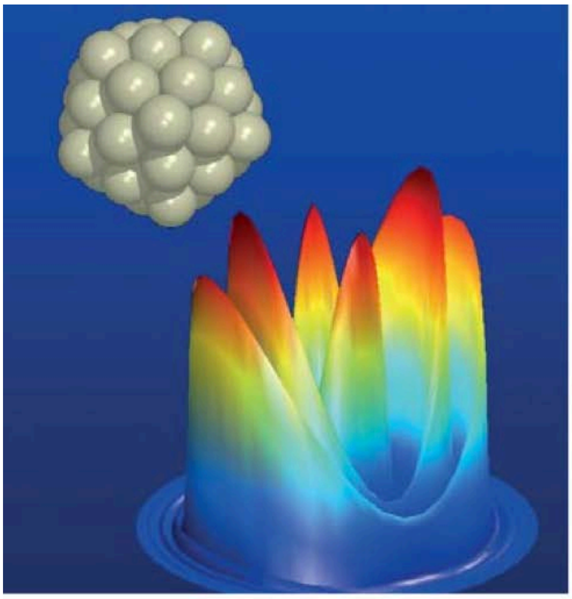
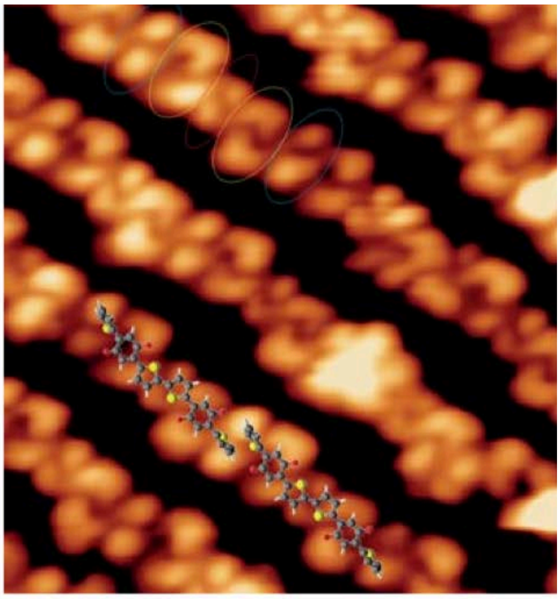
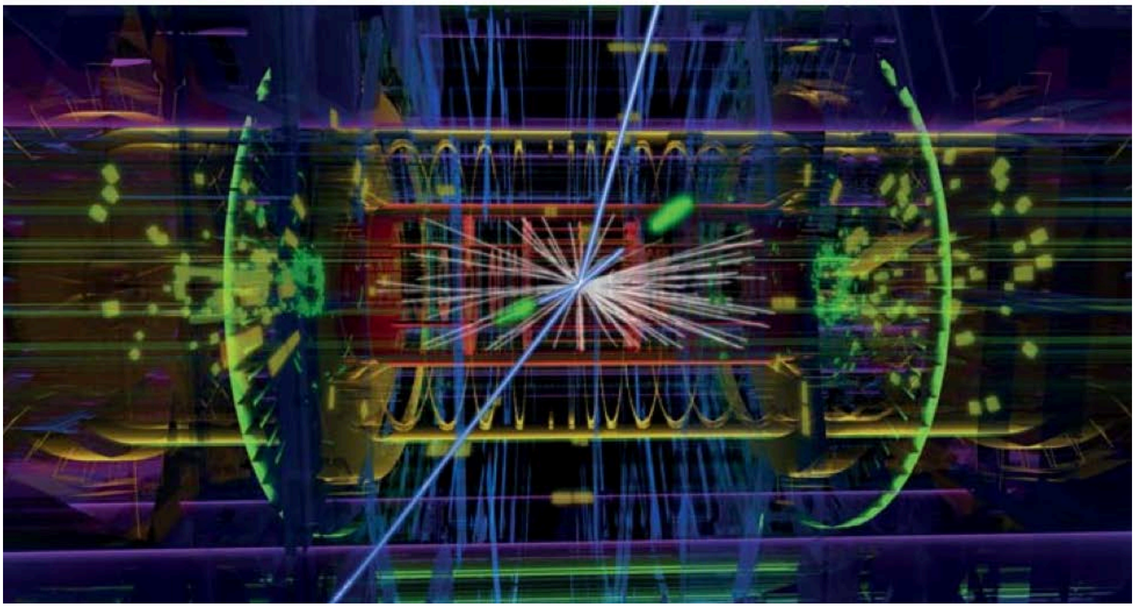
Handbook of Modules

Master-of-Science (M.Sc.) Physics

Physikalisches Institut
Albert-Ludwigs-Universität Freiburg







Preliminary notes:

The handbook of modules does not substitute the course catalogue, which is updated every semester to provide variable information about the courses (e.g. time and location).

Note that only the examination regulations (Prüfungsordnung) are legally binding.

List of Abbreviations

M.Sc.	Master of Science
Credit hrs	A credit hour corresponds to a course of a duration of 45 minutes per week (in German: Semesterwochenstunden, SWS)
SL	Assessed coursework („Studienleistung“)
PL	Exam („Prüfungsleistung“)
L	Lecture
E	Exercise/Tutorials
S	Seminar
Lab	Laboratory
SoSe	Summer semester (summer term)
WiSe	Winter semester (winter term)
ECTS	Credit Points based on the European Credit Transfer System (ECTS-Points)

Table of Contents

1. The Master-of-Science (M.Sc.) Physics in Freiburg

1.1. The Master Programme

The Institute of Physics is actively involved in a wide range of research areas with students enjoying a broad diversity of topics covered by lecture courses and seminars. The diversity and quality of the research and teaching programme of the institute, embedded in the rich and interdisciplinary research landscape defined through the University of Freiburg and other institutions committed to research and development in the larger Freiburg area are key ingredients for the attractiveness of the institute nation-wide, but also at the international level.

The Master programme in Freiburg aims to continue, deepen and broaden studies begun at Bachelor level. It provides a comprehensive scientific education in advanced theoretical and experimental physics, covering state-of-the-art topics in the institute's core research areas *Atomic, Molecular and Optical Sciences*, *Condensed Matter and Applied Physics*, and *Particles, Fields and Cosmos*. The M.Sc. Physics in Freiburg is an English-Taught Master's programme and therefore sufficient language skills are required (see 1.2.)

In the first year of their studies participants consolidate their knowledge in advanced theoretical and experimental physics. Advanced quantum mechanics and the Master Laboratory are mandatory classes. Advanced physics courses can be selected from a range of state-of-the-art topics in the main research areas of the department. Students can choose each semester among various term papers, where they learn to give oral presentations and prepare written hand-outs in English on a specific topic of modern research. In addition, students can select from a variety of elective courses in physics, or from course programmes of other faculties.

During their final one-year Master thesis, students specialize in a particular field by participating in a cutting-edge research project at the Institute of Physics or one of the associated research centers, e.g. the Freiburg Materials Research Center (FMF), the Freiburg Institute for Interactive Materials and Bioinspired Technologies (FIT), the Fraunhofer Institute for Solar Energy Systems (ISE), the Fraunhofer Institute for Material Mechanics (IWM), the Kiepenheuer Institute for Solar Physics (KIS), the Freiburg Center for Data Analysis and Modelling (FDM), the Freiburg Institute for Advanced Studies (FRIAS), or with one of the co-opted members at the Faculty of Biology, the Faculty of Medicine, or the Department of Microsystems Engineering (IMTEK).

Successful students are qualified for independent research in physics and will be prepared for a scientific career in research, academia, or industry. Furthermore, they are on the next step towards a PhD study, which generally is a prerequisite for leading positions in economy or industry, or for a later academic career.

