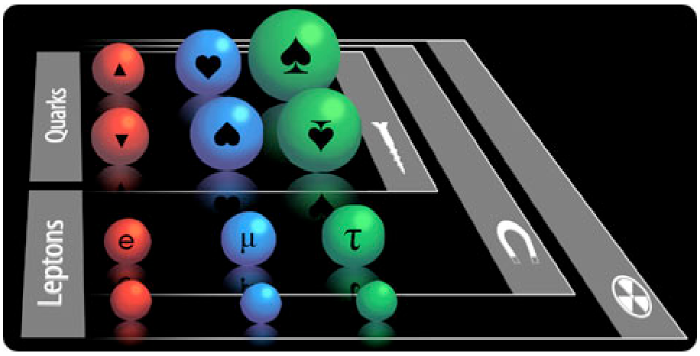
Nuclear and Particle Physics 3:

Particle Physics

Lecture 1: Introduction to Particle Physics

February 5th 2007



Particle Physics (PP)
a.k.a. High-Energy Physics (HEP)

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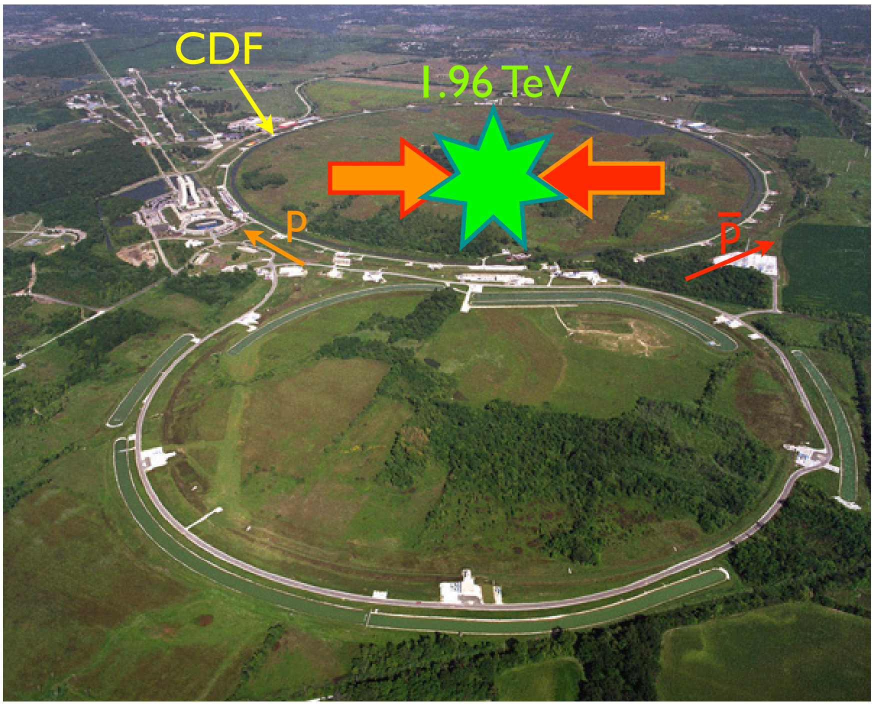
My research: Particle Physics at Colliders

- CDF at the Fermilab Tevatron, near Chicago: colliding protons and anti-protons at ~2TeV. Currently the world's highest energy collider.
- The international linear collider (ILC), the world's next electron-position collider. Won't start operation until ~2018!!

CDF and the Tevatron



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International Linear Collider

A future project

Many elements still under design and discussion, including...

- location
- cost
- will we build it at all?

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Course Contents

Lecture 1 - Introduction
- The fundamental particles and forces

Lecture 2 - Tools
- Natural Units
- Kinematics
- Antiparticles

Lecture 3 - Feynman Diagrams
- The electromagnetic force
- Feynman Diagrams

Lecture 4 - Interactions with matter
- Particle accelerators, detectors and experiments.

Lecture 5 - Quarks
- Mesons, Baryons
- Isospin and strangeness

Lecture 5 - Strong Interactions
- Colour, gluons
- confinement, running coupling constant

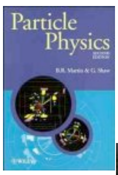
Lecture 7 - Weak Interactions
- Muon and tau decay
- Heavy quarks, CKM mechanism

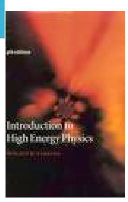
Lecture 8 - Neutrinos
- Neutrino Mass and oscillations

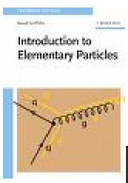
Lecture 9 - Electroweak Theory
- W and Z bosons
- LEP
- Spontaneous Symmetry Breaking and the Higgs Boson

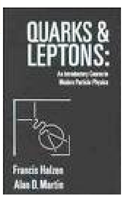
Books!

