High Energy Physics:
An Overview of Objectives, Challenges and Outlooks

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Outline

Introduction

Objectives:

- Elementary Particles
- Fundamental Forces
- Unification

Means and Techniques:

- Experimental
- Theoretical

Strong Interaction

- Hadrons, and their Strong Interaction
- Models for the Physics of Hadrons

Future Outlooks
Introduction:

- What is an elementary particle?
Introduction:

- What is an elementary Particle?
  A particle that is not consist of other particles
Introduction:

- What is an elementary Particle?
  A particle that is not consist of other particles

Ex. Water molecule is NOT elementary
Introduction:

- What is an elementary Particle?
  A particle that is not consist of other particles

  Ex. Water molecule is NOT elementary

Atoms and molecules are not elementary.
General structure of atoms:
General structure of atoms:
General structure of atoms:

- **Electron**
- **Nucleus**
- **Quarks**
General structure of atoms:

Quarks

Nucleus

Electron

Photon

Electron
Elementary Particles:

- Quarks (S=1/2)
- Leptons (S=1/2)
- Gauge Bosons (S=1)
Elementary Particles:

- **Quarks (S=1/2):**

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Charge (e)</th>
<th>Mass (MeV/C^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>2/3</td>
<td>&lt; 10 200 - 400</td>
</tr>
<tr>
<td>d</td>
<td>-1/3</td>
<td>&lt; 15 200 - 400</td>
</tr>
<tr>
<td>s</td>
<td>-1/3</td>
<td>100-300 200 - 400</td>
</tr>
<tr>
<td>c</td>
<td>2/3</td>
<td>~ 1,500</td>
</tr>
<tr>
<td>b</td>
<td>-1/3</td>
<td>~ 5,200</td>
</tr>
<tr>
<td>t</td>
<td>2/3</td>
<td>~ 180,000</td>
</tr>
</tbody>
</table>

- **Leptons (S=1/2):**

- **Gauge Bosons (S=1):**

- **Quarks:** (not explicitly listed in the table)
**Elementary Particles:**

- **Quarks (S=1/2)**
- **Leptons (S=1/2)**
- **Gauge Bosons (S=1)**

- **Leptons:**

<table>
<thead>
<tr>
<th>Charge (e)</th>
<th>Mass (MeV/C^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>-1</td>
</tr>
<tr>
<td>(\nu_e)</td>
<td>0</td>
</tr>
<tr>
<td>(\mu)</td>
<td>-1</td>
</tr>
<tr>
<td>(\nu_\mu)</td>
<td>0</td>
</tr>
<tr>
<td>(\tau)</td>
<td>-1</td>
</tr>
<tr>
<td>(\nu_\tau)</td>
<td>0</td>
</tr>
</tbody>
</table>
Elementary Particles:

- Quarks ($S=1/2$)
- Leptons ($S=1/2$)
- Gauge Bosons ($S=1$)

Gauge Bosons:

<table>
<thead>
<tr>
<th>Charge (e)</th>
<th>Mass (MeV/C$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Photons</td>
<td>0</td>
</tr>
<tr>
<td>$W^{+(-)}$</td>
<td>+1 (-1)</td>
</tr>
<tr>
<td>Z</td>
<td>0</td>
</tr>
<tr>
<td>Gluons</td>
<td>0</td>
</tr>
</tbody>
</table>
Fundamental Forces:

- Gravitational \( (10^{-39}) \)
- Electromagnetic \( (1) \)
- Weak \( (10^{-11}) \)
- Strong \( (10^3) \)
Objectives of HEP:

- Identify and classify the elementary particles
- Understand the fundamental forces among the elementary particles
- Unify the fundamental forces into a single theory: “Theory of Everything”
Gravitational

Electromagnetic
  Weak

Nuclear
  Strong
Gravitational
Electromagnetic
Weak
Nuclear
Strong

Electricity + Magnetism
Maxwell (1865)
Gravitational
Electromagnetic
Weak
Nuclear
Strong

Electricity + Magnetism
Maxwell (1865)

Glashow, Salam, Weinberg
Nobel prize (1979)

Electroweak
Gravitational
Electromagnetic
Weak
Nuclear
Strong

Electricity + Magnetism
Maxwell (1865)

Electroweak

GUTs

Glashow, Salam, Weinberg
Nobel prize (1979)
Gravitational
Electromagnetic
Weak
Nuclear
Strong

Electricity + Magnetism
Maxwell (1865)

Electroweak

GUTs
TOE

Glashow, Salam, Weinberg
Nobel prize (1979)
Means and Techniques of HEP:

- **Experimental:**
  
  Particles are accelerated and collided at high speeds (comparable to the speed of light)
Detector:
Approx. 10 m high
Several thousands of tones

Approx. 5.3 mi
Other facts about CERN

“WWW invented at CERN”

Initial accelerator LEP e- e+
Next (2005) LHC p p (~14 TeV) for 10-15 yrs

Involves Approx. 6,000 physicists from around the world

Main goals: Z, W+/-, Higgs, SUSY particles

LHC material cost: approx. $2 Billion
Annual cost: approx. $600 M
LHC detectors: ATLAS and CMS ($300 M each)
Energy (GeV)

Electroweak

GUTs

String

Planck Mass
Energy (GeV)

SUSY ?

