# Special Topics in Physics (Experiment)

PHYS 8361

Tuesday +Thursday 12:30 pm – 1:50 pm

Hyer Hall G 021

**Course Objective:**

The course covers selection of special topics to prepare students for research in particle physics. The emphasis is on experimental aspects of the detector. Elements of theory important for data analyses are included.

## Textbooks

**Theory**

*P.Langacker, The Standard Model and Beyond

F. Halzen and A. Martin, Quarks and Leptons

V.D. Barger and R.J.N. Phillips, Collider Physics

A. Seiden, Particle Physics, a Comprehensive Introduction

**Experimental techniques**

* R. Fernow, Introduction to Experimental Particle Physics

K. Kleinknecht, Detectors for Particle Radiation

C. Grupen and B. Shwartz: Particle Detectors

* preferred

# Tentative Syllabus

## *From Hydrogen Gas to a Publication in Scientific Journal ( Particle Physics with ATLAS)*

| | |
|---|---|
| Jan 19 (Tue) | no class |
| Jan 21 (Thu) | no class |
| Jan 26 (Tue) | Introduction |
| Jan 28 (Thu) | Theory overview: |
| Feb 2 (Tue) | Problems with the Standard Model: neutrino mass |
| Feb 4 (Thu) | Problems with the Standard Model: strong CP problem |
| Feb 9 (Tue) | Parton Distribution Functions |
| Feb 11 (Thu) | Fragmentation of partons into observable particles |
| Feb 16 (Tue) | Monte Carlo models |
| Feb 18 (Thu) | Charged particles' acceleration technique |
| Feb 23 (Tue) | CERN accelerator complex, issues related to proton beam |
| Feb 25 (Thu) | Luminosity |
| Mar 1 (Tue) | ATLAS detector: inner tracker |
| Mar 3 (Thu) | ATLAS detector: tracking techniques |
| Mar 8 (Tue) | **Spring Break** |
| Mar 10 (Thu) | **Spring Break** |
| Mar 15 (Tue) | ATLAS detector: calorimetry, electron vs photon identification |
| Mar 17 (Thu) | ATLAS detector: muon system and other particle identification |
| Mar 22 (Tue) | ATLAS detector: |
| Mar 24 (Thu) | ATLAS detector: data transfer limitations and trigger |
| Mar 29 (Tue) | ATLAS detector: trigger techniques, requirements, menus |
| Mar 31 (Thu) | Monte Carlo - Standard Model |
| Apr 5 (Tue) | Monte Carlo – new processes |
| Apr 7 (Thu) | Basic approach to data analysis for new physics effects |
| Apr 12 (Tue) | **Individual projects: HH kinematics for HH→4b decays** |
| Apr 14 (Thu) | **Individual projects: Search for BSM Higgs** |
| Apr 19 (Tue) | **Principles of Madgraph5 – how to generate MC data** |
| Apr 21 (Thu) | |
| Apr 26 (Tue) | GEANT workshop |
| Apr 28 (Thu) | GEANT workshop |

# PHYS 8361

What is "High Energy Particle Physics"?

"Noble" goals include answers to the following questions:

- What is the world made of?
- What are its basic building blocks?
- What are the fundamental interactions that hold the matter together and what are the rules of transformations from one type of matter to another?
- What are the symmetries that nature obeys?

Physics is an empirical science – observation of "facts" followed by systematization, connection to one or more fundamental symmetries and development of mathematical description we call "theory". Today's theoretical description is usually based on Lagrange function formulation.

In turn the mathematical description can provide predictions for new "facts" extrapolated from the mathematical formulation that can be "tested".

Good "theory" e.g., quantum electrodynamics has been tested with a precision of 1 part on $10^{14}$.

There one simple answer and two simple formulas that provide the answer to why we are doing accelerator based observations.

Lets start with formulas:

We probe **small distances** therefore we need **high energy**

$$\lambda = \frac{\hbar}{p}$$

We search for **new particles** therefore we need **high energy to observe large invariant mass** (we already know those particles that are produced at low energies)

$$E = mc^2$$

Finally the answer**s**:

-We need reproducible results that cannot be due to statistical fluctuations.

-We want to control the environment in which we do our measurements and be independent on uncontrollable and poorly understood astronomical effects.

-We also want to do it within our lifetime and not wait for next observable supernova or other astrophysical phenomenon.

-> **We can have full control of experiment that is made at an accelerator/collider**.

