Discovering new particles at the LHC

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

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Rocky Mountain
CUWiP
19 Jan. 2014

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.

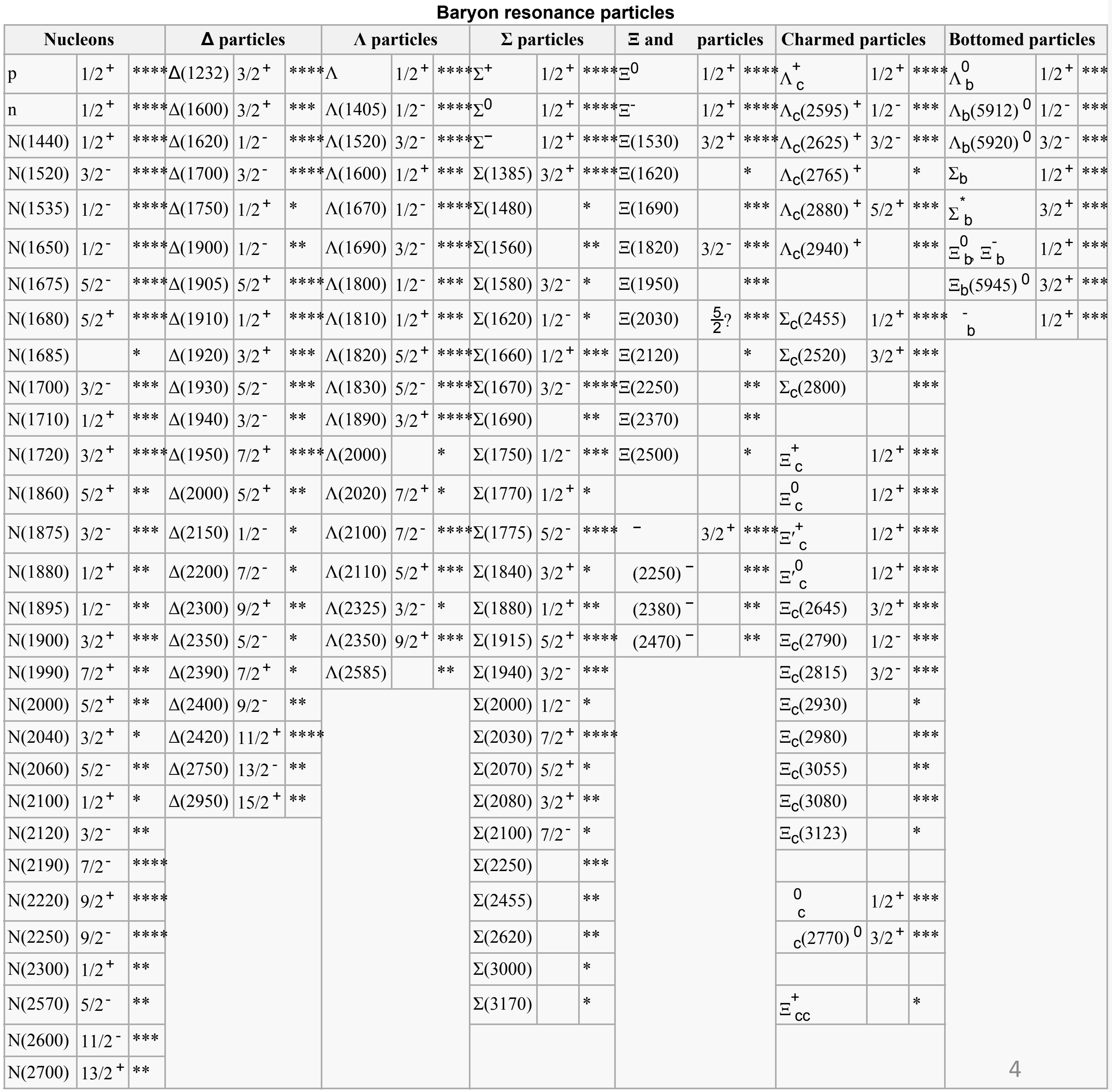
People gathered in Germany
to watch the live stream➔

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 1500 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^0_b, 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.

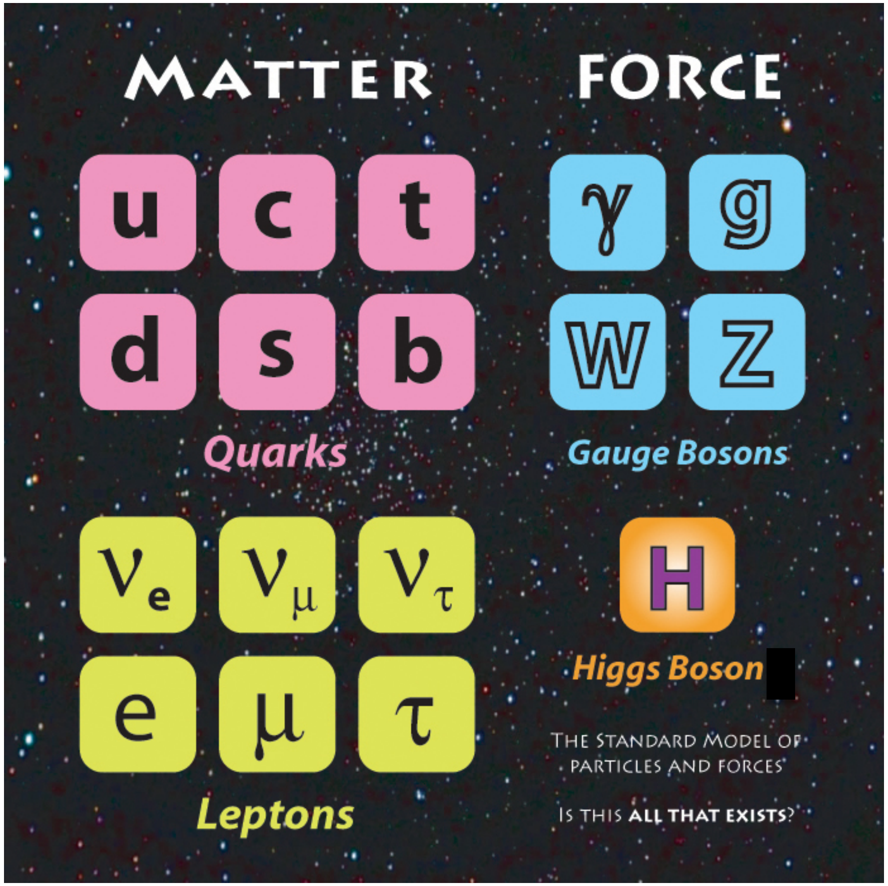
This talk addresses the questions:

- *Why is discovering new particles important?*
- *What do the particles discovered at the LHC tell us?*
- *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***.

