The Standard Model (1)

- Today we will be discussing the Standard Model of particle physics—an attempt to explain all of the fundamental forces and particles in the universe.
- The theory has been very successful in explaining (and even predicting) properties of subatomic particles.
- The theory is not perfect—more on this later.

Standard Model (2)

- The theory includes:
  - Strong interactions due to the color charges of quarks and gluons.
  - A combined theory of weak and electromagnetic interaction, known as electroweak theory.
- The theory does not include the effects of gravity. Gravity is tiny compared to the other forces and can be neglected in describing atoms.

Four Fundamental Forces

Force	Particles	Strength	Range	Mediator
Gravity	All	6E-39	Infinite	Graviton
Weak	All	1E-5	1E-17 m	$W^{\pm}$, Z^0
Electro-magnetic	Charged Particles	1/137	Infinite	Photon
Strong	Hadrons (protons and neutrons)	1	1E-15 m	Gluon

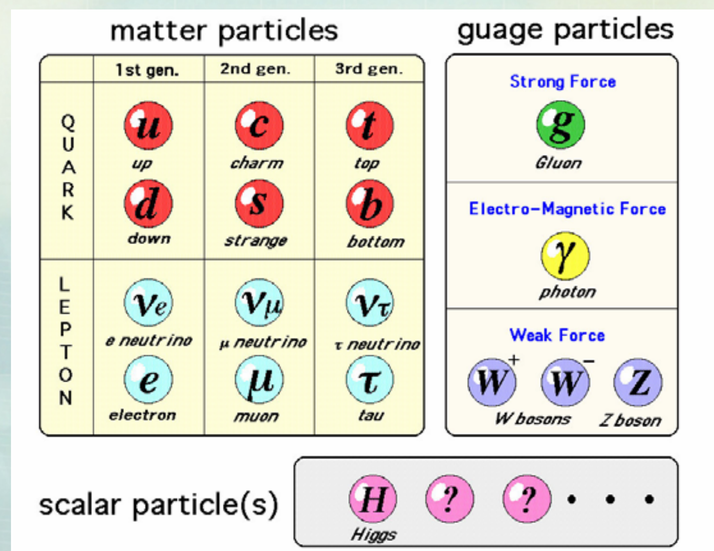
Standard Model Particles

Charge

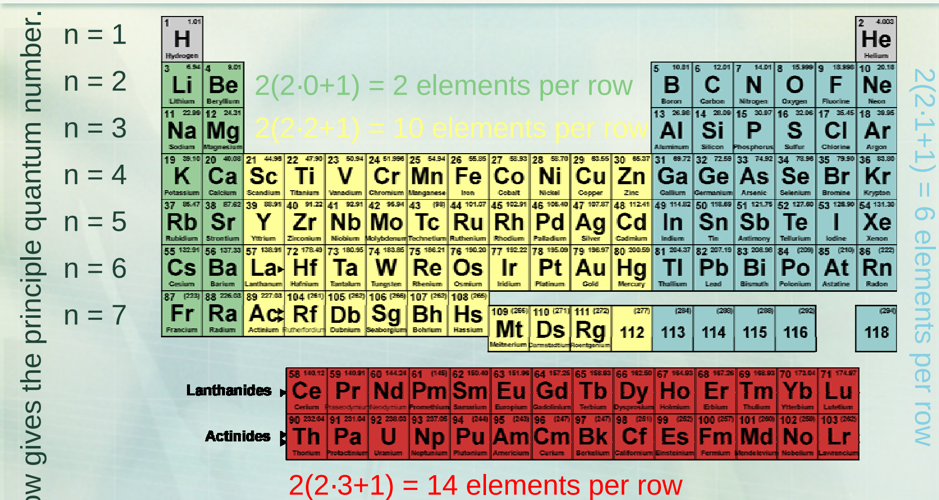
+2/3 →

-1/3 →

Anti-particles have the opposite charge.



Quantum Numbers (1)



- The structure of the periodic table arises from the underlying quantum numbers.

Quantum Numbers (2)

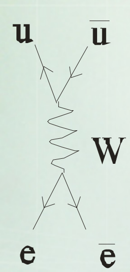
- Names like top, charm, strange, color, etc. do not mean the same things they do in everyday life. They are just identifiers.
- These names represent a set of quantum numbers that explain the number and types of particles that we observe.
- Chemistry, nuclear science, and particle physics all use different sets of quantum numbers, although they are all based on related ideas.

