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1 The Standard Model

"Potentielle citation sans aucun rapport avec le sujet"

— Personne inconnue, *contexte à déterminer*

The SM of particle physics is a quantum field theory that postulates the existence of three generations of quarks and leptons interacting through three fundamental forces: electromagnetic, weak and strong. From the mathematical point of view the SM is a gauge quantum field theory that has internal symmetries of the unitary product group $SU(3) \times SU(2)_l \times U(1)$. The fourth fundamental force, namely the gravity, is not included in the SM. Nevertheless, since the magnitude of the gravity interaction is negligible on the microscopic scale, it has no effect on the precision of the SM predictions. The model has 18[1] free input parameters - the physical constants that can not be predicted from within the theory and must be measured experimentally. Evidently, the SM predictions are based on these parameters, so the better we know them - the better we can predict how nature behaves on the micro level. The free parameters of the SM are briefly described in section 1.1

A comprehensive description of the quantum field theory formalism goes beyond the scope of current dissertation and can be found in the corresponding textbooks [1], [2], [3], [4], [5], [6]. In the following sections a brief overview of key SM features and constituent parts is provided.

1.1 General composition and key parameters

In this section I will describe the fields that enter the SM. Their existence and interactions result in the three fundamental forces that are taken into account by the theory. The quanta of these fields are also called fundamental particles and possess a number of properties like mass, charge (or charges), spin etc (see figure 11). The fundamental particles are divided into two groups based on their spin: particles with integer spin are called fermions and those with half-integer spin are bosons.
Let's start from the fermion sector. According to the Pauli exclusion principle[7] two fermions can not occupy the same quantum numbers. This in turn, has a consequence that the fermions must occupy

[1] There are SM extentions that take into account the non-zero neutrino mass. Then the model gets 7 additional parameters, so their total number reaches 25. Although current thesis only considers the SM where neutrinos are massless.

a finite volume in space-time and as a result make up matter. Half of the fundamental fermions have color charge and therefore take part in strong interaction - they are called quarks. The other six fermions do not have color charge and are called leptons (from Greek "$\lambda\epsilon\pi\tau o\sigma$" meaning "little", as they are lighter than the quarks of the same generation). Different types of quarks and leptons are also called flavours, so there are 6 flavours of quarks and 6 flavours of leptons.

For some reason which is yet unknown the twelve elementary fermions make three generations. Particles in the second and third generations have exactly the same charge and spin as the particles of the first generation, but are heavier and also unstable. Normally the particles of higher generations quickly decay down to their lighter kins of the first generation and can only be observed in cosmic rays and particle accelerators. That means all the matter that surrounds us consists of four fundamental fermions of the first generation[2](the first column in Fig. 11).

The two quarks of the first generation are called up-quark and down-quark (or u-quark and d-quark for short). All the nuclei of the ordinary matter we see around are built with these two quarks. Quarks are capable of interacting through all three SM forces: electromagnetic, weak and strong. Electrons, muons and tau-leptons are sensitive to electromagnetic and weak interaction, while neutrinos can interact (and therefore to be detected) only through weak force. For this reason in particle physics the term "leptons" is sometimes used in a narrow sense refering to electron-like particles only. For all quarks and electron-like particles the antiparticles were observed as well as the corresponding anihilation phenomena. It is still not clear if neutrinos anihilate.

From our experience we know that matter interacts with itself. But within the SM fermions do not interact with each other immediately. The interaction is mediated by bosons-type particles. The SM includes five bosons: four vector bosons serving as force carriers for electromagnetic, weak and strong interactions, and a scalar Higgs boson whose role would be described in more detail in the corresponding subsection. The Higgs boson along with W and Z bosons are massive, while photos and gluons are massless.

The masses of the fundamental particles make 12 out of 18 free parameters of the SM[3].

As it was mentioned, bosons interact with fermions through fundamental interactions. The interaction depends on the charge of the interacting particles and on the type of the interaction itself. Each type interaction has a coupling constant that defines the scale of the interaction. However, weak coupling constant is redundant as i can be obtained from other parameters. So we add another two parameters to the SM: the strong and electriomagnetic coupling constants (the latter is also called the fine structure constant).

And the remaining four parameters are coming from the Cabibbo–Kobayashi–Maskawa matrix (CKM matrix), that contains the information on the strength of the flavour-changing weak interaction. [8].

