

Course Description

<http://physics.uoregon.edu/~jimbrau/ph661>

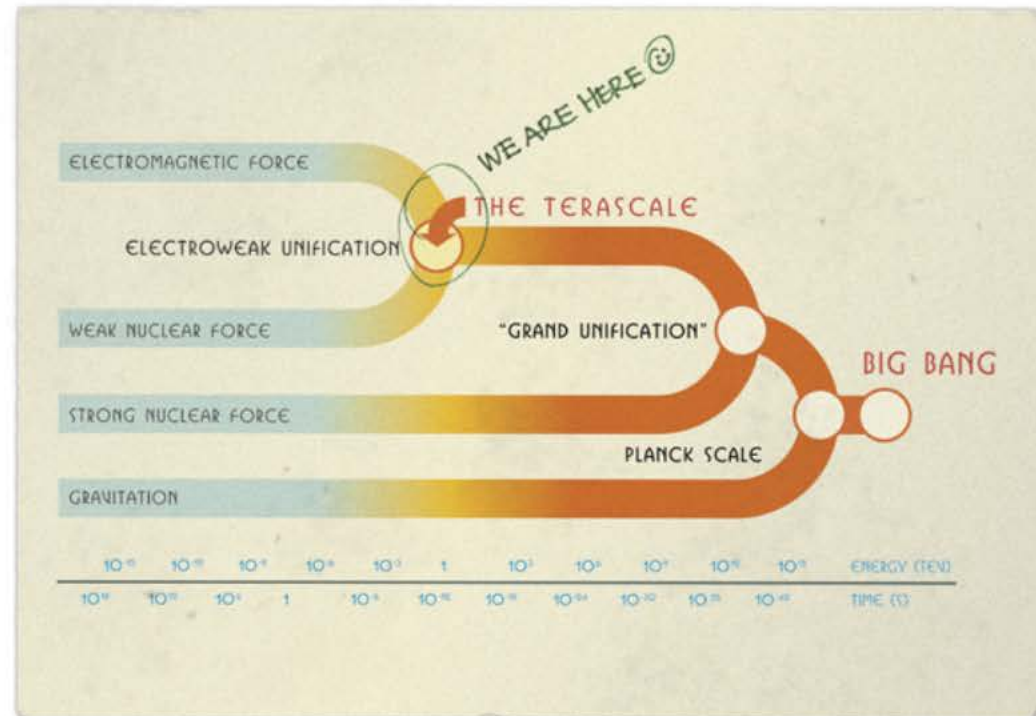
Elementary Particle Phenomenology

Physics 661

Fall 2017

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, **Physics 662**.

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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)

LECTURE NOTES

These notes are outlines of the material covered during the sequence of lectures. Refer to textbooks for details.

- [Introduction](#)

Reading and Study Material

Required Textbook

[Particle Physics, 4th Edition \(2017\)](#)

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 Elementary Particles, 2nd, Revised Edition \(2008\)](#)

David Griffiths

[Modern Particle Physics, \(2013\)](#)

Mark Thomson

[Introduction to High Energy Physics, 4th Edition \(2000\)](#)

Donald H. Perkins

[Gauge Theories of the Strong, Weak, and Electromagnetic Interactions, 2nd Edition \(2015\)](#)

Chris Quigg

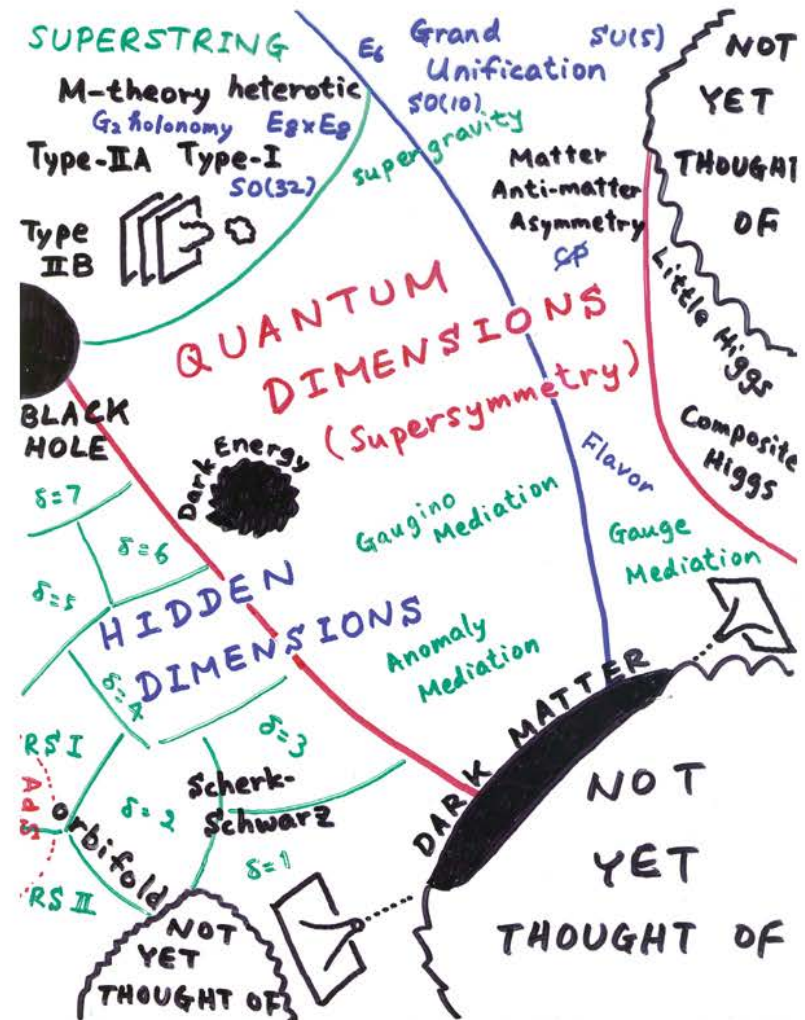
[Concepts of Elementary Particle Physics \(2017\)](#)

