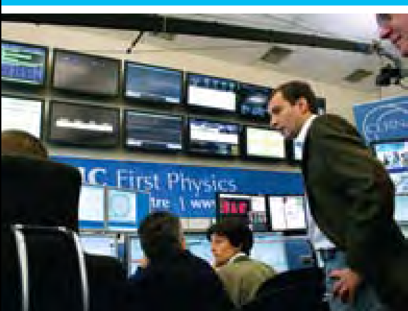
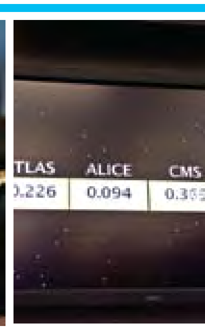
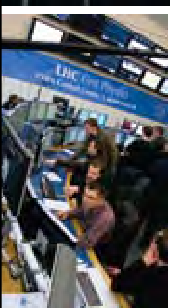
THE LHC DECODED

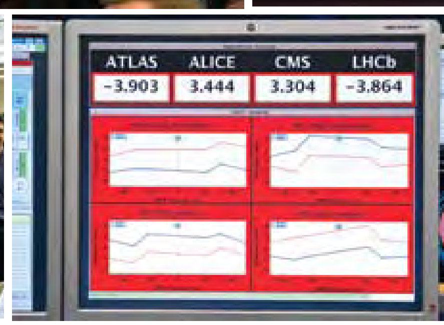
Walk like a physicist, point by point, through three of the displays that highlight scientific and technical milestones from the Large Hadron Collider's first months of operation.

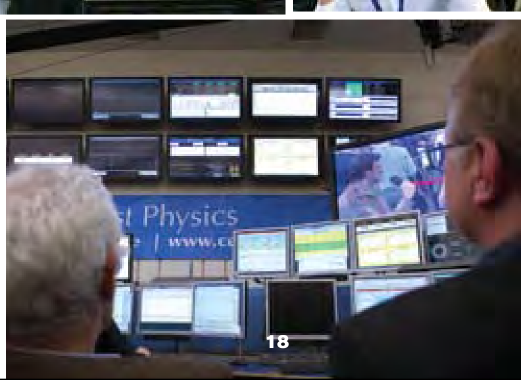








Capturing the moment

For every important event in particle physics—such as the record-setting collisions at the Large Hadron Collider that marked the official start of its research program, shown at left—there is a picture that shows at a glance what would take hundreds or thousands of words to explain.

Painted by pixels on computer screens, these images tell scientists what is happening in their machines and document key moments in the lives of the accelerator, its detectors, and the scientists who work with them. They come in two types. Status displays show the workings of the accelerator and its particle detectors, and event displays reveal what happens in a detector when particles collide.

All are made possible by interactive software that physicists can operate from their desktops or laptops nearly anywhere in the world, as well as from remote monitoring centers like the one at Fermi National Accelerator Laboratory in Illinois, which monitors the CMS detector. Researchers can call up many different forms of data, superimpose them on one anther to gain deeper insights, and rotate images to get a better view of the fleeting, messy aftermath of a particle collision. They scan for patterns that may reveal new physics or glitches in software or equipment. When they go off duty, they can hand off monitoring chores to colleagues in the next time zone over.

When the accelerator reaches a milestone or interesting physics results pop up in a detector, specialists create a version of the computer display that shows what happened and highlights particular features of interest. It may be cropped, rotated, or rendered in different colors than the displays physicists use on a daily basis. It may take just an hour to put together the first draft; the process of refining an event display until all 2000-3000 members of an experimental collaboration are pleased with the result takes a whole lot longer. Yet that's what it takes to get an event display approved for release to the rest of the scientific community and the public.

Today's event displays are the product of decades of evolution. For most of the history of particle physics, scientists recorded and displayed particle interactions by taking photographs. They shot photos of the tracks particles left in a cloud chamber or bubble trails they left in a bubble chamber, and measured the features in those photos using protractors and other hand tools.

