# A Conjecture on Deducing General Relativity and the Standard Model with its Fundamental Constants from Rational Tangles of Strands 

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#### Abstract

It appears possible to deduce black holes, general relativity and the standard model of elementary particles from one-dimensional strands that fluctuate at the Planck scale. This appears possible as long as only switches of skew strand crossings are observable, but not the strands themselves. Woven fluctuating strands behave like horizons and imply black hole entropy, the field equations of general relativity and cosmological observations. Tangled fluctuating strands in flat space imply Dirac's equation. The possible families of unknotted rational tangles produce the spectrum of elementary particles. Fluctuating rational tangles also yield the gauge groups $\mathrm{U}(1)$, broken $\mathrm{SU}(2)$, and $\mathrm{SU}(3)$, produce all Feynman diagrams of the standard model, and exclude any unknown elementary particle, gauge group and Feynman diagram. The conjecture agrees with all known experimental data. Predictions for experiments arise, and the fundamental constants of the standard model can be calculated. Objections are discussed. Predictions and calculations allow testing the conjecture. As an example, an ab initio estimate of the fine structure constant is outlined.


Keywords: strand conjecture, tangle model, quantum gravity, standard model constants, coupling constants, fine structure constant.

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## 1 The quest for the fundamental constants

The calculation of the fundamental constants of the standard model of elementary particles is an open issue in physics. The fundamental constants, all dimensionless, consist of the fine structure constant, the nuclear coupling constants, the ratios of the elementary particle masses to the Planck mass, and the mixing angles. Calculating these fundamental constants requires a unified theory of physics.

To be unified, a theory must combine the standard model with general relativity: a unified theory must describe particles and curved space. In nature, one particular kind of systems can be said to be made from particles and also to be made from curved space: black holes. They can be seen as dense collections of particles and also as specific horizon configurations. Due to this duality, black holes show effects at Planck scales: they have entropy and evaporate. Together, these connections suggest that a correct Planck-scale model for black holes is also a candidate unified model for curved space and particles.

In the following, it will be argued that black hole entropy and evaporation can be deduced from one-dimensional strands fluctuating at the Planck scale. Then it will be argued that fluctuating strands imply general relativity, Dirac's equation, as well as the gauge groups $\mathrm{U}(1), \mathrm{SU}(2)$ and $\mathrm{SU}(3)$, all without alternative. A new aspect is that rational tangles of strands appear to imply the observed particle spectrum, all the Feynman diagrams of the standard model, and the fundamental constants - all without alternative. Unexpectedly, only a limited amount of calculation is required, because past research provides several results that are central for reaching the conclusions.

## 2 From fluctuating strands to observations

The finiteness of black hole entropy and its surface dependence suggest that black holes are made of a finite number of constituents that are extended. A simple Planck-scale model of a black hole is illustrated in Figure 1 and in Figure 2;

A black hole is conjectured to be a weave of fluctuating strands. However, strands are not observable only the switches of two skew strands are.

In the strand conjecture, black holes, horizons and the rest of nature consist of fluctuating strands. The fundamental physical event is a skew strand switch and characterized by $\hbar / 2$. Strands are onedimensional and have no additional features. In particular, they have no ends, no cross section, no fixed length, no branches, no mass and no torsion. Strands have no tension, cannot oscillate, carry neither fields nor quantum numbers, and exist only in three dimensions - in contrast to strings or loops. Strands are impenetrable: they cannot cross or pass through each other; they cannot be cut or divided. Skew strand switches thus always occur only through deformations, as in the example illustrated in Figure 3 , Strands come from the cosmological horizon, criss cross three-dimensional space, and then return to the cosmological horizon. A useful way to imagine strands - though with certain limitations - is to picture them as having an effective Planck radius.

In the strand conjecture, all physical observables are measured in terms of skew strand switches, or crossing switches. As mentioned, a single skew strand switch is the process that defines the action value

The fundamental principle of the strand conjecture


Figure 1: The fundamental principle of the strand conjecture: the simplest observation in nature, the almost point-like fundamental event, results from a skew strand switch, or crossing switch, at a given position in three-dimensional space. The strands themselves are not observable. The switch defines the action unit $\hbar / 2$, the Planck length, the Planck time, and the entropy unit as half the Boltzmann constant $k / 2$.


Figure 2: The strand conjecture for a Schwarzschild black hole: the horizon is a cloudy surface produced by the crossing switches of the strands woven into it. Due to the additional crossings, the number of microstates per smallest area is larger than 2.
$\hbar / 2$. Physical action is, in the strand conjecture, the number of observed crossing switches. (The principle of least action thus minimizes the number of crossing switches.) The most localized skew strand switch that is possible defines the (double) Planck length $\sqrt{4 G \hbar / c^{3}}$. The fastest possible crossing switch defines the (double) Planck time $\sqrt{4 G \hbar / c^{5}}$. These units then allow to define and measure all length and time intervals. The different configurations of strands also define the microstates of black holes and vacuum, and thus define the Boltzmann constant $k$ and the entropy unit. Once $\hbar, G, c$ and $k$ are defined with the help of crossing switches of strands - a statement called the fundamental principle - all other physical observables can also be defined with crossing switches. For example, mass and energy are measured as the number of crossing switches per unit time. In fact, all observations, all measurements and all interactions are due to and composed of crossing switches.
 4)


Figure 3: An example of a strand deformation leading to a skew strand switch, or crossing switch. In the strand conjecture, strands cannot pass through each other.

## 3 Deriving black hole thermodynamics

In the strand conjecture for a Schwarzschild black hole, all strands are expected to come from far away, to be woven into the horizon, and to leave again to far away. Figure 2 illustrates the strand configuration of a Schwarzschild horizon as seen from the side and from above. If strands are imagined with Planck radius, the weave of strands forming a horizon is as tight as possible.

The strand horizon model allows to determine the energy of a spherical horizon. The energy $E$ is given by the number $N_{\mathrm{cs}}$ of crossing switches per unit time. In a tight weave, crossing switches propagate across the horizon surface. Since the horizon weave is tight, the propagation speed is one crossing per shortest switch time: switch propagation thus occurs at the speed of light. In the time $T$ that light takes to circumnavigate a spherical non-rotating horizon of radius $R$, all crossings of the horizon switch. This yields:

$$
\begin{equation*}
E=\frac{N_{\mathrm{cs}}}{T}=\frac{4 \pi R^{2}}{2 \pi R} \frac{c^{4}}{4 G}=R \frac{c^{4}}{2 G} \tag{1}
\end{equation*}
$$

Strands thus reproduce the relation between energy (or mass) and radius of Schwarzschild black holes. Strands also illustrate both the hoop conjecture and the Penrose conjecture: for a given mass, because of the minimum size of crossings, a spherical horizon has the smallest possible diameter. Other possible weave shapes have larger size. Even though a tight ball, clew or skein of strands - thus many strands in an involved three-dimensional tight tangle - would in principle seem to be more dense than a tight weave, such a configuration is physically indistinguishable from a woven horizon: in such a configuration, only crossing switches at the surface of the ball are possible and observable. The strand conjecture thus naturally implies that, for a given mass value, black holes are the densest objects in nature.

In the strand conjecture, also the number of microstates per horizon area can be determined from Figure 2. The figure shows that for each smallest area on the horizon, i.e., for each area that contains just one strand crossing, the effective number $N$ of possible microstates above that smallest area turns out to be larger than 2, because of the neighbouring strands that sometimes cross above that area. The crossing probability depends on the distance at which the neighbouring strand leaves the horizon; this yields

$$
\begin{equation*}
N=2+\frac{1}{2!}+\frac{1}{3!}+\frac{1}{4!}+\ldots+\frac{1}{n!}+\ldots=\mathrm{e}=2.718281 \ldots \tag{2}
\end{equation*}
$$

The term 2 is due to the two options at the very bottom of the minimal surface; the term $1 / 2$ ! arises from the neighbouring ring shown in Figure 2; the following terms are due to the subsequent rings. Expression
(2) directly yields an horizon entropy value $S$ that is related to the black hole surface $A$ as

$$
\begin{equation*}
\frac{S}{k}=\frac{A}{4 G \hbar / c^{3}} . \tag{3}
\end{equation*}
$$

This is the usual expression for black hole entropy. It arises directly from the extension of the strands and the fundamental principle. Figure 2 also shows that the entropy is located at and slightly above the horizon. Taking into account the different options for the location of the poles and the different angular orientations of the horizon sphere yields the usual logarithmic correction to the black hole entropy $\Delta S / k=-3 / 2 \ln \left(A c^{3} / 4 G \hbar\right)$. However, this correction is too small to be tested in experiments.

In short, strands appear to imply black hole energy and entropy. Their ratio determines the temperature of black holes. Strands also reproduce black hole evaporation: evaporation is due to strands detaching from the horizon. Furthermore, the fundamental principle of strands implies the power and luminosity limit $P \leq c^{5} / 4 G$ and the force limit $F \leq c^{4} / 4 G$ for every system in nature.

## 4 Predictions about gravitation

It is known since a long time that either the existence of a power limit, or a description of gravity that reproduces black hole entropy, energy and temperature, or the existence of a force limit, each separately imply the field equations of general relativity [1, 2, 3, 4]. In the ground-breaking paper [2], Jacobson showed, among others, that the field equations follow from the thermodynamics of horizons and the three-dimensionality of space; these assumptions imply Raychaudhuri's equation and then Einstein's field equations.

Because strands imply black hole thermodynamics, maximum force and maximum power, strands imply the field equations. This result of the strand conjecture agrees with independent approaches that find general relativity to be due to fluctuating lines [5]. In particular, the strand conjecture thus predicts the lack of modifications and the lack of extensions to general relativity.

Strands also appear to imply the lack of singularities: there are none expected inside a black hole, as shown in Figure 2, nor anywhere else, because the fundamental principle intrinsically limits not only force and power, but the value of every physical observable. In addition, strands appear to imply that no negative energy regions, no wormholes, no black hole hair (when the particle tangles from section 11 are explored), no torsion, no modified newtonian dynamics (MOND), no double or deformed relativity, no time-like loops, no cosmic strings, no domain walls, no matter or space outside the cosmological horizon, no counterexamples to the Penrose conjecture and no running of $G$ will be observed. Graviton detection seems extremely hard, if not impossible, because of the low interaction probability and the difficulty to distinguish graviton absorption from other fluctuation processes with similar effects. The strand conjecture thus suggests that observable quantum gravity effects other than particle masses and the cosmological constant are extremely hard to find. The conjecture also suggests that gravity is asymptotically safe.

So far, the predicted validity of unmodified general relativity agrees with all experiments; however, each specific prediction remains open to future tests. In short, strands appear to successfully model black holes. Therefore, strands appear to be a candidate model for both space and particles.

Lambda(t) $>0$ and
very small
Correct baryon
number density
No inflation

Figure 4: A schematic illustration of the strand conjecture for cosmology and the early universe: the universe increases in complexity over time and thereby forms a boundary: the cosmological horizon.


| Observation | Predictions |
| :--- | :--- |
| Nothing <br> (for long <br> observation <br> times) | Vanishing energy |
| Virtual pairs | Emergent, <br> Lorentz-invariant, <br> and unique <br> for short <br> observation <br> times) |

Figure 5: An illustration of the strand conjecture for the flat vacuum: on sufficiently long time scales, the lack of crossing switches leads to a vanishing energy density; on short time scales, particle-antiparticle pairs, i.e., rational tangle-antitangle pairs, arise.

## 5 A Planck-scale model of nature and her parts

Looking at the starry night sky, we are struck by the vast space, the plentiful particles and the dark horizon. A unified description must explain these three observations.

In the proposed conjecture, nature is a wobbly criss-crossing strand woven into the night sky. This is illustrated in Figure 4 and explains the appearance of the black night sky; it is a boundary and a horizon. Instead of describing nature as made of points, the strand conjecture describes nature as one long, fluctuating, tangled strand. In everyday life, the strand conjecture implies flat and curved space, as illustrated in Figure 5 and Figure 6, and also implies the existence of particles, as illustrated in Figure 7 ,

For cosmology, the strand conjecture holds that the universal strand gets more and more tangled over time. As a result, the strand conjecture implies that there is a horizon at the border of the universe, that there is nothing outside the horizon, that the cosmological constant is positive and small. From the horizon properties, strands imply that the universe has an integrated luminosity $P=c^{5} / 4 G$, trivial topology, and scale-invariant early fluctuations. Strands also imply that the universe is flat and homogenous and that the observed baryon number $N_{\mathrm{b}}$ is close to the observed one, namely $N_{\mathrm{b}} m_{\mathrm{b}} \approx t_{0} c^{5} / 4 G$, where $t_{0}$ is the age of the universe. The strand conjecture also implies that there has been no inflation in the usual


| Observation | Predictions |
| :--- | :--- |
| Curved space | Black hole entropy |
| Non-trivial metric | Pure general relativity |
| Black holes | $\mathrm{P} \leqslant \mathrm{c}^{5} / 4 \mathrm{G}, \mathrm{F} \leqslant \mathrm{c}^{4} / 4 \mathrm{G}$ |
|  | Gravitons hard <br> to detect |

Figure 6: An illustration of the strand conjecture for the curved vacuum. The strand configuration is halfway between that of a horizon and that of the flat vacuum.