An important feature of the Quantum Field Theory (QFT) is that particles also interact with physical

[2]Strictly speaking we already know that this is not completely true for the neutrinos, as they oscilate between the flavours due to their tiny mass. But in the SM neutrinos are assumed massless.

[3]The masses of W and Z bosons can be replaced by other parameters, e.g. weak mixing angle θ_W and Higgs potential vacuum expectation value (v.e.v.).

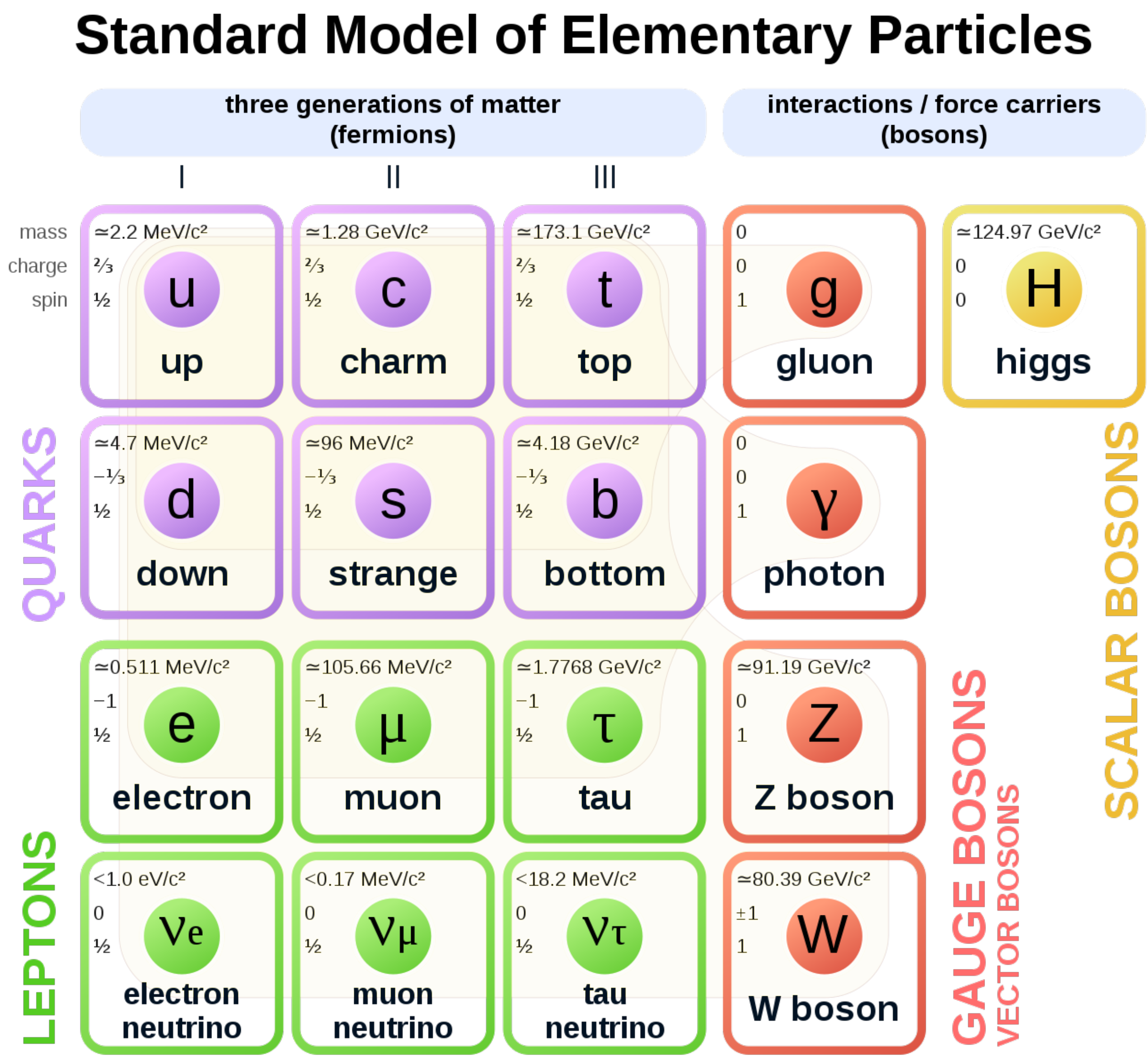

Figure 11: The list of particles that enters the SM[9].

vacuum. For instance, a charged particle polarises the physical vacuum, so the vacuum screens the charge of the particle[10].This interaction with virtual particles depends on the energy scale and so do the observed quantities like charge, mass etc. The SM is able to predict parameter evolution, so if the value of a cernain input parameter q_0 is known at the energy Λ_0 then it is possible to predict its measurable value q at the energy Λ. This changing of physical parameters is an integral part of the QFT and is called *renormalisation*[2] [11]. In the picture 12 the dependence of the SM coupling constants on the energy is shown.