Rules for particle interactions

Example: $e^- + \bar{e}^+ \to u + \bar{u}$ ALLOWED

$n \to p^+ + e^-$ NOT ALLOWED (lepton number)

$n \to p^+ + e^- + \bar{\nu}$ ALLOWED



Conserved: Electric charge, lepton number (e = +1, $\bar{e}$ = -1), color charge, baryon number (could also count quarks: quarks +1/3, antiquarks -1/3), energy, momentum, and angular momentum.

State whether the following are allowed (A) or not allowed (B):
(Hint: pions are made of a quark and an antiquark)

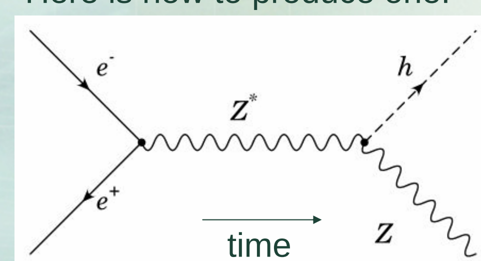
$n + p^+ \to \pi^+ + \pi^+ + \pi^-$

$\pi^- \to e^- + \bar{\nu}$

Where does mass come from?

- Space is filled with a (scalar) particle called the Higgs boson. The more a particle interacts with the Higgs field, the greater its mass is.
- The Higgs is the most famous undiscovered particle. A new collider called the Large Hadron Collider may find it.

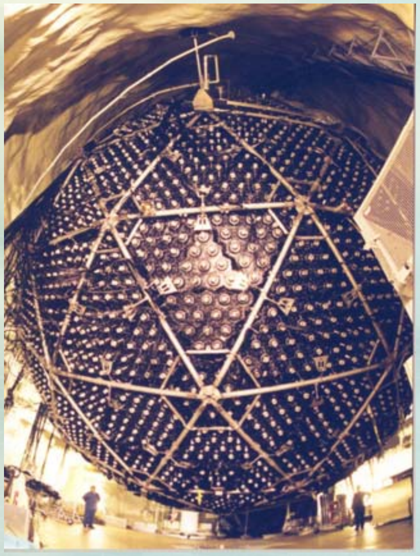
Here is how to produce one:



Problems with the Standard Model

- Why so many particles?
- Are there more particles we don’t know about yet?
- What is charge? Why does it come in fixed units?
- Why is the standard model so complicated? Why 4 forces?
- How is gravity related to the other forces?
- In general the standard model does not answer the WHY question. Everyone agrees it is not a complete theory.

Sudbury Neutrino Observatory



- The sphere is filled with heavy water, which is weakly sensitive to neutrinos.
- The “dots” on the outside are detectors that observe the interactions.
- SNO solved the “Solar Neutrino Problem.”

Problems with the Standard Model

- In 2001, it was discovered that neutrinos have mass, meaning that a key assumption of the Standard Model was false.
- Gravity has still not been unified into the theory, and so-called gravitons have never been observed.
- This is creating an atmosphere where scientists don’t know exactly how things will turn out in the end.

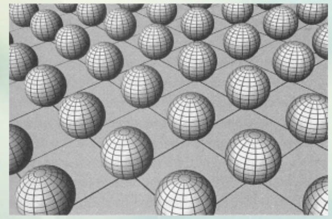
What comes next?

- There are attempts to extend the standard model to include gravity; these are called supersymmetric theories.
- These say that all fermions (which make up matter) and bosons (that transmit forces) have a corresponding partner boson (to go with our standard fermions) and fermion (to go with our standard bosons).
- Supersymmetric theories predict a whole set of new particles called s-particles, e.g. selectron, sneutrino, photino, Wino, and so on
- A new accelerator (Large Hadron Collider at CERN [Europe]) may be able to produce some of these particles in the next two years.

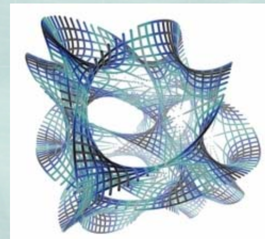
Superstring Theory

- One of the most promising new theories is string theory. It says that the fundamental building blocks of nature are tiny (10^{-35} m) strings.
- The particles we observe in nature are difference ways for strings to vibrate.
- String theory is not accepted because so far it has not devised an experiment that could test it.
- String theories require at least 10 dimensions.
- Gravity is weak because the graviton exists mostly in another dimension, but there is a slight overlap with us.
- String theory may be a theory of everything where all phenomena can be described by one equation.

