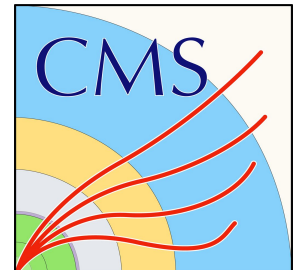
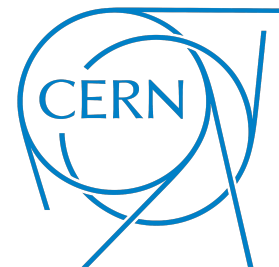




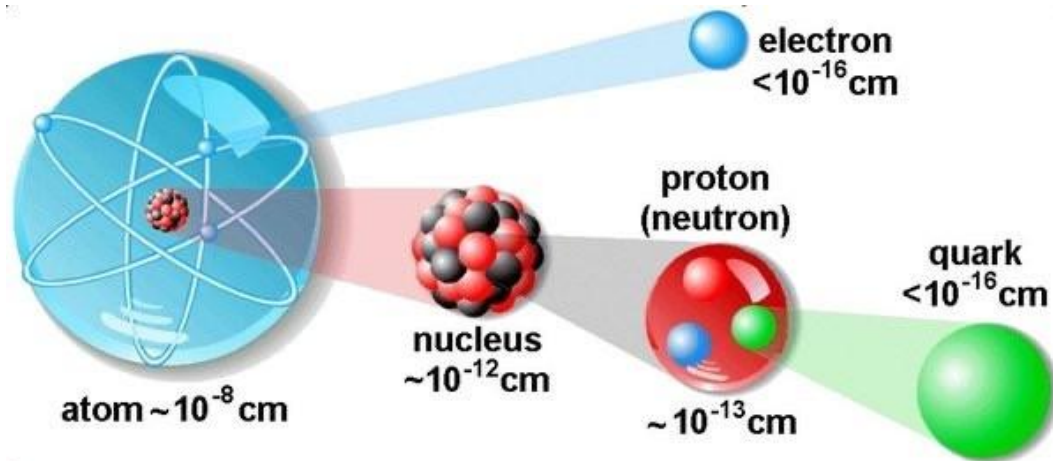
Physics at the Large Hadron Collider

Christina Wang
Saturday Morning Physics
October 10, 2026



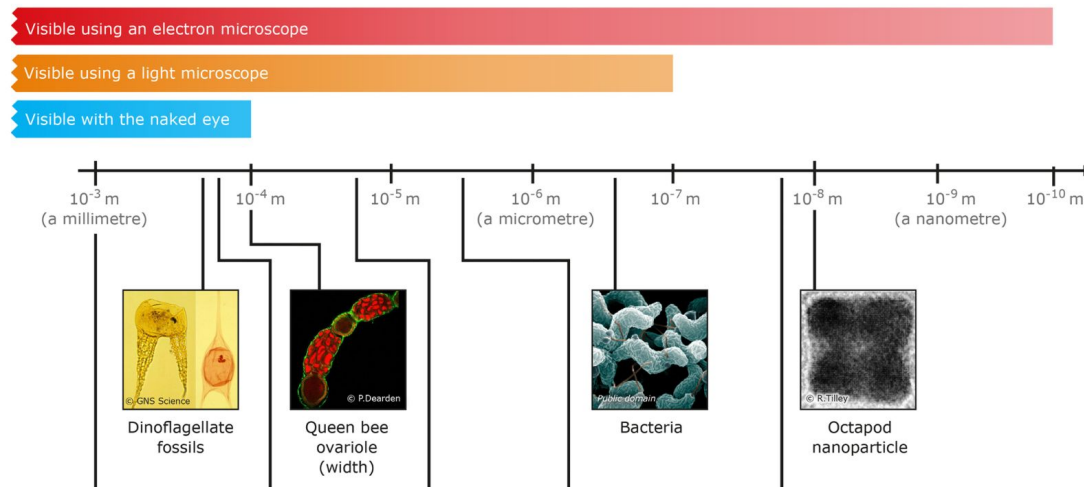
Why build a high energy particle collider?

- To study the smallest things
- Quantum Mechanics tells us that **particles ~ waves**
 - A particle with energy **E** has wavelength $\lambda = hc/E$
 - **c** = the speed of light
 - **h** = Planck constant
- Studying **high energy** = studying **small distances**



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What is high energy?

- A proton weighs 10^{-24} grams, or 1 Giga-electron-volt (GeV)
 - eV = energy an electron gains over 1 volt
 - 1 GeV = 10^9 electron-volts
- Proton collision energy at the Large Hadron Collider is **~ 13 TeV i.e. 13 trillion (10^{12}) eV**
 - High enough to probe length scales of 10^{-19} m !

Quick exercise

Question: how many AA batteries are needed to accelerate an electron to 1 GeV?

Hint: a) $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$

b) Typical AA battery is rated at 2,400 mAh at 1.5 volts

c) $\text{Energy} = \text{Current} * \text{Voltage} * \text{time}$

Quick exercise

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Hint: a) $1 \text{ eV} = 1.602 \times 10^{-19} \text{ J}$

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c) $\text{Energy} = \text{Current} * \text{Voltage} * \text{time}$

Answer

1 battery has $2400 \text{ mAh} * 1.5 \text{ V} * 3600 \text{ s/h} = 12,960 \text{ J}$

$12960 \text{ J} = 8 * 10^{22} \text{ eV} = 8 * 10^{13} \text{ GeV} = 8 * 10^{10} \text{ TeV}$

So 1 battery is sufficient!

But wait .. 1 battery has much more energy than the LHC!!??!!

.. Did we miss something ?? ...



So why is it so hard to accelerate particles?

- As particles approach the speed of light c
 - need increasingly large amounts of energy to continue accelerating
 - They become “**Relativistic**”
- Their energy doesn’t just go into speed
 - it also adds to their effective mass

$$E = \frac{mc^2}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- Need **powerful electro-magnetic fields** to accelerate particles in a small space
 - Need special magnets!



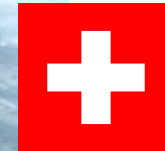
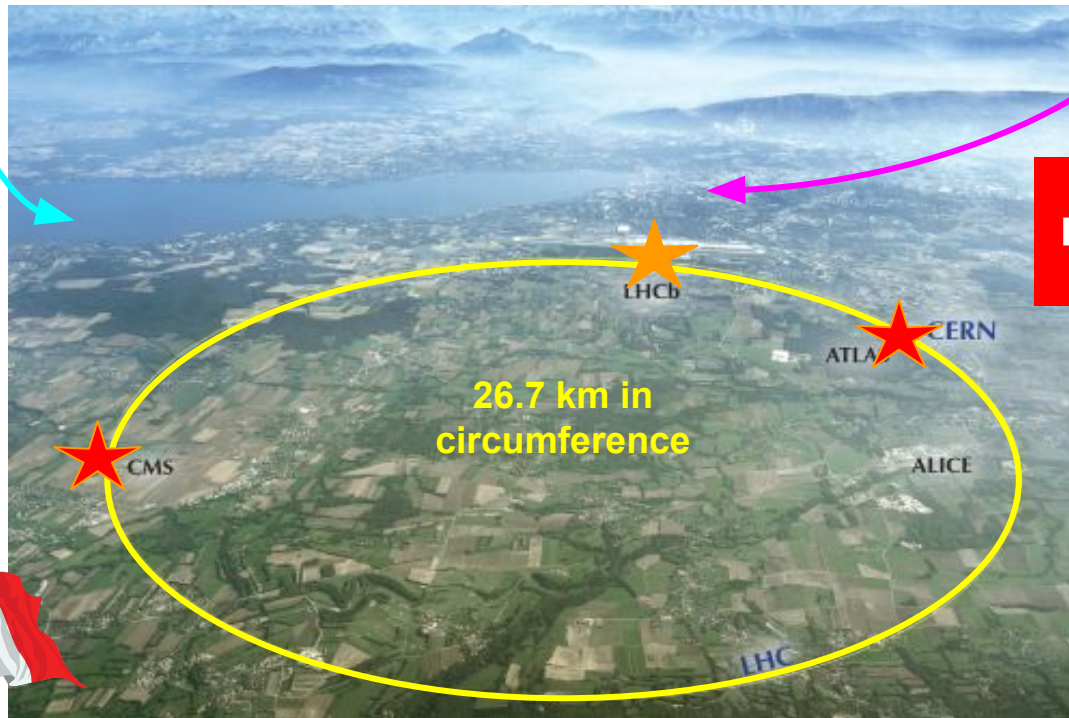
The Large Hadron Collider (LHC)



- Circular proton-proton collider at CERN
- CERN = European Center for Nuclear Research (in French)
 - International physics laboratory in Geneva, Switzerland

