

## ***SUMMER SCHOOL ON PARTICLE PHYSICS***

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### **THE STANDARD MODEL AND HIGGS PHYSICS**

#### **Lecture I**

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# The Standard Model & Higgs Physics

( 5 Lectures )

## Outline

### 1.) Overview & Perspective

"Symmetry Dictates Dynamics"

### 2.) The Standard Model

- i) Basic Properties
- ii) QCD
- iii) Electroweak Parameters
- iv) Higgs Mechanism
- v) Outstanding Problems - Possible Solutions
- vi) Experimental Probes (3 Prong Approach) Frontiers

### 3.) Precision Electroweak Measurements & Rad. Corrections

- i) Fine Structure Constant  $\alpha$  &  $g_e^{-2}/2$
- ii) Muon Anomalous Magnetic Moment,  $a_\mu = g_\mu^{-2}/2$
- iii) Fermi Constant  $G_\mu$  &  $\Gamma_\mu$
- iv)  $m_Z, m_W, \sin^2\theta_W, \Gamma_Z, A_{LR} \dots$

#### 4.) Natural Relations - Loop Probes

- i)  $e_0^2/g_{Z_0}^2 = 1 - m_W^2/m_Z^2 = \sin^2 \theta_W^0$
- ii) Top Quark Mass
- \* iii) Higgs Mass

#### 5.) Some Other Precision Studies

- i) Atomic Parity Violation
- ii) Deep-Inelastic Neutrino Scattering
- \* iii) Polarized  $e^+e^-$  (SLAC E158)

#### 6.) "New Physics" Effects

- i) S, T, U
- ii) SUSY,  $Z'$ , Extra Dimensions

#### 7.) Higgs Phenomenology

- i) Basic Properties
- ii) Collider Searches
- iii) Future  $e^+e^-$  Studies
- iv) Giga Z

#### 8.) Higgs Extensions - Alternatives

- i) SUSY
- ii) Dynamics
- iii) Extra Dimensions

#### 9.) Outlook & Conclusion

## 1.) Overview & Perspective "Symmetry Dictates Dynamics"

## Brief History (~400BC-Present)

Symmetry  $\Rightarrow$  Beauty, Simplicity, Harmony

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Greeks - Circle & sphere: "Nature's Perfect Symmetries"

→ Euclidean Geometry (Tremendous Achievement)

→ Astronomy



## Ptolemy Epicycles - Circles upon Circles

## Symmetry Became an Obsession!

Dogma with no dynamical basis

~ 2000 years of scientific stagnation

### The Renaissance (~1500 AD)

Copernicus, Brahe, Kepler, Galileo → Fall of Epicycle Model

Birth of The Scientific Method } Observations  
Experiments

Newton: "Universal Theory of Gravity"

*Physics Replaces Metaphysics!*

## "Age of Reason"

Equations of Motion + Dynamics replace Aesthetics

Calculus + Algebra replace Geometry

Problem Solving, Experiments, Careful Observation

Science prospered

⋮

Maxwell's Equations (1860s) E+M Conquered!

"The more important fundamental laws and facts of Physical Science have all been discovered, and these are now so firmly established that the possibility of their ever being supplanted in consequence of new discoveries is exceedingly remote ...

Our future discoveries must be looked for in the sixth place of decimals."

A. Michelson 1894

1896 Radioactivity Discovered! (Becquerel)

AGE OF MODERN PHYSICS BEGINS

1897 Electron Discovered! (Particle Physics)

What About Symmetry?

Maintained + Nurtured by Mathematicians

## Symmetry Strikes Back

1905 Special Relativity	}	Einstein's Insights
1916 General Relativity		
1925 Quantum Mechanics	}	Global Symmetries - Eigenvalue Class. Group Theory Meets Physics

## Einstein's Revolutionary View of Symmetry:

### 1.) Space & Time are symmetric (Hidden Symmetry)

Poincaré Invariance 10 Generators  $P_\mu, M_{\mu\nu}$

Irreducible Representations  $|mass, spin\rangle$  Casimir Inv  
elementary particles

### 2.) Equivalence Principle: Invariance under general coordinate transformations } local symmetry



Gravitational Field Equations!

Symmetry Dictates Dynamics!

