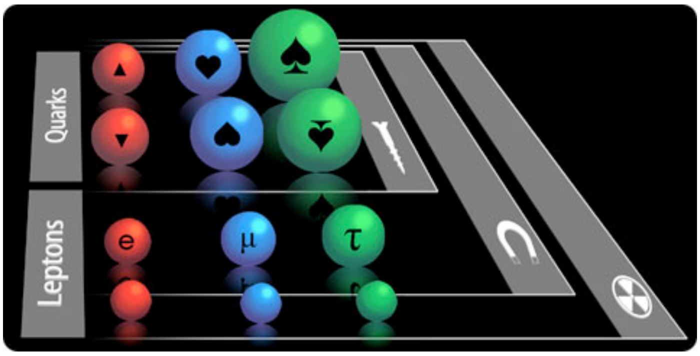
Physics 3:

Particle Physics

Lecture 1: Introduction to the Standard Model of Particle Physics

February 11th 2008



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

Particle Physics and Me

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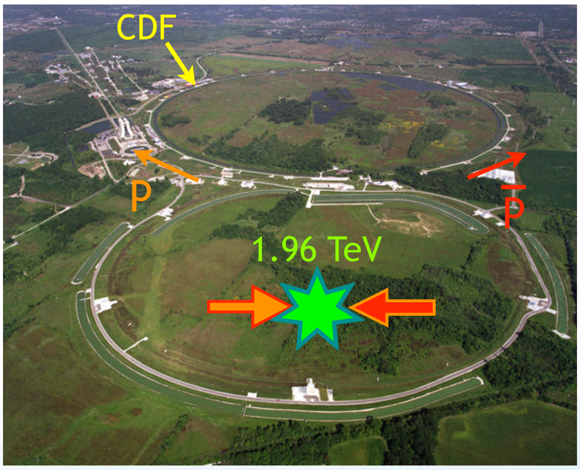
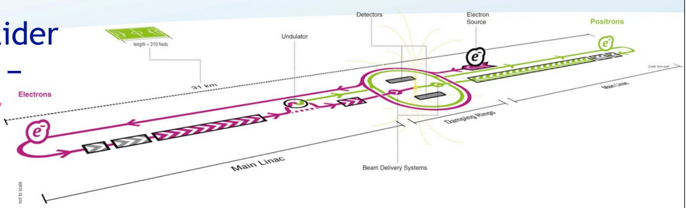


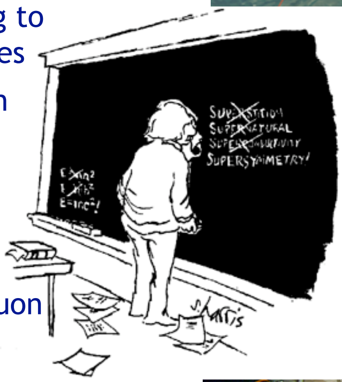
My research deals with Particle Physics at Colliders. Two projects:

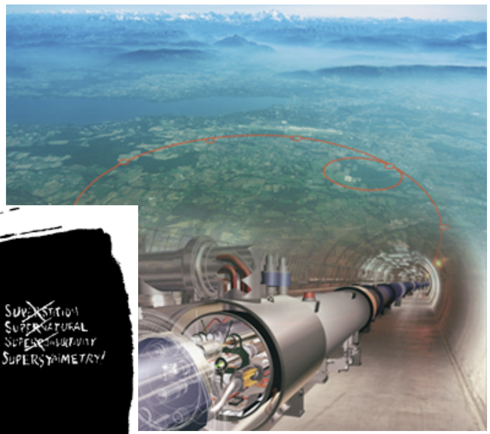
- CDF at the Fermilab Tevatron, near Chicago: colliding protons and anti-protons at ~2TeV. Currently the world's highest energy collider.
- The international linear collider (ILC). World's next electron – position collider. Currently under design.

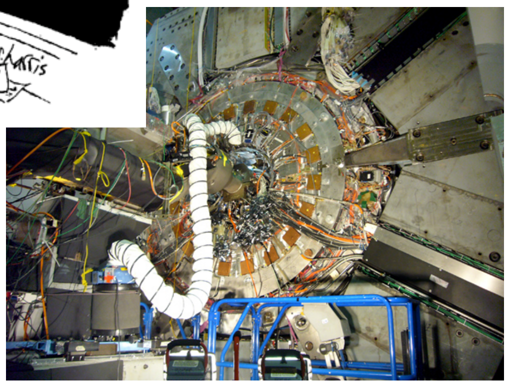


Today's Particle Physics

- High-energy colliders: trying to produce new, heavy, particles
- Study of difference between matter and anti-matter
- Studying neutrinos from the atmosphere, the sun, and man-made neutrinos.
- Precise measurements of muon decay properties
- Developing new detector technologies and computing strategies for TBs of data
- Developing theories for the shortcomings of our models
- Massive numerical calculations of quantum chromodynamics







Particle physics looks at physics at:

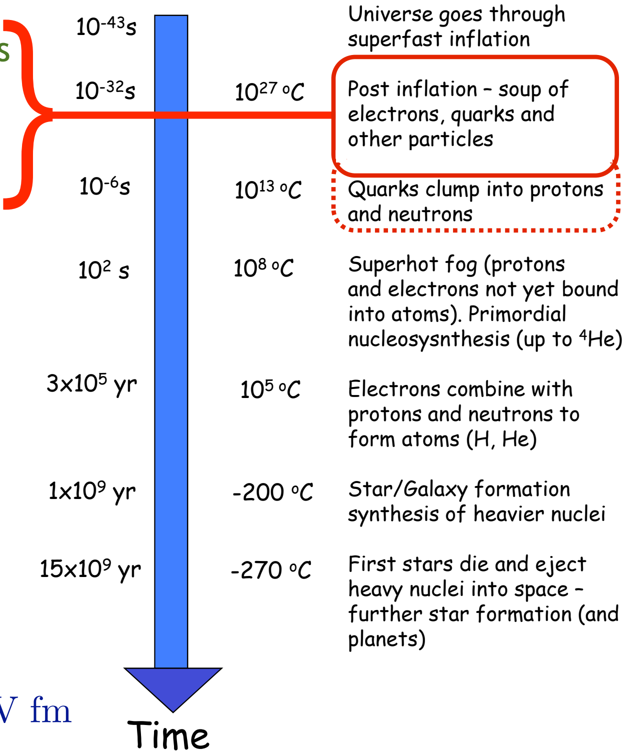
- very high energy densities
- very short distances
- very early times

At high energies, neutrons, protons (and other *hadrons*) break into their constituent quarks.

Particle physics always uses relativity (high energy) and quantum mechanics (very small).

Scale set by $\hbar c = 197.3 \text{ MeV fm}$

Origin of nuclear matter (Background)



Course Outline

Lecture 1 - Introduction

The fundamental particles and forces

Lecture 2 - Practical Particle Physics

Natural units, kinematics

Collisions, scattering and decay

Lecture 3 - Electromagnetic force and Feynman Diagrams

Anti-particles and virtual particles

Quantum electromagnetic force (QED)

Feynman diagrams

Lecture 4 - Experimental Methods

Particle accelerators, detectors and experiments.

Lecture 5 - Quarks and Leptons, Mesons and Baryons

Quantum numbers

Evidence for quarks and colour

$e^+e^- \rightarrow$ hadrons

Lecture 6 - Strong Interactions

Gluons, hadronisation

Confinement, running coupling constant

Lecture 7 - Weak Interactions

Muon and tau decay

Lepton universality

Weak quark decays

Lecture 8 - Neutrinos

Neutrino mass and oscillations

Lecture 9 - Electroweak Theory and beyond

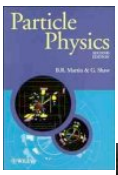
W and Z bosons, LEP

Higgs Boson

...

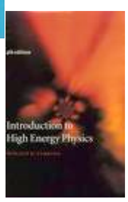
Books!

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

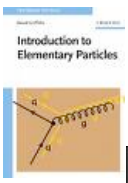


Particle Physics, second edition, by B.R. Martin & G. Shaw. 2nd edition (Wiley 1997)

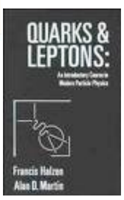
7 copies in JCMB Library.



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



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

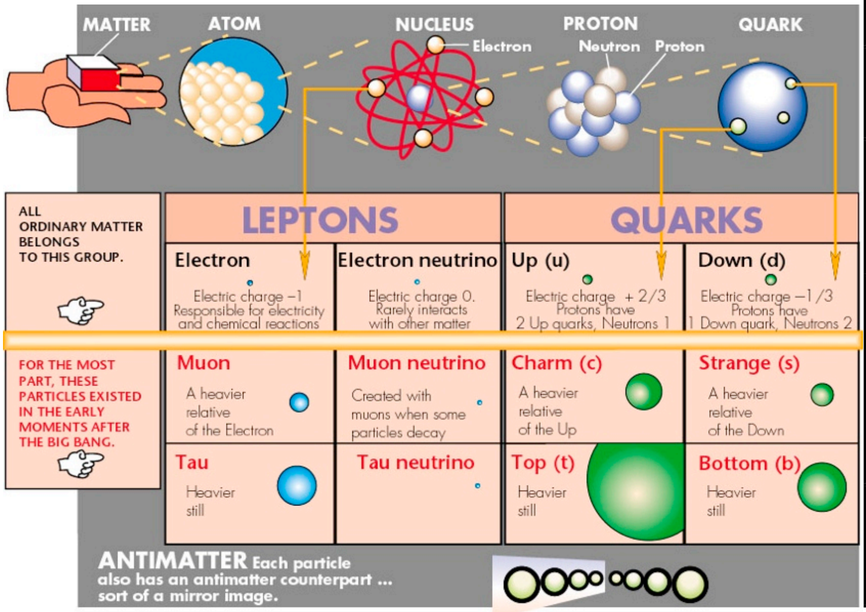


Quarks and Leptons –F. Halzen & A.D. Martin (Wiley 1984)

