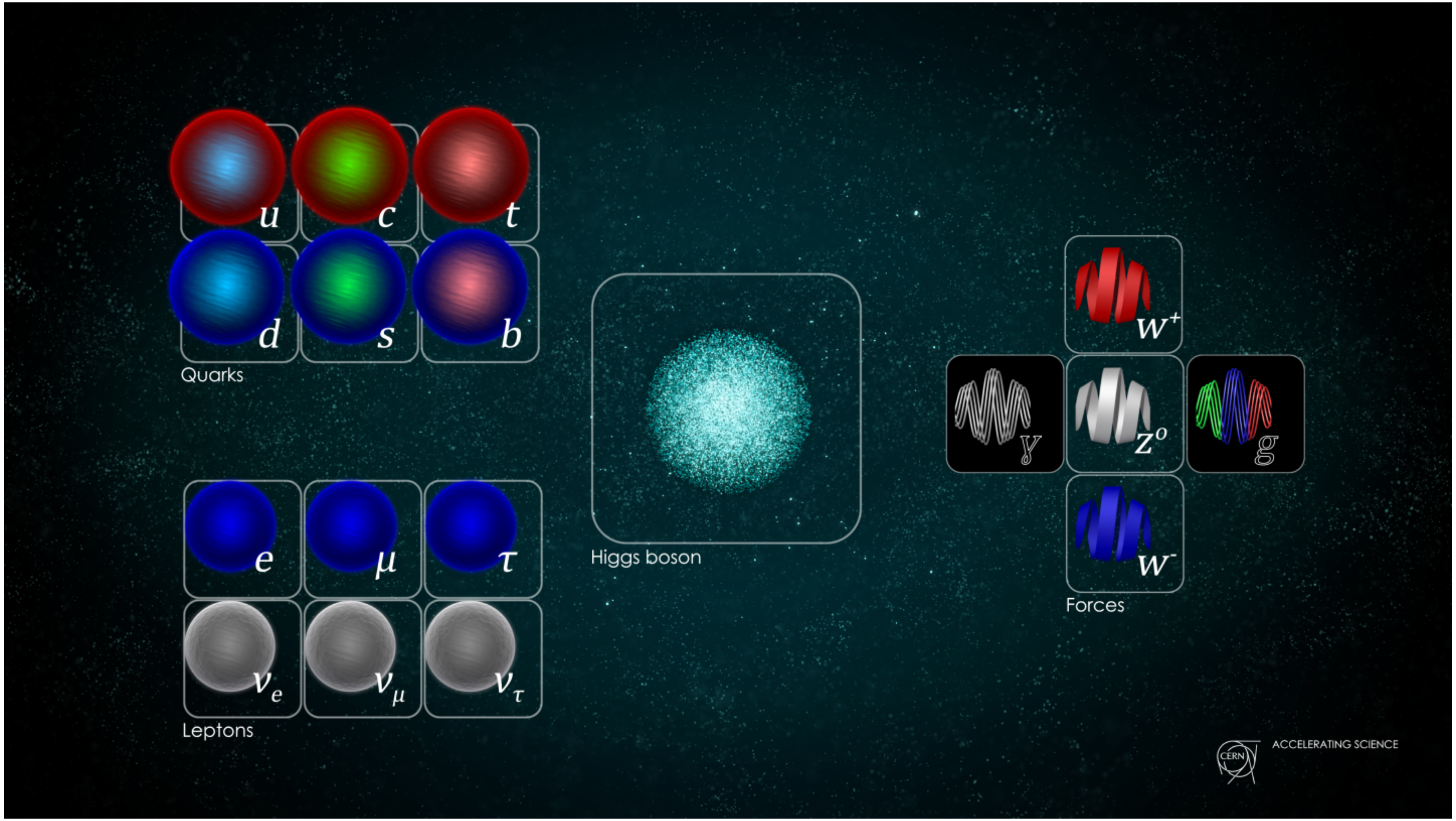
PHYS 6361 Spring 2021

- This is the first half of the course where I will concentrate on the physics of the Higgs boson. In the second half Professor Jodi Cooley will concentrate on the Dark Matter.

- Although the topics seem somehow incongruous there is a deep connection that as yet has to be discovered. Higgs boson completes the Standard Model of particle Physics where it is intrinsically connected to the generation of masses of all components of matter. Dark Matter is identified by the gravitational effects. It has mass and it would be strange if Higgs boson had no connection to it.

