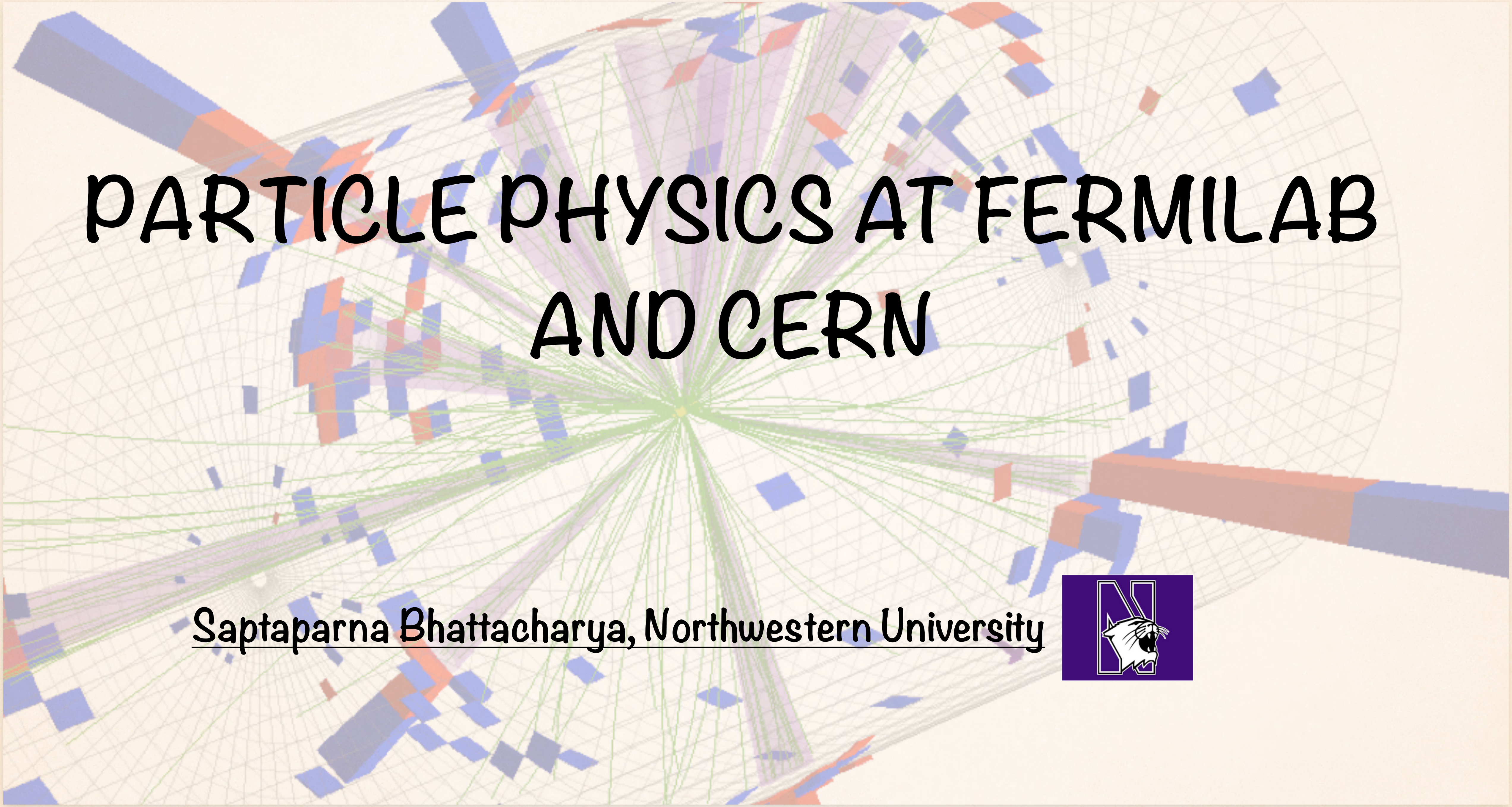


PARTICLE PHYSICS AT FERMILAB AND CERN

Saptaparna Bhattacharya, Northwestern University

The Team!

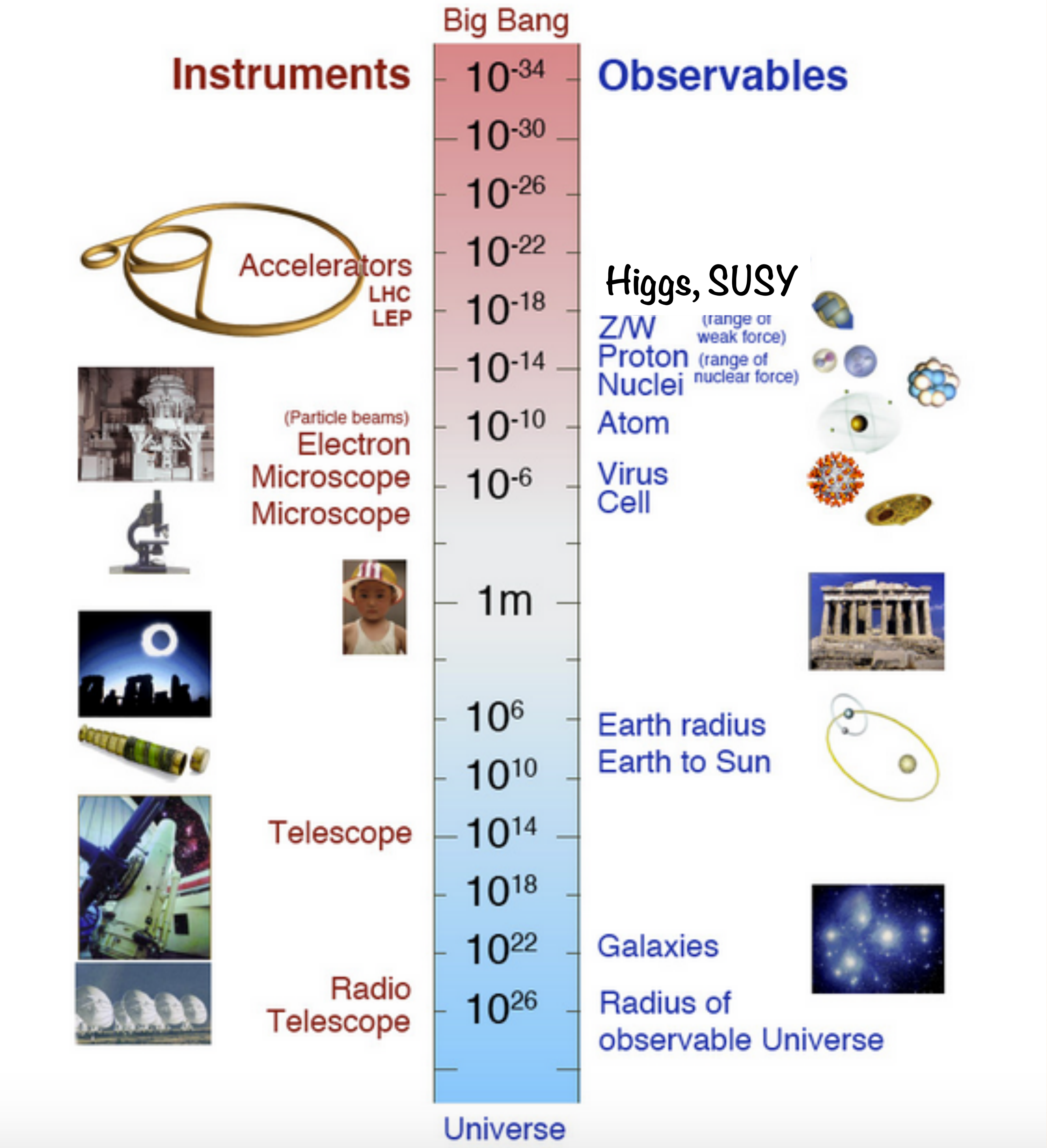
Javier Duarte, Lederman Fellow at Fermilab
Helped set up the cloud chamber

Souvik Das, Post-doc at Purdue
Helped with setting up the camera for observation

Thank you!!

Sense of scale

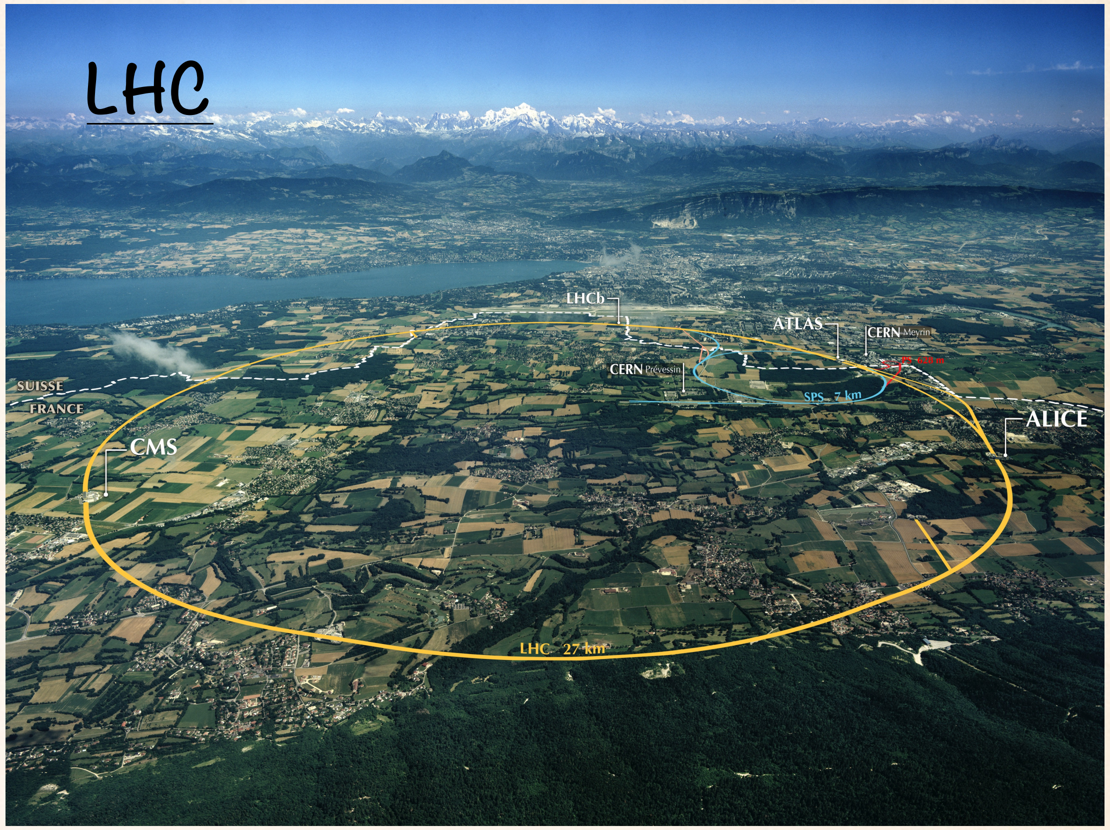
From the microscopic to the large scale structures.

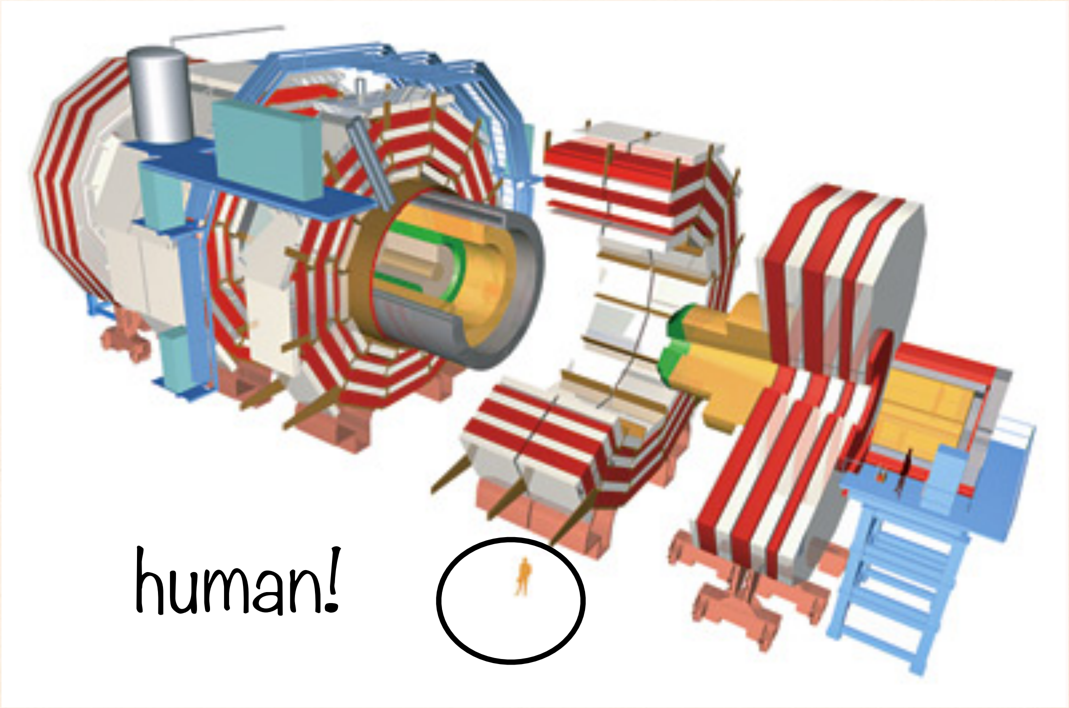


Interesting paradox! Why do we need large detectors to detect such small "particles"?

Small particles —> big detectors

- Remember that we are creating these subatomic particles in a detector
- The more energetic we make the particles, the more "stuff" (mass) can be created
- We are looking at very rare particles
- We need to collide many particles to get just a handful of "interesting" particles
- The history of particle physics can be traced through a succession of accelerators of increasing sizes





Units in physics

Powers of ten

The powers of ten are commonly used in physics and information technology. They are practical shorthand for very large or very small numbers.

Power of ten	Number	Symbol
10^{-12}	0.000000000001	p (pico)
10^{-9}	0.000000001	n (nano)
10^{-6}	0.000001	μ (micro)
10^{-3}	0.001	m (milli)
10^{-2}	0.01	
10^{-1}	0.1	
10^{0}	1	
10^{1}	10	
10^{2}	100	
10^{3}	1000	k (kilo)
10^{6}	1 000 000	M (mega)
10^{9}	1 000 000 000	G (giga)
10^{12}	1 000 000 000 000	T (tera)
10^{15}	1 000 000 000 000 000	P (peta)

Length scales

Energy units

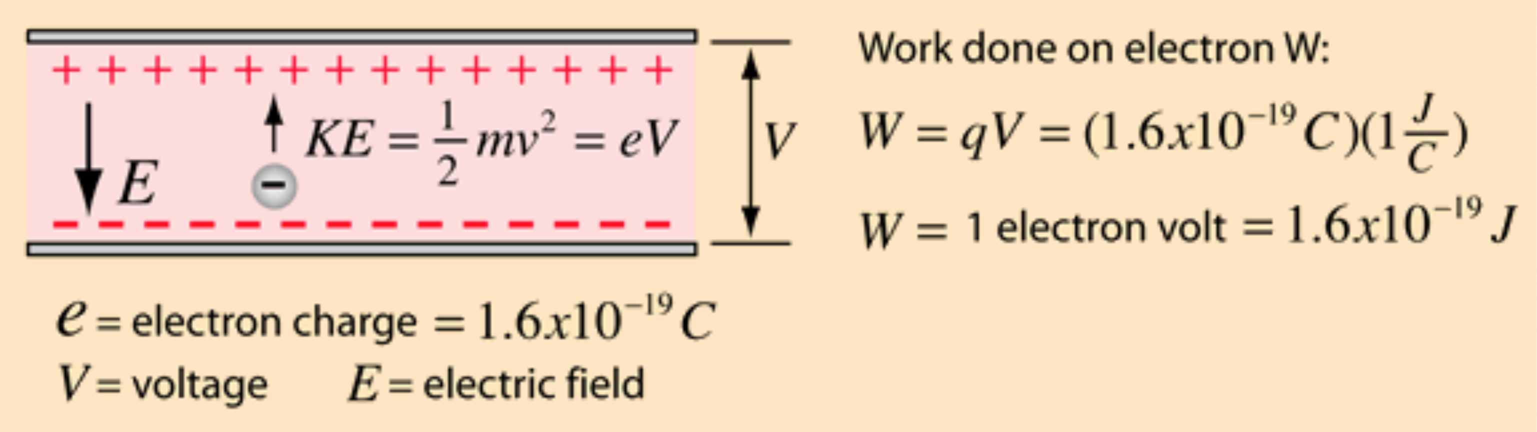
Natural units

Our unit of choice in this lecture will be the electron-volt: eV

In more familiar units:

1 electron volt = $1.60217657 \times 10^{-19}$ joules

It is the amount of energy gained (or lost) by an electron moving across an electric potential difference of one volt.



We will use natural units in this lecture, which means, speed of light, c=1. Therefore, mass and energy units will be the same. So, don't be alarmed when I say that the mass of the proton is ~1 GeV.

Let's make sure that we all understand our system of units

Exercise:

- what is $10^{13} \times 10^{-10}$?
- mass of the electron is 511 keV and the mass of the muon (to be introduced shortly) is 105 MeV. How much heavier is the muon with respect to the electron?
- how much heavier is the Higgs boson (mass of 125 GeV) with respect to the electron?

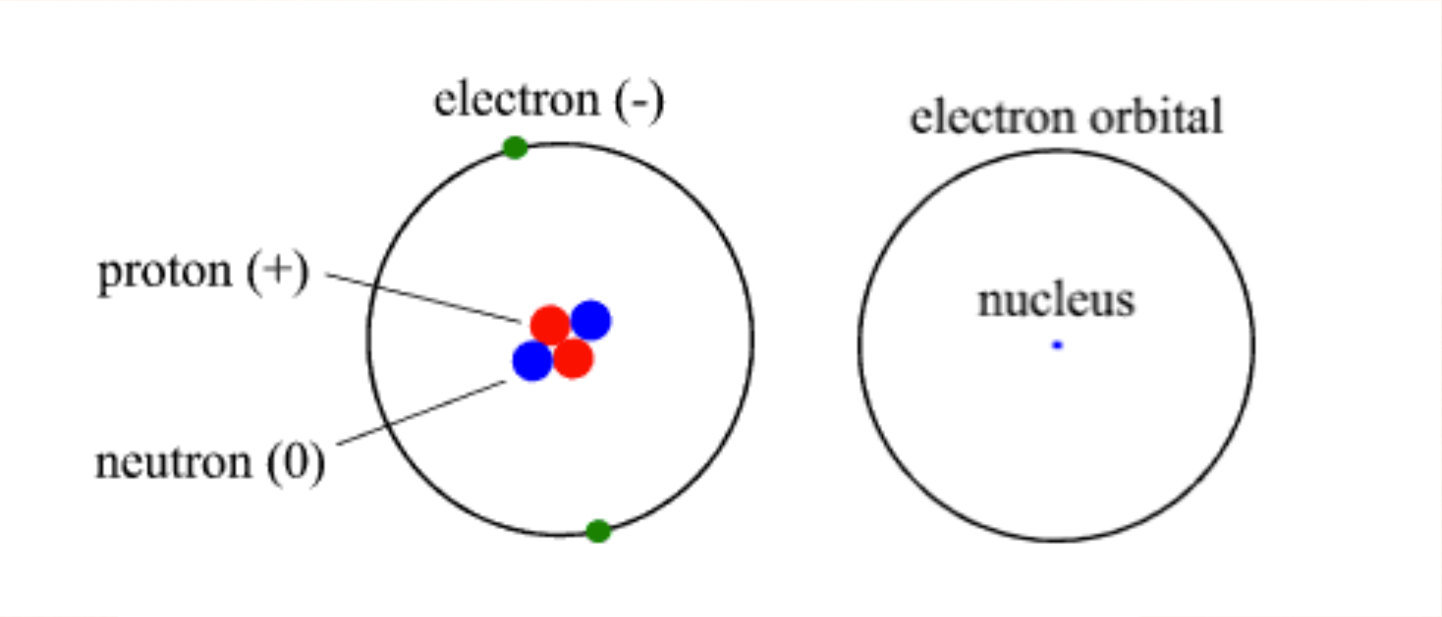
Let's make sure that we all understand our system of units

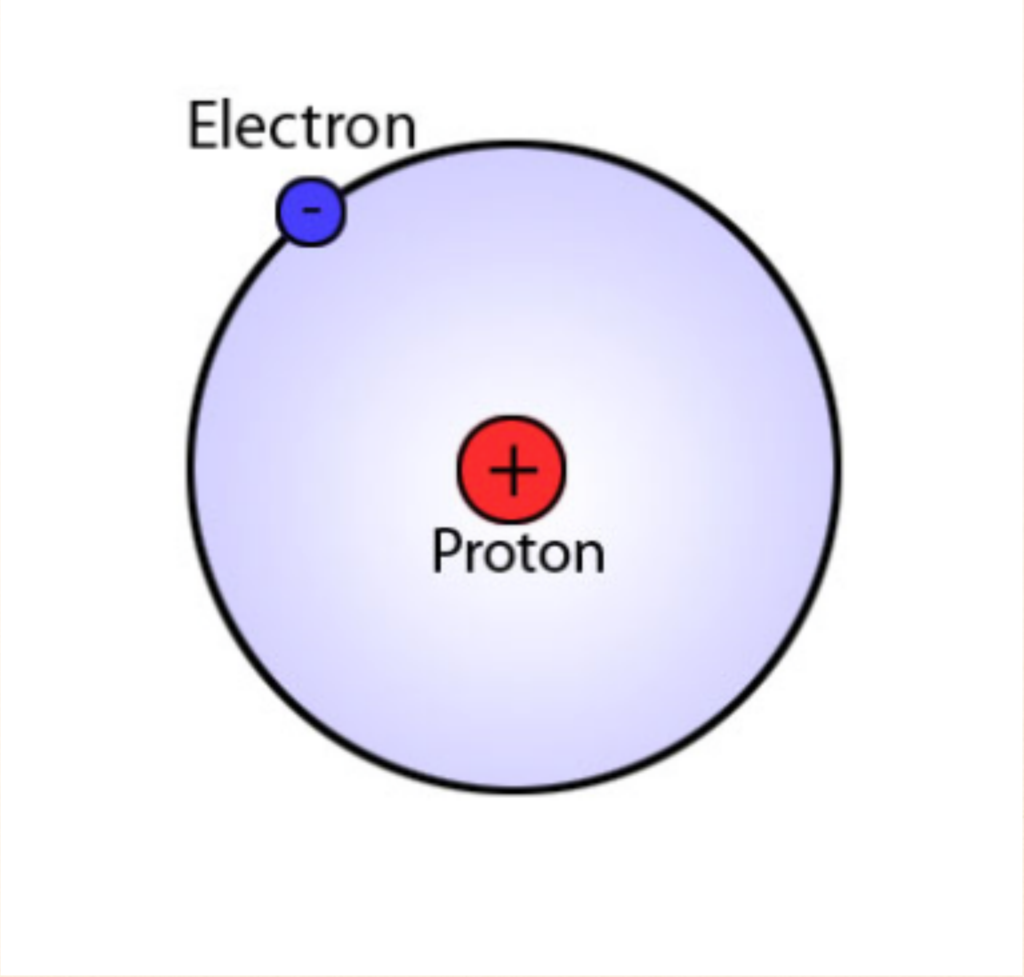
Exercise:

- what is $10^{13} \times 10^{-10}$? 10^3
- mass of the electron is 511 keV and the mass of the muon (to be introduced shortly) is 105 MeV. How much heavier is the muon with respect to the electron? 105/0.5 = 200 times
- how much heavier is the Higgs boson (mass of 125 GeV) with respect to the electron?

  125*1000 MeV/0.5 MeV = 250,000 times!

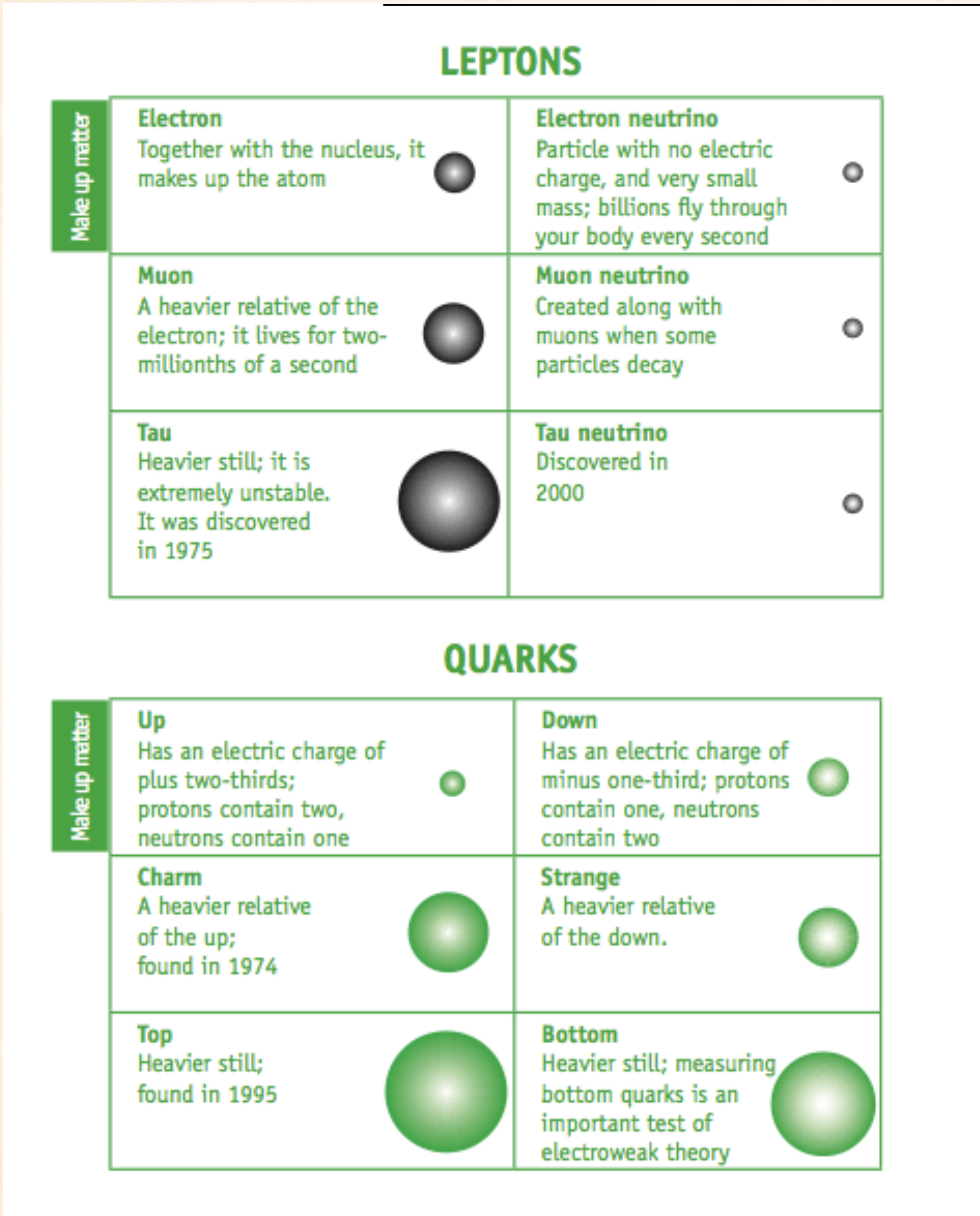
Constituents of Matter: What is an atom?





