Particle Physics beyond the Standard Model

Heidelberg University

Proposed funding period: 01.04.2014 to 30.09.2018

Submission deadline: 10.04.2013

May 21, 2015

CONTENTS

1 RESEARCH PROGRAM

1.1 SCIENTIFIC THEME

Over the last decades experiments and theory in particle physics and astrophysics have been extraordinarily successful in developing Standard Models of particle physics and cosmology. They describe a wealth of measurements based on first principles of field theory. The discovery of a Higgs boson candidate by ATLAS and CMS marks the climax of this development — the LHC experiments have discovered a new scalar, fundamentally new to the structure of the matter and interaction of particles, but proposed by field theory including its detailed properties.

The discovery of the Higgs boson at the electroweak scale clearly completes our understanding of electroweak symmetry breaking and the appearance of massive gauge bosons. To appreciate the impact of the Higgs discovery on the fundamental understanding of particle physics and cosmology we remind ourselves that the main arguments for its existence are tied to the underlying theory at high energies: unitarity and renormalizability of the Standard Model with the observed Higgs boson imply that we can extrapolate our experimental and theoretical understanding from the electroweak scale to higher energy scales, for example the huge Grand Unification scale where the three gauge couplings essentially unify. In addition, the exact value of the Higgs mass suggests that such an extrapolation does not encounter technical problems in the Higgs sector itself. Would the Higgs mass have come out larger, the Higgs self-couplings would have developed a Landau pole between the electroweak and the Grand Unification scale; would it have come out just a little lower the Higgs potential might have become unstable. This is why we interpret the Higgs discovery as a triumph of a perturbative field theory approach to particle physics, opening the door for controlled extrapolations from the LHC energy to higher, more fundamental energy scales.

The structural success of our approach to particle physics and cosmology, on the other hand, still leaves many questions open. The most obvious short-coming in our model for particle physics is the absence of dark matter altogether. Many measurements point to a particle nature of the observed dark matter density in the universe. Moreover, the flavor or generation structure of the quark and lepton sector with its observed symmetry structure is not explained by the Standard Model. This includes the generation of light neutrino masses for essentially left-handed fields. Pointing towards higher energies, the Standard Model has no explanation for the baryon asymmetry of the universe, i.e. the experimentally observed absence of large amounts of anti-matter. Finally, we observe an almost perfect unification of the three gauge couplings in the Standard Model, pointing towards a unified description of this interaction structure. All these questions are experimental in nature.

Also on the theory side the Standard Model leaves questions unanswered. First, scalar masses in field theory are unstable with respect to quantum effects. If we assume there exist physical energy scales where quark flavor or lepton flavor effects change the particle content and the interaction structure of the Standard Model the mass of the Higgs boson tends to escape to these energy scales. Because the Higgs boson is light we need to fix its mass to the electroweak scale by brute force. Theoretically, this situation is not satisfactory. Linked to the observed approximate gauge coupling unification, the weak-scale gauge structure of the Standard Model appears ad-hoc. Combining the $SU(3) \times SU(2) \times U(1)$ gauge structure into a common $SU(5)$ or $SO(10)$ gauge group is an obvious and predictive improvement of our theoretical understanding. Finally, quantizing gravity leads to a non-renormalizable theory. String theory might be the framework to combine quantum field theory and gravity into a common theory at very high energy scales.

The discovery of the Higgs boson suggests that we should be able to formulate and answer the experimental and theoretical questions in the framework of perturbative field theory. This defines the physical basis for our consistent and comprehensive research program. It starts from experimental observations at the electroweak or TeV scale, focusing on structures or effects which cannot be explained by the Standard Model. Appropriate field theoretical extensions of the Standard Model at the weak scale can be evolved to higher energy scales, in the hope of encountering fundamental structures which can be quantitatively linked to experiment.

While the first three years of operating the LHC have been a great success for Higgs searches we have not gained significant insight into physics beyond the now complete Standard Model. One reason might well be that the LHC energies attained to far have not been sufficient to produce new states. On the other hand, we might also not have looked in the right places. As an example, supersymmetric models lead us to search for dark matter or missing energy in the decay of new, strongly interacting squarks and gluinos. In the coming years we should complement the model-driven direct searches at the LHC with general searches for new physics in as many channels as possible. In Heidelberg, we can test the Standard Model at ATLAS, LHCb, and lepton-flavor precision experiments, including a detailed study of the Higgs boson, without searching for specific new physics models. At the same time, models solving the dark matter or hierarchy problems point towards signatures which we can formulate with the help of specific models. They give us an idea where to look for new physics, for example in ATLAS, in dark matter searches, or close to cosmology. Finally, we can link the different indirect and direct searches through their universal field theory interpretation, possibly defining the key route for particle physics in the coming years. Consequently, we structure our approach to physics beyond the Standard Model as three main themes:

1. Tests of the Standard Model
2. Direct searches at the TeV scale
3. Towards the Planck scale

While it is not guaranteed that we will discover the ultraviolet completion of the Standard Model with the help of the LHC, we do expect to see effects in the coming years. If quantum field theory is indeed confirmed as the fundamental tool of particle physics understanding its ability to predict physics all the way to the Planck scale is a unique opportunity which we should not let pass.

1.2 Heidelberg involvement

The individual Heidelberg research groups cover all three branches listed as the key research directions of this RTG. Common projects already exist in different research topics, e.g. in QCD studies and Monte Carlo tuning, lepton flavor violation, or developing tools to identify boosted top quarks as prominent signatures of many physics processes. However, these connections rely on the exchange of individual researchers or on post-doctoral fellows bridging different theory groups.

This RTG and its qualification program aims at an intense structured exchange among all involved research groups. This will benefit our research in multiple ways: students and young researchers will obtain a broad view beyond their own research field which will inspire them to exploit new ideas and tools in their analysis. This spirit will then automatically trigger more common research projects, stabilizing these communicational structures in the longer term.

1.2.1 Tests of the Standard Model

The Standard Model is an exceptionally predictive quantum theory. With the Higgs mass the last unknown parameter of the model has been measured. Precise predictions are now available for all sectors of the theory (fermion sector, gauge sector and Higgs sector). Thorough experimental verification of these theoretical predictions tests the model and provides an indirect way to search for new phenomena.

The least understood part of the Standard Model are the fermion mass matrices. We observe three generations of quarks and leptons without being able to relate their structures to each other. We neither understand the observed fermion mass hierarchies nor the mixing between the fermion generations. A careful study of the lepton and quark flavor sector should provide hints to underlying new symmetries and a better understanding of the flavor property. Several, internationally-renowned research groups participating in the RTG are active in the lepton and quark flavor sector and cover a broad research program ranging from neutrino oscillations, to the search for lepton flavor violation and precision studies of the decays of heavy mesons.

Lepton flavor

In the Standard Model the lepton number is conserved at tree level. The observation of neutrino oscillations opens the possibility of lepton flavor violation (LFV) for charged leptons. The Standard Model prediction for this effect is extremely tiny, but many extensions of the Standard Model, such as grand unified models, supersymmetric models, left-right symmetric models, or models with an extended Higgs sector can enhance LFV for charged leptons to an observable amount. In such models the recent observation of a large neutrino mixing angle θ_{13} can be linked to enhanced LFV.

Since the Standard Model prediction of LFV for charged leptons is well below a measurable value, any observed LFV is an unambiguous sign for new physics. Within the RTG, the study of LFV is pursued by experimental and theoretical groups: the initiative for the Mu3e experiment at PSI and the project coordination lies in the hands of members of the RTG (Berger, Schöning); the Heidelberg LHCb group has significantly contributed to determining the LHCb limit of the flavor violating tau decay $\tau \to \mu\mu\mu$ (Uwer); theoretical studies of models for neutrino mass generation which are expected to lead to sizable LFV for charged leptons are performed by groups at the MPIK (Lindner, Rodejohann) and complement our experimental efforts.

