

PARTICLE PHYSICS AT FERMILAB AND CERN

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The Team!



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

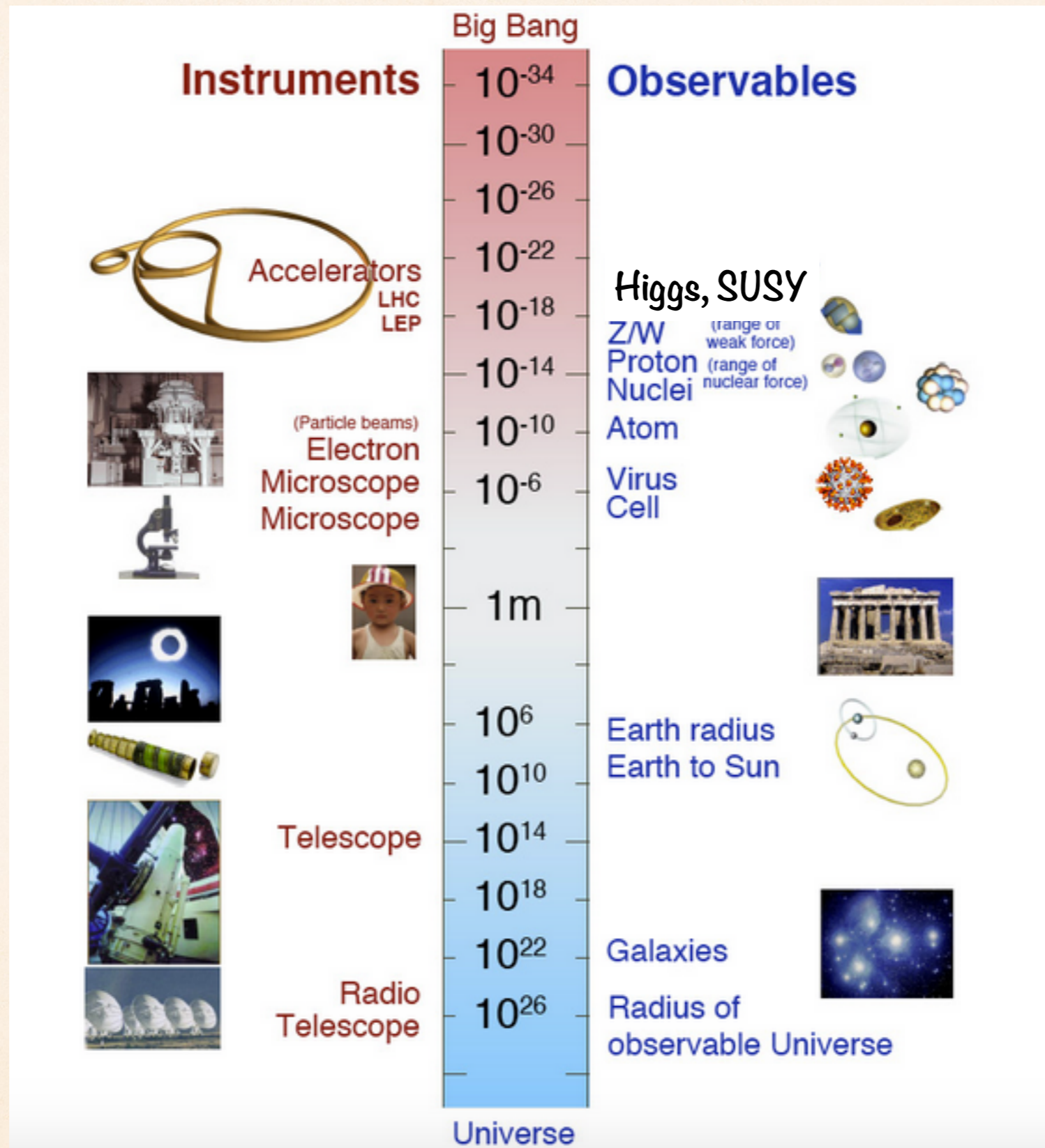


Souvik Das, Post-doc
at Purdue
Helped with setting up the
camera for observation

Thank you!!

Sense of scale

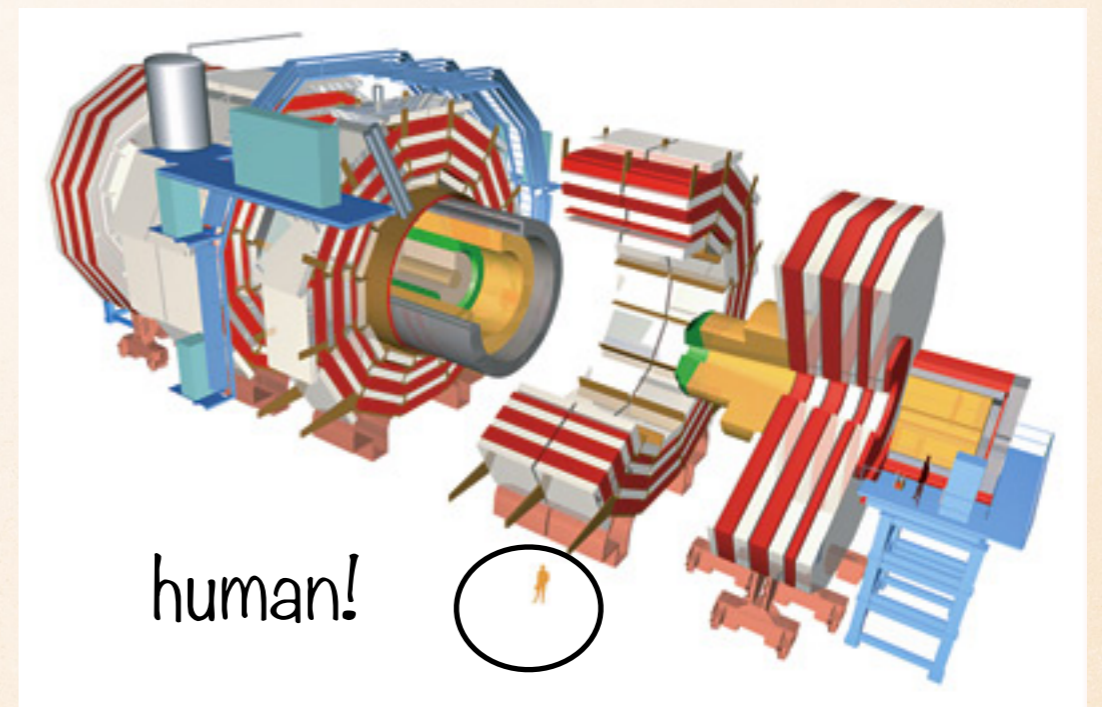
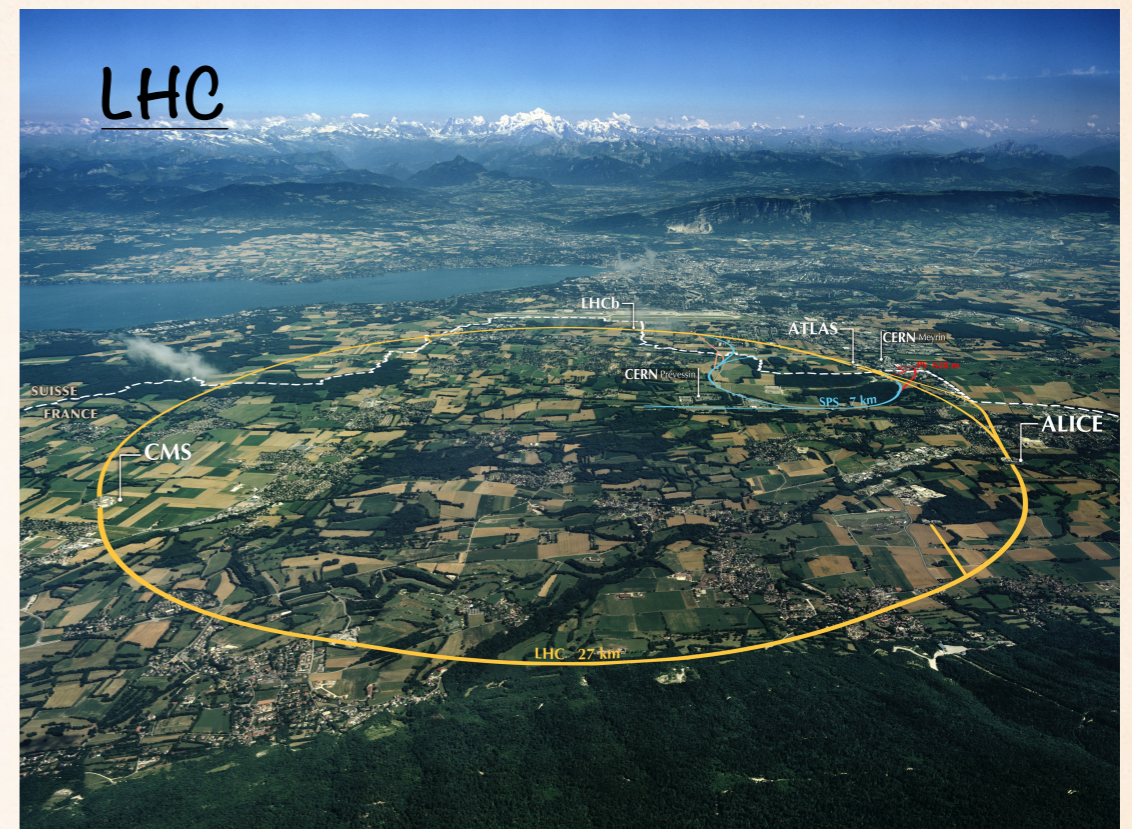
From the microscopic to the large scale structures.



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**.

Work done on electron W :

$$W = qV = (1.6 \times 10^{-19} \text{ C})(1 \frac{\text{J}}{\text{C}})$$
$$W = 1 \text{ electron volt} = 1.6 \times 10^{-19} \text{ J}$$

e = electron charge = $1.6 \times 10^{-19} \text{ C}$
 V = voltage E = electric field

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 $\sim 1 \text{ GeV}$.

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

Exercise:

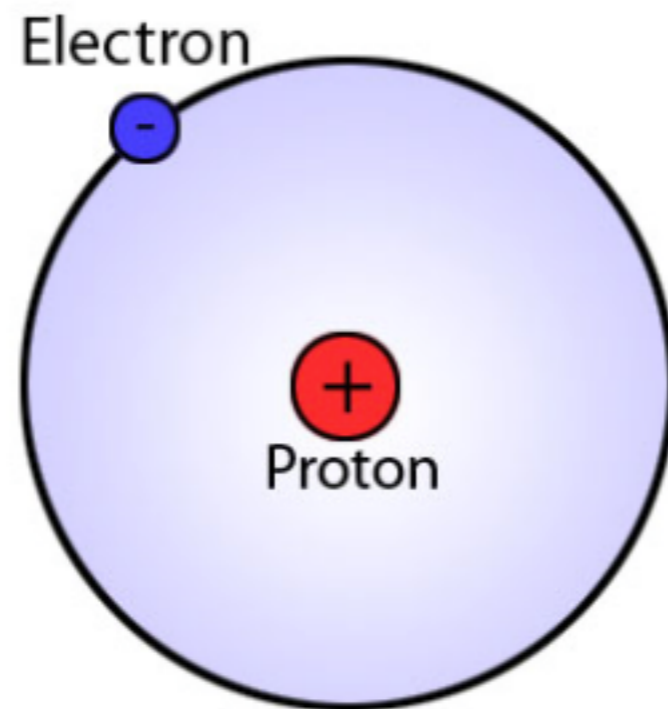
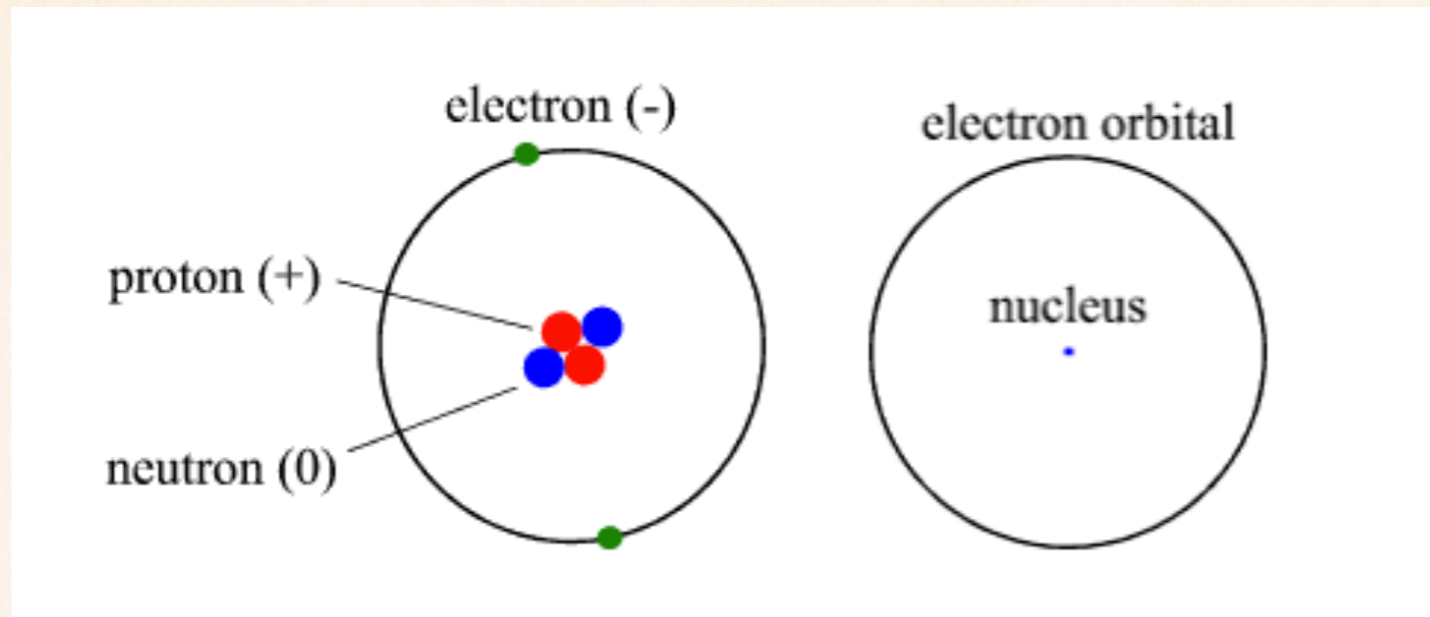
- what is $10^{13} \times 10^{-10}$?
- mass of the electron is 511 keV and the mass of the muon (to be introduced shortly) is 105 MeV. How much heavier is the muon with respect to the electron?
- how much heavier is the Higgs boson (mass of 125 GeV) with respect to the electron?

