We have a basic theory of strings. Our model includes open and closed strings with quantized modes of oscillation. They live in multiple dimensions. Now we want to describe their interactions; isolated strings moving through spacetime aren't very interesting. We want them to build things – atoms and galaxies – and we want them to blow things up – bombs and supernovas. To find how they push and pull and stick and sever, we need a scattering amplitude for strings. On the way, we will build the fundamental equation of string theory, the Polyakov (Susskind) action.

## Feynman diagrams

Physicists test particle theory by comparing model predictions (the Standard Model of particle physics) with experimental results from particle colliders. The key ingredient in collider data is the scattering amplitude. What happens when two protons collide head-on at the enormous energies in the Large Hadron Collider? The products of collision are predicted by the scattering amplitudes and compared to measurements obtained by particle detectors at the LHC. It seems reasonable to use the same regime to determine whether particles are made of strings. Find the scattering amplitudes predicted by string theory, and compare with collider data.

We need tools. The great tools of particle interactions are Feynman diagrams, which trace particle motion and particle interactions in spacetime. The basic interaction occurs between a fermion and its associated boson.

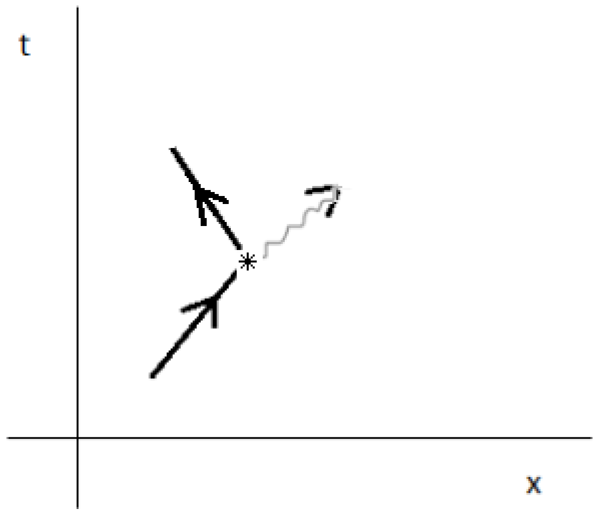


Figure 13.1. Basic interaction: a particle accelerates and emits a boson. This could be an electron emitting a photon.

Note the axes. Time flows upward. A particle moving toward the right is represented by a solid line tilted right. In the jargon of Feynman diagrams, that line is called a propagator. A wavy squiggle represents a boson. The asterisk represents the interaction between fermion and boson.

Its position on the diagram is called a vertex. We attach a number to it, the interaction amplitude, representing the (square root of the) probability that the interaction would occur. As an example, this diagram could represent an electron initially moving to the right. It emits a photon, and the emission accelerates the electron backward. The interaction amplitude for the emission of a photon (the basic electromagnetic interaction) is the fine structure constant, $\alpha$ , about $1/_{137}$ . i.e. such an interaction would occur in about one out of 137 electrons in a sea of photons. Similar interactions occur between quarks and gluons and, in general, between all the fermions and their associated bosons.

We build all possible particle interactions from this basic one. If a fermion (e.g. electron) can emit a boson (e.g. photon), it can also absorb one.

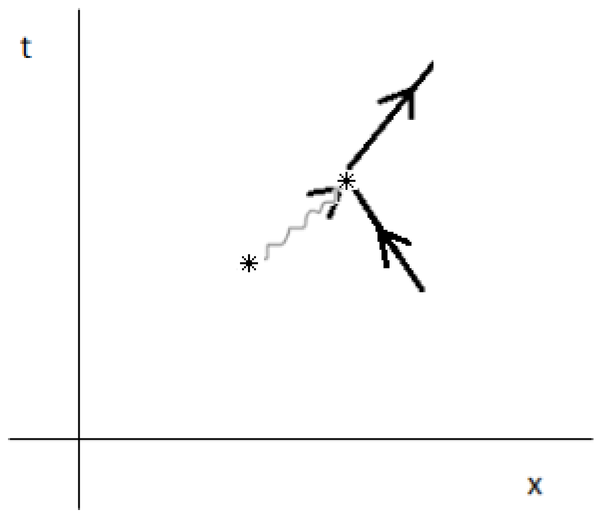


Figure 13.2

And if both emission and absorption can occur, then two electrons can interact with each other by exchanging a photon. This is the mechanism of the electromagnetic interaction: e.g. the two electrons repel each other.