Geneva, Switzerland

Lac Léman
(Lake Geneva)



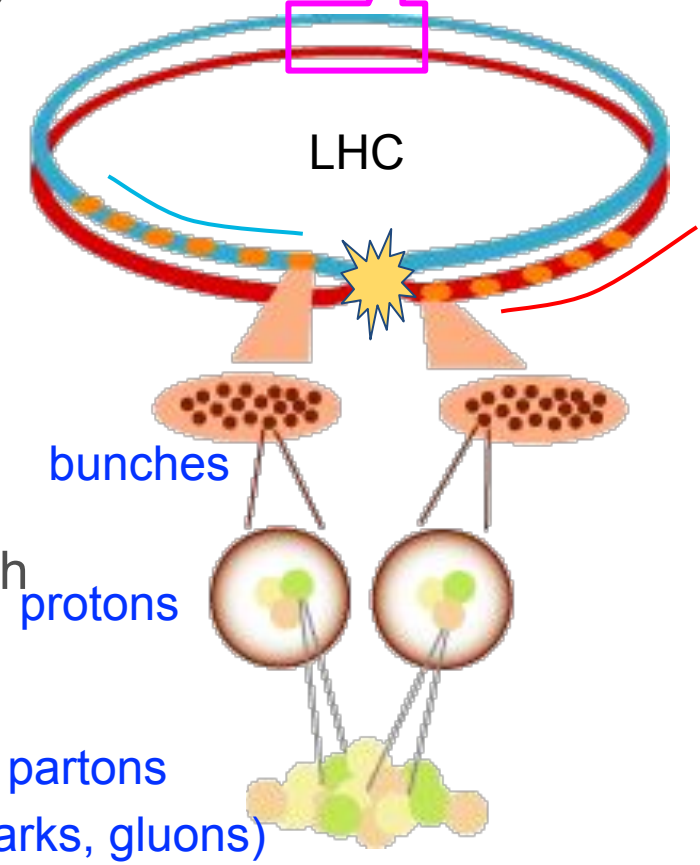
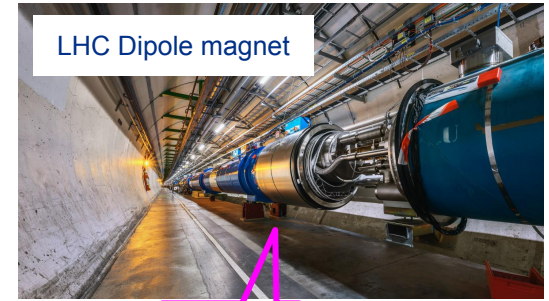
Partially in
Switzerland!

Partially in
France!



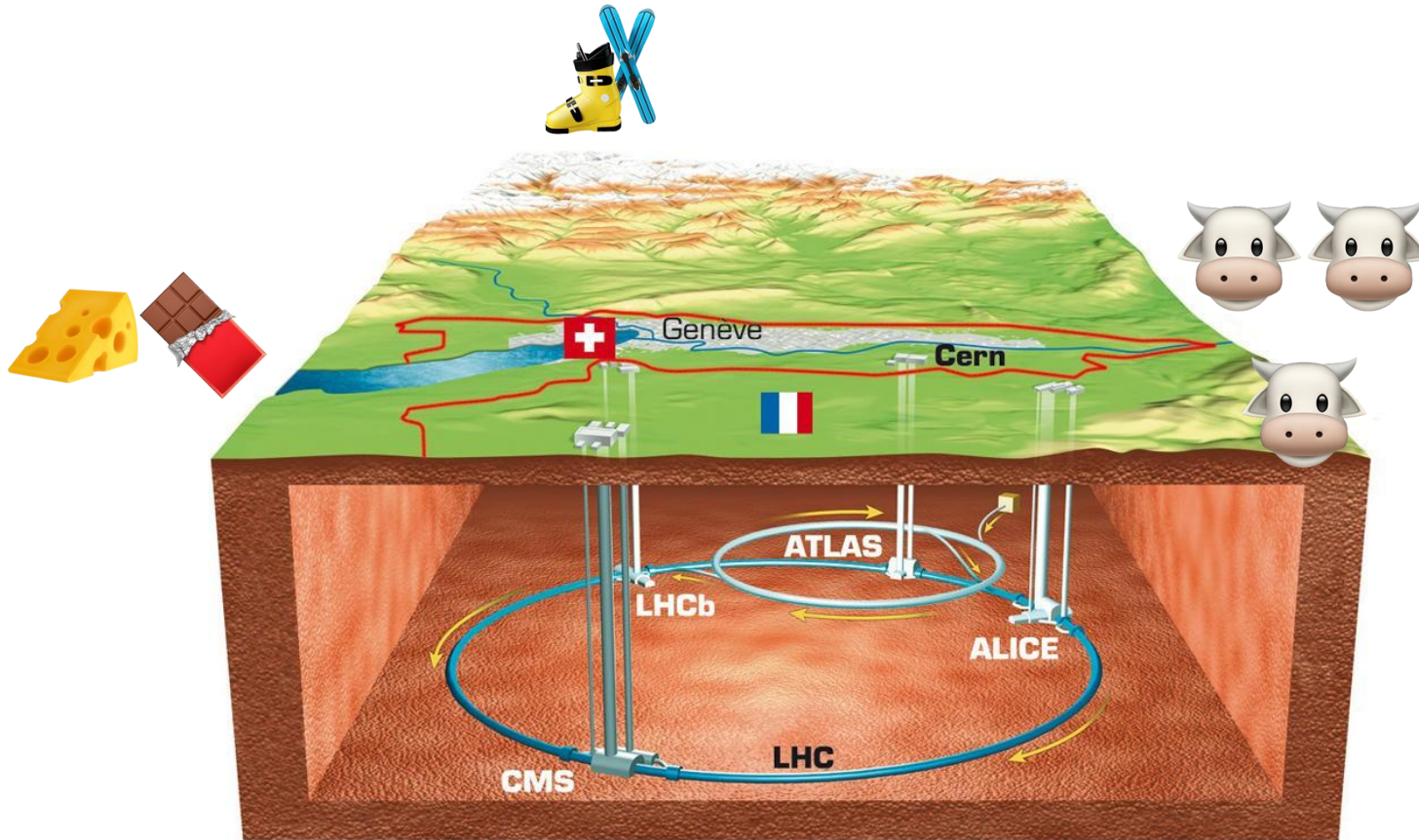
What happens in an LHC collision?

- Proton **bunches** circulated in two rings in the LHC using **powerful magnets (~8 T)**
 - Circle in opposite directions, crossing 40 million times per second
 - ~3000 bunches, 7.5m apart
 - Each bunch = 100 billion (10^{11}) protons ~5ng!
 - Each bunch ~ 6.5 TeV;
 - Collision energy (two bunches) ~13 TeV
- When the bunches cross, **partons** within each proton interact
- Each parton only carries **a fraction of the proton's total energy**



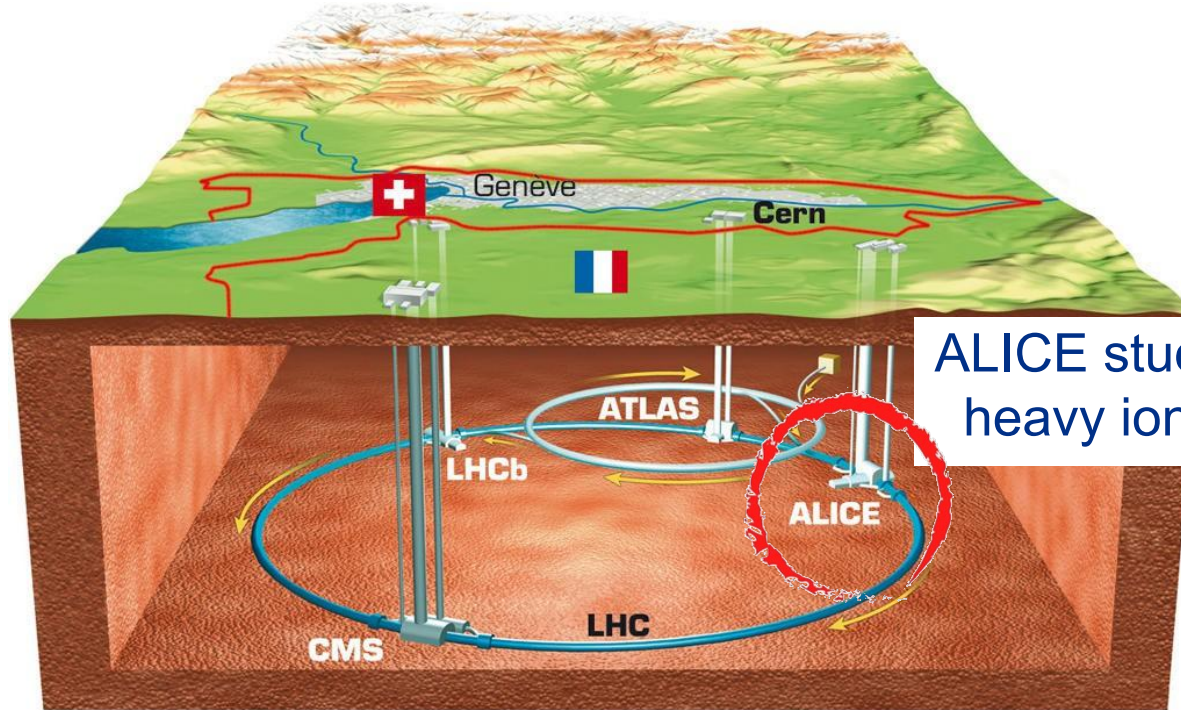
The LHC experiments

- Four main experiments are located at the points where the proton beams intersect



