Discovering new particles

The ATLAS Experiment Control Room at the Large Hadron Collider, 20 November 2009.

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at:
WoPhyS2016

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On 4 July 2012, two international experiments announced simultaneously the discovery of the Higgs Boson. This was the culmination of a project that began 20 years earlier, with the formation of those collaborations in 1992.

The announcement was made at 9am in Geneva, Switzerland. ➔

Five hundred thousand people around the world watched the presentation streamed live.

700 people gathered in a conference hall in Australia to watch.➔

250 people gathered in a conference hall at Fermilab, Chicago, *AT 2AM* to listen.

1000 television stations and 5000 news programs showed video footage of the announcement.

People gathered in Germany
to watch the live stream➔

People gathered in Japan
to watch the live stream🡇

People gathered in California
to watch the live stream➔

Why would people all over the world stop what they were doing, or wake up in the middle of the night, to watch this announcement about the discovery of a particle?

We already know of hundreds of types of particles. The Particle Data Book, a printed catalog listing all of them, is 1700 pages long. ***Here are a few of them,*** from a list in Wikipedia.

Baryon resonance particles

Nucleons			Δ particles			Λ particles			Σ particles			Ξ and particles			Charmed particles			Bottomed particles		
p	$1/2^+$	****	Δ(1232)	$3/2^+$	****	Λ	$1/2^+$	****	Σ^+	$1/2^+$	****	Ξ^0	$1/2^+$	****	Λ_c^+	$1/2^+$	****	Λ_b^0	$1/2^+$	***
n	$1/2^+$	****	Δ(1600)	$3/2^+$	***	Λ(1405)	$1/2^-$	****	Σ^0	$1/2^+$	****	Ξ^-	$1/2^+$	****	$\Lambda_c(2595)^+$	$1/2^-$	***	$\Lambda_b(5912)^0$	$1/2^-$	***
N(1440)	$1/2^+$	****	Δ(1620)	$1/2^-$	****	Λ(1520)	$3/2^-$	****	Σ^-	$1/2^+$	****	Ξ(1530)	$3/2^+$	****	$\Lambda_c(2625)^+$	$3/2^-$	***	$\Lambda_b(5920)^0$	$3/2^-$	***
N(1520)	$3/2^-$	****	Δ(1700)	$3/2^-$	****	Λ(1600)	$1/2^+$	***	Σ(1385)	$3/2^+$	****	Ξ(1620)		*	$\Lambda_c(2765)^+$		*	Σ_b	$1/2^+$	***
N(1535)	$1/2^-$	****	Δ(1750)	$1/2^+$	*	Λ(1670)	$1/2^-$	****	Σ(1480)		*	Ξ(1690)		***	$\Lambda_c(2880)^+$	$5/2^+$	***	Σ^*_b	$3/2^+$	***
N(1650)	$1/2^-$	****	Δ(1900)	$1/2^-$	**	Λ(1690)	$3/2^-$	****	Σ(1560)		**	Ξ(1820)	$3/2^-$	***	$\Lambda_c(2940)^+$		***	Ξ_b^0, Ξ_b^-	$1/2^+$	***
N(1675)	$5/2^-$	****	Δ(1905)	$5/2^+$	****	Λ(1800)	$1/2^-$	***	Σ(1580)	$3/2^-$	*	Ξ(1950)		***				$\Xi_b(5945)^0$	$3/2^+$	***
N(1680)	$5/2^+$	****	Δ(1910)	$1/2^+$	****	Λ(1810)	$1/2^+$	***	Σ(1620)	$1/2^-$	*	Ξ(2030)	$\frac{5}{2}$?	***	$\Sigma_c(2455)$	$1/2^+$	****	^-_b	$1/2^+$	***
N(1685)		*	Δ(1920)	$3/2^+$	***	Λ(1820)	$5/2^+$	****	Σ(1660)	$1/2^+$	***	Ξ(2120)		*	$\Sigma_c(2520)$	$3/2^+$	***			
N(1700)	$3/2^-$	***	Δ(1930)	$5/2^-$	***	Λ(1830)	$5/2^-$	****	Σ(1670)	$3/2^-$	****	Ξ(2250)		**	$\Sigma_c(2800)$		***			
N(1710)	$1/2^+$	***	Δ(1940)	$3/2^-$	**	Λ(1890)	$3/2^+$	****	Σ(1690)		**	Ξ(2370)		**						
N(1720)	$3/2^+$	****	Δ(1950)	$7/2^+$	****	Λ(2000)		*	Σ(1750)	$1/2^-$	***	Ξ(2500)		*	Ξ_c^+	$1/2^+$	***			
N(1860)	$5/2^+$	**	Δ(2000)	$5/2^+$	**	Λ(2020)	$7/2^+$	*	Σ(1770)	$1/2^+$	*				Ξ_c^0	$1/2^+$	***			
N(1875)	$3/2^-$	***	Δ(2150)	$1/2^-$	*	Λ(2100)	$7/2^-$	****	Σ(1775)	$5/2^-$	****	$^-$	$3/2^+$	****	Ξ'^+_c	$1/2^+$	***			
N(1880)	$1/2^+$	**	Δ(2200)	$7/2^-$	*	Λ(2110)	$5/2^+$	***	Σ(1840)	$3/2^+$	*	$(2250)^-$		***	Ξ'^0_c	$1/2^+$	***			
N(1895)	$1/2^-$	**	Δ(2300)	$9/2^+$	**	Λ(2325)	$3/2^-$	*	Σ(1880)	$1/2^+$	**	$(2380)^-$		**	$\Xi_c(2645)$	$3/2^+$	***			
N(1900)	$3/2^+$	***	Δ(2350)	$5/2^-$	*	Λ(2350)	$9/2^+$	***	Σ(1915)	$5/2^+$	****	$(2470)^-$		**	$\Xi_c(2790)$	$1/2^-$	***			
N(1990)	$7/2^+$	**	Δ(2390)	$7/2^+$	*	Λ(2585)		**	Σ(1940)	$3/2^-$	***				$\Xi_c(2815)$	$3/2^-$	***			
N(2000)	$5/2^+$	**	Δ(2400)	$9/2^-$	**				Σ(2000)	$1/2^-$	*				$\Xi_c(2930)$		*			
N(2040)	$3/2^+$	*	Δ(2420)	$11/2^+$	****				Σ(2030)	$7/2^+$	****				$\Xi_c(2980)$		***			
N(2060)	$5/2^-$	**	Δ(2750)	$13/2^-$	**				Σ(2070)	$5/2^+$	*				$\Xi_c(3055)$		**			
N(2100)	$1/2^+$	*	Δ(2950)	$15/2^+$	**				Σ(2080)	$3/2^+$	**				$\Xi_c(3080)$		***			
N(2120)	$3/2^-$	**							Σ(2100)	$7/2^-$	*				$\Xi_c(3123)$		*			
N(2190)	$7/2^-$	****							Σ(2250)		***									
N(2220)	$9/2^+$	****							Σ(2455)		**				^0_c	$1/2^+$	***			
N(2250)	$9/2^-$	****							Σ(2620)		**				$_c(2770)^0$	$3/2^+$	***			
N(2300)	$1/2^+$	**							Σ(3000)		*									
N(2570)	$5/2^-$	**							Σ(3170)		*				Ξ_{cc}^+		*			
N(2600)	$11/2^-$	***																		
N(2700)	$13/2^+$	**																		

Do we really need to know about any more particles?

Yes.

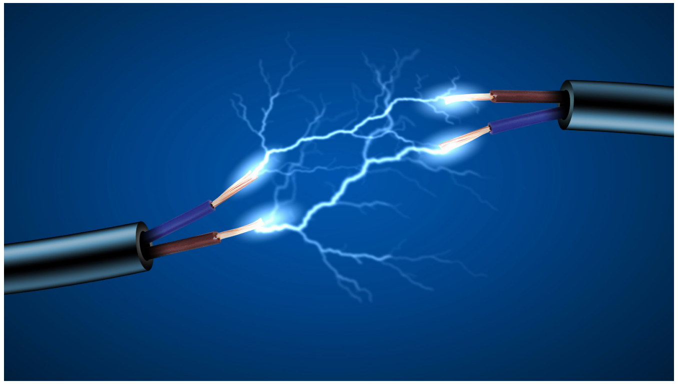
This talk addresses the questions:

- *What are particles?*
- *Why is discovering new particles important?*
- *What can a particle tell us about the nature of the universe?*
- *What might be discovered next?*

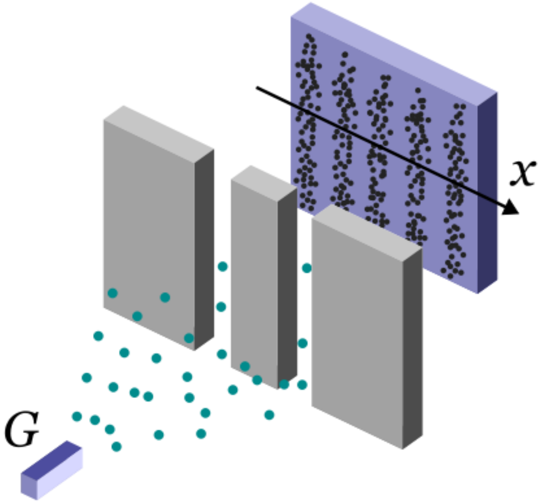
Particle physicists are in the business of finding out the content of nature's cookbook. We want to know the full set of ingredients available in nature's pantry AND (more important) ***the rules that nature uses when combining them***.

Particles and the forces are the ingredients.

One common particle is the electron: the stuff of electricity.



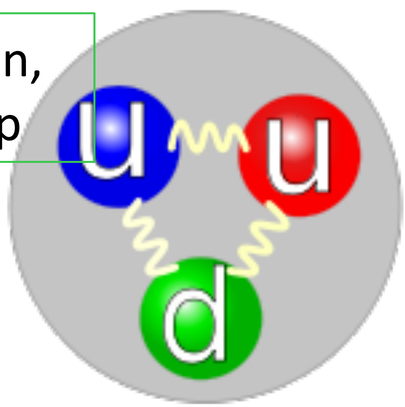
Another common one is the photon: the particle of light.

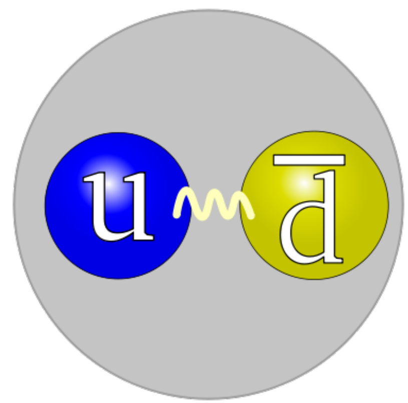


All of the most fundamental particles we know about have the interesting property that THEY OCCUPY NO VOLUME AT ALL. They are "point-like." But at the same time: most of them have mass, which is like weight.

When fundamental particles bind together in clusters ("bound states") of 2 or 3, we sometimes call those clusters "particles" too. An example: the proton, a cluster of 3 fundamental particles called quarks. The clusters are not point-like.