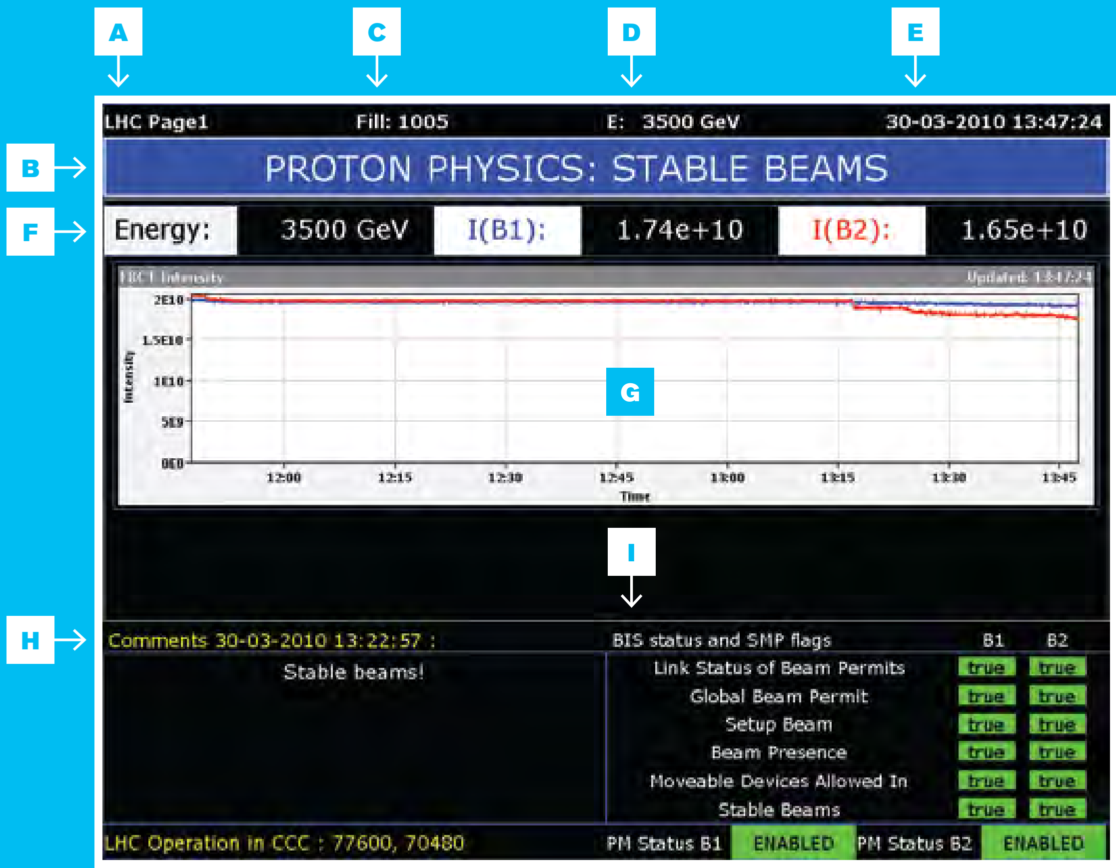
Joseph Perl of SLAC National Accelerator Laboratory remembers watching his father, Martin Perl, who later would win the Nobel Prize, conduct experiments with a spark chamber at the lab. When a particle hit the chamber's 12-foot-tall metal plates, "A bolt of lightning would flash and a camera would capture it, and you would actually have this crashing sound," he says with relish. Joseph Perl went on to develop event displays for four SLAC experiments over the past 20 years.

In 1968, the invention of the multi-wire proportional chamber at CERN allowed physicists to hook their detectors directly up to computers so they could collect and analyze data without scanning photos. This breakthrough nudged particle physics into the electronic age and eventually led to computerized displays.

Today's electronic depiction of a particle event is "a diagram rather than a photograph," Perl says. "It's like a good subway map; it's highly formalized to pack as much information as you can into that space. The trick with the software is to make it so you can generate this thing very quickly on the fly for anything that people would want to study. The standard is that you should be able to do that from any desktop anywhere. I want it to work on the cheap computer that some grad student has at home, late at night."

