UNIMORE
UNIVERSITÀ DEGLI STUDI DI MODENA E REGGIO EMILIA
Dipartimento di Scienze Fisiche, Informatiche e Matematiche

M.Sc. program in Physics – Laurea Magistrale Internazionale – A.Y. 2024/2025

Curriculum **Theoretical and Computational Physics**

The curriculum provides a solid understanding of fundamental theories and advanced modeling techniques in modern physics, combined with state-of-the-art computational methods, preparing students to address complex physical problems across a wide range of scales and applications.

A solid up-to-date training in theoretical, mathematical and computational physics

Theoretical physics supplies the formal framework for describing physical phenomena, from elementary particles and fundamental interactions to condensed-matter systems and quantum devices.

In this Curriculum, **four mandatory courses** establish rigorous foundations in quantum mechanics, quantum field theory, the physics of condensed matter, and modern statistical mechanics. Students acquire the mathematical structures and conceptual tools needed to analyze physical systems ranging from few-particle problems to complex many-body phenomena. **Analytical methods** are complemented by **formal reasoning** and **critical thinking**, preparing students for advanced theoretical challenges in both academic and applied contexts.

Computational physics is a core component of the curriculum. Advanced numerical simulations, high-performance computing, and data analytics are integrated across different areas, from quantum system simulations and electronic and optical properties of matter to astronomic scale modeling. Students gain hands-on experience with state-of-the-art research tools, preparing them for theoretical research and simulation-driven innovation.

Two complementary tracks: condensed matter and high-energy physics

The broad range of courses and the flexible structure of elective choices support two main **specialization tracks**, while allowing interdisciplinary study.

The **quantum theory of condensed matter** track addresses the fundamental properties of matter, from strongly correlated systems to low-dimensional and topological phases, including electronic, magnetic, and superconducting phenomena. It connects with nanoscience, quantum simulation, and quantum information processing, with applications in materials science, energy, and emerging quantum technologies.

The **high-energy physics** track focuses on fundamental interactions through quantum field theory and particle physics, covering gauge theories, the Standard Model, general relativity, and string theory. It also includes courses in astrophysics and cosmology, explored through modern theoretical and computational approaches.

Students may specialize in one area or build an interdisciplinary profile combining both tracks. **Free-choice courses** encourage exploration of connections with fields such as quantum technologies, computational biology, and advanced numerical methods.

Opportunities and perspectives

The final thesis project is carried out within research groups with strong **international connections**, often in collaboration with **national research institutes** and **international centers**.

Graduates are well prepared for **doctoral programs** in physics and for **research-oriented careers** in **academic and research institutes**, and **high-tech** industries. Their combined expertise in theoretical modeling and computational methods also supports interdisciplinary roles in **quantitative R&D** and **data-driven science**.

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Below is a list of the courses available in this curriculum, each with a short description, organized into groups. Please follow the rules indicated for each group when selecting your preferred courses. You also have two free-choice courses, which may be selected from this curriculum, from other curricula, or even from other degree programmes, allowing you to design a highly interdisciplinary personal study plan (subject to approval by the Programme Coordinator). For guidance, you are encouraged to consult the Coordinator or academic tutor.

