THE LHC PROJECT

An Elementary Review of Concepts, Discoveries and Achievements of Particle Physics

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Overview

• The purpose of Particle Physics is to understand:
  – Fundamental Constituents of Matter
  – Interaction between these constituents

• Today our understanding of the above is based upon the Standard Model of Particle Physics

• The Large Hadron Collider (LHC) will address some fundamental questions related to SM.
What and Where is CERN, LHC, CMS?

European Center for Nuclear Research (CERN)

Large Hadron Collider (LHC)

Compact Muon Solenoid (CMS)
12 Unresolved Fundamental Questions in HEP

1. How do the $Z$ and $W$ acquire mass and not the photon?
   - What is $M_H$ and how do we measure it?
   - Why are there 3 and only 3 light “generations”?
   - What explains the pattern of quark and lepton masses and mixing?
   - Why are the known mass scales so different?
     $\Lambda_{\text{QCD}} \sim 0.2 \text{ GeV} \ll \text{EW vev} \sim 246 \text{ GeV} \ll M_{\text{GUT}} \sim 10^{16} \text{ GeV} \ll M_{\text{PL}} \sim 10^{19} \text{ GeV}$
   - Why is charge quantized?
12 Unresolved Fundamental Questions in HEP

7. Why do neutrinos have such small masses?
8. Why is matter (protons) ~ stable?
9. Why is the Universe made of matter?
10. What is “dark matter” made of?
11. Why is the cosmological constant small?
12. How does gravity fit in with the strong, electromagnetic and weak forces?
The “elementary particles” in the 19th century:

**The Atoms of the 92 Elements**

1. Hydrogen
2. Helium
3. Lithium

.......... 
.......... 
92. Uranium

**Mass** $M_H \approx 1.7 \times 10^{-24}$ g

**increasing mass**

Mass $\approx 238 M_H$

**Estimate of a typical atomic radius**

Number of atoms /cm$^3$: 

$$n = \frac{N_A}{A} \rho$$

Atomic volume: 

$$V = \frac{4}{3} \pi R^3$$

Packing fraction: 

$$f \approx 0.52 \rightarrow 0.74$$

**Example:** Iron ($A = 55.8$ g; $\rho = 7.87$ g cm$^{-3}$)

$$R = (1.1 \rightarrow 1.3) \times 10^{-8} \text{ cm}$$
1894 – 1897: Discovery of the electron

Study of “cathode rays”: electric current in tubes at very low gas pressure (“glow discharge”)
Measurement of the electron mass: $m_e \approx M_H/1836$

“Could anything at first sight seem more impractical than a body which is so small that its mass is an insignificant fraction of the mass of an atom of hydrogen?” (J.J. Thomson)

ATOMS ARE NOT ELEMENTARY

Thomson’s atomic model:
- Electrically charged sphere
- Radius $\sim 10^{-8}$ cm
- Positive electric charge
- Electrons with negative electric charge embedded in the sphere
1896: **Discovery of natural radioactivity**  
(Henri Becquerel)

1909 – 13: **Rutherford’s scattering experiments**  
**Discovery of the atomic nucleus**

**α – particles**: nuclei of Helium atoms spontaneously emitted by heavy radioactive isotopes  
Typical $\alpha$ – particle velocity $\approx 0.05 \, c$  
($c$ : speed of light)
Expectations for $\alpha$ – atom scattering

$\alpha$ – atom scattering at low energies is dominated by Coulomb interaction

$\alpha$ – particles with impact parameter $= b$ “see” only electric charge within sphere of radius $= b$ (Gauss theorem for forces proportional to $r^{-2}$)

For Thomson’s atomic model
the electric charge “seen” by the $\alpha$ – particle is zero, independent of impact parameter

$\Rightarrow$ no significant scattering at large angles is expected
Rutherford’s observation:
significant scattering of $\alpha$ – particles at large angles, consistent with scattering expected for a sphere of radius $\approx$ few $\times 10^{-13}$ cm and electric charge $= Z e$, with $Z = 79$ (atomic number of gold) and $e = |\text{charge of the electron}|$

an atom consists of
a positively charged nucleus
surrounded by a cloud of electrons

Nuclear radius $\approx 10^{-13}$ cm $\approx 10^{-5}$ x atomic radius
Mass of the nucleus $\approx$ mass of the atom
(to a fraction of 1%)
Two questions:

- Why did Rutherford need $\alpha$ – particles to discover the atomic nucleus?
- Why do we need huge accelerators to study particle physics today?

Answer to both questions from basic principles of Quantum Mechanics

The **RESOLVING POWER** of the observation depends on the wavelength $\lambda$

Visible light: not enough resolution to see objects smaller than 0.2 – 0.3 mm
**Photoelectric effect:** evidence that light consists of particles

- **Observation of a threshold effect** as a function of the frequency of the light impinging onto the electrode at negative voltage (cathode):
  - Frequency \( \nu < \nu_0 \): electric current = zero, independent of luminous flux;
  - Frequency \( \nu > \nu_0 \): current > 0, proportional to luminous flux

**INTERPRETATION (A. Einstein):**

- Light consists of particles (“photons”)
- Photon energy proportional to frequency:
  \[ E = h \nu \]  
  (Planck constant \( h = 6.626 \times 10^{-34} \) J s)
- Threshold energy \( E_0 = h\nu_0 \): the energy needed to extract an electron from an atom (depends on the cathode material)
1924: De Broglie’s principle

Not only light, but also matter particles possess both the properties of waves and particles

Relation between wavelength and momentum:

\[ \lambda = \frac{h}{p} \]

