Introduction to **CERN** and **CMS**…

and background for the CMS analysis

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What do I do?

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- I am a “phenomenologist”: a theorist who is very interested in experiment
- During my last postdoc, at the University of Florida, I was an “associate member” of the CMS collaboration.

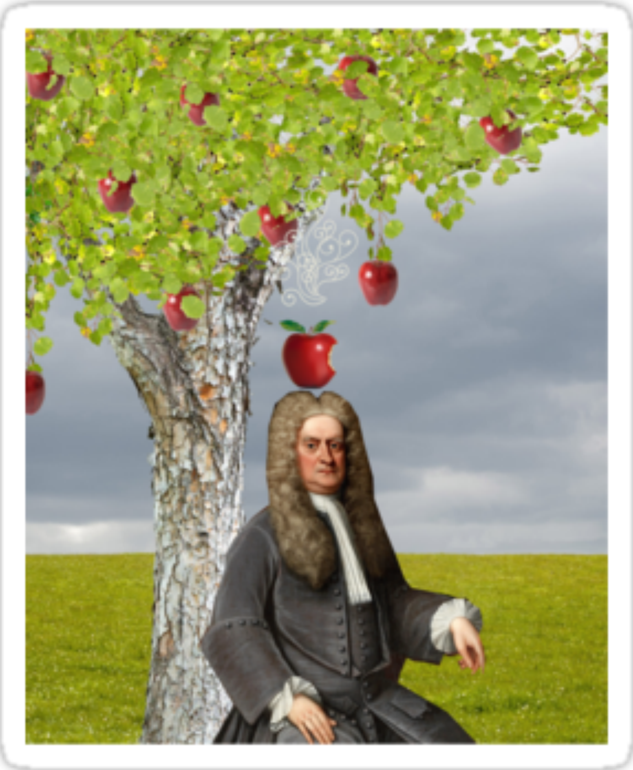
Outline

- **Theory** (brief)
- **Experiment**
  - How do we test theories in particle physics?
  - CERN
  - LHC
  - Detectors
  - CMS
  - Some notes on Ws, Zs, and Higgses

Theory

Four Forces

Gravity



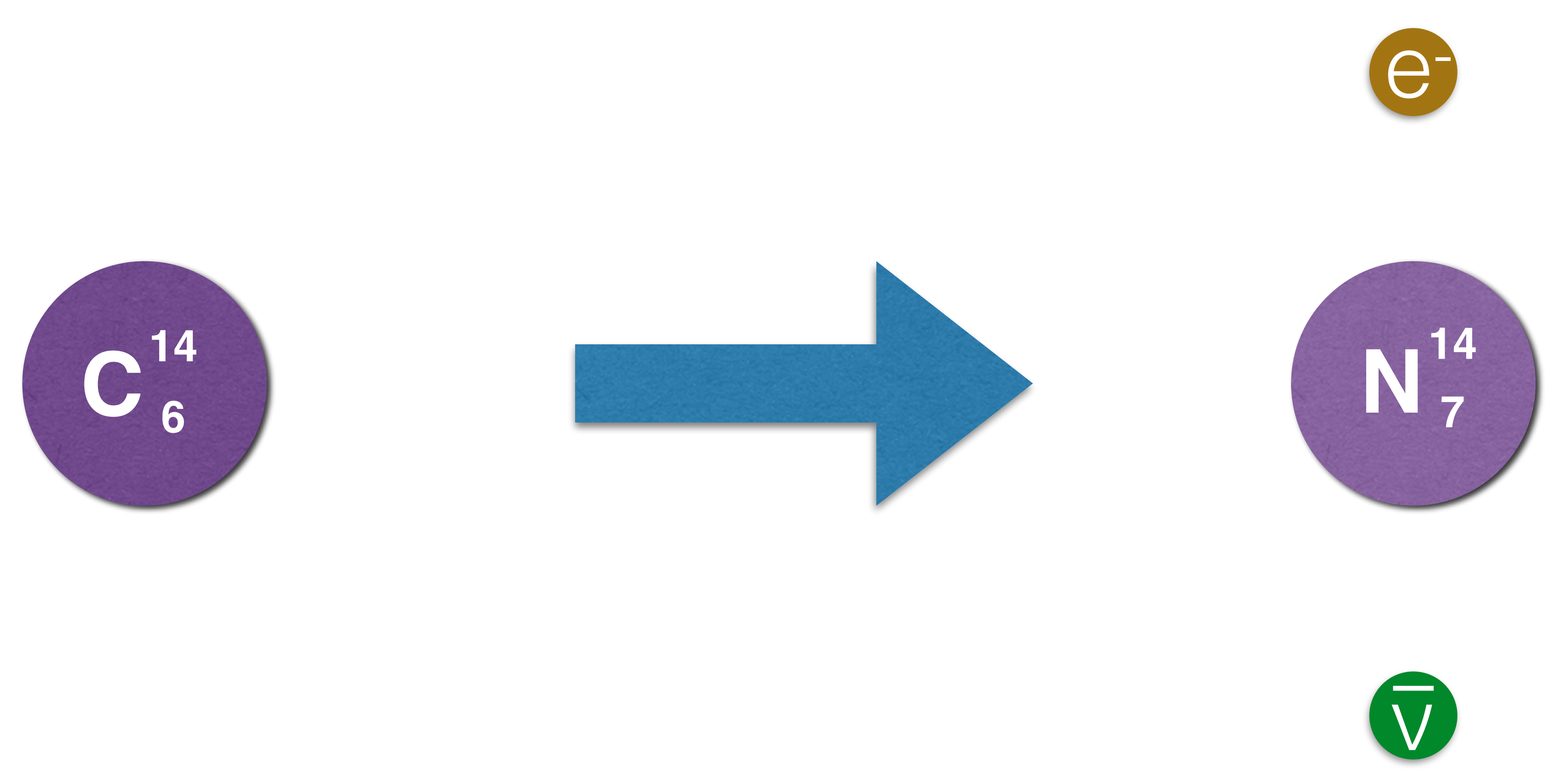
Electromagnetism

Weak Force

?

Strong Force

Weak Force



Carbon-14 beta decay to nitrogen-14 is used to date organic remains.

- "Weak" nuclear force. Responsible for beta decay: nuclear decays that produce an **electron** and an **anti-neutrino**, or its antiparticle a **positron**.

Weak Force

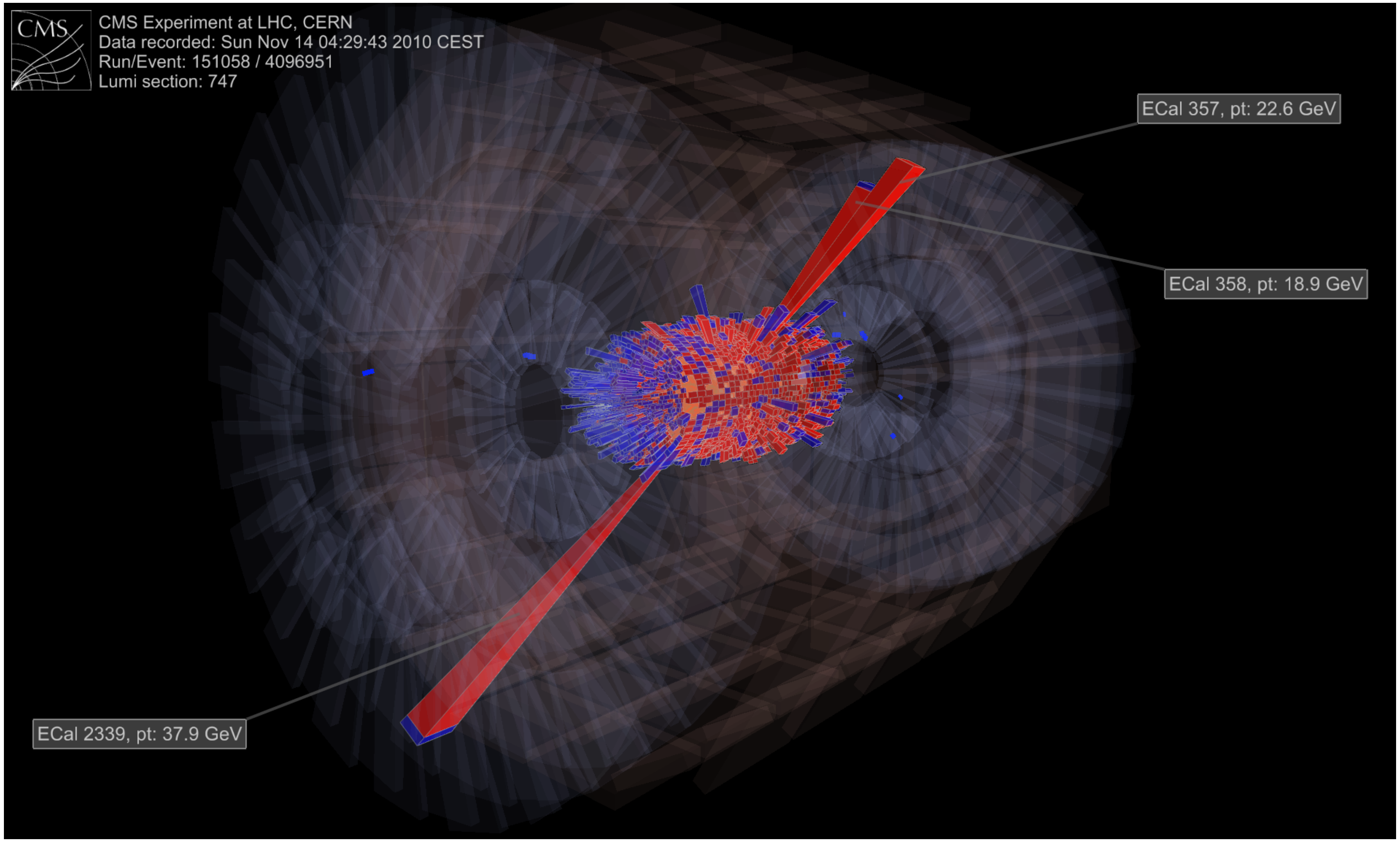
- **Why is it "weak"?**
  Really why does it only act over short distances ~ nucleus (~10^{-15} m)?

