Places to learn more:
Particle and nuclear physics links

http://pdg.lbl.gov
http://particleadventure.org
http://www.slac.stanford.edu/gen/edu/aboutslac.html
http://www.bnl.gov/rhic/
http://public.web.cern.ch/public/
http://www.fnal.gov/
http://www.science.doe.gov/hep/index.shtm
Inquiring minds want to know ...

Yo! What holds it together?
Fermi National Accelerator Laboratory (near Chicago)
Event display from the SLD experiment at SLAC
What forces exist in nature?

What is a force?

How do forces change with energy or temperature?

How has the universe evolved?

How do they interact?
$\pi^0$

Mass $m = 134.9766 \pm 0.0006$ MeV (S = 1.1)

$m_{\pi^0} - m_{\pi^0} = 4.5036 \pm 0.0005$ MeV

Mean life $\tau = (8.4 \pm 0.6) \times 10^{-17}$ s (S = 3.0)

$\sigma = 25.1$ nm

For decay limits to particles which are not established, see the appropriate Search sections ($A^0$ (axion), Other Light Boson ($X^0$) Searches, etc.).

<table>
<thead>
<tr>
<th>J$^P$ DECAY MODES</th>
<th>Fraction ($\Gamma_0/\Gamma$)</th>
<th>Scale factor/Confidence level</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3\gamma$</td>
<td>(0.7083±0.0032) % S=1.1</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>(1.098±0.032) % S=1.1</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \pi^0$</td>
<td>$\gamma$ positronium</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \pi^0$</td>
<td>($1.14 \pm 0.20 \times 10^{-5}$)</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \pi^0$</td>
<td>($3.14 \pm 0.30 \times 10^{-8}$)</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$\pi^0 \pi^0$</td>
<td>($6.2 \pm 0.5 \times 10^{-8}$)</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$4\gamma$</td>
<td>$&lt; 2 \times 10^{-4}$ CL=60%</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$\nu\nu$</td>
<td>$[\nu] &lt; 8.3 \times 10^{-4}$ CL=60%</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$\nu e\bar{\nu}_e$</td>
<td>$&lt; 2.1 \times 10^{-4}$ CL=60%</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$\nu \mu\bar{\nu}_\mu$</td>
<td>$&lt; 2.1 \times 10^{-4}$ CL=60%</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$\nu \mu\bar{\nu}_\mu$</td>
<td>$&lt; 2.1 \times 10^{-4}$ CL=60%</td>
<td>S=1.1 67</td>
<td></td>
</tr>
<tr>
<td>$\gamma\nu\nu$</td>
<td>$&lt; 2 \times 10^{-4}$ CL=60%</td>
<td>S=1.1 67</td>
<td></td>
</tr>
</tbody>
</table>

