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High-Energy Physics from a Theoretical Perspective: Major Results, Recent Results and Future Projects

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Abstract. This contribution summarizes a talk given at the "Phenikaa International Physics Conference 2025: Celebrating 100 years of quantum physics" from 13 to 15 October 2025 at the Phenikaa University, Hanoi, Vietnam. It gives a compact overview of the highlights and milestones of particle physics and an outlook on future developments.

1 Introduction

This contribution is about mankind's most fundamental questions: How did the Universe start and how did it develop? What is the Universe made of, what are the building blocks of matter? What are the forces that hold them together? With the Standard Model (SM) of particle physics, we have a framework that describes our current knowledge of the particle world and has been tested experimentally to highest precision. Yet, some deep questions remain unanswered within the framework of the SM. These open mysteries continue to inspire us to explore with unabated enthusiasm and curiosity. It is in this spirit that we can appreciate the quantum legacy of particle physics.

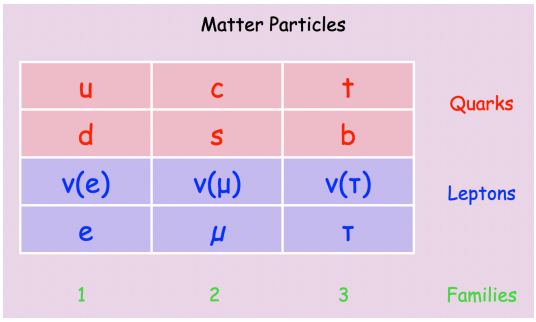
Quantum field theory forms the basis of modern particle physics. Quantum field theory is the theoretical framework that unifies field theory, special relativity, and quantum mechanics. In this so-called second quantization it is the fields that are quantized, and particles are understood as quantum excitations of these fields. Through quantum fluctuations manifestations of quantum physics are omnipresent in the particle world and can be tested in high-precision experiments.

In the derivation of the theory which describes the particle world, symmetries, namely gauge symmetries, play a fundamental role. According to Noether's theorem [1] every continuous symmetry of the action of a physical system with conservative forces has a corresponding conservation law. These symmetries must also hold at the quantum level and are a powerful tool for consistency tests.

2 The Standard Model of Particle Physics

The SM of particle physics is based on four pillars: symmetries, particle content, fundamental forces, and the Higgs sector. The particles building up matter are given by six quarks and six leptons, divided into three families, cf. Fig. 1 (left), where the up- and down-quarks and the electron build up ordinary matter. With the exception of gravity, the SM consistently describes the fundamental forces that interact between these particles, the electromagnetic, the weak, and the strong force. The former two are unified into the electroweak force. The forces are mediated by the interaction particles, which are the photon for the electromagnetic force, the charged W and neutral Z bosons for the weak force, and the gluons for the strong force, cf. Fig. 1

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Fundamental Forces	Mediators/Interaction Particles
Electromagnetic Force	Photon γ
Weak Force	W and Z Bosons
Strong Force	Gluons g
Not in the Standard Model:	
Gravity	Graviton

Figure 1: Left: The SM particle content given by the up (u), charm (c), top (t), down (d), strange (s), and top (t) quark; the neutral leptons given by the electron- ($\nu(e)$), muon- ($\nu(\mu)$), and tau-neutrino ($\nu(\tau)$); the charged leptons electron (e), muon (μ), and tau (τ); grouped into three families. Right: Fundamental forces of the SM with the exception of gravity, together with the mediator particles.

(right). The conserved charges underlying these forces are manifestations of the underlying gauge symmetries. These are the $U(1)_Y \times SU(2)_L$ symmetry for the conserved weak hypercharge and weak hyperspin, respectively, forming the basis of the electroweak interaction, and the $SU(3)_C$ symmetry for the conserved color charge at the basis of the strong interaction.

Massive interaction particles such as the W and Z bosons are in conflict with the underlying $U(1)_Y \times SU(2)_L$ gauge symmetry. This puzzle is solved with the introduction of the Higgs mechanism [2, 3, 4, 5]. The Higgs mechanism allows for the generation of particle masses without violating the underlying gauge symmetries. Spontaneous symmetry breaking induces a non-vanishing vacuum expectation value in the ground state, and massive particles acquire masses through their interaction with the Higgs boson in the ground state.

