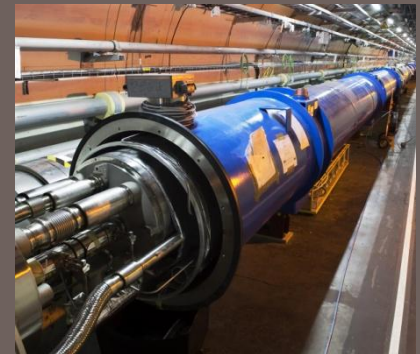
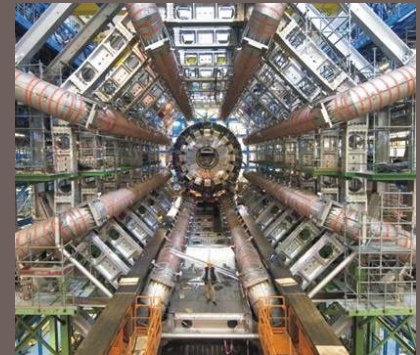
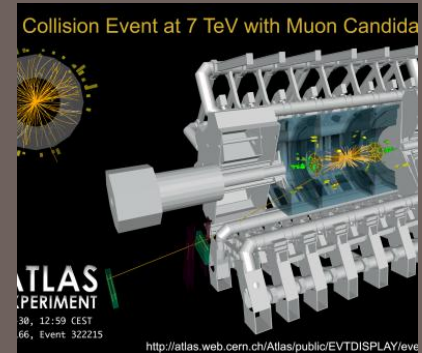


Collision Course:

ATLAS and the Large Hadron Collider

A smashing success...

Isabel Trigger | ATLAS Group Leader | TRIUMF



The LHC & ATLAS: Overview

- **Who** is working on the LHC?
- **What** is the LHC (and ATLAS)?
- **Where** is the LHC?
- **When** will we get the results?
- **Why** do we need the LHC?
- **How** will the LHC work?
- I won't go exactly in that order!

So what is *stardust* made of?

- Particle physicists want to know what ***everything*** is made of, everywhere in the universe, what holds it together & keeps it apart
- We want it to be really simple
 - Ideally, *one* type of particle and *one* force
- Why should the universe be simple?
 - Because that would be very elegant
 - We think it started as pure energy. Very simple.
 - Because then we could understand everything
 - (At least in the same way knowing the alphabet means we “know” poetry and philosophy)



- # History of the Universe



Phase Transition? Symmetry breaking?

- **Analogy:**
 - Glass of water at room temperature
 - Very simple, all the same!
 - Lower the temperature
 - Ice crystals, frost patterns form
 - Very complex, all different!
- At higher temperatures (energies) the system has more symmetry
- At lower temperatures, phase transition occurs, symmetry is broken, system becomes more complex



How close are we to “simple”?

- Matter particles:

- “up”-like Quarks: 3 types with charge $+2/3$
- “down”-like Quarks: 3 types with charge $-1/3$
- Electrons (plus 2 things that are like electrons but heavier)
- Neutrinos (3 types)
- ...and they all have anti-matter partners
- So $4 \times 3 = 12$ “fundamental” matter particles (too many?)

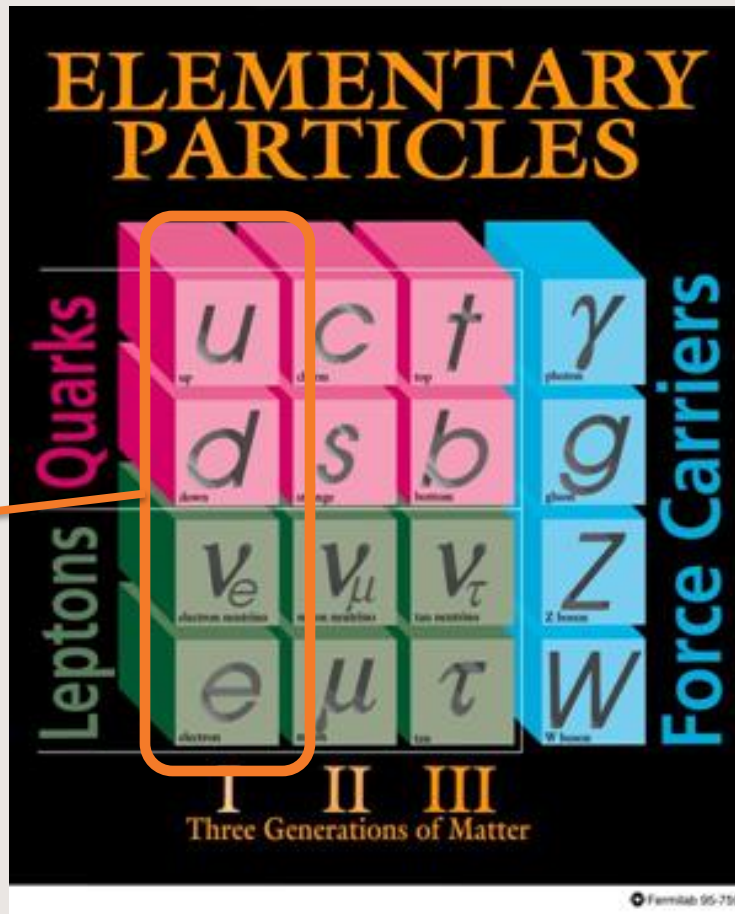
- Forces:

- We know of 4 (which unfortunately is more than 1):
 - Electromagnetism, Gravity, Strong & Weak Nuclear Forces
 - The Standard Model of Particle Physics describes all but gravity



Particle “Periodic Table”

All stable matter made of just these



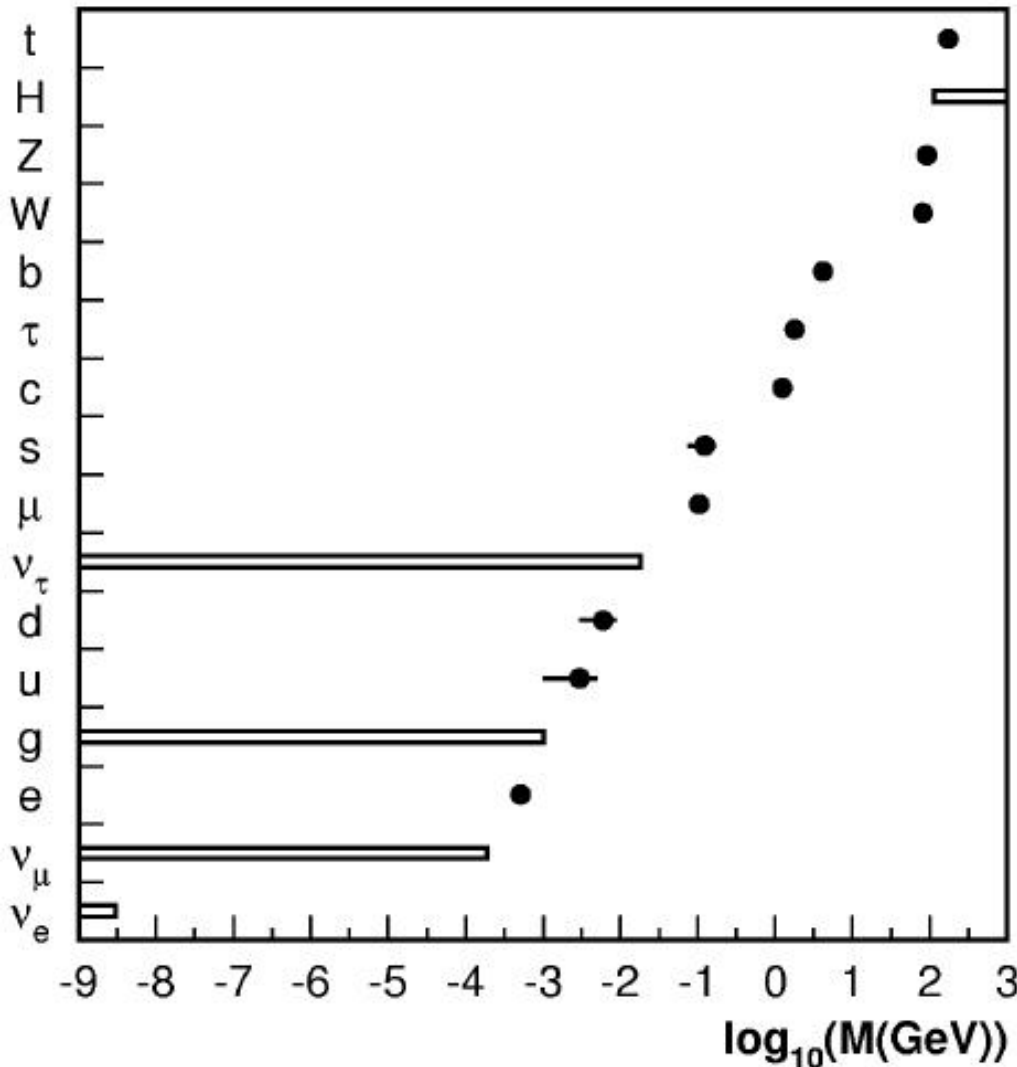
- Not sure why 3 copies of each matter particle
- BUT can't generate matter-antimatter asymmetry without at least 3 families
- And we know there's more matter than antimatter (because we exist!)

What *are* all those particles?

- “Elementary” or “fundamental” particles are point-like particles with no substructure
- We think electrons are elementary particles
 - With charge $Q=-1$
- Neutrinos are like electrons with no electric charge... and very, very small masses
 - Almost not there at all...
- But protons and neutrons are made of **quarks**:
 - 2 up + 1 down quark = proton ($Q=2*2/3-1/3=+1$)
 - 2 down + 1 up quark = neutron ($Q=2*(-1/3)+2/3=0$)
 - Which *sounds* more complicated, but you can also make LOTS of other things out of up and down quarks and anti-quarks, (pions...) and many more when you include the other 4 quark “flavours”

Fundamental Mass Values

Experimental values or limits: known particles



Theory says nothing about origin of **VALUES** of masses of *matter* particles... They have to be obtained from **EXPERIMENT**

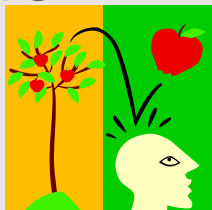
But photons and gluons are *predicted* to be massless, masses of **W** and **Z** are *predicted*

Why such a large range of fundamental masses?

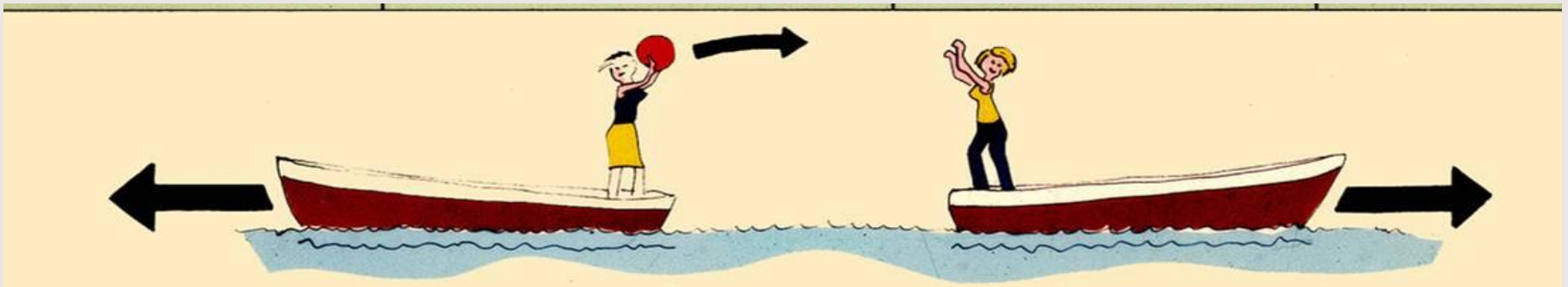
Indirect searches yield very small neutrino masses... why are neutral fermions so light?

Four Forces

- **Electromagnetism**
 - Unification of Electric and Magnetic forces
 - Familiar as light, radio waves, X-rays, microwaves, ...
- **Weak Nuclear Force**
 - Makes sun burn really slowly fusing hydrogen into helium... also β decays
- **Strong Nuclear Force**
 - Holds protons and neutrons together inside nuclei
- **Gravity**
 - Holds together everything with mass. Only attractive. Much, much weaker than the other 3.