For the optical microscope the maximum spatial resolution is given by the wavelength of the visible light $\lambda \sim 450$ nm. De Broglie wavelength of a particle in motion

$$\lambda = \frac{h}{p} = \frac{2\pi\hbar c}{pc} = \frac{2\pi(200\,MeV - fm)}{pc}$$

Acceleration of electrons (electron microscope) provides better resolution.
For electron with p ~ 1 GeV, $\lambda \sim 1$ fm ~ $10^{-15}$ m, i.e., about the size of the proton.
Todays accelerators allow to limit the size of the quark to ~ $10^{-17}$ m. So far quarks look like fundamental, point-like particles.
Another component of high energy physics program is the search for new particles.
There are several motivation for those searches:

Taxonomy - do we know all elements of basic building blocks of matter?
- are they really basic or composite ?

Unification – unification of known forces appears incomplete. There are unexplained problems and various tensions in the measurements that may indicate new phenomena.
- If the unification is indeed driven by symmetry they may be new types of interactions that are associated with either changes of detailed properties of known particles or with the existence of new fundamental objects.

# Constituents and Forces

40 years ago if I were teaching this course I would list

**fundamental forces**

gravity (see Newton and Einstein)

electricity and magnetism (seems to work but g-2 anomaly problem)

weak interactions ($n \to p\ e^- \bar{\nu}_e$)

strong interactions (binds p,n to make nuclei)

**fundamental particles**

leptons: $e$, $\nu_e$, $\mu$, $\nu_\mu$ (no $\tau$ yet)

photon: $\gamma$

mesons: $\pi^\pm$, $\pi^0$, $K^\pm$, $K^0$, $\bar{K}^0$, $\eta$, ….. s = 0, 1, 2….

baryons: p, n, $\Lambda^0$, $\Sigma^\pm$, $\Sigma^0$, $\Xi^0$, ….. s = ½, 3/2, …

Empirical rules of classification of mesons and baryons – like botanical taxonomy in 17th century

based on quark picture, but doubtful since no one have seen quarks

No fundamental dynamical theory

**Enormous leap forward**.

Today we have

calculable phenomenological picture of multi-quark states and initial successes of lattice field theory in predicting particle masses

Standard Model based on quantum field theory describing electroweak interactions

phenomenological extension to include elements of QCD

Paradigm change - role of **symmetry in physics.**
In the **past**, symmetry was seen as a **property of interactions**.
Now, symmetry is seen as **dictating interactions** in the gauge theory.

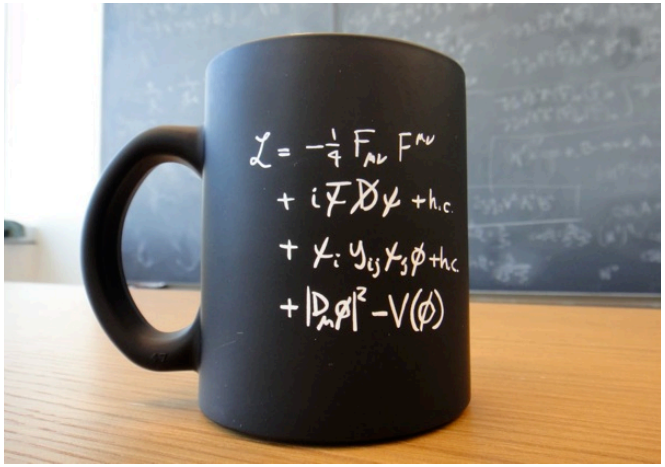
New fundamental particles in our present formulation of Quantum Field Theory

| | |
|---|---|
| quarks: u, d, s, c, b, t and their antiparticles | $s = 1/2$ |
| charged leptons: e, $\mu$, $\tau$ and their antiparticles | $s = 1/2$ |
| neutrinos: $\nu_e$, $\nu_\mu$, $\nu_\tau$ and their antiparticles | $s = 1/2$ |
| gauge bosons: $\gamma$, $W^+$, $W^-$, $Z^0$ | $s = 1$ |
| gluons: | $s = 1$ |
| Higgs boson: H | $s = 0$ |