Figure 7: An illustration of the tangle model of a massive free spin $1 / 2$ fermion, its phase and its probability density: the crossings define the quantum phase, whereas the crossing switch distribution, averaged over time, defines the probability density, and thus the particle position. The predictions are deduced in the text.
sense, because fluctuating strands already solve the horizon problem, the homogeneity problem and the flatness problem.

A region of flat vacuum is described by a set of fluctuating strands, each of which is on average straight and untangled. The configuration is illustrated in Figure 5, As a result, the long-term density of crossing switches vanishes and a unique vacuum state with zero energy density forms. The vacuum energy problem or cosmological constant problem - the false estimate of the value by a factor $10^{100}$ or more - does not arise. The vacuum state is emergent and Lorentz-invariant, because the time-averaged density of crossing switches is Lorentz-invariant. The strand conjecture of the vacuum thus defines a specific set of spatial microstates that differs markedly from quantum foam and from non-commutative space.

A region of curved vacuum is described by a set of fluctuating strands, some of which are curved on average, as illustrated in Figure6. In curved space, strands are thus tangled and curved on a macroscopic scale. Such configurations produce crossing switches that are distributed over macroscopic distances. As a result, strands imply pure general relativity, as shown in section 3.

For fermions and bosons, the conjecture implies that they are rational open tangles of strands; in other words, particles are modelled as unknotted open tangles. This is illustrated in Figure 7for a general fermion; it is explored in detail for each elementary particle in section 11 The focus on unknotted open tangles, and in particular, on rational tangles, is new and seems to be a key aspect of the strand conjecture. Only rational open tangles appear to lead to full agreement with experimental observations, i.e., to agreement with the standard model.

Strands thus promise to describe space, particles and horizons. To fully understand the starry sky however, more details need to be explored.

## 6 Dimensionality, background space and fluctuations

The strand conjecture only works in three spatial dimensions. Only three dimensions allow crossing switches of skew strands, weaves and tangles. Only three dimensions allow spin $1 / 2$, particles and Dirac's equation; and only three dimensions allow horizons and Einstein's field equations. In short, only three dimensions allow a description of nature that is unified, self-consistent, and agrees with experiment.

The strand conjecture uses a three-dimensional background space for the description of nature. On the one hand, this background space is introduced and defined by any observer. On the other hand, the observable physical space itself is a consequence of strand fluctuations. The artificial distinction between physical space and background space is necessary and useful: First, the distinction avoids the difficulties - maybe even the impossibility - of a background-free description of nature. Secondly, the distinction reproduces the basic circularity of fundamental physics, which defines space with the help of particles (e.g., via rulers made of matter or light) and particles with the help of space (e.g., via energy and spin localized in three dimensions).

In the strand conjecture, the fluctuations of any particular piece of strand are due to the other strands in the universe, including those of the observer. On the one hand, strand fluctuations arise whenever an observer introduces a continuous, three-dimensional background space. The fluctuations of the vacuum


Figure 8: A configuration of two skew strands, called a strand crossing in the present context, allows defining density, orientation, position and a phase. The freedom in the definition of phase is at the origin of the choice of gauge - for each gauge interaction. For a full tangle, the density, the phase and the two (spin) orientation angles define, after spatial averaging, the four components of the Dirac wave function $\Psi$ of a particle and, for the mirror tangle, the four components of the antiparticle.
have precisely the behaviour that allows introducing such a background: they are homogeneous and isotropic. The fluctuations are also important because they hide sub-Planckian scales and thus prevent observing sub-Planckian phenomena; this hiding is central to the strand conjecture. On the other hand, strand fluctuations are due to neighbouring strands and result from their impenetrability. These strandstrand correlations have important effects in the quantum domain.

## 7 From tangles to wave functions and Dirac's equation

Two skew strands, i.e., a configuration called a strand crossing here, are characterized by a shortest distance between them. This shortest distance allows defining four properties: a density, an orientation, a position, and a phase, i.e., the orientation around the shortest distance. The definitions of these four properties are illustrated in Figure 8 Even though there is a freedom in the definition of the absolute value of the phase, there is no freedom in defining phase differences.

In quantum theory, wave functions have exactly the same four properties that skew strand crossings have. In the strand conjecture, the wave function is therefore taken as the averaged (smoothed) crossing density produced by the fluctuating strands and, in particular, by all the crossings in a tangle core. (No exact smoothing scale is specified; it is expected to be at most a few times the Planck scale.) It turns out that this definition of a wave function allows defining addition and s-multiplication (as tangle stretching), thus generates a Hilbert space, and implies Heisenberg's uncertainty relation (as a result of the fundamental principle). Superpositions, interference and quantum entanglement also arise. For example, quantum entanglement turns out to be due to topological entanglement of the tethers. The strand definition of a wave function does not contradict the impossibility of hidden variables or the Kochen-Specker theorem, as strands are intrinsically both non-local and contextual. In fact, the tangle definition of wave function agrees completely with the textbook definition, as a detailed exploration shows [6]. Once the wave function is defined as tangle crossing density, the probability density can be defined as the tangle crossing


Figure 9: The belt trick or string trick: rotations by $4 \pi$ of a tethered object are equivalent to no rotation. This allows a tethered object, such as a belt buckle or a tangle core, to rotate forever.
switch density. This is illustrated in Figure 7
In the strand conjecture, free propagating quantum particles are tangle cores that rotate and advance. They reproduce Feynman's idea of particles as moving rotating arrows [7]. The rotation axis of the tangle core is the spin axis and the rotation phase of the tangle core is the quantum phase of the wave function, i.e., Feynman's arrow. Indeed, both the tangle rotation phase and the quantum phase have the same freedom of definition. The rotation frequency $\omega$ times $\hbar$ is the particle energy; the wavelength of the helix drawn by the tip of the phase arrow determines the momentum.

As shown already decades ago, modelling a quantum particle as a localized structure (a tangle core in the present conjecture) that is tethered with several unobservable strands yields Dirac's equation [8]. In the derivation by Battey-Pratt and Racey, Dirac's equation is in fact seen as the infinitesimal description of Dirac's string trick, also called the belt trick. This trick, illustrated in Figure 9, demonstrates that rearrangement of tethers implies that a (core) rotation by $4 \pi$ is equivalent to no rotation at all. In other words, the belt trick, with its tether rearrangement, allows continuous (tethered) core rotation - independently of the number of belts, strands or tethers. This continuous rotation is best visualized with animations [9]. Antiparticles are mirror tangles with opposite belt trick. $C P T$ invariance holds.

In short, a spinning quantum particle can be fully and correctly modelled as a spinning tangle core. Strands thus reproduce Dirac's equation in addition to Einstein's field equations.

## 8 Spin 1/2 and SU(2)

The rotations of the core (or buckle) around the three coordinate axes generate an $\mathrm{SU}(2)$ group, the double cover of $\mathrm{SO}(3)$. This happens because the rotations of the buckle by the angle $\pi$ along $x, y$ and $z$ behave like the three generators of $S U(2)$ : their square is -1 , their fourth power is the identity (as shown by the
belt trick), and the concatenation of two different generators yields the third one, with a sign that depends on the order of the two. By generalizing buckle rotations to arbitrary angles, the full group $\mathrm{SU}(2)$ arises. Spin $1 / 2$ behaviour is thus fully reproduced by tangles.

The belt trick also implies that tangles reproduce fermion behaviour. When two multi-tethered objects are exchanged in position twice, they can be untangled - independently of the number of belts, strands or tethers. Again, animations provide the best visualization of this property [10]. The untangling implies that two fermion tangles can orbit each other forever, without any hindrance. The untangling also implies the spin-statistics theorem for fermions. The full spin-statistics theorem is completed by the boson tangles given in section 11 below.

## 9 Strands and quantum theory

In summary, the averaged crossing distribution of a particle tangle with many tethers behaves like a wave function [8]: the crossing distribution obeys the Heisenberg uncertainty principle, has spin $1 / 2$, is a fermion, and follows Dirac's equation. In addition, the tangle crossing switch distribution behaves like the probability density. In short: Free fermions are blurred spinning tangle cores. This microscopic model reproduces quantum theory in all its aspects. For example, probabilities appear in the theory whenever one attempts to overcome the uncertainty principle or the quantum of action $\hbar$. Also entanglement and decoherence are reproduced.

In fact, the fundamental principle leads to an incisive statement: All quantum effects are due to extension. This might well be the most pointed formulation of the strand conjecture. The statement underlines that the strand description of nature neither uses points in space nor point particles. Following the strand conjecture, whenever one is observing a simple quantum process with action $\hbar$, one is in fact observing a crossing switch.

## 10 Predictions beyond Dirac's equation and the origin of particle mass

The strand conjecture does more than just reproduce Dirac's equation. First, the tangle model predicts that Dirac's equation is valid up to Planck energy. Secondly, the strand conjecture leads to the prediction that particle mass is not a free parameter, but a constant that is determined by the structure of the tangle core. In other words, the strand conjecture predicts that particle mass values are calculable.

Since the belt trick has low probability, the mass $m$ of any elementary particle is predicted to be much smaller than the Planck mass: the relation

$$
\begin{equation*}
m \ll m_{\mathrm{Pl}} \tag{4}
\end{equation*}
$$

is automatic in the strand conjecture. Strands thus suggest a solution to the mass hierarchy problem.
In the strand conjecture, more complex tangles cores are expected to imply larger mass values. However, any particle mass calculation based on tangles must first deduce the specific tangles that are associated to each elementary particle.

Rational, i.e., unknotted tangle


Knotted tangle


Figure 10: A rational tangle (left) compared to a knotted tangle (right): only a rational tangle can be produced or be undone by moving the strands around each other.

## 11 The particle spectrum from rational tangles

Given that both quantum gravity and quantum theory appear to follow from the strand conjecture, can the observed particle spectrum be deduced as well? This indeed appears to be the case, provided that elementary particles are taken to be rational tangles of fluctuating strands. A tangle is called rational if it is constructed by moving strands around each other. An example with two strands is illustrated on the left hand side of Figure 10, The common three-stranded braid, shown on the bottom of Figure 11, is an example of a rational tangle made of three strands.

Rational tangles are thus localized defects of space. Rational tangles are not knotted, but they do allow reproducing localized particle properties such as mass, spin and all quantum numbers. In contrast to knotted tangles, rational tangles have two essential properties: they allow propagation through the vacuum and they allow transformation from one kind of tangle to another - thus reproducing the observed particle transformations, including those of the weak interaction. Both properties are explored in section 14. According to the strand conjecture, elementary particles are rational tangles made of 1,2 or 3 strands. Rational tangles of 4 or more strands turn out to be composite particles, because they can be described as composed of rational tangles of fewer strands. Furthermore, tangles of at most three strands imply interaction vertices that are at most quadruple, as will become clear in section 14. An overview of the conjectured elementary particle tangles is given in Figure 11 for the bosons, in Figure 12 for the quarks and in Figure 13 for the leptons. It is instructive to describe them in detail, together with the arguments leading to the assignments.

One-stranded elementary particles can only be of one kind: the photon with its built-in twist is the only possibility for a rational tangle and thus for an observable particle. Since photons are topologically trivial, they are elementary and have zero mass. Their cores return to themselves after a rotation of $2 \pi$ : they thus have spin 1 and are bosons. There is exactly one kind of photon, with two helicities. A further argument for assignment of this tangle to the photon appears in section 13 on gauge interactions, where the tangle is shown to generate a $U(1)$ gauge group. When the photon tangle propagates, the strands of the vacuum make room around it and make its twist rotate while it advances. Picturing that the propagating photon twist also regularly transfers from one strand to the next explains double-slit interference [6].

Two-stranded elementary particles can have several configurations. They can be asymptotically axial:


Figure 11: The conjectured tangles for the bosons. In interactions, bosons have an effective radius of a few Planck lengths and thus are point-like for all practical purposes. The tangles for the massive bosons W and Z shown on the right are each the simplest members of a tangle family that arises by repeatedly adding virtual Higgs boson braids. Note that the W is the only topologically chiral, thus electrically charged boson tangle. $\mathrm{W}^{+}$and $\mathrm{W}^{-}$are mirrors of each other.

