From Quantum Mechanics to String Theory

- Relativity (why it makes sense)
- Quantum mechanics: measurements and uncertainty
- Smashing things together: from Rutherford to the LHC
- Particle Interactions
- Quarks and the Strong Force
- Symmetry and Unification
- String Theory: a different kind of unification
- Extra Dimensions
- Strings and the Strong Force
Strings and the Strong Force
String Theory Origins

- We introduced string theory as a possible solution to our problems with gravity.
- We proposed that quarks and leptons were actually little strings of different shapes.
- This was not the first reason physicists considered the idea of strings.
- It was originally introduced as an alternate explanation of the strong force.
- Mesons, instead of being quark/anti-quark pairs, were thought to be little open strings.
Meson Patterns

- We used the patterns mesons can be arranged in to motivate the quark picture
  
- The nonets are not the only pattern we can arrange mesons into
  
- There are many more mesons than the ones in the nonets (heavier mesons)
  
- We can form families of these mesons that act very similar (e.g. are made up of the same quark content) but with different masses and spins

- $K^+ (\bar{s}u)$  $K^0 (\bar{s}d)$
- $\pi^+ (\bar{d}u)$  $\pi^0, \eta^0$  $\pi^- (\bar{u}d)$
- $\bar{K}^0 (\bar{d}s)$  $K^- (\bar{u}s)$
- $K^{*+} (\bar{s}u)$  $K^{*0} (\bar{s}d)$
- $\rho^+ (\bar{d}u)$  $\rho^0, \omega^0$  $\rho^- (\bar{u}d)$
- $\bar{K}^{*0} (\bar{d}s)$  $K^{*-} (\bar{u}s)$
Meson Patterns

- The $\omega$ and $\rho$ mesons are each spin 1, and have very similar mass.

- Each has heavier particles in the same family.

- $\omega_3$ and $\rho_3$ are spin 3, and are heavier, but otherwise are very similar to $\omega$ and $\rho$.

- $a$ and $f$ also represent types of mesons, with even spins.

- As you increase the spins, the particles have increasing angular momentum, falling on a line called a Regge trajectory.
Strings have exactly this relationship between spin and mass

the more wiggles the string has, the greater both its mass and its spin

String theory also leads to a linear relationship between the two
Splitting Strings

- Quark picture: mesons are pairs of quark and anti-quark, with a strong field between them that doesn’t spread out (doesn’t decrease with distance)

- As you pull them apart, they generate a new quark/anti-quark pair and you end up with two mesons

- Suppose instead the meson is an open string

- As you pull it apart, what you get is two smaller open strings
Interactions

Proton and neutron interactions are explained by the exchanges of pions and other mesons.

If two particles can exchange a meson, they can exchange any meson on that trajectory.

To get full effect, sum over all these interactions.

Creates the same result as exchanging an open string (exchanged string can have any number of wiggles on it).
Other QCD particles

If mesons are open strings, what are closed strings?

These are glueballs: colorless bound states of gluons that have mass from the binding energy.

Glueballs have not been confirmed experimentally (some evidence but it’s difficult to tell the difference between a glueball signal and a highly unstable meson, for example).

Numerical calculations of QCD (called lattice QCD) can show their existence and predict their masses.

Baryons are more difficult to describe: they might be explained as some complicated combination of open strings.
Interactions in QED

- For a theory like electrodynamics, the interaction of two electrons most often occurs by exchange of one photon.
- It is also possible for them to exchange two photons, but this is much less likely.
- More complicated interactions are even less likely.
- Organize what occurs by the biggest contributions first, then the next biggest, etc...
Interactions in QCD

The strong force is so strong that the more complicated the diagram I try to draw, the more likely it is that it occurred.

Interactions with two gluons are more likely than those with one, and so on...

A typical interaction between a quark and an anti-quark might look like this:

This “netting”, as it gets more dense, begins to look like an open string moving through time
Colors and Interactions

- Draw an interaction keeping track of colors
- Each quark carries one unit of color
- Each gluon carries a unit of color and a unit of anticolor
- Each line drawn represents the flow of color
- The incoming and outgoing quarks have definite color
- Every closed loop in the middle can be any color
In QCD, there are 3 colors. Suppose instead there were $N$ colors.

Every time there is a loop, there are $N$ possibilities for what color it is. This makes the interaction (as observed) $N$ times as likely.

This diagram is less likely than one where the quark loop is replaced by a loop of gluons by a factor of $N$. 
String Interaction Picture

- A quark loop like this maps onto a hole in the string path.

- This is a type of string interaction: the string splits into two and then rejoins.

- If the number of colors is large, then extra string interactions are less likely, just like extra photon interactions was less likely in QED.

- Can organize the string interactions in terms of how likely they are.
Holography

- A 3+1 dimensional QCD-like theory can also be described as a 4+1 dimensional gravitational theory.
- String theory with 5 compact dimensions makes a 4+1 dimensional gravitational theory.
- One direction of the 4+1 space is warped.
- The 3+1 QCD theory lives on the boundary of the 4+1 space.
Different Holographies

- Depending on the shape of the curved 4+1 space and the compact 5 space you get a different 3+1 dimensional theory.

- Best understood example: If the 4+1 space is a special shape called “Anti-de-Sitter” space (it’s like a sphere, but with negative curvature).

- The compact 5-space is a 5-sphere.

- This has the most symmetry possible.

- The QCD-like theory has a high degree of symmetry (supersymmetry, etc), no quarks (just gluons) and doesn’t confine color.
QCD and strings

This extremely symmetric, simple system we can come close to proving can be equally well described by the strings and by the 3+1 dimensional theory of gluons.

For QCD, what we don’t have is an accurate picture of how the string theory background is curved.

We know it should have much less symmetry, and therefore the compact space should be more complicated than a 5-sphere.

We also know that the AdS shape (negative curvature) is associated with the lack of confinement of color, so it should be changed, too.
Mesons fall on lines where increasing spin is correlated to increasing mass. If mesons are open strings, this pattern is explained by wiggles on the strings.

When you try to pull a meson apart, you get two mesons. This might be strings splitting into smaller strings.

QCD interactions in terms of quarks and gluons is complicated by the strength of the force: interactions where many quarks and gluons are exchanged are favored. This “netting” interaction resembles a string interaction.

It’s possible that there might be more than one description for the strong force: QCD in 3+1 dimensions and a gravitational string theory in 4+1 dimensions.