3 Particle Road

The success story of the SM began more than a century ago with the discovery of the first elementary particle, the electron, in 1897. The first discovered species of weakly interacting neutrinos was the electron neutrino in 1956. The up-, down- and strange-quarks were postulated theoretically by Murray Gell-Mann [6] and George Zweig [7, 8] in 1964. From 1968 on deep-inelastic scattering experiments at SLAC indicated that protons have a substructure and that they are built up by more fundamental particles, the quarks. At first, the quark model was received only reluctantly and was considered a mathematical fiction. This ended latest on 11 November 1974 with the discovery of the J/ψ meson and thereby the discovery of a fourth quark, the charm. This initiated a series of breakthroughs and was dubbed November revolution. The first discovered interaction particle was the photon. It was introduced 1905 by Albert Einstein in order to explain the photoelectric effect. The latest culmination on the discovery road of particle physics, cf. Fig. 2, was the discovery of the Higgs boson at the Large Hadron Collider (LHC) at CERN, announced on 4 July 2012 by the LHC experiments ATLAS [9] and CMS [10]. This discovery structurally completed the SM of particle physics.

4 Highlights and Milestones in the History of Particle Physics

In the following, a few milestones shall be highlighted on the path from the discovery of the first elementary particle to the structural completion of the SM of particle physics.

One of the first observations of the manifestations of the weak force in laboratory was the

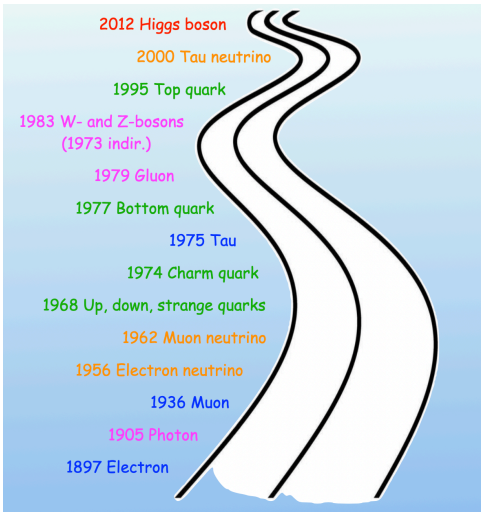


Figure 2: The particle discovery road. Blue: charged leptons, orange: neutral leptons, green: quarks, magenta: interaction particles, red: the Higgs boson. The dates indicate their discovery year.

weak beta decay. While in the early 1900's theories predicted that the electron emitted from this neutron decay into the proton should have a specific energy, experiments showed that its energy spectrum is continuous. In 1930, Wolfgang Pauli suggested that there must be an additional undetected particle that carries away the energy-momentum difference between the initial and final particles. In his letter to the "dear radioactive ladies and gentlemen" [11] at the Physical Institute of the Federal Institute of Technology, Zürich, he called this particle neutron, which was then later called the electron-neutrino. The beta decay is hence described by the process

$$n \to p + e^- + \bar{\nu}_e \,, \tag{1}$$

where n denotes the neutron, p the proton, e^- the electron, and $\bar{\nu}_e$ the anti-electron-neutrino.

Enrico Fermi proposed in 1933 a theoretical description of this process through the Fermi theory, where the four fermions of Eq. (1) interact directly with one another. While this theory

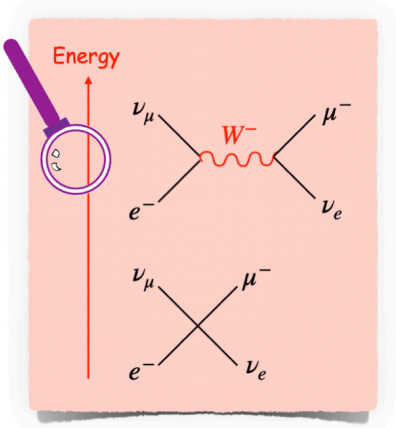


Figure 3: Resolving the effective low-energy four-point Fermi interaction with the introduction of the massive charged W boson.

describes the beta decay remarkably well, it fails at high energies as the cross section increases with the energy squared. This behavior was later cured by the introduction of the exchange of the massive W boson that resolves the contact interaction. The electroweak theory was born, and the Fermi theory is understood to be the low-energy effective theory of the more complete electroweak theory with the W and Z bosons mediating the weak force, cf. Fig. 3. The W and Z bosons were finally directly discovered in 1983 at UA1 and UA2 at CERN.

