

Lecture 1 : Overview

In “PHYS 437 High Energy Physics I” course we will mainly cover the following titles :

1. Overview of particle physics, its concepts and theoretical structure, latest experimental discoveries. Latest physics news from the leading accelerators and detectors. (Chapter 1-7 of D.Griffiths’ well-known textbook “Introduction to Elementary Particles second Ed. J.Wiley 2008) which is adopted as our main textbook). The students are expected to learn these chapters well enough, which constitute the basic groundwork.
2. Historical introduction to the world of elementary particles
3. Elementary particle dynamics
4. Relativistic kinematics
5. Symmetries, groups, and conservation laws
6. Bound states, fine and hyperfine structures of hydrogen atom, positronium, quarkonium.
7. The Feynman Calculus, lifetime and cross section calculations for a toy model of quantum field theory.
8. Dirac equation
9. Feynman rules for quantum electrodynamics (QED)
10. Analysis of basic QED processes.

On the other hand weak interactions, basics of quantum chromodynamics and neutrino physics are left for the Spring semester and they will be thoroughly elaborated in PHYS 438.

All the necessary derivations and the details of the mathematical calculations will be presented on the blackboard in the class.

Elementary particle physics deals mainly with two big problems of the physics which are connected to each other : what are the basic building blocks of the matter and the interactions between them. The right framework to study these questions is the quantum field theory, which is certainly beyond the level of the undergraduate curriculum. So in the beginning we will suffice with using the special relativity and quantum mechanics and in foregoing discussions the relativistic quantum mechanics will be our main tool.

The following concepts are vital for the elementary particle physics so let us mention them at the very beginning :

Indistinguishability : For example all the electrons in the universe are identical. However in macroscopic world we don't observe this striking fact : the televisions, or cell phones of the same model are surely perfectly similar but can never be identical.

Fermions and bosons :

Pauli exclusion principle :

Fundamental forces of nature : Electromagnetic force, weak nuclear force, strong nuclear force, gravitational force

Symmetries : Spacetime symmetries, internal symmetries, continuous symmetries, discrete symmetries, gauge symmetries, local or global symmetries, exact or broken symmetries etc.

Sources of the experimental information and data : Scatterings, decays and bound states

Experimental facilities : Cosmic rays, particle colliders (accelerators), nuclear reactors, and various detectors for specific purposes. The well known Lorentz force law plays a crucial role in detecting the charged particles.

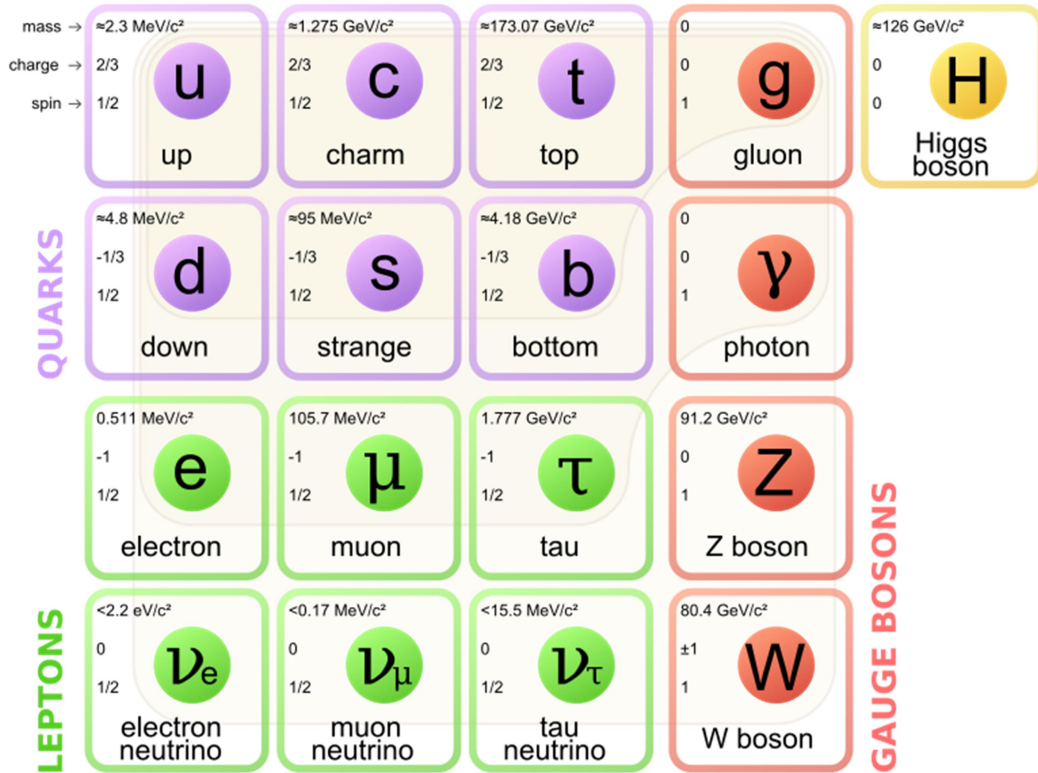
$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Examples from the past and present : LEP and LHC at CERN, SLAC, Fermilab, HERA at DESY, ATLAS, CMS, LHCb and ALICE detectors at LHC, Neutrino detectors SNO, SuperKamiokande, OPERA, many others

