TEACHING THE STANDARD MODEL OF PARTICLE PHYSICS AT SCHOOL – AN ALTERNATIVE APPROACH

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Abstract

Research in particle physics, especially the one done at the Large Hadron Collider at the European Organization for Nuclear Research (CERN) has frequently been picked up by the media. The coverage peaked in 2012 when CERN announced the discovery of the Higgs Particle as the missing piece of the so-called Standard Model of particle physics (SM). Although the SM is the most precise theory we know to describe the elementary processes in our universe and has been validated in countless experiments since its development more than fifty years ago, it is not yet part of most curricula at German schools. But, probably also driven by the media attention and the involved interest on the side of students, it is getting more and more implemented.

To support this process and to help the teachers who have to educate students on the subject, Netzwerk Teilchenwelt (NTW) has developed material to provide the necessary background knowledge. NTW is a Germany-wide network of students, teachers and scientists. Since 2010 NTW has taken real data from particle physics experiments into school to give students an insight into the research methodology. The recently developed didactic approach for teaching the key concepts of the SM differs from those usually used in schoolbooks. Different ways of its implementation in the classroom are regularly discussed with teachers during further training courses.

One major goal of this approach is to give students an idea which of the many things we know about elementary particles and their interactions can be fully explained by the SM and which are experimental facts we cannot predict by theory.

Therefore, it has to be pointed out that all processes in the universe can be explained by four fundamental interactions, three of which are described by the SM. These interactions can be ascribed to very similar reasons, named charges. Students are quite familiar with one of them, the electric charge, being the reason for the electromagnetic interaction. There are several more points of contact between particle physics and other contents of the curricula, which makes teaching the SM not as difficult as one might think.

Charges and fundamental interactions are very well described by theory. They set the rules every particle we know follows. That is why the understanding of charges and interactions is the deepest insight into the functionality of the universe mankind has achieved so far. As opposed to this, there are several aspects in particle physics that cannot be predicted by the SM. One of them is the spectrum of existing matter particles. In this light it is somehow absurd that the SM is often reduced to the elementary particles we know. To understand the fundamental interactions, students do not need to know about all existing matter particles. Besides, it is not particularly motivating to learn all their names, especially because most of them do not play a direct role for ourselves, since all of the stable matter is built by only three elementary matter particles. Saying that, starting a course on particle physics by listing all known matter particles and their properties does not seem to be the best approach. The described concept by NTW takes that into account and starts with very few matter particles to define the rules of the game, namely the fundamental interactions they and every other known matter particle have to follow.

Keywords: Particle physics, Standard Model, fundamental interactions, charges, elementary particles

1 INTRODUCTION AND MOTIVATION

Research in particle physics, especially the one done at the *Large Hadron Collider* at the European Organization for Nuclear Research (CERN) is frequently picked up by the media. The coverage peaked in 2012 when CERN announced the discovery of the Higgs Particle, boldly labeled as the God Particle, as the missing piece of the so-called Standard Model of particle physics (SM). In this context the Nobel Prize in Physics was awarded to Francois Englert and Peter Higgs in 2013. In 2015 the prize was again awarded for research in particle physics, honoring Takaaki Kajita and Arthur B. McDonald for the direct discovery of neutrino oscillations. In addition to these success messages, there are regularly promoted dystopic ideas about the research at particle colliders and especially at CERN by the media and particularly on the Internet, stating that these high-energy experiments might be dangerous for humanity, for example by causing the production of black holes. Of course, these ideas are no more than science fiction, just like the possibility to build an ominous bomb using antimatter produced at CERN as described by Dan Brown in his novel Angels & Demons [1] and the movie with the same name. Considering the given examples, it is probably safe to say that most people are faced with aspects of particle physics at some point in one way or other. This, of course, also applies to students, thus leading to a keen interest in particle physics, especially in the mysteriously sounding concepts as antimatter, dark matter and dark energy or extra dimensions [2].

We know that the theoretic framework of particle physics is not complete yet and could be revolutionized at any point in time. This is different to most other fields in physics that students encounter at school. Although the SM is the most precise theory we know to describe the elementary processes in our universe and has been validated in countless experiments since its development more than fifty years ago, there are still many open questions. For example, what exactly the so-called dark matter and dark energy are and why matter particles have exactly the masses we observe in experiments.

Although the SM is fundamental for our understanding of the universe and the motivational opportunities particle physics provides in education, the subject is not part of most curricula at German schools yet, but it is getting more and more implemented. Since its founding in 2010, Netzwerk Teilchenwelt (NTW), a Germany-wide network of scientists, teachers and students with direct contact to CERN, has been taking original data from particle physics experiments to classrooms by offering so-called Particle Physics Masterclasses and has also been giving students the chance to run experiments on cosmic radiation themselves. To support teachers who have to give lessons on particle physics at school, NTW has started to develop teaching material and to provide the necessary background knowledge by publishing a textbook [3]. In this context a didactic approach for teaching the key concepts of the SM has been developed in close contact with teachers. One major goal of the approach is to give students an idea which of the many things we know about elementary particles (particles that do not have any substructure) and their interactions can be fully explained by the SM and which are experimental facts we have not yet been able to predict by theory.