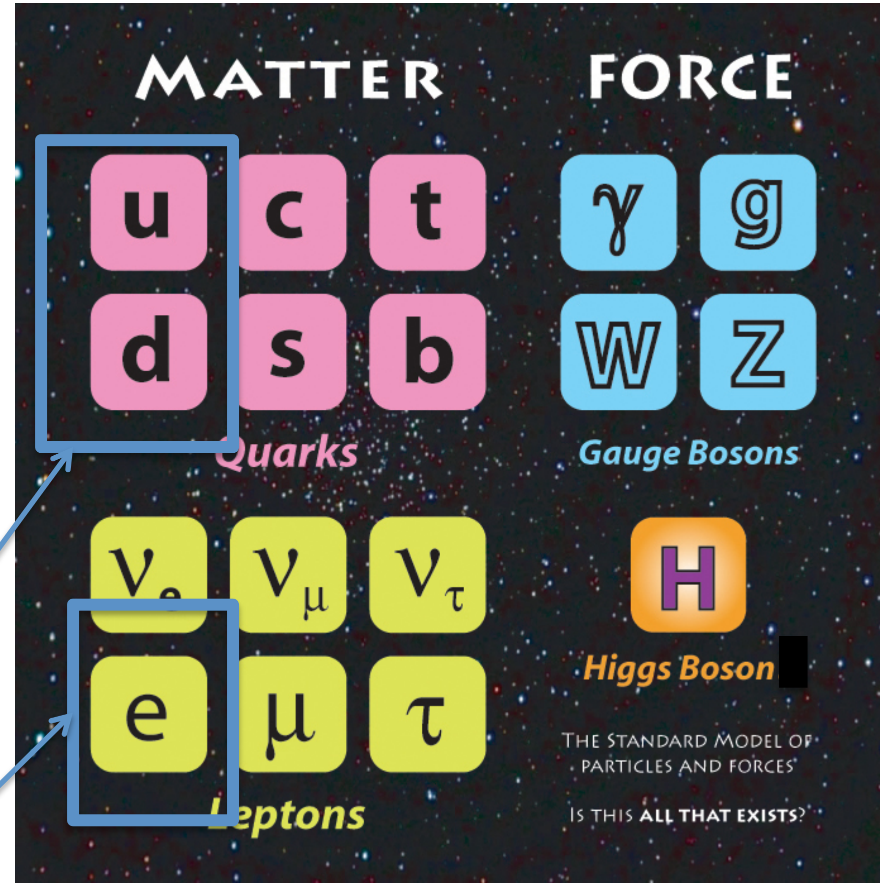
a proton, close up





Here's the complete set of the point-like fundamental ones.➔

The bound states ("clusters") fill up the other 1699-or-so pages in that Particle Data Book.



The u and d quarks make up the protons and neutrons that compose a nucleus.

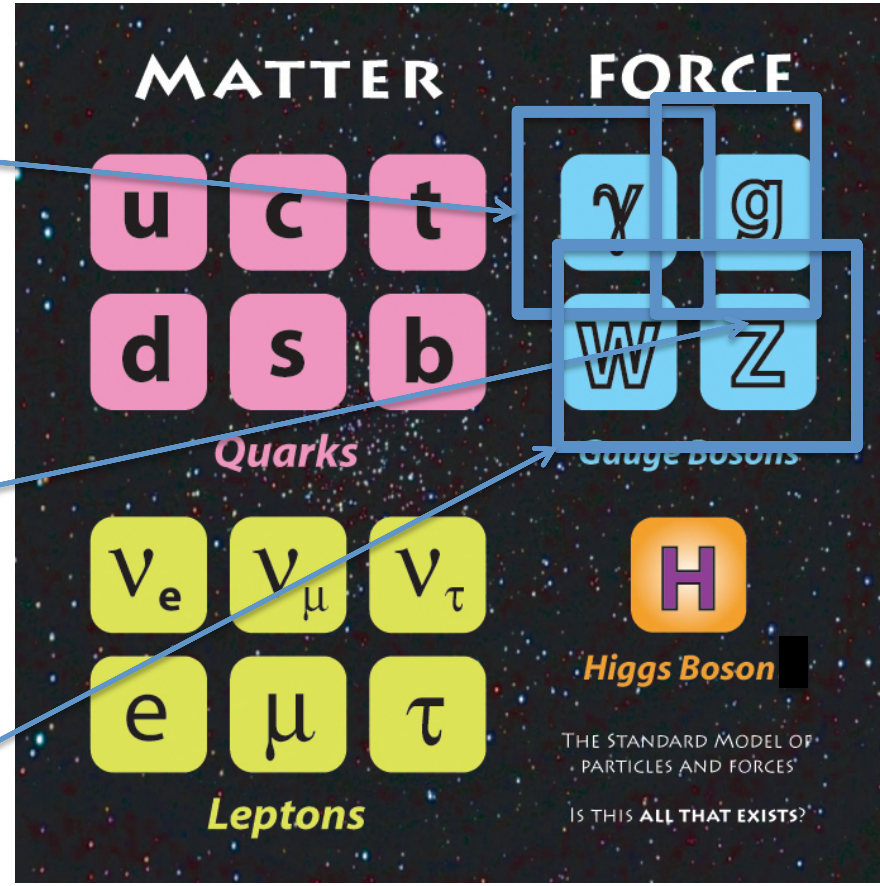
The electron orbits the nucleus.

And there's antimatter, which does exist, but is not classified as a separate fundamental type of particle.

The photon γ transmits the electromagnetic force between any 2 charged particles.

The gluon g transmits the strong force between any 2 quarks. Especially: it holds the nucleus together.

The W and Z carry the weak force that produces radioactive decay.

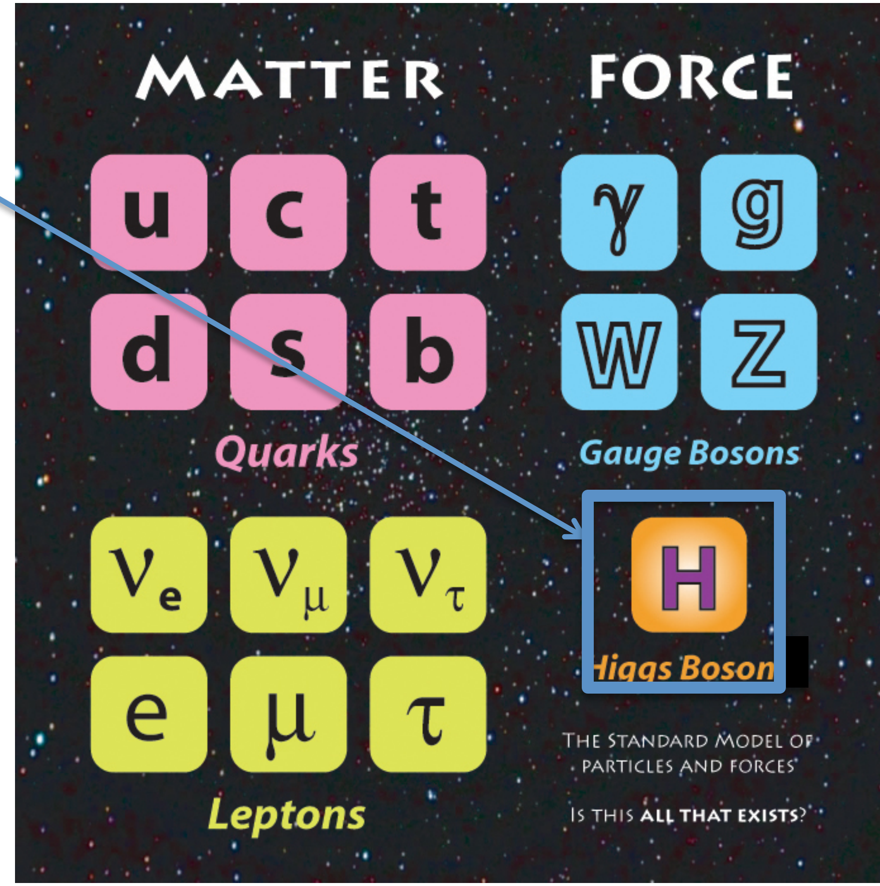


Notice there is no particle shown here for the transmission of gravity. The graviton has not been discovered.

Notice also that there are particles here we haven't mentioned yet...c, s, t, b, ν, μ, τ...they HAVE been observed, but their role in nature is still unclear.

There's also the Higgs boson H...more about it later.

Many more have been proposed, but until they are observed, they're classified as Beyond the Standard Model, "BSM." **What we have here is The Standard Model.**



Searching for new things and finding them is fun---but ***what's most interesting is seeing whether they form a pattern.***

THE KEY WORD FOR THIS SLIDE IS: "PATTERN"

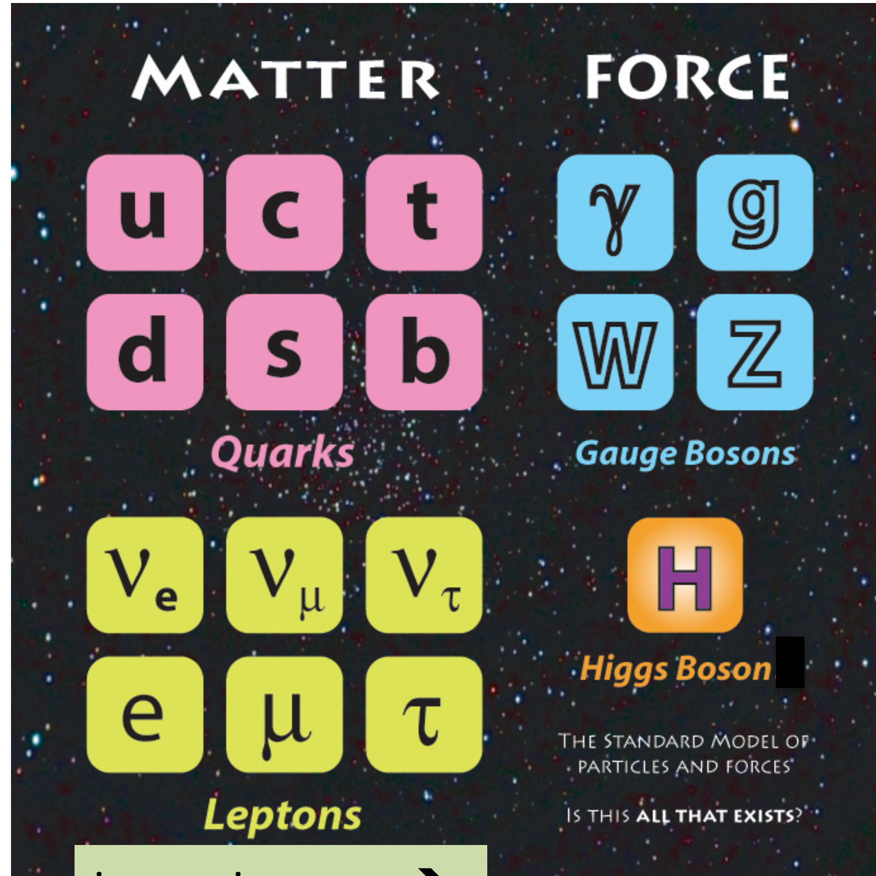
We see curious patterns among the particles....

The pair of light quarks u and d is practically replicated in two other heavier pairs (c,s and t,b).