## Quarks

Parity $P=+1$, baryon number $B=+1 / 3$, $\operatorname{spin} S=1 / 2$,
charge $Q=-1 / 3$

$$
\mathrm{Q}=+2 / 3
$$

$$
\begin{array}{ll}
\mathrm{S}=1 / 2, & \mathrm{Q}=-2 / 3 \\
\mathrm{Q}=+1 / 3 &
\end{array}
$$



## Antiquarks

$P=-1, B=-1 / 3$,

$$
S=1 / 2
$$



$\mathrm{u} \longrightarrow$





Figure 12: The conjectured tangles for the quarks, all made of two strands. In interactions, quarks have an effective radius of a few Planck lengths and thus are point-like for all practical purposes. Each quark tangle is the simplest of the corresponding tangle family that arises by repeatedly adding virtual Higgs boson braids.

Leptons - tangles made of three strands (here the simplest family members)


Figure 13: The conjectured lepton tangles, all made of three strands. In interactions, also leptons have an effective radius of a few Planck lengths and thus are effectively point-like. The tangles for the higher generations arise by helically twisting three strands along the space diagonal defined by the tethers, i.e., orthogonally to the paper plane. Each tangle is the simplest member of a family that arises by repeatedly adding virtual Higgs boson braids above or below the paper plane.

The graviton core returns to itself after a rotation by $\pi / 2$, thus has spin 2 . Its structure makes it a boson. Also the unbroken weak vector bosons $W_{1}, W_{2}$ and $W_{3}$ have cores that return to themselves after a rotation by $2 \pi$, thus have spin 1 ; also their exchange behaviour is that of bosons. The assignment of these tangles is deduced in section 13 on gauge interactions, where they are shown to generate an $\mathrm{SU}(2)$ group. A further class of two-stranded elementary particles has asymptotical tethers that span a solid: the quark tangles, illustrated in Figure 12, return to themselves after a core rotation by $4 \pi$, thus have spin $1 / 2$ and are fermions. The assignment of these tangles to the quarks result from their ability to reproduce the hadrons and their quantum numbers, as illustrated in Figure 14 and Figure 15, A final class of elementary two-stranded rational tangles spans a plane; these flattened versions of the quarks represent the weak quark eigenstates. Additionally, two strands can also represent two photons.

Three-stranded elementary particles are those that undergo quadruple interaction vertices (shown below in Figure 24): the Higgs boson, the gluons, the W and the Z. Three-stranded elementary particles can be localized (the real Higgs boson with spin 0), asymptotically axial (the gluons that generate $\mathrm{SU}(3)$ and the virtual Higgs), asymptotically flat (the W and Z bosons with spin 1) or asymptotically solid (the neutrinos and charged leptons, with spin $1 / 2$ ).

The tangle assignment for the Higgs arises from the spin 0 requirement and from the requirement to reproduce Yukawa coupling of all massive particles. The tangle assignments for the gluons arise from their ability to generate $\mathrm{SU}(3)$, as shown in section 13.5 . The tangles of the W and Z arise through symmetry breaking from the $W_{1}, W_{2}$ and $W_{3}$ tangles: a vacuum strand is included into the tangle and leads to a localized core and thus to a non-vanishing mass. The tangle assignments for the leptons arise from consistency requirements, in particular from their behaviour under the weak interaction, as shown in section 14. Three-stranded composite systems of photons, gravitons or quarks also exist.

In the strand conjecture, every massive particle is localized in space and is represented by a tangle family with an infinite number of tangles, because (virtual) Higgs braids can be added repeatedly to the simplest tangle of each massive particle. All the family members represent the same particle, as illustrated in Figure 12, Such a family exists for the quarks, the leptons, the W , the Z and the Higgs bosons. The virtual Higgs braid cannot be added to the photon or graviton tangle, due to the wrong number of strands, and cannot be added to the gluon, as the braid is not localized by it. Therefore, photons, gravitons and gluons remain massless in the strand conjecture. This reproduces observations. In the strand conjecture, massless particles are thus 'weakly' localized and are represented by a unique tangle.

In summary, in the strand conjecture, different particle types differ in their tangle cores.

## 12 Predictions about particles

The conjectured particle-tangle assignments lead to the following conclusions:

- All quantum numbers of particles are topological properties. Spin, parity, the various charges, baryon and lepton number and flavours can be deduced from tangle structure. The quantum numbers behave as observed. Exceptions from known conservation laws are predicted not to occur.
- The strand conjecture suggests that relative mass estimates are much easier than absolute mass estimates. In particular, the strand conjecture suggests that tangle ropelength - defined as the extra length

Pseudoscalar and vector mesons made of up and down quarks


Discs indicate a pair of tethers

Pseudoscalar and vector mesons containing strange and charm quarks


Figure 14: The basic tangle models for the simplest $L=0$ mesons (all with vanishing orbital angular momentum) constructed from the quark tangles. Mesons on the left side have spin 0 and negative parity; mesons on the right side have spin 1 and negative parity as well. Circles indicate crossed tether pairs. All meson quantum numbers are reproduced correctly. The mass values are the observed ones and given only as reference; the ab initio calculation of mass values has not yet been performed. Grey boxes indicate tangles whose structure mixes with their antiparticles - because the tangles are identical - and which are thus predicted to show $C P$ violation. All these predictions agree with observations. Mesons with bottom and top quarks, not shown here, are constructed in the same way. The observed prolate shape of mesons, i.e., their negative quadrupole moment, is reproduced. All heavier strange and charmed mesons and all mesons containing bottom and top quarks are also reproduced.


Figure 15: Baryon tangles built from quark tangles for the lowest $J=L+S=1 / 2$ octet - showing just one specific quark spin configuration of each baryon. The observed quantum numbers, the gluon distribution between the quarks, and the mass sequence and the sign of their quadrupole moments - their oblate shape - are reproduced. Also the $J=3 / 2$ decuplet (not shown) is reproduced.
introduced by a tight tangle compared to an untangled vacuum configuration with the same tether configuration - or tangle core volume and shape are fairly good measures of tangle complexity, and can be used to estimate mass sequences and mass ratios: Longer ropelength values and larger core volumes appear to imply higher mass. This estimation method agrees with experiment for all elementary and composed particles, except for the up and down quark. This exception still needs to be clarified. Despite this issue, all meson and hadron mass sequences are retrodicted correctly from Figure 14 and Figure 15: more complex tangles have higher mass.

- The three-stranded Z is more massive than the three-stranded W , because its ropelength is longer. The three-stranded Higgs boson is even more massive than the Z boson. This agrees with observations.
- The list of one-stranded tangles is complete.
- The two-stranded tangles that are mapped to the quarks naturally imply exactly three generations because higher braiding states correspond to the same family members: a quark tangle with $n$ crossings corresponds to the same quark as a quark tangle with $n+6$ crossings, or $n+12$ crossings, etc. (This corresponds to a quark with one Higgs braid attached, one with two Higgs braids attached, etc.) This period 6 behaviour explains the existence of 6 quarks, or 3 generations. The quark tangles also imply the absence of free quarks: their tetrahedral tether structure would imply 'infinite' energy content because it does not blend into the vacuum.
- Quark tangles reproduce quark quantum numbers and mixing (see section 14.1), and imply the quark model of mesons and baryons. A short impression of the tangle model for hadrons is given in Figure 14 and Figure 15, In particular, the tangle model explains which mesons are $C P$-violating and which ones are not. The two figures reproduce confinement, and predict hadron quantum numbers. The figures explain mass sequences (more complex tangles have higher mass), imply common Regge slopes, and explain the signs of quadrupole moments for all hadrons:

$$
\begin{equation*}
Q_{\text {mesons }}>0 \quad, \quad Q_{\text {baryons }}<0 \tag{5}
\end{equation*}
$$

All these retrodictions are in agreement with observations. Unknown hadrons with unobserved quantum numbers do not arise. The equivalence between the tangle model and the quark model can be extended to cover all known hadron states; also the common Regge trajectories are explained [6]. More complex states, such as tetraquarks, also seem likely. This option might shed some light on the nature of at least some of the scalar mesons. As mentioned below, the interpretation as glueballs does not seem likely.

- The list of two-stranded elementary tangles is complete. There is no room for additional tangles and thus no room for additional elementary particles. All rational tangles made of two strands studied by topologists [11], including the one on the left in Figure 10, correspond to configurations with several elementary quarks and vector bosons.
- The three-stranded leptons appear to imply Dirac neutrinos, with tiny mass and with normal mass ordering. Neutrinos have a natural strong preference for one helicity, as their tangles show. The electron neutrino, being very weakly localized, has an extremely small mass. It appears questionable whether its mass value is higher than the 0.3 eV detection limit of the KATRIN experiment. Strands allow only three neutrinos, because further helical twisting results in composed particles, as can be checked by exploring actual tangles made of ropes. Neutrino-less double beta decay is predicted not to occur.
- The charged leptons differ from neutrinos through tether braiding. Each charged lepton tangle core has three crossings of the same sign. Each charged lepton core is more complex and thus more massive than all three neutrino cores. There are only three charged leptons for the same reason that there are only three neutrinos: more complex tangles - i.e., tangles with more than three helical twists along the axis orthogonal to the paper plane - are composed from the first three ones. Strands thus also predict that the see-saw model for neutrino mass is not correct; sterile neutrinos are predicted not to exist.
- The arguments given for the presented lepton tangle assignments leave one open issue: it could well be that an additional $2 \pi / 3$ twisting around the direction vertical to the paper plane needs to be added to all six lepton tangles illustrated in Figure 13. These alternative assignments would still reproduce all Feynman diagrams and would still limit the lepton generations to three.
- The list of three-stranded elementary rational tangles is complete. An exploration shows that all more complex rational tangles of three strands are composed of elementary bosons and fermions.
- A rotating tangle core implies that all charged elementary particles have - to the lowest order -a $g$-factor of

$$
\begin{equation*}
g=2 \tag{6}
\end{equation*}
$$

because charge, a topological property of the tangle core, rotates - to lowest order - with the same frequency as the tangle core. This agrees with observations, in particular those for the spin-1 W boson. Also charged black holes are predicted to have $g=2$.

- The results from the next sections also imply that the electric dipole moments of elementary particles have the (small) standard model values. The same is valid for the magnetic dipole moments of neutrinos. Proton decay and neutron decay occur at the extremely low standard model rates.
- All rational tangles made of four or more strands are composite, essentially because space has three dimensions. Baryons are examples of such tangles. But also the 4 -strand, 5 -strand and higher analogs of the W boson tangle are composites. Given that there is also no room for additional rational tangles made of one, two or three strands, there seems to be no room for elementary particles outside the known ones. As usual in physics, the argument is not watertight, but it is suggestive.

As argued in section 14, the particle-tangle assignments reproduce all Feynman diagrams of the standard model and exclude all the others. However, one topic needs to be clarified first.

## 13 Deducing the gauge interactions from tangles

In nature, and in its description by quantum field theory, the phase of a wave function is found to change in two ways: first, in free particle propagation, the phase (arrow) performs a helical motion while the particle advances. Secondly, in interactions, the absorption or emission of a vector boson changes the phase of the particle wave function.

In the strand conjecture, wave functions are averaged crossing densities of fluctuating particle tangles. The phase of a tangle core can also change in two ways: first, the core of a freely propagating particle can rotate, as a rigid whole, while advancing. The resulting helical motion of the phase arrow was deduced


Figure 16: The three Reidemeister moves, the twist, the poke and the slide, from which all tangle deformations containing crossing switches can be composed. The crossing sign in the slide move is not important, thus it is not specified.


Figure 17: Each Reidemeister move describes a tangle deformation. Because each Reidemeister move is related to a gauge group, each move describes a gauge interaction. Nevertheless, each particle is point-like and each interaction is local for all practical purposes.


Figure 18: The first Reidemeister move generates the $\mathrm{U}(1)$ gauge group and yields a tangle for the photon.
above; it leads to Dirac's equation for free particles. Secondly, in interactions with vector bosons, $a$ deformation of a charged tangle core changes the phase.

It is known since several decades that geometric deformations of continuous bodies are described by gauge groups. But that research programme had not explored the possible deformations of open tangles, and thus had not found the possibility to generate non-Abelian gauge groups. As will be shown below, deformations of open tangles are described by Abelian or non-Abelian gauge groups.

Classifying tangle deformations was achieved already in 1926, when Kurt Reidemeister proved that every observable tangle deformation involving a crossing can be constructed from just three basic types, nowadays called Reidemeister moves [12]. The three moves are illustrated in Figure 16 and are called twist, poke and slide; they involve one, two and three strands respectively. Reidemeister moves are the building blocks of tangle deformations.

