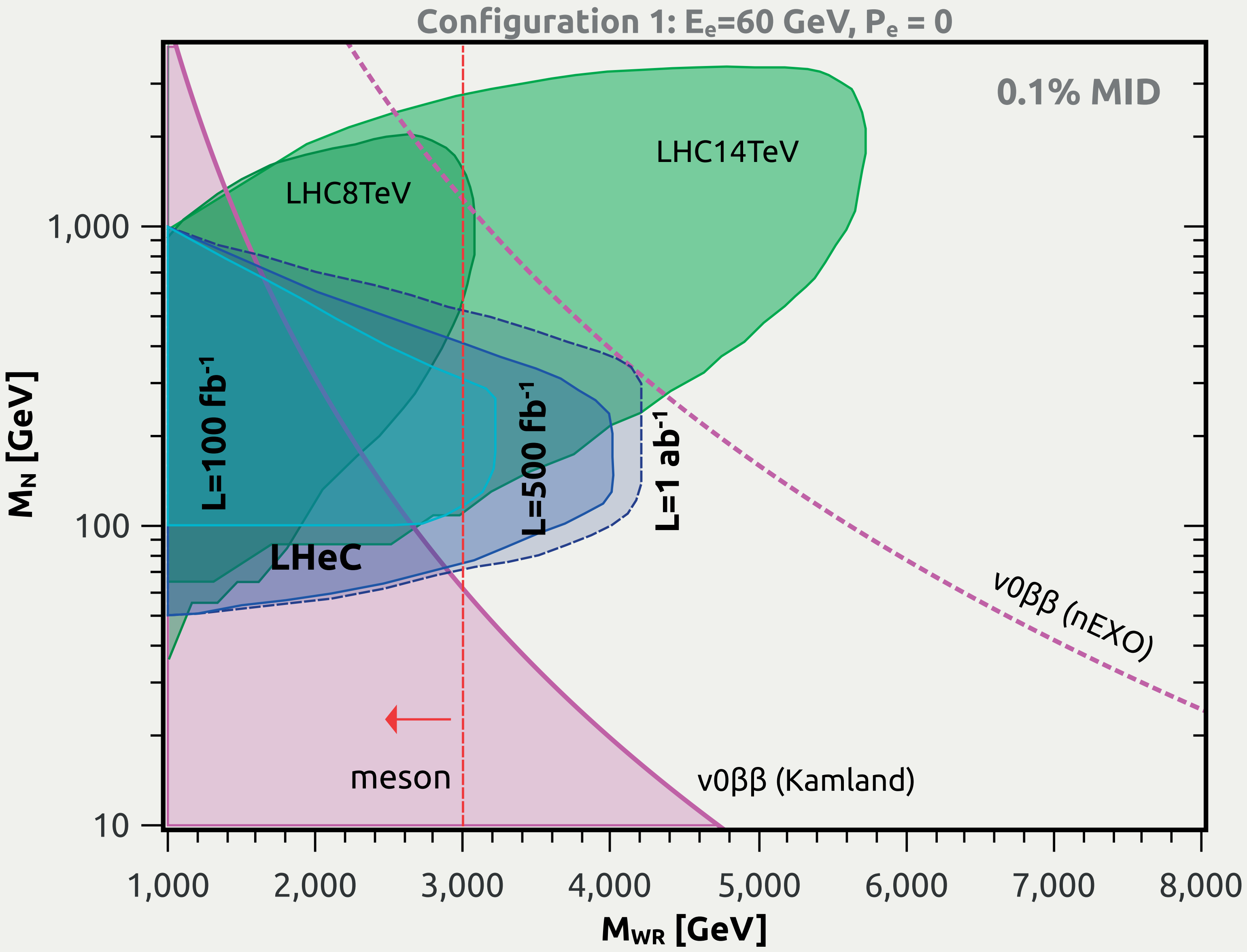

1.6 Physics beyond the Standard Model

Parameter space of right-handed neutrino and W_R mass as reachable by the LHC and the LHeC. The regions constrained by neutrinoless double beta decay experiments and meson oscillations are also shown. From [3].

Introduction

The Standard Model (SM) of particle physics is very successful in describing subatomic physics. A number of experimental and theoretical reasons are, however, known which strongly point to the fact that the SM is incomplete and that at some higher energy it must be embedded into some new theory. The experimental facts beyond the SM are finite neutrino masses, the baryon asymmetry of the Universe and the existence of Dark Matter (DM). On the theory side, there exists in addition a whole list of arguments pointing in the same direction. Various aspects concerning new physics beyond the Standard Model were therefore studied in the reporting period, applying very different viewpoints and methods to test the ideas.