- **Electromagnetism**: "long range" carried by massless photon

- **Gravity**: "long range" carried by massless graviton

- **Weak force**: carried by massive particles, **W** and **Z** bosons.

W and Z Bosons



- Discovered at CERN in 1983
- W boson: charged (W+, W-), 80.4 GeV/c^2 ~ 85 times the proton mass
- Z boson (neutral), 91.19 GeV/c^2 ~ 97 times the proton mass

Electroweak Theory

- **But why are the W and Z bosons so heavy, when the photon is massless?**
- Our best answer is called the “electroweak theory”: electromagnetism and the weak force are the same interaction, but something makes the W and Z bosons heavy
- We think that the W and Z bosons become heavy because of the “**Higgs mechanism**”
- So studying the Higgs boson can tell us about why the weak force is weak.

Other Important Particles

- In the rest of the talk I'll mention
- electrons/ positrons
- muons/ anti-muons
- photons
- protons
- neutrons
- "hadrons" like pions

From https://www.particlezoo.net/ where you can buy stuffed particles.

Experiment

How do we test theories in particle physics?

- In physics we test our ideas with experiments
- Many different types of experiments
- I'm going to talk about a particular experiment, the **Large Hadron Collider**, which is located at a laboratory called **CERN**.
- "**Collider**": collides two beams of particles (protons)
- These beams have to be accelerated so we call the experiment a "**particle accelerator**"
- There are also accelerators which shoot a beam at a "**fixed target**"

CERN

- On the Swiss/ French border near Geneva
- Founded 1954— symbol of postwar European collaboration.

CERN

Statute of Cosmic Dance of Shiva at CERN.

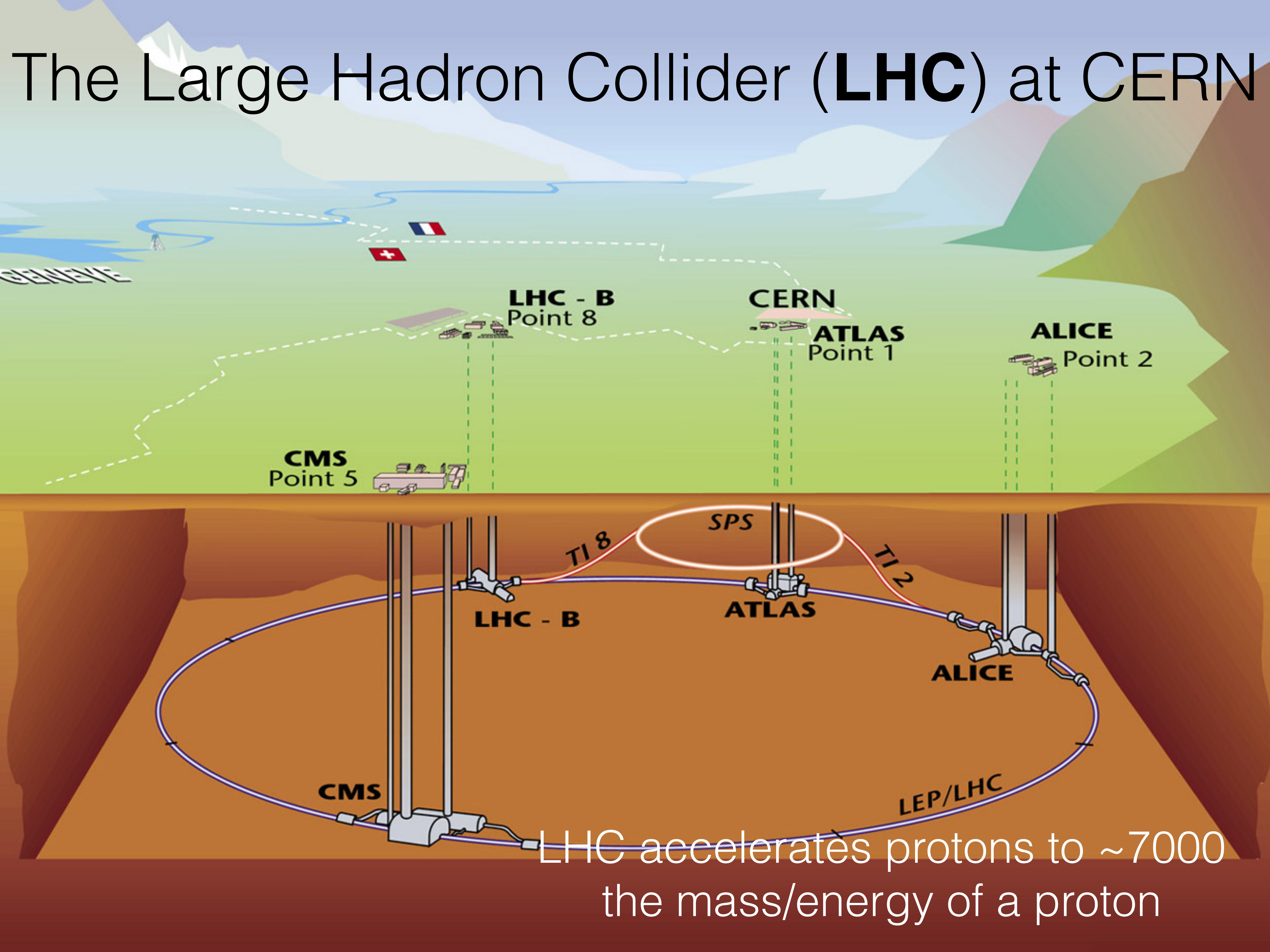
- 22 member states, all in Europe (except Israel)
- United States has “observer” status

CERN

The Globe of Science and Innovation

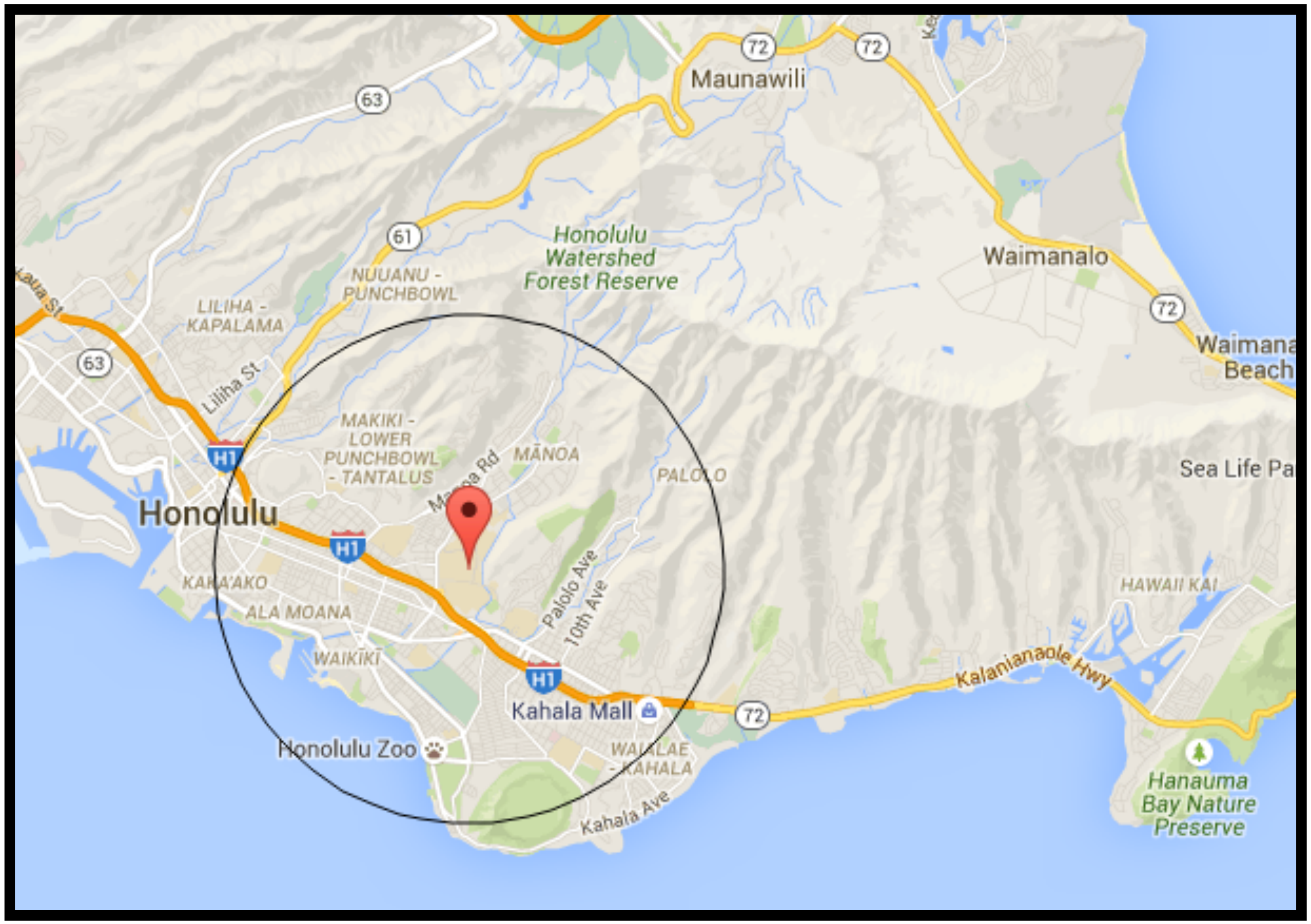
- Site of the discovery of the gluon, the W and Z bosons, and the Higgs boson
  - and the invention of the world wide web!