Quark flavor

Precision studies of B decays at the B factories and at the Tevatron have confirmed the quark mixing mechanism of the Standard Model and opened the door for the next generation B experiments. There, we use precision measurements of very rare loop-suppressed B-hadron decays to search for new contributions via quantum effects. In recent years the LHCb experiment has taken over the leadership in the exploration of the heavy meson physics sector. Experimental observables are the rates of extremely rare B decays, their kinematic distributions, in particular angular distributions of the B decay products, and the determination of CP violation. For many of these observables precise theoretical predictions exist and significant deviations from the measurements will be a signal for physics beyond the Standard Model. LHCb has demonstrated that the experiment can also successfully explore the D meson system. The Heidelberg LHCb group is one of the leading groups within LHCb and has contributed to many key measurements in the B and D systems (Hansmann-Menzemer, Uwer).

QCD at the LHC

Hard jets accompany or define almost all hard scattering processes at the LHC. Moreover, hard jets in association with missing energy or leptons are a typical signature for many new physics searches. To successfully separate new physics signals from backgrounds we need to understand QCD effects and multi-jet production with high precision (Plehn). This will be particularly relevant for the 13 TeV run of the LHC, because new physics events might be more rare than we would have hoped for.

The ATLAS groups involved in the RTG have key expertise in analyzing inclusive, dijet and associated multi-jet production both in the context of testing the Standard Model (Dunford, Stamen) as well as with emphasis on physics beyond the Standard Model (Schultz-Coulon). Moreover, if parton densities should indeed become the bottle neck of precision studies for example in the Higgs sector we will benefit from our involvement in their combined HERA-LHC extraction (Schöning).

HIGGS AND GAUGE SECTOR

The Higgs boson is currently making a rapid transition from a spectacular discovery to the most sensitive probe for the underlying structures of the Standard Model. It is not clear that the extremely minimal implementation of the Higgs mechanism in the Standard Model is what we observe. Most models for new physics require a slightly more complex version, for example adding an additional Higgs singlet or Higgs doublet. Even though electroweak precision data strongly constrains such extensions and the recently measured decay rate $B_s \to \mu^+\mu^-$ strongly constrains their mass spectra, such extensions are central targets of LHC searches. Additional Higgs states always lead to modifications of the observed light Higgs couplings, where the patterns of possible deviations from the Standard Model can lead us towards more fundamental structures of the extended Higgs sector (Plehn).

Apart from constraining the Higgs sector, a precise determination of triple and quartic gauge boson couplings also provides important insight into the structure of the Standard Model and possible extensions. The production of W bosons in association with two photons is the first measurable triple gauge boson final state at the LHC and potentially the first process to probe a quartic gauge coupling; it is presently studied within ATLAS under leading participation of Heidelberg (Stamen). An expansions of these activities into general di-boson final states (WW, WZ, ZZ) will be our next step.

1.2.2 DIRECT SEARCHES AT THE TEV SCALE

Some of the shortcomings for the Standard Model are quite specific: if dark matter does not only interact gravitationally but also weakly, its observed relic density points towards a mass in the TeV range. If the measured value of the anomalous magnetic moment of the muon is indeed different from the Standard Model prediction, the size of the deviation also indicates new electroweak states at the TeV scale. Finally, loop corrections from the top quark and the electroweak gauge bosons contribute to the quadratic divergence of the Higgs mass. This gives rise to the hierarchy problem in the presence of the relevant physical scales between the weak scale and the Planck scale. Naturally, this problem would be solved at the same energy where it appears — at the TeV scale.

Following these hints, we supplement the general tests of the Standard Model and the indirect search for physics beyond its description in the last section by dedicated searches at the TeV scale. They include collider searches as well as different classes of dark matter searches.

TOP QUARK

In many aspects the top quark is unique. It is the heaviest particle of the Standard Model which means that its Yukawa coupling to the Higgs field governs the quadratic divergences of the Higgs mass. The renormalization group evolution of the Higgs mass or Higgs self-coupling critically depends on the top quark. It determines the stability of the vacuum (Lindner) and predicts a fixed point for the ratio of the Higgs and top masses (Wetterich). New physics models linked to the hierarchy problem or to the Higgs sector single out the top sector for precision tests.

The possibly most interesting measurement in the Higgs sector is therefore the direct measurement of the top Yukawa coupling. This analysis poses big challenges for the LHC experiments, and so-called top taggers might become the method of choice. In searches for heavy resonances, coupling preferably to tops, these methods have recently shown excellent potential (Plehn, Schöning). In supersymmetry or other models targeting the hierarchy problem a new partner state of the top quark can be produced at the LHC. If it follows a flavor-diagonal decay path the identification and reconstruction of the top quark will again be the key ingredient of the analysis. The development and experimental implementation of the HEPTopTagger is the first major success of a close collaboration between an experimental and theoretical group participating in this RTG and might serve as model for future projects (Plehn, Schöning).

Dark matter

The most striking shortcoming of our Standard Model is the complete absence of a dark matter candidate or even the underlying symmetry structure for such a state. Astrophysics and cosmology have firmly established the existence of dark matter and measured many of its properties with impressive precision. The big open question is whether the dark matter agents are stable, weakly interacting particles. If an electroweak interaction of the dark matter agent indeed mediates dark matter interactions over the evolution of the universe and leads to the observed density of dark matter, we should be able to observe these states at the LHC. This would imply a strong experimental link between astro-particle physics (Kopp, Lindner), collider physics (Kopp, Plehn) and cosmology (Amendola).

Present experimental limits constrain dark matter models up to the TeV scale. However, the parameter space of many of these models has only just been touched. In Heidelberg we search for direct production of dark matter candidates at the LHC in mono-jet events (Schultz-Coulon) or in association with leptons (Stamen). Another key signature of dark matter is multiple high-energy jets, multiple high-energy leptons and large missing momentum. As W plus multi-jet production shares the same experimental signature a precision measurement of this channel provides a powerful test for new physics sources of missing momentum (Dunford).

Convincing theoretical models for weakly interacting dark matter can be built based on symmetries that tie the dark matter sector to electroweak precision data or proton decay. Examples are the minimal supersymmetric extension of the Standard Model, large extra dimensions, or little-Higgs models. Their critical property is the symmetry structure that provides a long-lived particle, which might be linked to the general high-scale structure of physics beyond the Standard Model (Hebecker).

1.2.3 Towards the Planck scale

Field theory tells us how to start from experimentally accessible energy scales and how to extrapolate from there to more fundamental (higher) energy scales. This leads us to energy scales relevant for quark flavor physics, for see-saw models explaining the neutrino masses, for the baryon asymmetry of the universe and where we observe an approximate unification of all three forces of the Standard Model. Experimental observations distinctly raise questions about physics at higher energy scales. At the same time, theoretical consistency serves as an important guideline for formulating theories valid at the Planck scale. Their low-energy consequences are to be studied with regards to unsolved problems at the TeV scale.

Grand Unification in the LHC era

With the discovery of a light, likely fundamental Higgs boson, renormalization group evolution and Grand Unification have clearly gained attractiveness (Lindner, Wetterich). The observed approximate unification of the three gauge couplings is a puzzling hint for such theories. In addition GUTs are theoretically well-motivated, for example, because the observed matter spectrum appears to fit perfectly into representations of an overarching gauge group containing the gauge group of the Standard Model. Well-studied but not the only examples are $SU(5)$ or $SO(10)$. Theory and experiment really seem to point to the same concepts. The theory group in Heidelberg studies models of Grand Unification both in the framework of four- and higher-dimensional field theory and from the perspective of string theory. String compactifications with D-branes (F-theory) have the potential to go significantly beyond purely four-dimensional approaches to unification and to address specific problems of grand unified models such as proton decay or the doublet-splitting in a theoretically well-motivated manner (Hebecker, Weigand).

COSMOLOGY AND TEV SCALE PHYSICS

Cosmological and astrophysical observations suggest the existence of a cosmological constant or a very weakly varying dark energy component. The smallness of the cosmological constant cannot be explained at the electroweak or even lower energy scales. It is linked to the ultraviolet completion of our non-renormalizable and hardly predictive theory of gravity (Wetterich). Similar large energy scales are probed for example by the Planck satellite, whose data have been recently released. A well established candidate for completing the Standard Model up to the Planck scale is string theory, which can play a central role in understanding the corresponding data. While string theory cannot completely remove the fine tuning required by the small cosmological constant, it can lead to a low-energy theory consistent with a small cosmological constant based on a wide variety of compactifications of its additional small spatial dimensions. This is one of the immediate motivations for the detailed investigation of the string vacua landscape as pursued by our Heidelberg string theory group (Hebecker, Weigand). Large-scale cosmological projects like the Euclid satellite, in which Heidelberg plays a leading role (Amendola), will contribute to pin down the properties of the dark energy field and will help to understand the low-energy limit of gravity.