In the strand conjecture, an interacting particle is a tangle core that is being deformed by one of the three Reidemeister moves. More precisely, the application of a Reidemeister move to a tangle core corresponds to the absorption of a gauge boson. In fact, tangle deformations by Reidemeister moves lead to the three observed gauge groups $\mathrm{U}(1), \mathrm{SU}(2)$ and $\mathrm{SU}(3)$.

## 13.1 $U(1)$ from strands

The first Reidemeister move, the twist, adds a loop to a strand. The twist deformation is a local rotation by the angle $\pi$ (plus a small translation). The twist can be generalized to arbitrary angle $\vartheta$. Such generalized


Figure 19: The strand conjecture for the fundamental process of QED: photon absorption and its Feynman diagram can be described in terms of strands. This process generates minimal coupling.
twists can be concatenated, and thus they form a group. A double twist can be undone by moving the strands around, and is thus equivalent to no twist at all. Therefore, a generalized twist deformation behaves like $\mathrm{e}^{i \vartheta}$; the multiplication table

$$
\begin{array}{c|c}
\cdot & \mathrm{e}^{i \pi}  \tag{7}\\
\hline \mathrm{e}^{i \pi} & 1
\end{array}
$$

generates a $\mathrm{U}(1)$ group. The connection between twists and $\mathrm{U}(1)$ is illustrated in Figure 18 , The same group $\mathrm{U}(1)$ arises also for the freedom of phase choice.

The strand conjecture posits that twist transfer is the electromagnetic interaction. The transfer of a twist is usually called the emission or absorption of a photon. The connection between twists and $U(1)$ also implies that the phase of an electrically charged matter core has a $\mathrm{U}(1)$ gauge freedom when defining its phase value.

As a result of the relation between twists and $\mathrm{U}(1)$, photons are conjectured to be single strands with a twist. Photon energy is then given by twist rotation speed and photon momentum by twist size. As a result of this assignment, photons have zero mass and zero charge, two polarizations, spin 1 , and are bosons. Photons move like corkscrews and advance, on average, with the speed give by the Planck length divided by the Planck time, i.e., with speed $c$. Depending on the charge sign that emitted them, the handedness of the screw and the rotation sense have the same or the opposite sign. Photons automatically have negative $C$-parity. The twist model of the photon also implies that photons do not interact, as they can cross each other, and cannot disappear or split. In fact, describing photons with twisted strands in which only crossing switches can be observed reproduces all properties of photons.

In the strand conjecture, macroscopic fields consist of many photons. The electric field is the twist crossing density, and the macroscopic magnetic field is the twist crossing flow. These relations yield Coulomb's law. Coulomb's law is a consequence of the random emission, by charged fermions, of twisted loops into all directions of space, as illustrated in Figure 18 . In particular, charged particles of one core handedness prefer to emit photons of the same handedness. As a result, particles of the same core dynamic handedness - the product of twist handedness and rotation handedness - repel, and particles of different handedness attract.

In the strand conjecture, electric charge is due to topologically chiral tangle cores. (Tangle cores are called topologically chiral if they differ from their mirror image in the minimal crossing projection.) The two mirror forms of a chiral tangle correspond to the two signs of electric charge. For example, as illustrated in Figure 13, the tangle of the neutrino is achiral and thus neutral, whereas the tangle of the electron is chiral and thus charged. The same is valid for the other particles.

The topological model of electric charge explains why charge is quantized, invariant, and why only massive particles can have electric charge. In particular, the unit electric charge e results from three crossings of the same sign. This connection yields the correct electric charges for all particles. In addition, strands imply the conservation of electric charge and the lack of magnetic charges. Together with the invariance of the speed of light $c$, strands thus imply Maxwell's equations [13].

The way that the transfer of twists, i.e., photon absorption or emission, leads to the observed phase change and to the Feynman diagram for quantum electrodynamics, or QED, is illustrated in Figure 19 ,

The strand conjecture predicts that the electromagnetic interaction conserves $C$-parity, $P$-parity, charge, spin, energy, momentum and flavour. This agrees with observations.

Charge conjugation parity or $C$-parity is the behaviour of tangles under charge conjugation. In the strand conjecture, charge conjugation is the exchange of each crossing with its opposite. The tangle model implies that only neutral particles can have a defined $C$-parity value, and that the photon has negative $C$-parity, as observed.

### 13.2 Predictions about QED

The strand conjecture predicts that all Planck units are limit values. For example, in the same way that the maximum energy speed is $c$, also the maximum elementary particle energy is the Planck energy and the shortest measurable length is the Planck length $\sqrt{4 G \hbar / c^{3}}$. In the strand conjecture, all limit values for observations have a simple explanation: limit values appear when strands are as closely packed as possible. In the strand conjecture, strands cannot be packed more closely than to Planck distances. For QED, this yields a maximum electric field value $E_{\max }=c^{4} / 4 G e \approx 2.4 \cdot 10^{61} \mathrm{~V} / \mathrm{m}$ and a maximum magnetic field value $B_{\max }=c^{3} / 4 G e \approx 8 \cdot 10^{52} \mathrm{~T}$. All physical systems - including all astrophysical objects such as gamma ray bursters or quasars - are predicted to conform to these limits. So far, all observations agree.

The field limit values imply that no deviations from QED at measurable fields and energies are expected. In fact, the equivalence of QED Feynman diagrams and strand diagrams implies that deviations of the tangle model from QED are expected only when short-time fluctuation averaging is not applicable any more. This will not happen below the Planck energy $\sqrt{\hbar c^{5} / 4 G}$ - if it ever happens at all.

In summary, strands predict that the $\mathrm{U}(1)$ invariance of electromagnetism and thus QED itself are valid for all energies below the Planck energy. In particular, no higher or other gauge group is predicted to appear at higher energies.

### 13.3 Broken $\operatorname{SU}(2)$ from strands

The second Reidemeister move, the poke, together with two similar moves or deformations along the other two coordinate axes, generates an $\mathrm{SU}(2)$ group. This result is almost immediate, because the poke move can be generalized to the various motions of a tethered belt buckle, as shown in Figure 20. In other words, pokes are related to the belt trick, whose relation to $\mathrm{SU}(2)$ was mentioned in Section 8 in the (different) context of particle spin. Figure 20 illustrates how pokes can be generalized to 3 dimensions and to arbitrary angles. The three pokes $\tau_{x}, \tau_{y}$ and $\tau_{z}$ are local rotations of two strand segments by $\pi$; their squares are -1 and there is a cyclic anticommutation relation between them. These results yield the multiplication table

| $\cdot$ | $\tau_{x}$ | $\tau_{y}$ | $\tau_{z}$ |
| :---: | :---: | :---: | :---: |
| $\tau_{x}$ | -1 | $i \tau_{z}$ | $-i \tau_{y}$ |
| $\tau_{y}$ | $-i \tau_{z}$ | -1 | $i \tau_{x}$ |
| $\tau_{z}$ | $i \tau_{y}$ | $-i \tau_{x}$ | -1 |

1. The poke move, or second Reidemeister move, is a local rotation by $\pi$

2. Pokes can be generalized to three dimensions and then imply the belt trick analogy; the circled region behaves like a belt buckle: $\mathrm{SU}(2)$ arises.

$\tau_{y}$


3. Pokes thus yield the "unbroken" weak bosons

4. The massive weak bosons arise when a vacuum strand (or partial Higgs braid) is included


5. Given that the weak interaction is poke transfer, random pokes affect tangles of only one parity


A poke of one sign affects only tangles for which rotation and belt trick are parallel, and of the same sign as the poke.

Figure 20: The second Reidemeister move generates the $\operatorname{SU}(2)$ gauge group, leads to the tangles for the weak bosons, and explains parity violation.

Therefore, pokes generate an $S U(2)$ group. The same group also arises for the choice of phase, i.e., for the choice of gauge.

Given that pokes generate an $\mathrm{SU}(2)$ structure, it is natural to conjecture that poke transfer is the weak nuclear interaction. The transfer is usually called the emission or absorption of a weak intermediate boson. The connection also implies that the phase of a weakly charged matter core has a $\mathrm{SU}(2)$ gauge freedom when defining its phase value.

The (broken, as it will turn out) $\mathrm{SU}(2)$ gauge symmetry of the weak interaction is realized by the deformation of the tangle core, whereas the (unbroken) $\mathrm{SU}(2)$ group due to the Pauli matrices of spin $1 / 2$ is realized through deformations of the tangle tethers, keeping the core rigid. However, the $\operatorname{SU}(2)$ gauge deformations of the core and the belt trick of the tethers are not fully independent from each other. This occurs for all particles with weak charge.

As a result of the relation between pokes and $\mathrm{SU}(2)$, weak intermediate vector bosons before symmetry breaking are conjectured to be (essentially) two strands with a poke. Due to this assignment, the weak bosons have zero mass, two polarizations, and spin 1: their cores are not tangled, and thus a rotation by $2 \pi$ and an exchange of a core with another leaves them unchanged. The poke model of the weak bosons also implies that they interact among themselves, as shown by the multiplication table (8).

When weak bosons grab a vacuum strand, they become massive. Among others, the mass generation implies that the weak nuclear interaction is indeed weak, has an extremely short effective range, and never leads to macroscopic observable fields. When the weak bosons mix with a vacuum strand, their symmetry is broken. Figure 20 shows the result; two localized, thus massive tangles arise, a chiral, thus electrically charged one, and an achiral, neutral one. This is the description of $\mathrm{SU}(2)$ breaking in the strand conjecture. No such process is possible for the other two gauge interactions.

The Z , the $\mathrm{W}^{+}$and the $\mathrm{W}^{-}$bosons can be seen as a broken weak isospin triplet representation of the $\mathrm{SU}(2)$ gauge group of the weak interaction. The degeneracy is explicitly broken: the differences in shape - e.g., in crossing numbers - of the two tangles are the reason for the symmetry breaking. In summary, the strand conjecture predicts that mass is a result of tangledness, and that mass generation (for bosons and for fermions) is related to the weak interaction.

Certain tangle cores will be affected by large numbers of similar pokes, whereas others will not be. Those who are, are said to be weakly charged. Weak charge - the weak isospin - first of all requires localization of the tangle. In other words, the strand conjecture predicts that only massive particles can interact weakly, as is observed.

When the core of a massive spinning fermion is subject to a large number of random pokes, a special effect arises. When a spinning core has rotated by $4 \pi$, the belt trick can occur along various axes; these axes include two extremes, namely those parallel and antiparallel to the sense of core rotation. (An animation showing the two extreme options is available on the internet [14].) Now, a poke will affect a core for which rotation and belt trick sense are parallel and of opposite sign as the poke. A poke will not affect cores for which rotation and belt trick sense are antiparallel. In other terms, the effect of pokes on a fermion depends on its handedness. Antiparticles, which are represented by mirror tangles rotating backwards, will only be affected by those pokes which do not affect particles. In short, only tangles of one handedness are weakly charged; tangles of the other handedness have no weak charge. Pokes thus
reproduce the observed maximal parity violation of the weak interaction and the spin-like behaviour of weak charge.

Weak currents can be reduced to two Feynman diagrams: a leptonic vertex and a hadronic vertex, either fo which can be neutral or charged. In the strand conjecture, leptonic neutral currents leave the topology of the interacting matter particles unchanged, as shown in section 14 In this way, weak neutral currents are automatically flavour-conserving in the tangle model, as is observed. In the case of weak charged currents, the topology of the involved fermion tangles changes. However, the process only changes leptons into leptons and quarks into quarks, as is observed.

Pokes transform core topology, and thus transform particle type. Despite this, pokes conserve total electric charge, spin, baryon number and weak isospin - as is observed. $C$-parity violation by the weak interaction pokes appears in the same way as $P$-parity violation. The observation of the tiny $C P$ violation by the weak interaction can also be explained, as shown in Figure 14 ,

### 13.4 Predictions about the weak interaction

The strand conjecture predicts that pokes and $\mathrm{SU}(2)$ differ from twists and $\mathrm{U}(1)$ in four aspects: they can change topology, they violate parity, they interact among themselves, and they break the $\mathrm{SU}(2)$ symmetry. In addition, the weak interaction mixes with the electromagnetic interaction. All these properties agree with experiments.

Strands also predict a maximum weak field. However, it is not accessible experimentally.
In section 14 it will appear that the tangle model reproduces all Feynman diagrams of the weak interaction. Therefore, the usual description of the electroweak interaction is predicted to be valid for all energies up to Planck energy. No other gauge group is predicted to appear at higher energies.