Finding new things is fun---but ***what's most interesting is seeing whether they form a pattern.***

Usually the presence of the pattern hints at the presence of a unifying concept --- ***a new force, a new symmetry, a new conservation law*** --- and that is what interests us.



Emmy Noether showed (1915) that observed symmetries are evidence for conservation laws.

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."

(BTW, Prof. Noether was required to advertise her courses at Goettingen University under the name of a male professor, pretending to be "his assistant." Her theorem was introduced to the world in a talk to the German Academy (Gesellschaft) by a man, because women were not granted membership. She may not have been in the room for the presentation.)

*L. M. Lederman and C.T. Hill, "Symmetry and the Beautiful Universe," (2004) Here are a few examples of some curious patterns and symmetries that have been observed. ***Each raises a question that could be answered by discovering a particle.***

- 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 particles*** that transform them into each other. Or, are there more than 6 leptons, and could those extras be the dark matter? ***Then we should look for extra leptons.***

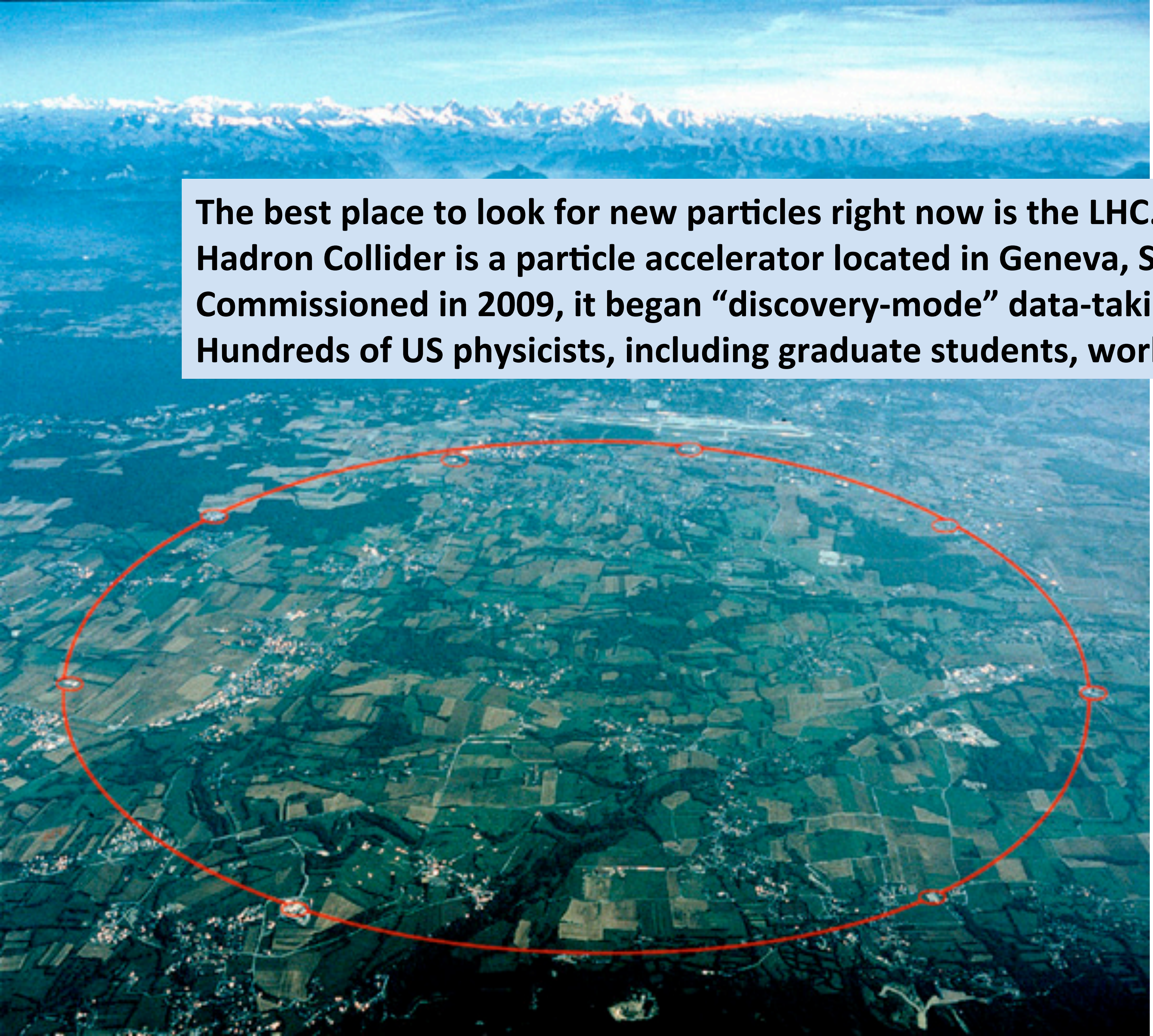
- Quarks cannot exist alone. They bind in bundles of 2 (quark-antiquark) or 3 (qqq). Are 4 or 5 or more allowed? The size of the bundle tell us what mathematical group describes the strong force, which binds the nucleus. Mathematical groups are the basis for unifying the fundamental forces. ***Searches for 4q 'molecules' and 5q 'pentaquarks' are underway.***

- Three of the fundamental forces have strengths that were almost, but not exactly, identical, in the early universe. Does that mean that they are actually different faces of the same force? ***There is a set of hypothesized fundamental particles that will give the forces identical strength in the early universe.*** Hundreds of people are searching for them.