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









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

7 copies in JCMB Library.

Introduction to High Energy Physics - D.H. Perkins, 4th edition (CUP 2000)

Introduction to Elementary Particles - D. Griffiths (Wiley 1987)

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

For more information that you could ever need on every particle ever: http://durpdg.dur.ac.uk/lbl/

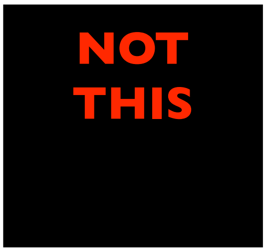
Motivation

What's the interest in particle physics?

Particle physics collisions recreate conditions just after the **big bang**; the closest we'll ever get to the big bang on earth.

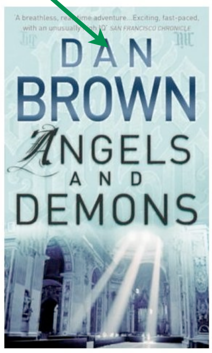
Matter and **anti-matter** were made in equal amounts:
so why does the universe look like

&



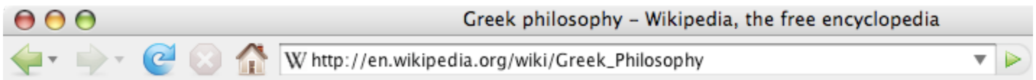
?

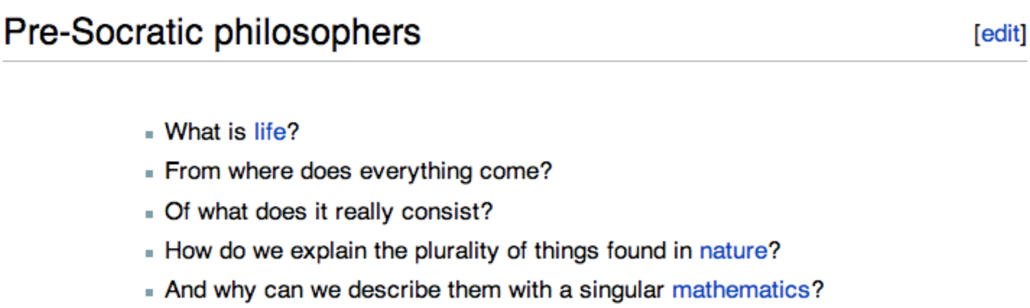
To be able to explain what's correct and what's not in this book



Technology spin-offs
CERN: where the web was born!
Medical applications: e.g. PET
Magnetic resonance imaging (MRI)

The Questions of Particle Physics



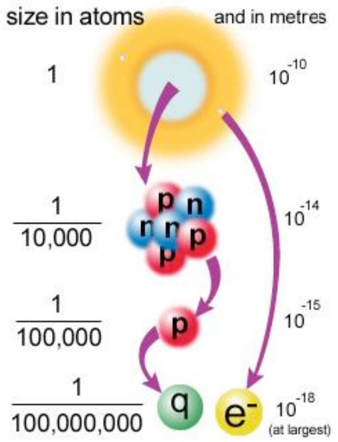


Pre-Socratic philosophers [edit]

- What is life?
- From where does everything come?
- Of what does it really consist?
- How do we explain the plurality of things found in nature?
- And why can we describe them with a singular mathematics?

Particle Physics still deals with the last four of these questions!

- What is matter made from?



atoms

nucleus & electrons

protons & neutrons

particle physics

quarks and electrons

- How does these particles interact?
  - What are electromagnetic forces?
  - What holds nucleus together?
  - What causes radioactivity?
  - How does gravity act at such large distances?

Standard Model of Particle Physics

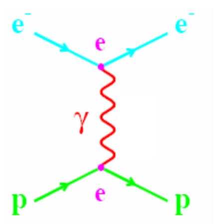
The simplest classification of the **fundamental particles** and their **interactions**

Matter - the fundamental constituents of the universe

- All mater elementary particles are fermions, spin ½ħ
  - leptons e^-, ν
  - quarks u, d   proton = uud
- Every particle has an antiparticle e.g. positron(e^+), antiproton ($\bar{p}$)

Forces - the interactions between elementary particles

- Interactions between quarks and leptons are mediated by exchange of gauge bosons-spin 1ħ
  - Electromagnetic interaction - photons (γ)
  - Strong force - gluons (g)
  - Weak force - W and Z
  - Gravity - graviton

