A Conjecture
On the Origin of the Standard Model and Its Constants

Christoph Schiller

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Abstract

It is argued that a specific Planck-scale model of nature allows deducing the entire standard model of particle physics, including its fundamental constants. The conjectured model derives from an idea popularized by Dirac. The model, a specific realization of qubits, appears to explain the principle of least action, the Dirac equation, the observed particle spectrum of bosons and fermions, and the three observed gauge interactions. The specific models for each elementary particle appear to determine spin, quantum numbers, particle masses and mixing angles.

The conjecture appears to imply the observed propagators, the observed Feynman diagrams and all terms of the full Lagrangian of the standard model. Only specific interaction vertices are allowed. They correspond to the observed ones. Non-perturbative effects appear to be reproduced. Modifications or extensions of the standard model appear to be excluded. Predictions and tests are deduced from the conjecture. They agree with the observations performed so far.

The conjectured particle models imply specific Planck-scale processes that occur at interaction vertices. These processes in turn suggest ways to perform ab initio calculations of the coupling constants. An approximate calculation of the fine structure constant arises, as well as ways to improve it.

Keywords: standard model, strand conjecture, tangle model, fundamental constants, fine structure constant.

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Christoph Schiller, Motion Mountain Physikverein, Sperberstraße 32, 81827 München, Germany.
cs@motionmountain.net, tel. +49 89 44109266.

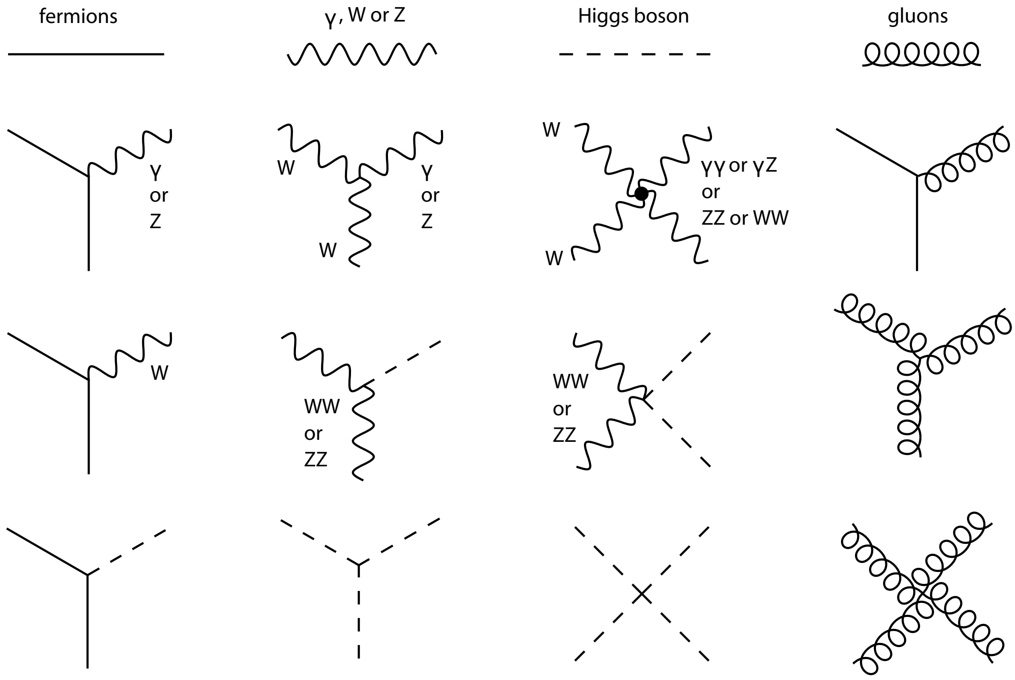

Figure 1: An overview of all the propagators and all the Feynman diagrams of the standard model. The complete Lagrangian of the standard model arises when these diagrams are completed with the particle spectrum, the equations of motion of free fields, the gauge group algebra, and the fundamental constants. All these structures and constants appear to arise from the strand conjecture.

1 The quest for the fundamental constants

At first sight, the Lagrangian of the standard model of particle physics seems rather involved. When the Lagrangian is described with the help of Feynman diagrams, it consists of 4 propagator classes and about 12 vertex classes, as illustrated in Figure 1. The complete list of propagators and vertices arises when all quarks, leptons and gluons, with all their properties, are included [1]. In the standard model Lagrangian, three questions are open:

- What determines the particle spectrum and the particle propagators?
- What determines the interactions, their gauge groups and the observed vertices?
- What determines the fundamental constants, i.e., the coupling constants, the mixing angles and the particle masses?

The so-called *strand conjecture* proposes to answer these questions using a single fundamental principle that describes nature at the Planck scale. The present paper summarizes the answer proposals made recently to the first and second question [2], proposes answers to the third, and provides tests for checking them. Given the ambition of the model, the tests are formulated as strictly as possible.

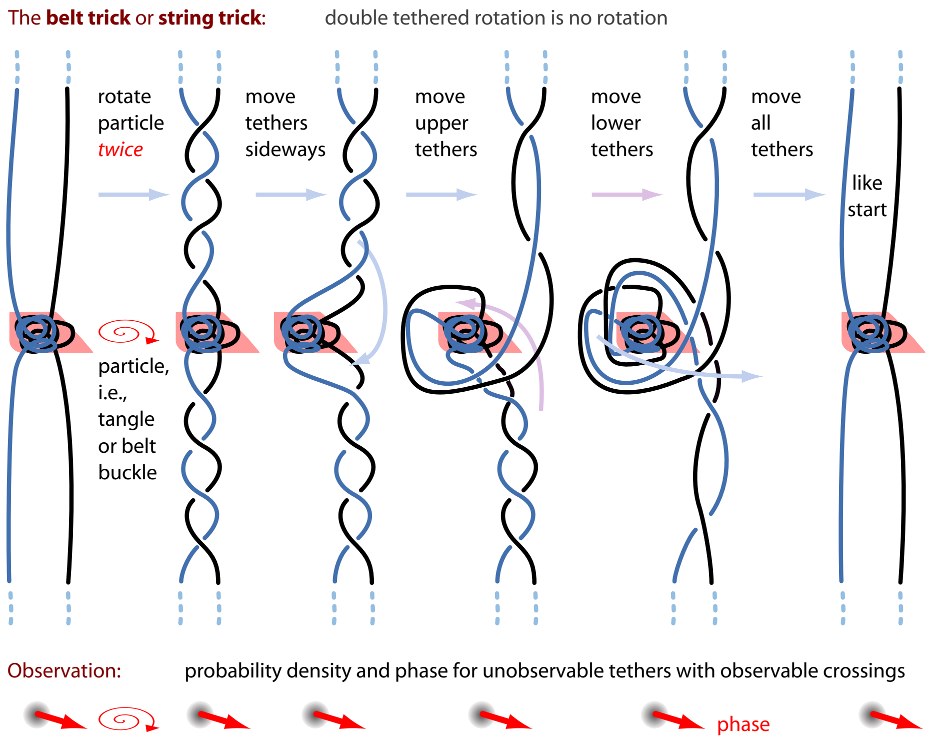

Figure 2: The *belt trick* or *string trick*: a rotation by 4π of a tethered particle, such as a belt buckle or a tangle, is equivalent to no rotation – when the tethers are allowed to fluctuate and untangle as shown. This equivalence allows the tethered particle to rotate forever. Untangling is impossible after a rotation by 2π only. This illustrates *spin 1/2*. In addition (not shown), when two tethered particles are interchanged twice, all tethers can be untangled. Untangling is impossible after a single interchange only. This illustrates *fermion statistics*. Both equivalences work for any number of tethers and assume that tethers are not observable, but crossing switches are.

2 The origin of the conjecture

When Max Planck discovered the quantum of action $\hbar$ in 1899, he found the underlying quantity that explains the observation of particles and of all quantum effects [3]. Bohr described quantum theory as consequence of the minimum observable action value $\hbar$ [4]. Pauli then added spin 1/2, and Dirac included the maximum energy speed c into quantum theory. From around 1929 onwards, Dirac also regularly mentioned the so-called *string trick* or *belt trick* in his lectures. With this trick, illustrated in Figure 2, he described spin 1/2 as result of tethered rotation, though he never published anything about it. When Gardner wrote to Dirac, he answered that the trick also shows that in nature, angular momenta below $\hbar/2$ are not possible [5].

Historically, tethers were the first hint that nature might be built from extended constituents that are unobservable but with crossing switches that are observable. It took several decades to understand that also the complete Dirac equation could be deduced from unobservable extended constituents: Battey-Pratt and Racey did so first, in 1980 [6]. It thus appeared that *every quantum effect* can be thought as being due to unobservable extended constituents. Independently, in 1987, Kauffman conjectured a direct relation between the canonical commutation relation and a crossing switch [7]. Again independently, reference [8] deduced the Dirac equation from extended constituents. It thus appeared that all quantum effects can be thought as being due to unobservable extended constituents whose crossing switches are observable. Because the term 'string' had acquired a different meaning in the meantime, the alternative term *strand* appeared more appropriate.