FUNDAMENTAL STRUCTURES

Once we include gravity in our theoretical picture we obviously cannot rely on the same perturbative field theory which governs physics up to the scale of Grand Unification. It is here that a top-down approach becomes particularly fruitful: theoretical consistency of a theory of quantum gravity is extremely constraining for physics at the Planck scale and points to structures which may - under very favorable circumstances - be observable also at the TeV scale. The most spectacular signatures in that sense would be large extra dimensions, leading to graviton production at the LHC or the production of small black holes (Plehn, Schultz-Coulon). Such a TeV scale observation would directly probe gravitational quantum effects and allow us to experimentally distinguish alternative theories of quantum gravity like string theory and fixed-point gravity (Wetterich). Another prediction of string theory is supersymmetry at the ten-dimensional Planck scale, which — in the presence of TeV scale partner states — has direct impact on collider physics. Other top-down motivated concepts relevant at the TeV scale are flavor symmetries or protecting symmetries for dark matter and electroweak precision data. It is important to appreciate that if the LHC were to find no experimental hints for new physics at the TeV scale, theoretical guidance from consistent ultraviolet completions of particles physics and gravity is likely to play an even more prominent role in high energy physics.

1.3 PROJECTS AND DISSERTATION TOPICS

Following the general description of the physics program of this RTG we specify the physics topics, indicate the preparational work by the participating scientists, and give possible thesis topics in this section. The three themes start with more experimental questions and move towards higher energy scales and more theoretical considerations. The important feature of the participating groups is that these topics manage to build a bridge between model unspecific experimental searches all the way to GUT and string models without leaving a gap. Whenever topics are closely related, it is indicated in the brief description.

1. TESTS OF THE STANDARD MODEL

(a) LEPTON FLAVOR

Due to the observation of neutrino oscillations, LFV in the charged lepton sector is expected. As the exact mechanism and the size of LFV is unknown, its study is of large interest for understanding neutrino mass generation, CP violation and new physics beyond the Standard Model [ML1,ML2]. Experimental groups in Heidelberg have taken major responsibility for the Mu3e experiment, which aims to improve the existing bound of $BR(\mu \to 3e) < 10^{-12}$ by up to 4 orders of magnitude [AS1/NB1,AS2]. The fact that Z-penguins can give dominant contributions to FCNC for the muon-to-electron conversion and for the $\mu \to 3e$ decay has received some attention recently. It might open a window to new physics at high mass scales [JK9]. The study of tau decays at LHCb will allow one to constrain further lepton flavor violating processes involving the third lepton family. Members of the Heidelberg LHCb group recently published the limit of the LFV $\tau \to \mu\mu\mu$ [UU2] decays which is close to the limit reached at the B factories (2.1×10^{-8}). Significant improvements on this bound are expected due to optimized analysis tools similar to those implemented in the search of the rare decays $B^0_{d,s} \to \mu^+\mu^-$ [UU1]. In addition, the decay $B^0_{s,d} \to e^+\mu^-$ is a promising candidate for searches for LFV at LHCb.

In general, models for neutrino mass generation are naturally expected to have sizable charged lepton flavor violation [WR7,WR8]. At different colliders, we can search for processes which violate lepton number and which can be connected to low-energy lepton number violation in neutrinoless double beta decay [WR2,WR4,WR9].

(Berger, Lindner, Rodejohann, Schöning, Uwer)

Potential dissertation topics:

Test of lepton flavor violation in the decay $\mu \to eee$
Angular correlations in $\mu \to 3e$ within left-right symmetric models and experimental tests
Sensitivity studies for the Mu3e experiment
Lepton flavor violation in the μ-e sector and neutrino physics
Searches for LFV decays at LHCb

(b) QUARK FLAVOR

The combination of huge available data sets and precise theoretical predictions makes the B system a unique place for indirect searches for physics beyond the Standard Model. The Heidelberg LHCb group has been the major player in several key analyses of the LHCb experiment, such as the measurement of B_s mixing [SHM3,SHM6] or the measurement of the CP violating phase ϕ_s in $B_s \to J/\Psi KK$ decays [SHM7,SHM8/UU5]. Despite earlier hints of potentially large deviations, the LHCb experiment measured ϕ_s to be consistent with the Standard Model value very close to zero. To improve the measurement and check for potentially small beyond the Standard Model contributions significantly more statistics are needed. These will be available with the LHCb upgrade. In addition, theoretical uncertainties from penguin contributions need to be handled by precision measurements of several SU(3)$_F$ related channels [X4-X6].

With more available data, new analyses will be performed by the Heidelberg LHCb group. The search for CP violation in interference between mixing and decay in the rare penguin-dominated $B_s \to \phi\phi$ decay is, from the analysis techniques, very similar to the analysis of $B_s \to J/\Psi KK$. The expected CP violation in the Standard Model in this case is exactly zero without any theoretical uncertainties. Any possible new physics contribution showing up in $B_s \to J/\Psi KK$ has to be visible in $B_s \to \phi\phi$ as well. Additional new physics contributions might enter into the $B_s \to \phi\phi$ penguin decay.

CP violation in B_s or B_d mixing is predicted to be very small in the Standard Model [X7], however, measurements from the D0 experiment in high statistics samples of semileptonic B decays have indicated potential deviations [X8]. To test this per-mille level asymmetry is extremely challenging, especially in the B_d system. The Heidelberg LHCb group has significant experience in B meson mixing [SHM3,SHM6] and in the analysis of semileptonic B decays [SHM9] and have thus started to work on this analysis.

Asymmetries and ratios in the flavor changing neutral current process $B^0 \to K^{*0}\mu^+\mu^-$ are theoretically well predicted. They are sensitive to physics beyond the Standard Model that changes the operator basis by modifying the mixture of the vector and axial-vector components [i.e. X9-X11]. First statistically limited results are available from the LHCb collaboration [X12,X13]. One of the main authors of this analysis has recently joined the Heidelberg LHCb group, thus this analysis will be part of the future Heidelberg research program.
(Hansmann-Menzemer, Uwer)

Potential dissertation topics:

Precision measurement of penguin pollution in $B_s \to J/\psi KK$ decays at LHCb.
Measurement of CP violation in $B_s \to \phi\phi$ decays at LHCb.
Measurement of the semileptonic asymmetry in the B^0 system at LHCb.
Measurement of angular distributions in the $B^0 \to K^*\mu\mu$ decays at LHCb.

(c) QCD AT THE LHC

The production of hadronic jets is the dominant feature of high energy proton-proton interactions. Measurements of their cross-sections serve as fundamental tests of various aspects of perturbative and non-perturbative QCD such as the parton densities, the calculations of the hard matrix element, the parton shower and fragmentation models. Since the perturbative calculations are believed to be reliable, the measurements can be used to constrain and to improve the knowledge of underlying parton densities and implement them into Monte Carlo generators, needed for many LHC searches. Parton density functions will soon become the limiting factors, for example, in precision Higgs physics. They are considered to be best measured at the LHC in inclusive vector boson production [AS4,AS5]. The ATLAS group at PI is working on combining HERA data [AS6,AS7] and LHC data to extract parton densities.

Members of the Heidelberg ATLAS group at KIP have significantly contributed to recent measurements of jet and W+jet total and differential cross-sections and as well to earlier measurements of the corresponding angular distributions [MD2-MD4,RS1-RS2,SC2,SC4,SC5]. Especially in extreme phase space regions (e.g. for events with large jet momenta or larger scalar transverse momentum sum) for which the Standard Model is least well understood, measuring the cross-section using larger data samples will greatly improve our knowledge of the theoretical modeling [TP1,TP4,X1,X2].
Other key ingredients for these measurements are a detailed understanding of the trigger behavior, the detector calibration, and potential effects which alter the detector behavior from its expectations. The expertise of the Heidelberg ATLAS group in jet reconstruction and calorimeter calibration and trigger performance [MD1,RS3,RS5,RS6,SC6] in combination with the local expertise on MC generators especially Madgraph [X3] will be the basis for further contributions in this area.