In the next few pages we'll walk you through displays from the Large Hadron Collider control room and from two of its four major experiments, ATLAS and CMS.

Daisy Yuhas, Katie Yurkewicz, and Glennda Chui contributed to this article, which is based on information from a series of articles in the *CERN Bulletin* and *symmetry breaking*. Links to those articles and other information are at http://www.symmetrymagazine.org/LHC_display/



LHC: Page 1

A → **LHC page 1:** Indicates which status display is shown. Page 1 shows the overall status of the collider; eight other LHC-related pages can be displayed, as well as pages for other CERN accelerators.

B → **Mode of operation:** PROTON PHYSICS indicates the machine mode; STABLE BEAMS indicates the beam mode.

C → **Fill:** An archiving number that increases every time a new beam is injected into the LHC.

D → **E:** The energy of each beam, 3500 billion electronvolts, or GeV.

E → **Date and local time:** At top right are the date and local time in Central European Summer Time.

F → **Energy and intensities:** The energy and intensities of the two proton beams. B1 (blue) and B2 (red).

G → **The chart:** Plots the beam's intensity over time. LHC operators can show any image or text of their choosing in this space, or leave it blank.

H → **Comments:** A space for LHC operators to express themselves. Here the operator is celebrating the first day of collisions with stable 7 TeV beams.

I → **BIS status and SMP flag:** In the lower right corner, the Beam Interlock System (BIS) and Safe Machine Parameter (SMP) flags indicate the status of a number of accelerator settings that can be critical for the scientists running the LHC and its experiments.

Page 1: A window into the heart of the big machine

The Large Hadron Collider, or LHC, is a 27-kilometer ring beneath the Swiss-French border where two beams of protons going in opposite directions are accelerated to nearly the speed of light. They collide in the hearts of four detectors—enormous, multilayered machines studded around the ring—and give off sprays of particles.

Each detector is composed of sub-detectors that measure specific properties of certain types of particle. By combining all of this information, scientists determine the types and quantities of particles produced in the collision.

The status display on this page, known as Page 1, shows the overall status of the collider. It changes throughout the day with the changing activity of the machine—whether it is preparing for beam, testing an accelerator system, or providing experimental collisions—and includes comments from LHC operators.

Let's start with the mode of operation. PROTON PHYSICS indicates the "machine mode"; in this status display, collisions are being provided to the experiments for physics studies. STABLE BEAMS indicates the "beam mode"; in this case two proton beams are circulating and colliding, and accelerator operators will make no further major adjustments to the beams. This particular display was captured less than one hour after the LHC collided its first protons at an energy of 7 trillion electronvolts, or TeV, in the process setting a new world record and launching the LHC's research program.

Above this title are three sets of numbers. Fill is an archiving number that increases every time a new beam is injected into the LHC. E is the energy of each beam, 3500 billion electronvolts, or GeV. This is the maximum energy for the LHC's current run, which will last until late 2011. At top right are the date and local time: March 30, 2010, at 1:47 p.m. Central European Summer Time.

The line below the title shows the energy and intensities of the two proton beams, called B1 (blue) and B2 (red). The graph below plots the beams' intensities over time. You can see that they were pretty much identical over the previous two hours, drooping slightly toward the end. The slight drop was caused by the insertion of collimators—beam cleaners—into their normal positions before the beams were declared stable. In the comments section at lower left, one of the operators has written, "Stable beams!"

In the lower right corner, the Beam Interlock System (BIS) and Safe Machine Parameter (SMP) flags indicate the status of a number of accelerator settings that can be critical for the scientists running the LHC and its experiments. Green means "true" and red means "false."

Here's what each flag means:

Link Status of Beam Permits: Indicates whether the two beam permits are linked. If they are linked, the dumping of one beam will cause the dumping of the other.

Global Beam Permit: Beam is allowed into the LHC.