What is a force?



- A **push** or a **pull**
- $F = ma$
- Ball in the picture is the “force carrier”
 - Transfers momentum between the two boats
- If ball heavy, can’t be thrown very far (weak force)
- If ball weightless, anyone can throw it *infinitely* far (EM force)
- Have to keep on throwing the ball back and forth (“hot potato”)
- Never try to push an analogy too far!!!

Four *Different* Forces

- **Electromagnetism**
 - Couples to electric charge (which comes in “quanta”, so it’s a “quantum number”)
- **Weak Nuclear Force**
 - Couples to a quantum number we call “weak hypercharge”
- **Strong Nuclear Force**
 - Couples to a quantum number whimsically called “colour”; quarks are the only “coloured” matter particles and they always combine to make hadrons which are “colour-neutral”
- **Gravity**
 - Couples to mass.
 - Mass does not appear to be quantized – it doesn’t come in chunks.

Four (OK, 13) Force Carriers

- Electromagnetism

- Carried by **Photons** (particles of light, X-rays, radio waves, microwaves...) which couple to everything which carries electric charge

- Weak Nuclear Force

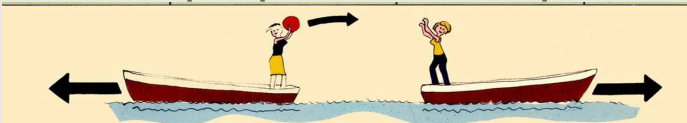
- A lot like electromagnetism except carried by 3 photon-like particles (**W^+ , W^- , Z^0**), 2 of which (W^\pm) are electrically charged and all of which are very massive... which is why it seems weak... and which interact with each other too

- Strong Nuclear Force

- Carried by 8 “**gluons**” which are massless and carry “colour” themselves, so they interact with each other as well as with quarks (but not electrons or neutrinos) so the strong force is only strong at very short distances (like inside nuclei)

- Gravity

- Thought to be carried by massless “**graviton**” (very different properties from photon, weak bosons, gluons) – never detected



Four Forces: peculiarities

- Electromagnetism
 - Photons themselves have 0 electric charge and 0 mass which only interact with charged particles (so **never** with other photons)
- Weak Nuclear Force
 - We can only make a consistent theory with massive force carriers through the “Higgs Mechanism”
- Strong Nuclear Force
 - We never see “naked colour” charge – quarks always form “hadrons” with neutral “colour”. Either 3 quarks of different “colour” form a “baryon” like a proton or neutron or else a quark and anti-quark of identical colour / anti-colour form a “meson” like a pion.
- Gravity
 - Too weak to have much effect in particle physics... (unless there are more than 3 space dimensions!)

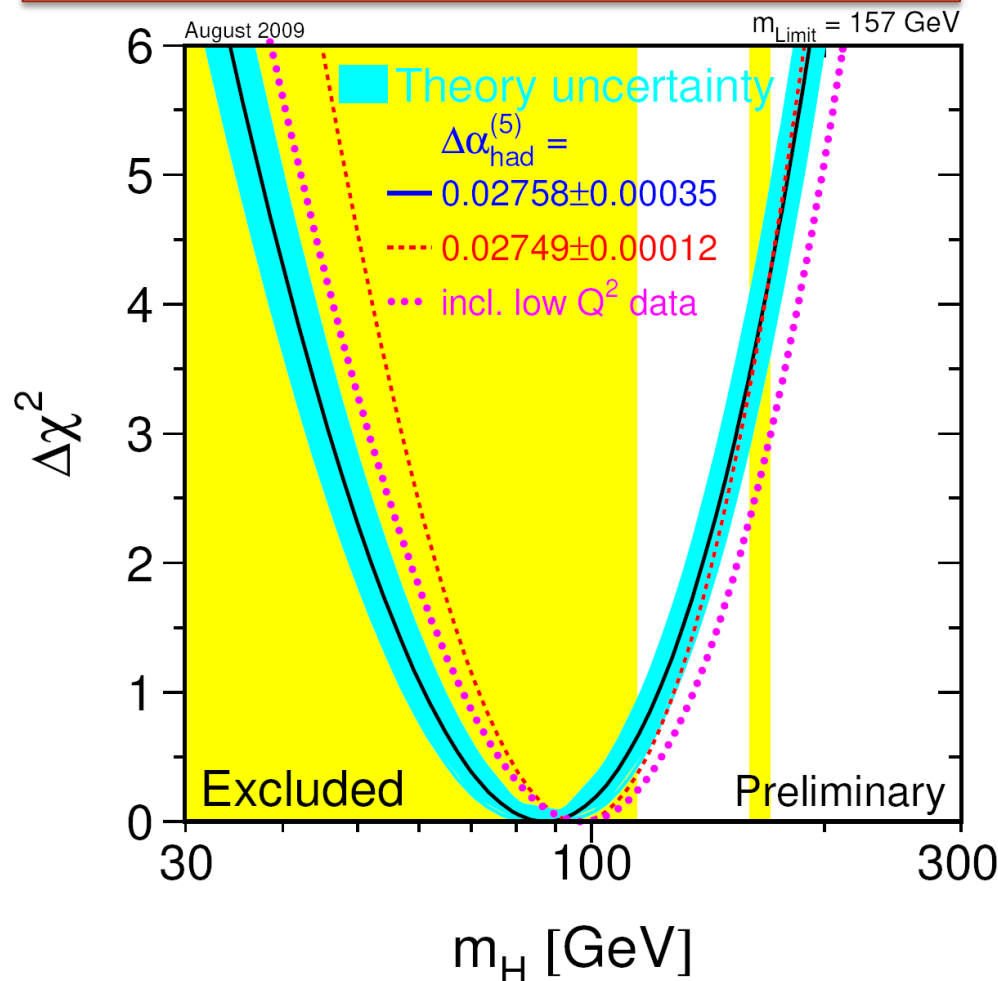
What is the Higgs Boson?

- Very nice model (the “**Standard Model**”) describes electromagnetic and weak interactions in a **combined** framework – basically they are different aspects of same force
 - Theory *only works for massive weak bosons* if we play a trick called the **Higgs Mechanism**
- Not only does this *allow* the W and Z bosons to have masses – it also *predicted* them. They were *then* discovered at those exact masses, and measured very precisely.
 - So we **believe (very strongly)** that the Higgs mechanism works.
- But Higgs mechanism predicts at least one more particle: the **Higgs boson**. It *does not* predict its mass.
- There could be more than one Higgs boson, but there *must be at least one*. We haven’t found it yet.
- Higgs boson couples to quarks and leptons with strength proportional to their mass. So, very intimately linked to **mass**!

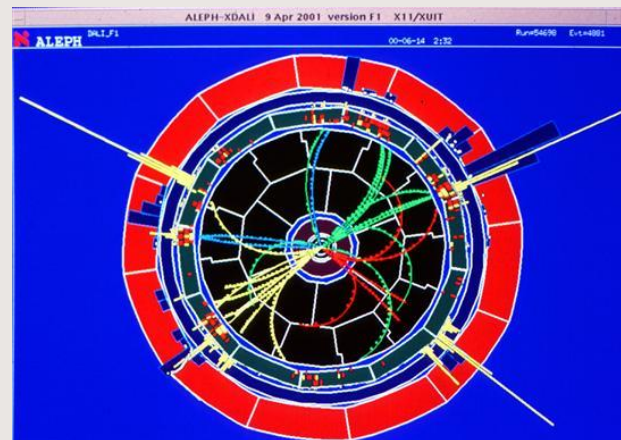


Experimental Constraints on Higgs Mass

Fits to 2 decades of precision measurements sensitive to M_H

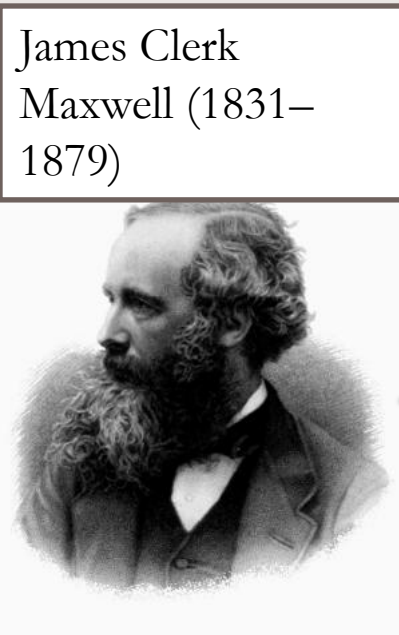


- M_H (summer 2009)
 - χ^2 minimum:
 - 87 GeV (excluded!)**
 - Direct Search LEP:
 - > 114 GeV @ 95% C.L.**
 - Indirect EW fit constraints:
 - < 157 GeV @ 95% C.L.**
 - Including LEP direct search limit
 - < 186 GeV @ 95% C.L.**

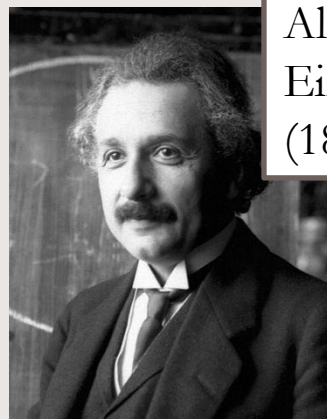
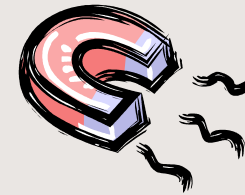
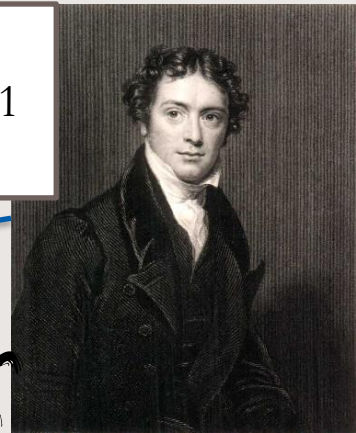
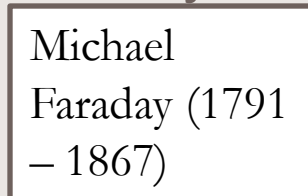


How did we figure out that much?

- Two approaches: theory & experiment
 - For every Maxwell, we also need a Faraday...



$$\begin{aligned}\nabla \cdot \mathbf{E} &= 0 \\ \nabla \cdot \mathbf{B} &= 0 \\ \nabla \times \mathbf{E} &= -\frac{1}{c} \frac{\partial \mathbf{B}}{\partial t} \\ \nabla \times \mathbf{B} &= \frac{1}{c} \frac{\partial \mathbf{E}}{\partial t}\end{aligned}$$



Albert Einstein (1879-1955)