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?
 $125*1000 \text{ MeV}/0.5 \text{ MeV} = 250,000$ 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

LEPTONS

Make up matter	Electron Together with the nucleus, it makes up the atom 	Electron neutrino Particle with no electric charge, and very small mass; billions fly through your body every second 
	Muon A heavier relative of the electron; it lives for two-millionths of a second 	Muon neutrino Created along with muons when some particles decay 
	Tau Heavier still; it is extremely unstable. It was discovered in 1975 	Tau neutrino Discovered in 2000 

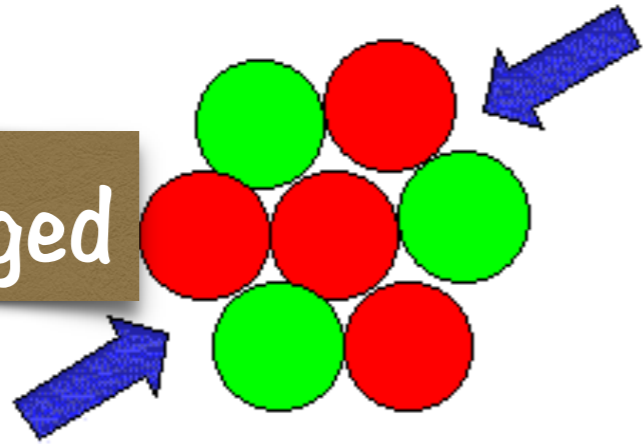
QUARKS

Make up matter	Up Has an electric charge of plus two-thirds; protons contain two, neutrons contain one 	Down Has an electric charge of minus one-third; protons contain one, neutrons contain two 
	Charm A heavier relative of the up; found in 1974 	Strange A heavier relative of the down. 
	Top Heavier still; found in 1995 	Bottom Heavier still; measuring bottom quarks is an important test of electroweak theory 

- 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

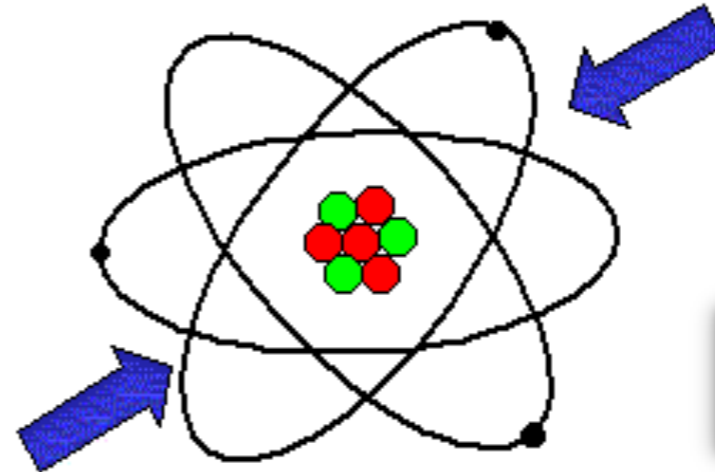
The four fundamental forces

Short ranged

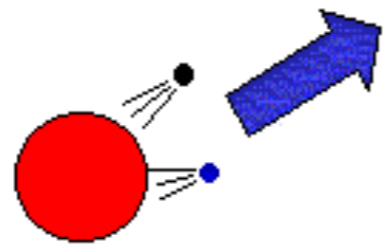


**Strong force
binds the nucleus**

Long ranged

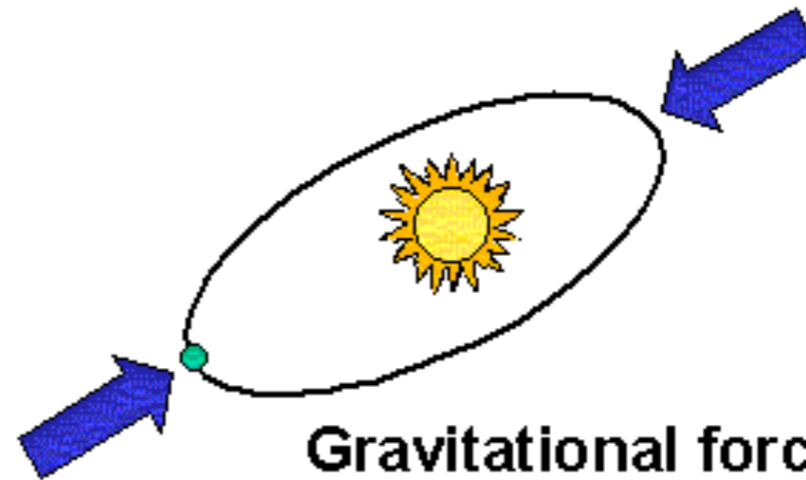


**Electromagnetic
force binds atoms**



**Weak force in
radioactive decay**

Weak and
short ranged



**Gravitational force
binds the solar system**

Weak, but very
long ranged

The Standard Model of Particle Physics

Three Generations of Matter (Fermions) spin $\frac{1}{2}$

	I	II	III		
mass →	2.4 MeV	1.27 GeV	171.2 GeV	0	0
charge →	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0
name →	u up	c charm	t top	g gluon	
	Left Right	Left Right	Left Right		
	4.8 MeV	104 MeV	4.2 GeV	0	0
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0	0
	d down	s strange	b bottom	γ photon	
	Left Right	Left Right	Left Right		
	0 eV	0 eV	0 eV	91.2 GeV	>114 GeV
	0	0	0	0	0
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	Z⁰ weak force	H Higgs boson
	Left	Left	Left		
	0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV	
	-1	-1	-1	± 1	
	e electron	μ muon	τ tau	W[±] weak force	
	Left Right	Left Right	Left Right		

Quarks

Leptons

Bosons (Forces) spin 1

spin 0

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

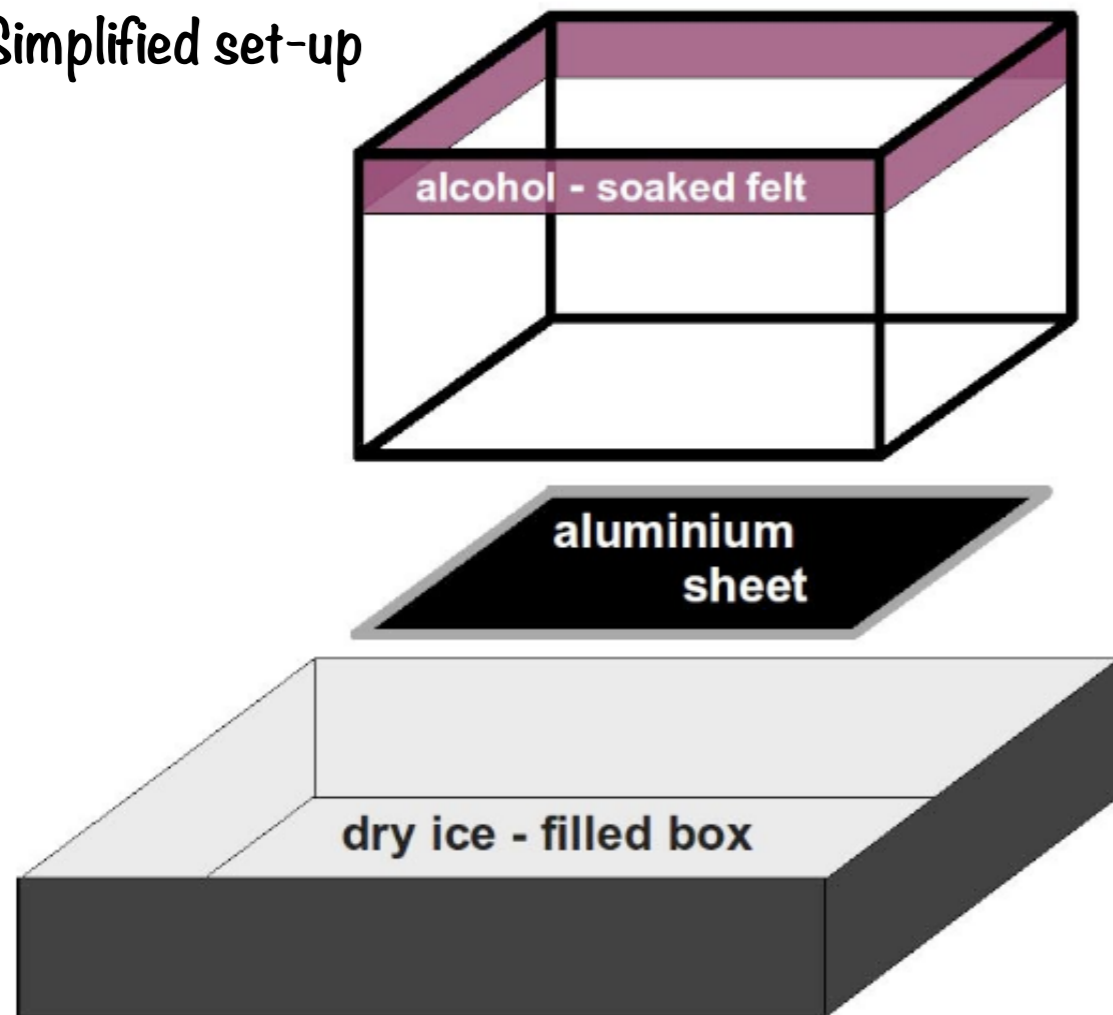
See the apparatus set up here?



This apparatus is called a cloud chamber

How does it work?

Simplified set-up

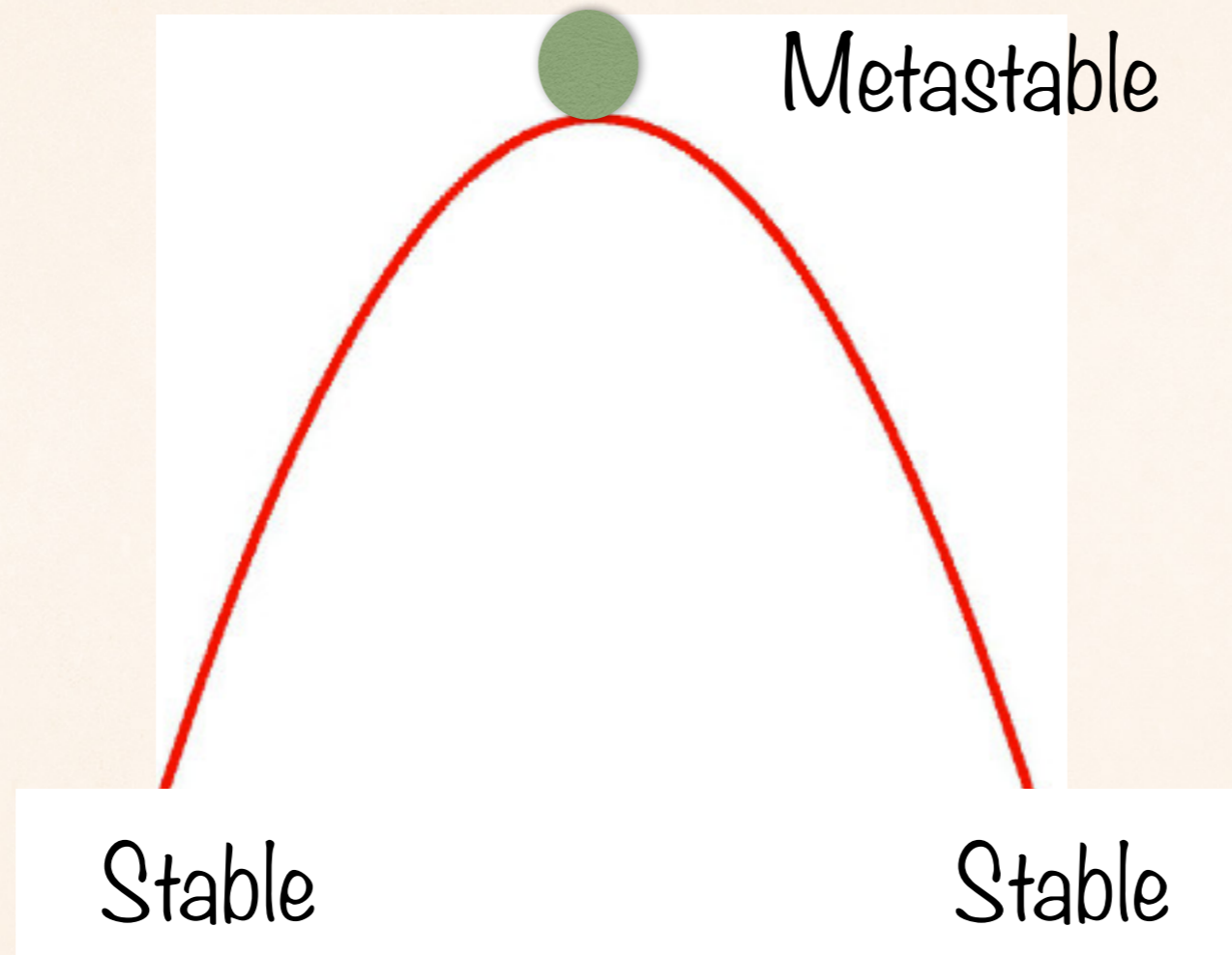


- The dry ice keeps the lower layer very cold (in this case the cooling is done differently)
- So, while the top layer has alcohol at a higher temperature, the bottom layer is much colder
- When a particle passes through the chamber it ionizes the alcohol which then causes alcohol droplets to condense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