- \( h \): Planck constant
- \( p = m v \): particle momentum

Hypothesis soon confirmed by the observation of diffraction pattern in the scattering of electrons from crystals, confirming the wave behaviour of electrons \((\text{Davisson and Germer, 1927})\)

Wavelength of the \( \alpha \) – particles used by Rutherford in the discovery of the atomic nucleus:

\[ \lambda = \frac{h}{m \alpha v} \approx \frac{6.626 \times 10^{-34} \text{ J s}}{(6.6 \times 10^{-27} \text{ kg}) \times (1.5 \times 10^7 \text{ m s}^{-1})} \approx 6.7 \times 10^{-15} \text{ m} = 6.7 \times 10^{-13} \text{ cm} \]

\( \lambda \) ~ resolving power of Rutherford’s experiment
Typical tools to study objects of very small dimensions

<table>
<thead>
<tr>
<th>Tool</th>
<th>Resolution Power</th>
<th>Source of Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical microscopes</td>
<td>~ $10^{-4}$ cm</td>
<td>Visible light</td>
</tr>
<tr>
<td>Electron microscopes</td>
<td>~ $10^{-7}$ cm</td>
<td>Low energy electrons</td>
</tr>
<tr>
<td>Radioactive sources</td>
<td>~ $10^{-12}$ cm</td>
<td>$\alpha$–particles</td>
</tr>
<tr>
<td>Accelerators</td>
<td>~ $10^{-16}$ cm</td>
<td>High energy electrons, protons</td>
</tr>
</tbody>
</table>
Units in particle physics

Energy

1 electron-Volt (eV):
the energy of a particle with electric charge = $|e|$, initially at rest, after acceleration by a difference of electrostatic potential = 1 Volt
($e = 1.60 \times 10^{-19} \text{ C}$)

$$1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$$

Multiples:

1 keV = $10^3$ eV ; 
1 MeV = $10^6$ eV
1 GeV = $10^9$ eV; 
1 TeV = $10^{12}$ eV

Energy of a proton in the LHC:

7 TeV = $1.12 \times 10^{-6}$ J

(the same energy of a body of mass = 1 mg moving at speed = 1.5 m/s)
Basic principles of particle detection

Passage of charged particles through matter

Interaction with atomic electrons

- **ionization**
  (neutral atom $\rightarrow$ ion$^+$ + free electron)

- **excitation of atomic energy levels**
  (de-excitation $\rightarrow$ photon emission)

**Ionization + excitation of atomic energy levels**

**Energy loss**

**Mean energy loss rate** $-dE/dx$

- proportional to $(\text{electric charge})^2$
  of incident particle

- for a given material, function only
  of incident particle velocity

- typical value at minimum:
  $-dE/dx = 1 - 2 \text{ MeV/(g cm}^-2\text{)}$

**NOTE:** traversed thickness $(dx)$ is given in g/cm$^2$ to be independent of material density (for variable density materials, such as gases) – multiply $dE/dx$ by density (g/cm$^3$) to obtain $dE/dx$ in MeV/cm
Residual range

Residual range of a charged particle with initial energy $E_0$ losing energy only by ionization and atomic excitation:

$$R = \int_0^R \frac{Mc^2}{dE/dx} \, dE = MF(v)$$

$M$: particle rest mass
$v$: initial velocity
$E_0 = Mc^2 / \sqrt{1 - (v/c)^2}$

$\Rightarrow$ the measurement of $R$ for a particle of known rest mass $M$ is a measurement of the initial velocity

Passage of neutral particles through matter: no interaction with atomic electrons
$\Rightarrow$ detection possible only in case of collisions producing charged particles

Neutron discovery:
observation and measurement of nuclear recoils in an “expansion chamber” filled with Nitrogen at atmospheric pressure

An old gaseous detector based on an expanding vapour; ionization acts as seed for the formation of liquid drops. Tracks can be photographed as strings of droplets

March 2, 2010
H. Hoorani - Scientific Spring
Assume that incident neutral radiation consists of particles of mass $m$ moving with velocities $v < V_{\text{max}}$.

Determine max. velocity of recoil protons ($U_p$) and Nitrogen nuclei ($U_N$) from max. observed range.

\[
U_p = \frac{2m}{m + m_p} V_{\text{max}} \quad \quad \quad U_N = \frac{2m}{m + m_N} V_{\text{max}}
\]

From non-relativistic energy-momentum conservation

\[m_p: \text{proton mass}; \quad m_N: \text{Nitrogen nucleus mass}\]

\[
\frac{U_p}{U_N} = \frac{m + m_N}{m + m_p}
\]

From measured ratio $U_p / U_N$ and known values of $m_p, m_N$ determine neutron mass: $m = m_n \approx m_p$

Present mass values: $m_p = 938.272 \text{ MeV/c}^2$; $m_n = 939.565 \text{ MeV/c}^2$
Pauli’s exclusion principle

In Quantum Mechanics the electron orbits around the nucleus are “quantized”: only some specific orbits (characterized by integer quantum numbers) are possible.

Example: allowed orbit radii and energies for the Hydrogen atom

\[ R_n = \frac{4\pi\varepsilon_0 \hbar^2 n^2}{me^2} \approx 0.53 \times 10^{-10} n^2 \text{ [m]} \]

\[ E_n = -\frac{me^4}{2(4\pi\varepsilon_0)^2 \hbar^2 n^2} \approx -\frac{13.6}{n^2} \text{ [eV]} \]

In atoms with \( Z > 2 \) only two electrons are found in the innermost orbit – WHY?