## 13.5 $\mathrm{SU}(3)$ from strands

The third Reidemeister move, the slide, can be generalized to nine moves or deformations. Three of these moves form a set of which only two are linearly independent. The remaining eight deformations generate an $\operatorname{SU}(3)$ gauge group. This connection, less obvious than for the first two Reidemeister moves, is illustrated in Figure 21. The top of the figure shows three deformations out of a set of nine that form eight linearly independent generators. The first hint for the $\operatorname{SU}(3)$ structure of twists arises when noting that every deformation leaves the crossing of the other two strands fixed. The three deformations shown in Figure 21thus form an $\operatorname{SU}(2)$ subgroup - this is the belt trick once again. Each of the other two sets of three deformations that is not shown in the figure also generates an $\mathrm{SU}(2)$ group. And indeed, $\mathrm{SU}(3)$ contains three independent $\mathrm{SU}(2)$ subgroups.

The final confirmation of the $\mathrm{SU}(3)$ group property arises when the concatenation (i.e., multiplication) of infinitesimal deformations is explored in detail. First, the slides of Figure 21] correspond to $i$ times the Gell-Mann generators $\lambda_{1}, \lambda_{2}, \lambda_{3}$. Second, the slide $\lambda_{8}$ that makes $\lambda_{9}$ unnecessary is orthogonal to $\lambda_{3}$. Third, as already mentioned, the triplet $\lambda_{1}, \lambda_{2}, \lambda_{3}$ forms a $\operatorname{SU}(2)$ subgroup, as does the triplet $\lambda_{5}, \lambda_{4}$, $-\lambda_{3} / 2-\lambda_{8} \sqrt{3} / 2$ and the triplet $\lambda_{6}, \lambda_{7},-\lambda_{3} / 2+\lambda_{8} \sqrt{3} / 2$. For this reason, their square is not -1 , but involves $\lambda_{8}$ and/or $\lambda_{3}$. Fourth, multiplying slides is slide concatenation, whereas adding slides is kind

Generalized slide move, or third Reidemeister move


The first 3 of 9 possible final configurations arise by rotating the circled region of the black strand


Three gluon tangles arise from these three generalized slide moves



Figure 21: The third Reidemeister move, the slide, can be generalized to 9 deformations that change crossings. Three of the nine deformations are shown: those that deform the black strand. Of the nine deformations, $\lambda_{3}$ and its other two analogues are linearly dependent and define a 2 -dimensional subspace. The remaining 8 linearly independent deformations generate an $\mathrm{SU}(3)$ group. The three deformations shown in the picturereproduce the belt trick and thus generate an $\operatorname{SU}(2)$ subgroup of $\operatorname{SU}(3)$. The deformations of the other two strands generate the other two $\mathrm{SU}(2)$ subgroups of $\mathrm{SU}(3)$.


Figure 22: Composing slides: a schematic illustration of the tangle model for gluon-gluon interactions.
of averaging, as explained in section 7, Loosely speaking, slide addition connects partial tangles without additional crossings. This exploration shows that concatenations of slides yield the $\mathrm{SU}(3)$ multiplication Table 1 .

Two example concatenations in the strand representation of $S U(3)$ are illustrated in Figure 22. The resulting Feynman diagram is also given.

The strand conjecture therefore posits that slide transfer is the strong nuclear interaction. The slide deformation of a tangle is the emission or absorption of a gluon. The connection between slides and $\operatorname{SU}(3)$ also implies that the phase of a strongly charged matter core has a $\mathrm{SU}(3)$ gauge freedom when defining its phase value: the usual $\mathrm{SU}(3)$ coupling to the gluon field arises.

As a result of the relation between slides and $\mathrm{SU}(3)$, gluons are conjectured to be three strands forming a slide, as illustrated in Figure 17 and in Figure 21. As a result of this assignment, gluons have zero mass, zero electric charge, two polarizations, spin 1 and they are bosons. There are eight types of gluons. In contrast to photons, gluons form a representation of a non-Abelian group. Thus gluons interact among themselves.

Like for the electromagnetism, the strand conjecture predicts a highest possible field value for the strong interaction. And again, the limit value is given by the maximum force value divided by the elementary strong charge. No macroscopic fields are observable, because the interactions among gluons imply that strong fields have very short range.

Certain tangle cores will be affected by large numbers of random slides, or random gluons - they have 'colour' - whereas others will not - they are 'white'. For example, the strand conjecture predicts that the W and the Z are 'white' (i.e., neutral, or singlets), because they do not have three different orientations is space. Also the photon is predicted to be 'white' and thus to transform under a singlet representation of $\operatorname{SU}(3)$. The same happens for all fermions that are tangles of three strands: the tangle model predicts that none of these particles interacts strongly, as indeed is observed.

Only tangles made of two strands, i.e., quark tangles, are affected by large numbers of random slides. A slide can rotate such a tangle. Every quark tangle can have three orientations in space: they correspond to the three possible charges of the strong interaction. For a quark tangle, colour charge thus specifies the orientation change of the tangle around their threefold axis: there are three possible colours, they form a triplet representation of $\operatorname{SU}(3)$, and they add up to white. The absorption or emission of a gluon changes the orientation of a quark core by $2 \pi / 3$, as illustrated in Figure 23 .

Elementary tangle cores with mass that transform following other - e.g., faithful - representations of $\mathrm{SU}(3)$ are impossible. In other words, the tangle model implies that all massive elementary particles are either singlet ('neutral') or triplet ('coloured') representations of $\mathrm{SU}(3)$, as is observed. Only gluons are predicted to form a faithful (and adjoint) representation of $\mathrm{SU}(3)$, and thus to carry two colour values.

Because quarks are made of two strands, quarks tangles can be rotated by a slide move, i.e., by a gluon. Thus, quarks undergo colour charge. Particles of one or three strands cannot be rotated by gluons; they do not interact strongly.

Gluons only deform the quark core; they do not change its topology. Thus gluons only change quark colour, and do not change quark flavour or electric charge. No gluon emission or absorption diagram for other massive particles is possible.

Table 1: The multiplication table for the deformations $\lambda_{1}$ to $\lambda_{8}$, deduced from Figure 21, is the multiplication table of the generators of $\mathrm{SU}(3)$. The table includes the additional, linearly dependent elements akin to $\lambda_{3}$, namely $\lambda_{9}=-\lambda_{3} / 2-\lambda_{8} \sqrt{3} / 2$ and $\lambda_{10}=-\lambda_{3} / 2+\lambda_{8} \sqrt{3} / 2$; these are not generators, but are used to construct $\lambda_{8}$. The three $\mathrm{SU}(2)$ subgroups are generated by the triple $\lambda_{1}, \lambda_{2}$, and $\lambda_{3}$, by the triple $\lambda_{4}, \lambda_{5}$ and $\lambda_{9}$, and by the triple $\lambda_{6}, \lambda_{7}$, and $\lambda_{10}$. Note that, despite the appearance, $\lambda_{4}^{2}=\lambda_{5}^{2}=\lambda_{9}^{2}$ and $\lambda_{6}^{2}=\lambda_{7}^{2}=\lambda_{10}^{2}$.

|  | $\begin{array}{lll}\lambda_{1} & \lambda_{2} & \lambda_{3}\end{array}$ | $\begin{array}{lll}\lambda_{4} & \lambda_{5} & \lambda_{9}\end{array}$ | $\begin{array}{ll}\lambda_{6} & \lambda_{7}\end{array}$ | $\lambda_{10}$ | $\lambda_{8}$ |
| :---: | :---: | :---: | :---: | :---: | :---: |
| $\lambda_{1}$ | $\begin{array}{ccc} 2 / 3 & i \lambda_{3} & -i \lambda_{2} \\ +\lambda_{8} / \sqrt{3} \end{array} \quad l l l$ | $\begin{array}{ccc} \lambda_{6} / 2 & -i \lambda_{6} / 2 & -\lambda_{1} / 2 \\ +i \lambda_{7} / 2 & +\lambda_{7} / 2 & +i \lambda_{2} / 2 \end{array}$ | $\begin{array}{cc} \lambda_{4} / 2 & -i \lambda_{4} / 2 \\ +i \lambda_{5} / 2 & +\lambda_{5} / 2 \end{array}$ | $\begin{gathered} \lambda_{1} / 2 \\ +i \lambda_{2} / 2 \end{gathered}$ | $\lambda_{1} / \sqrt{3}$ |
| $\lambda_{2}$ | $\begin{array}{lcc} -i \lambda_{3} & 2 / 3 & i \lambda_{1} \\ & +\lambda_{8} / \sqrt{3} & \end{array}$ | $\begin{array}{ccc} i \lambda_{6} / 2 & \lambda_{6} / 2 & -i \lambda_{1} / 2 \\ -\lambda_{7} / 2 & +i \lambda_{7} / 2 & -\lambda_{2} / 2 \end{array}$ | $\begin{array}{ll} -i \lambda_{4} / 2 & -\lambda_{4} / 2 \\ +\lambda_{5} / 2 & -i \lambda_{5} / 2 \end{array}$ | $\begin{gathered} -i \lambda_{1} / 2 \\ +\lambda_{2} / 2 \end{gathered}$ | $\lambda_{2} / \sqrt{3}$ |
| $\lambda_{3}$ | $\begin{array}{ccc} i \lambda_{2} & -i \lambda_{1} & 2 / 3 \\ & & +\lambda_{8} / \sqrt{3} \end{array}$ | $\begin{array}{ccc} \lambda_{4} / 2 & -i \lambda_{4} / 2 & -1 / 3-\lambda_{3} / 3 \\ +i \lambda_{5} / 2 & +\lambda_{5} / 2 & +\lambda_{9} / 3 \end{array}$ | $\begin{array}{cc} -\lambda_{6} / 2 & i \lambda_{6} / 2 \\ -i \lambda_{7} / 2 & -\lambda_{7} / 2 \end{array}$ | $\begin{gathered} -1 / 3+\lambda_{3} / 3 \\ +\lambda_{10} / 3 \end{gathered}$ | $\lambda_{3} / \sqrt{3}$ |
| $\lambda_{4}$ | $\begin{array}{ccc} \lambda_{6} / 2 & -i \lambda_{6} / 2 & \lambda_{4} / 2 \\ -i \lambda_{7} / 2 & -\lambda_{7} / 2 & -i \lambda_{5} / 2 \end{array}$ | $\begin{array}{ccc} 2 / 3+\lambda_{3} / 2 & -i \lambda_{9} & i \lambda_{5} \\ -\lambda_{8} / 2 \sqrt{3} & & \end{array}$ | $\begin{array}{cc} \lambda_{1} / 2 & i \lambda_{1} / 2 \\ +i \lambda_{2} / 2 & -\lambda_{2} / 2 \end{array}$ | $\begin{aligned} & -\lambda_{4} / 2 \\ & -i \lambda_{5} / 2 \end{aligned}$ | $\begin{aligned} & -\lambda_{4} / 2 \sqrt{3} \\ & -i \sqrt{3} \lambda_{5} / 2 \end{aligned}$ |
| $\lambda_{5}$ | $\begin{array}{ccc} i \lambda_{6} / 2 & \lambda_{6} / 2 & i \lambda_{4} / 2 \\ +\lambda_{7} / 2 & -i \lambda_{7} / 2 & +\lambda_{5} / 2 \end{array}$ | $\begin{array}{cc} i \lambda_{9} & 2 / 3+\lambda_{3} / 2 \\ & -\lambda_{8} / 2 \sqrt{3} \end{array}$ | $\begin{array}{cc} -i \lambda_{1} / 2 & \lambda_{1} / 2 \\ +\lambda_{2} / 2 & +i \lambda_{2} / 2 \end{array}$ | $\begin{gathered} i \lambda_{4} / 2 \\ -\lambda_{5} / 2 \end{gathered}$ | $\begin{aligned} & i \sqrt{3} \lambda_{4} / 2 \\ & -\lambda_{5} / 2 \sqrt{3} \end{aligned}$ |
| $\lambda_{9}$ | $\begin{array}{ccc} -\lambda_{1} / 2 & i \lambda_{1} / 2 & -1 / 3-\lambda_{3} / 3 \\ -i \lambda_{2} / 2 & -\lambda_{2} / 2 & +\lambda_{9} / 3 \end{array}$ | $\begin{array}{ccc} -i \lambda_{5} & i \lambda_{4} & 2 / 3+2 \lambda_{3} / 3 \\ & +\lambda_{9} / 3 \end{array}$ | $\begin{array}{cc} \lambda_{6} / 2 & i \lambda_{6} / 2 \\ -i \lambda_{7} / 2 & +\lambda_{7} / 2 \end{array}$ | $\begin{gathered} -1 / 3-\lambda_{9} / 3 \\ +\lambda_{10} / 3 \end{gathered}$ | $\begin{gathered} -1 \\ +\lambda_{10} \end{gathered}$ |
| $\lambda_{6}$ | $\begin{array}{lll} +\lambda_{4} / 2 & i \lambda_{4} / 2 & -\lambda_{6} / 2 \\ -i \lambda_{5} / 2 & +\lambda_{5} / 2 & +i \lambda_{7} / 2 \end{array}$ | $\begin{array}{ccc} \lambda_{1} / 2 & i \lambda_{1} / 2 & \lambda_{6} / 2 \\ -i \lambda_{2} / 2 & +\lambda_{2} / 2 & +i \lambda_{7} / 2 \end{array}$ | $\left\lvert\, \begin{array}{cc} 2 / 3-\lambda_{3} / 2 & i \lambda_{10} \\ -\lambda_{8} / 2 \sqrt{3} & \end{array}\right.$ | $-i \lambda_{7}$ | $\begin{aligned} & -\lambda_{6} / 2 \sqrt{3} \\ & -i \sqrt{3} \lambda_{7} / 2 \end{aligned}$ |
| $\lambda_{7}$ | $\begin{array}{ccc} i \lambda_{4} / 2 & -\lambda_{4} / 2 & -i \lambda_{6} / 2 \\ +\lambda_{5} / 2 & +i \lambda_{5} / 2 & -\lambda_{7} / 2 \end{array}$ | $\begin{array}{ccc} -i \lambda_{1} / 2 & \lambda_{1} / 2 & -i \lambda_{6} / 2 \\ -\lambda_{2} / 2 & -i \lambda_{2} / 2 & +\lambda_{7} / 2 \end{array}$ | $\begin{array}{cc} -i \lambda_{10} & 2 / 3-\lambda_{3} / 2 \\ & -\lambda_{8} / 2 \sqrt{3} \end{array}$ | $i \lambda_{6}$ | $\begin{aligned} & i \sqrt{3} \lambda_{6} / 2 \\ & -\lambda_{7} / 2 \sqrt{3} \end{aligned}$ |
| $\lambda_{10}$ | $\begin{array}{ccc} -\lambda_{1} / 2 & -i \lambda_{1} / 2 & -1 / 3+\lambda_{3} / 3 \\ +i \lambda_{2} / 2 & -\lambda_{2} / 2 & -\lambda_{10} / 3 \end{array}$ | $\begin{array}{ccc} -\lambda_{4} / 2 & -i \lambda_{4} / 2 & -1 / 3-\lambda_{9} / 3 \\ +i \lambda_{5} / 2 & -\lambda_{5} / 2 & +\lambda_{10} / 3 \end{array}$ | $i \lambda_{7} \quad-i \lambda_{6}$ | $\begin{gathered} 2 / 3-\lambda_{3} / 3 \\ +\lambda_{9} / 3 \end{gathered}$ | $\begin{gathered} 1 \\ +\lambda_{9} \end{gathered}$ |
| $\lambda_{8}$ | $\begin{array}{lll}\lambda_{1} / \sqrt{3} & \lambda_{2} / \sqrt{3} & \lambda_{3} / \sqrt{3}\end{array}$ | $\begin{array}{cc} -\lambda_{4} / 2 \sqrt{3}-i \sqrt{3} \lambda_{4} / 2 & -1 \\ +i \sqrt{3} \lambda_{5} / 2-\lambda_{5} / 2 \sqrt{3} & +\lambda_{10} \end{array}$ | $\begin{aligned} & -\lambda_{6} / 2 \sqrt{3} \\ & +i \sqrt{3} \lambda_{6} / 2 \\ & +i \sqrt{3} \lambda_{7} / 2 \end{aligned}-\lambda_{7} / 2 \sqrt{3}$ | $\begin{gathered} 1 \\ +\lambda_{9} \end{gathered}$ | $\begin{gathered} 2 / 3 \\ -\lambda_{8} / \sqrt{3} \end{gathered}$ |