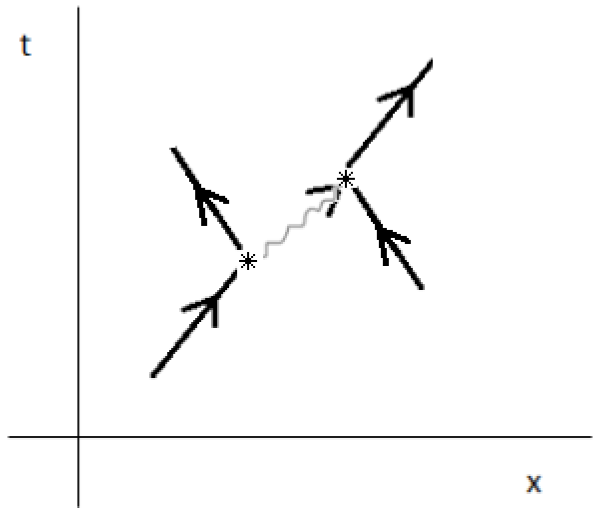


Figure 13.3

We see another possible interaction if we tilt the fundamental interaction on its side.

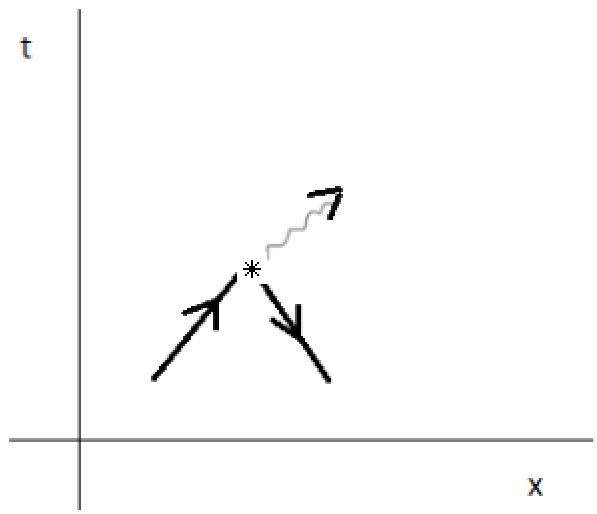


Figure 13.4

The arrow-down particle, a particle going backward in time, represents an anti-particle. This diagram could represent the annihilation of an electron with its anti-particle (the positron) with the emission of a photon.

From these basics, we build all the possible particle interactions and calculate the probability that they will occur. The diagrams quickly get more complicated.

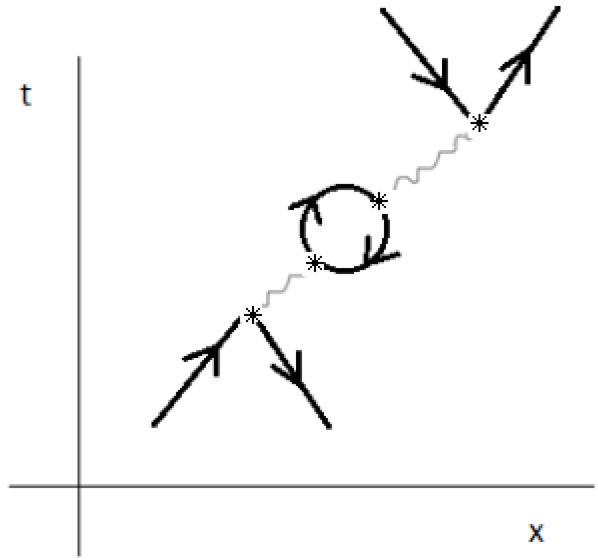


Figure 13.5

Here, an electron and positron annihilate (bottom left).  The emitted photon produces another particle-antiparticle pair (show as a loop) which quickly annihilate.  The energy of the photon finally produces another electron-positron pair.

Curiouser and curiouser, the possible interactions pile up.

