Particle Physics (Senior Honours)

Spring Semester 2009

Prof. Steve Playfer - JCMB 5420

Lectures:	**Tuesday**	**12:10-13:00**	JCMB 3317
	Friday	**12:10-13:00**	JCMB 3317
Tutorials:	**Wednesday**	**10:00-10:50**	JCMB 3317
Office Hours:	**Thursday**	**15:00-17:00**	JCMB 5420

There will be 18 lectures and 6 tutorials in total

Tutorials start in Week 3 and end in Week 10

Not all the slots will be used!

Provisional break Thursday 19/2 - Thursday 26/2

Synopsis

1) Overview of Standard Model
2) The LHC
3) Feynman Diagrams
4) Dirac Spinors
5) Quantum Electrodynamics
6) Electron-proton collisions
7) Deep Inelastic Scattering
8) Quantum Chromodynamics
9) Quark Model of Hadrons
10) Hadron Production & Jets
11) Weak Interactions
12) Discrete Symmetries
13) Weak Decays of Hadrons
14) Mixing and CP Violation
15) Neutrinos
16) Electroweak Physics
17) The Higgs Boson
18) Beyond the Standard Model

Recommended Texts

F. Halzen & A.D. Martin - Quarks and Leptons, Wiley (1984)

B.R. Martin & G. Shaw - Particle Physics,
2nd edition, Wiley (1997)

D.H. Perkins - Particle Physics,
4th edition, Oxford University Press (2000)

D. Griffiths - Introduction to High Energy Physics,
4th edition, Cambridge University Press (2000)

I.J.R. Aitchison & A.J.G. Hey - Gauge Theories in Particle Physics,
2nd edition, Adam Hilger (1989)

... and the particle physics bible:

Particle Data Group (PDG), http://pdg.lbl.gov/
C. Amsler et al., Physics Letters B667, 1 (2008)

Lecture 1

The Standard Model

Particle physics describes the interactions of the most fundamental constituents of matter in terms of a "Standard Model"

- A quick tour of the particles and their interactions as we understand them today within the Standard Model.
  Most of this should be familiar from Junior Honours
- A series of thought-provoking questions about the things that we don't understand and are still investigating.

The Fundamental Fermions

There are twelve point-like spin 1/2 fermions:

- Three quarks with charge +2/3e: u, c, t
  $m_u \approx 2.5$MeV, $m_c \approx 1.3$GeV, $m_t \approx 171$GeV
- Three quarks with charge −1/3e: d, s, b
  $m_d \approx 5$MeV, $m_s \approx 105$MeV, $m_b \approx 4.2$GeV
- Three leptons with charge −e: $e,\ \mu,\ \tau$
  $m_e = 511$keV, $m_\mu = 106$MeV, $m_\tau = 1777$MeV
- Three neutrinos with zero charge: $\nu_e,\ \nu_\mu,\ \nu_\tau$
  $m_\nu \ll$eV with differences $\Delta m^2_{12} \approx 8 \times 10^{-5}$eV^2 and $\Delta m^2_{23} \approx 2.5 \times 10^{-3}$eV^2

Every fermion has an antiparticle with equal mass and opposite charge. Can convert energy into fermion/antifermion pair. *Reverse process is annihilation, e.g.* $e^+e^- \to 2\gamma$ *with* $E_\gamma = 511 keV$.

Open Questions about Fermions

- Are fermions really pointlike objects?
  (No composite structure seen $r_e < 10^{-20}m$)
- Is the pattern of four different types of fermion charge, with three different *generations of flavour* for each charge, evidence for underlying structures?
- Could there be a fourth generation of flavour?
- Are there other types of fermions?
- Why do the fermions have such different masses, and what determines these masses?
  (Many orders of magnitude between m_ν and m_t)
- Are neutrinos their own antiparticles $\nu_\ell = \bar{\nu}_\ell$ (Majorana)?
- Why does the universe contain matter but not antimatter?
  What are the differences between matter and antimatter?

Electromagnetic Interactions

Charged particles couple to each other by photon exchange.

Described by *Quantum Electrodynamics (QED).*

- Quark and lepton couplings are proportional to fermion charge.
- Neutrinos do not have electromagnetic interactions.
- Infinite range because photon is massless S=1 boson.
- Coupling constant at low energy is fine structure constant $\alpha = 1/137$.

There are no open questions about electromagnetism!

Strong Interactions

Quarks couple to each other by gluon exchange.
Described by *Quantum Chromodynamics (QCD).*

Accounts for binding of quarks into mesons and baryons, and for binding of protons and neutrons into nuclei.