Due to their large masses, top quarks play a special role in many Standard Model and beyond Standard Model physics' signatures. Therefore identifying jets including boosted hadronic top quark decays is important to distinguish potential physics signals from large

QCD backgrounds. The HEPTopTagger [TP7] developed in close collaboration between the Heidelberg ATLAS group at the PI and one of our theory groups is already exploited in several (published and about to be published) analyses [AS3]. One of its potential applications in the QCD sector is the measurement of top quark production at high transverse momentum, which can be used to constrain the gluon density at high x-values. This range is up to now experimentally only very weakly constrained, but its knowledge is important for any high energy search in hadron collisions.
(Dunford, Plehn, Schöning, Schultz-Coulon, Stamen)

Potential dissertation topics:

Measurement of the inclusive jet cross section and cross section ratios with ATLAS
Measurement of multi-jet cross sections and multi-jet cross section ratios with ATLAS
Measurement of the di-jet angular distribution and search for new physics with ATLAS
Determination of the gluon density from boosted top quarks with ATLAS
Combined analysis of contact interaction and parton pdfs at LHC
Theoretical uncertainties in staircase scaling
Staircase tails in multi-jet Poisson patterns

(d) HIGGS AND GAUGE SECTOR

With the discovery of the Higgs boson, the study of electroweak symmetry breaking has entered a data-driven phase. One of the key tasks for the LHC will be to determine the Higgs parameters as precisely as possible, testing the Higgs sector for physics beyond the Standard Model. Already at TeV energy scales this includes the coupling strengths of the new particle [TP3,X16].

Looking towards the 13 TeV run of the LHC, the focus will shift from the Higgs discovery channels to alternative Higgs signals which probe as many couplings as possible. Examples are Higgs production in weak boson fusion [TP4], in association with a weak gauge boson, and in association with top quarks. Applying some of the tools developed as part of project 1(c), but also extending it to other analysis strategies, we will focus on the measurement of the top Yukawa coupling in $t\bar{t}H$ production [TP7]. A direct measurement of the Yukawa couplings is crucial for a comprehensive Higgs coupling analysis, for example using the combined theoretical and experimental SFitter tool [TP3,X14]. Going beyond establishing the Standard Model couplings such a general analysis should include any kind of anomalous Higgs couplings, including flavor-non-diagonal couplings related to LFV and our project 1(a) [JK9].

Beyond Higgs properties the electroweak sector and the Higgs mechanism can be tested measuring the triple and quartic couplings of the gauge bosons. The couplings are fixed by the gauge group of the Standard Model, and cross sections can be calculated using standard Monte Carlo techniques. Of particular interest are the couplings of the massive gauge boson to photons [X18]; whereas vertices with one or two photons coupling to W bosons exist, they are forbidden in the case of the Z boson. In addition, the $W\gamma\gamma$ final state is the first tri-boson final state that is measurable at the LHC. The gauge couplings can be measured by investigating di- and tri-boson final states. With the high energy data after the current LHC shutdown detailed studies including the extraction of limits on anomalous quartic gauge couplings will be possible.
(Kopp, Plehn, Schöning, Stamen)

Potential dissertation topics:

Measuring Higgs couplings with extended Higgs sectors
Flavor-non-diagonal Higgs couplings
Solving the combinatorial backgrounds in $t\bar{t}H$ searches

Extracting $t\bar{t}H$ production using top tagging at ATLAS
A measurement of the process $pp \to Ht\bar{t}$ using fully hadronic top decays at ATLAS
Measurement of $W\gamma\gamma$ production at ATLAS
Search for $Z\gamma\gamma$ final states and anomalous quartic gauge couplings at ATLAS

2. DIRECT SEARCHES AT THE TEV SCALE

(a) THE HIGGS-TOP SECTOR

The renormalization group equation for the Higgs potential shows an obvious close link between the Higgs sector and its coupling to the top quark [CW1,CW2]. The evolution of the top–Higgs sector from the weak scale to higher scales might be the key to understanding the fundamental nature of electroweak symmetry breaking. Three features dominate the behavior of the Higgs sector between weak and high scales: the Landau pole in the Higgs self-coupling (triviality bound), the stability of the Higgs self-coupling, and the combined fixed point of the Higgs self-coupling and the top Yukawa coupling. In addition, the leading contribution to the quadratically divergent Higgs mass arises from virtual top quark loops [ML5]. This is why in solving the hierarchy problem new physics models typically include a partner for the top quark. All of this points to a need for a thorough analysis of the top quark and its role in electroweak symmetry breaking.

Many models for physics beyond the Standard Model include additional states affecting the Higgs–top sector [TP6]. The properties of top partners for example in supersymmetry, little-Higgs models, or models with extra dimensions are very different. Typical decays of the top partner produce top quarks, possibly in association with a dark matter agent. Again, top reconstruction plays a crucial role in the corresponding ATLAS searches and detailed analysis of such top partner signals [TP2,X19,AS3]. In models with a fourth fermion generation heavy top-like quarks are ruled out or they receive their mass entirely from the Higgs coupling, but heavy vector quarks are still allowed [CW6]. These facets of models that change the extrapolation of the Higgs–top sector to high energies will have a strong impact on unification, which is a research aim of our project 3(a).
(Lindner, Plehn, Schöning, Wetterich)

Potential dissertation topics:

Search for scalar top quarks using fully hadronic boosted top quarks at ATLAS
Search for top pair production in association with missing energy at ATLAS
Search for heavy vector-like quarks decaying to top/bottom quarks at ATLAS
Measuring the properties of a top partner
Living in a meta-stable vacuum?
Rescuing four generations with vector-like quarks

(b) SIGNALS FOR NEW PHYSICS

New physics models might not be obviously linked to the hierarchy problem and testable in top partner searches. One example is the ATLAS search for extra dimensions which solves the hierarchy problem by identifying the fundamental Planck scale with the TeV scale. This means that the LHC will directly probe quantum gravity, for example via the radiation or virtual exchange of gravitons [TP6,X15,SC1,SC4], the production of black holes [SC2,SC3,SC5] or excited string states. Such LHC analyses require theoretical input: first, the usually assumed compactification of the extra dimensions on a torus is only a first guess and, second, all observations should be compared to simulations, that include quantum effects. The further we move from an observable anomaly to the analysis of the underlying physics from observations, the more model details we need to specify.

Another example for model-specific searches are those for squarks and gluinos decaying to missing energy [MD5,MD6,RS4]. More generally, we search for the production of heavy new states decaying to jets plus a weakly interacting dark matter state. This strategy is based on our understanding of multi-jet production or associated multi-jet production, i.e. it follows from project 1(c). An anomaly based on multi-jets can, for example, be analyzed using jet scaling patterns, returning the color charge as well as the mass of the new states [TP1,TP5]. Alternatively, future precision measurements of the W+jets production cross section could also reveal first indirect signs of supersymmetry. The searches for jets plus missing energy can be extended to searches for jets plus a lepton or a photon.

Finally, searches for new resonances decaying to leptons, light quarks, or heavy quarks can also provide first indications for physics beyond the Standard Model. While a Kaluza-Klein graviton signal would point to extra dimensions motivated by the hierarchy problem, an extra gauge boson could be linked to gauge extensions of the Standard Model [AS3], and a low-lying string resonance would imply the most serious modification of TeV scale physics. While to first order these three signals cannot be distinguished, a detailed analysis, for example of the width-to-mass ratio, should reveal that nature of such a resonance, if found [TP6].
(Plehn, Schöning, Schultz-Coulon, Stamen).