The light lepton pairs are similarly replicated by heavier lepton pairs.

We see the same number of quarks as leptons.

The building blocks (quarks and leptons) come in even numbers.



increasing mass →

APPARENT PATTERNS AMONG THE PARTICLES

Why we're interested in patterns...

Mathematician Emmy Noether showed (1915) that observed patterns ("symmetries") indicate that some quantity is being conserved.

For example : The conservation of angular momentum tells us that space is the same in all directions. We could bisect space with any line, and the two hemisphere would have the same properties.

PATTERN ⇔ CONSERVATION LAW

Noether's Theorem has been called "one of the most important mathematical theorems ever proved in guiding the development of modern physics, [fundamental] on a par with the Pythagorean theorem."*

Why we're interested in conservation laws: *they reveal that phenomena that might seem different are really just alternative forms of the same thing.*

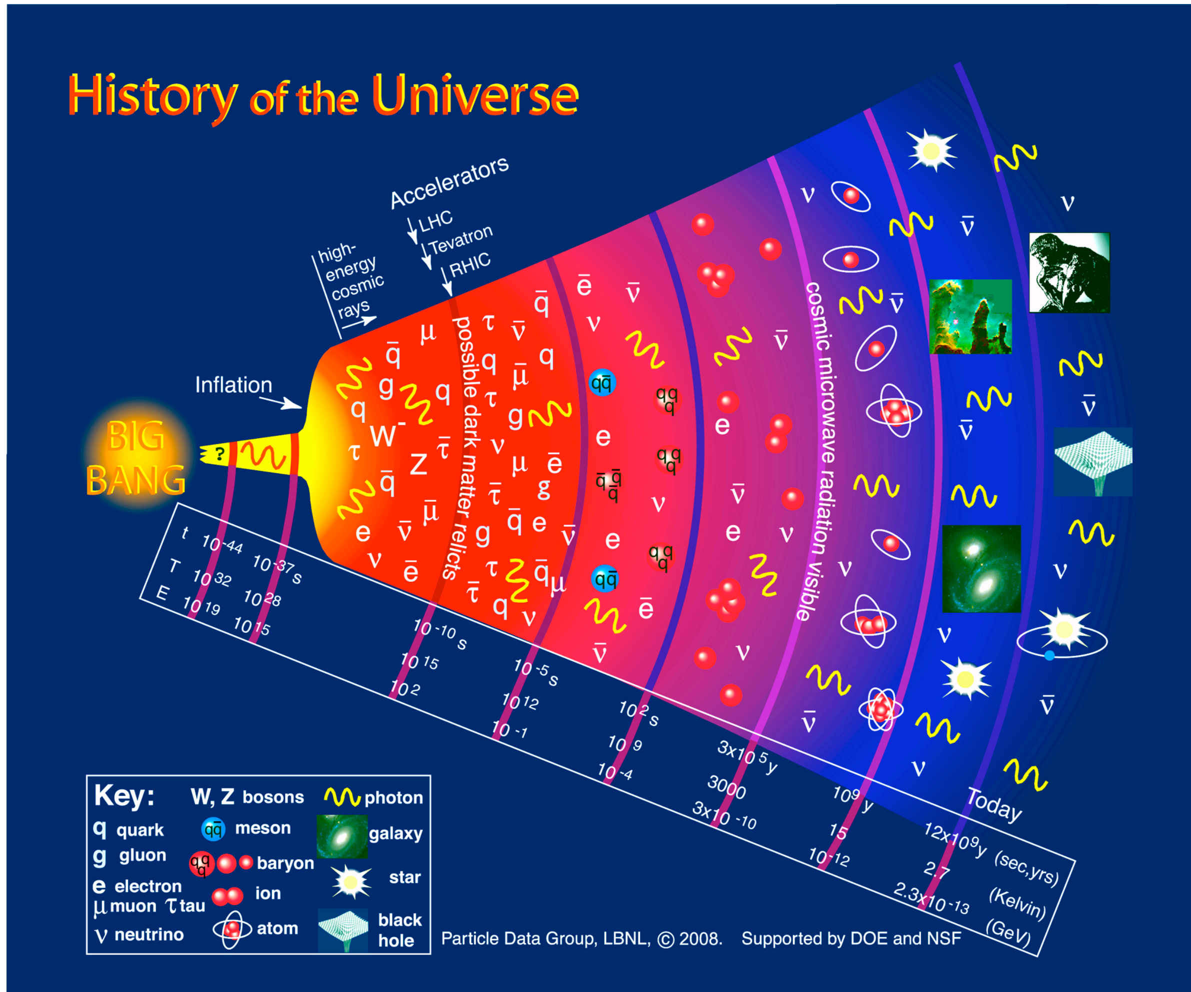
For example: once we know the Law of Conservation of Energy, we see that heat, light, vibration, momentum, and mass are all different forms of the same thing: "energy."

CONSERVATION LAWS ⇔ UNIFICATION OF PHENOMENA

*L. M. Lederman and C.T. Hill, "Symmetry and the Beautiful Universe," (2004) This unification of phenomena is a philosophical ideal that most physicists seem to hold. Maybe the grand diversity of the universe all flows from a single field, taking different forms in different realms.

In many cases, the evidence for the conservation law, the unification, is a PARTICLE.

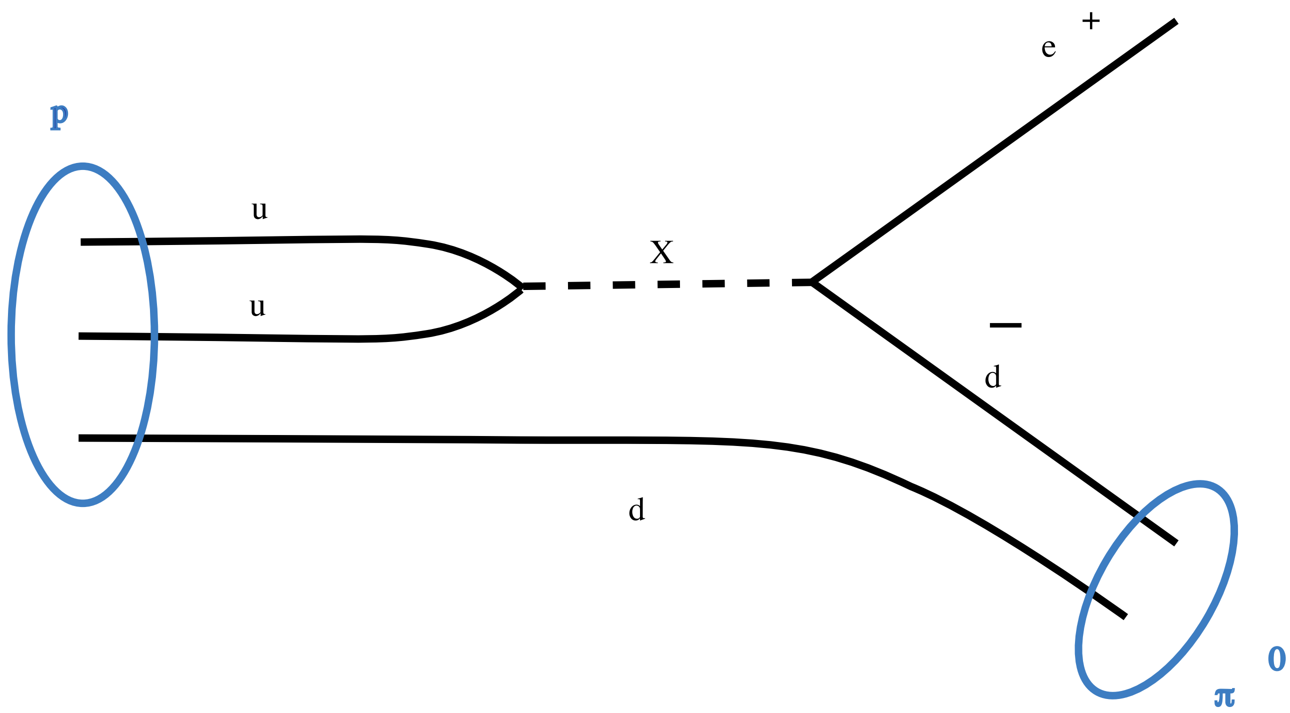
Some illustrations of this follow...



Let's look into some of those patterns…

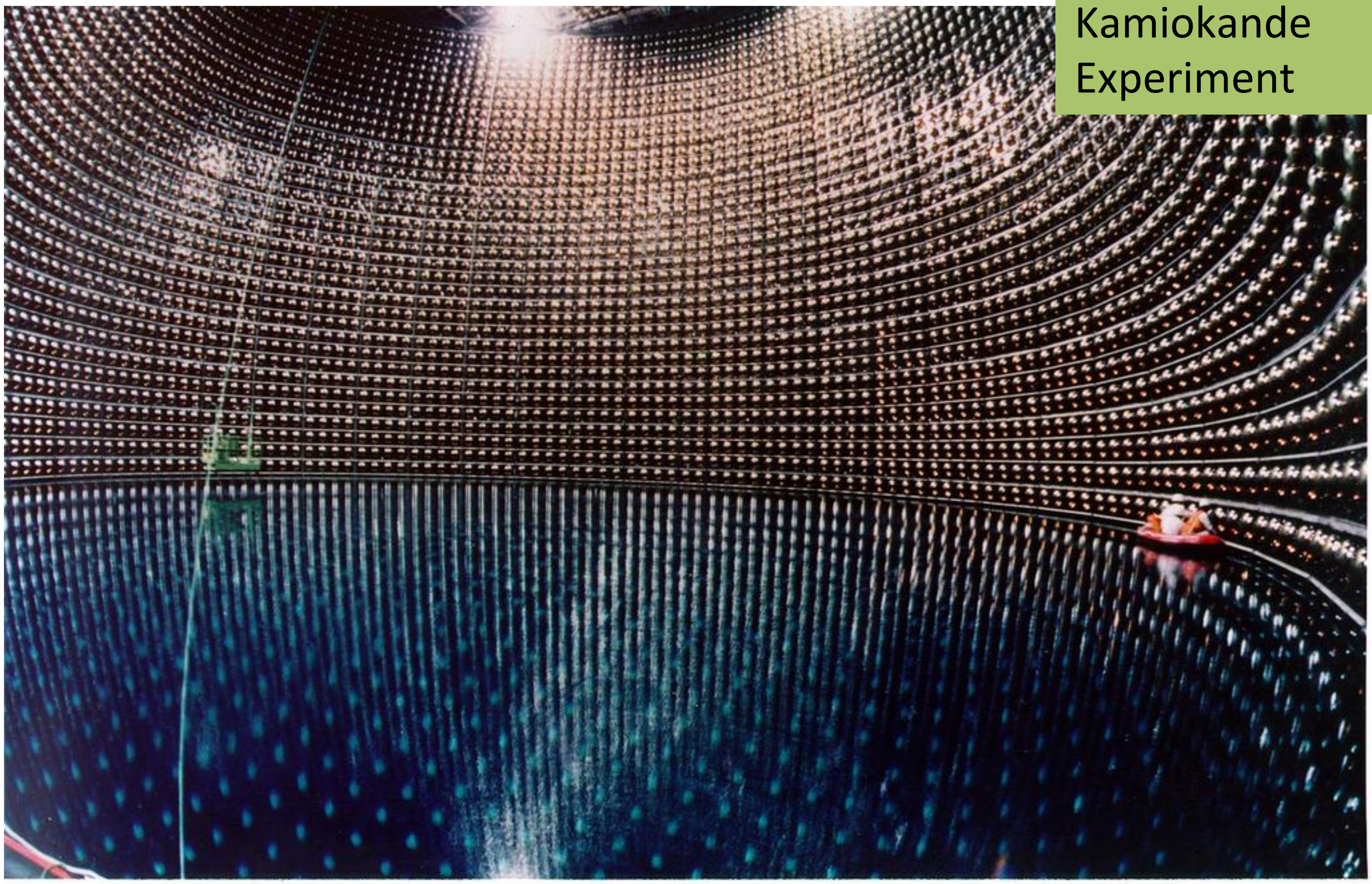
- 6 quarks, 6 leptons --- does everything come in sixes? Or is this a sign that quarks and leptons are just different forms of the same thing? ***Then we should look for the Grand Unification ("GUT") particles*** that transform particles from quarks to leptons.

