WHAT ARE WE MADE OF?

1. The Early Years:
   Dirac (1929) and anti-matter
   Pauli (1931) and the neutrino
   Chadwick (1932) and the neutron
   Cosmic Rays, Yukawa and Pions

2. Hadrons and Quarks
   the 50’s and the “hadron explosion”
   Gell-Mann (1963) and the quarks

3. The Standard Model and Unification of Forces
1. The Early Years

• early 20’s: electrons (atomic orbits), protons (nuclei), photons

• “beta decay” shows missing energy: \( n \rightarrow p + e + \text{missing energy} \)
  
  1931: Pauli proposes the neutrino

• 1929: Dirac applies special relativity to quantum mechanics and predicts a positive (proton first) electron, the POSITRON DISCOVERY OF ANTI-MATTER (1931 positron is found) 
  
  \( E=mc^2 \) implies energy \( \leftrightarrow \) matter (photons to \( e^+ + e^- \))

• 1932: Chadwick discovers neutron, unstable outside nucleus (10m.)

  • 1910-1930: Discovery of “cosmic rays”: the muon \((m=200m_e)\)

• 1930’s, Yukawa proposes pions to explain strong nuclear force

  number of “elementary” particles grows fast!
2. Hadrons and Quarks

- In the 50’s huge number of “hadrons” are found but maybe analogy w/ atoms: 92 but made of 3 particles

- 1963: Gell-Mann proposes “quarks” to make all hadrons:
  - Baryons (3 quarks): p, n, etc.
  - Mesons (quark-antiquark): pions, etc.

6 quarks: up, down charm, strange bottom, top
3. The Standard Model and Unification

• Matter is made of 6 quarks and 6 leptons

Leptons: electron, electron neutrino
          muon, muon neutrino
          tau, tau neutrino

2002: all evidence points to massive neutrinos!

• Matter arranged in 3 families:

\[
\begin{align*}
\{ & e, \nu_e & \} \\
\{ & u, d & \} \\
\{ & \mu, \nu_\mu & \} \\
\{ & c, s & \} \\
\{ & \tau, \nu_\tau & \} \\
\{ & b, t & \}
\end{align*}
\]

Normal matter
• There are 4 fundamental forces in Nature:
  Gravity, electromagnetism, strong, weak

• Forces are also transmitted by particles:
  * Electromagnetism: photons
  * Weak nuclear forces: gauge bosons, $W^+$, $W^-$, $Z^0$
  * Strong nuclear force: 8 “gluons”
  * Gravity: gravitons

<table>
<thead>
<tr>
<th>FORCE</th>
<th>RANGE</th>
<th>STRENGTH (at $10^{-13}$cm)</th>
<th>CARRIER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>infinite</td>
<td>$10^{-38}$</td>
<td>graviton</td>
</tr>
<tr>
<td>EM</td>
<td>infinite</td>
<td>$10^{-2}$</td>
<td>photon</td>
</tr>
<tr>
<td>Weak</td>
<td>$&lt; 10^{-16}$cm</td>
<td>$10^{-13}$</td>
<td>gauge bosons</td>
</tr>
<tr>
<td>Strong</td>
<td>$\sim 10^{-13}$cm</td>
<td>$1$</td>
<td>8 gluons</td>
</tr>
</tbody>
</table>

*This is not the final picture: Weak and EM forces are “unified” above 100 GeV!! What about other forces?