Higgs Physics



Why Higgs

In the Standard Model of Particle Physics, the Higgs mechanism is essential to explain the generation mechanism of the property called mass for the gauge bosons. Without the Higgs mechanism, all bosons would be considered massless, but measurements show that the W^+, W^-, and Z^0 actually have relatively large masses. The Higgs field resolves this conundrum. The simplest description of the mechanism adds to the Standard Model a quantum field (the Higgs field) that permeates all space. Below some extremely high temperature, the field causes spontaneous symmetry breaking during interactions. The breaking symmetry triggers the Higgs mechanism causing the bosons it interacts with to have mass.

- In the Standard Model, at temperatures high enough the electroweak symmetry is unbroken, all elementary particles are massless. At a critical temperature, the Higgs field develops a vacuum expectation value; the symmetry is spontaneously broken by tachyon condensation, and the W and Z bosons acquire mass. In the history of the universe, this is believed to have happened shortly after the hot big bang, when the universe was at a temperature 159.5 ± 1.5 GeV.

- Fermions in the Standard Model, can also acquire mass as a result of their interaction with the Higgs field, but not in the same way as the gauge bosons.

From Wikipedia – one page summary of ”why Higgs″

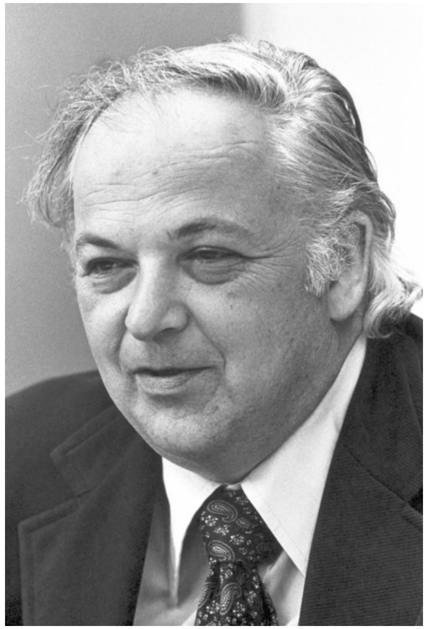
Many ideas and mathematical techniques are needed to understand and acquire practice of the theory behind the concepts in this course. They usually require year-long courses in quantum field theory, symmetry groups and general relativity. We will mainly discuss the concepts and consequences. On the intro level the recommended textbooks are:

- 1. W.N. Cottingham and D.A. Greenwood "An introduction to the Standard Model of Particle Physics"
- 2. Andrew J. Larkoski "Elementary Particle Physics"
- 3. David Griffith "Introduction to Elementary Particles"

Prof. Nadolsky uses

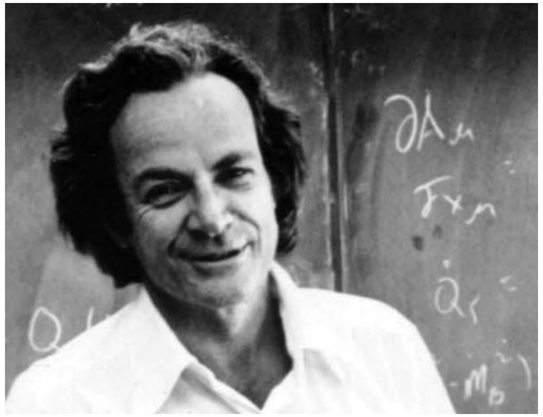
Mark Srednicki "Quantum Field Theory"

<u>Disclaimer</u>: This is an experimentalist view of the theory and its today's frontier. I had to update last 50 years of my theoretical preparations and there are large gaps in my understanding. I hope that you will take active part in its update and ask lots and lots of questions. I would like to see this course as interactive as it is possible in zoom.



Burton Richter

“……it is necessary for experimenters and accelerator physicists to have some understanding of where theory is, and where it is going. Not to do so makes most of us nothing but technicians for the theorists… “



Richard Feynman

To those who do not know mathematics it is difficult to get across a real feeling as to the beauty, the deepest beauty of nature…If you want to learn about nature, to appreciate nature, it is necessary to understand the language that she speaks in.”