FIRST YEAR

Title and description of the course	Hours	ECTS	SSD	Term I	Term II	
Distinctive courses [B]		36				
mandatory courses						
Advanced quantum mechanics *A course addressing several aspects of quantum mechanics relevant to modern developments of physics, from condensed-matter theory to particle physics and their fundamental interactions. Emphasis will be given to the concept of Berry phase, the path integral formulation, and scattering theory.(Prof. M Gibertini)*	48	6	FIS/02	I		☑
Quantum field theory *An introductory course on QFT providing the quantization of scalar, spinor and vector fields, and covering the computation of scattering processes and decay rates in ϕ^4, Yukawa and QED theory. The course also provides a first discussion of radiative correction and renormalization.(Proff. D Trancanelli, E Bertuzzo)*	48	6	FIS/02	I		☑
Statistical mechanics and phase transitions *An advanced course in statistical mechanics covering theoretical foundations, phase transitions, and critical phenomena. Students will explore Ginzburg-Landau theory, statistical field theory, the renormalization group approach, and selected exactly solvable models, offering a comprehensive perspective on this modern area of physics.(Prof. G Goldoni)*	48	6	FIS/03		II	☑
Fundamentals of condensed matter physics *An introductory course on the quantum theory of condensed phases of matter, focusing on the microscopic principles that govern the behavior of solids. Topics include crystal structures, lattice vibrations, electronic band theory, and transport phenomena. The course provides a solid foundation for understanding a wide range of phenomena and for pursuing further studies in advanced condensed matter physics.(Prof. R Bianco)*	48	6	FIS/03	I		☑
choose two courses among						
Advanced condensed matter theory *A modern course on theoretical aspects of condensed matter, in the light of current research and computational methods. Topics span from the modern theory of polarization, Wannier functions, theory of screening and plasmons, to the description of the electron-phonon interaction and the microscopic theory of superconductivity.(Prof. F Grasselli)*	48	6	FIS/03		II	☐
Laboratory of quantum simulation of materials *Frontal lectures and hands-on tutorial sessions introduce attendees to theoretical/computational techniques for the electronic structure simulation of condensed matter systems. Special emphasis is given to Density Functional Theory, the present state-of-the-art, parameter-free and atomistic scheme for the predictive description of materials.(Prof. A Ruini)*	60	6	FIS/03	I	II	☐
Theoretical astroparticle physics *What is the universe made of? We will learn how particle physics and cosmology get together to provide a comprehensive framework. After a recap of the Standard Model of Particle Physics, we will describe the concordance model of Cosmology and its successes. We will then turn our attention to dark matter, presenting knowns and unknowns about this fascinating component of the universe.(Prof. E Bertuzzo)*	48	6	FIS/04		II	☐
Elementary particles *A course on the elementary constituents of matter, their properties and their interactions, including the most recent discoveries in this field and an introduction to particle accelerators and particle detectors.(Prof. A Bizzeti)*	48	6	FIS/04	I		☐
Related courses [C]		24				
choose four courses among						
Advanced quantum field theory *A follow-up course on Relativistic Quantum Field Theory introducing quantization of theories based on local (gauge) symmetry, the main ingredients of the Standard Model, the theory that describes with amazing precision the interactions of elementary particles. More advanced topics, including Supersymmetry and/or BRST-BV formalism, will be covered.(Prof. O Corradini)*	48	6	FIS/02		II	☐
Nanoscience and quantum materials *Nanosystems are both quantum worlds with astonishingly new properties and the basis of new nanodevices. The course provides a conceptual and practical framework dealing with the physics and description of a set of prototype nanosystems, from nanotubes and graphene structures to nanocrystals, quantum wells, wires and dots.(Prof. E Molinari)*	48	6	FIS/03		II	☐
Relativity *Learn the elegant mathematical framework behind Special and General Relativity and apply it to fascinating physical problems, including GR effects on planetary motion, the physics of black holes, gravitational waves and cosmology. The course also provides a first discussion of quantum gravity.(Prof. D Trancanelli)*	48	6	FIS/02	I		☐

Title	Hours	ECTS	SSD	Term I	Term II	
Astrophysics	48	6	FIS/05		II	☐

A course exploring key modern topics in astrophysics, with focus on the complex universe of multi-scale black holes and their profound influence on galaxies throughout the cosmic evolution. It blends theoretical, numerical, and observational approaches. Students delve into the fascinating areas of extragalactic astrophysics, from the basics to the cutting-edge concepts and recent discoveries, such as gravitational waves and weather-like feedback mechanisms.(Prof. M Gaspari)

Title	Hours	ECTS	SSD	Term I	Term II	
Quantum many-body theory	36	6	FIS/03		II	☐

A course covering concepts and physical pictures behind various phenomena that appear in vast assemblies of interacting quantum particles. The most widely used many-body methods are presented (many-body perturbation theory, large-scale diagonalization methods, Feynman diagram, and Green's function approaches) and applied to selected physical systems.(Proff. A Ferretti, M Rontani)

Title	Hours	ECTS	SSD	Term I	Term II	
Quantum information processing	48	6	FIS/02	I		☐

An introduction to the theory behind quantum computers and QIP in general. Topics range from the basic concepts of QIP such as quantum entanglement and generalized quantum dynamics, to fundamental QIP algorithms, such as Shor's factoring, and quantum cryptography.(Prof. P Bordone)