**ANSWER** (Pauli, 1925): two electrons (spin = ½) can never be in the same physical state

- Hydrogen \( (Z = 1) \)
- Helium \( (Z = 2) \)
- Lithium \( (Z = 3) \)

Pauli’s exclusion principle applies to all particles with half-integer spin (collectively named Fermions)
ANTIMATTER
Discovered “theoretically” by P.A.M. Dirac (1928)

Dirac’s equation: a relativistic wave equation for the electron

Two surprising results:

- Motion of an electron in an electromagnetic field: presence of a term describing (for slow electrons) the potential energy of a magnetic dipole moment in a magnetic field ⇒ existence of an intrinsic electron magnetic dipole moment opposite to spin

\[ \mu_e = \frac{e\hbar}{2m_e} \approx 5.79 \times 10^{-5} \text{ [eV/T]} \]

- For each solution of Dirac’s equation with electron energy \( E > 0 \) there is another solution with \( E < 0 \)

What is the physical meaning of these “negative energy” solutions?
Generic solutions of Dirac’s equation: complex wave functions $\Psi(\vec{r}, t)$

In the presence of an electromagnetic field, for each negative-energy solution the complex conjugate wave function $\Psi^*$ is a positive-energy solution of Dirac’s equation for an electron with opposite electric charge ($+e$)

**Dirac’s assumptions:**

- nearly all electron negative-energy states are occupied and are not observable.
- electron transitions from a positive-energy to an occupied negative-energy state are forbidden by Pauli’s exclusion principle.
- electron transitions from a positive-energy state to an empty negative-energy state are allowed $\Rightarrow$ electron disappearance. To conserve electric charge, a positive electron (positron) must disappear $\Rightarrow e^+e^-$ annihilation.
- electron transitions from a negative-energy state to an empty positive-energy state are also allowed $\Rightarrow$ electron appearance. To conserve electric charge, a positron must appear $\Rightarrow$ creation of an $e^+e^-$ pair.

$\Rightarrow$ empty electron negative–energy states describe positive energy states of the positron

Dirac’s perfect vacuum: a region where all positive-energy states are empty and all negative-energy states are full.

**Positron magnetic dipole moment** = $\mu_e$ but oriented parallel to positron spin
Experimental Observation of Anti-matter

Production of an ep pair by a high-energy photon in a Pb plate

Cosmic-ray “shower” containing several $e^+ e^-$ pairs

63 MeV positron

6 mm thick Pb plate
Theory of $\beta$-decay (E. Fermi, 1932-33)

$\beta^-$ decay: $n \rightarrow p + e^- + \bar{\nu}$

$\beta^+$ decay: $p \rightarrow n + e^+ + \nu$ (e.g., $^{14}O_8 \rightarrow ^{14}N_7 + e^+ + \nu$)

$\nu$: the particle proposed by Pauli
   (named “neutrino” by Fermi)
$\bar{\nu}$: its antiparticle (antineutrino)

Fermi’s theory: a point interaction among four spin ½ particles, using
the mathematical formalism of creation and annihilation
operators invented by Jordan
$\Rightarrow$ particles emitted in $\beta$ – decay need not exist before emission –
they are “created” at the instant of decay

Prediction of $\beta$ – decay rates and electron energy spectra as a function of
only one parameter: Fermi coupling constant $G_F$ (determined from experiments)

Energy spectrum dependence on neutrino mass $\mu$
(from Fermi’s original article, published in German
on Zeitschrift für Physik, following rejection of the
English version by Nature)

Measurable distortions for $\mu > 0$ near the end-point
($E_0$: max. allowed electron energy)
**Particle interactions** (as known until the mid 1960’s)

In order of increasing strength:

- **Gravitational interaction (all particles)**
  Totally negligible in particle physics
  Example: static force between electron and proton at distance $D$

  Gravitational: $f_G = G_N \frac{m_e m_p}{D^2}$
  Electrostatic: $f_E = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{D^2}$

  Ratio $f_G / f_E \sim 4.4 \times 10^{-40}$

- **Weak interaction (all particles except photons)**
  Responsible for $\beta$ decay and for slow nuclear fusion reactions in the star core
  Example: in the core of the Sun ($T = 15.6 \times 10^6$ °K) $4p \rightarrow ^4\text{He} + 2e^+ + 2\nu$
  Solar neutrino emission rate $\sim 1.84 \times 10^{38}$ neutrinos / s
  Flux of solar neutrinos on Earth $\sim 6.4 \times 10^{10}$ neutrinos cm$^{-2}$ s$^{-1}$
  Very small interaction radius $R_{\text{int}}$ (max. distance at which two particles interact)
  ($R_{\text{int}} = 0$ in the original formulation of Fermi’s theory)

- **Electromagnetic interaction (all charged particles)**
  Responsible for chemical reactions, light emission from atoms, etc.
  Infinite interaction radius
  (example: the interaction between electrons in transmitting and receiving antennas)
Strong interaction (neutron, proton, .... NOT THE ELECTRON !)
Responsible for keeping protons and neutrons together in the atomic nucleus
Independent of electric charge
Interaction radius $R_{\text{int}} \approx 10^{-13}$ cm

In Relativistic Quantum Mechanics static fields of forces DO NOT EXIST; the interaction between two particles is “transmitted” by intermediate particles acting as “interaction carriers”

The photon ($\gamma$) is the carrier of the electromagnetic interaction

In the electron – proton centre-of-mass system

Energy – momentum conservation:

\[ E_\gamma = 0 \]
\[ \not{p}_\gamma = \not{p} - \not{p}' \quad (|\not{p}| = |\not{p}'|) \]

“Mass” of the intermediate photon: $Q^2 = E_\gamma^2 - p_\gamma^2 c^2 = -2 p^2 c^2 (1 - \cos \theta)$