Outline

1. Introduction
2. Concept of field in classical electrodynamics
3. Quantization
4. Lorentz invariance
5. Lagrangian and Hamiltonian
6. Quantum Field Theory
   - Yukawa Interactions
7. Gauge theory and symmetry
8. Symmetry Breaking, Yang-Mills theory
9. Particle content of the Standard Model
10. Weak Interactions
11. Electroweak unification, running coupling constant
12. Spontaneous symmetry breaking – the Higgs mechanism
13. Quantum Chromodynamics
14. Theoretical expectations for the Higgs boson properties
15. Data
16. If time permits

    Detector

    BSM – supersymmetry, EFT

    Slides at www.physics.smu.edu/Ryszard/6361sp21/

    Homework problems

    Homework project: Higgs portal to dark matter

Facts and constraints – summary and warnings

- In order to talk about Higgs physics, we must first introduce the Standard Model of Particle Physics. The Higgs is a triumphal confirmation of the Model predictions and a hope to become an avenue for understanding how to bring the "model" into full "theory". It took over 50 years of experimental and theoretical effort to arrive at the Standard Model's present form.

- Standard Model is consistent with all experimental measurements made so far. It has several uncomfortable problems. Higgs field appears to be a necessary component of the unification of electromagnetic and weak interactions and its interactions with both fermions, representing known matter components, and the vector bosons of the force carriers. Its properties partly explain the generation of particle masses. The mechanism of electroweak symmetry breaking has not yet been fully understood: the many order of magnitude variations of strengths of Higgs couplings to fermions remains unexplained, the existence of massive neutrinos generates problem with gauge invariance, the extrapolation to higher energy remains unclear, end so on.

- Thus, in absence of options to explore experimentally much higher energies (multi-TeV scale), the best avenue to identify where the answers to the presently challenging problems can be found are the precision studies of the properties of the Higgs.

The concept of field and classical electrodynamics

Ancient history is full of various media and forces acting on matter, people, weather, health, melancholy and everything else. By the time of establishment of scientific thinking the question of forces acting at a distance became most important. Until the 19th century the common concept was that of an all permeating medium, analog to molecules of air transmitting the sound. II found a discussion of "seeing flowers" in the letter of Cicero - famous Roman orator in living in the first century BC. – that describes a pictures of flowers moving from the bushes to the eyes through the air by yet unknown process.

Most widely used among the proposed mediums was a massless and optically transparent **Aether**, or quintessence, that filled the space and purported to explain the travel of light through the vacuum. Not a one proposition was satisfactory. The great breakthrough came with Maxwell's description of electric and magnetic field.

Maxwell's Equations – consistent classical field theory of electrodynamics

$$\nabla \bullet E = \rho, \qquad \nabla \times B - \frac{dE}{dt} = J,$$

$$\nabla \bullet B = 0, \qquad \nabla \times E + \frac{dB}{dt} = 0.$$

E and B are electric and magnetic fields

ρ and J are electric charge and current densities

Continuity equation:

$$\frac{d\rho}{dt} + \nabla \bullet J = 0,$$

Next step - quantization and Lorentz invariance

E&M Quantization

For the charged-current densities making the four vector field

$$J^{\mu} = (\rho, J)$$

The continuity equation is Lorentz invariant

$$\partial_{\mu} J^{\mu} = 0.$$

We can introduce scalar potential φ and vector potential **A**

$$B = \nabla \times A \qquad\qquad E = -\nabla\varphi - \frac{\partial A}{dt}$$

with $A^{\mu} = (\varphi, A)$ and the Maxwell's equation can be written in terms of antisymmetric tensor

$$F^{\mu\nu} = \partial^{\mu} A^{\nu} - \partial^{\nu} A^{\mu} = \begin{pmatrix} 0 & -E_x & -E_y & -E_z \\ E_x & 0 & -B_z & B_y \\ E_y & B_z & 0 & -B_z \\ E_x & -B_y & B_x & 0 \end{pmatrix}$$

Field is a tensor quantity and A and F became space and time dependent operators.

Spin introduces 2 x 2 matrices: $\sigma = (\sigma^1, \sigma^2, \sigma^3)$

$$\sigma^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \qquad \sigma^2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \qquad \sigma^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Lagrangian for the wave function ψ

$$L = \frac{1}{2}\Big[\Big(i\psi_L^*\tilde{\sigma}^\mu\,\partial_\mu\psi_L^* + i\psi_R^*\sigma^\mu\,\partial_\mu\psi_R\Big) + Hermitian\ conjugate\Big] - m(\psi_L^*\psi_R + \psi_R^*\psi_L)$$

I will come back in more detail to quantization in the section for mechanics