The Large Hadron Collider (**LHC**) at CERN



LHC accelerates protons to ~7000 the mass/energy of a proton

If the LHC Were Here…



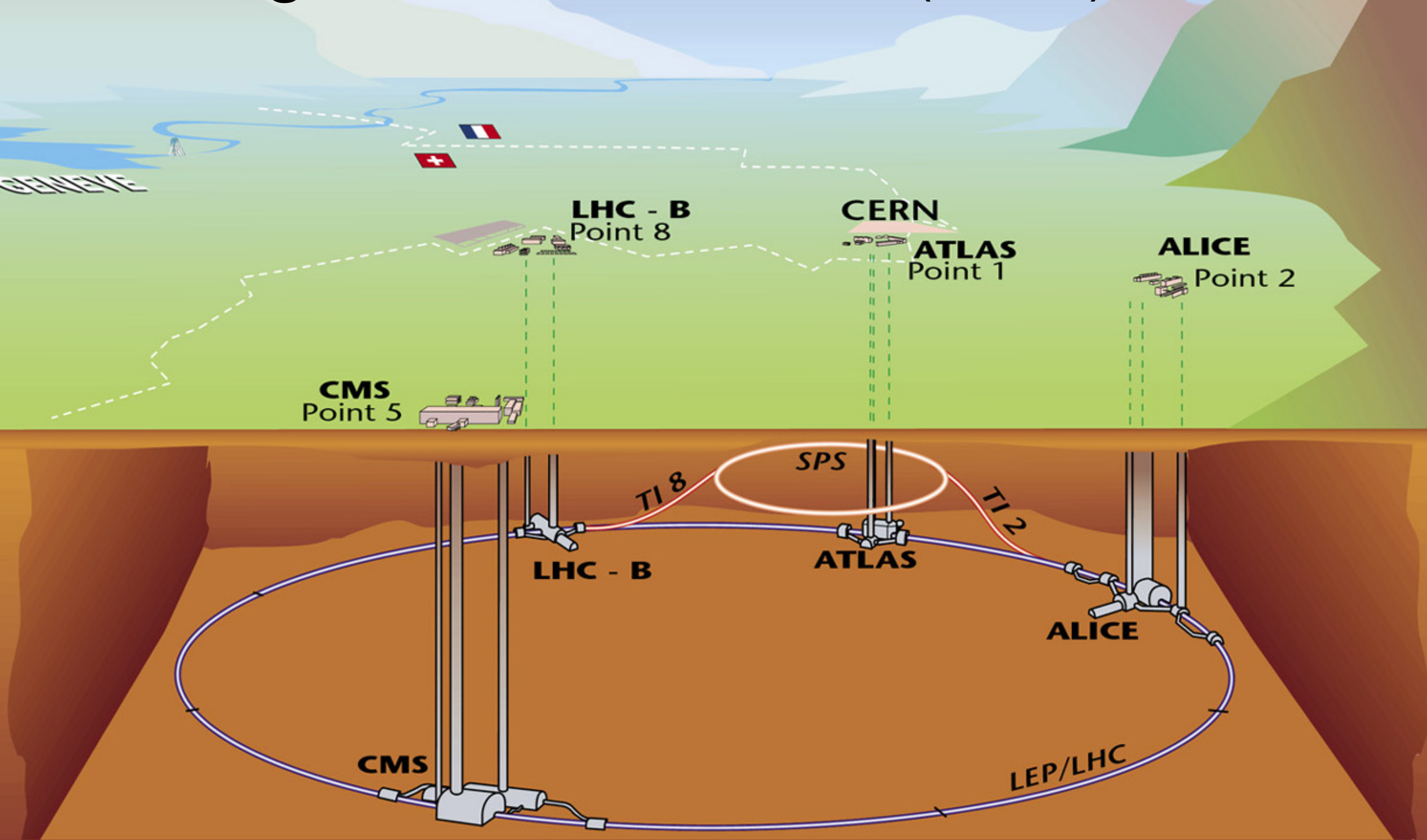
27 km in circumference

The Large Hadron Collider (**LHC**) at CERN

Aircraft Carrier USS John C. Stennis at Pearl Harbor

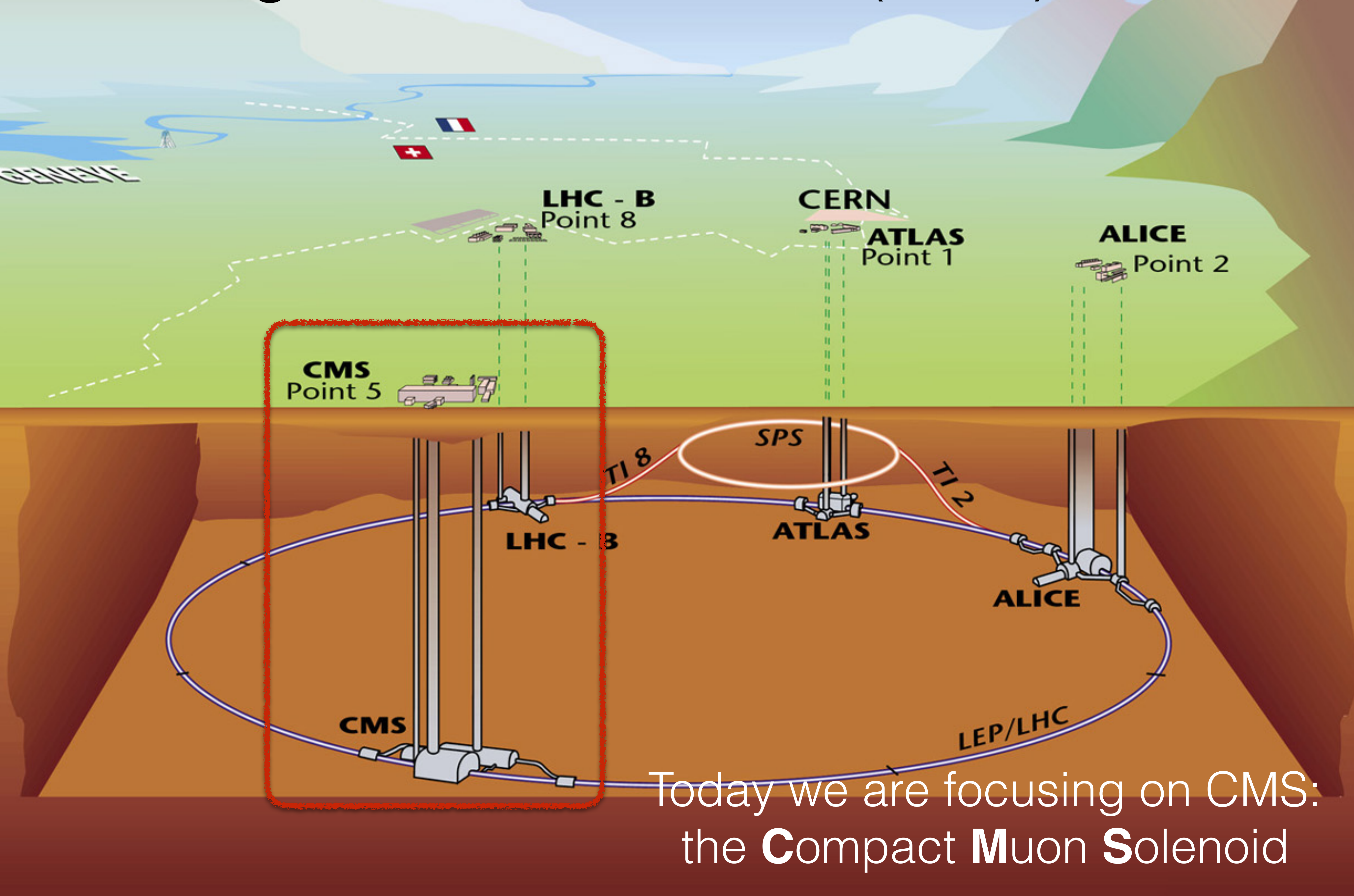
- The energy in the LHC beams is the same as an aircraft carrier moving at a couple of knots

The Large Hadron Collider (**LHC**) at CERN



LHC has 4 detectors, two “multipurpose”

