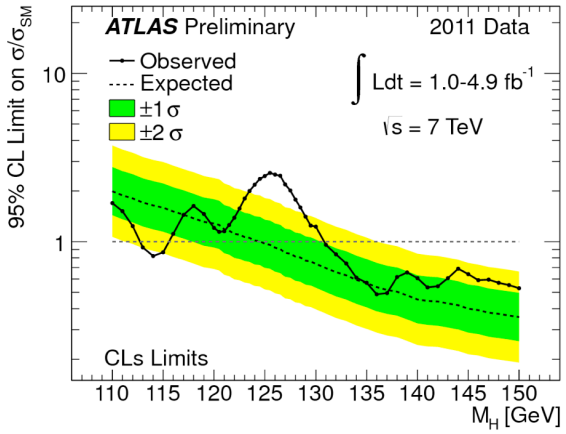
Particle Physics

Dr Victoria Martin, Spring Semester 2012
Lecture 1: The Mysteries of Particle Physics,
or "Why should I take this course?"



Contents:

- Review of the Standard Model
  - ➡ What we know
  - ➡ What we don't know
- Highlights from 2011 particle physics
  - ➡ Superluminal neutrinos
  - ➡ CP violation in charm physics
  - ➡ Constraining the Higgs boson mass

Course Organisation

Teaching weeks: 16 January - 17 February; 27 February - 6 April
ILW: 20 - 24 February (no lectures)

Particle Physics course:

- **18 Lectures**: Tuesday, Friday 12:10-13:00 (JCMB 5215)
  - No PP lectures: 10 Feb, 6 April
  - Two themes: **Particles & interactions of the Standard Model, Current topics in particle physics**
- **Tutorials**: *Can we decide now?*
- **Office Hours**: Thursday 15:00-17:00 (JCMB 5419)
- I'd like to recommend reading for the course from *Introduction to Elementary Particle Physics* by David Griffiths. (7 copies in Darwin Library)

- Printed notes and problem sheets handed out periodically and available on the web.
- Lecture slides (and eventually solution sheets) will only be available on the web.

- About VJM: http://vimeo.com/33722851

References & Websites

Introductory textbooks

- D.Griffiths – Introduction to Elementary Particles (Wiley 2008)
- B.R.Martin & G.Shaw – Particle Physics (Wiley 1997)
- D.H.Perkins – Introduction to High Energy Physics (CUP 2000)

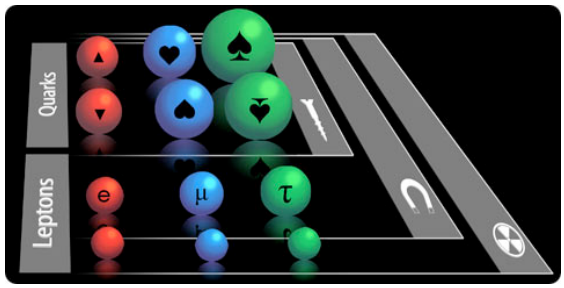
More advanced textbooks

- F.Halzen & A.D.Martin – Quarks & Leptons (Wiley 1984)
- A.Seiden – Particle Physics: A Comprehensive Introduction (Addison-Wesley 2005)
- I.J.R.Aitchison & A.J.G.Hey – Gauge Theories in Particle Physics (Hilger 1989)

Useful websites

- CERN/LHC http://public.web.cern.ch/public
- Particle Data Group (PDG) http://pdg.lbl.gov

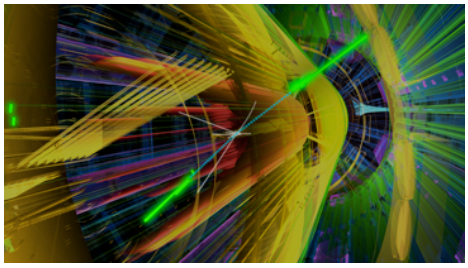
Particles & Interactions of the Standard Model

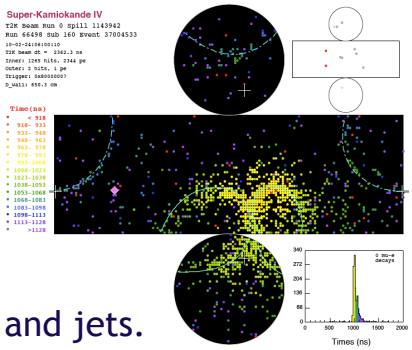


1. Introduction:"The mysteries of the Standard Model."
2. Forces, feynman diagrams
3. Kinematics & scattering.
4. Dirac equation & spinors.
5. Electromagnetic interactions: Quantum Electrodynamics (QED).
6. Weak Interactions, Weak decays & Neutrino scattering.
7. Deep inelastic scattering, the parton model & parton density functions.
8. Strong interactions: Quantum Chromodynamics (QCD) and Gluons.
9. Quark model of hadrons. Isospin and Strangeness. Heavy quarks.