The photon is in a VIRTUAL state because for real photons $E_\gamma^2 - p_\gamma^2 c^2 = 0$ (the mass of real photons is ZERO) – virtual photons can only exist for a very short time interval thanks to the “Uncertainty Principle”
The Uncertainty Principle

**CLASSICAL MECHANICS**
Position and momentum of a particle can be measured independently and simultaneously with arbitrary precision

**QUANTUM MECHANICS**
Measurement perturbs the particle state \( \Rightarrow \) position and momentum measurements are correlated:

\[
\Delta x \Delta p_x \approx \hbar
\]

(also for \( y \) and \( z \) components)

Similar correlation for energy and time measurements:

\[
\Delta E \Delta t \approx \hbar
\]

Quantum Mechanics allows a violation of energy conservation by an amount \( \Delta E \) for a short time \( \Delta t \approx \hbar / \Delta E \)

Numerical example: \( \Delta E = 1 \text{ MeV} \iff \Delta t \approx 6.6 \times 10^{-22} \text{ s} \)
CONSERVED QUANTUM NUMBERS

Why is the free proton stable?

Possible proton decay modes (allowed by all known conservation laws: energy – momentum, electric charge, angular momentum):

\[ p \rightarrow \pi^0 + e^+ \]
\[ p \rightarrow \pi^0 + \mu^+ \]
\[ p \rightarrow \pi^+ + \nu \]

\ldots .

No proton decay ever observed – the proton is STABLE

Limit on the proton mean life: \( \tau_p > 1.6 \times 10^{25} \) years

Invent a new quantum number: “Baryonic Number” \( B \)

\[ B = 1 \] for proton, neutron
\[ B = -1 \] for antiproton, antineutron
\[ B = 0 \] for \( e^\pm, \mu^\pm, \) neutrinos, mesons, photons

Require conservation of baryonic number in all particle processes:

\[ \sum_i B_i = \sum_f B_f \]

( \( i \): initial state particle; \( f \): final state particle)
Strangeness

Late 1940’s: discovery of a variety of heavier mesons (K – mesons) and baryons (“hyperons”) – studied in detail in the 1950’s at the new high-energy proton synchrotrons (the 3 GeV “cosmotron” at the Brookhaven National Lab and the 6 GeV Bevatron at Berkeley)

Examples of mass values
Mesons (spin = 0): \( m(K^\pm) = 493.68 \text{ MeV}/c^2 \); \( m(K^0) = 497.67 \text{ MeV}/c^2 \)

Hyperons (spin = 1/2): \( m(\Lambda) = 1115.7 \text{ MeV}/c^2 \); \( m(\Sigma^\pm) = 1189.4 \text{ MeV}/c^2 \)
\[ m(\Xi^0) = 1314.8 \text{ MeV}/c^2; \quad m(\Xi^-) = 1321.3 \text{ MeV}/c^2 \]

Properties

- Abundant production in proton – nucleus, \( \pi \) – nucleus collisions
- Production cross-section typical of strong interactions (\( \sigma > 10^{-27} \text{ cm}^2 \))
- Production in pairs (example: \( \pi^- + p \rightarrow K^0 + \Lambda; \ K^- + p \rightarrow \Xi^- + K^+ \))
- Decaying to lighter particles with mean life values \( 10^{-8} \) – \( 10^{-10} \) s (as expected for a weak decay)

Examples of decay modes
\( K^\pm \rightarrow \pi^\pm \pi^0 \); \( K^\pm \rightarrow \pi^\pm \pi^0 \pi^- \); \( K^\pm \rightarrow \pi^\pm \pi^0 \pi^0 \); \( K^0 \rightarrow \pi^+ \pi^- \); \( K^0 \rightarrow \pi^0 \pi^0 \); . . .
\( \Lambda \rightarrow p \pi^- \); \( \Lambda \rightarrow n \pi^0 \); \( \Sigma^+ \rightarrow p \pi^0 \); \( \Sigma^+ \rightarrow n \pi^+ \); \( \Sigma^+ \rightarrow n \pi^- \); . . .
\( \Xi^- \rightarrow \Lambda \pi^- \); \( \Xi^0 \rightarrow \Lambda \pi^0 \)
Invention of a new, additive quantum number “Strangeness” (S)  
(Gell-Mann, Nakano, Nishijima, 1953)

- **conserved in strong interaction processes:** \[ \sum_i S_i = \sum_f S_f \]

- **not conserved in weak decays:** \[ S_i - \sum_f S_f = 1 \]

\( S = +1: K^+, K^\circ; \quad S = -1: \Lambda, \Sigma^\pm, \Sigma^\circ; \quad S = -2: \Xi^\circ, \Xi^-; \quad S = 0: \) all other particles  
(and opposite strangeness \(-S\) for the corresponding antiparticles)

Example of a \( K^- \) stopping in liquid hydrogen:  
\( K^- + p \rightarrow \Lambda + \pi^\circ \)  
(strangeness conserving)  
followed by the decay  
\( \Lambda \rightarrow p + \pi^- \)  
(strangeness violation)
THE “STATIC” QUARK MODEL

Late 1950’s – early 1960’s: discovery of many strongly interacting particles at the high energy proton accelerators (Berkeley Bevatron, BNL AGS, CERN PS), all with very short mean life times ($10^{-20} – 10^{-23}$ s, typical of strong decays) ⇒ catalog of $> 100$ strongly interacting particles (collectively named “hadrons”)

ARE HADRONS ELEMENTARY PARTICLES?