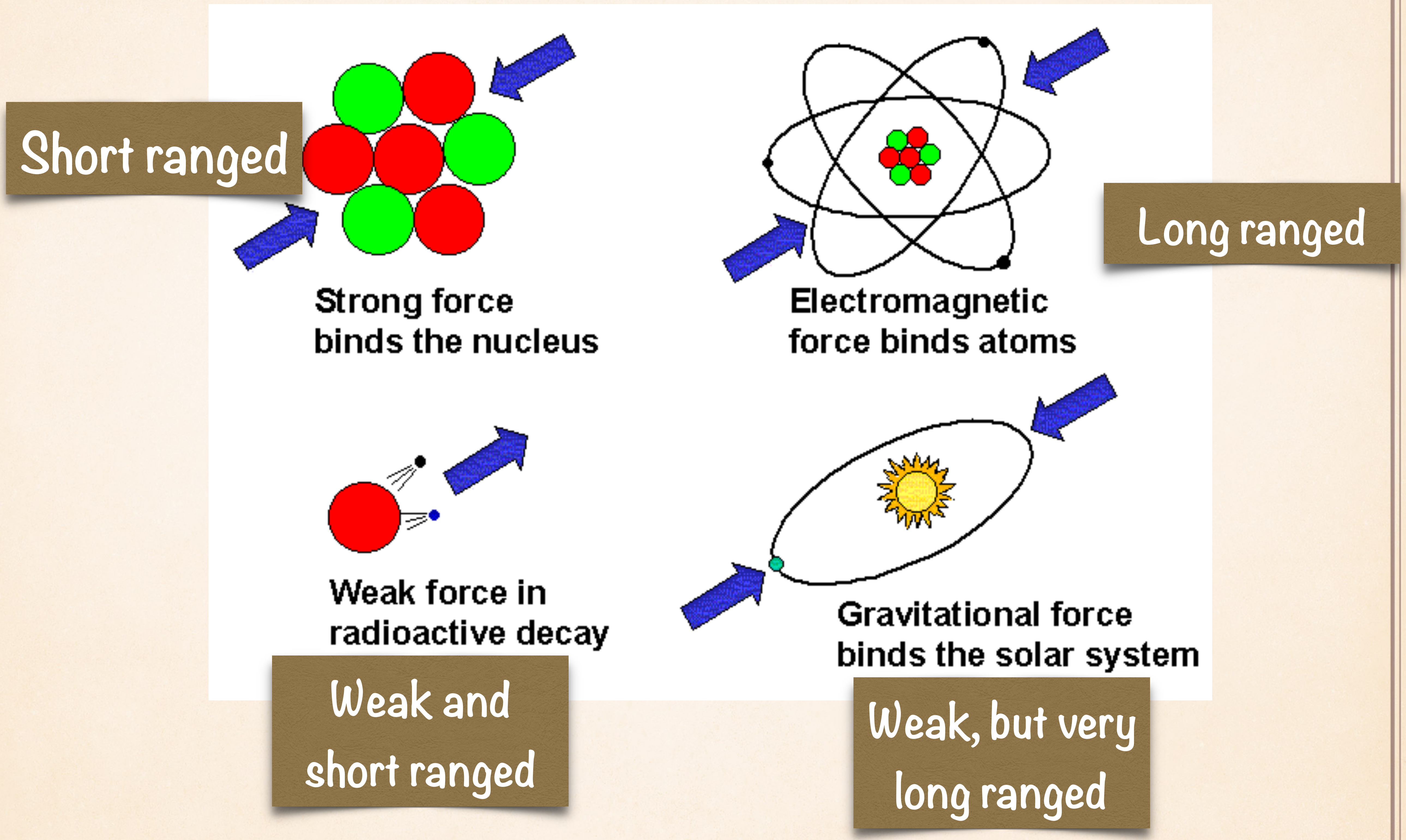
The Hydrogen Atom: simplest possible atom. Remember this as we will later connect it to the Large Hadron Collider.

Constituents of Matter

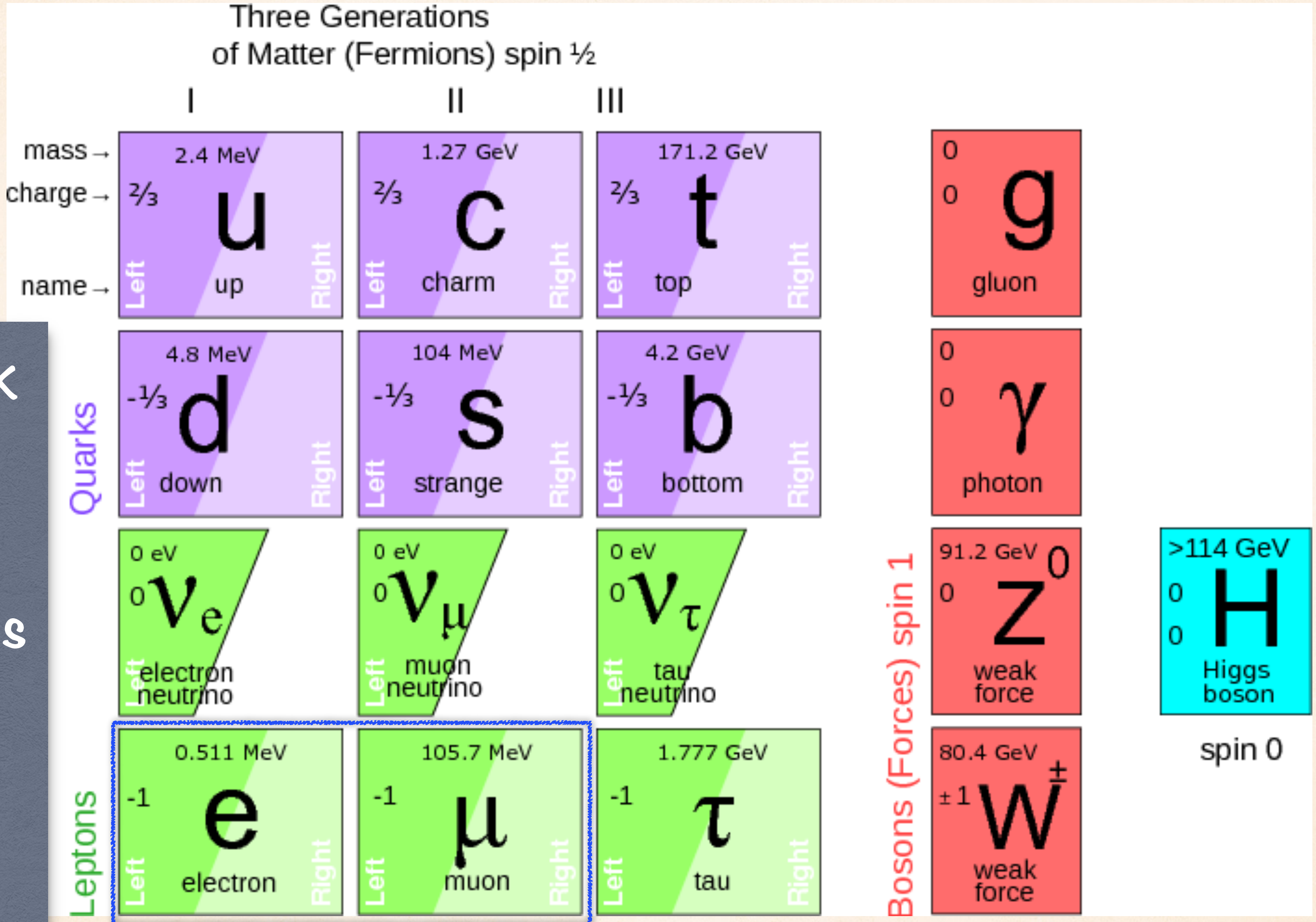


- Turns out that the previous slide only tells you half of the truth
- Protons and neutrons are not fundamental and are composed of quarks
- Look at the mass hierarchy!
- Why the masses exactly what we observe is an interesting question

The four fundamental forces



The Standard Model of Particle Physics

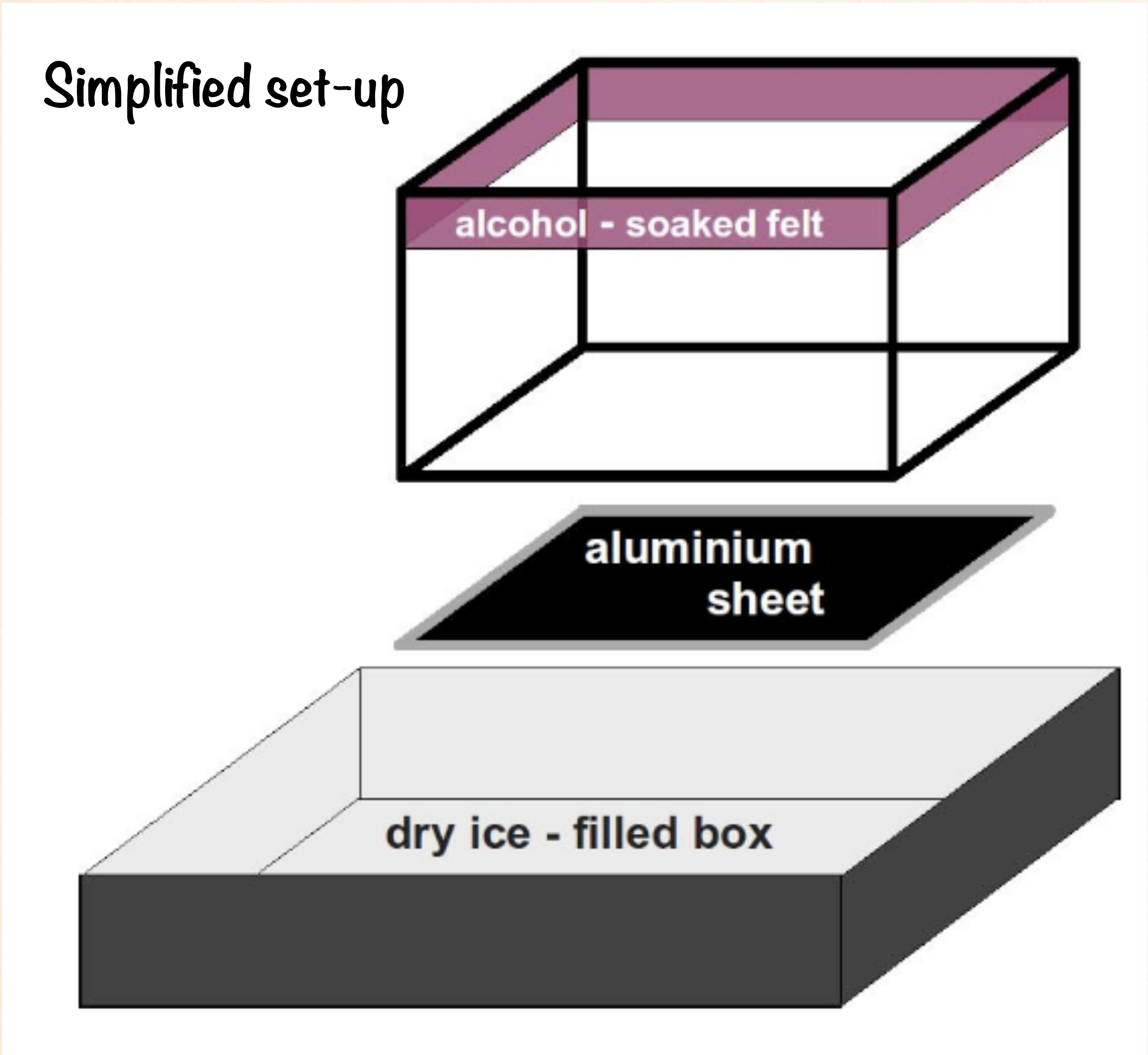


Let's talk about leptons (electrons and muons) next

See the apparatus set up here?

This apparatus is called a cloud chamber

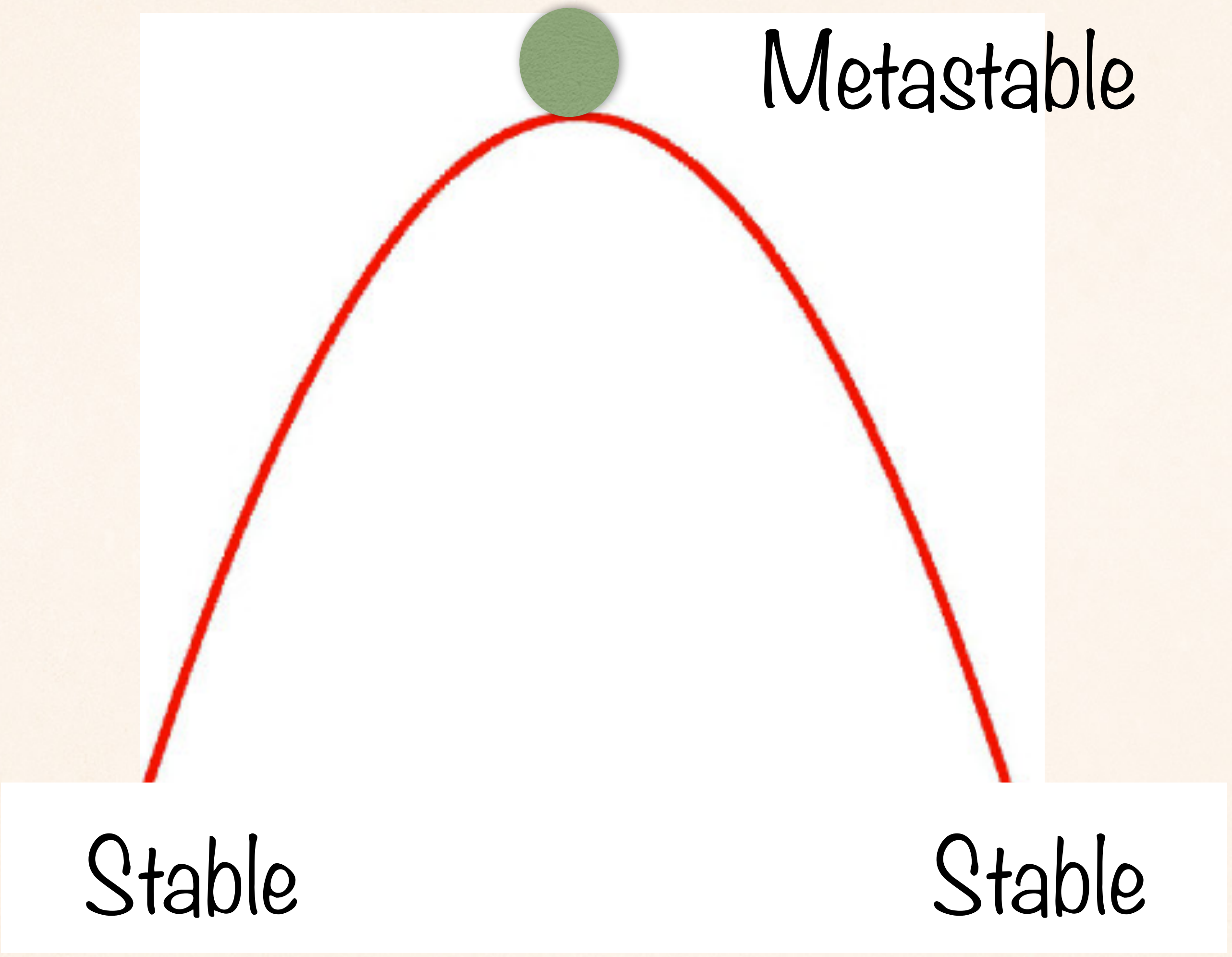
How does it work?



- The dry ice keeps the lower layer very cold (in this case the cooling is done differently)
- So, while the top layer has alcohol at a higher temperature, the bottom layer is much colder
- When a particle passes through the chamber it ionizes the alcohol which then causes alcohol droplets to condense around the path of the particle

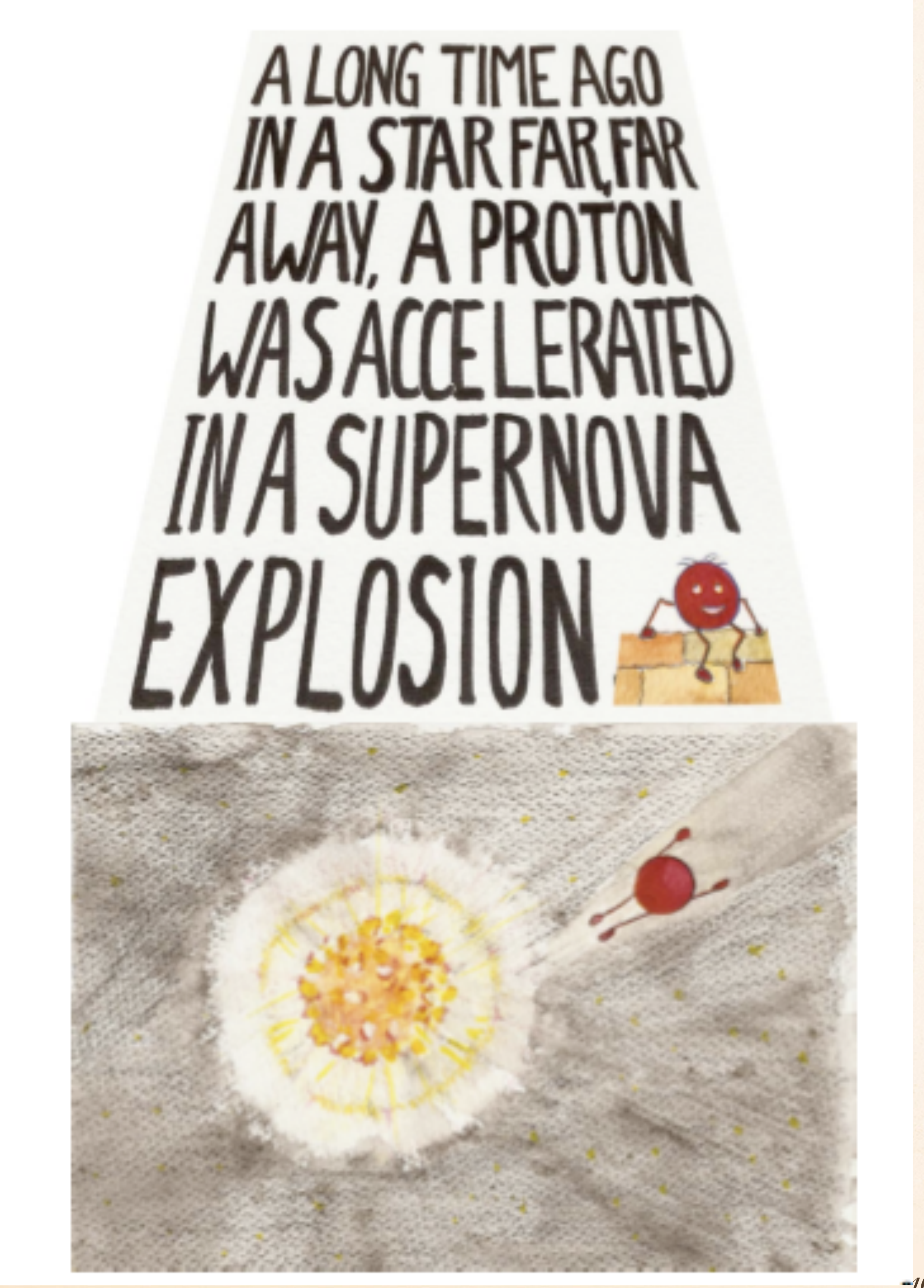
Same principle here

Very brief detour



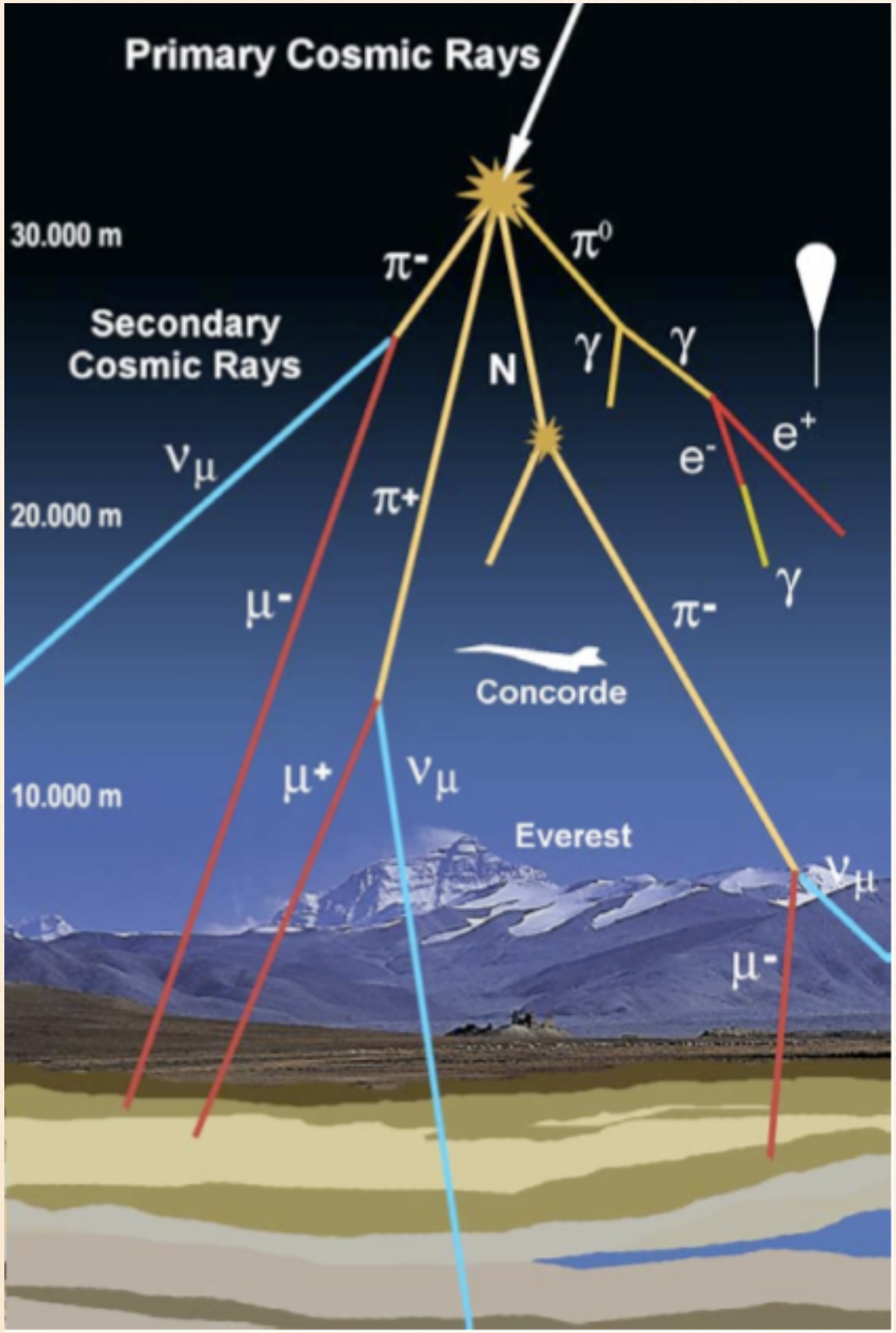
To be drawn on the black-board

What are we trying to observe?



This proton travels through interstellar space and reaches the earth. It then interacts with air molecules.

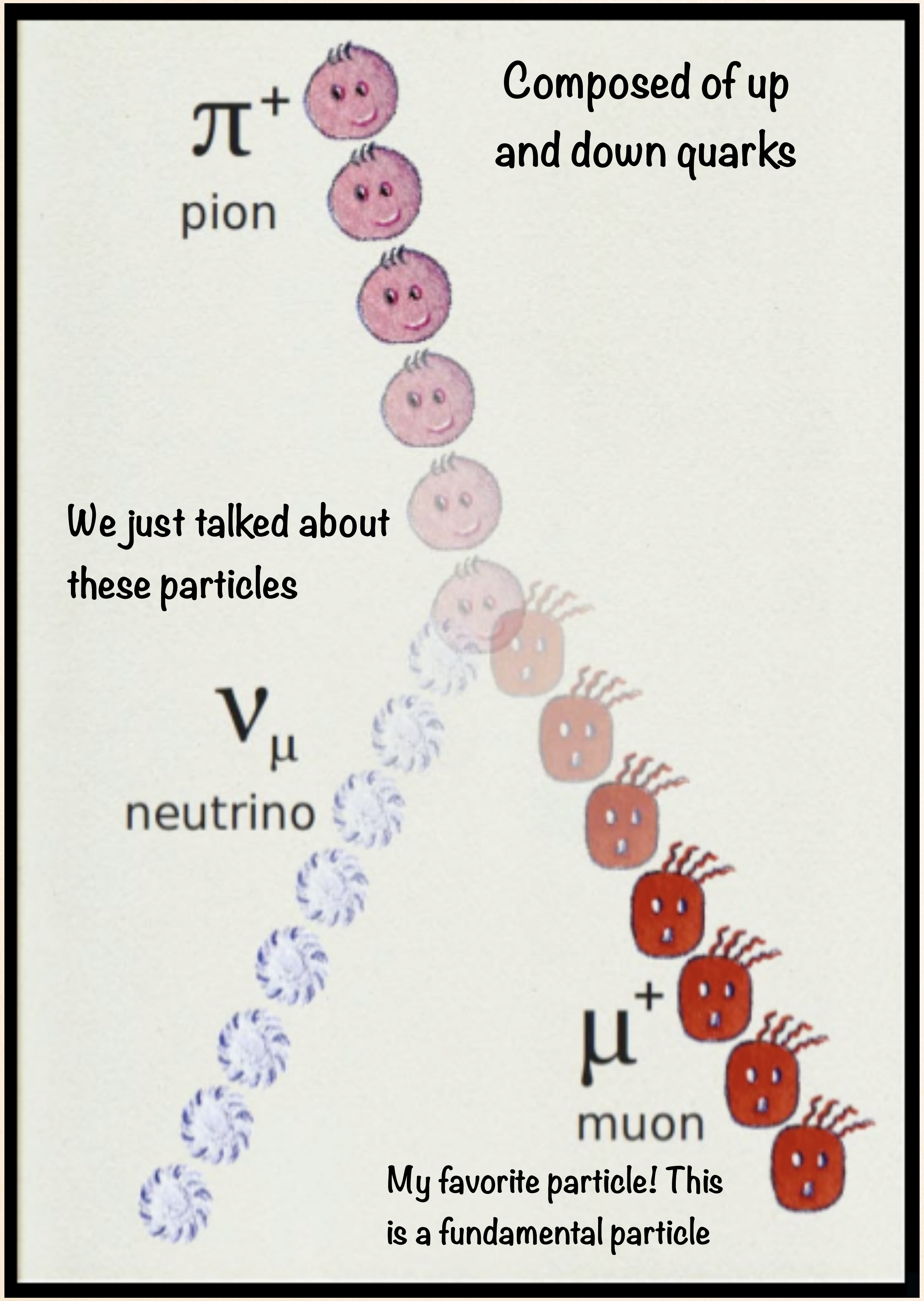
What are we trying to observe?