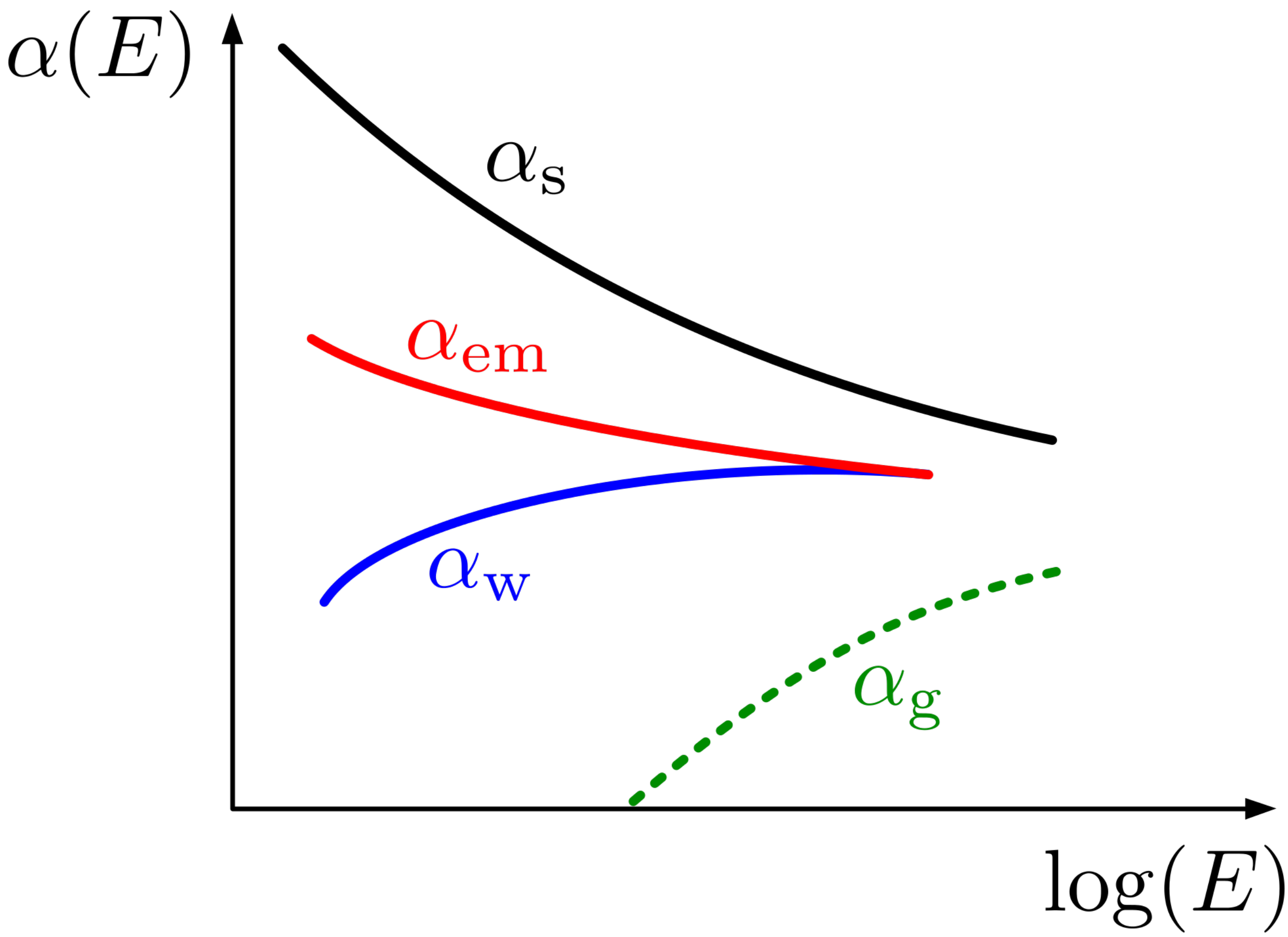

Figure 12: The evolution of the running constantsSM [12].

As we can see from picture 12 the strong coupling constant is getting smaller with the energy. This phenomena is called *the asymptotic freedom* [13], [14], [15].