The Large Hadron Collider (**LHC**) at CERN



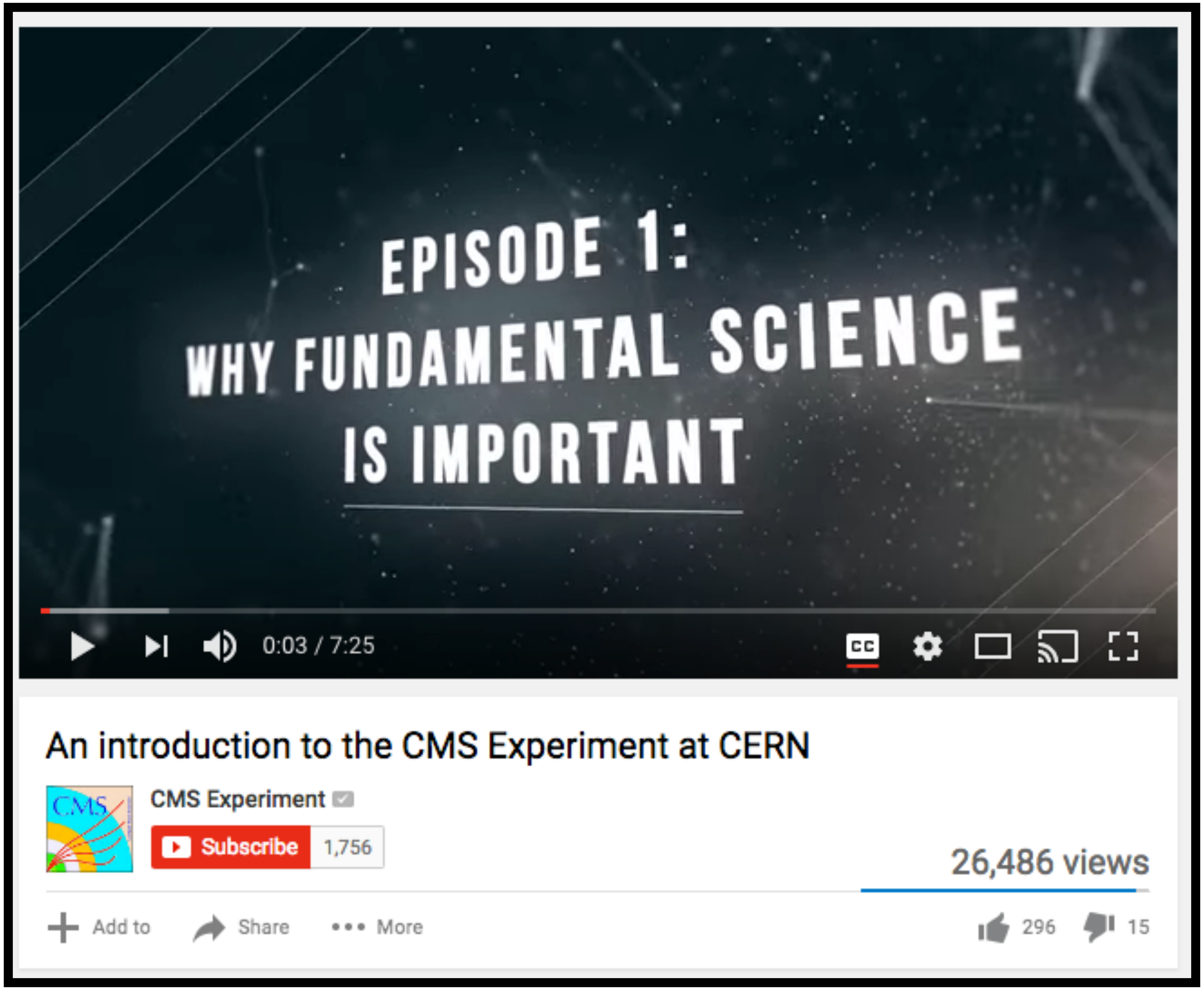
Today we are focusing on CMS:
the **C**ompact **M**uon **S**olenoid

Detecting Particles at CMS

Sources

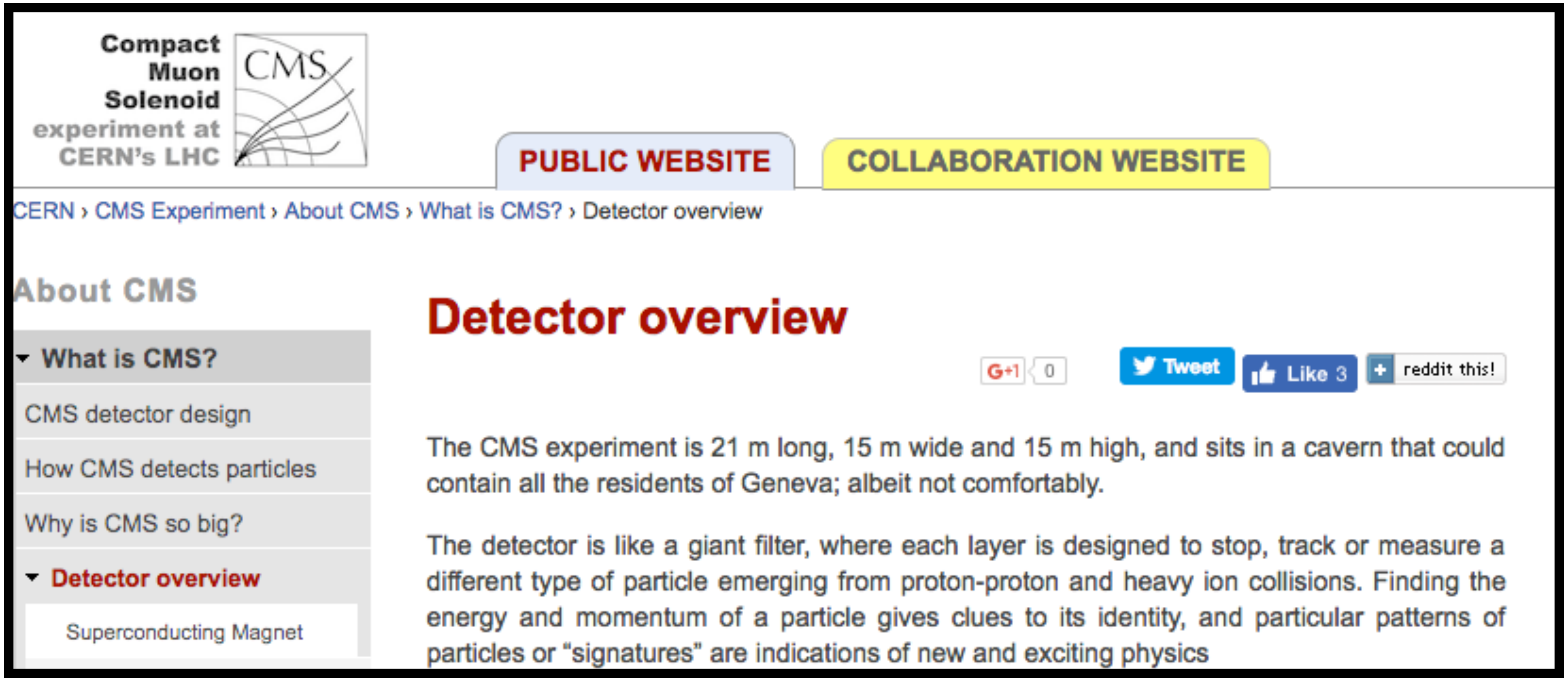
- Some sources that I used in preparing these slides and that you might find useful…

