Two readings on Direct Searches for Dark Matter using Particle Colliders

1. "How to Use the Large Hadron Collider to Search for Dark Matter," Antonio Boveia and Christopher S. Hill, *Nautilus* blog, September 2018.

2. "Searching for Dark Matter at the LHC", Matt Strassler, *Of Particular Significance* blog, April 2015, https://profmattstrassler.com/articles-and-posts/relativity-space-astronomy-and-cosmology/dark-matter/searching-for-dark-matter-at-the-lhc/

# How to Use the Large Hadron Collider to Search for Dark Matter

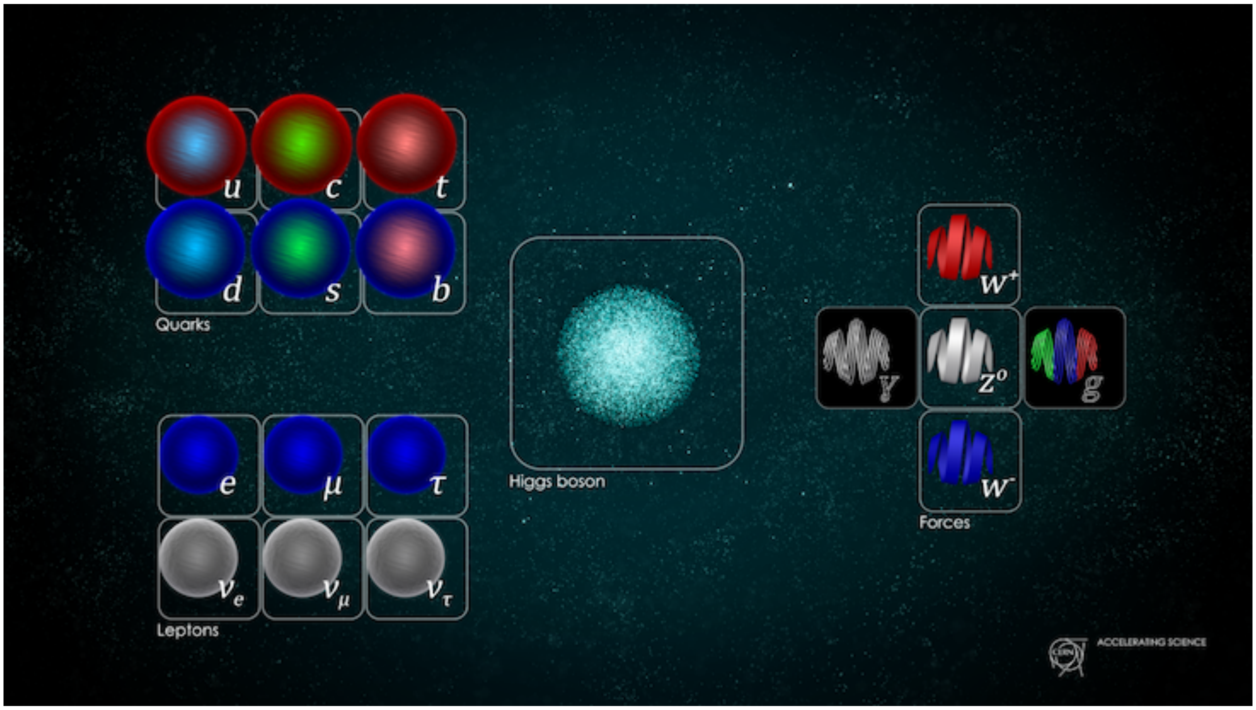
Posted By Antonio Boveia & Christopher S. Hill on Sep 03, 2018

http://nautil.us/blog/how-to-use-the-large-hadron-collider-to-search-for-dark-matter

*If you can't find dark matter, look first for a dark force.*

While cosmologists may be fascinated by what dark matter *does*, particle physicists are fascinated by what dark matter *is*. For us, dark matter should be—naturally—a particle, albeit one that is still lurking hidden in our data. For the last few decades, we've had a tantalizing guess as to what this particle might be—namely, the lightest of a new class of supersymmetric particles. Supersymmetry is an extension to the Standard Model of particles and forces that nicely addresses lingering questions about the stability of the mass of the Higgs boson, the unification of the forces, and the particle nature of dark matter. In fact, supersymmetry predicts a vast number of new particles—one for each particle we already know about. Yet while one of those new particles could constitute dark matter, to many of us that would be just a happy byproduct.

But after analyzing data from the first (2010–2012) and second (2015–2018) runs of the Large Hadron Collider (LHC), we haven't found supersymmetric particles yet—indeed, no new particles at all, beyond the Higgs boson. So, while we continue to hunt for supersymmetry, we're also taking a fresh look at what our cosmology colleagues can tell us about dark matter. It is the strongest experimental evidence for new physics beyond the Standard Model, after all.




**What we know:** *Every particle in the Standard Model may have a partner that has yet to be seen. But finding these unseen particles is proving to be harder than physicists anticipated.*Illustration by Daniel Dominguez / CERN

In fact, some might say that a principal goal of the LHC and future colliders will be to create and study dark matter. For that to happen, there must be a means for the visible universe and the dark universe to communicate with each other. In other words, the constituents of the particles that we collide must be capable of interacting with the putative dark-matter particles via fundamental forces. A force requires a force carrier, or boson. The electromagnetic force is carried by the photon, the weak nuclear force by so-called vector bosons, and so on. Interactions between dark matter and normal matter should be no different: They could happen by exchanging dark bosons.

Even if our detectors are oblivious to the dark bosons themselves, we have some hope of identifying them if they have some tiny interaction with observable particles—in other words, if they are not completely dark. Given how feeble these interactions would be, the Large Hadron Collider could already be producing these particles and we simply haven't been able to notice them yet.