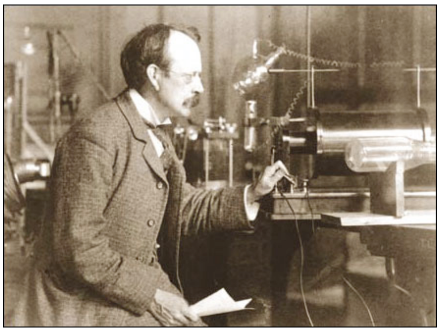


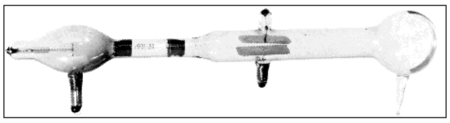
- Every force couples to a property of the fermions, e.g. electromagnetic force acts on the electric charge

The Electron

Discovered in 1897 by J. J. Thomson

1916 Noble Prize in Physics





Electron - elementary particle

- Point-like: size < 10^{-6} fm (10^{-21}m)
- Stable: lifetime > 4.6×10^{26} yrs
- Electric charge,

$$q_e = -e = -1.60217653(14)\times 10^{-19}\ \mathrm{C}$$

- Mass,

$$m_e = 0.510998918(44)\ \mathrm{MeV}/c^2 = 9.11\times10^{-31}\ \mathrm{kg}$$

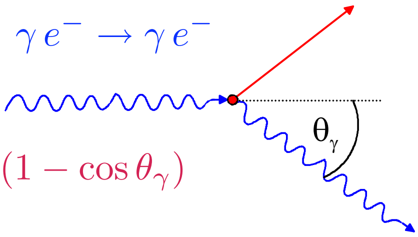
- Spin, intrinsic property: ½ħ

The electron is a **fermion** *i.e.* electrons satisfy Pauli exclusion principle.

The Photon

Particulate nature of light was confirmed in 1924 by A. H. Compton.

Compton scattering: $\gamma\, e^- \to \gamma\, e^-$



$$\lambda - \lambda' = \frac{h}{m_e c}(1-\cos\theta_\gamma)$$

1927 Noble Prize in Physics

Photon - elementary particle

- pointlike: size < 10^{-6} fm (10^{-21}m)
- stable

No electric charge $q_\gamma \le 5\times10^{-30} q_e$

Massless $m_\gamma \le 6\times10^{-17}\ \mathrm{eV}/c^2 \approx 10^{-52}\ \mathrm{kg}$

Energy $E_\gamma = h\nu = hc/\lambda$

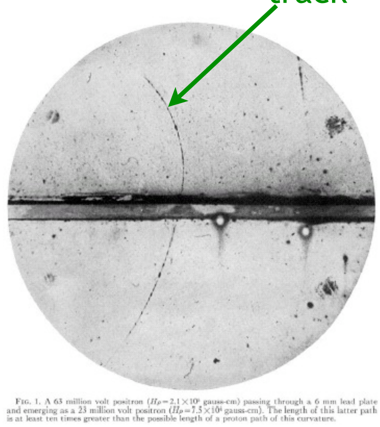
Spin intrinsic property spin-1ħ photons are **bosons**

Antiparticles

Every particle has a corresponding antiparticle

Antiparticles of the SM particles are **antimatter**

Positron "track"



Compared its matter partner, an antiparticle has:

- equal mass
- opposite electric charge
- opposite "additive" quantum numbers

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

Notation: bar over symbol or minus↔plus

e.g. $\mathrm{u} \leftrightarrow \bar{\mathrm{u}}$ $\quad e^- \leftrightarrow e^+ \quad \nu_e \leftrightarrow \overline{\nu_e}$

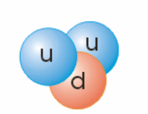
Elementary Particles

The particles that you know already; describes (most) of nuclear physics.