Here's what a hypothetical GUT particle called X could do: cause protons to vanish, or "decay" by turning their quarks into leptons.



The goal: to find the particle X. The X is thought to live so briefly that no camera in the world can operate fast enough to image it. So instead we look for X indirectly by looking for evidence of its effect: proton decay.

Kamiokande Experiment

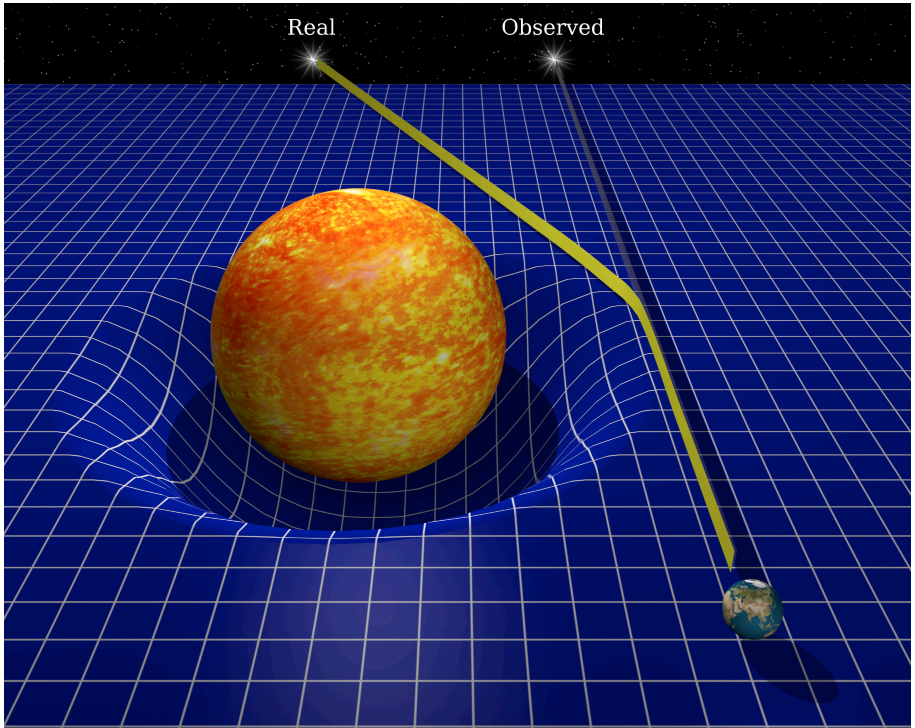


The water in this vessel is the protons. If one decays, it will produce a flash of light that will be recorded by the sensors that cover the wall.

Still thinking about the patterns...could they help us understand the Dark Matter?

You may have heard of Dark Matter...that stuff the scientists hypothesize exists, that bends light by gravitational attraction, but otherwise doesn't interact.

There is more than 5 times more dark matter than normal matter! Many scientists are trying to discover what this Dark Matter is.



We think we see a pattern of 6 quarks, 6 leptons --- or *are there more than 6 leptons*, and could those extra leptons be *part of the dark matter?* ***Then we should look for extra leptons.***

From New Scientist Magazine, 25 February 2014: "**Fresh Hint of Dark Matter Seen in Neutrino Search"**: Astronomers observed light of an unexpected frequency, postulated that it was produced **when a previously undiscovered neutrino** of mass 7 keV transformed itself into 2 photons.

And still thinking about patterns and unification...

- Recall there are 4 fundamental forces: gravity, electromagnetism, the strong force, and the weak force. *Is it possible that they might all be unified as a single force which just seems different in different contexts?*

- Each of the fundamental forces has its own characteristic strength.

  Strongest: the strong nuclear force
  Weakest: gravity
  In-between: electromagnetism and the weak force

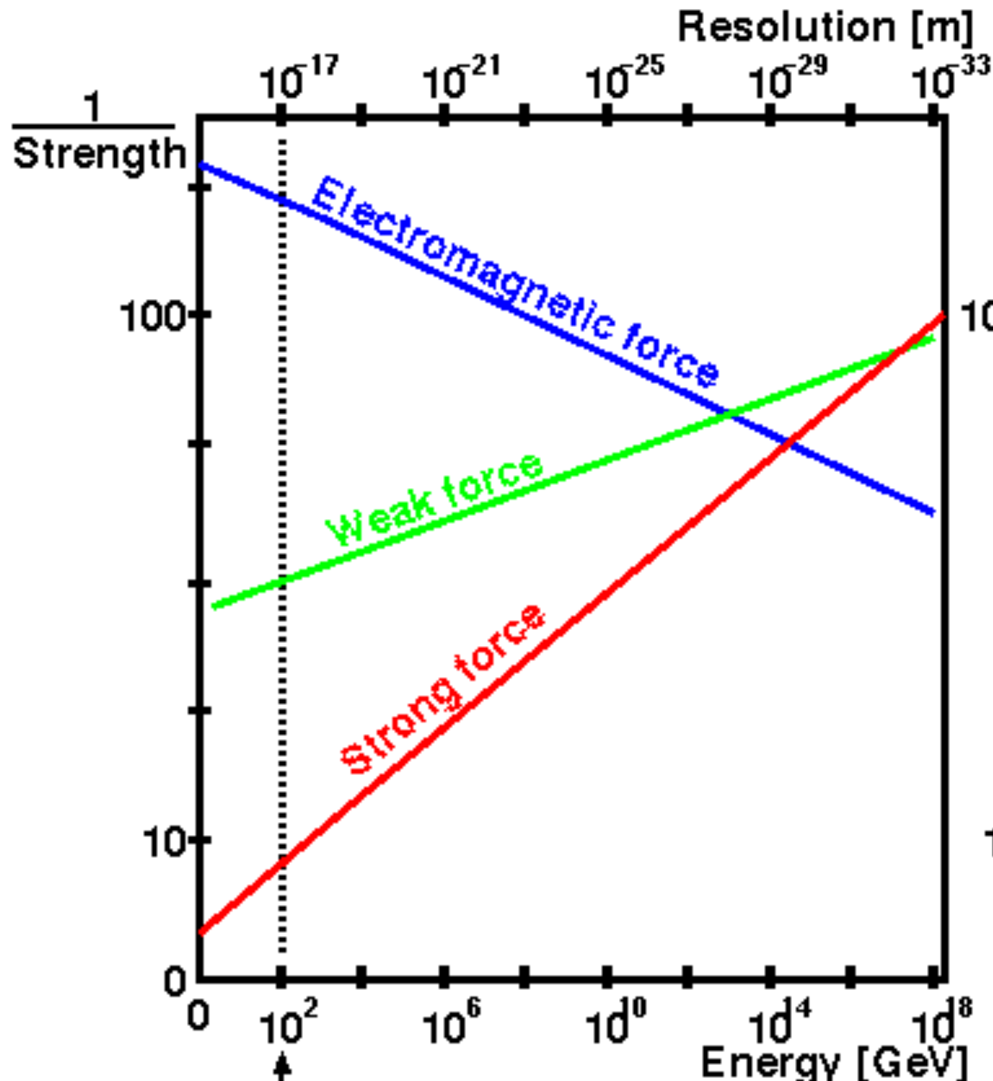
- We call the strength of a force its “coupling.”

- The strength of each coupling depends on the ambient energy. At earlier stages of the universe, when the universe was smaller and hotter, the density of the energy was higher---so the couplings were different.

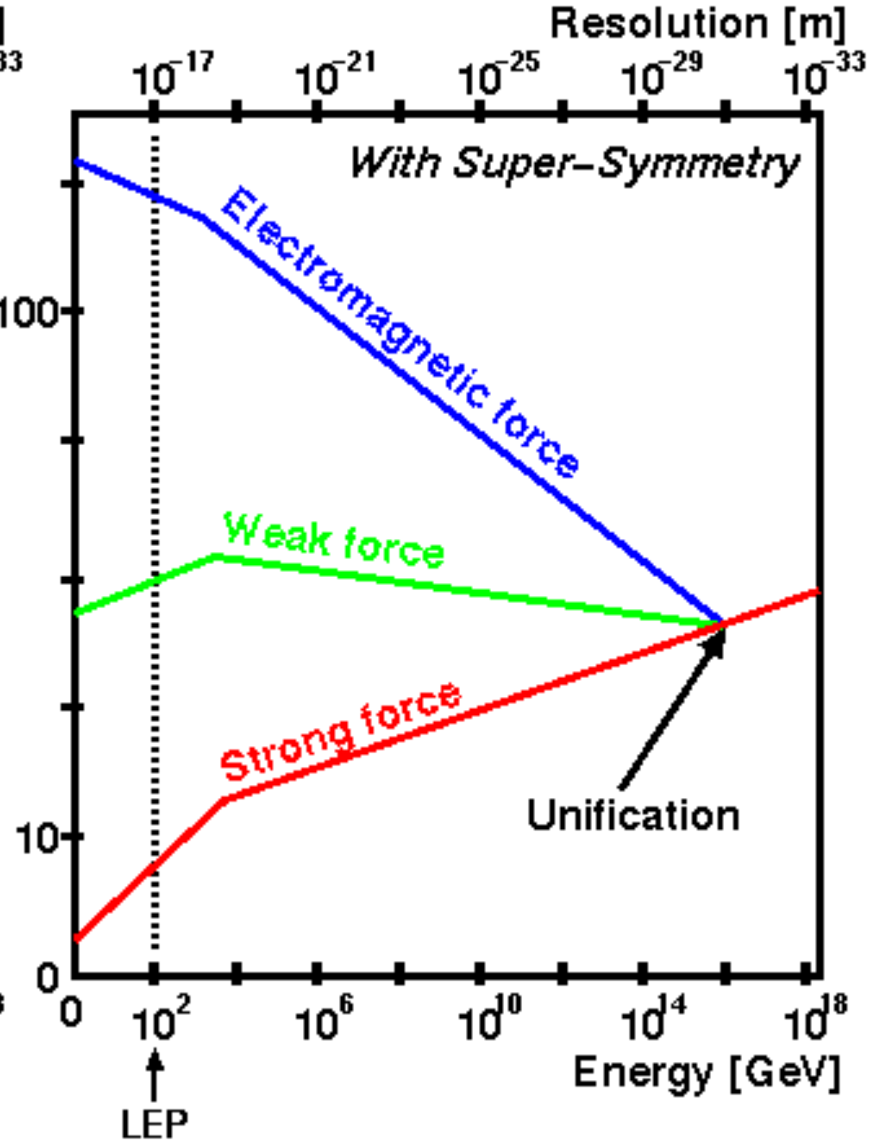
- Knowing the couplings now, and how they depend on energy, we can extrapolate them back to the moment of the Big Bang:

The strength of a force depends on the numbers of types of particles that it could affect.