The LHC experiments

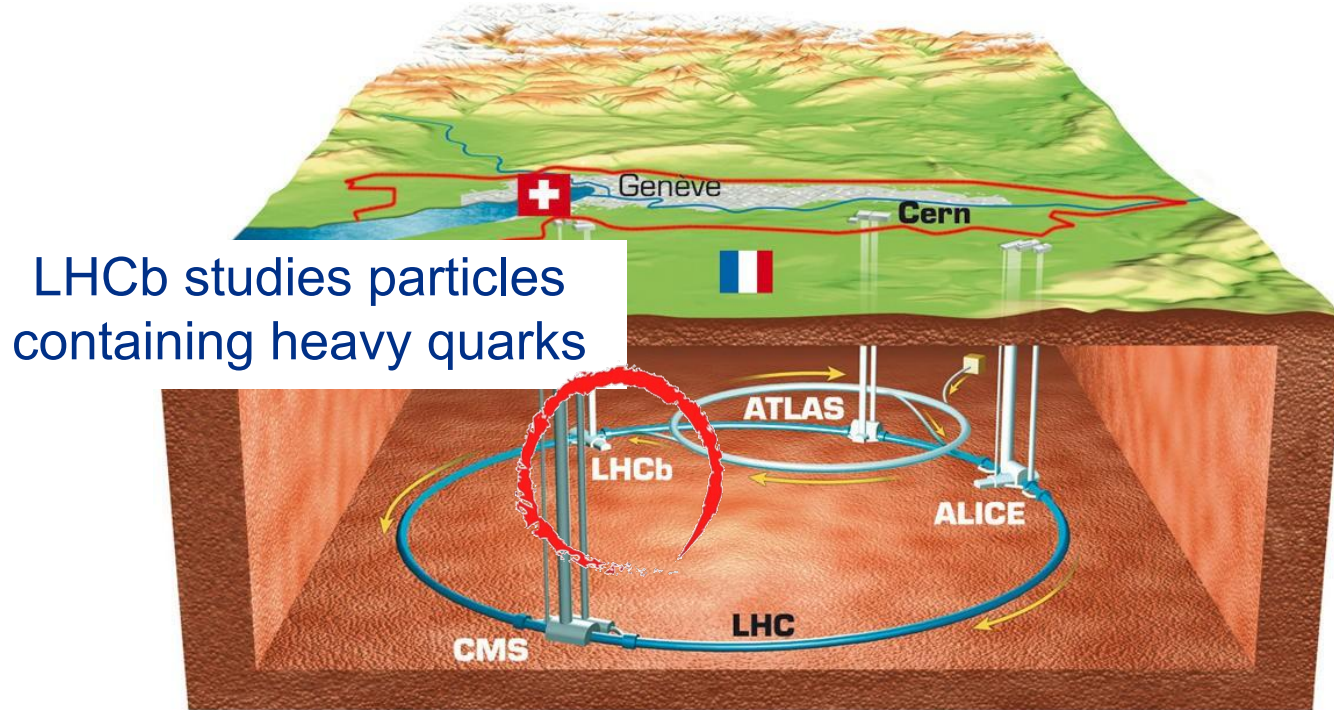
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ALICE studies collisions of heavy ions (not protons)

The LHC experiments

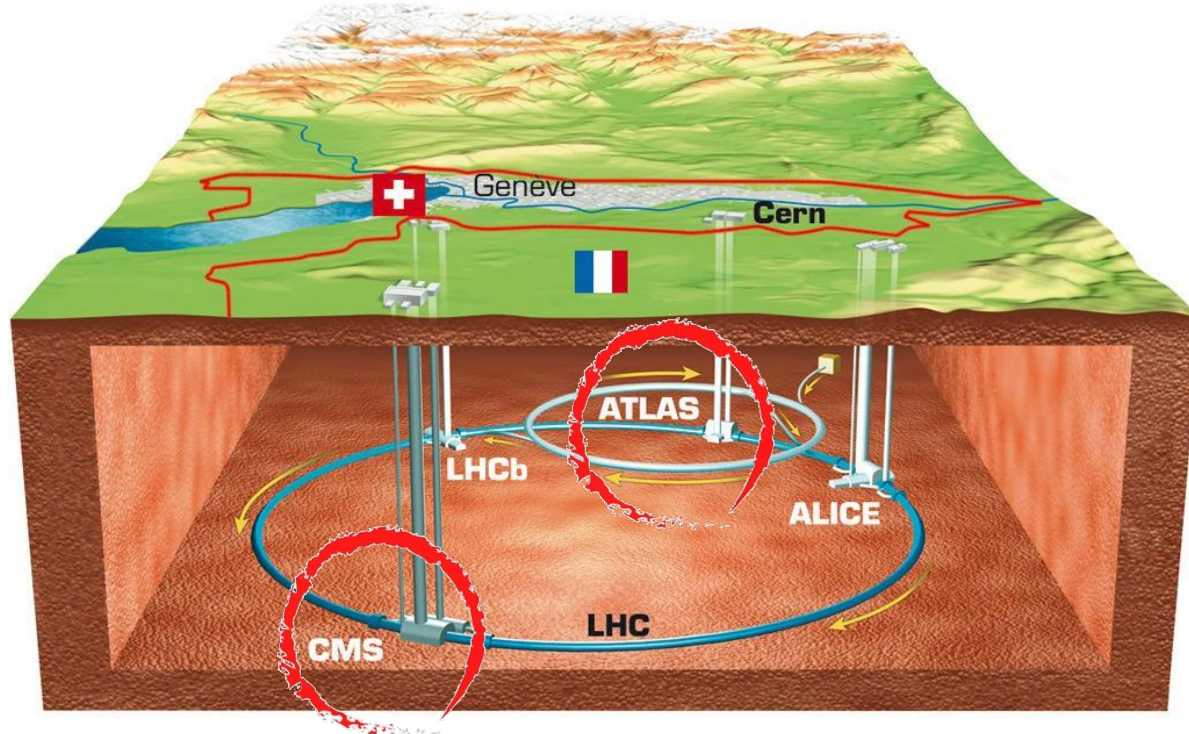
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The LHC experiments

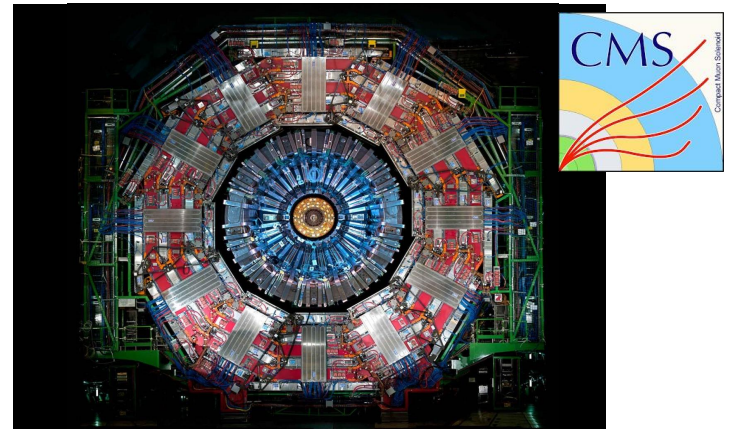
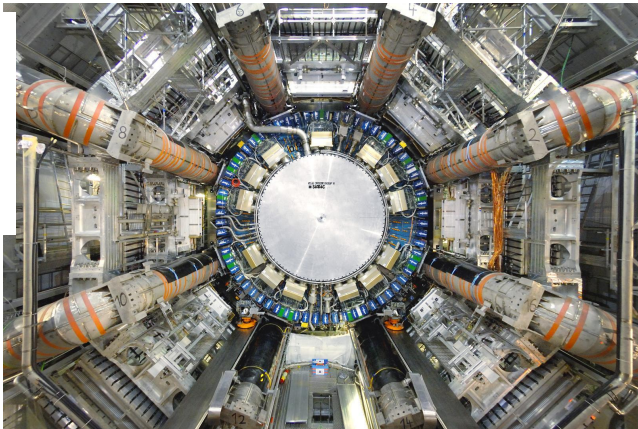
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ATLAS and CMS are **general purpose** experiments