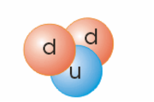
<u>Leptons</u>
Electron and neutrino

<u>Quarks</u>
Nucleons are bounds states of up- and down-quarks

The Proton



The Neutron

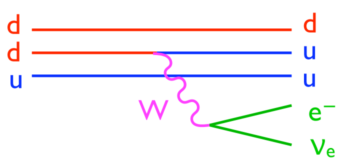


<u>Basic Constituents of Matter</u>
Four spin-½ fermions

Particle	Symbol	Electric Charge	Type
Electron	e^-	−1	lepton
Neutrino	ν_e	0	lepton
Up-quark	u	+2/3	quark
Down-quark	d	−1/3	quark

<u>Beta Decay</u>

$$n \rightarrow p + e^- + \bar{\nu}_e$$
$$d \rightarrow u + e^- + \bar{\nu}_e$$



$d \rightarrow W^- u$
↳ $e\ \bar{\nu}_e$

Generations

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

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

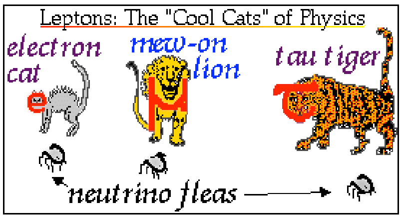
Ordinary Matter: built from the 1st generation

Higher Generations:

- copies of (ν_e, e^-, u, d)
- undergo identical interactions
- only difference is mass of particles
- generations are successively heavier

Why 3 generations?
symmetry/structure not understood!

Leptons



Leptons are particles that **do not** interact via the **strong force.**

Fermions - spin ½ħ

There are six distinct flavours:

- electron and its electron neutrino partner
- muon discovered by Anderson in 1936 in cosmic rays.
  Very similar to electrons but ~200 times heavier
  Unstable: lifetime is 2.2μs
  - muon neutrino partner
- tau: even heavier 3500 × m_e
  Unstable: lifetime is 291 fs
  - tau neutrino partner

The additive quantum numbers are charge, Q, and Lepton Family Number, L_e, L_μ, L_τ

Lepton	Symbol	Charge e	Mass (MeV/c^2)	Lepton Family Number L_e	L_μ	L_τ
Electron Neutrino	ν_e	0	< 0.001	+1	0	0
Electron	e^-	-1	0.511	+1	0	0
Muon Neutrino	ν_μ	0	< 0.001	0	+1	0
Muon	μ^-	-1	105.7	0	+1	0
Tau Neutrino	ν_τ	0	< 0.001	0	0	+1
Tau	τ^-	-1	1777	0	0	+1

Leptons Properties

Charge and **lepton family** number are **conserved** in all interactions.

Question: how does a muon decay?

$\mu^+ \rightarrow e^+\gamma$ FORBIDDEN

$\mu^- \rightarrow e^-\bar{\nu}_e\,\nu_\mu$ ALLOWED $\mu^+ \rightarrow e^+\nu_e\,\bar{\nu}_\mu$

Charged leptons interact via electromagnetic and weak forces.

Neutrinos interact only via weak force.

- neutrinos are almost massless
- ν_e and $\bar{\nu}_e$ are distinct particles with different quantum numbers

$$L_e(\nu_e) = +1 \qquad L_e(\bar{\nu}_e) = -1$$

Quarks

- **Quarks** are fundamental fermions with spin-½ħ
- Six distinct flavours: u, d, s, c, t, b. Fractional charge: +2/3 *e* or −1/3 *e*
- Quark carry **isospin**, **quark flavour** and **electric charge** quantum numbers

Quark	Symbol	Charge e	Mass	Isospin (I, I_z)	Quark Flavour quantum number
up	u	$+2/3$	1.5 - 4.5 MeV/c^2	$(1/2, +1/2)$	-
down	d	$-1/3$	5 - 8.5 MeV/c^2	$(1/2, -1/2)$	-
charm	c	$+2/3$	1 - 1.4 GeV/c^2	-	$C = +1$
strange	s	$-1/3$	80 - 155 MeV/c^2	-	$S = -1$
top	t	$+2/3$	171.4 ± 2.1 GeV/c^2		$T = +1$
bottom	b	$-1/3$	4 - 4.5 GeV/c^2		$B = -1$

m(proton) = 938 MeV/c^2

- Quarks interact via the strong, electromagnetic and weak forces
- Quarks are never found isolated, they always combine into bound states called "hadrons" - **confinement**
- Quarks carry a new quantum number known as colour -
  - each quark has either red, blue or green colour charge
  - anti-quarks have anti-red, anti-blue or anti-green colour charge

Hadrons: Mesons & Baryons

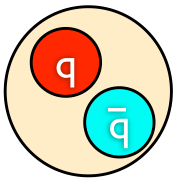
- Free quarks have never been observed - quarks are locked inside **hadrons**
- Hadrons are bound states of quarks: either (qqq) or ($q\bar{q}$)
- Charge of hadron is always integer multiple of electric charge, e
- Colour charge of hadron is always neutral
- Two types of hadrons - **mesons** and **baryons**

Mesons = $q\bar{q}$

Bound states of quark anti-quark pair

Bosons: spin 0, 1ħ, 2ħ

e.g. pions



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

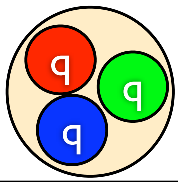
Baryons = qqq

Three quark bound states

Fermions: spin 1/2ħ, 3/2ħ ...