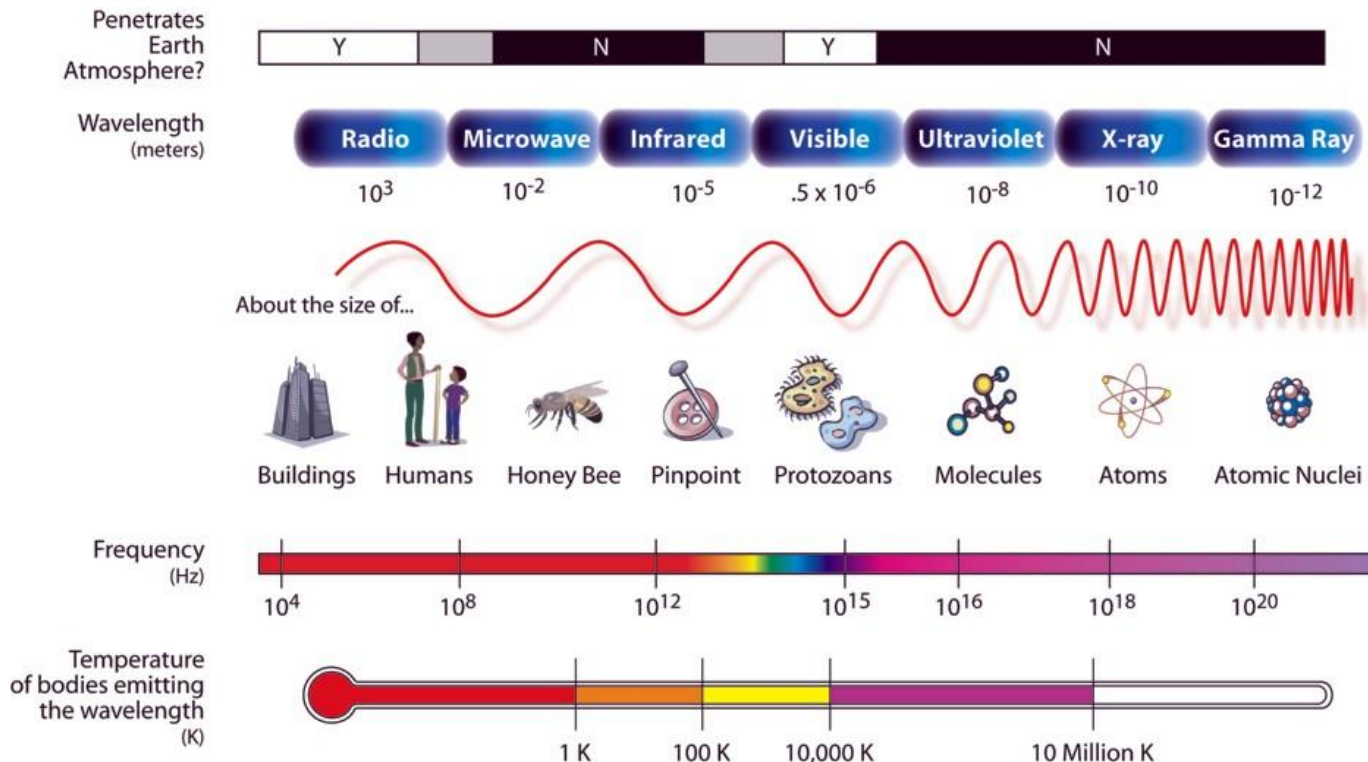


Heinrich Hertz (1857-1894)



How do we see small things?

THE ELECTROMAGNETIC SPECTRUM



Accelerator
(charged particles
easier to
accelerate
than
photons)



Target

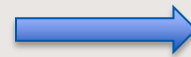
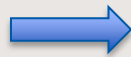
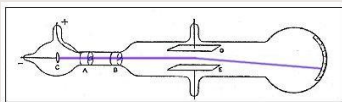


Detector

Smaller wavelengths (=higher energy) lets us see smaller things

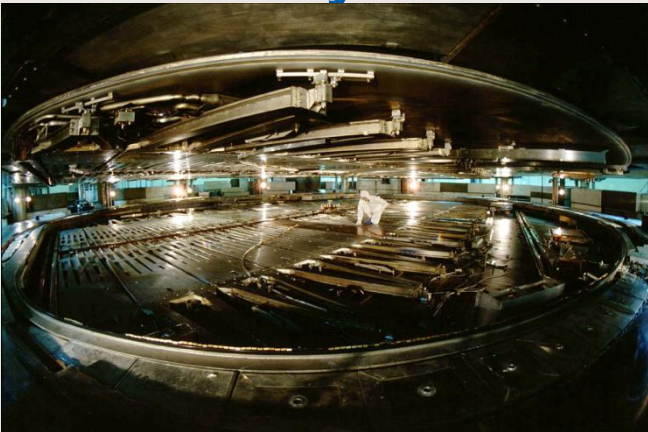
Faraday didn't need an LHC – what's different today?

- Huge progress in the last 150 years!
- Knowing about **electromagnetic radiation** was key – knowing how to produce and detect it at different frequencies let us explore whole new field
- First elementary particle discovered was the electron (J.J. Thomson, 1897) – during experiments with electric and magnetic fields
 - Weak, relatively low-energy EM fields, which could be easily produced with 19th century tabletop equipment
 - BUT electrons are **stable** and **light** and **interact electromagnetically**
 - so they are easy!
- The **last** elementary particles to be detected were:
 - **Top Quark** (1995, CDF & D0) – mass about 175 times the proton mass, close to a gold atom... since $E=mc^2$, needed a lot of energy to make this much mass – lifetime $\sim 0.5 \times 10^{-24} \text{s}$ (NOT stable!)
 - **Tau Neutrino** (2000, DONUT) – mass too small to measure so far, only weak interactions, not produced in decays of anything stable...
- Massive particles can only be **produced** at very high energies
- Particles with only weak interactions are very hard to **detect**

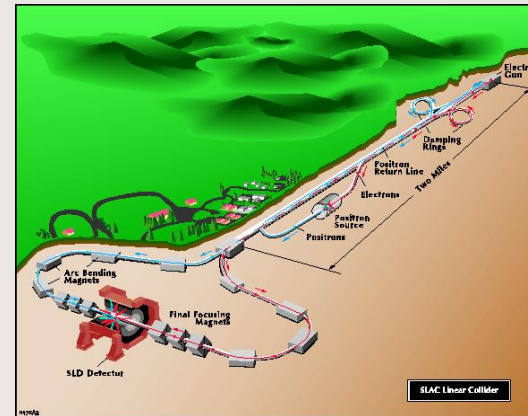


Some examples of particle accelerators

TRIUMF Cyclotron



SLC: e+e- linear collider



LEP: e+e- collider ring

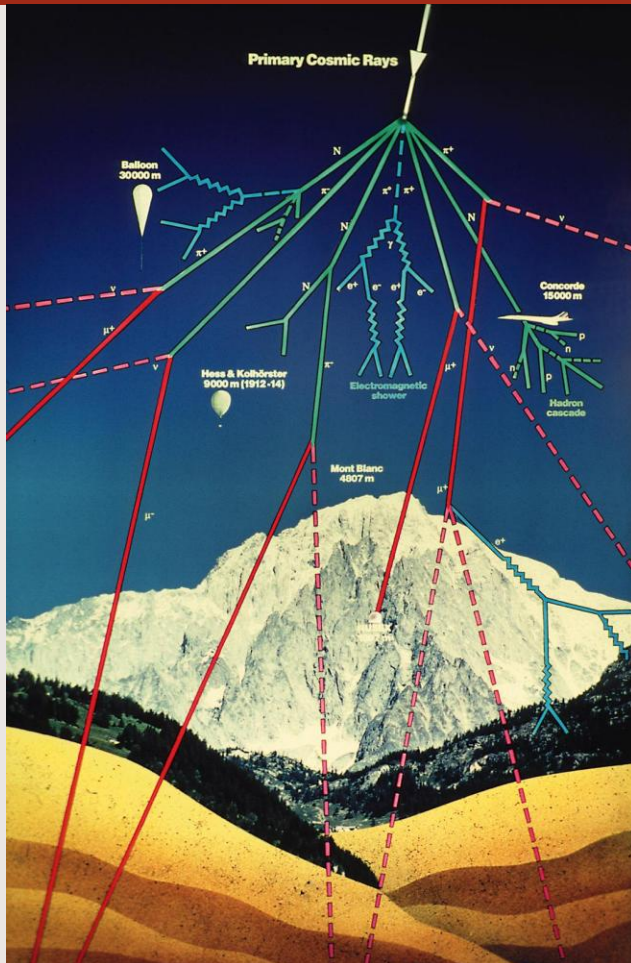


Tevatron: proton-antiproton collider

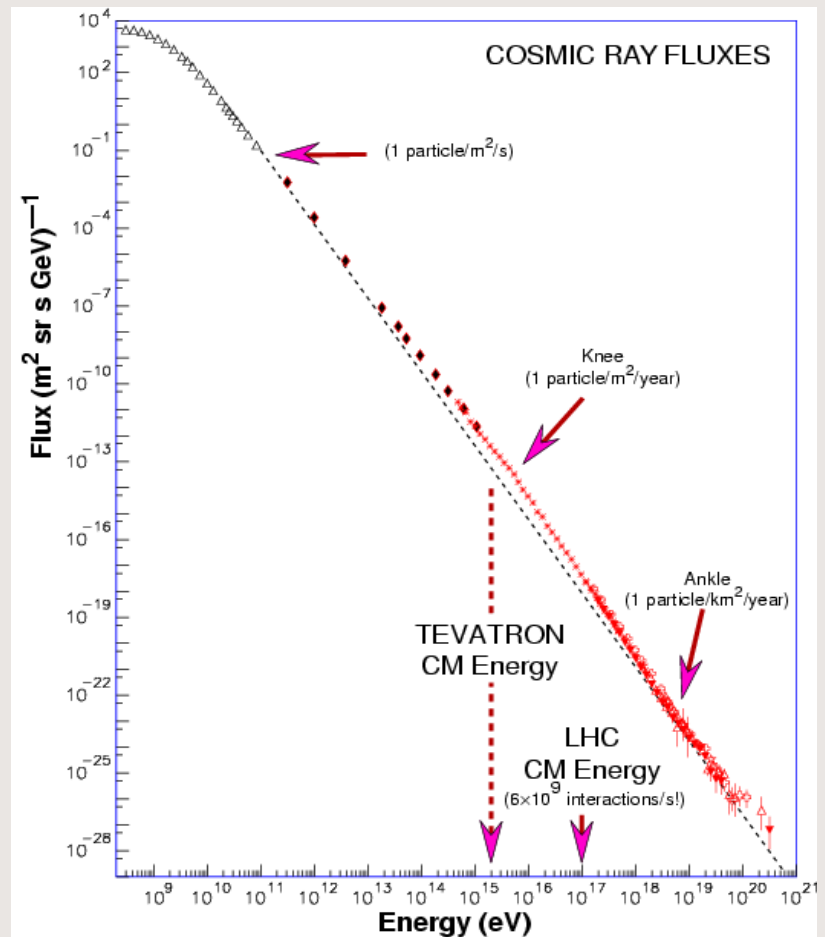


Nature's Accelerators

Cosmic Rays – accelerated in cataclysmic events, perhaps in faraway galaxies...



... reaching energies far higher than human-built accelerators



TRIUMF How Accelerators Work: basic idea

See video at

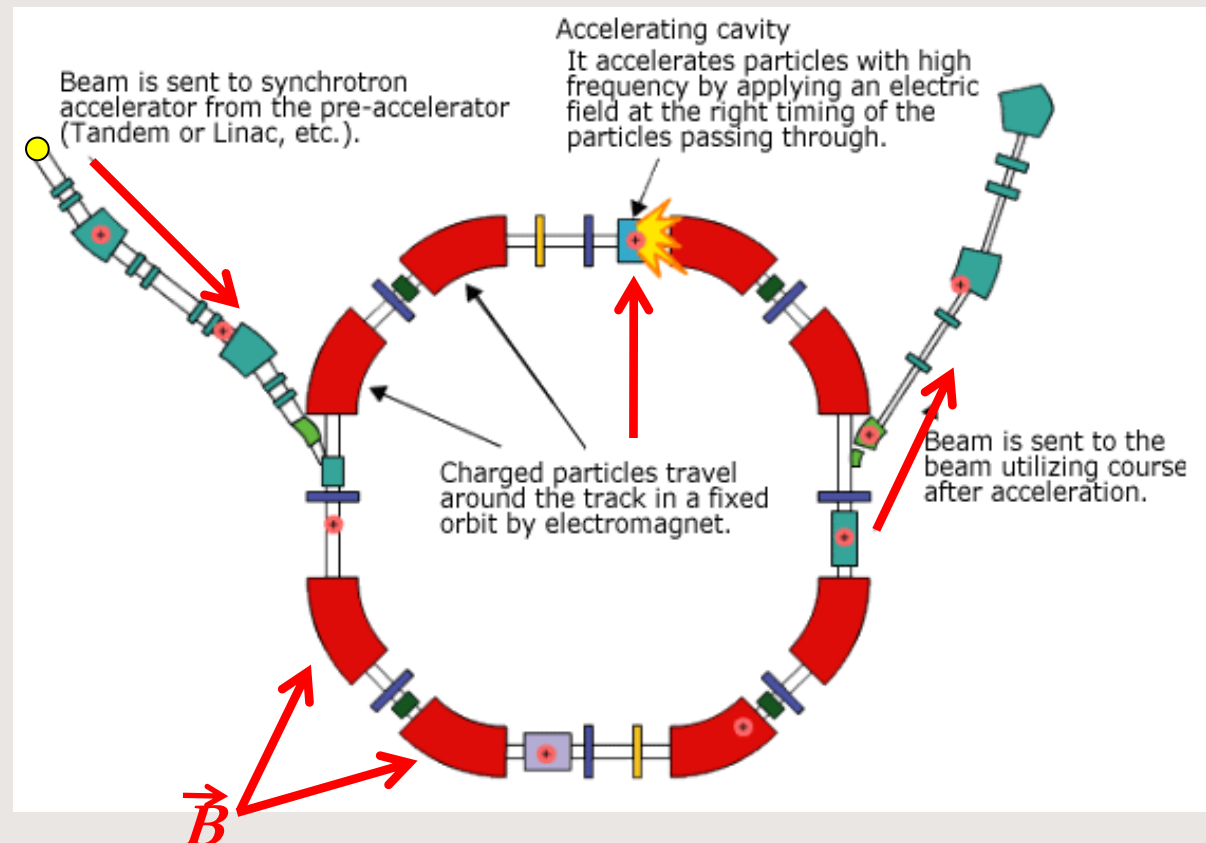
<http://www.triumf.ca/physicsinaction>

- Accelerate charged particles with electric fields
- Bend them with magnetic fields
- When they are going really fast, smash them into other particles so their mass (& kinetic energy) is available as pure energy when they annihilate
- $E=mc^2$ so if you have energy E you can create a particle of mass m (at rest)
- Put a detector around the collision point to see what comes out
- Remember that momentum and energy are always conserved!