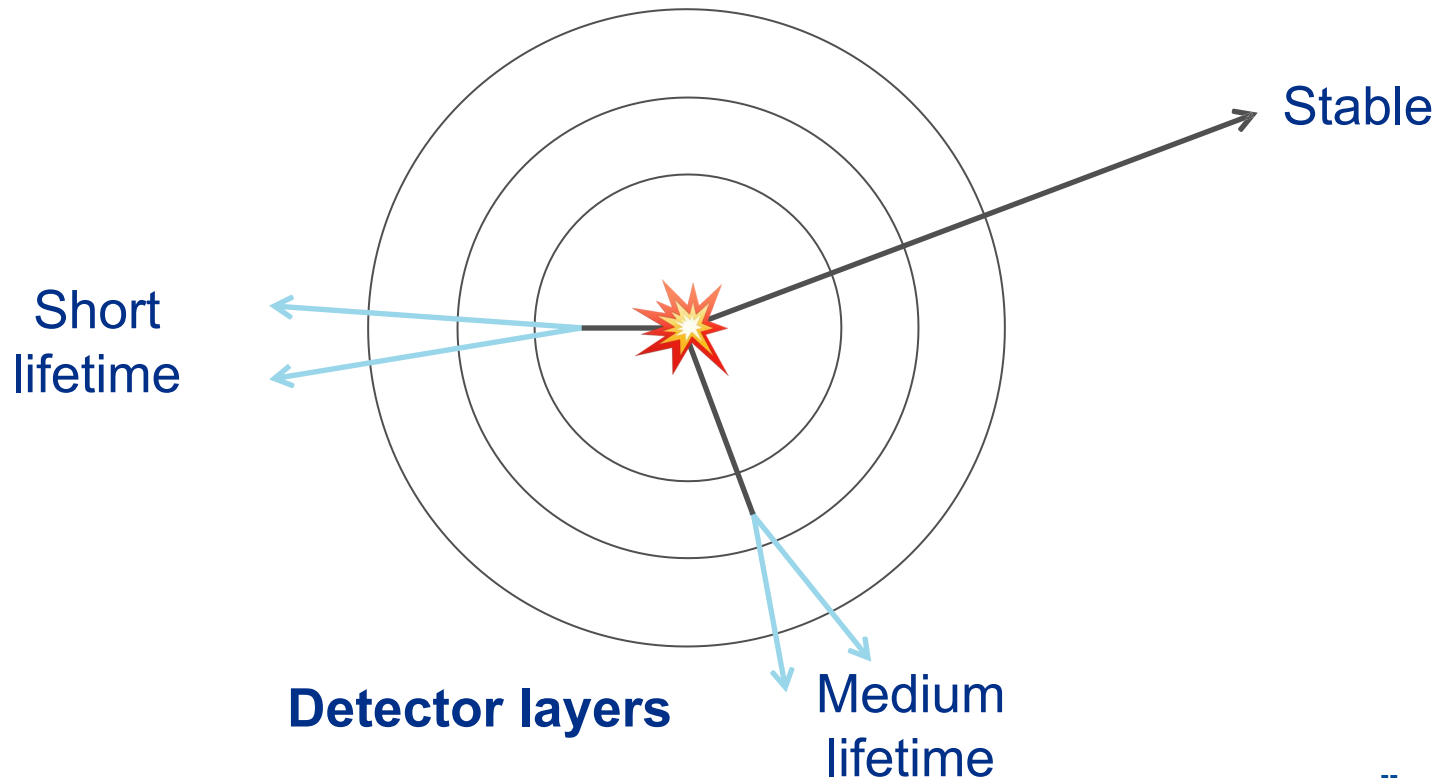
What does general purpose mean?

- Study everything we can!
 - Measure what we already know about very precisely
 - Look for new things we've never seen before, including things we haven't thought of yet
- Goal: detect as many particles as possible
 - Identify them correctly
 - Measure their energy/momentum precisely



What particles can we detect?

- **Short lifetime:** some particles decay immediately into other particles, never reaching the detector
- **Medium lifetime:** other particles decay inside the detector
- **Stable particles:** travel through the entire detector

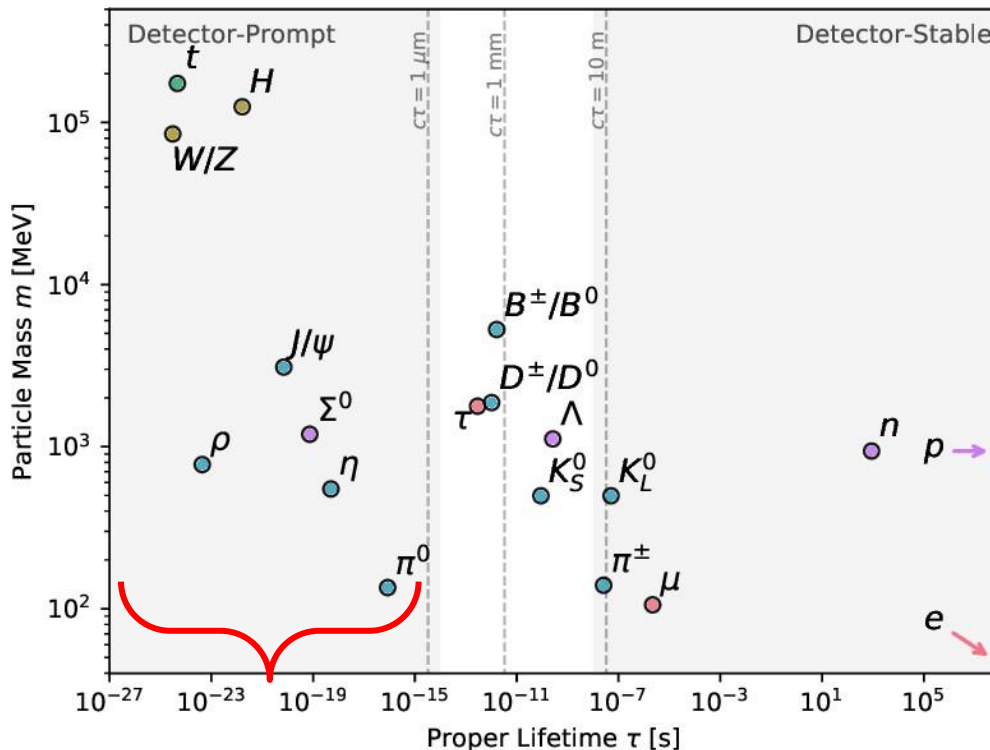


What particles can we detect?

- **Short lifetime:** some particles decay or group together immediately into other particles, never reaching the detector
- **Medium lifetime:** other particles decay inside the detector
- **Stable particles:** travel through the entire detector

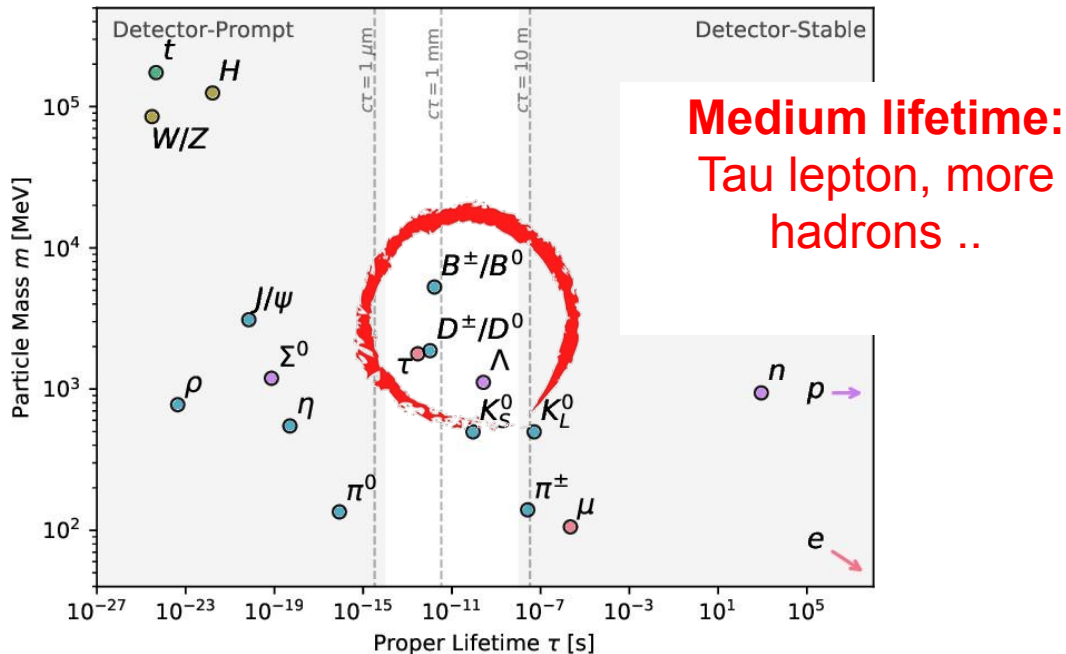
Short lifetime:

top quark,
Higgs boson,
W & Z bosons,
Some hadrons ..