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

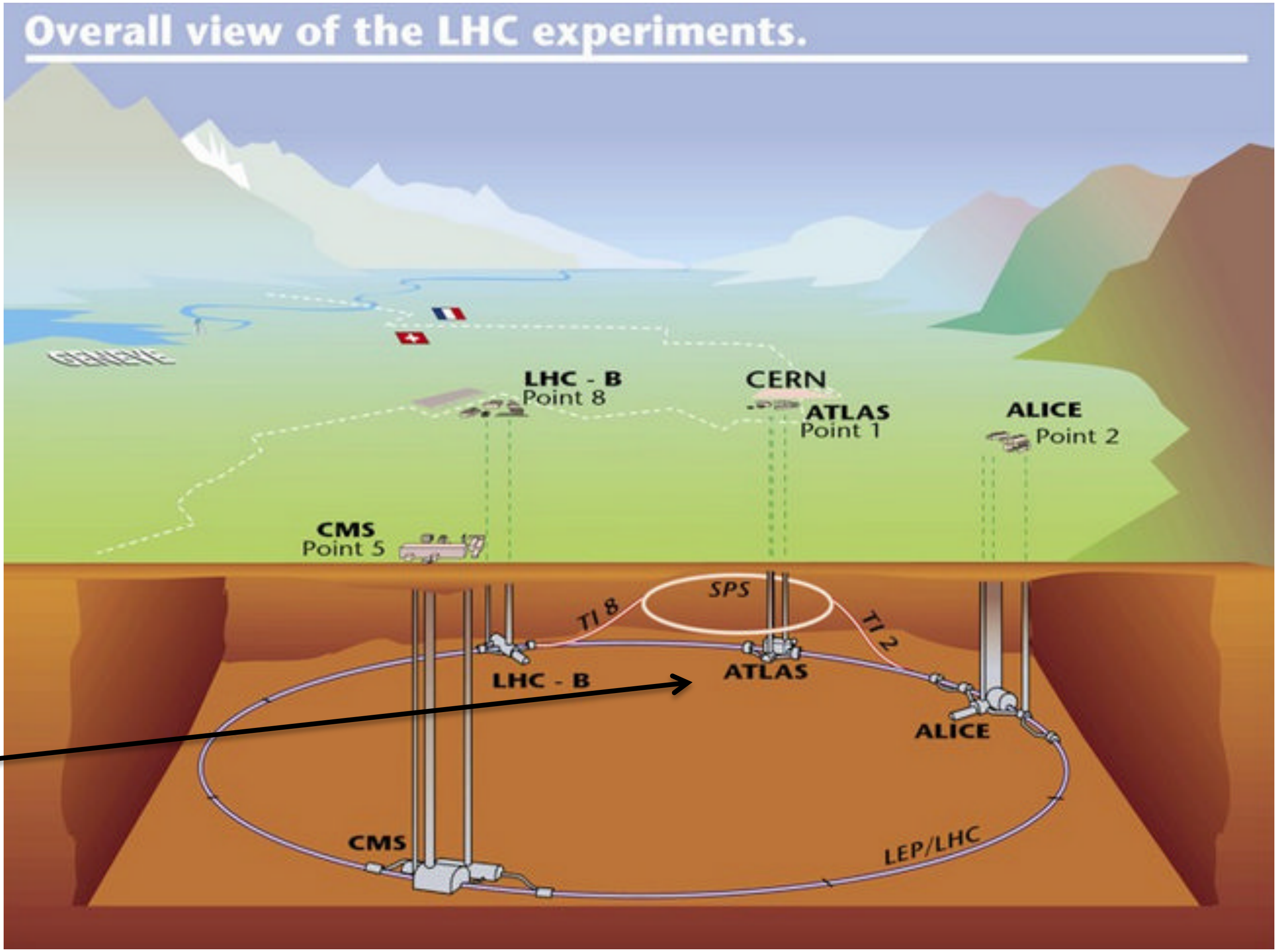
In one of the most misguided pieces of science journalism ever, Malcolm Browne wrote (New York Times, 5 January 1993) about a groundbreaking measurement by the CDF Collaboration, an article titled **“315 Physicists Report Failure in Search for Supersymmetry.”** Far from a failure, the non-observation 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.



The best place to look for new particles right now is the LHC. The Large Hadron Collider is a particle accelerator located in Geneva, Switzerland. Commissioned in 2009, it began “discovery-mode” data-taking in 2011. Hundreds of US physicists, including graduate students, work here.

Two beams of protons circulate in the LHC, one clockwise and the other counter-clockwise. They come together at the heart of each of 4 detectors. The detectors are located up to 175 meters underground, to shield them from false signals from cosmic rays.