Same principle here

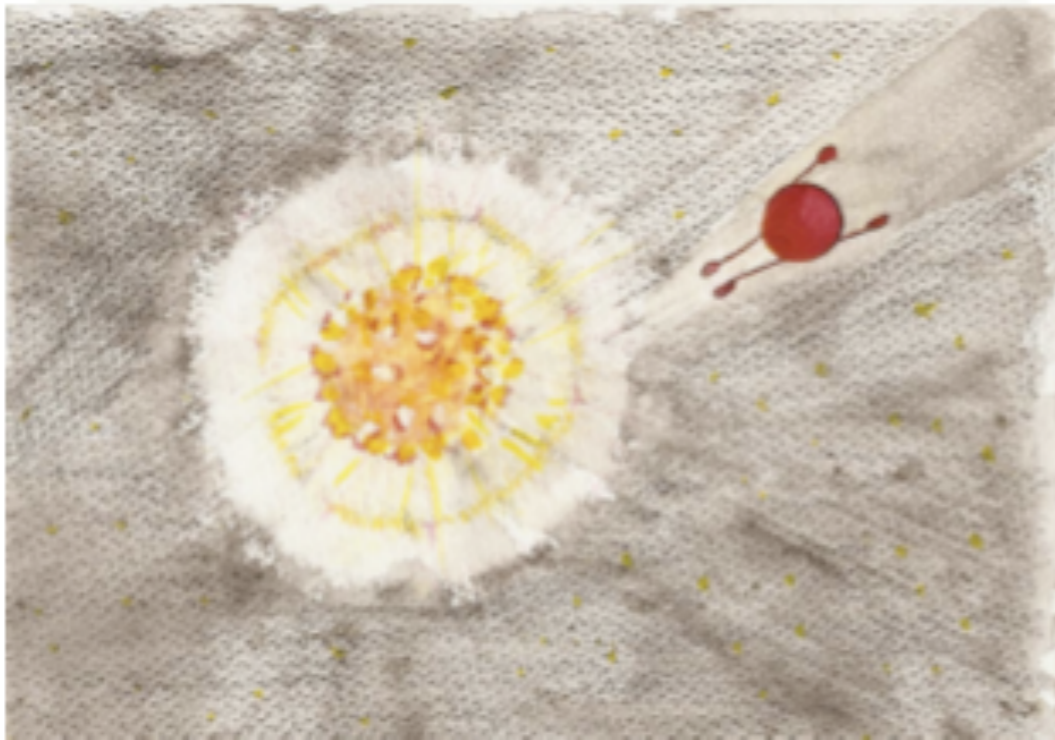
Very brief detour



To be drawn on the black-board

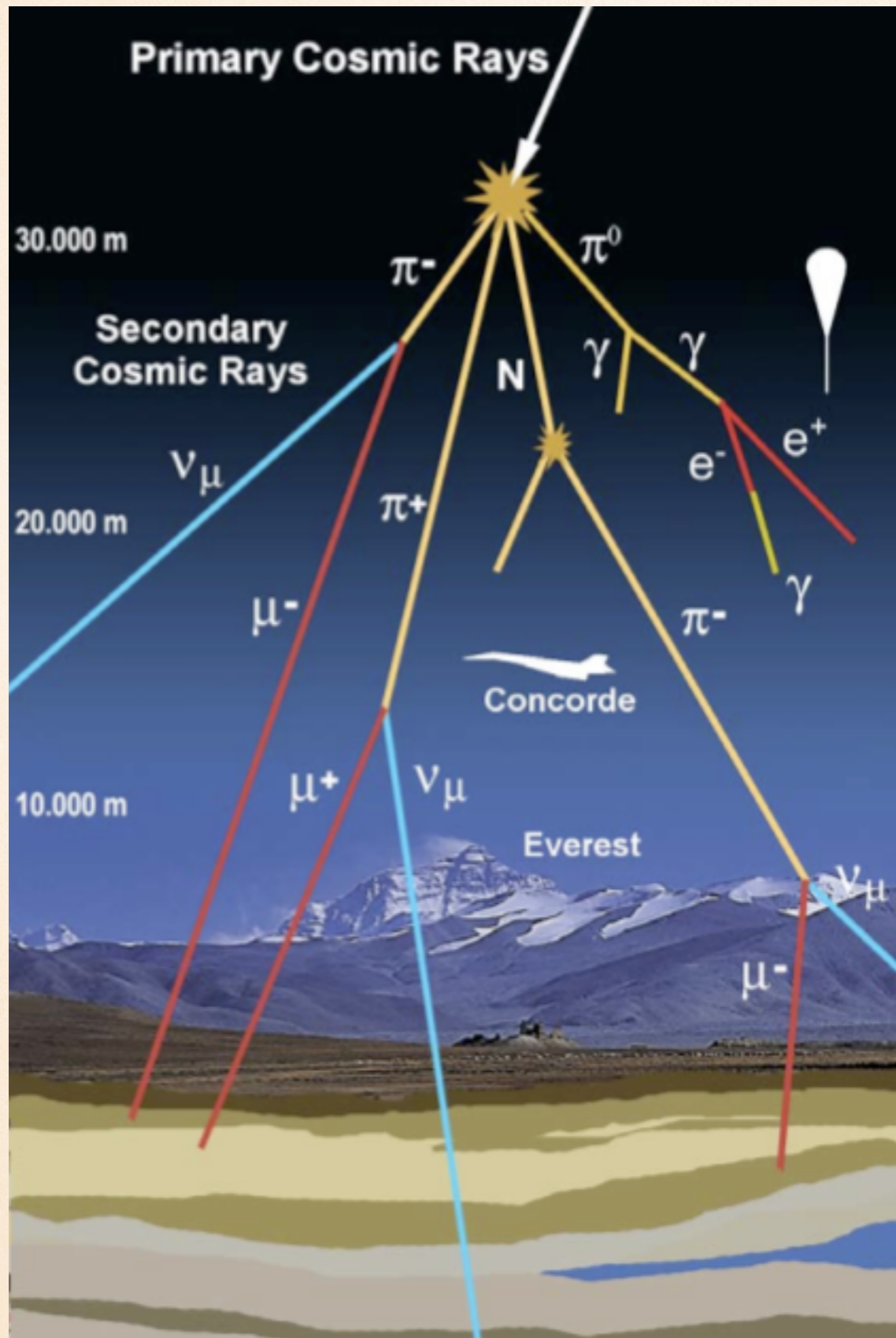
What are we trying to observe?

A LONG TIME AGO
IN A STAR FAR, FAR
AWAY, A PROTON
WAS ACCELERATED
IN A SUPERNOVA
EXPLOSION



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

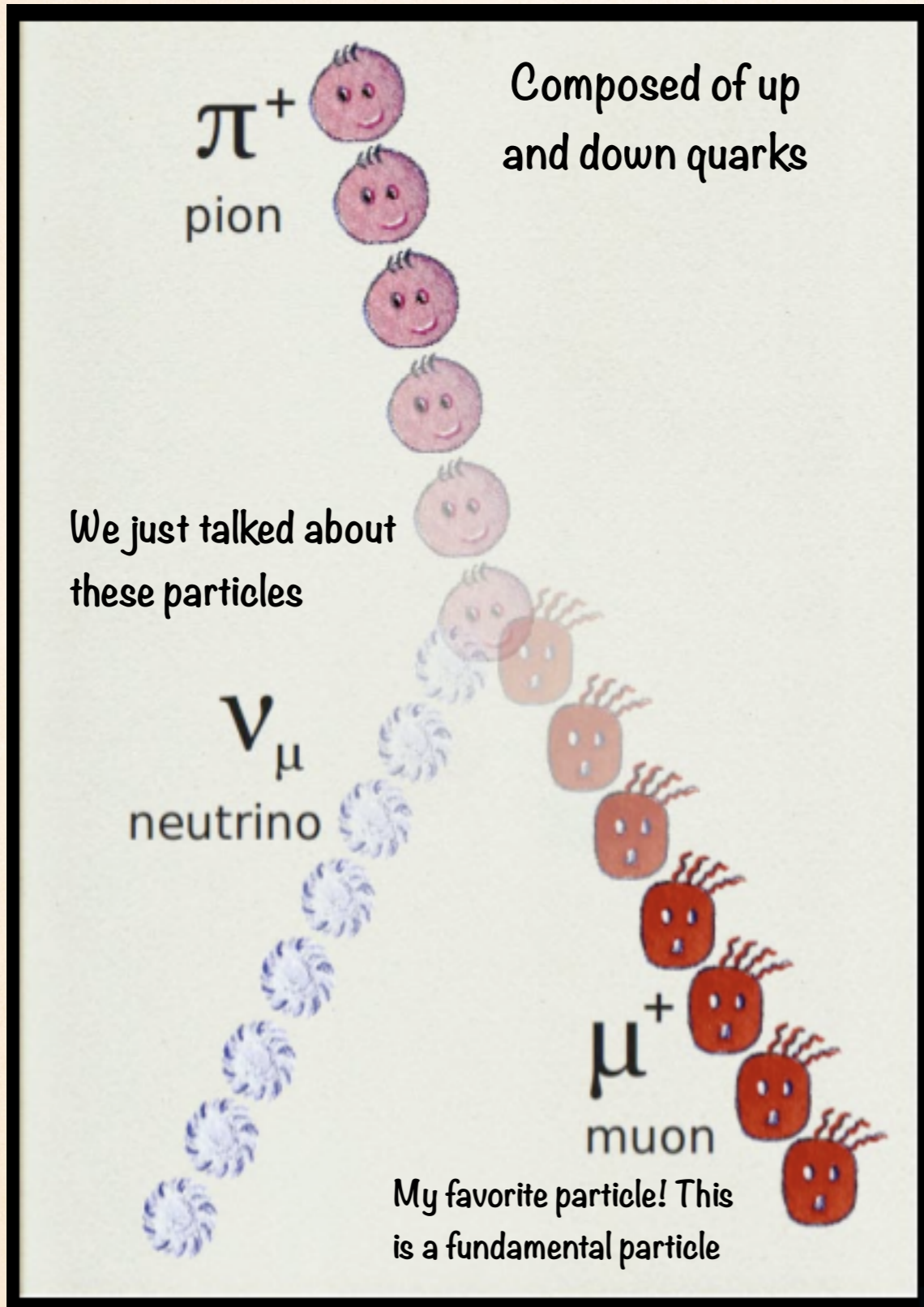
What are we trying to observe?



- 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

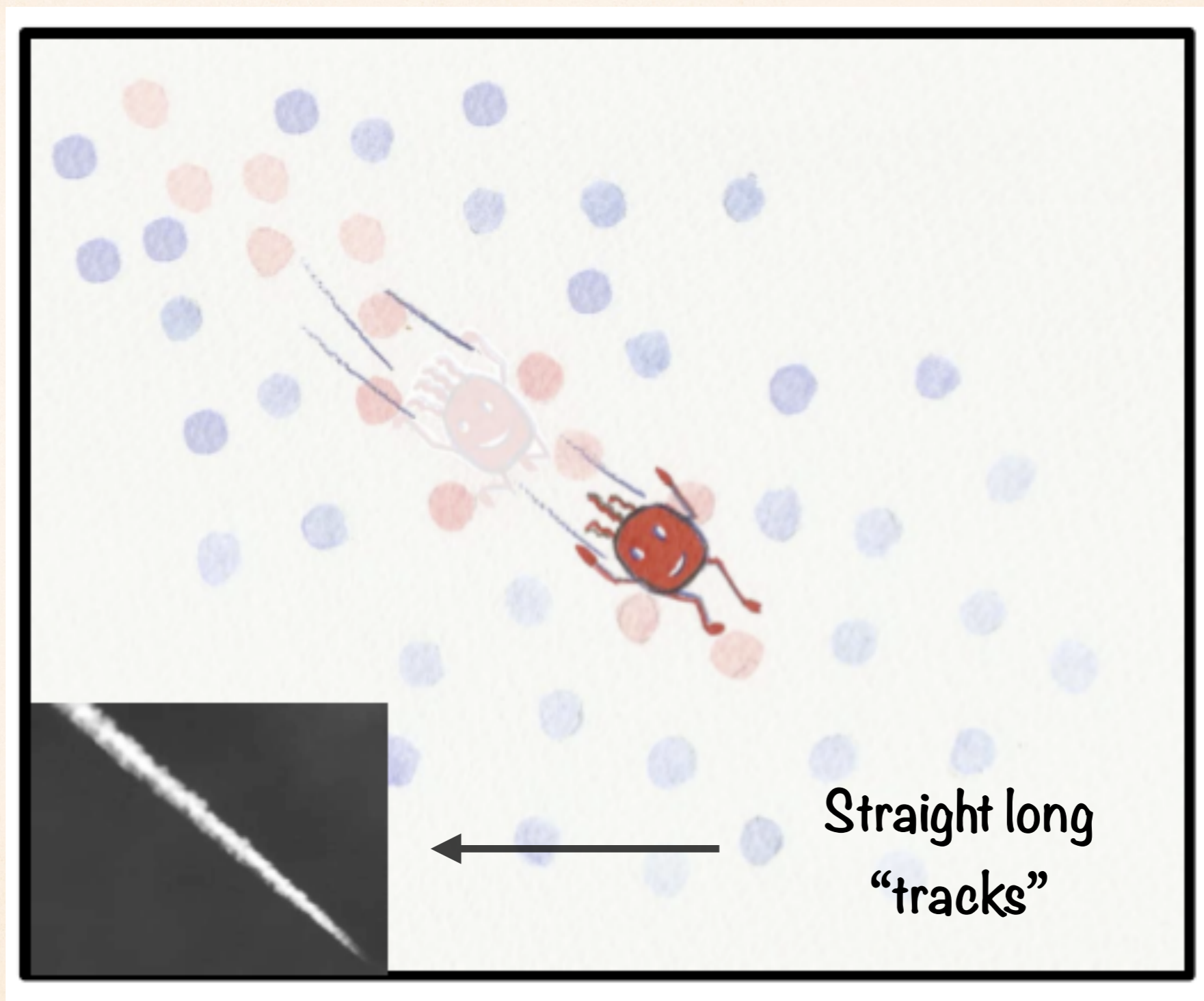
Pretty incredible!!

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

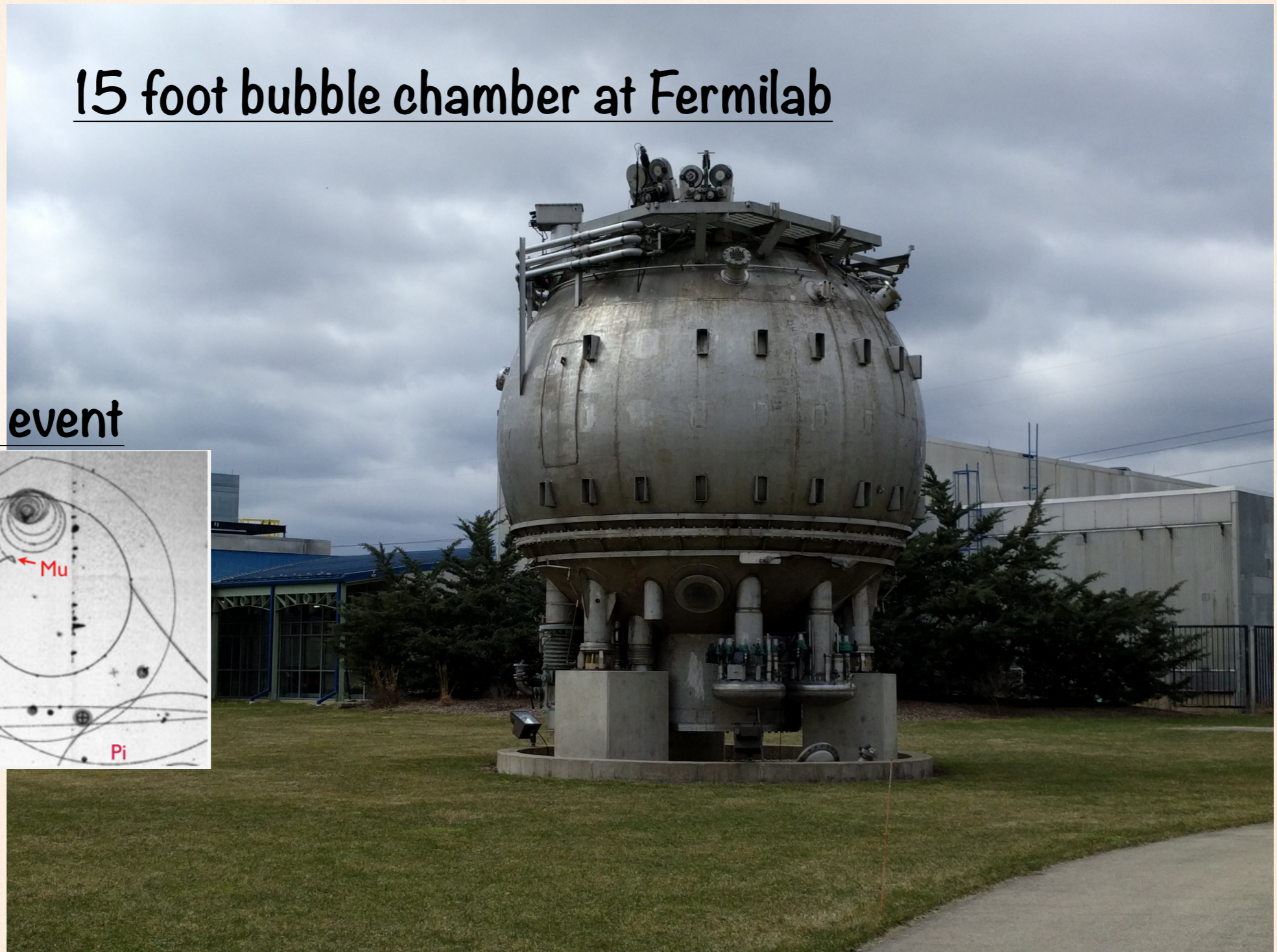
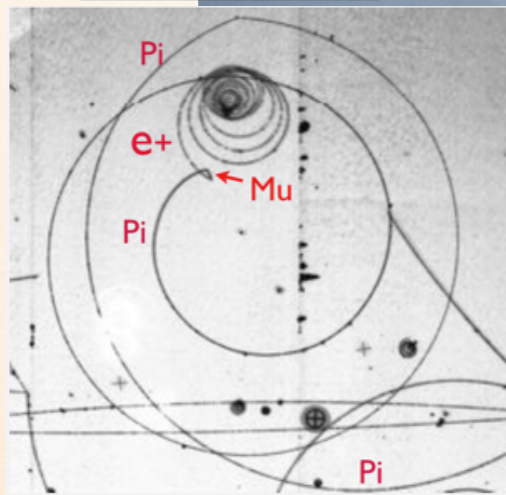
What does the muon look like?



