Particle Physics Lectures Outline

1 - Introduction
   The Standard Model of particle physics
   The fundamental particles and forces
2 - Practical Particle Physics
   Measuring particle physics
   Units, decays, scattering
   Quantum numbers
3 - Quantum Electrodynamics (QED)
   Anti-particles
   Quantum description of electromagnetism
   Feynman diagrams
4 - The LHC and colliders
   Particle acceleration
   Colliders
5 - Detecting particles
   Interactions of particles in matter
   The ATLAS Detector
6 - Protons, Quarks and Strong Interactions
   Evidence for quarks and colour
   Gluons, hadronisation
   Quark Confinement
   Running coupling constant
7 - Weak Interactions
   Muon and tau decay
   Weak quark decays
8 - Electroweak and the Higgs boson
   $W$ and $Z$ bosons
   The Higgs mechanism
9 - Neutrinos
   and maybe some B-physics
10 - Beyond the Standard Model
    Supersymmetry
    Extra dimensions …
Particle Physics and Me

Dr Victoria Martin
JCMB room 5419  victoria.martin@ed.ac.uk

My research deals with Particle Physics at Colliders.
I’m currently involved with two projects:

1. The ATLAS experiment at the Large Hadron Collider. The LHC collides protons on protons at 14 TeV.

2. The international linear collider (ILC). Design is to collide electrons and positrons at 0.5 - 1 TeV (or more?)

Books etc

- In conjunction with attending the lectures you will need to read around the subject to fully understand the material.

Most up to date:

- Level of this course: Particle Physics, by B.R. Martin & G. Shaw, 3rd edition (Wiley 2008)
  - 10 copies in JCM Library
  - 4 copies in JCM Library

Oldies (but goodies):


Further Resources:

- For more information that you could ever need on every particle ever: http://durpdg.dur.ac.uk/lbl/
- Information about LHC and LHC physics: www.cern.ch
  www.atlas.ch
Subatomic Physics:
Particle Physics Lecture 1

Our current understanding:
“The Standard Model of Particle Physics”

From the Atom to Subatomic

atom

nucleus

protons & neutrons

quarks & electrons

Nuclear Physics

Particle Physics

from introductory Subatomic slides
The current understanding of the fundamental particles and the interactions between them is called the “Standard Model of Particle Physics”.

- **LEPTONS**
  - Electron
  - Electron neutrino
  - Muon
  - Muon neutrino
  - Tau
  - Tau neutrino

- **QUARKS**
  - Up (u)
  - Down (d)
  - Charm (c)
  - Strange (s)
  - Top (t)
  - Bottom (b)

- **MATTER**
- **ATOM**
- **NUCLEUS**
- **PROTON**
- **QUARK**

**FOR THE MOST PART, THESE PARTICLES EXISTED IN THE EARLY MOMENTS AFTER THE BIG BANG.**

**ANTIMATTER** Each particle also has an antimatter counterpart ... sort of a mirror image.

**Boson-mediated FORCES**

- **Gravity**
- **Electromagnetism**
- **Weak**
- **Strong**

**Subatomic physics looks at:**

- (very) short distances
- (very) early time in the universe
- (very) high energy densities
Basic Particles (1st Generation)
The particles that you know already, e.g. from beta decay: \( n \rightarrow p \ e^- \bar{v}_e \)

**Leptons**
Electron and neutrino

**Quarks**
Nucleons are bound states of up-quarks and down-quarks

<table>
<thead>
<tr>
<th>Particle</th>
<th>Symbol</th>
<th>Electric Charge</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>( e^- )</td>
<td>-1</td>
<td>lepton</td>
</tr>
<tr>
<td>neutrino</td>
<td>( \nu_e )</td>
<td>0</td>
<td>lepton</td>
</tr>
<tr>
<td>up-quark</td>
<td>( u )</td>
<td>+2/3</td>
<td>quark</td>
</tr>
<tr>
<td>down-quark</td>
<td>( d )</td>
<td>-1/3</td>
<td>quark</td>
</tr>
</tbody>
</table>

- Nuclear physics description of beta decay: \( n \rightarrow p \ e^- \bar{v}_e \)
- Particle physics description of beta decay: \( d \rightarrow u \ e^- \bar{v}_e \)

Basic Constituents of Matter
Four spin-\( \frac{1}{2} \) fermions

Higher Generations
Nature replicates itself: there are three generations of quarks and leptons