1.2 Classical fields and gauge invariance principle

A consistent mathematical description of fields appears to be more challenging task compared to the description of physical objects that have definite size and shape. The derivation of Maxwell's equations has been a great success and allowed to obtain the first equations of motion of relativistic fields. It also subseqently led to understanding of special relativity [**einstein**], [**pointcarre**], [**lorentz**]. Although for a more general case of fields other than electromagnetic it would be very useful to adopt a more systematic approach like that of Lagrangian or Hamiltonian in classical mechanics.

It has turned out that for the relativistic case Hamiltonian approach was not quite convenient, as the dedicated role of time over other degrees of freedom was in discord with relativistic space-time unification. However it was found possible to describe the fields within the Lagrangian approach. In the classic mechanics the action of a mechanical system of i mechanical objects is defined as:

$$S = \int L dt = \int \left(\sum_i T_i - U_i \right) dt,$$

where T_i and U_i are the kinetic and potential energies of the i^{th} object. Considering that by definition a field exists in every point of space-time, we need to define the Lagrangian density such that $L = \int \mathcal{L}(\phi, \partial_k \phi, \dot{\phi}) d^3x$, where ϕ is a field and $\partial_k \phi = \nabla \phi$ - the field gradient, $\partial_k = \frac{\partial}{\partial x^k}$, k = 1, 2, 3. Here and further latin indices run through (1, 2, 3) and are used to denote spacial coordinates, while greek indices denote space-time coordinates and run though (0, 1, 2, 3). So the action would look like:

$$S = \int L dt = \int \mathcal{L}(\phi, \partial_\mu \phi, \dot{\phi}) d^4x, \tag{1.1}$$

Now we may use the principle of least action to obtain the equations of motion using the Euler-Lagrange formalism. Let's check it with the example of electromagnetic fields. The lagrangian density of electromagnetic fields in vacuum can be written like:

$$S = -\frac{1}{4} \int F^{\mu\nu} F_{\mu\nu} d^4x. \tag{1.2}$$

Electromagnetic tensor can be defined in terms of electric and magnetic field intensities: $F_{i0} = -F_{0i} = E_i$, $F_{ij} = \epsilon_{ijk} H_k$, where ϵ_{ijk} - antisymmetric Levi-Civita symbol. Alternatively $F_{\mu\nu}$ can be defined in terms of 4-potential A_μ:

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \tag{1.3}$$

Now we can safely apply the variational principle and putting $\delta S = 0$ obtain the Maxwell equations in vacuum:

$$\partial_\mu F_{\mu\nu} = 0. \tag{1.4}$$

Noticing the symmetries of the system and using the Noether's theorem[16] we can get the invariants of electromagnetic field. For example, translational symmetry in time and space ensures conservation of energy and momentum. Let's consider one of such symmetries, namely the fact that field potential can be shifted by a gradient of an arbitraty function $\alpha = \alpha(x^\mu)$:

$$\begin{aligned} &A_\mu(x) \to A'_\mu(x) = A_\mu(x) + \partial_\mu \alpha(x) \\ &F_{\mu\nu} \to F'_{\mu\nu} = \partial_\mu (A_\nu(x) + \partial_\nu \alpha(x)) = \partial_\mu A_\nu - \partial_\nu A_\mu = F_{\mu\nu}. \end{aligned} \tag{1.5}$$

Let's not consider the electromagnetic theory in the precence of charges and currents:

$$\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + j^{\mu} A_{\mu}. \tag{1.6}$$

Now we have an interaction of a field potential A_μ with 4-current $j^\mu = (-\rho, j^i)$. It turns out to be a general property of the field theories: the only form of interaction allowed is between a gauge field and a current. After applying the gradient field transformation and the least action principle we can obtain the corresponding coservation law:

$$\partial_\mu j^\mu = 0. \tag{1.7}$$

So this gradient symmetry[2] or as it is called more often gauge symmetry leads to the conservation of electric current. If a theory is invariant under gauge transformations then it is called a gauge invariant theory. As we have just seen electrodynamics is the simplest example of such a theory. Taking gauge symmetries into consideration [17] has played a huge role in the development of the SM.
Gauge degree of freedom can be constrained in arbitrary way by applying additional conditions on the gauge function. This is called fixing the gauge and becomes necessary after quantization. Any physical results must be gauve-invariant, i.e. must not depend on the gauge.

