Particle Zoo and Feynman Diagrams

Cristina Lazzeroni
Professor in Particle Physics
STFC Public Engagement Fellow

ASE Conference 2016
University of Birmingham
Muirhead 118
7th January 2016, 10:00-12:00
Particles accelerated to speed of light:

\[ E = mc^2 \]

Energy and mass are related, in general

\[ E^2 = p^2 + m_0^2 , \: c=1 \]

\[ (\text{Invariant mass})^2 = E^2 - (p_x^2 + p_y^2 + p_z^2) \]

Protons smashing together can produce all sorts of particles, seen in the earliest moments of the universe.
In 1969, an experiment at SLAC using a 2-mile long 20 billion eV electron accelerator showed that protons have structure → “quarks”

- Protons and neutrons made from Up (u) and Down (d) quarks.
- u-quarks have $+2/3$ of electron charge, d-quarks have $-1/3$
Discovery of Quarks

\( \gamma \) carries momentum

\[
\begin{align*}
\text{Large } \bar{p}, \text{ small } \lambda & \quad \bar{p} = \frac{\hbar}{\lambda} \\
\text{Large } E, \text{ large } \omega & \quad E = \hbar \omega
\end{align*}
\]

Wave-function oscillates rapidly in space and time \( \Rightarrow \) probes short distances and short time.

Rutherford Scattering

Excited states

Elastic scattering from quarks in proton

\( \lambda \ll \text{size of proton} \)
A Nice Happy Family of Particles

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass in Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up quark (u)</td>
<td>0.003</td>
</tr>
<tr>
<td>Down quark (d)</td>
<td>0.006</td>
</tr>
<tr>
<td>Electron (e-)</td>
<td>0.0005</td>
</tr>
<tr>
<td>Electron neutrino (νₑ)</td>
<td>10⁻⁸</td>
</tr>
</tbody>
</table>

Everything around us (the whole Periodic Table) is made of up quarks, down quarks and electrons. But the masses don’t add up....
... for some reason, there is more ...

Nature supplies us with a copy of the family but heavier ...
... and another copy of the family but even heavier ...

- **quarks**
  - up
  - charm
  - down
  - strange
  - beauty

- **leptons**
  - $e$
  - $\mu$
  - $\tau$
  - $\nu_e$
  - $\nu_\mu$
  - $\nu_\tau$
The Top Quark

Weighs about the same as a gold nucleus!

... and that is where it seems to stop

Top has no time to hadronize
Antimatter

1928: Paul Dirac put together Relativity with Quantum Mechanics into the theory of the electron ... it also predicted anti-electrons (‘positrons’)

Every fundamental fermion particle has an antiparticle, with the same mass, but opposite charge.

electron \( e^- \) \( e^+ \) positron

up quark \( u^{+2/3} \) \( \bar{u}^{-2/3} \) up anti-quark

etc etc ...
Antimatter

In unifying QM and Relativity, there is the need of negative-energy particles: antimatter
Gravitational Force  Electromagnetic Force

Isaac Newton  (1642 - 1727)

James Clerk Maxwell  (1831 - 1879)

Size of atoms is set by strength of EM force
How stars generate energy

**Weak Force**

Enrico Fermi (1901 - 1954)

radioactive decays

neutron decay

holding proton, nucleus

**Strong Force**

Size of nuclei is set by strength of strong force

enriched iron

epsilon particles

nucleus

gluons
### Bosons:
Force carriers
integer charge

### Leptons:
integer charge,
DON'T feel STRONG

### Quarks:
fractional charge
feel ALL forces

<table>
<thead>
<tr>
<th></th>
<th>LEPTONS</th>
<th>QUARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$q$</td>
<td>$m$/GeV</td>
</tr>
<tr>
<td><strong>First Generation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e^-$</td>
<td>$-1$</td>
<td>0.0005</td>
</tr>
<tr>
<td>$\nu_1$</td>
<td>0</td>
<td>$\approx 0$</td>
</tr>
<tr>
<td><strong>Second Generation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>$-1$</td>
<td>0.106</td>
</tr>
<tr>
<td>$\nu_2$</td>
<td>0</td>
<td>$\approx 0$</td>
</tr>
<tr>
<td><strong>Third Generation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau^-$</td>
<td>$-1$</td>
<td>1.77</td>
</tr>
<tr>
<td>$\nu_3$</td>
<td>0</td>
<td>$\approx 0$</td>
</tr>
</tbody>
</table>