Constants of nature : speed of light (c), universal gravitational constant G , charge of the electron (e), Planck's constant h ...

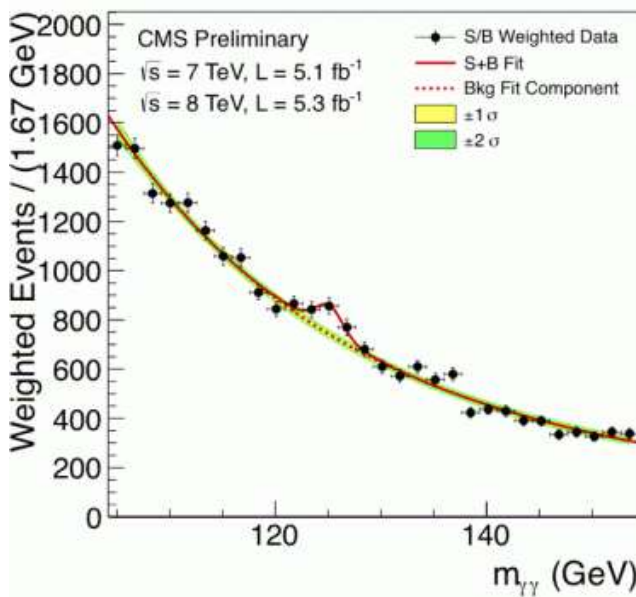
Unit systems : SI, Gaussian, Heaviside-Lorentz, natural unit system $c = \hbar = 1$

Standard Model (SM) of the elementary particle physics perfectly describes the subnuclear world and is summarised by the tables given below (taken from the US Lawrence Berkeley Lab web page) :



The discovery of the Higgs boson on July 4, 2012 at LHC CMS and ATLAS detectors constitutes surely an historical landmark for the whole humanity.

CMS Preliminary Data 2012

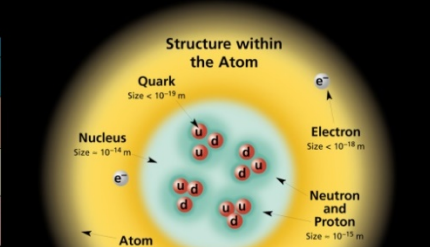


CERN – Geneva July 04, 2012

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

LEPTONS			Quarks		
Flavor	Mass GeV/c ²	Electric charge	Flavor	Approx. Mass GeV/c ²	Electric charge
ν_e electron neutrino	<1.10 ⁻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



Unified Electroweak			Strong (color)		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
γ photon	0	0	g gluon	0	0
W^-	80.4	-1			
W^+	80.4	+1			
Z^0	91.187	0			

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = 1.054 \times 10^{-34}$ GeV s + 1.054×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy unit** of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember $E = mc^2$, where $1 \text{ GeV} = 10^9 \text{ eV} = 1.60 \times 10^{-10}$ joule. The mass of the proton is $0.938 \text{ GeV}/c^2 = 1.67 \times 10^{-27}$ kg.

Color Charge
Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrons and protons interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons
One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons $q\bar{q}$ and baryons qqq .