1.2. Admission to the Master Programme

Application to the M.Sc. programme is possible both, for the winter and summer semester. The application deadline for the summer semester is **January 15** and for the winter semester **July 15** each year.

Applicants must hold a Bachelor's degree in physics or equivalent with above average academic performance. The admission committee decides on the equivalence of the degree. According to the admission regulations applicants must also have a working knowledge of English and are required to provide appropriate evidence of their language skill. An adequate certification of the English language skill is for example the school-leaving certificate of a German Gymnasium (Abitur). Applicants who do not hold a German "Abitur" are required to provide a B 2 (CEFR) certificate or equivalent for the English language. Native speakers of English are not required to provide proof of language proficiency.

The application form is available online on the webpage of the Physics Institute at
http://www.physik.uni-freiburg.de/studium-en/MSc_Physics

1.3. Programme Structure

The Physics Institute offers a research-oriented curriculum leading to a Master of Science degree in Physics. The programme comprises a total of 120 ECTS credit points (CP), which are collected in various compulsory and elective modules as defined by the study regulations.

The programme comprises the following modules and courses:

Module	Type	Contact hours	ECTS	Compulsory/ Elective	Recommended semester	Assessment
Advanced Quantum Mechanics	L+E	4+3	10	C	1 or 2	PL: written
Advanced Physics 1	L+E	4+2	9	E	1 or 2	PL: written or oral
Advanced Physics 2	L+E	4+2	9	E	1 or 2	PL: written or oral
Advanced Physics 3	L+E	4+2	9	E	1 or 2	SL
Elective Subjects	variable	variable	9	E	1 or 2	SL
Term Paper	S	2	6	E	1 or 2	PL: written or oral
Master Laboratory	Lab	10	8	C	1 or 2	PL: written or oral
Research Traineeship	-	-	30	C	3	SL
Master Thesis	-	-	28 2	C	4	PL: Thesis SL: Presentation

Abbreviations in table:
Type = type of course; L = lecture; E = exercises; S = seminar; Lab = laboratory;
C = compulsory module; E = elective module;
SL = assessed coursework (´Studienleistung´); PL = exam (‘Prüfungsleistung’)

1.4. Workload / ECTS-Point System

The *European Credit Transfer and Accumulation System (ECTS)* is a standard for comparing the study attainment and performance of students of higher education across the European Union and other collaborating European countries. It provides more compatibility and mobility between the programmes at different institutions and different countries.

The ECTS credit points (CP), which can be acquired, determine the time requirements for a module with one CP corresponding to a workload of about 30 hours. This workload includes participation in courses, preparation and post-processing of the courses, exercises and exams. The ECTS-System enables the accumulation of credits and marks throughout the entire studies and facilitates documenting the study progress.

1.5. Contents of Modules

Within the Master's programme some modules are compulsory and others offer the possibility to select courses at the student's own choice.

Advanced Quantum Mechanics (10 ECTS credit points)

All students have to accomplish the compulsory module Advanced Quantum Mechanics. The module mark is the mark of the final exam (PL).

Advanced Physics 1 (9 ECTS credit points)

Within the module Advanced Physics 1 students may select an lecture on Advanced Experimental or Advanced Theoretical Physics by their own choice. Eligible lectures are listed in section 4 and in the course catalogue for the current semester. The module mark is the mark of the final exam (PL).

Advanced Physics 2 (9 ECTS credit points)

Within the module Advanced Physics 1 students may select an lecture on Advanced Experimental or Advanced Theoretical Physics by their own choice. Eligible lectures are listed in section 4 and in the course catalogue for the current semester. The module mark is the mark of the final exam (PL).

Advanced Physics 3 (9 ECTS credit points)

Within the module Advanced Physics 1 students may select an lecture on Advanced Experimental or Advanced Theoretical Physics by their own choice. Eligible lectures are listed in section 4 and in the course catalogue for the current semester. If both lectures in Advanced Physics 1 and 2 are from the same field (Experimental/Theoretical Physics) a lecture from the other field has to be selected. The module is an unmarked course achievement (SL).

Elective Subjects (9 ECTS credit points)

All 9 ECTS credits of this module can be acquired by selecting different courses by own choice. The selected courses have to be at the Master's level, i.e. from the M.Sc. programme in Applied Physics and/or other Master programmes. The examination committee may permit other courses on request.
Note that for courses at other faculties different application modalities and requirements may apply. Students are responsible to proof successful participation, so that the credits can be booked by the examination office of physics.

Term Paper (6 ECTS credit points)

Within the elective module Term Paper students select a seminar on a specific topic, with several seminars offered each term.

Master Laboratory (8 ECTS credit points)

In the Master Laboratory students accomplish different lab experiments with the total workload of 8 ECTS credit points. Successful completion of the Master Laboratory is prerequisite for beginning the Research Traineeship.

Research Traineeship (30 ECTS credit points)

Before working on their Master Thesis students engage in a Research Traineeship, which is accomplished in a six-month period. The aim of this module is to acquire preliminary knowledge in a certain research topic in preparation for the Master Thesis. For their traineeship and thesis students select a supervisor at the Institute of Physics or the associated research institutes. Admission to the Master Research module requires successful accomplishment of the module *Master Laboratory* and three of the four marked courses in the modules *Advanced Quantum Mechanics, Advanced Physics 1 and 2* and *Term Paper*.

Master Thesis (30 ECTS credit points)

In the final six-months master thesis students perform independent research on a specialized topic in applied physics and prepare a written thesis. Typically, the Master Thesis is accomplished at the same research group as the traineeship. In a period of 2 weeks before to 4 weeks after submitting the Master Thesis, the students present the results of their thesis work in a public presentation.

1.6. Determination of final mark

The individual module marks contribute to the final mark with the following weights:

Module	**weight**
Advanced Quantum Mechanics	11 %
Advanced Physics 1	11 %
Advanced Physics 2	11 %
Term Paper	7 %
Master Laboratory	10 %
Master Thesis	50 %

2. Organisation of studies

2.1. Study plan

In the first year the master students consolidate their knowledge in compulsory and elective courses. For the first and second semester an equally balanced workload is recommended with a total of about 30 ECTS credit points each. If necessary Elective Subjects and one of the courses for academic record (AR) can still be accomplished during the research phase in the second year.

The following study plan is recommended for students starting their studies in the winter term:

FS	Module					∑ ECTS
1	**Advanced Quantum Mechanics** 10 ECTS	Advanced Physics 1 9 ECTS		**Term Paper** 6 ECTS	**Master Laboratory** 8 ECTS	33
2		Advanced Physics 2 9 ECTS Advanced Physics 3 9 ECTS	**Elective Subjects** Advanced Physics and/or other discipline by own choice 9 ECTS			27
3	**Research Traineeship** 30 ECTS					30
4	**Master Thesis** (Thesis and Presentation) 30 ECTS					30

Note that, *Advanced Quantum Mechanics* is only offered in the winter term, so dependent on the start of the Master studies (start in winter or summer term) it will be either in the first or second semester.

The *Master Laboratory* is offered as a block course during the semester break following the winter term. Dependent on the subscription date students participate either in the first or second semester.

2.2. Specialization (optional)

Students may specifically select their *Advanced Lectures*, their *Term Paper* and their courses in the *Elective Subjects* module in order to obtain a specialized knowledge in a particular field of physics. Specific study plans are recommended in section 5.

2.3. (Online-) Registration

During their studies students have to participate in various courses as well as to take part in examinations. Registration to courses and exams is in the student's own responsibility!

Participation in courses

In order to take part in the Master Laboratory students have to register in due time with the head of the laboratory course.
For the participation in lectures an advanced registration is possible but not required. A registration is possible via the HISinOne Campus-Management System (https://campus.uni-freiburg.de).