After being created in the LHC when two protons collide, a dark boson might decay into dark-matter particles, which would escape our detectors without leaving a trace. But we could deduce their presence by adding up all the particles we did observe and looking for an imbalance of momentum, indicating that something had gone missing. Alternatively, dark bosons could decay into ordinary particles, such as quarks, and leave clear patterns in our data. We could do some particle forensics to infer the properties of the unseen bosons. This is just the sort of job for which the LHC detectors were designed, and we are continually scouring our collider data for these signals.

In doing dark boson searches this way, though, we have made one assumption that might not be warranted: that the dark boson decays instantaneously. What if it doesn't? The dark universe, in order to be dark, has to be sequestered from the normal universe in some way. This can cause dark bosons to survive for a short—but measurable—moment before disintegrating back into normal matter. The debris of the disintegration would not show up in our experiments at the point where the two protons collided, but displaced by some significant distance.

The LHC experiments were designed to look for particles originating from the interaction point. Tracing the trajectories of long-lived particles (dark or not) is complicated by several factors. They would be composed of fewer measurements, making it harder to connect the dots; they would follow atypical geometric paths, further hampering our pattern-recognition algorithms; and they could produce signals that would arrive much later than the usual algorithms anticipate.

But this is just the kind of challenge physicists embrace. By reviving decades-old tricks and inventing brand new methods, we have modified our algorithms to be sensitive to these atypical particle patterns. We think we can now detect dark bosons that decay up to several meters away from the place of origin, which covers most plausible scenarios. It almost doesn't even matter what the dark boson decays into, as long as particles of normal matter, which our detectors will register, end up in the debris.

So far, we have found nothing in the data from the first, low-energy run of the LHC. But we are still working on data from the second, higher-energy run. With the addition of these techniques to the supersymmetric searches that have come before it, we now have an excellent chance to discover dark matter, a dark force, or both. Considering that it has so far delivered only 1 percent of the total amount of data it will ultimately produce, the LHC's search for dark particles has really only just begun.

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# Searching for Dark Matter at the LHC

*© Matt Strassler [April 13, 2015]*

Dark matter — more elusive than your missing car keys, and more mysterious than that funny light on your dashboard. It probably exists, and if it does, it makes up most of the matter in the universe. It may be made from particles, and if so, and if scientists are lucky, the Large Hadron Collider [LHC] may actually be *making* a few of these particles. Well, whether they're making dark matter or not, the LHC experimenters can look for it. (Though they might have an easier time finding your car keys.)

In this article, I'll try to answer some obvious questions about how LHC scientists could observe effects of a new undetectable particle, and how they could try to obtain evidence that this new particle **is** actually the dark matter of the universe.

- *Detective: "Is there any other point to which you would wish to draw my attention?"*
- *Sherlock Holmes: "To the curious incident of the dog in the night-time."*
- *Detective: "The dog did nothing in the night-time."*
- *Sherlock Holmes: "That was the curious incident." [A.C. Doyle]*

**How Can LHC Experiments Detect the Undetectable?**

The LHC experiments ATLAS and CMS can indeed search for dark matter. This isn't like looking for your keys, though, because ATLAS and CMS have no hope at all of detecting dark matter **directly**. But then again, neither experiment detects neutrinos directly either!

Neutrinos, which LHC's proton-proton collisions produce many times a second, go right through ATLAS and CMS without hitting anything, and leave no trace. Despite this, ATLAS and CMS can and do still infer that neutrinos have probably been produced, and they can use the same technique for dark matter. I'll describe that technique now; it's pretty simple. In the following sections I'll explain how one might hope to distinguish dark matter from neutrinos; that's much more subtle.

*[Note: when I say "**undetectable**" in this article, I specifically mean "**undetectable by the LHC experiments**." Neutrinos are undetectable at the LHC, but they can be detected, with great difficulty and with very low probability, in experiments of a very different type. These tend to be very large experiments, involving, say, huge water tanks, and in some cases they may only detect a few neutrinos a month! The situation with dark matter may be similar; numerous experiments are counting on it.]*

The basic principle that underlies the technique is known as "momentum conservation". This is easily illustrated, if you're sufficiently clumsy. Take a glass of water, and pour it suddenly, and **straight down**, onto the floor of your shower. A splash results. Notice (Figure 1a) that the water goes in all directions, leaving a roughly circular pattern on the floor. The important phrase is "in all directions". You won't ever see all of the water splashing to the left, with none of it splashing to the right. Well, this is a consequence of momentum conservation, and that principle governs the trick I'm about to describe.

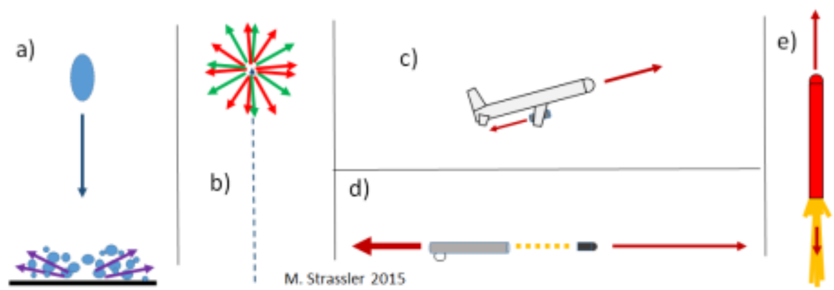


Fig. 1. Consequences of momentum conservation. (a) Water dropped straight down onto the floor splashes to all sides. (b) A firework explodes in all directions. (c) An aircraft accelerates forward by using its engines to blow jets of air backward. (d) When a bullet is fired forward from a gun, the gun recoils backward. (e) Downward exhaust launches a rocket upward.