### Force

<table>
<thead>
<tr>
<th>Force</th>
<th>Boson(s)</th>
<th>$m$/GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM (QED)</td>
<td>Photon $\gamma$</td>
<td>0</td>
</tr>
<tr>
<td>Weak</td>
<td>$W^\pm / Z$</td>
<td>80 / 91</td>
</tr>
<tr>
<td>Strong (QCD)</td>
<td>8 Gluons $g$</td>
<td>0</td>
</tr>
<tr>
<td>Gravity (?)</td>
<td>Graviton?</td>
<td>0</td>
</tr>
</tbody>
</table>
Forces

Quantum Mechanically: Forces arise due to exchange of VIRTUAL FIELD QUANTA

\[ \vec{F} \]

\[ Q_1 \quad \rightarrow \quad Q_1 \quad \rightarrow \quad -\Delta E \quad \sqrt{m^2 + \Delta E^2} \]

\[ \gamma \quad \frac{\Delta E}{\Delta E} \]

<table>
<thead>
<tr>
<th>Force</th>
<th>Boson</th>
<th>Strength</th>
<th>Mass (GeV/c^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Gluon</td>
<td>( g )</td>
<td>1</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Photon</td>
<td>( \gamma )</td>
<td>( 10^{-2} )</td>
</tr>
<tr>
<td>Weak</td>
<td>( W ) and ( Z )</td>
<td>( W^\pm, Z^0 )</td>
<td>( 10^{-7} )</td>
</tr>
<tr>
<td>Gravity</td>
<td>Graviton</td>
<td>?</td>
<td>( 10^{-39} )</td>
</tr>
</tbody>
</table>
Range of Forces

The range of a force is directly related to the mass of the exchanged bosons.

\[ \Delta E \Delta t \sim \hbar \quad E = mc^2 \]
\[ mc^2 \sim \frac{\hbar}{\Delta t} \sim \frac{\hbar c}{r} \]
\[ r \sim \frac{\hbar}{mc} \quad \hbar = c = 1 \text{ natural units} \]

1 fm distance at speed c means \(3 \times 10^{-23} \text{ s}\)

Uncertainty principle: \(E \sim 200 \text{ MeV}\) i.e. pion
Predicted in 1935; discovered in cosmic ray interactions in 1947

<table>
<thead>
<tr>
<th>Force</th>
<th>Range (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>(\infty)</td>
</tr>
<tr>
<td>Strong (Nuclear)</td>
<td>(10^{-15})</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>(\infty)</td>
</tr>
<tr>
<td>Weak</td>
<td>(10^{-18})</td>
</tr>
<tr>
<td>Gravity</td>
<td>(\infty)</td>
</tr>
</tbody>
</table>
Feynman diagrams
Feynman devised a pictorial method to evaluate probability of interaction between fundamental particles.

Represent particles (and antiparticles):

<table>
<thead>
<tr>
<th>Spin 1/2</th>
<th>Quarks and Leptons</th>
<th>————</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spin 1</td>
<td>$\gamma, W^\pm$ and $Z^0$</td>
<td>••••</td>
</tr>
<tr>
<td></td>
<td>$g$</td>
<td>••••</td>
</tr>
</tbody>
</table>

and their interaction point (vertex) with a “●”.

Each vertex gives a factor of the coupling constant, $g$. 
### External Lines (visible particles)

<table>
<thead>
<tr>
<th>Spin $\frac{1}{2}$</th>
<th>Particle</th>
<th>Incoming</th>
<th>Outgoing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Antiparticle</th>
<th>Incoming</th>
<th>Outgoing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spin 1</th>
<th>Particle</th>
<th>Incoming</th>
<th>Outgoing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Internal lines (propagators)

<table>
<thead>
<tr>
<th>Spin $\frac{1}{2}$</th>
<th>Particle (antiparticle)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spin 1</th>
<th>$\gamma$, $W^{\pm}$ and $Z^0$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spin 1</th>
<th>$g$</th>
</tr>
</thead>
</table>
Virtual particles

Forces arise due to the exchange of unobservable virtual particles.