Registration for examinations

For the participation in exams, an early registration is mandatory, either online via the HISinOne Campus-Management System (https://campus.uni-freiburg.de) or directly at the examination office of the Physics Institute. A registration in due time is in the responsibility of the students. The registration period is from the beginning of the semester until one week before the first exam (typically two weeks before the end of the semester). The registration period will be announced on the physics website.

2.4. Forms of assessment

There are various forms of assessing a student's performance during her/his studies such as written and oral examinations, participation in exercises, or written reports. The credits for a certain course are only awarded if the assessments have been successfully passed. The requirements for passing are defined and announced by the lecturer at the beginning of each lecture/course.

The **assessed coursework (SL, "Studienleistung")** is an unmarked form of assessment, which has to be passed in order to receive credit for the respective course. It typically consists of active participation in the lecture and exercises and might include passing a final exam. Assessed courseworks do not contribute to the final mark of the Master's degree.

Marked assessments consist of final **exams (PL, "Prüfungsleistung")**, which can be written or oral exams, marked reports or an oral presentation. The received marks contribute to the final mark of the Master's degree. For participation a registration is mandatory (see section 2.3).

Retaking examinations

Failed examinations may be retaken twice in the modules *Advanced Quantum Mechanics* and *Advanced Physics 1* and *2*, and once in the modules *Term Paper*, *Master Laboratory*, and *Master Thesis*. It is not permitted to retake examinations to improve the marks.

3. List of Modules and Description

3.1. Advanced Quantum Mechanics (10 ECTS credit points)

<table>
<tr><th>Module:</th><th colspan="5">Advanced Quantum Mechanics</th><th>10 ECTS</th></tr>
<tr><td>Responsibility</td><td colspan="6">Dean of Studies,
Lecturers for Theoretical Physics</td></tr>
<tr><td rowspan="3">Courses</td><td></td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assess-sess-ment</td><td>Term</td></tr>
<tr><td>Advanced Quantum Mechanics</td><td>L+E</td><td>4+3</td><td>10</td><td>PL</td><td>WiSe</td></tr>
<tr><td>Total:</td><td></td><td></td><td>10</td><td></td><td></td></tr>
<tr><td>Organisation</td><td colspan="6">Advanced Quantum Mechanics is compulsory for participants in the Master of Science Programme in Physics.
Students have to register online for the final exam according to the announcements of the examination office.</td></tr>
<tr><td>Module mark</td><td colspan="6">The final module mark is the mark of the final written exam.</td></tr>
<tr><td>Qualification objectives</td><td colspan="6">• Students know the foundations of scattering theory and are able to apply these to problems involving simple potentials.
• Students know the representations of the rotational group and their relevance for quantum theory. They have a fundamental knowledge in group theory and representation theory in general. They know the meaning of product representations and irreducible representations. They are able to apply Clebsch-Gordon coefficients to simple problems involving angular momentum and spin in atomic spectra.
• Students know the connection between spin and statistics. They are able to symmetrize respectively anti-symmetrize multi-particle states. They can describe the methods of Hartree- and Hartree-Fock and apply them to simple multi-particle systems.
• Students know the fundamentals of time-dependent perturbation theory and can apply it to specific time-dependent problems.
• Students know Dirac’s equation and can solve it for the free case.</td></tr>
<tr><td>Course content</td><td colspan="6">• Scattering theory: scattering amplitude and cross-section, partial wave expansion, Lippmann-Schwinger equation and Born series.
• Fundamentals of the representation theory of groups, in particular of the rotation group SO(3). Tensor product representations and irreducible representations. Wigner-Eckart theorem. Applications to angular momen-</td></tr>
</table>

	tum and spin couplings in atomic, molecular and condensed matter physics. • Time-dependent perturbation theory: Dyson-expansion, Fermi's Golden Rule, examples of application to important time-dependent quantum processes. • Many-particle systems: identical particles, spin-statistic theorem, variational principles, Hartree and Hartree-Fock approximations. • Interaction between radiation and matter. Quantization of the electromagnetic field. Interaction Hamiltonian, emission and absorption. • Relativistic quantum mechanics and quantum field theory; Dirac equation, quantization of Klein-Gordon and Dirac's equation.			
Work load (hours)	**Course**	**Contact time**	**Self-studies**	**Total**
	Advanced Quantum Theory	105 h	195 h	300 h
	Total:	**105 h**	**195 h**	**300 h**
Usability	M.Sc. programme			
Previous knowledge	Contents of lectures Theoretical Physics I-V			
Language	English			

3.2. Advanced Physics 1 (9 ECTS credit points)

Module:	Advanced Physics 1					9 ECTS
Responsibility	Dean of Studies, Lecturers of the Institute of Physics					
Courses		**Type**	**Credit hrs**	**ECTS**	**Assess-sess-ment**	**Term**
	Advanced Physics lecture	L+E	4+2	9	PL	WiSe+SoSe
	Total:			**9**		
Organisation	A suitable lecture has to be selected by own choice from the list of Advanced Experimental or Advanced Theoretical Physics lectures given below. Students have to register online for the final exams according to the announcements of the examination office.					
Module mark	The final module mark is the mark of the final written exam.					
Qualification objectives	• Students obtain advanced knowledge in particular field of modern physics. • Students are familiar with current problems and research topics in particular fields of modern research in physics. • Students know advanced tools and methods in particular fields. • Specific qualification objectives for each lecture are listed in individual course descriptions section 4.					
Course content	A range of advanced courses is offered on a regular or irregular basis. The content of each lecture is specified in the course descriptions in section 4. **List of eligible Advanced Lectures offered regularly:** (Exp = Experimental Lectures; Theo = Theoretical Lectures)					

Lecture Course:		Term
Advanced Atomic and Molecular Physics	Exp	WiSe
Advanced Optics and Lasers	Exp	SoSe
Condensed Matter I: Solid State Physics	Exp	WiSe
Condensed Matter II: Interfaces and Nanostructures	Exp	SoSe
Advanced Particle Physics	Exp	WiSe
Hadron Collider Physics	Exp	SoSe
Particle Detectors	Exp	WiSe
Theoretical Condensed Matter Physics	Theo	SoSe
Classical Complex Systems	Theo	WiSe
General Relativity	Theo	WiSe

<table>
<tr><td></td><td colspan="4">Quantum Field Theory Theo SoSe

In addition, various lectures on specialized physics topics are offered on an irregular basis and are indicated in the course catalogue as Advanced Physics lectures.

List of eligible Advanced Lectures offered irregularly:

Astro Particle Physics Exp
Theoretical Quantum Optics Theo
Complex Quantum Systems Theo
Quantum Chromodynamics Theo</td></tr>
<tr><td rowspan="3">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Advanced physics lecture</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Total:</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. programme</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Basic experimental or theoretical physics lecture in the respective field</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

