Chapter 7: 
The Standard Model
Electro-Magnetic Fields
Electric Fields
Einstein and Maxwell

Photon is a particle of light
Modern Physics
Since Einstein

- discovery of many new particles
- discovery of substructure of proton and others
- detailed understanding of three forces
  - Quantum ElectroDynamics (QED)
  - Weak Interactions
  - Strong Interactions
Electrons
Dirac

relativity +
quantum physics

antisymmetric
Emission

e_L \rightarrow s \rightarrow \gamma \rightarrow s \rightarrow e_R

e_L \rightarrow s \rightarrow \gamma \rightarrow s \rightarrow e_R

time
Absorption
Scattering

boost changes space or time ordering
Scattering

time

$e_L$ $\gamma$ $\gamma$ $e_L$

---

The diagram illustrates a scattering process with time going upwards. The notation $e_L$ and $\gamma$ represents particles involved in the scattering event.
Scattering

time

e_L \quad s \quad s

\gamma

e_L \quad s
Scattering

antimatter!
Pair Creation

e_L \rightarrow e_L

e^+_R \rightarrow e^+_R

time

\gamma \rightarrow \gamma

\gamma \rightarrow \gamma

\gamma \rightarrow \gamma
Radioactivity
Weak Interactions

- Beta Rays
- Spinning Cobalt Nuclei
- Beta Rays (Electrons)
- This World
- Mirror World
- Mirror Wibbob
Radioactivity Heats Earth

16.2 million antineutrinos/square centimetre/second streaming out from Earth
Weak Decays
Weak Decays

\[ d \rightarrow u e^- \bar{\nu}_e \]
Weak Decays

d → u e⁻ \bar{\nu}_e
Weak Decays

\[ d \rightarrow u e^- \bar{\nu}_e \]
Fermi’s Theory
Fermi's Theory

QED:

Weak:
Weak Interactions
Weak Charged Interactions

\[ \nu_L \rightarrow e_L \]  \hspace{2cm}  \[ u_L \rightarrow d_L \]  

Violates Parity!
Pions and Muons

Isidor Isaac Rabi
Pions and Muons

Isidor Isaac Rabi
Too Many Particles

...and many more!
"Young man, if I could remember the names of all these particles, I would have been a botanist!"
Inside the Proton
Quarks

"Three quarks for Muster Mark!"
Charged Pion Decay

Prob. amplitude proportional to electron mass
Charged Pion Decay

\[ \text{Probability: } \propto m_e^2 \]

\[ \propto m_\mu^2 \]
Charged Pion Decay

Probability: \( \propto m_e^2 \)

Experimentally ratio is \( 10^{-4} \)
Color Fields
Flux Tube or String
Flux Tube Breaking
Flux Tube Breaking

If quarks and gluons are confined, how do we know they exist?
Generations

The diagram illustrates the generations of matter, consisting of quarks and leptons. The three generations are labeled I, II, and III. Quarks are denoted as up (u), charm (c), top (t), down (d), strange (s), and bottom (b). Leptons include electron (e⁻), muon (μ⁻), and tau (τ⁻) neutrinos, with their respective lepton types - e, μ, and τ. Each generation is represented by a row, with the leftmost column showing the quarks and the rightmost column showing the leptons.
Quark Bound States

### Baryons qqq and Antibaryons q̅q̅q̅

Baryons are fermionic hadrons. There are about 120 types of baryons.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>proton</td>
<td>uud</td>
<td>1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>$\bar{p}$</td>
<td>anti-proton</td>
<td>$\bar{u}\bar{d}\bar{d}$</td>
<td>-1</td>
<td>0.938</td>
<td>1/2</td>
</tr>
<tr>
<td>n</td>
<td>neutron</td>
<td>udd</td>
<td>0</td>
<td>0.940</td>
<td>1/2</td>
</tr>
<tr>
<td>$\Lambda$</td>
<td>lambda</td>
<td>uds</td>
<td>0</td>
<td>1.116</td>
<td>1/2</td>
</tr>
<tr>
<td>$\Omega^-$</td>
<td>omega</td>
<td>sss</td>
<td>-1</td>
<td>1.672</td>
<td>3/2</td>
</tr>
</tbody>
</table>

### Mesons q̅q̅

Mesons are bosonic hadrons. There are about 140 types of mesons.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Name</th>
<th>Quark content</th>
<th>Electric charge</th>
<th>Mass GeV/c²</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+$</td>
<td>pion</td>
<td>u$d$</td>
<td>+1</td>
<td>0.140</td>
<td>0</td>
</tr>
<tr>
<td>$K^-$</td>
<td>kaon</td>
<td>s$u$</td>
<td>-1</td>
<td>0.494</td>
<td>0</td>
</tr>
<tr>
<td>$\rho^+$</td>
<td>rho</td>
<td>u$d$</td>
<td>+1</td>
<td>0.770</td>
<td>1</td>
</tr>
<tr>
<td>$B^0$</td>
<td>B-zero</td>
<td>d$b$</td>
<td>0</td>
<td>5.279</td>
<td>0</td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>eta-c</td>
<td>c$c$</td>
<td>0</td>
<td>2.980</td>
<td>0</td>
</tr>
</tbody>
</table>
The Standard Model of Particle Physics

All known forces except gravity
- QED
- Weak Interactions
- Strong Interactions

Gauge theory of quarks and leptons
- 1 photon, 3 weak gauge bosons, 8 gluons
  - $\gamma$, $W^+$, $W^-$, $Z^0$, $G^\alpha$
The Standard Model of Particle Physics

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gauge theory of quarks and leptons

1 photon, 3 weak gauge bosons, 8 gluons

Mass (GeV/c^2)

1000
10
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}

ν_e, ν_μ, ν_τ

d, u, s, c, t, b, e, ν_e, ν_μ, ν_τ
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gauge theory of quarks and leptons
- 1 photon, 3 weak gauge bosons, 8 gluons
  \[ \gamma, W^+, W^-, Z^0, G^\alpha \]
The Standard Model

- consistent with all precision data
- fine-tuned to 1 part in $10^{30}$
- must be wrong
consistent with all precision data
fine-tuned to 1 part in $10^{30}$
must be wrong