Einstein's Profound Legacy

(More Sym. ? - Kaluza - Klein  $\rightarrow$  5 dimensions)

3.) Herman Weyl - local  $U(1)$  symmetry  $\rightarrow E \rightarrow M$   
Gauge Sym  $e^{i\theta(x)}$ ,  $A_\mu(x)$  photon

Quantum Electrodynamics: Renormalizable Quantum Field Theory!  
Precision Studies!

4.) Yang-Mills (1954): local Non-Abelian Gauge Symmetry

$$\left. \begin{aligned} U(1) &\rightarrow SU(N), N=2,3,\dots \\ A_\mu(x) &\rightarrow A_\mu^a(x), a=1,2,\dots,N^2-1 \end{aligned} \right\} e^{i\lambda^a \theta^a(x)}$$

$N^2-1$  Massless, Interacting Gauge Bosons!

Non-Linear Field Theory  $\rightarrow$  Unusual Quantum Dynamics!

1967 Weinberg-Salam  $SU(2)_L \times U(1)_Y$  Electroweak Unification

$W^\pm, Z, \gamma$  Broken local gauge sym.  
(Higgs Mechanism)

1972 't Hooft proves renormalizability (underlying symmetry)

Precision EW calculations possible!

1973 Quantum Chromodynamics (QCD): Exact local  $SU(3)_c$  Sym.  
8 Massless Gluons + quarks

Complete Theory of Strong Interactions!

A Perfect Theory - No Free Parameters!

Ideas Guided, Inspired & Confirmed by Experiments

$W^\pm, Z, \text{gluons, charm, } b, t, \phi, \gamma$  - Expected Properties

No Big Surprises?

Heavy Top, Long lived  $b$ , Large Neutrino Mixing...



All known interactions associated with some local symmetry  
(Except perhaps EW mass generation - Higgs Mechanism)

General Coord. Inv.	→	Gravity
$SU(3)_c$	→	Strong
$SU(2)_L \times U(1)_Y$	→	Weak & E.M.

"Symmetries Dictate Dynamics"

## 2.) The Standard Model

$SU(3)_c \times SU(2)_L \times U(1)_Y + \text{Higgs Mechanism}$

A relativistic quantum field theory based on the principle of local gauge invariance that incorporates:

Quantum Electrodynamics (QED) -  $U(1)_{em}$

V-A Theory of Weak Int. CVC etc

Quark Model, Color, Flavor Sym. Current Algebra  
etc

Many Confirmed Predictions

A Proven Standard Against Which all measurements  
are to be compared.

## Some Ingredients:

<u>Poincaré Invariance:</u>	$\phi(x)$	scalars	$S=0$
$(P_\mu, M_{\mu\nu})$	$\psi(x)$	spinors	$S=1/2$
	$A_\mu(x)$	vectors	$S=1$

Fermions: 4 component spinors  $\psi(x) = \psi_L(x) + \psi_R(x)$   
 $\psi_R = \frac{1+\gamma_5}{2} \psi \quad \gamma_5 = i\gamma^0\gamma^1\gamma^2\gamma^3$

The world is left-right asymmetric  $SU(2)_L$

1st generation:  $\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \begin{pmatrix} u_i \\ d_i \end{pmatrix}_L, e_R, u_{iR}, d_{iR} (\nu_n?)$

2nd generation  $\nu_\mu, \mu, c, s$  3rd generation  $\nu_\tau, \tau, t, b$

<u>Poincaré Inv.</u>	<u><math>SU(3)_c \times SU(2)_L \times U(1)_Y</math></u>	<u>Higgs Mechanism</u>
$\langle \text{spin, mass} \rangle$	gluons, $W^\pm, Z, \gamma$	$\lambda(\phi^2 - v^2/2)$
ar. cov. inv	+ 3 Generations	$\phi = \text{complex } S=0 \text{ doublet}$
$\downarrow$	Other? (susy?)	$v \approx 250 \text{ GeV!}$
Gravity		(scale of EW sym. br.)

12 Fundamental Gauge Fields  
 45 Chiral Ferm. Comp.  
 All Discovered

25 years of precision testing!  
 Spectacular Success!