3.3. Advanced Physics 2 (9 ECTS credit points)

<table>
<tr><th>Module:</th><th>Advanced Physics 2 — 9 ECTS</th></tr>
<tr><td>Responsibility</td><td>Dean of Studies,
Lecturers of the Institute of Physics</td></tr>
<tr><td>Courses</td><td>
<table>
<tr><th></th><th>Type</th><th>Credit hrs</th><th>ECTS</th><th>Assess-sess-ment</th><th>Term</th></tr>
<tr><td>Advanced Physics lecture</td><td>L+E</td><td>4+2</td><td>9</td><td>PL</td><td>WiSe+SoSe</td></tr>
<tr><td>Total:</td><td></td><td></td><td>9</td><td></td><td></td></tr>
</table>
</td></tr>
<tr><td>Organisation</td><td>A suitable lecture has to be selected by own choice from the catalogue of Advanced Experimental or Advanced Theoretical Physics lectures given in the (online) course catalogue of the Physics Institute.
Students have to register online for the final exams according to the announcements of the examination office.</td></tr>
<tr><td>Module mark</td><td>The final module mark is the mark of the final written exam.</td></tr>
<tr><td>Qualification objectives</td><td>• Students obtain advanced knowledge in particular field of modern physics.
• Students are familiar with current problems and research topics in particular fields of modern research in physics.
• Students know advanced tools and methods in particular fields.
• Specific qualification objectives for each lecture are listed in individual course descriptions section 4 or in the online course descriptions.</td></tr>
<tr><td>Course content</td><td>A range of advanced courses is offered on a regular or irregular basis. The specific content of each lecture is detailed in individual course descriptions section 4 or in the online course descriptions.</td></tr>
<tr><td>Work load (hours)</td><td>
<table>
<tr><th>Course</th><th>Contact time</th><th>Self-studies</th><th>Total</th></tr>
<tr><td>Advanced physics lecture</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Total:</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
</table>
</td></tr>
<tr><td>Usability</td><td>M.Sc. programme</td></tr>
</table>

Previous knowledge	Basic experimental or theoretical physics lecture in the respective field
Language	English

3.4. Advanced Physics 3 (9 ECTS credit points)

<table>
<tr><th>Module:</th><th colspan="5">Advanced Physics 3</th><th>9 ECTS</th></tr>
<tr><td>Responsibility</td><td colspan="6">Dean of Studies,
Lecturers of the Institute of Physics</td></tr>
<tr><td rowspan="3">Courses</td><td></td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assess-sess-ment</td><td>Term</td></tr>
<tr><td>Advanced Physics lecture</td><td>L+E</td><td>4+2</td><td>9</td><td>SL</td><td>WiSe+SoSe</td></tr>
<tr><td>Total:</td><td></td><td></td><td>9</td><td></td><td></td></tr>
<tr><td>Organisation</td><td colspan="6">A suitable lecture has to be selected by own choice from the catalogue of Advanced Experimental or Advanced Theoretical Physics lectures given in the (online) course catalogue of the Physics Institute.</td></tr>
<tr><td>Module mark</td><td colspan="6">unmarked</td></tr>
<tr><td>Qualification objectives</td><td colspan="6">• Students obtain advanced knowledge in particular field of modern physics.
• Students are familiar with current problems and research topics in particular fields of modern research in physics.
• Students know advanced tools and methods in particular fields.
• Specific qualification objectives for each lecture are listed in individual course descriptions section 4 or in the online course descriptions.</td></tr>
<tr><td>Course content</td><td colspan="6">A range of advanced courses is offered on a regular or irregular basis. The specific content of each lecture is detailed in individual course descriptions section 4 or in the online course descriptions. If both lectures Advanced Physics 1 and 2 have been selected from one field (Advanced Experimental or Advanced Theory) Advanced Physics 3 has to be chosen from the other field.</td></tr>
<tr><td rowspan="3">Work load (hours)</td><td colspan="2">Course</td><td colspan="2">Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td colspan="2">Advanced physics lecture</td><td colspan="2">90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td colspan="2">Total:</td><td colspan="2">90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="6">M.Sc. programme</td></tr>
<tr><td>Previous knowledge</td><td colspan="6">Basic experimental or theoretical physics lecture in the respective field</td></tr>
<tr><td>Language</td><td colspan="6">English</td></tr>
</table>

3.5. Elective Subjects (9 ECTS credit points)

<table>
<tr><th>Module:</th><th colspan="6">Elective Subjects 9 ECTS</th></tr>
<tr><td>Responsibility</td><td colspan="6">Dean of Studies,
or Faculty/Department responsible for selected course</td></tr>
<tr><td rowspan="3">Courses</td><td></td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assess-sess-ment</td><td>Term</td></tr>
<tr><td>Advanced Physics courses and/or Mathematics courses and/or courses by own choice</td><td>L+E</td><td>According to selected courses</td><td>9</td><td>SL</td><td>WiSe + SoSe</td></tr>
<tr><td>Total:</td><td></td><td></td><td>9</td><td></td><td></td></tr>
<tr><td>Organisation</td><td colspan="6">Students select different courses by own choice in order collect at least 9 CP in total. The selection may contain physics courses of the M.Sc. programme in physics, or of the M.Sc./M.A. programmes of other disciplines.

Also lectures of the B.Sc. programme in Mathematics can be chosen with the exception of Analysis I and II, and Linear Algebra I and II. The examination committee may admit courses of other external programmes upon application.</td></tr>
<tr><td>Module mark</td><td colspan="6">unmarked</td></tr>
<tr><td>Qualification objectives</td><td colspan="6">The qualification objects are subject to the selected course.</td></tr>
<tr><td>Course content</td><td colspan="6">The course content is subject to the selected course.</td></tr>
<tr><td rowspan="3">Work load (hours)</td><td colspan="2">Course</td><td colspan="2">Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td colspan="2">Elective courses</td><td colspan="3">subject to selected courses</td><td>270 h</td></tr>
<tr><td colspan="2">Total:</td><td colspan="3"></td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="6">M.Sc. programme</td></tr>
<tr><td>Previous knowledge</td><td colspan="6">Subject to selected courses</td></tr>
<tr><td>Language</td><td colspan="6">Subject to selected courses</td></tr>
</table>

3.6. Term Paper (6 ECTS credit points)

Module:	Term Paper					6 ECTS
Responsibility	Dean of Studies, Lecturers of the Institute of Physics					
Courses		**Type**	**Credit hrs**	**ECTS**	**Assess-sess-ment**	**Term**
	Term paper seminar	S	2	6	PL	WiSe+SoSe
	Total:			**6**		
Organisation	The research groups of the Institute of Physics offer various seminars each term. Allocation and registration to a particular seminar will be in a common event generally held in the first week of the semester.					
Module mark	A mark is given for the oral presentation on a current research topic and the written documentation (hand-out).					
Qualification objectives	• Students are able to handle scientific literature and to search in scientific publications • Students are able to prepare and present a topic of current physical research in front of a broad audience • Participants have the skills to lead a discussion in a group of students • Students can give scientific lecture and are able to incorporate didactical elements					
Course content	The *Term Paper* seminar comprises approximately 10 lectures from a coherent field of physics or a neighbouring scientific area and consists of the elaboration of a lecture to a physics topic or an adjacent area with written documentation (hand-out) and an oral presentation. Active participation in all lectures of the seminar is expected.					

Work load (hours)	Course	Contact hrs	Self-studies	Total
	Term paper seminar	21 h	159 h	180 h
	Total:	**21 h**	**159 h**	**240 h**
Usability	M.Sc. programme			
Previous knowledge	Basic knowledge in respective topic as acquired in self-studies or lecture			
Language	English			

3.7. Master Laboratory (8 ECTS credit points)

Module:	Master Laboratory	8 ECTS
Responsibility	Head of the master laboratory	

Courses

Course	**Type**		**ECTS**	**Assess-ment**	**Term**
Master Laboratory	Lab	block course	8	PL	WiSe
Total:			**8**		

Organisation	The Master Laboratory is offered as a block course during the semester break. Students have to register for the course online 10 weeks before the start of the course (http://www.mathphys.uni-freiburg.de/physik/praktika.php). Students perform 3 experiments and prepare written reports. Two experiments have to be completed within one week each. One experiment is performed within an allocated time of two weeks. For this extended experiment the students prepare an oral presentation held in a common seminar at the end of the Master Laboratory.
Module grade	For each of the 3 experiments a grade is given based on an initial written and oral questioning (test of the preparatory knowledge), the experimental performance and the written report (incl. lab report and analysis). In addition, a grade is given for the oral seminar presentation. All marks contribute equally to the final module grade (arithmetic mean).
Repetition	Individual experiments have to be repeated at specially offered dates immediately after the regular end of the laboratory course. In case the entire Laboratory course has to be repeated, this is only possible by participating in the next year's course is.
Qualification objectives	• Students are able to perform complex advanced experiments running over several days • Students are able to apply advanced statistical data analysis methods • Students are able to prepare a written lab report • Students are able to critically evaluate and assess their experimental results
Course content	Performance of three Advanced Physics Experiments from Particle & Nuclear Physics, Atomic & Molecular Physics, Solid State Physics and Optics. The current catalogue of laboratory experiments is available online on https://www.physik.uni-freiburg.de/studium/labore/fp/fp2/#section-3