- Coupling is through **colour**. Quarks have three colour states r, g, and b. Antiquarks have anticolours $\bar{r}$, $\bar{g}$, and $\bar{b}$.
- Coupling strength is the same for all quark flavours and colours.
- Coupling $\alpha_s \approx 1$ at low energy, but $\alpha_s \approx 0.1$ at high energy.
- Gluons have eight colour/anticolour states, which means there are gluon-gluon couplings.
- Even though gluons are massless S=1 bosons, strong interactions are short range due to *colour confinement*.
- There are no free quarks or gluons.

Open Questions about Strong Interactions

- Do we understand the "running" of α_s from large values at low energy to small values at high energy?
- Does QCD account for the colour confinement of quarks and gluons in hadrons?
- Do we understand the distribution of quarks and gluons inside the proton (parton density functions)?
- Do we understand the spectra of meson and baryon states?
- Can the strong nuclear force that binds protons and neutrons into nuclei be understood using QCD?

Weak Interactions

- Charged currents couple fermions to $W^{\pm}$ vector bosons.
  - Couplings to lepton+neutrino do not change lepton flavour (only $e^+\nu_e$, $\mu^+\nu_\mu$, $\tau^+\nu_\tau$ or $e^-\bar{\nu}_e$, $\mu^-\bar{\nu}_\mu$, $\tau^-\bar{\nu}_\tau$).
  - Couplings to quarks can change flavour (any +2/3e q and +1/3e $\bar{q}$ or −2/3e $\bar{q}$ and −1/3e q)
  - Couplings to quarks depend on flavour (CKM matrix).
- Neutral currents couple fermions to Z^0 vector bosons.
  - There are no flavour-changing Z couplings.
  - Coupling strengths depend on fermion type.
- The bosons are heavy, $M_W = 80\text{GeV}$ and $M_Z = 91\text{GeV}$, so weak interactions are short range.
- Fermi constant at low energy $G_F = 1.166 \times 10^{-5}\text{GeV}^{-2}$
- Neutrinos only have weak interactions.

Open Questions about Weak Interactions

- Are W and Z couplings the same for all leptons (lepton universality)?
- What determines the parameters of the CKM matrix that describes W couplings to quarks?
- Weak interactions violate the discrete symmetries Parity(P), Charge Conjugation (C), Time Reversal (T) and CP. Is this the only source of CP violation? Is CPT conserved?
- Why do neutrinos oscillate between different flavours, and what determines their mixing parameters?
- What is the origin of the masses of the W and Z bosons (electroweak symmetry breaking)?

Electroweak Unification

Electromagnetic and weak interactions are unified at $\approx 250\text{GeV}$
Electroweak gauge bosons are W^+, W^-, W^0, B^0

- Electroweak symmetry is *spontaneously broken* at lower energies. This is known as the **Higgs mechanism**.
- Produces physical bosons γ and Z^0, and gives masses to the W and Z.
- Weinberg angle $\sin^2\theta_W = 0.231$ relates $M_W/M_Z = \cos\theta_W$.
- Requires at least one neutral spin zero Higgs boson with $M_H \approx 120\text{GeV}$.
- Higgs couplings to fermion/antifermion pairs are proportional to fermion mass.

Open Questions on Electroweak Theory

- We need to find the Higgs boson and measure its mass!
- Is there only one Higgs boson?
- Does the Higgs mechanism account for electroweak symmetry-breaking?
- Are precision electroweak measurements, e.g. $\sin^2\theta_W$, consistent with the Standard Model?
- Are there anomalous couplings between vector bosons? What are the Higgs couplings to vector bosons and to itself?
- What are the Higgs couplings to fermions?

Beyond the Standard Model

- Are fermions and bosons fundamental or composite objects?
- Is there a Supersymmetry (SUSY) between fermions/bosons? (Requires a super-partner for each fermion/boson!)
- Is there a Grand Unified Theory (GUT) of strong and electroweak interactions? (*GUT scale at* 10^{14} *GeV?*)
- Are lepton and baryon number conserved quantities? (Baryon number violation $\Rightarrow$ matter asymmetry of universe)
- How do we include Gravity? (*Planck scale is* 10^{19} *GeV*)
- Does string theory have anything to do with reality?

The Dark Side

Astrophysical measurements tell us that the universe contains:

74% "Dark Energy"   22% "Dark Matter"

Only 4% is baryonic matter (mostly non-luminous as well)

Embarrassingly we don't understand 96% of the universe!

- What is Dark Energy?
  A cosmological constant?
  A dynamic energy field ("quintessence")?
- What is Dark Matter?
  Weakly-interacting massive particles (WIMPs)?
  Other neutral particles, e.g. axions, neutrinos?