Probing the Structure of Matter
A History of Fundamental Particle Physics
Steve Schnetzer
Rutgers University
Fundamental Particle Physics
What are the fundamental constituents of the universe?
Fundamental Particle Physics

★ What are the fundamental constituents of the universe?

★ How do they interact with each other?
Constituents

- Number: economical
- Properties: few and simple
- Point-like? (no structure)

Theory

- Mathematically consistent
- Explains all observations
- Able to make predictions
Ancient Greece

Plato

Aristotle
Ancient Greece

All is mathematical form

Plato

Aristotle
Ancient Greece

All is mathematical form

I can figure out the universe by pure thought

Plato

Aristotle
The universe is built on the five Platonic solids

Democritus

Circa 500 B.C.

Fundamental Physics
Fundamental Physics

Circa 500 B.C.

The universe is built on the five Platonic solids

PSST! The universe is made up of atoms

Democritus
The Classical Period
1687 – 1897
Newton
Newton

The world is made of point particles
Newton

\[ F = ma \]
Newton

Newton's world is made of point particles. I have no idea what they are.
Chemists Discover Evidence for Atoms

1802

John Dalton

- Gay-Lussac’s Law
- Boyle’s Law
- Charles’s Law
- Law of Multiple Proportions
World’s First Particle Physicist

1827

Discovered Brownian Motion

Robert Brown

Botanist

movie
Periodic Table

1869

a classification scheme

Mendeleev
Periodic Table

1869

Mendeleev
End of 19th century

92 Atoms
The Romantic Period

1897 – 1932
The Cavendish

World's premier physics laboratory late 19th century

Cambridge University

Bunsen Cell

A Typical Lab
Discovery of the Electron

A new particle
electrically charged

J. J. Thomson

Thomson’s CRT
The Plum Pudding Model

can knock electrons out of atoms  \(\text{(photoelectric effect)}\)

\[ \Rightarrow \text{electrons are a part of atoms} \]

How to make a stable electrically neutral atom?

negatively charged electrons distributed like raisins in a positively charged “pudding”
Lord Rutherford

World’s first high energy physicist

1910

Use high energy (5 MeV) alpha particles from radium decay to study structure of the atom.

very light electrons should have no effect on the alpha’s scattering of the alpha’s will indicate structure of the “pudding”
Rutherford Scattering

A surprise

Data is described by assuming alpha’s scattered of a massive point charge

some of the alpha’s scattered at large angles
Rutherford Scattering

A surprise

Data is described by assuming alpha's scattered of a massive point charge

\[ \frac{d\sigma}{d \cos \theta} = \frac{\pi Z^2 z^2 \alpha^2 \hbar^2 c^2}{2E_k^2} \frac{1}{(1 - \cos \theta)^2} \]
Nearly all of the mass of the atom concentrated in a very small positively charged nucleus.

How small is the nucleus?
Heisenberg Uncertainty Principle

Why we need large, expensive high energy accelerators

if you want to probe something at small distances, you have to kick it hard

Rutherford couldn’t resolve the nucleus. It looked like a point.
Discovery of the Neutron

1932

Alpha particles interacting in air found to knock out neutral particles.

Rutherford had earlier discovered the proton (the nucleus of the hydrogen atom)

Atoms made out of: protons, neutrons, electrons
The Neutrino

A free neutron decays to a proton and electron in about 15 minutes

- not a 2-body decay
- must be a third unseen particle

\[ n \rightarrow p + e^- + \bar{\nu} \]

Ghost-like neutrino

Predicted in 1930 by Pauli
Discovered in 1956 by Cowan and Reines
Fundamental Particle Physics

1932

neutrino $\nu$

electron $e^-$

proton $p$

neutron $n$

photon $\gamma$
The Modern Period

1932 – 1974
Cosmic Rays

The cosmic accelerator
much higher energies
than available in the lab
with higher energies can
produce more massive particles

cloud chamber
Antimatter

1932 Carl Anderson discovers anti-electrons (positrons)

poseron track
Discovery of the Muon

1937: the muon a heavy electron discovered by Anderson

\[ \mu \]

Just like electron except about 200 times more mass

I.I. Rabi
Discovery of the Muon

1937: the muon a heavy electron discovered by Anderson

Just like electron except about 200 times more mass

Who ordered that?