Potential dissertation topics:

Search for anomalous sources of mixing E_T in W+jets-like events at ATLAS
Search for new physics in the cross section ratio of W+jet events at ATLAS
Search for a heavy resonance decaying to top quarks at ATLAS
Measurement of the di-jet mass spectrum and search for new physics at ATLAS
Comparing Multi-jet scaling with leptons, photons, and missing energy
High-multiplicity jet events using Sherpa2
Heavy resonances and their width-to-mass ratio

(c) PROPERTIES OF DARK MATTER

Dark matter can be observed at the LHC as missing transverse energy [MD5,RS4,X5]. The lack of a complete reconstruction of cascade decays makes it hard to confirm that an observed missing-energy particle is indeed the dark matter agent. A standard scenario is a Majorana fermion such as the lightest neutralino in supersymmetry. We can test it using consistent models with different spin assignments as alternative hypotheses [TP8]. The alternative interpretation of an LHC signal could be extra dimensions, flipping the spin of all new particles [TP6].

XENON is one of the leading experiments studying the interaction of dark matter with visible matter [ML3,ML6]. Its results have to be combined for example with collider searches and indirect detection. Bringing together these observations is a challenge for phenomenology. It requires a detailed understanding of individual data sets [JK7,JK5] as well as an appropriate combination of orthogonal measurements [JK2,JK6]. In addition, the dark matter annihilation cross section can be constrained by the big bang nucleosynthesis primordial abundances. Vice versa, an observation of dark matter should be confronted with the early universe expansion, where accurate estimates of dark matter densities within the Milky Way and in other galaxies are crucial. Finally, dark matter is usually assumed to be cold, but warm dark matter is not excluded. Instead, it requires different production mechanisms, detection techniques and model building strategies [WR1,X17].

Many properties of dark matter can also be tested through cosmological observations. Masses and abundances of dark matter constituents may depend on the cosmological

evolution, if dark matter interacts directly with scalar fields, or if gravity deviates from standard gravity at large scales [LA6,CW7]. If neutrinos couple to such a field, then neutrino lumps form at red shifts $z \simeq 1$, mimicking dark matter structures [LA2,CW3] and offering new phenomenological ways to test neutrino properties. Alternatively, if dark matter is an ultra-light scalar field, the power spectrum of linear cosmological fluctuations will show a break in the power law corresponding to the Compton wavelength and a modified growth of fluctuations [LA4], similar to gravity modified at large scales. We can search current data like cosmic microwave background, galaxy clustering, or weak lensing [LA5] for these effects and forecast the performance of next-generation large-scale observatories like the Euclid satellite recently approved by the European Space Agency [LA1].
(Amendola, Kopp, Lindner, Rodejohann, Wetterich)

Potential dissertation topics:

Constraints on dark matter from precision tests of the Standard Model
Identifying multi-component dark matter
Cascade decays and WIMP signals beyond minimal supersymmetry
Testing the Majorana nature of the gluino in cascade decays
Neutralinos — Majorana vs Dirac dark matter
Warm vs. cold dark matter in theories beyond the Standard Model
Dark matter annihilation cross section, halo profiles, and early universe expansion
Time evolution of gravitational potential in growing neutrino quintessence
Observing an ultra-light scalar field with weak lensing and galaxy clustering
Effects of interacting dark matter and modified gravity on cosmological observations

3. Towards the Planck scale

(a) Grand Unification in the LHC era

The quest for unification of the three gauge groups and the embedding of the particles in GUT multiplets has been a central theme since the introduction of the Standard Model. Experimental tests of such theories are based on renormalization group analyses starting at the TeV scale. The determination of the new physics particle spectrum at this scale is one of the crucial inputs expected from the LHC. At higher scales additional particles may affect the running of the coupling constants. Eventually, the explicit GUT breaking mechanism influences the pattern as well as the scale of coupling unification. These latter aspects are particularly important for the proton lifetime.

At present, the standard paradigm remains low-scale supersymmetry, where gauge coupling unification works well at the leading-logarithms level. For higher precision, a detailed knowledge of the superpartner spectrum is essential. Given the limited access to TeV scale parameters at the LHC, this is challenging [TP9,X14]. With conventional superpartner spectra we face a one-loop-level discrepancy in coupling unification. It can be cured, for example, by extra light states coming in full GUT multiplets [AH3]. Alternatively, it might find an explanation in high-scale corrections related to the detailed structure of the specific GUT model [AH4,AH5,AH8] or string theory construction [TW2-TW7].

Depending on LHC findings, the GUT paradigm in absence of low-energy supersymmetry may become of dominant interest. In this case, gauge couplings do not unify even at the leading-log level, asking for extra contributions to the running of the couplings, which may be natural in some current string theoretic GUT models. Alternatively, specifically in F-theories tree-level effects may resolve the issue. In contrast to conventional SUSY GUTs, the non-SUSY GUT scale has a significant model dependence. Nevertheless, in certain classes of models one observes a tendency for this scale to be low enough for dimension-6 proton decay to become an issue. This is an interesting challenge to be overcome. The final aim of such analyses is to identify classes of high-scale physics models which are compatible with LHC data [AH1]. (Hebecker, Lindner, Plehn, Rodejohann, Weigand)

Potential dissertation topics:

Upwards renormalization group evolution from LHC observations
Constraints Renormalization group analyses bottom-up — errors and ambiguities
Non-SUSY GUTs: Phenomenology and stringy foundations
LHC implications of the NMSSM with large λ
Gauge coupling unification in F-theory GUTs

(b) COSMOLOGY AND TEV SCALE PHYSICS

The dynamics of reheating and the subsequent thermal evolution of the universe strongly constrain various new physics scenarios. This has been widely discussed in the context of the gravitino and moduli problems. After the end of inflation, a certain amount of energy is deposited in all light degrees of freedom, within the Standard Model and its extensions or in hidden sectors [AH6]. Moreover, the model-independent presence of a de-Sitter temperature during inflation leads to the excitation of all sufficiently light fields.

Our goal is to analyze the complete post-inflationary evolution of the universe in models where the full 4-dimensional effective theory (including higher-dimensional operators and hidden sectors), the perturbations produced by inflation, and the dynamics of reheating are in principle known. Such models exist as global string constructions [TW6,TW7] supplemented by an appropriate string-theoretic inflationary sector [AH2]. The latter sector is constrained by CMB anisotropy and structure formation.
The challenge lies in the complexity of these models. Many interesting features and their experimental constraints need to be accommodated. This includes for example light fields associated with supersymmetry or alternative new physics at the LHC as well as dark matter with the correct couplings and abundance. Various energy scales involved will be strongly interdependent. We can hope to discover unavoidable effects of different observables in particular scenarios or exclude whole classes of models based on these requirements.
For example, recent analyses of nucleosynthesis and CMB data have lead to a renewed interest in dark radiation [AH7,AH9]. The analysis of a possible dark radiation component in the late universe is particularly suited for our global approach, since many string constructions include weakly coupled light or massless fields. Furthermore, if inflation is driven by two or more fields, we expect correlated adiabatic/isocurvature perturbations and possibly non-gaussian components. CMB temperature anisotropies measured by Planck can then reveal the masses and the dynamics of the inflationary fields [LA3]. This can give crucial hints towards the couplings of those fields and the energy deposition during reheating. (Hebecker, Weigand, Amendola)

Potential dissertation topics:

Inflationary constraints on light scalar fields in late cosmology
Dark radiation from string theory
Cosmological constraints on global F-theory GUTs
Correlated non-gaussian inflationary perturbations

(c) FUNDAMENTAL STRUCTURES

TeV scale supersymmetry is one of the most popular solutions to the hierarchy problem. Yet, Tevatron, LEP and LHC data, including the recent Higgs discovery, are consistent with just the Standard Model valid up to very high energies. High-scale supersymmetry, in contrast, is well motivated from the perspective of fundamental physics and independent of future experimental developments. It is conceivable that this tension between weak-scale and high-scale physics will be resolved by a better understanding of mechanisms and scales of supersymmetry breaking.