- Cosmic ray interactions with the atmosphere
- A slew of particles are created
- One of these particles are muons which can be detected in a cloud chamber

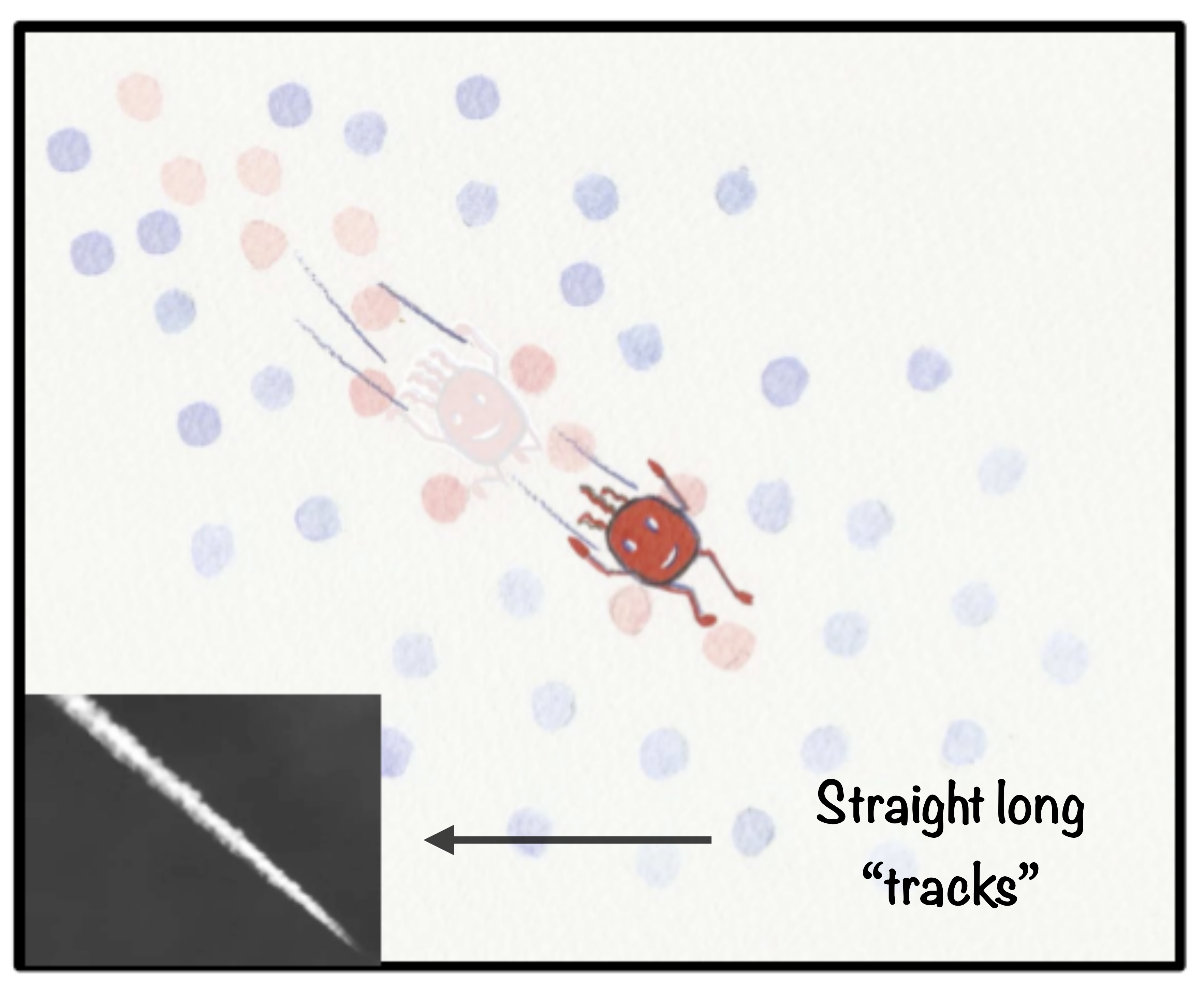
Pretty incredible!!

How exactly do we see the muon?



- The pion decays to a neutrino and a muon
- The muon is a stable particle that can be detected using a cloud chamber.
- Notice that the muon and the neutrino are of the same kind
- This is a muon neutrino. There are electron and tau neutrinos that are produced when electrons and taus decay. These decay chains involve interactions different from the one shown here

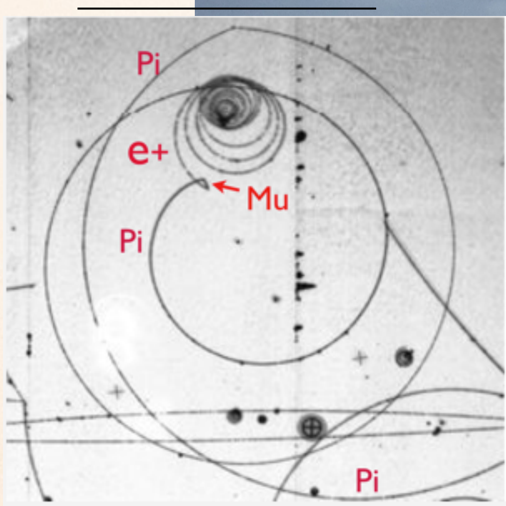
What does the muon look like?



The first particle physics detectors

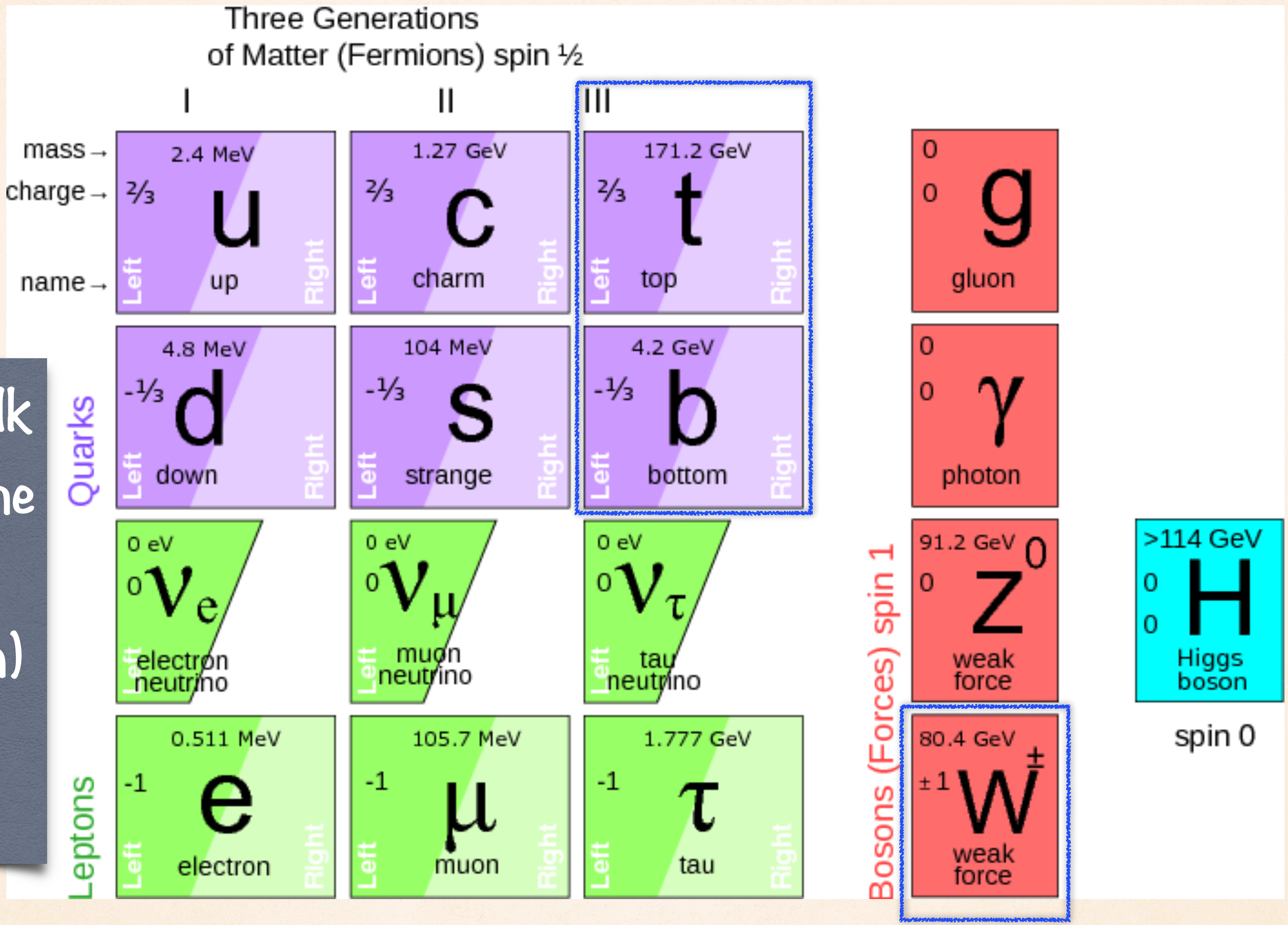
15 foot bubble chamber at Fermilab

An event



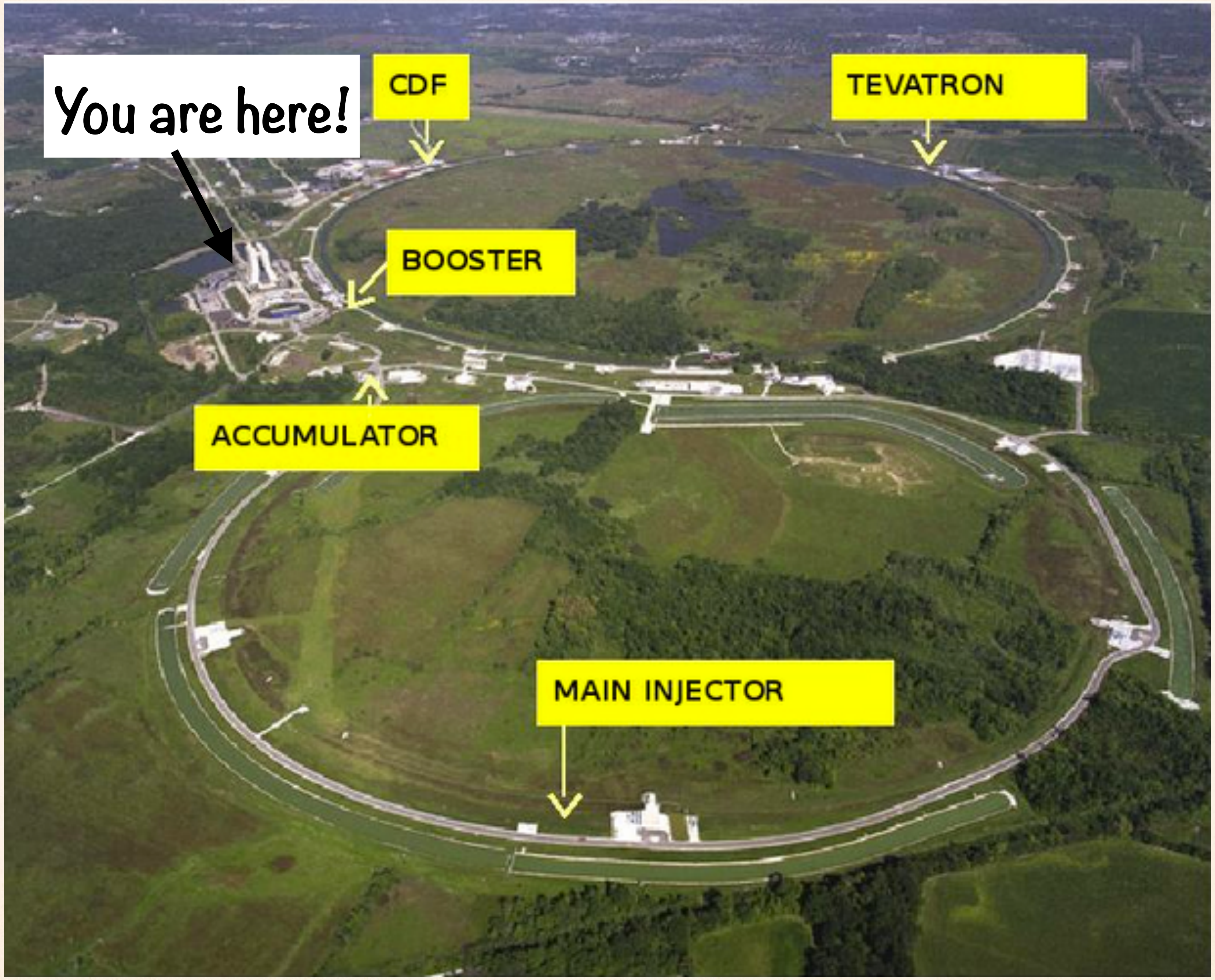
Uses super heated hydrogen (metastable state) to detect "tracks"

The Standard Model of Particle Physics

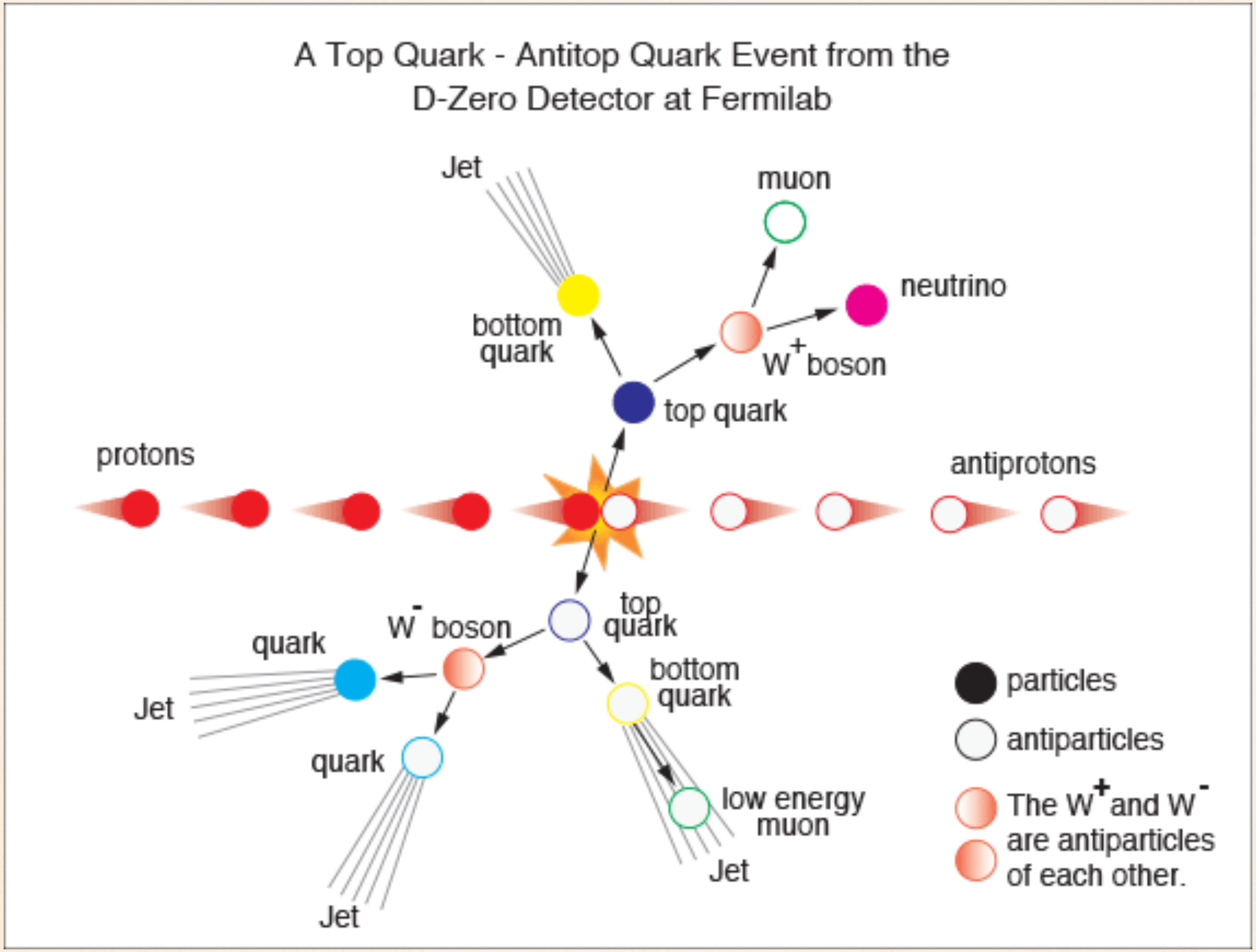


Let's talk about the top (bottom) quark next

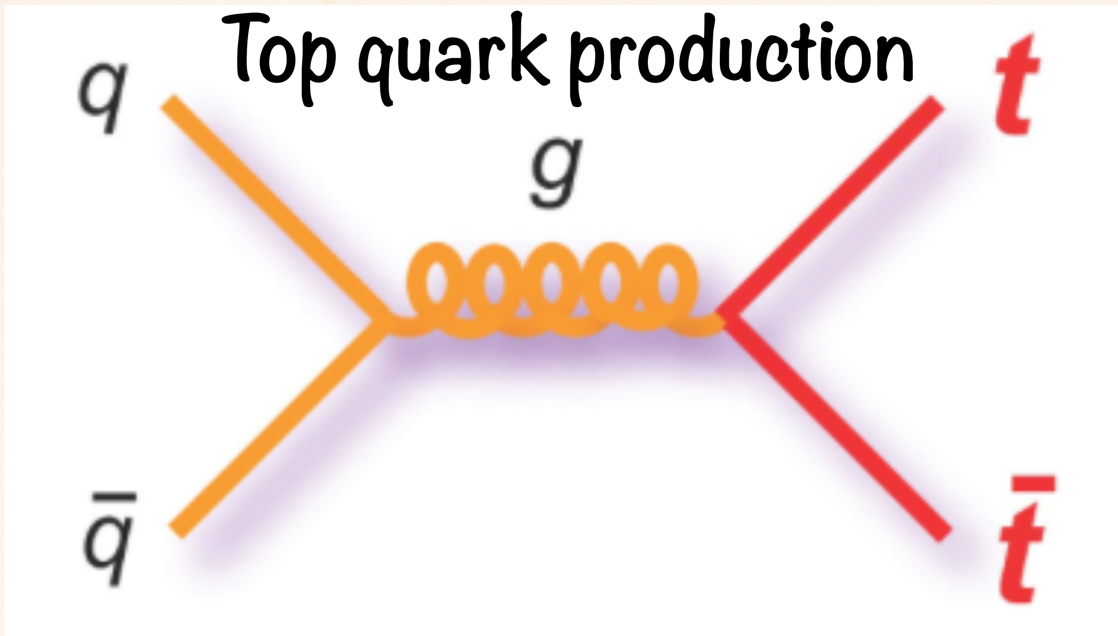
An aerial view of the Tevatron



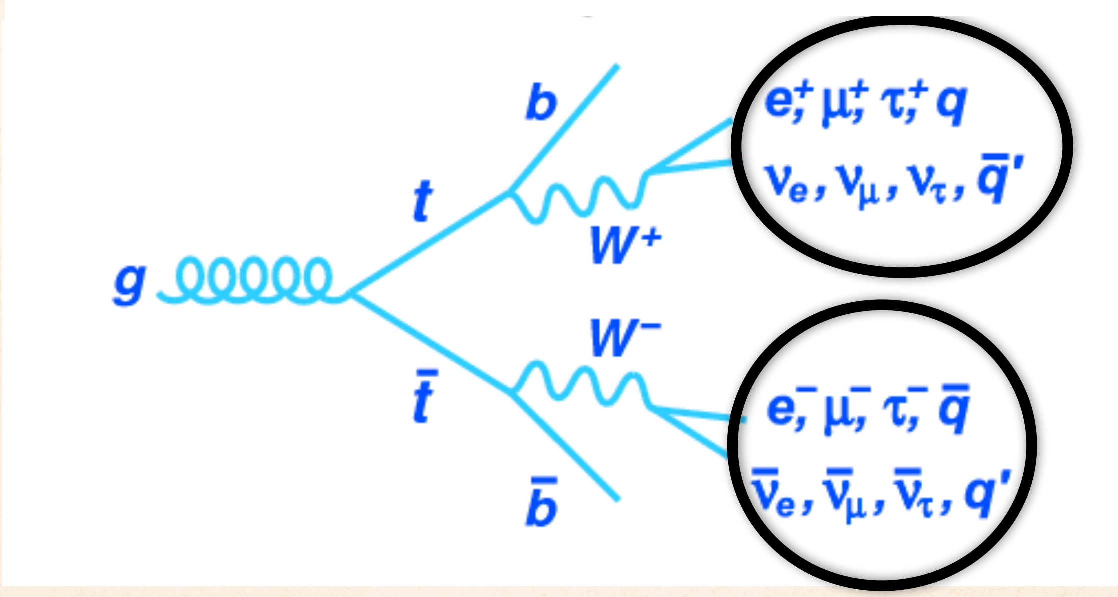
Discovery of the top quark



Discovery of the top quark: Feynman Diagrams



Top quark decay

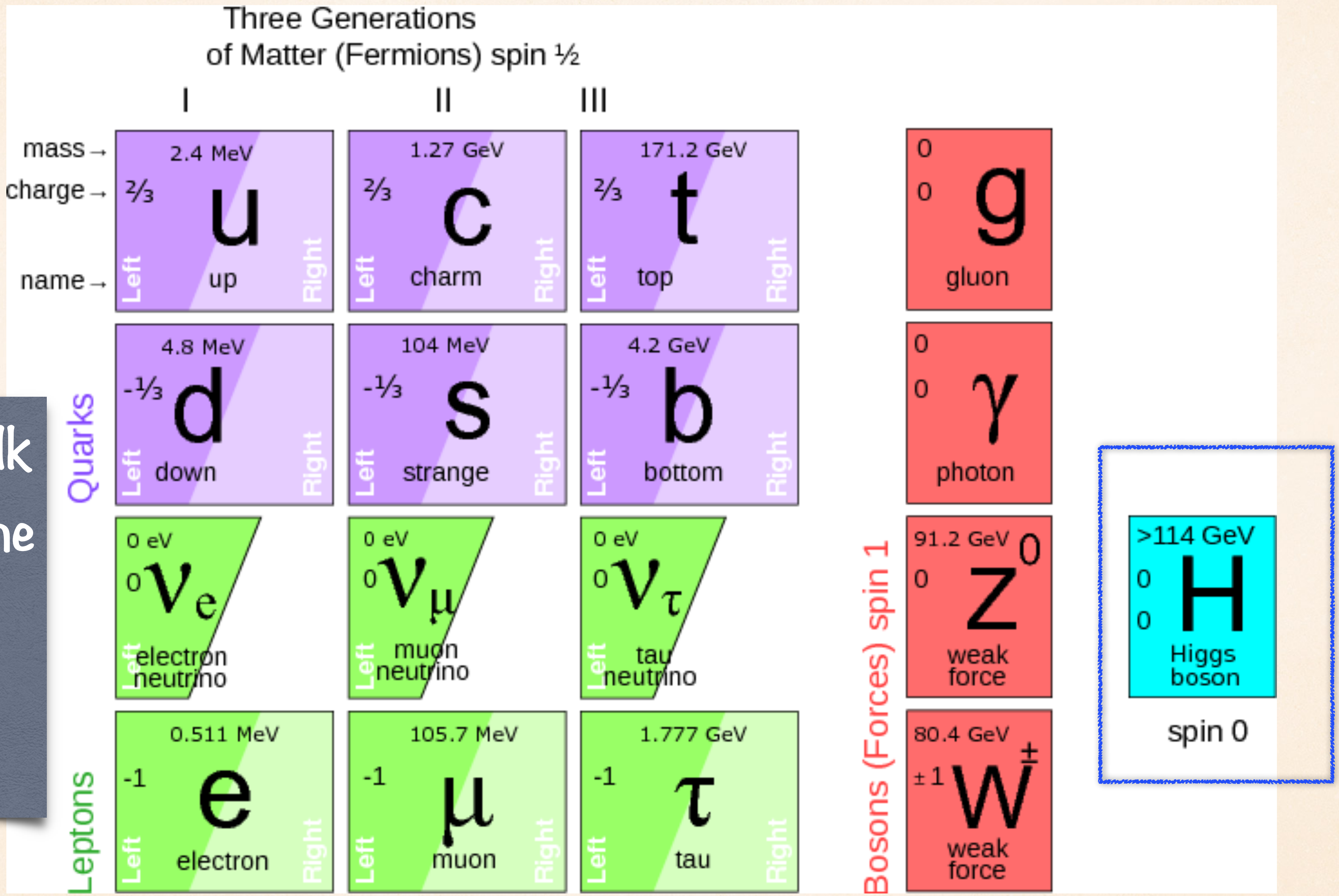


The detector sees these "particles"

Let's pause for a moment...

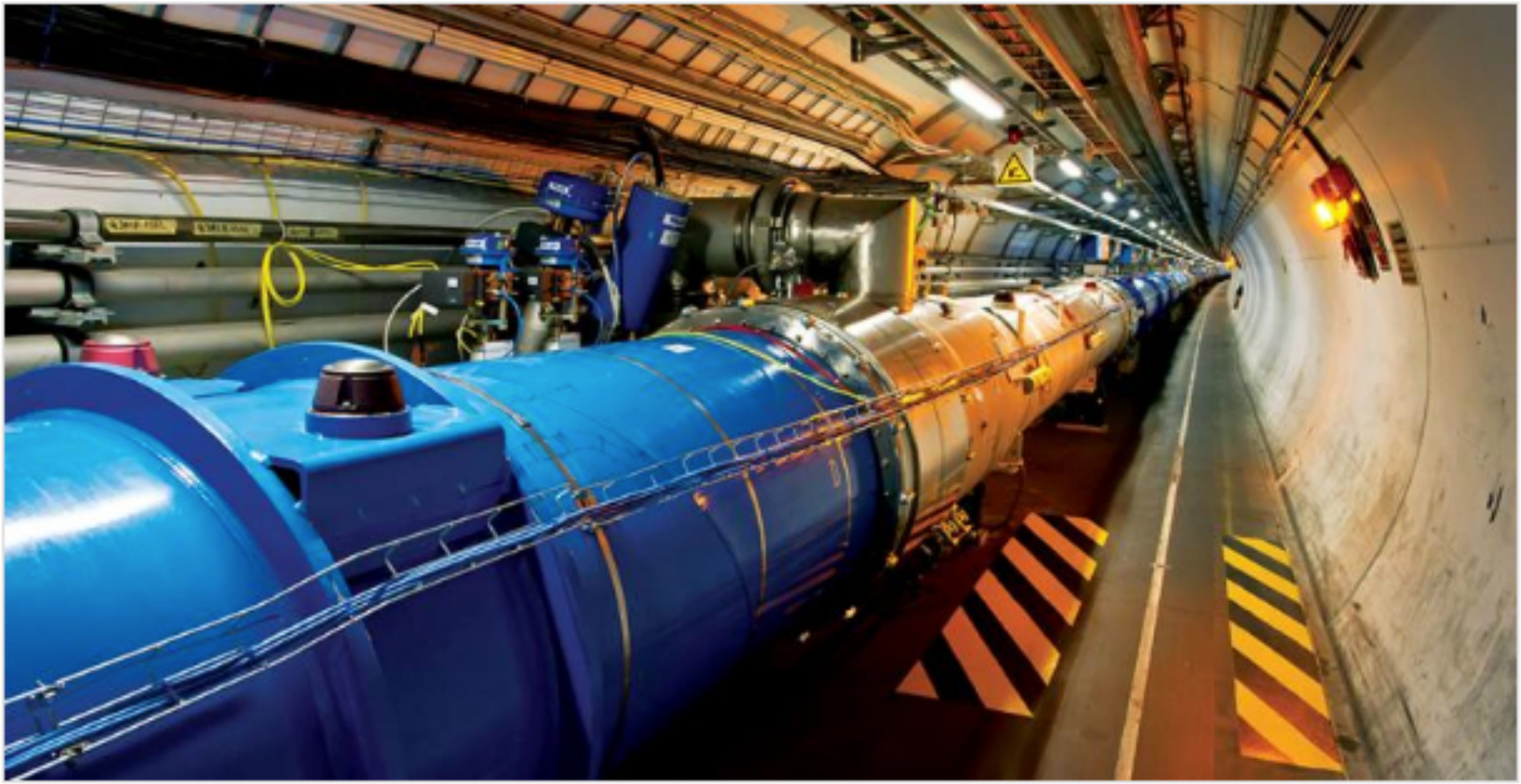
Any questions?