If we extrapolate the couplings and assume that the universe doesn't have any other kinds of particles than the ones we currently know about, the couplings don't quite come together at the birth of the universe----the forces don't unifiy.



NOW (Direction of time➔) Big Bang



But if we hypothesize that there is a class of particles in the universe, waiting to be discovered, called Supersymmetric ("SUSY") particles, the forces unify.

The idea of SUSY is that every kind of particle we know has a partner particle with a different spin.

These hypothesized partner particles have amazingly silly names, for example:

- The Zino – partner of the Z
- The squark – partner of the quark
- And my new favorite, the sgoldstino, distantly related to Professor Jeffrey Goldstone of MIT.

A non-observation of a particle can be as important as an observation in aiming us toward a new direction.

In one of the most misguided pieces of science journalism ever, Malcolm Browne wrote (New York Times, 5 January 1993) about a groundbreaking measurement by the CDF Collaboration, an article titled **"315 Physicists Report Failure in Search for Supersymmetry."** Far from a failure, the non-observation of a supersymmetric particle demonstrated that the relationship between the "matter particles" (quarks and leptons) and the "force particles" (bosons) is more subtle and complex than our first simple models. This was a major ***advance.*** The The New York Times got that wrong***.***

The point here is:
when we look for a particle, we are not engaged in "stamp collecting." We are not trying to get the 501st member of a huge set of things. On the contrary, the presence or absence of ***every particle has the potential to tell us something foundational*** about nature.

Some particles are hard to find now, because they were most abundant in the hot early universe, but are less common in this cold later era. But they're still in the rule book, so we want to study them....sort of like looking for sunflowers in February.

We need a time machine that can replicate the conditions of the early universe.

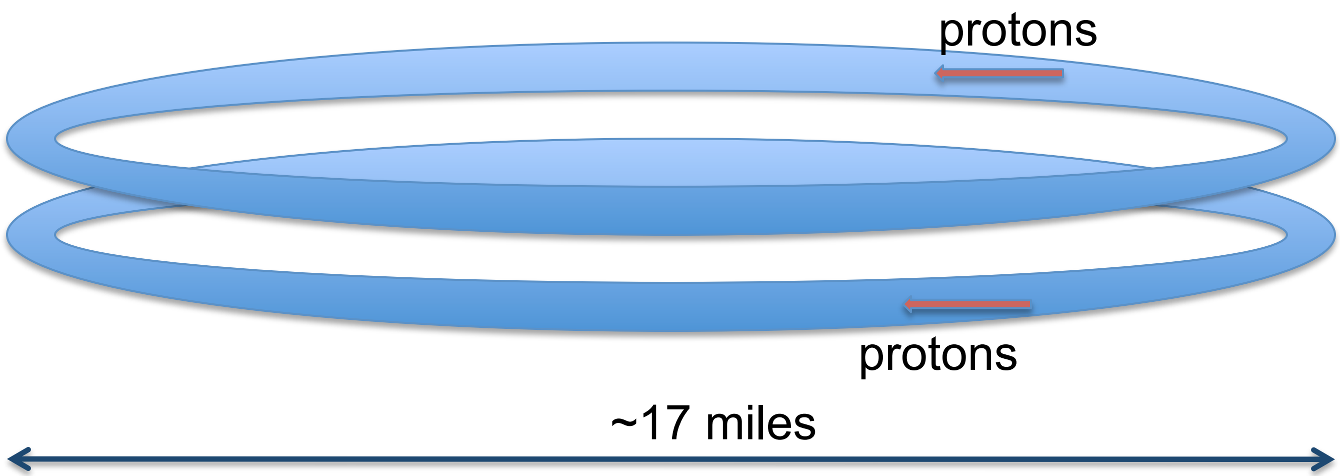
With modern technology, we can replicate the conditions in the universe 1/1000 of a second after the Big Bang. We can build a machine that can concentrate a lot of energy in a small space. This replicates the dense young universe. Then we watch what kinds of particles form naturally in this machine.

The interesting thing is, there is NOT an unlimited variety. Nature seems to have a limited set of ingredients in its cookbook.

Even when we give nature "all the energy it might want" to create anything at all, it "forbids" certain things to exist and "permits" others. Observing what's allowed and what is not allowed is how we infer the rules of nature.

How do these "energy concentrator" machines work?

Take 2 hollow circular pipes with diameter a few miles. Place one below the other.

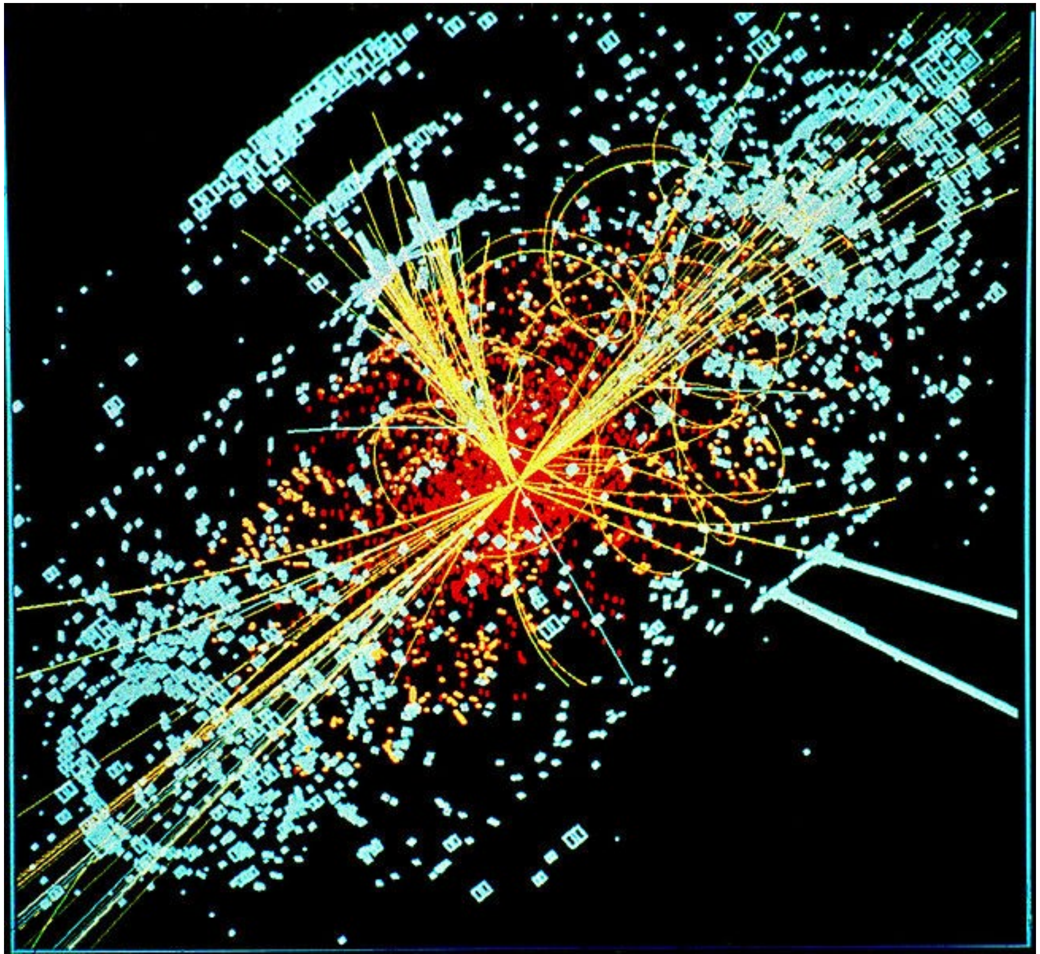


Put common particles in both, for example protons.
Make the protons circulate in opposite directions at speeds of almost ***1 billion miles per hour.***

Now divert their paths so they collide and annihilate at a few points.

When 2 protons collide, they produce a fireball with energy equal to the sum of their 2 masses plus their momenta. These protons have velocity v = 0.999999991 times the speed of light, so the momentum is huge. The energy that results is 8 TeV, equivalent to the energy stored in 8000 protons at rest.

This fireball is a small replica of the condition in the universe 10^{-12} seconds after the Big Bang.

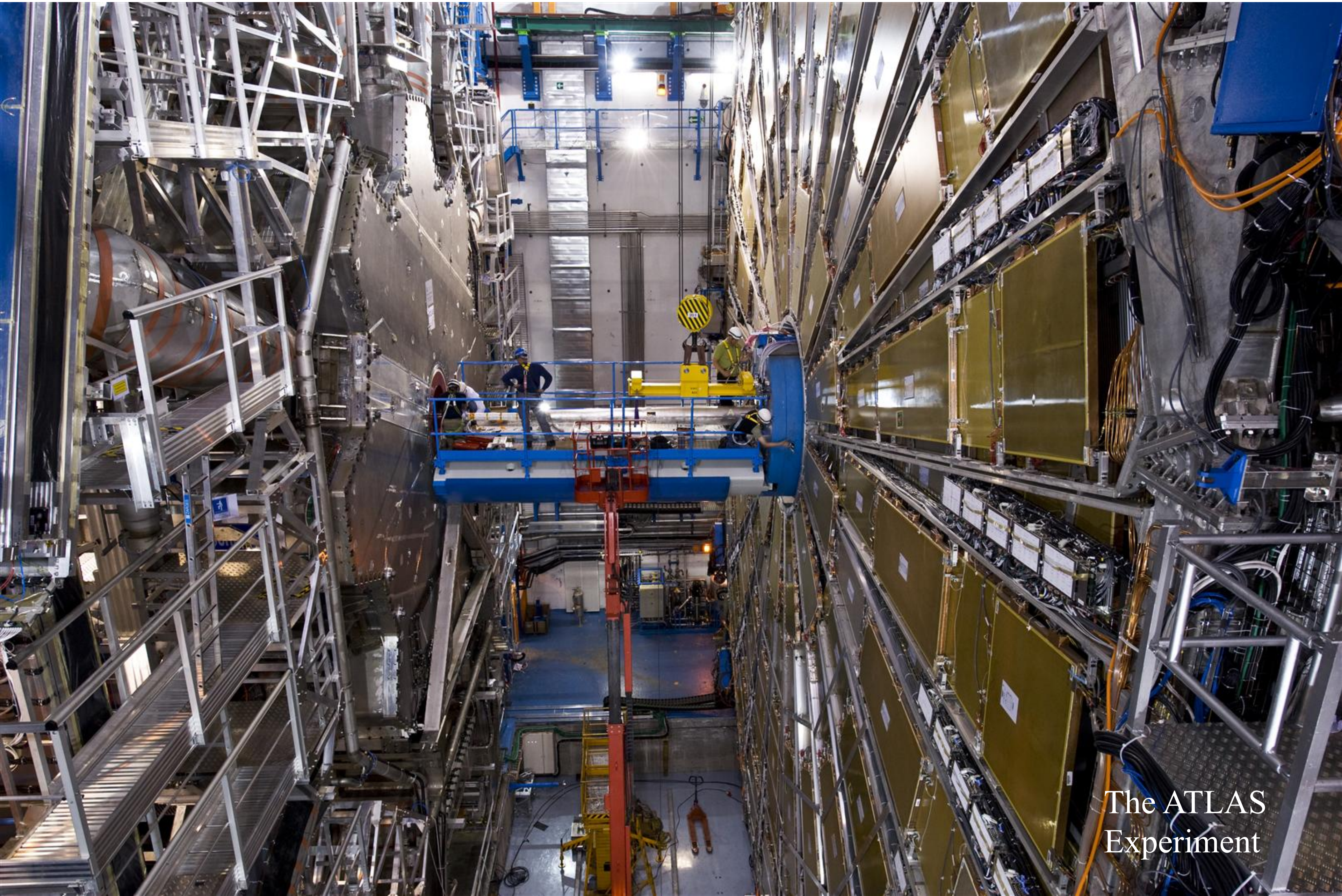


The largest such device is the Large Hadron Collider, located in Switzerland. Commissioned in 2009, started data-taking in 2011. Hundreds of US physicists, including students, work there.

