## 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.

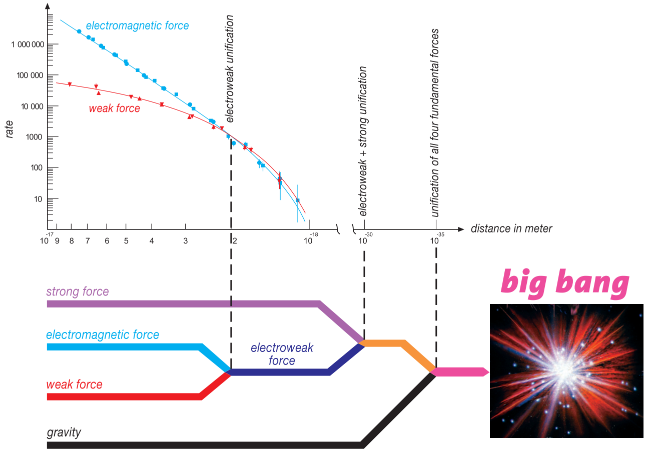



*Illustration of grand unification. State-of-the-art particle detectors reach a resolution of approximately $10^{-18}$ m and thus penetrate into the region where the common origin of the electromagnetic force and the weak nuclear force emerges. Regions of higher energies are mainly accessible by theoretical considerations. (DESY press archive)*

## Experimental Consequences of New Physics

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 signatures such as particle types, their masses, reaction pathways and rates are calculated. The theoretical particle physicists at MPIK include in their studies all existing results of measurements at particle accelerators, experiments in neutrino physics and about Dark Matter, as well as results from astroparticle physics and cosmology. The close interplay between theory and experiment shows whether specific theories are compatible with the data, and vice versa, experimental search strategies result from it.


*Contact:*

Prof. Dr. Dr. h.c. Manfred Lindner
Phone: 06221 516800
Email: manfred.lindner@mpi-hd.mpg.de

Dr. Werner Rodejohann
Phone: 06221 516824
Email: werner.rodejohann@mpi-hd.mpg.de

Dr. Florian Goertz
Phone: 06221 516822
Email: florian.goertz@mpi-hd.mpg.de



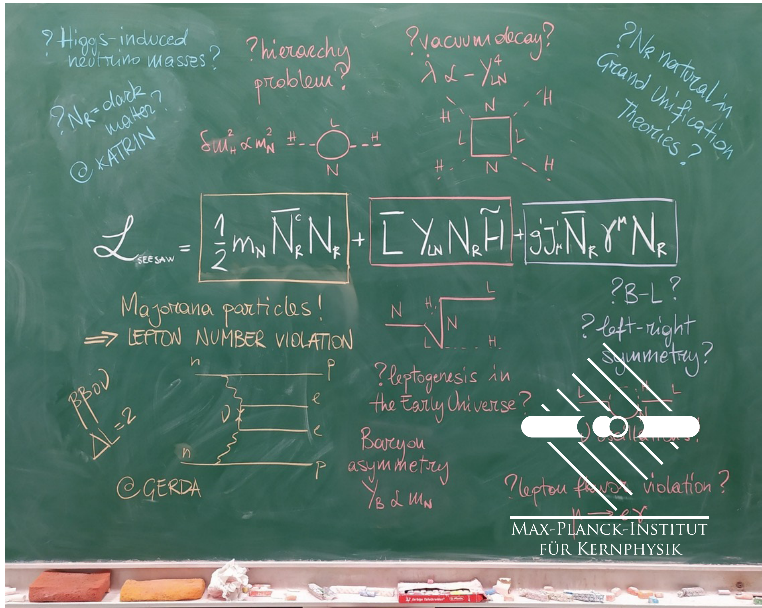
MAX-PLANCK-INSTITUT FÜR KERNPHYSIK HEIDELBERG

**Saupfercheckweg 1**
**69117 Heidelberg**

**www.mpi-hd.mpg.de**

The Max-Planck-Institut für Kernphysik (MPIK) is one of 86 institutes and research establishments of the Max-Planck-Gesellschaft. The MPIK does basic experimental and theoretical research in the fields of Astroparticle Physics and Quantum Dynamics.