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

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



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

Interactions: Classical & Quantum

Classical Interactions

electromagnetism and gravity - action at a distance

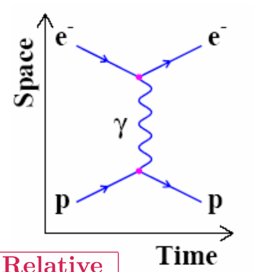
"...that one body may act upon another at a distance through a vacuum without the mediation of anything else, by and through which their action and force may be conveyed from one to another, is to me so great an absurdity that, I believe no man, who has in philosophic matters a competent faculty of thinking, could ever fall into it."

(Newton in a letter to Richard Bentley, 25 Feb. 1693)

Interactions and Forces in Particle Physics

quarks and leptons interact via exchange of spin-1ħ gauge bosons

gravity does not (yet) fit into this framework



Force	Gauge boson	Symbol	Charge e	Mass GeV/c^2	Relative strength
Strong	(8) gluons	g	0	0	1
Electro-magentic	photon	γ	0	0	$\sim 10^{-2}$
Weak	'intermediate vector bosons'	Z^0 $W^\pm$	0 ± 1	91.188 80.40	$\sim 10^{-7}$
Gravity	graviton		0	0	$\sim 10^{-40}$

The Fundamental Forces

Strong Force (gluon, g)

- Acts on **colour charge** *i.e.* only on quarks
- Holds hadrons together and nuclei together

Weak Force (W & Z)

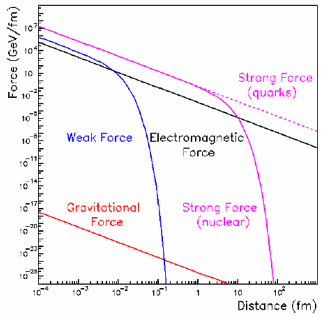
- Acts on **“weak hypercharge”** *i.e.* on all quarks and leptons
- Responsible for fission, fusion and radioactive decays

Electromagnetic force (photon, γ)

- Acts on **electric charge** *i.e.* on all charged particles
- Hold atoms and molecules together

Gravity (graviton)

- Acts on **mass** … *i.e.* on all particles except the photon and gluons
- v. weak on subatomic scales
- Responsible for large scale structure of the universe



Summary

The Standard Model of Particle Physics

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

Matter

- fermions
- 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

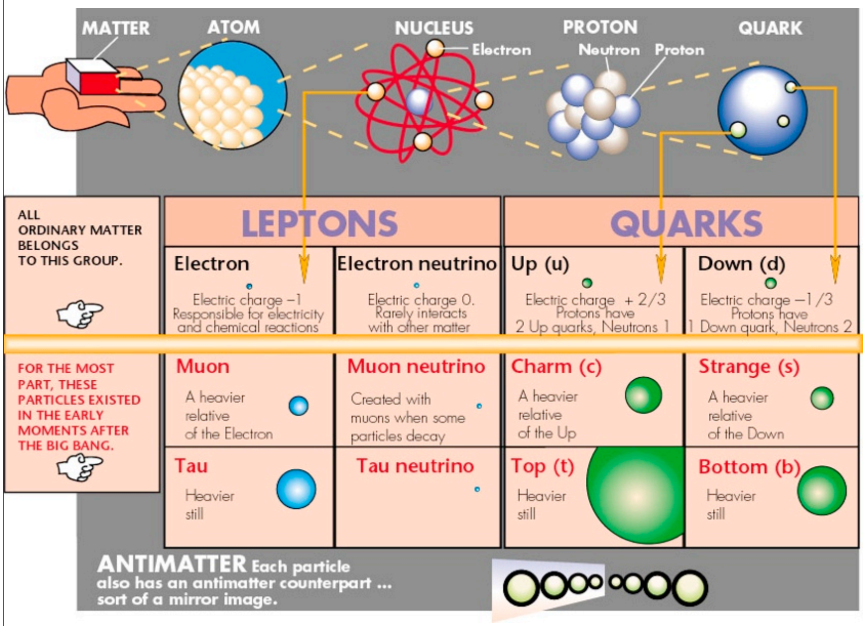
- Antimatter
- Quarks form into hadrons - **mesons** and **baryons**

Forces

- mediated by the exchange of gauge bosons

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

Standard Model of Particle Physics



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