Nanyang Technological University
Division of Physics and Applied Physics

Academic Year	AY2021-22	**Semester**	1
Course Coordinator	Visiting Profs. Albert De Roeck and Emmanuel Tsesmelis		
Course Code	PH4411		
Course Title	Introduction to Experimental Particle Physics		
Pre-requisites	Approval by Division of Physics and Applied Physics		
No of AUs	3 AU		
Contact Hours	Total 39 hours 30 hours (lectures given over two weeks in total) 9 hours (computational lab project / tutorials / tests)		
Proposal Date	15 December 2020		

Course Aims

This course aims to introduce the students to Experimental Particle Physics and applications of the technology used (accelerators, detectors, computing and statistics). Particle physics is at the cutting edge of technological requirements needed for its detectors and accelerators. The students will get a detailed introduction of the basic concepts of fundamental physics of particles and forces and especially to experimental techniques used in experiments and accelerators. The huge computing challenges and application of modern analysis methods, such as machine learning in experimental data analysis, will also be discussed. Connections with areas such as medical applications and materials science will also be made.

The CERN Large Hadron Collider (LHC) and potential new future collider projects are used as the main thread throughout the course.

Intended Learning Outcomes (ILO)

By the end of this course, you (as a student) would be able to:

1. Unpack in a pragmatic way the inner workings of the Standard Model of Particle Physics and decipher interactions between fundamental particles and how the four fundamental forces work.
2. Decipher so-called Feynman diagrams, a universally used tool in Particle Physics, to comprehend particle interactions.
3. Identify in detail the basic physics principles on which particle detectors are based.
4. Determine how these basic physics principles are used in real particle physics experiments in practice, and what are the challenges.
5. Follow in detail an analysis at a huge particle physics experiment at the LHC works, through the example of the Higgs particle discovery at CERN.
6. Present an up-to-date overview on the research for finding cracks in the Standard Model of Particle Physics that could explain, for example, what dark matter is or where the baryon asymmetry of the Universe comes from.
7. Explain the basic grounding of particle accelerators (transverse and longitudinal dynamics, beam imperfections, RF acceleration, beam diagnostics & instrumentation, and synchrotron radiation) as well as in plasma physics and lasers for the development of laser-driven devices for particle acceleration.
8. Describe in detail how a modern particle accelerator works through the example of the LHC and potential new future collider projects.

9. Become aware of applications beyond particle physics of the technologies and techniques used in particle physics experiments and accelerators.
10. Interpret accurately how particle physics experiments and accelerators work from published literature.

11. Present a clear view of the present status of particle physics and show the future directions of research in this field, and how to connect to that.

Course Content

Introduction
What are the fundamental forces and particles What is the Standard Model of particle physics?
Introduction to one of the most important tools in particle physics, to understand and work with so called Feynman diagrams.

Interactions of sub-atomic particles with matter
The physics principles of sub-atomic particles passing through matter.
Detailed discussion of the energy loss of particles when traversing matter.
Separate discussions for charged and neutral particles, and special attention to electrons and photons.

Detector principles for particle detectors
Introduction of the different types of detectors, tracking detectors, calorimeters, muon detectors.
Discussion of the different types of calorimeters used.
Specialized detectors such a Cherenkov, time of flight, transition radiation detectors and more.
Discussion of the major challenges in detector design and construction

Analysis of data of particle physics experiments
Introduction of the major challenges of modern particle physics experiments, including the large data volume, the required computing on a world scale level, and the analysis techniques that are being adopted to an increasing larger extent in particle physics, such as Machine Learning and deep neural network technologies The Higgs boson discovery is used as an explicit example to demonstrate these concepts.

Review of the cutting edge results from particle physics experiments

Review of experiments used in particle physics which cover the LHC and other major accelerators around the world, cosmic ray experiments, neutrino experiments and more.
The latest findings of these experiments are reported and will give a clear up to date picture of the status of the field in experimental particle physics, the next physics challenges ahead and the future in general of the field.

Introduction - Types of Particle Accelerators
This lecture provides an overview of the development of accelerators throughout history, including some of the key innovations such as phase stability and focusing principles. After this lecture, students should be able to explain the basic operating principles of a range of different types of accelerators, including electrostatic accelerators, linear accelerators, cyclotrons, synchrotrons and fixed-field alternating- gradient accelerators.

Transverse Optics
This series of two lectures gives an introduction to transverse dynamics in periodic accelerators. The lectures take students through a treatment of weak focusing in synchrotrons, introduces the multipole description of magnetic fields, motivates strong (alternating gradient) focusing and derives the equation of motion (Hill's equation) and its solution. This lecture introduces the concepts of transfer matrices, stability of focusing, betatron tune, and phase space.

Longitudinal Beam Dynamics and Momentum Effects
This series of two lectures provides an introduction to longitudinal beam dynamics in the periodic accelerators. The lectures include phase stability in a repetitive acceleration system; transition and momentum compaction; and the effect of momentum spread.

Lattice Design and MAD-X
This lecture introduces the students to understanding accelerator lattices. It includes installing and running the MAD-X software on the students' computers; the input of elements and beamline; the understanding of the outputs, such as the beta functions, tunes and dispersion; carrying out lattice matching routines; and working through examples.