The Standard Model of Particle Physics



Let's talk about the Higgs boson next

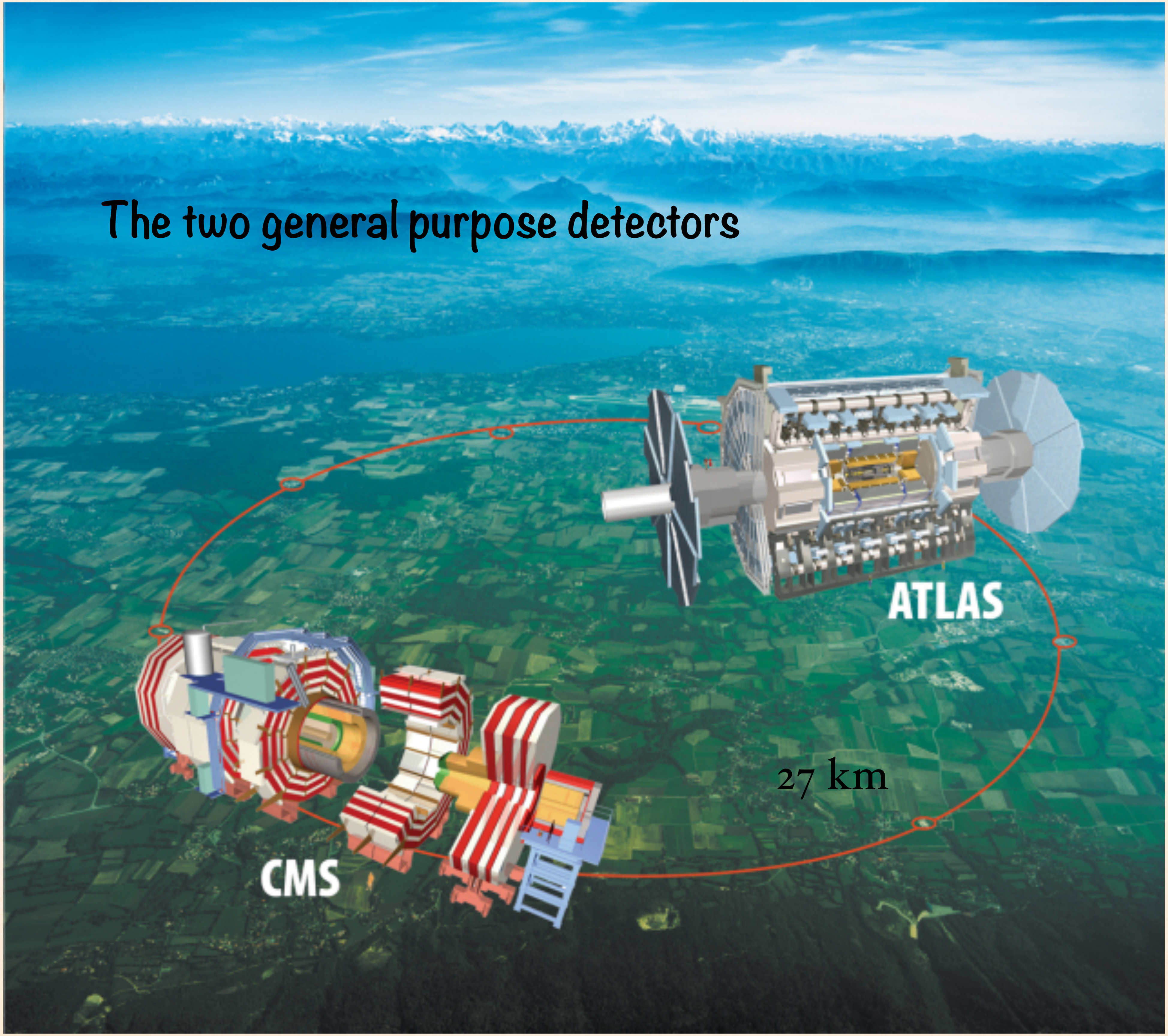
The Large Hadron Collider



The Large Hadron Collider is the world's largest and most powerful particle accelerator (Image: CERN)

Aerial view of The Large Hadron Collider

Aerial view of The Large Hadron Collider



The Large Hadron Collider (LHC)

- The LHC is the world's largest and most powerful particle accelerator. It first started up on September, 10th, 2008

- Two high-energy particle beams travel at close to the speed of light, guided by super conducting magnets
- The coils of this electromagnet operates in a superconducting state -> conducting electricity without resistance or loss of energy

- This requires chilling the magnets to -271.3°C
- Cooling achieved with liquid helium

The Large Hadron Collider

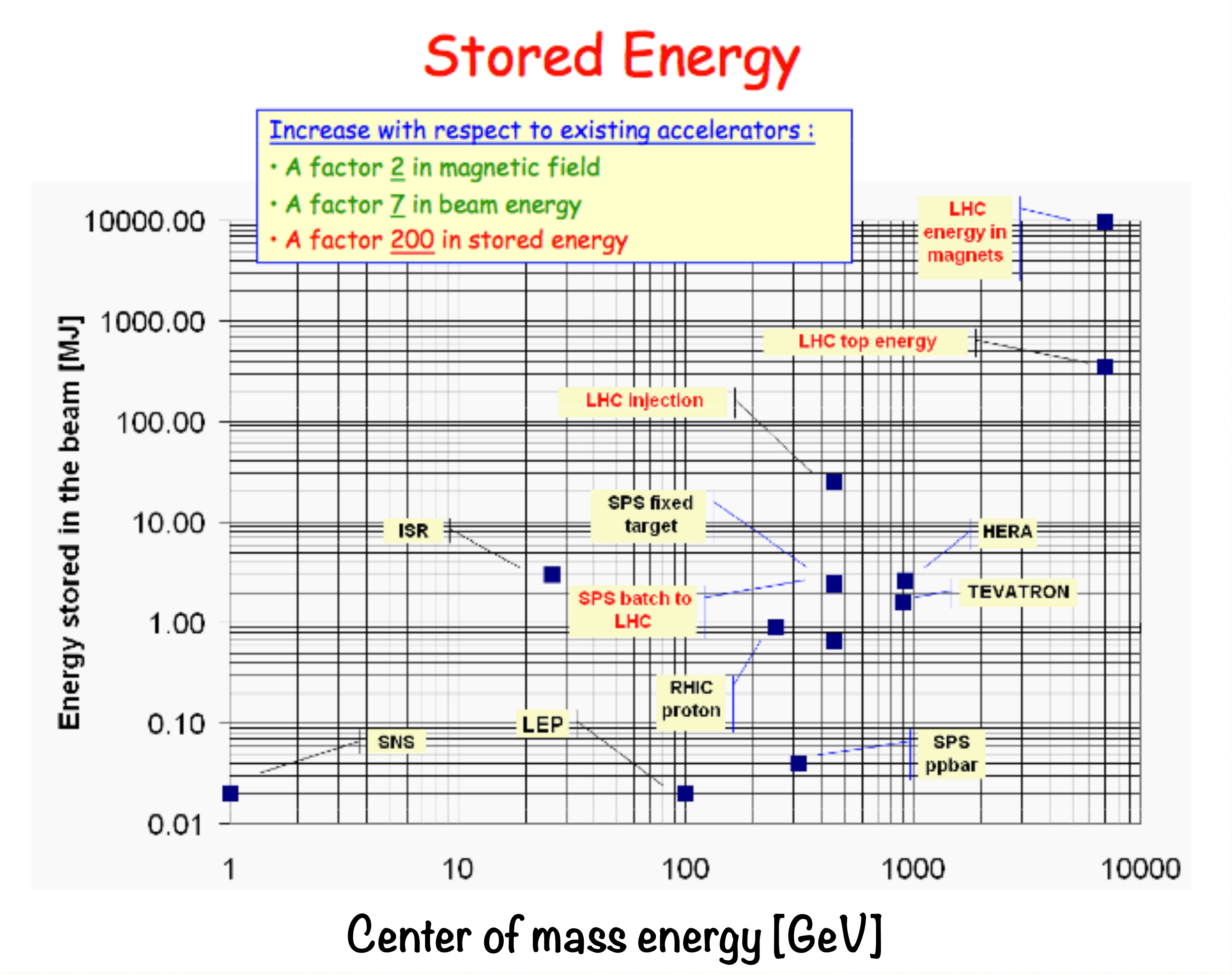
Magnets squeeze the beam to a space narrower than human hair

Special magnets focus beams so maximum number of collisions occur

Beams bent by magnets

Protons accelerated in bunches

The Large Hadron Collider



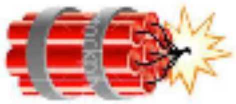
The Tevatron at Fermilab operated at 1.96 TeV

The Large Hadron Collider: Facts

Comparison...

The energy of an A380 at 700 km/hour corresponds to the energy stored in the LHC magnet system :

Sufficient to heat up and melt 12 tons of Copper!!



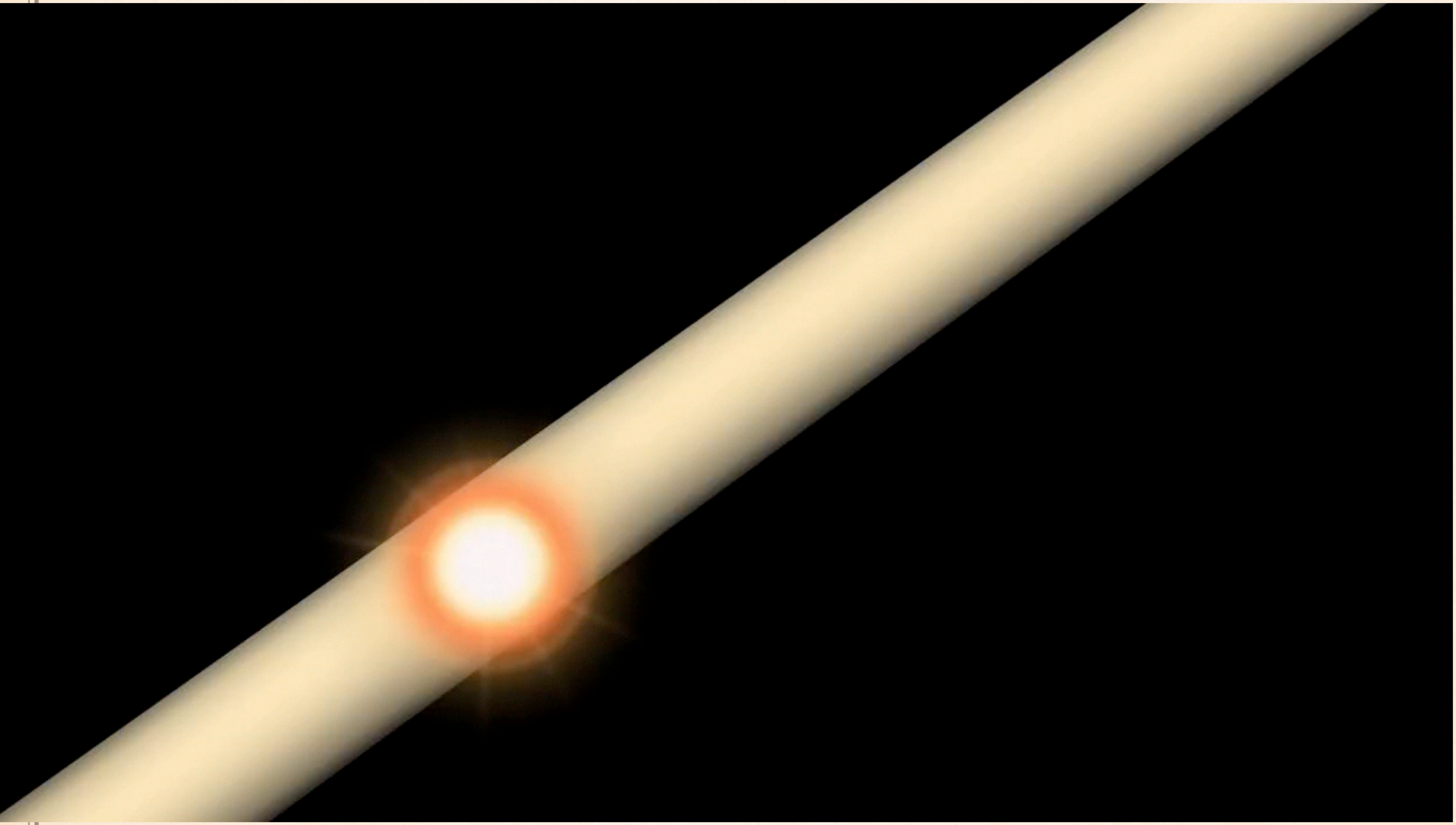
The energy stored in one LHC beam corresponds approximately to...

- 90 kg of TNT
- 8 litres of gasoline
- 15 kg of chocolate

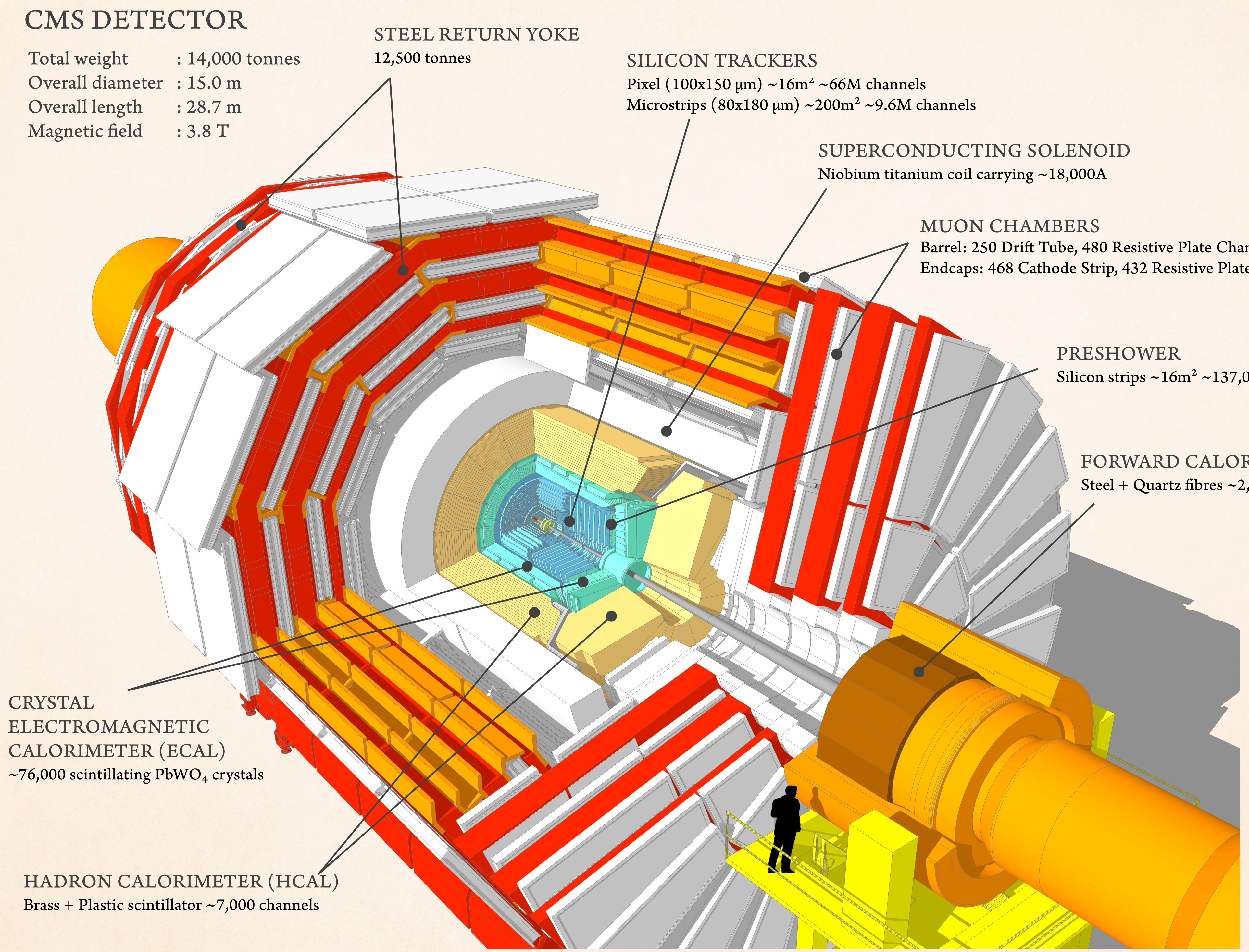
Panoramic view of the LHC.

http://home.web.cern.ch/about/updates/2013/09/explore-cern-google-street-view

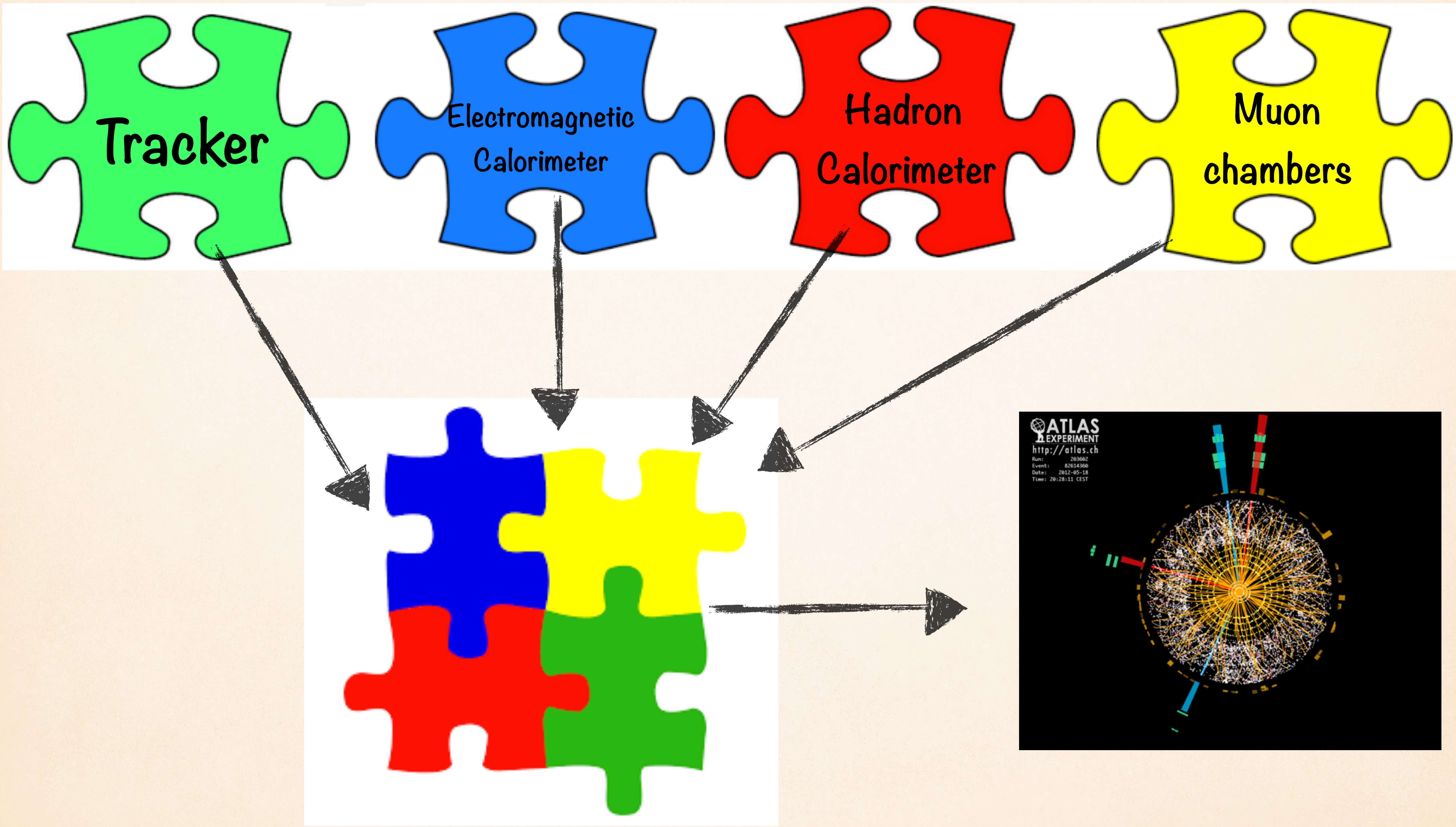
What happens at the LHC



The CMS Detector



Let's try to analyze what each part of the detector does?



Central Feature of CMS

- The CMS magnet is the largest superconducting magnet ever built weighs 12,000 tonnes
- It is cooled to -268.5°C
- It is 100,000 times stronger than the Earth's magnetic field
- It stores enough energy to melt 18 tonnes of gold
- It uses almost twice as much iron as the Eiffel Tower

The crux of particle detection

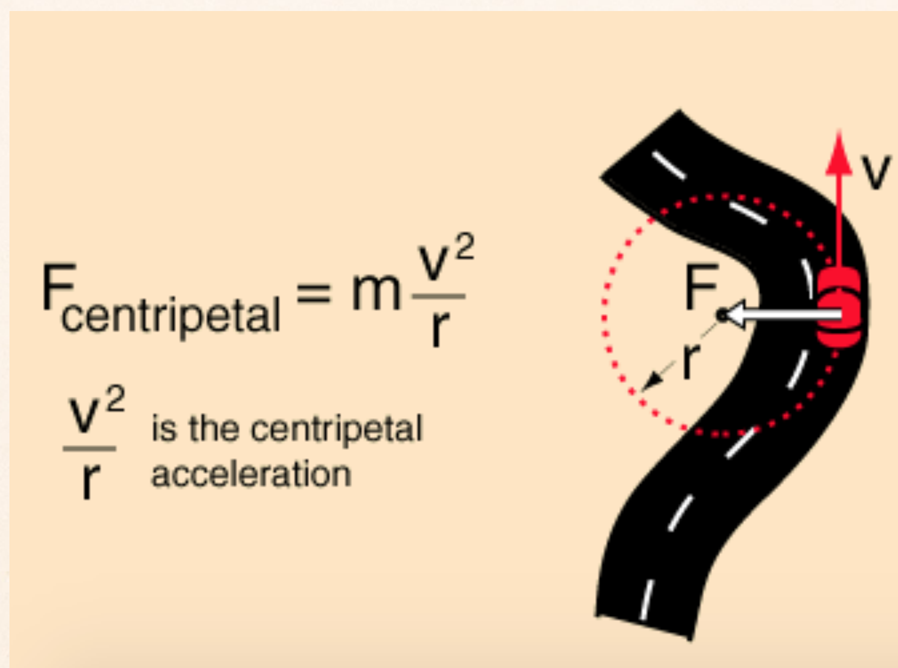
- $E=mc^2$ if a particle of mass m is at rest. So $E^2=(mc^2)^2$
- If a particle has momentum p, then $E^2=(mc^2)^2+(pc)^2$
- For a massless particle (m=0), you get $E=|p|c$
- Particle detection relies on measuring E and p in a detector, so that the mass of a particle can be computed
- Often, in particle physics, easier to measure the transverse momenta, $pT=\sqrt{(p_x^2 + p_y^2)}$

A brief detour

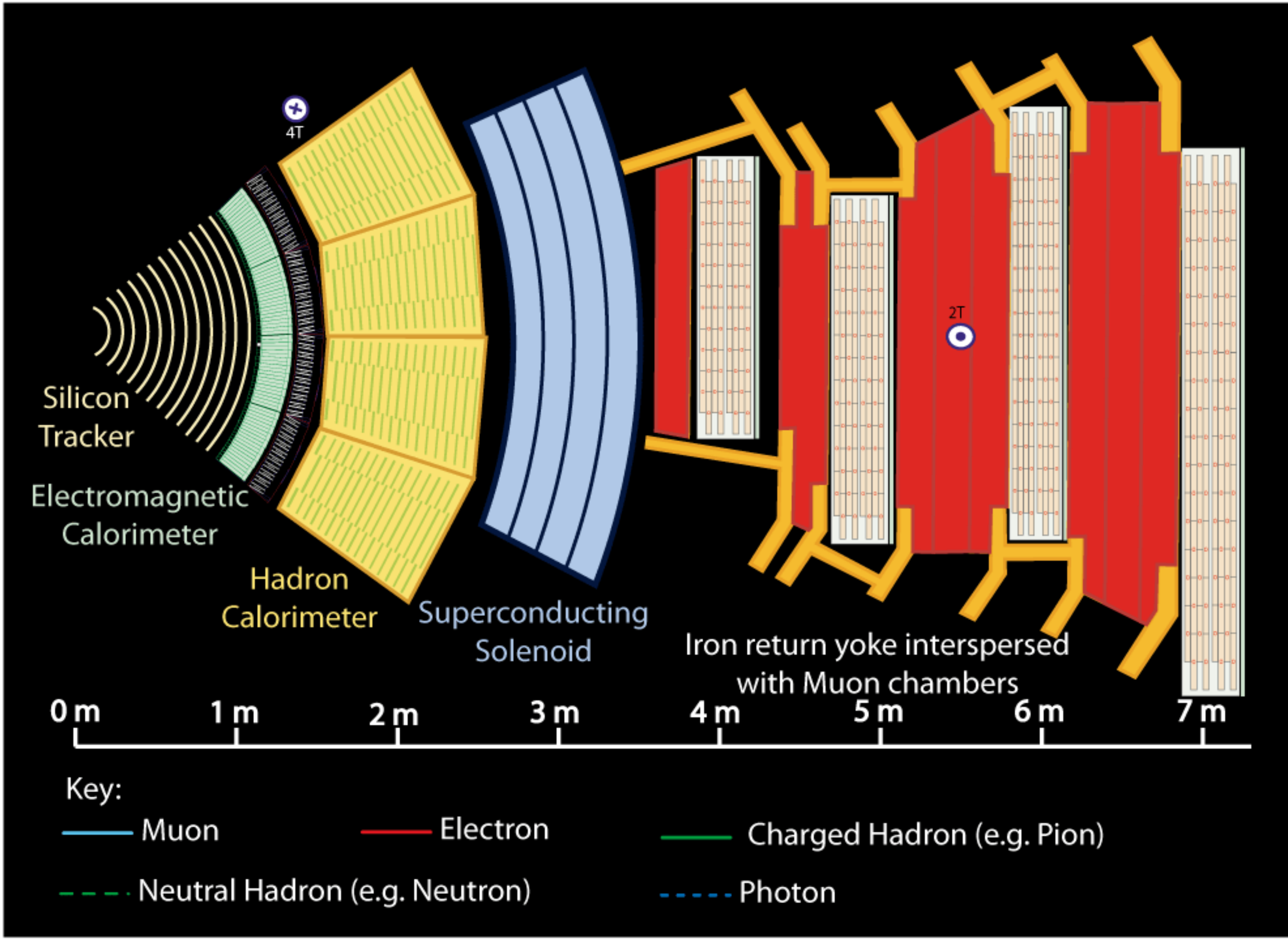
Force is acting on a particle in a magnetic field (called Lorentz force)

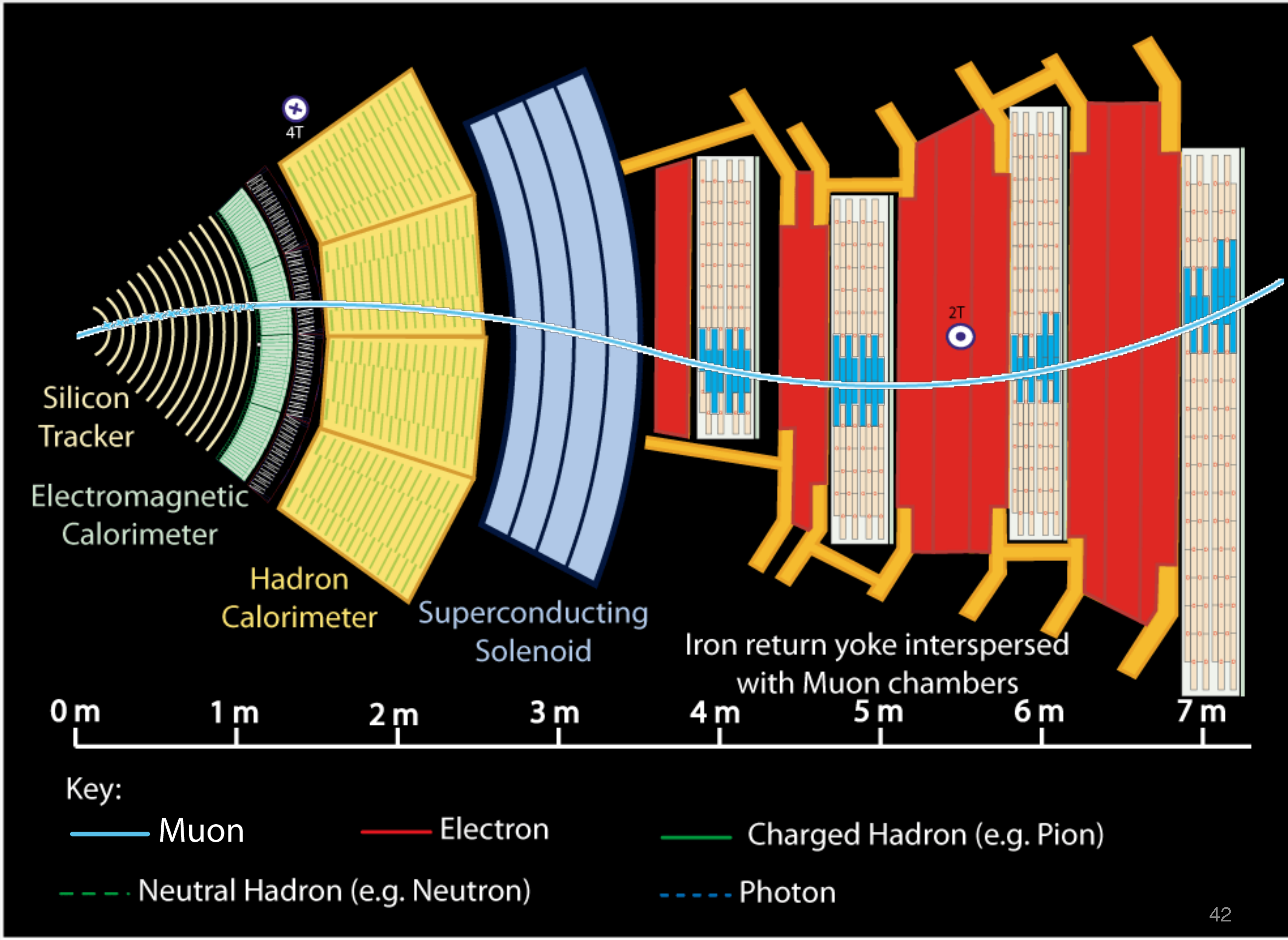
$$\vec{F} = q\vec{v} \ x \ \vec{B}$$

What other force is acting on a particle?