There are many other examples where momentum conservation plays a central role, and a few are shown in Figure 1b-1e. An exploding firework makes a symmetric pattern, with pieces flying up and down, right and left, forward and back. Those of you who have fired a gun know that when the bullet goes out forward, the gun recoils backward, and you need to have a firm hold on it or it will go flying. Here's a video showing an example of this. A jet plane accelerates to high speed by using jet engines that push heated air out the back. Similarly, a rocket is launched upward by directing its hot exhaust downward. The details of the momentum and its conservation are slightly different (and sometimes subtle) in each case, but the underlying principle, and the basic intuition, is the same.

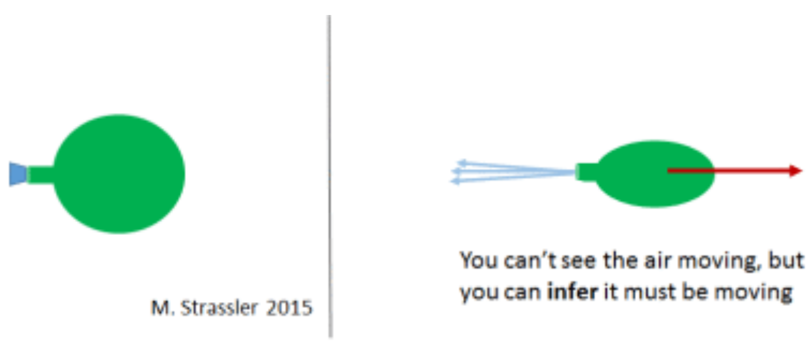


Fig. 2. Left: a balloon is filled with air. Right: when the nozzle is released, the air rushes out of the balloon to the left, and the balloon responds by whizzing to the right. Even though the air can't be seen, **its motion can be inferred** just by watching the balloon's motion.

Here's something you can try yourself (Figure 2). Blow up a balloon, but then aim the nozzle at your face and let go of it. The balloon will go whizzing across the room away from you. Why? Because the air is rushing out of the balloon toward you — as you can feel on your face. But your friend watching this from across the room can't feel the air, nor can s/he see it moving since it is invisible. Still, because your friend knows about momentum conservation, s/he can **infer** the air must be moving out of the balloon toward you; that's the only way that the initially stationary balloon could have begun moving away from you when you released it. This possibility of inferring the presence of something you cannot see, or detect in any other way, is the key idea.

A collision of two protons at the Large Hadron Collider is a little bit like the splash of water in your shower, rotated to make vertical into horizontal. The collision is head-on in one direction — let's call that the "beam direction", which is left-right in Figure 3. Let's call the other directions, namely up-down and toward-away-from-you, the "transverse directions" — transverse, or perpendicular, to the beam direction.

After the collision, dozens of particles (other hadrons created with the energy of the collision) go flying, most of them in roughly the beam direction. We don't care much about them; they are hard to measure and they are not usually interesting for questions that particle physicists are interested in nowadays. There are also some particles that don't carry much momentum at all — and we don't care much about them either.

But sometimes some particles go flying in the transverse directions, with a **lot** of momentum — we say that they have a lot of "transverse momentum". Well, momentum conservation says that since the initial protons had no transverse momentum at all, ***the transverse momentum of all particles after the collision has to balance***. If one particle goes up, there have to be one or more particles going downward. If there are particles going toward you, there must be particles going away from you too.

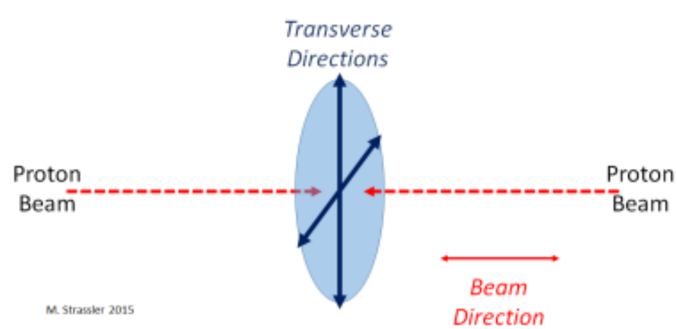


Fig. 3: We refer to the directions of motion of the proton beams before they collide as the beam direction(s), and we refer to the other directions as the "transverse" directions, meaning they are perpendicular to the beam direction.

A classic example of a collision of this type is shown in Figure 4. A proton-proton collision occurred in the center of the ATLAS detector, and the particles that were produced and went flying outward were detected, and their tracks measured. Then these tracks were drawn (by a computer) in this figure, to show scientists where they went. Most of the particles went right or left and aren't even shown. The blue tracks indicate the trajectories of particles that carried very low momentum, so we don't care about them. But the two yellow tracks that end in a yellow splotch are particles with large amounts of energy and momentum. One of them is an electron, heading upward in the picture. And before we even look for a second particle with large transverse momentum, we already know, from momentum conservation, that *there must be at least one particle going down with large transverse momentum*. And there is! It's the yellow track at the bottom, which happens to be an anti-electron, or "positron" for short.

