Astronomy Cast Episode 69:
The Large Hadron Collider and the Search for the Higgs-Boson

Fraser Cain: When it was first developed, the standard model predicted a collection of particles, and thanks to more and more powerful colliders, physicists have been able to find them all except one: the Higgs-Boson. It's an important one because it should explain how objects have mass. The European Large Hadron Collider should have the power and sensitivity to find the Higgs-Boson.

All right Pamela, can you give us a bit of history on the standard model without explaining the whole thing?

Dr. Pamela Gay: For a long time, scientists tried to figure out how to piece all these crazy different particles we have and all the forces we have into one coherent model. The standard model is about the best way we have of doing this. It is able to combine electromagnetism, the strong force and the weak force (it unfortunately can't quite get to gravity) in one coherent framework that explains things like why an electron and a proton are stable, while other particles like muons just fall apart on very short timescales.

In the process of pulling all these different things together, they realised photons carry the electromagnetic force, the force that causes magnets to stick to your refrigerator and your lights to light up when you flow electricity through them. They were able to figure out that gluons glue together the centres of atoms and that W- and Z-Bosons are part of the process that allows different atomic decays to take place.

In the process, they realised we still need something to give mass to different particles.

Fraser: It's funny when you think about that. Mass just seems like such a part of reality, everything has mass – you pick it up, it's hard to move – and yet, there has to be some underlying framework. Even in the vacuum of space, it's harder to move something that has more mass than something else.

Pamela: This is one of the things that has been extremely troubling. Why is it an electron's mass is so much smaller than a proton's mass? How do photons not have mass at all, whereas W- and Z-Bosons, which, just like a photon, are force carriers, have a lot of mass.

What scientists figured out is there's a field called a Higgs field that permeates all of space. The field contains energy. Different particles are coupled to this field in different ways, depending on how they interact with this Higgs-Boson (if it exists – and we really think it does).

Fraser: I can imagine all of space as molasses, and particles are stuck in that molasses, and it's hard to get them moving in that background.

Pamela: But once you get them moving, it's hard to stop them. One of the standard ways of trying to explain this is imagine you have a room full of people. They're all just hanging out. If a movie star comes into the room, and is amiable to signing autographs and things, and has a large entourage, that movie star is said to have a lot more weight. As the movie star tries to move through the room with her big entourage attached to her, it's hard to stop that moving swarm of people.

If the movie star stops and people collect around her, it's very hard to get that movie star moving again because there's so much mass to try and get moving.

Fraser: I've never heard that analogy before, that's a good one.

Pamela: It's a really neat way of thinking of it, just in terms of the more bosons, the harder it is for you to move, or once moving, the harder it is to stop moving.

Fraser: Why hasn't this particle been seen so far?

Pamela: The problem is, it has a lot of mass. In order to discover new particles, what scientists have to do is take a whole bunch of energy and force that energy to fall out into new particles. What they typically do is take a couple of protons, a couple of positrons and electrons – some sort of small, easy to accelerate particle, and accelerate it extremely fast.

As that particle is usually flying in a circle in some sort of a cyclotron device, it's getting faster and faster and faster because of magnets. We take these charged particles and you can actually use a magnet to move charges. So we accelerate the charges faster and faster and faster. The energy they have, it's tied up in their velocity. That energy adds to their mass, so in a way the faster the proton or electron is moving, the more mass-energy it has.

At the end of this, we slam (with great violence) that particle that has been accelerated into a target or into another accelerated particle. When they collide, all of a sudden all that velocity is gone. All that energy ends up freezing out as new particles. This is how the top-quark was discovered at Fermilab. This is basically how all the large particles that we know about that are extremely unstable have been discovered.

Fraser: So the particle is destroyed, and all of the energy that was in the particle turns into whatever sub-particles it has energy for.