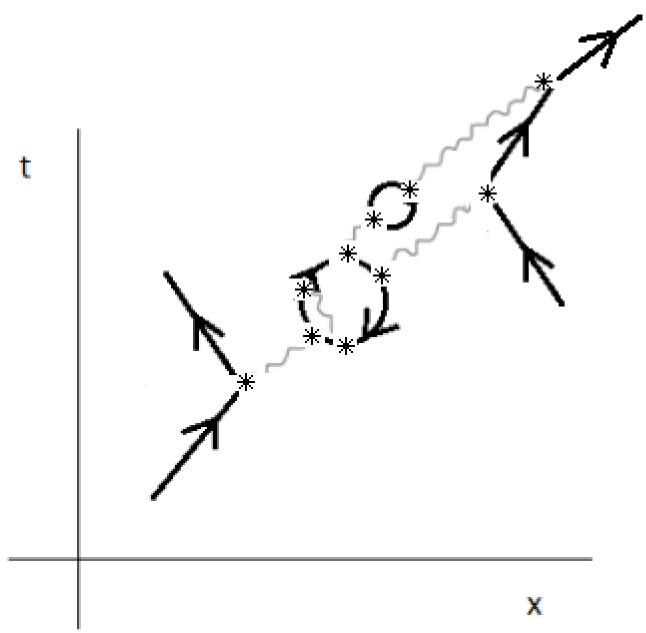


Figure 13.6

The more vertices there are in a diagram, the less probable it is that the process will occur. The interaction amplitudes at each vertex have magnitude less than one. The total process includes the products of all the interaction amplitudes, so the probability rapidly approaches zero if there are many vertices.

In order to determine whether string theory correctly predicts the outcome of particle interactions, we will be interested particularly in the diagrams of particle collisions. Two basic processes can occur. The particles can smash together to form some amalgam, which then disintegrates. This is referred to as a "T-channel" process.

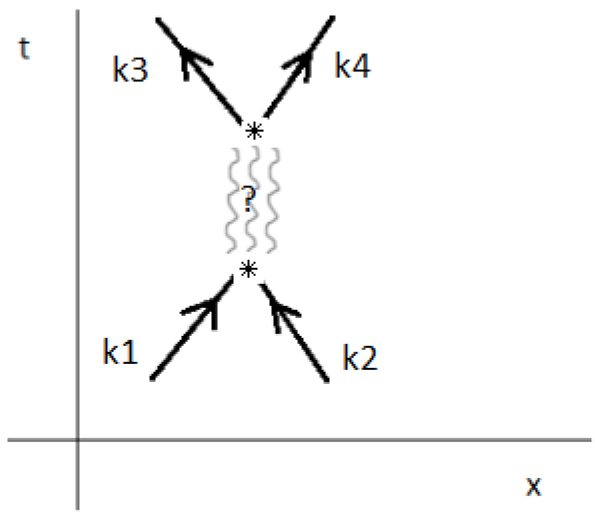


Figure 13.7. T-channel process.

The $k$'s represent the momenta of the incoming and outgoing particles. For simplicity, we have suppressed the $45°$ tilt of the squiggles, which now represent a "black box" of interacting components.

The second possible outcome of a particle collision is the "S-channel" process.

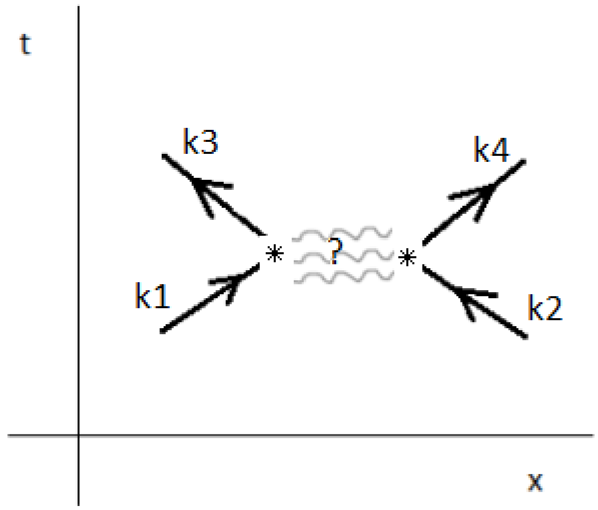

Figure 13.8. S-channel process.

Here, the incoming particles, with momenta k1 and k2 , exchange a "black box" of virtual particles without physically merging.

It turns out that both processes, T and S, occur together in particle collisions. This was a head scratcher in the Standard Model. Why both channels? Strings make clear why this must be the case.

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