Higgs Doublet:  $\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1(x) + i\omega_2(x) \\ H + v_0 + i\omega_3(x) \end{pmatrix} \quad v_0 \approx 250 \text{ GeV}$

$\omega^\pm = \frac{1}{\sqrt{2}} (\omega_1 \pm i\omega_2)$ ,  $\omega$  would be massless goldstone bosons

Longitudinal Components of  $W^\pm$ ,  $Z$  Bosons

(They have been discovered!)

H (The Remnant Higgs Scalar) Remains Elusive

Direct Exp. Searches  $\rightarrow m_H \gtrsim 114 \text{ GeV}$  } It may be  
Precision Measurement  $\rightarrow m_H \lesssim 180 \text{ GeV}$  } found soon?  
(Quantum Loops)

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ii) QCD (Quantum Chromodynamics) Pure Yang-Mills  
Perfect Theory - On its own  $\rightarrow$  No Free Parameters!

quarks  $q = u, d, c, s, t, b$  L or R

$$\mathcal{L}_{QCD} = \sum_q \overline{q}_1 \overline{q}_2 \overline{q}_3 \left( i \not{\partial}_\mu \gamma^\mu - g_3^0 \frac{\lambda^a}{2} G_\mu^a(x) \gamma^\mu \right) \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix} - \frac{1}{4} G^{a\mu\nu} G_{\mu\nu}^a$$

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - g_3^0 f^{abc} G_\mu^b G_\nu^c$$

Massless Quark + Gluons  $\rightarrow$  EW (Higgs Mechanism) -  $\pi \bar{q}q$   
very diverse quark mass spectrum  
Many Scales!

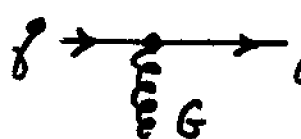
$\mathcal{L}_{QCD}$  invariant under:  $q(x) \rightarrow U(x)q(x)$ ,  $U(x) = \exp(i\theta^a \lambda^a/2)$


$$G_\mu(x) \equiv G_\mu^a(x) \lambda^a/2 \rightarrow U G_\mu U^{-1} - \frac{i}{g_3} U \partial_\mu U^{-1}$$

$a=1,2,\dots,8$

Local  $SU(3)_c$  Invariance

Interactions:

  $i g_3 \frac{\lambda^a}{2} \gamma_\mu$

  $\sim g_3 \dots$         $\sim g_3^2 \dots$

Renormalizable  $\rightarrow$  Short-distance divergences  $g_3 \rightarrow g_{3R} \equiv g_3$

Effective Coupling Depends on  $Q^2$  via vacuum pol.

   $\dots$        $\alpha_3 \equiv g_3^2/4\pi$

$$\alpha_3(Q^2) = \frac{g_3^2(Q^2)}{4\pi} = \frac{4\pi}{(11 - \frac{2}{3}N_f)} \ln Q^2/\Lambda^2 + \mathcal{O}\left(\frac{1}{\ln^2 Q^2/\Lambda^2}\right)$$

4 Active Flavors       $\Lambda^{(4)} \simeq 250 \text{ MeV}$       Dimensional Transmutation

$\Lambda = \text{mass units}$  (No Absolute Meaning)

$$m_{\text{hadron}} \simeq C \Lambda$$

Ratios of Masses Important  
C = Calculable Constants  
(eg lattice)

QCD exhibits rich dynamics { low energies  
high Temp. + Density  
Non-Linear + Strong Coupling

Quark Confinement  
Asymptotic Freedom  $\alpha_3(91\text{GeV}) \approx 0.118$   
Hadron Spectroscopy  
Nuclear Physics  
Proton Structure  
Chiral Sym. Br  
 $\langle 0 | \bar{q}q | 0 \rangle \neq 0$  Breaks EW!  $m_W \approx 80\text{MeV}$   
Dynamical Mass Generation  
Exotics - Glueballs  
Color Superconductivity  
Quark-Gluon Plasma  
⋮

} All  $SU(3)_c$  Dynamics!

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QCD is a major scientific triumph of 20th Century

It completely solved strong interaction physics  
which had been a big mess!

