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Today

- Announcements:
  - HW#10 is due April 9 at 8:00 am.
  - The Spring Break Story Winner is ..
- What is matter? What is mass?

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Standard Model

- The fundamental theory of nature's constituents and their interaction is called the Standard Model
- The theory includes:
  - Strong interactions due to the color charges of quarks and gluons.
  - A combined theory of weak (weak charge) and electromagnetic interaction (charge), 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.

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What is matter

• Matter is the collection of objects made of baryons and leptons.

• Objects have quantum numbers that describe their nature

Electron:
Charge, lepton number, baryon number, etc.

Electrons also have mass. What is mass?

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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

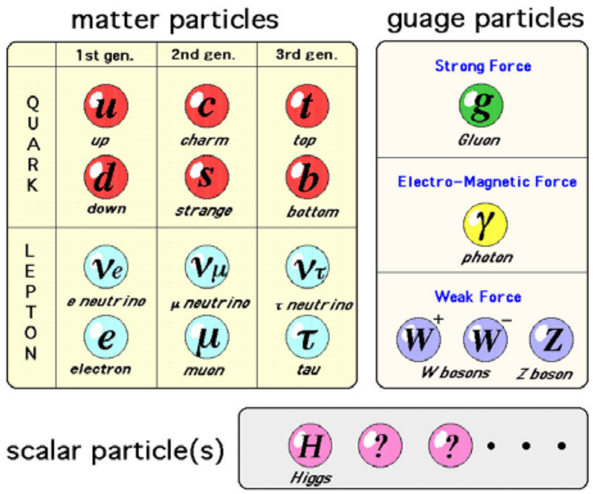
Standard Model Particles

Charge

+2/3 →

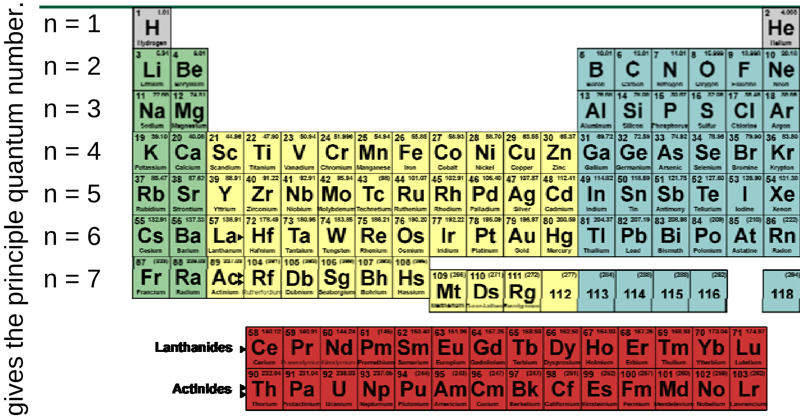
-1/3 →

Anti-particles have the opposite charge.



Quantum Numbers (1)

The row gives the principle quantum number.



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

$n \rightarrow p^+ + e^-$ NOTALLOWED (lepton number)

$n \rightarrow p^+ + e^- + \bar{\nu}$ 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.

$n + p^+ \rightarrow \pi^+ + \pi^+ + \pi^-$ $\pi^- \rightarrow e^- + \bar{\nu}$

The standard model explains how particles interact and transform.

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What is mass

- Most mass in matter comes from energy: $E=mc^2$
- The mass of the quarks that make up a proton is only a few percent of the mass. Most of the mass is in gluons (the carriers of the force).

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What is mass? The interaction with a field

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.

CERN

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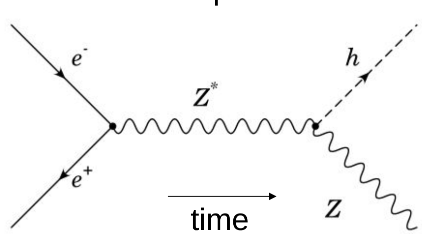
Higgs Particle

- The Higgs is the most famous undiscovered particle. A new collider called the Large Hadron Collider may find it.
- The world community is spending 10 billion $ to find this.

Here is how to produce one:



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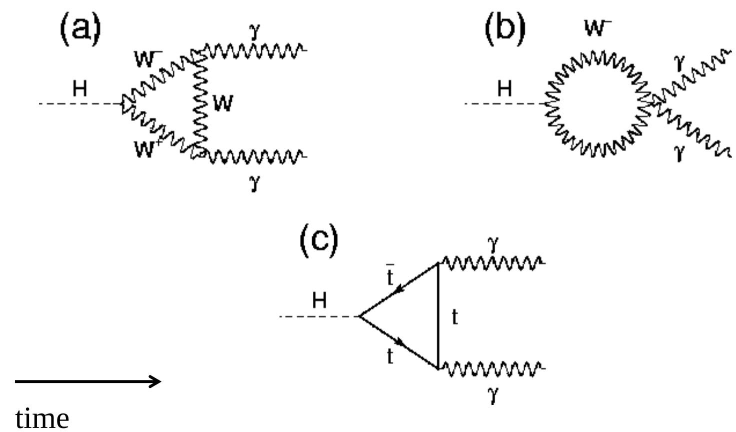
How the Higgs will decay and be detected



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? Same for lepton number and baryon number…
- 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.