At this point a detailed description of the teaching concept is only available in German, either as printed version or digitally at www.teilchenwelt.de. It is intended to publish an English translation in future.

2 KEY IDEAS OF THE CONCEPT

The most common way of introducing the SM is to focus on the elementary matter particles we know and ordering them into a scheme like the one to be found on Wikipedia [4] by arranging them into three generations (Fig. 1). This approach does not seem to be the best one due to several reasons. Most importantly, it is not exactly what could be called motivating for students when they have to memorize names and properties of all elementary particles. Especially considering that only three types of them, namely up-quarks (u) and down-quarks (d), which are the elementary particles protons and neutrons are built of, and electrons (e^-) are necessary to describe all known stable matter in our universe. Most other particles are only produced in high-energy processes like particle collisions happening for example in the earth's atmosphere and in experiments. Neutrinos (ν) are produced in particle conversions, for example in beta conversions (section 3.3).

The idea behind the alternative approach developed by NTW can be illustrated with an analogy. How do you explain a game, for example soccer, to someone who has no clue at all about it? You would probably not start by naming all different positions and roles on the field or even names of certain players. To acquire a brief understanding of the game, one has to know its important rules and goals. For example, in soccer, the ball has to be shot into the opposing team's goal and touching the ball with your hand is not allowed. Whether there are eleven, seven or any other number of players on the pitch for each team and in which formation they are playing is not really important. As long as they follow the rules of the game, it is a soccer match. In this analogy the players represent the elementary particles and the rules of the game of particle physics are the way these particles interact with each other. In order to describe the way of interaction and the rules these interactions follow, only a few elementary particles are needed as examples. As soon as the rules are known, they can be applied to describe any interaction between all elementary particles and the particles can be systematized according to the way they behave in those interactions. In fact, the scheme in which the elementary matter particles are usually organized is a result of observed interactions and particle conversions and there can be found analogies to the periodic table of elements in chemistry, which gives a point of contact to other contents of curricula at school. Expressed in a different way, the arrangement system of matter particles cannot be understood without knowing about particle interactions.

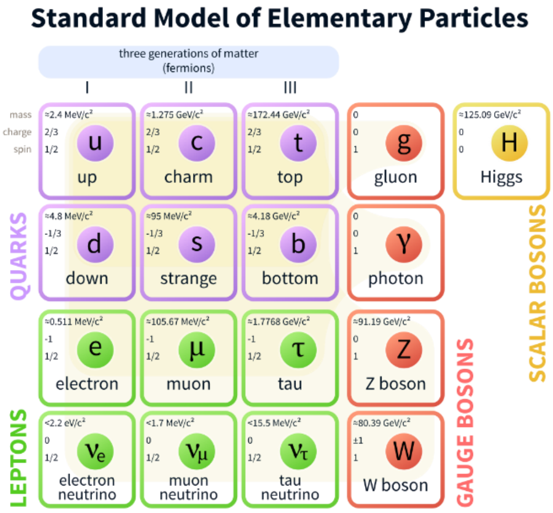

Figure 1. Commonly used scheme of elementary particles [4].

Furthermore, the spectrum of elementary matter particles we observe is not predicted by theory, but is a completely experimental insight. When someone wants to understand what exactly makes the SM the most predictive and exact theory we have in particle physics to date, the focus has to be on the fundamental interactions that elementary particles participate in.

It has always been a research goal in physics to simplify the way we describe nature. That does not mean it is the aim to find very simple mathematical equations for describing the processes in the universe. In fact, the goal is to reduce the amount of underlying core principles and assumptions when describing different phenomena. There have been various key moments in the history of science when such unifications were accomplished which also play a role in physics education at school. One of them is the unification of Galilei's law of falling bodies on earth and Kepler's description of the movement of celestial bodies by Newton, who described these phenomena as a result of gravity. Another example is the unification of magnetic and electric phenomena within the theory of electromagnetism described by the Maxwell equations. Albert Einstein took our understanding of the world a huge step forward by combining two concepts that had been perceived completely independently of each other before by stating that space and time are influenced by each other and introducing the concept of spacetime. State of the art today is, that all phenomena can be attributed to four fundamental interactions. One of them is gravity. Gravity is not part of the SM, but is described by Einstein's general relativity. The other three, namely the electromagnetic, the strong and the weak interaction, are described by the SM.