1964 (Gell-Mann, Zweig): Hadron classification into “families”; observation that all hadrons could be built from three spin $\frac{1}{2}$ “building blocks” (named “quarks” by Gell-Mann):

<table>
<thead>
<tr>
<th></th>
<th>$u$</th>
<th>$d$</th>
<th>$s$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric charge ($</td>
<td>e</td>
<td>$)</td>
<td>$+\frac{2}{3}$</td>
</tr>
<tr>
<td>Baryonic number</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
<td>$\frac{1}{3}$</td>
</tr>
<tr>
<td>Strangeness</td>
<td>$0$</td>
<td>$0$</td>
<td>$-1$</td>
</tr>
</tbody>
</table>

and three antiquarks ($\bar{u}$, $\bar{d}$, $\bar{s}$) with opposite electric charge and opposite baryonic number and strangeness
Mesons: quark – antiquark pairs

Examples of non-strange mesons:
\[ \pi^+ \equiv u\bar{d} \quad ; \quad \pi^- \equiv \bar{u}d \quad ; \quad \pi^0 \equiv (d\bar{d} - u\bar{u})/\sqrt{2} \]

Examples of strange mesons:
\[ K^- \equiv s\bar{u} \quad ; \quad K^0 \equiv s\bar{d} \quad ; \quad K^+ \equiv \bar{s}u \quad ; \quad K^0 \equiv \bar{s}d \]

Baryons: three quarks bound together
Antibaryons: three antiquarks bound together

Examples of non-strange baryons:
proton \equiv uud \quad ; \quad neutron \equiv udd

Examples of strangeness \(-1\) baryons:
\[ \Sigma^+ \equiv suu \quad ; \quad \Sigma^0 \equiv sud \quad ; \quad \Sigma^- \equiv sdd \]

Examples of strangeness \(-2\) baryons:
\[ \Xi^0 \equiv ssu \quad ; \quad \Xi^- \equiv ssd \]
Prediction and discovery of the $\Omega^-$ particle

A success of the static quark model

The “decuplet” of spin $\frac{3}{2}$ baryons

<table>
<thead>
<tr>
<th>Strangeness</th>
<th>$N^{*++}_{uuu}$</th>
<th>$N^{*+}_{uud}$</th>
<th>$N^{*0}_{udd}$</th>
<th>$N^{*-}_{ddd}$</th>
<th>Mass (MeV/c$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N*++ uu</td>
<td>N*+ uud</td>
<td>N*0 udd</td>
<td>N*– ddd</td>
<td>1232</td>
</tr>
<tr>
<td>−1</td>
<td>Σ*+ su</td>
<td>Σ*0 sud</td>
<td>Σ*– sdd</td>
<td></td>
<td>1384</td>
</tr>
<tr>
<td>−2</td>
<td>Ξ*0 ssu</td>
<td>Ξ*– ssd</td>
<td></td>
<td></td>
<td>1533</td>
</tr>
<tr>
<td>−3</td>
<td>Ω$^-$ sss</td>
<td></td>
<td></td>
<td></td>
<td>1672 (predicted)</td>
</tr>
</tbody>
</table>

$\Omega^-$: the bound state of three $s$ – quarks with the lowest mass with total angular momentum = $3/2$  

Pauli’s exclusion principle requires that the three quarks cannot be identical
The first $\Omega^-$ event (observed in the 2 m liquid hydrogen bubble chamber at BNL using a 5 GeV/c K$^-$ beam from the 30 GeV AGS)

Chain of events in the picture:

$K^- + p \rightarrow \Omega^- + K^+ + K^0$  
(strangeness conserving)

$\Omega^- \rightarrow \Sigma^0 + \pi^-$  
($\Delta S = 1$ weak decay)

$\Sigma^0 \rightarrow \pi^0 + \Lambda$  
($\Delta S = 1$ weak decay)

$\Lambda \rightarrow \pi^- + p$  
($\Delta S = 1$ weak decay)

$\pi^0 \rightarrow \gamma + \gamma$  
(electromagnetic decay)  
with both $\gamma$ – rays converting to an $e^+e^-$ in liquid hydrogen  
(very lucky event, because the mean free path for $\gamma \rightarrow e^+e^-$ in liquid hydrogen is ~10 m)

$\Omega^-$ mass measured from this event = $1686 \pm 12$ MeV/$c^2$
“DYNAMIC” EVIDENCE FOR QUARKS


The modern version of Rutherford’s original experiment: resolving power ≈ wavelength associated with 20 GeV electron ≈ 10^{-15} \text{ cm}

Three magnetic spectrometers to detect the scattered electron:
- 20 GeV spectrometer (to study elastic scattering e^- + p \rightarrow e^- + p)
- 8 GeV spectrometer (to study inelastic scattering e^- + p \rightarrow e^- + hadrons)
- 1.6 GeV spectrometer (to study extremely inelastic collisions)
The Stanford two-mile electron linear accelerator (SLAC)

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Electron elastic scattering from a point-like charge $|e|$ at high energies: differential cross-section in the collision centre-of-mass (Mott’s formula)

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 (\hbar c)^2 \cos^2 (\theta/2)}{8E^2 \sin^4 (\theta/2)} \equiv \sigma_M$$

$$\alpha = \frac{e^2}{\hbar c} \approx \frac{1}{137}$$

Scattering from an extended charge distribution: multiply $\sigma_M$ by a “form factor”:

$$\frac{d\sigma}{d\Omega} = F(|Q^2|)\sigma_M$$

$|Q| = \hbar / D$ : mass of the exchanged virtual photon
$D$: linear size of target region contributing to scattering
Increasing $|Q|$ $\Rightarrow$ decreasing target electric charge

$F(|Q^2|) = 1$ for a point-like particle
$\Rightarrow$ the proton is not a point-like particle
Inelastic electron – proton collisions

Incident electron \( (E_e, p) \)

Scattered electron \( (E_e', p') \)

