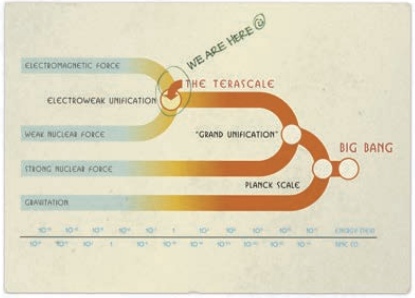
Physics 661 — Elementary Particle Phenomenology
Fall 2013

http://physics.uoregon.edu/~jimbrau/ph661-2013/

Elementary Particle Phenomenology
Physics 661
Fall 2013

Physics 661 begins a survey of the phenomena of the elementary particles of matter and their interactions. For this term we will study (time permitting):

- Introduction to Antiparticles, Interactions and Feynman Diagrams, and Particle Exchange;
- Leptons and the Weak Interaction;
- Quarks and Hadrons;
- Space-Time Symmetries;
- The Quark Model;
- QCD, Jets and Gluons.



These topics cover important introductory material in particle physics. Throughout the course, the interplay between theory and experiment will be emphasized. This first quarter course (**Physics 661**) begins the study of the field of particle physics, with further introductory material and applications to follow in the second term,

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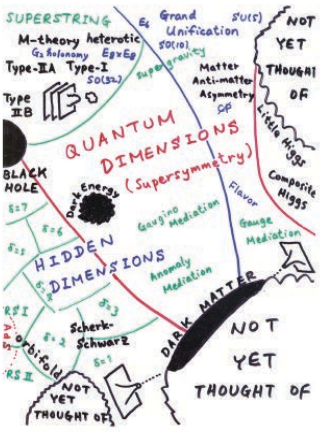
Tentative Course Outline

Introduction	**Martin & Shaw, Chapter 1 (1 week)**
Leptons and the Weak Interaction	**Martin & Shaw, Chapter 2 (1 1/2 weeks)**
Quarks and Hadrons	**Martin & Shaw, Chapter 3 (1 week)**
Space-Time Symmetries	**Martin & Shaw, Chapter 5 (1 1/2 weeks)**
The Quark Model	**Martin & Shaw, Chapter 6 (1 1/2 weeks)**
QCD, Jets and Gluons	**Martin & Shaw, Chapter 7 (1 1/2 weeks)**

Reading and Study Material

Required Textbook

Particle Physics, 3rd Edition (2008)
B. R. Martin and G. Shaw



Recommended Supplementary Textbooks and Resources
Each of the supplementary textbooks will be placed on reserve in the Science Library.

Introduction to High Energy Physics, 4th Edition (2000)
Donald H. Perkins

Introduction to Elementary Particles, 2nd, Revised Edition (2008)
David Griffiths

An Introduction to the Standard Model of Particle Physics, 2nd Edition (2007)
W.N. Cottingham and D.A. Greenwood

An Introduction to Particle Physics and the Standard Model (2009)
Robert Mann
Errata

Elementary Particle Physics in a Nutshell (2011)
Christopher G. Tully

Particle Data Group Tables and Reports
http://pdg.lbl.gov/

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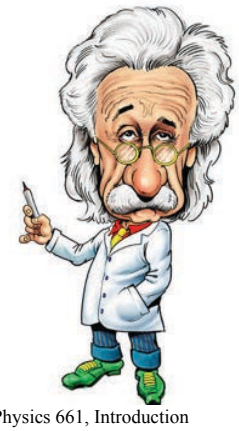
Grading Policy

Grades will be based on homework problem sets, a mid-term exam and a final exam.



J. Brau — Physics 661, Introduction — 4

Some fundamental questions

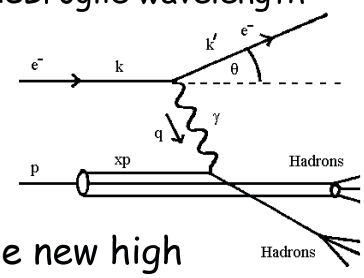
- What is the standard model of elementary particles and their interactions?
- What is the origin of mass and electroweak symmetry breaking?
- What is the role of anti-matter in Nature?
- What is dark matter?
- What are the masses of the neutrinos and how have they shaped the evolution of the universe?
- Are there additional spacetime dimensions?
- What is the nature of the dark energy?
- Are protons unstable?
- How did the universe begin?
- What was the role of gravity in the early universe?
- How do cosmic accelerators work, and what are they accelerating?
- Are there new states of matter at exceedingly high density and temperature?
- Is a new theory of matter and light needed at the highest energies?