1.3 Quantum electrodinamics

Quantum Electrodynamics (QED) is a theory of interaction between light and electrically charged particles. Historically it was the first quantum field theory to reach good agreement between quantum mechanics and special relativity. QED vacuum has zero expectation value. Nowadays it is considered to be one of the most precise physical theories ever: theory predictions and experiment results agree up to $O(10^{-8})$. It has also served as a model for composition of the subsequent parts of the SM, describing other fundamental interactions.
Let's consider free Dirac field based lagrangian:

$$\mathcal{L} = \bar{\psi}(x)(i\partial\!\!\!/ + m)\psi(x), \tag{1.8}$$

where ψ and $\bar{\psi}$ are Dirac wave function and its complex conjugate respectively, $\partial\!\!\!/ \equiv \gamma_\mu \partial^\mu$, γ_μ is one of the four gamma-matrices and m is the mass of the Dirac field. Such a theory, though, would not be physically consistent. This reflects the fact the quantum nature of spin and spinor fields have to be treated as quantum fields. For instance, an attempt to calculate the energy of a Dirac field would lead to a contradiction: the energy would not be positively defined, as some spinors would have negative energies.
This lagrangian has an internal symmetry to the U(1) transformation: $\psi \to e^{-i\alpha(x)}\psi, \bar{\psi} \to e^{i\alpha(x)}\bar{\psi}$. Just like in the case of the electromagnetic field that leads to curent conservation: $j^\mu = \bar{\psi}\gamma^\mu\psi$. Now let's get the combined lagrangian of electromagnetic and Dirac fields, adding the interaction term:

$$\mathcal{L} = \mathcal{L}_{Dirac^{free}} + \mathcal{L}_{EM^{free}} + \mathcal{L}_{Interaction} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \bar{\psi}(x)(i\partial\!\!\!/ + m)\psi(x) - q\bar{\psi}\gamma^\mu A_\mu \psi, \tag{1.9}$$

where q represents the elementary electric charge. This lagrangian above is gauge invariant and can be rewritten in a more convenient form:

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \bar{\psi}(x)(i\not{D} + m)\psi(x), \tag{1.10}$$

where $D_\mu = \partial_\mu + iqA_\mu$ is a covariant derivative. If one considers space-time in the presence of a field as curved, then A_μ would play a role of connectivity. It must be noted that values like m and q meaning electron mass and charge[4] are the SM input parameters metioned in 1.1.

Further calculations are to be performed by the means of the quantum field theory formalism that treats interaction terms like a perturbation to the free fields, making power series expansion in the coupling constant. In the case of electrodynamics the coupling constant is quite small so good precision is reached soon.

PUT HERE ELECTRODINAMIC DIAGRAMS AND LOOPS Although the tree-level processes and diagrams were well unterstood by 1930th, the loop diagrams were properly explained only by the end of the 1940th making it possible obtain numerical results of the higher orders of power series expansion and achieve higher precision predictions for QED processes[18], [10], [19], [20], [21], [22], [23], [24].

1.4 Electroweak theory and the Higgs mechanism

All the fermions of the standard model are subject to weak interaction, so its importance for physical processes can not be underestimated. At low energy it manifests itself mainly through flavour-changing decays like beta-decay and muon decay. The electroweak theory was created in the end of 1950s[11][5][25] thanks to numerous experimental results that allowed to shape its properties. The theory assumed that the electromagnetic and weak fundamental forces are actually manifestation of the same field that has a gauge symmetry $SU(2)_L \quad U(1)$ and what has massive charged and neutral bosons. A few years later the structure of electroweak vacuum was explained along with the mechanism that has allowed the bosons to gain mass [26], [27]. Assuming this the lagrangian of the electroweak theory must consist of three parts[28]:

- Gauge fields that would mediate the interaction.
- Fermions that interact with gauge fields
- A scalar Higgs field with non-zero vacuum energy that breaks the SU(2) symmetry and couples to the fermions.

$$\mathcal{L}_{EW} = \mathcal{L}_{Gauge} + \mathcal{L}_{Higgs} + \mathcal{L}_{Fermions} \tag{1.11}$$

[4] Charge of the electron is related to the electromagnetic coupling constant.

