Particle physics
- Have talked about several particles: electron, photon, proton, neutron, quark.
- There are a plethora of others that we haven’t talked about.
- Most of these are composite, meaning that they have internal constituents.
- Just as an atom is not ‘fundamental’, but has internal constituents electron, proton, neutron.

Particles and fields
- But what are particles?
- We say that particles are quanta of a corresponding field.
- But what does this mean?
- Think about photons.
  - One photon means the electromagnetic field has (Planck’s const)\(\times\)frequency = \(\hbar f\) of energy.
  - Two photons means \(2\hbar f\) of energy.
  - Three photons means \(3\hbar f\) of energy.

Electrons and Photons: Quantum Electrodynamics
- QED is the relativistic quantum theory of electrons and photons, easily generalized to include other charged particles.
- Feynman popularized the idea that all QED processes reduce to photon emission or absorption which may be represented by a simple diagram - a Feynman diagram.

Antiparticles
- There is such a thing as antimatter.
- There is a particle with exact same mass as electron, but with a positive charge.
- It is called the positron.
- All particles have an antiparticle.

Pair production, annihilation
- Electron and positron can ‘annihilate’ to form two photons.
- Photon can ‘disappear’ to form electron-positron pair.

Seeing antiparticles
- Photons shot into a tank of liquid hydrogen in a magnetic field.
- Electrons and positrons bend in opposite directions and, losing energy to ionization, spiral to rest.
Fields for other particles

- Works for other particles as well
- An electron is a quantum of the electron field.
- What is the energy?
  - Smallest energy is rest energy of electron = 0.5 MeV/c^2
- Can also work for electron-positron pairs
  - These are also quanta of the field.

Creating more particles

- All that is needed to create particles is energy.
- Energy can be provided by high-energy collision of particles.
- An example:
  - Electron and positron annihilate to form a (virtual) photon.
  - This can then create particles with mc^2-photon energy.

High-energy experiments

- Source of high-energy particles required
- Originally took advantage of cosmic rays entering earth’s atmosphere.
- Now experiments are done in large colliders, where particles are accelerated to high energies and then collides.

Three happy families...

- In 1975, researchers at the Stanford Linear Accelerator discovered a third charged lepton, with a mass about 3500 times that of the electron. It was named the τ-lepton.
- In 2000, first evidence of the τ’s partner, the tau-neutrino (ν_τ) was announced at Fermi National Accelerator Lab.

<table>
<thead>
<tr>
<th>Family</th>
<th>Leptons</th>
<th>Antileptons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Q = -1</td>
<td>Q = 0</td>
</tr>
<tr>
<td>1</td>
<td>e^-</td>
<td>μ^-</td>
</tr>
<tr>
<td>2</td>
<td>ν_e</td>
<td>ν_μ</td>
</tr>
<tr>
<td>3</td>
<td>τ^-</td>
<td>τ^-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Q = +1</th>
<th>Q = 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>e^+</td>
<td>μ^+</td>
</tr>
<tr>
<td>2</td>
<td>ν_μ</td>
<td>ν_τ</td>
</tr>
<tr>
<td>3</td>
<td>τ^+</td>
<td>τ^+</td>
</tr>
</tbody>
</table>

Cosmic rays

- New particles were discovered in cosmic ray air showers in which a high energy extraterrestrial proton strikes a nucleus (N or O) in the atmosphere and secondary particles multiply.

Electrostatic Accelerators

- An electrostatic accelerator uses mechanical means to separate charged and create a potential V.
- An electron or proton dropped through the potential achieves an energy eV.
- V~ 1 million volts is achievable, limited by spark break down
Linear accelerators

- A metal cavity contains a standing wave. An injected particle surfs the wave acquiring energy of order 1 MeV/m.
- Larger cavity electric fields cause electron emission from the walls and breakdown.
- A succession of cavities properly phased yields high energy.
- The Stanford Linear Accelerator (SLAC) is 3 km in length and achieves ~50 GeV per electron.

SLAC

- Stanford Linear Accelerator Center

Cyclic accelerators

- Run particles through a linac then thru a string of electromagnets around a circle for successive kicks. Increases the magnetic field strength as the energy increases.
- The radius is determined by the maximum B field strength ~10 T.
- The Fermilab Tevatron accelerates protons to 1 TeV=1000 GeV = 1e6 MeV in a four mile circumference ring.

Fermilab

- Fermi National Accelerator Center, Batavia IL
- Cyclic accelerator

CERN (Switzerland)

2300 employees (+ 2000)
6000 visitors
20 Member states (+ US, Canada, Japan, Russia, China, India, ...)
ACCELERATORS (LHC, 2007),
DETECTORS (ATLAS, CMS, LHCb, ALICE)

Large hadron collider (CERN)

Largest cryogenic system
(1.8 K, superfluid helium)
27 km of 8 T magnets
100 m below surface
Measuring particle collisions

Detectors are required to determine the results of the collisions. Many collisions per second result in extremely high data rates.

