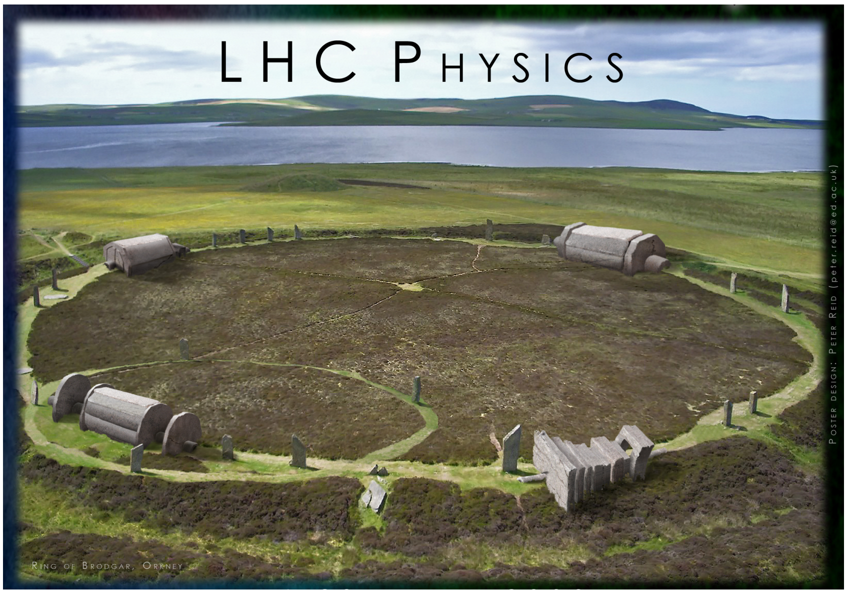
Subatomic Physics:

Particle Physics Lectures

"Physics of the Large Hadron Collider"
(plus something about neutrino physics)



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

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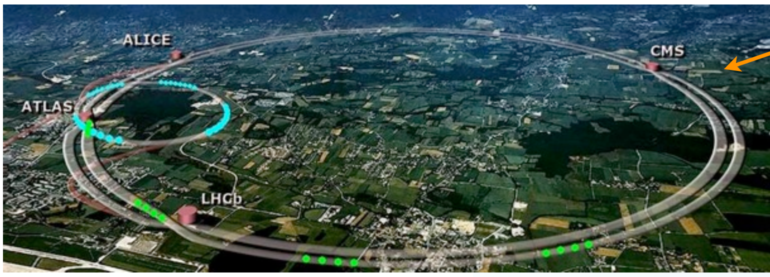
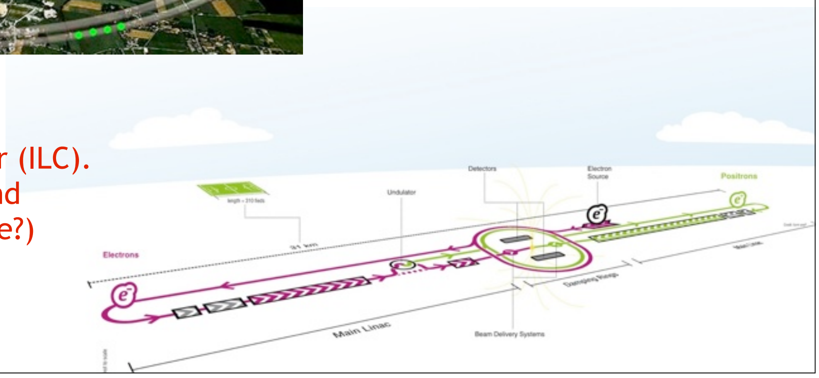
My research deals with Particle Physics at Colliders.
I'm currently involved with two projects:



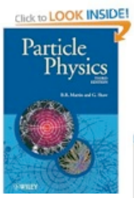
1. The ATLAS experiment at the Large Hadron Collider. The LHC collides protons on protons at 14 TeV.

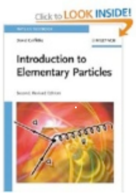
2. The international linear collider (ILC). Design is to collide electrons and positrons at 0.5 - 1 TeV (or more?)