A second development also led to the strand conjecture. The surface dependence of black hole entropy implies that black hole properties are due to microscopic degrees of freedom that are extended. In the early twenty-first century, it became clear that Einstein's field equations can also be deduced from crossing switches of unobservable extended constituents whose crossings are observable [2]. It thus appeared that *every gravity effect* can be thought as being due to unobservable extended constituents.

A third development that supports the strand conjecture is the growing interest in qubits. Extended entities provide a simple and visual implementation of a qubit [2]. The strand conjecture can thus be seen as a conjecture on describing all of nature with the help of qubits.

Finally, a fourth train of thought led to the strand conjecture. A large part of quantum field theory can be summarized in the statement that observable action values W obey $W \geq \hbar/2$, and in the statement that observable energy speeds v obey $v \leq c$. De Sabbata and Sivaram [12] showed that the observable power values P in general relativity obey $P \leq c^5/4G$. Together, these three statements lead to a number of consequences. First, the Planck units are invariant, universal and encode fundamental aspects of nature. Second, equations of motion, such as the Dirac equation and Einstein's field equations, follow from the Planck units [4, 2]. Third, at Plank scales, nature is fundamentally simple, being described by limit statements. Finally, at Plank scales, a description of nature that only makes use of algebra and combinatorics appears possible; in other words, the Planck units suggest that a unified description of nature with a minimal amount of mathematics is possible. These four consequences are realized by the strand description of nature [2].

3 The strand conjecture and its fundamental principle

The strand conjecture states that everything in nature – matter, radiation, space, and horizons – is made of strands that fluctuate at the Planck scale. More precisely, the strand conjecture can be formulated in the following way:

> Space is a *network* of strands. Horizons are *weaves* of strands. Particles are *tangles* of strands. Though strands are unobservable, crossing switches are observable. Crossing switches determine the Planck units, and in particular $\hbar$, as illustrated in Figure 3.

Apart from their crossing switches, strands have no observable properties. It is easiest to imagine strands as having Planck-size radius, in order to visualize the minimum length. Strands cannot interpenetrate and never form an actual crossing. When the term *crossing* is used in the present context, only the

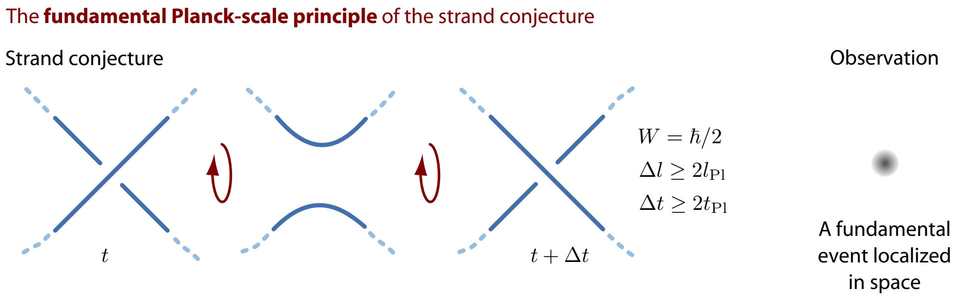

Figure 3: The fundamental principle of the strand conjecture concerns the simplest observation possible in nature: the almost point-like fundamental event results from a *skew strand crossing switch* at a given position in three-dimensional space. The strands themselves are not observable, are impenetrable, and are best imagined as having Planck size radius. The switch defines the action unit $\hbar/2$. The Planck length and the Planck time arise, respectively, from the smallest and from the fastest crossing switch possible. The crossing (switch) can be taken as the strand realization of a qubit.

two-dimensional projection shows a crossing. In three dimensions, strands are *always* at a distance, as illustrated in Figure 3 and Figure 4. In particular, crossing *switches* cannot arise via strand interpenetration, but only via strand deformation.

The fundamental strand principle illustrated in Figure 3 can be seen as visualizing the two possible states of a *qubit*. In this view, the strand conjecture describes nature with qubits.

In the strand conjecture, all physical observables – action, momentum, energy, mass, velocity, length, surface, volume, tension, entropy, field intensities, quantum numbers, etc. – arise from combinations of crossing switches, or qubits. All physical observables are thus emergent.

The strand conjecture allows to deduce black hole entropy, black hole evaporation, spatial curvature, as well as full general relativity from *woven* strands fluctuating at the Planck scale. The gravitational aspects, including the emergence of continuous three-dimensional space from a strand network, have been deduced and explored in a previous paper [2] and are not discussed in the following. Only one result is worth mentioning in the present context: in the case of flat space, fluctuating strands yield Poincaré symmetry. Cosmology arises from the *full* strand conjecture; it states that nature consists of a *single strand* that connects all particles to the cosmological horizon. The consequences of strand cosmology will be explored in a subsequent paper.

In flat space, fluctuating strands forming *rational tangles*, i.e., unknotted tangles, appear to imply wave functions, the Dirac equation, and the gauge groups U(1), broken SU(2), and SU(3), all without alternative [2]. Rational tangles of strands also appear to imply the observed particle spectrum and all the Feynman diagrams of the standard model – again without alternative. The deduction of quantum field theory and the Lagrangian of the standard model is summarized in the following sections. Surprisingly, *almost the whole deduction can be performed with the help of tangle diagrams only.* Effectively, this means deriving the entire standard model from qubits.

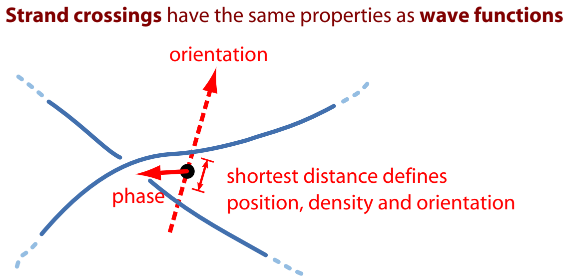

Figure 4: The geometry of a (skew) strand crossing suggests a relation to wave functions. In both cases, absolute phase around the orientation axis can be chosen freely. In contrast, phase differences due to rotations around that axis are always uniquely defined.

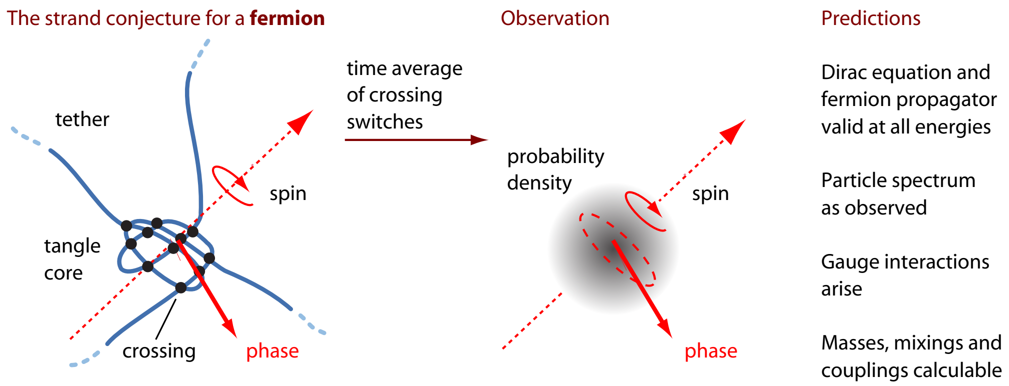

Figure 5: In the strand conjecture, the wave function and the probability density are due, respectively, to crossings and to crossing switches at the Planck scale. The wave function arises as time average of all crossings in fluctuating tangled strands. A Hilbert space also arises. The probability density arises as time average of the crossing switches in a tangle. The tethers – connections that continue up to large spatial distances – generate spin 1/2 behaviour under rotations and fermion behaviour under particle exchange. The tangle model ensures that fermions are massive and move slower than light. The quantum phase arises as sum of all crossing phases.

4 From the strand conjecture to fermions and their propagators

This section summarizes how strands lead to the Dirac equation and to the fermion propagator [2, 8].

Once crossing switches are taken as the basis of the description of nature, one notes that a skew strand crossing allows defining the same observables that characterize a wave function. This relation is illustrated in Figure 4. A skew strand crossing allows defining density, orientation, position, and phase. As summarized below, the freedom in the definition of the phase of crossings turns out to be at the origin of the freedom of gauge choice.

In the strand conjecture, elementary fermions are fluctuating *rational* tangles, i.e., tangles that are unknotted. Their average crossing distribution is the wave function. The result of the averaging is illustrated in Figure 5. For a complete tangle of strands, the density, the phase, and the two (spin) orientation angles of each crossing define, after averaging, the two complex components of the Dirac wave function Ψ for a particle and, for the mirror tangle, the two complex components of the antiparticle wave function.

As Dirac demonstrated in his lectures [5] using a system equivalent to that of Figure 2, a tethered core behaves like a spin 1/2 particle under rotation. Tethers also imply that cores behave as fermions under exchange, because a double exchange of tethered cores can be undone by rearranging the tethers only; in contrast, this is impossible after a single exchange. All this applies independently of the number of tethers a particle has. Given that tethered particles reproduce spin (rotation) and particle exchange (a double translation), the suspicion arises that every quantum motion can be described with tethers.