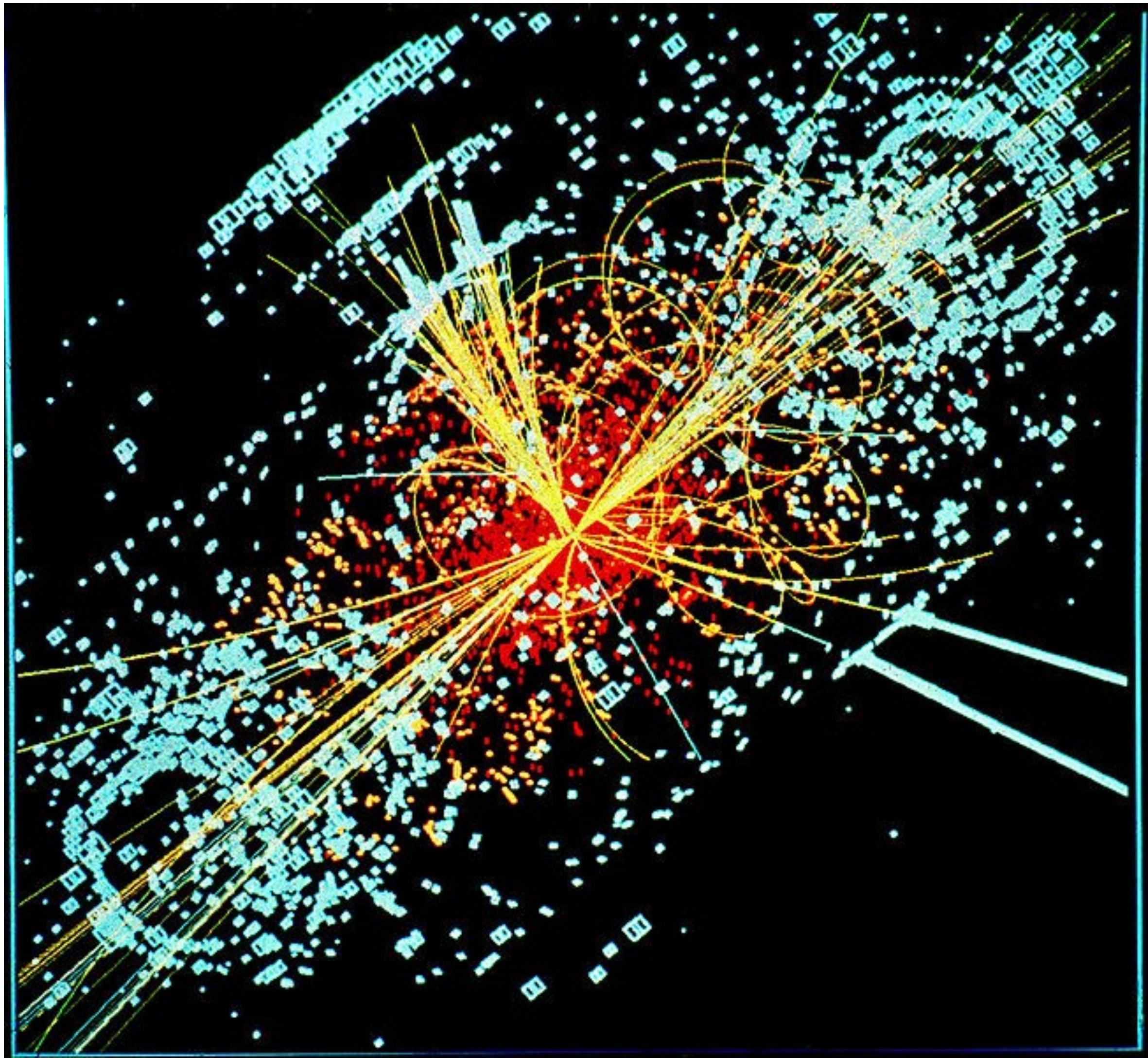


Our detector, ATLAS, is here

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.

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.



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

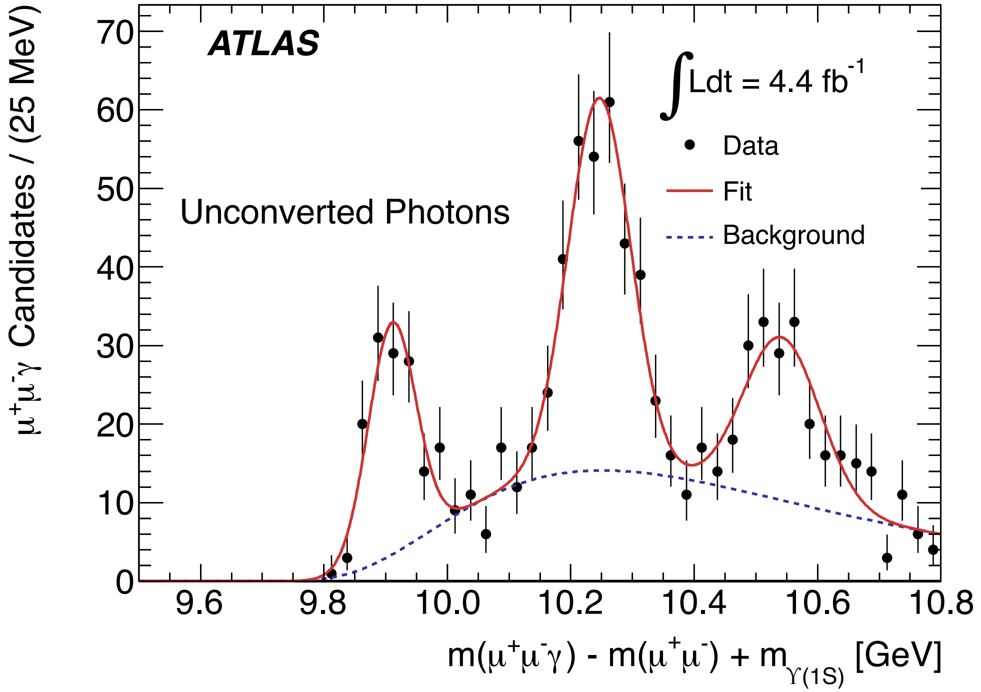
... of the ATLAS Experiment at the LHC.

ATLAS is the world’s largest camera, poised to record new particle signatures.

ATLAS reported* discovery of its first new particle, the $\chi_b(3P)$, on 21 December 2011 in a paper called:

“Observation of a New χ_b State in Radiative Transitions to Υ(1S) and Υ(2S) at ATLAS.”