Sources



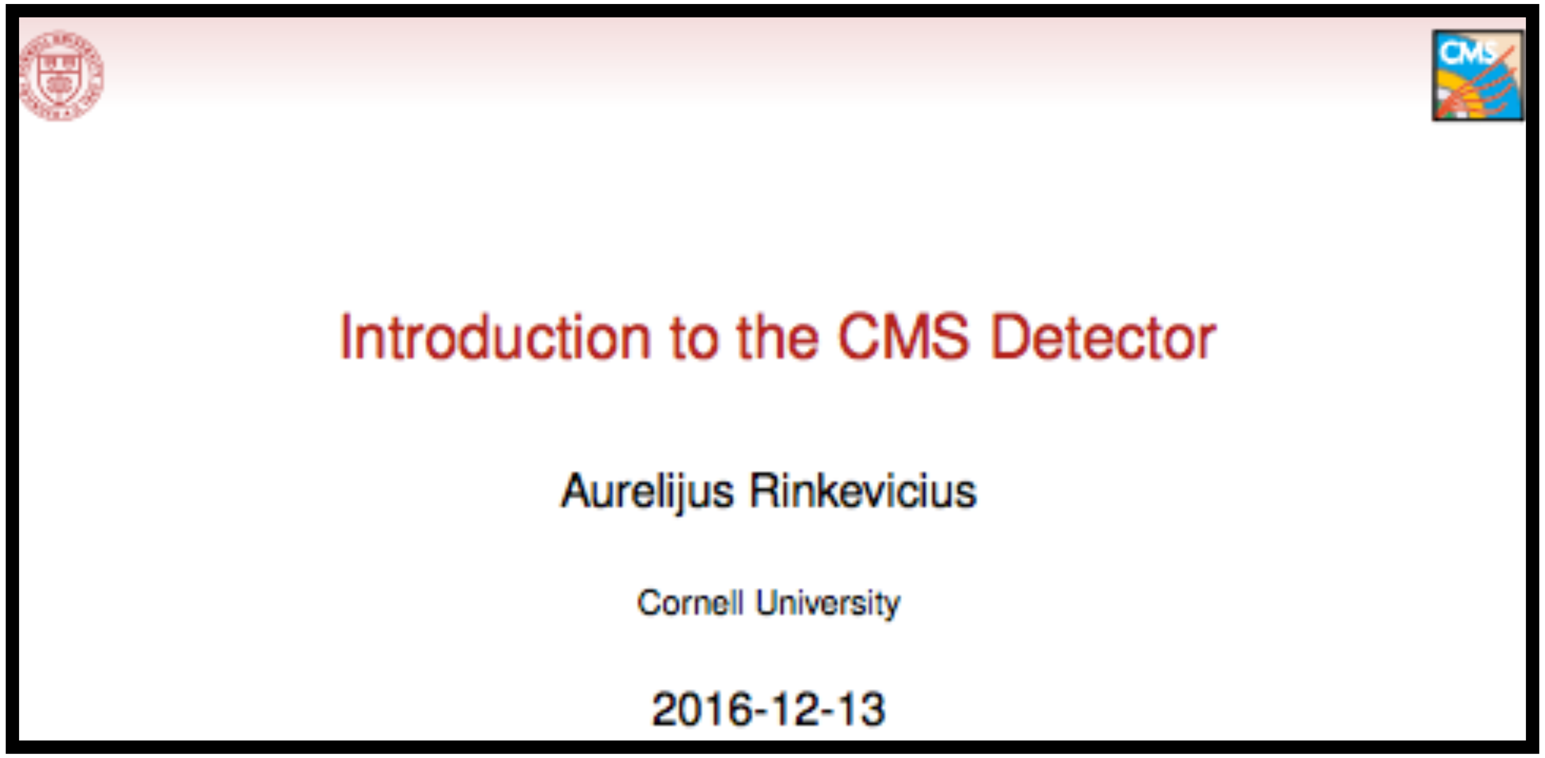
- Introduction to CMS video on youtube

Sources



- Detector overview on public CMS webpage
- http://cms.web.cern.ch/news/detector-overview
- Most of the images in the remainder of the talk from here

Sources

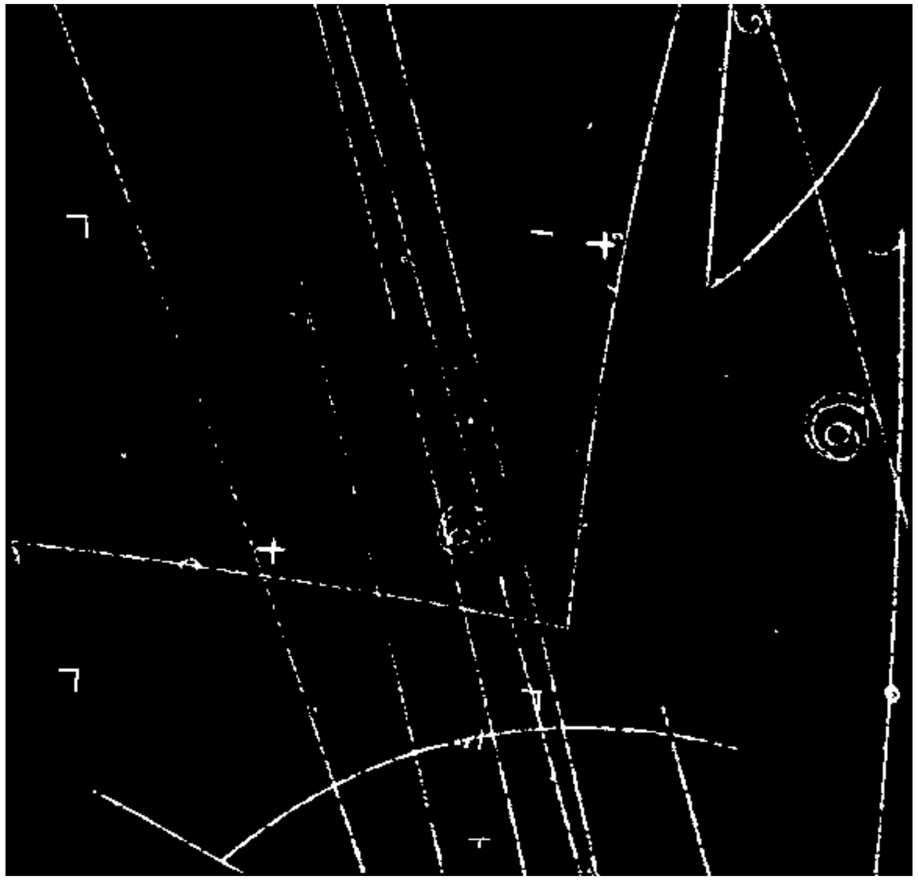


- A. Rinkevicius talk: “Introduction to the CMS Detector”
- Available online
- More technical (and a short talk)

Big Picture

- I’m going to go through the different parts of the CMS detector
- The punchline is that different parts of the detector see different particles
- At the end you will understand how we know we are looking at an electron, at a muon, etc.
- On the technical side…

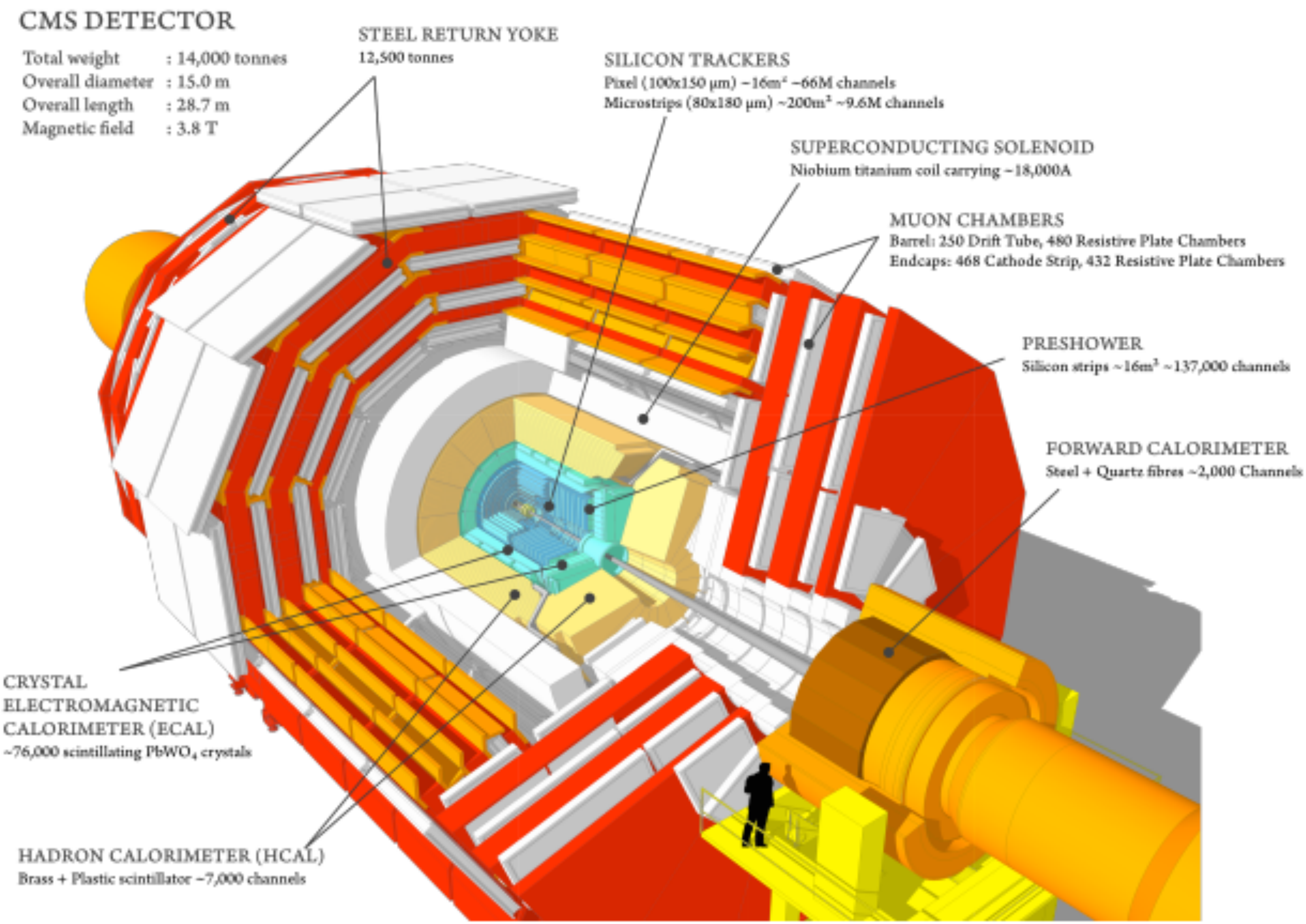
Detectors



“Tracks” of ionized particles due to charged particles traversing a “bubble chamber”— one kind of particle detector.