New Physics at Colliders

The Large Hadron Collider (LHC) provides unprecedented energies to probe the existence of new particles from theories beyond the Standard Model. Moreover, it is the only direct way to probe properties of the Higgs boson. As the Standard Model can't be the final description of nature at fundamental scales, there must be new physics, possibly in reach of the LHC's centre-of-mass energy of currently 13 TeV.

Theories beyond the Standard Model (SM) always predict new particles of all types, fermions, scalars or bosons. In particular left-right symmetric theories, a very elegant and natural extension of the SM, predict three new gauge bosons, require for consistency right-handed neutrinos, and for successful breaking to the SM depend upon new scalar Higgs particles.

Among the three gauge bosons the neutral Z' can be easily looked for, as its decay produces two opposite-sign leptons ("dileptons"). The two charged gauge bosons denoted W_R are more difficult to look for as their decay produces two jets or a charged lepton and a neutrino which escapes undetected. However, in standard left-right symmetric theories the W_R is lighter than the Z' by a fixed factor of about 1.7, and if the mass limit of the W_R is translated into a Z' limit with the help of this factor, it turns out that direct Z' limits are weaker. However, it was noticed that if the gauge couplings of the left- and right-handed interactions are different, or if the left-right symmetry is broken in a different way, the Z' can in fact be much lighter than the W_R. In this case, dilepton data provides the best constraint on left-right symmetric theories [1]. Moreover, the dilepton limit on the Z' can be translated into a limit on the lifetime of neutrinoless double beta decay.

It was also shown how such theories can accommodate various anomalies in the data, such as hints for resonances at about 2 TeV in the di-electron + di-jets channel.

Assessing the sensitivity of future hadron colliders to the scalar sector of left-right symmetric models, it was concluded that the heavy Higgs sector can be effectively probed up to 15 TeV with a 100 TeV proton-proton collider [2].

A different method to probe new physics is provided by the proposed Large Hadron Electron Collider, which would collide electrons with protons. As the electrons can be polarised, it provides an excellent opportunity to test the right-handed nature of the interaction in left-right symmetric theories. It was shown [3], using different potential configurations of the LHeC, that right-handed neutrinos up to masses of 1 TeV and W_R up to 5 TeV are reachable, and that the testable parameter space is complementary to the one of the LHC and of neutrinoless double beta decay. The usually neglected electron misidentification was demonstrated to be an important source of background. Nevertheless, the LHeC is not only a precision machine, but also has the potential to be a discovery machine.

Regarding properties of the Higgs particle, hints of nonstandard decays into muons and taus were interpreted. Moreover, within models containing a very light scalar particle coupled to the Higgs boson, its decay into three of these light scalars was studied. Model-independent conditions which the scalar sector after electroweak symmetry breaking has to satisfy in order for the three-body channel to become relevant exist, and were shown to allow for scenarios in which the rates of scalar three-body Higgs decays are comparable to or even exceed those of the well-studied two-body channel. Such three-body Higgs decays can lead to exciting new collider signatures with six SM fermions in the final state, and it was demonstrated that e. g. six-muon or six-tau final states may be in reach of dedicated searches at the LHC or ILC experiments [4].

Lepton Flavour Physics

In the quest for the high-energy completion of the Standard Model (SM) of particle physics, it is vital not only to look for direct signatures of new physics at colliders. Instead, one should also study the effects which currently inaccessible physics might have on low-energy observables. The persisting absence of new physics at the LHC indicates that new physics may live at much higher energy scales than current experiments can access. Therefore, one could think of such low-energy measurements as being our telescope to get a glimpse of what comes far beyond the SM.

A prime example of such an observable is the decay of one charged lepton into another, lighter charged lepton of a different 'flavour' plus a photon that carries away the difference in energy. Although such decays are strictly forbidden in the SM, they are expected to occur at a tiny rate due to the nonzero mixing of neutral leptons, as manifest in neutrino oscillation experiments. For the SM muons, taking into account this effect only, one expects a branching ratio of roughly 10^{-55}. This negligibly small number is readily enhanced by augmenting the field content of the SM yielding typically sizeable contributions to the branching fraction. As an example, we have studied the implications of lepton flavour violation (LFV) on a model of loop-induced neutrino masses and dark matter. Neutrino masses are generated radiatively by one-loop processes involving new fields, while the dark matter candidate is the lightest neutral particle among them. The conclusion of this analysis is that neither collider searches, nor direct or indirect detection of the dark matter candidate give considerable constraints on the parameter space. Instead, LFV is a promising observable for the verification or falsification of this setup. Future $\mu \to 3e$ and μ-e conversion experiments, in particular, have the potential to probe the entire viable parameter space of this model.