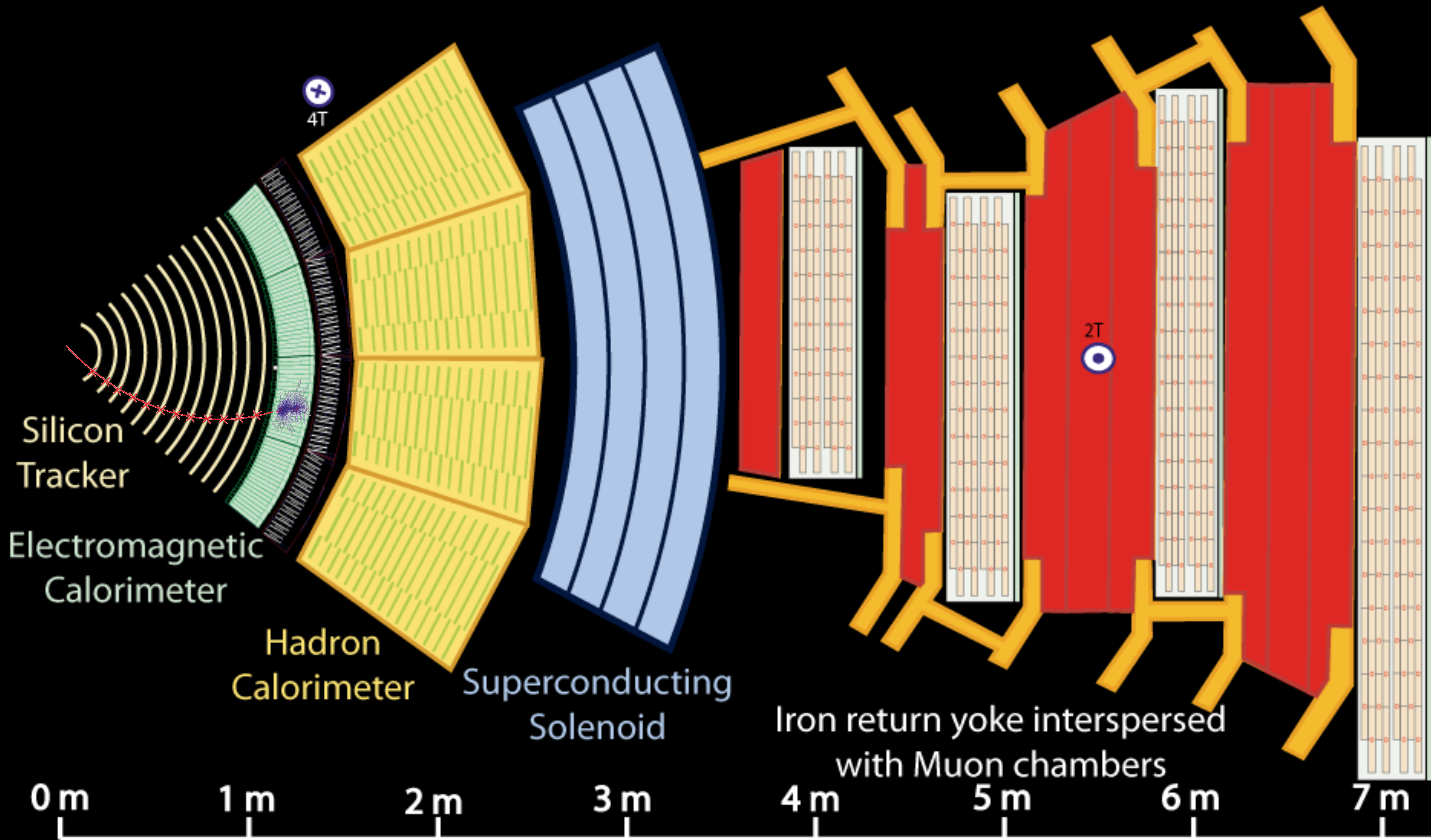


So, $Bqv = mv^2/r$, or, $Bq=mv/r$, $Bq=p/r$


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



Key:

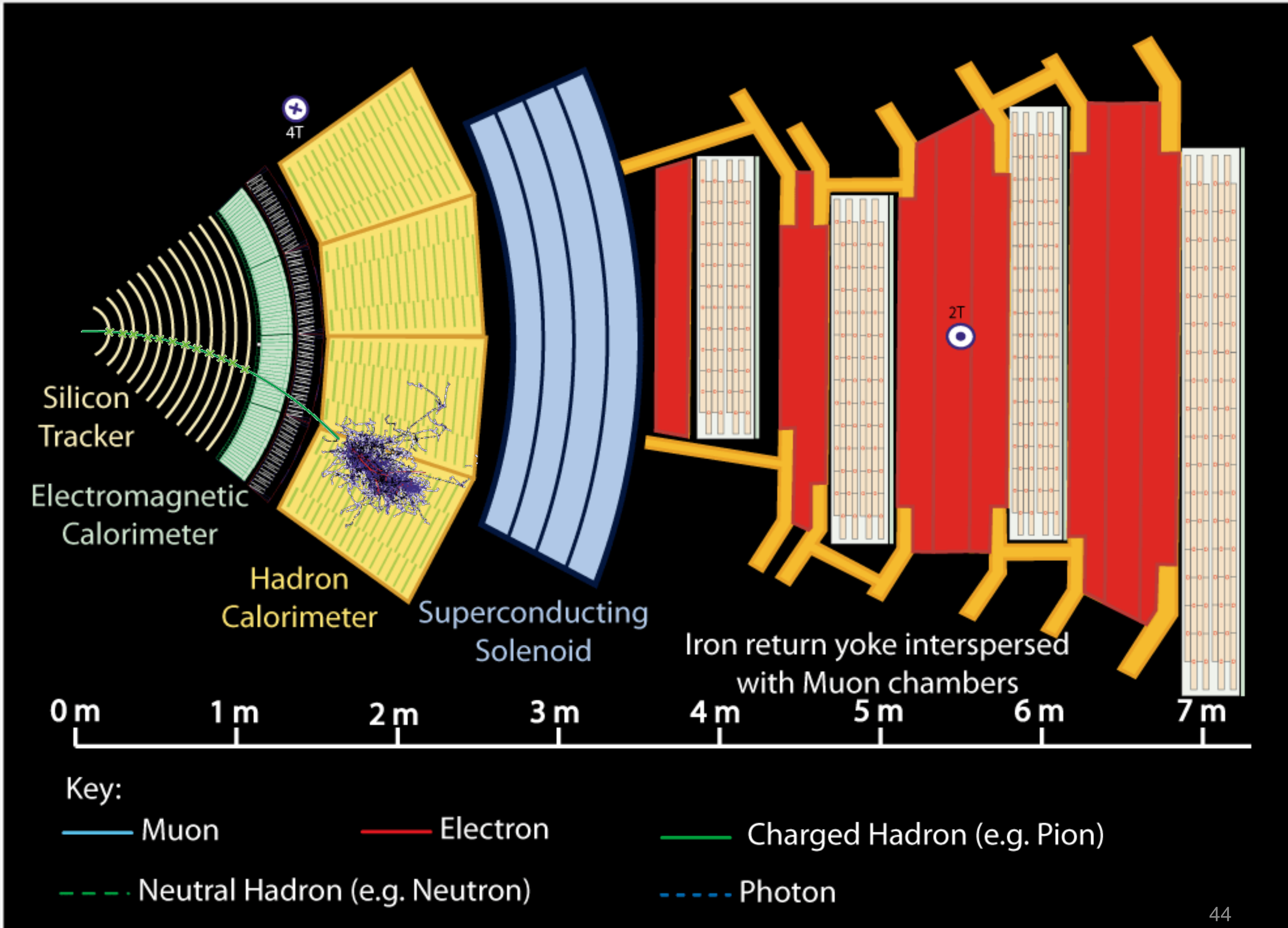
Muon

Electron

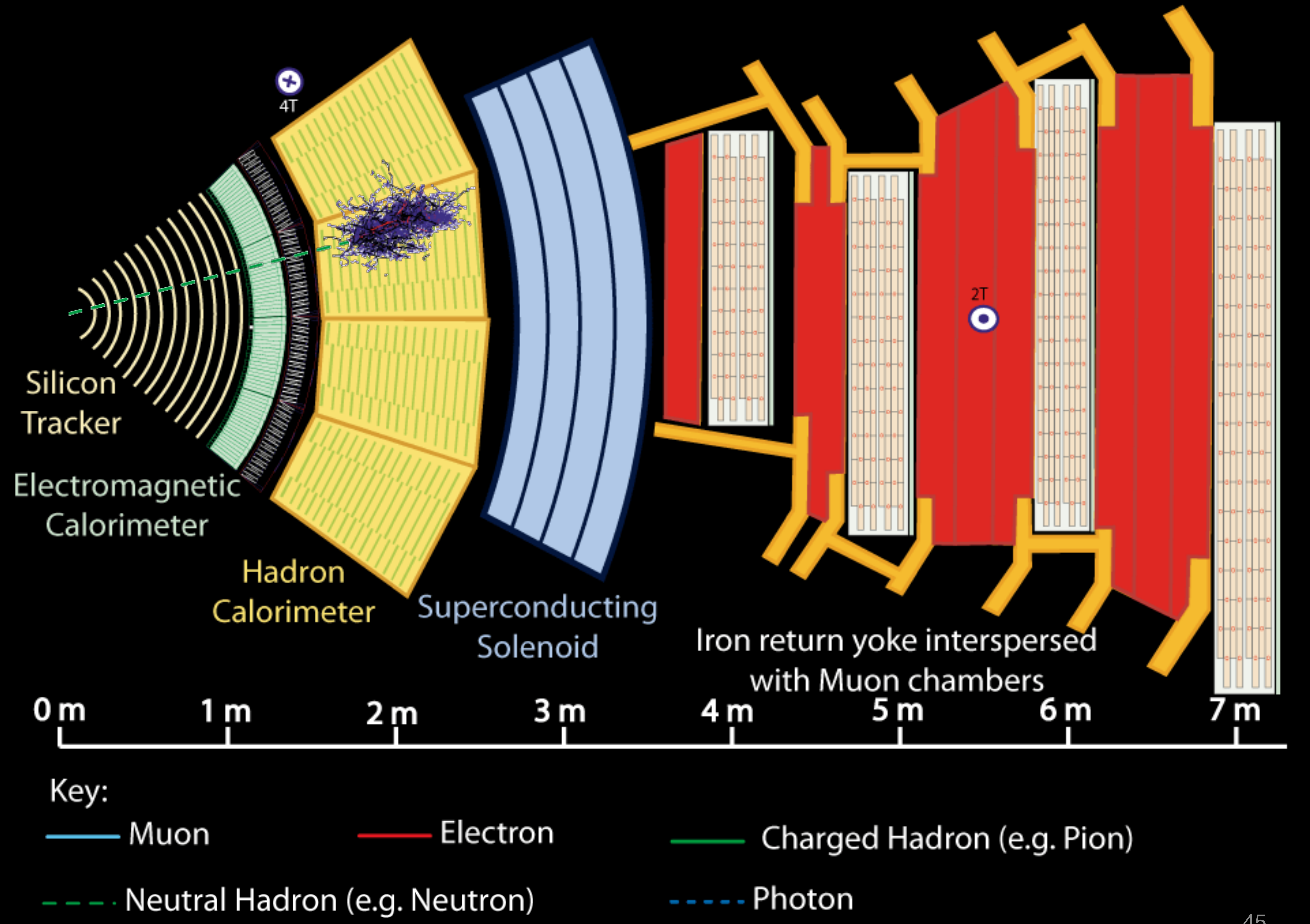
Charged Hadron (e.g. Pion)

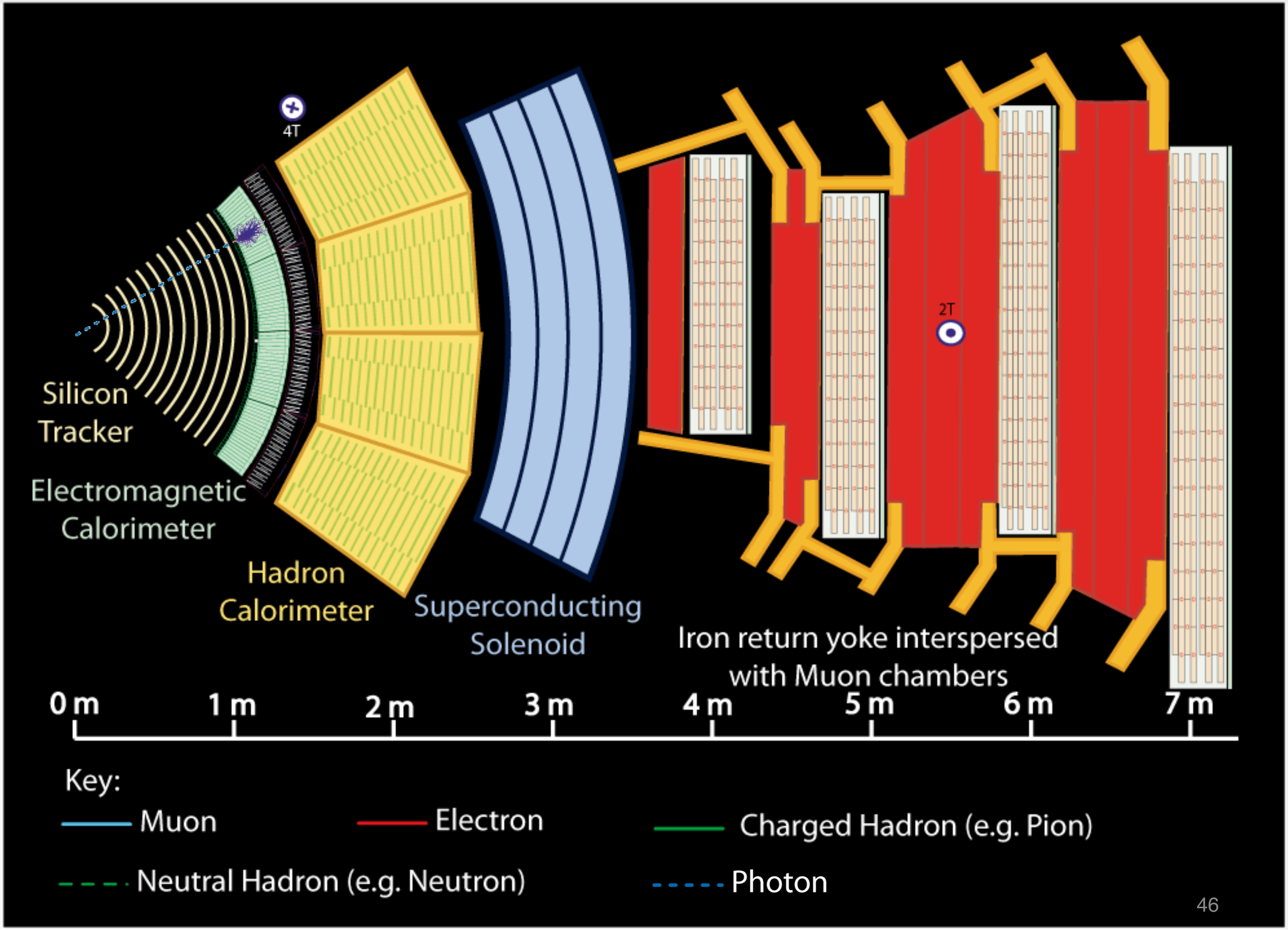
Neutral Hadron (e.g. Neutron)

Photon



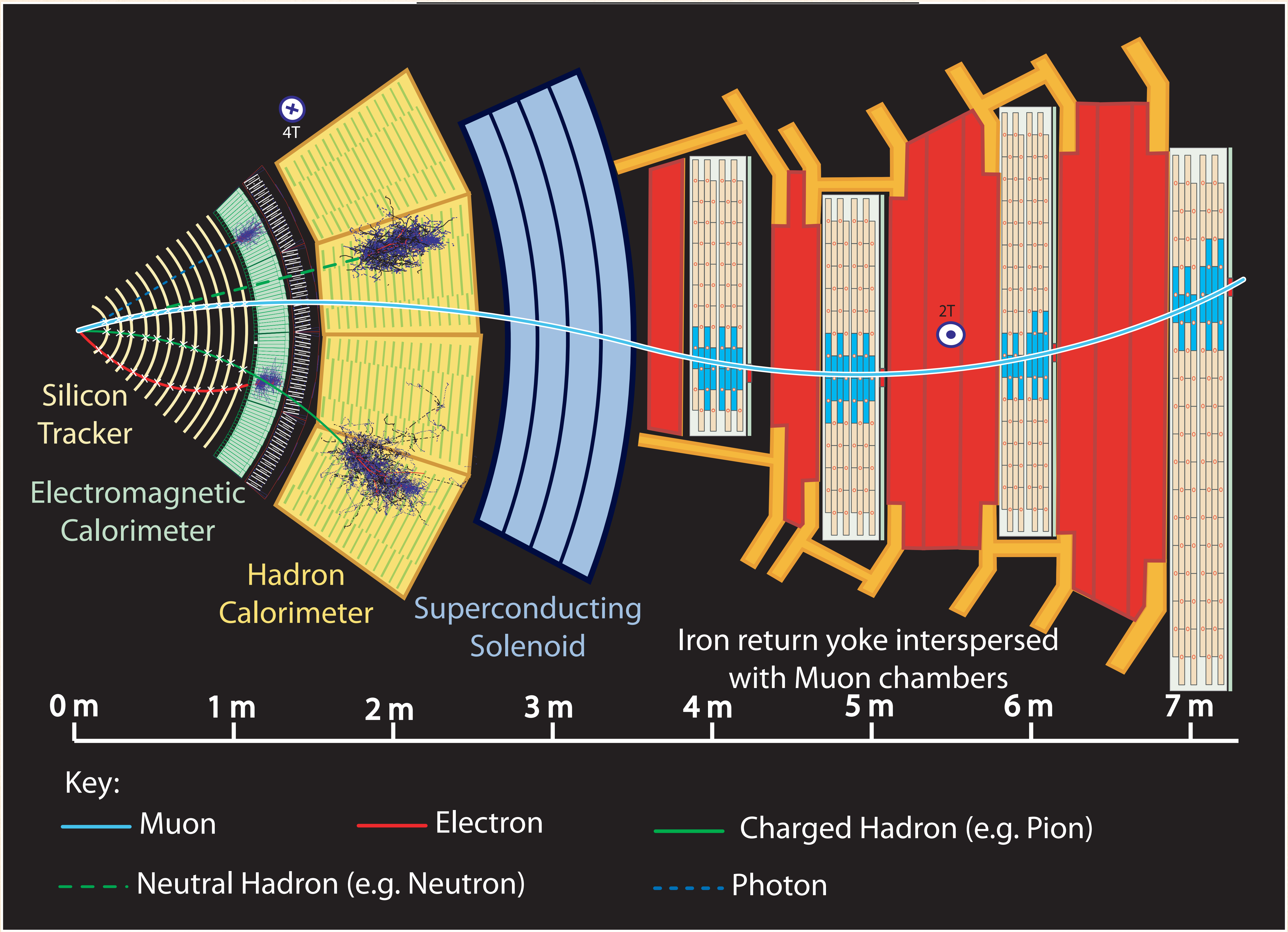
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

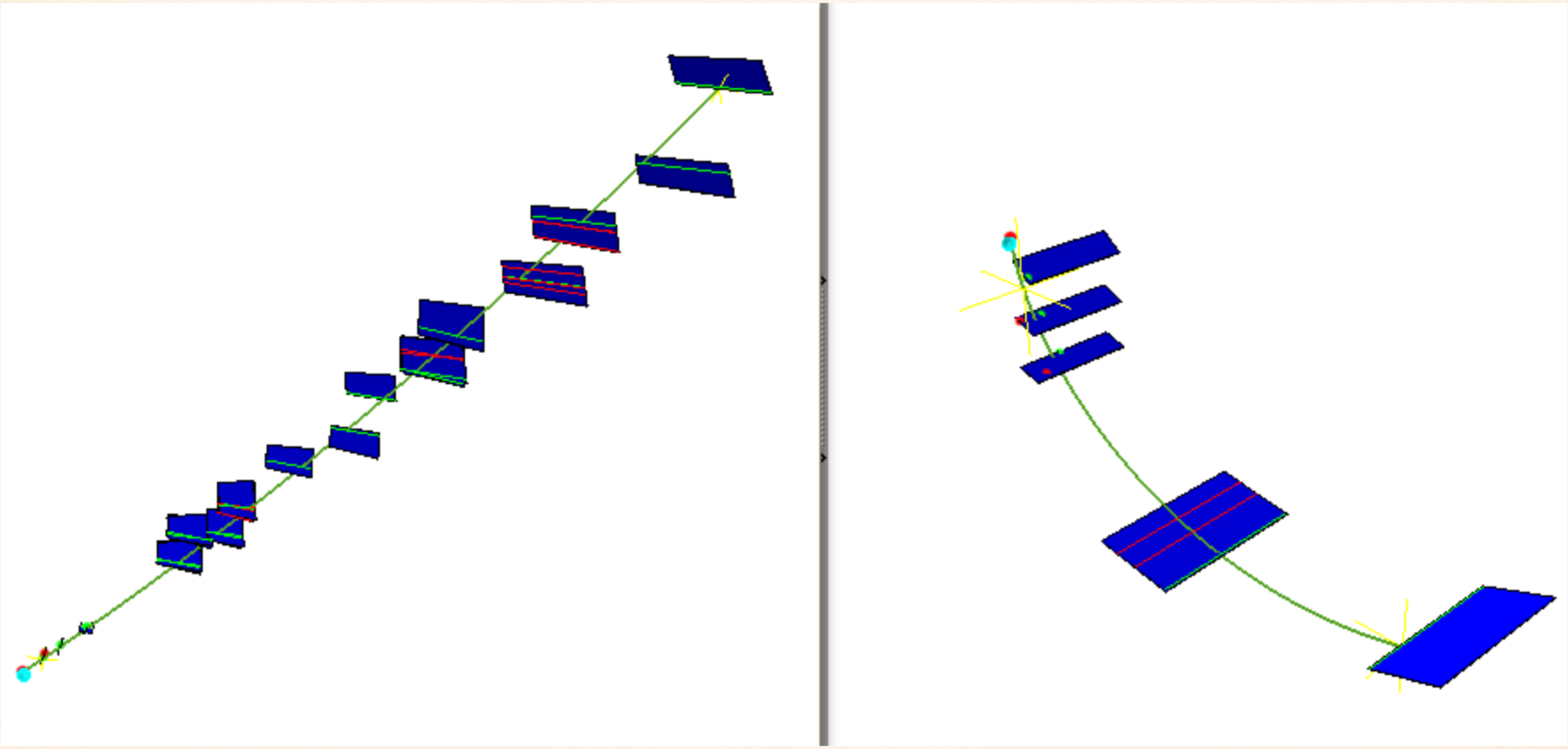


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

Particle Detection in CMS

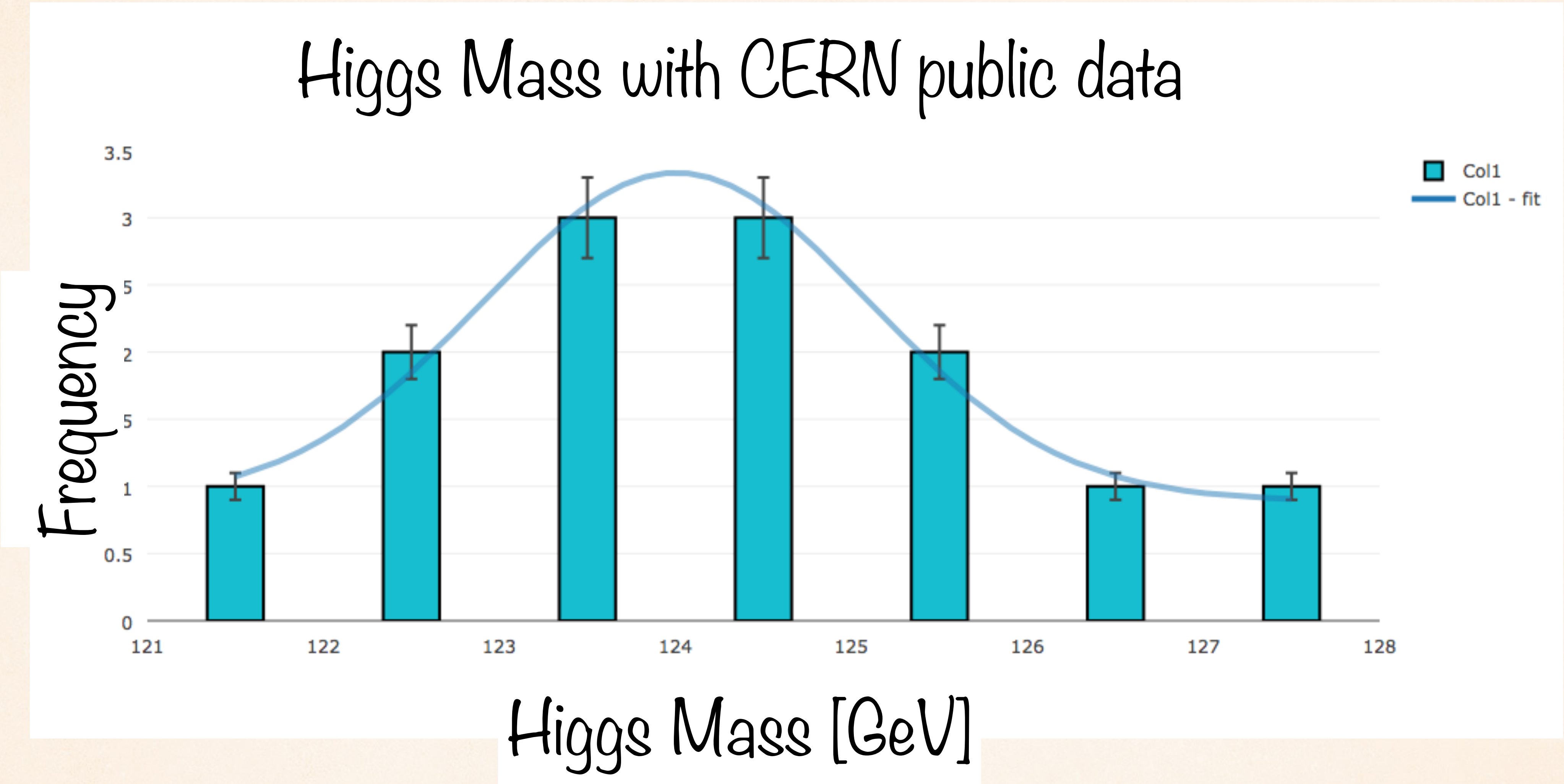


Do we understand how tracks are created from individual hits in sensors?