Figure 23: The tangle model a colour-changing the quark-gluon interaction diagram.

The strand conjecture also explains how gluons hold mesons together: when the quark in one meson rotates the other rotates as well; thus mesons are always in a colour-anticolour state, as Figure 144shows. And the gluons pull the two quarks in a meson towards each other.

Slides, i.e., gluon emission or absorption, never change the topology of tangles. Thus, the tangle model predicts that the strong interactions conserve electric charge, baryon number, weak isospin, flavour, spin and all parities. Slide transfers conserve total colour. In particular, there is a natural lack of $C P$ violation by slides, i.e., by the strong interaction. The strong $C P$ problem is thus solved by the tangle model. All this agrees with experiments.

### 13.6 Predictions about the strong interaction

Also for the strong interaction, the strand conjecture predicts a highest possible field value. And again, the limit value is given by the maximum force value divided by the elementary strong charge.

Also for the strong interaction strands predict that the $\mathrm{SU}(3)$ symmetry and thus QCD are valid for all energies below the Planck energy, i.e. for all measurable energies. In particular, no higher gauge group is predicted to appear at higher energies.

### 13.7 Predictions about gauge unification

The strand conjecture states that tangle core deformations determine the three observed gauge groups. Building on the phase definition at each strand crossing, each Reidemeister move defines a phase observable; with it, the freedom in the definition of the various phases becomes the freedom of gauge choice. In
fermions














Figure 24: The propagators and Feynman diagrams of the standard model. All diagrams conserve electric charge.
short, the strand conjecture generates both gauge symmetries and gauge interactions from strand deformations.

Given that Reidemeister moves arise from strand deformations, the strand conjecture implies that the three observed gauge interactions are fundamental. Given that there are only three fundamental moves, the strand conjecture also implies that only the three observed gauge interactions exist in nature. In particular, the tangle model denies the existence of a quantum gauge theory for any additional compact simple gauge group.

The strand conjecture thus implies that the three observed gauge interactions are not low-energy approximations of some larger symmetry group. Instead, topologists tell that, effectively, there is only one Reidemeister move [15]. This becomes evident when looking at the three-dimensional versions, not the two-dimensional projection, of the three Reidemeister moves: all three can be seen to arise from the same combination of pulling and rotating a segment of a single strand of the tangle core. In the terms of the strand conjecture, the unity of the three observed gauge interactions is the unity of the three Reidemeister moves. However, this result is not sufficient for full unification.

## 14 Deducing Feynman diagrams

Researchers have searched for the microscopic details of Feynman diagrams for several decades. The strand conjecture posits that all observations, all measurements and all interactions are composed of

Fermion propagation


Figure 25: The propagation of a fermion tangle through the strand vacuum is possible because fermion tethers do not follow the core rigidly on a larger scale, but 'trail behind' the core.
crossing switches resulting from strand deformations. Therefore, the strand conjecture agrees with experiments only if it reproduces every Feynman diagram for every interaction for every particle - i.e., all the diagrams listed in Figure 24- and if it excludes any other imaginable diagram. Detailed checks are called for.

### 14.1 Fermion propagators and mixing

In the strand conjecture, the propagation of a fermion occurs via a rotating and advancing tangle core. Figure 7 illustrates the strand conjecture for a fermion propagator. Since all fermion tangles are localized, all fermions are predicted to be massive, neutrinos included. As mentioned, the tangle model of fermion propagation reproduces the rotating arrow image of elementary particles: the tethered rotation of the tangle core reproduces the rotating phase of quantum particles.

In the strand conjecture, the vacuum is itself made of (untangled) strands, as illustrated in Figure 5, The propagation of a fermion through the vacuum thus requires to explain how a tangle advances through the strands - including the case of an electron crossing the whole universe. First of all, in the strand conjecture, the density of the vacuum strands in nature is low. Secondly, during particle propagation, tethers do not propagate rigidly alongside with the core. In general, after some time has elapsed, the tethers will trail behind the core, as illustrated in Figure 25. Vacuum strands are thus no obstacles to fermion propagation.

In the strand conjecture, the propagation of massive tangles goes along with the rotation of the par-


Figure 26: The tangle model of the quark and the neutrino propagators, illustrating the mixing between s to u quarks and the mixing between muon and electron neutrinos. The mixing occurs when tethers get swapped (two in the quark case, three in the neutrino case).
ticle core. The rotation occurs relative to the surrounding vacuum strands, and the propagation requires coordinated fluctuations of many strands. Such a coordination of fluctuations is not required for photons, which thus move with the (maximum) speed of a lone single crossing. In short, massive particle cores move slower than light. From this statement, all of special relativity can be deduced.

For certain particles, during propagation, the fluctuations of the tethers can sometimes lead to a change of particle type, as illustrated in Figure 26 The strand conjecture thus reproduces both quark mixing and neutrino oscillations. The figure also implies that the magnitude of the effects is unique and fixed; in particular, the so-called mixing angles of the CKM and the PMNS matrices appear to be determined by the average tangle shapes of the quarks and leptons. The strand conjecture thus predicts that mixing angles and phases are calculable from fermion tangle geometry. Indeed, the strand conjecture leads to predictions on the sequence in magnitude of the elements of the mixing matrices for quarks: the mixing matrix is unitary, the mixing between adjacent generations is larger than between the first and the third generation, and the CP violation angle is non-vanishing. For neutrinos, a unitary mixing matrix is predicted, with only one non-zero CP violating phase, due to their non-vanishing mass. However, a precise calculation of the matrix elements of both mixing matrices is still due.

As argued above, no other elementary fermion made of rational tangles seems possible. Thus no additional elementary fermion propagator seems to arise in the strand conjecture.

### 14.2 Gauge boson propagators

In the strand conjecture, only a small number of elementary bosons appear to be possible, as argued above. Thus, only a few boson propagators require exploration.

The propagation of a free massless gauge bosons like the photon occurs either by helically sliding the core along the tethers; alternatively, the photon core can advance perpendicularly to the tethers and hop from one strand to another.

For the weak bosons, the situation differs from that of photons. The propagation of massive gauge bosons occurs by rotation of the core. The rotation can occur along an axis in the plane spanned by the three strands or along an axis perpendicular to the plane - as expected for spin 1 particles.

The propagation of gluons occurs in the same way as the propagation of other massless gauge bosons. Gluons propagate as illustrated in Figure 11 .

### 14.3 Properties of interaction vertices

In the strand conjecture, all elementary particles are effectively point-like: their interaction size, most evident when tangle cores are tightened, is of the order of the Planck length. The extension of the vertex of a Feynman diagram is thus of this magnitude.

Whenever an interaction takes place, tangle cores are pulled apart or transformed into vacuum strands. This process occurs by extending strands or by transferring deformations. At an interaction vertex, no strand is ever cut. This property is not always evident, but is realized in all Feynman diagrams that follow - even if the time direction is chosen differently or the diagram is deformed.

In particular, in all observed diagrams of the standard model, electric charge is conserved. In the strand conjecture, this occurs because no interaction vertex changes the total chirality, or crossing number, of the involved particles. This is impossible for topological reasons: chirality cannot disappear or be created when splitting or combining tangle cores according to the rules of the strand conjecture; due to the lack of strand cutting, chirality is a topologiacal invariant.

For similar reasons, spin $S$ and parity $P$ are also conserved at interactions. The same holds for lepton and baryon number.

### 14.4 Electroweak interactions of leptons and quarks

Combining the strand definition of the electromagnetic interaction illustrated in Figure 19, together with the tangles of the leptons, yields all Feynman diagrams of QED. For example, pair creation is illustrated in Figure 27, the figure also illustrates lepton-antilepton annihilation. Because all tangles of charged particles are rational, pair creation and annihilation are correctly reproduced. No unobserved QED Feynman diagrams are possible; the strand conjecture reproduces QED exactly.

In Figure 27, it is a helpful shortcut to imagine that the strands are connected; however, connection is not required. The grey disks indicate that the Feynman diagrams are recovered also if the tethers alternate in their configuration in space.

Also the strand description for the emission or absorption of a Z or W boson behaves as observed. For example, both a lepton or a quark can emit or absorb a Z boson or a W boson. Example processes for a quark are illustrated in Figure 28, and for a muon in Figure 29. The figures show that neutral weak currents do not change flavour, whereas charged currents, due to W absorption or emission, do.


Figure 27: The tangle model for two common QED processes.


Figure 28: The tangle model for neutral and charged weak currents for the case of a strange quark.


Figure 29: The tangle model for neutral and charged weak currents in the case of a muon.


Figure 30: The strand conjecture for the fermion-Higgs vertex, shown here for the case of a strange quark.

### 14.5 Fermion-Higgs interactions

In the case of quarks, like for all other particles, the interaction with the Higgs adds or removes one braid. The end situations were already shown on the bottom of Figure 12, the full process is illustrated in Figure 30. Charge and flavour is naturally conserved.