Pamela: What's cool is there's basically this rain of particles. If you collide together two electrons, they create a shower of new particles that are initially unstable. Those unstable particles will collapse into more particles, and if any of those are unstable, they'll collapse into more particles. As they do this, they're raining out of the target chamber, where the collision took place, and passing through different types of gasses and crystals. They interact with the material in the detector and often give off faint flickers of light.

Particle physicists and experimental cosmologists use these flickers of light to create trails of the particles as they pass through the detector to try and figure out where different things are at different points in time, and to figure out what that entire rain of particles was – what were all the different things that came out of the collision.

Fraser: Before, you said it was a matter of mass, that the Higgs-Boson is very massive, and that's why they're not able to find it yet. Can you explain that?

Pamela: With your standard collider, for instance the one at Michigan State University, you take a particle and you can accelerate it only so fast. It's sort of like my Jeep Wrangler that really doesn't go faster than 95mph. So if you accelerate something as fast as you can and slam it into a target, the combination of the mass in that particle and the energy in the form of kinetic energy (velocity) in that particle can get transformed into new particles.

You only have as much energy as was stored in the mass of the original particle, and that you were able to give the particle by accelerating it. That number usually has some maximum value, and anything that has a mass that has an equivalent energy greater than what you're able to get out of that particle, you can't make. It's sort of like you can't make a two-layer cake if you only have enough mix for one and a half layers. If you have a particle that has more mass than that initial particle plus all that energy you gave it by accelerating it, you can't ever create that larger particle.

Fraser: So, there has never been a collider that's had enough energy to generate particles with that high enough amount of mass.

Pamela: They tried really hard with the last detector they had at CERN. CERN is the world's largest particle accelerator. It straddles the border between France and Switzerland, located near Geneva.

They used to have the Large Electron Positron Collider, LEP. In its final days, when they weren't so worried about breaking it, they pushed it past all of its limits, and tried really hard to find the Higgs-Boson. If you look down in the noise, there's stuff that people (if you squint really hard and force your statistics really hard) think might be hints of the Higgs-Boson. But no one's really sure.

Fraser: Is that one of the situations where there are a bunch of predictions for the particle, and you're able to at least knock off some of the predictions? It may be its mass is between this amount and that amount, and if you don't see it with the most powerful collider that you have so far, that doesn't mean it doesn't exist: it just isn't in that range, right?

Pamela: Yeah. It's sort of like if your eyes can only see things that are as bright as a lightening bug. If something's half as bright as a lightening bug, you can't see it. All you've done by looking for it is saying that is has to be fainter than a lightening bug.

Fraser: Right.

Pamela: With LEP, they tried and tried and tried. They were able to say it must be greater than about 200 giga-electron volts. That's a really weird unit to be talking in.

When talking about these particles, we talk about them in terms of their equivalent energy: how much energy does it take to make this particle. An electron, for instance, has an equivalent energy of 0.5 mega-electron volts (a million electron volts). We're looking for something substantially bigger than that – on the order of billions of electron volts.

Fraser: All right. Let's talk a little bit about the Large Hadron Collider then. What capability is it going to have?

Pamela: It's going to be able to get into the hundreds of giga-electron volt values.

Fraser: So before… what was the number?

Pamela: Before we were just barely starting to get to about 200 giga-electron volts when they pushed the system beyond its safety limits, where you're in danger of not hurting yourself but hurting the equipment. Now we're going to be able to get substantially higher than that.

Just to give some more scale to this, the equivalent of 725 milli-joules is the type of energy you can get out of these collisions. That's the equivalent of 157kg of TNT. So we're looking at very large amounts of energy, coming out of streams of these giga-electron volt particles.

Fraser: This is microscopic particles colliding together, generating the force of dynamite explosions.

Pamela: They're looking at having billions of collisions per second, in some cases.

Fraser: All right. Is the Large Hadron Collider purely looking for the Higgs-Boson?

Pamela: No. We wouldn't have spent so many billions of dollars building one apparatus if it was designed just to look for one lonely particle that we're all pretty sure is there.