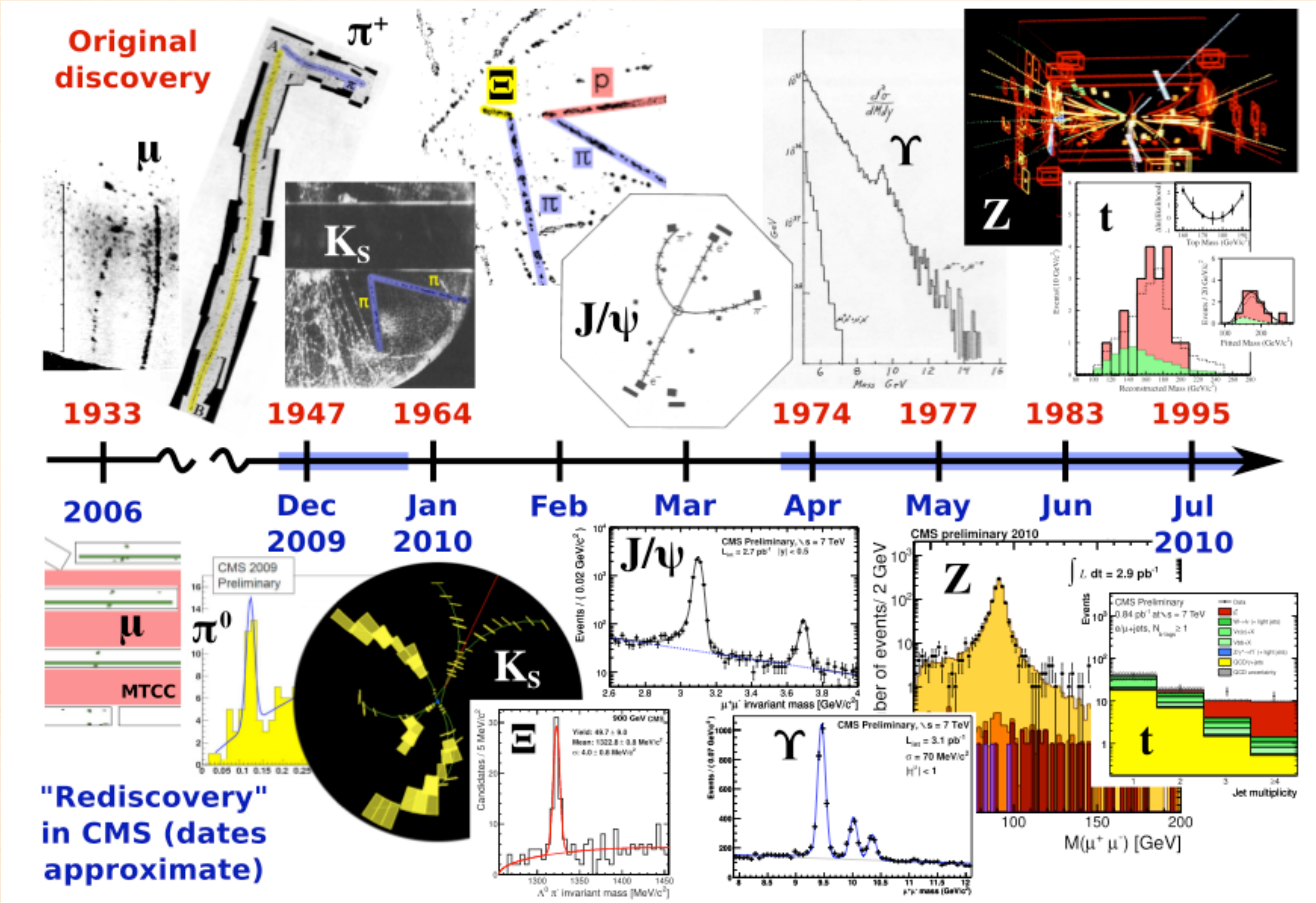
Pattern recognition algorithm used

A brief detour

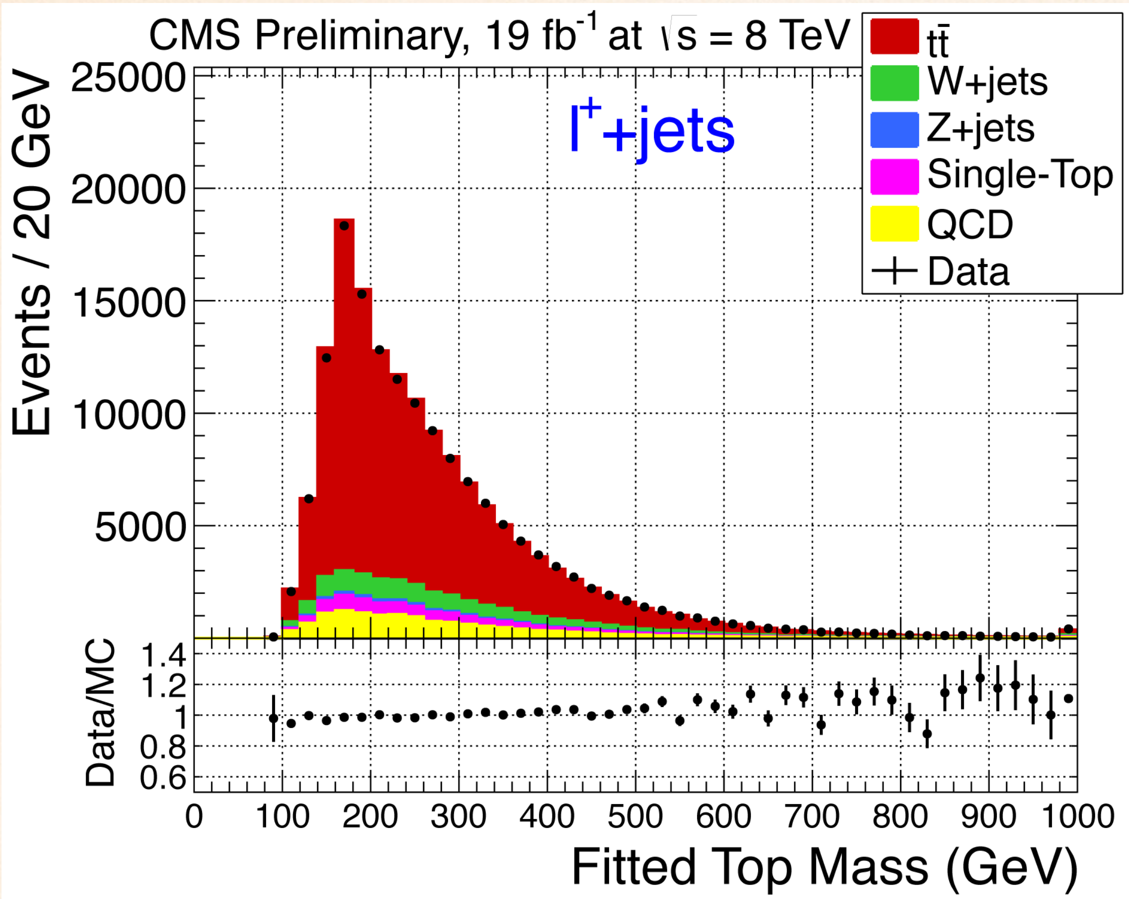


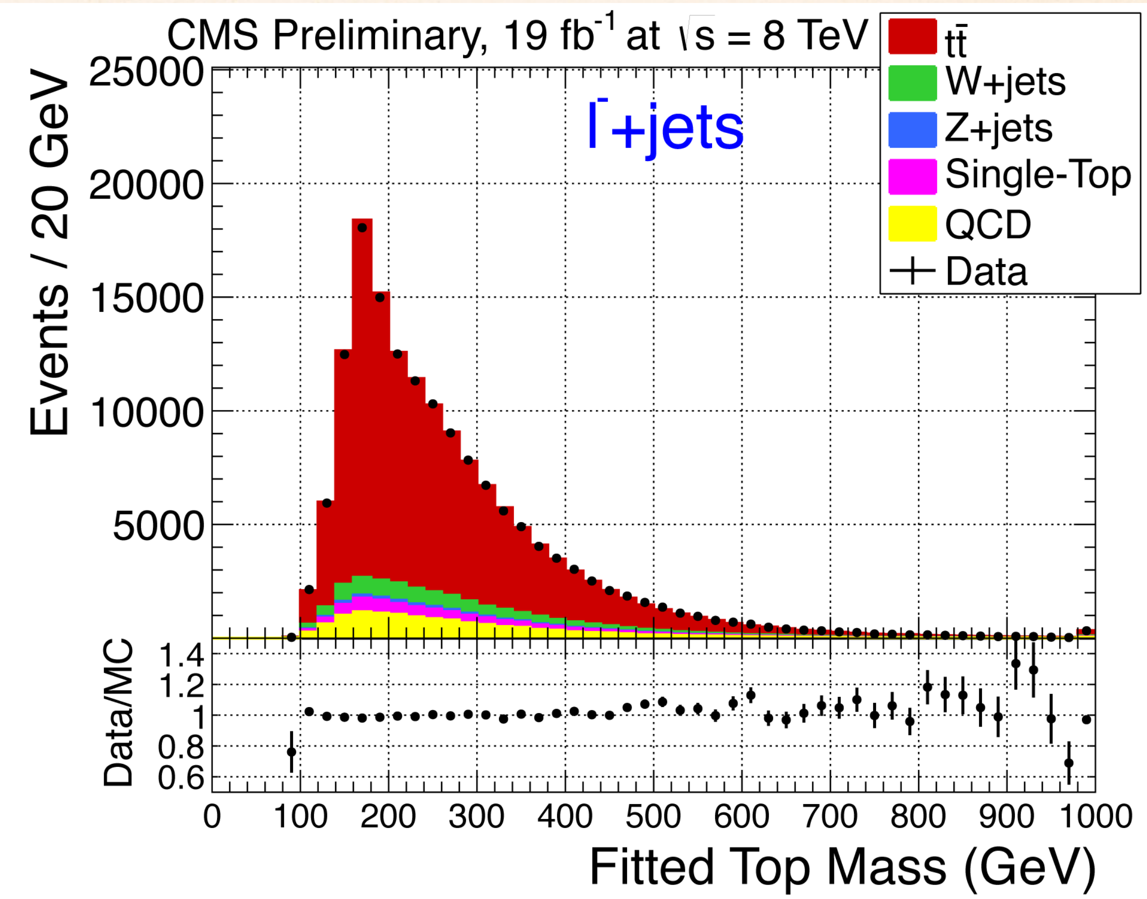
- What's a histogram? It's a frequency graph
- We usually make a plot per event
- What's an event? 1 p-p collision
- Plots made with y-label: Events/x-axis units

The rediscovery of particles at the LHC

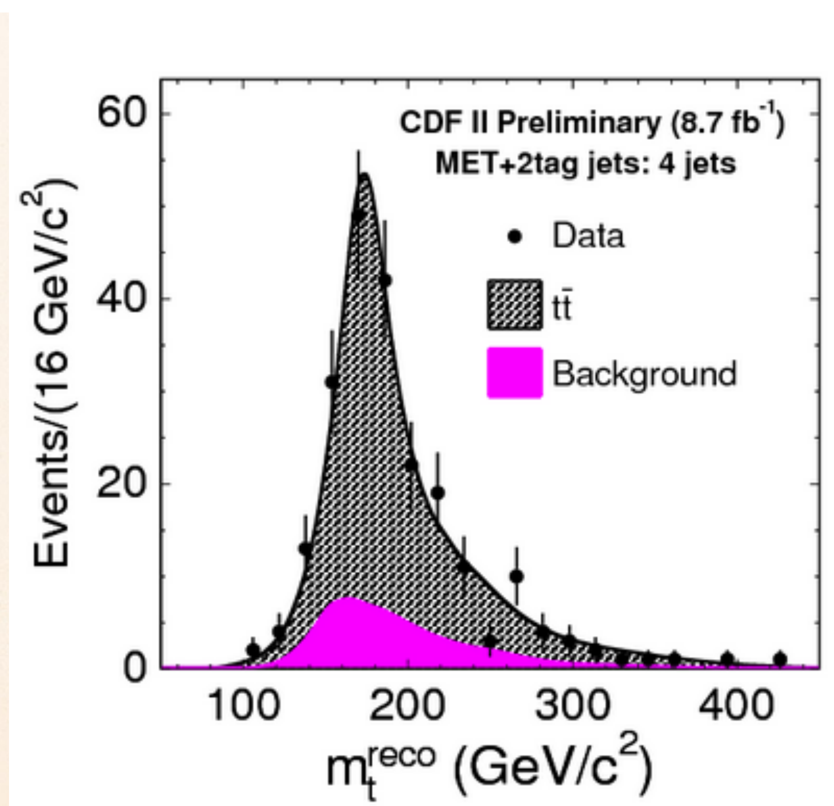


Top quark at the LHC



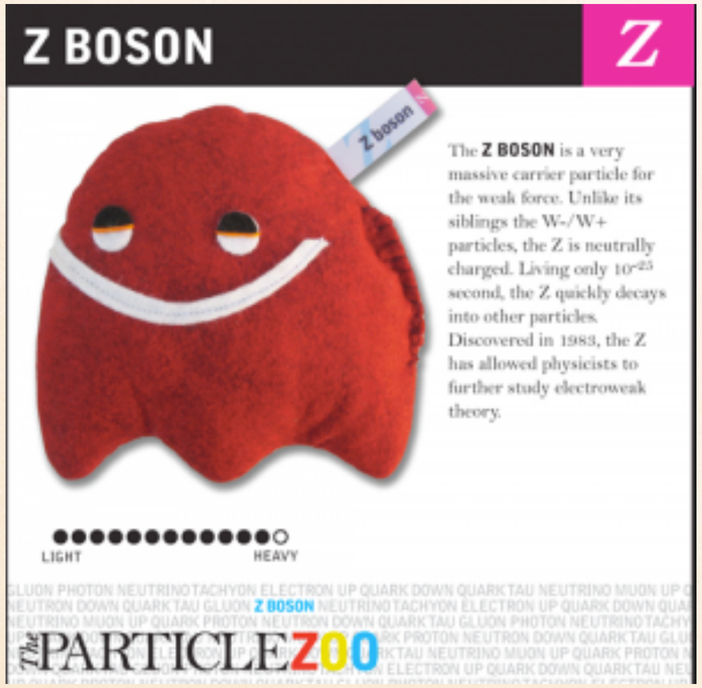


Compare with top quark at the Tevatron



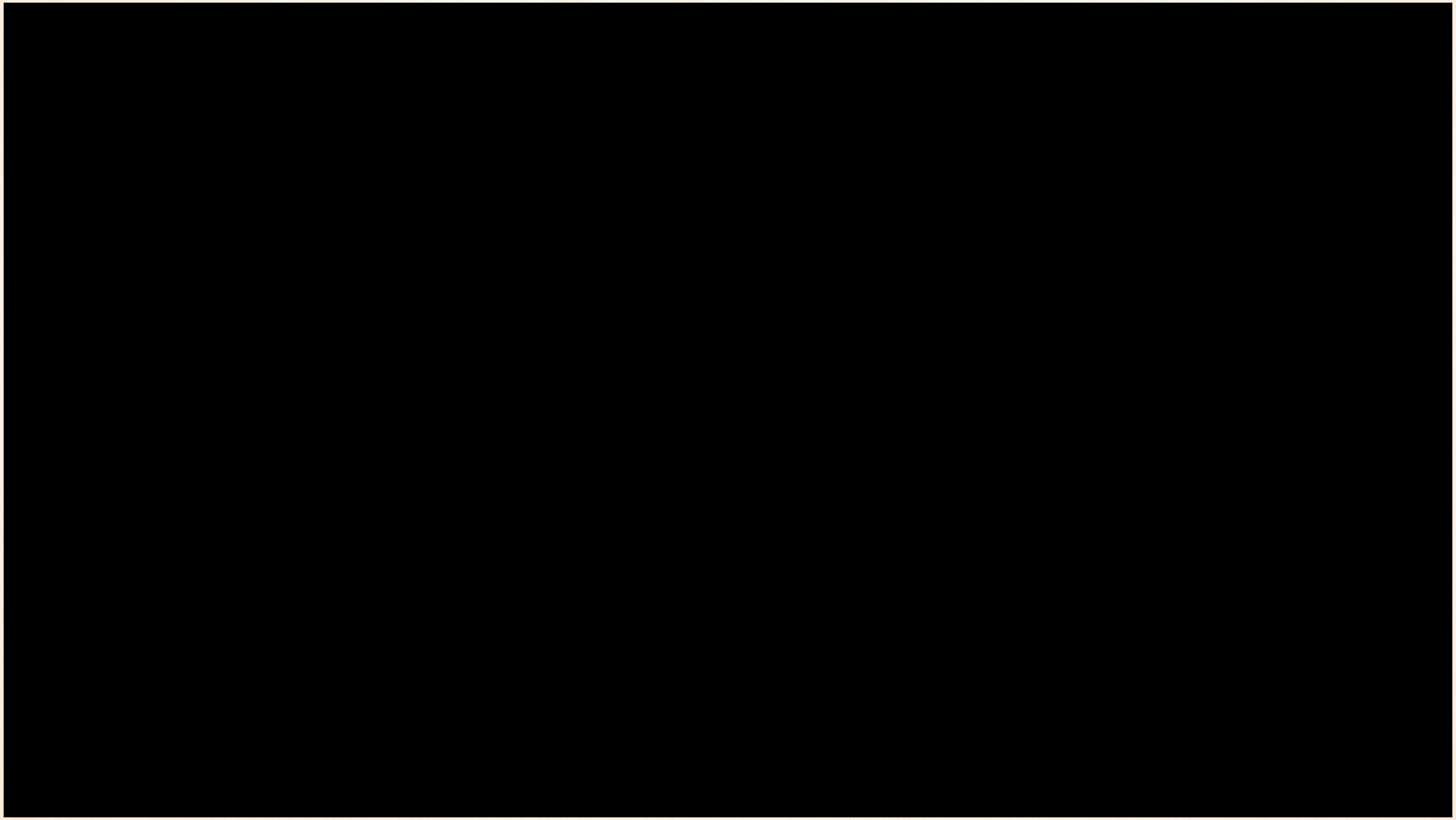
The discovery train

"Yesterday's discovery, today's calibration, tomorrow's background"



Literally referred to as a standard candle!

A word about the Higgs boson



- Remember Einstein's equation? **$E^2=(mc^2)^2+(pc)^2$, if m=0 particle travels at the speed of light**
- What if there is a f**orce field filling the universe** that somehow **slows particles down to below the speed of light**?
- This would make them have **mass** !

Timeline of the Higgs discovery

October 19th, 1964: Higgs, Brout and Englert independently work out the Higgs mechanism

July 14th, 1989: Large Electron-Positron collider: First injection

December 16th, 1994: LHC construction approved

Timeline of the Higgs discovery

September 10th, 2008: The LHC starts up

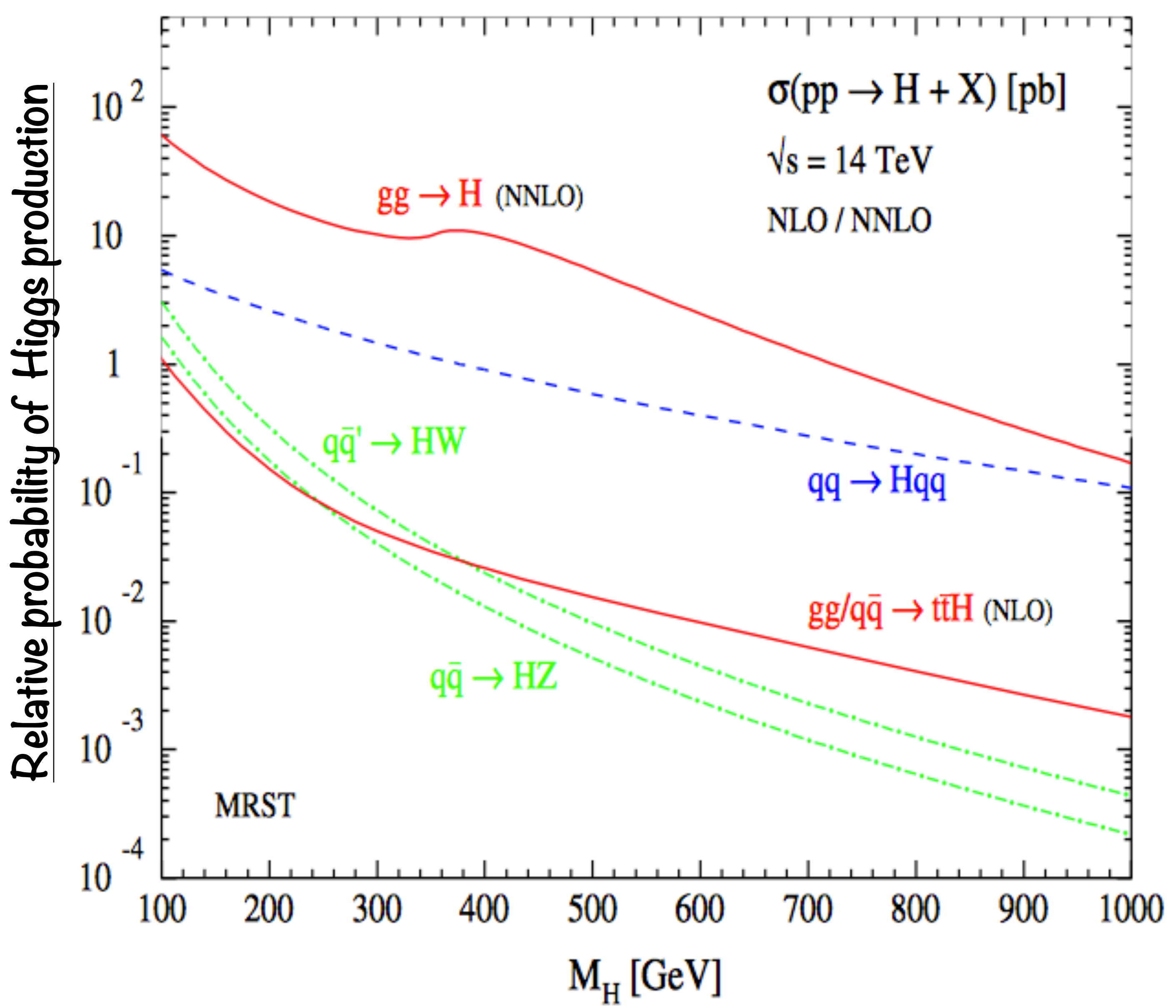
December 13th, 2011: Tantalizing hints of the Higgs

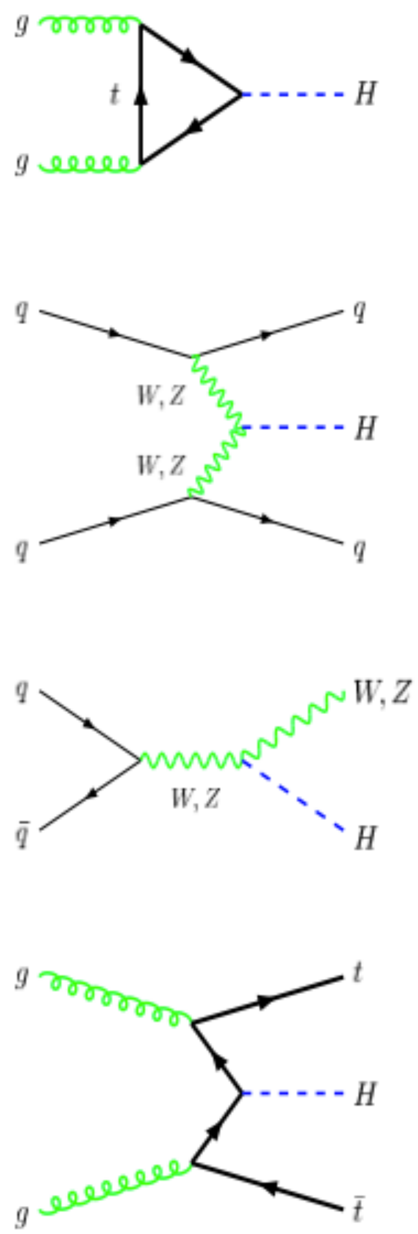
July 4th, 2012: ATLAS and CMS observe a particle consistent with the Higgs boson

July 4th, 2012: ATLAS and CMS submit Higgs-search papers

Higgs Production

affectionately known as...