- How do detectors work? Many detectors use
  - **ionization**: Charged particles ionize detector material— we can detect the resulting tracks
  - **scintillation**: Charged particles traveling through a medium produce photons which we detect

Sliced CMS detector



A. Rinkevicius

Magnet

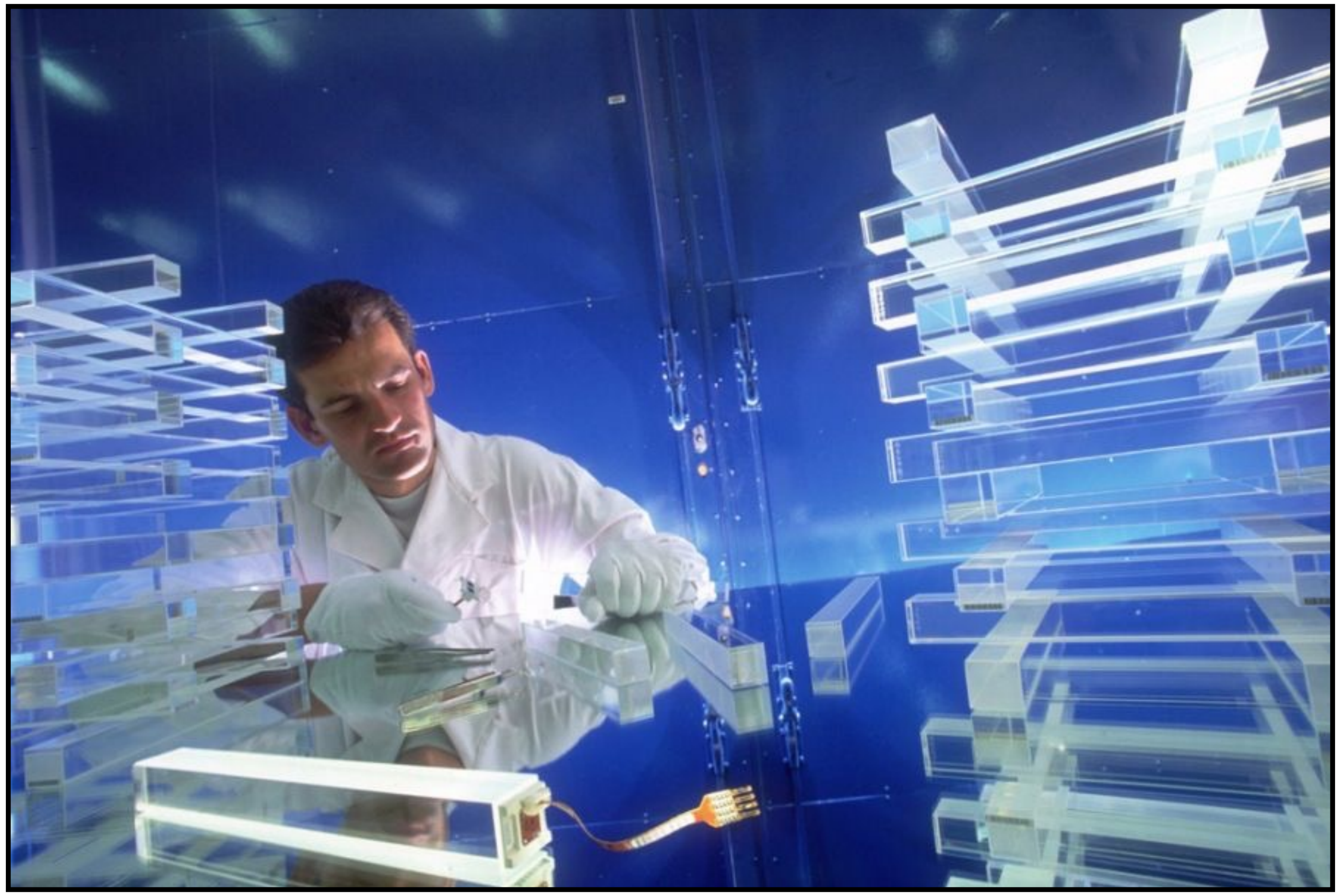
- Charged particle tracks bend in magnetic fields
- If there is a magnetic field we can tell whether particles are positively or negatively charged
- Needs to be a strong field, especially to measure charge of high energy charged particles

- Muons (heavier so tracks are less curved) are especially hard in a “compact” (small!) “solenoid” (helical coil with currents)
- CMS magnet is superconducting, in fact its the largest superconducting magnet ever built
- Because superconducting, it must be cooled to ~4 K
- Contains almost twice as much iron as the Eiffel Tower

Tracker

- Innermost part of the detector.
  Detects “tracks” of charged particles.
- CMS: Two parts: Silicon pixel detector and silicon strips
- Charged particles eject electrons from silicon atoms
- Leads to voltage differences that can be read out electronically
- Lets us detect charged particles, measure charge from bending of tracks

Electromagnetic Calorimeter

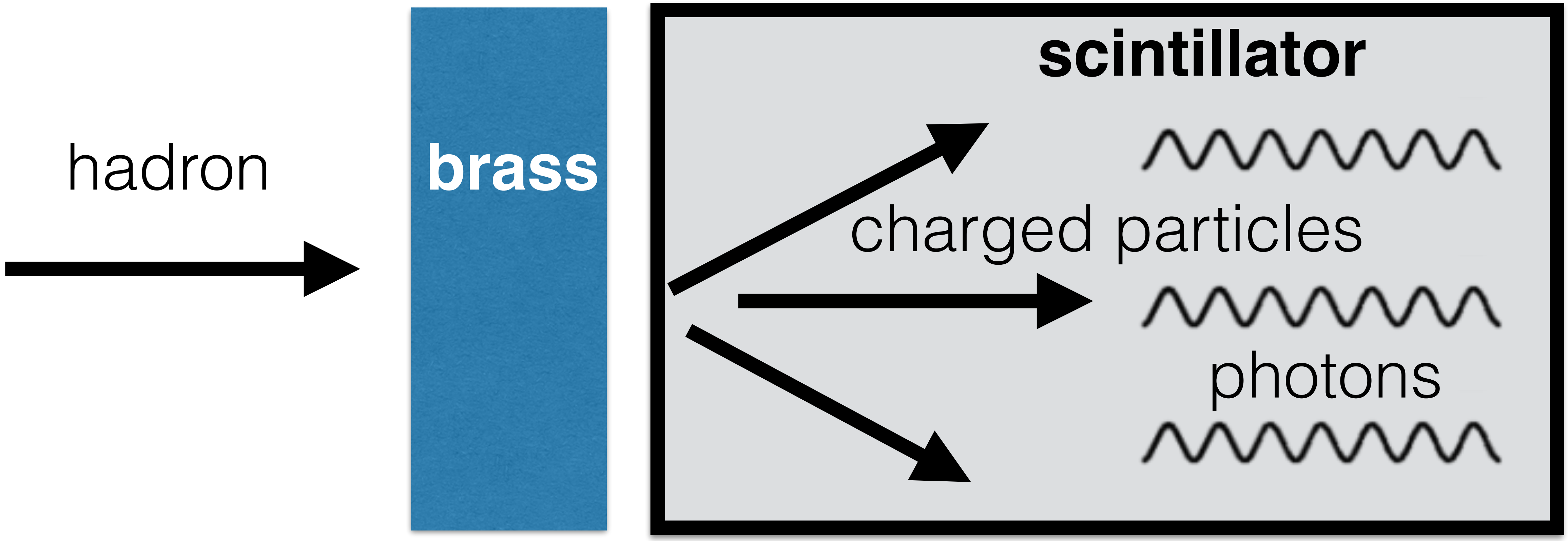


- Lead tungstate ($PbW0_4$) crystals: **scintillator**
- Charged particles produce light in the crystals: that light is detected by the detector electronics
- Has to be resistant to massive amounts of radiation

Hadronic Calorimeter

- The electromagnetic calorimeter (ECal) lets us charged particles and photons
- We also need to be able to detect "**neutral hadrons**"
- **hadrons** = particles made of quarks (and sometimes antiquarks)
- Examples of neutral hadrons include neutrons, and neutral pions
- We also want to tell the difference between electrons (or positrons) which leave almost all of their energy in the electromagnetic calorimeter and charged hadrons (like protons, charged pions, etc.) which still have energy left

Hadronic Calorimeter

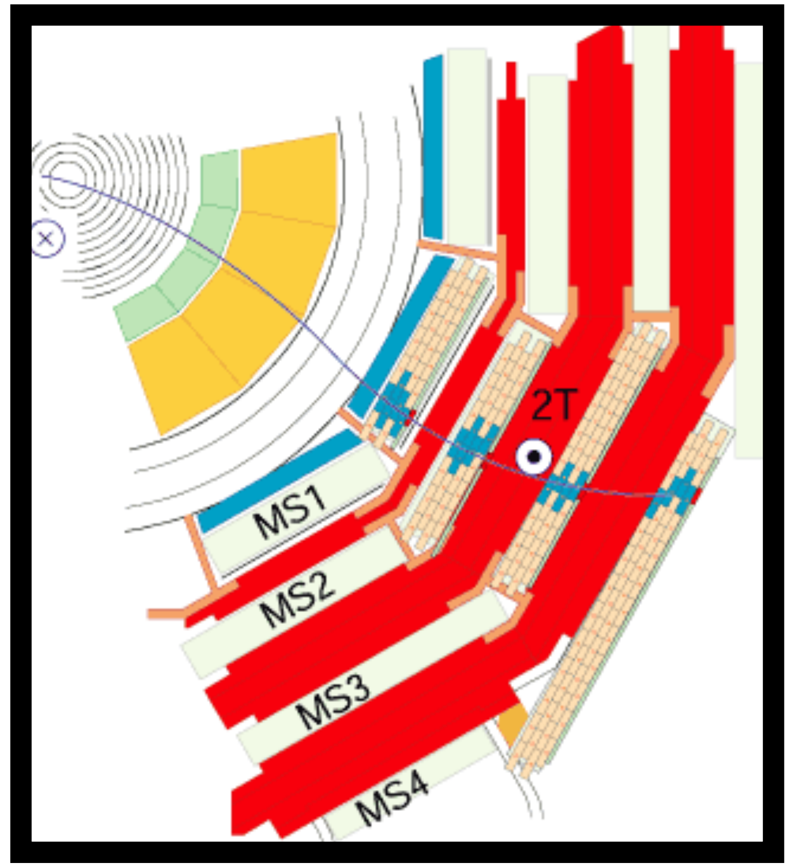


- Remember the things that are easier to detect are charged particles or photons
- So we put a thick layers of brass in front of layers of a plastic scintillator
- Hadrons produce charged particles in showers when they collide and interact via the strong force with the nuclei in the layer
- These charged particles produce photons in the scintillator layer which is what we detect