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

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name →	Left u Right up	Left c Right charm	Left t Right top	g gluon	
	Left d Right down	Left s Right strange	Left b Right bottom	γ photon	
	Left ν_e electron neutrino	Left ν_μ muon neutrino	Left ν_τ tau neutrino	91.2 GeV 0 Z⁰ weak force	>114 GeV 0 H Higgs boson
	Left e Right electron	Left μ Right muon	Left τ Right tau	80.4 GeV ± 1 W[±] weak force	spin 0

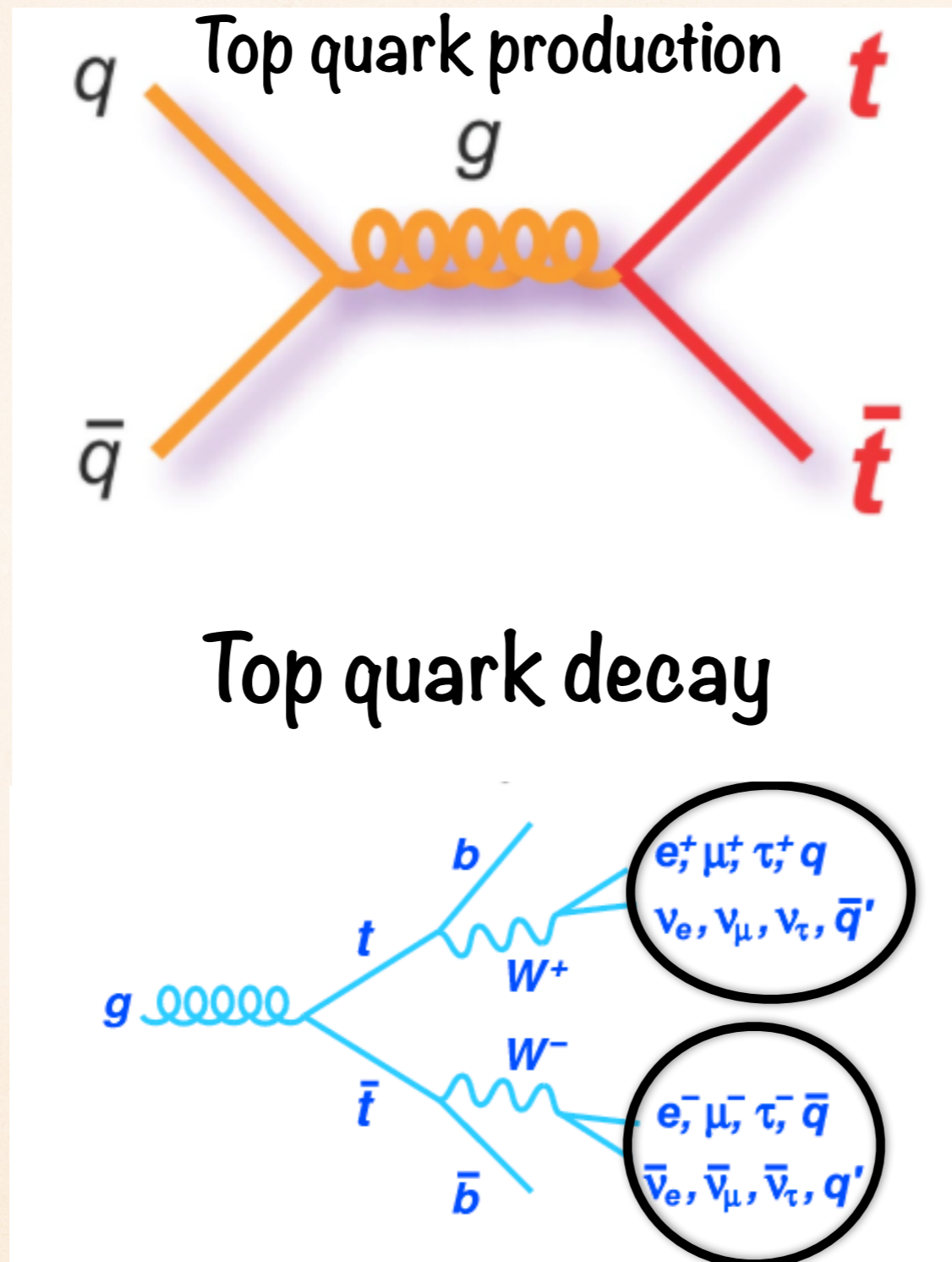
Let's talk about the top (bottom) quark next

Bosons (Forces) spin 1

An aerial view of the Tevatron



Discovery of the top quark: Feynman Diagrams



Let's pause for a moment...

Any questions?

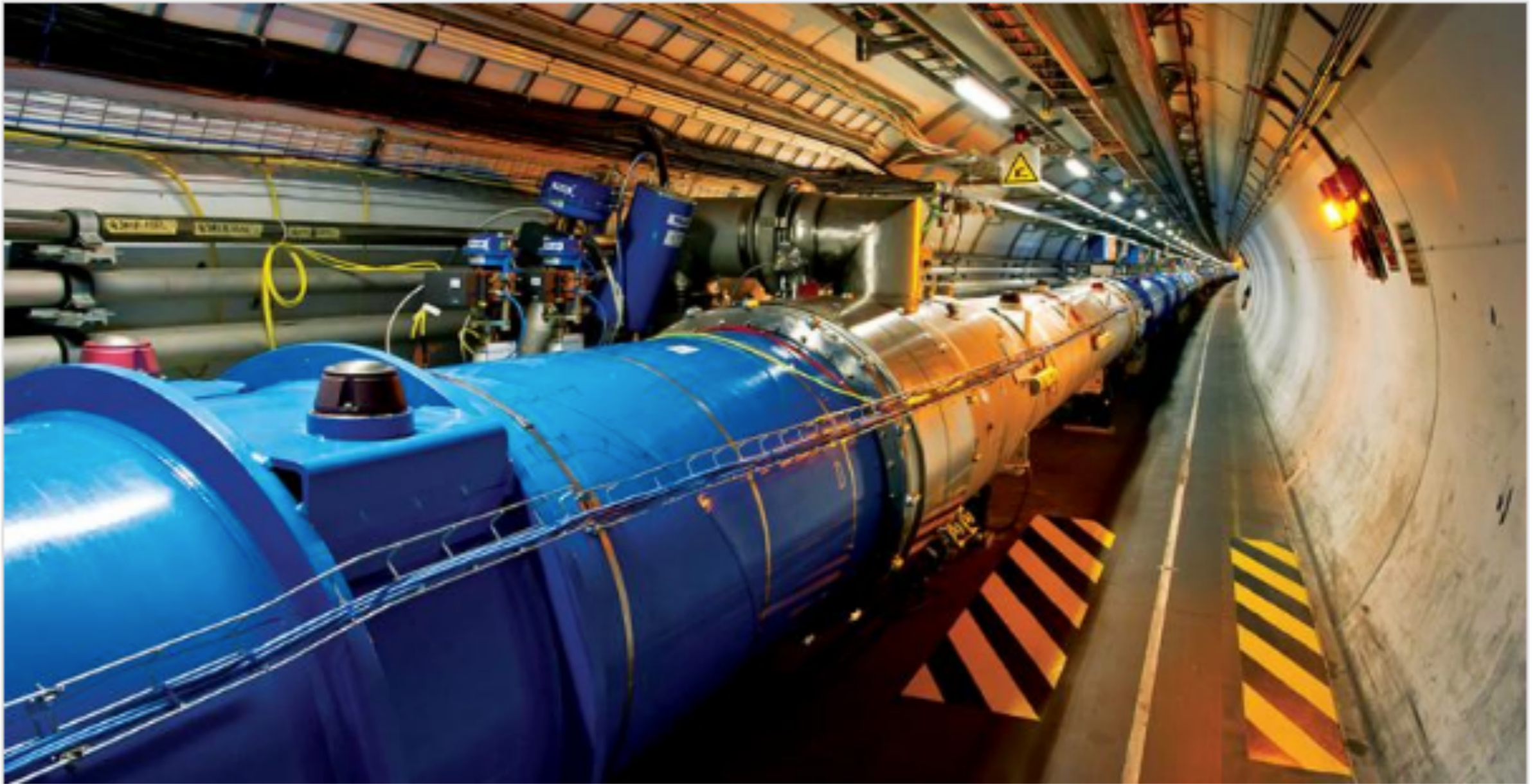
The Standard Model of Particle Physics

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Quarks	0 eV	0 eV	0 eV	Z⁰ weak force	>114 GeV
	Left ν_e electron neutrino	Left ν_μ muon neutrino	Left ν_τ tau neutrino	80.4 GeV	0
	0.511 MeV	105.7 MeV	1.777 GeV	W[±] weak force	0
	-1	-1	-1		0
Leptons	Left e Right electron	Left μ Right muon	Left τ Right tau		H Higgs boson
					spin 0

Let's talk about the Higgs boson next

The Large Hadron Collider



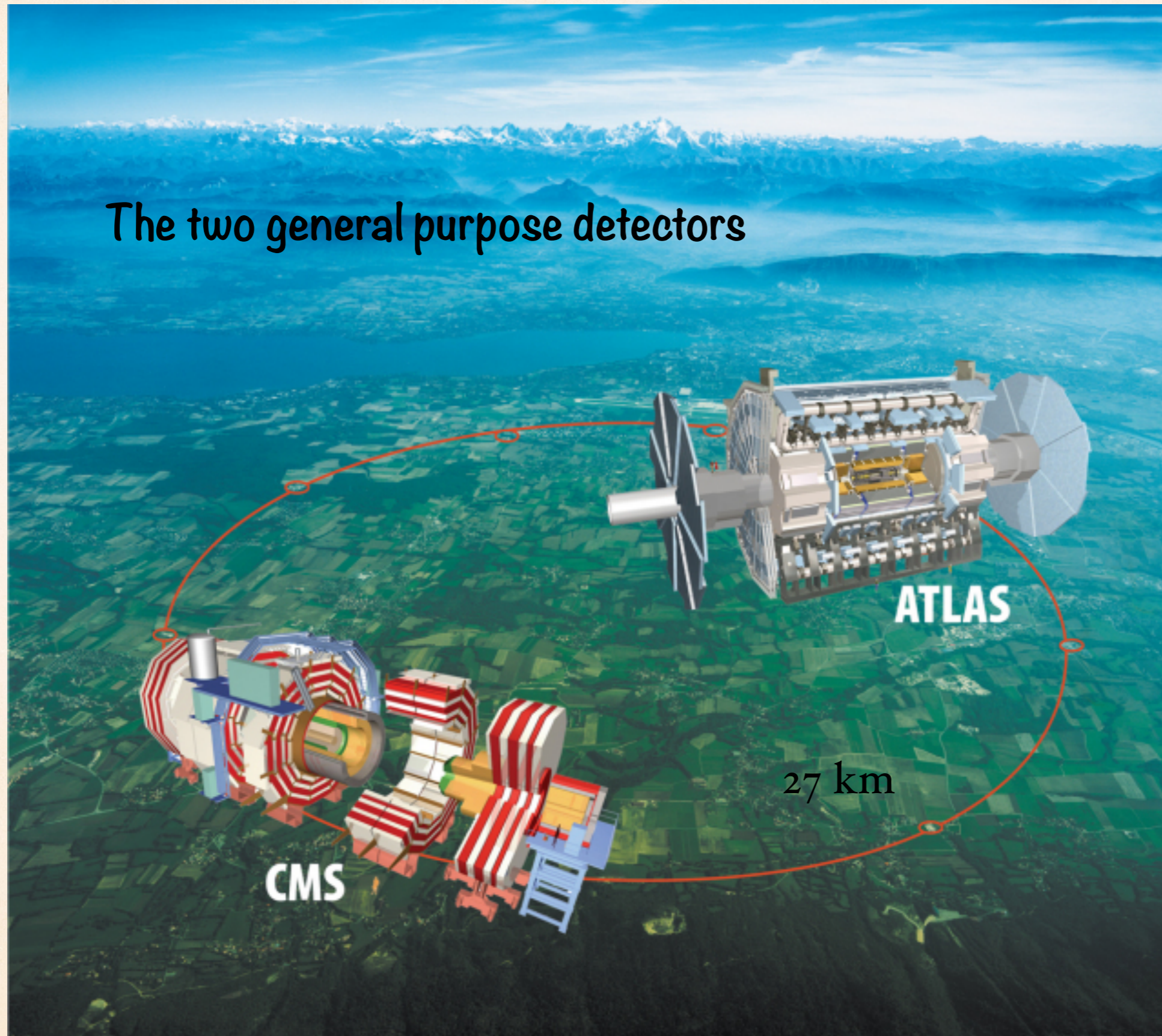
The Large Hadron Collider is the world's largest and most powerful particle accelerator (Image: CERN)

Aerial view of The Large Hadron Collider



Aerial view of The Large Hadron Collider

The two general purpose detectors

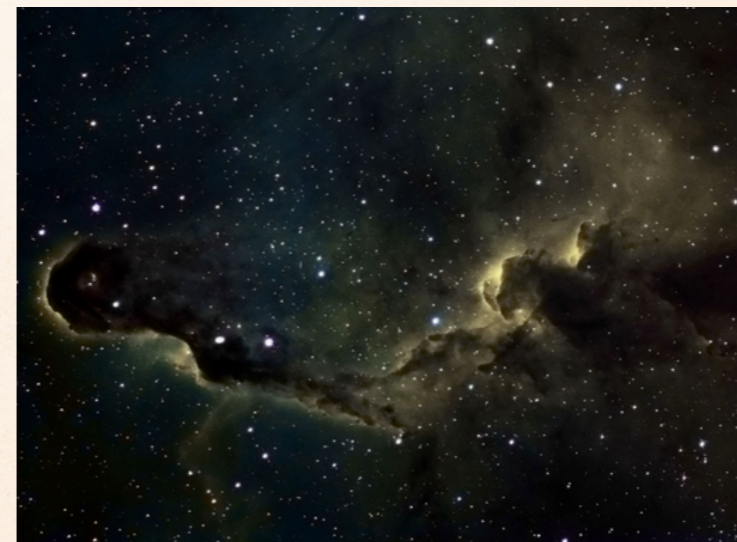


The Large Hadron Collider (LHC)

- 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



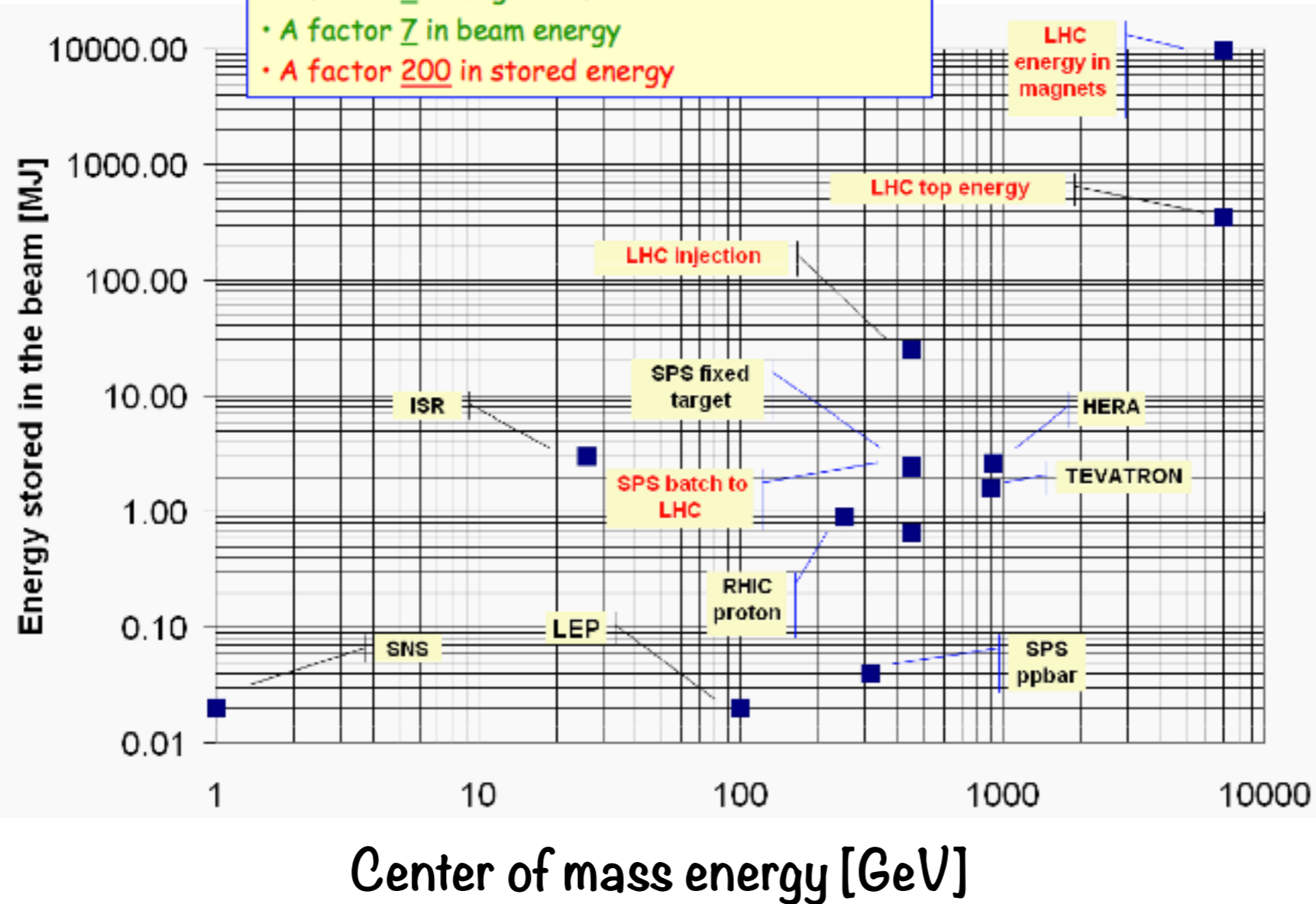
Protons accelerated in bunches

The Large Hadron Collider

Stored Energy

Increase with respect to existing accelerators :