Synchrotrons

“Ring” accelerator, contain particles with magnets

- 1) Inject particles into the ring at a given energy
- 2) Magnetic field keeps them in the ring
- 3) Accumulate particles
- 4) Accelerate a number of times per turn; magnetic field must increase as energy increases



Getting the most out of your synchrotron

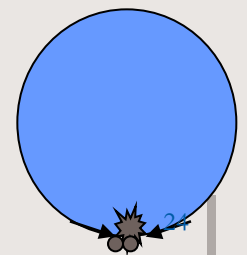
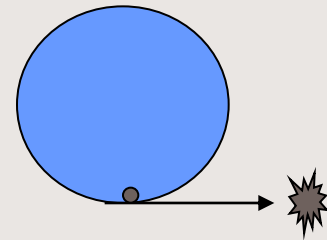
● Fixed target?

- All particles in beam hit target (easy – high rate or “luminosity”) but max energy in collision rest frame $\sim \sqrt{E_{\text{beam}}}$

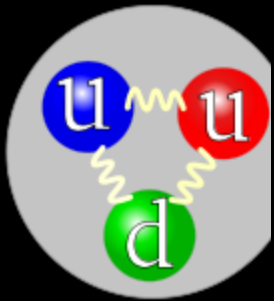
● Or collider?

- Beam hits other beam, max energy in collision rest frame: $2E_{\text{beam}}$

“Like firing a needle across the Atlantic and hitting another needle”

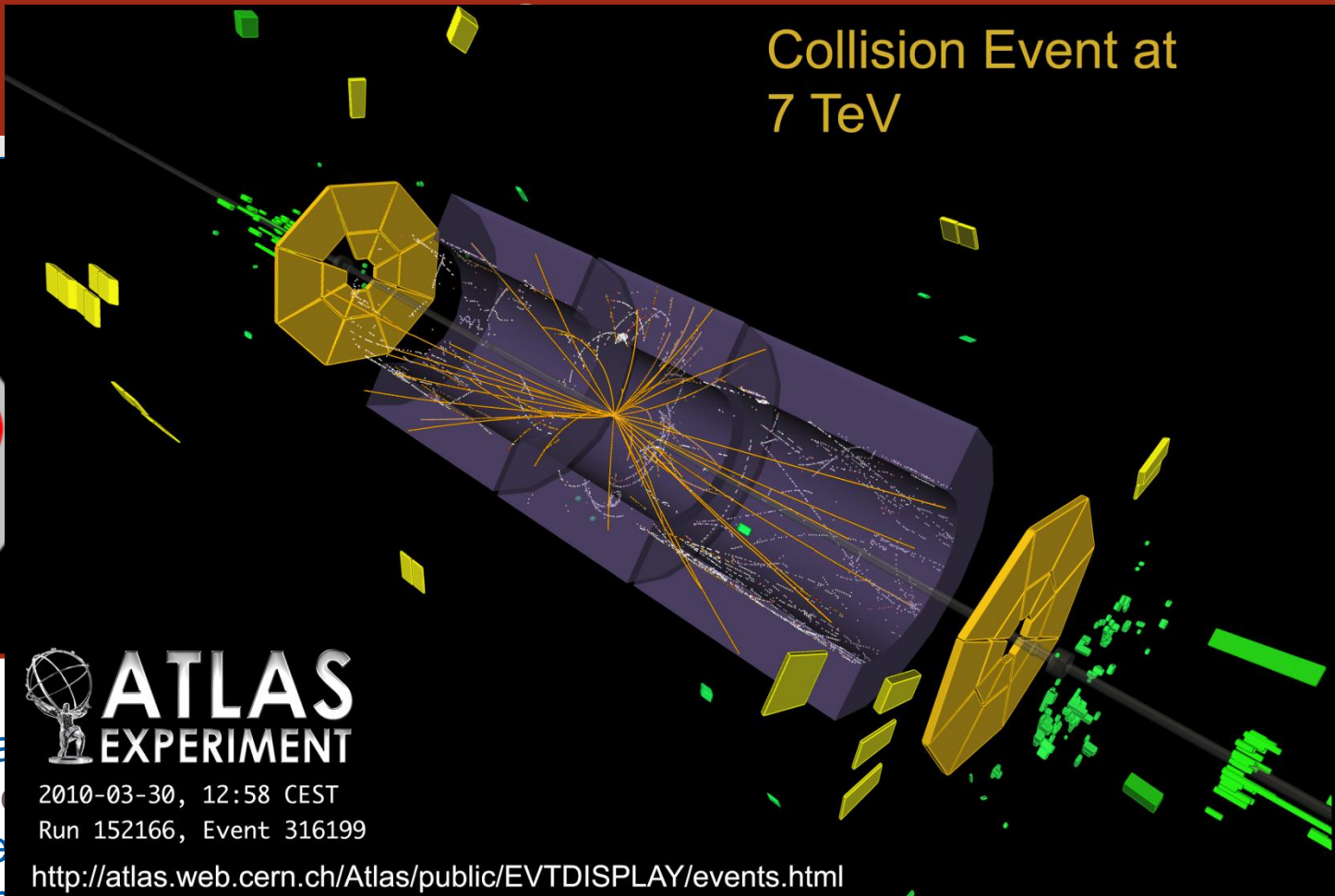


Collision Event at 7 TeV



2010-03-30, 12:58 CEST
Run 152166, Event 316199

<http://atlas.web.cern.ch/Atlas/public/EVTDISPLAY/events.html>



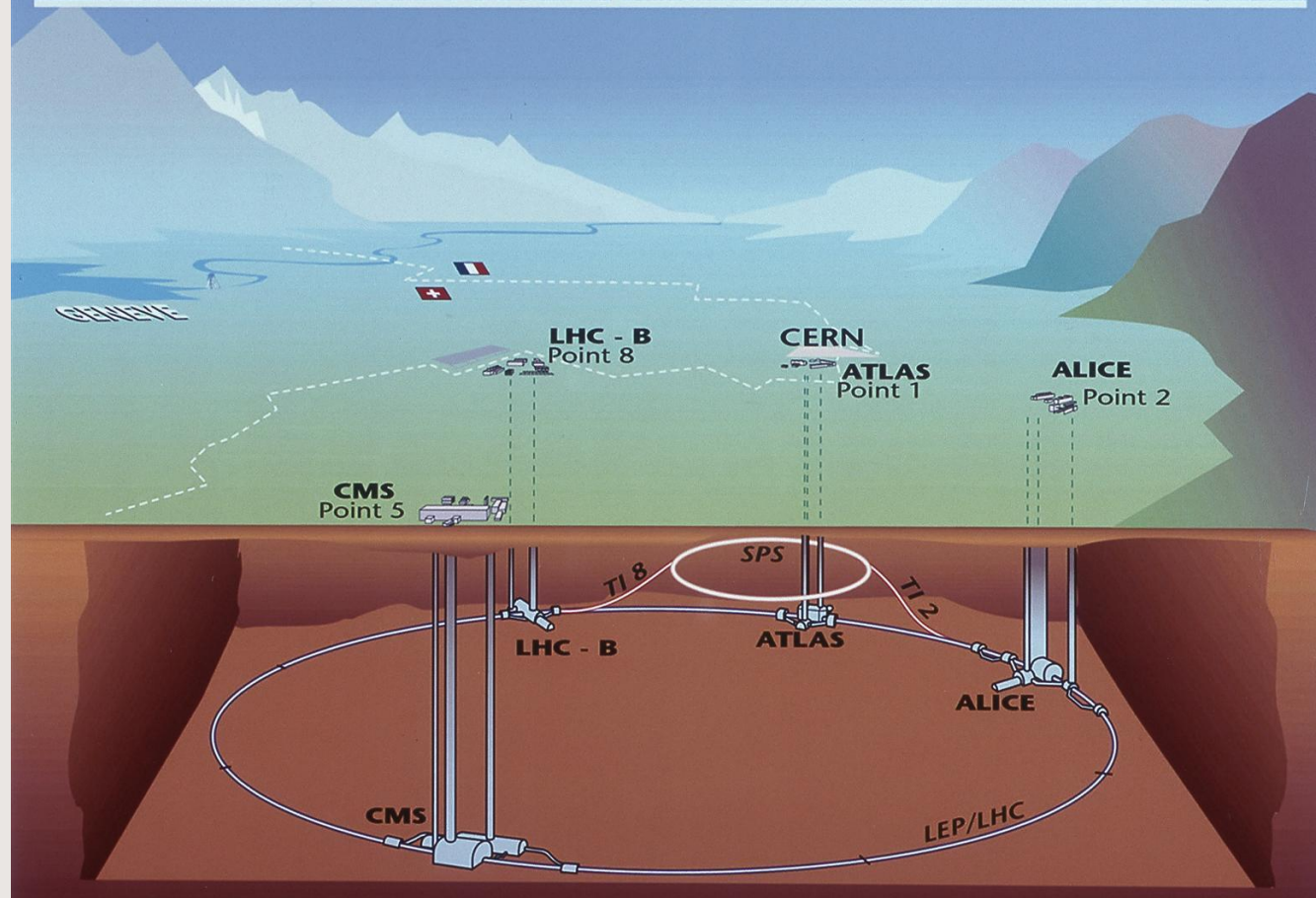
- Protons are made of quarks and gluons, plus a sea of virtual particles
- So they don't collide directly
- Typically when a quark or gluon from one proton (carrying a small fraction of the proton's momentum) annihilates with one anti-quark, quark or gluon from the other
- Strong nuclear force
- So, **rare** to get a collision with anything like total centre-of-mass energy of the 2 protons
- We **love** those rare events!

What is the Large Hadron Collider?

VITAL STATISTICS

- 27 km circumference (big synchrotron!)
- Biggest machine in world
- 1200 dipole magnets at 1.9 K (colder than space)
- protons go at 99.999999% of light speed
- make 11000 circuits/s
- tunnel previously used for LEP collider (measured W and Z properties in 90s)
- injector is SPS (used to discover W and Z in 80s)
- Canada (through TRIUMF) contributed magnets (kickers, cleaning inserts), injector upgrades

Overall view of the LHC experiments.