On the other hand, the very same amplitude that enhances the LFV decay described above will contribute to the leptons' magnetic moments. From quantum mechanical considerations, one expects the magnetic moment of an elementary fermion to be enhanced by a factor of $g = 2$. However, loop corrections to this g-factor, calculable in quantum field theory, shift its actual value away from 2. The measurement of the electron's so-called anomalous magnetic moment $(g_e - 2)$ has lead to the most precise measurement in the history of modern physics: the determination of the electromagnetic fine structure constant with a precision better than one part in a billion.

A similar effort is undertaken to measure the muon's anomalous magnetic moment $(g_\mu - 2)$. Previous experiments indicate a slight deviation of the measured $(g_\mu - 2)$ from the SM prediction with a statistical significance of about 3.3σ. However, it remains unclear whether or not this is due to new physics, or some not yet fully understood hadronic contribution. In the case that this excess prevails in future experiments, and the errors on the hadronic contributions are under control, we may be facing a new era in particle physics. As previously stated, both phenomena – LFV decays and the $(g-2)$ – are intimately correlated. While the latter seems to indicate the presence of new physics, the former tightly constrains many theories beyond the SM as recently reviewed in Ref. [5]. In this reference it was shown that, if the upcoming experiments should verify the new physics origin of the anomaly in $(g_\mu - 2)$, many popular models also predict a signal for LFV. Conversely, if this anomaly is resolved otherwise, e. g. by hadronic uncertainties, the high accuracy of the $(g_\mu - 2)$ measurements will give important constraints on LFV. In either case, any potential signal must be reconciled with all available constraints and thus, it is of great interest to the high-energy physics community to have these tools ready when a positive signal is observed. In the meantime, more theoretical work is needed, extending existing analyses to other LFV decays, such as $\mu \to 3e$ or muon-electron conversion in nuclei, and furthermore including constraints due to, e. g. dark matter, neutrino physics, and collider searches.

Hierarchy Problem

One of the most severe theoretical problems in particle physics is the so-called hierarchy problem of the Higgs boson mass. It was discussed and studied long before the discovery of the Higgs particle. However, as the LHC has confirmed the existence of the Higgs field the question why its mass is relatively small, in comparison with other scales we expect to exist in nature, becomes more pressing than ever. For a long time Supersymmetry (SUSY) was the most popular attempt to solve the hierarchy problem and other way around the hierarchy problem is the strongest argument for low-energy SUSY. However, as the LHC cuts deeper in the SUSY parameter space without any hints for the existence of this theory, other approaches are needed.

An often used explanation which has been explored is based on the idea that no explicit mass scales exist in nature, but are rather spontaneously generated by dynamic processes. The symmetry forbidding explicit mass scales is called conformal symmetry.

Starting with this assumption, that the theory must not contain any dimensional parameters, different methods have been studied in order to spontaneously generate scales and masses. Two major directions have been pursued. On the one hand the spontaneous mass scale generation can be achieved by strong dynamics, as known from quantum chromodynamics [6]. The electroweak symmetry breaking is triggered here dynamically via the Higgs portal by the condensation of the coloured scalar field around 1 TeV. It can be produced at the LHC. This non-perturbative generation of the electroweak scale can serve as a new starting point for more realistic model building in solving the hierarchy problem.

The other possibility is the mechanism named after Coleman and Weinberg which is weakly coupled at all scales and generates energy scales spontaneously by radiative symmetry breaking and inducing vacuum expectation values of the Higgs and other scalar fields. This framework has been implemented in a set of models which are designed to explain the fact that neutrinos have a small but non-vanishing mass [7]. Within these scale-invariant models neutrino masses and the scale of lepton number violation are detached from each other. This effect roots in the possibility of the existence of small coupling constants which can increase or decrease the scale of lepton number violation without changing the resulting value for the neutrino mass. A more detailed study of a particularly interesting model from a phenomenological point of view, the conformal inverse seesaw, was also performed, see Fig. 1. In addition to neutrino mass generation in this model a dark matter candidate emerges at the keV scale. This type of dark matter is not only produced naturally within the conformal inverse seesaw but also can resolve some of the observational difficulties in the dark matter distributions due to a larger free streaming length than more massive particles, which are normally considered as dark matter candidates.