The term interaction in particle physics is a hypernym. There are four different phenomena, in which an interaction can occur. These are forces between particles, the production and annihilation as well as the conversion of particles. All these phenomena are considered as interactions. In literature interactions are often referred to as forces. There you find statements like "the weak force [...] manifests itself in nuclear β-decay" [5] or "this [strong] force is the fundamental strong interaction" [6]. From a didactic point of view this is very problematic, since it is not compatible with the physical concept of force as taught to students in the context of Newtonian mechanics. In fact, it is not compatible with the concept of force in any way, since particle conversions, production or annihilation cannot be explained by forces. This makes it necessary to clearly distinguish between the terms force and interaction and to use force only when an attractive or repulsive force caused by one of the fundamental interactions is actually meant.

The three fundamental interactions of the SM can be ascribed to very similar reasons, named charges. Students are quite familiar with one of them, the electric charge, which is the reason for the electromagnetic interaction. Analogously, there are the weak charge and the strong charge (also called color charge) for the weak and the strong interaction. Every prediction of the SM can directly be deduced from symmetries regarding these charges. For the exact description of these so-called local gauge symmetries mathematical group theory is necessary, which makes it almost impossible to take them as a starting point for teaching particle physics at school. More or less, the insistence that the charges have to fulfil the symmetries, can be described as follows. Taking the electric charge as an example, it has to be possible to change every positive electric charge into a negative one and vice versa without causing the functionality of the universe and the laws of physics to change. This sounds reasonable, since it should be totally irrelevant what we define as a positive and a negative electric charge. The captivating part of the local gauge symmetries is that these changes concerning the charges do not have to be made globally, that means all over the universe in the same way, but can be made locally. So at every point in space it can be decided independently if the charges are changed or not. The fact that this has to be possible, directly leads to the existence of the fundamental interactions which carry out these changes. Furthermore, these symmetries require the existence of so-called messenger particles (also called gauge bosons). These are particles related to the fundamental interactions. By emitting or absorbing a messenger particle, a matter particle can convert into another one, which is equivalent to a change in one or more charges. This is the way the messenger particles realize the symmetry operations regarding the charges and the gauge symmetries can be fulfilled. The SM is not to be reduced to being a theory of elementary particles. This might be what physicists were looking for in the first place but, as described, it is definitely not what has been found. We have found a theory of interactions and charges. So Fig. 1 definitely does not reflect the really deep understanding we have of particle physics to date.

The basic concepts of charges, interactions and particles and their relations, as illustrated in Fig. 2, define today's understanding of particle physics and represent therefore the basis of the developed teaching approach. All three types of charges are additive (the respective charge of a system of elementary particles equals the sum of the charges of its components) and quantized (charges can only have discrete values or states) conserved quantities. In particle physics the charges have a similarly outstanding role as the different kinds of energy and its conservation law for physics overall.

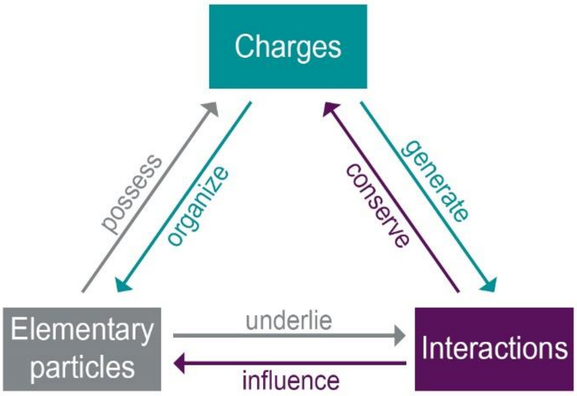

Figure 2. The basic concepts in particle physics and their relations [3, translated].

Furthermore, charges are unchangeable properties of particles. By changing one of the charges, the particle can never remain the same and therefore changes in charges, as described above, are equivalent to particle conversions. When talking about particles here, all statements are also valid for their respective antiparticles. Antiparticles differ from their corresponding particles. They have the same masses but opposite charges, meaning the respective charges of particles and antiparticles differ by a factor of -1. For every matter particle an antiparticle exists.

At school, the stringent necessity of the existence of three different kinds of charges has to be made comprehensible and so the introduction of the strong and weak interaction has to be the starting point. The connection between messenger particles and the symmetries may be discussed at a later point, after the messenger particles have been introduced.

3 OUTLINE OF IMPORTANT STEPS IN THE CONCEPT

Saying that the SM is the most precise theory on elementary particles, it might seem questionable if it can be explained to students in an understandable way. Despite being quite difficult to understand when it comes to complex calculation, for example of probabilities of certain particle interactions, the fundamental ideas, concepts and assumptions the SM is based on are not too hard to understand, especially since there are numerous points of contact with knowledge students have already acquired in other fields of physics. In the following sections it will be described how certain aspects of the SM can be introduced at school, which simplifications should or have to be made and what points of contact there are with other aspects of the physics curriculum. Moreover, didactic suggestions will be given that may facilitate the discussion of the SM.