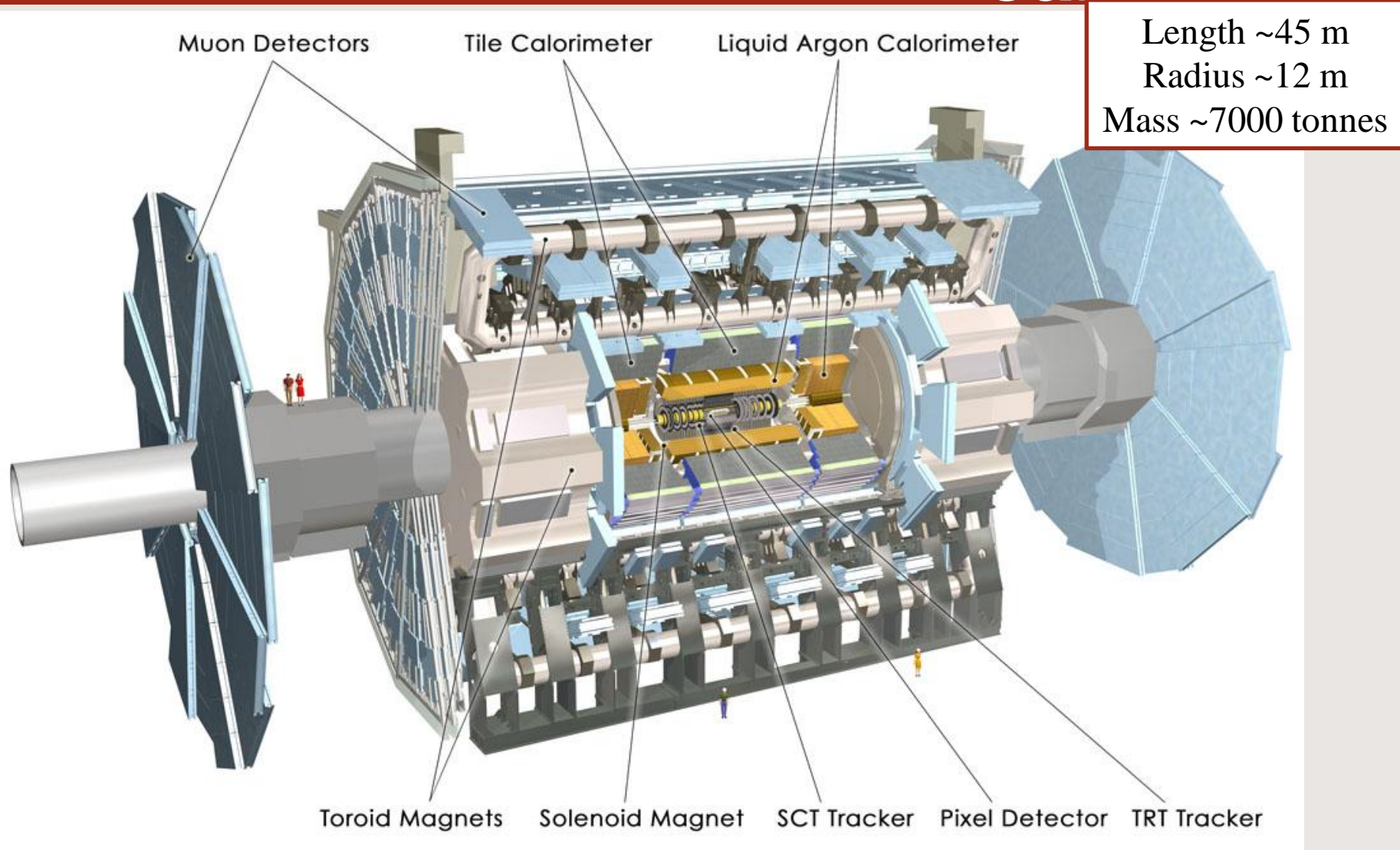
Design beam energy: 7 TeV (trillion electron-volts)
Current max beam energy: 3.5 TeV

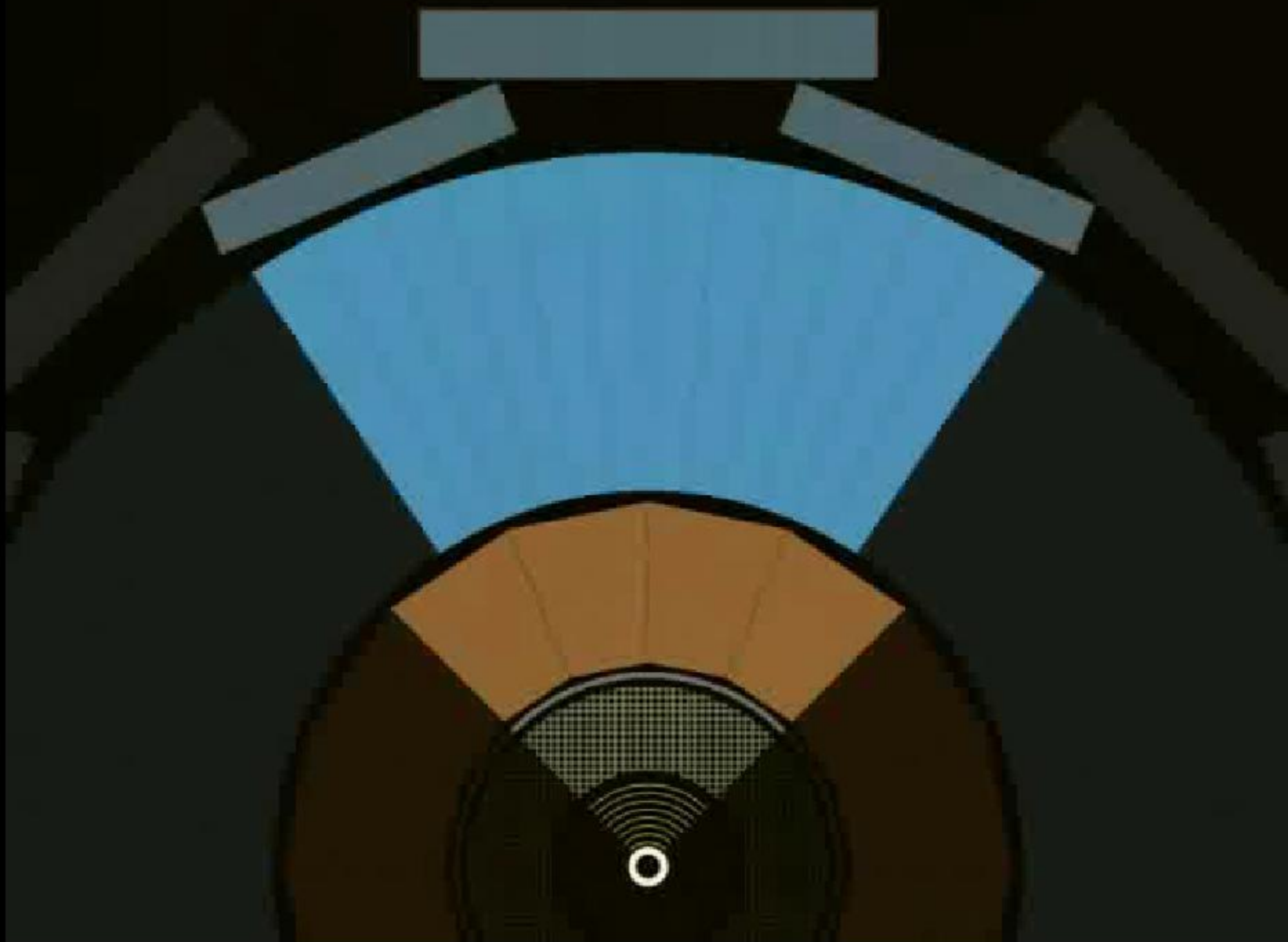
Who works on the LHC?

- **ATLAS:**
 - 37 countries
 - >173 universities & labs
 - Canada: 10 uni, TRIUMF
 - >3000 physicists including ~1000 students
 - Canada: 40 faculty, ~25 post-docs, 70-80 grad students
- CMS ~3600 people (of whom 3000 scientists & engineers)
- ALICE ~1000 scientists
- LHCb ~700 scientists
- TOTEM ~60 members
- LHCf ~ 30-40
- Accelerator: few hundred
- **TOTAL:** at least 8000 scientists and engineers around the world



The ATLAS Detector: our “camera”



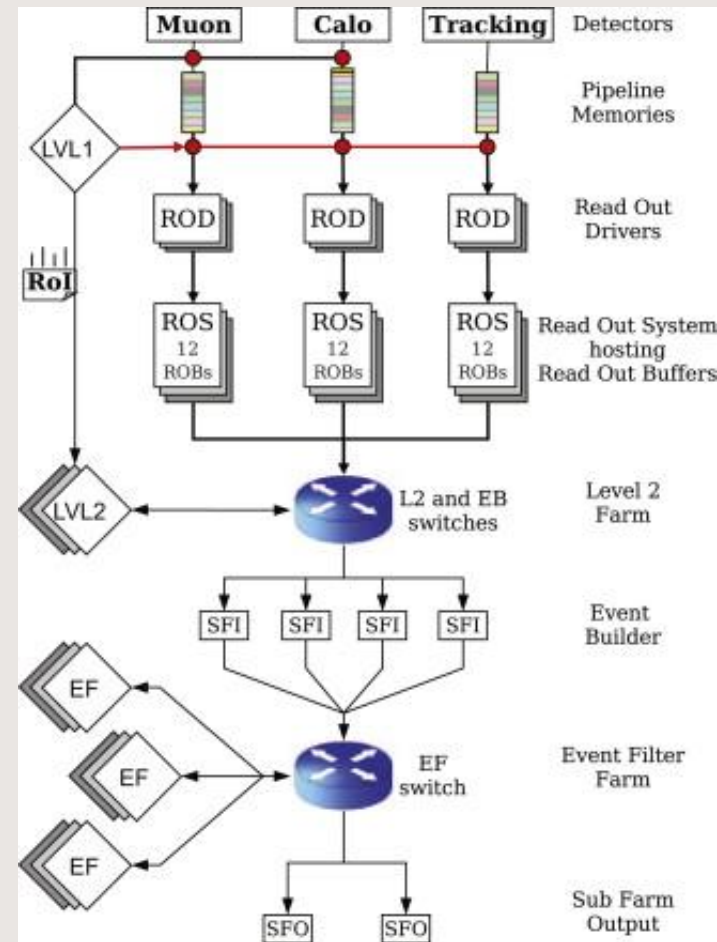


How does it run?

- Proton collisions where something “interesting” happens are very, very rare – so we need to look at a **lot** of them
 - LHC beams consist of (eventually) thousands of “bunches” of protons; each bunch contains about 10^{11} protons (~100 billion)... eventually more!
 - Bunches come (as little as) 25 ns apart
 - When the bunches collide in the middle of the detector, a few (~2-6, ultimately ~25) pairs of protons actually collide – this can happen up to 40 million times per second
- Beams keep circulating for **more than a day**, then it takes a couple of hours to accelerate new beams
- There is a **day or so of down-time every couple of weeks** or so to defrost the accelerator
 - superconducting magnets operate at 1.9 degrees above absolute zero
- There are longer shut-downs for machine upgrades and maintenance (few months if magnets need to warm up)
- But basically we **run like that for a couple of years at a time**, and the projected lifetime of the LHC and ATLAS is **at least 10 years** and maybe 20

Finding interesting events

- Proton bunches collide 40 Million times / s
- 2 – 20 pp collisions each bunch crossing
- Can write out 200 events / second (NOT 80M!)
 - That's OK – most of the events are not interesting. But we have to make sure we keep the 200 interesting ones!
- 3-level trigger decides which



TRIUMF How we reconstruct & analyze the data

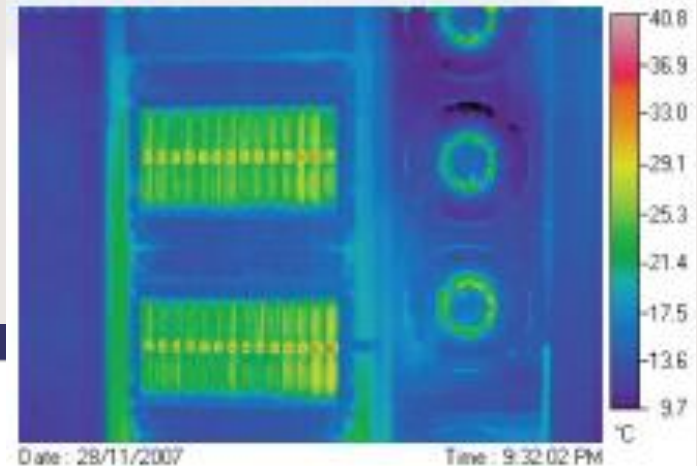
- 1st reconstruction done at CERN (Big “Tier 0” computing cluster)
- Data then distributed to 10 “Tier 1” sites around the world (TRIUMF is one)
- Subsequent reprocessing done at Tier 1s
 - e.g. when people have looked at 1st pass, better calibration & alignment constants available, bugs fixed in software, ...
- Simulated data made at Tier 2s
- Analysis data copied to Tier 2s
- Individuals run analysis jobs on GRID
 - Look for whatever signal is of interest
 - Look in **all** the data for **every** signal
 - Not like a shared telescope!!!