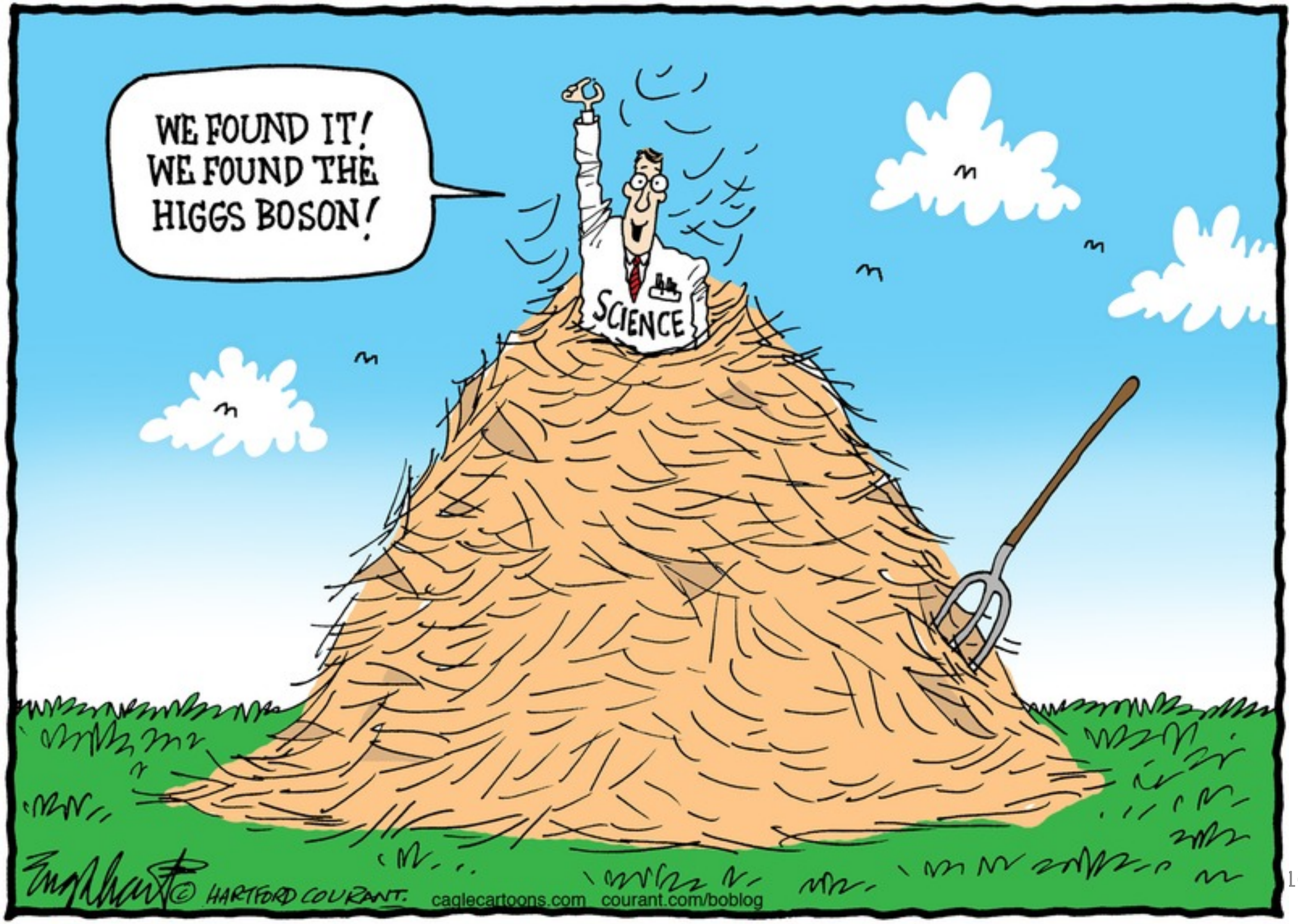
This is a bound b-quark and anti-b-quark manifested as a family of three states (a “triplet”). The precise values of the masses of this state clarify the values of parameters of the theory of the strong force, called Quantum Chromodynamics (QCD). QCD applies universally to all quarks, including those that form nuclei (*u* and *d*) and those that don’t (such as *b*).



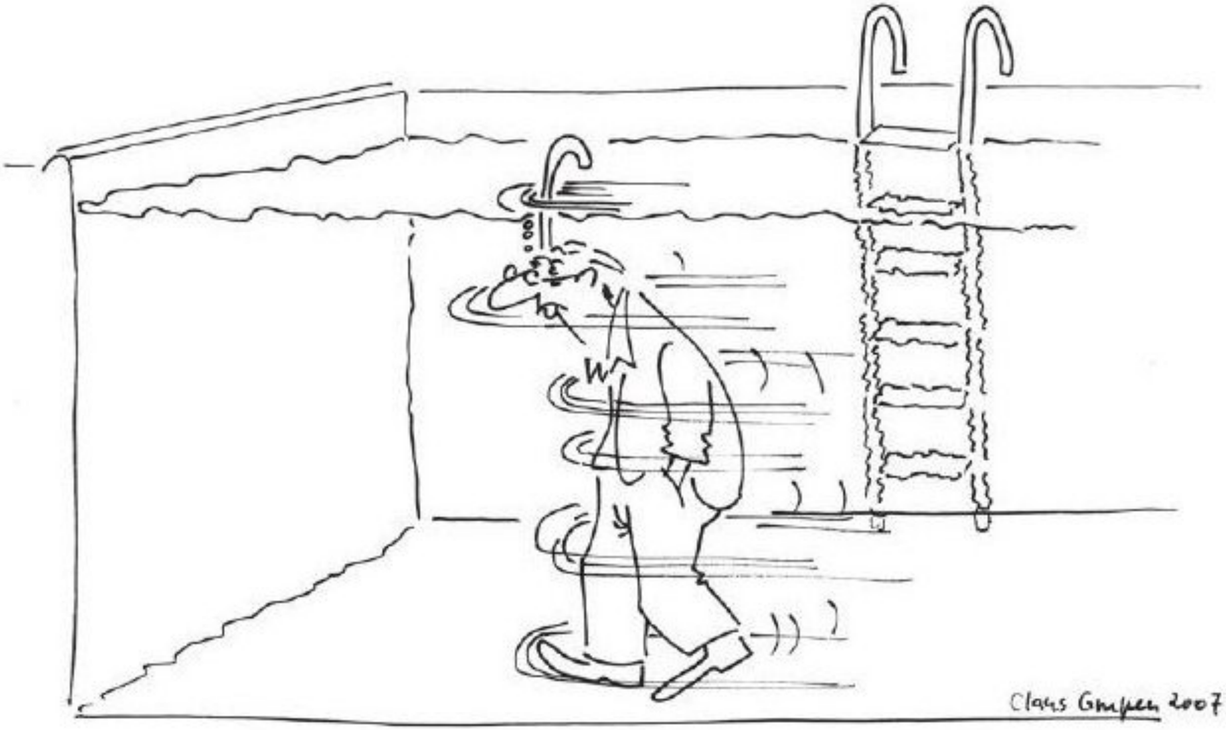
These χ_b’s were discovered when they spontaneously converted (“decayed”) into 2 leptons (μ^+ and μ^-) and a photon (γ).

*Phys. Rev. Lett. 108, 15, 152001.

Interesting, ok, but not like what glued people to their screens on 4 July 2012: the discovery at LHC of the Higgs boson.