The introduction of the W boson introduced yet another problem. The amplitude of the now possible scattering of a pair of longitudinally polarized W bosons, W_L, into a pair of longitudinally polarized W bosons turned out to diverge with the energy. This violation of unitarity can be cured with the introduction of a scalar particle that couples to the W boson pair with a strength proportional to m_W^2, the squared mass of the W boson, namely the Higgs boson H, cf. Fig. 4. The discovery of the Higgs boson marked a triumph of particle physics

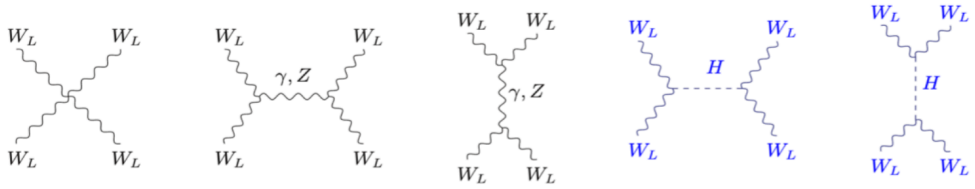


Figure 4: Unitarization of the $W_LW_L \to W_LW_L$ scattering through the introduction of the Higgs boson H which couples to the W pair proportional to m_W^2.

and earned P. Higgs and F. Englert the Nobel Prize in 2013. The symmetry requirement at the quantum level provides the raison d'être for the Higgs boson. It must moreover inevitably be introduced in a theory with massive gauge bosons that remains weakly interacting up to the Planck scale. The Higgs boson ensures the consistency of the electroweak theory at the quantum level. The physicists 't Hooft and Veltman were awarded the Nobel Prize in 1999 for elucidating this quantum structure of the electroweak interactions in physics.

Let us now turn towards quantum chromodynamics (QCD) which describes the strong force acting between quarks. During the 1950's more and more mesons and baryons were discovered leading to a veritable particle zoo. This called for an organizational scheme. Murray Gell-Mann [12] and Yuval Ne'eman [13] proposed independently the eightfold way that led to the development of the quark model. The non-Abelian color $SU(3)_C$ which underlies the strong interaction leads to the increase of the strong coupling constant with rising distance, respectively, decreasing energy due to quantum fluctuations. Consequently, quarks cannot be isolated and observed as free particles, which is known as confinement. At high energies on the other hand, the quarks become asymptotically free, dubbed asymptotic freedom, Fig. 5.

5 Standard Model Tests at the Large Hadron Collider

High-energy colliders like the LHC at CERN near Geneva allow for the experimental tests of theoretical ideas. The LHC started operation in 2009 and currently is in its run 3 phase at a center-of-mass energy of 13.6 TeV. From late 2026 on major upgrades will be made towards the high-luminosity phase of the LHC that will become operational in mid-2030. The LHC enables all steps necessary to verify the Higgs mechanism experimentally. Right after the discovery of the Higgs boson the experimental collaborations started with the investigation of its properties [14, 15]. The measurement of the Higgs couplings to the SM particles were found to be proportional

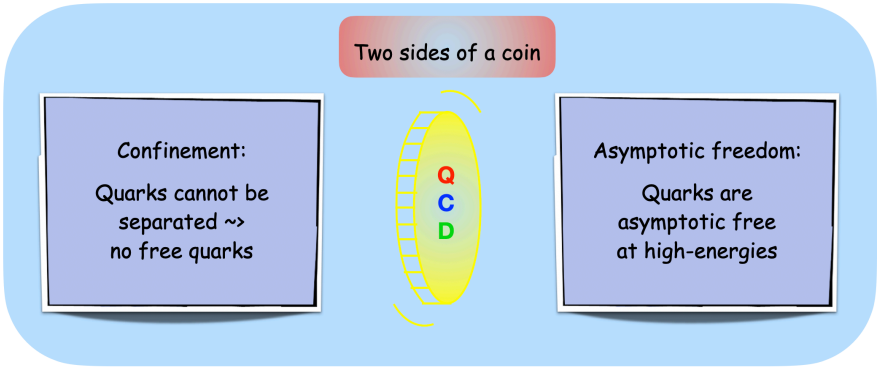


Figure 5: Two sides of a coin in QCD: confinement and asymptotic freedom.

to the respective particle mass (squared) as predicted by the Higgs mechanism, Fig. 6 (left). The hypothesis of spin 0 and even parity were confirmed, Fig. 6 (right).

