Standard Model of Elementary Particles and Fundamental Forces

12 PARTICLE-ZOO ANIMALS AND 4 ZOO KEEPERS

12 elementary particles are known fundamental building blocks of matter. 4 fundamental forces govern the transitions between particles. The Standard Model, a mathematical rule, includes 12 particles and 3 forces.

- **g** (gluons) → strong force
  - Quarks experience them.
  - Protons & neutrons are stick together.

- **γ** (photons) → electromagnetic force
  - Quarks, leptons (other than neutrinos) experience this force.

- **W** (weak bosons) for weak forces
  - Quarks, leptons experience this force.

- **G** (graviton – not found yet 😊) carries gravitational force.

All masses in MeV, ANIMAL MASSES SCALE WITH PARTICLE MASSES.
Standard Model (SM)

... is a theory of elementary particles and its fundamental interactions.

6 quarks, 6 leptons and gauge particles

SM at Low Energy

... can explain the neutron decay (weak interaction).

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) $W$ boson. This is neutron $\beta$ decay.
SM at High Energy

... helps the discovery of the top quark in 1995.

Very Successful at $E \sim 100$ GeV 😊

**Predictions were tested in various experiments:**

<table>
<thead>
<tr>
<th>Year</th>
<th>Degree</th>
<th>Discovery</th>
<th>Experiment/Setup</th>
</tr>
</thead>
<tbody>
<tr>
<td>1973</td>
<td>B.S.</td>
<td>Neutral current</td>
<td>@ CERN SPS (400 GeV $p$)</td>
</tr>
<tr>
<td>1983</td>
<td>M.S.</td>
<td>“W/Z discovery”</td>
<td>@ CERN SpS (540 GeV $p\bar{p}$)</td>
</tr>
<tr>
<td>1995</td>
<td>Ph.D.</td>
<td>“Top discovery”</td>
<td>@ Fermilab Tevatron (1.8 TeV $p\bar{p}$)</td>
</tr>
</tbody>
</table>

**Remarkable accuracy:**

$$M_Z^{\text{exp}} = 91.1876 \pm 0.0021 \text{ GeV}$$

$$M_Z^{\text{theory}} = 91.1874 \pm 0.0021 \text{ GeV}$$

Explains most of the data!

What happens at higher energy?
Feynman Diagrams

Graphical way to describe the particle interactions ...

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

$\tau_p = 887 \text{ s}$

$\pi \rightarrow \mu^+ \bar{\nu}_e$

$\tau_\pi = 2.60 \times 10^{-8} \text{ s}$

$\tau_\mu = 2.2 \times 10^{-6} \text{ s}$
Strength of Force
“Coupling Constant”
Three Fundamental Interactions

**Photon:** carriers of the electromagnetic force

\[ \alpha = \frac{e^2}{4\pi} = \frac{1}{137} \]

**Gluons:** carriers of the strong force

\[ \alpha_s = \frac{g_s^2}{4\pi} \approx 0.12 \]

**W, Z bosons:** carriers of the weak force

\[ \alpha_2 = \frac{g^2}{4\pi} \approx 0.033 \]
Running Couplings

e.g., \( \sigma(e^+e^- \rightarrow e^+e^-) \propto \alpha^2 \)

\[ \alpha = 1/134 \]

\[ Q_{\text{low}} \]

Energy Scale

\[ \alpha = 1/127 \]

\[ Q_{\text{high}} \]

\[ \alpha(Q = M_{\text{pl}}) = ? \]
“Running” Coupling

\[ \alpha_s(Q^2) = \frac{12\pi}{(11n_{\text{color}} - 2n_{\text{flavor}}) \log(Q^2/\Lambda^2)} \]

\( n_f = 6 \) (quark flavors); \( n_c = 3 \) (colors)

The Nobel Prize in Physics 2004

3 Couplings at “Higher” Energy

Three gauge couplings do not meet at a single point.

We need a theory which goes to a higher scale.

The SM works very well at \(~100\ \text{GeV}\).

Grand Unified Theory \( \rightarrow \) Supersymmetry
Supersymmetrized SM

The fundamental law(s) of nature is hypothesized to be symmetric between bosons and fermions.

Fermion ($S = \frac{1}{2}$) $\leftrightarrow$ Boson ($S = 0$ or $1$)

Have they been observed? ⇒ Not yet.