1.4.1 Electroweak gauge fields

As it was already pointed our before, knowing the symmetries of a physical system allows one to compose the gauge fields lagrangian. The part with U(1) symmetry would look like the electromagnetic field from 1.2 having the hypercharge Y, a vector potential B_μ and a gauge coupling g_1. The SU(2) field would have 3 vector components $W_\mu^{1,2,3}$, three isospin operators I_1,I_2,I_3 and a gauge coupling g_2. We can pick the Pauli matrices σ^i as the representation of generators of the SU(2) group, then the structure constants are ϵ_{abc} - Levi-Civita symbol.

$$\begin{aligned}&\mathcal{L}_{\mathcal{G}} = -\tfrac{1}{4}B_{\mu\nu}B^{\mu\nu} - \tfrac{1}{4}W^a_{\mu\nu}W^{\mu\nu,a} B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu \\ &W^a_{\mu\nu} = \partial_\mu W_\nu - \partial_\nu W_\mu + g_2\epsilon_{abc}W^b_\mu W^c_\nu,\end{aligned} \tag{1.12}$$

where the term $g_2\epsilon_{abc}W^b_\mu W^c_\nu$ appears due to the non-Abelian nature of the SU(2) group (the generators don't commute).

1.4.2 Fermion sector

Each fundamental fermion generation expressed as left-handed doublets and right-handed singlets is a fundamental representation of the group $SU(2) \times U(1)$:

$$\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L, \begin{pmatrix}\nu_\mu \\ \mu\end{pmatrix}_L, \begin{pmatrix}\nu_\tau \\ \tau\end{pmatrix}_L, (e_R), (\mu_R), (\tau_R), \tag{1.13}$$

$$\begin{pmatrix}u \\ d\end{pmatrix}_L, \begin{pmatrix}c \\ s\end{pmatrix}_L, \begin{pmatrix}b \\ t\end{pmatrix}_L, (u_R), (d_R), (c_R), (s_R), (t_R), (b_R). \tag{1.14}$$

Their quantum states are classified using the following quantum numbers: weak isospin I_3, I, weak hypercharge Y. Their electric charge can be obtained using the Gell-Mann-Nishijima relation:

$$Q = I_3 + \frac{Y}{2}. \tag{1.15}$$

The fermions are divided by their chirality: only the left-handed particles take part in weak interaction. The left-handed fermion fields of each lepton and quark generation j

$$\psi_j^L = \begin{pmatrix}\psi^L_{j+} \\ \psi^L_{j-}\end{pmatrix} \tag{1.16}$$

make SU(2) doublets, with indices $\sigma = \pm$, while the right-handed fermions can be written as singlets:

$$\psi_j^R = \psi^L_{j\sigma}. \tag{1.17}$$

Like in the the electromagnetic case we can define the covariant derivative that would ensure the gauge invariance of the lagrangian:

$$D_\mu = \partial_\mu - ig_2 I_a W^a_\mu + ig_1 \frac{Y}{2} B_\mu, \tag{1.18}$$

with $I_a \equiv \frac{\sigma_a}{2}$, then fermion lagrangian takes the following form:

$$\mathcal{L}_{Fermions} = \sum_f \bar{\psi}^L_j i\gamma^\mu D_\mu \psi^L_j + \sum_{f,\sigma} \bar{\psi}^R_{f,\sigma} i\gamma^\mu D_\mu \psi^R_{f,\sigma}. \tag{1.19}$$

1.4.3 Higgs fields breaking the symmetry

The Higgs field is represented by single complex scalar doublet field $\Phi(x)$, that has 4 independent components. It spontaneously breaks the $SU(2) \times U(1)$ gauge symmetry, leaving the $U(1)_{EM}$ symmetry intact. The Higgs field doublet has the hypercharge $Y = 1$:

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x). \end{pmatrix} \tag{1.20}$$

The Higgs field lagrangian with non-zero vacuum expectation value:

$$\mathcal{L}_{Higgs} = (D_\mu \Phi)^+ (D_\mu \Phi) - V(\Phi) + \mathcal{L}_{Yukawa}. \tag{1.21}$$

The gauge invariance of the Higgs lagrangian is ensured in the traditional way by using the covariant derivative:

$$D_\mu = \partial_\mu - ig_2 I_a W^a_\mu + i\frac{g_1}{2} B_\mu. \tag{1.22}$$

Higgs potential contains the mass term and quartic self-interaction:

$$V(\Phi) = -\mu^2 \Phi^+ \Phi + \frac{\lambda}{4} partial_\mu (\Phi^+ \Phi)^2. \tag{1.23}$$

Valuum expectetion value $< \Phi >$ does not vanish:

$$< \Phi(x) >= \frac{1}{\sqrt(2)} \begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = \frac{2\mu}{\sqrt(\lambda)}. \tag{1.24}$$