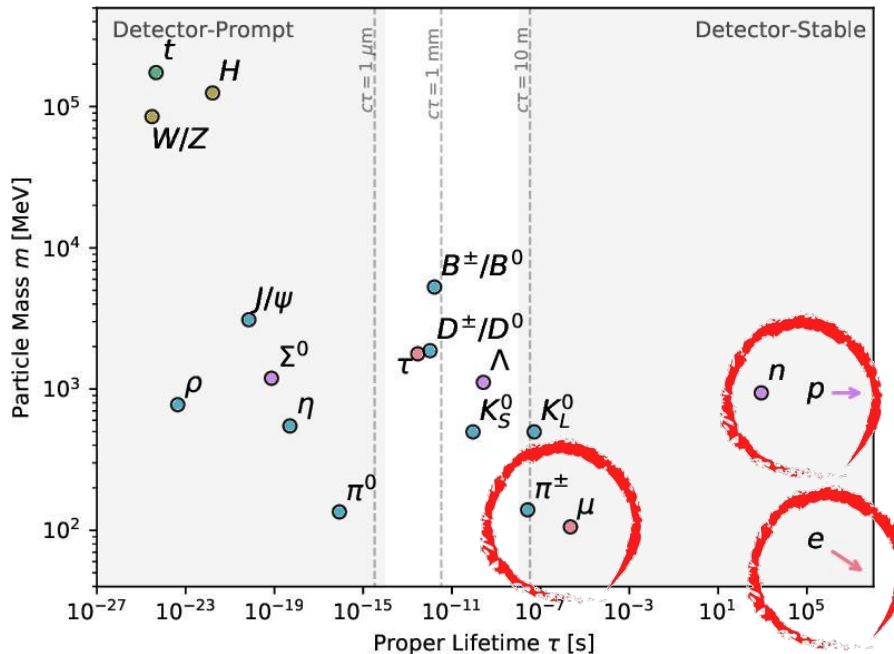
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What particles can we detect?

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Stable particles:
muon*, electron,
photon, hadrons ..

What particles can we detect?

- The detector is optimized to mostly detect stable particles
 - Hadrons, photons, electrons, and muons
- These objects can be used as **building blocks** to reconstruct any type of particle
 - Grouping building blocks particles together
 - Analyzing the relationship between them

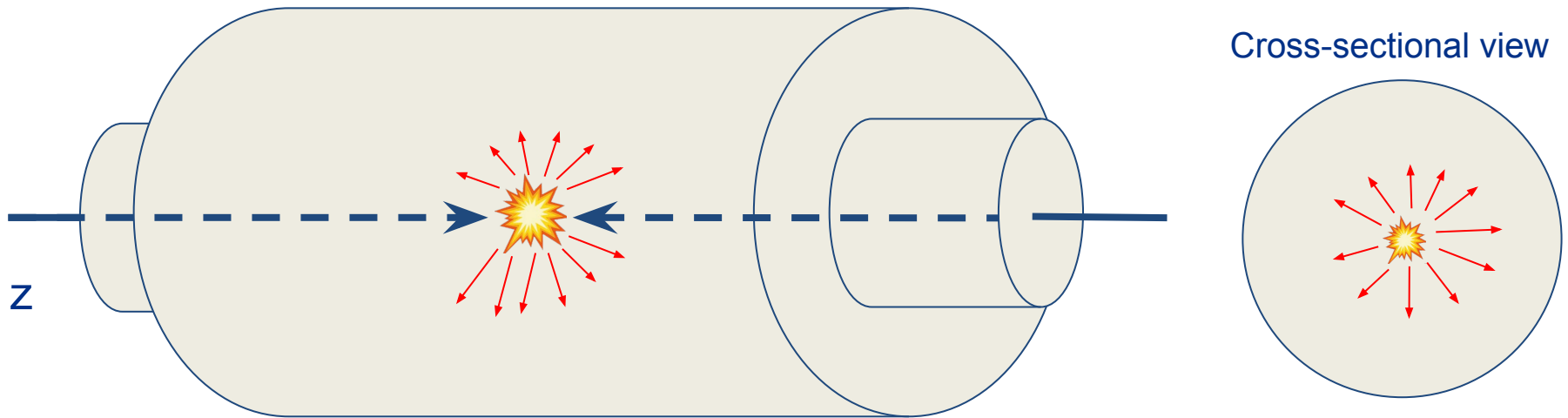


**So how do we measure particles with our
detector?**

Let's design an LHC experiment

Detector design

- **Goal:** Designing a particle detector is like playing pokemon.... Gotta catch 'em all!!
- The more particles you can capture, the better you can understand and explain what occurred during the collision.
- So we make the detector **hermetic**.