- A factor 2 in magnetic field
- A factor 7 in beam energy
- A factor 200 in stored energy



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

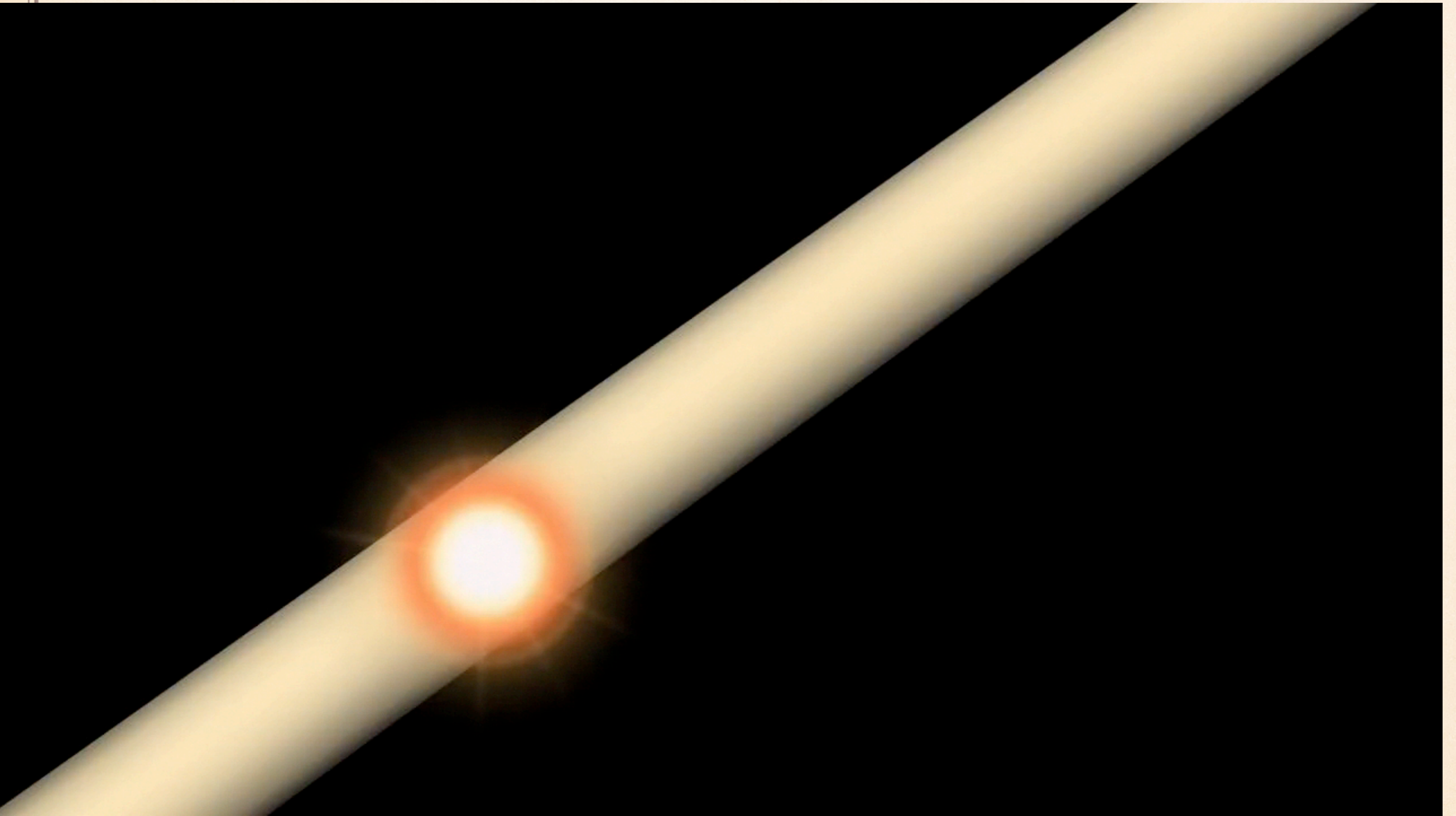


Panoramic view of the LHC.



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

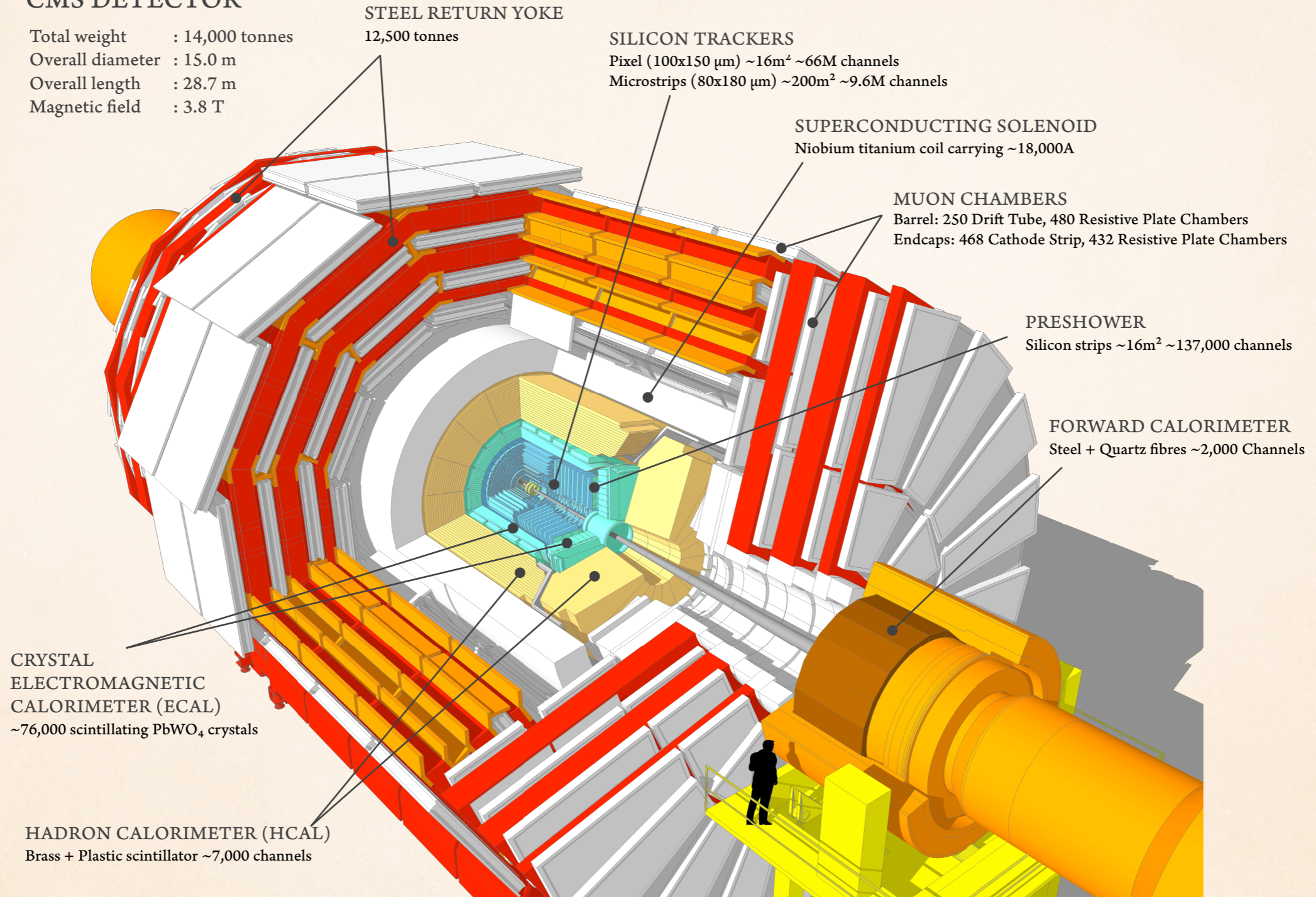
What happens at the LHC



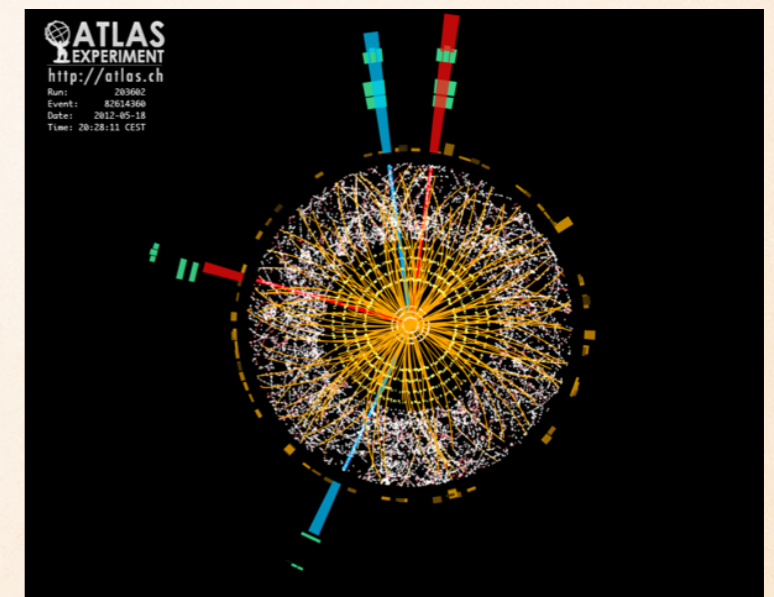
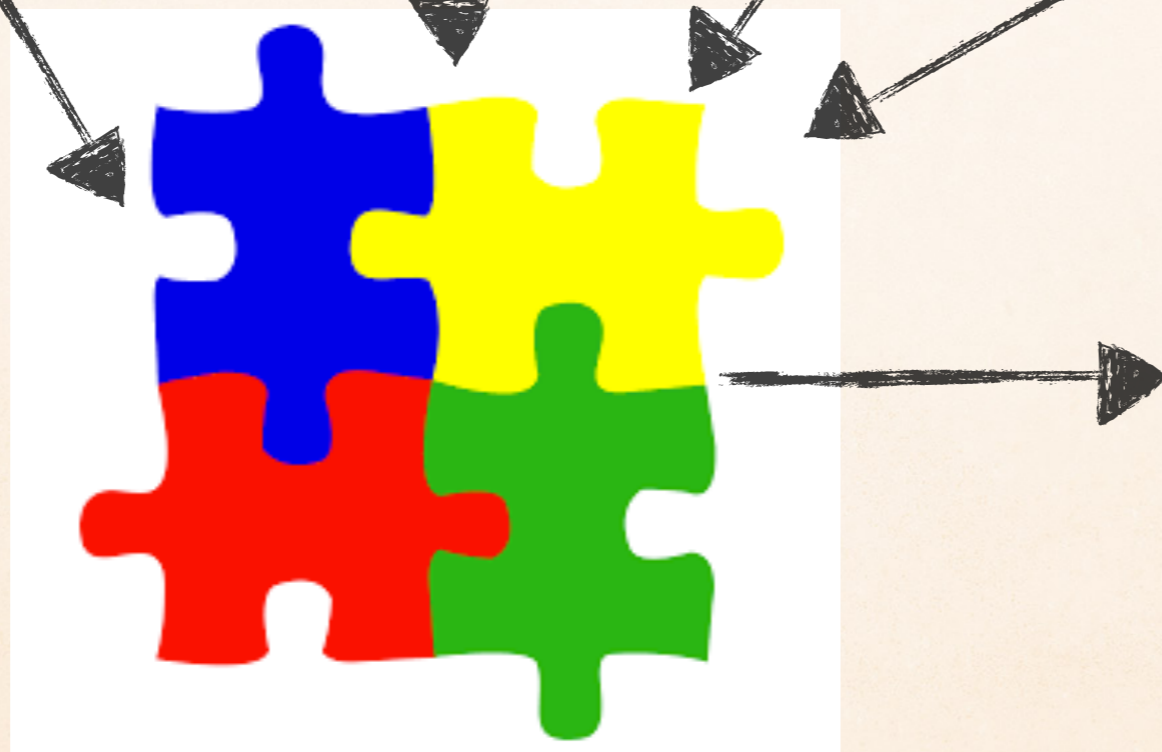
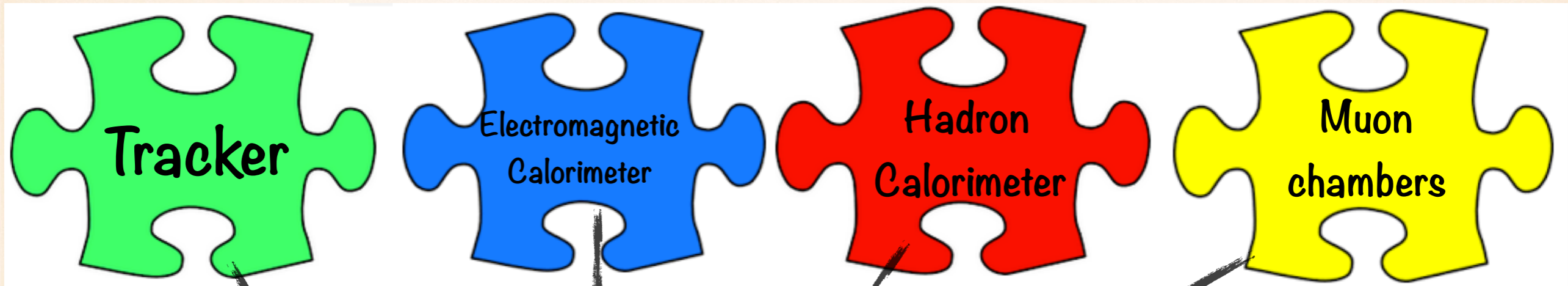
The CMS Detector

CMS DETECTOR

Total weight : 14,000 tonnes
 Overall diameter : 15.0 m
 Overall length : 28.7 m
 Magnetic field : 3.8 T