Indeed, Battey-Pratt and Racey showed [6] that every tethered massive quantum particle – a tangle core in the case of the strand conjecture – is described by the Dirac equation for free particles. In particular, a moving and free quantum particle is described by a moving and constantly rotating tangle core. In the language of wave functions: when the region of maximum density advances, the phase rotates. In the language of Feynman diagrams: tangles with rotating cores model fermion propagators.

The deduction by Battey-Pratt and Racey can be summarized with help of the fundamental principle in the following concise manner. The Dirac equation arises because crossings switches are defined to obey $v \leq c$ and $W \geq \hbar/2$. In addition, crossing switches naturally define four components for spin 1/2 wave functions: spin up and spin down, both for particles and antiparticles; antiparticles are defined as mirror tangles of particles. As a result of these correspondences, the Dirac equation holds.

In fact, all of relativistic quantum theory can be reproduced with strands. A detailed discussion of the equivalence has been given elsewhere [8]. Simply speaking, when strands are unobservable, but crossing switches are not, the Dirac equation turns out to be a differential version of Dirac's string trick. Probabilities, interference, entanglement, mixing, decoherence, antiparticles and all other quantum effects appear, without modification. All these effects are reproduced fully – without any addition or modification – with the help of strands [8].

In summary, in the tangle model, free elementary fermions obey the Dirac equation [6, 8]. Equivalently, tangles explain the Dirac Lagrangian. Or again: qubits made of strands explain the Dirac equation. In particular, in the strand conjecture, the principle of least action becomes the "principle of fewest crossing switches". The validity of the Dirac equation also implies: *the usual expression for the fermion propagator follows from strands.*

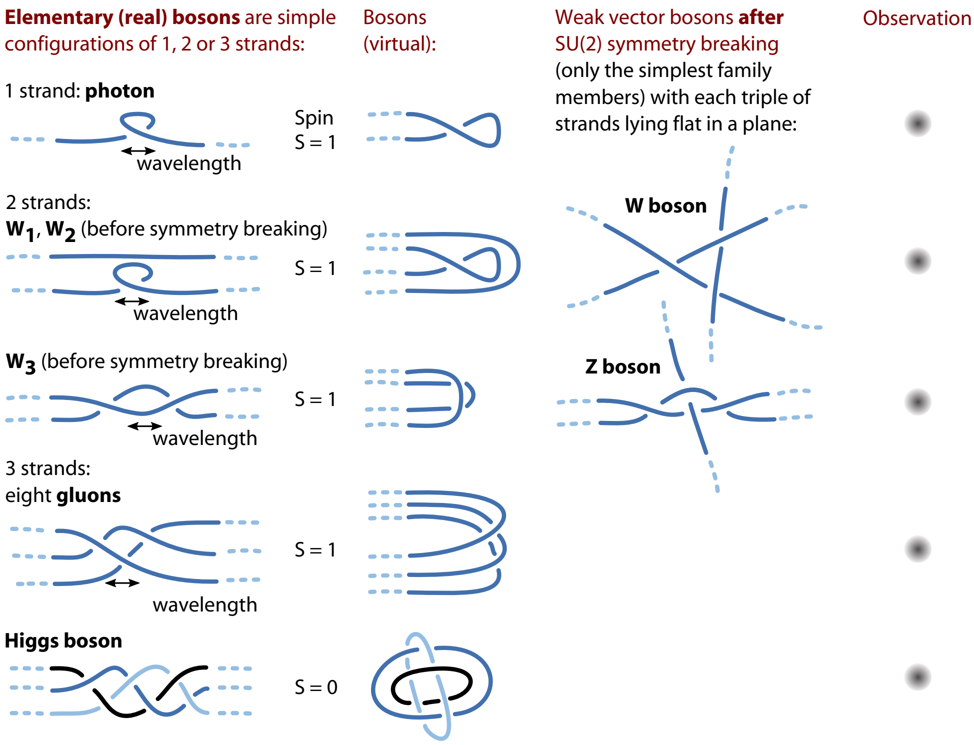

Figure 6: The tangle models for the elementary bosons. These tangles determine the spin values, the corresponding propagators, and ensure that the massless photons and gluons move with the speed of light. No additional elementary bosons appear to be possible.

The strand conjecture further implies that a fermion propagator line in a Feynman diagram shows the motion of the centre of a tangle core. In the conjecture, particles are not actual points; the smallest possible propagator line width is given by a moving tangle core that is tight, and thus has a diameter of a few Planck lengths. The approximation of a vanishing strand radius leads to the appearance of infinities in perturbation theory; the Planck-size, thus finite, strand radius cures the issue. The fundamental principle also implies that Planck units are limits to physical observables in the quantum domain [8].

Strands imply and predict the lack of deviations from quantum theory. *Finding an energy or situation for which quantum theory is not valid or finding an elementary particle whose energy is larger than* $\sqrt{\hbar c^5/4G} = 3.05 \cdot 10^{18}\,\mathrm{GeV}$ *would falsify the strand conjecture.* One new result also arises. The conjecture that elementary particles are rational tangles implies that their spectrum, their mass and their properties are not free, but are *fixed* by their tangle structure.

5 Predictions about the particle spectrum

This section summarizes how strands lead to the particle spectrum. Both bosons and fermions arise [2].

Elementary bosons can be made of one, two or three strands. More strands imply composite particles,

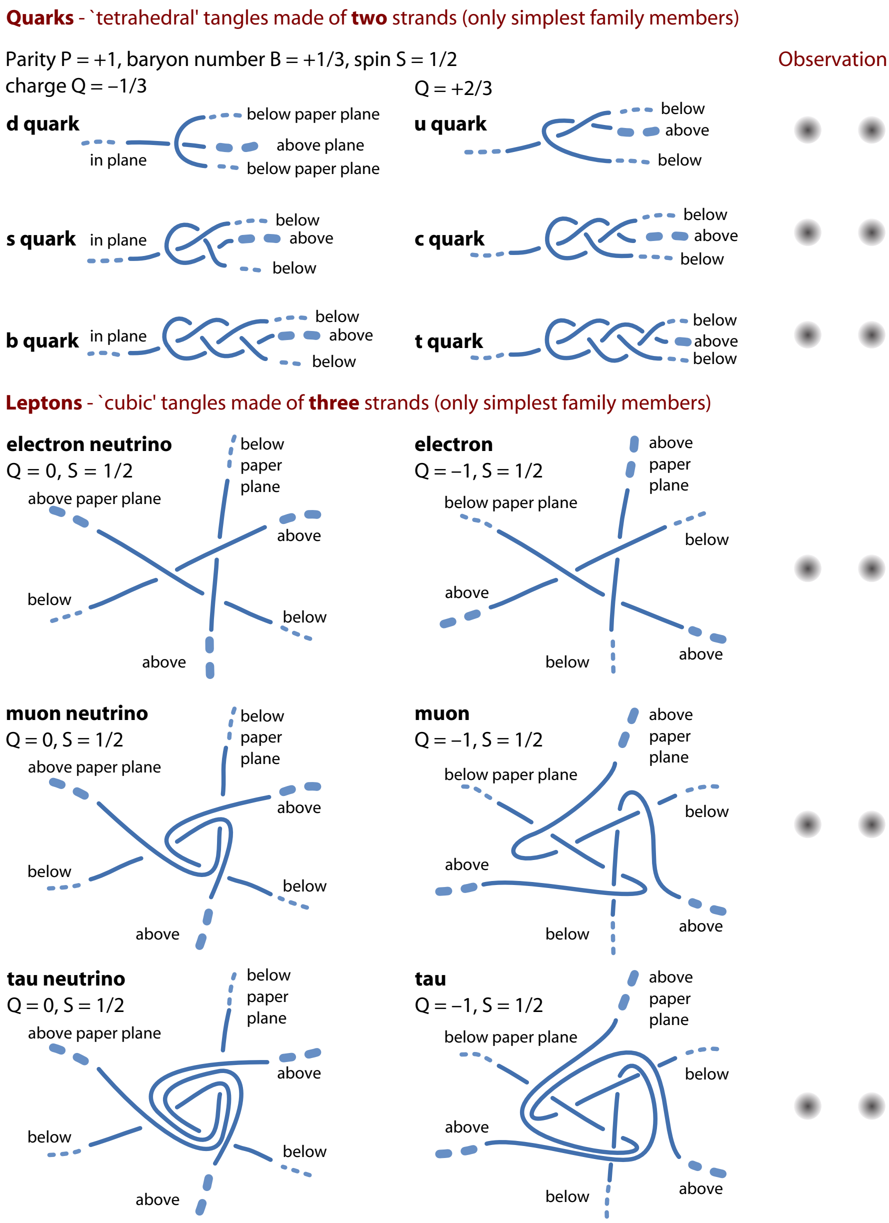

Figure 7: Elementary fermions are described by rational, i.e., unknotted tangles. Their structures lead to coupling to the Higgs, as illustrated in Figure 11, produce positive mass values, and limit the number of generations to 3. The tangles determine the specific fermion propagators. The tethers of the quark tangles follow the axes of a tetrahedron. The neutrino cores are simpler when seen in three dimensions: they are simply twisted triples of strands. The tethers of all lepton tangles approach the three coordinate axes at large distances from the core. No additional elementary fermions appear to be possible.

as playing with real strands show. As argued below, one-stranded bosons correspond to photons, three-stranded bosons to gluons or to the Higgs, and two-stranded bosons to the W_1, W_2 or W_3. After symmetry breaking, when two-stranded boson tangles incorporate a vacuum strand, they yield the three-stranded W and the Z boson. The boson tangles are given in Figure 6. No additional elementary boson appears possible. Photon and gluon tangles are massless, because they can rotate unhindered, whereas the W and the Z boson have mass.