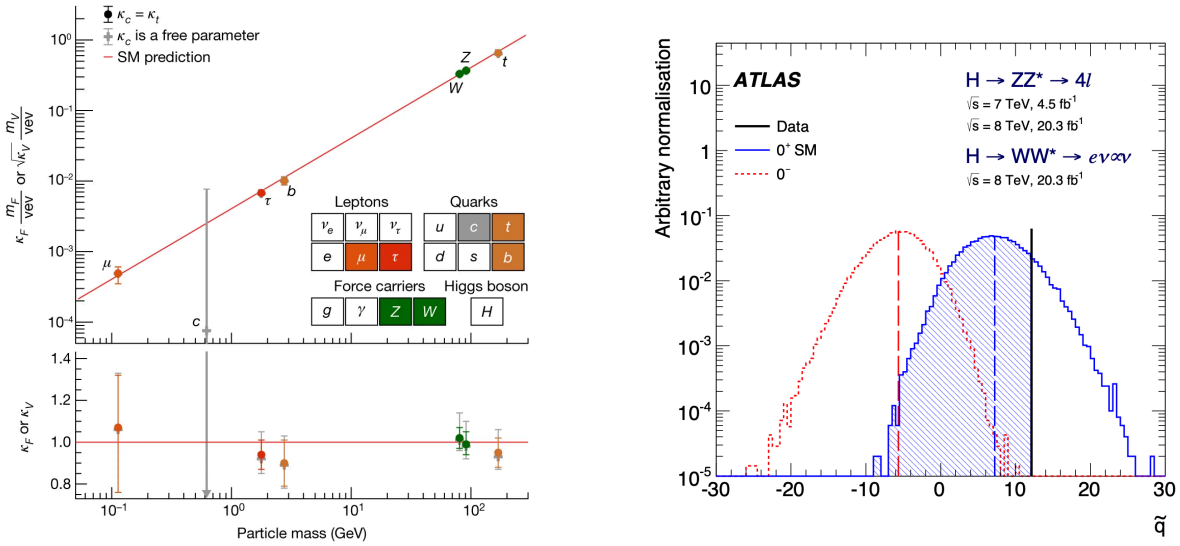


Figure 6: Left: Reduced Higgs boson coupling strength modifiers and their uncertainties as a function of the particle mass. Taken from [14]. Right: Distribution of the test statistic $\tilde{q}$, 0^+ (SM) versus 0^-. Taken from [16].

The determination of the trilinear and quartic Higgs self-couplings is the ultimate test of the Higgs mechanism [17, 18]. First limits on the trilinear Higgs self-couplings have been derived from the production of two Higgs bosons. At the LHC, the dominant di-Higgs production cross section is given by gluon fusion which is loop mediated already at leading order [19]. Due to the smallness of the cross section and the large QCD background the measurement is a real challenge. So far, the trilinear Higgs self-coupling has been constrained to -1.24 to 6.49 times the SM value at 95% confidence level (CL) by CMS [15] and to -1.2 to 7.2 times the SM value at 95% CL by ATLAS [20].

6 Neutrinos

It is fair to say that neutrinos take a special role among the elementary particles of the SM [21]. They are electrically neutral, and their masses are extremely small. They are only subject to the weak interaction, and their reactions are extremely rare. While this means on the one hand that neutrinos have a far reach, it makes on the other hand the detection of neutrinos extremely challenging. After their postulation by W. Pauli in 1930, it took until 1956 to detect the electron neutrino ν_e in an experiment by Cowen and Reines at one of the first nuclear reactors [22, 23]. The muon neutrino ν_μ was discovered in 1962 by Steinberger, Schwartz and Lederman [24], and the τ neutrino ν_τ was detected only in 2000 at the DONUT experiment [25].

Already in 1957, Bruno Pontecorvo investigated the theoretical possibility of neutrino oscillations, in case the neutrinos are massive, contrary to what was assumed at that time. A first experimental hint for neutrino oscillations was the deficit of low-energetic solar neutrinos as observed in the Homestake experiment at the end of the 1960s. This was confirmed in 1987 at the Kamiokande-II experiment. Since then, numerous experiments have been conducted to determine the parameters of the neutrinos. The KATRIN experiment at KIT provides the presently world best upper limit on the neutrino mass of 0.45 eV at 90% CL derived from the tritium decay [26].

7 Open Questions of the Standard Model

The SM has been tested with highest precision at the quantum level, including higher-order corrections. Despite its great success, there are open puzzles that cannot be explained within the SM. To the most prominent mysteries belong the questions for the nature of Dark Matter (DM) and why there is more matter than antimatter in the Universe as well those on the Dirac or Majorana nature of neutrinos and CP violation in the neutrino sector. While there are numerous evidences for the existence of DM, to date it remains unclear what DM is made of [27]. If it is a particle, it must be electrically neutral and weakly interacting. Neutrinos as DM candidates are in conflict with the cosmological evolution and could also not make up for the total amount of observed DM. The existence of DM hence requires the extension of the SM to new physics models. As for the observed matter-antimatter asymmetry, a dynamical mechanism for the generation of the baryon-antibaryon asymmetry is given by electroweak baryogenesis, cf. e.g. [28]. This requires the three Sakharov conditions [29] to be fulfilled, namely baryon number violation, C and CP violation, and departure from thermal equilibrium. All three ingredients are found within the SM. However, departure from thermal equilibrium requires a Higgs mass of around 70 GeV [30, 31], which is in contradiction with the discovered Higgs mass of 125 GeV. This calls for extensions beyond the SM.