Hadronic Calorimeter

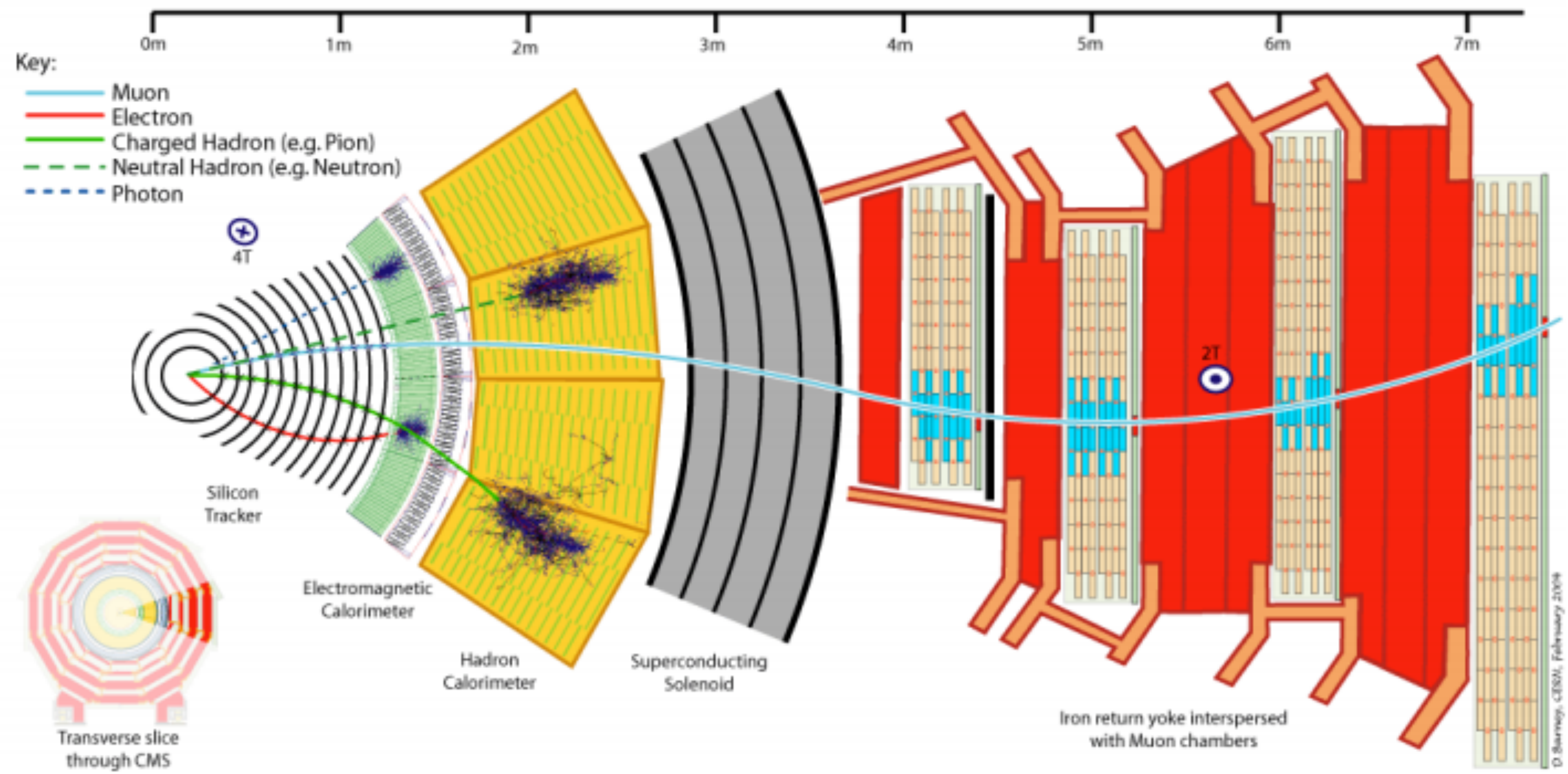
- Much of the brass in CMS came from old Russian naval artillery shells

Muon Chamber



- The outermost level of the detector is the muon chamber
- Muons are like heavy electrons (~200 x heavier)
- Because they are heavier they do not deposit much energy in the ECal or the HCal
- In CMS muons are detected by observing the ionization of gas (85% Argon, 15% CO_2)