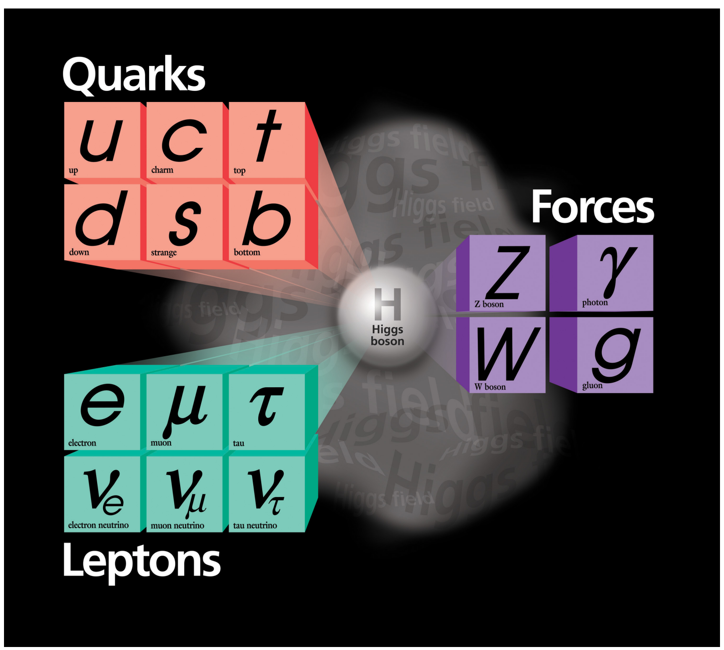
In total 37 fundamental objects. Quite a lot.

The polarization of the spin of the fundamental particles (except neutrinos) follows the standard quantum mechanics rules for helicity (projection of the spin vector on the direction of motion). Neutrinos are the exception. The observed ones are always left-handed (maximum CP violation). Why?

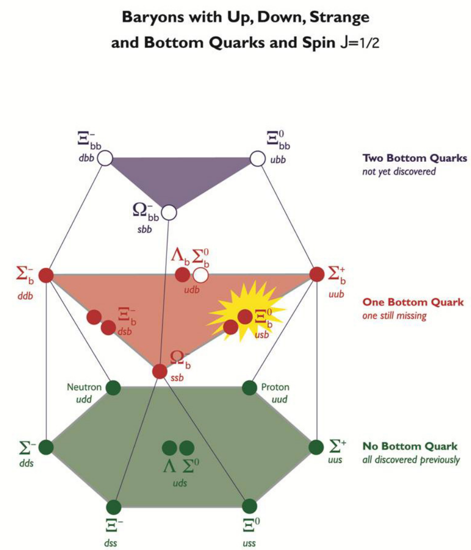
## Complete theory ?

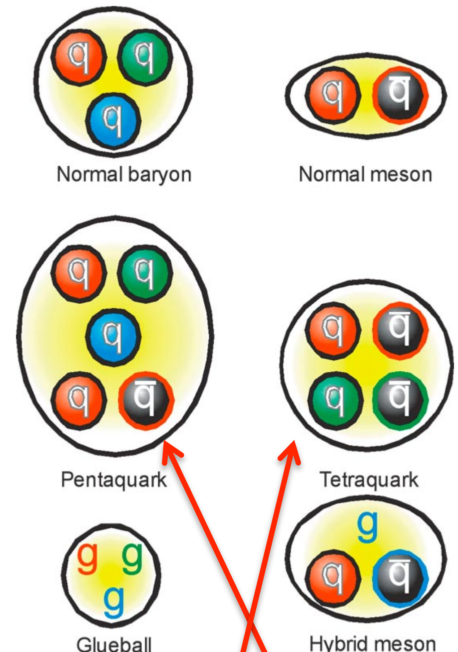


## Complete set of constituents?

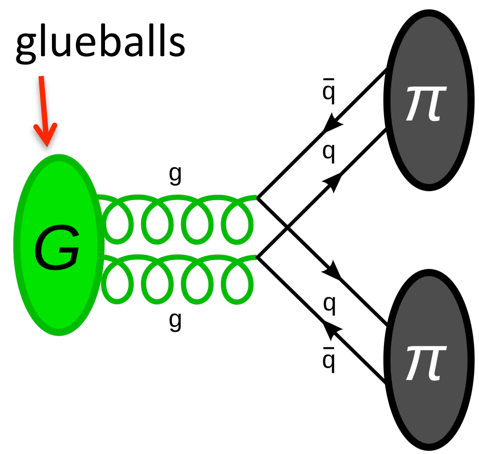



## Missing elements ?




glueballs




multiquark baryons
and mesons

hybrids

# Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

| Property | Gravitational Interaction | Weak Interaction (Electroweak) | Electromagnetic Interaction (Electroweak) | Strong Interaction |
|---|---|---|---|---|
| Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge |
| Particles experiencing: | All | Quarks, Leptons | Electrically Charged | Quarks, Gluons |
| Particles mediating: | Graviton (not yet observed) | $W^+$ $W^-$ $Z^0$ | $\gamma$ | Gluons |
| Strength at $10^{-18}$ m | $10^{-41}$ | 0.8 | 1 | 25 |
| Strength at $3\times10^{-17}$ m | $10^{-41}$ | $10^{-4}$ | 1 | 60 |

Notes:

- Short range of weak interactions indicate massive(heavy) carriers of the force.
- Gravitational interactions ~40 orders of magnitude weaker than electromagnetic can be neglected in all measurements that involve electroweak or strong forces

THE 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).