Applying the unitarity gauge [29] we can constraint three out of four degrees of freedom of the Higgs field and rewrite the Higgs doublet in the following way:

$$\Phi(x) = \frac{1}{2} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}, \tag{1.25}$$

which leaves us with a physical real neutral scalar field $H(x)$ with

$$M_H = \sqrt(2)\mu. \tag{1.26}$$

This real field would couple to itself forming triple and quartic self-coupling vertices, to the gauge fields through the covariant derivatives and to the charged fermions, giving them mass. Yukawa term in lagrangian the unitary gauge:

$$\mathcal{L}_{Yukawa} = -\sum_f m_f \bar{\psi}_f \psi_f - \sum_f \frac{m_f}{v} \bar{\psi}_f \psi_f H, \tag{1.27}$$

where

$$m_f = g_f \frac{v}{\sqrt(2)} = \sqrt(2)\frac{g_f}{g_2} M_W. \tag{1.28}$$

Higgs coupling constants to the corresponting fermion flavour are denoted as g_f. This relation between the Higgs coupling and the mass of the W boson illustrates how mush the SM parameters are intertwined and in particular underlines the importance of the M_W measurement.

1.4.4 Physical interpretation of gauge fields and parameters

Higgs coupling to the gauge fields results in the following terms in the lagrangian:

$$\frac{1}{2}\frac{g_2}{2} v(W_1^2 + W_2^2) + \frac{v^2}{4}(W_\mu^3, B_\mu)\begin{pmatrix} g_2^2 & g_1 g_2 \\ g_1 g_2 & g_1^2 \end{pmatrix}\begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}. \tag{1.29}$$

In order to get the physical meaning of this expression let us make a transition to the basis of physical fields:

$$\begin{aligned} W_\mu^\pm &= \tfrac{1}{\sqrt{2}}(W_\mu^\mp \mp i W_\mu^\mp) \\ \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} &= \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & cos\theta_W \end{pmatrix}\begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}, \end{aligned} \tag{1.30}$$

where θ_W is called the weak mixing angle or the Weinberg angle. In the new basis expression 1.29 has transparent physical sense:

$$M_W^2 W_\mu^+ W^{-\mu} + \frac{1}{2}(A_\mu, Z_\mu)\begin{pmatrix} 0 & 0 \\ 0 & M_Z^2 \end{pmatrix}\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix}, \tag{1.31}$$

with

$$\begin{aligned} M_W &= \tfrac{1}{2} g_2 v \\ M_Z &= \tfrac{1}{2}\sqrt{g_1^2 + g_2^2} v. \end{aligned} \tag{1.32}$$

The mixing angle θ_W also has a very clear physical meaning:

$$\cos\theta_W = \frac{g_2}{g_1^2 + g_2^2} = \frac{M_W}{M_Z}. \tag{1.33}$$

With A_μ having a sense of electromagnetic potential its coupling to the electron must have a physical meaning of the electric charge $e = \sqrt{4\pi\alpha}$ we can express e in terms of gauge couplings:

$$e = \frac{g_1 g_2}{g_1^2 + g_2^2}, \quad g_2 = \frac{e}{\sin\theta_W}, \; g_1 = \frac{e}{\cos\theta_W}. \tag{1.34}$$

Thus the demonstrated Weinberg rotation fully replaces the original parameters g_1, g_2, λ, μ^2, g_f by another set of measurable values e, M_W, M_Z, M_H, m_f which are the input parameters of the SM.

1.5 Chromodynamics

The Quantum Chromodynamics (QCD) is a non-Abelian gauge theory that describes strong interaction. The QCD is symmetric under unbroken SU(3) color symmetry, so the interaction scheme is built in the same way as electromagnetic and electroweak theories. To preserve the gauge invariance a gauge field of gluons is introduced with 8 components, since SU(N) group has $\frac{N^2-1}{2}$ independent elements. The guons are massles vector bosons like the photons, although because of the non-Abelian nature of the gauge group they couple not only to the fermions but also to the other gluons. The gauge invariant QCD Lagrangian with kinetic term containing covariant derivative would look like:

$$\begin{aligned} \mathcal{L}_{QCD} &= -\tfrac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + \bar{\psi}_a (i(\gamma^\mu D_\mu)^{ab} - m\delta^{ab})\psi_b, \\ F^a_{\mu\nu} &= \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g_s f^{abc} A^b_\mu A^c_\nu, \\ D_\mu &= \partial_\mu + i g_s A^a_\mu t_a. \end{aligned} \tag{1.35}$$

with ψ being the quark field, m is the mass of the quark, a,b = 1, 2, ..., 8 are the color indices, g_s is the strong coupling constant, f^{abc} are the structure constants of the SU(3) group and t_a are the generators of the SU(3) group.