The Higgs boson is a braid made of three strands. For all massive particles, the mass value is influenced by – single or multiple – Higgs boson addition to a simplest particle tangle. This process is illustrated in Figure 11. The figure also shows that the Higgs couples to itself; it is thus massive. Massive particles – fermions or bosons – are thus described by an infinite 'family' of tangles that contain the simplest core, the core plus one Higgs braid, the core plus two braids, etc. In contrast, massless particles are described by a single tangle, because no 'addition' of a Higgs braid to cores of massless particles is possible.

Elementary fermions can be made of two or three strands. Again, four or more strands imply composite particles. One-stranded particle tangles cannot have spin 1/2 or mass because the belt trick does not work for them. Two-stranded fermions are quarks, three-stranded fermions are leptons. Their tangles are given in Figure 7. Both quarks and leptons are limited to three generations by the coupling to the Higgs (and the three-dimensionality of space). The quark tangle assignments appear to reproduce the quark model of hadrons [2, 8], including the correct retrodiction of which mesons violate CP and of all meson and hadron mass sequences. The neutrino assignments explain their handedness. Neutrino are massive. No additional elementary fermions appear possible.

The tangles of the elementary particles also explain their parities (from the mirror behaviour of their tangles and their core rotation), their spin (from the rotation behaviour of their core), their baryon number and lepton number (from the number of strands), and their other flavour quantum numbers (from the quark content). Strong and weak charges are introduced in reference [8]; electric charge is defined and explored in detail below. In brief, in the strand conjecture, *all observed quantum numbers are topological properties of particle tangles.*

In summary, tangles lead to the fermion and boson spectrum found in nature. Equivalently, tangles lead to the kinetic terms for the fermions and the bosons of the standard model Lagrangian, as well as to the Higgs coupling terms. For the gauge bosons, the appearance of the gauge group structure is summarized below. *The discovery of any new elementary particle – such as a fourth fermion generation, an additional Higgs boson, an additional gauge boson, a WIMP, a sterile neutrino, a leptoquark, an axion, or a yet unknown dark matter particle – would falsify the tangle model.*

6 Predictions about particle masses and mixing angles

In quantum theory, particle mass is the constant that fixes the dispersion relation, i.e., the relation between rotation and displacement. More specifically, the mass value relates the rotation frequency and the wavelength of a quantum particle.

In the strand conjecture, the mass value is determined by the relation between rotation and displace-

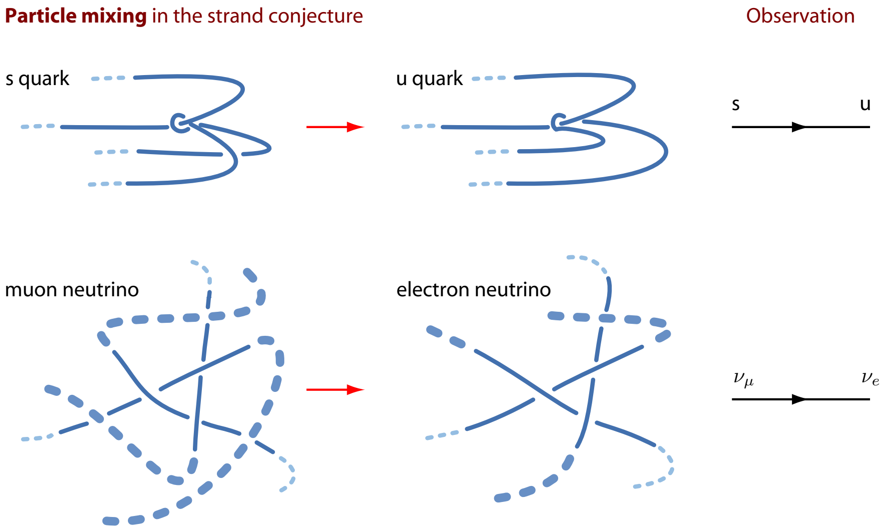

Figure 8: Particle mixing during propagation is due to tangle untangling or tangling.

ment of the tangle core. The tangle core rotates and advances through the vacuum network of strands. As a result, more complex tangles have more difficulties and thus have higher mass. In addition, all elementary particles have mass values *much smaller* than the Planck mass. Indeed, a Planck mass would correspond to a crossing switch per Planck time; a tethered core however, has a much lower rotation frequency. The tangle tethers have to move as illustrated in Figure 2. This process has a low probability and thus generates a small number of crossing switches per time. Therefore, particles have a mass value much smaller than the Planck mass.

In the strand conjecture, the mass values of particles are thus predicted to be unique, fixed, positive, constant in time and space, and much smaller than the Planck mass. Mass values are predicted to depend on the tangle details, and to be calculable. In particular, *more complex* tangles have *higher* mass. This relation yields the correct mass sequences for all hadrons and predicts normal mass ordering for neutrinos. The exceptional mass sequence for the down and the up quark – whose mass values do not follow the tangle complexity rule – seems to arise from the specific details of the down quark tangle and the resulting Yukawa coupling to the Higgs. This point is still open.

An estimate of tether shape probabilities, using a typical core circumference of around 6 Planck lengths, yields upper limits for the mass m of an elementary particle with four tethers and with six tethers of about

$$m_4/m_{\rm Pl} < ({\rm e}^{-6})^4 \approx 10^{-10} \ \text{ respectively, } \ m_6/m_{\rm Pl} < ({\rm e}^{-6})^6 \approx 10^{-15}. \tag{1}$$

However, experimental values are lower. They lie between about $4 \cdot 10^{-30}$ for neutrinos and about $3 \cdot 10^{-17}$ for the top quark. Using the *ropelength* of tangles as measure of tangle complexity, all mass *sequences* among elementary particles except the down quark (see [2]) and all hadron mass sequences are predicted correctly. The down quark is an exception. The mass of the down quark is higher than expected from its ropelength alone because the four-fold tangle symmetry of its tangle leads to a higher coupling (probability) to the Higgs boson than all the other quark tangles, for which this symmetry is absent.

It is simpler to estimate mass *ratios* of elementary particles. This can be achieved by comparing the (rope)length of tight tangle cores with the same number of tethers. The estimated Higgs/Z boson and W/Z boson mass ratios are compatible with measurements [8].

Estimating the rotation probability of a tangle core more precisely will allow calculating the mass value of the corresponding particle. So far, however, this calculation remains an open challenge – though it is one of the best tests for the model, especially in the case of neutrinos. One reason for the difficulty is that crossing switches arise rarely; mass is a small effect. A second reason is that fluctuation probabilities for extended entities are difficult to estimate. Therefore, precise mass calculations are not easy; this applies to neutrino masses in particular.

In nature, fermions show an additional effect. Quarks *mix* among each other, and so do neutrinos. In the strand conjecture, the mixing is due to changes in the type of tangle core during propagation. A general impression is given in Figure 8. The change in the tangle core is due to a change in tether shape; in the tangle model, the difference between mass eigenstates and weak eigenstates is due to different tether shapes. In a weak quark eigenstate (all tethers in a plane), the switch from one quark flavour to the other is easier. Again, estimating the probability for such a process will allow calculating the mixing angles. Also this calculation remains an open challenge. At present, the strand conjecture just predicts that both the CKM and the PMNS mixing matrices are non-trivial, with non-vanishing CP phases [2], unique, constant in time and space, running with energy, and unitary. This is observed.

In summary, localized tangle cores lead to positive mass, and lepton and quark tangles lead to mixing. In other terms, the exact propagators of all elementary fermions and all massive elementary particles arise in the tangle model. *Unusual propagators, Majorana neutrinos, non-normal ordering of neutrino mass values, particle masses or mixings that vary across the universe, or a non-unitary mixing matrix would falsify the tangle model.*

7 Predictions about gauge interactions

This section summarizes how strands lead to the three observed gauge groups, as explained in [2].

Given that particles are tangles, the following connection arises, illustrated in Figure 9: Interactions, and thus interaction vertices, are *tangle core deformations.* In particular, the deformation of a localized tangle core changes the phase of a particle. This is the strand description of how an externally applied field changes the phase of a fermion wave function.