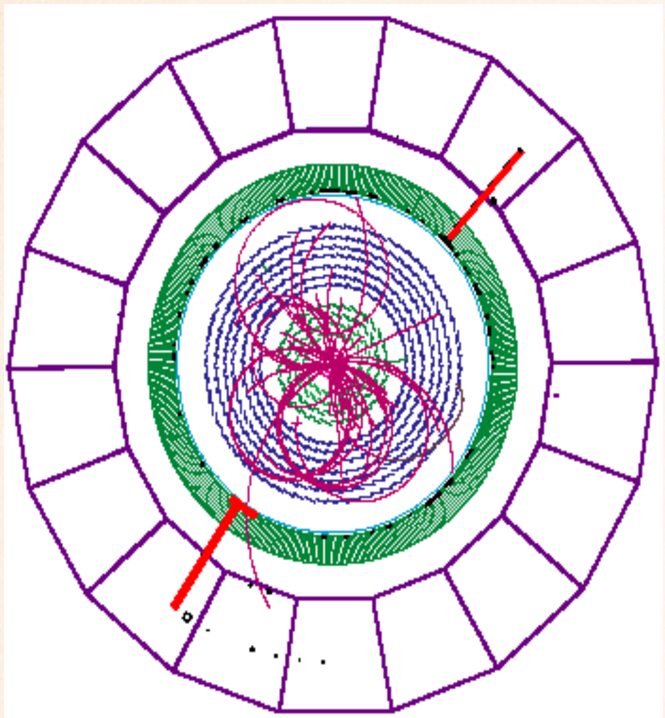
gg fusion

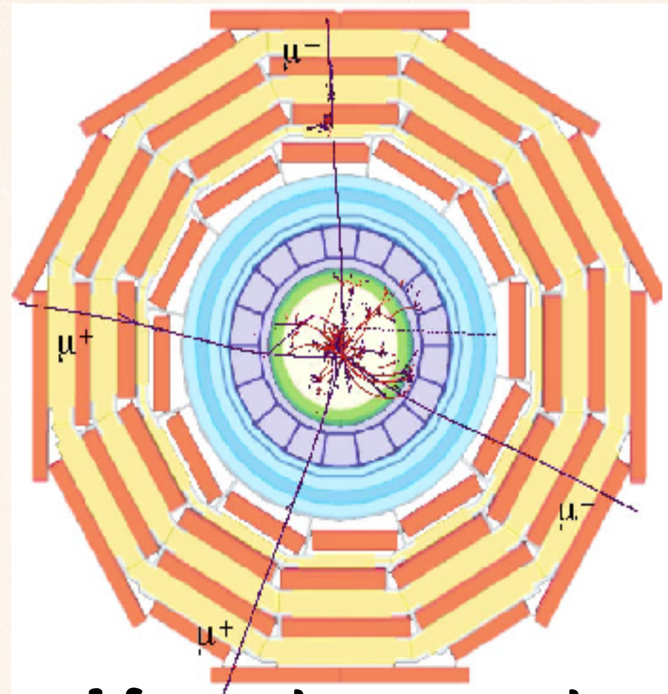
WZ fusion

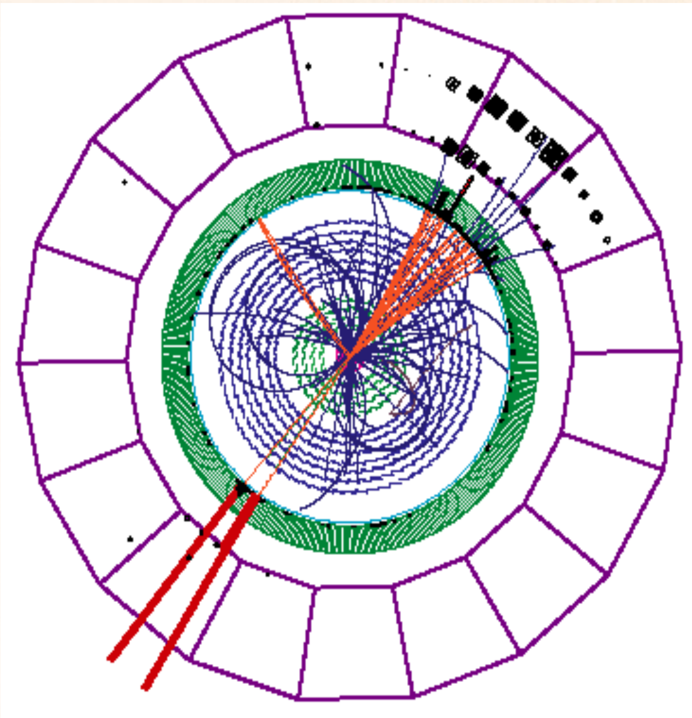
Higgs-Strahlung

t-tbar fusion

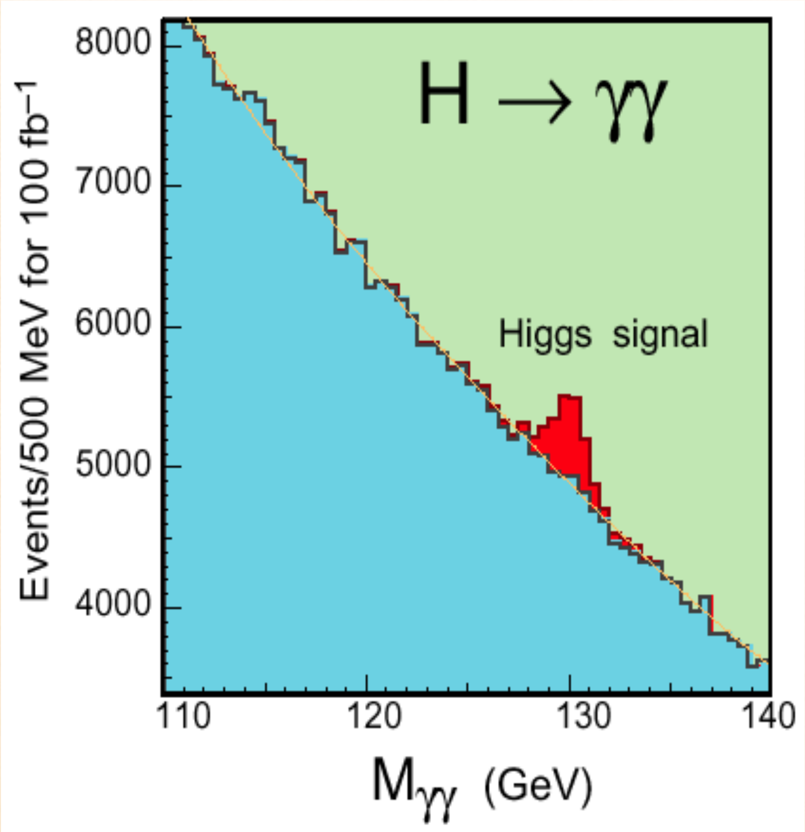
Observing the Higgs boson

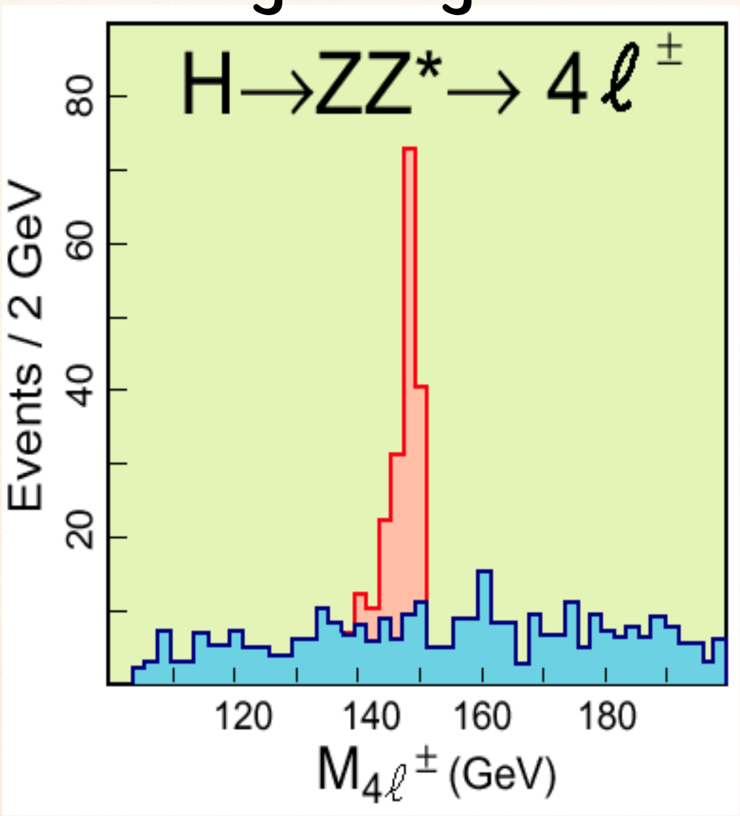


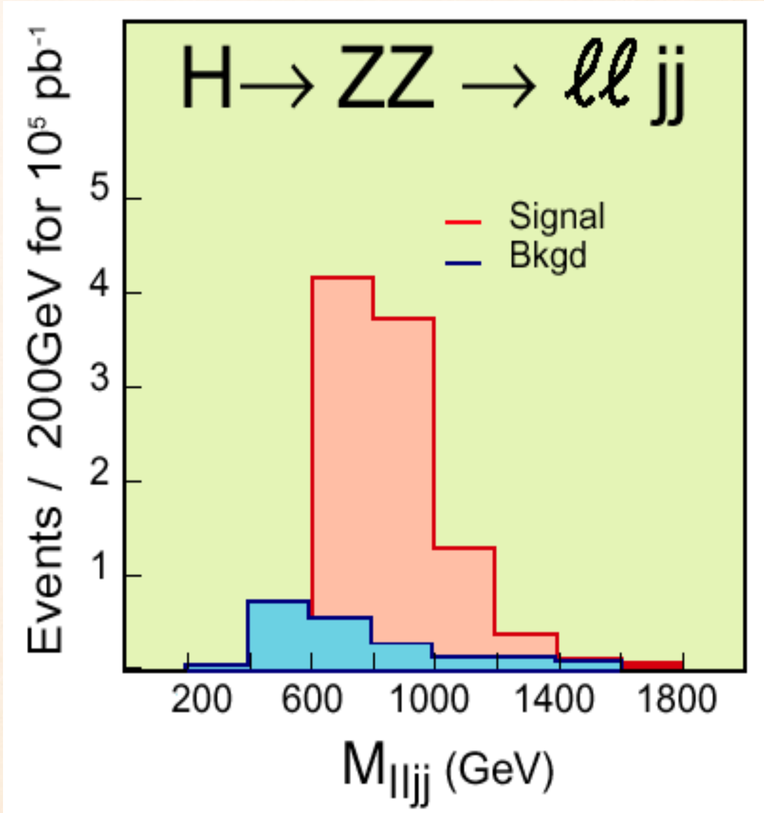




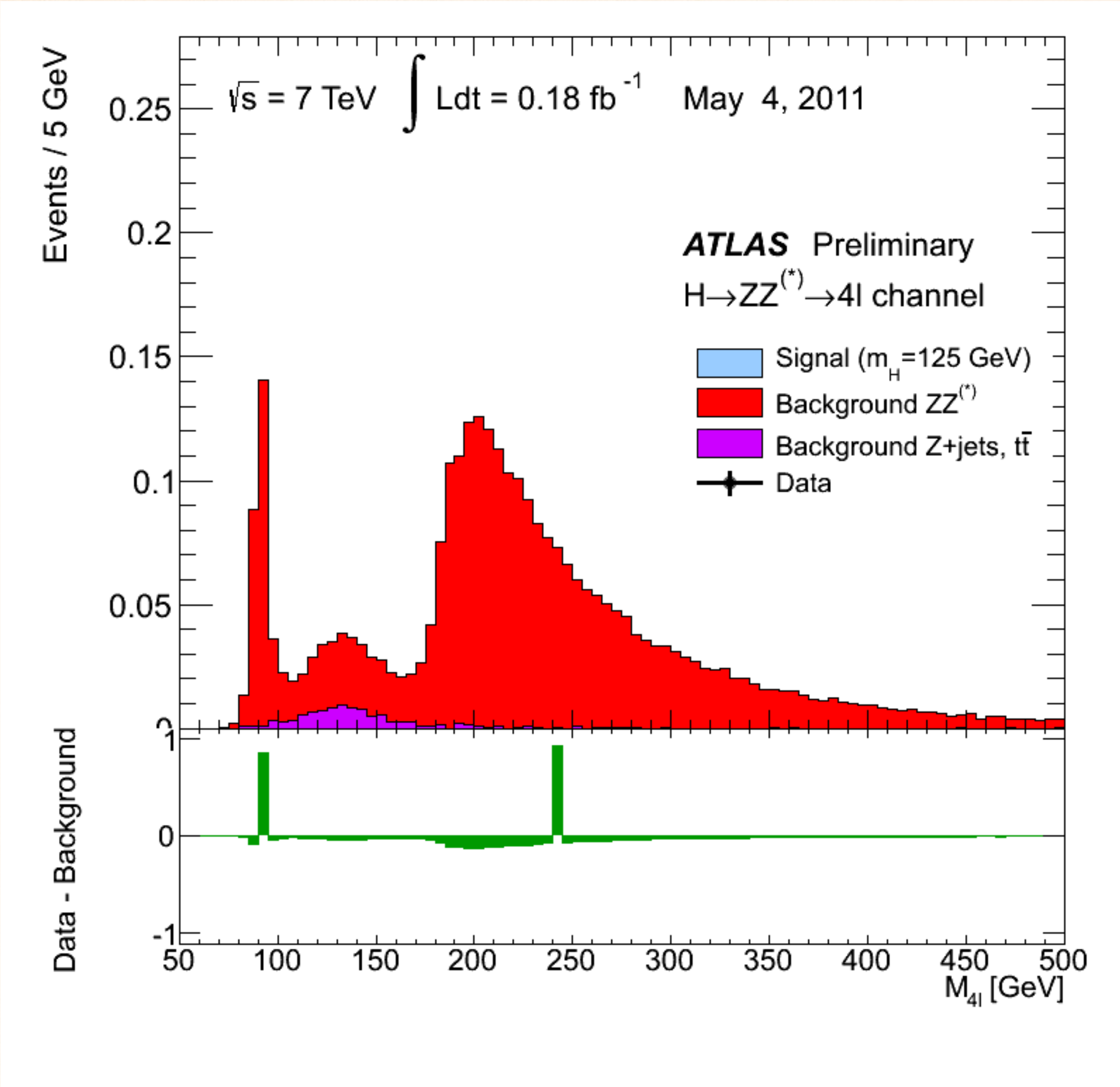
Many decay modes



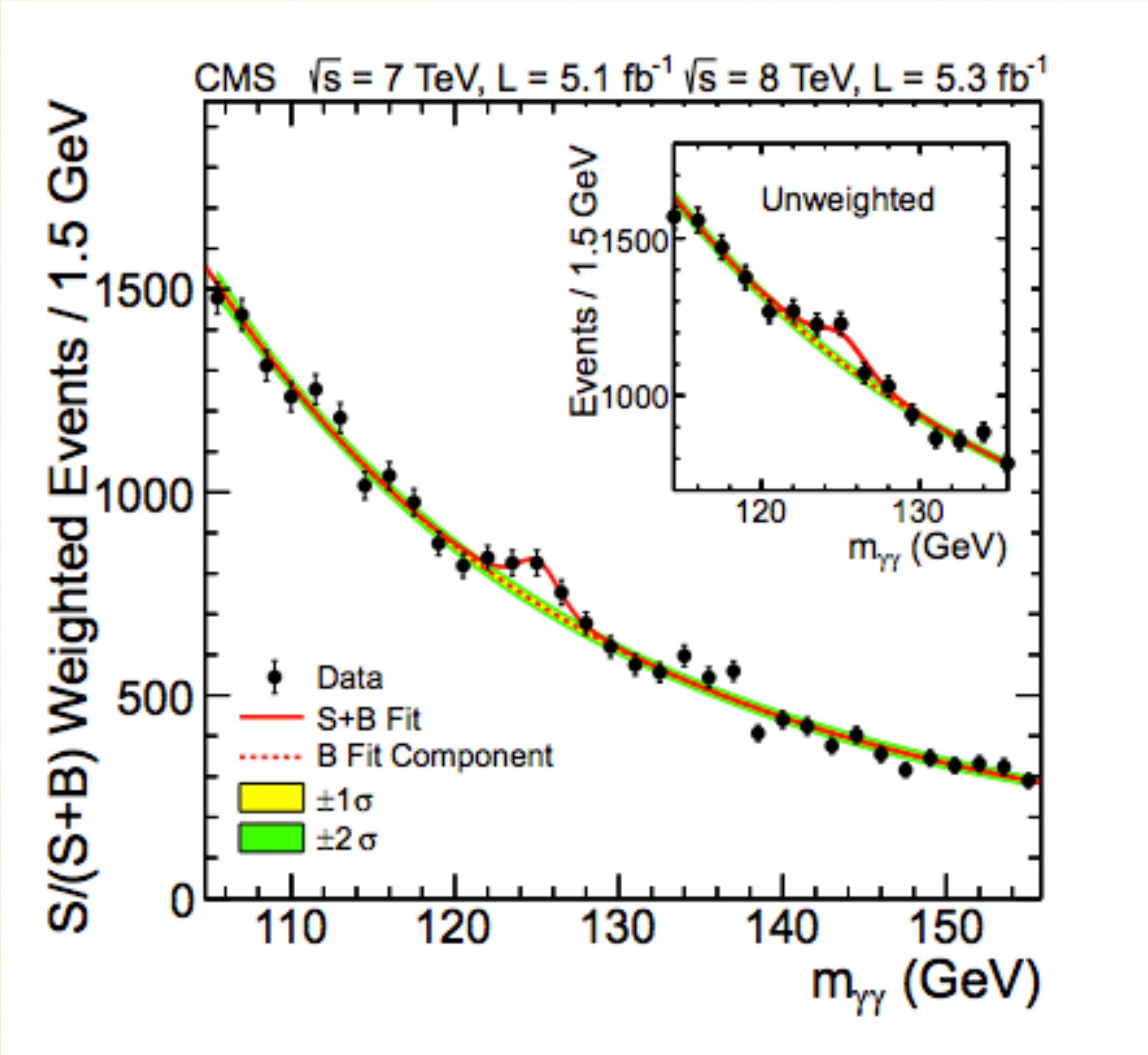


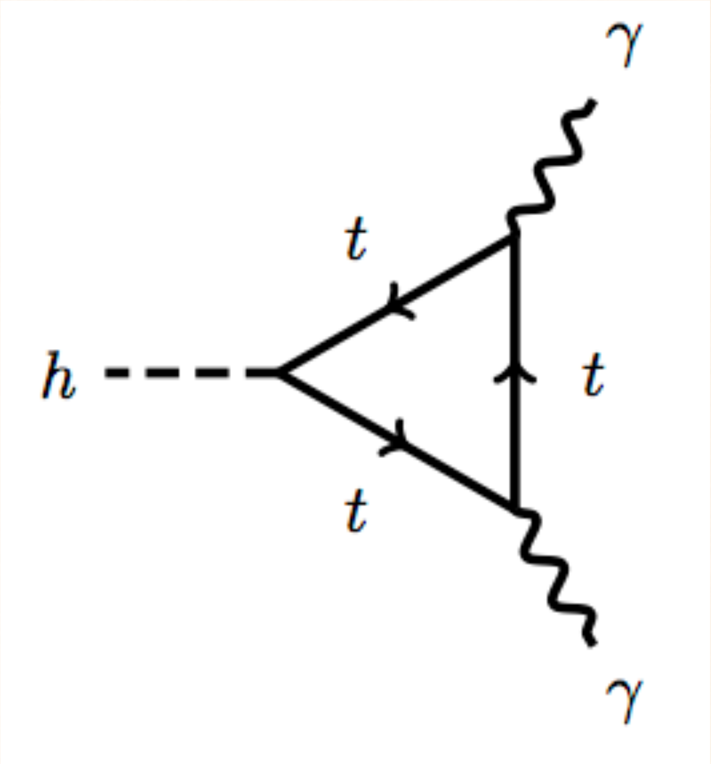


Higgs boson discovery

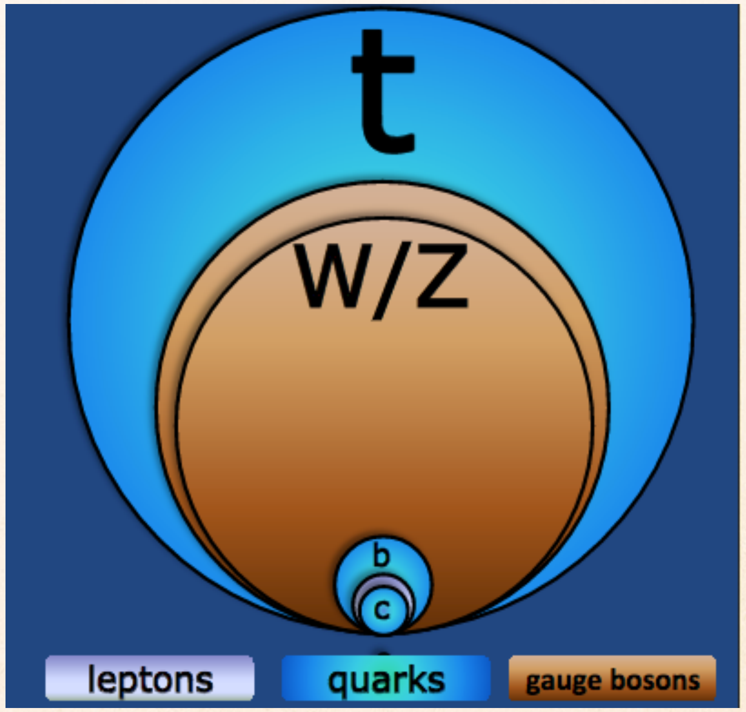


What's next: Understand the relationship between the top and the Higgs

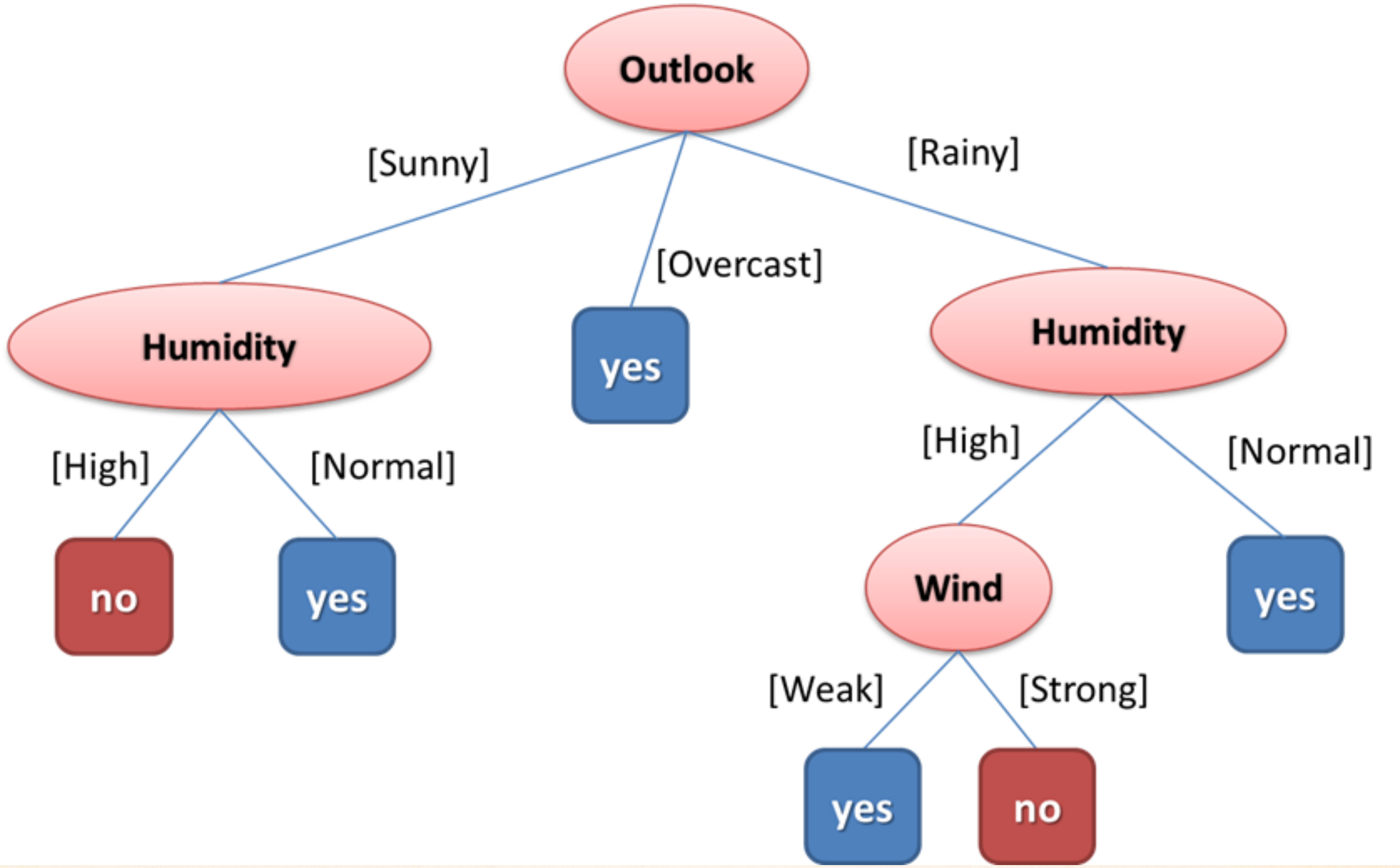




Higgs->largest coupling with the top

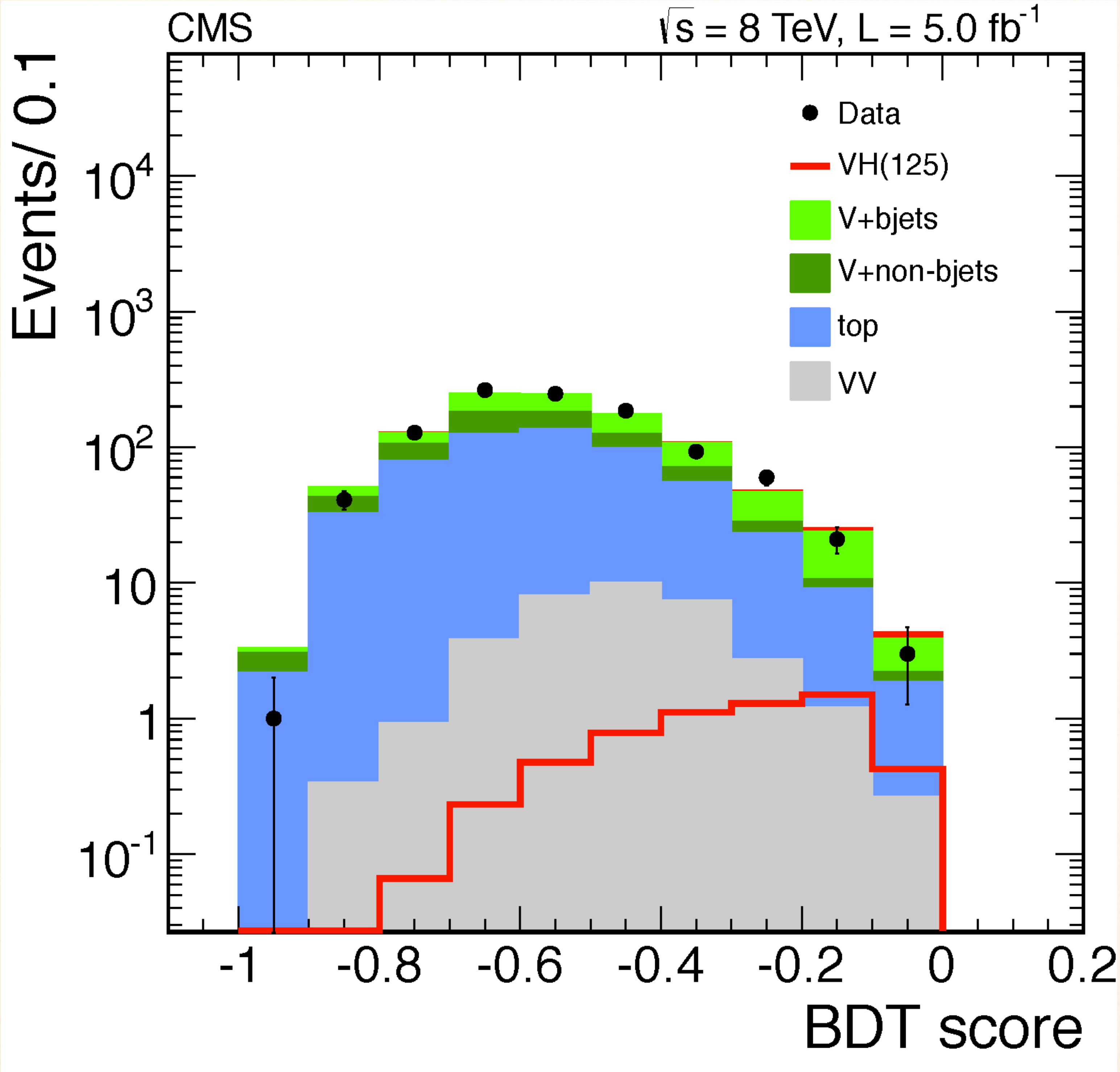


What's next: Use machine learning to probe further



Ask enough questions to fully characterize weather

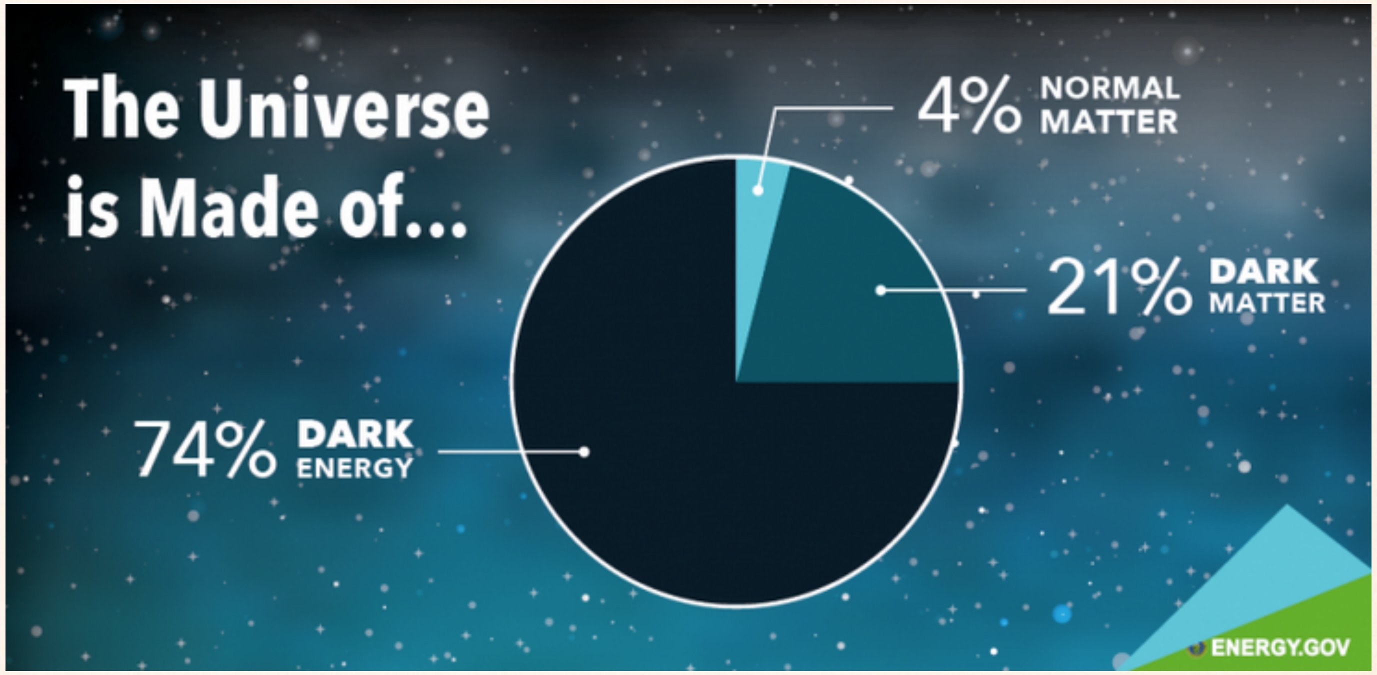
What's next: Use machine learning to probe further



- Super variable identified by the computer
- Not enough signal yet

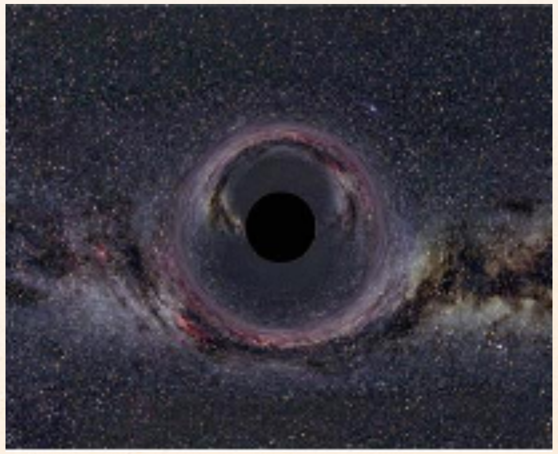
Open questions?