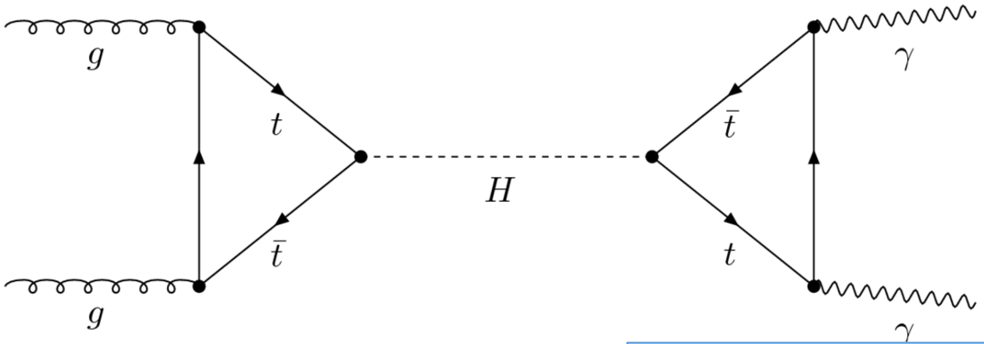
The Higgs field gives mass to all of the particles in the universe. *It fills the universe, causing drag on everything in motion---like molasses. Particles experience that drag as inertial mass.* ***Responding to it is like trying to run when you're under water: you feel heavier, more massive***.



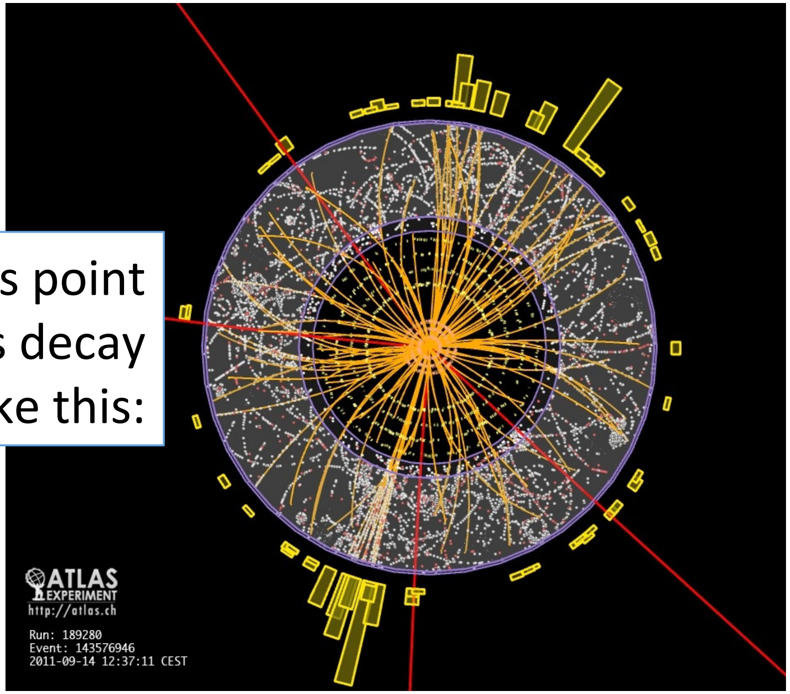
"Bewegung durch das Higgs-Feld"

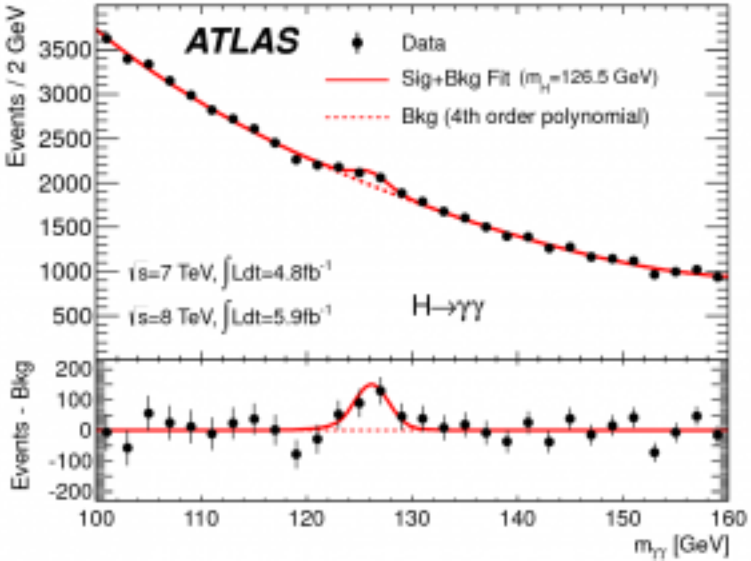
The field can condense into particles, and these are the Higgs boson. You can also think of the Higgs particles as ripples in the Higgs field.

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:





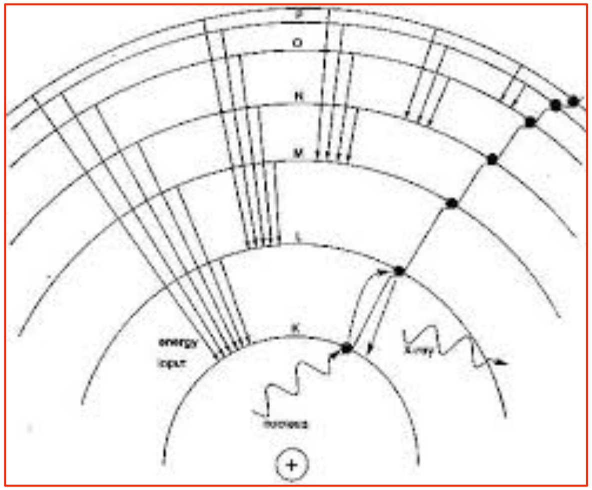
This Higgs signal is an enhanced number of decays to 2 photons whose combined energy is the Higgs's mass

Are there more particles still to be discovered?

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.

