I will describe my field of physics, known as High Energy Physics (HEP) or Elementary Particle Physics. We use high energy particle accelerators (such as the Large Hadron Collider at CERN, Geneva, Switzerland) to study the elementary constituents of matter. This “big science” enables us to study the very smallest sub-atomic particles such as quarks. I will also present the latest results on the search for the Higgs boson (and attempt to explain what that means!).

Program:

1. *The Birth of Modern Physics*  
   (coffee break)
2. *From Nucleus to Quarks*  
   (lunch)
3. *The LHC and the Higgs Boson*
Introduction to Bernard Pope

Professor at Michigan State since 1982

Worked at the European Lab for Particle Physics (CERN), Geneva since 1971

Experiments at Fermilab (Illinois) since 1977. Founder member of the DØ Collaboration

Institutional Representative on the ATLAS Experiment

(from Wales ==> funny accent!)
The Birth of Modern Physics

The 1890s
<table>
<thead>
<tr>
<th>Year</th>
<th>Inventor</th>
<th>Discovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>1895</td>
<td>Roentgen</td>
<td>X-Rays</td>
</tr>
<tr>
<td>1896</td>
<td>Becquerel</td>
<td>Radioactivity</td>
</tr>
<tr>
<td>1897</td>
<td>Thomson</td>
<td>The Electron</td>
</tr>
</tbody>
</table>
1895  Roentgen  →  X-Rays
1896  Becquerel  →  Radioactivity
1897  Thomson  →  The Electron
1900  Planck  →  Blackbody Radiation
1895  Roentgen  →  X-Rays
1896  Becquerel  →  Radioactivity
1897  Thomson  →  The Electron
1900  Planck  →  Blackbody Radiation
1905  Einstein  
        - Relativity
        - Brownian Motion
        - Photoelectric Effect
        - \( E = mc^2 \)
1895  Roentgen  →  X-Rays
1896  Becquerel  →  Radioactivity
1897  Thomson  →  The Electron
1900  Planck  →  Blackbody Radiation

1905  Einstein  
      Relativity
      Brownian Motion
      Photoelectric Effect
      $E = mc^2$

1912  Rutherford  →  Rutherford Scattering
1895  Roentgen  X-Rays
1896  Becquerel  Radioactivity  Atomic Physics
1897  Thomson  The Electron
1900  Planck  Blackbody Radiation  Quantum Physics

1905  Einstein
       Relativity
       Brownian Motion
       Photoelectric Effect
       $E = mc^2$  Relativity

1912  Rutherford  Rutherford Scattering  Nuclear Physics & High Energy Physics
Important discoveries of 1895-1897 (X-rays, radioactivity, the electron)

- Made while experimenting with cathode ray tubes

![Cathode Ray Tube Diagram]

- Plucker (1858-1859) - glow moves with a magnet.
- Hittorf (1869) - objects in front of cathode cast shadows
- Goldstein (1876) coins term "cathode rays"
But what were cathode rays?

- Electromagnetic waves?
  - conclusion of German establishment
  (Hertz failed to bend rays with electric field (1892).)

- Electrically-charged particles?
  - prevailing view in England
J.J. Thomson (1856-1940)

- In 1897 he proved conclusively that cathode rays were indeed streams of negatively-charged particles.

- Obtained better vacuum

- Deflected the rays by both electric and magnetic fields.

- Able to calculate

\[
\frac{\text{Charge}}{\text{Mass}} = \frac{e}{m} = 1.7 \times 10^{11} \text{ Coulombs/kg}
\]

(about 2000 times larger than that of Hydrogen atom)
Hot wire

Screen with a small hole in it

Evacuated glass tube

Undeflected electron beam
ADD AN ELECTRIC FIELD POINTING DOWN. THIS CAUSES THE ELECTRON BEAM (NEGATIVELY CHARGED) TO BE BENT UP.

\[ \vec{F} = q \vec{E} \]
ADD AN ELECTRIC FIELD POINTING DOWN. THIS CAUSES THE ELECTRON BEAM (NEGATIVELY CHARGED) TO BE BENT UP.

\[ \vec{F} = q \vec{E} \]

ADD A MAGNETIC FIELD POINTING INTO THE PAGE. THIS CAUSES THE ELECTRON BEAM TO BE BENT DOWN.