Dealing with the Data Flow



Photo: N. Bienvenu

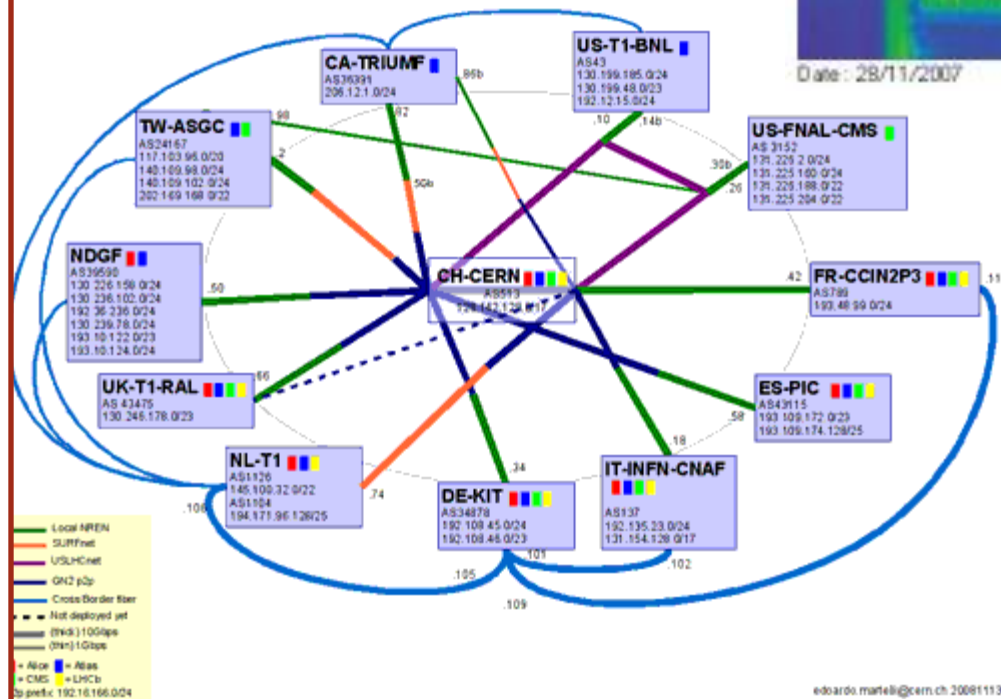


TRIUMF Tier 1

Current capacity:
1210 CPU cores,
2.1 Petabytes disk,
1.6 Petabytes tape

About 5% of
ATLAS Tier 1
capacity

5/10 Gbps optical
link to CERN



What if we don't find a Higgs?

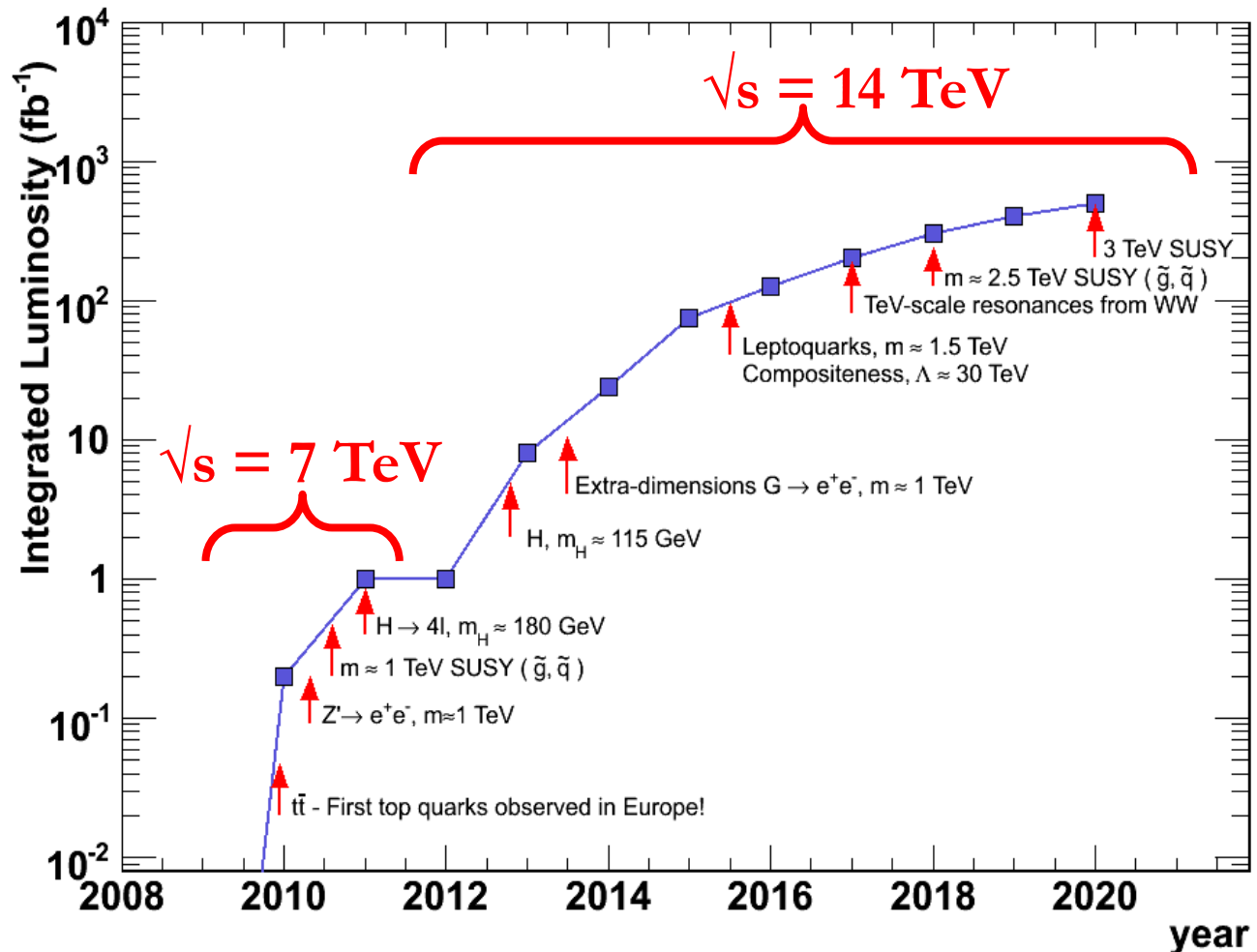
- Well, it depends...
 - Don't find *Standard Model* Higgs at LHC, that's OK!
 - Don't find *some kind* of Higgs Boson, or *something else which looks* like a Higgs Boson and does Higgs Boson's job in Higgs mechanism, then *last 4 decades of precision measurements don't make sense!*
- We would be happiest if we found something which did the job of the Higgs Boson, and looked like a Higgs Boson, but was accompanied by lots of other new particles
 - Would help us understand where masses of quarks and leptons come from
 - Maybe how to relate gravity (the force that couples to mass) to the seemingly random masses of the elementary particles

When will we get the results?

- For the Higgs?
 - Easiest case (heavy) could be some time in 2011
 - “Most likely” case needs full energy and a lot of data, would take until 2013 at least
- For other “new” particles?
 - If we are very lucky, some could be seen in 2010 if beam intensities keep increasing as well as so far
 - Really depends what Nature looks like! Lots of theories for high-energy compatible with low-energy data, but we don’t know which, if any, is right...

What else can LHC look for?

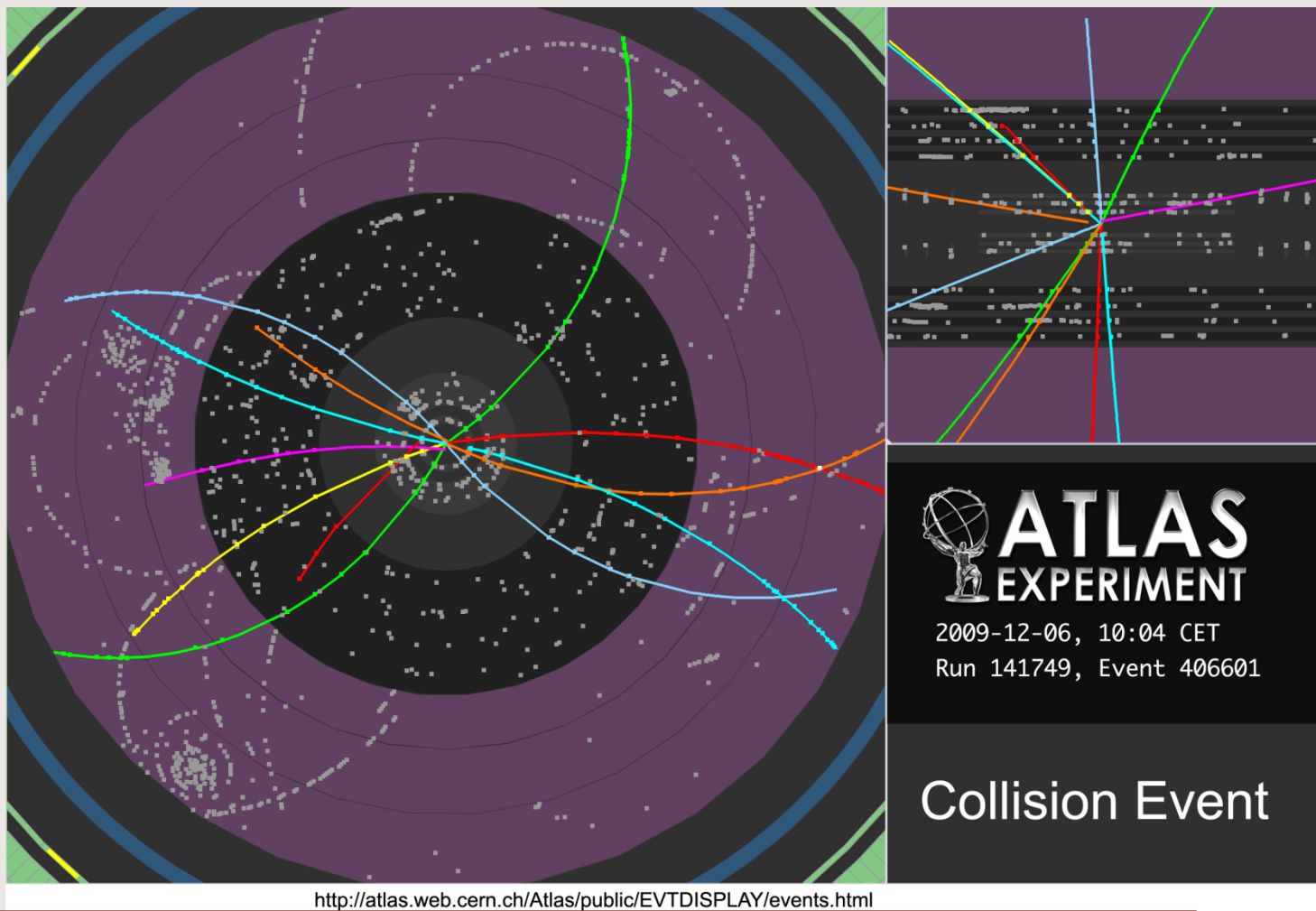
- Just finding a Higgs would be boring... we are hoping for much more!



When will we get the results?