Residual Strong Interaction
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

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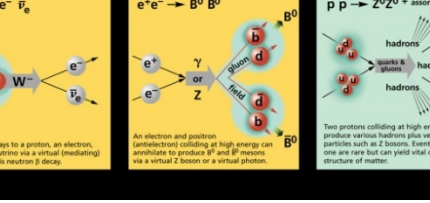
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PROPERTIES OF THE INTERACTIONS

Property	Interaction	Gravitational		Weak Interaction (Electroweak)		Electromagnetic Interaction		Strong Interaction	
		Mass - Energy	Flavor	Electric Charge	Color Charge	Fundamental	Residual		
Acts on:	All	Mass, Energy	Flavor	Electric Charge	Color Charge	Quarks, Leptons	Quarks, Gluons	Quarks, Gluons	Hadrons
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Mesons				
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons					
Strength relative to electromagnetism for two u quarks at:	10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks	25	Not applicable to quarks	
	3×10^{-17} m	10^{-41}	10^{-4}	1	60		60		
	for two protons in nucleus	10^{-36}	10^{-7}	1	1	Not applicable to hadrons	20	20	

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$					
Symbol	Name	Quark content	Electric charge	Mass GeV/c ²	Spin
p	proton	uud	1	0.938	1/2
\bar{p}	anti-proton	$\bar{u}\bar{u}\bar{d}$	-1	0.938	1/2
n	neutron	udd	0	0.940	1/2
\bar{n}	anti-neutron	$\bar{u}\bar{d}\bar{d}$	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
$\bar{\Lambda}$	anti-lambda	$\bar{u}\bar{d}\bar{s}$	0	1.116	1/2
Σ^+	sigma plus	uus	2	1.189	1/2
Σ^0	sigma zero	uds	0	1.189	1/2
Σ^-	sigma minus	dds	-1	1.189	1/2
Ξ^0	xi zero	uds	0	1.321	1/2
Ξ^-	xi minus	dds	-1	1.321	1/2
Ω^-	omega minus	sss	-1	1.672	3/2



Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless ν or $\bar{\nu}$ - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0 , γ , and π^0 , but not K^0 or D^0) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons in the gluon field, and red lines the quark paths.

The Particle Adventure
Visit the award-winning web feature *The Particle Adventure* at <http://ParticleAdventure.org>

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IBM, INTEL, INDUSTRIES, INC.

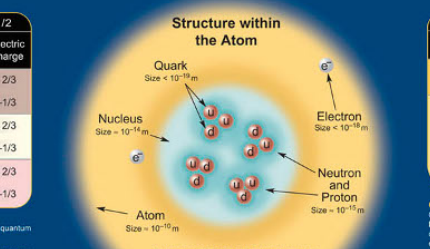
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<http://CPEPweb.org> (Contemporary Physics Education Project)
This web page has very rich educational charts and other valuable materials. Visit the web page and examine the updated charts and discuss them.

Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).

LEPTONS			Quarks		
Flavor	Mass GeV/c ²	Electric charge	Flavor	Approx. Mass GeV/c ²	Electric charge
ν_e lightest neutrino*	(0-0.13) $\times 10^{-9}$	0	u up	0.002	2/3
e electron	0.000511	-1	d down	0.005	-1/3
ν_μ middle neutrino*	(0.009-0.13) $\times 10^{-9}$	0	c charm	1.3	2/3
μ muon	0.106	-1	s strange	0.1	-1/3
ν_τ heaviest neutrino*	(0.04-0.14) $\times 10^{-9}$	0	t top	173	2/3
τ tau	1.777	-1	b bottom	4.2	-1/3



Unified Electroweak			Strong (color)		
Name	Mass GeV/c ²	Electric charge	Name	Mass GeV/c ²	Electric charge
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W^+	80.39	+1			
Z^0	91.188	0			

*See the neutrino paragraph below.

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Neutrinos
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states (ν_e , ν_μ , or ν_τ), labeled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_1 , ν_2 , and ν_3 for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.

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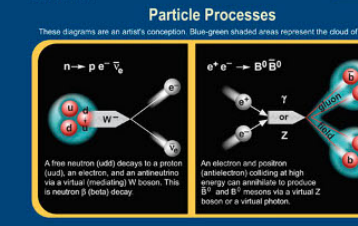
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Color Charge
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Two types of hadrons have been observed in nature: mesons $q\bar{q}$ and baryons qqq . Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda (Λ), and omega (Ω). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ (u \bar{d}), kaon K^+ (u \bar{s}), B^+ (u \bar{c}), and π^0 (u \bar{u} and d \bar{d}). Their charges are +1, -1, 0, respectively.

Unsolved Mysteries
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new worlds and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.



Universe Accelerating?
The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?
Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does the dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?
In the Standard Model, for fundamental particles to have mass, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

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