\[ \vec{F} = q \vec{v} \times \vec{B} \]
If both $E$ and $B$ fields are applied, and adjusted so that the net effect is again an undeflected beam, then:

$$q \nu B = qE$$

\[ \therefore \text{the velocity (in the x direction) is} \]

$$\nu = \nu_x = \frac{E}{B}$$

If the $B$ field is turned off then the observed deflection is given by

$$\tan \theta = \frac{\nu_y}{\nu_x} = \frac{q_y t}{\nu_x} = \frac{2E}{m} \frac{L}{\nu_x^2}$$

Where $L$ is the length of the deflecting plate.

$$\therefore \frac{q}{m} = \frac{\nu_x^2 \tan \theta}{EL} = \frac{E^2}{B^2} \frac{\tan \theta}{EL}$$

$$\therefore \frac{q}{m} = \frac{E \tan \theta}{B^2 L}$$
Quick Quiz

• J.J. Thomson discovered that cathode rays were:
  A. very heavy positively charged particles
  B. very light positively charged particles
  C. very heavy negatively charged particles
  D. very light negatively charged particles
  E. massless electromagnetic radiation
J.J. Thomson discovered that cathode rays were:

A. very heavy positively charged particles
B. very light positively charged particles
C. very heavy negatively charged particles
D. very light negatively charged particles
E. massless electromagnetic radiation
Explanation of the “glow”:

- Electrons striking and exciting residual molecules of air left in the tube (by inferior pumps).

- Thomson (using techniques of Wilson) later measured charge and mass separately.

  - Charges attach on water droplets

- Technique refined by Robert Millikan (1910).

The electron charge is

\[ e = -1.6 \times 10^{-19} \text{ Coulombs}. \]
**X-rays**

- Roentgen (1895) studying cathode ray tube, noticed glass tubing glowing some distance away.

- He covered the tube with black paper in a dark room. A fluorescent screen lit up, even if faced away from the discharge tube.

- Then he placed his hand between the discharge tube and the screen and saw the shadow of his bones!

⇒ **X-Rays!** (later shown to be high frequency electromagnetic waves)

⇒ 1st Nobel prize (1901)
X-Ray Spectra

The wavelength distribution of X-rays produced by bombarding electrons on a high-Z target (fig. 3.17):

Relative Intensity

\( \lambda \times 10^{-2} \) nm

(Visible light is \( \sim 400-700 \) nm)
Sharp peaks: due to atomic excitations at specific frequencies.

Continuum: due to sudden deceleration of electron by heavy nucleus in the anode. The deceleration causes the electron to radiate. Called Bremsstrahlung (German for Braking radiation).

The smallest possible wavelength corresponds to maximum energy loss by the electron (i.e. it loses all of its energy).

\[ \lambda_{\text{min}} = \frac{h \cdot c}{KE} = \frac{1243 \text{ eV } \cdot \text{nm}}{KE} \]

Wilhelm Röntgen
1845-1923
Nobel Prize 1901
(the first one!)
In a cathode ray tube, the change in potential energy of the electron is $eV$, where $V$ is the voltage difference between cathode and anode.

Thus, $eV$ is the Kinetic Energy of the electron when it hits the anode.

If all of this energy is converted into a single quantum of X-ray radiation (called a photon), then the photon would have a frequency given by

$$\nu = \frac{eV}{h}, \quad \lambda = \frac{c}{\nu}$$

This is the maximum frequency X-ray that could be emitted in the process.

For example, $2000 \, V \quad \rightarrow \quad \lambda = 0.621 \, \text{nm}$
• Wihelm Roentgen discovered X-rays that were found to be:-

A. very heavy positively charged particles
B. very light positively charged particles
C. very heavy negatively charged particles
D. very light negatively charged particles
E. massless electromagnetic radiation
• Wihelm Roentgen discovered X-rays that were found to be:-

A. very heavy positively charged particles
B. very light positively charged particles
C. very heavy negatively charged particles
D. very light negatively charged particles
E. massless electromagnetic radiation
An increase in the voltage of an X-ray tube results in some X-rays of:

A. a higher velocity
B. a longer wavelength
C. a lower velocity
D. a shorter wavelength
E. a lower frequency
An increase in the voltage of an X-ray tube results in some X-rays of:-

A. a higher velocity
B. a longer wavelength
C. a lower velocity
D. a shorter wavelength
E. a lower frequency
Radioactivity

- Becquerel (1896) was testing various fluorescent materials to see if they emitted X-rays.