Total hadronic energy:
\[
W^2 = \left( \sum_i E_i \right)^2 - \left( \sum_i \vec{p}_i \right)^2 \]

For deeply inelastic collisions,
the cross-section depends only weakly on \(|Q^2|\), suggesting a collision with a POINT-LIKE object.
PHYSICS WITH $e^+e^-$ COLLIDERS

Two beams circulating in opposite directions in the same magnetic ring and colliding head-on

\[ \begin{array}{c}
\text{e}^+ \\
E, \vec{p}
\end{array} \quad \begin{array}{c}
\text{e}^- \\
E, -\vec{p}
\end{array} \]

A two-step process: $e^+ + e^- \rightarrow \text{virtual photon} \rightarrow f + \overline{f}$

$f$: any electrically charged elementary spin $\frac{1}{2}$ particle ($\mu$, quark)
(excluding $e^+e^-$ elastic scattering)

Virtual photon energy – momentum: $E_\gamma = 2E$, $p_\gamma = 0 \Rightarrow Q^2 = E_\gamma^2 - p_\gamma^2c^2 = 4E^2$

Cross-section for $e^+e^- \rightarrow f \overline{f}$:

\[ \sigma = \frac{2\pi\alpha^2\hbar^2c^2}{3Q^2} e_f^2 \beta (3 - \beta) \]

$\alpha = e^2/(hc) \approx 1/137$
$e_f$: electric charge of particle f (units $|e|$)
$\beta = v/c$ of outgoing particle $f$

(formula precisely verified for $e^+e^- \rightarrow \mu^+\mu^-$)

Assumption: $e^+e^- \rightarrow \text{quark (q) + antiquark (}\overline{q}) \rightarrow \text{hadrons}$
$\Rightarrow$ at energies $E >> m_qc^2$ (for $q = u, d, s$) $\beta \approx 1$:

\[ R \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)} = e_u^2 + e_d^2 + e_s^2 = \frac{4}{9} + \frac{1}{9} + \frac{1}{9} = \frac{2}{3} \]
Experimental results from the Stanford $e^+e^-$ collider SPEAR (1974–75):

For $Q < 3.6 \text{ GeV}$, $R \approx 2$. If each quark exists in three different states, $R \approx 2$ is consistent with $3 \times (2/3)$. This would solve the $\Omega^-$ problem.

Between 3 and 4.5 GeV, the peaks and structures are due to the production of quark-antiquark bound states and resonances of a fourth quark (“charm”, $c$) of electric charge +2/3.

Above 4.6 GeV, $R \approx 4.3$. Expect $R \approx 2$ (from $u, d, s$) + $3 \times (4/9) = 3.3$ from the addition of the $c$ quark alone. So the data suggest pair production of an additional elementary spin ½ particle with electric charge = 1 (later identified as the $\tau$–lepton (no strong interaction) with mass $\approx 1777 \text{ MeV}/c^2$).
Evidence for production of pairs of heavy leptons $\tau^{\pm}$
1962-66: Formulation of a Unified Electroweak Theory  
(Glashow, Salam, Weinberg)

4 intermediate spin 1 interaction carriers (“bosons”):

- the photon ($\gamma$)  
  responsible for all electromagnetic processes

- three weak, heavy bosons $W^+$ $W^-$ $Z$  
  $W^\pm$ responsible for processes with electric charge transfer $= \pm 1$  
  (Charged Current processes)

  Examples:
  $n \rightarrow p$ $e^- \bar{\nu}$ : $n \rightarrow p$ $W^-$ followed by $W^- \rightarrow e^- \bar{\nu}$
  $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ : $\mu^+ \rightarrow \bar{\nu}_\mu$ $W^+$ followed by $W^+ \rightarrow e^+ \nu_e$

- $Z$ responsible for weak processes with no electric charge transfer  
  (Neutral Current processes)  
  PROCESSES NEVER OBSERVED BEFORE  
  Require neutrino beams to search for these processes, to remove  
  the much larger electromagnetic effects expected with charged  
  particle beams
First observation of Neutral Current processes in the heavy liquid bubble chamber Gargamelle at the CERN PS (1973)

Example of
\[ \nu_\mu + e^- \rightarrow \nu_\mu + e^- \]
(elastic scattering)
Recoil electron energy = 400 MeV
(\( \bar{\nu}_\mu \) beam from \( \pi^- \) decay in flight)

Example of
\[ \nu_\mu + p (n) \rightarrow \nu_\mu + \text{hadrons} \]
(inelastic interaction)
(\( \nu_\mu \) beam from \( \pi^+ \) decay in flight)
Measured rates of Neutral Current events ⇒ estimate of the W and Z masses (not very accurately, because of the small number of events):

$$M_W \approx 70 - 90 \text{ GeV}/c^2 \; ; \; M_Z \approx 80 - 100 \text{ GeV}/c^2$$

too high to be produced at any accelerator in operation in the 1970’s

1975: Proposal to transform the new 450 GeV CERN proton synchrotron (SPS) into a proton – antiproton collider (C. Rubbia)

Beam energy = 315 GeV ⇒ total energy in the centre-of-mass = 630 GeV

Beam energy necessary to achieve the same collision energy on a proton at rest:

$$(E + m_p c^2)^2 - p^2 c^2 = (630 \text{ GeV})^2 \quad \Rightarrow \quad E = 210 \text{ TeV}$$

Production of W and Z by quark – antiquark annihilation:

$$u + \bar{d} \, \rightarrow \, W^+ \quad \quad \bar{u} + d \, \rightarrow \, W^-$$

$$u + \bar{u} \, \rightarrow \, Z \quad \quad d + \bar{d} \, \rightarrow \, Z$$
UA1 and UA2 experiments (1981 – 1990)
Search for $W^\pm \rightarrow e^\pm + \nu$ (UA1, UA2) ; $W^\pm \rightarrow \mu^\pm + \nu$ (UA1)
$Z \rightarrow e^+e^-$ (UA1, UA2) ; $Z \rightarrow \mu^+ \mu^-$ (UA1)