Deformations of spatial structures are described by gauge groups. This connection becomes even more meaningful through a mathematical result from 1926 due to Kurt Reidemeister. He showed that all tangle core deformations are composed of three basic types: twists, pokes and slides. Together they are now called the *Reidemeister moves*. The three Reidemeister moves have an important property that is not well known [2]:

Tangle core deformations determine the observed gauge groups U(1), broken SU(2) and SU(3).

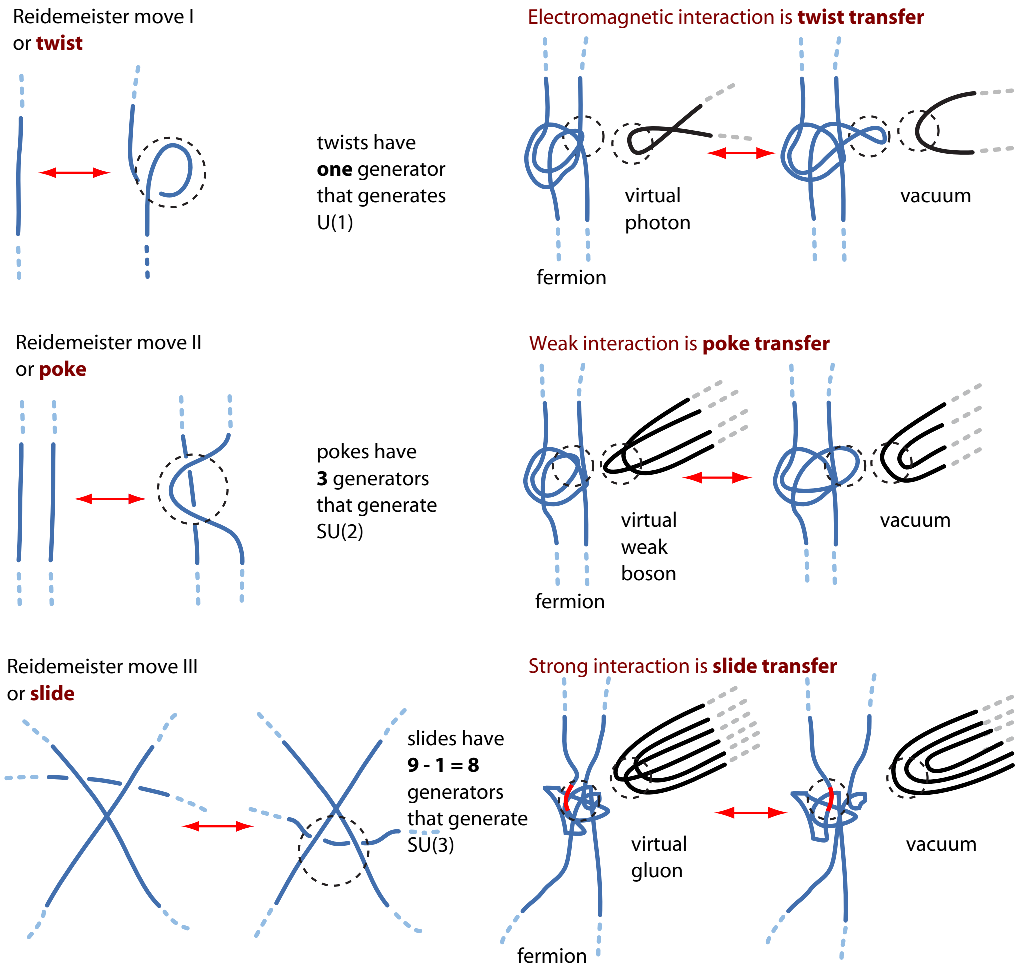

Figure 9: The three Reidemeister moves, i.e., the three possible deformations of tangle cores, determine the generators of the observed gauge interactions and thus determine their generator algebra [2, 8]. The generators rotate the regions enclosed by dotted circles by π. The full gauge groups arise by generalizing these rotations to continuous angles. The relation of these strand deformations to observation is illustrated, for QED, in Figure 12.

In particular, U(1) arises because twists can be generalized to arbitrary angles and concatenated. Also, a double twist can be rearranged to no twist at all, so that the non-trivial topology of U(1) arises. Electric charge is defined below, in section 12, as 1/3 of the sum of chiral crossings. Electric fields are volume densities of virtual photons, i.e., of twists. Magnetic fields are flow densities of twists. Electric charge is conserved. The Maxwell equations follow [9, 10] and so does the free electromagnetic field term of the standard model Lagrangian [2, 8]. Due to the fundamental principle, electric fields are limited by $E \leq c^4/4Ge = 1.9 \cdot 10^{62}\ \mathrm{V/m}$ and magnetic fields by $B \leq c^4/4Ge = 6.3 \cdot 10^{52}\ \mathrm{T}$.

SU(3) arises because slides reproduce the algebra of the eight generators of SU(3). This is the main result of the previous paper [2]. The full gauge group SU(3) arises because slides can be seen as local rotations by π, which can be generalized to arbitrary angles or phases. No CP violation occurs in the strong interaction. The strong CP problem is solved automatically. Color charge is orientation of the three-ended side of a quark tangle in space. Color fields are densities of virtual gluons. Together with the SU(3) structure, the free gluon Lagrangian follows.

SU(2) arises because pokes can be generalized to the three independent rotations of a belt buckle in the belt trick. The rotations of a belt buckle around the three coordinate axes by the angle π yield the generator algebra of SU(2). Rotations around the three axes by arbitrary angles yield the full SU(2) gauge group. Strands imply that only massive fermions can exchange weak bosons. Due to the tangle structure of particles, SU(2) breaking arises, and so does maximal parity violation. These effects occur because core rotations related to spin 1/2 interfere with core deformations related to SU(2) of the weak interactions. All these effects together yield the (electro-)weak Lagrangian. The details have been explored before [2, 8].

In summary, given that photons and gluons are massless, and that W and Z bosons are massive, the propagators for all gauge bosons are recovered. Strands imply the gauge group algebra of the three gauge interactions. Equivalently, the pure boson terms in the Lagrangian of the standard model are recovered, including the interaction terms among bosons, as defined by the gauge groups. Given that only three Reidemeister moves exist [11], the tangle model also predicts that there is *no* additional or different gauge group in nature. *The discovery of a new fundamental interaction, of grand unification, of a higher gauge group, of electromagnetic fields stronger than the Planck limits, of an incorrect running of particle properties with energy, or of any other deviation from QED, QCD or the weak interaction would falsify the strand conjecture.*

8 Predictions about the standard model Lagrangian

This section summarizes how strands lead to the known interactions – and to no other ones [2].

Elementary gauge bosons, after SU(2) breaking, are made of one or three strands. Among elementary gauge bosons, massless bosons have no localized core. Additional elementary gauge bosons do not exist. To each elementary boson there is a corresponding deformation of fermion tangle cores. The detailed strand deformation is given in reference [2]. The deformations follow the algebra of the generators for each gauge group. The gauge structure of the generators of tangle deformations – summarized in Figure 9 – implies that the emission and absorption of gauge bosons is exactly as described in the interaction terms

