Fundamental Particles and the Forces that Move Them

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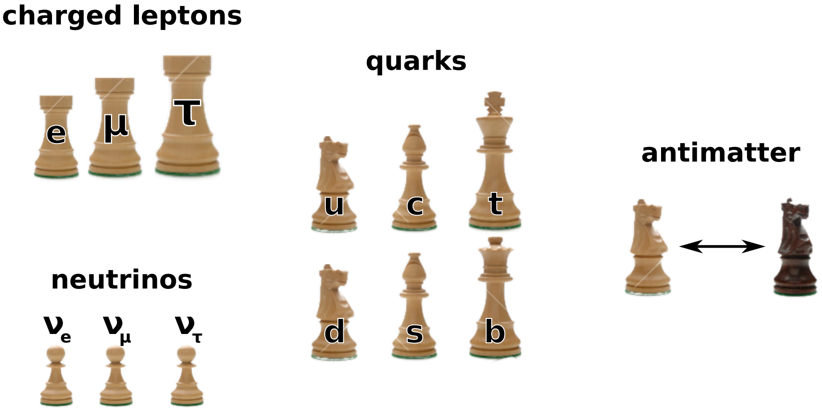
The basic idea: an analogy

- Studying particle physics is like trying to figure out the rules of the universe's chess game
- Other sciences study game-strategies using rules we already know
- But there's still more to learn about the basic rules


charged leptons
e
μ
τ
neutrinos
ν_e
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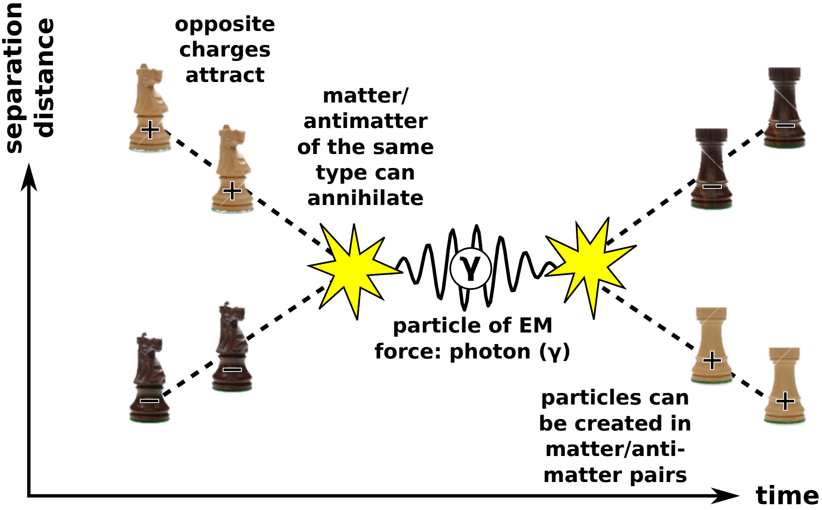
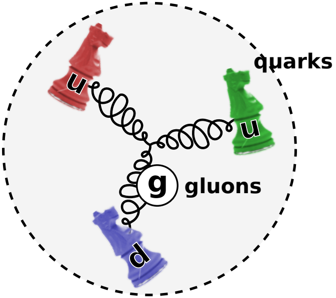
quarks
u
c
t
d
s
b
antimatter

The electromagnetic force:

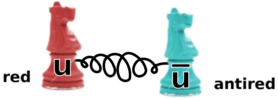


different "colors" of quarks attract; bound quarks form composite particles

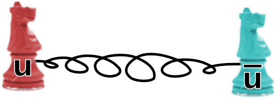


proton

bound quarks can never be truly separated

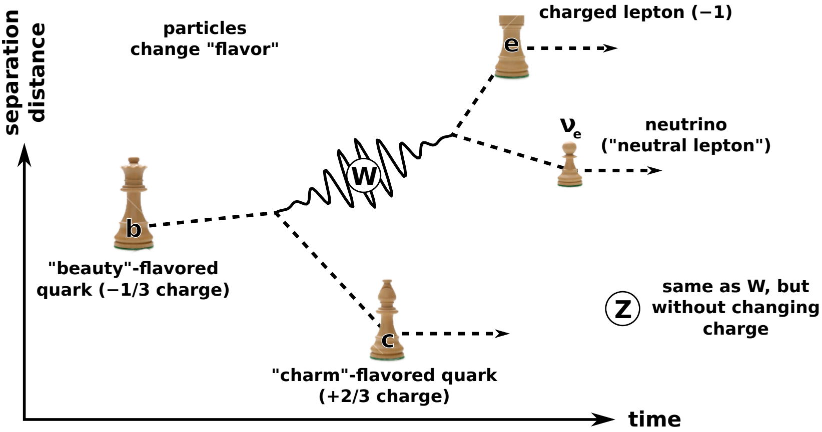


attempting to do so requires so much energy



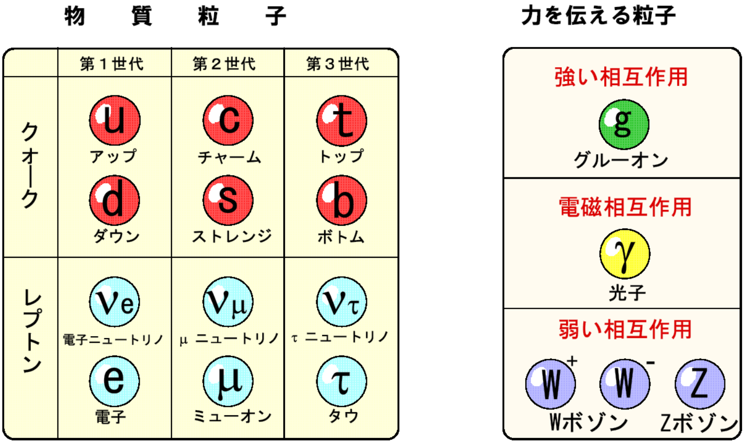
that you just end up making more quarks

The weak interaction:

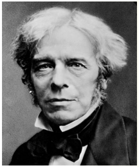


Is this all? How did we get here?

The Standard Model of Particle Physics



Timeline 1: everything settles into place

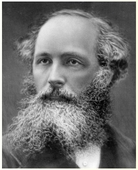


1830: Faraday's Law

Unification of electricity and magnetism

1900

1860: Maxwell's Equations



Basic rules of the universe seemed to be understood: any new phenomena were explained in terms of electromagnetism

Timeline 2: everything jumps out of place!

1902: Discovery of Radium

1924: Intrinsic Spin

1934: Weak Interaction and the Neutrino

1900

1940

1900: Quantization of Energy

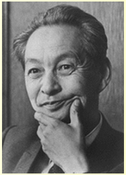
Discovery of radiation, quantum effects, nuclear force: there were surprises everywhere

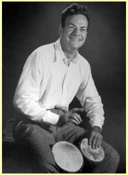
Clearly, we had more to learn about the basic rules!

1939: Nuclear Fission

Timeline 3: everything starts settling again

1926: Quantum Mechanics





Late 1940's: Quantum Field Theory and
Quantum Electrodynamics

1920 → **1950**

1930's: Nuclear Models

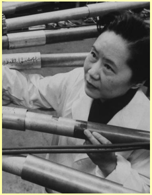
Quantum theory describes electromagnetism very well... now, on to nuclear/weak forces!

Timeline 4: everything gets more complex

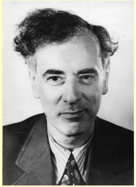
1950's and 60's: Too Many "Fundamental" Particles

1950 **1974**

1956: Parity Violation



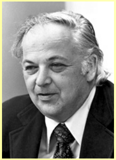
1960's: Quantum Field Theory
is Not Fundamental?



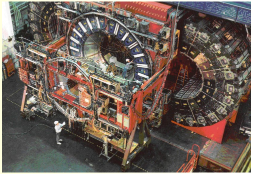
**Nuclear and weak forces
are very strange!
Even quantum mechanics
doesn't know what to
do with them...**

Timeline 5: it all makes sense again!

. . . or does it?



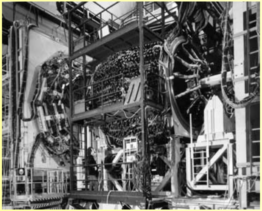
1974: Discovery of Charm Quark helps Standard Model to coalesce

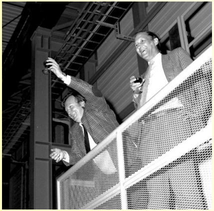


1995: Discovery of Top Quark and many precision tests of the Standard Model

1974 → **now**

1983: Discovery of W and Z bosons; Standard Model is Confirmed

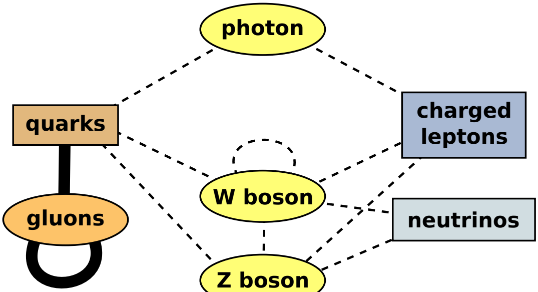




Standard Model is amazingly well-verified... but we know that it is incomplete

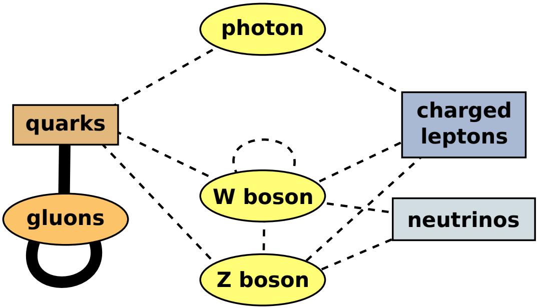
#1: The Standard Model *needs* a Higgs

Couplings between particles (matter and forces):