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

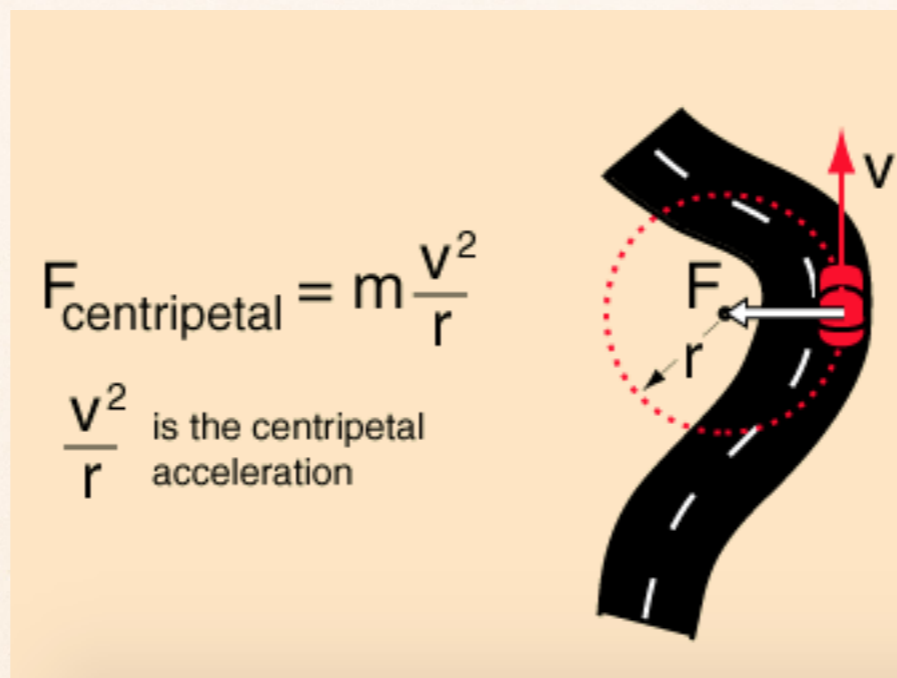
- $E=mc^2$ if a particle of mass m is at rest. So $E^2=(mc^2)^2$
- If a particle has momentum p , then $E^2=(mc^2)^2+(pc)^2$
- For a massless particle ($m=0$), you get $E=|p|c$
- Particle detection relies on measuring E and p in a detector, so that the mass of a particle can be computed
- Often, in particle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

A brief detour

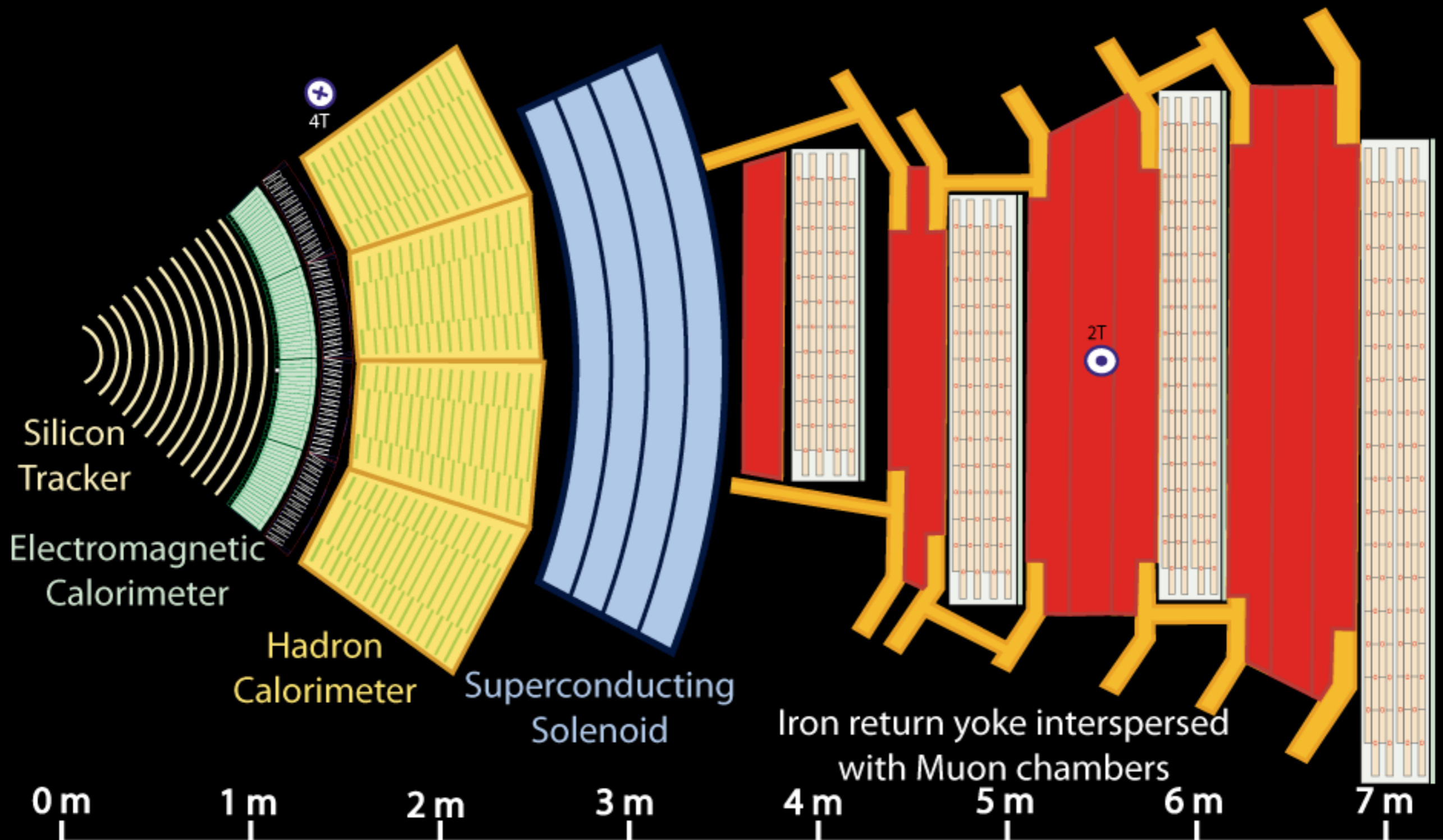
Force is acting on a particle in a magnetic field (called Lorentz force)

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

What other force is acting on a particle?



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



Key:

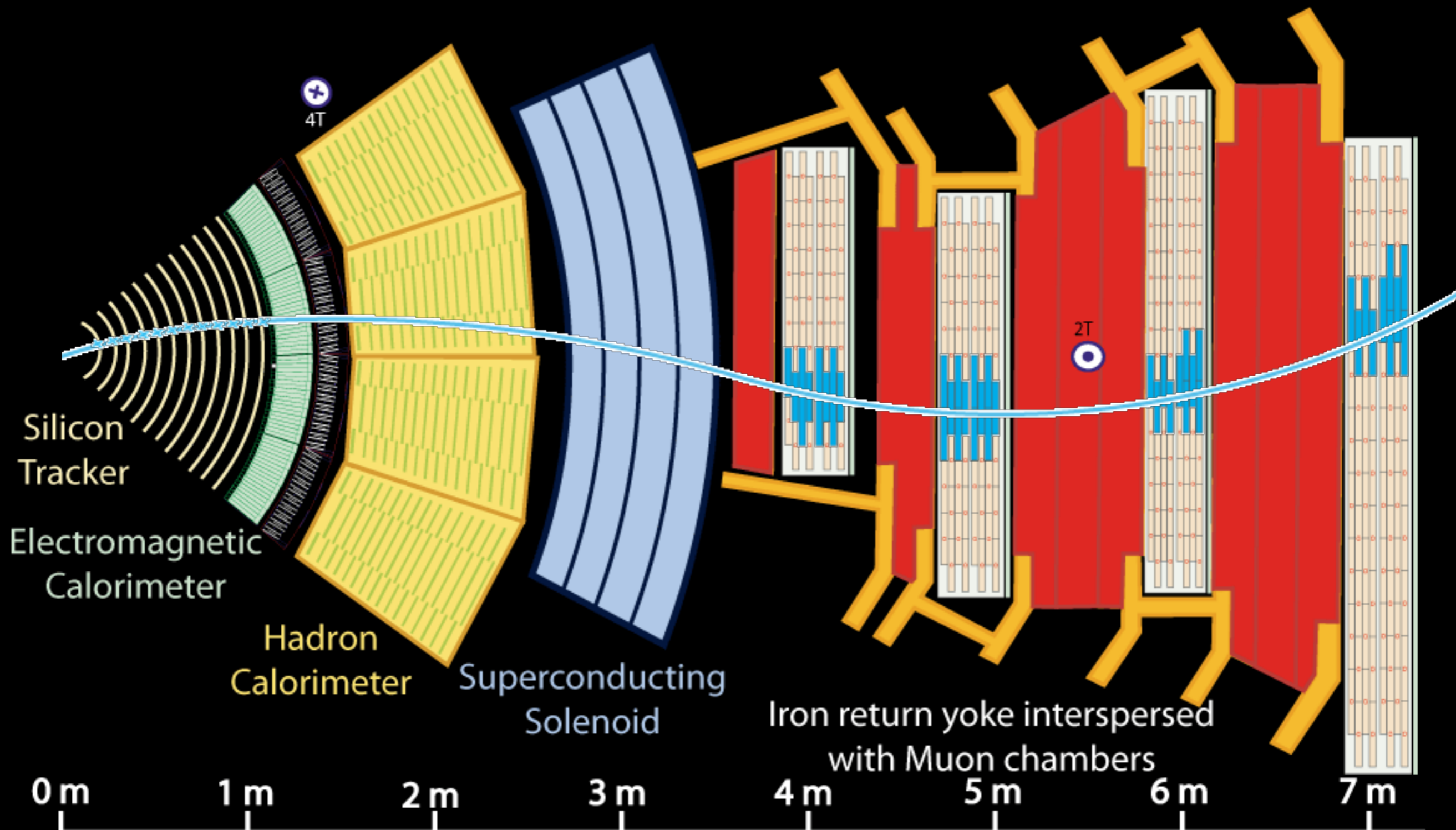
— Muon

— Electron

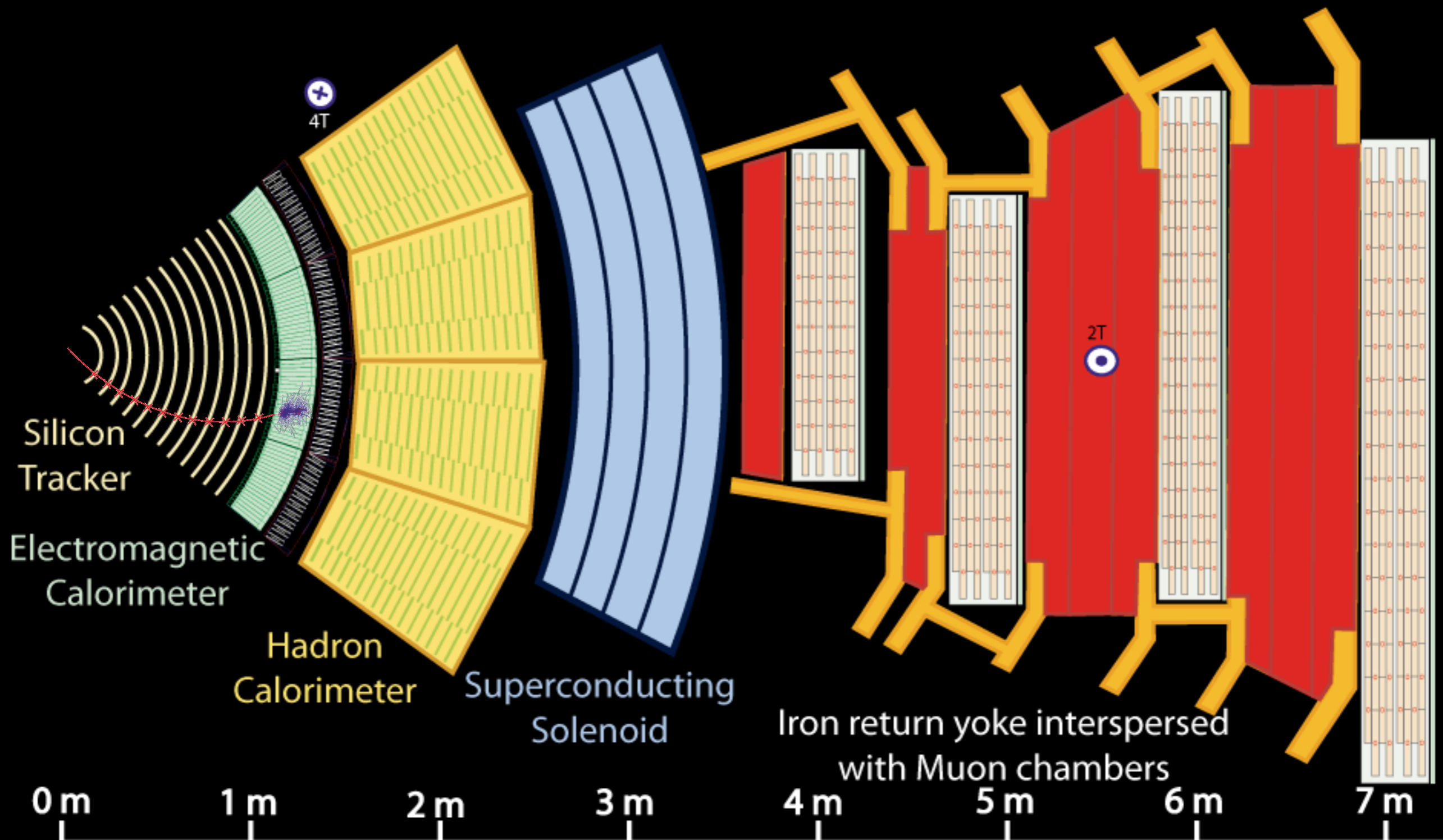
— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