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

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

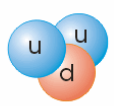
Basic Particles (1st Generation)

The particles that you know already, *e.g.* from beta decay: $\mathbf{n} \rightarrow \mathbf{p}\, e^- \bar{\nu}_e$

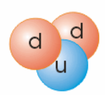
Leptons
Electron and neutrino

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

- Particle physics description of beta decay: $\mathbf{d} \rightarrow \mathbf{u}\, e^- \bar{\nu}_e$

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

Relativistic QM ⇒ 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

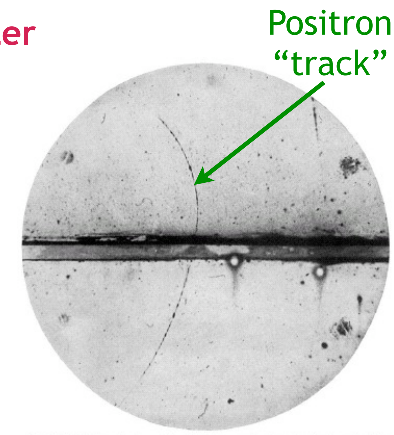


FIG. 1. A 63 million volt positron ($H\rho = 2.1\times10^5$ gauss-cm) passing through a 6 mm lead plate and emerging as a 23 million volt positron ($H\rho = 7.5\times10^4$ gauss-cm). The length of this latter path is at least ten times greater than the possible length of a proton path of this curvature.

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

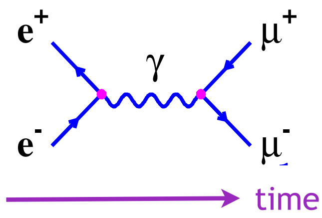
Notation: bar over symbol or minus ↔ plus

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

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.* $e^+e^- \to \mu^+\mu^-$ scattering propagated by photon



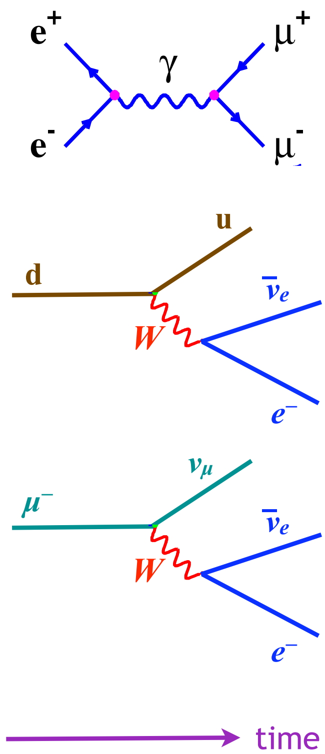
What do the particles do?

Dynamics and relativity 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: $\mu^- \to e^- \bar{\nu}_e \nu_\mu$



Fermi's Golden Rule

The rate at which a decay or a scattering proceeds is given by **Fermi's Golden Rule**:

$$T_{i\to f} = \frac{2\pi}{\hbar} |\mathcal{M}|^2 \rho$$

Where:

- $\mathcal{M}$ is the matrix element - we will see how these are calculated for different processes in future lectures.
- ρ is the density of states - we will consider this only for some key processes.

- T is related to the cross section of scattering, σ.
  e.g. $\sigma(e^+e^- \to \mu^+\mu^-) \propto |\mathcal{M}(e^+e^- \to \mu^+\mu^-)|^2$.
- T is related to the inverse lifetime of a decay, τ.
  e.g. $\tau(\mu^- \to e^- \bar{\nu}_e \nu_\mu) \propto 1/|\mathcal{M}(\mu^- \to e^- \bar{\nu}_e \nu_\mu)|^2$.

Quantum Numbers

Every particle carries a set of quantum numbers, *e.g.*

- electric charge, Q
- *strangeness*, S: number of (anti-strange – strange) quarks

Each force **conserves** some or all of the quantum numbers, *e.g.*:

- all forces conserve electric charge $\sum Q_{\text{initial}} = \sum Q_{\text{final}}$
  - *e.g.* $e^+e^- \to \mu^+\mu^-$ $\sum Q_{\text{initial}} = 0 = \sum Q_{\text{final}}$

- strong and electromagnetic forces conserve strangeness
- weak force does not conserve strangeness

We can use conservation of quantum numbers to work out if a process (decay, scattering) is allowed or forbidden.

- In addition, four-momentum and energy are conserved:

$$\sum \underline{p}_{\text{initial}} = \sum \underline{p}_{\text{final}}, \quad \sum E_{\text{initial}} = \sum E_{\text{final}}$$

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** (also anti-baryons! $\overline{\mathrm{qqq}}$)

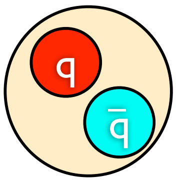
Mesons = q$\bar{q}$

Bound states of quark anti-quark pair

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

e.g. pions

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



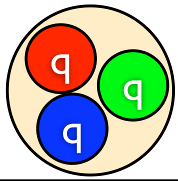
Baryons = qqq

Three quark bound states

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

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

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



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

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