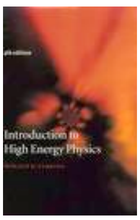


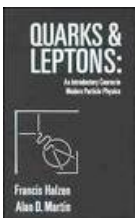
Books etc

- 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
- *More advanced:* Introduction to Elementary Particles by D. Griffiths, 2nd edition (Wiley 2008)
  - 4 copies in JCM Library

Oldies (but goodies):

- Introduction to High Energy Physics - D.H. Perkins, 4th edition (CUP 2000)
- Quarks and Leptons –F. Halzen & A.D. Martin (Wiley 1984)

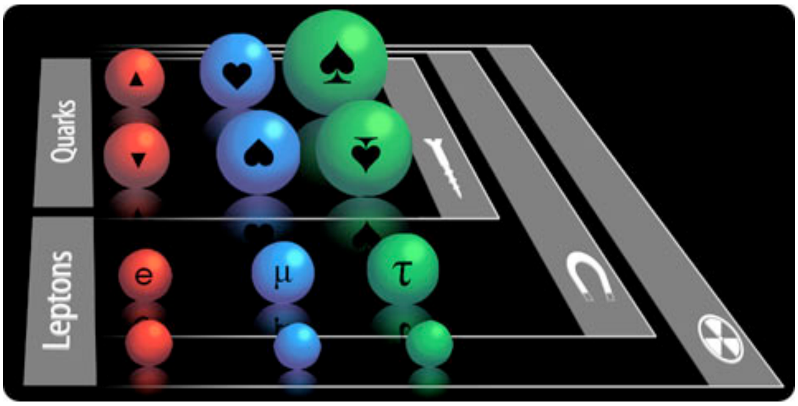
Further Resources:

- 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:

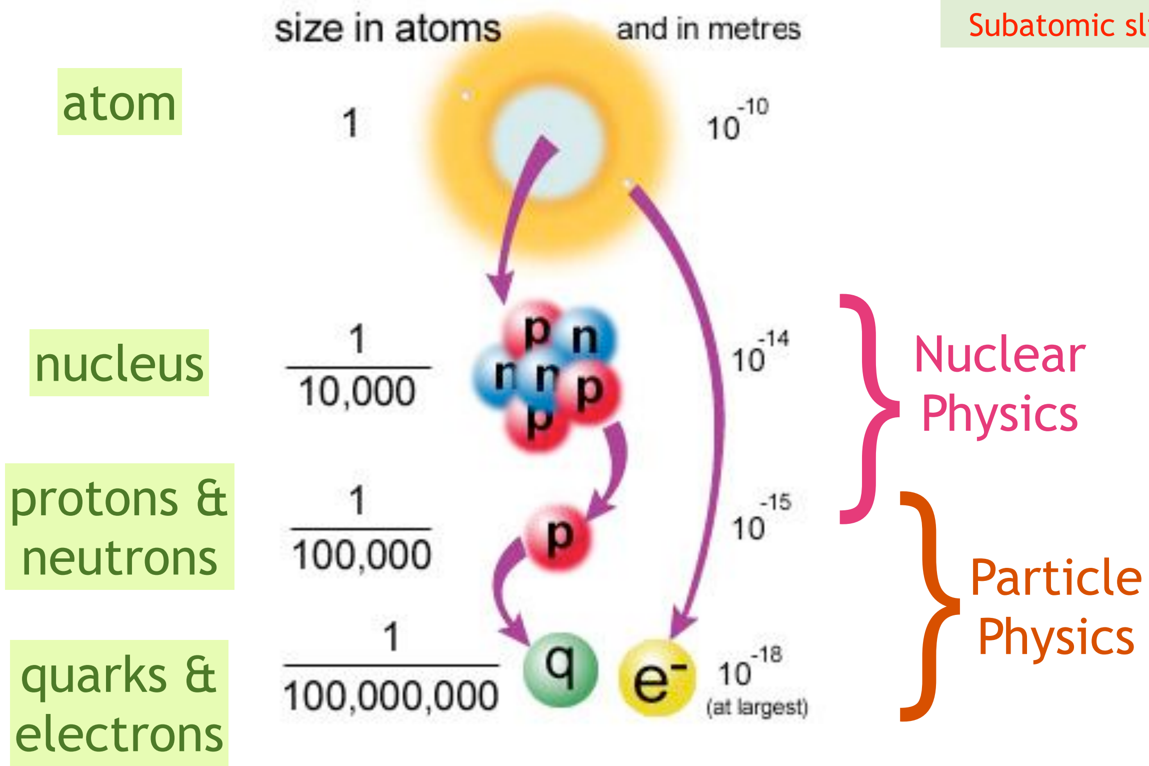
Particle Physics Lecture 1

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



From the Atom to Subatomic

from introductory Subatomic slides



History of the Universe

from introductory Subatomic slides

Time	Temperature	Event
10^{-43}s		Universe goes through superfast inflation
10^{-32}s	10^{27} °C	Post inflation – soup of electrons, quarks and other particles
10^{-6}s	10^{13} °C	Quarks clump into protons and neutrons
10^{2} s	10^{8} °C	Superhot fog (protons and electrons not yet bound into atoms). Primordial nucleosynthesis (up to ^{4}He)
3×10^{5} yr	10^{5} °C	Electrons combine with protons and neutrons to form atoms (H, He)
1×10^{9} yr	-200 °C	Star/Galaxy formation synthesis of heavier nuclei
15×10^{9} yr	-270 °C	First stars die and eject heavy nuclei into space – further star formation (and planets)

Time

Particle Physics (from Post inflation to Quarks clump into protons and neutrons)

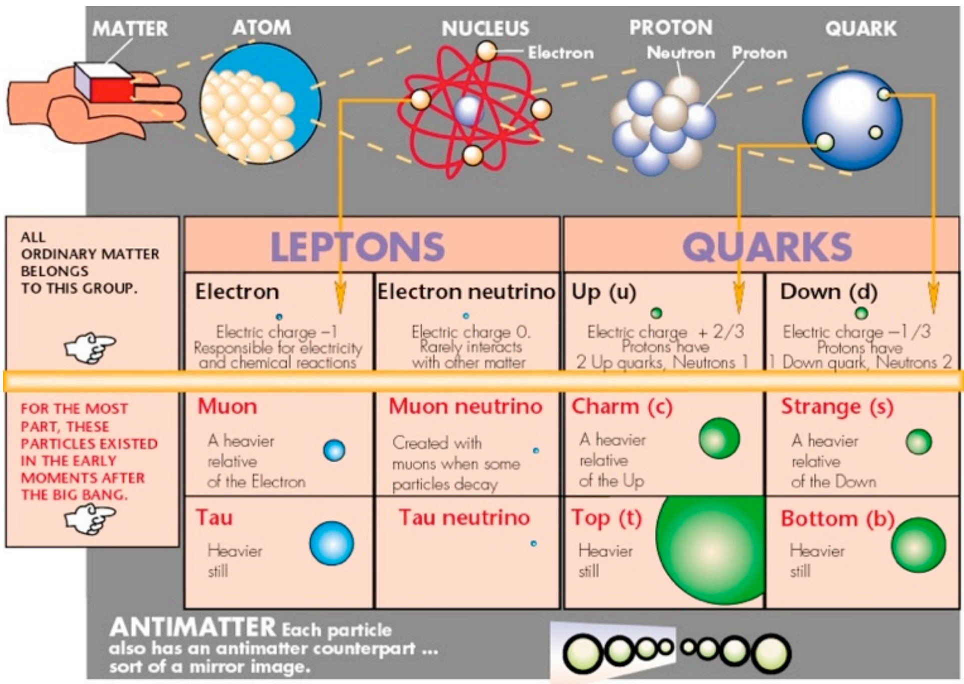
Nuclear Physics (from Quarks clump into protons and neutrons to Primordial nucleosynthesis)

Subatomic physics looks at:

- (very) short distances
- (very) early time in the universe
- (very) high energy densities

The Standard Model

The current understanding of the fundamental particles and the interactions between them is called the "**Standard Model of Particle Physics**".



Boson-mediated **FORCES**	
Gravity	**?**
Electro-magnetism	γ photon
Weak	$W^{\pm}$ Z^{0}
Strong	gluons

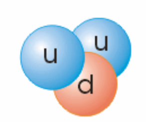
Basic Particles (1st Generation)

The particles that you know already, *e.g.* from beta decay: $\mathbf{n} \to \mathbf{p}\, e^- \overline{\nu_e}$

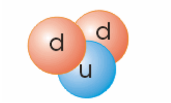
Leptons
Electron and neutrino

Quarks
Nucleons are bounds states of up-quarks and down-quarks

The Proton



The Neutron



Basic Constituents of Matter
Four spin-½$\hbar$ **fermions**

Particle	Symbol	Electric Charge	Type
electron	e^-	-1	lepton
neutrino	ν_e	0	lepton
up-quark	$\mathbf{u}$	+2/3	quark
down-quark	$\mathbf{d}$	−1/3	quark