- - - Photon

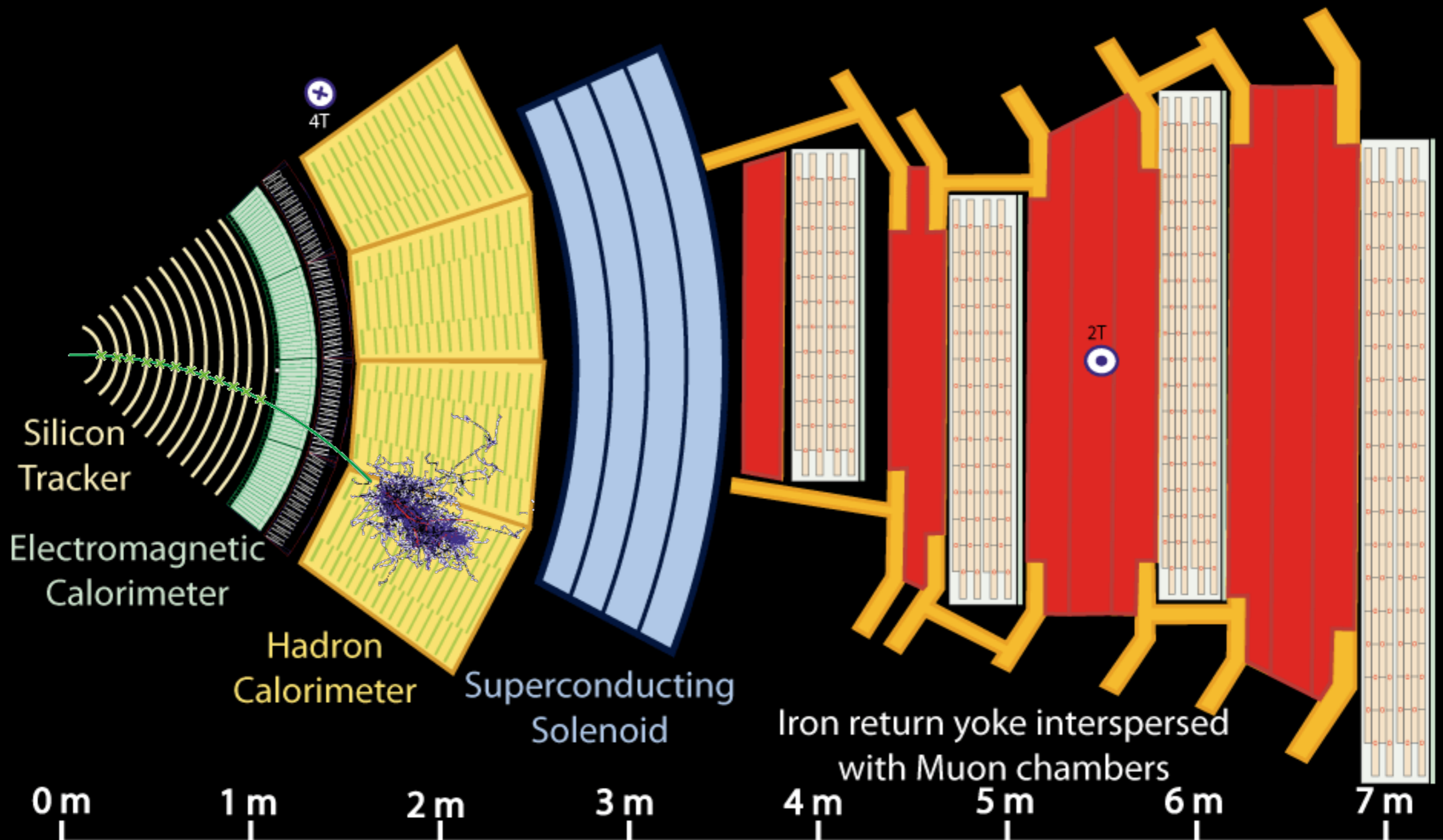


- Key:
- Muon
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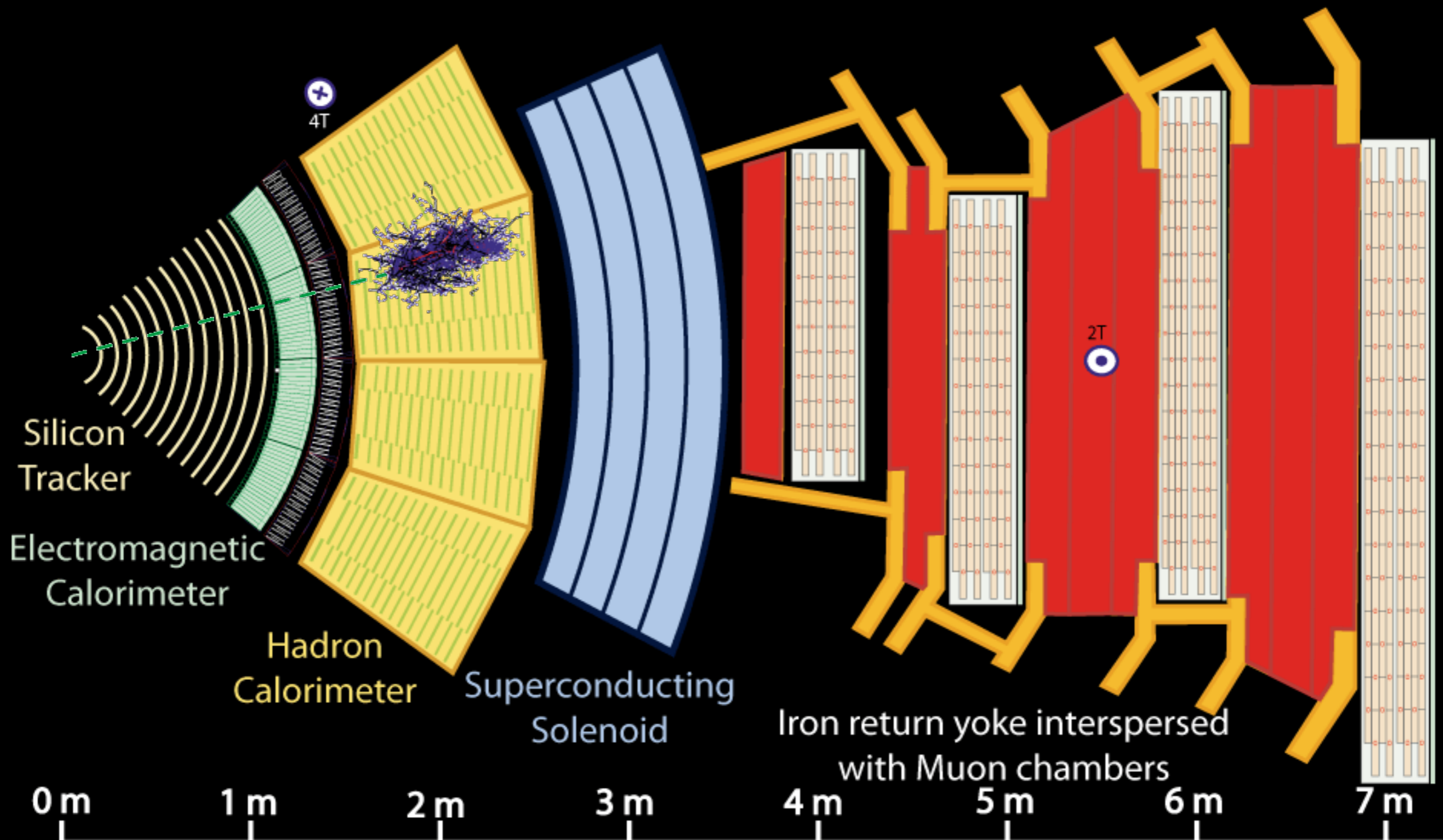
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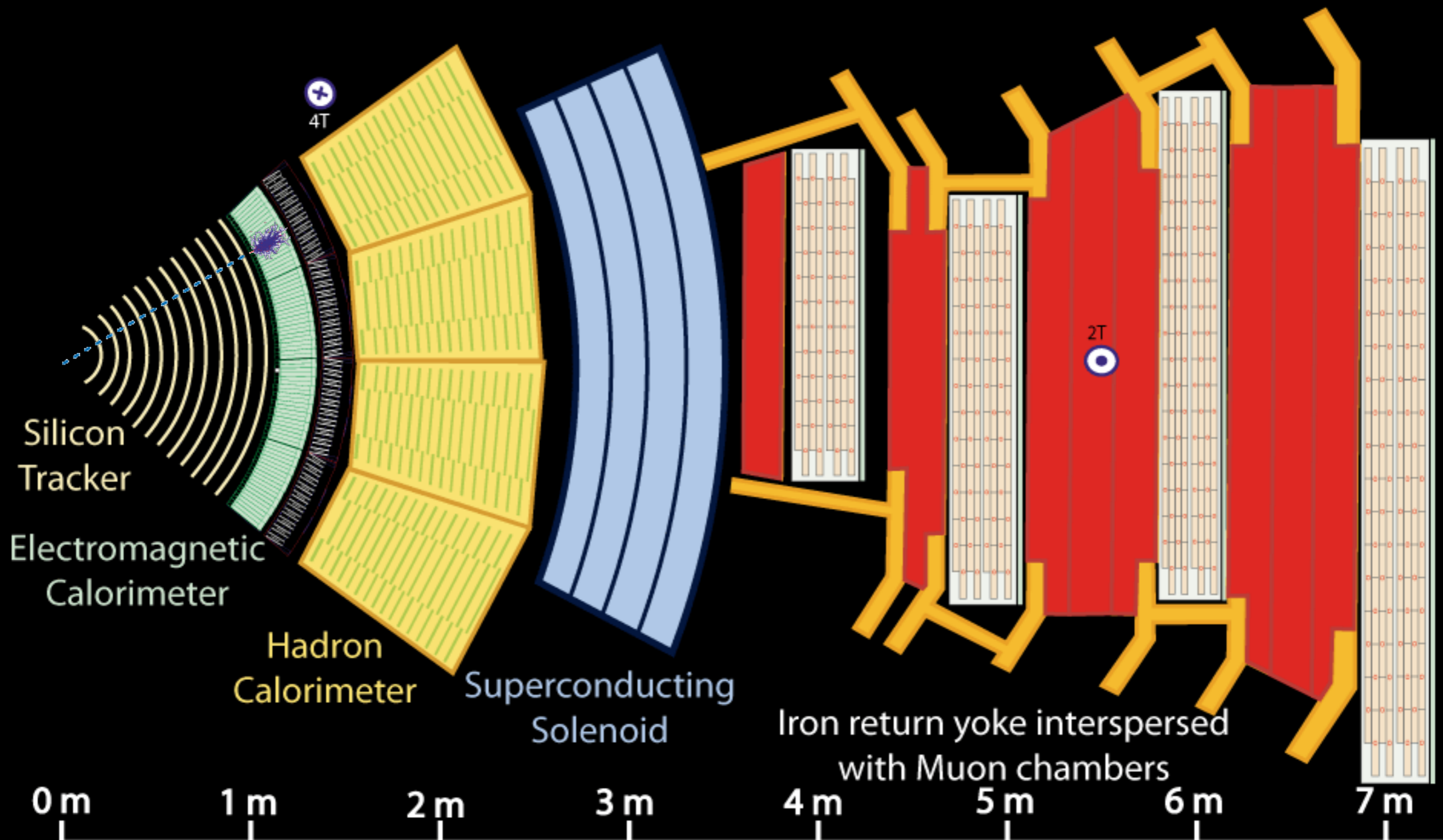
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Key:

— Muon

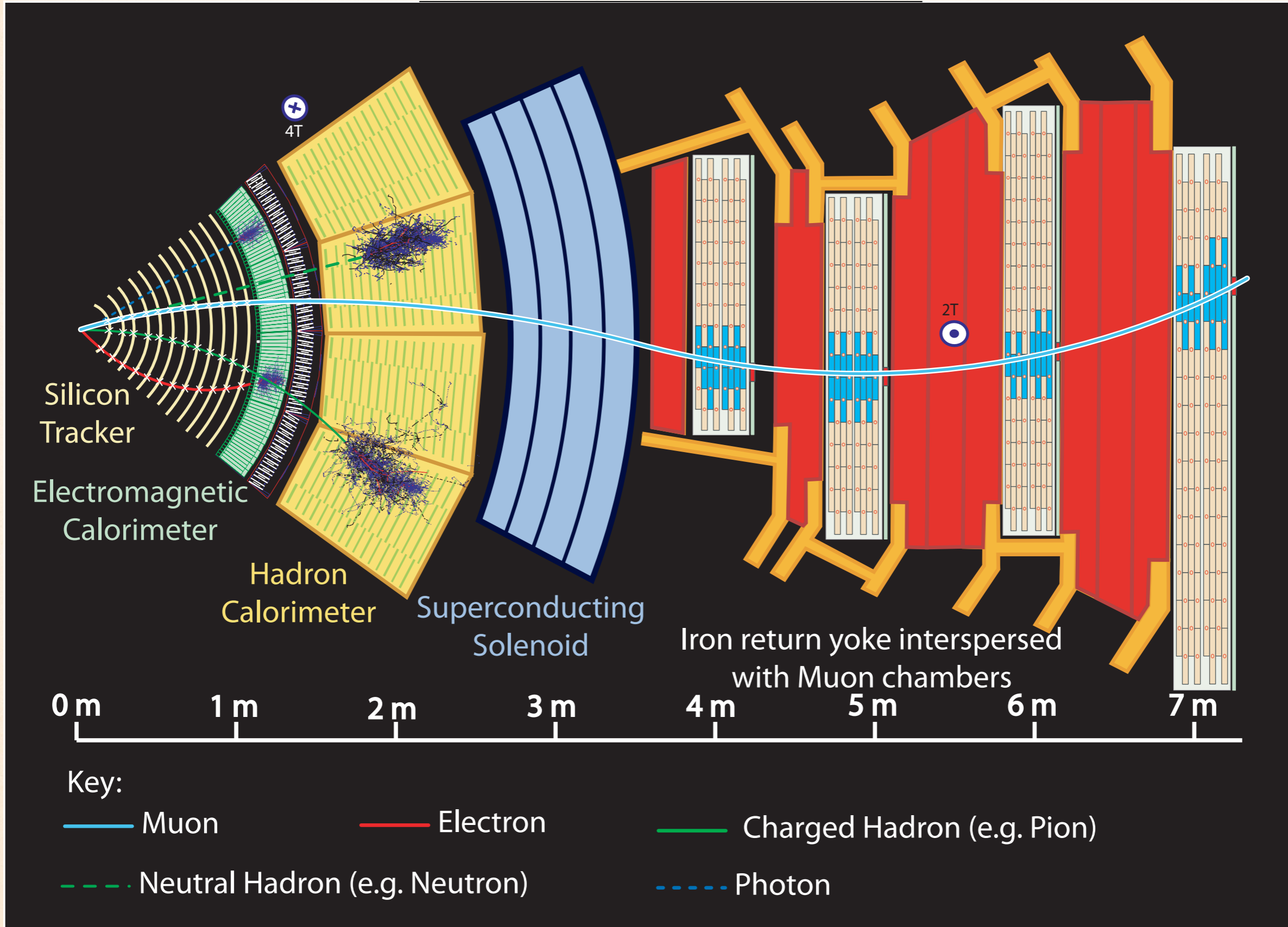
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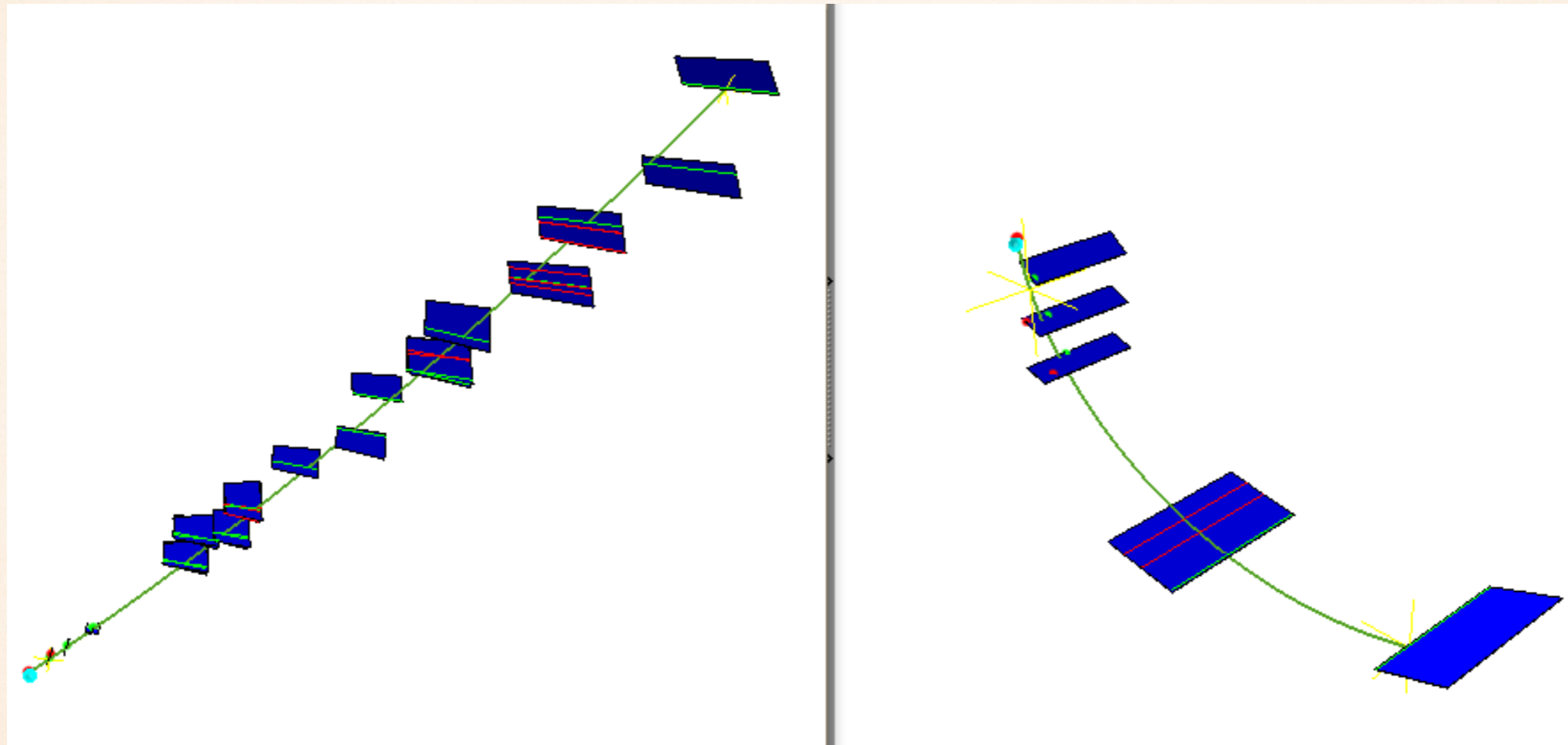
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Particle Detection in CMS