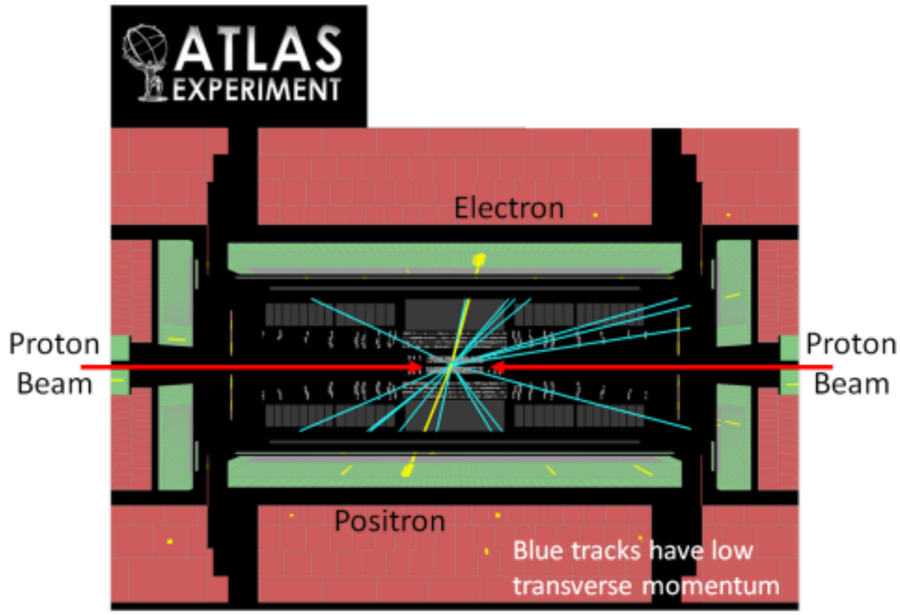


Fig. 4: A collision of two protons (entering along the red arrows) at the ATLAS experiment. There are two particles with large transverse momentum, with trajectories indicated by yellow lines, and their large amounts of momentum and energy indicated by the yellow splotch at the end of each line. These particles were determined to be an electron and a positron, and they have balancing transverse momentum. Blue tracks have low transverse momentum. Many other tracks with low transverse momentum travel closer to the beams and are not shown.

But in Figure 5, you can see another collision, from the CMS experiment. This one has an electron going up, as in Figure 4. ***But there's no particle with large transverse momentum going down.*** What's happening here?

Well, the most likely possibility is that *there really* ***was*** *a particle going down, but the CMS experiment was unable to detect it.* Since scientists already know that

- neutrinos and anti-neutrinos are not detected at CMS, and
- electrons and anti-neutrinos are often produced together, in the decay of a W particle,

it is natural to assume that this is what we are seeing here: an upward-going electron that CMS detected, and a recoiling anti-neutrino, moving down, that CMS did not detect.

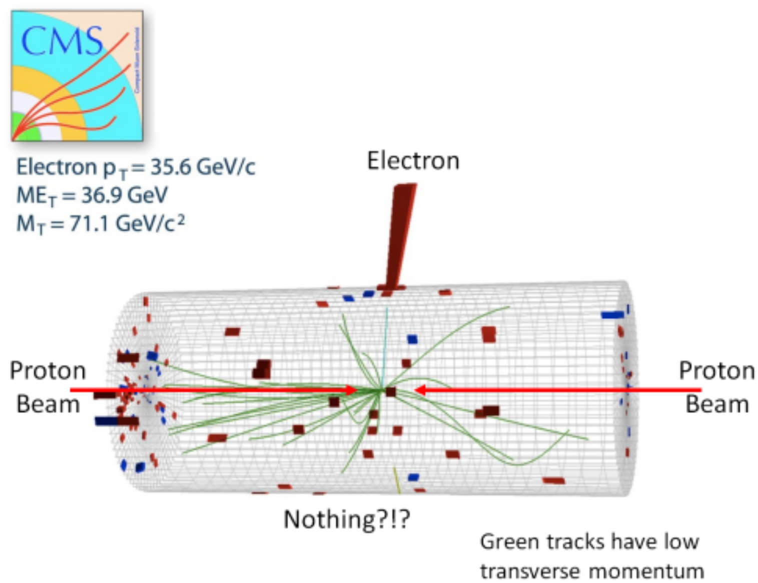


Fig. 5: A proton-proton collision at CMS, very similar to that of Figure 4, except for a change in color coding. The blue track and red splotch at the end indicate a high transverse momentum electron. No other particles have high transverse momentum, so the upward-going transverse momentum of the electron is not balanced by any detected particle with large downward transverse momentum. A natural, though only circumstantial, conclusion is that a downward-moving anti-neutrino balanced the electron's upward transverse momentum.

*Of course, one could wonder if momentum might **not** be conserved. To see why this is profoundly unlikely, we would have to look at a much wider set of experiments over decades, including but not limited to many other measurements made at ATLAS and CMS, to see all the evidence in favor of momentum conservation. To discuss this would be a long article all its own, so let's set that aside.*

Up to this point, I've been schematic and qualitative, but it's important to realize that physicists can make precise *quantitative* statements about momentum conservation. One such statement is this: *if you know that the momentum in the transverse directions is **initially** zero before a collision, then when you look at the **final** particles, take each one's momentum in the transverse directions, and add these transverse momenta all together (as vectors), the sum, which is the total transverse momentum, must be zero.*

Specifically, in a proton-proton collision, the momentum of two protons in the directions transverse to the beam direction — the "transverse momentum" — is zero. After the collision at ATLAS, the experiment measures all the particles that it can observe. Some particles go in the beam direction and aren't measured, but those have no transverse momentum; all their momentum is in the beam direction.  Others have small transverse momentum — too small to matter. But one or more may have large transverse momentum. If we add up their transverse momentum and the sum is zero *[or rather, if the sum is close to zero — because no measurement is perfect]*, we can conclude that ATLAS probably succeeded in detecting all of the particles that had large transverse momentum. However, if the sum is far from zero, then we can conclude that ATLAS **failed** to detect one or more particles with large transverse momentum. Such particles could be of a known type — neutrinos — or of an unknown type, such as (but not limited to) dark matter.