I.I. Rabi
Particle Discoveries
1947: **pions** discovered using photographic emulsions at high altitudes
Structure of the Nucleus

Scattered 125 MeV electrons off of nuclei

Hofstadter

1953

nuclear size: $\sim 10^{-13}$ cm
Structure of the Proton

1956

Scattered 550 MeV electrons off of nuclei

Hofstadter’s spectrometer

The proton has a size
it is not a point-like object
The Bevatron

6 GeV proton synchrotron in the hills of Berkeley

Designed to discover the anti-proton
“Seeing” Particles

The bubble chamber

Donald Glaser

Luis Alvarez

What does it all mean?
Quarks

Three quarks

up  down  strange

mesons:  \( qq \)

baryons:  \( qqq \)

1964

Murray Gell-Mann

proton

neutron
Classification Again

meson octet

baryon octet

prediction:

bound state of 3 strange quarks

baryon decaplet
Brookhaven

The AGS

33 GeV proton synchrotron
Discovery of the Omega Minus

1964

Nick Samios

80 - inch bubble chamber
Discovery of the Omega Minus
Stanford Linear Accelerator Center

SLAC  30 GeV electrons

2-mile long linear accelerator
Inside the Proton

1968

SLAC - MIT Group

Kendall

Friedman

Taylor

deep inelastic scattering

proton
Inside the Proton

1968

SLAC - MIT Group

Kendall

Friedman

Taylor

deep inelastic scattering

Rutherford scattering off of point objects again

![Diagram of electron, photon, fragment, proton, and quark interactions]
Fundamental Particle Physics

1974

leptons

$\nu_e \quad \nu_\mu$
$e^- \quad \mu^-$

gauge boson

$\gamma$

quarks

$u \quad d \quad s$
The Golden Period

1974 – 1982
Discovery of a New Quark

1974

resonance

$e^+e^- \rightarrow J/\psi$

SPEAR
Electron-positron collider

bound state of charm and anti-charm quarks

Charmonium
Simultaneous Discovery

Simultaneous Discovery

Sam Ting

AGS Experiment

Double-arm spectrometer

$pp \rightarrow J/\psi + X$

$J/\psi \rightarrow e^+ e^-$
Discovery of a New Heavy Electron

1975 The tau lepton

Just like electron except about 2000 times more mass

\[ e^+ e^- \rightarrow \tau^+ \tau^- \rightarrow \mu^+ e^- \nu_\tau \bar{\nu}_\tau \bar{\nu}_\mu \bar{\nu}_e \]
Fermilab

400 GeV Proton Synchrotron

2 km diameter ring

Robert Wilson
Discovery of Another New Quark

1976

bound state of bottom and anti-bottom quarks

\[ pp \rightarrow \gamma + X \]

\[ \gamma \rightarrow \mu^+ \mu^- \]
Discovery of Another New Quark

1976

\[ pp \rightarrow \gamma + X \]

\[ \gamma \rightarrow \mu^+ \mu^- \]

bound state of bottom and anti-bottom quarks

Leon Lederman
Discovery of the Gluon

1979

30 GeV $e^+e^-$ Collider

Sau Lan Wu

carrier of the strong force
Quantum Chromo Dynamics

binds quarks together
to make proton
The Standard Model

Quantum Electrodynamics
charged particles interacting
by photon exchange
atomic physics

Quantum Chromodynamics
quarks interacting
by gluon exchange
binding of quarks

Weak Force
particles interacting
by W and Z exchange
heavy lepton decay
heavy quark decay
neutrino interactions
CERN

Off to the French Alps

proton – antiproton collisions at 450 GeV
Discovery of the W and Z

1982

\[ W \rightarrow e \nu \]

\[ Z \rightarrow e^+ e^- \]

UA 1 Detector
Fundamental Particle Physics

1982

leptons

$\nu_e$, $\nu_\mu$, $\nu_\tau$

$e^-$, $\mu^-$, $\tau^-$

quarks

$u$, $c$, $d$, $s$, $b$

gauge bosons

$\gamma$, $g$

$W^+$, $W^-$, $Z^0$
The Recent Period
1982 – 2008
LEP

100 GeV electron - positron collisions at CERN

1989 - 2000

27 kilometer tunnel
Over 10 million Z’s produced and decays studied by four large detectors