- He sealed a photographic plate in black paper and sprinkled a layer of Uranyl Potassium sulfate onto the paper.

- He wanted to expose the salt to sunlight in order to make it fluoresce, but that day Paris was gray and overcast.

- Despite this images exposed with great intensity.

- The new phenomenon was named "radioactivity" by Marie Curie.
The radiation from uranium was found to consist of 3 distinct components -- illustrated by its behavior in a magnetic field:

β-rays: electrons (Becquerel, 1900). They have a range of energies and are fast and penetrating. Can be absorbed by ~1 mm of lead.

α-rays: Helium nuclei (Rutherford, et al). They are heavy, slow, positively-charged particles. Absorbed by ~few cm of air.

γ-rays: Electromagnetic radiation, with a higher frequency, lower wavelength, even than X-rays.
Ernest Rutherford and co-workers discovered that α rays were:-

A. very heavy positively charged particles
B. very light positively charged particles
C. very heavy negatively charged particles
D. very light negatively charged particles
E. massless electromagnetic radiation
Ernest Rutherford and co-workers discovered that α rays were:-

A. very heavy positively charged particles
B. very light positively charged particles
C. very heavy negatively charged particles
D. very light negatively charged particles
E. massless electromagnetic radiation
Transmutation

Pierre and Marie Curie found new radioactive elements, including Thorium, Polonium, and Radium.

A considerable amount of chemistry detective work, especially by the Curies, Rutherford, and Soddy led to a remarkable conclusion:

Every Radioactive decay is a transmutation of the elements, a change from one element to another.
Transmutation of the elements is performed frequently at the following location on the MSU campus:-

A. the Administration building
B. Biomedical Physical Sciences building
C. Spartan stadium
D. Breslin
E. the NSCL
Transmutation of the elements is performed frequently at the following location on the MSU campus:-

A. the Administration building
B. Biomedical Physical Sciences building
C. Spartan stadium
D. Breslin
E. the NSCL

National Superconducting Cyclotron Laboratory
Models of the Atom

Required features:

1. Electrons as constituents.

2. Some positive charges to neutralize the negative charges of the electrons.

3. Some scheme to account for the various different atomic weights.

4. Something to account for the different chemical properties of atoms
The “Plum Pudding” Model

(J.J. Thomson, 1904)

In this model, “a number of negatively-charged corpuscles were enclosed in a sphere of uniform positive electrification”

- A blob of positive “pudding” with electron “plums”. The charges cancel.
Rutherford Scattering

In 1907 Ernest Rutherford, a New Zealander who had been working in Canada, moved to England as Professor of Physics at Manchester University.

He made up a list of possible subjects for research. Number 7 on the list was “scattering of α-rays”. Rutherford had studied α-rays for several years (concluding that they were helium atoms) and had come to appreciate their great value as atomic probes. They were much more massive than β-rays and they interacted vigorously with matter.

Rutherford worked with an experienced physicist, Hans Geiger, as his research assistant, and an 18-year old Manchester undergraduate, Ernest Marsden, on the problem of α-ray scattering.
It had been shown that it was possible to “observe” α-rays using a phenomenon called scintillation. If a screen was coated with Zinc Sulfide (or similar) then, when an α-ray struck the screen, it emitted a short and faint flash of light. It was extremely tedious to dark-adapt and then focus on a screen to observe the effect of the α-rays.

Rutherford, Geiger and Marsden assembled an experimental array that looked like this:-
To the amazement of Rutherford, it was discovered that the $\alpha$-rays were often scattered through very large angles. (1 in 20,000 even bounced back in the direction from which they had come - a scattering angle of 180 degrees.) It was an incredible result.

Rutherford said “It was as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”

$\alpha$-rays, which were hardly deflected by the strongest electrical forces then known, could be turned around by a gold foil only a few hundreds of atoms thick.

Under Rutherford’s direction, Geiger and Marsden published the results of their experiment. Rutherford pondered the meaning of the results for more than a year.

Late in 1910 with the aid of a simple calculation, Rutherford at last saw what the results must mean. He calculated just how close to the positive charge of the gold atom the positive charge of the $\alpha$-rays could get before Coulomb’s law stopped them and reversed their direction. The calculation showed distances of approximately $10^{-14}$ m, (one ten-thousandth of the size of the atom).
This means that the positive charge of the atom is found only at the very center of the atom, not distributed throughout the atom as Thomson had proposed in his plum pudding model.