CDF

• Collider Detector Facility at Fermilab
• Apparatus to measure particles produced in high-energy collisions.

In a nutshell (not quite)

• "Matter is made of atoms"
• "Atoms are made of leptons and quarks"

Leptons: \( e, \nu_e \)  
Quarks: \( u, d \)

Hierarchy of structure

R ~ 10^{-15} m (strong) protons and neutrons are made from quarks

R ~ 10^{-10} m (electromagnetic) Atoms are made from protons, neutrons, and electrons

R > 10^6 m (gravitational) We’ll talk about the rest of the universe later

The particle garden

• Particle physics at this point has settled on a countable number of ‘fundamental particles’.
• The bad news:
  - There are (6 leptons +6 quarks) + (4 electroweak bosons +8 gluons +1 graviton) = 25 fundamental particles, not counting antiparticles!
• The good news:
  - These are not just random, but have some relationships that lets us understand the ideas without thinking immediately about all the particles.

Three ‘generations’ of particles

• Three generations differentiated primarily by mass (energy).
• First generation
  - One pair of leptons, one pair of quarks
• Leptons: 
  - Electron, electron-neutrino.
• Quarks:
  - Up, down.
The 'generations'

Leptons and quarks: what's the difference?
- One important difference is how they interact.
- We said the Coulomb interaction is between particles with electrical charge.
- Understood by exchanging photons.
- The other interactions:
  - Weak
  - Strong
  - Gravitational

The vacuum
- Modern particle physics says that the vacuum is not as simple as one might think.
- We talked about an uncertainty principle, that momentum and position cannot be simultaneously determined.
- There is an equivalent relation in the time domain.

Energy uncertainty
- To make a very short pulse in time, need to combine a range of frequencies.
- Frequency related to quantum energy by $E=hf$.
- Heisenberg uncertainty relation can also be stated
  - (Energy uncertainty)$\times$(time uncertainty) $\sim$ (Planck's constant)

The vacuum is not empty
- This says the vacuum is continually 'fluctuating', with virtual photons, electron-positron pairs, etc.
- Vacuum is really empty at all.
Four Gauge forces

Exchange bosons

- Each interaction has one or more associated particles that mediate the interaction.
- The exchange particles are associated with the known interactions:

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Mediating particle(s)</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electro-magnetic</td>
<td>photon</td>
<td>(1)</td>
</tr>
<tr>
<td>Weak</td>
<td>W⁺, W⁻ and Z⁰</td>
<td>(3)</td>
</tr>
<tr>
<td>Strong</td>
<td>gluons</td>
<td>(8)</td>
</tr>
<tr>
<td>Gravity</td>
<td>graviton</td>
<td>(1)</td>
</tr>
</tbody>
</table>

- These all have integer spins, hence are bosons

Interaction via particle exchange

- Exchange boson
- Classical collision

- These are the exchange bosons.
- What are they exchanged between?
- Or... on what are the corresponding forces exerted?
- Example:
  - When a photon is exchanged between two particles, there is a Coulomb force.
  - We know that only particles with electrical charge interact via the Coulomb force
  - Zero charge -> zero Coulomb interaction

- In this language, we say that the electrical charge is a 'source' of an EM field.
- A mass 'charge' is the source of a gravitational field
- A weak 'charge' (sometimes called 'flavor') is the source of a weak interaction field
- A strong 'charge' (sometimes called 'color') is the source of a strong interaction field

- Quarks interact via the strong force by exchanging gluons, leptons do not.
- The source of the gluon field is color charge.
- Quarks carry color charge.
A little complicated

- But things don’t separate quite so cleanly.
- Electrons interact via the Coulomb force and also the weak force.
- So the electron carries both electric charge and weak charge.
- And the some of the bosons that mediate the weak force carry electrical charge
  - They can absorb and emit photons!

<table>
<thead>
<tr>
<th>Bosons</th>
<th>Force Carriers</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Mass (GeV/c²)</td>
<td>Electric Charge</td>
</tr>
<tr>
<td>Photon</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>W⁻</td>
<td>80.4</td>
<td>-1</td>
</tr>
<tr>
<td>W⁺</td>
<td>80.4</td>
<td>+1</td>
</tr>
<tr>
<td>Z⁰</td>
<td>91.187</td>
<td>0</td>
</tr>
<tr>
<td>Gluon</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

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- Fermi National Accelerator Center, Batavia IL