Feynman Diagrams for SUSY Decays

SUSY partner of $W$ boson: chargino

$W^+ \rightarrow \tau^+ \nu_\tau$

SUSY partner of $\tau$ lepton: stau

$\tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$

SUSY partner of $Z$ boson: neutralino

$Z^0 \rightarrow \tau^+ \tau^-$

Lightest neutralinos are always in the final state! This neutralino is the dark matter candidate!!
To be (SUSY), Not to be

☐ It doubles the number of particles in the nature.

This is not the first time. The electron-positron (particle-antiparticle) symmetry was predicted before the discovery of positron by P.A.M. Dirac:

$$H\psi = (\vec{\alpha} \cdot \vec{p} + \beta m)\psi$$

☐ What do we gain if the theory is supersymmetric?
“How to Look for?
“Collisions”

“Quarks. Neutrons. Mesons. All those particles you can’t see. That’s what drove me to drink. But now I can see them!”
\( \bar{p} + p \rightarrow \pi \pi \pi \pi \pi \pi \pi \pi \) in Bubble Chamber
Historical Observations

Observation of an $e^+e^-$ pair in $\pi^0 \rightarrow \gamma e^+e^-$ decay mode

Liquid-hydrogen bubble-chamber photograph of antiproton colliding with a proton, producing $\Xi$ and anti-$\Xi$

The first $\Omega$ event (Barnes et al., 1964) in $K^- + p$ interaction.

A neutral current ($Z^0$ boson) reaction.
One more – Colliding Beams
Real way to see Top (or Heavy Particles)

\[ E = mc^2 \]

The energy of the colliding proton and antiproton is transformed into the masses of the much more massive top and antitop quarks.

The production of the massive top and antitop quarks from protons is like making steel balls by colliding Ping-Pong balls.
Brief History of Top Quark Discovery in Proton-Antiproton Collisions

**TOP QUARK**

One of the key reactions to discover the top quarks at the Tevatron.

We had to extract this reaction out of 5 trillion p̅p collisions.
ANALYZER: A TOP QUARK EVENT

Name: Top
ID No.: 40758-44414
Date of Birth: Sep. 24, 1992
Place of Birth: Batavia, IL, USA

Collision in Calorimeter

"TOP QUARK" DISCOVERY IN 1995

Collision!
In this artist's representation of a particle collision, a proton and antiproton collide at high energy to produce top and antitop quarks.
Too Heavy $t$ and Non-Zero $\nu$

**QUARK MASSES**

$$M_{\text{top}} = 178 \times 10^9 \text{ eV}$$

$$M_{\text{up}} \sim 5 \times 10^6 \text{ eV}$$

Yet to be discovered

**LEPTON MASSES**

$$\frac{M_{\mu}}{M_e} = 205$$

$$\frac{M_{\tau}}{M_e} = 3550$$

$$M_{\nu} < 1 \text{ eV}$$

Neutrino masses are non zero! The SM can not accommodate nonzero neutrino mass!!! See recent results from SuperKamiokande, SNO, KamLAND, K2K, MACRO (Webb et al.). For future results, see MINOS (Webb et al.), MiniBoone, T2K, …
Despite the Standard Model being very successful, it has structural defects. This is why we believe new physics must exist. A cosmological connection with SUSY will guide us what to do.
Vision for HEP
“Cosmological Connection”
CDM = The matter which is present without any electromagnetic interaction.

CDM = Neutralino ($\tilde{\chi}_1^0$)

To explain the amount of the CDM, there must be another SUSY particle whose mass must be closer to the neutralino. (see the next slide.)

Is it possible to observe these features in other experiments (e.g., Dark matter detection, Collider experiments)?