- We are getting them already!
 - First ATLAS “collisions” paper published in January on data with 450 GeV colliding beams in fall of 2009
 - Not a “discovery” paper – measurements of some properties of “ordinary” events at that energy, comparison with other accelerators (proton-antiproton instead of proton-proton) at similar energy, and with CMS (our friendly competition)
 - Crucial to show the detector works and is calibrated right and measures the correct energies and masses for particles which have already been discovered and measured

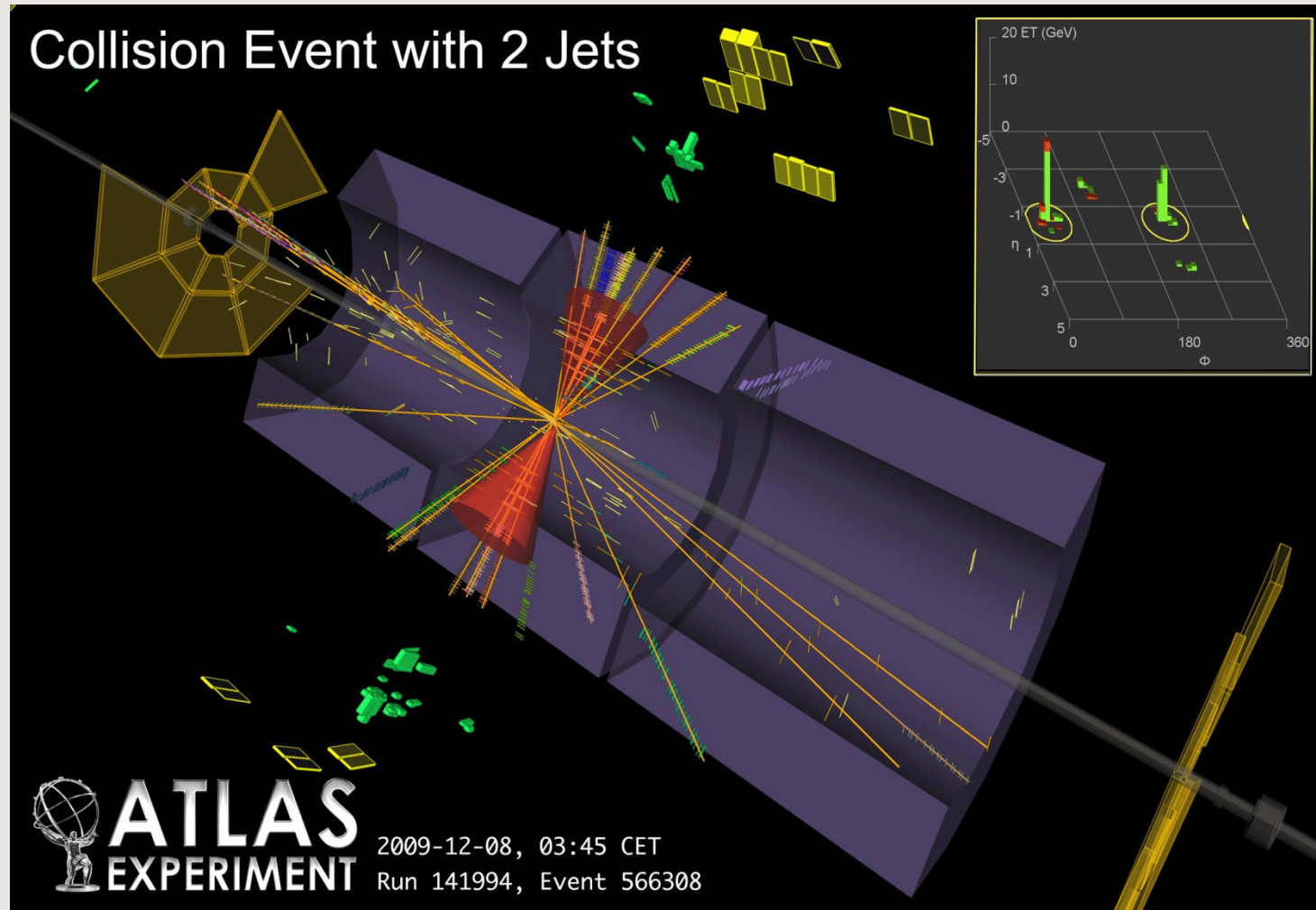
First results from ATLAS



How we reconstruct tracks of charged particles in the Inner Trackers...

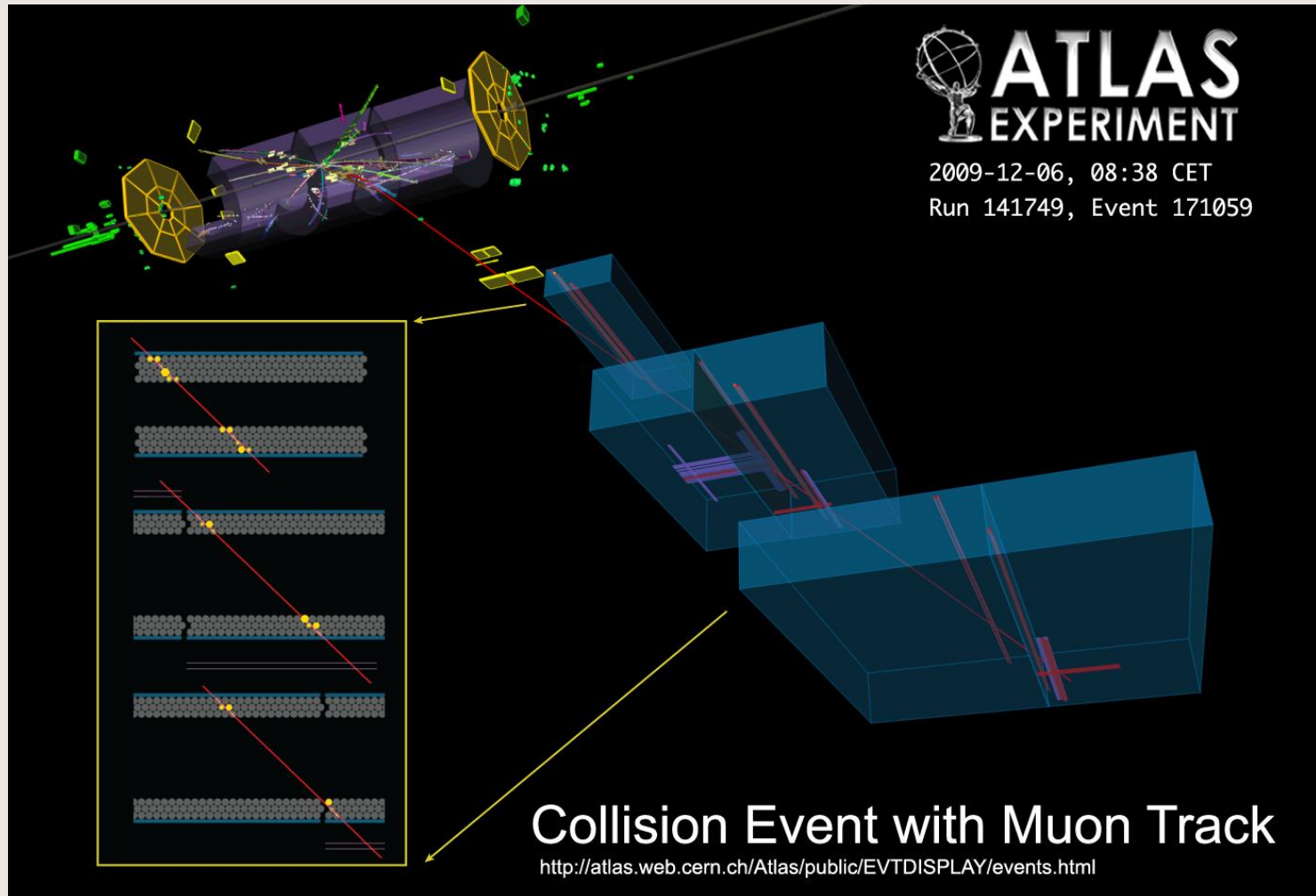
First results from ATLAS

Quarks
hadronize and
make “jets” of
charged and
neutral particles
which are
stopped in the
hadron
calorimeters
(end caps built at
TRIUMF)



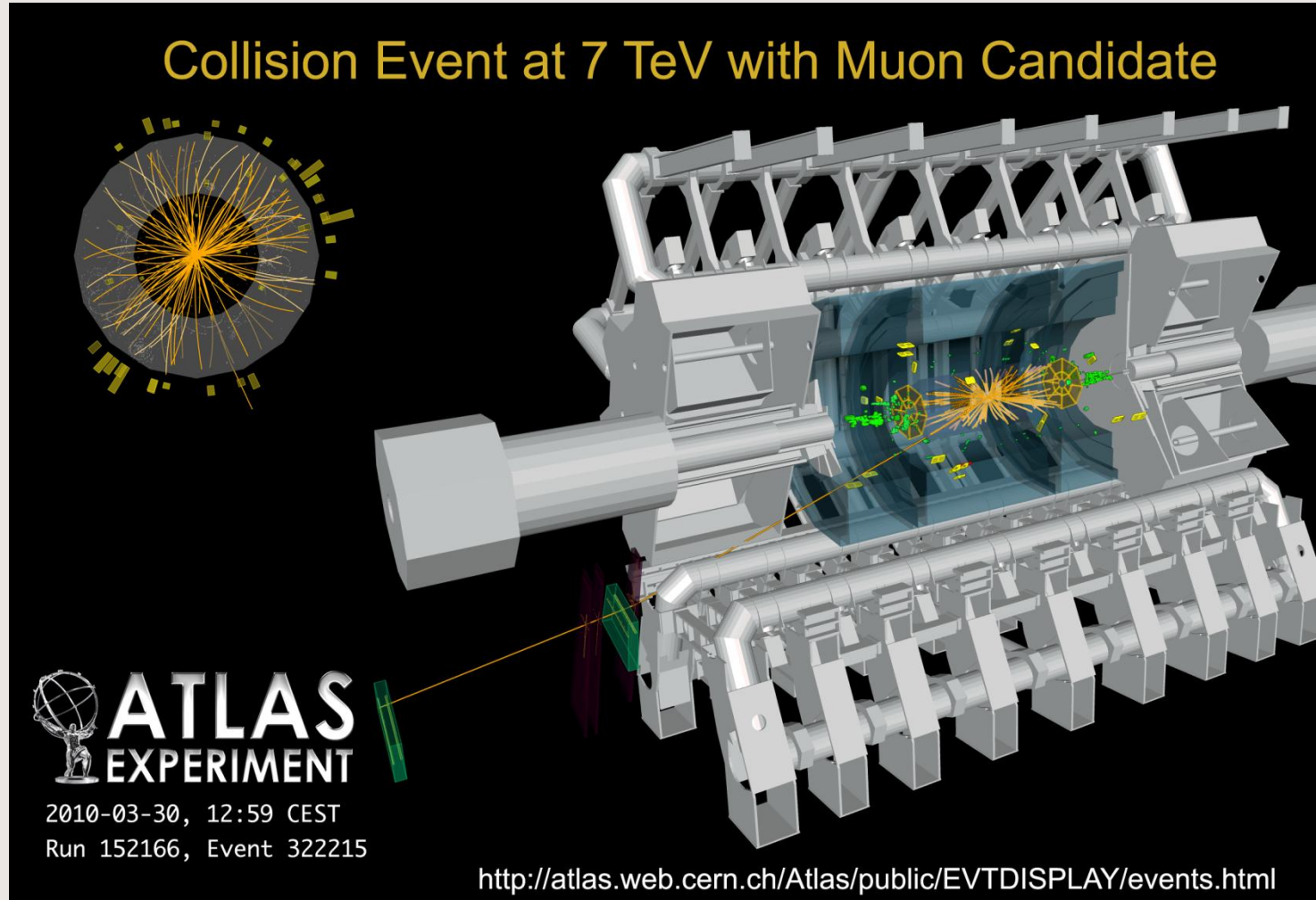
First results from ATLAS

Muons (heavy electron cousins) go right through calorimeters and leave tracks in muon chambers