So now you know that if dark matter particles are produced at an ATLAS or CMS proton-proton collision, the experiments won't actually detect them. But still, the experimenters will be able to **infer**, from the fact that the transverse momentum of the detected particles doesn't add to zero, that *one or more undetectable particles of some kind were produced*.

Of course, the same thing happens if neutrinos are produced by ATLAS and CMS — and that happens many times per second. So how could LHC experimenters possibly figure out that they had made something ***other*** than neutrinos? And how could they figure out that this new thing **is** dark matter?

I'll address the first question in the next section, and the second question in the section after that.

## How Can the LHC Experiments Distinguish Dark Matter From Neutrinos?

The previous section explained how ATLAS or CMS experimentalists can infer that one of their proton-proton collisions has produced one or more particles that passed through the experiment without being detected. But how can the experimenters know whether they have produced something new and potentially exciting, such as particles that might make up dark matter, rather than just neutrinos, which are familiar particles that we've known about for many decades now? Why not just round up the usual suspects, instead of declaring that there's a new criminal in town?

The simple answer is that there *isn't* a way to tell, ***in any one collision***, what *type* of undetectable particles have been produced. There's also typically no way to tell *how many* of them have been produced. Instead, information has to be obtained from the patterns seen over many collisions. Specifically, knowledge comes from comparing those patterns to the predictions of the equations used to describe the known particles and forces, equations called "the Standard Model". What I'm going to do next is give you a one example of how this is done.

The simplest case to imagine is that two neutrinos, or two dark matter particles, or two of something undetectable, are produced in a proton-proton collision. Suppose (Figure 6) that these two particles are the only ones that have large transverse momentum (recall that there are always lots of hadrons produced in a proton-proton collision, but these mainly go in the beam direction and have very low transverse momentum). Well, then there would be nothing to see! For instance, one of these particles might go up and the other might go down, with equal and opposite transverse momentum — just like the electron and positron in Figure 4. But if both of them are undetected, transverse momentum of the **detected** particles will still appear to balance, and we won't have any idea that the **undetected** particles were produced at all!

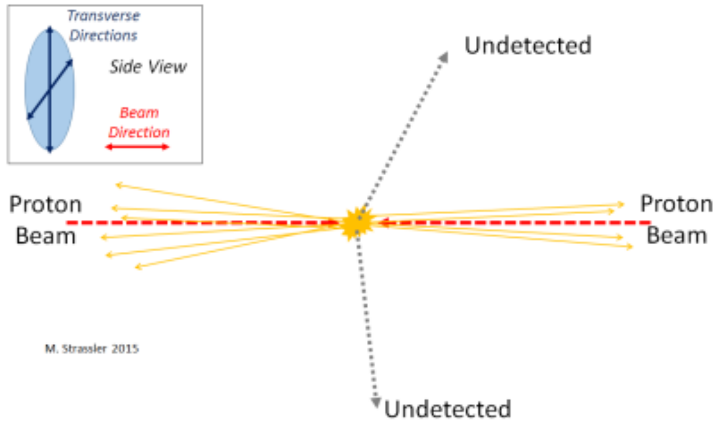


Fig. 6: Two undetected particles are produced in a proton-proton collision. The detected outgoing particles (orange lines) all have small transverse momentum; many other particles (not shown or measured) travel nearly in the beam direction. The transverse momentum of the detected particles is small, and balances to within the experimental uncertainty — so scientists would have no idea that the undetected particles were produced!

But all is not lost. It's a general feature of proton-proton collisions that when any particles, of any type, are produced at high transverse momentum, stray high-energy gluons are produced in the process too. Occasionally one (or more) of these gluons itself goes off into the transverse directions, and therefore has high transverse momentum. In this case we'll see something similar to Figure 7. This is called a "mono-jet event", in which one sees a high transverse momentum jet (a spray of hadrons created by the gluon, see here for details of how this happens) recoiling against "nothing", presumably an unseen neutrino and anti-neutrino (from a decaying Z particle). Compare Figure 7 to Figure 6; now we have a jet with high transverse momentum, while the two undetected particles will recoil against this jet. Since we do observe the jet, we'll conclude that transverse momentum of the observed particles doesn't balance, and undetected particles of some type were produced.

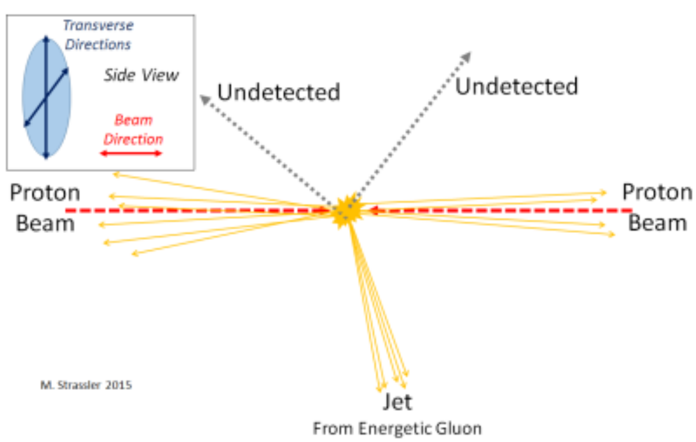


Fig. 7: Fortunately, the production of the two undetected particles is accompanied by the production of a gluon with large transverse momentum. This produces a "jet" (a spray of hadrons) which appears, like the electron of Figure 5, to recoil against "nothing". (This is called

a “mono-jet event.) Scientists then infer that one or more undetected particles must have been produced.