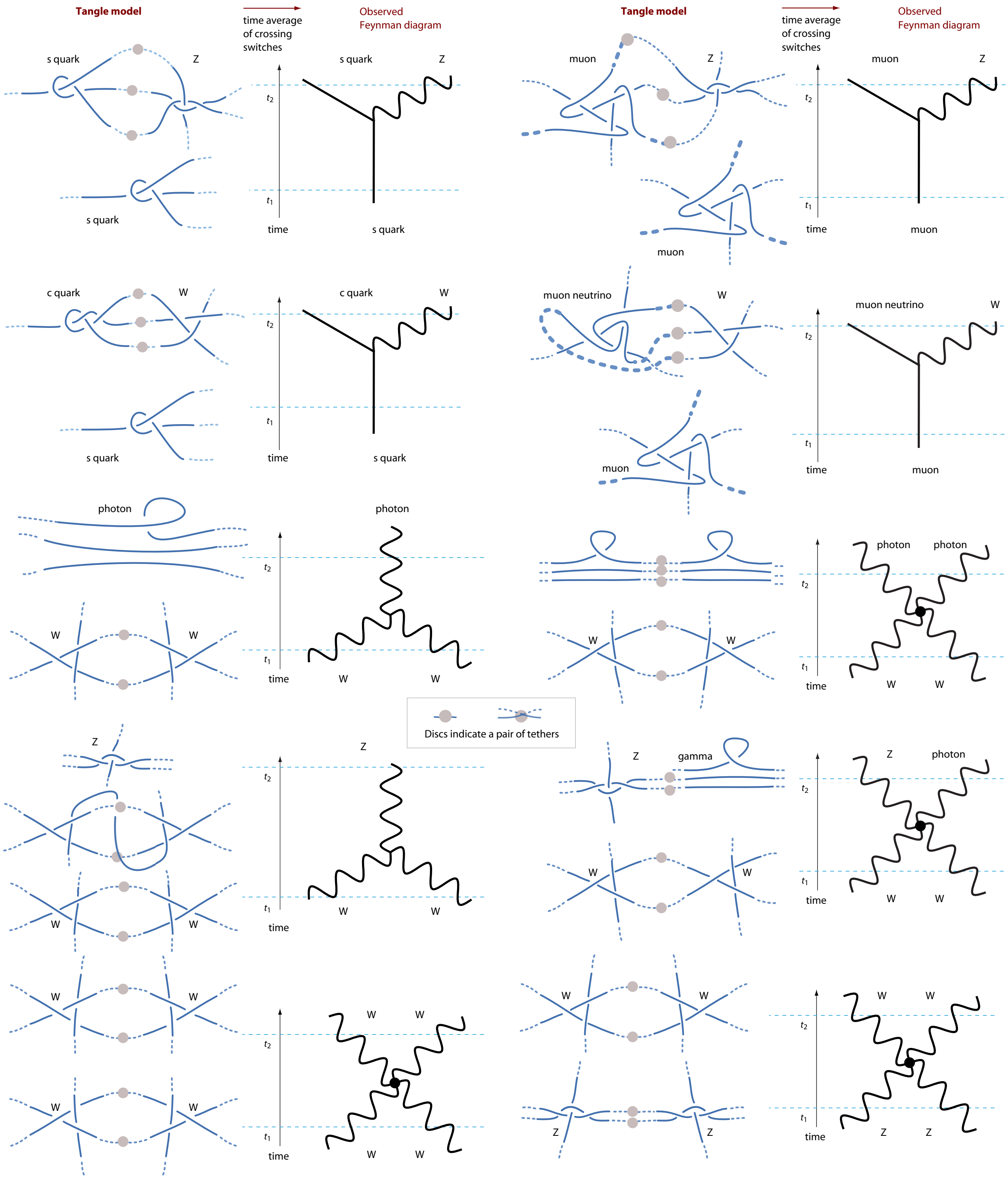

Figure 10: The vertices allowed by the topology of the fermion and boson tangles (part one).

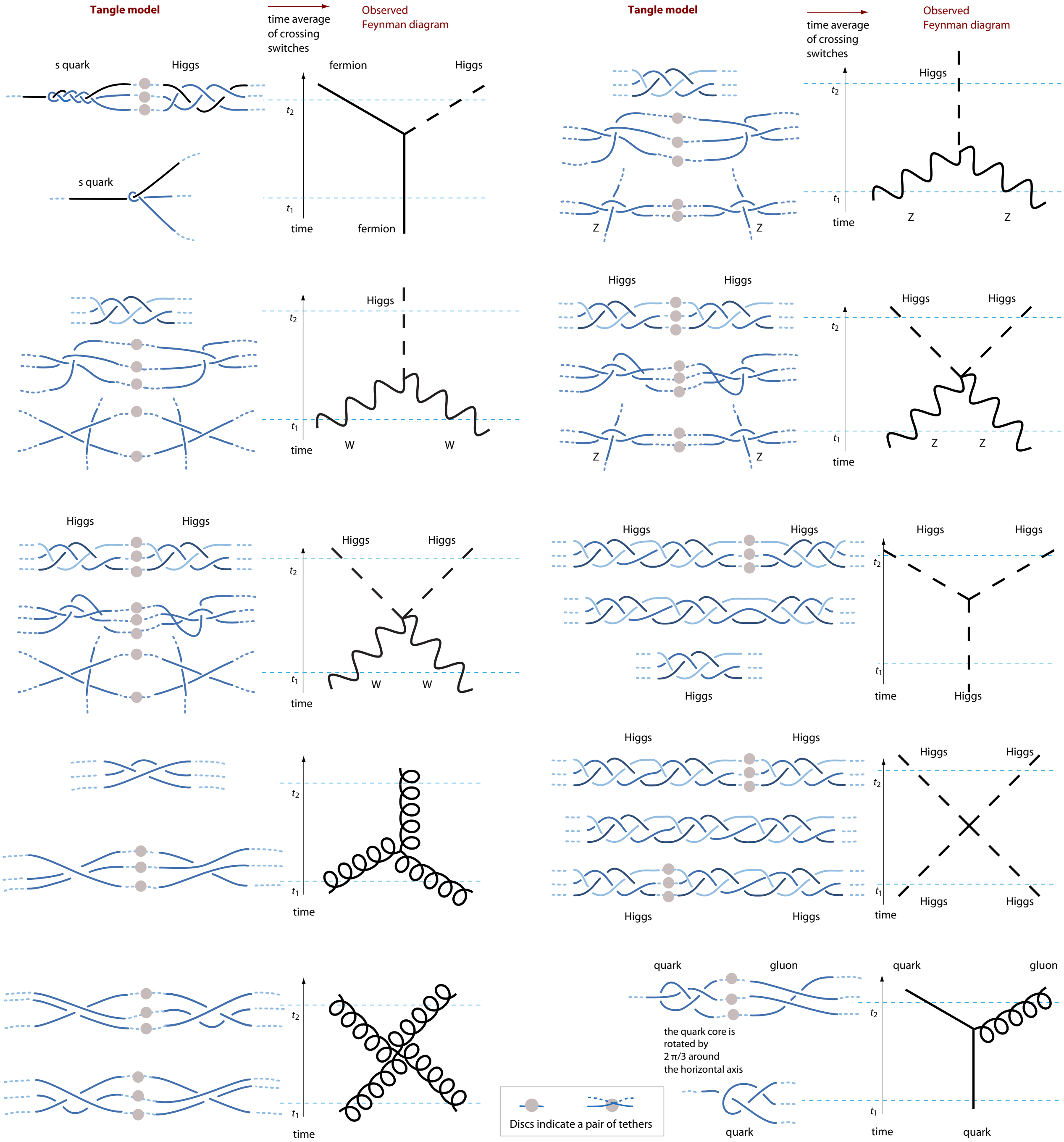

Figure 11: The vertices allowed by the topology of the fermion and boson tangles (part two).

of the standard model. Thus, the elementary boson tangles reproduce all the *field terms* of the standard model Lagrangian.

Elementary fermions are rational tangle families made of two or three strands, with a localized core. They follow the Dirac equation. Strands imply that the fermion generations mix. Thus, fermion tangles reproduce all the *matter terms* of the standard model Lagrangian.

The one-, two-, and three-stranded tangles for the fermions and the bosons – together with the three Reidemeister moves – determine and limit the possible interaction vertices [2]. The possible vertices are illustrated in Figure 10 and Figure 11. The figures show that all Feynman diagrams of the standard model, listed at the beginning in Figure 1, are found. Deformations of elementary particle tangles do not allow any additional diagram. This can be checked by using actual ropes. In short, the topology of tangles determines all the interaction vertices of the standard model. Particle tangles yield the observed *interaction terms* of the standard model Lagrangian. Together, this yields the result:

The standard model results from tangle diagrams.

Because of the limited spectrum of rational tangle families and because of the limited spectrum of gauge interactions, the tangle model predicts that *there is no physics beyond the standard model.* This is the central prediction of the strand conjecture. *Any effect beyond the standard model – equivalently, any new interaction vertex not included in Figure 1, such as a triple-Z vertex or a vertex involving a new elementary particle of any kind – would falsify the model presented here.*

9 Baryogenesis and other non-perturbative effects

In 1967, Sakharov showed that the observed matter–antimatter asymmetry in the universe requires three properties of particle interactions [13]. In modern terms, the three properties are (1) violation of baryon number conservation, (2) C and CP violation, and (3) a non-equilibrium situation during the expansion of the universe. In the tangle model, the third property is realized intrinsically; the second property was summarized above and explored previously [2, 8]. The essential new process for baryogenesis is the first property; it is usually described by the sphaleron. The tangle model of quarks and leptons also realizes it: rearranging the two strands of a quark and combining them with an additional, properly shaped strand allows nature to form a three-stranded lepton. The inverse process is equally possible. This non-perturbative strand process – different from the Feynman diagrams and from particle mixing – models baryon number non-conservation.

Providing an analytic estimate of the probability for baryon non-conservation is not easy. In any case, the strand conjecture does suggest that the process only arises at highest energy – much higher than that for perturbative processes – because the involved strand rearrangement is rather 'wild'. The strand conjecture thus promises to help resolving the ongoing discussion whether the standard model is sufficient or not to explain the observed baryon–antibaryon asymmetry. The relative importance of baryogenesis and leptogenesis during the early universe might also be clarified. More precise answers should appear after computer simulations of fluctuating strands have been performed.

The strand conjecture thus also contains a conjecture on the non-perturbative description of interactions. This allows testing the conjecture in quark-gluon plasmas and similar situations. Also the possibility to calculate QED effects to all orders – including the g-factor of the electron – seems a possibility. The calculation of parameters describing SU(2) breaking is another. The topic is still subject of research.

It might be mentioned in this context that, by design, the strand conjecture appears to be finite. Given that the conjecture claims the lack of elementary particle energies above the Planck scale, one can argue whether the term 'UV-completeness' applies or not.

In summary, the tangle model allows for three kinds of processes in nature: at highest energy, non-perturbative processes are due to addition or removal of strands to or from cores; at lowest energy, space and gravity are due to the fluctuations and deformations of untangled tethers; and at intermediate energy, gauge interactions are due to deformations of tangle cores. These deformations of tangle cores are of interest for a further reason.