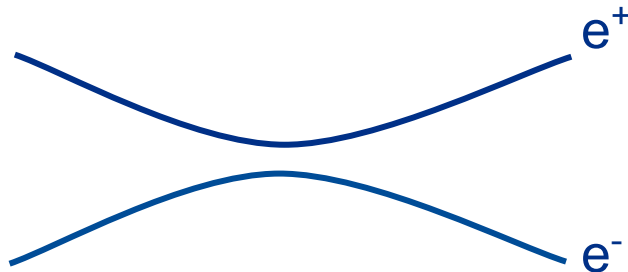
Bend it like Beckham

.. use a **Magnet**



Starter kit:
- Cylindrical design ✓

- Direction of curvature tells you the **charge**

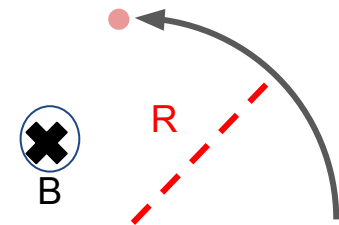


- Radius of curvature tells you **momentum**

Very curved → low momentum

Almost straight → high momentum

$$\frac{mv^2}{r} = qvB$$



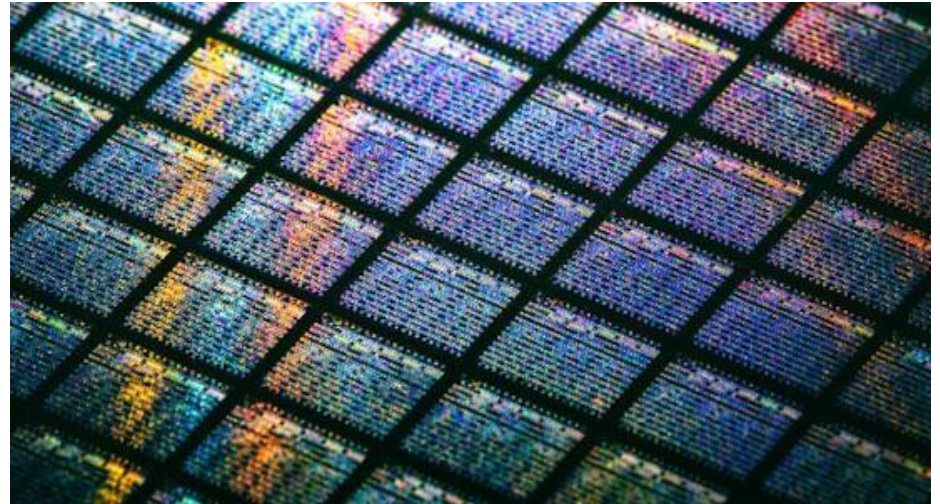
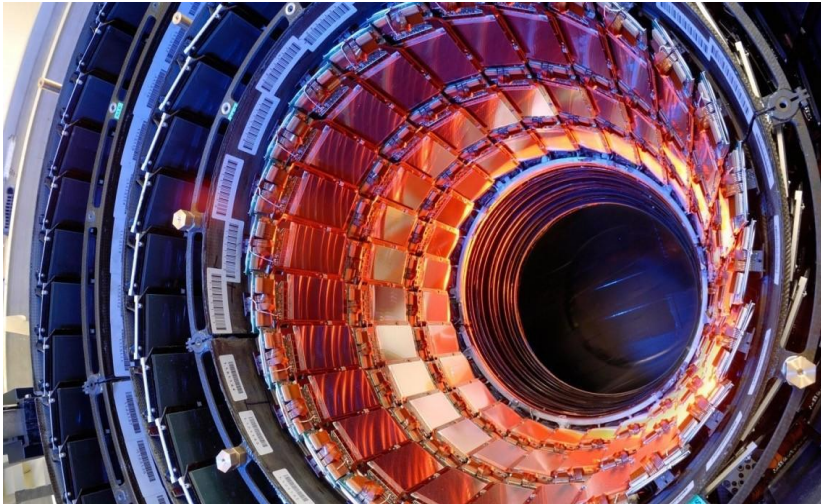
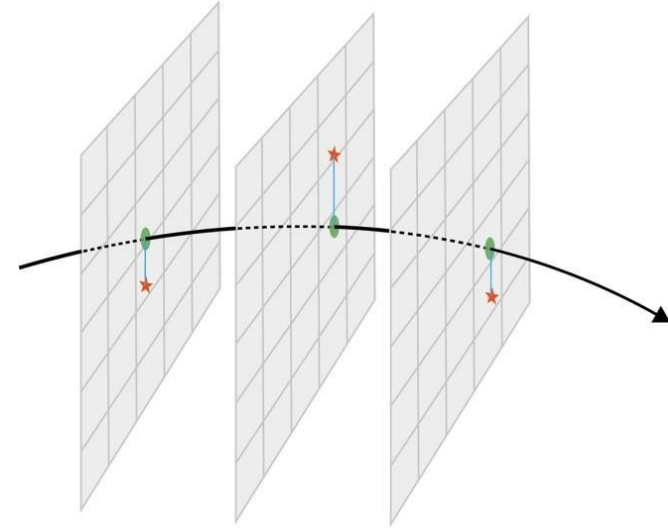
Can you think of a magnet that is cylindrical in shape?

Measure the particle's trajectory .. with a Tracker

- Made of tiny pixels
 - register hits from charged particles
 - Connect the dots b/w hit pixels to create a **track**
 - Must be lightweight
- Typically Si semiconductor detectors

Starter kit:

- Cylindrical design ✓
- Strong solenoid ✓

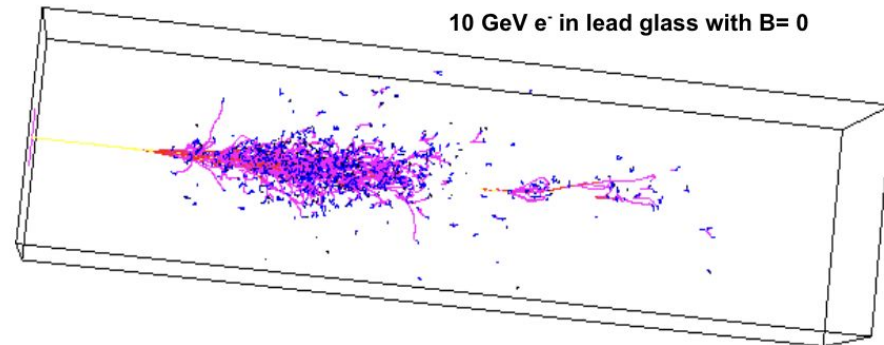
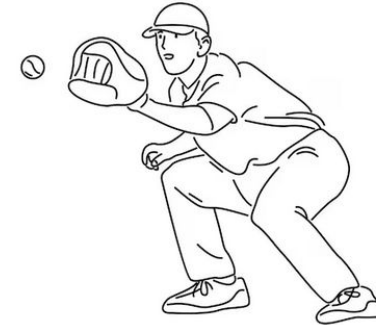


Measure the energy

.. with **Calorimeters**

- Starter kit:
- Cylindrical design ✓
 - Strong solenoid ✓
 - Tracker ✓

- Dense material - **stop** the particle
- Absorber - **absorb** the energy of the particle's slowdown



10 GeV e^- in lead glass with $B=0$

For **high momentum particles** flying straight through the tracker - use calorimeters for a **better energy/momentum measurement**

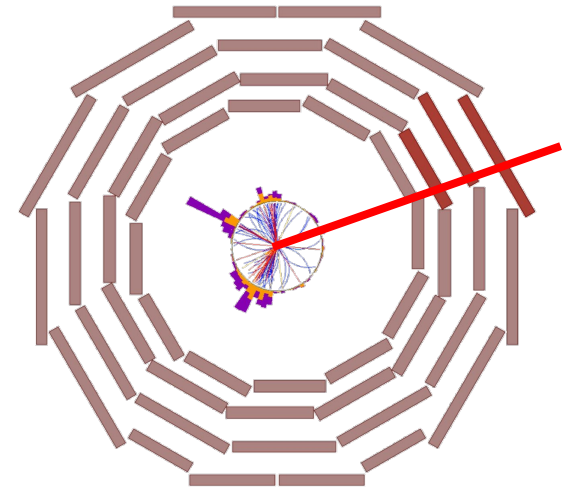
Remember muons?

.. add a muon system in the end

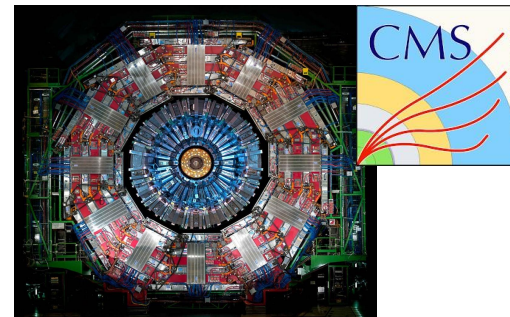
Starter kit:

- Cylindrical design ✓
- Strong solenoid ✓
- Tracker ✓
- Calorimeters ✓

- Muons are a decay product of many interesting particles
 - travel all the way through detector
- Install a **Muon system** as the outermost layer of detector.
 - registers hit from muons and give complementary information to the tracker



CMS = Compact Muon Solenoid!



Putting it all together

Compact Muon Solenoid

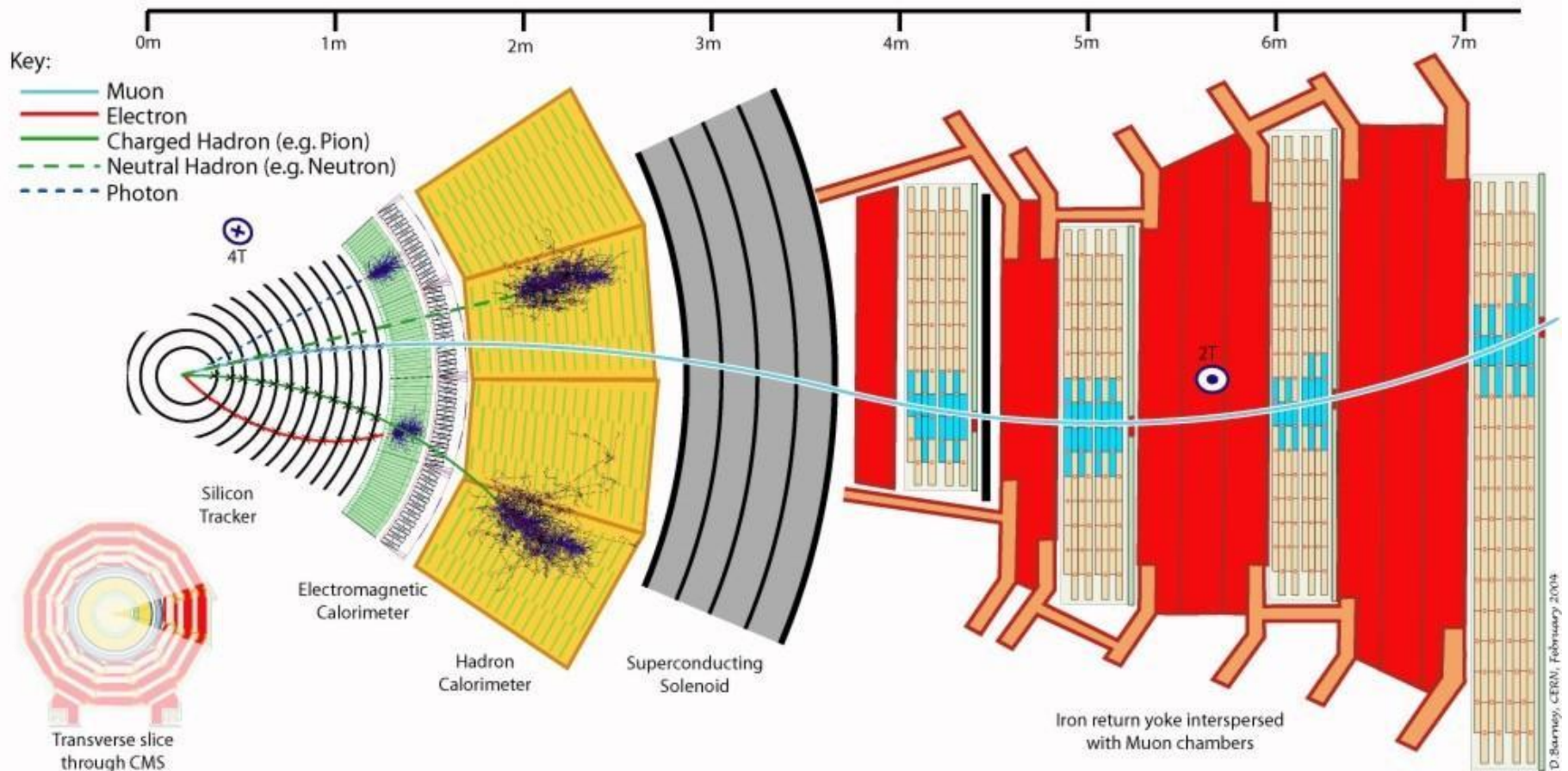
Cylindrical design : 15m diameter, 21 m long