- The mass of the virtual particle, $q^2$, is given by
  \[ q^2 = E^2 - |\vec{p}|^2 \]
  and is not the physical mass $m$, i.e. it is OFF MASS-SHELL.

- The mass of a virtual particle can be +ve, -ve or imaginary.

- A virtual particle which is off-mass shell by amount $\Delta m$ can only exist for time and range
  \[ t \sim \frac{\hbar}{\Delta mc^2} = \frac{1}{\Delta m}, \quad \text{range} = \frac{\hbar}{\Delta mc} = \frac{1}{\Delta m} \]
  $\hbar = c = 1$ natural units

- If $q^2 = m^2$, then the particle is real and can be observed.
Virtual Particles

“Time-ordered QM”

- Momentum conserved at vertices
- Energy not conserved at vertices
- Exchanged particle “on mass shell”

\[ E_x^2 - |\vec{p}_x|^2 = m_x^2 \]

Exchanged particle “off mass shell”

\[ E_x^2 - |\vec{p}_x|^2 = q^2 \neq m_x^2 \]

VIRTUAL PARTICLE

Feynman diagram

- Momentum AND energy conserved at interaction vertices
- Exchanged particle “off mass shell”

- Can think of observable “on mass shell” particles as propagating waves and unobservable virtual particles as normal modes between the source particles
Conservations

Energy, momentum, charge
Baryon number, lepton number
Strangeness (and Colour) in Strong interactions

\[ p + p \rightarrow \bar{p} + p + p + p \]

\[ p \rightarrow \pi^0 e^+ \]
\[ n \rightarrow p e^- \gamma \]
\[ n \rightarrow p e^- \nu_e \]
\[ \nu_\mu n \rightarrow e^- p \]
\[ \Lambda p \rightarrow K^- p p \]
\[ \Lambda \rightarrow \pi^+ \pi^- \]
\[ \gamma \rightarrow e^+ e^- \]
The story of penguin diagrams

*European Laboratory for Particle Physics
Geneva, Switzerland

Short's Arcade on the Grand-Rue of Geneva's Old Town, June 1977

SCORE
Melissa: 1, John: 3

FINAL SCORE
Melissa and Serge: 7, John: 4

John's apartment, several weeks later

University physics departments around the world, December 1977

“We now turn to the ‘penguin’ diagrams... We believe that they play an important role in the matrix element enhancement for strange particle decay...”
Particle Spin

Introduced by Pauli in 1924 as new quantum degree of freedom which allowed formulation of Pauli exclusion principle.

In 1925, it was suggested that it relates to self-rotation, but heavily criticised... only useful as a picture.

In 1927 Pauli formulated theory of spin as a fully quantum object (non-relativistic). In 1928 Dirac described the relativistic electron as a spin object.

In 1940 Pauli proved the spin-statistic theorem: fermions have half-integer spin and bosons have integer spin.
Particle Spin

Quantum mechanical, intrinsic angular momentum.

Particles are observed to possess angular momentum that cannot be accounted for by orbital angular momentum. Although the direction of its spin can be changed, an elementary particle cannot be made to spin faster or slower.

Spin cannot be explained by postulating that they are made up of even smaller particles rotating about a common centre of mass. Truly intrinsic property.

Same behavior as angular momentum, quantised. Integer and half-integer values: fermions (Pauli exclusion principle) and bosons (Bose-Einstein condensation).
Hadrons = massive

Single free quarks are NEVER observed, but are always CONFINED in bound states, called HADRONS. Macroscopically hadrons behave as point-like COMPOSITE particles. Hadrons are of two types:

MESONS (qq)
- Bound states of a QUARK and an ANTIQUARK
- All have INTEGER spin, Bosons
  \[ \pi^- = (\bar{u}d) \quad \pi^+ = (u\bar{d}) \]

BARYONS (qqq)
- Bound states of 3 QUARKS
- All have HALF-INTEGER spin, Fermions
  \[ p = (uud) \quad n = (udd) \]

PLUS ANTIBARYONS
  \[ (q\bar{q}\bar{q}) \quad \bar{p} = (u\bar{u}\bar{d}) \quad \bar{n} = (u\bar{d}\bar{d}) \]
Heisenberg in 1932 suggested that neutron and proton are treated as different charge states of one particle, the nucleon. Idea originally introduced in nuclear physics to explain observed symmetry between protons and neutrons: e.g. mirror nuclei have similar strong interaction properties.