Current Topics in Particle Physics

Content to be finalised, but probably including...





10. Hadron production at Colliders, Fragmentation and jets.
11. Weak decays of hadrons. CKM matrix.
12. Symmetries. Parity. Charge conjugation. Time reversal. CP and CPT.
13. Mixing and CP violation in K and B decays.
14. Neutrino oscillations. MNS matrix. Neutrino masses.
15. Electroweak Theory. W and Z masses. Precision tests at LEP.
16. Spontaneous symmetry breaking. The Higgs boson.
17. Beyond the Standard Model. Supersymmetry. Grand unification.
18. Recent physics results at the LHC.

Review: Spin

- Spin is the intrinsic angular momentum of a quantum state.
- Two quantum numbers describe the spin
  - ➡ total spin: $\hat{S}^2$ Eigenvalues: $s\,(s+1)\,\hbar$, $s = 0, \frac{1}{2}, 1, \frac{3}{2}, 2, \ldots$
  - ➡ third component: $\hat{S}_Z$ Eigenvalues: $m_s\hbar$, $m_s = -s, -s+1, \ldots, s-1, s$
- Particles with an integer value of s are **bosons**
- Particles with a half-integer values of s are **fermions**

- **Two examples:**

Photon, γ
- A **boson** with spin, $s=1$
- Three possible polarisation states: $\lambda = m_s = -1, 0, 1$

Electron, e^-
- A **fermion** with spin, $s=\frac{1}{2}$
- Two possible spin orientations $m_s = +\frac{1}{2}, -\frac{1}{2}$
- "Spin-up" or "Spin-down"

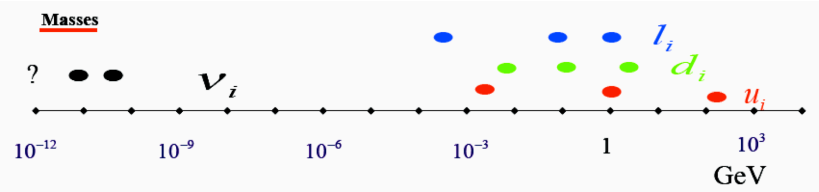
Standard Model Matter Particles

- Matter particles are observed to be s=½ fermions.
- Two distinct types: **quarks** and **leptons**.
- Grouped into three, successively heavier, generations.
- Four key quantum numbers: charge (Q), isospin (I_Z), baryon number (B), lepton number (L)

Q Charge	I_Z Isospin	Three Generations of Matter (Fermions) I	II	III	B Baryon Number	L Lepton Number
		mass→				
+2/3 e	+1/2	charge→ ⅔ spin→ ½ **u** up	⅔ ½ **c** charm	⅔ ½ **t** top	+1/3	0
-1/3 e	-1/2	Quarks -⅓ ½ **d** down	-⅓ ½ **s** strange	-⅓ ½ **b** bottom	+1/3	0
0	+1/2	0 ½ ν_e electron neutrino	0 ½ ν_μ muon neutrino	0 ½ ν_τ tau neutrino	0	+1
-1 e	-1/2	Leptons -1 ½ **e** electron	-1 ½ μ muon	-1 ½ τ tau	0	+1

Mysteries of the Fermion Masses

- These are well measured (apart from the very low mass ν_i) but the hierarchy not understood:



- Logarithmic scale covers 15 orders of magnitude!

- Charged leptons (ℓ_i=e,μ,τ), up-type quarks (u_i = u,c,t) and down-type quarks (d_i=d,s,b) quarks have similar masses but the patterns are not identical

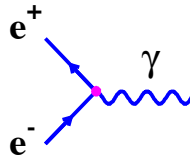
- Absolute scale of neutrino (ν_i) masses is unknown apart from upper bound on $m(\nu_e) < 2eV$
- Only two independent ν_i mass differences are known:

$$\Delta m_{12}^2 = (7.6 \pm 0.2) \times 10^{-5}\ eV^2,\ \Delta m_{23}^2 = (2.4 \pm 0.1) \times 10^{-3}\ eV^2$$

Antimatter

According to relativistic Quantum Mechanics (Lecture 4), every $s=½$ fermion (f) has an anti-fermion partner ($\bar{f}$)