In a top-down approach starting from a specific ultraviolet completion of the Standard Model, e.g. in terms of an F-theory GUT [TW2,TW6], these questions can be studied and linked to experimental results. Both at the LHC and in the dark matter sector, gravitational and gauge-mediated supersymmetry breaking have measurable consequences [AH3,AH4]. We need to search systematically for such implications of high-scale SUSY on different observations. In particular, a light Higgs boson points towards a specific almost zero value of the Standard-Model quartic Higgs coupling at large energy scales. This can be viewed as a significant constraint on the fundamental theory and motivates a class of high- or intermediate-scale SUSY models with $\tan\beta = 1$ [AH1]. We will work out the phenomenological consequences for the Higgs sector, dark matter and unification. Specifically with a focus on dark matter, the analysis of the string-theory origin of the QCD axion appears to be a promising strategy to relate high-scale SUSY models to experimental data. Another, more theoretical issue is the detailed analysis of the high-scale Higgs mass matrix. This matrix should be calculated explicitly from compactification data and it has to be demonstrated that the required fine-tuning for a small eigenvalue corresponding to a light Standard Model Higgs boson can be realized. (Hebecker, Lindner, Weigand)

Potential dissertation topics:

Phenomenological implications of high-scale SUSY breaking
Higgs physics in non-supersymmetric string compactifications
Gauge mediation with a heavy Higgs from string compactifications
Moduli stabilization and supersymmetry breaking in F theory
Mass spectra in realistic F theory GUTs

1.4 Post-doctoral researchers

We request funding for two rotating post-doctoral positions to retain former doctoral students of the RTG who have worked on structurally important topics to continue for periods of 6-12 months in the groups. This guarantees the transfer of knowledge to the next generation of doctoral students [for more details see Section 4.1.5].

In addition, at least two senior post-doctoral researchers from experimental groups and two from theoretical groups will actively contribute to the research program of the RTG. For complex or very technical analysis topics, it is common to build up analysis teams consisting of a senior post-doc and 3-4 students. Examples for such complex projects are the measurement of A_{sl} in semileptonic B^0 decays, the development and application of top tagging tools and developing the Madgraph Monte Carlo generator. The senior post-docs are responsible for the analysis planing and coordination and discuss the results with the students on a day-by-day basis. Only with this team work and close supervision can competitive analyses be performed on tight time scales, dictated by the conference schedules of the large LHC collaborations.

The senior post-doctoral researchers will also contribute to the qualification program, e.g. help students to prepare the student lectures and participate actively in the annual retreats [for more details see Section 4].

2 QUALIFICATION PROGRAM

2.1 QUALIFICATION PROGRAM

The proposed research training group targets specific opportunities for graduate students working in the broad field of physics beyond the Standard Model in Heidelberg. The program is tailored to the structure of the Heidelberg environment and makes optimal use of it. It builds on the motivation and the communicative skills of our graduate students to use this environment to enhance their education and prospects for a research career. All participants of the RTG are expected to participate actively in the program. It will allow students to

- bridge the gap between the underlying physics questions and their every-day research work and obtain a broad physics education relevant for their future careers by extending their knowledge beyond their thesis projects.
- understand the experimental and theoretical tools and methods relevant to their area of research. This requires scientific exchange between neighboring research areas of the RTG, most notably between the experimental and theoretical research groups.
- present their own research work to a wide range of audiences, ranging from a non-expert student lecture to specialized research seminars.
- make contact with the leading theoretical and experimental experts from all over the world and learn from them in topical workshops.
- build up their own networks starting from contacts to their fellow RTG students.

2.1.1 HGSFP FRAMEWORK

All particle physics doctoral students at the faculty of Physics and Astronomy are members of the Heidelberg Graduate School for Fundamental Physics (HGSFP). The two most important regulations which apply to all of them are:

> Every student is supervised by his/her main advisor and two co-advisors to monitor the progress of the research work. The student decides together with the advisors which lectures and seminars to follow and which conferences and workshops to attend. In this fashion, students follow individualized programs.
>
> Every student is requested to spend a total of at least 16 SWS (weekly hours over one semester) within the three years of his/her thesis work on physics education in Heidelberg. At least 8 SWS should be dedicated to general physics education, while the remainder can be spent on topics close to the person's own research field. This is a minimum requirement. Students in experimental and theoretical particle physics stationed in Heidelberg spend typically a total of 30-40 SWS.

The broad physics requirement is usually covered by the Heidelberg Physics Graduate Days, a very well received key event of the HGSFP. They take place twice a year and consist of one week of block courses. International experts are invited to give introductory or in-depth lectures in the different research directions encompassed by the HGSFP. The students can choose one morning course and one afternoon course out of up to eight lecture series. In addition, the graduate days offer special soft skill courses like project management, time management and presentation techniques. An industry lecture is offered on one evening, enabling interested students to make contact. The students of this RTG are strongly encouraged to participate in this HGSFP program.

2.1.2 Dedicated RTG program

The focus of this RTG is to offer the students a broader perspective on experimental and theoretical aspects of their research project, to encourage exchange between the groups, and, wherever possible, to trigger collaboration among students and researchers from all participating groups. We propose five specific measures spread over the three years of graduate education.

- independent study in interdisciplinary physics teams (early stage)
- student lectures consisting of small lecture series by fellow students (intermediate stage)
- presentation in our established research seminars (final stage)
- student pre-seminars for particle physics colloquia
- annual retreats

All of them will stimulate the exchange between students and researchers participating in the proposed RTG. They provide the platform for scientific exchange, especially between theoretical and experimental groups.

Early stage: Physics teams

Physics teams are the key RTG element in the first three semesters of the doctoral study. Made up of 4 students, half of whom are from experiment and half from theory, the team will spend one term working on a particle physics topic of their choice. Ideally, all students in a team work on different research projects, in order to enhance their knowledge beyond their individual research projects. The aim of the physics teams is to bring students from different research groups, into contact. Currently, some exchange is fostered by personal contacts between individual advisors, but there is no structure guaranteeing or supporting it. The concept of physics teams will formally bring the connections already existing at advisor level down to the students' level.

In particular, students who are at the beginning of their thesis work will benefit from discussions in small student teams. At this stage, students usually focus on building up basic experimental or theoretical knowledge and are not yet directly working on a specialized research topic. These students are highly motivated to study a physics topic in parallel to their every-day work and this way maintain their excitement for continued education and fundamental physics research. During the first half of their three years of doctoral study, the physics teams can trigger research oriented learning through intensive scientific discussion amongst students.

The students themselves will organize the physics teams, their frequent meetings, as well as the topics and format. Possible formats include a follow-up on an advanced lecture, independent studies of advanced text books or review articles, journal clubs based on recent research developments, or tutorials for numerical tools. If needed, the participating researchers or advisors will assist in finding suitable topics and trigger discussions. At the end of each term there will be a half-day seminar where all physics teams report on what they have learned. This outcome should not be a presentable physics result, but a progress report inspiring the other RTG students. A highly desirable effect could be that the students suggest that they continue working on a topic and invite a speaker for a lecture series to one of the annual retreats. In addition to their specific training, the physics teams foster informal communication and networking among the students of the different research areas of the RTG, especially among students from experimental and theoretical research groups.

To illustrate this measure, we give some examples for physics team projects. All of them must include a theoretical as well as experimental aspect and should be of interest for all members of the team:

- Monte Carlo simulations. What are the appropriate Monte Carlo generators for a toy LHC signal-background study? What do theoretical considerations say about differences between?
- dark matter observations. Where do different possible signals of dark matter come from? What theory would they point to? How sensitive are they to astrophysics effects?
- fate of supersymmetry. What do we know about supersymmetry based on direct and indirect searches? How can we accommodate the experimental situation in different models of supersymmetry breaking?
- non-WIMP dark matter. What are alternative scenarios describing cosmological observations? What is their field theoretical background? What are possible signals in ongoing experiments?
- renormalization group evolution. How can we link high-scale Lagrangian parameters to experimental measurements? What are the available numerical tools? For supersymmetry vs mSUGRA/CMSSM, this could include a tutorial on the public SoftSUSY tool.

These examples should illustrate how physics teams can fulfill their multiple goals: communication with other fields of particle physics, an active involvement in physics at the beginning stage of the doctoral project and transfer of knowledge beyond the scope of their own research topic.

INTERMEDIATE STAGE: STUDENT LECTURE

In a weekly lecture the students participating in the RTG present their own research field and work. All students are required to be present in these lectures until they move into their final phase of writing their thesis. Faculty or post-docs should stay in the background so as not to interfere with open discussions among the students. The student lecture will give all students the opportunity to learn about the open questions and methods in other branches of the RTG. This lecture will fill the gap between the focused physics teams and the very broad program offered by the HGSFP. It covers the whole range of particle physics from theoretical students working on string theory to experimental students developing flavor tagging tools as part of a new physics search.