- We know about ~27% of the universe is made up of dark matter from cosmological evidence



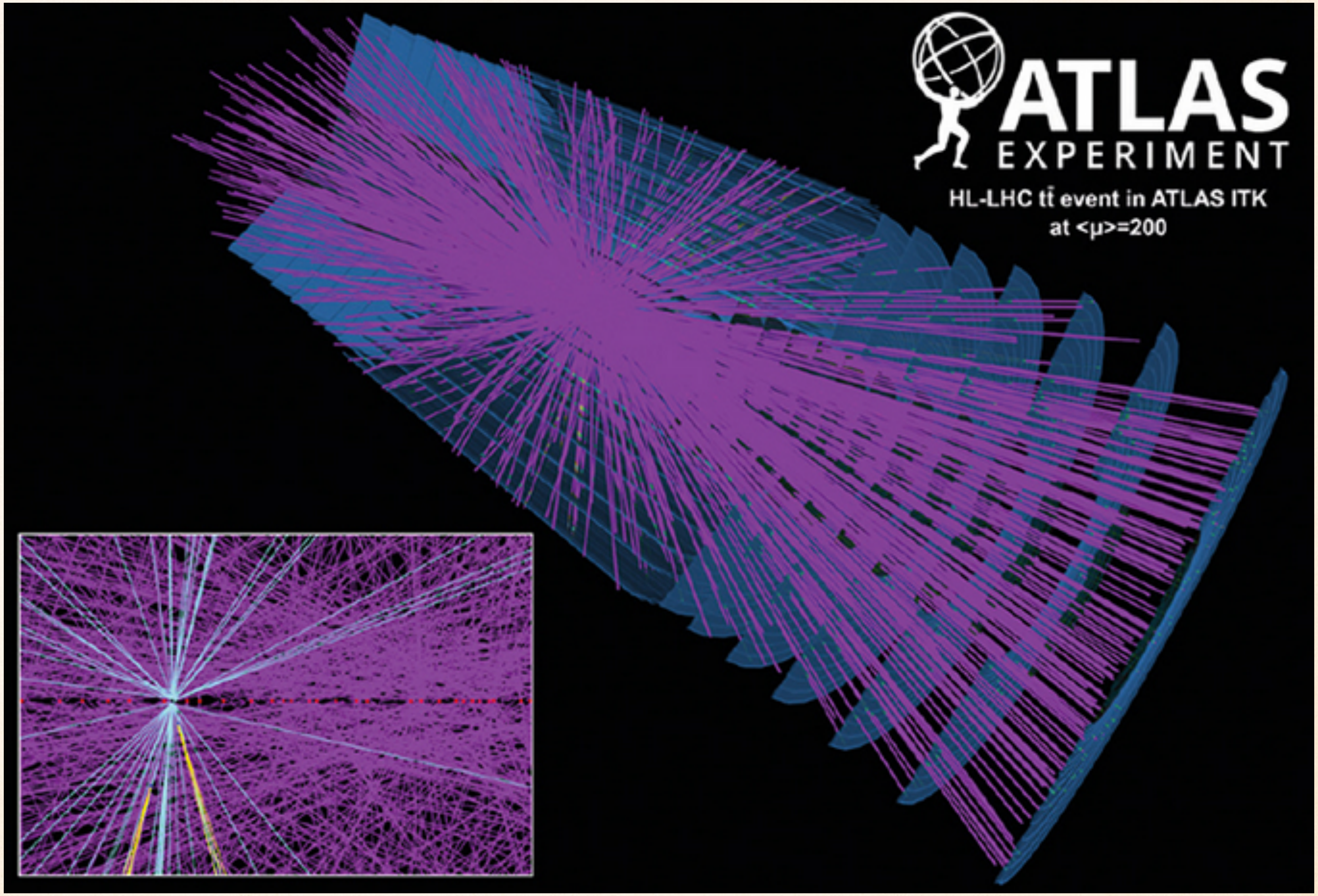
- Where is all the anti matter?

- We haven't included gravity into the mix yet!

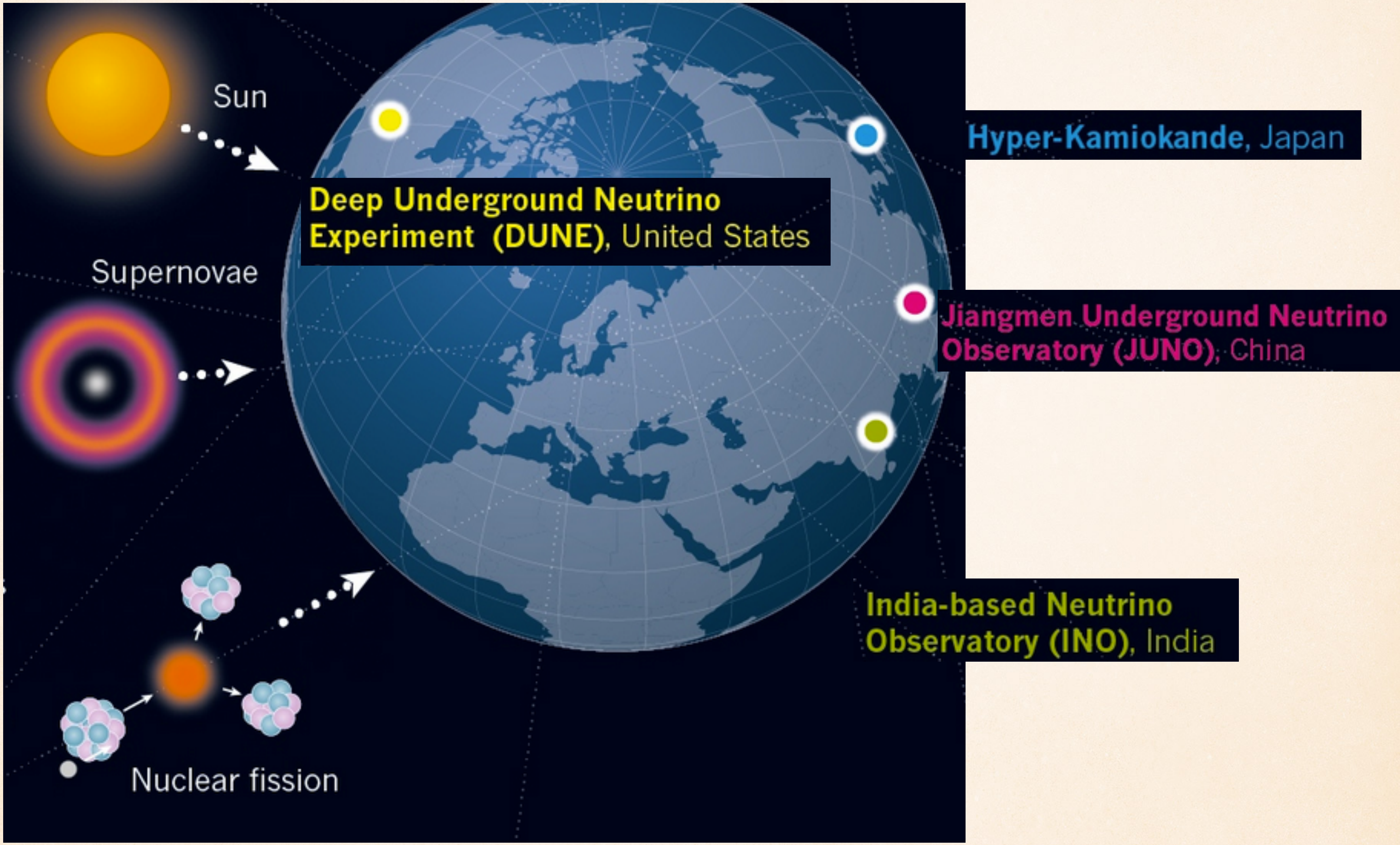


Where do we see ourselves in the next 10 years?

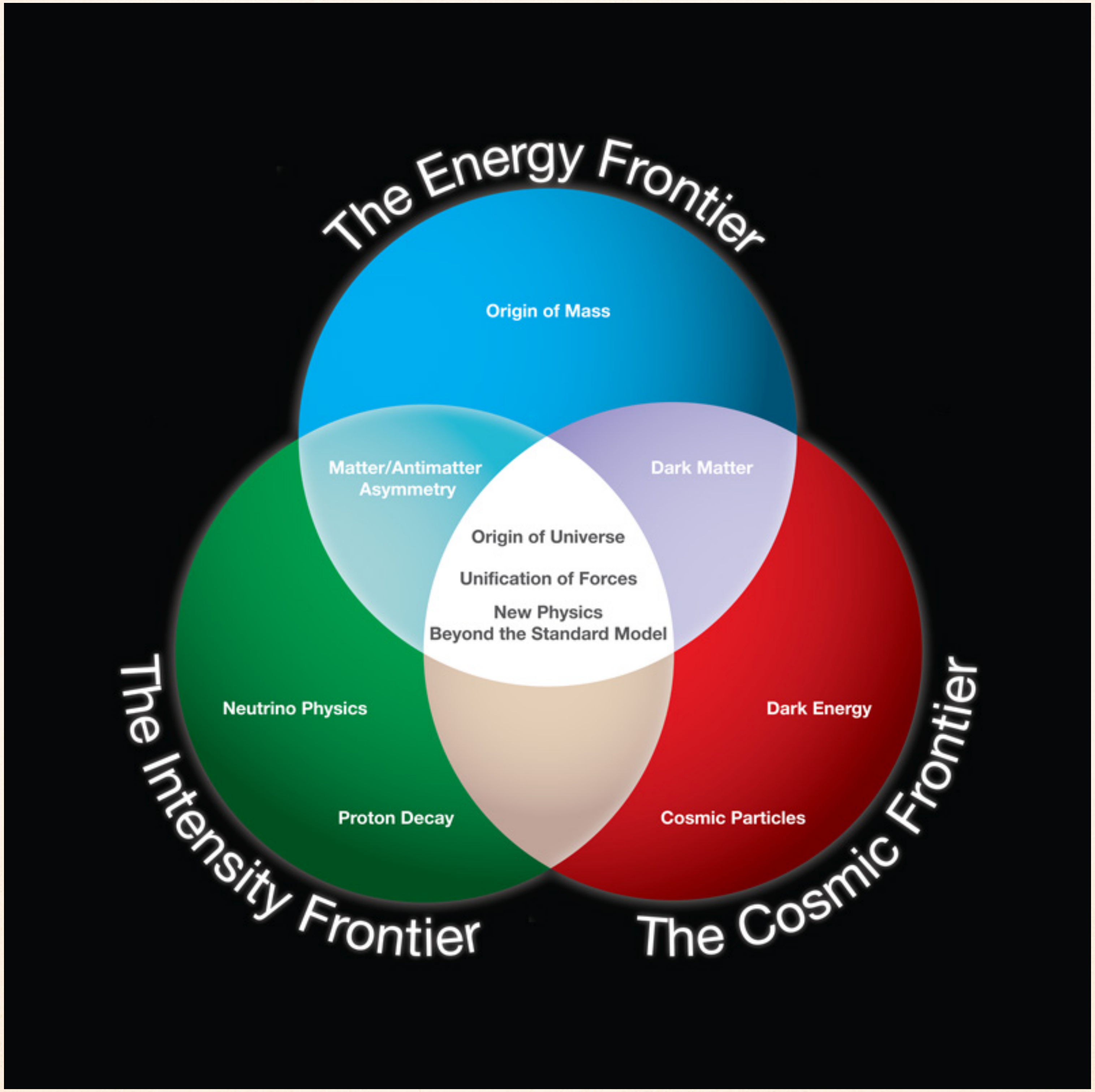
- Plan on collecting at least 15 times more data
- Many technical challenges associated with designing upgraded detectors

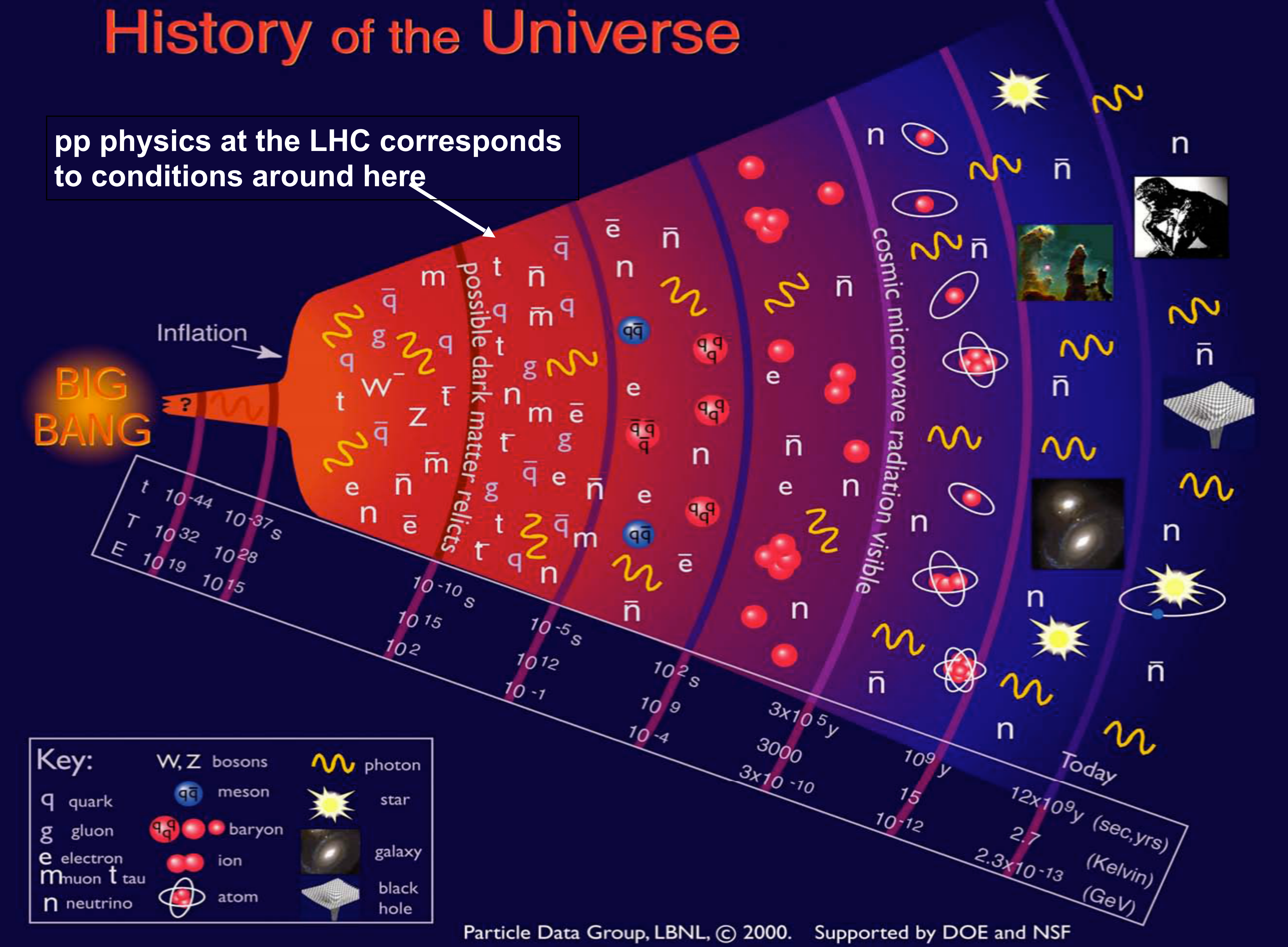


Where do we see ourselves in the next 10 years?



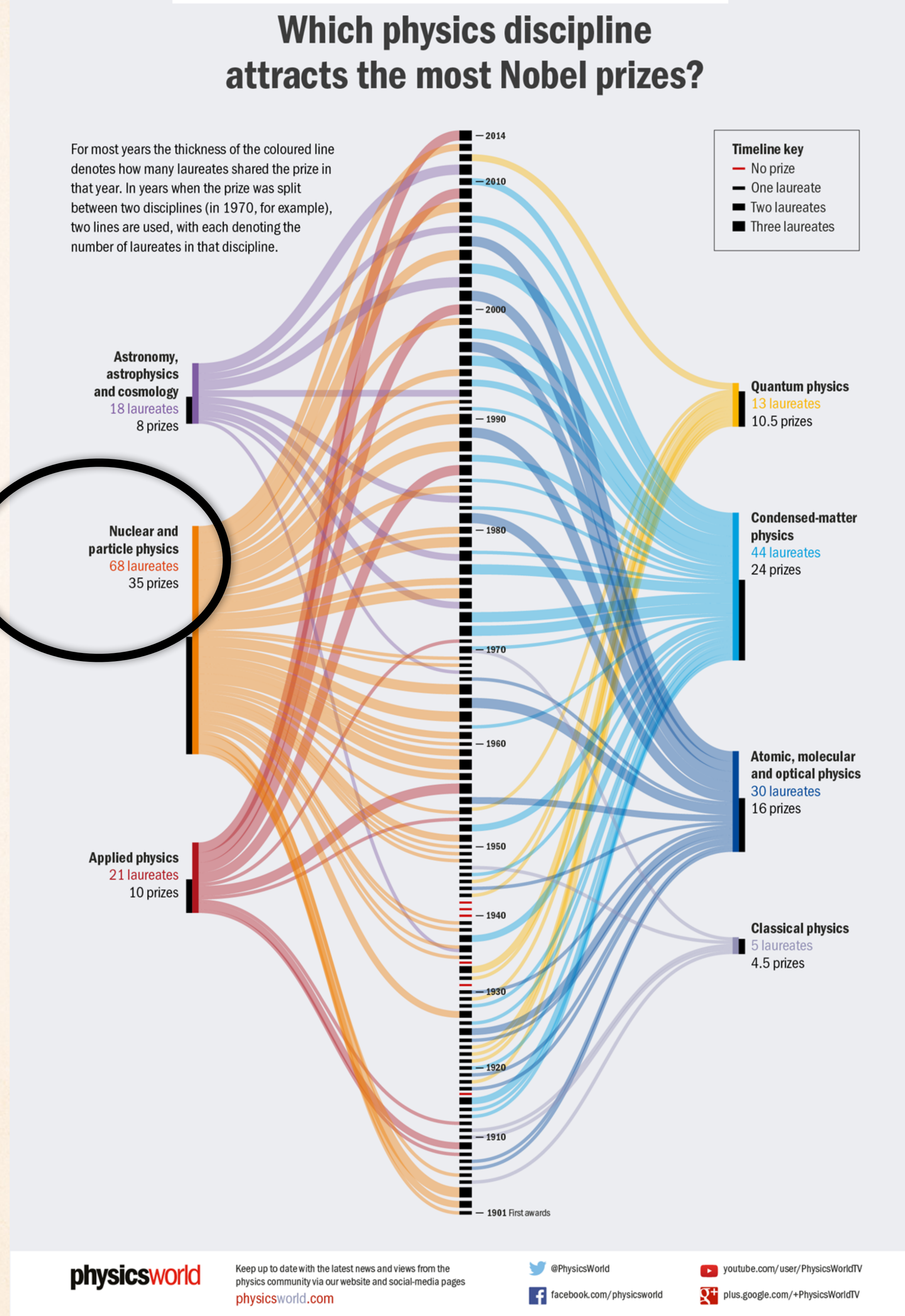
It's all connected!




History of the Universe
pp physics at the LHC corresponds to conditions around here
BIG BANG
Inflation
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Nobel Prizes

Particle Physics: 68 laureates, 35 prizes!



References

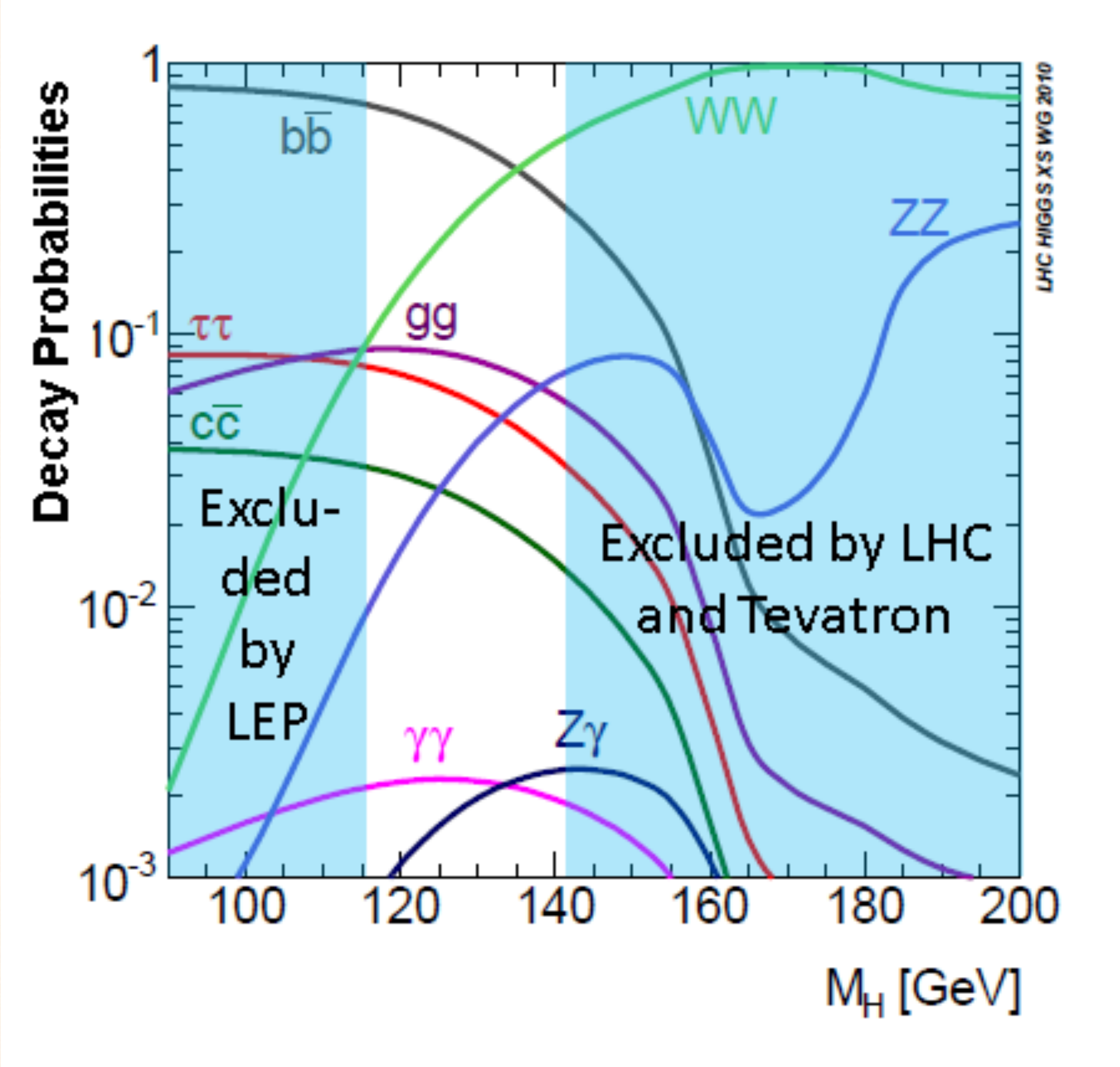
- Used CERN resources
- Used journals like Nature
- Borrowed from talks given by my colleagues: Dave Barney, Joe Incandela

ADDITIONAL MATERIAL

Higgs Decay

If you were to follow the curve for a 125 GeV Higgs, you'd get the following numbers:

60% of such particles would decay to bottom (b) quark/antiquark pairs
21% would decay to W particles
9% would decay to two gluons (g)
5% would decay to tau (τ) lepton/antilepton pairs
2.5% would decay to charm (c) quark/antiquark pairs
2.5% would decay to Z particles.
0.2% would decay to two photons (γ)
0.15% would decay to a photon and a Z particle



Let's look at the sources of neutrinos