Change conjugation (C) or Lepton Family number (LF) violating modes

<table>
<thead>
<tr>
<th>C $\gamma$</th>
<th>C $\gamma$</th>
<th>C $\gamma$</th>
<th>C $\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3\gamma$</td>
<td>$3\gamma$</td>
<td>$3\gamma$</td>
<td>$3\gamma$</td>
</tr>
<tr>
<td>$\mu^+ \mu^-$</td>
<td>$\mu^+ \mu^-$</td>
<td>$\mu^+ \mu^-$</td>
<td>$\mu^+ \mu^-$</td>
</tr>
<tr>
<td>$\mu^- \mu^-$</td>
<td>$\mu^- \mu^-$</td>
<td>$\mu^- \mu^-$</td>
<td>$\mu^- \mu^-$</td>
</tr>
<tr>
<td>$\mu^+ \mu^- + \mu^- \mu^+$</td>
<td>$\mu^+ \mu^- + \mu^- \mu^+$</td>
<td>$\mu^+ \mu^- + \mu^- \mu^+$</td>
<td>$\mu^+ \mu^- + \mu^- \mu^+$</td>
</tr>
<tr>
<td>$&lt; 3.1 \times 10^{-8}$ CL=60%</td>
<td>$&lt; 3.1 \times 10^{-8}$ CL=60%</td>
<td>$&lt; 3.1 \times 10^{-8}$ CL=60%</td>
<td>$&lt; 3.1 \times 10^{-8}$ CL=60%</td>
</tr>
<tr>
<td>$&lt; 3.8 \times 10^{-10}$ CL=60%</td>
<td>$&lt; 3.8 \times 10^{-10}$ CL=60%</td>
<td>$&lt; 3.8 \times 10^{-10}$ CL=60%</td>
<td>$&lt; 3.8 \times 10^{-10}$ CL=60%</td>
</tr>
<tr>
<td>$&lt; 3.4 \times 10^{-8}$ CL=60%</td>
<td>$&lt; 3.4 \times 10^{-8}$ CL=60%</td>
<td>$&lt; 3.4 \times 10^{-8}$ CL=60%</td>
<td>$&lt; 3.4 \times 10^{-8}$ CL=60%</td>
</tr>
<tr>
<td>$&lt; 1.72 \times 10^{-8}$ CL=60%</td>
<td>$&lt; 1.72 \times 10^{-8}$ CL=60%</td>
<td>$&lt; 1.72 \times 10^{-8}$ CL=60%</td>
<td>$&lt; 1.72 \times 10^{-8}$ CL=60%</td>
</tr>
</tbody>
</table>

The Measurement

mioKande

Itow, T. Kajita, J. Kameda, M. Nakamura, Y. Orito

26 May 1975

G. Golhaber, J. A. Kadyk, Trilling, J. S. Whitaker,

California, Berkeley, California 94720

near 3095 MeV. The
Lesson 1:

Size actually does matter.
Determine the position and velocity of a car ... no problem
Determine the position and velocity of a small particle ... no problem
Problem!

Heisenberg uncertainty principle

Cannot have perfect knowledge of both the position and velocity.
The fundamental nature of forces: virtual particles

$\Delta E \Delta t \approx h \quad \text{Heisenberg}$

$E = mc^2 \quad \text{Einstein}$

Dear Steve,

Party relatively hard!

-Al
Quantum Field Theory $\rightarrow$ Exchange force
<table>
<thead>
<tr>
<th>Force</th>
<th>Source</th>
<th>Range</th>
<th>Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravitation</td>
<td>mass</td>
<td>infinite</td>
<td>$10^{-39}$</td>
</tr>
<tr>
<td>Electromagnetism</td>
<td>Electric charge</td>
<td>infinite</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Strong nuclear</td>
<td>Color charge</td>
<td>$10^{-15}$ m</td>
<td>1</td>
</tr>
<tr>
<td>Weak nuclear</td>
<td>Weak charge</td>
<td>$10^{-18}$ m</td>
<td>$10^{-5}$</td>
</tr>
</tbody>
</table>
The "Fundamental" Particles
Anti-matter

\[ e^- \rightarrow e^+ \text{ Positron} \]
\[ \text{Anti-electron} \]

\[ e^- + e^+ \rightarrow \gamma \gamma \]

All particles have antiparticles

Why is universe made of matter rather than anti-matter?
We don't know why this is true... yet.
Active area of study... believe it is probably due to a basic matter-anti-matter asymmetry in one of the forces of nature.
Standard Model of Particle Physics