Road Map to Unified Theory

String Theory

SUSY

GUT

Leptons Quarks

$\nu_e \nu_\mu \nu_\tau$

I II III

The Generations of Matter
BACKUPS
Cross Section for Point-like Particle Collision
$e^+e^- \rightarrow \mu^+\mu^-$

Parton Model

\[
\sigma = \hat{\sigma}(e^+e^- \rightarrow \mu^+\mu^-) = \frac{4\pi\alpha^2\hbar^2c^2}{3s}
\]
Parton Model

\[ e^+ e^- \rightarrow q\bar{q} \]

\[ \sigma = \hat{\sigma}(e^+ e^- \rightarrow q\bar{q}) = \frac{4\pi\alpha^2 \hbar^2 c^2}{3s} e_q^2 N_c \]
Parton Model

\[ q\bar{q} \rightarrow \mu^+ \mu^- \]

\[
\sigma = \hat{\sigma}(q\bar{q} \rightarrow \mu^+ \mu^-) = \frac{4\pi\alpha^2\hbar^2c^2}{3s}e_q^2N_c
\]
\[ p\bar{p} \rightarrow l^+ l^- + X \]

Parton Model

\[
\sigma = \sum_{q,\bar{q}} \int dx dy f_{q/p}(x) f_{\bar{q}/\bar{p}}(y) \hat{\sigma}(q\bar{q} \rightarrow l^+ l^-)
\]
Parton Model

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

\[ \sigma = \sum_{q,\bar{q}} \int dx dy f_{q/p}(x) f_{\bar{q}/\bar{p}}(y) \hat{\sigma}(q\bar{q} \rightarrow t\bar{t}) \]

PDFs

\[ \sum_i \int dx [x \cdot f_i^p(x)] = 1 \]
\[ \sum_j \int dy [y \cdot f_j^p(y)] = 1 \]
Elementary Particles Are Point-like Particles

**Scale**

- Size in atoms: $10^{-10}$
- Size in meters: $10^{-14}$
- Size in atoms: $10^{-15}$
- Size in meters: $10^{-18}$ (at largest)

**Hadrons, Mesons**

- Proton: $+\frac{2}{3}e$, $+\frac{2}{3}e$, $-\frac{1}{3}e$
- Neutron: $+\frac{2}{3}e$, $\frac{1}{3}e$, $-\frac{1}{3}e$
- $\pi^+$: $+\frac{2}{3}e$, $u\bar{d}$
- $\pi^-$: $-\frac{2}{3}e$, $u\bar{d}$
- $K^-$: $-\frac{2}{3}e$, $u\bar{s}$
37. Plots of cross sections and related quantities

Muon Neutrino and Anti-Neutrino Charged-Current Total Cross Section

Figure 37.17: $\sigma_T/E_V$, for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are the averaged values over all energies as measured by the experiments in Refs. [1-4]: $0.577 \pm 0.014 (0.334 \pm 0.008) \times 10^{-38}$ cm$^2$/GeV. Note the change in the energy scale at 30 GeV. (Courtesy W. Seligman and M.H. Shaevitz, Columbia University, 2000.)

\( \sigma(pp) \) and \( \sigma(\bar{p}p) \)

Figure 37.10: Total and elastic cross sections for \( pp \) and \( \bar{p}p \) collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/xsect/contents.html (Courtesy of the COMPAS Group, IHFP, Protvino, Russia, August 1999.)
\( \sigma(pd) \) and \( \sigma(pn) \)

Figure 37.29: Total and elastic cross sections for \( pd \) (total only), \( np \), \( pd \) (total only), and \( pn \) collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at [http://pdg.lbl.gov/ssect/contents.html](http://pdg.lbl.gov/ssect/contents.html) (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, August 1999.)
\( \sigma(\pi p) \) and \( \sigma(\pi d) \)

**Figure 37.21:** Total and elastic cross sections for \( \pi^+ p \) and \( \pi^\pm d \) (total only) collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at [http://pdg.lbl.gov/xsect/contents.html](http://pdg.lbl.gov/xsect/contents.html) (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, August 1999.)
$\sigma(K^-p)$ and $\sigma(K^-d)$

Figure 37.22: Total and elastic cross sections for $K^-p$ and $K^-d$ (total only), and $K^-n$ collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/abssect/contents.html (Courtesy of the COMPAS Group, IHEF, Protvino, Russia, August 1999.)
\[ \sigma(K^+p) \text{ and } \sigma(K^+d) \]

Figure 37.23: Total and elastic cross sections for \( K^+p \) and total cross sections for \( K^+d \) and \( K^+n \) collisions as a function of laboratory beam momentum and total center-of-mass energy. Corresponding computer-readable data files may be found at http://pdg.lbl.gov/xsect/contents.html (Courtesy of the COMPAS Group, IHEP, Protvino, Russia, August 1999.)