Work load (hours)	**Course**	**Contact time**	**Self-studies**	**Total**
	Master Laboratory	150 h (20 days*7.5 h)	90 h	240 h
	Total:	**150 h**	**90 h**	**240 h**
Usability	M.Sc. programme			
Previous knowledge	- Experimental skills as acquired e.g. in the Physics Laboratory B (B.Sc.) - Statistical methods of data analysis			
Language	English			

3.8. Research Traineeship (30 ECTS credit points)

<table>
<tr><th>Module:</th><th colspan="4">Research Traineeship 30 ECTS</th></tr>
<tr><td>Responsibility / Supervision</td><td colspan="4">Dean of Studies,
Group leaders at the Institute of Physics and associated Institutes</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td></td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Research (under supervision)</td><td>6 months</td><td>30</td><td>SL</td></tr>
<tr><td>Organisation</td><td colspan="4">Prior to their Master thesis students engage in a Research Traineeship which is accomplished in a six-month period. The aim of this module is to acquire basic knowledge in a certain research topic and field in preparation for the subsequent Master Thesis. For the traineeship, students select a supervisor at the Institute of Physics or at one of the associated and participating research institutes.
The research traineeship can be started any time and has a duration of exactly 6 months. The students have to register for the research traineeship at the examination office.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students have a specialized basic knowledge in a certain research topic.
• Students know and are able to apply specific experimental and/or theoretical tools and methods in a specialised field of research.
• Students are prepared for performing a self-dependent research project (preparation for Master Thesis)</td></tr>
<tr><td>Course content</td><td colspan="4">• Students acquire basic knowledge in a certain field of research in preparation for their Master Thesis.
• Participants obtain training in applying experimental and/or theoretical tools in a specialized field of research.
• Students participate in a current research project under the supervision of lecturers and researchers (post-docs and doctoral researchers).</td></tr>
<tr><td>Work load (hours)</td><td colspan="4">900 h distributed over a six-month period</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. programme</td></tr>
<tr><td>Precondition</td><td colspan="4">Admission to the Research Traineeship requires successful accomplishment of the module Master Laboratory and of three of the four marked courses (AR) of the modules Advanced Quantum Mechanics, Advanced Physics 1, Advanced Physics 2, and Term Paper.</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

3.9. Master Thesis (30 ECTS credit points)

Module:	**Master Thesis**			**30 ECTS**
Responsibility / Supervision	Dean of Studies, Group leaders at the Institute of Physics and associated Institutes			
Module details	**Type**		**ECTS**	**Assessment**
	Master Thesis (Research and written thesis)	6 months	28	PL
	Master Colloquium (Oral presentation)	45 min	2	SL
	Total:		**30**	
Organisation	For their master thesis students select a supervisor at the Institute of Physics or at one of the associated and participating research institutes. Typically, the master thesis is pursued within the same work group as the traineeship. The Master Thesis starts at the latest 2 weeks after successful completion of the Research Traineeship. Registration has to be arranged with the examination office.			
Qualification objectives	• Students have acquired specialized and in-depth knowledge of a certain research topic and field. • Students have a strong expertise in applying specific experimental and/or theoretical tools and methods in their field of research. • Students are able to perform independent research and can critically evaluate and assess their scientific results. • Students can search and read scientific literature and apply and relate reported results to their research.			
Module content	• Acquiring in-depth knowledge in the field of the master thesis work. • Working on a particular problem in a specialized field of research. • Development of the required experimental and/or theoretical tools and methods. • Preparation of a written report on the performed research work. • Preparation and performance of an oral presentation in the form of a public colloquium, discussing the topic of the master thesis, its physical context, and the underlying physical concepts.			
Work load (hours)	900 h distributed over a six-month period. This workload includes research, preparation of the written thesis and preparation of the final presentation.			
Usability	M.Sc. programme			

Precondition	Admission to the Master Thesis requires successful accomplishment of the module *Research Traineeship*.
Language	English or German (in case of German the written thesis has to comprise an abstract in English)

4. Advanced Physics Lectures

4.1. Advanced Atomic and Molecular Physics

Lecture:	**Advanced Atomic and Molecular Physics** Adv. Experiment			
Lecturer/s	Lecturers from Experimental Atomic, Molecular and Optical Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	SL or PL
Frequency	In general the course will be offered each WiSe.			
Qualification objectives	Students have a deeper understanding of both, the properties of matter based on the nature and interactions of atoms and molecules, and of current and future technologies based on controlled quantum processes, such as employed in atomic clocks, atom interferometers, quantum optics and quantum computing, nanoscale engineering, photochemistry and energy conversion.			
Course content	• Light-matter interaction: scattering, absorption and emission of light, dressed states, coherence, strong fields • Scattering of atomic and molecular systems • Properties of diatomic molecules: vibrations and rotations • Properties of polyatomic molecules: electronic states, molecular symmetries, chemical bonds • Modern AMO applications in science and technology			
Previous knowledge	Experimental Physics I-IV			
Work load (hours)	**Course**	**Contact time**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)			
Language	English			

4.2. Advanced Optics and Lasers

<table>
<tr><th>Lecture:</th><th colspan="4">Advanced Optics and Lasers — Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Atomic, Molecular and Optical Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">In general the course will be offered each WiSe.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">Students are familiar with the physical concepts of lasers and know the fundamentals of the interaction between laser light and matter.
Students are able to describe in detail the inherent behaviour and functionality of the many different types of modern lasers.
Students have a deep understanding of the properties of coherent laser light and are able to understand and analyse nonlinear optical effects, as e.g. induced by lasers in transparent materials.</td></tr>
<tr><td>Course content</td><td colspan="4">Light-matter interaction: Absorption/emission, line broadening
Coherence and interference: temporal, spatial coherence, interferometers
The laser principle: 2, 3, 4-level lasers, rate equation models, output power of a laser;
Optical resonators: transmission spectra, stability
Laser modes: Paraxial approximation, Gaussian beams, longitudinal and transverse modes, mode selection
Short laser pulses: Dynamic solutions of rate equation, Q-switching, mode locking, intense short pulses, generation of ultra-short laser pulses
Nonlinear optics: Second, third order polarizability, frequency conversion, optical parametric amplification, high-harmonics generation</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics I-IV</td></tr>
<tr><td rowspan="2">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.3. Condensed Matter I: Solid State Physics

<table>
<tr><th>Lecture:</th><th colspan="4">Condensed Matter I:
Solid State Physics   Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Condensed Matter and Applied Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Form</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">In general the course will be offered each WiSe.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students know the reciprocal space description of crystals and related quasiparticles like phonons
• Students know the quantum mechanical description of electrons in periodic potentials (Bloch- and Wannier-functions)
• Students have a good overview of experimental state of the art techniques for the study of the properties of solid state materials
• Students know how to obtain and are able to interprete experimental data like measurements of electronic band structures or phonon dispersion curves
• Students know about newer developments in the experimental characterization of many-body quantum effects like magnetism or superconductivity</td></tr>
<tr><td>Course content</td><td colspan="4">• Atomic structure of matter
• lattice dynamics, phonons
• electronic structure of materials
• optical properties
• magnetism/superconductivity</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics I-IV</td></tr>
<tr><td rowspan="2">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.4. Condensed Matter II: Interfaces and Nanostructures