<table>
<thead>
<tr>
<th>1st Generation</th>
<th>2nd Generation</th>
<th>3rd Generation</th>
<th>charge, ( e )</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>( e^- )</td>
<td>muon</td>
<td>( \mu^- )</td>
</tr>
<tr>
<td>electron neutrino</td>
<td>( \nu_e )</td>
<td>muon neutrino</td>
<td>( \nu_\mu )</td>
</tr>
<tr>
<td>down quark</td>
<td>( d )</td>
<td>strange quark</td>
<td>( s )</td>
</tr>
<tr>
<td>up quark</td>
<td>( u )</td>
<td>charm quark</td>
<td>( c )</td>
</tr>
</tbody>
</table>

Ordinary Matter: built from the 1st generation

Higher Generations:
- copies of \( (\nu_e, \ e^-, \ u, \ d) \)
- undergo identical interactions
- only difference is mass of particles
- generations are successively heavier

Why 3 generations? symmetry/structure not understood!
Antiparticles

Combining relativity and quantum mechanics implies every particle has a corresponding antiparticle.

Antiparticles of the SM particles are antimatter.

Compared to its matter partner, an antiparticle has:
- equal mass
- opposite electric charge
- opposite “additive” quantum numbers (e.g. opposite colour charge)

**Example:** positron \((e^+)\) antiparticle of the electron (“anti-electron”)

Discovered in 1931 by Carl Anderson.

**Notation:** bar over symbol or minus \(\leftrightarrow\) plus

e.g. for first generation: \(u \leftrightarrow \bar{u}\) \(d \leftrightarrow \bar{d}\) \(e^- \leftrightarrow e^+\) \(\nu_e \leftrightarrow \bar{\nu}_e\)

---

Schrödinger and Klein Gordon

- Quantum mechanics describes momentum and energy in terms of operators:
  \[
  \hat{E} = i\hbar \frac{\partial}{\partial t} \quad \hat{p} = -i\hbar \nabla
  \]

- \(E=p^2/2m\) gives time-dependent Schrödinger:
  \[
  -\frac{\hbar^2}{2m} \nabla^2 \Psi(\vec{r}, t) = i\hbar \frac{\partial}{\partial t} \Psi(\vec{r}, t)
  \]

- The solution with a definite energy, \(E\):
  \[
  \Psi_E(\vec{r}, t) = \psi_E(\vec{r}) \exp \left\{ -iEt/\hbar \right\}
  \]

- However for particles near the speed of light \(E^2=p^2c^2+m^2c^4\) \(\Rightarrow\)
  \[
  -\hbar^2 \frac{\partial^2}{\partial t^2} \Psi(\vec{r}, t) = -\hbar^2 c^2 \nabla^2 \Psi(\vec{r}, t) + m^2 c^4 \Psi(\vec{r}, t)
  \]

- Solutions with a fixed energy, \(E_p=+(p^2c^2+m^2c^4)^{\frac{1}{2}}\), and three-momentum, \(p\):
  \[
  \Psi(\vec{r}, t) = N \exp \left\{ i(\vec{p} \cdot \vec{r} - E_p t) / \hbar \right\}
  \]

- Also solutions with a negative energy, \(E_n=-E_p=-(p^2c^2+m^2c^4)^{\frac{1}{2}}\), and momentum, \(-p\):
  \[
  \Psi^*(\vec{r}, t) = N^* \exp \left\{ i(-\vec{p} \cdot \vec{r} + E_p t) / \hbar \right\}
  \]

- Negative energy solutions are a direct result of \(E^2=p^2c^2+m^2c^4\).

- We interpret these as anti-particles.
Subatomic Forces

At subatomic scales interactions between particles and nuclei are caused by the three subatomic forces:

- The **electromagnetic** force
- The **weak** nuclear force
- The **strong** nuclear force

The interactions due to these forces are evident in:

- **Scattering**: e.g. scattering of protons on protons at the LHC
- **Particle Decay**: e.g. decay of radioactive nuclei, decays of cosmic-ray muons
- **Nuclear Fission and Fusion**, e.g.: reactions in a nuclear reactor

\[ \frac{235}{92} U + n \rightarrow \frac{236}{92} U \rightarrow \frac{144}{56} Ba + \frac{89}{36} Kr + 3n \]