- Anti fermions have been discovered experimentally:
  Positron e^+ (1933), Antineutrino $\bar{\nu}_e$ (1956), Antiproton $\bar{p}$ (1955)
  - Masses and lifetimes of fermion and anti-fermions are equal
  - Charges are equal and opposite
  - Baryon & lepton numbers equal and opposite
  - Massless fermions are left-handed, massless anti-fermions are right-handed (more in lecture 4)



- Fermion/antifermion annihilate into energy (bosons)
  … or can be created in pairs at high energy colliders
- From observations the universe contains matter (fermions), but there is almost no antimatter…

Discovery of positron

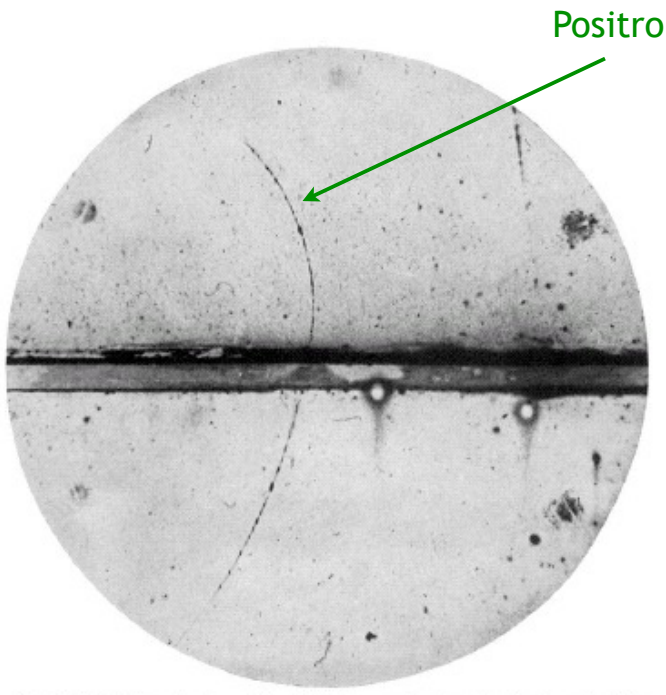


FIG. 1. A 63 million volt positron ($H\rho = 2.1 \times 10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5 \times 10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

Colour Charge and Hadrons

- All quarks carry an additional degree of freedom, a colour charge either: red (r), green (g) or blue (b).
- More correct to think of 18 fundamental quarks in the SM:
  u_r u_g u_b d_r d_g d_b s_r s_g s_b c_r c_g c_b b_r b_g b_b t_r t_g t_b
- Anti-quarks carry anti-colour charge, 18 fundamental anti-quarks:
  $\bar{u}_r$ $\bar{u}_g$ $\bar{u}_b$ $\bar{d}_r$ $\bar{d}_g$ $\bar{d}_b$ $\bar{s}_r$ $\bar{s}_g$ $\bar{s}_b$ $\bar{c}_r$ $\bar{c}_g$ $\bar{c}_b$ $\bar{b}_r$ $\bar{b}_g$ $\bar{b}_b$ $\bar{t}_r$ $\bar{t}_g$ $\bar{t}_b$

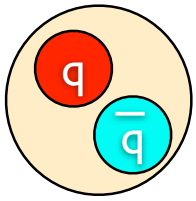
Mesons = $q\bar{q}$

Bound states of quark anti-quark pair

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

e.g. pions

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



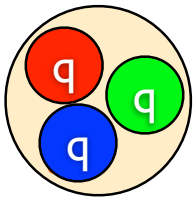
Baryons = qqq

Three quark bound states

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

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

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



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

In principle, the quark in a hadron can be any flavour

Mysteries of the Fermions

- Are the fermions really point-like objects ($r_e < 10^{-20}$m)?
- Why are there exactly twelve (or 24) elementary fermions?
- Why are there three "generations" with different "flavours"?
- Why do quarks have strong interactions with three "colour charges"?
- Why do weak interactions change quark flavour, but not lepton flavour?
- Why do neutrinos have flavour oscillations?
- Why more matter than anti-matter (baryon asymmetry)?