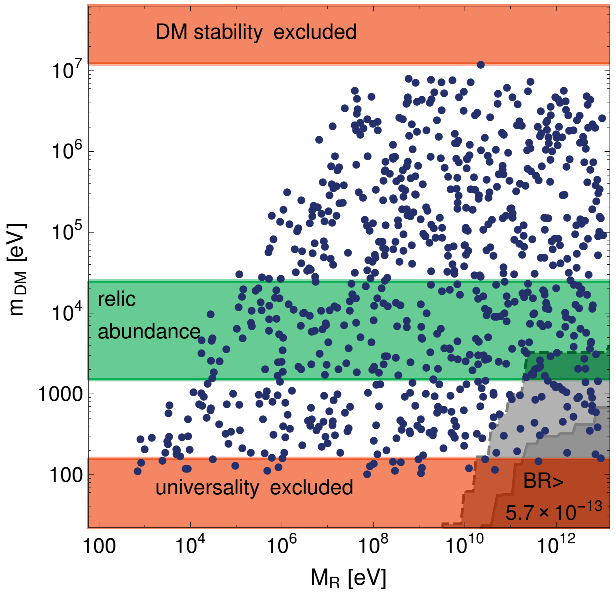

Fig. 1: Parameter space of the conformal inverse seesaw model. Displayed are mass of the dark matter candidate and the induced scale of lepton number violation. Various constraints in terms of sucessful dark matter and laboratory limits are also given.

In order to generate energy scales, the underlying conformal symmetry must be broken and indeed it is violated by quantum effects. This fact on the other hand poses a difficulty, as the quantum breaking of conformal symmetry puts in question its validity as protective symmetry to ensure the absence of explicit scales. A possible explanation was proposed by embedding the theory in the context of gravity. In this way at a high-energy scale the quantum effects of gravity and the scalar field sector can compensate each other and ensure the vanishing of the conformal anomaly.

Inflation and Baryogenesis

Two major indications for the incompleteness of the Standard Model (SM) follow from cosmology: On the one hand, the paradigm of cosmic inflation requires an extended scalar sector, including a so-called inflaton field; on the other hand, the observed baryon asymmetry of the Universe needs to be generated via some sort of mechanism (baryogenesis) that involves new physics beyond the Standard Model. Both aspects of early Universe cosmology, inflation and baryogenesis, are therefore crucial to a better understanding of the completion of the Standard Model at higher energies. In the reporting period, both topics were studied.

Inflation is one of the main pillars of modern cosmology. Not only does it account for the vast size of the observable Universe and its high degree of homogeneity and isotropy on cosmological scales; it also seeds the post-inflationary formation of structure on galactic scales. At present, a consensus about how to correctly embed inflation into particle physics is, however, still pending. In view of this situation, a promising approach appears to be to ask to what other known or hypothetical phenomena in high-energy physics inflation might possibly be connected. Here, an attractive option is to identify the SM Higgs boson itself as the inflaton field. As we studied in more detail, this is a viable possibility, as long as the SM Higgs potential is sufficiently stabilised via new scalar degrees of freedom. Alternatively, inflation might be intimately linked to the spontaneous breaking of supersymmetry (SUSY) – a novel idea that we proposed in [8] and which we dubbed “Polonyi inflation”. SUSY offers several particle candidates for dark matter, allows for gauge coupling unification, and sets the stage for a UV completion of the Standard Model within string theory. Since we have not yet seen any superparticles in experiments, SUSY is necessarily broken in Nature. As we have shown, if SUSY is broken at an energy scale close to the scale of grand unification, it may in addition also provide a dynamic explanation for the occurrence of cosmic inflation. This is an intriguing scenario, which yields a new perspective on the interplay between SUSY breaking and inflation within the framework of high-scale SUSY: Inflation is driven by the SUSY-breaking vacuum energy density, while the field responsible for SUSY breaking, the Polonyi field, serves as the inflaton. The mechanism is in accord with the data on the power spectrum of the cosmic microwave background and predicts a large mass for the gravitino, the superpartner of the graviton. While hard to test, if confirmed one day, it would provide strong evidence for “Polonyi inflation”, that is, the unification of the dynamics of inflation and spontaneous SUSY breaking.

An elegant way of generating the baryon asymmetry of the Universe is baryogenesis via leptogenesis. In this scenario, one first generates a primordial lepton asymmetry, which is subsequently processed into a baryon asymmetry by sphalerons, non-perturbative effects in the electroweak sector of the Standard Model at high temperatures. In the reporting period, we investigated a particular version of leptogenesis (resonant leptogenesis after sneutrino inflation) and again its possible connection to the spontaneous breaking of SUSY. In addition, we studied the impact of a so-called theta vacuum angle in the electroweak sector on the predictions of various baryogenesis scenarios. While conceptually interesting, it was concluded that a nonzero electroweak vacuum angle leaves the predictions of most baryogenesis scenarios more or less unaffected. On the other hand, our analysis points to the yet unexplored possibility that the electroweak vacuum angle alone could be responsible for the bias between baryons and antibaryons during baryogenesis.