The lecture will be held by students in the 4th or 5th semester of their doctoral studies. After the physics teams phase the students should have a good idea about the level of such an introductory lecture to their peers. To explain their own research field to a broad audience requires a solid understanding of the underlying physics concepts and the overall context. In many oral thesis defenses we have realized that students who have delivered excellent work in their thesis project sometimes miss the broader view on their field, simply because they have never taken the time to study it. These lectures will be part of a training for oral doctoral examinations as well as for job interviews.

Every student will prepare a short series of lectures (3×60 minutes) on his/her research field. The main advisor will closely supervise the preparation both in view of the scientific and the didactic aspects. Ideally, the student will have attended a training course on presentational skills, frequently offered by the HGSFP as part of the graduate days. The first two of the three one-hour lectures should be spent on a pedagogical introduction of the research field to all RTG students. The third and final lecture can be spent on the specific research project, but should still be aimed at a broad audience of fellow particle physics students. Such a lecture series will benefit the speaker as well as the audience. Around the end of the second year of their research project students should present the specific basis of their physics problem, instead of simply postponing these aspects to the thesis writing. The material collected in preparing this lecture will often serve as the basis of the introductory part of a doctoral thesis.

Aside from the obvious benefit to the student audience this lecture will benefit the speakers in two ways: an early confrontation with the broader basis of their thesis project and a solid training in didactic presentations in the more collegial student environment.

Final stage: Research seminar

After 5 semesters participating in physics teams and teaching in the student lecture the final step of our program will be a research talk in one of our established seminars, for example the theoretical Teilchentee or the Teilchenkolloquium. At this stage the students should be in a position to present their work to an expert audience. The training program, especially the student lectures, are an excellent preparation for this talk in the final year. We expect our students to give talks comparable in quality to the national and international speakers whom we usually invite to these seminars.

The research seminar will be prepared in close collaboration with the thesis advisors. It serves as a direct preparation for a part of the oral thesis defense, for presentations at large international conferences, and for job interviews as part of a post-doctoral application. Its didactic aspects should benefit from the experience during the student lecture, and its broader content should be enhanced by the network built as part of the physics teams.

Student pre-seminar

The standard weekly program for all students in experimental particle physics includes the Teilchenkolloquium, while all students in theoretical particle physics attend the Teilchentee. Particularly in the early phase of the doctoral studies many of the research talks go beyond the physics knowledge and technical abilities of most students. Our goal is to make excellent research seminars, usually given by internationally leading experts, more accessible to doctoral students.

We propose to arrange for a 30-minute student pre-seminar before the actual research seminar takes place. This talk will ideally be given by the speaker, but can also be covered by a local faculty member. No staff members will be present in this introduction, so the speaker can focus exclusively on needs of the students. Content and format are entirely in the hands of the speaker and the audience. For example, a speaker can use the introductory slides of the research seminar and a blackboard for a pedagogical introduction to some of the topics that will be covered in the actual talk. Alternatively, a speaker can trigger questions from the student audience and discuss them at a suitable pace. Many of our speakers work at universities and will be able and enjoy to give such a presentation. If required, a pre-seminar will be covered by the RTG scientists in coordination with the seminar speaker.

In addition to the improved engagement of students in research talks, another benefit of such a student pre-seminar is the relaxed interaction between the speaker and our students. This way the speaker can trigger physics excitement in the students without having to focus on the faculty audience at the same time. Student pre-seminars are standard tools to attract students to the seminars of the quantum optics group of the PI and of the Sussex physics colloquium. We are currently considering introducing them to the main Heidelberg physics colloquium, but in that case aiming at a much younger audience.

Annual Retreats

physics teams	semesters 1-3
student lecture (attending)	semesters 1-5
student lecture (teaching)	semesters 4-5
research seminar	semester 6
student pre-seminar: Teilchentee/Teilchenkolloquium	semester 1-6
annual retreats	semester 1-6

Table 1: Courses and activities offered by the RTG, assuming a 3-years doctoral program.

Several of the groups involved in this proposal have established annual retreats as a useful measure to get focused input on a dedicated topic, to encourage discussion between different research groups, and to strengthen the team spirit of the group. For example, the Heidelberg LHCb group organizes an annual 3-day B physics workshop together with other experimental and theoretical flavor physics groups in Germany since 2007. The ATLAS groups at the KIP and the PI started to organize a yearly common analysis workshop. The HGSFP offers an annual winter retreat, organized by the students, which enjoys great popularity with our students. Building on these successful experiences, we propose to organize one such retreat for each of the three main topics of the RTG per year.

The retreats will be organized in close collaboration with the students. They will contain introductory lectures as well specialized talks by renowned national and international experts. All students are expected to participate in one of these retreats in the first two years of their thesis project. These retreats will be organized by at least two participating research groups, for example ATLAS and LHCb, LHC phenomenology and ATLAS, or string theory and cosmology. As is the case for the annual flavor physics workshops, that were already mentioned, the aim is either to strengthen the connection of the groups involved or to bring in external knowledge not covered by our participating scientists.

Beyond RTG activities

In the environment generated by the five measures described above we expect scientific exchange far beyond the organized activities. We are optimistic that common research projects will evolve out of these discussions. The students should be trained for an open-minded scientific discourse, to prepare them for their future careers in fundamental science and beyond. We summarize the main RTG activities in Table 1. These courses, seminars and workshops are organized in turn by the participating scientists of the RTG, if appropriate by one scientist from experimental and one from theoretical particle physics.

2.1.3 Established Heidelberg courses

Heidelberg Physics Graduate Days

As mentioned above, the HGSFP offers block courses on general physics topics twice a year. The program of recent years can be found under
`gsfp.physi.uni-heidelberg.de/graddays/index.php?m=9`

Standard Particle Physics Lectures

Several advanced master-level lectures are regularly offered by the participating scientists and associated members of the proposed RTG. These include

- Detector and accelerator physics
- Physics at the LHC
- Statistical methods of data analysis
- Quantum field theory 1 + 2
- Cosmology
- Standard Model of particle physics 1 + 2
- Higgs physics/QCD at the LHC
- String theory
- Recent LHC results (master seminar)

Most of our doctoral students have followed a significant fraction of these lectures during their master studies. If not, they are encouraged to sign up for one or two lectures during their doctoral program. Similarly, a selection of these lectures can be required for incoming doctoral students who lack a similar specialization on particle physics. We are strongly engaged in providing such advanced lectures to attract the best students and prepare them for a thesis project in our research groups and in the RTG.

A few of the advanced lectures have been taught together by experimentalists and theorists. They are particularly popular with the students. This can be seen in the high attendance as well as by the number of bachelor and master students recruited for theses in particle physics. Examples are the annual course on the Standard Model (last term taught by Andre Schöning and Werner Rodejohann) and the seminar on recent LHC results (last term taught by Tilman Plehn and Ulrich Uwer). The participating researchers of this RTG aim to increase co-teaching between different fields. A lecture on Higgs physics by Hans-Christian Schultz-Coulon and Tilman Plehn is planned for the Fall of 2013. We expect many more suitable co-teaching lectures to be triggered by the proposed RTG. Co-teaching at the master level allows students to realize that particle physics is more than a collection of separate research areas and that communication is essential to tackle the urgent questions at the current forefront of research.