**UA1**: magnetic volume with trackers, surrounded by “hermetic” calorimeter and muon detectors

**UA2**: non-magnetic, calorimetric detector with inner tracker
One of the first $W \rightarrow e + \nu$ events in UA1
UA2 final results

Events containing two high-energy electrons:
Distributions of the “invariant mass” $M_{ee}$

$$(M_{ee}c^2)^2 = (E_1 + E_2)^2 - (\vec{p}_1 + \vec{p}_2)^2 c^2$$

(for $Z \rightarrow e^+e^-$ $M_{ee} = M_Z$)

$Z$ Boson

$W$ Boson

Events containing a single electron with large transverse momentum (momentum component perpendicular to the beam axis) and large missing transverse momentum (apparent violation of momentum conservation due to the escaping neutrino from $W \rightarrow ev$ decay)

$m_T$ (“transverse mass”): invariant mass of the electron – neutrino pair calculated from the transverse components only

$M_W$ is determined from a fit to the $m_T$ distribution: $M_W = 80.35 \pm 0.37$ GeV/c$^2$
$e^+e^-\text{ colliders at higher energies}$

$$R = \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

between 0.3 and 200 GeV

$Q = 2E$ (GeV)

$e^+e^- \rightarrow b \overline{b}$

(the 5th quark: $e = -1/3$)

$e^+e^- \rightarrow Z \rightarrow q \overline{q}$
STANDARD MODEL

The elementary particles today:

3 x 6 = 18 quarks
+ 6 leptons
= 24 fermions (constituents of matter)
+ 24 antiparticles
48 elementary particles
consistent with point-like dimensions within the resolving power of present instrumentation
(~ 10^{-16} cm)

12 force carriers (\gamma, W^\pm, Z, 8 gluons)

+ the Higgs spin 0 particle (NOT YET DISCOVERED)
responsible for generating the masses of all particles
The LEP 1989 - 2000

- The Large Electron-Positron Collider (LEP) at CERN provided the precision tests of electroweak theory:
  - LEP1 (1989-1995): $\sqrt{s} \sim m_Z \rightarrow 2 \times 10^7 Z$ recorded, number of $\gamma$
  - LEP2 (1996-2000): $\sqrt{s} \rightarrow 209 \text{ GeV} \rightarrow WW$
    production, $m_W$, TGC
  - search for Higgs and new particles
- Shutdown in 2000 to give way for the construction of LHC
- Small excess of events around $M_H \approx 115 \text{ GeV}$
  $$e^+e^- \rightarrow ZH \text{ with } H \rightarrow bb$$

Precision Tests of Electroweak Physics
Measured observables:

- $m_Z$, $\Gamma_Z$
- $Z$ production cross-section
- all properties of $Z$ couplings to fermions
- decay modes, angular distributions

Achieved precision: better than $10^{-3}$

WHY precision tests of the SM at high energy?
The precise measurement of top quark mass helps to narrow down the mass range for Higgs search.

Radiative corrections depends on precise determination of electroweak parameters

Today $M_W$ is known to a precision of 0.05%

$M_{\text{top}}$ is known to a precision of 3%

\[ \sim m_{\text{top}}^2 \quad \sim \log m_H \]
W-Boson Mass [GeV]

TEVATRON  
80.432 ± 0.039

LEP2  
80.376 ± 0.033

Average  
80.399 ± 0.025  
$\chi^2$/DoF: 1.2 / 1

NuTeV  
80.136 ± 0.084

LEP1/SLD  
80.363 ± 0.032

LEP1/SLD/$m_t$  
80.364 ± 0.020

$m_W$ [GeV]
Top Quark

- In 1994 from electroweak data assuming $M_H = 300$ GeV, $M_{\text{top}} = 178 \pm 11$ GeV
- First measurement of top mass at Tevatron by D0 & CDF $M_{\text{top}} = 180 \pm 12$ GeV
- Lepton+Jet channel was used.
- Production X-sec of ttbar at 1.8 TeV = 5.7 pb
- Properties of top quark:
  - Charge $2/3$ e
  - Spin 1/2
  - Color triplet
  - Weak isospin partner of b quark $T_3 = 1/2$
• Why top quark should exist?
  – Theoretical consistency of SM
    • Anomaly Cancellation
    • Consistency of b quark measurements with the SM.
  – Consistency of precision measurements.
• Top quark was discovered in 1995 at Tevatron Run I with:
  \[ m_t = 174.3 \pm 5.1 \text{ GeV} \]
  \[ \sigma_{tt} = 5.9 \pm 1.7 \text{ pb} \]

2004 (D0) : \[ m_t = 178 \pm 4.3 \text{ GeV} \]
• **Interesting points about Top:**
  - Heaviest known elementary particle.
  - $\tau_+ = 4 \times 10^{-25}$ s
  - $\tau_{\text{had}} = 28 \times 10^{-25}$ s
  - Production & decay vertices $10^{-16}$ m
  - $m_+ > \Lambda_{\text{qcd}} \approx 200$ MeV
  - Perturbative QCD can be applied.
  - $m_+$ is very close to EWSB scale. $\langle \Phi \rangle = 246.21$ GeV
  - Yukawa coupling is close to 1. ($m_+ = G_f \langle \Phi \rangle / \sqrt{2}$)
  - Due to large mass of top, $\beta < 0.5$, little boost
    - Decay products
      - Good Angular Separation, High momenta
      - Central region of the detector with high $p_T$
Production of Top