Introduction to Quarks and Leptons

- Elem. Particles and High Energy Physics
- Fixed Targets and Colliding Beams
- The Standard Model
  - fundamental fermions, interactions, time scales
- Limitations of the Standard Model
- Fermions and Bosons
- Particles and Antiparticles
- Lepton Flavors
- Quark Flavors

Elementary particles and High Energy Physics

- In order to explore the substructure of matter we need to go to <u>high energy</u>
  - resolution is limited by deBroglie wavelength
  - $\lambda = h/p$



- Also, in order to produce new high mass particles we need <u>higher energy</u>

$$E=mc^2$$

Fixed Target and Colliding Beam Accelerators

- Early experiments were done with a beam of particles and a fixed target
  - The energy in the center-of-mass is

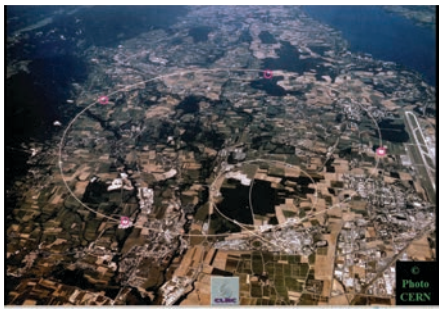
$$s \equiv E_{cm}^2 = (E_{beam} + m_{target})^2 - p_{beam}^2$$
$$= 2\, E_{beam}\, m_{target} + m_{target}^2 + m_{beam}^2$$

  - E_{cm} only increases as the square root of E_{beam} (note $\sqrt{s} \equiv E_{cm}$)
- By colliding beams of particles, E_{cm} increases linearly with E_{beam}

$$s \equiv E_{cm}^2 = (E_{beam} + E_{beam})^2 - (p_{beam} - p_{beam})^2$$
$$= 4\, E_{beam}^2$$

Colliding Beam Experiments

- Many experiments now use colliding beams
  - ATLAS & CMS (CERN - LHC)
    - p p @ 4 TeV/beam
    - World's highest energy
    - Going to 7 TeV/beam
  - CDF & D0 (Fermilab)
    - $p\bar{p}$ @ 1 TeV/beam
    - Was highest energy
  - KEKB (Japan)
    - 3.5 GeV $e^+ \otimes$ 8 GeV e^-
    - B Factory
  - International Linear Collider (ILC) – future
    - $e^+ \otimes e^-$ E_{CMS} = 1 TeV



The Standard Model

A very successful model of elementary particles and their interactions (the Standard Model) has been developed (~1970s). It has stood up to all experimental tests, but we know it is incomplete

- The fundamental fermions
- The interactions
- The limitations

The Fundamental Fermions

- All matter is built from small number of fermions (spin 1/2) particles
- Leptons (integer charge) - six 'flavors'
  - charged leptons (electron, muon, tau)
    - τ(muon) = 2.2 microsec τ(tau) = 0.3 picosec.
  - neutral leptons (electron-neutrino, muon-neutrino, tau-neutrino)
- Quarks (fractional charge) - six 'flavors'
  - up-type quarks (up, charm, top)
  - down-type (down, strange, bottom)
    - only up and down are stable

The Fundamental Fermions

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3

Fundamental Fermions in Nature

- Leptons exist as free particles
- Quarks have never been observed as free particles, only bound within composites, such as the proton (uud), the neutron (udd), the pion (u, anti-d), etc.
- This property of quarks is called 'confinement' and it is an important property of the strong interaction
- The stable particles are the lightest: the electron, u and d quarks, neutrinos.