3.1 Introducing the three fundamental interactions of the Standard Model

As we will see, it is useful to plan a concrete discussion of particle physics and the SM in the context of atomic and nuclear physics. It has to be pointed out that particle physics should not and cannot be dealt with as an independent and isolated topic. Instead, there have to be identified points in the curriculum where certain aspects can be integrated. This way it is possible to impart the basic concepts of the SM and point out the relations to other fields of physics.

When the strong and weak interaction are introduced, the students are already quite familiar with the electromagnetic interaction, since it is usually mentioned various times throughout the curriculum. Students know the laws which describe the force between electrically charged particles, known as Coulomb's law, as well as the field line model. They also know that the force on two interacting electrically charged particles, in spite of some constants, only depends on their distance and their electric charges. At a given distance, the only free parameter for describing the force on these particles is the electric charge *Q*. The electric charge of a particle can be described by a number called electric charge number *Z*. This number, multiplied with the elementary charge *e,* gives the electric charge. With this number the Coulomb's law can be written as

$$F_{\mathrm{C}} = \frac{e^2}{4 \cdot \pi \cdot \varepsilon_0} \cdot \frac{Z_1 \cdot Z_2}{r^2}$$

with F_{C} being the electromagnetic force known as Coulomb force and Z_1 and Z_2 being the electric charge numbers of the two interacting particles. For an electron for instance *Z* is -1.

The strong interaction can be introduced in the context of nuclear physics. Naturally the question will arise, why certain nuclei are stable although the protons repel each other. It can be easily verified, that gravity is far too weak to compensate for this repulsion. Usually the reason for the attractive force stabilizing these nuclei is called the strong nuclear force. The exact reason behind this force is the strong interaction. Since at this point the only discussed reason why bodies repel or attract each other is their masses and their electric charges, it seems natural that another type of charge causes the attractive force that is responsible for the stability. However, it is not the nucleons (protons and neutrons) themselves that possess a strong charge, but the particles they are built of, the quarks. The attractive force between the nucleons is directly related to the strong interaction between the quarks of neighbouring nucleons. There are some analogies with the covalent bond of electrons to be found and pointed out in this context.

The weak charge and interaction are fairly harder accessible. There are two different possible approaches. Ideally, both should be dealt with during the discussion. The phenomenon that is the pivot of both approaches is the beta decay of nuclei or better to say the beta conversion. Unlike in the alpha decay, where the resulting particles were parts of the original nuclei, in this process particles are converted, which makes the term decay inappropriate. In a beta conversion the converted particles are quarks. A down-quark converts into an up-quark, which makes a neutron in the nucleus turn into a proton, (beta minus conversion) or vice versa (beta plus conversion).

The central argument in the first approach is that particles are only affected by a certain fundamental interaction when they possess the respective charge. Therefore, also in the production of particles during conversions, all involved particles must have the charge of the responsible fundamental interaction. In every beta conversion a neutrino comes into existence. To be able to understand the argumentation, students have to be aware of certain properties of neutrinos. These elementary particles are not part of any stable matter. They interact extremely rarely with other particles. This is why we need huge detectors like at the IceCube Neutrino Observatory at the south pole, where one cubic kilometre of ice is used as detector material to have a chance to see some neutrinos in the experiment. If neutrinos had an electric or a strong charge, these particles should interact with other particles much more frequently than we observe and should also be found in stable matter due to attractive forces caused by these charges. Knowing that neutrinos do not have one of these charges, it can be concluded that they do not participate in the electromagnetic and strong interaction. Particularly, they cannot be produced in processes that are caused by these interactions. As they are produced in every beta conversion, there must be another underlying fundamental interaction, the so-called weak interaction.

For the second possible approach to introducing the weak interaction, students have to be well aware of the fact that charges are conserved quantities and that any process that does not violate any law of conservation should occur with a given probability at some point. The usual approach of giving a reason for the existence of neutrinos in beta conversions is the experimental finding that the observed electrons (or positrons in beta plus conversions) never have the maximum possible energy they could have.

Instead, in every beta conversion the emerging electron has a not well-defined energy lower than this maximum. This leads to the existence of a beta spectrum describing the energies of the produced electrons. This makes us conclude that beta conversions cannot be two-body problems where only an electron and the new nucleus are produced during the conversion. Such a process would lead to a discrete and well-defined electron energy in every beta minus conversion.