Fraser: We should talk about a scale – sorry, I know I asked you a question, and now I'm asking a different one – but we need a little background because it's gigantic.

Pamela: It's huge. The tunnels they accelerate the particles through are 27 miles long. There's a pair of these circular tunnels, one next to another, to accelerate particles through.

Fraser: They go through multiple countries.

Pamela: Two different countries. America alone has over 1000 scientists working on this one detector system, this one giant facility. It actually has multiple detectors in it, but this one accelerator facility.

We're looking at something that cost on the order of about $3 Billion. It's a bit expensive.

Fraser: Okay, now we'll go back to the original question. So what else is it going to be looking for? It's so much of an investment just to look for one particle.

Pamela: It's going to be looking to see if there's a theory that's superior to the Standard Model. It's going to be looking for things like this particle called a neutralino. These hypothetical particles come out of super-symmetry theories.

The Standard Model, a lot of scientists are kind of uncomfortable with that has all these different parameters they actually have to go and measure. A lot of theorists don't want to have to measure things. They want theories to make solid predictions of "this is going to be this big and have this value and nothing has to be measured in a lab, everything comes from some magical first principle".

Fraser: So they make their predictions of the particles, but they find it frustrating that they've had to actually go and perform the experiments to find out how much those particles weigh, or how much energy they take to show up.

Pamela: Right. So for instance, the Higgs-Boson, we think we know how much mass it has: we think it's around 200 giga-electron volts, but it could be much bigger. What's worse, it could be the Higgs-Boson is actually a family of different particles, so there's more than one version. We don't know – we have to go measure that, which annoys a lot of theorists that want everything to be nice, clean and predicted entirely from mathematics.

Fraser: It doesn't include gravity, right?

Pamela: Right, and that's always a problem.

Fraser: Yeah.

Pamela: People would like gravity to fit into their grand unified theories of the universe.

Fraser: Right.

Pamela: Or at least into their grand unified theories of particle physics.

Fraser: Right, so there's a whole force we're well aware of, that we see everywhere, which isn't predicted or explained at all by the best-known model of physics. So what is super-symmetry?

Pamela: The super-symmetric theory basically says all these different particles have super-particles. They have this other set of particles that have matching, but flipped characteristics. For every one particle we know of now, there must be a second particle: a matching, super-symmetric particle. They've come up with all sorts of crazy names for them.

The lightest of these is the neutralino. If we can find it, then we're going to find it with the Large Hadron Collider. It's actually very close in mass (we think) to the Higgs-Boson. One or the other of them is going to pop out very early on in the experiments, if we've made our predictions correctly – rather, if these brilliant, mathematically gorgeous theories they've come up with have predicted correctly, we're going to find one of these.

We also might end up creating microscopic black holes. That's also kind of cool. So, if the super-symmetry model is predicted, then there's going to be some new Nobel Prizes handed out for that, probably.

Theorists can't get the Nobel Prize until someone actually finds the particles that were predicted, so if we find the Higgs-Boson, Peter Higgs will get the Nobel Prize. If we find the super-symmetric particles, the people who worked on the super-symmetry theories will get a Nobel Prize. If we create a microscopic black hole that, in fractions of a second, decays via Hawking's Radiation, then Stephen Hawking might finally get his own Nobel Prize as well.

Fraser: I did an article about microscopic black holes one time. These are black holes that could've been formed at the very beginning of the Big Bang, when you had a high concentration of mass. Since then, since only large amounts of mass can collapse, you'll never get those microscopic black holes since then. Now, physicists might be able to re-create them in the lab.

Pamela: This is one of the few times that you can refer to an astronomer as an experimentalist. In general, we're not experimentalists: we can't go out and build stars and stick probes in them and control variables. We're observationalists, sort of like a lot of animal behaviourists who go out into the wild and observe creatures in their natural habitat. They're not experimentalists, they're observers.