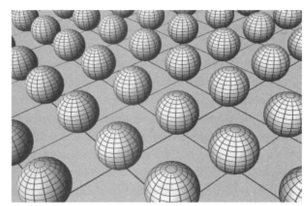
What comes next?

- 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.

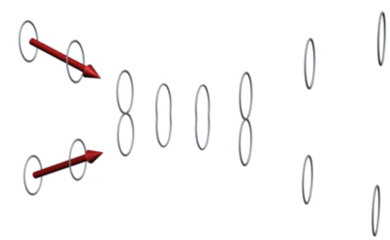
Superstring Theory

- One of the 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

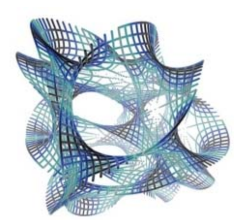
String Theory Pictures



Extra Dimensions



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



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

More energy – smaller wavelength

- It is a quirk of nature that, the smaller a particle is, the greater is the energy need to see it.
- To study a particle you have to have sufficient concentrated energy to create it.
- This has fueled the construction of particle accelerators, then colliders, which have continuously increased in size.

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Scale of Energy (per Particle)

- Chemistry Experiment ~0.1-5 eV
- First Cyclotron (USA) 8E4 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

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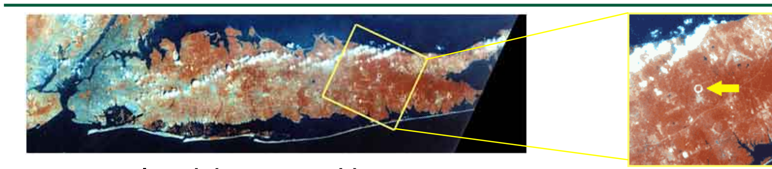
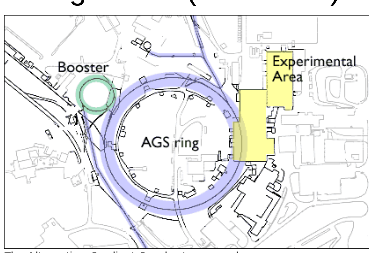
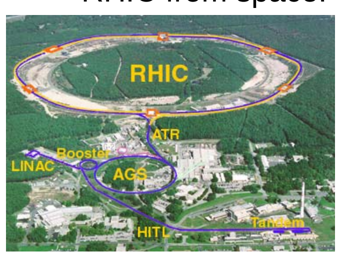
Relativistic Heavy-Ion Collider



Long Island (New York) RHIC from space!



The Alternating Gradient Synchrotron complex



Goal: Create a plasma of quarks and gluons

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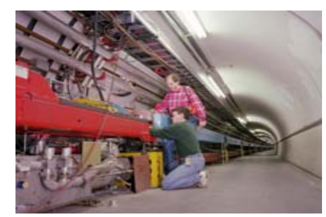
Tevatron – Fermilab (Illinois)



Goal: Produce the top quark

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Tevatron - Fermi National Laboratory (Illinois)

Goal: Produce the top quark

Drift Tube Linac

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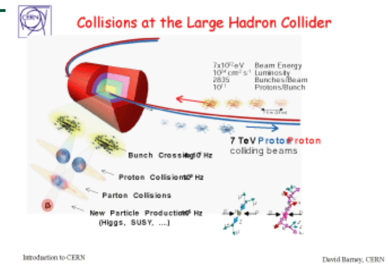
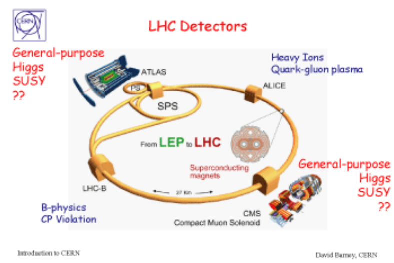
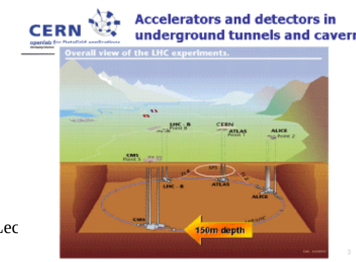
Large Hadron Collider – CERN (Europe)







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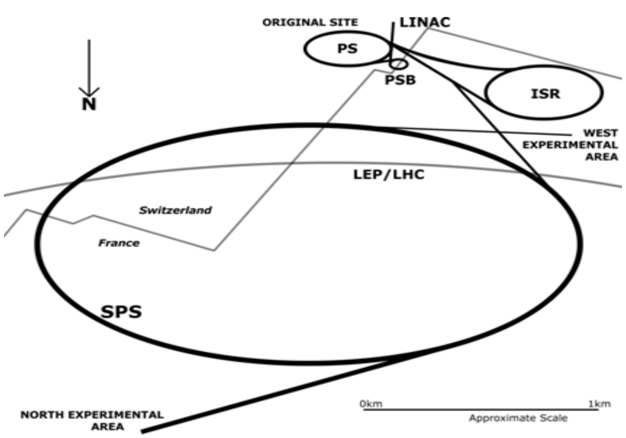
CERN Beam Gymnastics (2)



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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 isotope (^{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?