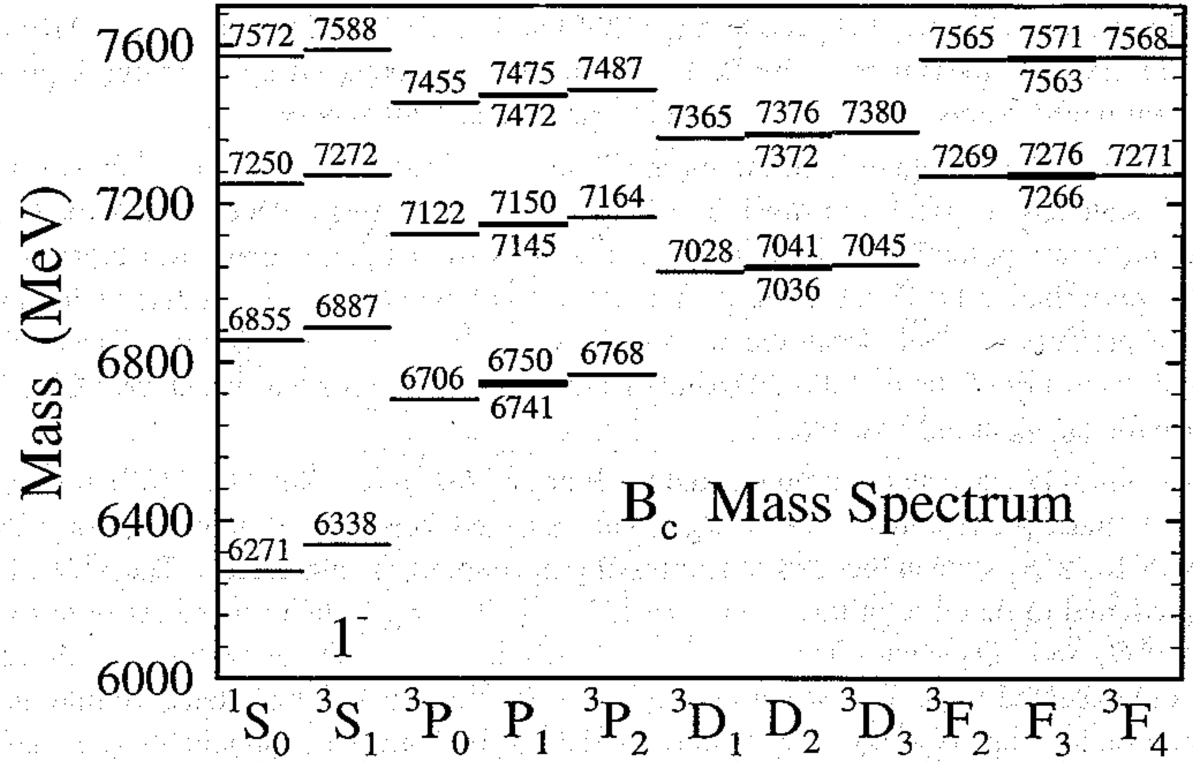
Think of the c-quark orbiting the b-quark, as an electron orbits a nucleus in a hydrogen atom.

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.



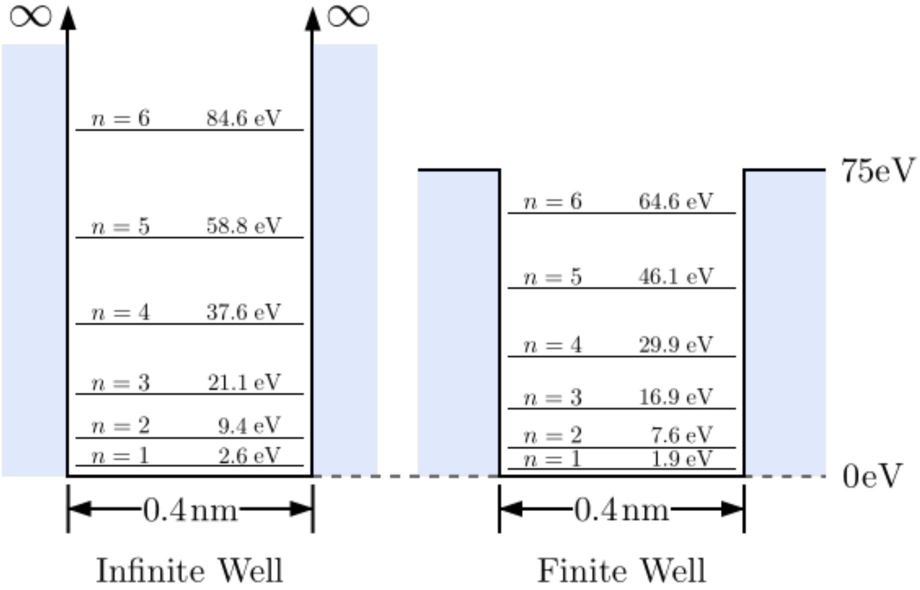
In the b-c case: This system can take on different energies too, even though no electron is present. The quarks themselves form shells. When the system transitions to a higher shell, it actually takes on a different mass. We name these states spectroscopically too. We record these different-mass states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

Those excited b-c states have never been observed. Here is one theoretical prediction* of what the masses should be. *Just as the energy differences between the hydrogen's electron shells are quantized, the energy (i.e., mass) differences between the b-c states are quantized as well.*



*S. Godfrey and N. Isgur, PRD 32, 189 (1986).

The energies of the hydrogen electron's shells depend upon the detailed form of the electromagnetic potential that binds the electron to the nucleus.