2.1.4 EXAMPLE STUDY PLAN

In addition to a comprehensive qualification program, it is important to allow sufficient time to exercise the acquired skills independently of the formal program. To illustrate the average lecture/seminar load foreseen for the students of this RTG we show one example study plan in Table 2. The overall load is well above the minimum requirement of the HGSFP (16 SWS) but within the usual range for doctoral students in experimental and theoretical particle physics. Because the measures are modular the students can combine their preferred courses and have as well the freedom to adapt their individual load. The choice of courses is discussed with and monitored by the three thesis advisors. Students stationed at CERN or at another university or research centers are expected to follow seminars and lectures at their host institutes, so they are exempt from the RTG program while absent. Lectures taken during Summer/Winter schools will also be credited to the student course account.

semester	course/activity	work load
1	physics team student lecture 2 courses at graduate days	2 SWS 1 SWS 2 SWS
2	physics team student lecture retreat	2 SWS 1 SWS 2 SWS
3	physics team student lecture Teilchenkolloquium/Teilchentee + pre-seminar	2 SWS 1 SWS 2 SWS
4	student lecture, 3 x 60 min Teilchenkolloquium/Teilchentee + pre-seminar retreat	3 SWS 2 SWS 2 SWS
5	2 courses at graduate days student lecture Teilchenkolloquium/Teilchentee + pre-seminar	2 SWS 1 SWS 2 SWS
6	Teilchenkolloquium/Teilchentee with talk	2 SWS
sum		29 SWS

Table 2: Example study plan of an RTG student.

2.1.5 TRANSFER OF KNOWLEDGE

When it comes to particle physics tools which are crucial for thesis projects, for example complex fitting frameworks, reconstruction techniques, or Monte Carlo event generation, it is important that this expertise gets transferred from one generation of students to the next. However, doctoral students in their last year are frequently too busy with finalizing their analysis and writing their thesis, so they cannot spend much time on instructing new students. Therefore, we propose to offer post-doctoral positions to structurally vital doctoral students for a period of 6-12 months after graduation. This way, the younger students can benefit optimally from existing knowledge in and around their research groups.

The topics we will target with a post-doc extension will typically be comparably technical or complex. The career of the post-docs/former doctoral students working on these topics can profit significantly from these extensions as well. For theorists, highly technical topics often mean that a post-doctoral application one year before graduation might not yet be supported by the necessary publications. In large experimental collaborations, the time required by the internal review processes of complex analysis, even if they are essentially ready for publication often exceeds a few months. The corresponding young researchers will thus benefit hugely from some extra time to gain visibility, finalize their publications, transfer their technical knowledge, and prepare a post-doctoral research plan.

This two rotating post-doctoral positions will actively contribute to our qualification program. The former RTG students are directly embedded in the research groups and have successfully passed the qualification program themselves. They naturally serve as the first contact for younger RTG students. This includes finding appropriate topics for the physics teams and for the student lectures. Based on their experience they can suggest speakers for the retreats or visiting guest scientists or even give talks at retreats themselves. We therefore expect the young post-doctoral fellows to significantly enrich our qualification program.

2.1.6 Future professional avenues

Students graduating from the proposed RTG program will be very well prepared for future careers inside and outside of academia. Our focus on a broad research education as well as teaching and presentational skills should be attractive to a wide range of possible employers. Typical avenues in fundamental research include post-doctoral positions at leading international universities, Marie-Curie fellowships, or fellowships at high-energy laboratories like CERN, DESY, Fermilab, or SLAC.

To foster communication with regional non-academic employers the Heidelberg physics department organizes regular meetings (Rhein-Neckar-Gesprächskreis) between local companies and our research groups. The key element of this meeting are presentations by our research groups and industry partners. They have been shown to stimulate exchange and give the students an idea of work and positions outside academia. In addition, the meetings foster contacts with potential future employers. After passing the extensive training in non-expert presentation the RTG students should stand out amongst the other participants in these meetings.
The Heidelberg Physics Graduate Days offer another series of industry lectures for graduate students, aiming to give students an overview of possible positions outside academia.

2.2 Visiting researchers and Mercator fellows

In our experience doctoral students profit hugely from visiting scientists, in particular when they stay in Heidelberg for a longer term. Meeting senior scientists as long term visitors allows our students to approach them informally, discuss physics, develop common interests, and finally work on a project together.

At the ITP the Jensen Professorship, funded by the Klaus Tschira Foundation, has been a major success. Unfortunately, it will terminate soon and cannot be renewed. It funds visitors for roughly three to six months, allowing us to invite faculty members from abroad for sabbatical stays. For example, in 2011 and 2012 Stefan Theisen (MPI for Gravitational Physics, Golm) and Valery Rubakov (Academy of Sciences, Moscow) visited the ITP for several months. In 2012 we were able to attract Markus Luty (UC Davis) for a full sabbatical stay in competition with SLAC. In late 2012 Rocky Kolb (Chicago) visited our cosmology group for two months. In 2013 we will host Peter Richardson from the IPPP Durham, one of the lead authors of the Herwig event generator. Such visitors make a great difference to our students, influencing their interests as well as their future post-doctoral careers.

While Heidelberg has no problem attracting these fellows, funding is an issue. We propose a visitor program for top-level faculty members with an active research program from abroad and with a clear focus on the benefit to our doctoral students. The RTG students will therefore be encouraged to propose candidates and will be involved in the selection procedure. All visitors will be asked to stay in Heidelberg for 3-6 months and encouraged to give a set of informal lectures on a topic of their choice. Candidates which bridge two or more groups participating in the RTG will be preferred, ideally benefiting theory and experiment and this way expanding on the success of the Jensen Professorship program. Two types of top-level Mercator fellowships should be combined:

1. Mercator fellows who come to Heidelberg for one to three months, if possible repeatedly. The RTG covers their travel and local expenses of about 2.000 Euros/month.
2. Mercator fellows which come to Heidelberg for a sabbatical stay of at least three months. For example for faculty members from the US we need to offer them a W3 salary to cover their reduced sabbatical salaries. Similarly, UK faculty members can take unpaid leave from their home universities to spend a term at Heidelberg, provided we offer them a W3 salary.

Which of the two funding schemes would be more appropriate needs to be determined together with the potential visitors. In some cases, we might be able to submit a proposal for a Humboldt Research Award or a Bessel Research Award to replace the Mercator fellowship. Candidates for such visits are Alexander Lenz (Durham) or Yossi Nir (Weizmann) in flavor physics. In LHC simulations we have key authors or the leading Monte Carlo tools in mind, like Peter Richardson (Durham) or Fabio Maltoni (Louvain la Neuve). In broad phenomenology we would consider Sally Dawson (Brookhaven), Carlos Wagner (Argonne/Chicago), Kaoru Hagiwara (KEK), or Jay Wacker (SLAC) as high-impact visitors. Experts on new physics models at higher scales include Valya Khoze (Durham), Graham Kribs (Oregon), Ben Allanach (Cambridge), John March-Russell (Oxford), Tony Ghergetta (Melbourne), or Matthew Kleban (NYU/IAS). Related to dark matter we would contact for example Mihoko Nojiri (IPMU), Simona Murgia and Tim Tait (both Irvine). Towards gravitational research and cosmology Shinji Tsujikawa (Tokyo) would be an excellent candidate.

2.3 Additional qualification measures

We encourage our students to attend international schools like the CERN summer schools, the Scottish summer school on particle physics, the Cargèse school, the Princeton school, or TASI. These schools provide excellent lectures and tutorials from world leading experts. As importantly, they allow the students to establish international networks with other graduate students. For example the annual TASI school in Boulder/Colorado has been a defining moment in many young researchers' careers and has served as a stepping stone for an international career.

Depending on the research topic it can be fruitful to spend several weeks as a visiting scientist at another institute. An example would be to finalize a paper in collaboration with scientists from another institute or to start a new common research project.

We therefore request funding to support schools and costs for short-term visits at other universities or research centers for the students participating in this RTG.

2.4 Rules of good scientific practice

The Heidelberg university has formulated their rules of good scientific practice.

`www.verkult.uni-heidelberg.de/sicherung-guter-wissenschaftlicher-praxis_en.html`

Before signing their contract every scientific employee of the university, including graduate students and post-doctoral researchers, is instructed in detail how to apply theses rules and whom to contact in case of observation of any violation.

In the early education of students the rules of good scientific practice are discussed when the students do their first own scientific work, thus at the beginning of the lab courses and seminars. During their work on their bachelor and master theses all students are specifically trained on how to apply the rules of good scientific practice.

We expect all our graduate students and post-doctoral fellows to be well informed and thus plan no dedicated courses on this topic for the moment. Together with the HGSFP, we will monitor the awareness of the rules among the members of this RTG and react accordingly in case any concern arises.