### iii) Electroweak Parameters (Many!)

Most From Higgs Sector

(Rich For Theoretical Speculation: "New Physics")

$SU(2)_L \times U(1)_Y$  Chiral Gauge Symmetries  
 Left & Right Different  
 Nature Abhors Chiral Gauge Theory  
 Break it!  
 Even QCD breaks EW!  
 Higgs Mech. ?  
 $U(1)_{em}$  (non-chiral)

$$\mathcal{L}_{EW} = -\frac{1}{4} W_{\mu\nu}^i W^{i\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} + \bar{L} (i\partial_\mu - g_2 W_\mu^i \frac{\tau^i}{2} - g'_0 B_\mu \frac{Y_L}{2}) L \\ + \bar{R} (i\partial_\mu - g'_0 B_\mu \frac{Y_R}{2}) R + \text{Higgs Mechanism}$$

$$g_{20} \rightarrow g_{2R}$$

$$g_{10} \rightarrow g_{1R}$$

$$g_{10} = \sqrt{5/3} g'_0 \text{ (Gut Normalization)}$$

Infinite Renorm.

$$\alpha_2(91\text{GeV}) \equiv \frac{g_2^2(91\text{GeV})_{\overline{MS}}}{4\pi} = \underline{0.0338}$$

$$\alpha_1(91\text{GeV}) \equiv \frac{g_1^2(91\text{GeV})_{\overline{MS}}}{4\pi} = \underline{0.0169}$$

$\overline{MS}$  = modified  
minimal  
subtraction

Everything Else Higgs Mechanism Related even

$$\sin^2 \theta_W^0 = \frac{g_0^2}{g_2^2} = 1 - m_W^2/m_Z^2$$

Weak Mixing Angle  $\sin^2 \theta_W^0 : \tan \theta_W^0 = g'/g_2$

Gauge Bosons  $W_\mu^1, W_\mu^2, W_\mu^3 \rightarrow B_\mu$

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \pm i W_\mu^2)$$

$$\left. \begin{aligned} Z_\mu &= W_\mu^3 \cos \theta_W^0 - B_\mu \sin \theta_W^0 \\ A_\mu &= B_\mu \cos \theta_W^0 + W_\mu^3 \sin \theta_W^0 \end{aligned} \right\} \text{very important parameter}$$

(i) Higgs Mechanism (Sector)

Fundamental or Effective (Order Parameter) ?

No Underlying Local Sym. (?)

It provides masses in an economical way  
(Hard to do better)

Introduce complex scalar doublet  $\psi = +1$

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1(x) + i\omega_2(x) \\ \sigma(x) + i\eta(x) \end{pmatrix}$$

$$\mathcal{L}_\phi = (\partial_\mu \phi^\dagger - ig_2 \phi^\dagger \frac{\tau^i}{2} W_\mu^i - ig_0 \phi^\dagger B_\mu \frac{Y}{2}) (\partial_\mu \phi + ig_2 \frac{\tau^i}{2} W_\mu^i \phi + ig_0 \frac{Y}{2} B_\mu \phi)$$

$$- \mu_0^2 \phi^\dagger \phi - \lambda_0 (\phi^\dagger \phi)^2 + \text{Fermion-Higgs Couplings}$$

$$\rightarrow M_\phi^2 = -\mu_0^2 < 0 \text{ Tachyonic} \rightarrow \text{Unstable } \phi=0 \text{ gr. state}$$

$$\text{True ground state } \langle 0 | \phi(x) | 0 \rangle = \mu_0 / \sqrt{\lambda_0}$$

Rewrite  
Potential

$$V(\phi) = -\lambda_0 (\phi^\dagger \phi - v_0^2/2)^2$$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} \omega_1 + i\omega_2 \\ H + v_0 + i\gamma \end{pmatrix}$$

$$\omega^\pm = \frac{1}{\sqrt{2}} (\omega_1 \pm i\omega_2), \gamma = \text{Massless Goldstone Bosons} \\ (\text{Long. Components of } W^\pm, Z)$$

$$H = \text{Higgs Scalar} \quad m_H^0 = \sqrt{2\lambda_0} v_0$$

$$m_W^0 = m_Z^0 \cos \theta_W^0 = \frac{1}{2} g_{Z0} v_0 \quad \tan \theta_W^0 = g'_0 / g_{Z0}$$

$$m_W = 80.46 \text{ GeV}, g_2 \approx 0.65 \rightarrow \underline{v_0 \approx 250 \text{ GeV}} \\ \text{Scale of EW sym. br.}$$

All EW Masses proportional to  $v_0$  !