10 Predictions about coupling constants

In nature, the coupling constants describe the strengths of the gauge interactions. Each coupling constant specifies the average phase change that a random absorbed gauge boson induces in a charged particle.

In the strand conjecture, Reidemeister moves allow only three gauge interactions. For each gauge interaction, the absorbed vector boson changes the fermion phase by inducing a Reidemeister move in the tangle core, as Figure 9 and Figure 12 illustrate. As a result, in the strand conjecture, each coupling constant is predicted to be the average phase change induced by random Reidemeister moves corresponding to that interaction.

Already before any calculation, the strand conjecture leads to a number of predictions for the coupling constants. The value of each coupling constant is predicted to be fixed, unique, smaller than one, and calculable. Because all Feynman diagrams are reproduced, quantum field theory remains valid. Therefore, the three effective coupling constants are predicted to run with energy. In particular, the coupling constants are predicted to be constant over time and space – despite the occasional claim to the contrary. Near Planck scales, when the effective diameter of strands plays a role, the running of the coupling constants is expected to differ from the standard model. The difference does not need to be small at Planck energy – but is predicted to be negligible at experimentally accessible energies.

Due to the relation of the coupling constants to the Reidemeister moves, the strand conjecture predicts that the values of the three coupling constants have no specific relation among each other; in particular, they are predicted *not to converge* to a common value. The argument applies – with high probability – to energy values below the Planck scale.

Above all, the strand conjecture predicts that each coupling constant is *the same* for all different particle (and antiparticle) types. Equivalently, the strand conjecture predicts that charges are quantized across all particle types and are related by simple integers. The explanation of these points is essential for the explanation of the Lagrangian of the standard model. So far, in the research literature, no other proposal appears to satisfy this requirement. *Any experiment disproving the particle-independence or the position-independence of the coupling constants would falsify the strand conjecture.*

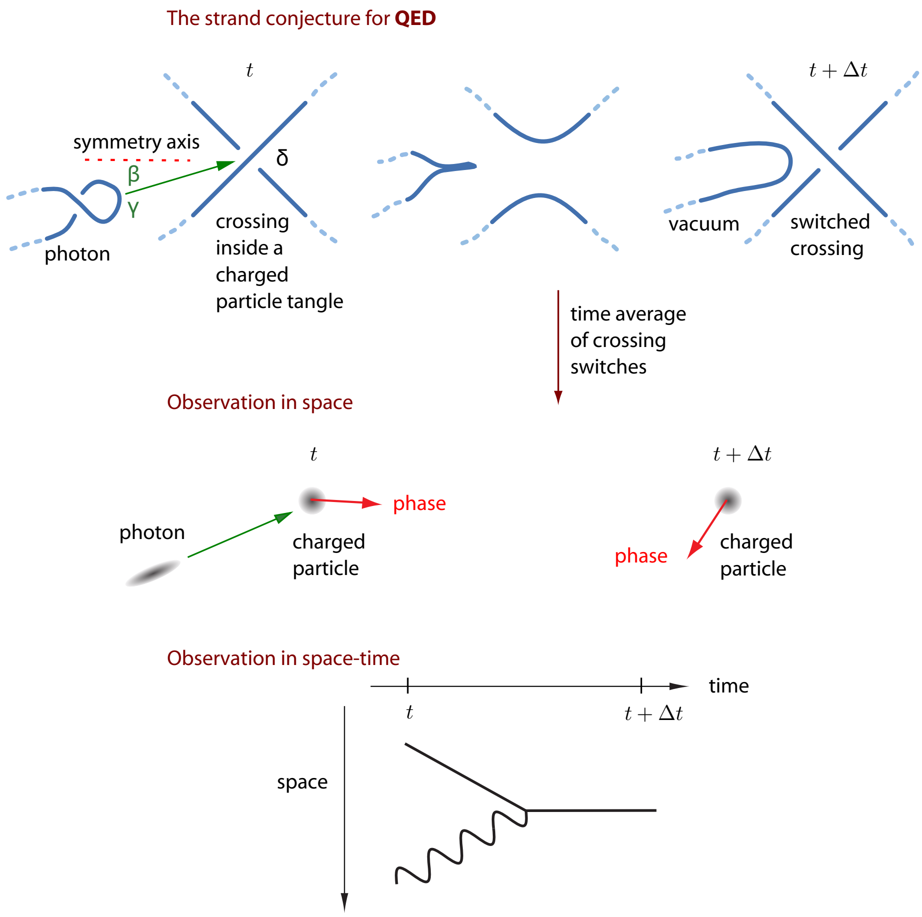

Figure 12: The geometric details of the basic process of quantum electrodynamics (QED). Top: the absorption of a photon by a tangle region carrying the charge $e/3$, viewed along the shortest distance of the crossing. Centre: the corresponding observation at usual experimental scales. Bottom: the basic Feynman diagram of QED. In short: twist transfer generates minimal coupling.

11 The basic process of quantum electrodynamics

In the strand conjecture, electromagnetism is due to the first Reidemeister move, i.e., to the addition or removal of a twist to a particle tangle. In fact, this statement can be amended to the more catchy equivalent:

> The electromagnetic interaction is the – partial or complete – switch of a skew strand crossing in a charged tangle core by the absorption or emission of a photon (twist).

Indeed, the addition or removal of a twist in a strand by a photon absorption or photon emission is a crossing switch as well. This highlighted definition thus encompasses the Reidemeister formulation.

The precise strand process at the basis of quantum electrodynamics (QED) is illustrated in Figure 12. In this process, an approaching photon transfers its twist to a crossing that is part of a tangle core. The photon deforms the tangle crossing and thereby loses its own twist, becoming a vacuum strand. As a result, the photon disappears, i.e., it is absorbed, and at the same time the quantum phase of the tangle core changes du to the crossing switch induced in the particle tangle. In short, the absorption of a photon changes the phase of a charged particle tangle.

The tangle model of QED also illustrates how a particle can have a spread-out wave function and still behave as (almost) point-like in interactions. The wave function is due to the tangle fluctuations of the complete tangle, which can be spread out in space, whereas the interaction occurs at a single crossing, which is almost point-like.

The average change of phase induced by a photon in a tangle core of unit charge determines the square root of the fine structure constant. The fine structure constant itself is then due to the combination of photon emission and photon absorption between two particles of unit charge.

Falsifying the proposed QED mechanism *alone* is not easy. Falsifying it probably requires falsifying at least one of the previous predictions as well. *Discovering a variation of the fine structure constant – or of any other fundamental constant – would falsify the strand conjecture.*

12 Predictions about electric charge and dipole moments

A particle is electrically charged if it changes phase in a preferred direction when absorbing random photons. In the strand conjecture, the tangle core of a *neutral* particle is *topologically achiral*, i.e., it is equal to its mirror image in the minimal crossing projection. As a result, a neutral particle has no preferred phase change when hit by random photons. In contrast, an *electrically charged* particle has a *topologically chiral* tangle core. Such a core differs from its mirror image in the minimal projection. A chiral tangle core has a preferred rotation direction when it absorbs random photons: it is electrically charged. As a result, electric charge has two signs, is quantized, is conserved, emits virtual photons, and only arises in particles with mass. Charges defined with chiral tangles are conserved, move slower than light, and imply massless photons. As a result, Coulomb's law and Maxwell's equations arise automatically [9, 10]. All this agrees with observations.

Electric charge is thus a topological property of tangle cores of particles. As explained in a previous paper [2], each crossing in the minimal projection of a particle tangle leads to an electric charge $+e/3$ or $-e/3$, depending on the topological sign of the crossing. This assignment leads to the observed charge of all elementary particles. The strand conjecture thus explains why the charge of the proton is observed to be equal to the charge of the positron.

The photon absorption process illustrated in Figure 12 implies and predicts that, inside charged elementary particles, the charge 'units' $e/3$ or $-e/3$ are, on average, at distances of the order of the Planck length. In the tangle model, the W, all leptons, the first quark generation, the photon and the gluons have charge units of the same sign – or none at all. This implies that their *intrinsic* electric dipole moment is predicted to vanish:

$$d = 0 \ . \tag{2}$$

For the Z and the other quarks, the *intrinsic* dipole moment d is at most of the order the Planck length times the charge unit e, thus

$$d \lesssim e \, l_{\mathrm{Pl}} \ . \tag{3}$$

These intrinsic dipole values – either zero or negligibly small – are valid *provided* that the tangles of Figure 6 and Figure 7 are correct. In the strand conjecture, *additional* electric dipole moments arise for elementary particles, however, because charges of opposite sign arise perturbatively, i.e., through strand fluctuations. This occurs in the same way as in the standard model. Strands thus appear to predict essentially the same electric dipole moment values as the standard model, where the electric dipole moment arises only for higher order operators. The values predicted by the standard model and by the tangle model are still several or even many orders of magnitude smaller than the experimental limits, and thus are not in contradiction with observations. Future experiments will hopefully allow tests.