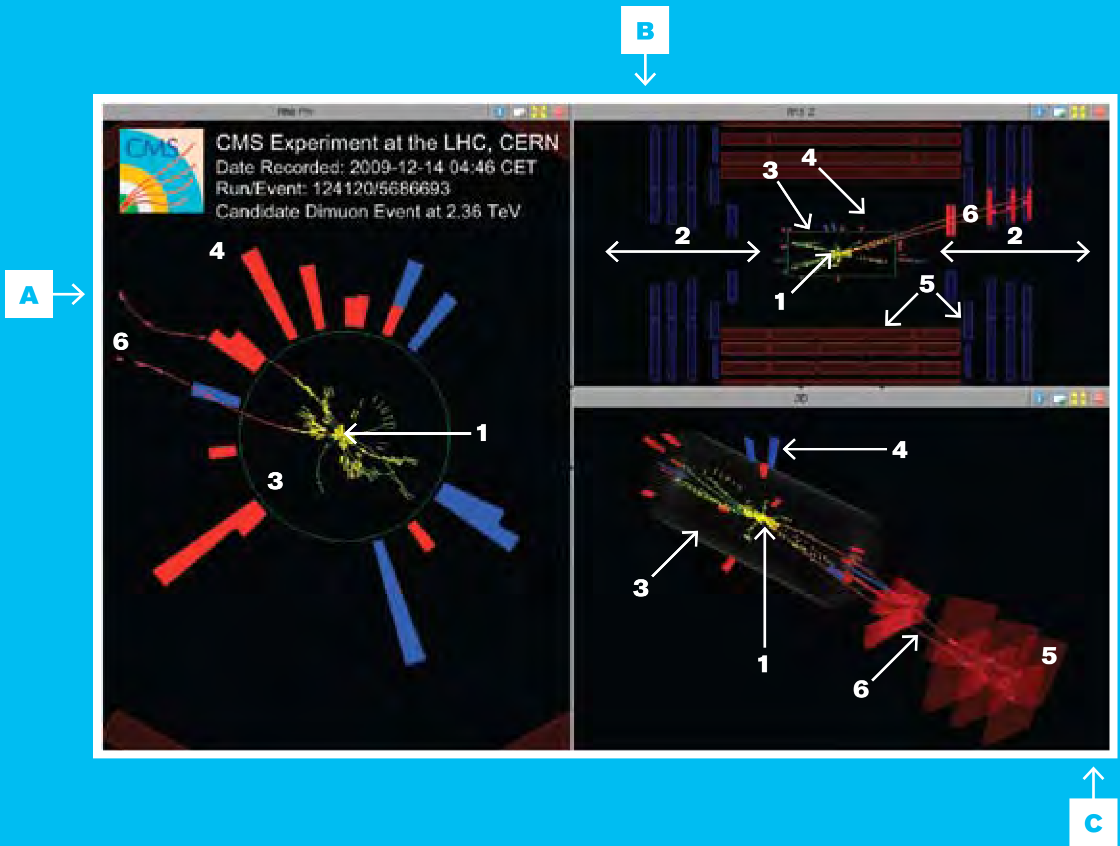
Setup Beam: The intensity of the beam is below a certain level, minimizing the risk to the accelerator.

Beam Presence: Beam is circulating in the LHC.

Moveable Devices Allowed In: Some of the parts that make up the LHC detectors sit very close to the particle beam, where they can be harmed by unstable beams. This flag indicates whether these detectors, which include the TOTEM experiment's "Roman pots" and LHCb's vertex detectors, may be moved into position next to the beam line.

Stable Beams: Beams are stably colliding; no major adjustments to the beams can be performed by the accelerator operators. This tells the scientists running the LHC experiments that they can turn on even the most sensitive parts of their detectors.

PM Status B1 and B2: The PM, or Post-Mortem, system provides a record of what happened in the accelerator during an event such as a magnet quench or beam abort, so LHC scientists and technicians can get the whole picture.



CMS: Dimuon event

A → Beam's eye view: Looking straight through the central collision point.