But why exactly did we not observe any beta conversion where the electron does have the maximum possible energy? Or in other words, why is there always a neutrino being produced that takes away some of this energy? There must be a law that forbids beta conversion to happen without neutrino production. So some sort of conservation law has to be violated in the process without a neutrino. It can be easily verified that the electric and strong charge can be conserved without the neutrino being necessary. Also, conservation of energy and momentum can easily be achieved without a neutrino. There must be another conserved quantity whose conservation law must be violated in this case. Since charges have been discussed as conserved quantities for the electric and the strong charge, the existence of another charge can be deduced. It is called the weak charge, the only type of charge neutrinos possess. As known by now, there is an interaction to every charge. So the weak interaction as the reason for beta conversions (as well as many other particle conversions) can be introduced.

Which of the given approaches should be chosen depends on the students' prior knowledge and where the focus has been in previous argumentations. But it is highly recommended to mention both justifications for the existence of a weak charge and interaction at some point in the dispute.

In analogy to the electric charge the weak charge of a particle can be described by a weak charge number *I.* This is a simplification that can be made at school because it is not intended to do calculations using the weak charge numbers. Actually the weak charge must be described by a three-dimensional vector. But, due to the same reasons why the spin of a particle most of the time can be reduced to a simple figure, this is also possible regarding the weak charge. Because of its mathematical similarity to the spin it is also called weak isospin. Every matter particle possesses a weak charge with possible charge numbers being ½ or -½. The strong charge however cannot be described by a charge number but by two-dimensional vectors called color charge vectors $\vec{C}$. These vectors can be visualized in a two dimensional color grid with three axes labeled with the colors blue, red and green. The possible color charge vectors of quarks are shown in Fig. 3 on the left. For antiquarks the possible charge vectors have the opposite orientation respectively and are named antiblue, antired and antigreen (Fig. 3, right). The three colors are abbreviations for the mathematical properties of the respective color charge vector and are used because of the analogy to the additive color mixing where these three colors together give white, just like the sum of the three different color charge vectors gives the zero vector. Every complex particle built by quarks has no effective color charge, meaning the color charge vectors of the quarks will always combine to the zero vector.

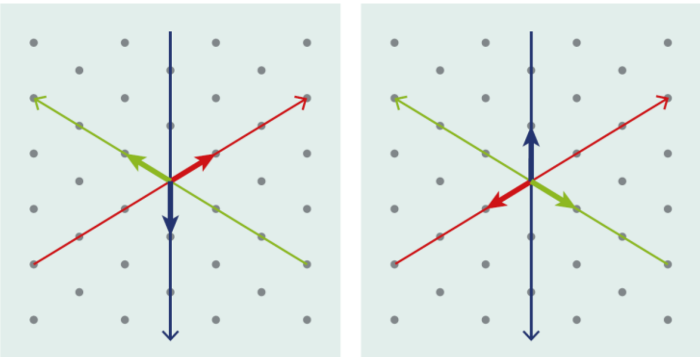

Figure 3. Color charge vectors of quarks (left) and antiquarks (right) [3].

To facilitate the extension of the concept of charge it is essential that the electric charge is not regarded as "the" charge of particles during the discussion of electromagnetism in lower classes. In textbooks one often finds only the term charge when the electric charge is meant. Even particle physicists and lecturers at university usually just speak of charge when they talk about the electric charge and specify only when the weak or strong charge are meant. Reinforcing the perception that the electric charge is the one and only type of charge a particle can have, will probably make the introduction of additional charges much more difficult. Therefore, it should always be added the specification "electric" even when the other charges are not known yet. This way it may also be prevented that the strong and weak charge are perceived as special forms of the electric charge but are seen independently.

3.2 Discussing the ranges of the fundamental interactions

Despite obvious differences, the fundamental interactions are very similar under certain circumstances. The shorter the distance between two particles is, the more similar the force laws for the three fundamental interactions of the SM will become. For very small distances all three force laws can be written as a product of a so-called coupling parameter and the product of the respective charge numbers or vectors of the interacting particles divided by the distance of the particles squared, just as Coulomb's law looks like at every distance. If the distance gets bigger, the laws of the strong and the weak force deviate from this form.

The weak forces on two weakly charged particles become almost zero very quickly at distances bigger than 0.002 fm (1 fm = 10^{-15} m is roughly the size of a proton or neutron). This is why there are no stable states of matter consisting of multiple neutrinos, which only possess a weak charge and it is also the reason why we do not see any effects of the weak interaction in our daily lives despite particle conversions which we cannot observe directly either. The same is true for the strong interaction and the respective force. But instead of becoming almost zero at larger distances, the strong force between two color-charged particles reaches a constant value at distances of about 0.2 fm. This is the reason why particles with a strong charge cannot exist independently. This phenomenon is known as confinement. If quarks, the only color-charged matter particles, move away from each other the attractive force becomes constant, leading to an extreme increase in energy of the quark system. At some point in the range of 1-2 fm this energy is big enough that new quarks can be produced. The production of particles from energy is exactly what the core principle of the particle production at particle accelerators is and is implied by Einstein's formula $E = m \cdot c^2$. The produced quarks and the original ones then build bound states again. Therefore, the effective range of the strong force and interaction is restricted by the possible distance quarks can have from each other without new quarks being produced.