http://particleadventure.org/

http://hepwww.rl.ac.uk/Pub/Phil/ppintro/ppintro.html

Structure within the Atom

Quark
Size < 10^{-19} m

Nucleus
Size ≈ 10^{-14} m

Electron
Size < 10^{-18} m

Neutron and Proton
Size ≈ 10^{-15} m

Atom
Size ≈ 10^{-10} m

If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
**BOSONS**

**Unified Electroweak**

- **Name**: $\gamma$ (photon)
- **Mass GeV/c²**: 0
- **Electric charge**: 0

- **Name**: $W^-$
- **Mass GeV/c²**: 80.39
- **Electric charge**: -1

- **Name**: $W^+$
- **Mass GeV/c²**: 80.39
- **Electric charge**: +1

**Strong (color)**

- **Name**: $g$ (gluon)
- **Mass GeV/c²**: 0
- **Electric charge**: 0

**Force carriers**

- Spin = 0, 1, 2, ...
## Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational Interaction</th>
<th>Weak Interaction (Electroweak)</th>
<th>Electromagnetic Interaction</th>
<th>Strong Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically Charged</td>
<td>Quarks, Gluons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td>$W^+$, $W^-$, $Z^0$</td>
<td>$\gamma$</td>
<td>Gluons</td>
</tr>
<tr>
<td>Strength at $10^{-18}$ m</td>
<td>$10^{-41}$</td>
<td>0.8</td>
<td>1</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td>$3\times10^{-17}$ m</td>
<td>$10^{-4}$</td>
<td>1</td>
<td>60</td>
</tr>
</tbody>
</table>
## Baryons $qqq$ and Antibaryons $q\bar{q}\bar{q}$

Baryons are fermionic hadrons. These are a few of the many 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>antiproton</td>
<td>$\bar{u}\bar{u}\bar{d}$</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 $q\bar{q}$

Mesons are bosonic hadrons. These are a few of the many 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$\bar{d}$</td>
<td>+1</td>
<td>0.140</td>
<td>0</td>
</tr>
<tr>
<td>$K^-$</td>
<td>kaon</td>
<td>s$\bar{u}$</td>
<td>$-1$</td>
<td>0.494</td>
<td>0</td>
</tr>
<tr>
<td>$\rho^+$</td>
<td>rho</td>
<td>u$\bar{d}$</td>
<td>+1</td>
<td>0.776</td>
<td>1</td>
</tr>
<tr>
<td>$B^0$</td>
<td>B-zero</td>
<td>d$\bar{b}$</td>
<td>0</td>
<td>5.279</td>
<td>0</td>
</tr>
<tr>
<td>$\eta_c$</td>
<td>eta-c</td>
<td>c$\bar{c}$</td>
<td>0</td>
<td>2.980</td>
<td>0</td>
</tr>
</tbody>
</table>
quarks

\[
\begin{array}{cccc}
\text{u} & \text{c} & \text{t} \\
\text{d} & \text{s} & \text{b}
\end{array}
\]

leptons

\[
\begin{array}{ccc}
\text{e} & \mu & \tau \\
\nu_e & \nu_\mu & \nu_\tau
\end{array}
\]

Gauge bosons

\[
W, Z, g, \gamma, G
\]

Strong interaction

Hadrons

Baryons

\[
\begin{array}{ccc}
\text{q} & \text{q} & \text{q}
\end{array}
\]

\[
\begin{array}{ccc}
\text{q} & \overline{\text{q}}
\end{array}
\]

mesons

\[
\begin{array}{ccc}
p = \text{uud} \\
n = \text{udd}
\end{array}
\]

\[
\begin{array}{ccc}
K = \text{u}\overline{s} \text{ or } \overline{u}s \\
\pi = \text{u}\overline{d} \text{ or } \overline{u}d
\end{array}
\]

nuclei

Electromagnetic interaction

atoms
Why bare quarks have never been observed.

Quantum Chromodynamics (QCD)

Energy grows with separation: $E = mc^2$

"white" proton (confined quarks)

Quark-antiquark pair created from vacuum

Strong color field

"white" $\pi^0$ (confined quarks)

Thanks to Mike Lisa (OSU) for parts of this animation.
Nucleon-nucleon force - exchange of $\pi$ (pion)

Fine point for completeness

Quarks bind quarks into protons and neutrons

Nucleus
**Particle Processes**

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.

---

**Example**

\[ n \rightarrow p e^- \bar{\nu}_e \]

A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron $\beta$ (beta) decay.

\[ e^+ e^- \rightarrow B^0 \bar{B}^0 \]

An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and $B^0$ mesons via a virtual $Z$ boson or a virtual photon.
The Vacuum

Much ado about NOTHING:
Nothing is something
Nothing has energy
Nothing interacts with something

- R. Kolb