A nucleon is given a number ISOSPIN $I$ and then there are 2 states with $I_3$ with value $+1/2$ or $-1/2$:

$I = 1/2, I_3 = +1/2, -1/2$

\[
\begin{pmatrix}
p \\
n
\end{pmatrix}
\]
Mesons were firstly postulated as the carrier of the strong force. In 1947, the charged pion was discovered by a group of scientists in Bristol, looking at photographic emulsions exposed to cosmic rays.

For \textbf{ISOSPIN}, one can put pions in a set of 3:
\[
\begin{pmatrix}
\pi^+ \\
\pi^0 \\
\pi^-
\end{pmatrix}
\]

They are formed by u and d quarks

Charge \( Q = I_3 + B/2 \quad B=\text{baryon number} \)

Relevance of \textbf{ISOSPIN} now understood as a consequence of very similar masses of u and d quarks, and conservation of isospin in strong interactions.
About at the same time, scientists from Manchester found another new particle in interactions of cosmic rays in a cloud chamber.

More and more were seen, and their rate of production in pion-proton reaction was measured and their lifetimes were also measured.

This new kind of particle was STRANGE in the sense that they decay very very slowly but the reaction production proceed very fast. Besides, they are always produced in at least 2 of them. So they were called STRANGE particles!

Produced in pairs

$$\pi^- + p \rightarrow K^0 + \Lambda^0$$
Now understood in terms of \( s \) quark and the fact the strong interaction conserve any quark type, so conserve also strangeness.

\[ Q = I_3 + (B+S)/2 \quad B=\text{baryon number} \]

This is purely because \( s \) quark is not so much heavier

Now classify mesons and baryons on basis of \( I_3 \) and \( B+S \):

**Quark Model**

![Diagram showing quark model with \( I_3 \) and \( B+S \) classification]

- Same jump in mass
- Same mass
- Same mass
Spin=0 mesons
Spin=3/2 baryons

- $\Omega^-$ not observed initially but predicted from pattern in quark model.
- Existence of the $S=3$ (sss) baryon at mass $\sim 1680$ MeV/c$^2$
- Identified based on a single event in bubble chamber (1964)
  - 3 very characteristic weak decays
  - 1st successful prediction of quark model!
Possible to extend to include charm and beauty but less and less precise the more the quark is heavier.
**Higgs mechanism**

An **energy field**, known as the **Higgs field**, is present everywhere in the Universe.

The **Higgs boson** is a short-lived particle that **transfers energy** between the Higgs field and other particles; it is an **energy carrier**.

The energy that a particle gains from the Higgs field is detected as the particle’s **mass**.
Supersymmetry

Particles outside of the Standard Model

Forces that affect particles

Particles of the Standard Model

Universe

Elementary particles, objects with no detected structure, include quarks, leptons, force carriers, and the Higgs boson.

the Higgs Boson and Beyond
Only a small fraction of the total is ordinary matter that we know!

70% dark energy

25% dark matter

5% ordinary matter
Resources:

Quark game
Top-trump card game

Plus various others from websites:

http://www.the-higgs-boson-and-beyond.org/
http://www.ep.ph.bham.ac.uk/DiscoveringParticles/
http://www.understanding-the-higgs-boson.org/
http://www.ep.ph.bham.ac.uk/user/lazzeroni/outreach/harry_card_game

Particle Zoo: http://www.particlezoo.net/
Other Particle Physics Sessions:

*Particle Zoo and Feynman Diagrams*
Muirhead 118
7th January 2016, 10:00-12:00

*ASE Frontier Science Lecture: The Mystery of Antimatter*
Poynting Physics S02
7th January 2016, 14:30-15:30

*Schools’ STEM exhibitions: HiSPARC project*
Aston Webb Great Hall
8th January 2016, 9:00-12:30

*Particle Teaching Resources: LHC Minerva*
Learning Centre LG13
8th January 2016, 9:30-11:30

*Particle World for Primary*
Arts LR8
8th January 2016, 13:45-15:45
Please don’t forget to complete the on-line evaluation for this session