### Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the “Standard Model.”

#### FERMIIONS

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Spin = 1/2</th>
<th>Quarks</th>
<th>Spin = 1/2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavor</td>
<td>Mass GeV/c²</td>
<td>Electric charge</td>
<td>Flavor</td>
</tr>
<tr>
<td>ν_e</td>
<td>&lt;1.6×10⁻¹⁷</td>
<td>0</td>
<td>e</td>
</tr>
<tr>
<td>μ</td>
<td>&lt;0.0002</td>
<td>0</td>
<td>μ</td>
</tr>
<tr>
<td>ν_μ</td>
<td>&lt;0.0002</td>
<td>0</td>
<td>τ</td>
</tr>
</tbody>
</table>

Spin is the intrinsic angular momentum of particles. Spin is given in units of \( \hbar \), which is the quantum unit of angular momentum, where \( h = 6.626 \times 10^{-34} \text{ J s} \).

Electric charges are given in units of the proton charge. In SI units the electric charge of the proton is \( 1.602 \times 10^{-19} \text{ C} \).

The energy unit of particle physics is the electron volt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember \( E = mc^2 \)), where \( 1 \text{ GeV} = 10^9 \text{ eV} = 1.602 \times 10^{19} \text{ J} \). The mass of the proton is 0.938 GeV/c² = 1.672 \times 10^{-27} \text{ kg}.

#### BOSONS

<table>
<thead>
<tr>
<th>Unified Electroweak</th>
<th>Strong (color)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Force carrier</td>
<td>Spin = 1</td>
</tr>
<tr>
<td>Name</td>
<td>Mass GeV/c²</td>
</tr>
<tr>
<td>γ</td>
<td>photon</td>
</tr>
<tr>
<td>W⁺</td>
<td>0.84</td>
</tr>
<tr>
<td>Z⁰</td>
<td>91.187</td>
</tr>
</tbody>
</table>

Color Charge
Each quark carries one of three types of “strong charge,” also called “color charge.” These charges have nothing to do with the colors of visible light. There are eight possible kinds of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and \( W \) and \( Z \) bosons have no strong interactions and hence no color charge.

**Quarks Confined in Mesons and Baryons**
One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color fields between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles we see emerge. Two types of hadrons have been observed in nature: mesons and baryons.

**Residual Strong Interaction**
The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can be also viewed as the exchange of mesons between the hadrons.

#### Properties of the Interactions

**Gravitational**
- No known carriers
- Interacts with all types of matter

**Weak**
- Carried by particles
- Interacts with all types of matter

**Electromagnetic**
- Carried by particles
- Interacts with all types of matter

**Strong (Color)**
- Carried by particles
- Interacts with all types of matter

**Residual Strong Interaction**
- No known carriers
- Interacts with all types of matter

#### Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (masses + or − charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (π, ρ, ω, φ, γ, and χ) are their own antiparticles.

#### Figures
These diagrams are an artist reconception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

---

**The Particle Adventure**
Visit the award-winning web feature: The Particle Adventure at http://ParticleAdventure.org

This chart has been made possible by the generous support of:
- U.S. Department of Energy
- U.S. National Science Foundation
- Lawrence Berkeley National Laboratory
- Stanford Linear Accelerator Center
- American Physical Society
- Division of Particle and Fields Physics

©2003 Contemporary Physics Education Project, CPEP is a nonprofit organization of teachers, physicists, and educators. For more info, email CPEP at 58.308. Lawrence Berkeley National Laboratory, Berkeley, CA 94720. For information on charts, text materials, workshop activities, and workshops, see: http://CPEPweb.org