Standard Model Forces

- Four interactions observed in nature: electromagnetic, strong, weak and gravity.
- The Standard Model describes interactions due to electromagnetic, strong, weak.
- Interactions between the fermions are transmitted by "force carrying" gauge bosons with ***S=1***.
- Each force couples to a property of the fermions.
- The properties of each force are described mathematically by a symmetry group

Interaction	Coupling Strength	Couples To	Symmetry Group	Gauge Bosons	Charge e	Mass GeV
Strong	$\alpha_s \approx 1$	colour charge	SU(3)	Gluons (g)	0	0
Electromagnetic	$\alpha = 1/137$	electric charge	U(1)	Photon (γ)	0	0
Weak	$G_F = 1 \times 10^{-5}$	weak hypercharge	$SU(2)_L$	$W^{\pm}$ Z^0	± 1 0	80.4 91.2
Gravity	0.53×10^{-38}	mass	?	Graviton?	0	0

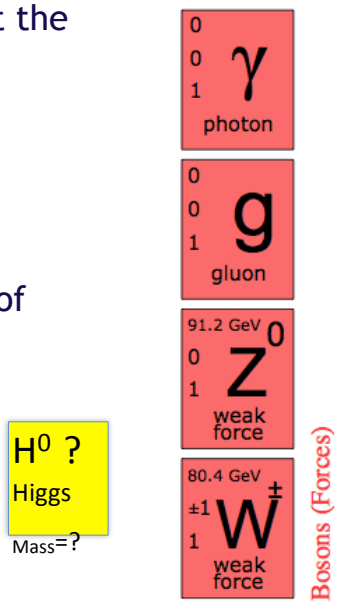
Symmetries (& Mysteries)

- Symmetries are key to understanding particle physics
- Noether's Theorem: Every symmetry of nature has a conservation law associated with it, and vice-versa.

- **Energy, Momentum and Angular Momentum**
  - ➡ Conserved in all interactions
  - ➡ Symmetry: translations in time and space; rotations in space
- **Charge conservation e.g. electric charge *Q*, colour charge**
  - ➡ Conserved in all interactions
  - ➡ Symmetry: gauge transformation - underlying U(1) and SU(3) symmetries in QM description of electromagnetism / strong force
- **Lepton Flavour L_e, L_μ, L_τ and baryon number *B***
  - ➡ Conserved in all interactions
  - ➡ Symmetry: mystery!
- **Quark Flavour *S, C, T, B,* Parity P, Charge Conjugation C, and Time Reversal T**
  - ➡ Conserved in strong and electromagnetic interactions
  - ➡ Violated in weak interactions
  - ➡ Symmetry: unknown!

Mysteries of the Bosons

- Electromagnetic and weak interactions are unified at the Electroweak scale (**246 GeV**)
  - ➡ Is there a "grand unified" scale where the strong interaction is also included?
- What is the mechanism that breaks electroweak symmetry, and how does it explain the large masses of the W and Z bosons?
- Are there 0, 1 or many Higgs bosons?
- What are the masses and couplings of Higgs bosons?
- How do we include gravity?



The Dark Side

- Only 4.6% of the current universe is normal matter (baryons + electrons = atoms)
- To account for rotation curves of galaxies, gravitational lensing and large scale structure need:

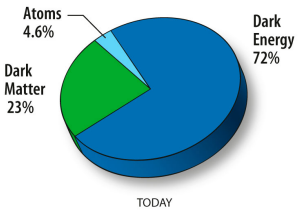
  23.3% "Dark Matter"

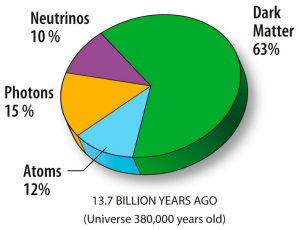
  Must be weakly interactive massive particles (not yet discovered) candidates are provided by a "supersymmetric" extension to the Standard Model
- To account for acceleration of expansion of the universe need:

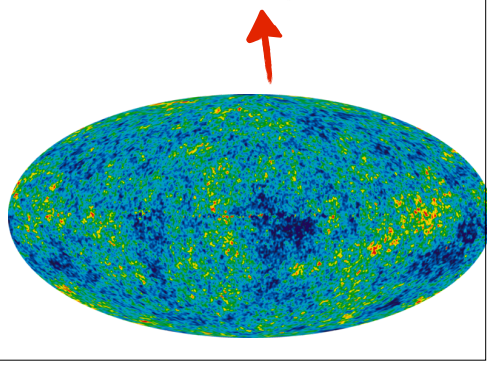
  72.1% "Dark Energy"

  May be described by a cosmological constant Λ

Could particle physics describe either dark matter or dark energy?







Beyond the Standard Model

Many models proposed to explain some mysteries in the Standard Model, *e.g.*

★ **Supersymmetry (SUSY):** every SM particle has a supersymmetry partner:
- ➡ $S=0$ squarks and sleptons
- ➡ $S=½$ neutralinos, charginos, higgsinos
- ➡ automatically introduces extra Higgs bosons

We are searching for these new particles directly at the LHC. Neutralinos may be candidates for dark matter.