In contrast, the tangle model implies that the *magnetic* dipole moment of charged elementary particles is not zero, because the charges effectively orbit around the spin axis. For the same reason, strands also imply a g-factor of $g = 2$ at tree level for all charged elementary particles, including the W boson. This is observed. *Discovering an exception to charge quantization, or finding a sizeable electric dipole moment in elementary particles would falsify the strand conjecture.*

13 Electromagnetism and measurements

Besides the explanation of charge and Maxwell's equations, the conjectured strand mechanism for the basic QED process has an additional aspect: it *explains* the fundamental principle of the strand conjecture. Indeed, the basic QED process shows that crossing switches are observable precisely *because they couple to electromagnetic fields*. In nature, every observation process and every observation device – from the measure of length, time and mass to the measure of any other physical observable – always makes use of electromagnetic fields. While the use of electromagnetism is often hidden or neglected – for example when reading off the position of a pointer on a scale using our eye – electromagnetism is essential in every measurement. Without electromagnetism, no measurement would be possible.

Strands thus reproduce the close relation between measurement and electromagnetism. In fact, the close relation between the fundamental principle and quantum electrodynamics makes the strand conjecture self-consistent at a deep level. *Modifying the strand conjecture and at the same time retaining this consistency would falsify it.*

14 Estimating the fine structure constant

By exploring Figure 12 in detail, the fine structure constant α can be calculated. The view shown in Figure 12 arises when looking or projecting along the shortest distance of the tangle crossing. Near the crossing, each strand is then parallel to the paper plane. In this projection, in order to get a simple geometric picture, the direction of view, perpendicular to the paper plane, is best imagined as the axis of a sphere containing a north pole above the paper plane and a south pole below it. Then the photon incidence angle β is a longitude on this sphere and varies from $-\delta/2$ to $+\delta/2$; the photon incidence angle γ is the angle from the incident photon direction to the paper plane, thus corresponds to a latitude on the sphere; for photons arriving 'inside' the crossings it varies from $-\pi/2$ to $+\pi/2$.

When a photon arrives at a tangle core, it twists the part of the crossing surrounding it. The details of the photon incidence determine the *probability* p that a crossing switch takes place at all and also determine the *value* ν of the induced phase change. Both quantities can be estimated.

The *probability* p for an induced crossing switch can be approximated geometrically. The probability vanishes for photons arriving along the poles of the crossing, i.e., for $\gamma = \pm\pi/2$. The probability for a crossing switch also vanishes for photons arriving perpendicularly to either of the two strands. Furthermore, the switch probability is expected to be highest for the case $\gamma = \beta = 0$, i.e., for symmetrical incidence. *Approximately*, for symmetrical photon incidence, the switch probability p varies with the crossing angle δ as the complement of the spherical angle spanned by the two strands when they are twisted. In other words, the approximate probability is $p \approx (\cos\delta/2)^2$. For general angles of incidence, the *approximate* probability for a crossing switch becomes $p \approx \cos\theta_1 \cos\theta_2$, where θ_i is the angle between the strand i and the direction of photon incidence. This approximation thus gives the probability of a crossing switch for all possible geometries. The angles θ_i are determined by the scalar products $\cos\theta_1 = (\cos(\delta/2), \sin(\delta/2), 0) \cdot (\cos\beta\cos\gamma, \sin\beta\cos\gamma, \sin\gamma)$ and $\cos\theta_2 = (\cos(\delta/2), -\sin(\delta/2), 0) \cdot (\cos\beta\cos\gamma, \sin\beta\cos\gamma, \sin\gamma)$. This yields an approximate probability

$$p \approx ((\cos(\delta/2)\cos\beta\cos\gamma)^2 - (\sin(\delta/2)\sin\beta\cos\gamma)^2) \; . \tag{4}$$

Below it will become clear why this expression is an overestimate.

Also the *value* ν of the phase change due to a crossing switch can be estimated. Geometry suggests that the phase due to a crossing with angle δ is a vector oriented perpendicularly to the symmetry axis and perpendicularly to the shortest distance of the crossing; in the figures, this vector thus lies in the paper plane. The phase vector is expected to have length $\sin\delta$. A switch that occurs due to a photon incident along the crossing symmetry axis changes the crossing phase from the original value to its opposite; the phase change is thus $\nu = 2\sin\delta$. For general angles of photon incidence, the induced crossing switch is only *partial*. The *approximate* value for the phase change becomes

$$\nu = 2 \sin\delta \cos\beta \cos\gamma \ . \tag{5}$$

Calculating the fine structure constant requires averaging the phase change times the probability over all incidence angles β and γ of the photon – using the spherical surface element $(1/4\pi)\cos\gamma$. The calculation also requires averaging over all strand crossing configuration angles δ – using the probability density for strand angles given by $\sin\delta$. The effects of photon phase and of strand crossing distance are assumed to be negligible. Averaging over all photon polarizations introduces a factor 1/2. Finally, multiplication by 3 gives the fine structure constant for a full unit charge, i.e., for a tangle core with three crossings.

In summary, the estimate of the electromagnetic coupling constant becomes

$$\sqrt{\alpha} = \frac{3}{8\pi} \int_{\delta=0}^{\pi/2} \int_{\beta=-\pi/2+\delta/2}^{\pi/2-\delta/2} \int_{\gamma=-\pi/2}^{\pi/2} p\,\nu\ \sin\delta\ \cos\gamma\ \mathrm{d}\gamma\,\mathrm{d}\beta\,\mathrm{d}\delta \approx \sqrt{1/31} \approx 0.18 \tag{6}$$

This numerical estimate has to be compared to the experimental value $\sqrt{1/137.03599914(3)} \approx 0.085$ at low energy or to the standard model prediction of $\sqrt{1/110(5)} \approx 0.095$ at Planck energy. There is *no agreement*.

On the one side, the proposed geometric approximation for the fine structure constant is an overestimate. There are two reasons for this. First, instead of using the value p of expression (6), a better estimate would use the difference between the probability p that the incoming photon *untwists* the crossing and the probability p_{inc} that the photon *increases* the twist. Secondly, the twist calculation is not strictly that of the electromagnetic interaction only; it includes an admixture from the weak interaction. The admixture can be deduced from the tangle for the (unbroken) weak W_3 boson shown in Figure 6; the exchange of (half of) that tangle is similar to the exchange of a twist.

On the other side, the Planck scale model for the basic QED diagram remains promising: it produces a value for the fine structure constant that is unique, constant, and equal for all charged particles. Moreover, the calculation does not need any input; it is ab initio. Finally, the calculation can be extended to the nuclear interactions. *Improving the calculation will thus allow a definite comparison with experiment and will then provide a conclusive test of the strand conjecture.*

15 Testing the strand conjecture

The tangle model is counter-intuitive: it requires to get used to the idea that every particle in nature is tethered. Nevertheless, the strand conjecture describes all observations; if at all, predictions could differ from the standard model exclusively at Planck scales.

Because experiments cannot reach Planck scales, the strand conjecture and the proposed tangle structures cannot be tested directly. The tangle model can only be tested by checking its implications at experimentally accessible scales. Given the ambition of the tangle model, tests must be particularly strict. So far, it appears that the following tests are possible:

1. Does the strand conjecture predict the observed elementary particle spectrum, the observed interaction spectrum and the observed standard model Lagrangian?

2. Do strand processes at interaction vertices predict the correct values for the coupling constants, mixing angles and particle masses?

3. Do strands reproduce the known non-perturbative behaviour, e.g., of the strong interaction?

4. Is no inequivalent ab-initio explanation of the elementary particle spectrum, the interaction spectrum and the fundamental constants available?

The first test has already been answered positively: the Lagrangian of the standard model is recovered. *Any future observation of an effect beyond the standard model or any observation exceeding a Planck limit would thus falsify the strand conjecture.* The second test is still open, as the numerical estimates of all fundamental constants need to achieve higher precision. *The inability to reproduce a single mass value, mixing angle or coupling constant at a single four-momentum value would falsify the conjecture.* The third test has not yet been investigated; numerical predictions that can be checked have not yet been deduced. On the fourth test, the research literature implies a preliminary positive answer – up to the present time. *Any alternative and inequivalent particle structure that explains the standard model Lagrangian and its constants would falsify the strand conjecture.*

16 Summary

The strand conjecture appears to derive, from one fundamental principle akin to a qubit, the standard model of particle physics, with its complete, unmodified Lagrangian. Perturbative and non-perturbative effects are described. The strand conjecture models the elementary particle spectrum as consequence of different rational tangle families and the three gauge interactions as consequences of the three Reidemeister moves. As a result, the strand conjecture appears to determine the value of all fundamental constants.

A crude estimate for the fine structure constant has been given. A more precise calculation can be achieved either with numerical simulations or with a better analytical approximation. Even though strands also imply general relativity, gravity does not appear to enter the calculation of the fundamental constants at low energy.

The strand conjecture is simple, consistent and hard to vary. If the conjecture is not falsified and if the calculations of the constants agree with measurements, then the elegance of the standard model of particle physics would become manifest. In that case, improved versions of Figure 6 and Figure 7, taken together, would depict the periodic tangle table of elementary particles.

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