The Forces of Particle Physics

<table>
<thead>
<tr>
<th>Strong</th>
<th>Electromagnetic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strongest force</td>
<td>2nd strongest force</td>
</tr>
<tr>
<td>Acts on quarks only</td>
<td>Acts on charged particles</td>
</tr>
<tr>
<td>propagated by (8) gluons, ( g )</td>
<td>propagated by photon, ( \gamma )</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Weak</th>
<th>Gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>3rd strongest force</td>
<td>weakest force - negligible at PP scale</td>
</tr>
<tr>
<td>Acts on all particles</td>
<td>Acts on all particles</td>
</tr>
<tr>
<td>propagated by ( W^\pm ) and ( Z^0 ) bosons</td>
<td></td>
</tr>
</tbody>
</table>

- Quantum mechanical description uses “messenger particles” to propagate the force between particles.
- Messenger particles are spin-1/2 bosons
- *e.g.* beta decay \( n \rightarrow p e^- \bar{\nu}_e \) propagated by a \( W^- \) boson
Colour Charge

- Every particle which feels the electromagnetic force carries an electric charge: either positive or negative.
- The **strong** and **weak** forces also have charges associated with them.

**Colour charge**
- Only quarks (and gluons) experience the strong force.
- Every quark carries a “**col**our **charge**” quantum number: either **red**, **blue** or **green**. (This is in addition to their electric charge.)
- Every anti-quark also carries a “**col**our **charge**” quantum number: either **anti-red**, **anti-blue** or **anti-green**.

**Weak Hypercharge**
- All quarks and all leptons experience the weak force.
- “**Weak hypercharge**” is charge associated with the weak force. We won’t use weak hypercharge much in these lectures.

What do the particles do?

see: JH D&R lectures 2, 14, 15

Particles interact via one of the forces: strong, electromagnetic or weak.

Two main interactions:
- **Particle scattering**
  - can be elastic or inelastic
  - we’ll mainly consider inelastic scattering
  - *e.g.* scattering of electron and positron, producing a pair of muons \( e^+e^- \rightarrow \mu^+\mu^- \)

- **Particle decay**
  - *e.g.* Beta decay: \( d \rightarrow u e^- \bar{\nu}_e \)
  - *e.g.* Muon decay: \( \mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu \)

We’ll learn all about these type of diagrams throughout the course.
Hadrons: Mesons & Baryons

- Free quarks have never been observed - quarks are locked inside hadrons
- Hadrons are bound states of quarks: either \((qqq)\) or \((\bar{q}q)\)
- Charge of hadron is always integer multiple of electric charge, \(e\)
- Colour charge of hadron is always neutral
- Two types of hadrons - mesons and baryons (also anti-baryons! \(\bar{qqq}\))

### Mesons = \(q\bar{q}\)

Bound states of quark anti-quark pair
Bosons: spin 0, 1\(\hbar\), 2\(\hbar\)

- e.g. pions
  - \(\pi^+ = (u\bar{d})\)
  - \(\pi^- = (\bar{u}d)\)
  - \(\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})\)

### Baryons = \(qqq\)

Three quark bound states
Fermions: spin 1\(\hbar\), 3\(\hbar\) ...

e.g. proton (uud), neutron (udd)

**anti-baryons** e.g. anti-proton

- \(p = (uud)\)
- \(n = (udd)\)
- \(\bar{p} = (\bar{u}\bar{u}\bar{d})\)

Summary

The Standard Model of Particle Physics
An elegant theory that describes accurately (almost) all measurements in particle physics

### Matter

- fermions, spin-\(\frac{1}{2}\)\(\hbar\)
- 3 generations of quarks & leptons

<table>
<thead>
<tr>
<th>Quarks and Leptons</th>
<th>Charge, (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v_e) (e) (\mu) (\tau)</td>
<td>0 (-1)</td>
</tr>
<tr>
<td>u (d) c s t b</td>
<td>+2/3 (-1/3)</td>
</tr>
</tbody>
</table>

- Antimatter partner for each fermion
- Quarks bind together to form hadrons - mesons and baryons

### Forces

- mediated by the exchange of spin-\(1\hbar\) bosons

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Gauge Bosons</th>
<th>Charge, (e)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>gluons, (g)</td>
<td>0</td>
</tr>
<tr>
<td>Electro-magnetic</td>
<td>Photon, (\gamma)</td>
<td>0</td>
</tr>
<tr>
<td>Weak</td>
<td>(W, Z)</td>
<td>0, (\pm1)</td>
</tr>
<tr>
<td>Gravity</td>
<td>graviton?</td>
<td>0</td>
</tr>
</tbody>
</table>