Strong solenoid: 3.8 T

Tracker: Si based pixel and strip tracker

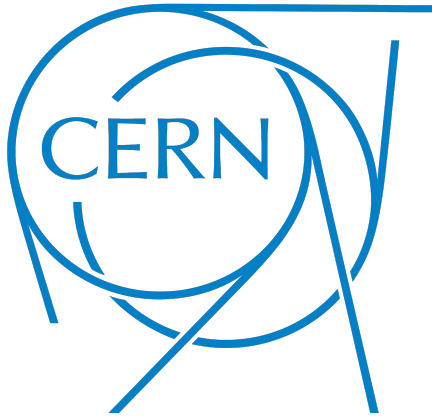
Calorimeter: homogeneous ECAL, sampling HCAL

Muon system: Best in the world



LHC data

- We make way too much data to save it all!
 - Choose ~ 1 in a million collisions using the **trigger system**



About 1 PB of data per second during peak operation - filtered down to a few GB per second

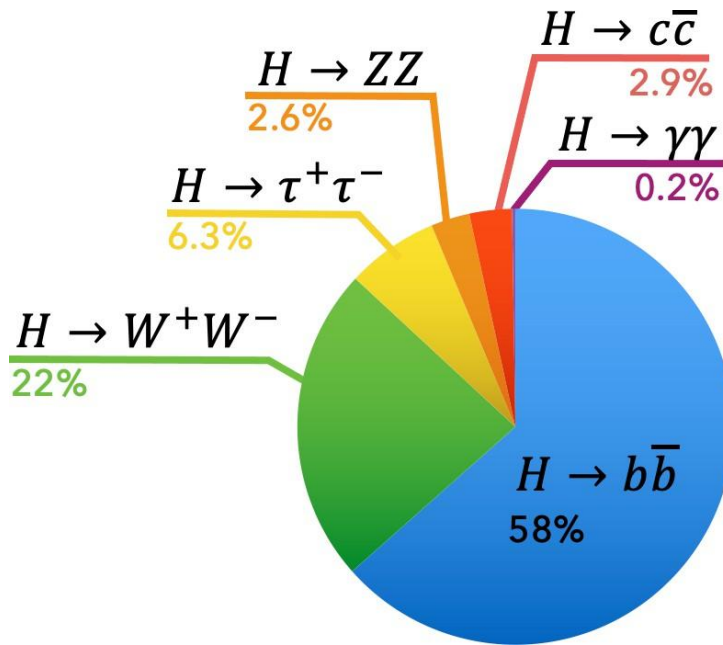
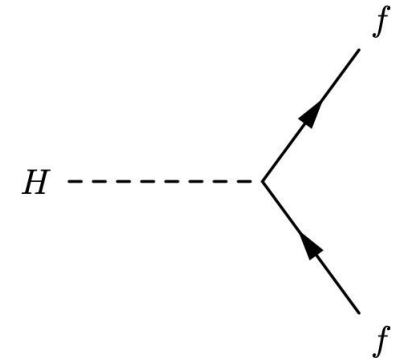


About 10 TB of data per day from users

Now let's use our particle building blocks
and detector starter kit to reconstruct a
Higgs Boson

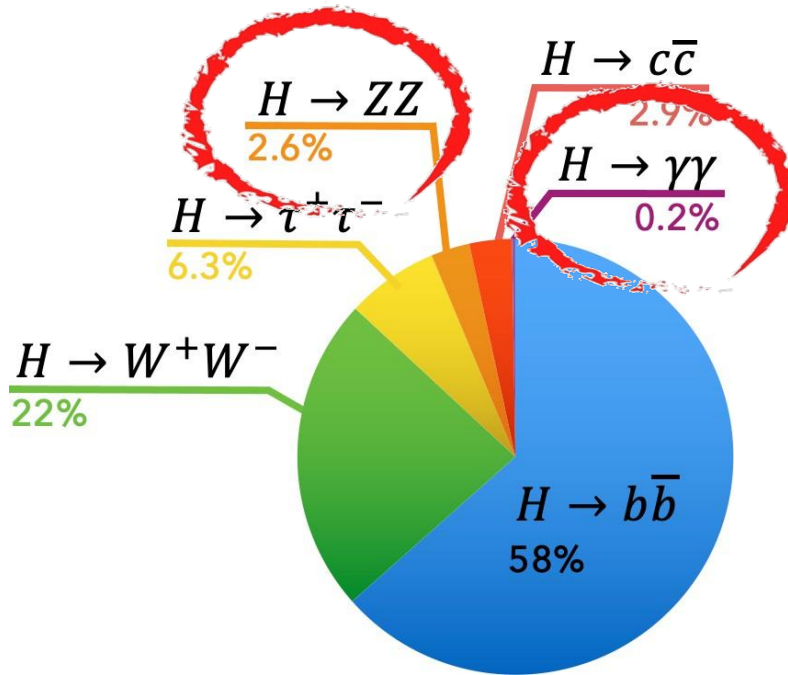
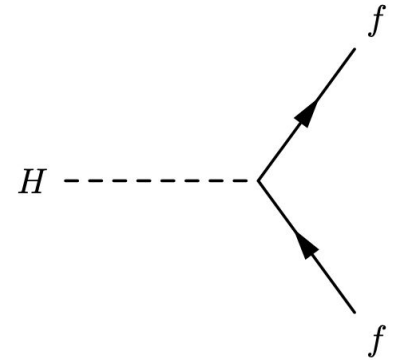
Higgs boson decays

- There are many ways the Higgs boson can decay
- Higgs decays can include every kind of object!
 - Jets, electrons, muons, photons



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Most of what we know about the Higgs comes from a small fraction of the decays!

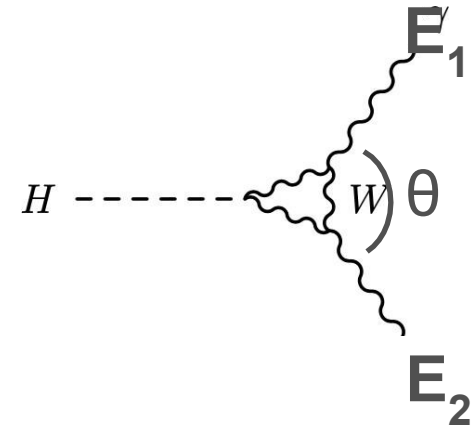
Our detectors are really, really good at measuring these

Reconstructing a Higgs boson

- Consider the Higgs decay to photons
 - $H \rightarrow \gamma\gamma$
- Calculate the invariant mass of the two photons