GUTs

String

Planck Mass

Electroweak

Tevatron Fermi Lab

LHC

Higgs ?

Large Extra Dimensions ?

Electroweak
Means and Techniques of HEP:

- **Theoretical:**
  What is going on here
Physics

Classical

Quantum

Relativistic

Statistical

Relativistic Quantum Mechanics
Classical Quantum Relativistic Statistical Physics

Relativistic Quantum Mechanics + Creation and Annihilation
Physics

Classical  Quantum  Relativistic  Statistical

Relativistic Quantum Mechanics + Creation and Annihilation

Quantum Field Theory
Strong Interaction:

- Bounds protons and neutrons inside the nucleus
Strong Interaction:

- Bounds protons and neutrons inside the nucleus
- Protons and neutrons $\in$ Hadrons
  \[
  \text{Hadrons} = \begin{cases} 
  \text{Baryons} (s = \frac{1}{2}, \ldots) \\
  \text{Mesons} (s=0,1,\ldots)
  \end{cases}
  \]
Simplest internal structure of hadrons in terms of quarks:

**Baryons:**  \( QQQ \)
Simplest internal structure of hadrons in terms of quarks:

**Baryons:** QQQ

- p : uud
  - charge = $2(2/3e) + (-1/3e) = e$
- n : udd
  - charge = $(2/3e) + 2 (-1/3e) = 0$
Simplest internal structure of hadrons in terms of quarks:

**Baryons:**  \( \text{QQQ} \)

- \( p : \text{uud} \)
  - charge = \( 2(2/3e) + (-1/3e) = e \)
- \( n : \text{udd} \)
  - charge = \( (2/3e) + 2(-1/3e) = 0 \)

**Mesons:**  \( \text{QQ}^* \)
Simplest internal structure of hadrons in terms of quarks:

**Baryons:**  
QQQ

p : uud  
charge = $2 \left( \frac{2}{3} e \right) + \left( -\frac{1}{3} e \right) = e$

n : udd  
charge = $\left( \frac{2}{3} e \right) + 2 \left( -\frac{1}{3} e \right) = 0$

**Mesons:**  
QQ*

$\pi^+ : u \, d^*$  
charge = $\left( \frac{2}{3} e \right) + \left( \frac{1}{3} e \right) = e$
Exotic structure of hadrons:

**Baryons:** QQQQQQ*

*(Physics Today, Feb. 2004)*
Exotic structure of hadrons:

**Baryons:** \[QQQQQQ^*\]

*(Physics Today, Feb. 2004)*

**Mesons:** \[QQQ^*Q^*\]

Hybrid: \[...QQ^* ...QQQ^*Q^* ... G\]

Basic Properties of the Strong Interaction:

- **Confinement**: Quarks are bounded inside the hadrons (no free quarks)

- **Asymptotic Freedom**: The strength of the interaction decreases with energy
Coulomb’s Force:

\[ |F| = \frac{1}{4\pi\varepsilon} \frac{qQ}{r^2} \]
Coulomb’s Force:

\[ |F| = \frac{1}{(4\pi\varepsilon)} \frac{qQ}{r^2} \]
Strong Interaction:

Strength of interaction vs. energy

Experimental Observation
Physics Nobel Prize (1990)
Friedman, Kendall & Taylor

Theoretical Explanation
Gross, Politzer & Wilczek
Why are there two different types of mass for light quarks?

Low energy processes:

High energy processes:
The computational difficulty:

A simple description:

\[ F(a) = F(0) + F'(0) a + \frac{1}{2} F''(0) a^2 + \ldots \]
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A simple description:

\[ F(a) = F(0) + F'(0) a + \frac{1}{2} F''(0) a^2 + \ldots \]
Theory of Strong Interactions:

Quantum Chromodynamics (QCD)

Light Hadrons?

QCD is a non abelian gauge field theory based on the color quantum number of quarks.
**Effective theories**: Models that are formulated in terms of hadrons

- Chiral perturbation theory (< 500 MeV)
- Chiral Lagrangians (< 2 GeV)

**Lattice QCD**: Computes physical quantities by directly working with the quark fields

**QCD Sum-rules**: Provides a bridge between QCD and the physics of hadrons
Chiral Lagrangian probe of intermediate states:

Symmetries of the low energy strong interaction

Lagrangian

+ ...
Future Outlook:

A number of important experiments will be performed within the next 10-15 years.

Exciting directions for research in HEP, such as neutrino physics, CP violation, beyond the SM, SUSY, Higgs physics, …

Students can participate at different levels, from undergraduate projects to Ph.D. theses.
Appendix
Why should quarks have color?
Why should quarks have color?

Experiment:

$\Delta^{++}$:

Spin = 3/2
Charge = +2e

$\Delta^{++}$: U↑ U↑ U↑
Theory of Strong Interactions:

Light Hadrons

Quantum Chromodynamics (QCD)

energy
energy