3.3 Introducing messenger particles

As stated in section 2, messenger particles are involved in every interaction between matter particles and in their production or annihilation. But how can this completely new concept be introduced at school? A useful way to justify its introduction is to produce a cognitive conflict by showing that the concept used thus far is contradictory. The concept students know for describing forces between objects and particles is the field line concept. The question is whether this model can be applied to the forces caused by the fundamental interactions of the SM or not. In the electric field line model the density of the field lines indicates the value of the force on an electrically charged particle in the field. As mentioned above, the weak force rapidly falls off at a distance of 0.002 fm. In the field line model this could only be described by the mysterious disappearing of the field lines as illustrated in Fig. 4 on the left side. This totally contradicts the known behavior of field lines. In this model field lines only end on other charged particles, not spontaneously. In the case of the strong force that reaches a constant value at distances of about 1 fm new field lines have to emerge from somewhere to keep the field line density constant. This is also at odds with the known model. An attempt of illustration is given on the right side of Fig. 4.

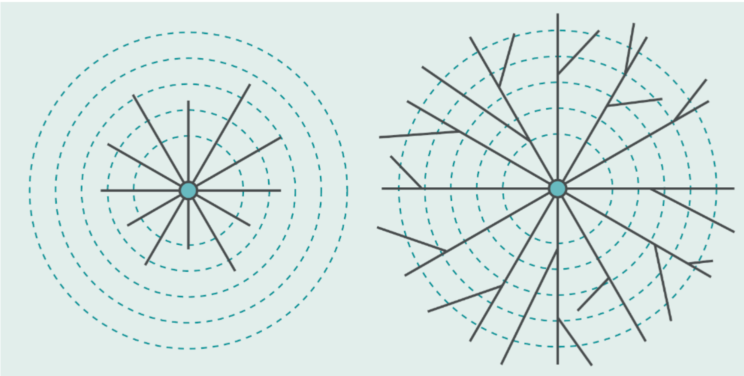

Figure 4. Visualization of the restricted range of the weak force (left) and the constancy of the strong force (right) with field lines [3].

Considering these problems, the field line model is not usable to describe the weak and the strong force. Furthermore, it is not possible to explain particle conversions or their production and annihilation with any concept known so far. Therefore, a new model has to be introduced, the messenger particles of the fundamental interactions. In this concept a messenger particle is emitted by one of the interacting particles and absorbed by the other, leading ether to an attractive or a repulsive force. A messenger particle of one of the fundamental interactions can only be emitted or absorbed by a particle that has the corresponding charge of the interaction. The reasons of the restricted ranges of the forces can be found in the properties of these messenger particles. The messenger particle of the electromagnetic interaction is the photon. Photons are massless particles. From quantum mechanics it can be deduced that the range of particles is correlated with their masses. Unfortunately, a professional derivation of this relation is out of reach at school, so it can only be given to students as an experimentally confirmed fact. Particles without mass have infinite range. That means that the electromagnetic force has infinite range, since the photon is massless. In contrast, the messenger particles of the weak interaction, the so-called Z and W particles, have very large masses. In fact, they belong to the heaviest elementary particles we know. This means they only have a very short range and this constrains the range of the weak interaction. There is an analogy to describe this phenomenon in the picture of field lines. It is possible to shield electric field lines by using a dielectric medium. Superconductors are perfectly dielectric and also diamagnetic. There is something like a superconductor for weak charges, which is homogenously present everywhere in the universe, the so-called Brout-Englert-Higgs field (BEHF). This field is weakly charged and so the W and Z particles interact with the field leading to the limited range of the weak force.

Unfortunately, even a didactically reduced physical explanation of the Higgs mechanism will be too complicated for most classes if there should not be a complete lack of physical correctness. Besides the analogy with superconductors there is a commonly used analogy explaining the Higgs mechanism using the behavior of people at a party under specific circumstances [7]. This widespread analogy can definitely be used. The widely-used statement, the Higgs particle would cause the masses of particles has to be avoided since not the particle is responsible, but the corresponding field. The Higgs particle has to be viewed as excitation of the BEHF and as our only accessible subject to study the properties of the field, since they match the respective properties of the Higgs particle.

The gaining of masses of matter particles can only be described by the Higgs mechanism by adding the experimentally measured values to the model. The sole masses that can be directly predicted by theory are the masses of the W and Z particles. The explanation of theses masses (and their extremely short range respectively) has been the reason why the Higgs mechanism was introduced in the first place in the 1960s. That means at this point we do not have any clue why matter particles have the masses we observe or even why they have masses at all.