Everything that was present in that early universe should be produced. The cookbook is open. "Everything not forbidden is compulsory." We try to find these particles in the tracks that exit the fireball.

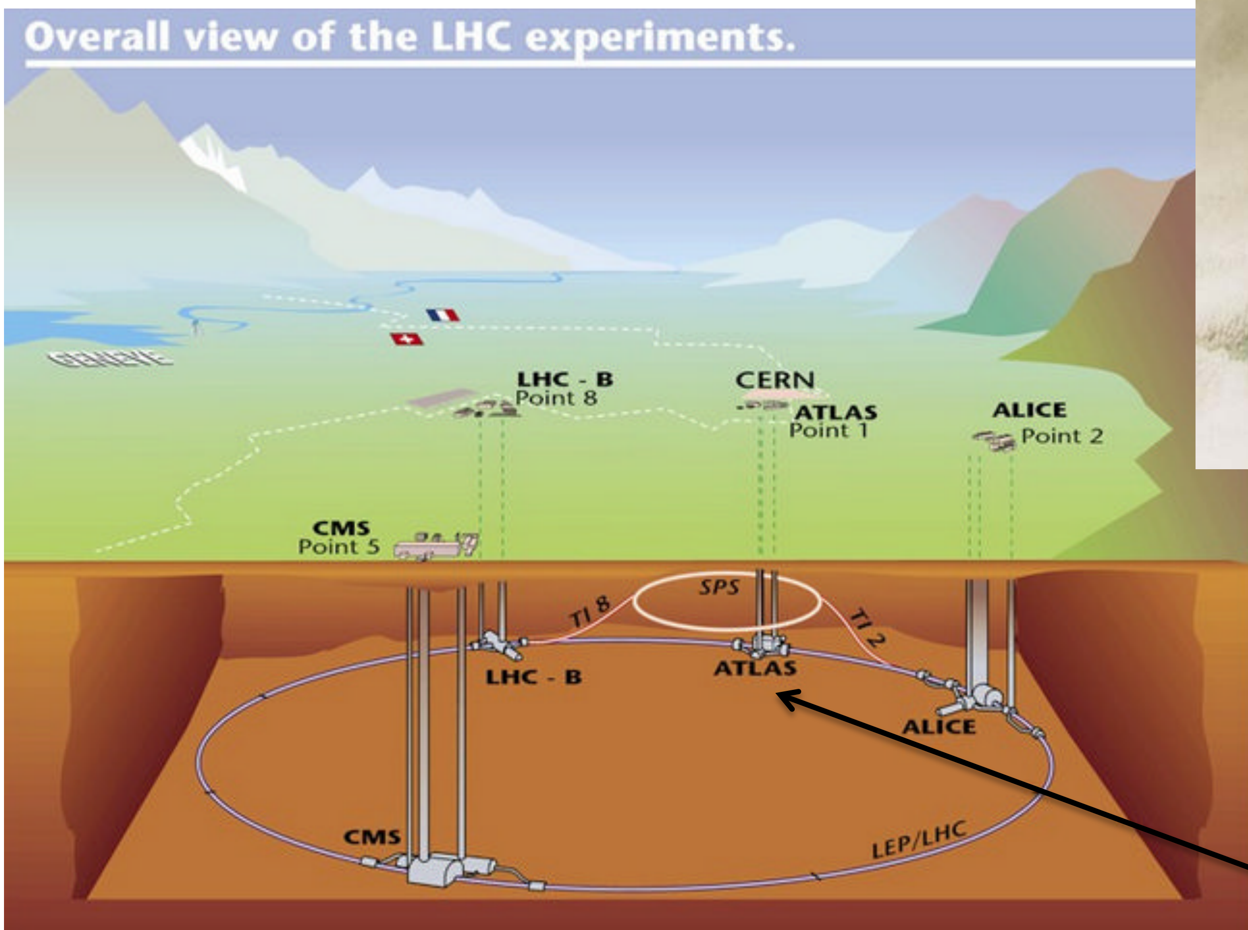
And we're watching for them.

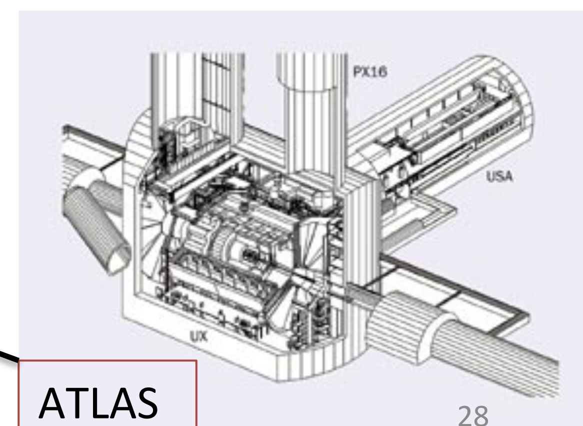
Like the collider itself, the particle detectors we use are enormous.



ATLAS and the other detectors at the LHC are located up to 175 meters underground, to shield them from false signals from cosmic rays.

Each was constructed like a “ship in a bottle”.





ATLAS

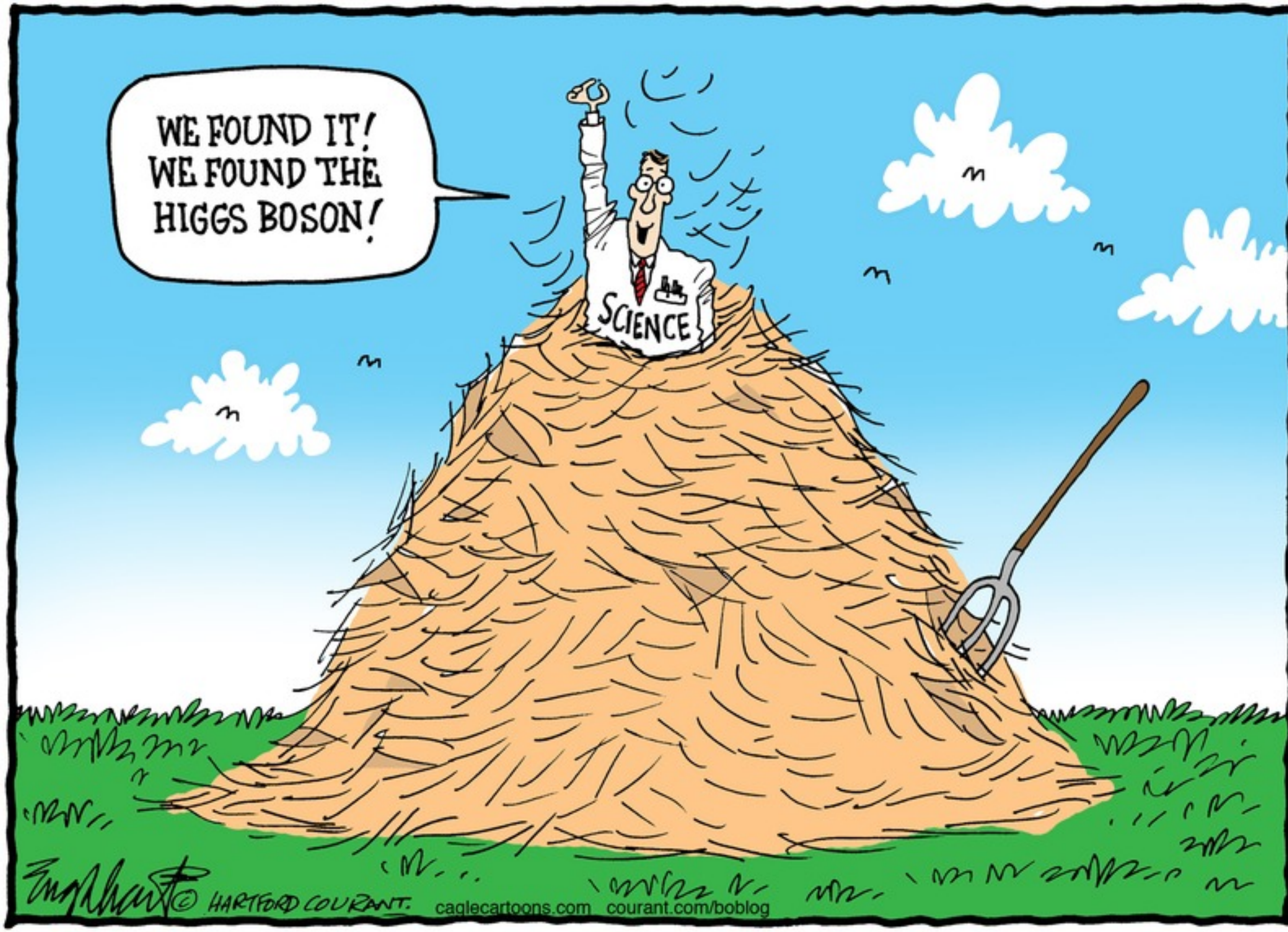
Parts of these detectors were built with help from students at the University of New Mexico, like this one:

The ATLAS Pixel Detector

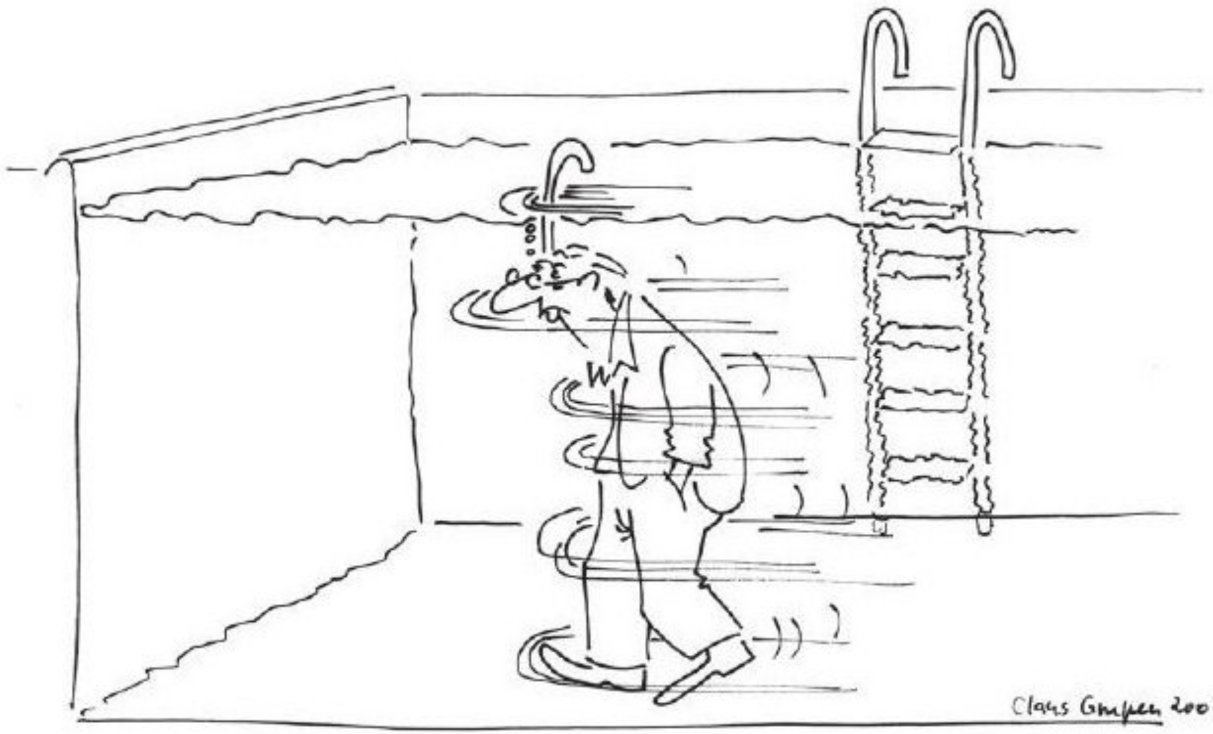
The University of New Mexico Collider Physics group are members, along with 2995 other people, from every continent but Antarctica,...

... of the ATLAS Experiment at the LHC.

The most famous particle discovered in the 21st Century is the Higgs boson.



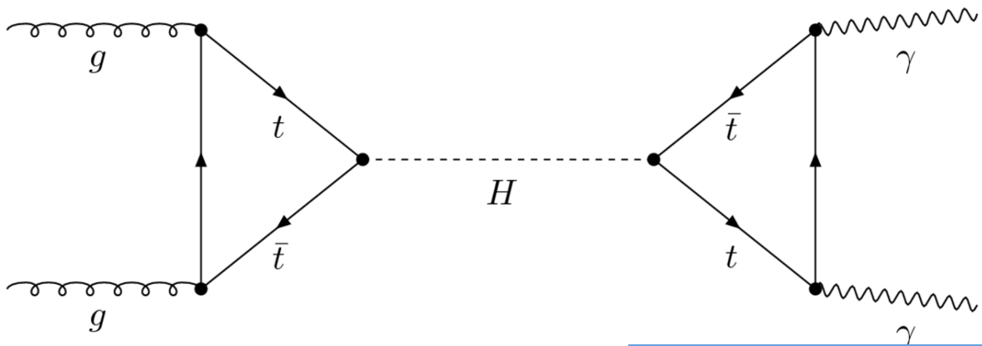
The Higgs field gives mass to all of the particles in the universe. It fills the universe, causing drag on everything in motion---like molasses. Particles experience that drag as inertial mass. **Responding to it is like trying to run when you're under water: you feel heavier, more massive**.



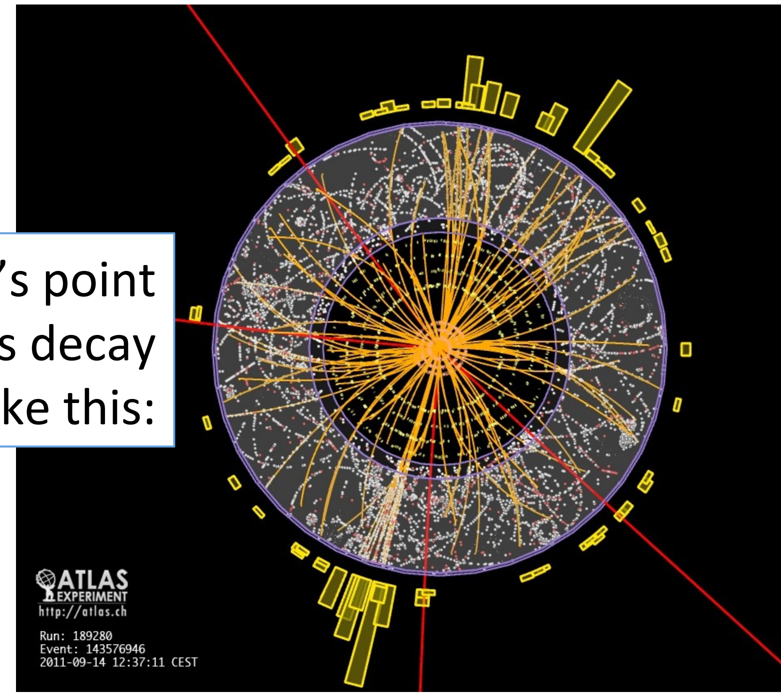
"Bewegung durch das Higgs-Feld"

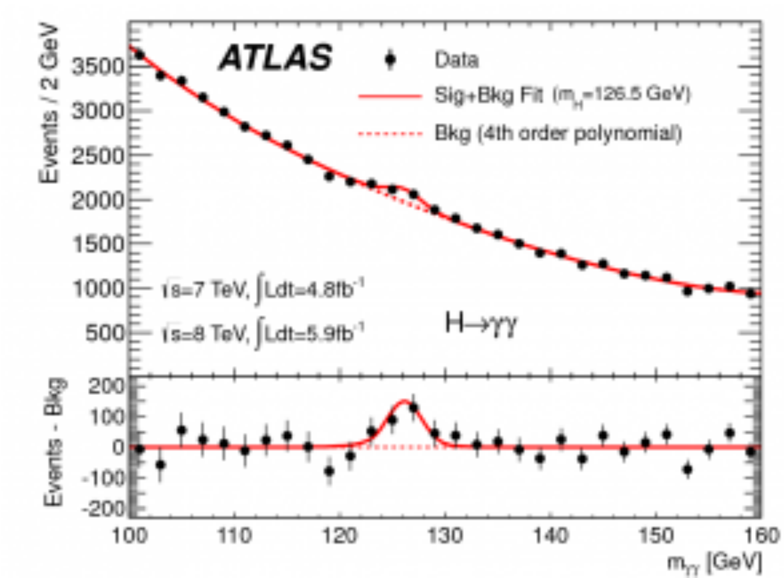
The field can condense into particles, and these are the Higgs boson. You can also think of the Higgs particles as ripples in the Higgs field.

This is one way the Higgs forms in the collider. Two gluon particles that ride along in the proton swarms, collide:



From the beam's point of view, the Higgs decay looks like this:





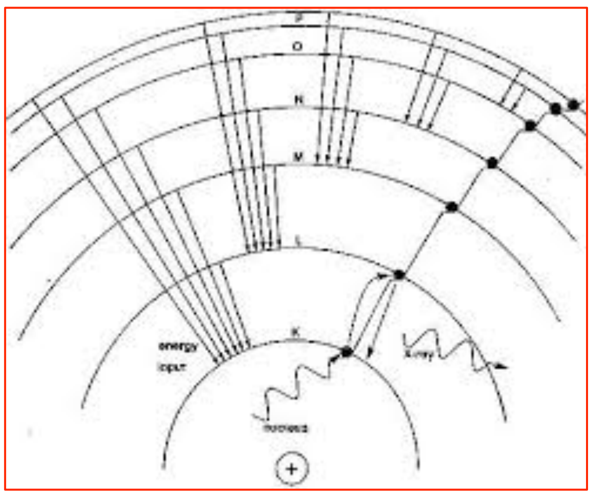
This Higgs signal is an enhanced number of decays to 2 photons whose combined energy is the Higgs's mass

New particles can help us understand how the strong force works too.

The University of New Mexico ATLAS group is studying particles formed as bound states of a c-quark and an anti-b-quark. The ground state has been observed and is called the B_c meson.

Think of the c-quark orbiting the b-quark, as an electron orbits a nucleus in a hydrogen atom.

In the hydrogen case: The electron can take on different energies, linked to being in different orbitals. Each allowed electron energy corresponds to a different excitation of hydrogen. The excited hydrogen does not change mass, but it's electron's radius is different. We name those excitations spectroscopically, $1s^1$, $1s^2$, $1p^1$, etc.

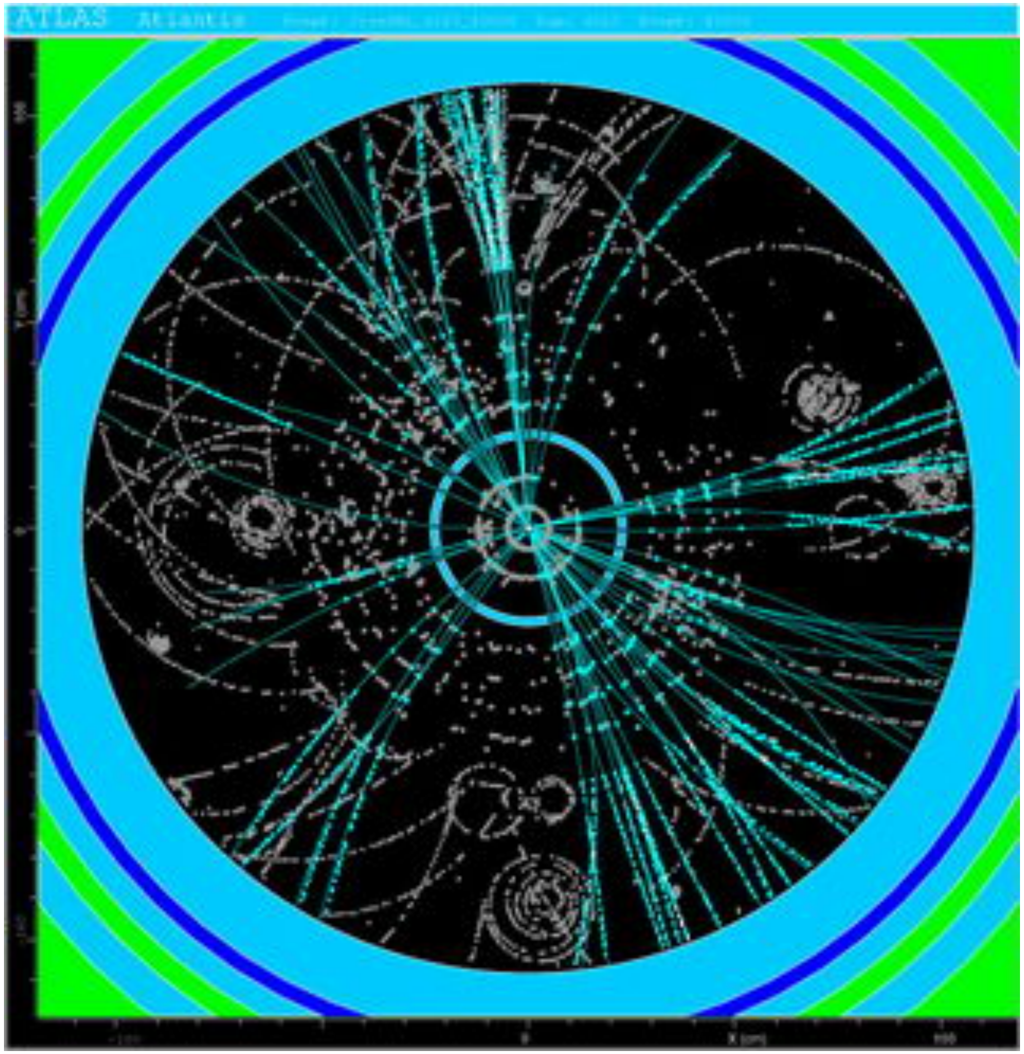


In the b-c case: This system can take on different energies too, even though no electron is present. The quarks themselves form shells. When the system transitions to a higher shell, it actually takes on a different mass. We name these states spectroscopically too. We record these different-mass states as distinctly different particles.

