdisciplinary, transdisciplinary skills	☒ Yes ☐ No
Available for PhD students from other courses	☒ Yes ☐ No
Prerequisites (not mandatory)	
Examination methods (if applicable)	Final seminar on a topic agreed upon with the teachers
Suggested readings	Slides of the lessons, books and articles suggested by the teachers

Additional
information