Michael E. Peskin

[Particle Data Group Tables and Reports](#)

<http://pdg.lbl.gov/>

J. Brau



<http://physics.uoregon.edu/~jimbrau/ph661>

Grading Policy

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



Image courtesy of Patrick Keough, Carteret Community College.



Some fundamental questions

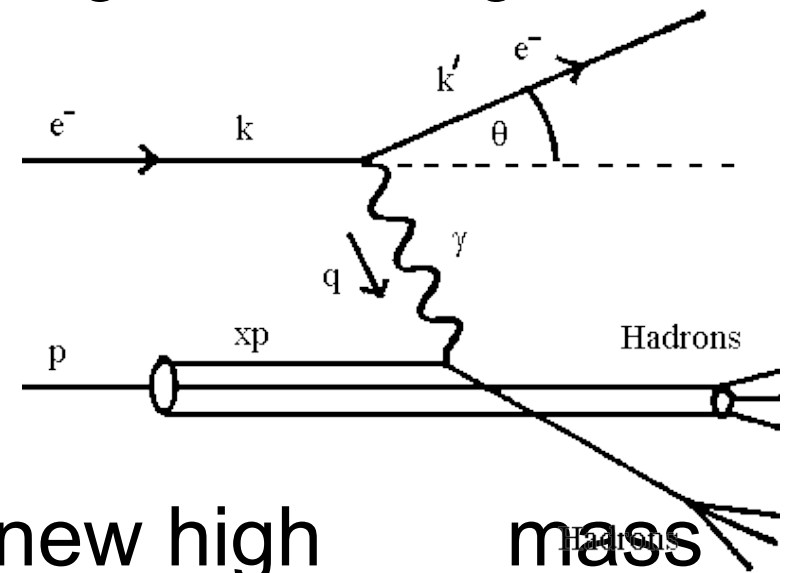
- ~~Why does the electroweak force have quanta with such different masses (photon = 0, $W \sim 80$ GeV, $Z \sim 91$ GeV)?~~ \Rightarrow Higgs Field
- Is this THE “standard model” Higgs field (origin of all masses)? - or New Physics?
- What are the precise properties of the Higgs discovered at the LHC?
- Is the universe supersymmetric? - with a parallel spectrum of particles matching all known particles (fermions \leftrightarrow bosons)?
- What is the source of dark matter detected by astrophysicists?
- Why is the universe dominated by matter over anti-matter?
- What is the origin of dark energy?
- Why are there 3 generations of particles? Or a 4th? Or 5th?
- Why is the top quark so heavy ($>300,000$ me)?
- What is scale of neutrino mass ($<me/1,000,000$)? Why is it so light?
- Why is all charge quantized? Why $q(e) \equiv -q(p)$?
- Why is the spin of the electron $\hbar/2$?
- Is quantum gravity relevant to the question of particle mass and other particle properties - String Theory? - are there more than 3 spatial dimensions? - are any large?
- Does Dark Energy relate to quantum gravity?
- Is the proton unstable?
- How did the universe begin? – what was role of gravity in early universe?
- Is new theory of matter and light needed at highest energies?
- How do cosmic accelerators work?
- Are there new states of matter at high density and temperature?