B → Side view: Shows the three main regions of the detector. The beams run horizontally through the middle.

C → Three-dimensional perspective: Here the beam line runs from upper left to lower right and can be rotated.

1 → Collision point: Marks the spot where protons from the two beams smash into each other.

2 → Beam line: The arrows show the paths of the beams. One travels right to left, the other left to right.

3 → Silicon tracker: The first layer of the detector tracks particles' momentums and paths.

4 → Calorimeters: Record the energies of electrons, photons, and hadrons.

5 → Muon chambers: The outermost component of the detector records information about muons.

6 → Muons: Physicists studying this display have hypothesized that this event produced two muons, whose trails are marked in red.

CMS: A dimuon trophy

Looking at the title and text on this event display from the Compact Muon Solenoid (CMS) experiment, we can see that this event occurred on December 14, 2009 at 4:46 a.m. Central European Time. It was the 5,686,693rd event recorded in Run 124120. A run is a period of continuous operation in a given part of the detector. Physicists use run and event numbers to catalog their data. The run number will increase throughout the life of the detector; the event number resets to zero at the start of each run.

The fourth line tells you that the energy level of the collision was 2.36 trillion electron volts (TeV).

Event displays are divided into multiple screens that view the split second of the collision and the resulting spray of particles in different ways and from different angles. This event display includes a beam's eye view, looking straight through the central collision point; the view from the side, which shows the beams entering from left and right, colliding, and spraying particle debris through the three main regions of the CMS detector; and a 3D perspective that can be rotated and examined from all sides. The 3D view shows the beam running diagonally from the upper left to lower right of the screen.

Looking at the side view, you can see the paths of the proton beams entering and leaving the detector. One is traveling from left to right, the other from right to left.

The collision point, which physicists call the interaction point, is the exact spot where two particles collide. It occurs within a broader area called the interaction region, where the two beams cross. Despite all efforts to pack the billions of protons in a beam into dense bunches, and thus maximize the number of collisions, the protons are so tiny and spaced just far enough apart that very few of them smack into each other head-on. Some just bump or nudge each other and the vast majority pass without interacting at all, like people in a crowded pedestrian crossing.

When a collision does take place, the resulting spray of particle debris flies off through the detector. Its layers are cleverly arranged to identify key properties of these particles—their paths, energies, masses, charges, and so on—and sort them into smaller and smaller bins, metaphorically speaking, until each one has been identified as an electron, hadron, muon, or photon of light.

In CMS, the first thing the particles encounter is the silicon tracker, which is best seen outlined in green on screens A and B.

The tracker sits in a magnetic field that curves the paths of particles traveling through. This affects only charged particles, such as muons, electrons, and charged hadrons; the rest keep going straight.

The degree of curvature reveals the particle's momentum. The direction of the curvature—clockwise or counter-clockwise—indicates positive or negative charge. Since the curve may bend in some directions but not in others, it's important to see it from multiple vantage points.