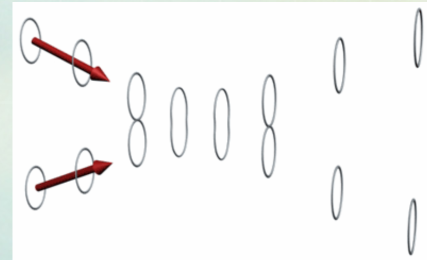
String Theory Pictures



Extra Dimensions



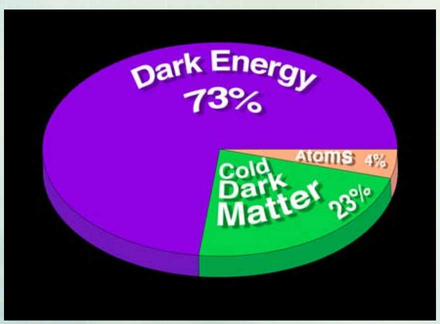
What one of the dimensions might look like (Calabi-Yau space)



Interaction of Strings: The finite size (10^{-35} m) overcomes many of the problems with the interaction of point particles.

The Ultimate Copernican Revolution

- In 1543 Nicolas Copernicus published his treatise *De Revolutionibus Orbium Coelestium* (The Revolution of Celestial Spheres).
- We are at the brink of a new revolution. What is the universe made of?
- All of the things we have been talking about amount to only about 4% of the mass of the universe.
- What is dark matter and dark energy? We don't know!



Basically there is a lot more gravity than we can explain.

Smaller Particles = More Energy

- In a strange law of physics, the smaller a particle is, the greater is the energy associated with it.
- To study a particle you have to create conditions with energy comparable to the particle's. This has fueled the construction of particle accelerators, then colliders, which have continuously increased in size.

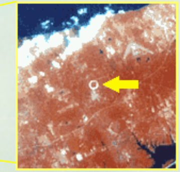
Scale of Energy (per Particle)

- Chemistry Experiment ~0.1-5 eV
- First Cyclotron (USA) 8E4 eV
- 88-Inch Cyclotron (USA) 1E7 eV
- National Superconducting Cyclotron Laboratory (USA) 1.4E8 eV
- Super Proton Synchrotron (Europe) 4E11 eV
- Relativistic Heavy Ion Collider (USA) 1E11 eV
- Tevatron (USA) 1E12 eV
- Large Hadron Collider (Europe) 7E12 eV
- [Superconducting Super Collider (USA)]* 2E13 eV

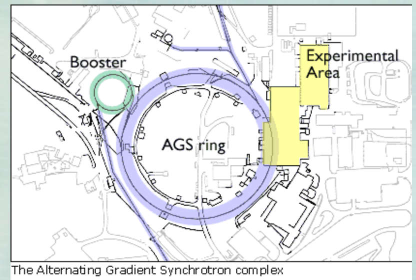
* Construction was cancelled in 1993.

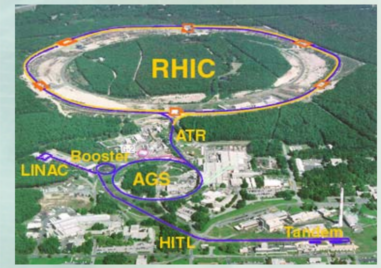
RHIC (1)

Long Island (New York)

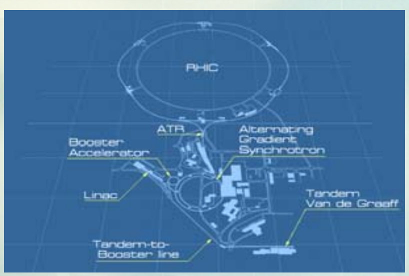


RHIC from space!