- Nuclear physics description of beta decay: $\mathbf{n} \to \mathbf{p}\, e^- \overline{\nu_e}$
- Particle physics description of beta decay: $\mathbf{d} \to \mathbf{u}\, e^- \overline{\nu_e}$

Higher Generations

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

1st Generation		2nd Generation		3rd Generation		charge,e
electron	e^-	muon	μ^-	tau	τ^-	-1
electron neutrino	ν_e	muon neutrino	ν_μ	tau neutrino	ν_τ	0
down quark	$\mathbf{d}$	strange quark	$\mathbf{s}$	bottom quark	$\mathbf{b}$	−⅓
up quark	$\mathbf{u}$	charm quark	$\mathbf{c}$	top quark	$\mathbf{t}$	+⅔

Ordinary Matter: built from the 1st generation

Higher Generations:
- copies of $(\nu_e,\, e^-,\, \mathbf{u},\, \mathbf{d})$
- 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**

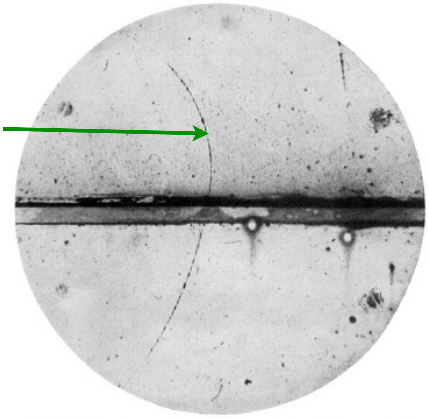
More in PP Lec 2 (& Quantum Physics §14.5)

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)

"Track" left by a positron



Example: positron (e^+) antiparticle of the electron ("anti-electron")
Discovered in 1931 by Carl Anderson

Notation: bar over symbol or minus ↔ plus

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

Schrödinger and Klein Gordon

- Quantum mechanics describes momentum and energy in terms of operators:

$$\hat{E} = i\hbar\frac{\partial}{\partial t} \qquad \hat{\vec{p}} = -i\hbar\vec{\nabla}$$

- $E=p^2/2m$ 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: $\Psi_E(\vec{r},t) = \psi_E(\vec{r})\exp\{-iEt/\hbar\}$

- However for particles near the speed of light $E^2=p^2c^2+m^2c^4$ ⇒

$$-\hbar^2\frac{\partial^2}{\partial t^2}\Psi(\vec{r},t) = -\hbar^2c^2\nabla^2\Psi(\vec{r},t) + m^2c^4\Psi(\vec{r},t)$$

- Solutions with a fixed energy, $E_p=+(p^2c^2+m^2c^4)^{1/2}$, and three-momentum, p:

$$\Psi(\vec{r},t) = N\exp\{i(\vec{p}\cdot\vec{r} - E_pt)/\hbar\}$$

- Also solutions with a negative energy, $E_n=-E_p = -(p^2c^2+m^2c^4)^{1/2}$, and momentum, $-p$:

$$\Psi^*(\vec{r},t) = N^*\exp\{i(-\vec{p}\cdot\vec{r} + E_pt)/\hbar\}$$

- Negative energy solutions are a direct result of $E^2=p^2c^2+m^2c^4$.
- We interpret these as **anti-particles**

Subatomic Forces

from introductory Subatomic slides

- 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

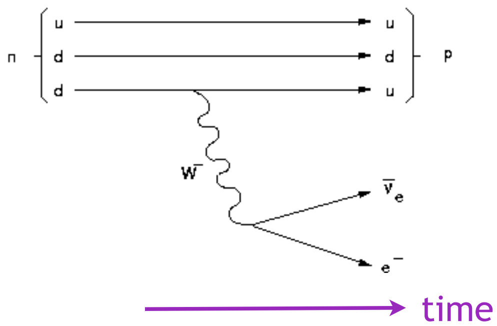
- The interactions due to these forces are evident in:
  - **Scattering:** e.g. scattering of protons on protons at the LHC
  - Particle **Decay**: e.g. decay of radioactive nuclei, decays of cosmic-ray muons
  - Nuclear **Fission** and **Fusion,** e.g.: reactions in a nuclear reactor

$$^{235}_{92}\mathrm{U} + \mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{144}_{56}\mathrm{Ba} + {}^{89}_{36}\mathrm{Kr} + 3\mathrm{n}$$