Gravitational Waves

A new window into the Universe was opened in 2016: The LIGO collaboration announced the first direct detection of gravitational waves. It is therefore especially interesting to consider particle physics models and effects which are extremely hard to test in laboratories but which could be probed by gravitational waves.

The thermal history of the Universe still remains a big mystery and many models beyond the Standard Model of particle physics predict enhanced symmetries at high energies. Two prominent examples are high-scale supersymmetry and Peccei-Quinn symmetry. Since we do not observe these symmetries at low-energy scales, they have to be broken. This symmetry breaking can give rise to strong first-order phase transitions which spread out through the Universe via bubble nucleation. Thereby, collisions of bubble-walls create gravitational waves. It was calculated that the LIGO interferometers can test, due to their frequency range, first-order phase transitions at energies of (10^7-10^8) GeV. This is far beyond any energies which can be produced in laboratories and thus an invaluable test of high-energy physics.

Observations such as the cosmic microwave background show that only ~5% of the energy content of the Universe is baryonic matter. About ~27% of the energy content is a yet unknown form of matter which was named dark matter. One particular theory of dark matter suggests that it is formed by ultra-light bosons with a mass of (10^{-22}-10^{0}) eV which form a Bose-Einstein condensate. If dark matter halos are Bose-Einstein condensates of galactic size, then a gravitational wave passing through the halo will excite phonons which introduce a mass for the graviton in the Bose-Einstein condensate and thus alter the propagation speed of the gravitational wave. We have shown that such a change in propagation could be measurable by future multi-messenger searches which search the sky for correlated gravitational wave, light and neutrino signals [9]. Testing Bose-Einstein condensate dark matter is difficult and thus gravitational waves could be a unique opportunity to clarify the nature of dark matter.

Other Topics

The theoretical particle physics work at MPIK has covered a large variety of topics. And so a number of publications cannot be attributed to any of the subject categories covered so far.

The stability of the proton in the framework of unified theories has been addressed by a series of publications. The first experiments which have set lower limits on the proton lifetime have pushed the scale of all up to now known theories for force unification to a mass scale close to the fundamental scale of gravity, the Planck scale. This makes the hierarchy problem extremely pressing and manifest even if low-scale SUSY was realised in nature. Motivated by this problem theories have been studied, in which baryon number is lifted to a local symmetry and spontaneously broken. However, the breaking is such that the proton cannot decay even though the scale of symmetry breaking can be slightly above the electroweak scale. Within this theoretical embedding interesting phenomena have been studied. On the one hand the possibility has been explored that unification is much lower than expected in traditional unification theories [10]. Furthermore, models with gauged baryon number can lead to an automatically stable dark matter candidate, which can induce gamma-line signatures.

Other studies include phenomenology of supersymmetric theories in which R-Parity is violated, which were shown to produce distinct signals in the IceCube experiment. Furthermore, in a dedicated study the possibility was explored to constrain new physics, formulated in terms of dimension-6 operators suppressed by high-energy scales, with precision measurements of the Higgs boson properties [11]. Those measurements could be performed at a future electron-positron collider and can reach new physics scales of up to 10 TeV.

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References:

[1] S. Patra, F.S. Queiroz, W. Rodejohann, Phys. Lett. B 752, 186 (2016)
[2] P.S.B. Dev, R.N. Mohapatra, Y. Zhang, J. High Energy Phys. 1605, 174 (2016)
[3] M. Lindner, F.S. Queiroz, W. Rodejohann, C.E. Yaguna, J. High Energy Phys. 1606, 140 (2016)
[4] A.J. Helmboldt, M. Lindner, arXiv:1609.08127
[5] M. Lindner, M. Platscher, F.S. Queiroz, arXiv:1610.06587
[6] J. Kubo, K.S. Lim, M. Lindner, Phys. Rev. Lett. 113, 091604 (2014)
[7] M. Lindner, S. Schmidt, J. Smirnov, J. High Energy Phys. 1410, 177 (2014)
[8] K. Schmitz, T.T. Yanagida, Phys. Rev. D 94, 074021 (2016)
[9] P.S. Bhupal Dev, M. Lindner, S. Ohmer, arXiv:1609.03939
[10] P. Fileviez Perez, S. Ohmer, Phys. Rev. D 90, 037701 (2014)
[11] S.F. Ge, H.J. He, R.Q. Xiao, J. High Energy Phys. 1610, 007 (2016)