Regarding the strong force, its restricted effective range has a different reason. The messenger particles of the strong interaction are called gluons. These particles are massless, which would allow an infinite range of the strong force. However, gluons possess a strong charge themselves. That leads to the possibility that gluons interact with each other resulting in attractive forces. Especially, it is possible that a gluon emits another one. Furthermore, as for every color-charged particle, gluons are liable to confinement. This self-interaction between gluons is the reason for the limited range of the strong force.

3.4 Visualizing particle interactions with Feynman diagrams

Of course, everyone who encounters scientific models and concepts seeks for a possibility to imagine and visualize them. A cautious attempt to do so with the concept of messenger particles is given in Fig. 5. The people on the boats represent the interacting matter particles. The thrown ball or the boomerang respectively represents the messenger particle causing a repulsive (ball) or attractive (boomerang) force on the matter particles.

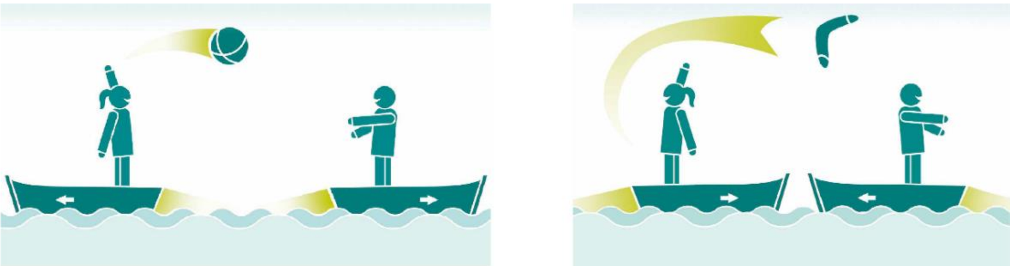

Figure 5. Classical analogy to messenger particles [3].

Like in every attempt to find classic analogies and pictures for processes that have to be described with quantum mechanics, this illustration lacks physical correctness in several points. First of all, the drawing is not to be understood in the way that the messenger particle is possessed by one of the matter particles and in the course of interaction is then given to the other one. Rather, the messenger particle is emitted by one particle and then absorbed by the other one. Furthermore, it cannot be told which the emitting and which the absorbing particle is. In addition, the pictures indicate that there are different messenger particles necessary to describe attractive and repulsive forces. This is not the case. The same messenger particle can cause an attractive and, under other circumstances, a repulsive force on matter particles. Besides, it is not possible to visualize particle conversions, production or annihilation in the given way. These are just some problems with this analogy on particle interactions via messenger particles.

In particle physics interactions are visualized with Feynman diagrams. But these diagrams are more than just simple illustrations. They are sketched calculation rules. From a Feynman diagram the probability of the visualized process and even the angular distribution of the participating particles can directly be calculated. Such calculations are clearly beyond the means of the suggested dealing with particle physics. But some simple estimations on rates of certain processes compared to others and therefore the discussion of selected research findings are definitely possible.

In these diagrams particles are represented by different types of lines (Fig. 6, left). Particles (e.g. u, d, e^- and ν) are indicated by straight lines with an arrow in the direction of time, antiparticles (e.g. $\bar{u}$, $\bar{d}$ e^+, $\bar{\nu}$) with arrows against it. The messenger particles of the weak (Z and W particles) and the electromagnetic interactions (photons, γ) are represented by wave lines and gluons (g), the messenger particles of the strong interaction, by curled ones.

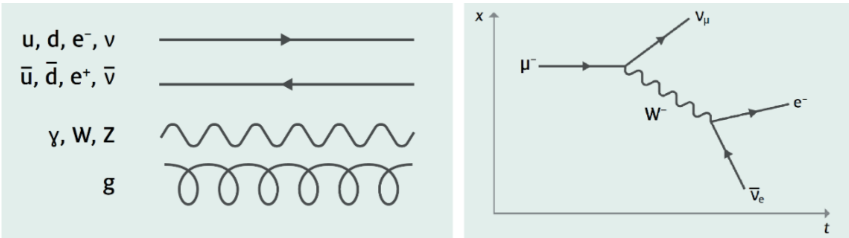

Figure 6. Line types for different particles in Feynman diagrams (left) and Feynman diagram of a muon conversion with a subsequent pair production (right) [3].

A complex Feynman diagram like that of a muon conversion with a subsequent pair production of an electron and an electron antineutrino shown on the right side of Fig. 6 can be created of simple building blocks, called fundamental vertices (sing.: vertex). A vertex is a point in a Feynman diagram where three lines meet. There are only four fundamental vertices necessary to construct any Feynman diagram that is suggested to be discussed at school (pure interactions of messenger particles are not included). These four building blocks for Feynman diagrams are shown in Fig. 7.