With particle physics, you can have a cosmologist who's trying to study the first moments of the universe go into one of these facilities (CERN, Fermilab, or any one of the many different colliders scattered around the planet) and set up situations that only existed in the earliest moments on the universe and play with particles in a way that no longer necessarily happens in the universe. They can also simulate things that happen in supernovae. They can actually do experiments on what happens in different astronomical conditions.

Fraser: So, with the neutralino being the first particle they should be able to tease out, where will they go from there?

Pamela: That's the question. There's so many directions things could go. We could start finding things that prove or don't prove super-symmetry. If super-symmetry isn't true, that's going to lead to a lot of head-scratching.

We can also start chasing things predicted by both super-symmetry and string theory, and maybe narrow down which versions of string theory may and may not be true.

We can start working with the baby black holes. That's just an odd idea, and who knows where that idea could go. At this point, we're all sort of holding our breath going, "what is the very first result going to be?" Once we have those first results, the theorists can go to work and start making predictions for the next rounds of particles, as we chase down super-symmetry.

There's so many different things we don't know, that we really need to find Higgs, find the neutralino, make the baby black holes. Then we can see what we've eliminated and what we can move on to discover next.

Fraser: I've heard some people kind of freaked out about the possibility – of course, they worry about this with every new particle collider – that it's going to…

Pamela: That we're going to destroy the universe?

Fraser: Yeah, that it's going to instantaneously destroy the universe and turn it all into some form of ice or something like that.

Pamela: Yeah, no.

Fraser: Uh, no? Can you put everyone's concerns to rest, and explain why the Large Hadron Collider isn't going to destroy the universe?

Pamela: At most, they're going to destroy part of their building. That's only going to happen if they've had some sort of safety mishap and a beam drops in the wrong place. That's where you get the air-dropped bomb energy coming out of the beam.

In general, this thing is built 100m underground and anything it creates is going to be completely unstable and will decay before it can really leave the building. So yeah, there are going to be radioactive particles created. There might be microscopic black holes created. There will be (hopefully, hopefully), Higgs-Bosons created.

All of these things are unstable, and it's sort of like taking an ice cube and shredding it into ice. If you throw that ice up into the air, it's going to be water before it hits the ground (if it's a hot day, at least). With the Higgs-Bosons, if you create one it's decayed into something completely safe before it hits the ground. We're creating unstable things and watching what happens as they decay.

They do it over small distances, the detector is completely buried, surrounded in cement and lead. They have done everything they can to make it a completely safe facility. If something goes wrong, the worst that will happen is they blow up one of their own detectors. That really sucks because you have to spend the money to rebuild the detector, but humans don't generally get hurt except when things like cranes drop. That's been the biggest danger in building these facilities: not the radiation, but the fact that you're working in compact spaces, with machines that are multiple stories tall, and you're doing it all underground between walls, wedged into tight spaces. It looks like human beings crawling around like ants on these detectors, when they're working on them.

The danger you're looking at for humans is more like what you get when you're building buildings than what you get even when you're taking x-rays in a medical facility. We're safe.

Fraser: It feels like people have been talking about the Large Hadron Collider for years and years and years, as it's been constructed. When is it finally going to go online?

Pamela: It is about 2 years behind schedule. It's had different financial crunches, different changes… yeah. Big science sometimes gets delayed. They're currently in the process of doing test runs. They're looking at doing their first science starting in May. Things are going, starting to go well and they're just ticking down their checklists and they have particle beams going and their equipment is working.

Fraser: So we could be six months away from learning some of the new results.

Pamela: Yes. It's going to be a great new year in 2008.

Fraser: No kidding. That will be big news. Even if they don't find anything – that'll be big news.

Pamela: One of the cool things is if they do find the neutralino, it's by many considered to be a candidate for dark matter. We may actually finally be able to identify a particle that could be associated with a lot of the dark matter that we otherwise have no way of detecting. We might be creating dark matter in a laboratory and finally be able to study it.

Fraser: That's cool. Thanks, Pamela.

This transcript is not an exact match to the audio file. It has been edited for clarity.