The Forces of Particle Physics

Strong	Electromagnetic
• Strongest force • Acts on quarks only • propagated by (8) gluons, g	• 2nd strongest force • Acts on charged particles • propagated by photon, γ
Weak	**Gravity**
• 3rd strongest force • Acts on all particles • propagated by $W^{\pm}$ and Z^0 bosons	• weakest force - negligible at PP scale • Acts on all particles

- Quantum mechanical description uses "messenger particles" to propagate the force between particles.
- Messenger particles are spin-1$\hbar$ bosons
- *e.g.* beta decay $\mathbf{n}\rightarrow\mathbf{p}\, e^-\, \bar{\nu}_e$ 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

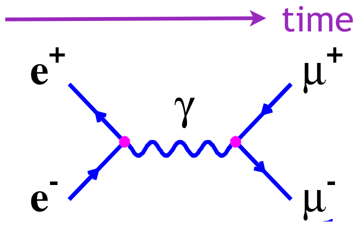
- Only quarks (and gluons) experience the strong force.
- Every quarks carries a "**colour charge**" quantum number: either red, blue or green. (This is in addition to their electric charge.)
- Every anti-quark also carries a "colour charge" quantum number: either anti-red, anti-blue or anti-green.

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?

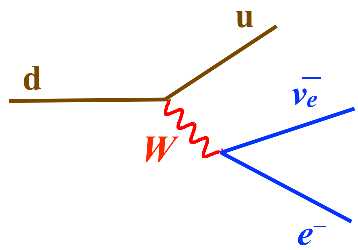
see: JH D&R lectures 2, 14, 15

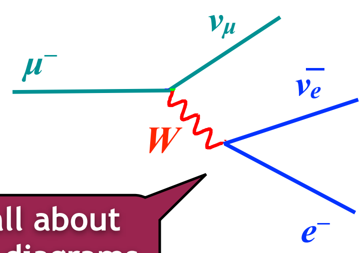


Particles interact via one of the forces: strong, electromagnetic or weak.

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 $e^+e^-\to\mu^+\mu^-$





- **Particle decay**
  - *e.g.* Beta decay: $\mathbf{d} \to \mathbf{u}\; e^-\, \bar{\nu}_e$
  - *e.g.* Muon decay: $\mu^-\to e^-\, \bar{\nu}_e\, \nu_\mu$

We'll learn all about these type of diagrams throughout the course

Hadrons: Mesons & Baryons

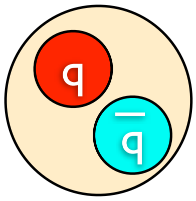
- Free quarks have never been observed - quarks are locked inside **hadrons**
- Hadrons are bound states of quarks: either (**qqq**) or (**q$\overline{\text{q}}$**)
- Charge of hadron is always integer multiple of electric charge, e
- Colour charge of hadron is always neutral
- Two types of hadrons –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

Mesons = q$\overline{\text{q}}$

Bound states of quark anti-quark pair

Bosons: spin 0, 1$\hbar$, 2$\hbar$

e.g. pions



$$\pi^+ = (\mathrm{u\bar{d}})$$
$$\pi^- = (\mathrm{\bar{u}d})$$
$$\pi^0 = \frac{1}{\sqrt{2}}(\mathrm{u\bar{u} - d\bar{d}})$$

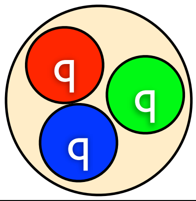
Baryons = qqq

Three quark bound states

Fermions: spin 1/2$\hbar$, 3/2$\hbar$ …

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

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



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

Summary

The Standard Model of Particle Physics

An elegant theory that describes accurately (almost) all measurements in particle physics

Matter

- fermions, spin-½$\hbar$
- 3 generations of quarks & leptons

Quarks and Leptons			Charge, e
ν_e e	ν_μ μ	ν_τ τ	0 −1
u d	c s	t b	+2/3 −1/3

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

Forces

- mediated by the exchange of spin-1$\hbar$ bosons

Interaction	Gauge Bosons	Charge, e
Strong	gluons, g	0
Electro-magnetic	Photon, γ	0
Weak	W, Z	0, ±1
Gravity	graviton?	0