Radiofrequency Cavities
This lecture introduces the principles and design of microwave cavities for acceleration, phase and group velocity, transit time factor and shunt impedance. This series also includes an introduction to the simulation of cavities using specialised software, such as SUPERFISH.

Properties of Synchrotron Radiation, Undulators and Wigglers
This lecture concentrates on synchrotron radiation and its effects on electron beam dynamics in storage rings. It includes an introduction to the properties of synchrotron radiation and synchrotron light sources. The series covers in detail the angular distribution of the power radiated by accelerated particles as well as the angular and frequency distribution of the radiated energy. It also covers the physics principles of radiation from wigglers and undulators.

Beams and Imperfections
This lecture introduces topics that result in imperfections in an accelerator design and operation. Topics covered include resonant conditions, closed-orbit distortion, gradient errors, and chromaticity corrections.

Beam Diagnostics and Instrumentation
This lecture covers introductory topics of beam diagnostic methods and instrumentation for their measurement. It includes topics such as the observation of beam and the measurement of beam current; the beam lifetime in a storage ring; the measurement of the momentum and energy of a particle beam; the measurement of the transverse beam position; and the measurement of beam optical parameters.

Luminosity and Colliders
This lecture introduces the students to a detailed description of the characteristics of modern particle accelerators, focusing on colliders in both linear and circular configurations. Requirements of colliders, such as energy and luminosity, are elaborated and discussed, emphasising the needs of the experiments at the LHC.

Future Colliders
This lecture provides an overview of possible future accelerator projects. It includes a description of circular colliders, such as the Future Circular Collider (FCC) and the Circular Electron Positron Collider (CEPC) / Super Proton Proton Collider (SppC), as well as linear colliders such as the International Linear Collider (ILC) and the Compact Linear Collider (CLIC). The lecture also covers developments in Muon Colliders and advanced acceleration techniques based on plasma accelerators.

Applications of Accelerators
This lecture provides an overview of applications of accelerators to a variety of fields. Applications in the fields of particle physics, medicine, industry, as well as the physical, environmental and life sciences will be highlighted.

Assessment (includes both continuous and summative assessment)

Component	Course LO Tested	Related Programme LO or Graduate Attributes	Weighting	Team/Individual	Assessment Rubrics
1. Final Test	All	Competence (Written)	50%	Individual	Point-based marking (not rubric-based)
2. CA: Computation Laboratory Project	All	Competence (Written)	40%	Individual	Appendix 1
3. Class Participation	All	Competence (Oral)	10%	Individual	Appendix 2
Total			100%		

Students will be assessed by:

a. Test (50%)
   Two final tests (25% each): One at the end of each week of the course: 2 hours each; open book; format: short–question answers, long-question answers and exercises/calculations.

b. Individual Project Work (50%)
   - Class participation (10%): Students will be encouraged to actively participate in class discussion.
   - Two final individual short project written reports (20% each): One for each week of the course; to demonstrate understanding of concepts introduced in the course.

Formative feedback

Feedback will be given constantly during lectures on the common mistakes and level of difficulty of the course materials and applied examples. Past exam questions and project descriptions will be discussed near the end of each week of the course.

Learning and Teaching approach

Approach	How does this approach support students in achieving the learning outcomes?
Final tests	Apply the theory and mathematical formulation learned in class to solve problems in experimental particle physics in order to develop the understanding, competence, and intuition on the topic, as well as to develop both analytical and computational skills.
Final projects	Sharpen the knowledge in experimental particle physics through creatively working on a project. It will also enhance the analytical and computational skills of the students as they work to deliver the requirements of the project.

Reading and References

a) *Introduction to Elementary Particles:* David J. Griffiths, Wiley-VCH (ISBN 978-3527406012; 2008)
b) *Introduction to High Energy Physics:* Donald H. Perkins, Cambridge University Press (ISBN 978-0521621960; 2000).
c) *Introduction to Experimental Particle Physics:* Richard C. Fernow, Cambridge University Press (ISBN 978-0521379403; 1989).
d) *Techniques for Nuclear and Particle Experiments:* William R. Leo, Second Edition, Springer (ISBN 978-3540572800; 1994).
e) *Detectors for Particle Radiation:* Konrad Kleinknecht, Cambridge University Press (ISBN 978-0521640329; 1999).
f) *An Introduction to Particle Accelerators:* Edmund Wilson, Clarendon Press (ISBN 978-0198508298; 2001).
g) *The Physics of Particle Accelerators:* Klaus Wille, Clarendon Press (ISBN 978-0198505495; 2001).
h) *Unifying Physics of Accelerators, Lasers and Plasma,* A. Seryi, CRC Press (ISBN 978-1482240580; 2016).

Course Policies and Student Responsibilities

Absence Due to Medical or Other Reasons

If you are sick and unable to attend your class / exams, you have to:

- Send an email to the instructor regarding the absence and request for a replacement class and make-up tests.
- Submit the original Medical Certificate* or official letter of excuse to administrator.
- Attend the assigned replacement class (subject to availability) and make-up tests.