Your mass depends on your coupling to  $\phi(x)$

large coupling  $\rightarrow$  big mass

small coupling  $\rightarrow$  little mass

Higgs Field is like an ether  $\equiv \phi$   
mass = drag

$$m_W = 80.45 \text{ GeV}$$

$$m_Z = 91.18756 \text{ GeV}$$

$$m_H \approx \sqrt{\lambda} \times 350 \text{ GeV}$$

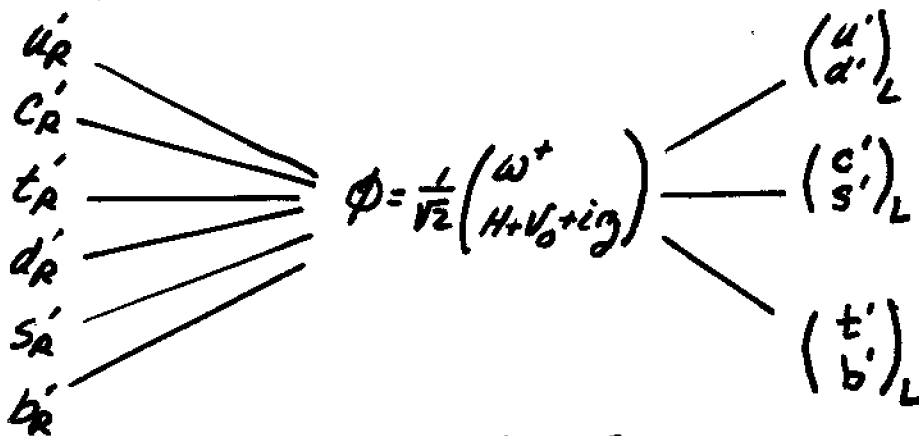
Heavy Higgs  $\lambda \approx 1$  strong self-coupl.

Light Higgs  $\lambda \approx 0 \rightarrow m_H \approx 190 \text{ GeV}$



# Quark Masses, Mixing & CP Violation

$R\phi L$  couplings



$6 \times 3 = 18$  Complex Couplings (Arbitrary)  $G_i^0 \quad i=1,2,\dots,18$   
36 Parameters

→ 6 masses, 3 mixing angles & 1 phase

(Similar for leptons)

These parameters are unrelated in SM!

No Relationships! Masses of Fermions, Mixing..

Unless one goes to a bigger theory  
with more symmetry

Higgs Mechanism - End of the Story?

or

Indicative of more to come?

## i) Outstanding Problems + Possible Solutions (Ideas)

### Origin of EW Mass?

- i) EW Sym. Br. Elementary Higgs vs Dynamics?  $m_H = ?$
- ii) Pattern of Fermion Masses + Mixing  
Quarks vs Leptons  
why is  $m_{top} \approx 175 \text{ GeV}$ ? Strongly Coupled  
Others light
- iii) Deeper Origin of P + CP Violation  
Other Sources of CP for Baryogenesis?
- iv) Quantum Gravity, Dark Energy? Cosmic Connection
- v) Why 3 Generations?
- vi) Why Gauge Symmetries?

etc

## Possible Answers - Hidden Symmetries (Extra Dimensions)

- i) Supersymmetry      Poincaré + Q (spinor)      Radical  
but Likely
- ii) GUTS       $SU(3)_c \times SU(2)_L \times U(1)$
- iii) Technicolor, Topcolor...      New Gauge Sym.

iv) Extra Dimensions      Kaluza-~~Klein~~ Klein - Superstrings  
etc

Do we need experiments?

"I am convinced that we can discover by means of purely mathematical constructions the concepts and the laws connecting them with each other, which furnish the key to the understanding of natural phenomena."

A. Einstein  
1933 Herbert Spencer Lecture

"It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories instead of theories to suit facts"

Sherlock Holmes

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Searching For "New Physics" Beyond The Standard Model

### 3 Prong Experimental Approach

- i) High Energy (Colliders) - Most Direct
- \* ii) High Precision (Deviations - Remember Michelson)
- iii) High Rate (Rare or Forbidden) eg proton decay

+ Astrophysics, Cosmology...