Rutherford had discovered that atoms consist of a compact positively-charged nucleus around which circulate the negative electrons at a (relatively) large distance. The nucleus occupies 1/10000 of the radius of the atom, or one trillionth of the atomic volume, but it contains almost all of the mass of the atom.

Rutherford worked out the scattering expected for the α-rays as a function of angle, thickness of material, initial velocity and charge of the target atom. The formula was fully verified by Geiger and Marsden in 1913.

It was Rutherford who coined the term nucleus, meaning the central positively-charged core of the atom.

The popular picture of the atom today is due to Ernest Rutherford.
Rutherford's Scattering Calculations

Rutherford assumed that the scattering occurred because a positively-charged $\alpha$-ray passed close to a (relatively massive) positive charge. The closer the distance, the larger the scattering.

$b$ is called the impact parameter. It is the closest distance of approach between the beam particle and the target if the particle had continued in a straight line. It is possible to derive an equation relating the impact parameter and the scattering angle.

$$b = \frac{d}{2} \cot\left(\frac{\theta}{2}\right)$$

where $d$ is the distance of closest approach for a head-on collision.
Any particle hitting an area $\pi b^2$ around the nucleus will be scattered through an angle of $\theta$ or greater.

This area is called the cross section (for angle $> \theta$). It is written:

$$\sigma = \pi b^2$$

(common unit of $\sigma$ is the barn $= 10^{-28}$ m$^2$)

Probability of scattering (with angle $> \theta$) is

$$f = \frac{\text{(\# atoms)} \cdot \sigma}{\text{Total Area}}$$
The minimum separation of the incident particle and the scattering nucleus is given by:

\[ d = \frac{kZ_1Z_2e^2}{E} \]

Energy = \( E + \sim 0 \)

Energy = \( 0 + \frac{kZ_1Z_2e^2}{d} \)

Conservation of energy \( \Rightarrow \)

\[ E = \frac{kZ_1Z_2e^2}{d} \]

Rutherford used 7.7 MeV α-rays scattered from gold.

\[ d = \frac{(8.99 \times 10^9) \cdot 2.79 \cdot (1.6 \times 10^{-19})^2}{(7.7 \times 10^6) \cdot (1.6 \times 10^{-19})} \]

\[ \Rightarrow d = 2.95 \times 10^{-14} \text{ m} \]
The Rutherford Scattering Formula

\[ N(\theta) = \frac{N_i \, n_t}{16 \, r^2} \left( r_{\text{min}} \right)^2 \frac{1}{\sin^4(\theta/2)} \]

\[ = \frac{N_i \, n_t}{16 \, r^2} \left( \frac{e^2}{4 \epsilon_0} \right)^2 \frac{Z_1^2 \, Z_2^2}{K^2 \, \sin^4(\theta/2)} \]

a) Proportional to \( Z_1^2 \) and \( Z_2^2 \)

b) Proportional to \( 1/K^2 \)

c) Proportional to \( 1/\sin^4(\theta/2) \)

d) Proportional to thickness \( t \) (for thin targets)
Using the Rutherford scattering formula, estimate the number of particles scattered from a nucleus of Mercury ($Z = 80$) compared with a nucleus of Calcium ($Z = 20$).

(A) 16
(B) 4
(C) 2
(D) 1/2
(E) 1/4
Using the Rutherford scattering formula, estimate the number of particles scattered from a nucleus of Mercury (Z = 80) compared with a nucleus of Calcium (Z = 20).

(A) 16  
(B) 4  
(C) 2  
(D) 1/2  
(E) 1/4
Using the Rutherford scattering formula, estimate the number of particles scattered at an angle of $\theta = 180$ degrees compared with those scattered at an angle of $\theta = 90$ degrees.

(A) 16
(B) 4
(C) 2
(D) $1/2$
(E) $1/4$
Quick Quiz

Using the Rutherford scattering formula, estimate the number of particles scattered at an angle of $\theta = 180$ degrees compared with those scattered at an angle of $\theta = 90$ degrees.

(A) 16  
(B) 4  
(C) 2  
(D) 1/2  
(E) 1/4