natures (e.g., particle masses, reaction rates, etc.) are duly noted. The theoretical particle physicists at the MPIK are dealing with the interpretation of measurements at particle accelerators, observations from astrophysics, neutrino experiments and experiments concerning the lepton-flavour violation. The latter means certain decay reactions of leptons that do not exist in the Standard Model, but play an important role in a number of its extensions.

Title: Feynman diagram of a lepton-flavour violating process (actively searched for), in which a muon is converted to an electron and a photon. The background shows the ATLAS detector at the LHC in Geneva during its construction phase. This experiment helps to elucidate the nature of "physics beyond the Standard Model".
Theoretical Elementary Particle Physics beyond the Standard Model

Tracing the Secrets of Matter

The “Standard Model” – the established theoretical framework for the description of the behaviour of the elementary particles – is increasingly reaching its limits. Therefore, the development of new, more comprehensive theories is one of the biggest challenges for theoretical particle physics. For example, these theories should be able to reduce the fundamental forces of nature down to a common origin, to explain the unusual properties of neutrinos, and to account for the existence of Dark Matter in the Universe.

The Standard Model

The Standard Model of elementary particle physics, developed in the 1970s, describes the behaviour of all known elementary particles with impressive accuracy and it all traces back to the relatively simple mathematical laws within the formalism of quantum field theory.

Symmetry groups play a particularly important role in this context. A certain class of mathematical transformations that leave the observable phenomena unchanged is called a symmetry group.

Besides the three generations of quarks and leptons, the Standard Model also contains the gauge bosons (photons, gluons, W- and Z-bosons), which mediate the interactions between the quarks and leptons. An electromagnetic interaction between two particles may, e.g., be regarded as the exchange of a photon. However, the most mysterious particle within the Standard Model is the Higgs boson, which forms a condensate filling the whole Universe just like the Cooper pairs in a superconductor. The motion of all other particles is influenced by this condensate which is how the particles gain their mass. This process is termed spontaneous symmetry breaking.

Despite its success, the Standard Model leaves some open questions, e.g.:

- Is it possible to further simplify the mathematical structure of the Standard Model?
- Why do the parameters of the model (e.g., the particle masses) exhibit certain patterns? Can their values be predicted?
- How are neutrino masses generated?
- What does Dark Matter in the Universe consist of?
- Why isn’t there the same amount of antimatter as matter in the Universe?
- How can gravitational interactions be described in terms of particle physics?

Particle theorists expect that many or even all of these questions may be answered by a theory beyond the Standard Model at a higher energy scale.

Novel Concepts in Particle Physics

In an effort to eliminate the deficiencies of the Standard Model, novel theoretical concepts have been developed. The scientists at the MPIK are focusing their work on the following topics:

The Higgs Boson and the Hierarchy Problem

The discovery of the Higgs boson at the Large Hadron Collider at CERN in 2012 completes the Standard Model. Nevertheless, many questions related to its properties remain open. One of them is the so-called hierarchy problem; this is the question of why its measured mass is smaller by many orders of magnitude than the energy scale of the above-mentioned new physics.

Neutrino Masses

Experiments investigating neutrino oscillations (the conversion of one neutrino flavour into another) unambiguously demonstrate that neutrino masses are not zero. However, these masses are smaller than the masses of all other known elementary particles by many orders of magnitude. This can be explained, for example, by the so-called “seesaw mechanism”, where very heavy additional neutrinos (see the particle zoo in the figure) are responsible for the tiny masses of the neutrinos.

Supersymmetry

There are strong theoretical arguments for the assumption that the Standard Model of particle physics possesses still further symmetries besides the known ones. In particular, the supersymmetry plays an important role in modern theoretical particle physics. In supersymmetric models, there is a superpartner for every type of particle which differs from it merely by its spin angular momentum.

Flavour Symmetries

The Standard Model does not provide an explanation for why there should be exactly three generations of massive particles. Additionally it does not answer the question of why the masses of the particles exhibit certain patterns. Because of the great importance of symmetries in the Standard Model, it is reasonable to expect that arguments invoking symmetries may also play a role in understanding the pattern of particle masses and the generational structure. Such new symmetries are called flavour symmetries.

Grand Unification

Another possibility to reduce the Standard Model to a still more elegant and comprehensive theory is offered by the grand unification. It has the goal of tracing all the interactions of the elementary particles – namely the electromagnetic, weak, and strong nuclear forces – back to a common origin, the grand unified force.

Experimental Observation of the Physics beyond the Standard Model

An important aspect with regard to the developments of novel particle physics models and formalisms is their experimental verifiability. For each hypothetical model, predictions are worked out carefully and unique experimental sig-