★ **Grand unified theories** merge strong & electroweak interaction at 10^{11} **to** 10^{16} **GeV**
- ➡ Proton decay? Lifetime >10^{29} to 10^{33} years (depending on model)

Search for evidence of proton decay

★ **Additional Heavy neutrino(s)** at GUT scale can explain neutrino oscillations and light neutrino masses.

★ **Extra dimension where only gravity interacts**
- ➡ Mini black holes, new resonances

Searches at the LHC.

Particle Physics in 2011

My personal four favourite results:

★Discovery of the $\chi_b(3p)$ meson

★Hunting down the Higgs boson

★Observation of Charge-Parity (CP) violation in charm mesons

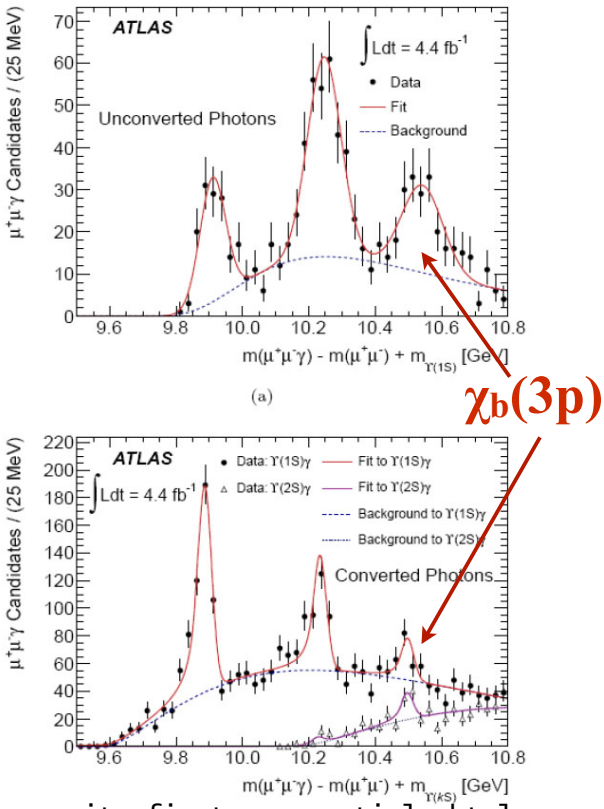
★Superluminal Neutrinos

Discovery of the $\chi_b(3p)$

Discovered by the ATLAS experiment at the LHC looking for the decay:

- $\chi_b(3p) \rightarrow \Upsilon(1s)\,\gamma$; $\Upsilon(1s) \rightarrow \mu^+\mu^-$
- $\chi_b(3p) \rightarrow \Upsilon(2s)\,\gamma$; $\Upsilon(2s) \rightarrow \mu^+\mu^-$

- $\chi_b(3p)$, $\Upsilon(1s)$, $\Upsilon(2s)$ are all bound states of $b - \bar{b}$
- *s* and *p* refer to the orbital angular momentum of the state, *l*
  - s: $l=0$
  - p: $l=1$
- Numbers refer the *n*th excited state with a given ang. mom.



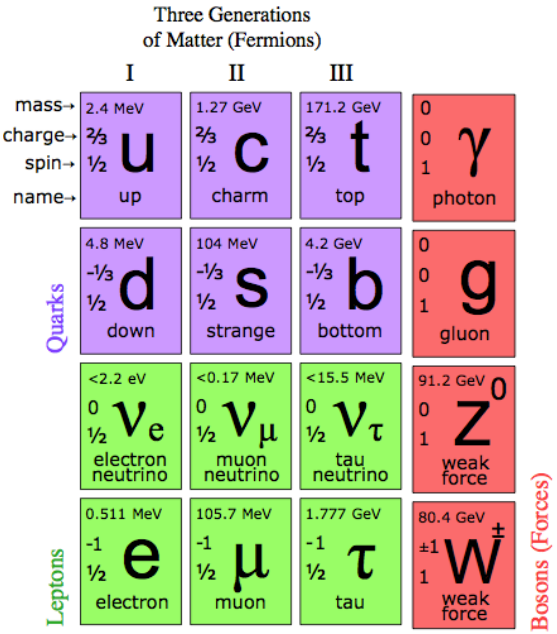
http://www.atlas.ch/news/2011/ATLAS-discovers-its-first-new-particle.html

Summary & Reading List

- Summary: the Standard Model is our current model for particle physics. But it doesn't explain all observations.

- Experiments are underway to try to make precise measurements and search for new phenomena.

- Key point from today: learn the Standard Model particles and forces.



Highly suggested reading:

- Today's lecture: Griffiths 1.1 -1.5
- Friday's Lecture: Griffiths chapter 2