In Figure 8 is the same collision as in Figure 7, viewed “end-on”, that is, looking down the beam direction toward the collision point.

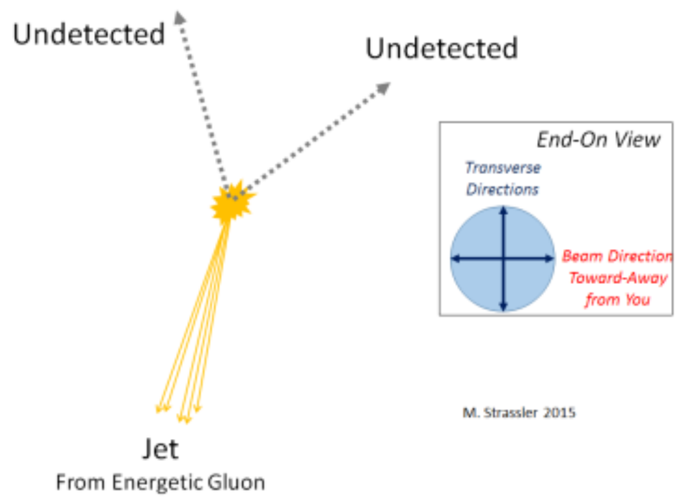


Fig. 8: Same as in Figure 7, but rotated so we are looking in the direction of one of the colliding protons. This shows how the momenta in the transverse directions balances to zero, which is not as obvious in Figure 7.

Now here’s an example of a real monojet event observed at ATLAS, viewed end-on as in Figure 8.

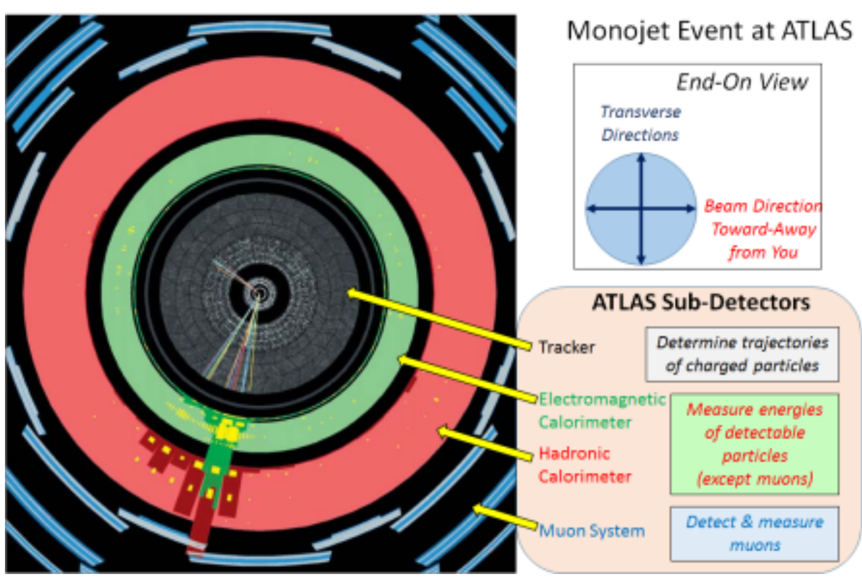


Fig. 9: A real mono-jet event observed at ATLAS, as represented to scientists in a computer reconstruction. Compare to Figure 8. ATLAS has an onion-like structure as shown, with various “subdetectors”. The collision occurred dead center. In the “tracker”, the trajectories of the

charged particles that make up the jet are indicated. In the "calorimeters", the energy deposited by the particles in the jet are indicated by green and red blotches. Note there are no other significant tracks or blotches anywhere, so clearly the transverse momentum does not add to zero. (Tracks going to up and to the left have very low transverse momentum and are close to the beam direction.) Scientists infer that this event was most likely one in which a gluon, a neutrino and an anti-neutrino were produced. Still, there's no way to be sure precisely what was produced in this collision.

The Standard Model allows us to predict, with pretty good precision, the fraction of proton-proton collisions that will produce a certain amount of missing transverse momentum. This is shown in Figure 10. The top of the light blue region represents the prediction of the Standard Model for the rate at which neutrinos will be produced with at least one jet (which has several components, shown as different colors; the light blue region represents the largest effect, arising from Z particles that produce neutrino/anti-neutrino pairs). The data are the black points, with uncertainties given by the vertical bars.