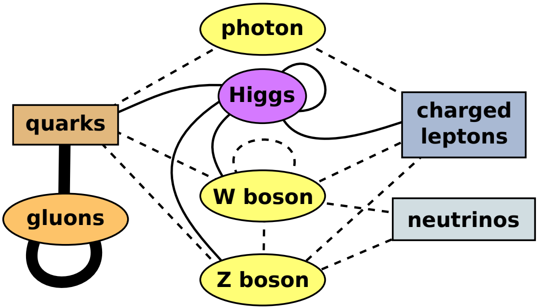
#1: The Standard Model *needs* a Higgs

Couplings between particles (matter and forces):



- Force particles cannot have mass in the fundamental theory
- W and Z have very large masses, in apparent contradiction

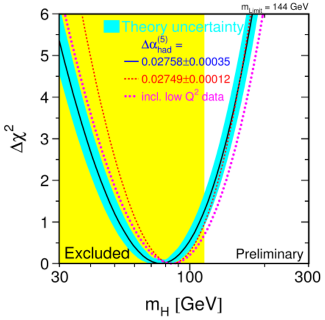
Couplings between particles (matter and forces):

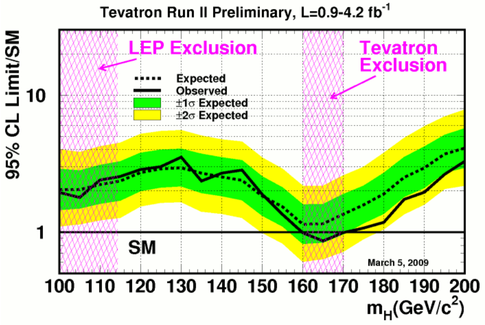


- Force particles cannot have mass in the fundamental theory
- W and Z have very large masses, in apparent contradiction
- Their masses can be dynamically generated by interacting with another field: the Higgs boson

But where is it?

- From W, Z, and top quark masses, best-fit Higgs mass should be 80 GeV
- Higgs mass below 114 GeV and between 160–170 GeV are ruled out by experiment
- The whole picture is possible, but increasingly unlikely as more possibilities are ruled out

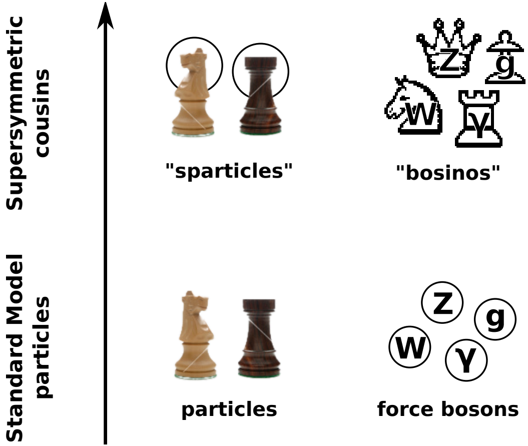




#2: The Standard Model is unnatural

- The Standard Model does not include quantum gravity
  - somehow, it needs to fit into a larger theory that does (string theory?)
- The connection between the Standard Model and a fully unified theory is awkward:
  - no explanation why Higgs mass would be as light as it needs to be
  - doesn't properly unify electromagnetic, nuclear, and weak forces at high energy
- Very likely, there is another piece to the puzzle between the Standard Model and quantum gravity

- Introducing a new relationship between matter particles and force particles solves both problems
- Also provides us with a lot more particles to discover!



#3: We know there's other stuff out there

Astronomers have determined the following composition of the universe from recent measurements:

- 0.03% of it is heavy elements (anything solid, like us)
- 0.3% neutrinos
- 0.5% stars
- 4% free-floating H, He gasses
- 25% some new kind of particle, *not in the Standard Model* ("dark matter")
- 70% something else, not even particle-like ("dark energy")

What to do about it: TeV-scale colliders!

From *Popular Mechanics*, 1978; immediately after the Standard Model was formulated and its implications realized

30-mile 'donut' to spin out atomic secrets

World's mightiest atomic accelerator, so huge it will span the border between two European countries, may unlock deep mysteries of the universe—and unleash virtually unlimited supplies of vital electric power.

by Hans Fantel

It will be so big you can see it in its entirety only by looking down from a mountaintop or airplane. A circular tube with a mind-boggling circumference of 30 miles, it's the largest machine ever conceived. It's still in the planning stage, but represents the most ambitious concept yet for building an atomic particle accelerator—popularly known as an atom smasher.