As it was already mentioned in 1.3 quantitative calculations in QFT treat particle interaction as a perturbation to the free field theory. Coupling constant is considered to be a small parameter so every next power of the coupling constant is much smaller than the previous. Thanks to the assyptotic freedom α_s gets small at higher energies and allows perturbative calculations. But at certain energy scale called $\Lambda_{QCD} \approx 200$ MeV QCD becomes non-perturbative. It means we may no longer assume that interaction is a small perturbation of the free fields. This phenomena is known as the *color confinement*.

Because of the color confinement we can only observe colorless objects like baryons and mesons, but not quarks and gluons. If a high-energetic parton gets torn out of a hadron then it creates an avalanche-like process creating quark-antiquark pairs until fully hadronizes (see pic. 13). Such an avalanche is called a hadronic jet.

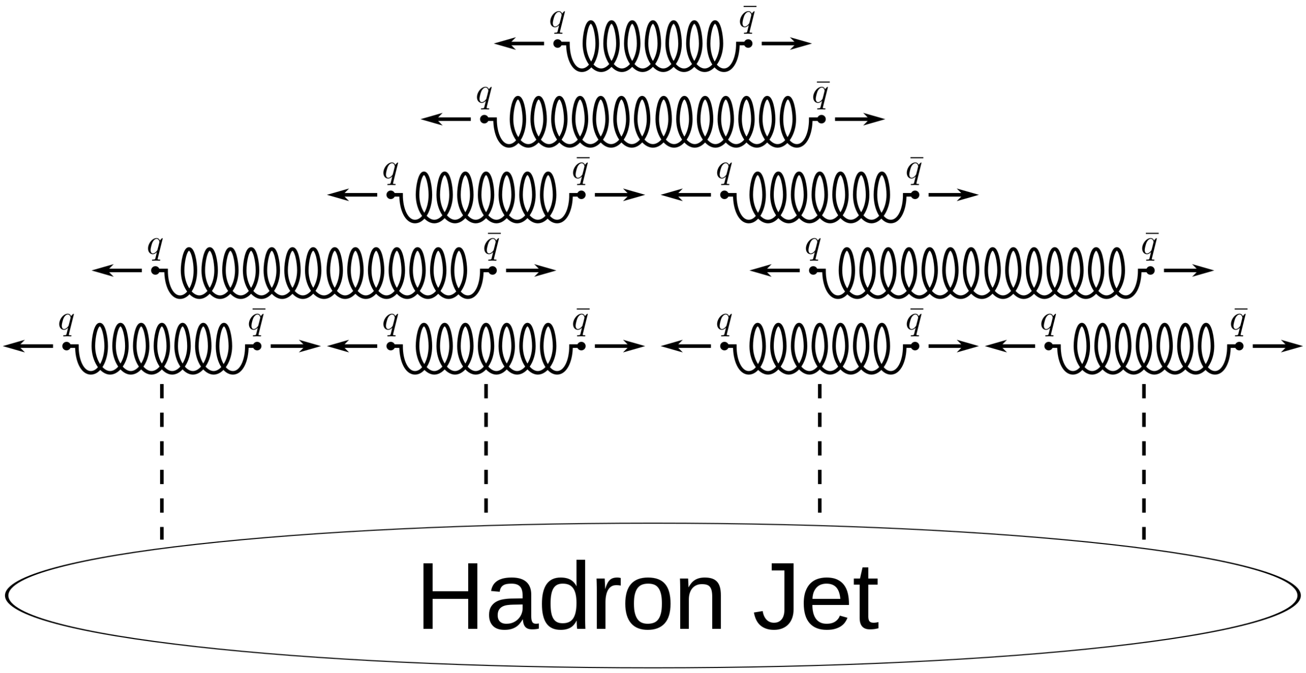

Figure 13: The formation of a jet [30].

Currently there is no viable physical theory that would describe QCD vacuum and low-energy behaviour of quarks and gluons. This also means that although nuclear forces are evidently resuduals of the QCD interaction of partons within the baryons, there is no continuity between the QCD and nuclear physics. Confinement and low-energy QCD remain to be an unsolved problem of modern physics.

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