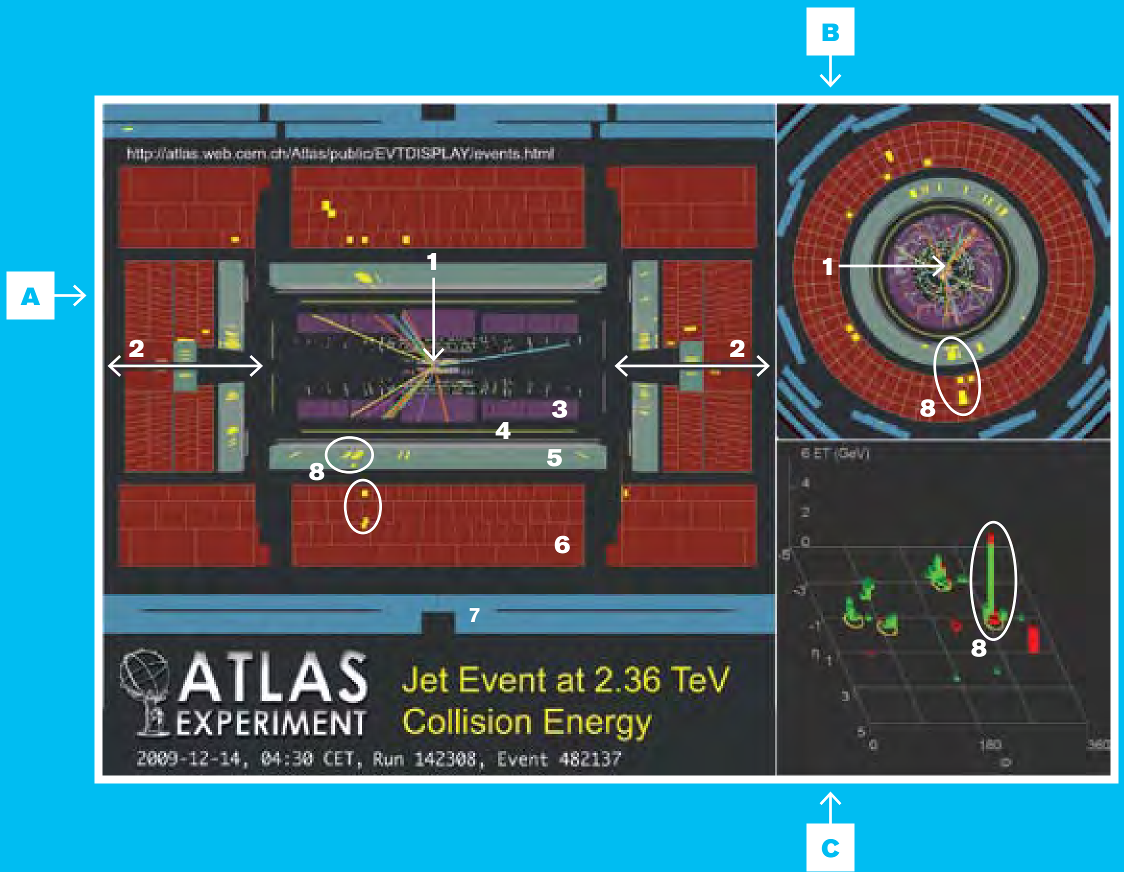
The tracker reconstructs the movements of charged particles point by point; those points appear as yellow dots. When we connect the dots we see the particle paths, represented here by red and green lines.

Next come the calorimeters, which stop certain particles and record the energy they deposit. This allows scientists to determine their mass.

First the particles hit the electromagnetic calorimeter, or ECal, which mostly records the energies of electrons and photons; it's represented by a red bar. Other particles continue to the hadronic calorimeter, or HCal, which traps hadrons and measures their energies; it's shown as a blue bar. The heights of the bars indicate the amount of energy deposited.

Finally, the remaining particles enter the third and outermost layers of the detector, the muon chambers. These show up on screen B as red blocks above and below the detector and blue blocks on either side; chambers that have recorded a muon hit are highlighted in red.

This particular event display shows a dimuon event, the production of two muons in a collision; their paths are shown as thin red lines on each screen. How can we be sure they're muons? Their tracks in the silicon tracker show they are charged particles that flew out from the collision in a particular direction and with a specific momentum. The energy they left in the calorimeters reveals their mass. And their passage through the muon chambers confirmed their IDs. Of course the scientists can't claim to see dimuon production based on one event alone; instead they wait until a number of events accumulate and analysis shows that the sighting was not a fluke.



ATLAS: Detector from the inside

A → Side view: Gives a good picture of the beamline and collision point.

B → Beam's eye view: Seen from the point of view of an incoming beam

C → Lego plot: Shows energy deposited by particles in the liquid argon and tile calorimeters.

1 → Collision point: Where the proton beams collided at a combined energy of 2.36 TeV.

2 → Beam line: The arrows show the paths of the beams. One travels right to left, the other left to right.

3 → Tracking detectors: Measure the momentums of charged particles.