Pair Production

Single Top Production
Decay modes of top

Semi leptonic decay mode of t\bar{t}

Purely leptonic decay mode of t\bar{t}

Purely hadronic decay mode of t\bar{t}
## Top Pair Decay Channels

<table>
<thead>
<tr>
<th>Decays</th>
<th>Electron+Jets</th>
<th>Muon+Jets</th>
<th>Tau+Jets</th>
<th>All-Hadronic</th>
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<tr>
<td>$\bar{c}s$</td>
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</tr>
<tr>
<td>$\bar{u}d$</td>
<td>electron+jets</td>
<td>muon+jets</td>
<td>tau+jets</td>
<td>all-hadronic</td>
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<tr>
<td>$e^-$</td>
<td>$e^-$</td>
<td>$\mu^-$</td>
<td>$\tau^-$</td>
<td>tau+jets</td>
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<td>$\mu^-$</td>
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<td>muon+jets</td>
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<td>$e^-$</td>
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<tr>
<td>$W$ decay</td>
<td>$e^+$</td>
<td>$\mu^+$</td>
<td>$\tau^+$</td>
<td>$u\bar{d}$</td>
</tr>
</tbody>
</table>
Decay of Top Quark

\[ W^+ W^- b \bar{b} \]

\[ t \rightarrow \text{Jet1, Jet2} \]

\[ W^+ \rightarrow e^- \nu_e \]

\[ W^- \rightarrow e^+ \nu_e \]

\[ t \rightarrow W^+ \nu_e \]

\[ t \rightarrow b \bar{b} \]

\[ t \rightarrow W^- \]

\[ t \rightarrow b \bar{b} \]

\[ t \rightarrow W^+ \nu_e \]

\[ t \rightarrow W^- \]

\[ t \rightarrow b \bar{b} \]

\[ t \rightarrow W^+ \nu_e \]

\[ t \rightarrow W^- \]

\[ t \rightarrow b \bar{b} \]

\[ t \rightarrow W^+ \nu_e \]

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\[ t \rightarrow W^- \]

\[ t \rightarrow b \bar{b} \]

\[ t \rightarrow W^+ \nu_e \]

\[ t \rightarrow W^- \]

\[ t \rightarrow b \bar{b} \]

\[ t \rightarrow W^+ \nu_e \]
Top-Quark Mass [GeV]

CDF: 172.4 ± 1.5
DØ: 174.3 ± 1.7
Average: 173.1 ± 1.3
\(\chi^2/\text{DoF}: 6.3 / 10\)

LEP1/SLD: 172.6 ± 13.3
LEP1/SLD/m_W/\Gamma_W: 178.9 ± 11.7

March 2009
Fit to Electroweak Data

• Number of electroweak parameters are very precisely measured and reported by LEPEW Group.

• Measurement of 20 separate quantities

• Fits are made to ensemble of all these electroweak data

• Measured value plus one σ is used e.g. $\Gamma_Z \pm \delta \Gamma_Z$

• $\chi^2 = \frac{[\Gamma_Z(M) - \Gamma_Z(SM)]^2}{\delta \Gamma_Z}$ is formed

• $\chi^2$ is minimized w.r.t. $M_t$ and $M_H$ and the best fitted values are extracted
<table>
<thead>
<tr>
<th>Measurement</th>
<th>Fit</th>
<th></th>
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<th>O_{meas}</th>
<th>O_{fit}</th>
<th>\sigma_{meas}</th>
</tr>
</thead>
<tbody>
<tr>
<td>\Delta a_{had}^{(6)}(m_{Z})</td>
<td>0.02758 ± 0.00035</td>
<td>0.02767</td>
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<tr>
<td>m_{Z} [GeV]</td>
<td>91.1875 ± 0.0021</td>
<td>91.1874</td>
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<tr>
<td>\Gamma_{Z} [GeV]</td>
<td>2.4952 ± 0.0023</td>
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<td>\sigma_{had} [nb]</td>
<td>41.540 ± 0.037</td>
<td>41.478</td>
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<tr>
<td>R_{l}</td>
<td>20.767 ± 0.025</td>
<td>20.742</td>
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<tr>
<td>A_{fb}^{0,1}</td>
<td>0.01714 ± 0.00095</td>
<td>0.01643</td>
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<tr>
<td>A_{l}(P_{T})</td>
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<tr>
<td>R_{b}</td>
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<tr>
<td>R_{c}</td>
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<tr>
<td>A_{fb}^{0,b}</td>
<td>0.0992 ± 0.0016</td>
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<td>A_{tb}^{0,c}</td>
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<tr>
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<tr>
<td>A_{c}</td>
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<td>A_{l}(SLD)</td>
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<tr>
<td>\sin^{2}\theta_{\text{eff}}(Q_{fb})</td>
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<tr>
<td>m_{W} [GeV]</td>
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<tr>
<td>\Gamma_{W} [GeV]</td>
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<tr>
<td>m_{l} [GeV]</td>
<td>173.1 ± 1.3</td>
<td>173.2</td>
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</tbody>
</table>

March 2009
To constrain the mass of Higgs particle
- $M_w$, known with a high precision
- $M_t$, is poorly known, higher precision will help
Higgs Mass

- Higgs mass is excluded through direct searches as follows:
  - \( M_H \leq 114 \text{ GeV}, \ 160 \leq M_H \leq 170 \text{ GeV} \)
- Using direct top-quark measurement: from the fit one obtains \( M_H = 92^{+60}_{-38} \text{ GeV} \)
- Excluding direct top-quark mass measurement:
  \[ M_H = 92^{+130}_{-48} \text{ GeV} \]