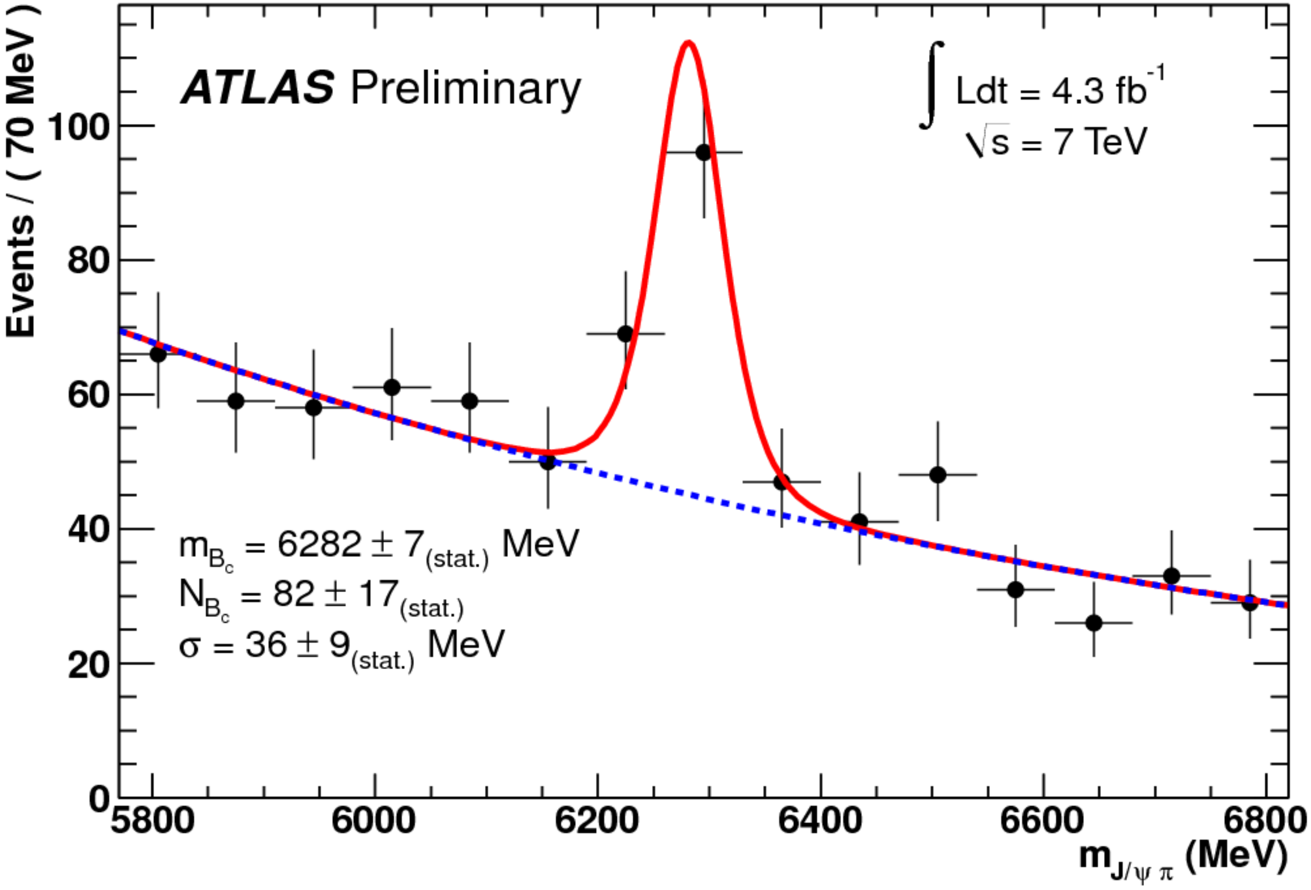


Similarly, the masses of the b-c states depend upon the shape of the strong potential, which binds the 2 quarks together.

The family of B_c excited states has never been seen because before the LHC, no collider had enough energy to produce them. The LHC has enough energy to produce them, if they are in nature's cookbook.

Our goal is to find them and measure their masses. Then, theorists can use these to work backward to infer the form of the strong force's potential.

We've got the first one,*
the ground state:



Now we're going for the first excited state....

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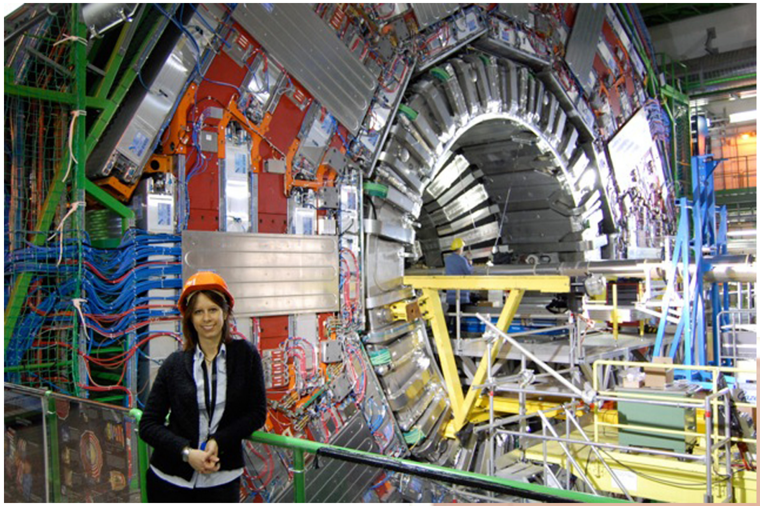
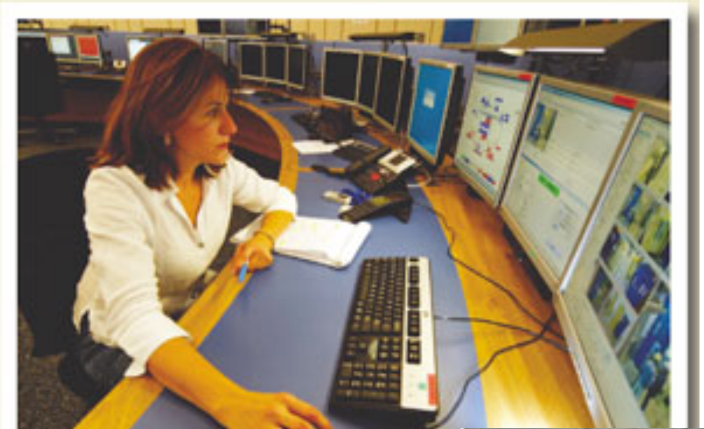
*Observation of the $B_c^{\pm}$ meson in the decay $B_c^{\pm} \to J/\psi(\mu^{-}\mu^{+})\pi^{\pm}$ with the ATLAS detector at the LHC, ATLAS-CONF-2012-028, 10 Mar. 2012.

Consider joining the subatomic community.



Detector designer



ATLAS Control Room physics shift leader

Professor, ATLAS super-symmetry research

LHC Magnet Surveyer

Accelerator Operations Engineers

Electronics Engineer