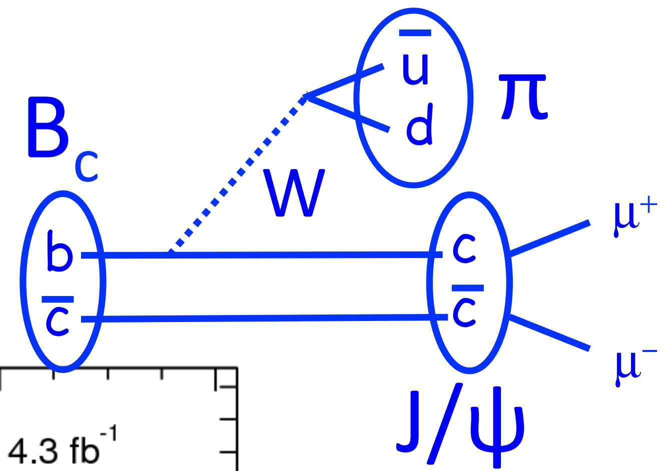
The UNM group is looking for these excited states of the B_c system. Each one tells us about an allowed "shell" in which the c quark can orbit the b quark. When we put this all together it will tell us about how the strong force, which binds those quarks, works.

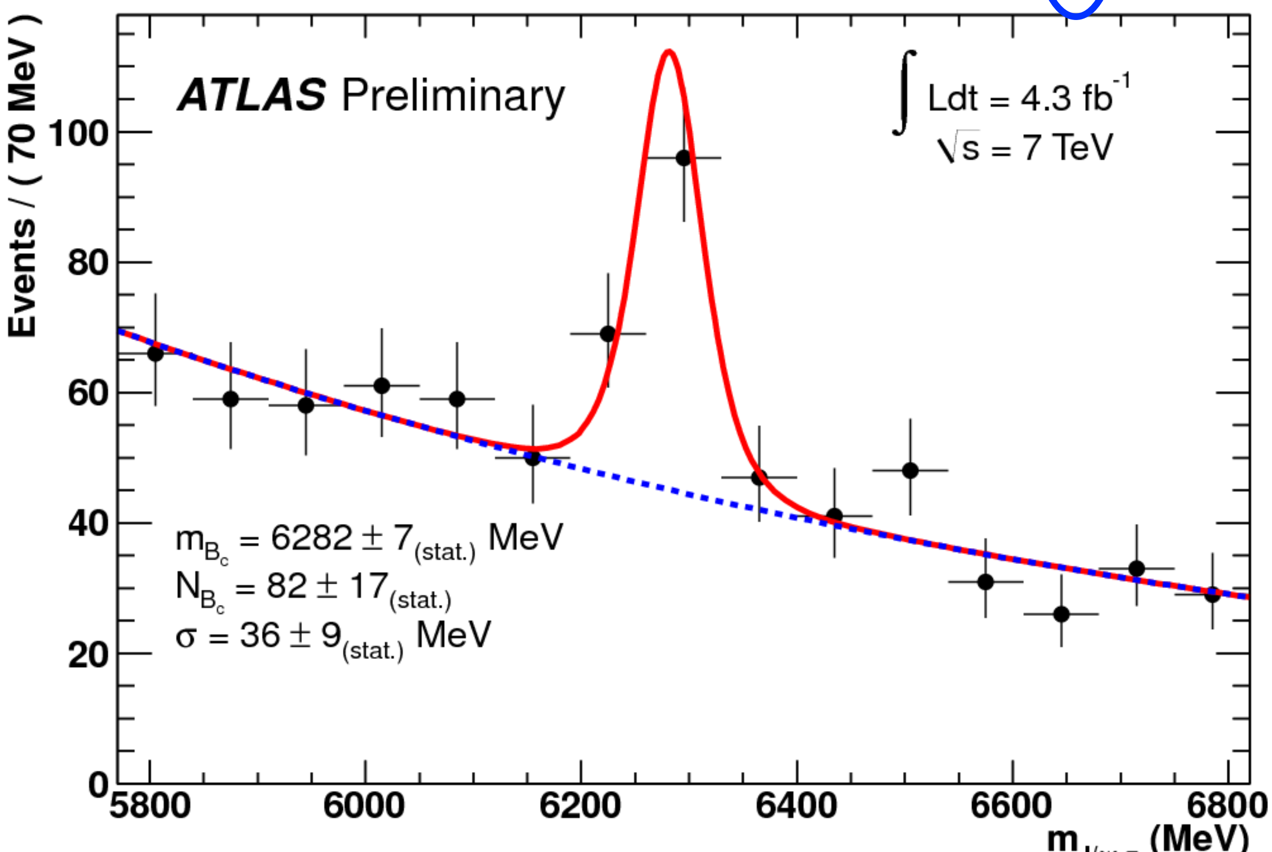
We look for these particles by:

- **imaging their tracks** in the detector
- tracing the tracks backward to their source while **requiring energy and momentum conservation**
- **inferring the energy, momentum, and mass of the parent particle** that was produced in the collision.

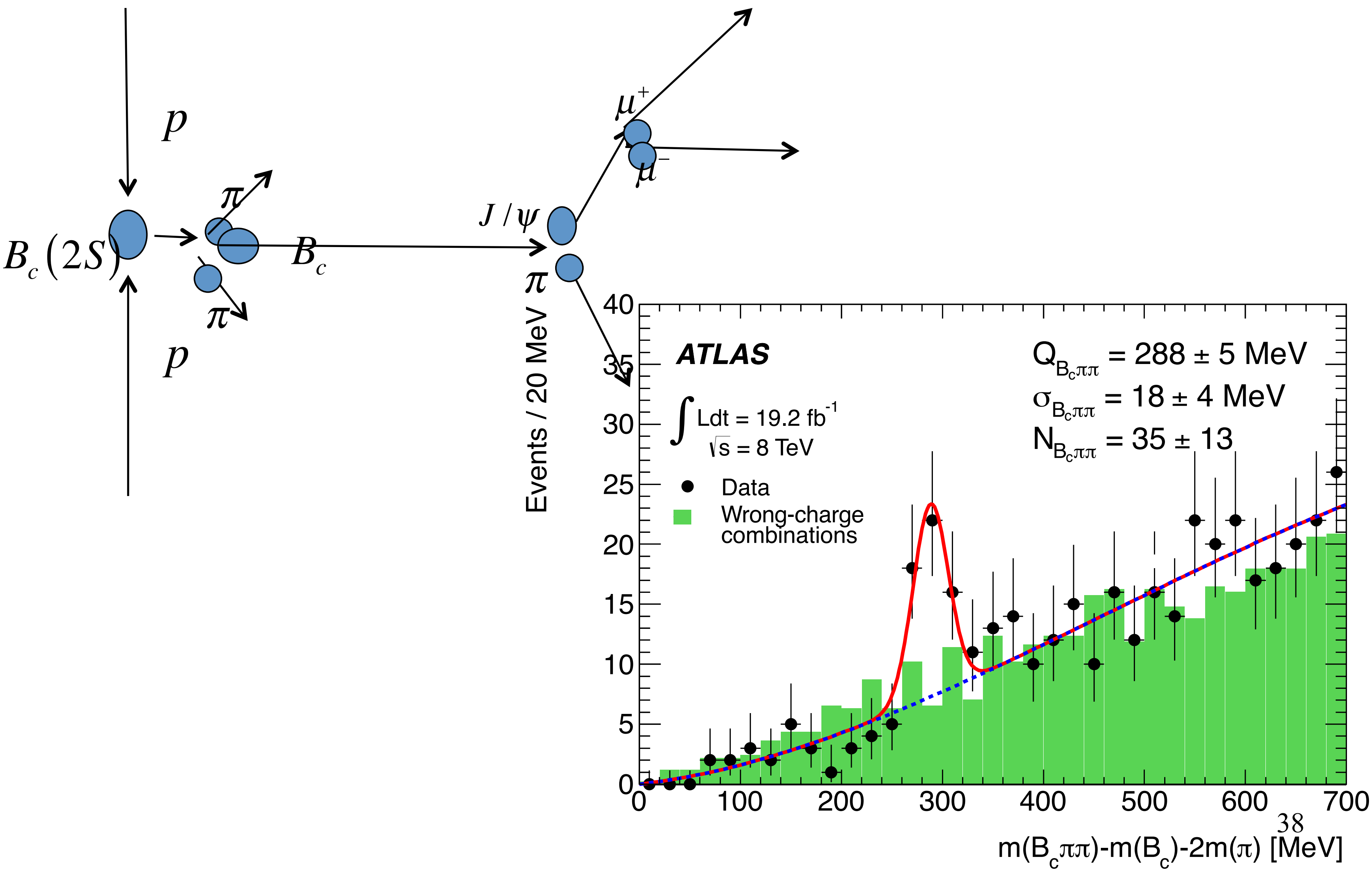


In 2012, we got the first one, the ground state, B_c(1S):





In 2014 we got the next one, $B_c(2S)$:



Summary

A particle can be the key to explaining a pattern in nature. (The X particle of Grand Unified Theory would transform quarks into leptons, revealing that they are fundamentally the same thing.)

A particle can provide direct explanation of a phenomenon only indirectly understood now. (Dark matter is known to exist because it bends light; to understand its properties, we should produce it directly in the laboratory.)

A particle can lead to a profound unification of parts of the natural world. (Supersymmetry's particles would unify the couplings of 3 forces in the early universe.)

A particle can provide the basis of fundamental quantities. (The Higgs boson is the origin of mass.)

A particle can elucidate structure in nature. (The $B_c(2S)$ sheds light on the nature of quantization of strongly bound states---like electron shells but for quarks.)

Every new particle we can find has a unique capacity to shed light on the nature of our universe. Every one is worth looking for.