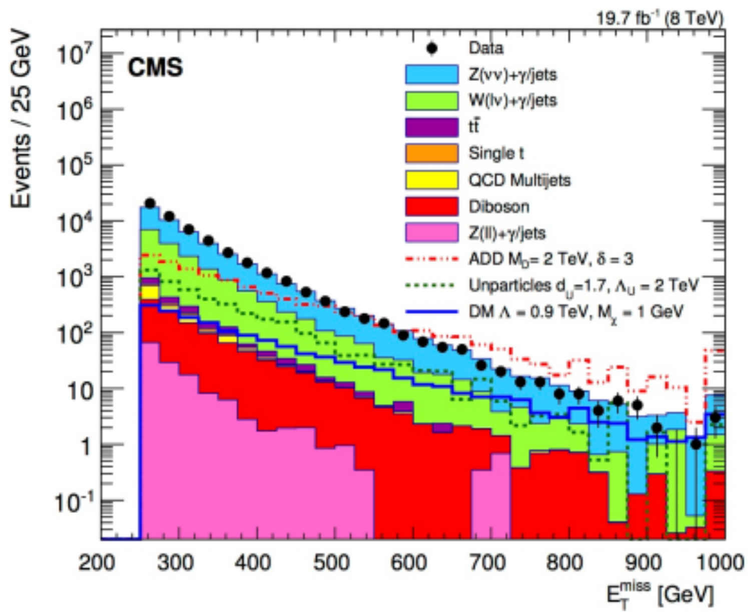


Fig. 10: Data from CMS (black points, with uncertainties given by vertical lines) and Standard Model predictions (colored regions, with uncertainties not shown to avoid clutter) showing the number of events (vertical axis) that have a certain amount of missing transverse momentum (horizontal axis, labelled $E_T^{miss}$). Notice the data agrees very well with the prediction!! An effect of certain extra dimensional gravitons would give the red dashed line and is clearly ruled out by the data. An effect of a certain type of dark matter would give the dark blue solid line and is just barely ruled out. [Note this is a logarithmic plot! The light blue colored region is by far the largest known effect, from Z particles decaying to neutrinos giving mono-jet events as in Figures 8 and 9. Other effects are several times smaller, even though they make misleadingly large splotches.]

The dashed red curve is the sort of thing that one might expect instead if extra dimensional gravitons of a certain type were being produced. The data clearly agree with the Standard

Model prediction, and rule out this type of extra dimensional graviton. The data also disagree (though it is harder to tell from the figure) with the effect of dark matter production (for a particular dark matter particle mass and interaction strength), shown in the solid blue curve. If such dark matter were being produced, it would have made the last two or three data points significantly higher.

In this example (and I could give you many others) you see the power of having the Standard Model's equations to predict the properties of the known particles. It allows us to determine ***how often we expect*** to see a single jet recoiling against "nothing", i.e. against undetected neutrinos. This prediction will match the data if there are no other types of undetected particles being produced by the LHC's collisions. We expect this prediction to fail **only** if the LHC is producing a new type of undetected particle, and/or if the LHC is producing neutrinos in an unexpected way, probably in the decay of a new type of unstable particle.

This is a general strategy. We have many predictions, and many measurements, in which we check the distribution of missing transverse momentum within large groups of collisions with similar features. If we see any of these predictions fail, then some process is happening that is not explained by the Standard Model, producing either unknown undetectable particles, or known ones (neutrinos) in an unexpected way.

Such a discovery would certainly be enough for showing the Standard Model does not describe all of the physics at the LHC, and would lead to many prizes for the experimental physicists. But the interpretation of the discovery would be highly ambiguous! Even if dark matter particles were being produced, it wouldn't be obvious at all! All we would know is there is some process generating undetected particles unexpectedly often. It would be a huge and unjustified logical leap to conclude that the undetected particles were dark matter particles!

How could scientists distinguish the various possibilities and eventually conclude that dark matter had been discovered? Well, it would not be simple and might take many years… decades, even. I'll address this in just a moment.

**Two More Examples**

*(Here's where I left off last week…)*

Before I do this, though, let me give you two other examples of how dark matter, or other undetectable particles, might show up. The newly discovered Higgs particle might sometimes decay (i.e. disintegrate) to dark matter, or to something else undetectable. Such so-called "invisible" decays of the Higgs are very rare in the Standard Model, so if they are found to be common, that would represent a profound discovery! Searches for such decays are already underway. The invisibly decaying Higgs can't be observed directly, but the Higgs is often made with W particles, Z particles, or distinctive quark pairs (which give distinctive jets relatively near the beams, Figure 11). These can be observed, along with missing transverse momentum from the Higgs itself as it decays to undetectable particles. However, as usual, there is a similar signal from the Standard Model — where a Z particle decaying to neutrinos takes the place of a Higgs particle decaying to dark matter. The two can only be distinguished by counting how many collisions of this type are observed, and checking whether the number is significantly more than predicted in the Standard Model.

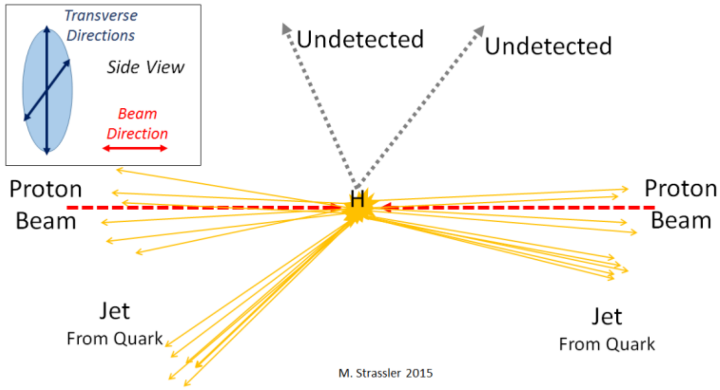


Fig. 11: A Higgs particle (H) can be produced along with two high-energy quarks, each of which produces a high-energy jet (a spray of hadrons). These unusual-looking jets recoil against the Higgs, whose decay to undetectable particles can provide large missing transverse momentum.  This same signal can arise, however, when a similar collision makes a Z particle instead of a Higgs, and the Z decays to a neutrino and anti-neutrino.

Another example: In many speculative ideas about particle physics that theorists have considered over the years, including but by no means limited to supersymmetry, the equations predict a new electrically charged particle that can decay to dark matter. In this circumstance it is not so unusual for proton-proton collisions to produce an electron (or a muon) and an anti-electron (or anti-muon), plus two dark matter particles that go undetected and provide missing transverse momentum (Figure 12).