<table>
<tr><th>Lecture:</th><th colspan="4">Condensed Matter II:
Interfaces and Nanostructures — Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Condensed Matter and Applied Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Form</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">In general the course will be offered each SoSe.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">Students are able to describe interaction forces at interfaces in terms of their range and their consequences on thermodynamic and kinetic properties.
Students understand processes at surfaces like adsorption/desorption, surface reconstruction, surface transport, or wettability.
Students are able to describe processes as well as structural transitions at liquid, solid-liquid, and solid interfaces with respect to their hydrodynamic and electronic properties.
Students know processes for preparing well defined and patterned surfaces.
Students identify the relevant processes for the formation of nanostructures and structuring of surfaces at the nm-scale.</td></tr>
<tr><td>Course content</td><td colspan="4">Surfaces and interface
structure formation on surfaces
self-assembly, morphology and transitions
optical and electronic properties</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics I-IV</td></tr>
<tr><td rowspan="2">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.5. Advanced Particle Physics

Lecture:	**Advanced Particle Physics** Adv. Experiment			
Lecturer/s	Lecturers from Experimental Particle Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	SL or PL
Frequency	In general the course will be offered each WiSe.			
Qualification objectives	• Students know the guiding principle of internal symmetries and how discrete and local gauge theories are constructed. They are able to analyse the symmetries of a Lagrangian and understand the implications for the phenomenology. • Students learn to discriminate different particles/processes via the characteristic signature in different detector components. • Students know the interplay of model building and experimental findings. They are able to critically compare theoretical predictions with experimental findings. • Students are able to perform simple cross section evaluations using the Feynman calculus. • Students know the structure and phenomenology of the Standard Model of Particle Physics and its limitations.			
Course content	• Quantum Electrodynamics as prototype of a local gauge theory: Feynman rules, calculation of matrix elements, higher order corrections, principle of renormalisation, running coupling strength, basic experimental tests at low (g-2, Lamb shift) and high energies (PETRA, LEP colliders) • Quantum Chromodynamics: phenomenological differences between abelian and non-abelian gauge theories, confinement, asymptotic freedom, stability of hadrons, jets, and basic experimental tests at PETRA, LEP, Tevatron and LHC. • Parton density functions of the proton and its determination in deep inelastic scattering, Bjorken scaling and its violation. • Electroweak theory and formulation of the Standard Model of particle physics: charged and neutral weak currents, from Fermi theory to the Glashow-Salam-Weinberg theory, massive weak gauge bosons, parity violation, CP violation, basic experimental tests at various colliders. • Observation and phenomenology of neutrinos oscillations. • Electroweak symmetry breaking: Higgs mechanism, Higgs boson physics (experimental aspects) • Limitations of the Standard Model (neutrinos masses, dark matter,…) and possible extensions (SUSY, extra dimensions,…)			
Previous knowledge	Experimental Physics V and Theoretical Physics IV			

Work load (hours)	**Course**	**Contact time**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)			
Language	English			

4.6. Particle Detectors

<table>
<tr><th>Lecture:</th><th colspan="4">Particle Detectors — Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">In general the course will be offered each WiSe</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students are able to understand the physics of particle detection
• Students are able to understand the different types of particle detectors
• Students are able to design a particle detector for specific experiments</td></tr>
<tr><td>Course content</td><td colspan="4">• Interaction of particles with matter
• General properties of particle detectors
• Tracking detectors
• Time measurement
• Energy measurement
• Particle identification
• Electronics, trigger and data acquisition
• Detector systems in Particle and Astroparticle Physics
• Applications of particle detectors in medicine</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics V</td></tr>
<tr><td rowspan="2">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.7. Hadron Collider Physics

<table>
<tr><th>Lecture:</th><th colspan="3">Hadron Collider Physics</th><th>Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">In general the course will be offered each SoSe</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">
• Students acquire the basic experimental concepts of experiments at hadron colliders (detector and trigger concept, soft and hard collisions, underlying event, pile-up)
• Students know the concept of cross section calculations at hadron colliders from first principles (Feynman diagrams) and from numerical calculations using Monte Carlo generators
• Students know the concepts of tests of the Standard Model at hadron colliders, including precision measurements in some areas
• Students acquire deeper insight and familiarize with modern multivariate techniques for the separation of signal and background processes in the search for new physics / deviations from the Standard Model
• Students know the up-to-date status on experimental tests of the
• Standard Model and on Searches for New Physics
</td></tr>
<tr><td>Course content</td><td colspan="4">
• Introduction to accelerators, with focus on the Large Hadron Collider
• Detector and trigger concepts of hadron collider experiments
• Phenomenology of pp collisions
• Structure functions, calculation of cross sections, Monte Carlo generators for pp collisions
• Particle signatures in LHC experiments
• pp collisions with low transverse momentum (underlying event, minimum bias)
• Test of QCD at hadron colliders (jet production, top quark production, W/Z + jet production)
• Measurements of important parameters of the Standard Model (m_t, m_W, gauge couplings, ..)
• Physics of heavy quarks (b-physics, the top quark and its properties)
• Higgs boson physics (experimental detection, measurements of Higgs boson properties, additional Higgs bosons,..)
• Search for supersymmetric particles
• Search for other extensions of the Standard Model
</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics V (Nuclear and Particle Physics)
Particle Physics II (desirable)</td></tr>
</table>

Work load (hours)	**Course**	**Contact time**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)			
Language	English			

4.8. Astroparticle Physics

<table>
<tr><th>Lecture:</th><th colspan="4">Astroparticle Physics Adv. Experiment</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Experimental Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>E CTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">The lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">Students are familiar with the standard models of particle physics and cosmology
Students acquire an understanding of the physics of the early universe
Students know the characteristics of the energy density in the universe
Students are familiar with up-to-date research on dark matter and dark energy
Students acquire insight on nuclear fusion and the evolution of stars
Students have knowledge of the nature of cosmic rays</td></tr>
<tr><td>Course content</td><td colspan="4">The standard model of particle physics
Conservation Rules and symmetries
The expanding universe
Matter, Radiation
Dark matter
Dark energy
Development of structure in the early universe
Particle physics in the stars
Nature and sources of high energy cosmic particles
Gamma ray and neutrino astronomy</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Experimental Physics V</td></tr>
<tr><td rowspan="2">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.9. Theoretical Condensed Matter Physics

<table>
<tr><th>Lecture:</th><th colspan="4">Theoretical Condensed Matter Physics Adv. Theory</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Theoretical Condensed Matter and Applied Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">In general the course will be offered each SoSe.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">Students are familiar with the relevant theoretical concepts in Condensed Matter Physics.
Students are able to calculate physical properties of various condensed matter systems based on quantum mechanics, and appreciate the physical ideas behind these approximation schemes, as well as their limitations.</td></tr>
<tr><td>Course content</td><td colspan="4">Crystal structures, crystal vibrations, quantization of harmonically coupled lattices, phonons.
Electrons in periodic potentials, Bloch waves, band structure. Application to conductors, insulators and semi-conductors.
Electron phonon coupling. BCS theory of superconductivity.
Spin degrees of freedom. Classical and quantum spin chains.</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Theoretical Physics I-V</td></tr>
<tr><td rowspan="2">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.10. Classical Complex Systems

<table>
<tr><th>Lecture:</th><th colspan="4">Classical Complex Systems Adv. Theory</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Theoretical Atomic, Molecular and Optical Sciences
or from Theoretical Condensed Matter and Applied Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">In general the course will be offered each WiSe.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students are able to use basic statistical tools to infer probabilistic statements from empirical observations.
• Students are able to relate microscopic laws to complex behaviour in macroscopic systems.
• Students are capable of recognizing and rigorously describing phenomena commonly encountered in complex systems.
• Students are able to use probabilistic notions to model systems subject to uncertainty about their microscopic states and laws.
• Students are able to run and interpret Monte Carlo computer simulations as well as to quantify the confidence in results produced by randomized algorithms.</td></tr>
<tr><td>Course content</td><td colspan="4">The first two thirds of the lecture cover basic theory, while the final third is concerned with concrete applications. Topics treated in the latter part depend more strongly on the lecturer.