Why the incredible size? Such devices need a long path to accelerate their subatomic particle "bullets" up to the tremendous velocities required to penetrate and break down matter at the atomic level—just as a jumbo jet needs a long runway to get up to flying speed. The longer the path, the greater the acceleration that can be achieved.

Is such a giant merely a paper dream? By no means. The technology for building it exists—the final design, financing, location of construction site, and certain political considerations must still be worked out. But atom smashers have been getting bigger and more powerful all the time—a sign of even more ambitious projects to come. The famed Brookhaven accelerator, half a mile in circumference, is already dwarfed by a similar one with a four-mile girth at Fermilab in Batavia, Ill., currently the biggest atom smasher in the world. And now being planned is another, more modern installation for Brookhaven that will outpower them all—at least until that 30-mile monster goes into operation.

The newly proposed superaccelerator still has no official name. It's just called the VBA—short for Very Big Accelerator, which is an understatement if there ever was one. While the primary objective of the VBA will be to explore the properties of the atom and physical laws governing the universe, its findings may also lead to new ways of mass-producing nuclear energy in safe, economical, commercially usable quantities. If so, such discoveries might well provide virtually unlimited supplies of urgently needed electric power.

Since the VBA will be such a gigantic and costly undertaking, it is unlikely that any one nation could afford to foot the bill by itself. Thus the United States, the Soviet Union and several European countries are expected to chip in, making the project a truly international effort.

While a site has not been definitely chosen, the VBA will probably be built near Geneva, Switzerland (see map at left). To accommodate its immense size—and also to symbolize its international character—it may lie partially in France, straddling the French-Swiss border.

Actually, you won't be able to see the VBA as a whole at all since most of it will be constructed underground, with above-ground service and laboratory facilities stationed along its length. If all goes according to plan, the giant machine will be switched on in the year 2000—a fitting technological milestone to mark the turn of the century.

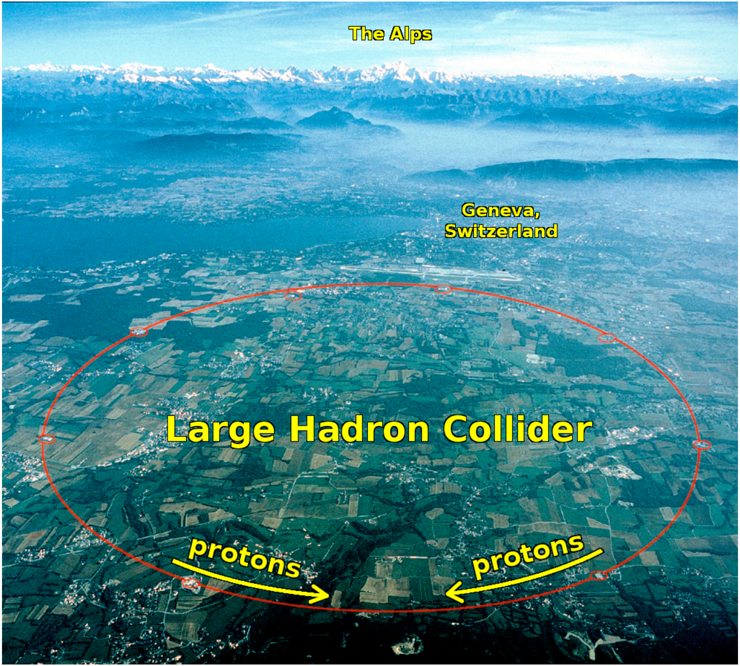
New twists in technology

All atomic accelerators are basically similar in principle and share the same purpose: to produce an intense beam of subatomic particles, such as protons, that will penetrate

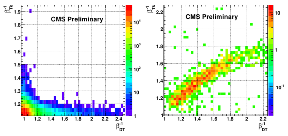
Map below shows one possible site for proposed new 30-mile-long atomic accelerator. If plan is adopted, the mammoth ring would span the boundary between France and Switzerland near Lake Geneva. It would be a joint international venture, built and operated by several countries.

Like an entry ramp to a superhighway, this 500-foot-long linear (straight-line) accelerator at Fermilab pushes protons up to velocities needed to enter high-speed lanes in main circular accelerator. Such "preboosters" will be used in proposed 30-mile atom smasher shown above.

Plan for new Brookhaven accelerator has twin tubes whirling counterrotating proton beams. Future 30-mile atom smasher depicted at left may use same arrangement.


The Alps
Geneva,
Switzerland
Large Hadron Collider
protons
protons

Hopefully, we'll soon be confused again



Lots of weird discoveries that will leave us wondering...

now **future**