The same diagram, but with horizontal time direction, shows one Higgs splitting in a quark and an antiquark, one of them with a braid. A split into two different quarks is not possible.

Charged and neutral leptons allow the same interactions with the Higgs boson as the quarks: a braid is added or removed.

A double Higgs emission from a fermion is not possible, as is easily checked. Neither can a fermionantifermion pair annihilate into two Higgs bosons, due to the structure of fermion cores.

### 14.6 Electroweak gauge bosons interacting among themselves

The strand conjecture does not allow a triple photon vertex, because a photon cannot split in two other photons: there is no way that one twisted strand can change into two twisted strands, because of the relations between action, energy and wavelength. The process would increase the number of crossings, and thus would not conserve energy and momentum. For the same reason, also a quadruple or higher order photon vertex is impossible.

In contrast, weak bosons can interact among themselves, because they are made of several strands. A number of vertices exist with two incoming W bosons. The triple vertices for $\mathrm{WW} \gamma$ and WWZ are illustrated in Figure 31. A triple W vertex is not possible, because of chirality; this reproduces the impossibility due to the lack of charge conservation.

WW to photon triple vertex
time average of crossing switches

Observed
Feynman diagram
photon




Figure 31: The strand conjecture for the WW-photon and WWZ triple vertices. Tangle diagrams can also be drawn if the time direction is chosen differently.


Figure 32: The tangle model for the quadruple $W$ vertex. Also other deformations oor time orientations of the vertex are reproduced.

Several quadruple vertices with two W bosons are possible. The $\mathrm{W}^{4}$ vertex is illustrated in Figure 32 , The $\mathrm{WW} \gamma \gamma$ and $\mathrm{WWZ} \gamma$ vertices are illustrated in Figure 33. The last possibility, the WWZZ vertex, is pictured in Figure 34, Rotated and deformed diagrams are also reproduced.

When two Z bosons collide, they can turn into two W bosons, into one Higgs boson, or into two Higgs bosons. These case are illustrated in Figure 34 and in Figure 35. Also in these cases, rotated diagrams are possible. However, there is no way to make two Z bosons turn into a single Z boson: there is naturally no triple $Z$ vertex in the strand conjecture. In the same way, quadruple $Z$ vertices, higher order $Z$ vertices or ZZ $\gamma \gamma$ vertices turn out to be impossible.

In the same way, no higher-order vertices involving the W and Z bosons are possible, such as quintuple or even more complex vertices; the three strands involved prevent such vertices.

### 14.7 Interactions between the Higgs and the weak bosons

The triple vertex for Higgs emission by a W or Z is the usual Higgs emission vertex for massive particles: a braid is added or removed. Rotating the time direction, two W or two Z tangles can annihilate into a Higgs braid, as illustrated on the upper half of Figure 35 and of Figure 36. A triple vertex with two Higgs and one W or one Z boson is not possible, because combining two Higgs boson tangles never generates a W or Z tangle.

In contrast, two Z tangles or two W tangles of opposite charge can combine into two Higgs bosons. This is illustrated in the bottom halves of Figure 35 and Figure 36. Rotating the Feynman diagram is also


Figure 33: The tangle model for the quadruple WW-photon-photon and the WWZ-photon vertices. A tangle diagram can also be drawn if the time direction is taken to be horizontal.


Figure 34: The tangle model for the quadruple vertex involving two Z and two W bosons. A tangle diagram can also be drawn if the time direction is taken to be horizontal.
possible: an incoming Higgs and W ( or Z ) boson can rearrange their strands to leave as a W ( or Z ) and a Higgs boson.

No quadruple vertex involving two Higgs bosons and one or two photon tangles is topologically possible. It is also not possible, for topological reasons, to have a quadruple with a fermion-antifermion pair yielding two Higgs bosons. Three strands do not allow this to occur.

All these Feynman diagrams can equally be read in the opposite time direction, and also with time evolving in other directions. The tangle model reproduces all these possibilities.

### 14.8 The Higgs propagator and the Higgs self-interactions

Virtual Higgs boson propagation occurs through motion, or sliding, of the braid core along its three strands. The sliding motion can be pictured with the help of the virtual Higgs drawing at the bottom centre of Figure 11 .

Higgs bosons also interact among themselves. A Higgs braid with 6 crossings can be extended by adding a braid pair. Separating the two braids yields two Higgs particles, one with 12 and one with 6 crossings. Alternatively, a double Higgs braid (with 12 crossings) can split into two. In both cases, one Higgs boson transforms into two bosons. And obviously, both processes can occur backwards. These processes are the tangle representations for the triple Higgs vertex; they are illustrated in Figure 37

Figure 37 also shows that a tangle process for the quadruple Higgs vertex appears naturally. Starting with a Higgs braid with 12 crossings and one with 6 crossings, an interaction can yield a braid with 6 crossings and one with 12 crossings.


Figure 35: The tangle model for the two vertices involving Z and Higgs bosons. Diagrams also exist with time in the horizontal direction.


Figure 36: The triple and quadruple vertices involving the W and Higgs bosons.


Figure 37: The tangle model for the triple and quadruple Higgs vertices.

There is no quintuple or higher Higgs vertex possible, because a braid does not allow for such processes at a single point in space.

### 14.9 Gluon self-interactions

Experiments observe the existence of a triple and of a quadruple gluon vertex. In the strand conjecture, like in quantum chromodynamics, these Feynman diagrams are consequence of the relations among slides, i.e., among gluons, that are due to the gauge symmetry group. Given that slides represent the generators of $\operatorname{SU}(3)$, the gluon self-interaction diagrams are direct consequences of Figure 21, which shows the strand origin of $\operatorname{SU}(3)$. Self-interacting gluons are a way to illustrate the concatenation of strand slides. This connection is detailed in Figure 22. Specifically, gluon self-interaction results from the three strands they are made of.

The $\mathrm{SU}(3)$ group structure that arises from slide deformations also limits the possible gluon-gluon interaction to the observed gluon diagrams only. The gluon slide disallows any other imaginable diagram: For example, quintuple or higher-oder gluon vertices are not possible.

Because the strand conjecture reproduces the triple and the quadruple gluon vertex, the tangle model reproduces QCD in its essential aspects: gauge symmetry, asymptotic freedom, and quark confinement. Again, the Planck value for the gluon field intensity is predicted to be the highest possible field value. Neutron stars, quark stars and all other astrophysical objects are predicted to have field values below this limit. This is observed. Deviations from QCD are thus only expected when the spatial and temporal averaging of crossing switches is not possible. In short, deviations from QCD are not expected for any measurable energy.

The tangle model for gluons yields the promise that non-perturbative QCD should be possible. In particular, the model implies that a structure made of two or three gluons is almost as unlikely as a structure made of three photons. Therefore it seems that glueballs should not exist.

### 14.10 Summary on Feynman diagrams

The strand conjecture suggests that there is no freedom in the particle-tangle assignments: gauge bosons tangles are determined by the Reidemeister moves, quark tangles by their strong charge, lepton tangles by their weak interaction properties, and the Higgs boson tangle by its spin 0 and coupling properties. With these specific particle-tangle assignments, it appears that the strand conjecture explains all the Feynman diagrams that are observed and excludes those that are not.

In short, the observed Feynman diagrams are those that are composed of and allowed by crossing switches. Equivalently: All Feynman diagrams are due to strand deformations. This explanation implies that the strand conjecture reproduces the full Lagrangian of the standard model of elementary particles - provided that the gauge coupling constants are independent of the involved particle types and that the Higgs couplings are proportional to particle mass.

Coupling constants are indeed independent of particle type in the strand conjecture: for the fine structure constant, the particle independence is due to the topological nature of electric charge. Details are
given in the following sections. Also the weak and the strong charges are topological properties of tangles, so that the weak and strong coupling constants are independent of particle type as well. In retrospect, it seems hard to imagine an explanation for the particle independence of coupling constants that differs from a topological explanation.

Particle couplings to the Higgs are indeed proportional to particle mass: both effects depend on fluctuations of tethers relative to the core, and describe the difficulty to rotate a core.

The strand conjecture thus reproduces the full standard model Lagrangian: the known particles and the known interactions are described and explained in full detail.

The strand conjecture also provides a new view on renormalization and on non-perturbative quantum field theory: higher-order Feynman diagrams appear to be deformations of lower-order diagrams. Higherorder Feynman diagrams are thus not distinct from lower-order diagrams, as in perturbative quantum field theory. Strands therefore provide a conjecture on how higher-order diagrams arise and how they behave at high energy. In particular, strands naturally imply ultraviolet finiteness. With more research, strands should allow non-perturbative calculations.

## 15 Predictions beyond the standard model

In nature, at a given point in space, we can observe flat or curved vacuum, or a particle from a limited spectrum, or an interaction from a small set of possibilities, or a horizon. In the strand conjecture, all these options, and even the point itself, are due to and composed of crossing switches. In summary, the strand conjecture appears to reproduce the standard model and general relativity exactly - without alternative, modification or extension.

Provided that the properties of the strand conjecture have been explored correctly and completely, strands predict that branching ratios, $g-2$ values, and electric dipole moments are as predicted by the standard model, that $C P T$ holds, and that neutrinos have mass. Strands also predict that dark matter is conventional matter plus black holes. No detectable proton decay and no detectable baryon number violation are expected. The strand conjecture also suggests the lack of glueballs and that the matterantimatter asymmetry is fully explained by the standard model.

Provided that the strand conjecture is complete and correct, there should be no additional gauge groups, no grand unification, no $C P$ violation for the strong interaction, no additional particles - such as axions, sterile neutrinos or WIMPS - no additional dimensions, no supersymmetry, and no different vacuum states. Strands also suggest the lack of bosonization, holography or non-commutative space-time in the usual sense. Strands appear to imply that the known gauge interactions are fundamental, that there is a high energy desert, and that there are no measurable deviations from the standard model up to Planck energy.

Because the strand conjecture predicts that general relativity and the standard model are correct at all experimentally accessible energies, predictions in contrast with the standard model can arise only at Planck scales. Provided that the strand conjecture is complete and correct, the Planck length and Planck time are the smallest measurable intervals. Planck momentum and energy are the highest measurable values for elementary particles. $c^{4} / 4 G$ and $c^{5} / 4 G$ are the maximum values for force and power/luminosity.

Maximum values for electric fields $E_{\max }=c^{4} / 4 G e \approx 2.4 \cdot 10^{61} \mathrm{~V} / \mathrm{m}$, for magnetic fields $B_{\max }=$ $c^{3} / 4 G e \approx 8 \cdot 10^{52} \mathrm{~T}$, and similar maximal values for strong and weak fields are predicted.

Together with the lack of new physics, strands predict that the fundamental constants of the standard model - masses, mixing angles and coupling constants - can be calculated.

## 16 The challenge to calculate particle masses

Dirac's equation suggests that mass is the difficulty to rotate a particle. In the standard model, the Higgs mechanism relates mass and the coupling to the Higgs particle.

In the tangle model, mass is given by the average number of crossing switches per time occurring around a particle tangle. In fact, the strand definition of mass contains the two conventional definitions: In the strand conjecture, the harder it is to rotate a tangle core, the easier it is to add a Higgs braid. Both conventional mass properties are thus naturally related to each other in the tangle model.

For a massive particle - at rest or moving - crossing switches occur when tethers move around the core. Such a motion of tethers around the core is induced by tether fluctuations only rarely, because, first of all, the required tether configuration is rather special. Nevertheless, for larger cores, more crossings per unit time arise, as the larger mass is harder to rotate. Larger cores thus have higher mass; but also the number of strands influences the mass value. Secondly, there must be a preference for one tether rotation direction over the other; this preference, remotely reminding a ratchet, arises because cores lack rotational symmetry. Thus, also the shape of the core influences the mass value. Thirdly, the effects of the other family members need to be taken into account. All three effects are small, and therefore, elementary particle masses are much smaller than the Planck mass.

To estimate particle masses numerically requires estimating the probability values for the three massgenerating effects. Using estimates of tether shape probabilities and a typical core circumference of around 6 Planck lengths yields upper limits for elementary particle masses $m$ of the order of

$$
\begin{equation*}
m / m_{\mathrm{Pl}}<\left(\mathrm{e}^{-6}\right)^{2}<10^{-5} \tag{9}
\end{equation*}
$$

but it is difficult to be more precise. (In fact, one might argue that 4 tethers implies an upper limit of $\left(\mathrm{e}^{-6}\right)^{4}<10^{-10}$ and correspondingly for 6 tethers.) For comparison, experimental values lie between abound $4 \cdot 10^{-30}$ for neutrinos and about $3 \cdot 10^{-17}$ for the top quark.