The explanation of the described open puzzles requires new physics extensions. So far, however, there has been no direct detection of new physics. Moreover, the discovered Higgs boson behaves very SM-like. New physics effects are hence very subtle and require sophisticated experimental techniques on the one hand and precise theory predictions on the other hand. The Higgs particle turns out to be a perfect laboratory for new physics searches, as it has connections to many different sectors of the quantum world. It can provide a portal to DM. And the evolution of its vacuum structure at non-zero temperature gives us deep insights in the evolution of the Universe and the nature of the electroweak phase transition, a key element of electroweak baryogenesis. Moreover, if the phase transition is of strong first order, it can generate gravitational waves, cf. e.g. [32], that can be tested at future gravitational wave observatories.

8 The Future

In order to gain further insights in the particle world and find answers to our open questions, we have to go on searching for new physics. This can be done e.g. at the existing and planned DM experiments, at gravitational wave experiments, or at collider experiments. After the LHC, several proposals are on the tablet. These comprise among others e^+e^- circular colliders like the FCC-ee and the CEPC, e^+e^- linear colliders, future hadron colliders like the FCC-hh, or a muon collider, cf. Fig. 7. Circular e^+e^- colliders distinguish themselves by high luminosities, while e^+e^- linear colliders can reach higher energies. Proton colliders can reach very high energies and thereby produce heavy particles, are less clean and precise, however, than e^+e^- machines.

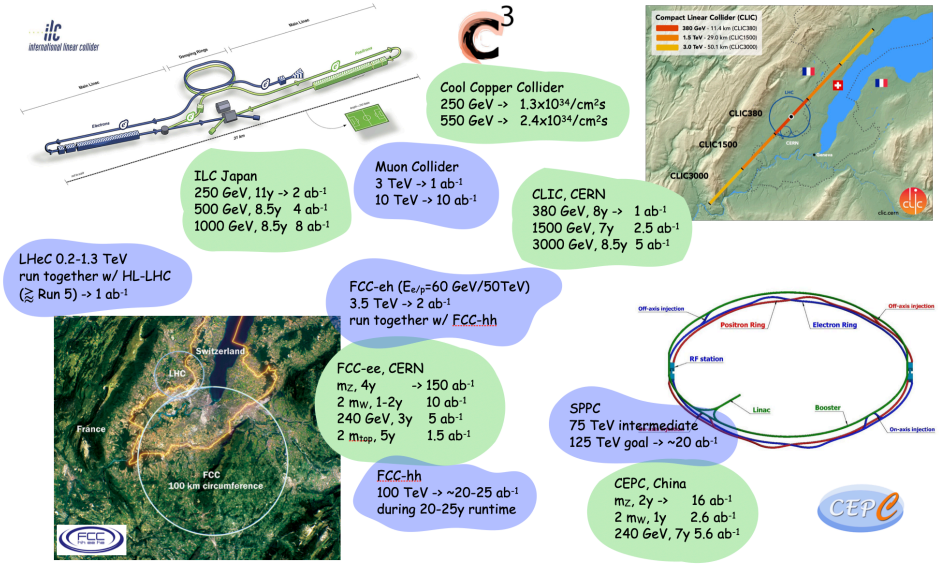


Figure 7: A selection of possible future collider experiments, together with their foreseen c.m. energies and planned accumulated luminosities.

The puzzles that nature has for us and which cannot be solved within the SM, the fact that so far we have no sign of new physics in sight, while present Higgs results are very SM-like, put us in a challenging situation. It will require combined efforts of particle physics, astrophysics, and cosmology, and the intense interplay of experiment and theory, to guide us to the answers of our questions and to the true theory underlying nature. The results of running and future experiments may still have many surprises for us and promise an exciting future.

9 Summary

In this contribution the deep connection between quantum physics and particle physics was reflected, to then move on to a compact overview of highlights and milestones of particle physics from the discovery of the first elementary particle at the end of the 19th century until the discovery of the Higgs boson in 2012 which structurally completed the SM of particle physics. The article ended with the open questions of the SM and the outlook on an exciting future, hopefully giving us answers to our most pressing open puzzles.

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