* The medical certificate mentioned above should be issued in Singapore by a medical practitioner registered with the Singapore Medical Association.

Academic Integrity

Good academic work depends on honesty and ethical behaviour. The quality of your work as a student relies on adhering to the principles of academic integrity and to the NTU Honour Code, a set of values shared by the whole university community. Truth, Trust and Justice are at the core of NTU's shared values.

As a student, it is important that you recognize your responsibilities in understanding and applying the principles of academic integrity in all the work you do at NTU. Not knowing what is involved in maintaining academic integrity does not excuse academic dishonesty. You need to actively equip yourself with strategies to avoid all forms of academic dishonesty, including plagiarism, academic fraud, collusion and cheating. If you are uncertain of the definitions of any of these terms, you should go to the academic integrity website for more information. Consult your instructor(s) if you need any clarification about the requirements of academic integrity in the course.

Course Instructors

Instructor	Office Location	Phone	Email
Visiting Prof. Albert De Roeck			Albert.de.Roeck @cern.ch

Visiting Prof. Emmanuel Tsesmelis			Emmanuel.Tsesmelis @cern.ch

Planned Weekly Schedule

The course will be conducted within two weeks (5 days a week). The topic for each day is given in the table below.

S/N	Topic	Lecture Hours	Tutorial / Problem Sheet / Project / Test Hours
1	Introduction to the fundamental interactions and their mediators	3 hours	-
2	The Standard Model of Particle Physics	3 hours	1
3	Particle interactions with matter	3 hours	1
4	Particle detectors	3 hours	1
5	Experimental techniques at the LHC	3 hours	2 (Final Test)
6	Introduction to particle accelerators Transverse optics I Transverse optics II	3 hours	-
7	Longitudinal dynamics I Longitudinal dynamics II Lattice designs	3 hours	1
8	Beams and imperfections RF cavities Beam diagnostics	3 hours	1
9	Synchrotron radiation Luminosity and colliders Future particle physics projects at the high-energy frontier	3 hours	1
10	Grid computing for the LHC Applications of particle accelerators Applications of particle detectors	3 hours	2 (Final Test)

Appendix 1: Laboratory Project Report

Standards	Criteria
A+ to A-	(a) Detailed and accurate description of experimental procedures, (b) precise presentation and understanding of relevant theoretical basis, (c) correct, accurate and complete data analysis, (d) critical discussion of assumptions, errors and inaccuracies, (e) in-depth interpretation of results and analysis, and (f) drawing of important conclusions and discussion of relevance to applications.
B+ to B-	(a) Methodical description of experimental procedures, (b) proper presentation of the underlying theories, (c) correct and complete data analysis, (d) relevant discussion of experimental errors and inaccuracies, (e) careful interpretation of results, and (f) drawing of relevant conclusions.
C+ to C	(a) Experimental procedures are described, but lack clarity or details, (b) the theoretical basis of the experiments is merely reproduced and is not fully understood, (c) the data analysis is presented, but is either incomplete or part of it is erroneous, (d) cursory discussion of experimental errors, (e) results are mostly interpreted correctly but may contain some errors, and (f) conclusions are drawn, but lack emphasis or miss the most important ones.
D+ to D	(a) Experimental procedures are not reported, (b) the theory presented is irrelevant or incorrectly applied, (c) largely incorrect data analysis, (d) possible experimental errors are not discussed, (e) inaccurate or faulty interpretation of results, and (f) conclusions drawn are unimportant or not relevant to the objectives.
F	(a) Experimental procedures are wrong or not reported, (b) the relevant theory is not included or understood, (c) the data analysis is clearly erroneous, (d) experimental errors are not reported or the student lacks awareness of them, (e) results are not interpreted, or interpreted wrongly, and (f) no conclusions, or erroneous/irrelevant conclusions are drawn.

Appendix 2: Class Participation

Standards	Criteria
A+ (Exceptional) A (Excellent)	Important contributions to class discussion; asks insightful questions; precisely answers questions; participates in a meaningful and constructive manner including enabling other students to contribute but does not dominate; demonstrates thoughtful ideas and opinions in a convincing manner.
A- (Very good) B+ (Good)	Meaningful contributions to class discussion; ask interesting questions; accurately answer the questions; capacity to articulate and present points of view clearly; participates in a meaningful and constructive manner; evidence of having read and assimilated the class material; Capable to demonstrate ideas and opinions in a convincing manner.
B (Average) B- (Satisfactory) C+ (Marginally satisfactory)	Some contributions to class discussion; ask some questions; some capacity to articulate and present points of view; some evidence of constructive engagement during discussion; Capable to demonstrate ideas and opinions.
C (Bordering unsatisfactory) C- (Unsatisfactory)	Minimal contributions to class discussion; ask very little questions; can answer a few questions; limited capacity to articulate and present points of view; limited evidence of constructive engagement during discussion.
D, F (Deeply unsatisfactory)	Very minimal or no contributions to class discussion; no questions; could not answer questions; no evidence of an individual viewpoint; failure to read the assigned reading; unexplained or unjustified absences from class activities.