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 high energy
 - resolution is limited by deBroglie wavelength
 - $\lambda = h/p$



- Also, in order to produce new high particles we need higher energy

$$E=mc^2$$

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

$$\begin{aligned} s \equiv E_{\text{cm}}^2 &= (E_{\text{beam}} + m_{\text{target}})^2 - p_{\text{beam}}^2 \\ &= 2 E_{\text{beam}} m_{\text{target}} + m_{\text{target}}^2 + m_{\text{beam}}^2 \end{aligned}$$

- E_{cm} only increases as the square root of E_{beam}
(note $\sqrt{s} \equiv E_{\text{cm}}$)

- By colliding beams of particles,
 E_{cm} increases linearly with E_{beam}

$$\begin{aligned} s \equiv E_{\text{cm}}^2 &= (E_{\text{beam}} + E_{\text{beam}})^2 - (p_{\text{beam}} - p_{\text{beam}})^2 \\ &= 4 E_{\text{beam}}^2 \end{aligned}$$

Colliding Beam Experiments

- Many experiments use colliding beams
 - ATLAS & CMS (CERN - LHC)
 - $p p$ @ 3.5, 4.0, 6.5 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
 - $e^+ \otimes e^-$ $E_{\text{CMS}} = 0.5$ TeV (250 GeV start – 1 TeV eventual)



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)
 - $\tau(\text{muon}) = 2.2 \text{ microsec}$ $\tau(\text{tau}) = 0.3 \text{ picosec.}$
 - 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		
Flavor	Mass GeV/c ²	Electric charge
ν_e electron neutrino	$<1 \times 10^{-8}$	0
e electron	0.000511	-1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	-1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	-1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c ²	Electric charge
u up	0.003	2/3
d down	0.006	-1/3
c charm	1.3	2/3
s strange	0.1	-1/3
t top	175	2/3
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 (massless, spin 1)
- 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

$$\mathcal{L}_F = \sum_i \bar{\psi}_i \left(i \not{\partial} - m_i - \frac{gm_i H}{2M_W} \right) \psi_i$$

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

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

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

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

$$e = g \sin \theta_W$$

$$\sin^2 \theta_W = 0.23$$

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
- Many arbitrary constants (<http://math.ucr.edu/home/baez/constants.html>)
 - masses (12) quarks and leptons
 - mixing angles (8) CKM matrix for the quarks & PMNS matrix for leptons
 - Higgs (2) mass and expectation value
 - coupling constants (3) G_F , α , α_s , $\sin^2\theta_w$
 - Cosmological constant (1)
- Six ‘copies’ of quarks and leptons assumed without understanding of reason for six
- Dark matter is not understood (or dark energy)

Natural Units used in HEP

Energy units - $\text{GeV} = 10^9 \text{ eV}$

$$\hbar = 1 \quad c = 1$$

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}

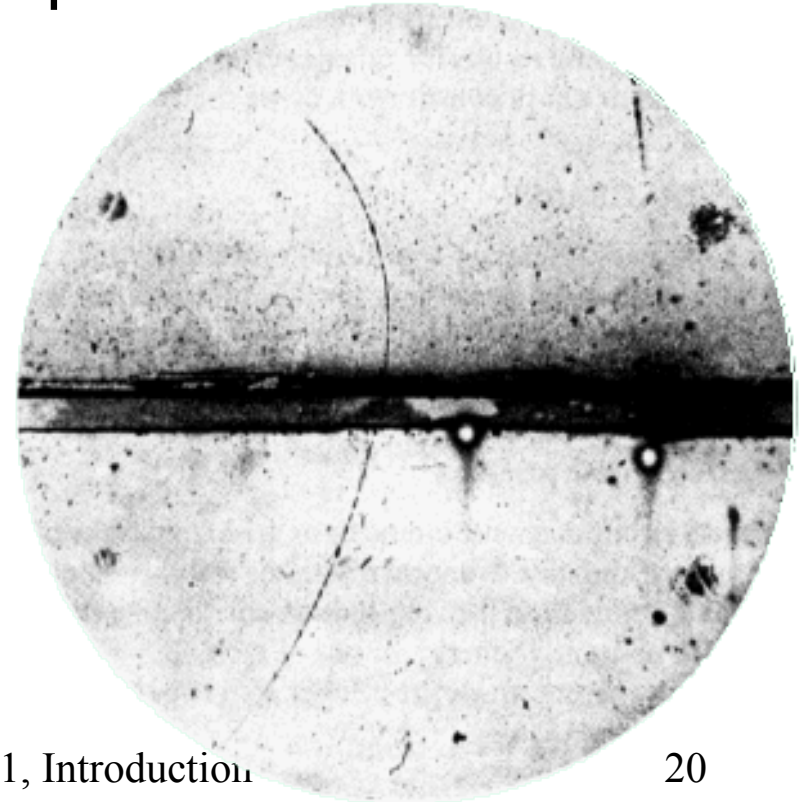
time has units of \hbar / E ,
so units of time are GeV^{-1}

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 $\Delta^{++} = (uuu)$ 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