Non-Linear Dynamics / Chaos Theory:
• Dynamical systems (discrete, differential equations, Hamiltonian)
• Lyapunov exponents
• Attractors and bifurcations

Stochastic Processes:
• Random walks, Markov model
• Stochastic differential equations and master equations (Langevin - and Fokker-Planck Equation)
• Numerical treatment and Monte Carlo techniques

Applications:
Molecular dynamics simulations
• Molecular driving forces and force field models
• Simulation techniques and sampling
• Energy landscapes and analysis of dynamics
Time series analysis and inverse problems
• Estimation and test theory</td></tr>
</table>

	• Spectral analysis • State space model			
Previous knowledge	Theoretical Physics I-V			
Work load (hours)	**Course**	**Contact time**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)			
Language	English			

4.11. Complex Quantum Systems

Lecture:	**Complex Quantum Systems** Adv. Theory			
Lecturer/s	Lecturers from Theoretical Atomic, Molecular and Optical Sciences or from Theoretical Condensed Matter and Applied Physics			
Course details	**Type**	**Credit hrs**	**ECTS**	**Assessment**
	Lecture and exercises (L+E)	4+2	9	SL or PL
Frequency	Lecture is offered on an irregular basis.			
Qualification objectives	• The students know the advanced physical concepts and mathematical techniques in the field of complex and open quantum systems; • They have the ability to apply these concepts and techniques to the theoretical modelling and analysis of specific complex systems and to derive emergent phenomena in open systems (e.g. macroscopic classicality) from microscopic laws of quantum mechanics (e.g. decoherence). • For structural track: The students know how to reason about counter-intuitive aspects of quantum theory using mathematically rigorous notions.			
Course content	• Quantum states: Pure and mixed states, density matrices, quantum state space • Composite quantum systems: Tensor product, entangled states, partial trace and reduced density matrix, quantum entropy • Open quantum systems: Closed and open systems, dynamical maps, quantum operations, complete positivity and Kraus representation • Dynamical semigroups and quantum master equations: Semigroups and generators, quantum Markovian master equations, Lindblad theorem • General properties of the master equation: Dynamics of populations and coherences, Pauli master equation, relaxation to equilibrium • Decoherence: Destruction of quantum coherence through interaction with an environment, decoherence versus relaxation Applied Track: • Microscopic theory: System-reservoir models, Born-Markov approximation, microscopic derivation of the master equation. • Applications: Quantum theory of the laser, superradiance, quantum transport, quantum Boltzmann equation Structural Track: • Uncertainty relations: Joint measurability, uncertainty relations for continuous and discrete observables, information-disturbance tradeoff • Contextuality: Non-Locality, Bell's Theorem, Marginals			

Previous knowledge	Theoretical Physics IV (Quantum Mechanics) and Advanced Quantum Mechanics			
Work load (hours)	**Course**	**Contact time**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)			
Language	English			

4.12. Quantum Field Theory

<table>
<tr><th>Lecture:</th><th colspan="4">Quantum Field Theory — Adv. Theory</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Theoretical Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">In general the course will be offered each SoSe.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students are able to write down the Lagrange function for the standard field theories (scalar, Dirac and gauge theories).
• They are familiar with concepts of canonical relativistic field quantization.
• They can derive the Feynman rules for perturbative expansions from a given Lagrangian and are able to construct Feynman diagrams.
• They can apply the standard methods for evaluating Feynman diagrams in Born approximation.
• They are familiar with quantum electrodynamics and its phenomenology.</td></tr>
<tr><td>Course content</td><td colspan="4">• Classical field theory, Lagrange formalism
• Relativistic wave equations: Klein-Gordon, Dirac, Maxwell, Proca equations
• Basics of Lie Groups, Lorentz group and its representations, Poincare group and its representations
• Canonical quantisation of free fields (scalar, Dirac, vector fields), causal propagator
• Interacting fields, gauge theories
• Scattering theory, S-matrix
• Perturbation theory, Wick's theorem, and Feynman diagrams
• Quantum electrodynamics and phenomenological applications (Compton scattering, pair creation and annihilation, Bhabha scattering in Born approximation)
• Optional: Functional Integrals, generating functionals, Grassman variables for fermionic fields
• Optional: Introduction to higher perturbative orders</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Electrodynamics, quantum mechanics, special relativity</td></tr>
<tr><td rowspan="2">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.13. General Relativity

Lecture:	General Relativity Adv. Theory			
Lecturer/s	Lecturers from Theoretical Particle Physics			
Course details	Type	Credit hrs	ECTS	Assessment
	Lecture and exercises (L+E)	4+2	9	SL or PL
Frequency	In general the course will be offered each WiSe.			
Qualification objectives	• Students know the fundamentals of special and general relativity, Lorentz transformations, Poincare-group. They can explain the fundamental phenomena related to relativity (perihel rotation of Mercury, relativistic Doppler effects, influence of gravity on clocks, accelerated systems). • They know the mathematical foundations of Riemannian geometry and know to interpret and obtain the metric, Christoffel symbols and Riemannian curvature components for simple geometric structures. • They can derive the geodesic equation from the action principle and know its relation to parallel transport. They can find geodesics in simple geometries. • They know how to calculate the energy-momentum tensor from a given field theory, for free particles and for collective systems (radiation dominated or matter dominated homogeneous universes). • They know how to read and construct space-time diagrams (Finkelstein, Kruskal, Carter-Penrose) for classical geometries (Minkowski space, Rindler space, Schwarzschild and Kerr geometries).			
Course content	• Equivalence principles: Minkowski space, Poincare group, space-time diagrams, world lines, proper time and distance, application to simple phenomena (elevator thought experiments, twin paradox, relativistic Doppler effect, accelerated systems), Lorentz transformations and general coordinate transformations. • Differential geometry: manifolds and tangent spaces, forms, metric tensor, integration, Stoke's theorem, outer derivative, Lie derivative, covariant derivative and Christoffel symbols, parallel transport, geodesics, curvature (Riemann tensor, Weyl tensor, Ricci tensor and scalar), torsion, Killing vectors, Riemann coordinates. • Dynamics of the gravitational field: Einstein equations, cosmological constant, energy-momentum tensor of matter systems (perfect fluids, point particles, Klein-Gordon and Maxwell theory). • Effects based on post-Newtonian approximations: red/blue shift effects, rotation of the perihel, effect of gravitation on clocks, deflection of light. • Gravitational waves: perturbative expansion of field equations, gauge invariance, origin and detection of gravitational waves. • Classical space times: Minkowski, Rindler, Schwarzschild, Kerr, Reiss-			

	ner-Nordstrøm, Kerr-Newman geometries; Robertson-Walker metrics, Friedmann universes and deSitter space. Discussion of causal structure, geodesic completeness, key coordinate systems and Carter-Penrose diagrams. • Optional: Einstein-Hilbert action and variational principle. • Optional: Modern topics in cosmology: CMB, the Inflation Model.
Previous knowledge	Electrodynamics, special relativity, Lagrangian mechanics

Work load (hours)	**Course**	**Contact time**	**Self-studies**	**Total**
	Lecture and exercises (L+E)	90 h	180 h	270 h
Usability	M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)			
Language	English			