Substantial progress in mass estimates is thus needed to allow testing the strand conjecture in the domain of mass values. Researchers on geometric knot theory, on polymers, on cosmic strings, or on vortices in superfluids might have suitable methods at hand.

Even without precise calculation, the strand conjecture suggests that the mass of the electron neutrino is extremely small, because its tangle is very similar to the structure of the vacuum. The conjecture also predicts that the other two neutrinos, shown in Figure 13, have larger mass values, and with normal ordering.

Using just the tangle ropelength, i.e., the length $L$ of the tight tangle core, a crude estimate for the Z/W mass ratio and the Higgs/Z mass ratio can be given. Computer calculations by Eric Rawdon yield
$L_{\mathrm{W}}=4.28$ rope diameters, $L_{\mathrm{Z}}=7.25$ rope diameters, and $L_{\mathrm{Higgs}}=17.1$ rope diameters. The crudest mass ratio estimates are the naive expressions

$$
\begin{equation*}
m_{\mathrm{Z}} / m_{\mathrm{W}}=\left(L_{\mathrm{Z}} / L_{\mathrm{W}}\right)^{1 / 3}=1.19 \text { and } m_{\mathrm{Higgs}} / m_{\mathrm{Z}}=\left(L_{\mathrm{Higgs}} / L_{\mathrm{Z}}\right)^{1 / 3}=1.33 \tag{10}
\end{equation*}
$$

that take into account only the volume, but not the shape of the tangle cores. These estimates can be compared to the observed values 1.13 and 1.37. The agreement is not good, but encouraging. The mass ratio of the weak bosons is also related to the weak mixing angle, so that the strand conjecture estimates

$$
\begin{equation*}
\sin ^{2} \theta_{W}=1-\left(m_{\mathrm{W}} / m_{\mathrm{Z}}\right)^{2}=0.30 \tag{11}
\end{equation*}
$$

The observed value is 0.22 ; again the agreement is not good, but can be called encouraging.

## 17 Predictions about coupling constants

In nature, the coupling constants describe the strengths of the gauge interactions: they specify the average phase change that an absorbed gauge boson induces in a charged particle.

In the strand conjecture, absorbed vector bosons change the fermion phase by inducing a Reidemeister move, as Figure 17 shows. 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. The coupling constants are thus not parameters, but have fixed, unique and calculable values.

The strand conjecture on coupling constants leads to predictions already before any calculation. Because all Feynman diagrams are reproduced in the strand conjecture, quantum field theory remains valid. In particular, the three effective coupling constants are predicted to run with energy, to be constant over time and space (despite the occasional claim to the contrary), and to be equal for all particles (an observation hard to explain otherwise) and also for all antiparticles. In fact, the strand conjecture directly predicts that coupling constants are larger than zero and smaller than one. But also their sum is predicted to comply with these limits:

$$
\begin{equation*}
0<\sqrt{\alpha}+\sqrt{\alpha_{\mathrm{w}}}+\sqrt{\alpha_{\mathrm{s}}}<1 \tag{12}
\end{equation*}
$$

This prediction for all energies is less obvious and agrees with data.
Given that the electromagnetic interaction is mediated by single strands, the weak interaction by double strands, and the strong interaction by triple strands, strands predict that at low energy

$$
\begin{equation*}
\alpha<\alpha_{\mathrm{w}}<\alpha_{\mathrm{s}} \tag{13}
\end{equation*}
$$

This agrees with observations.
In addition, because the three gauge interactions are fundamental and independent from each other, there is no a priori reason that the three coupling constants have the same value at any particular energy. This also agrees with extrapolated precision observations.

In the strand conjecture, the charge values of particles are automatically large enough to satisfy the weak gravity conjecture: the number of crossing switches per time due to gauge interactions is much larger than the number due to mass. The number difference results from the different ways in which charges (mainly of topological origin) and masses (mainly of dynamic origin) arise in tangle cores.


Figure 38: The geometric details of the fundamental QED process: (top) the absorption of a photon by a region of the tangle core carrying the charge $e / 3$, viewed along the shortest distance of the fermion crossing; (middle) the absorption geometry under ideal circumstances, when the photon arrives along the symmetry axis of the crossing and the strands span an angle of $\pi / 4$; (bottom) the corresponding observation in space.

## 18 Estimating the fine structure constant

In the strand conjecture, the electromagnetic interaction is the rotation of crossings by photon absorption or emission, as illustrated above in Figure 19. The detailed geometry is illustrated in Figure 38. In the QED diagram, an approaching photon transfers its twist to a crossing in the tangle core; the photon rotates the crossing, loses its own twistedness, and becomes a vacuum strand. As a result, the photon is absorbed and the quantum phase of the tangle core, and thus of the particle, has changed. The average phase change is the (square root of the) fine structure constant.

A particle is electrically charged if it changes phase in a preferred direction when absorbing random photons. As mentioned above, a neutral particle has a topologically achiral tangle core, i.e., a core that is equal to its mirror image in the minimal crossing projection. Such 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, one that differs from its mirror image in the minimal projection. Such a core has a preferred rotation direction when absorbing random photons. Electric (and other) charges are thus topological properties of tangles.

More precisely, a tangle has an electric charge unit $e$ if it contains 3 crossings of the same sign. (This is valid for elementary and for composed particles.) The strand process illustrated in Figure 38 thus describes the effect of a photon on a charge $e / 3$ : this is conjectured to be the Planck-scale strand process at the basis of QED. And this process allows estimating the fine structure constant $\alpha$.

The strand QED process explains why only crossing switches can be observed: only crossing switches can emit or absorb photons; and since every observation and every measurement in physics uses photons to trigger the measurement apparatus, crossing switches are observable, and other strand deformations are not. This unexpected return from QED back to the fundamental principle is one of the most appealing aspects of the strand conjecture.

It is worth noting that even though the strand configuration of Figure 19 is not chiral, the configurations of Figure 38 are. And by exploring Figure 38 in detail, the fine structure constant $\alpha$ can be estimated. A photon is absorbed under ideal circumstances if it is absorbed under ideal photon polarization, ideal photon phase, ideal fermion strand configuration and with ideal incidence angle. A photon absorbed under such ideal circumstances will yield a complete crossing switch, i.e., an ideal fermion phase change value of $\pi$. A photon absorbed under general, non-ideal circumstances will only yield a partial crossing switch, i.e., a phase change smaller than the ideal value.

The angles involved in the photon absorption process are specified in Figure 38, by looking along the shortest distance of the tangle crossing. The two strands are then both parallel to the paper plane. In this projection, we call $\beta$ the angle from the incident photon strand to the symmetry axis of the crossing, $\gamma$ the angle from the incident photon strand to the paper plane, and $\delta$ the angle between the two tangle strands. In the ideal case $\beta=\gamma=0$ the induced phase change is $\pi$; in the general case, the induced phase change is smaller.

Approximating the average phase change induced in a crossing by an absorbed photon is possible using Figure 38. First computer calculations that average the induced phase change over all incidence
angles $\beta$ and $\gamma$ and over all crossing angles $\delta$, multiplied by 3 to get the value for a unit charge, yield

$$
\begin{equation*}
\sqrt{\alpha} \approx 0.18 \tag{14}
\end{equation*}
$$

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

On the one hand, the calculations are still dubious. Also, the effect of different distances between the skew strands has not yet been taken into account; this distance might be related to the cutoff used in renormalization. Finally, the factor 3 will not be correct for highest energies, when the tangle is tight.

On the other hand, the Planck scale model for the fundamental QED diagram remains promising: it produces a value for the fine structure constant that is unique, constant, and equal for all charged particles. The same applies to the two nuclear coupling constants. Above all, the calculation does not need any input; it is ab initio. Improving the calculation will allow comparison with experiment and thus yield a conclusive test of the strand conjecture.

## 19 Objections and discussion

- When a person enters a room, walks around a table, and then exits the room through another door, is the person really pulling $10^{30}$ twisted tethers with it? Yes, that appears to be the case. On the one hand, the added number of tethers is tiny compared to the number already present in the room. On the other hand, fluctuations, string/belt tricks and strand hopping quickly restore the status quo ante. After all, empty space is made of tethers.
- The presented arguments consist mainly of pictures. True; the proposed particles tangles show above all that a consistent description of quantum field theory and gauge interactions is possible with strands.
- Both the conjecture to describe nature with strands and the conjectured particle tangles are not testable; even though the strand conjecture is one of the first attempts to explain the particle spectrum and the gauge groups, reproducing the particle spectrum and all the Feynman diagrams is not a sufficient argument for the existence of strands. True; therefore the expression 'strand conjecture' is used throughout. The strand conjecture is falsifiable through the various predictions that are listed above. The strand conjecture is verifiable only by comparing the calculated and the measured fundamental constants.
- The strand conjecture proposes a microscopic model for quantum theory, but such attempts have never been successful in the past. True; nevertheless, because the strand conjecture completely reproduces quantum theory and decoherence, without any changes, no issues are expected.
- The strand conjecture proposes an unusual mechanism for the appearance of the gauge groups. True; the mechanism differs from all proposals in the research literature so far, in particular because it does not introduce additional fundamental parameters or coupling constants, but eliminates them.
- The mass ordering of the up and down quarks is not settled. True; a future, more precise mass estimate that takes into account tangle shapes and fluctuations should settle this issue.
- No interesting statements about the cosmological constant $\Lambda$ are made. True; the topic will be treated in a future publication.
- The strand conjecture does not propose a fundamental evolution equation. True; this is expected from a unified approach, because when space is emergent, differential equations are not possible.
- The fundamental principle does not define an axiomatic system and does not define space and time clearly. True; on the one hand, space is needed to describe nature, and on the other hand, space is emergent. Therefore, a unified theory must contain a certain degree of circularity, and thus it cannot be formulated axiomatically and with full clarity.
- No new physics is predicted. True; the strand conjecture agrees with all experiments, makes numerous zero-outcome predictions, and, unexpectedly, also predicts the lack of new physics. Future precision tests of the standard model and of general relativity are predicted to show no deviations. But the conjecture shows the simplicity and beauty of the standard model.


## 20 Summary and outlook

Physics and all known experimental observations about motion appear to follow from strands fluctuating at the Planck scale. The fundamental principle - namely that switches of skew strand crossings define the Planck units - appears to imply general relativity, Dirac's equation, and all quantum effects. Strands appear to explain the $\mathrm{U}(1)$, broken $\mathrm{SU}(2)$ and $\mathrm{SU}(3)$ gauge groups as effects of Reidemeister moves, and to explain the known particle spectrum with all the observed Feynman diagrams as consequences of rational tangles and their possible deformations.

The strand conjecture appears to predict that general relativity and the standard model of elementary particle physics are final: no other elementary particle, gauge group or Feynman diagram exists, neutrinos are massive Dirac particles, and dark matter is conventional matter plus black holes.

The strand conjecture suggests that particle mass is due to crossing switches, that mixing angles are due to partial tether rearrangements, and that the gauge coupling constants are average effects of Reidemeister moves. Thus, the fundamental constants of the standard model are predicted to be calculable ab initio. A crude estimate for the fine structure constant has been attempted.

In summary, the strand conjecture claims that the standard model, with all its particles, symmetries and constants, is not ad hoc or ugly, but simple and beautiful: The standard model is due to switches of skew strand crossings.

In retrospective, a crossing switch could be seen as a specific embodiment of what is called an 'Ur' or a 'qubit'. In this sense, the strand conjecture is an approach realizing 'it from bit', and in particular, an approach that allows calculations. In addition, the full conjecture fits on a T-shirt.

Provided that the strand conjecture and the assumed particle-tangle assignments agree also with future experiments, the remaining challenge is to increase the calculation precision of the coupling constants, of the neutrino and other particle masses, and of the mixing angles. This definite test of the conjecture can occur by developing more accurate analytical calculations or by performing computer simulations.

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## 22 Appendix: tethering, spin $1 / 2$ and fermion behaviour

Two animations show that tethered particles have spin $1 / 2$, can rotate forever, and are fermions. These properties, intrinsically linked to the three-dimensionality of space, are important for the appearance of Dirac's equation in the case of tethered tangles. The animations, cited in the paper, are included here with permission.


Tethering in three-dimensional space implies the equivalence of no rotation and rotation by $4 \pi$ - but not $2 \pi$. Tethering thus yields spin $1 / 2$ behaviour and the possibility of tethered rotation to go on forever. The number of tethers is unlimited, as is easily checked. (Animation © by Jason Hise [9].)


Tethering in three-dimensional space implies the equivalence of no particle exchange with double particle exchange - but not of simple particle exchange. Tethering thus yields fermion behaviour. The number of tethers is again unlimited, as is easily checked. (Animation © by Antonio Martos [10].)

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