Aleph Detector
Precision Tests of Standard Model

- Standard Model tested to 0.1% level in agreement with all measurements down to $10^{-16}$ cm
- Only three light neutrinos
- Higgs still missing

$$e^+ e^- \rightarrow ZH$$

$$m_H c^2 > 114 \text{ GeV}$$

![Graph showing $\sigma_{had}$ vs $E_{cm}$](image)
Discovery of the Top Quark

1995 2 TeV Proton - Antiproton collisions

Fermilab Tevatron Collider

Production top anti-top

DO Collaboration
Fundamental Particle Physics

leptons
\[ \nu_e \quad \nu_\mu \quad \nu_\tau \]
\[ e^- \quad \mu^- \quad \tau^- \]
quarks
\[ u \quad c \quad t \]
\[ d \quad s \quad b \]
gauge bosons
\[ \gamma \quad g \quad W^+ \quad W^- \quad Z^0 \]
Higgs
missing

2008
SM Summary

Complete, consistent theory of fundamental physics

- **Fundamental constituents:**
  - 6 quarks and 6 leptons
  - plus antiparticles

- **Three fundamental forces:**
  - **Electromagnetic** mediated by photons
  - **Strong** mediated by gluons
  - **Weak** mediated by $W^+$, $W^-$, $Z^0$

- Agrees with all experiments to $10^{-16}$ cm

- Needs Higgs particle to be complete
The Large Hadron Collider

14 TeV proton antiproton collisions in the LEP tunnel

probing matter at the $10^{-17}$ cm scale

2008

Atlas Detector

CMS Detector
The Current Period

2009 – 2015
The Large Hadron Collider
Big Detectors, Big Collaborations

1/4 of the people who made CMS possible

3170 scientists and engineers (including ~800 students) from 169 institutes in 39 countries
Higgs Decay Fractions

\[ H \rightarrow b\bar{b} \quad 58\% \]
\[ H \rightarrow W^+ W^- \quad 22\% \]
\[ H \rightarrow gg \quad 8.6\% \]
\[ H \rightarrow \tau^+ \tau^- \quad 6.3\% \]
\[ H \rightarrow c\bar{c} \quad 2.9\% \]
\[ H \rightarrow ZZ \quad 2.6\% \]
\[ H \rightarrow \gamma\gamma \quad 0.2\% \]
The Higgs Discovery

CMS

19.7 fb\(^{-1}\) (8 TeV) + 5.1 fb\(^{-1}\) (7 TeV)

S/(S+B) weighted sum

- Data
- S+B fits (weighted sum)
- B component
- ±1\(\sigma\)
- ±2\(\sigma\)

\[ \hat{\mu} = 1.14^{+0.26}_{-0.23} \]

\[ \hat{m}_H = 124.70 \pm 0.34 \text{ GeV} \]

B component subtracted

m\(_{\gamma\gamma}\) (GeV)

ATLAS

Data 2011+2012

SM Higgs boson \(m_H=126.8\) GeV (fit)

Bkg (4th order polynomial)

Events / 2 GeV

\[ \sqrt{s} = 7 \text{ TeV} \]

\[ \sqrt{s} = 8 \text{ TeV} \]

Ldt = 4.8 fb\(^{-1}\)

Ldt = 20.7 fb\(^{-1}\)

m\(_{\gamma\gamma}\) [GeV]
Problems with the Standard Model

- “Natural” mass of the Higgs is $10^{19}$ GeV/c². Why is it 17 orders of magnitude smaller?
- The Standard Model does not include gravity.
- Why does matter dominate over antimatter?
- Why are there three generations of matter particles?
- What explains the values of the masses?
- Too many parameters (27).
- Higgs mechanism seems ad hoc.
- Doesn’t account for Dark Matter
- Doesn’t account for Dark Energy
LHC Physics

Discovery of the Higgs Boson
• Missing ingredient of the Standard Model (SM)
• Now have complete mathematically consistent theory
• Agrees with all experiments down to $10^{-18}$ m scale

What lies beyond the SM at smaller distance (higher energy) scales?
• Measure decay fractions of Higgs to 1% precision
• Search for Supersymmetry (SUSY)
  – Might explain why Higgs is unnaturally light
  – Lightest SUSY particle provides Dark Matter candidate
• Search for other exotics
  – Vector - Like quarks, . . .
• Find the unexpected
Future Circular Collider

A 100 TeV collider under discussion at CERN / China

No guarantee of new physics

Design report in 2018

Turn on in the 2050?