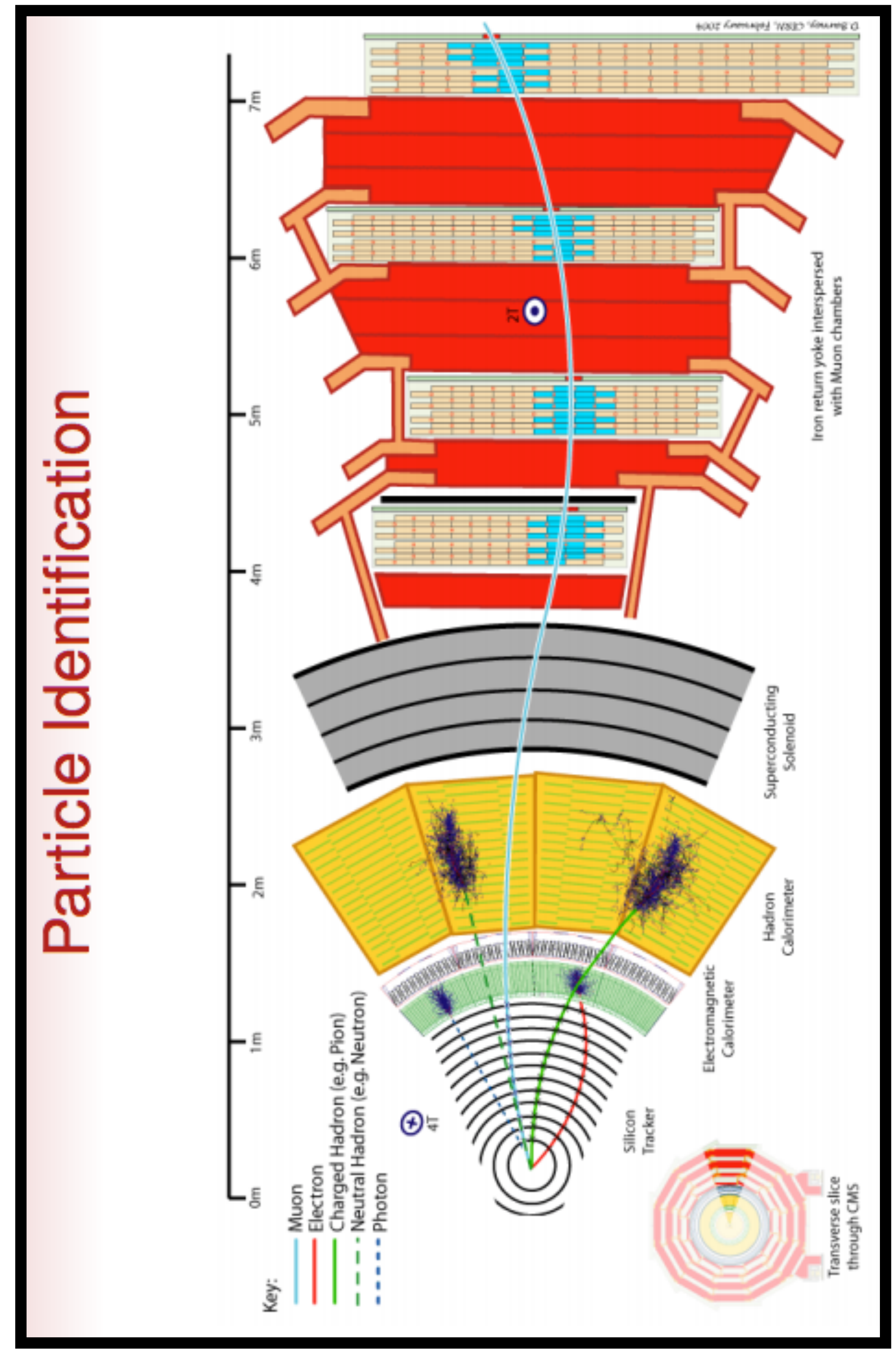
Particle Identification



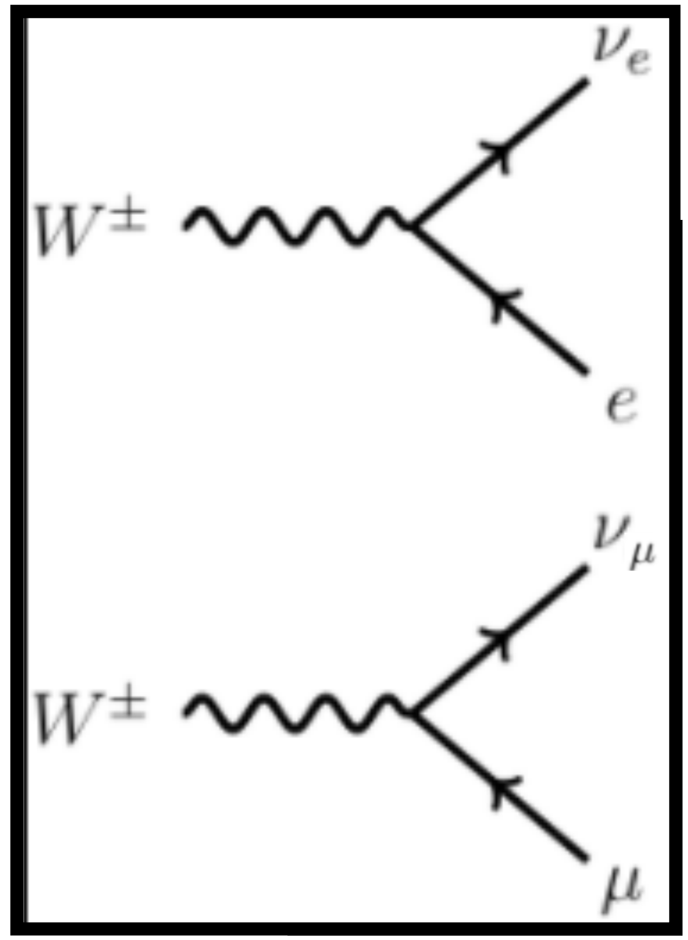
A. Rinkevicius

Particle Checklist

- **Tracker**
  - sees electrons, muons, charged hadrons
  - doesn't see photons neutral hadrons
- **ECal**
  - sees electrons, photons, charged hadrons
  - doesn't see muons or neutral hadrons
- **HCal**
  - sees charged hadrons, neutral hadrons
  - doesn't see electrons, photons, or muons
- **Muon Chambers**
  - see muons

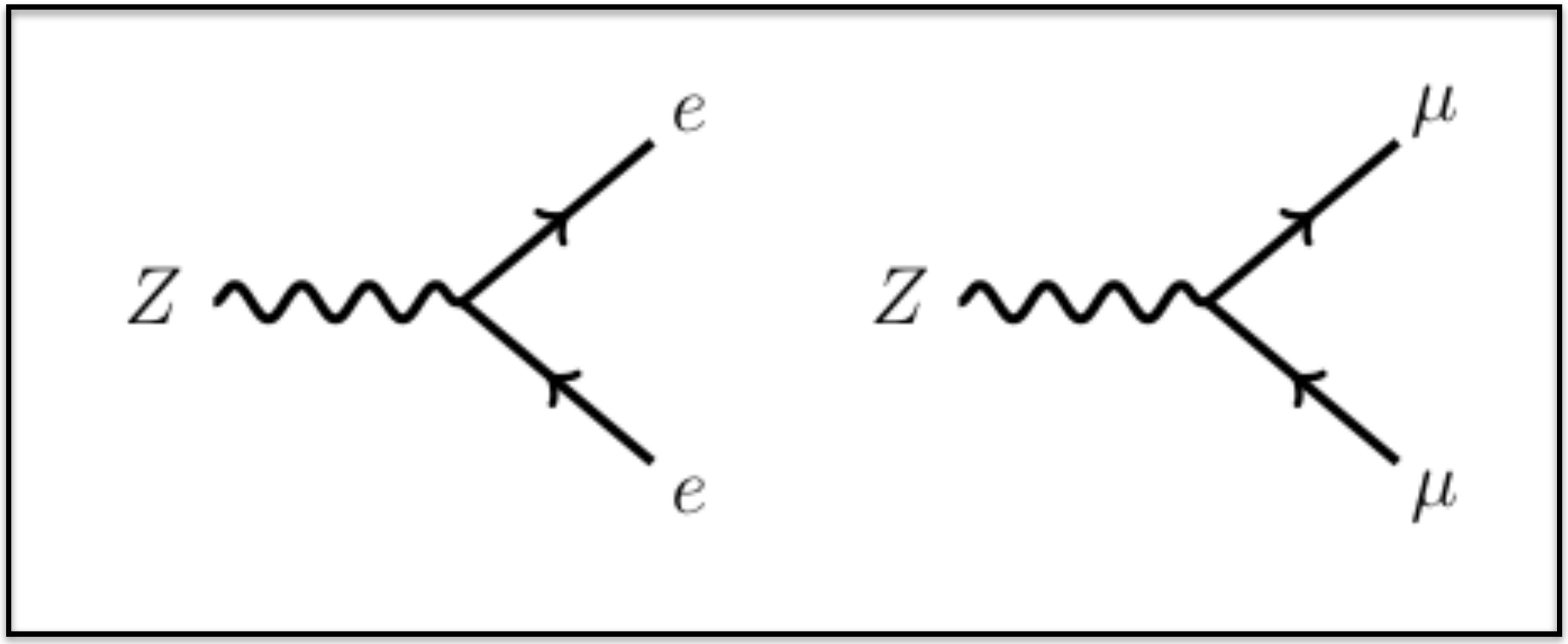


Detecting W Bosons



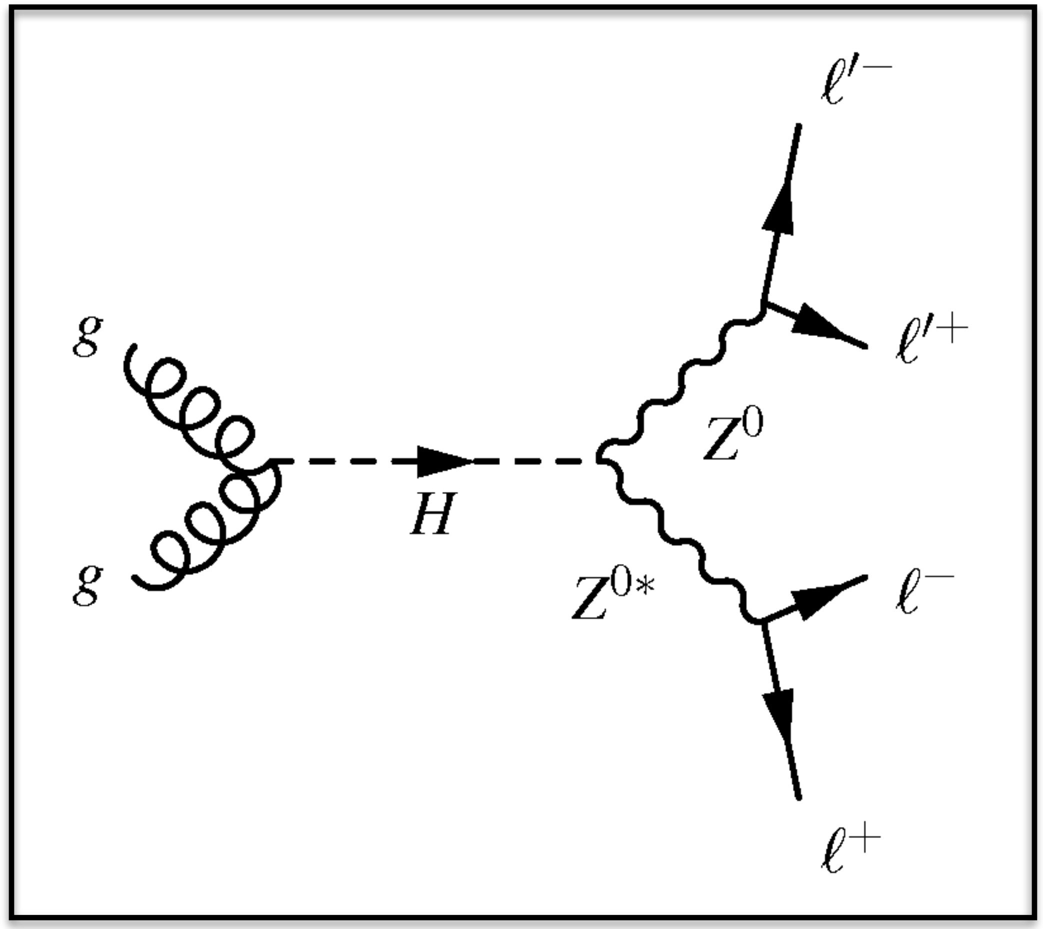
- W bosons can decay to an electron or muon and an (anti)-neutrino (among other possibilities)
- We can observe the electrons and muons in the detector
- We cannot see the neutrino: but we can infer its presence from missing momentum

Z boson mass



- Z bosons can decay to an electron and a positron or a muon and an anti-muon (among other possibilities)
- We can detect both the electron and the positron, or both the muon and the antimuon
- The magnetic field lets us determine charge: which particle is which
- Z boson mass is conserved in the decay: we can calculate a mass for, e.g., the electron positron pair which will be the same as the Z boson mass

Higgs Boson Decays



- Higgs bosons decay in many different ways
- Decays to two photons or to two Z bosons which in turn decay to electrons, positrons, muons, and antimuons ("four leptons") because
  - electrons, muons, and photons are easier to distinguish and measure than other particles
  - "backgrounds" (i.e. other processes that we are not interested in) are less for those processes

Higgs Boson Discovery

- The discovery of the Higgs boson was announced at CERN on July 4, 2012
- It was discovered by looking at Higgs to two photon and Higgs to four lepton events

Thanks!