4.14. Quantum Optics

<table>
<tr><th>Lecture:</th><th colspan="4">Quantum Optics   Adv. Theory</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Theoretical Atomic, Molecular and Optical Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">Lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">
• Students are able to characterize the quantum state of the electromagnetic field
• Students are able to interpret the dynamics of the quantized field in terms of canonically conjugate variables
• Students are able to distinguish classical from quantum features of the quantized field, and to perform the classical limit
• Students are able to infer the quantum state of the light field from multi-point correlation functions
• Students are able to describe the quantum state of strongly coupled light-matter systems
• Students are able to give a semiclassical description of light-matter systems
• Students are familiar with a selection of paradigmatic experimental settings to probe generic quantum properties of the light field</td></tr>
<tr><td>Course content</td><td colspan="4">
• Quantization of the radiation field
• Coherent states
• Phase space representation of quantum states
• Counting statistics
• Dressed states
• Floquet theory
• Special topics, e.g. micromaser theory, elements of entanglement theory, laser theory, master equations, coherent control
• Light-matter interaction</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Introductory courses of experimental and theoretical physics (mechanics, electrodynamics, quantum mechanics)</td></tr>
<tr><td rowspan="2">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

4.15. Quantum Chromodynamics

<table>
<tr><th>Lecture:</th><th colspan="4">Quantum Chromodynamics — Adv. Theory</th></tr>
<tr><td>Lecturer/s</td><td colspan="4">Lecturers from Theoretical Particle Physics</td></tr>
<tr><td rowspan="2">Course details</td><td>Type</td><td>Credit hrs</td><td>ECTS</td><td>Assessment</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>4+2</td><td>9</td><td>SL or PL</td></tr>
<tr><td>Frequency</td><td colspan="4">The lecture is offered on an irregular basis.</td></tr>
<tr><td>Qualification objectives</td><td colspan="4">• Students are able to construct Lagrangians for (abelian and non-abelian gauge theories).
• They are familiar with the concepts of field quantization via functional integrals, the concept of Green functions and of their gauge symmetries.
• They can evaluate gauge theories perturbatively at the one-loop level, including renormalization.
• They know quantum chromodynamics and its basic phenomenology.
• They are prepared to work on experimental or theoretical research at particle colliders such as the CERN Large Hadron Collider (LHC).</td></tr>
<tr><td>Course content</td><td colspan="4">• Quantization of field theories via functional integrals
• Perturbation theory and Feynman diagrams
• Gauge theories and their quantization
• BRS symmetry and Slavnov-Taylor identities
• Gauge theory of strong interaction (quantum chromodynamics)
• Quantum corrections, regularization, and renormalization
• Renormalization group equations
• Jet produktion in e+e- annihilation
• Parton model for hadronic particle reactions
• Parton distribution function and DGLAP evolution
• Deep inelastic electron-nucleon scattering
• Quantum corrections to the Drell-Yan process</td></tr>
<tr><td>Previous knowledge</td><td colspan="4">Electrodynamics, quantum mechanics, relativistic quantum field theory</td></tr>
<tr><td rowspan="2">Work load (hours)</td><td>Course</td><td>Contact time</td><td>Self-studies</td><td>Total</td></tr>
<tr><td>Lecture and exercises (L+E)</td><td>90 h</td><td>180 h</td><td>270 h</td></tr>
<tr><td>Usability</td><td colspan="4">M.Sc. modules “Advanced Physics” (PL or SL) or “Elective Subjects” (SL)</td></tr>
<tr><td>Language</td><td colspan="4">English</td></tr>
</table>

5. Example study plans for optional specialisation

Within their Master studies students may consolidate their knowledge in a particular field of physics by choosing their courses in the modules *Advanced Physics*, *Elective Subjects* and *Term Paper* accordingly, as well as performing their research phase (Research Traineeship and Master Thesis) in this field. In the following example study plans are recommended for different areas of specialisation.

Example Study Plan for consolidation in **Experimental Particle Physics**:

<table>
<tr><th>FS</th><th colspan="5"></th></tr>
<tr><td>1</td><td>Advanced Quantum Mechanics
10 CP</td><td>Advanced Particle Physics
9 CP</td><td></td><td rowspan="2">Term Paper
in Particle Physics
6 CP</td><td>Master Laboratory
8 CP</td></tr>
<tr><td>2</td><td>Quantum Field Theory
9 CP</td><td>Hadron Collider Physics
9 CP</td><td>Detectors
9 CP</td><td></td></tr>
<tr><td>3</td><td colspan="5">Research Traineeship in Experimental Particle Physics
30 CP</td></tr>
<tr><td>4</td><td colspan="5">Master Thesis in Experimental Particle Physics (Thesis and Presentation)
30 CP</td></tr>
</table>

Example Study Plan for consolidation in **Theoretical Particle Physics**:

<table>
<tr><th>FS</th><th colspan="5"></th></tr>
<tr><td>1</td><td>Advanced Quantum Mechanics
10 CP</td><td>General Relativity
9 CP</td><td></td><td rowspan="2">Term Paper
in Particle Physics
6 CP</td><td>Master Laboratory
8 CP</td></tr>
<tr><td>2</td><td>Quantum Field Theory
9 CP</td><td>Hadron Collider Physics
9 CP</td><td>Quantum Chromodynamics
9 CP</td><td></td></tr>
<tr><td>3</td><td colspan="5">Research Traineeship in Theoretical Particle Physics
30 CP</td></tr>
<tr><td>4</td><td colspan="5">Master Thesis in Theoretical Particle Physics (Thesis and Presentation)
30 CP</td></tr>
</table>

Example Study Plan for consolidation in **Atomic, Molecular and Optical Physics**:

<table>
<tr><th>FS</th><th colspan="5"></th></tr>
<tr><td>1</td><td>Advanced Quantum Mechanics
10 CP</td><td>Advanced Atomic and Molecular Physics
9 CP</td><td></td><td rowspan="2">Term Paper
in Atomic and Molecular Physics
6 CP</td><td>Master La-boratory
8 CP</td></tr>
<tr><td>2</td><td>Advanced Optics and Lasers
9 CP</td><td>suggested* theory lectures
9 CP</td><td>suggested** experimental lectures
9 CP</td><td></td></tr>
<tr><td>3</td><td colspan="5">Research Traineeship in Experimental Atomic and Molecular Physics
30 CP</td></tr>
<tr><td>4</td><td colspan="5">Master Thesis in Experimental Atomic and Molecular Physics (Thesis and Presentation)
30 CP</td></tr>
</table>

* Choose for example:
Classical Complex Systems
Theoretical Quantum Optics
Complex Quantum Systems
Theoretical Condensed Matter Physics

** Choose for example:
Condensed Matter I: Solid State Physics
Condensed Matter II: Interfaces and Nanostructures

Example Study Plan for consolidation in **Condensed Matter Physics**:

<table>
<tr><th>FS</th><th colspan="5"></th></tr>
<tr><td>1</td><td>Advanced Quantum Mechanics
10 CP</td><td>Condensed Matter I: Solid State Physics
9 CP</td><td></td><td rowspan="2">Term Paper
in Condensed Matter Physics
6 CP</td><td>Master La-boratory
8 CP</td></tr>
<tr><td>2</td><td>Theoretical Condensed Matter Physics
9 CP</td><td>Condensed Matter II: Interfaces and Nanostructures
9 CP</td><td>Complex Quantum Systems
9 CP</td><td></td></tr>
<tr><td>3</td><td colspan="5">Research Traineeship in Condensed Matter Physics
30 CP</td></tr>
<tr><td>4</td><td colspan="5">Master Thesis in Condensed Matter Physics (Thesis and Presentation)
30 CP</td></tr>
</table>