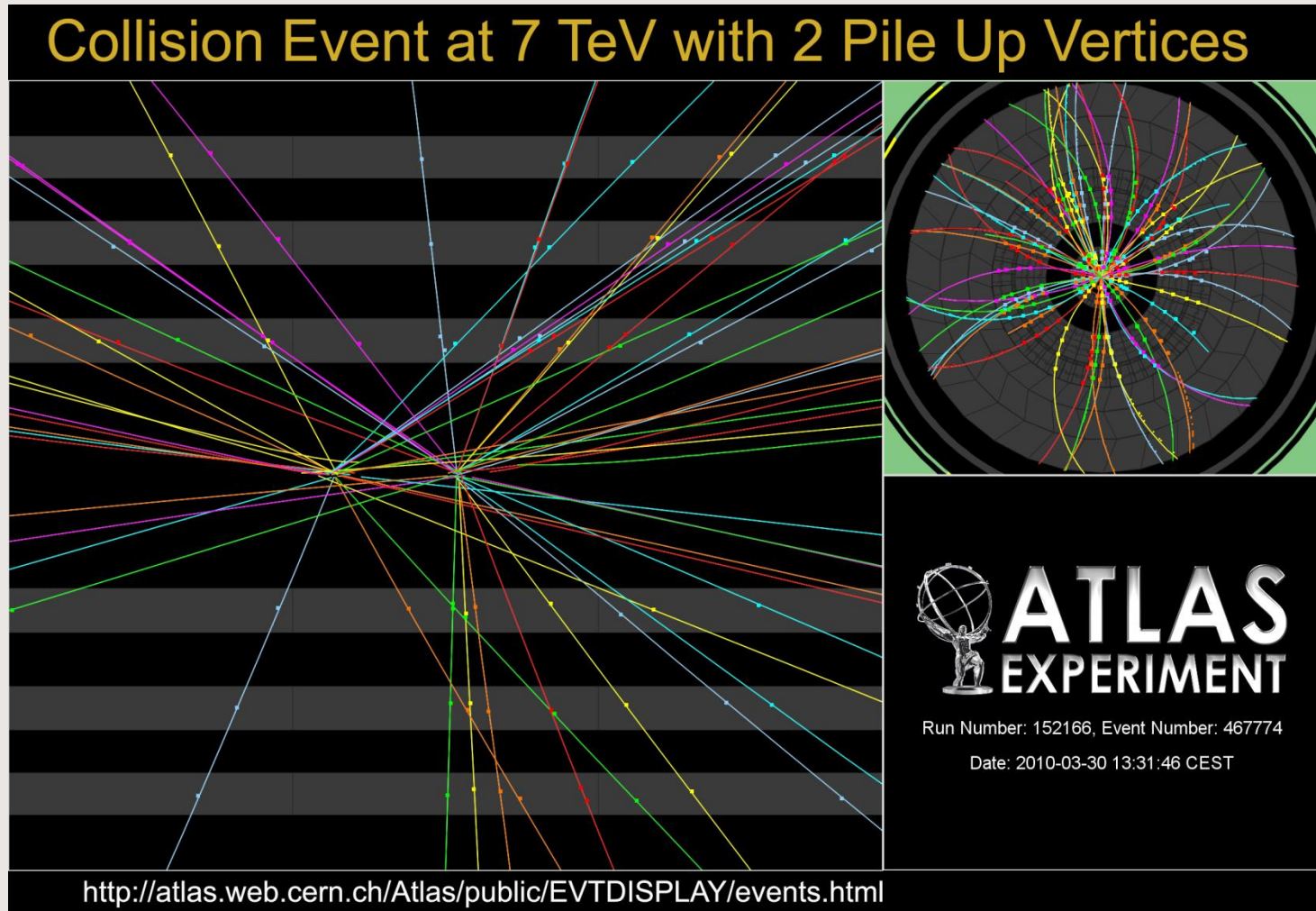
First ATLAS results at 7 TeV

Notice the big toroidal magnets of the muon spectrometer!

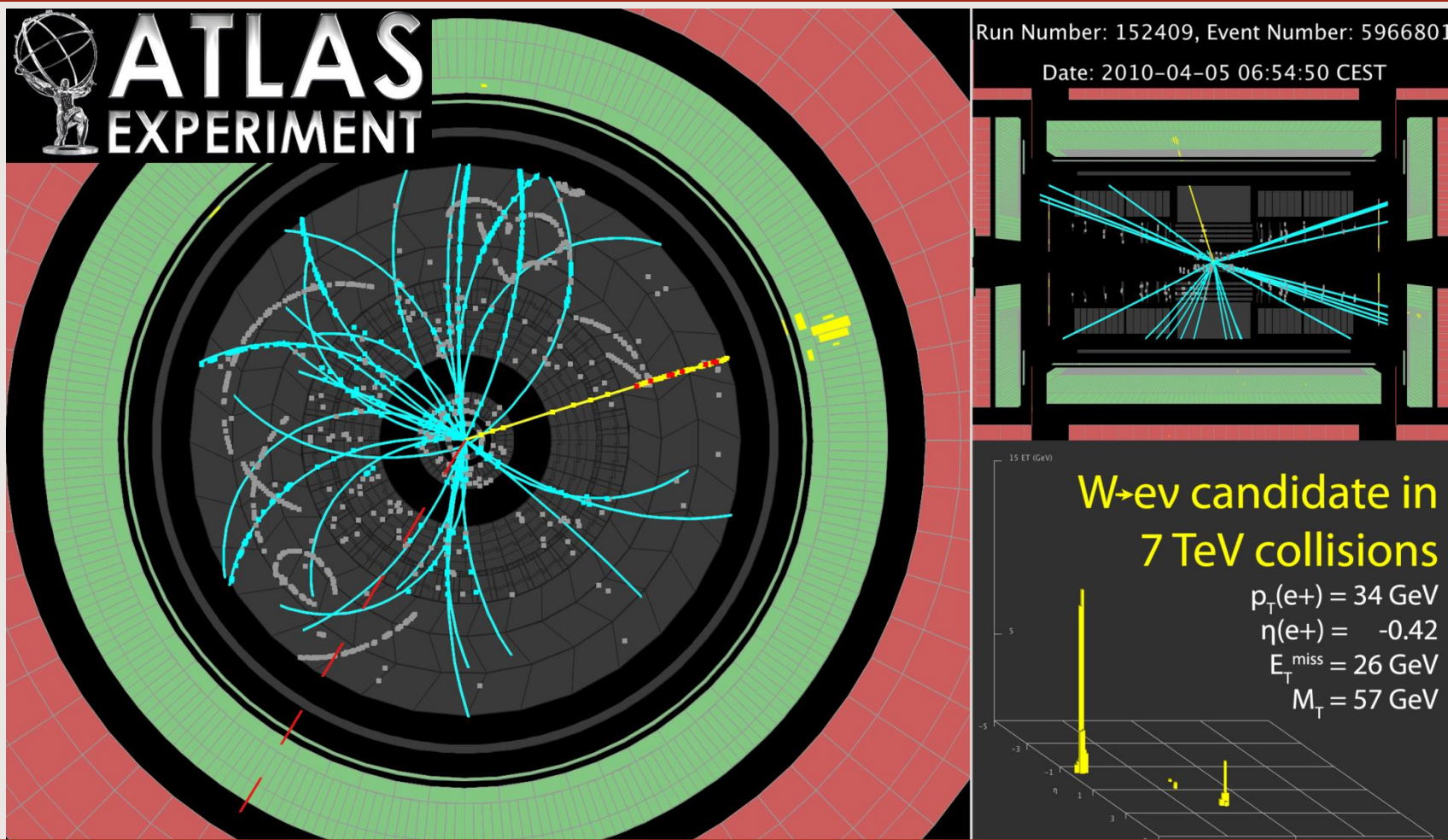


First ATLAS results at 7 TeV

We already have enough protons in each bunch to see events like this, where there are two collisions at the same time!



First ATLAS W boson candidates



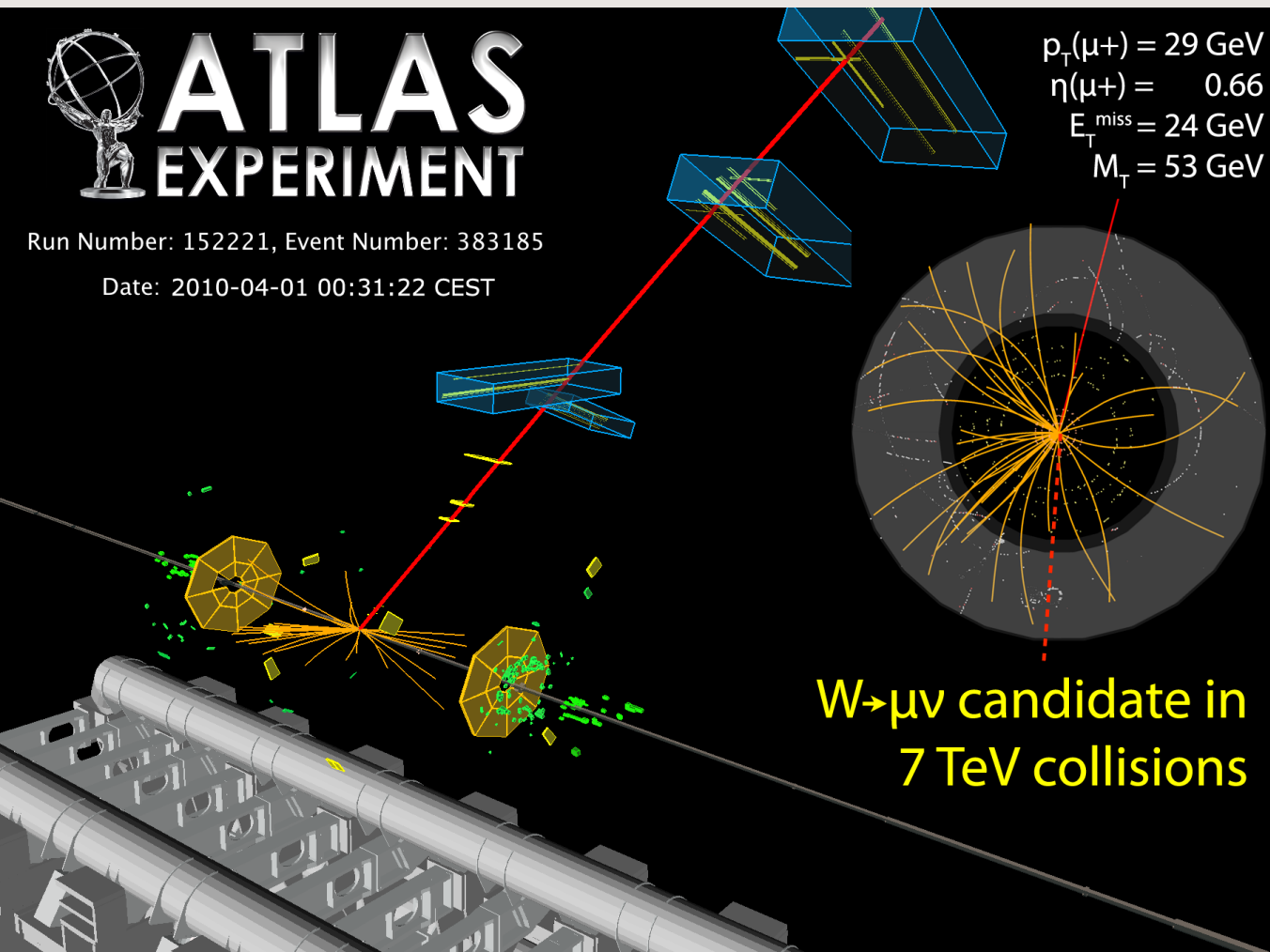
Electrons and photons dump all their energy in the first (electromagnetic) calorimeter. Electrons are charged, so they leave a track too.

First ATLAS W boson candidates



Run Number: 152221, Event Number: 383185

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We have studied 10s of thousands of W bosons at other colliders, but it is exciting to observe them for the first time at the LHC. The Z (rarer) will be better for calibration because it decays to two charged leptons – we cannot detect the neutrino in the W decay.

What will the LHC do for Society?

“One day sir, you may tax it.” Faraday's reply to William Gladstone, then British Chancellor of the Exchequer, when asked of the practical value of electricity (1850)

CERN “Where the Web was born” (WWW invented by Tim Berners-Lee in 1989 to solve the problems of collaboration among 1000s of scientists spread across the world)

Hertz (who had just made the first radio antenna and receiver) : **"It's of no use whatsoever[...] this is just an experiment that proves Maestro Maxwell was right - we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there."** Asked about the ramifications of his discoveries, Hertz replied, **"Nothing, I guess."**

“Of what use is a newborn child?”

Franklin's reply to a question about whether the newly invented hot air balloon would ever have any practical uses

Developing better candles never produced a lightbulb

Final Word

- Still baby steps for the LHC
 - But it is learning to run much faster than earlier accelerators!
- Half design-energy is more than 3x previous record
 - LHC works **very** well – clear path to full energy and luminosity
- Will take a **few years** to get enough data to find the answers we are looking for
- Answers may provoke more questions
 - Hard to imagine building a bigger accelerator, but might learn what energy to build a big e^+e^- linear accelerator for the next step
- Physics may be simpler in the future – and we don't know