Title	Hours	ECTS	SSD	Term I	Term II	
Physics of semiconductors	48	6	FIS/03		II	☐

A course providing all the necessary ingredients to understand the fascinating physical properties of semiconductors, from their electronic structure description to transport and optical phenomena, and how to exploit them in devices such as transistors, LASER, LED and solar cells, or to observe novel states of matter like the quantum Hall liquid.(Prof. S D'Addato)

Title	Hours	ECTS	SSD	Term I	Term II	
Theory and simulation of excitations in materials	48	6	FIS/03		II	☐

A course to master modern techniques to simulate excitations in solids and molecules from first principles: molecular dynamics for vibrational spectroscopies, time-dependent density functional theory, many-body perturbation theory, and quantum embedding methods for photoelectron spectroscopies, optical absorption, and excited-state phenomena in materials for energy and quantum information science.(Prof. M Govoni)

Title	Hours	ECTS	SSD	Term I	Term II	
Chemical physics of biomolecules	36	6	FIS/07	I		☐

A unique, multidisciplinary course to acquire advanced theoretical understanding of chemical physics, with emphasis on biomolecules, colloids and their application to nano-biophysics and nano-medicine.(Prof. G Brancolini)

Title	Hours	ECTS	SSD	Term I	Term II	
Physics education: theoretical and experimental methods	48	6	FIS/08		II	☐

How do people actually learn physics? This course examines the theoretical and experimental methods used of physics education research to investigate how student understand physics and design effective instruction. We examine studies on conceptual challenges across classical and modern physics, and critically assess teaching strategies, including laboratories, digital technologies (like AI), and active learning frameworks. Highly interactive, the course engages you with current literature and real-world case studies—ideal for those interested in teaching, educational research, or a research-informed view of the discipline.(Prof. E. Tufino)

Title	Hours	ECTS	SSD	Term I	Term II	
Lab. of machine learning and advanced computing for physics	60	6	FIS/03	I	II	☐

A course covering core concepts in machine learning and high-performance computing with a physicist's approach. Foundations and applications of supervised and unsupervised learning — from Bayesian inference to deep and convolutional neural networks — are practiced with Python-based exercises. High-performance and parallel computing are introduced also for students without experience in scientific computing. Fundamental concepts and tools are implemented with MPI and OpenMP on state-of-the-art heterogeneous HPC architectures.(Proff. F Grasselli, P Bonfà)

SECOND YEAR

Title and description of the course	Hours	ECTS	SSD	Term I	Term II	
Distinctive courses [B]		6				

choose one course among

Title	Hours	ECTS	SSD	Term I	Term II	
Magnetism, spintronics, and quantum technologies	48	6	FIS/01	I		☐

The course deals with quantum and statistical description of magnetic phenomena, with a focus on experimental techniques and advanced applications in spintronics and molecular magnetism. The course also offers an overview on quantum technologies introducing basic concepts on quantum sensing with spin centers, the functioning of superconducting devices/qubits and fundamentals of cryogenics.(Prof. M Affronte)

Title	Hours	ECTS	SSD	Term I	Term II	
Synchrotron radiation: basics and applications	48	6	FIS/01	I		☐

A course on the working principles of synchrotrons and the use of emitted radiation, from description of single ultra-relativistic particles sources to essentials of storage rings, bending magnets, wigglers and undulators, free electron lasers, beam lines. Examples of ensuing popular techniques, as X-ray diffraction, scattering, absorption and X-ray microscopy, are discussed and a visit to to ELETTRA labs in Trieste ends the course.(Prof. S D'Addato)

Free choice courses [D] — 12

Choose at least 12 ECTSs among all courses (of any curriculum), or any other course offered at UNIMORE

Title	Hours	ECTS	SSD	Term I	Term II	
Professional preparation [F]		6				
Good practices in research		3		I		☐
Physics and society		3		I		☐
Science-based innovation		6				☐

Attendance of CBI/SUGAR Unimore projects (see https://clab.unimore.it/)

Title	Hours	ECTS	SSD	Term I	Term II	
High-performance computing in sciences		3				☐

Attendance of HPC courses (see e.g. https://eventi.cineca.it/en/hpc/catalogue)

Thesis project and dissertation [E] — 36