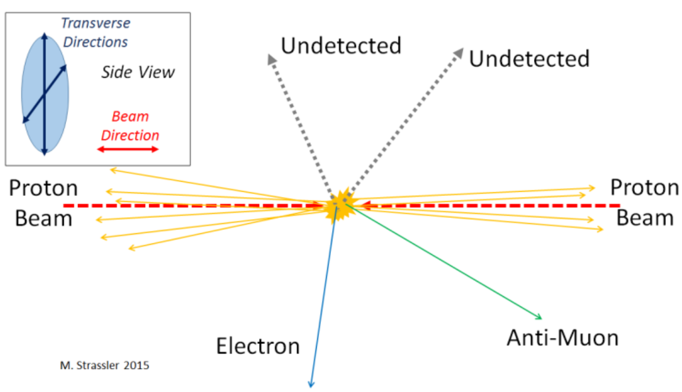


Fig. 12: Production of two new electrically charged particles (such as W-inos, the superpartner particles of W particles) can lead to two dark matter particles plus a charged lepton and a charged anti-lepton, as shown here in the example of an electron and an anti-muon. The large missing transverse momentum that results is easily noticed, but collisions in which W particles are produced, each of which decays to a charged lepton and an anti-neutrino (or their anti-particles), give a similar signal.

The only problem is that the *known* particles can make something that looks just like this. When collisions produce a positively charged W particle and its anti-particle, a negatively charged W particle, the W's can decay to something that looks identical to Figure 12, except that instead of dark matter particles, a neutrino and an anti-neutrino are produced. The only way to discover dark matter in this case is to count; if there are new particles as well as W's, there will be more collisions of this type than expected. Interestingly, there **are** more collisions than expected in LHC's current data… not so many that we should get excited yet, but enough that we should watch this closely as the LHC begins to collect another big batch of data.

The examples I've described are just three among many. There are more ideas about what dark matter could be than there are dark matter experts, and in each case there may be a wide variety of ways that dark matter might be created at the LHC. We therefore can't be sure how the experimenters should look for it — so they are preparing a broad-minded, diverse program of searches to make sure they aren't missing an opportunity.

**Even If LHC Discovers New Undetectable Particles, Are They Really Dark Matter Particles?**

How can the LHC experiments prove that they have produced dark matter? *They can't… not alone, anyway.* Even if they have made a new type of undetectable particle, they will have to partner with at least one other experiment that can directly check whether the dark matter itself — the stuff found abundantly in the universe — is **actually** made from LHC's new particles. Simply knowing that the type of particle exists doesn't prove that it makes up most of the matter in the universe. Just like neutrinos, it might make up only a ***small*** amount of the matter in the universe. Or it might even make up ***none***, if the new particles are unstable (as is the case for most types of particles), and have a lifetime *long* enough to travel out of the LHC detectors unseen before they decay, but *short* enough that they disappeared from the universe shortly after the Big Bang.

To say it more succinctly: ***even if the LHC makes and discovers a new class of undetectable particles, there's no way for LHC experimenters to figure out how many of these particles, if any, remain in the universe today.*** The LHC is the wrong machine for that purpose.

So what's to be done? Well, the LHC can be used to figure out some of the *properties* of the new particles, subject to some assumptions (which can be tested later.) For instance, in the previous section I gave you three examples (and there are many more) of how new undetectable particles could be discovered. In each case, *the new particles were produced in a distinct and distinctive way, and* ***other particles accompanied them*** *that gave an indication as to how they were produced.* For instance, if the new particles were produced alone, discovery occurred in collisions that made a single recoiling jet (Figure 8). If they were produced in Higgs decays, discovery could occur in events with two high-energy jets from two distinctive quarks (Figure 11). If they were produced in the decay of a new charged particle, discovery could occur (Figure 12) in events with a charged lepton and a charged anti-lepton (charged lepton = electron, muon or tau.) So by looking at what accompanies the new particles, and going even deeper into the details of how much missing transverse momentum is typically produced, scientists can potentially begin to put together one or more hypotheses regarding the nature of these new particles. Those hypotheses will be put into the form of ***equations***, which can be used to make ***predictions***.

Now we're almost there. If you have a hypothesis for what the new particle might be, you can ask, **how would dark matter of the universe behave if it was made from particles of this type?**

Specifically, you would ask: ***precisely*** *how rarely would these particles interact with ordinary matter? and how much* ***energy*** *would they typically leave behind when they do interact?* Knowing how much dark matter there is in the universe, you could predict how often existing underground experiments, such as LUX, XENON100, CDMS, etc., would see signals from this type of dark matter. Perhaps the rate is so large that the hypothesis is already invalidated? Or perhaps it is too small to have seen yet, but large enough to see soon?

The other question you would ask is: *What would happen if these dark matter particles encountered each other in the center of our galaxy, or in the centers of nearby dwarf galaxies? In these encounters, could they annihilate one another, and produce visible particles, such as electrons, anti-electrons, anti-protons, or photons (particles of light, probably in the form of gamma rays or X-rays)?* And you would ask whether existing satellites and telescopes looking for such signals, such as PAMELA, FERMI-LAT, AMS, etc., would have already detected these effects, or whether they could they do so soon.

***Only*** if and when we get enough information from the LHC (or future particle colliders) to formulate clear hypotheses for how the new particles might behave, and obtain clear predictions for what is expected in other experiments, and ***only*** if one of those other experiments clearly confirms at least one of these predictions, can we start to talk seriously about dark matter having been discovered at the LHC.

Could this happen, and could it happen soon? Sure. But as you can tell, it requires several fortunate things to happen in a row, so while it's not impossible, don't hold your breath. More likely, if it happens, it will take quite a while, perhaps decades. And if dark matter is made of particles that LHC can't produce, or isn't made of particles at all, or simply doesn't exist — well, LHC won't tell us that. It will simply remain silent on the matter. So we're hopeful, and they'll search, but many other approaches toward solving the great puzzles of the universe also need to be pursued.