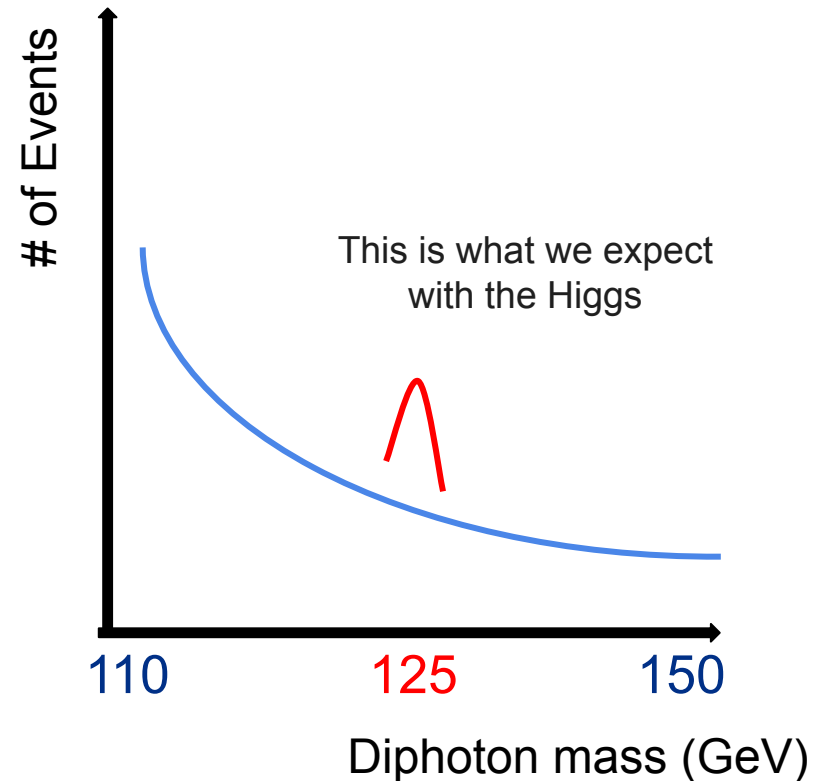
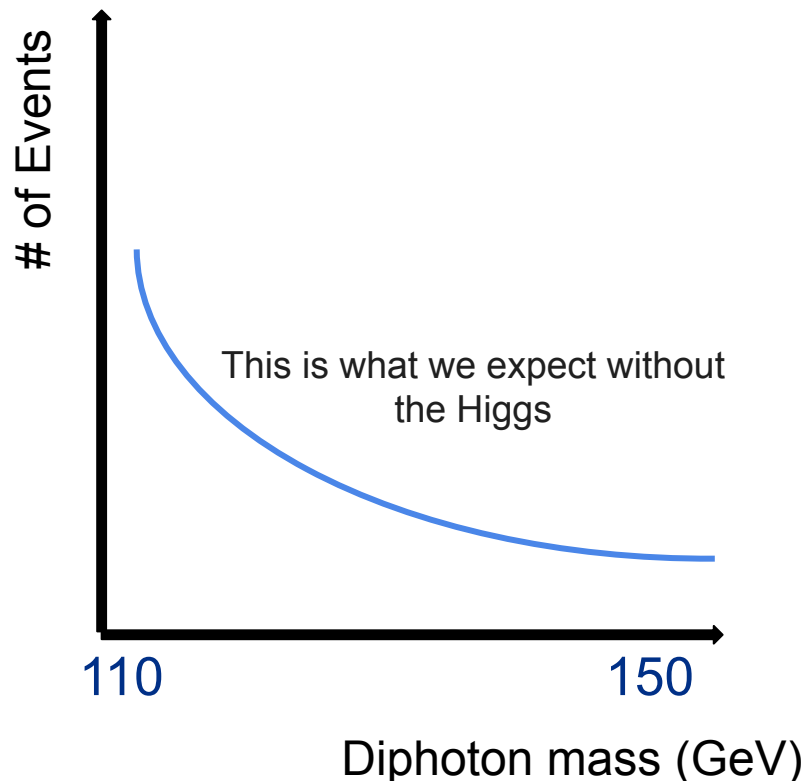
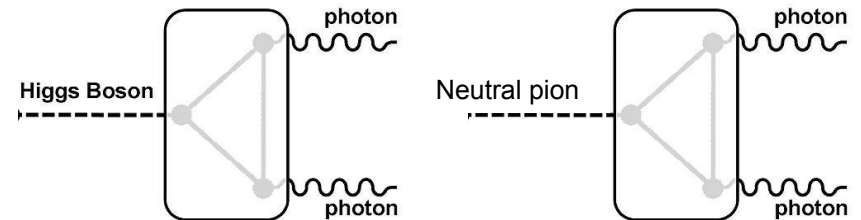
$$m_{\gamma\gamma} = E_1 E_2 \cos\theta$$

- If the photons truly came from the decay of a Higgs, we should see $m_{\gamma\gamma} \sim m_{\text{Higgs}} = 125 \text{ GeV}$
 - Never perfect, because our detector isn't perfect

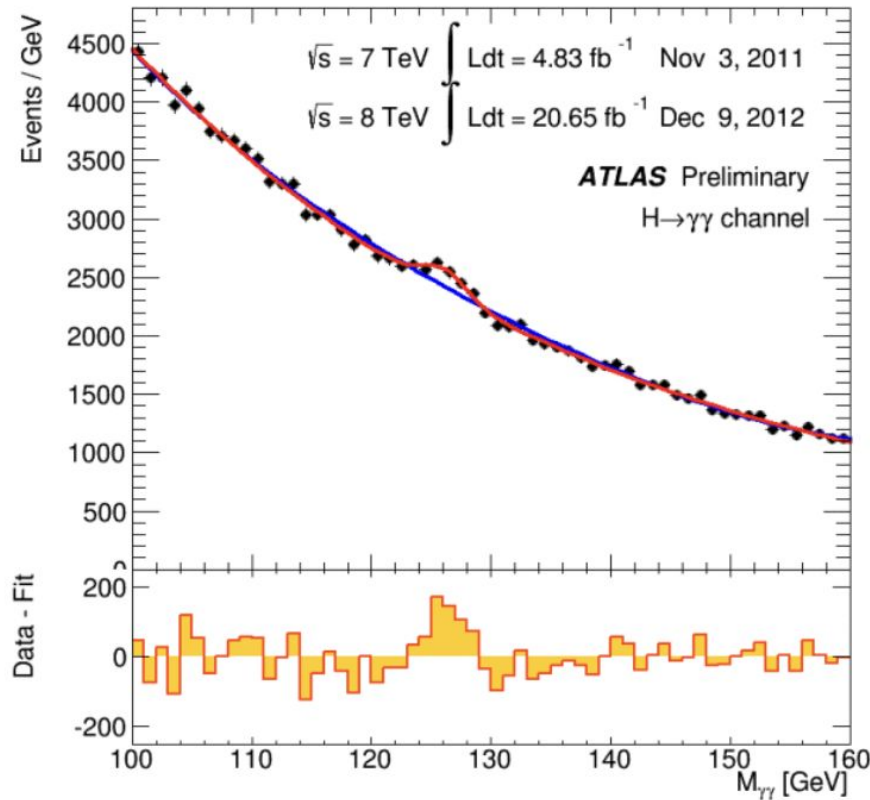


Discovering the Higgs boson

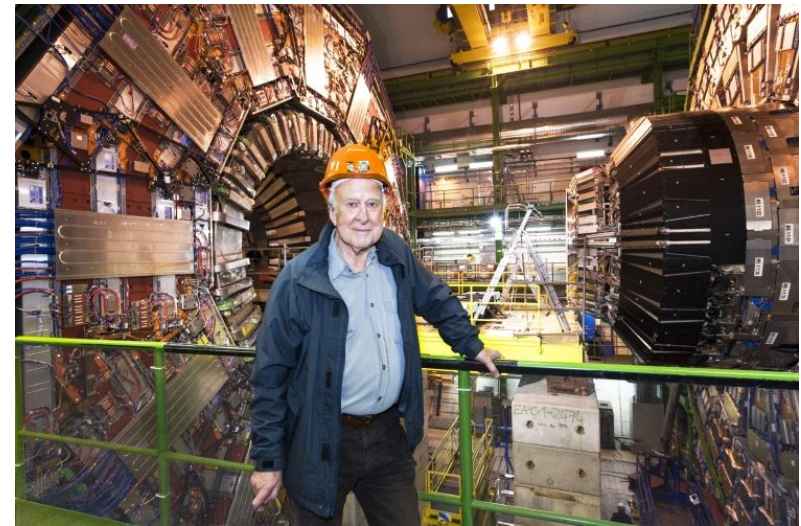
- Count collisions with 2 photons
 - Most of these are not from a Higgs decay (background)



Discovering the Higgs boson



.. this is what was observed in 2012



Peter Higgs won the Nobel Prize for predicting the existence of the Higgs Boson in 2013

What's next for the LHC community?

- **High Luminosity** at the LHC
 - Plan to collect **20x more data by 2040!**
 - Improvements to the ATLAS and CMS detectors
 - Measure the Higgs Boson properties, discover unknown particles, . . etc .

The future is exciting!

Any questions?

*Special thanks to I. Dutta, G. Cummings, J. Dickinson and S. Pandey for providing me materials and valuable input for this talk