4 → Central solenoid magnet: Bends the paths of charged particles as they pass through the tracker.

5 → Liquid argon calorimeter: Measures the energies of electromagnetic particles.

6 → Tile calorimeter: Measures the energies of hadronic particles.

7 → Muon spectrometer: Records the passage of muon particles.

8 → The energy deposited by the jet in the calorimeters: Shown in all three views.

ATLAS: Powerful jets

Dimuon events are one of a number of familiar phenomena seen by the LHC experiments during the collider's first few months of operation. As of May 2010, the list included energetic muons; events in which *W* and *Z* bosons, first discovered at CERN in 1983, may have been created; and Beauty particles, which combine one bottom quark and one quark of a different type.

Physicists call these "trophies." While they don't break new ground, they are exciting milestones for the thousands of scientists working on the experiments, because they confirm that the detectors are working as they should.

This image from the ATLAS event display shows another trophy: the production of jets.

Jets are sprays of particles that are produced only in violent, head-on proton collisions—the type of collision most likely to produce heavy new particles. So physicists expect to see jets in the signatures of almost every interesting collision at the LHC. The yellow marks that are circled in white represent energy deposited by jets in the detector.

In this case the protons collided at a combined energy of 2.36 electronvolts, or TeV. This is the same collision energy as in the CMS event display, and in fact the two events took place just 16 minutes apart on Dec. 14, 2009, a time when collision energies were being gradually ramped up following a one-year shutdown for repair and refurbishment. This was the highest collision energy that could be safely achieved, given the tests that had been completed at that point.

Why is collision energy important? It has to do with Einstein's famous equation, $E=mc^2$, which says matter and energy are equivalent. When particles collide, their mass instantly converts to energy. Then all the energy released by the collision turns back into particles. The higher the collision's energy, the heavier the particles it can produce. Scientists expect heavy, exotic, never-before-seen particles to come out of the record-setting collision energies at the LHC.

Three views of this particular collision are shown. One looks at the ATLAS detector from the side; another takes a beam's eye view. All the information collected by ATLAS's detector subsystems is projected onto these slices, translating a three-dimensional event into two dimensions. The third view shows information from just two sub-detectors, the calorimeters. It's called a Lego plot because it stacks the amounts of energy the calorimeters collected as if they were LEGO bricks. This gives physicists a quick impression of how much energy was carried away from the collision by a particle or jet.

As with CMS, the event display shows the collision point from two directions, and the side view shows the paths of the proton beams entering and leaving the detector. Particles go through these sub-detectors in the same sequence.

First, the three tracking detectors measure the momentums and determine the charges of charged particles.

The pixel detector sits directly above and below the collision point in the side view and surrounds the collision point in the head-on view. The semiconductor tracker is a bit farther from the collision point. In both of these trackers, the passage of a particle is indicated by a colored square. Gray squares show activity that, after more analysis, was determined not to be of interest. Black squares indicate no activity in that area of the detector. The transition radiation tracker is in purple.

Particles that registered in all three tracking detectors are shown as colored lines radiating from the collision point.

Next is the central solenoid magnet, in green. It curves the paths of particles as they pass through the tracking detectors, as seen in the side view. This is one of two large magnet systems in ATLAS; the second, much larger one, called the toroid magnet system, is not shown here.

On to the liquid argon calorimeter, in gray, which measures the energies of electromagnetic particles such as electrons and photons. The amounts of energy these particles deposit are shown as yellow rectangles.

Electrons can be distinguished from photons because they are charged particles that leave tracks in the tracking detectors before dumping energy in the liquid argon calorimeter. Photons, which have no charge, don't leave tracks.

The tile calorimeter, in red, measures the energies of hadronic particles such as protons and neutrons. Energy deposits are again indicated by yellow rectangles.

Protons can be distinguished from neutrons because they are charged particles, and leave tracks in the trackers. The neutral neutrons do not.

Finally the remaining particles hit the muon spectrometer. Since this collision produced no muons, only part of this spectrometer is shown.