# Theoretical Elementary Particle 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. New theories should be able to reduce the fundamental forces of nature down to a common origin, to explain the unusual properties of neutrinos and the Higgs boson, and to account for the existence of Dark Matter in the Universe. The goal is to understand what holds together the world in its innermost.*

## 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 matter particles formed from 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, for example, may 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 the other particles is affected 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?
- How can gravitational interactions be included?
- Why do the parameters of the model (e. g. 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?

## 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 new physics. There are several possible solutions of the hierarchy problem: extended models with supersymmetry, in which a superpartner is added to each particle, with conformal symmetry, in which no fundamental mass scale exists, or scenarios, in which the Higgs particle is a composite state bound by a novel strong interaction. Such ideas are investigated and developed further at MPIK.

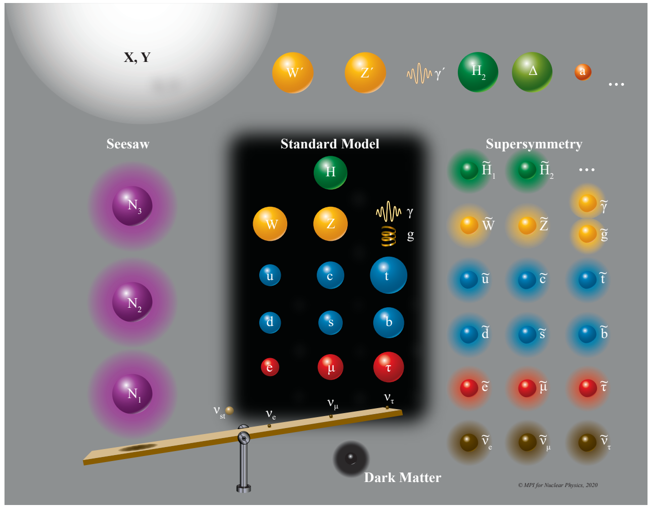
Since many of the open questions of the Standard Model are connected with the Higgs sector, being able to examine its properties directly in collider experiments offers a unique window to a more fundamental theory. Among the most important, not yet experimentally tested properties in this context are the interactions between the Higgs bosons among themselves, which for example are important for the understanding of the matter-antimatter asymmetry in the Universe, or the deeper dynamics behind the Higgs sector of its own.

## Neutrinos and New Physics

Contrary to the predictions of the Standard Model, neutrinos posses a mass differing from zero. This has been demonstrated unambiguously by experiments investigating neutrino oscillations, i. e., the conversion of one neutrino flavour into another. This proof of physics beyond the Standard Model implies a variety of questions. The conversion of the neutrinos is enabled by surprisingly large "mixing angles", whereas the corresponding angles in the quark sector are very small. The origin of this discrepancy may be better understood by precision measurements of the neutrino parameters.

A number of mechanisms may be responsible for the generation of the tiny neutrino masses, for example, by the so-called "seesaw mechanism", where very heavy additional neutrinos (see the particle-zoo figure) play a central role. These can couple to other particles such as the Higgs boson, or influence the development in the early Universe. In addition, they imply that the neutrinos are so-called Majorana particles which lead to processes violating the lepton number. These interesting cross-relations provide the clue to understand the mechanism behind the generation of the neutrino mass.

Moreover, many theories predict novel interactions of the neutrinos. Their verification may succeed, for example, by the production of new particles in the LHC or by measurements of neutrino interactions at particle accelerators.




## Particle Flavour and Number

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. So-called flavour symmetries could provide an explanation. Further, the Standard Model contains a number of conserved parameters. For example, the number of leptons and baryons (heavy particles consisting of three quarks, e. g. the proton or the neutron) is conserved in particle reactions, or certain decay processes of leptons are forbidden. Extensions of the Standard Model regularly lead to observable violations of these principles.