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

### Leptons spin =1/2

| Flavor | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| $\nu_L$ lightest neutrino* | $(0-2)\times10^{-9}$ | 0 |
| e electron | 0.000511 | –1 |
| $\nu_M$ middle neutrino* | $(0.009-2)\times10^{-9}$ | 0 |
| $\mu$ muon | 0.106 | –1 |
| $\nu_H$ heaviest neutrino* | $(0.05-2)\times10^{-9}$ | 0 |
| $\tau$ tau | 1.777 | –1 |

### Quarks spin =1/2

| Flavor | Approx. Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| u up | 0.002 | 2/3 |
| d down | 0.005 | –1/3 |
| c charm | 1.3 | 2/3 |
| s strange | 0.1 | –1/3 |
| t top | 173 | 2/3 |
| b bottom | 4.2 | –1/3 |

*See the neutrino paragraph below.

**Spin** is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.

**Electric charges** are given in units of the proton's charge. In SI units the electric charge of the proton is $1.60\times10^{-19}$ 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/$c^2$ (remember $E = mc^2$) where 1 GeV = $10^9$ eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/$c^2$ = $1.67\times10^{-27}$ kg.

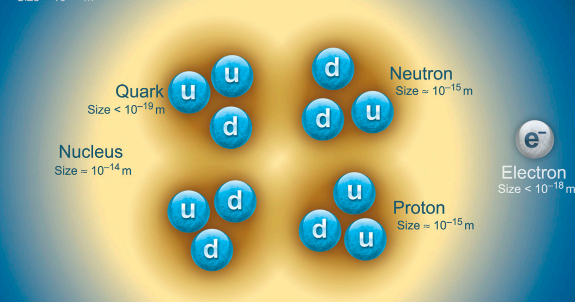
### Neutrinos

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 $\nu_e$, $\nu_\mu$, or $\nu_\tau$, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite-mass neutrinos $\nu_L$, $\nu_M$, and $\nu_H$ 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.

### Matter and Antimatter

For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., $Z^0$, $\gamma$, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.

## Structure within the Atom




If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

## BOSONS force carriers spin = 0, 1, 2, ...

### Unified Electroweak spin = 1

| Name | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| $\gamma$ photon | 0 | 0 |
| $W^-$ W bosons | 80.39 | –1 |
| $W^+$ W bosons | 80.39 | +1 |
| $Z^0$ Z boson | 91.188 | 0 |

### Strong (color) spin = 1

| Name | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| g gluon | 0 | 0 |

### Higgs Boson spin = 0

| Name | Mass GeV/$c^2$ | Electric charge |
|---|---|---|
| H Higgs | 126 | 0 |

### Higgs Boson

The Higgs boson is a critical component of the Standard Model. Its discovery helps confirm the mechanism by which fundamental particles get mass.

### Color Charge

Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.

### Quarks Confined in Mesons and Baryons

Quarks and gluons cannot be isolated – 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. 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. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), and neutron (udd). 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 $\pi^+$ ($u\bar{d}$), kaon $K^-$ ($s\bar{u}$), and $B^0$ ($d\bar{b}$).

Learn more at ParticleAdventure.org

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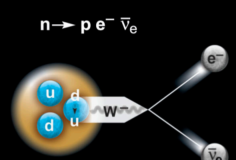
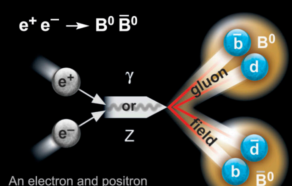
## Particle Processes

These diagrams are an artist's conception. Orange shaded areas represent the cloud of gluons.




A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

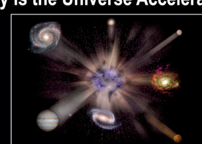



An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and $B^0$ mesons via a virtual Z boson or a virtual photon.

## Unsolved Mysteries

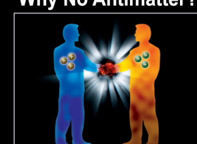
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, microscopic black holes, and/or evidence of string theory.

### Why is the Universe Accelerating?



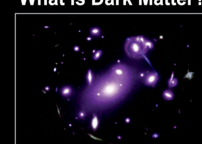
The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

### 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?

### What is Dark Matter?



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

### Are there Extra Dimensions?

An indication for extra dimensions may be the extreme weakness of gravity compared with the other three fundamental forces (gravity is so weak that a small magnet can pick up a paper clip overwhelming Earth's gravity).

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