The Interactions

- Strong
  - binds quarks, mediated by gluon (massless, spin 1)
- Electromagnetic
  - binds electrons in the atom (mediated by photon)
- Weak
  - responsible for β decay; mediated by $W^{\pm}$, Z^0 (massive, spin 1)
- Gravity
  - force between all matter, mediated by graviton (massless, spin 2)

The Electroweak Lagrangian

$$\mathscr{L}_F = \sum_i \overline{\psi}_i \left(i\,\partial\!\!\!/ - m_i - \frac{g m_i H}{2M_W} \right) \psi_i$$

$$- \frac{g}{2\sqrt{2}} \sum_i \overline{\Psi}_i \gamma^\mu (1-\gamma^5)(T^+ W_\mu^+ + T^- W_\mu^-)\,\Psi_i$$

$$- e \sum_i q_i \overline{\psi}_i \gamma^\mu \psi_i A_\mu$$

$$- \frac{g}{2\cos\theta_W} \sum_i \overline{\psi}_i \gamma^\mu (g_V^i - g_A^i \gamma^5)\,\psi_i Z_\mu \,.$$

- KE and mass
- Charged weak
- Electromag.
- Neutral weak

$$\boxed{e = g \sin\theta_W} \qquad \boxed{\sin^2\theta_W = 0.23}$$

Fermion Lagrangian

The Interactions

Table 2.2, Perkins

	Gravity	Electromag.	Weak	Strong
field boson	graviton	photon	$W^\pm$,Z	gluon
spin-parity	2^+	1^-	1^-, 1^+	1^-
mass, GeV	0	0	M_w=80.2 M_Z=91.2	0
range, m	∞	∞	10^{-18}	$\leq 10^{-15}$
source	mass	electric charge	'weak' charge	'color' charge
coupling constant	5×10^{-40}	1/137	1.2×10^{-5}	≤ 1
typical cross-section, m^2		10^{-33}	10^{-39}	10^{-30}
typical lifetime, s		10^{-20}	10^{-10}	10^{-23}

The Limitations of the Standard Model

- Gravity is not explicitly included
- Neutrinos are assumed to be massless
- 17 arbitrary constants
  - masses (9) quarks and charged leptons
  - mixing angles (4) CKM matrix for the quarks
  - coupling constants (4) G_F, α, α_s, $\sin^2\theta_w$
- Six 'copies' of quarks and leptons assumed without understanding of reason for six
- Dark matter is not understood

Natural Units used in HEP

Energy units - GeV = 10^9 eV

$\hbar = 1$ $c=1$

mass (E/c^2) and momentum (E/c) can be expressed in GeV

length has units of $\hbar c/E$, so units of length are GeV^{-1}

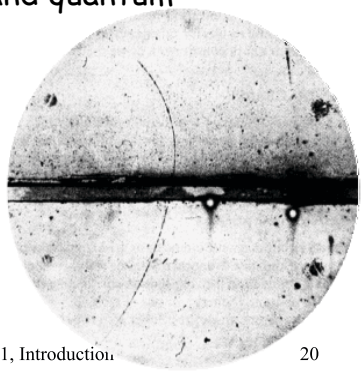
time has units of $\hbar/E$, so units of time are GeV^{-1}

Bosons and Fermions

- The fundamental particles are fermions (spin 1/2), but bosons can be constructed from even numbers of the fund. fermions
- For example, the pions are bosons and obey bose-statistics
- The application of Fermi-Dirac and Bose-Einstein statistics is important in the study of the fundamental particles, and we will make use of it:
  - an example is the understanding of the Δ^{++} = (uuu) particle, which led to the realization of a new quantum number, color

The particles and antiparticles

- Every particle has a corresponding antiparticle, with the same mass and lifetime, and opposite charge and magnetic moment
- Dirac predicted this from fundamental considerations of relativity and quantum mechanics
- The first antiparticle, the positron, was discovered in 1932 in a cloud chamber experiment with cosmic rays (Carl Anderson)



Particle and antiparticles

- Both bosons and fermions have antiparticles, however for fermions there is a conservation law: the difference in the number of fermions and antifermions is a constant
- This law is the origin of the conservation of baryons number and lepton family number:
  - $n \rightarrow p\, e^- \bar{\nu}_e$
  - $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$
  - $\mu^- \rightarrow e^- \bar{\nu}_e\, \nu_\mu$

Particle and antiparticles

- This conservation law does not exist for bosons, so that the following reactions are all possible
  - $p\, p \rightarrow p\, p\, \pi$
  - $p\, p \rightarrow p\, p\, \pi\, \pi$
  - $p\, p \rightarrow p\, p\, \pi\, \pi\, \pi$
- A boson may be its own antiparticle
  - eq. π^0