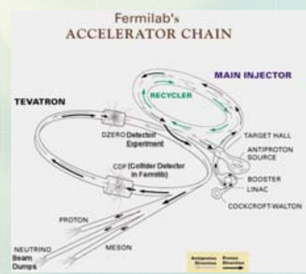
RHIC (2)



AGS

"Siberian Snake"

Tevatron (1)

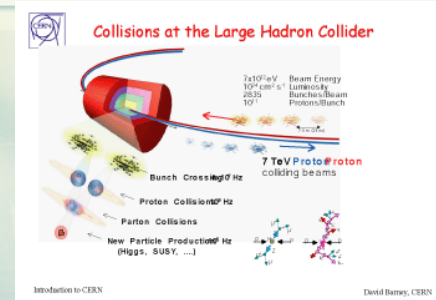


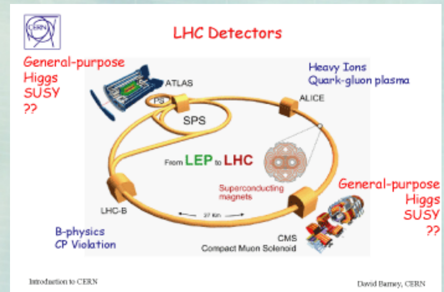
Tevatron (2)

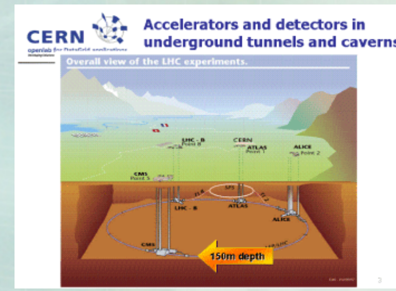
- Fermi National Accelerator Laboratory (Illinois)

Drift Tube Linac

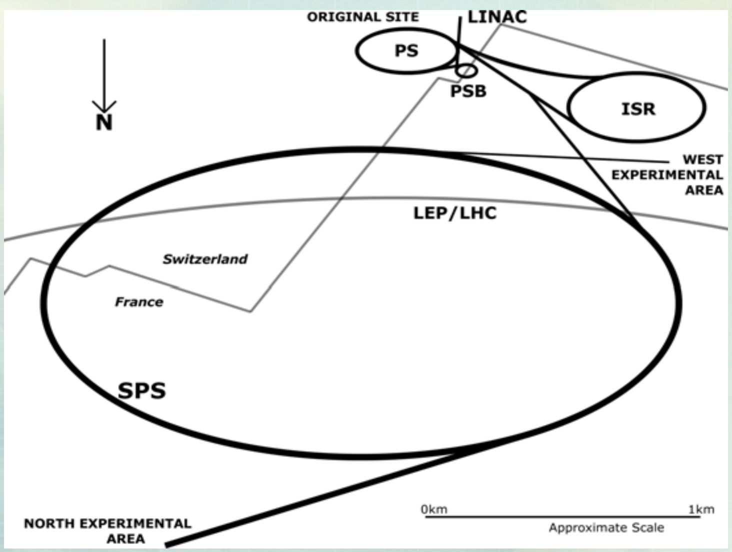
Large Hadron Collider (1)



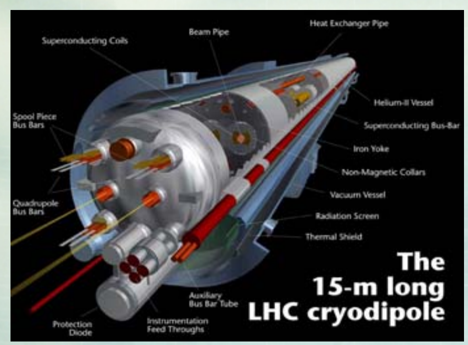


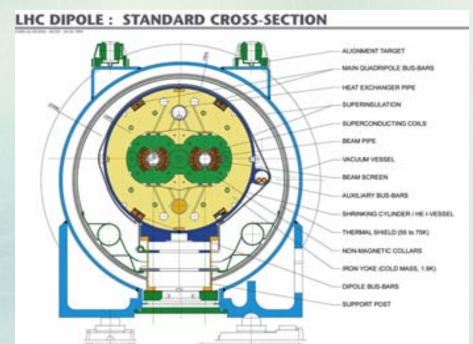


CERN Beam Gymnastics (2)



Large Hadron Collider (3)





Cost

- It is worth noting that these experiments are very expensive. The cost of a single particle:
  - Burning one carbon atom — tiny, almost free
  - Gold — small, almost free
  - Radioactive beam (^{64}Fe) — ~$0.001
  - Superheavy nucleus (^{272}Rg) — ~$200,000
  - Higgs particle — $0.1-1 billion
- How much are you/we willing to pay for a greater understanding of the universe?