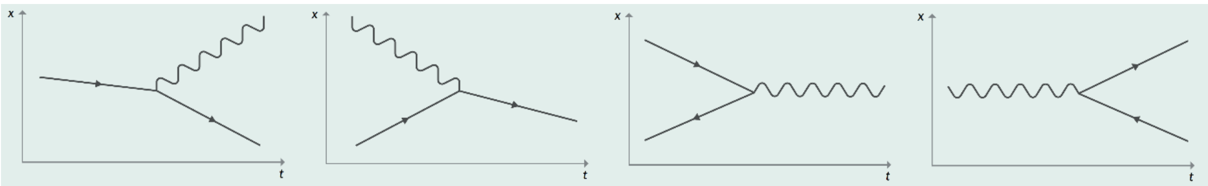

Figure 7. Fundamental vertices of Feynman diagrams [3].

The first fundamental vertex from the left shows the emission of a messenger particle by a matter particle. The emission in general causes the momentum of the matter particle to change (so there is a force). This is indicated by the knee of the matter particle's line. Furthermore, the matter particle can convert into another one, depending on the charges of the emitted messenger particle. Since at every vertex charges, momentum and energy are conserved, the emission of a messenger particle with any charge always leads to a matter particle conversion. The same is true for the absorption of a messenger particle by a matter particle as illustrated in the vertex second from left. The third vertex from the left shows the annihilation of one matter and one antimatter particle resulting in the production of a messenger particle. Conversely, a matter particle can convert into a pair of matter and antimatter particles. This pair production is shown in the right diagram.

Complex Feynman diagrams seem to require a lot of knowledge to be drawn or interpreted. On the other hand, it is desirable that students get used to working with them as soon as possible. It is useful to implement these graphs already in the early stages of the discussion of particle physics. To make this possible without students knowing all about messenger particles there can be used a simplified form. Fig. 8 on the left side shows a modified Feynman Diagram of the beta minus conversion. To illustrate that the converting quark here is part of a nucleon (proton p or neutron n respectively) the other two quarks are also included in the diagram. The permanent interactions between the three quarks as well as their color charges are not included.

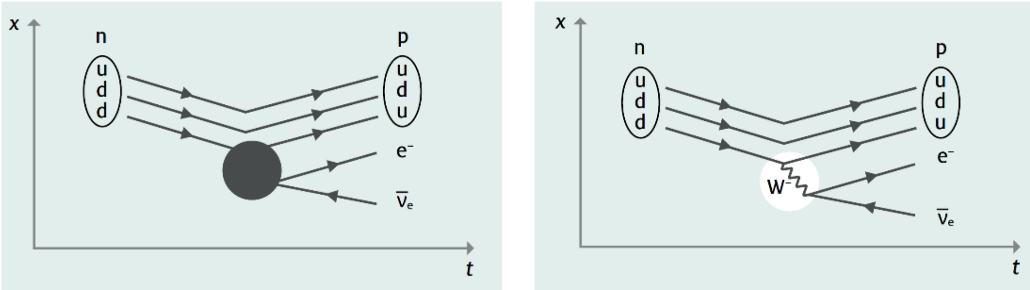

Figure 8. Feynman diagrams of the beta minus conversion with a black box covering the messenger particle (left) and without (right) [3].

This diagram has a black box hiding the actual interactions which cause the quark conversion and the production of the electron and the antineutrino. It shows the process as it is taught at school without knowing about the SM and the existence of messenger particles. Before the quarks have been introduced in class the diagram could be even more simplified by just drawing a neutron and a proton line. To fully understand why the quark (respectively the nucleon) conversion is happening and how other particles are being produced, messenger particles must be introduced. After that the inside of the black box can be revealed as shown on the right side of Fig. 8. The down quark converts into an up-quark by emitting a W^- particle (with negative electric and weak charge numbers). This particle almost immediately disappears while causing a pair production of an electron and an antineutrino. Another simplification can be made by replacing the time axis with another spatial axis just to get familiar with the line types first before introducing the actual Feynman diagrams.

4 CONCLUSION

Approaching particle physics by focusing on the basic concepts of today’s description of the elementary processes in our universe offers the possibility to show the general similarities in different physical phenomena. This may help students to see the big picture and to realize that essential concepts in the world of elementary particles, although it is not directly accessible for human senses, are very similar to a concept they already know, the concept of the electric charge. To point out that the SM is a theory that not only describes observed phenomena, but to some extent can predict them, may stimulate students to reflect the nature of science. Conveying the idea that in this context fundamental questions related to our universe still remain unanswered, will hopefully help to keep students interested in science beyond the physics education at school. This is a major goal of NTW and of all the people who have helped this concept to come alive and will help to refine it in future.

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