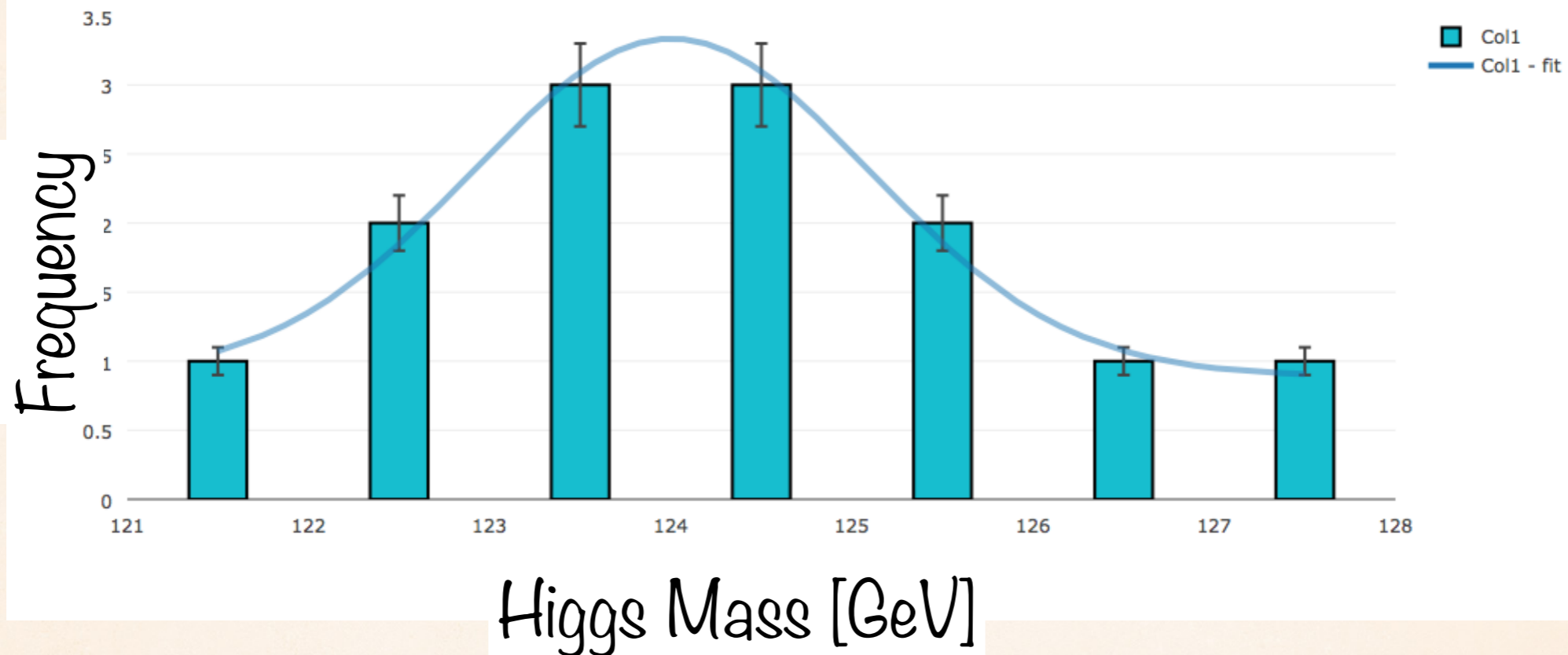
Do we understand how tracks are
created from individual hits in sensors?



Pattern recognition algorithm used

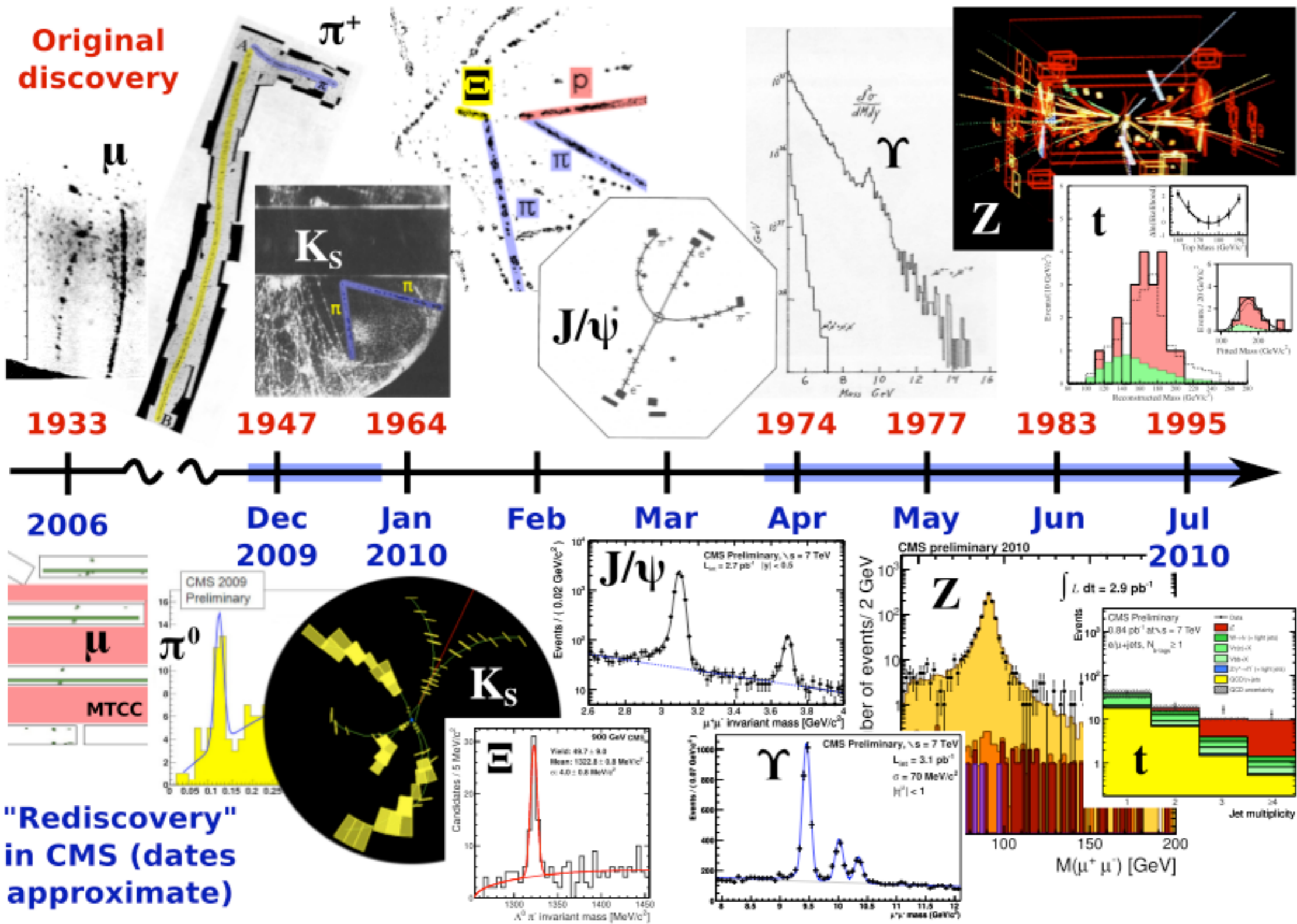
A brief detour

Higgs Mass with CERN public data

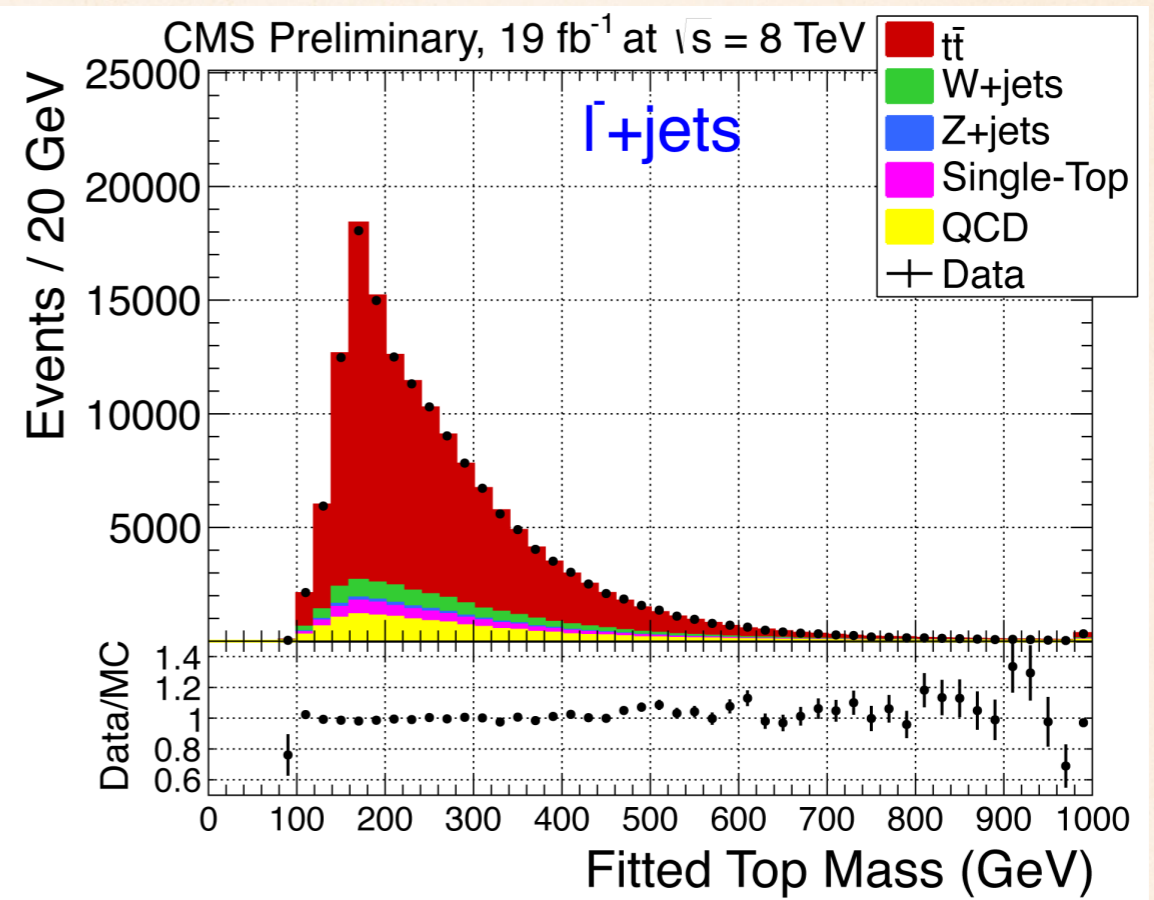
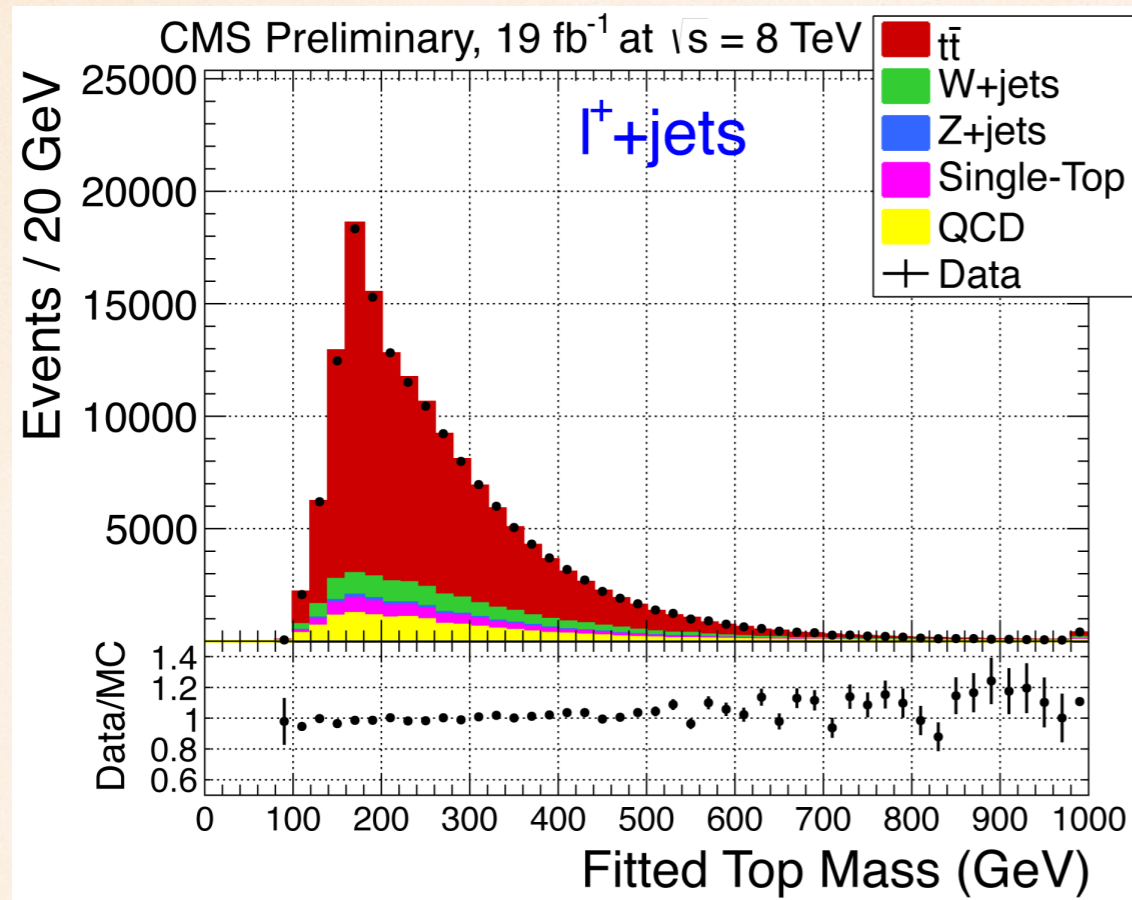


- What's a histogram? It's a frequency graph
- We usually make a plot per event
- What's an event? 1 p-p collision
- Plots made with y-label: Events/x-axis units

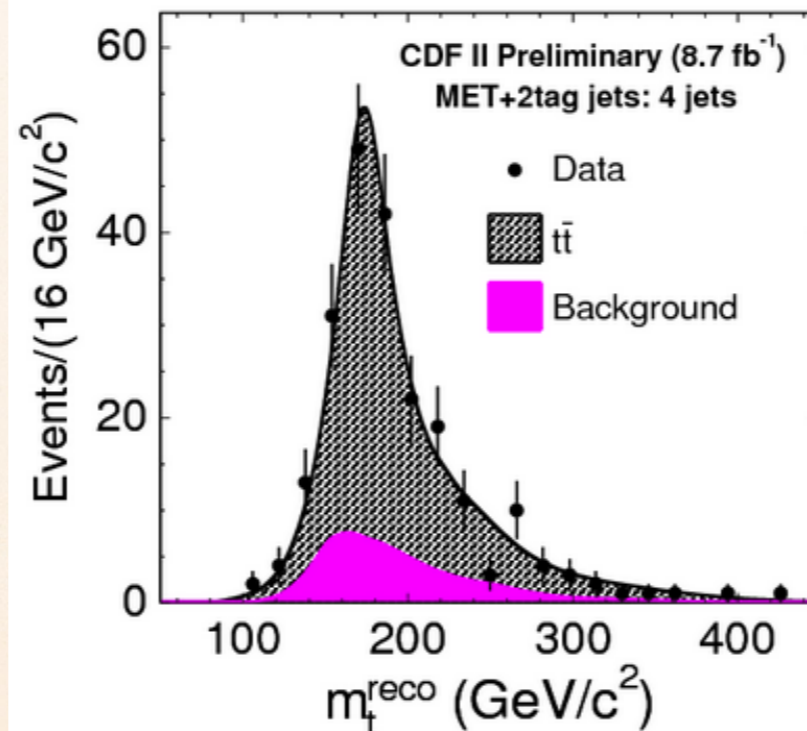
The rediscovery of particles at the LHC



Top quark at the LHC



Compare with top quark at the Tevatron



The discovery train

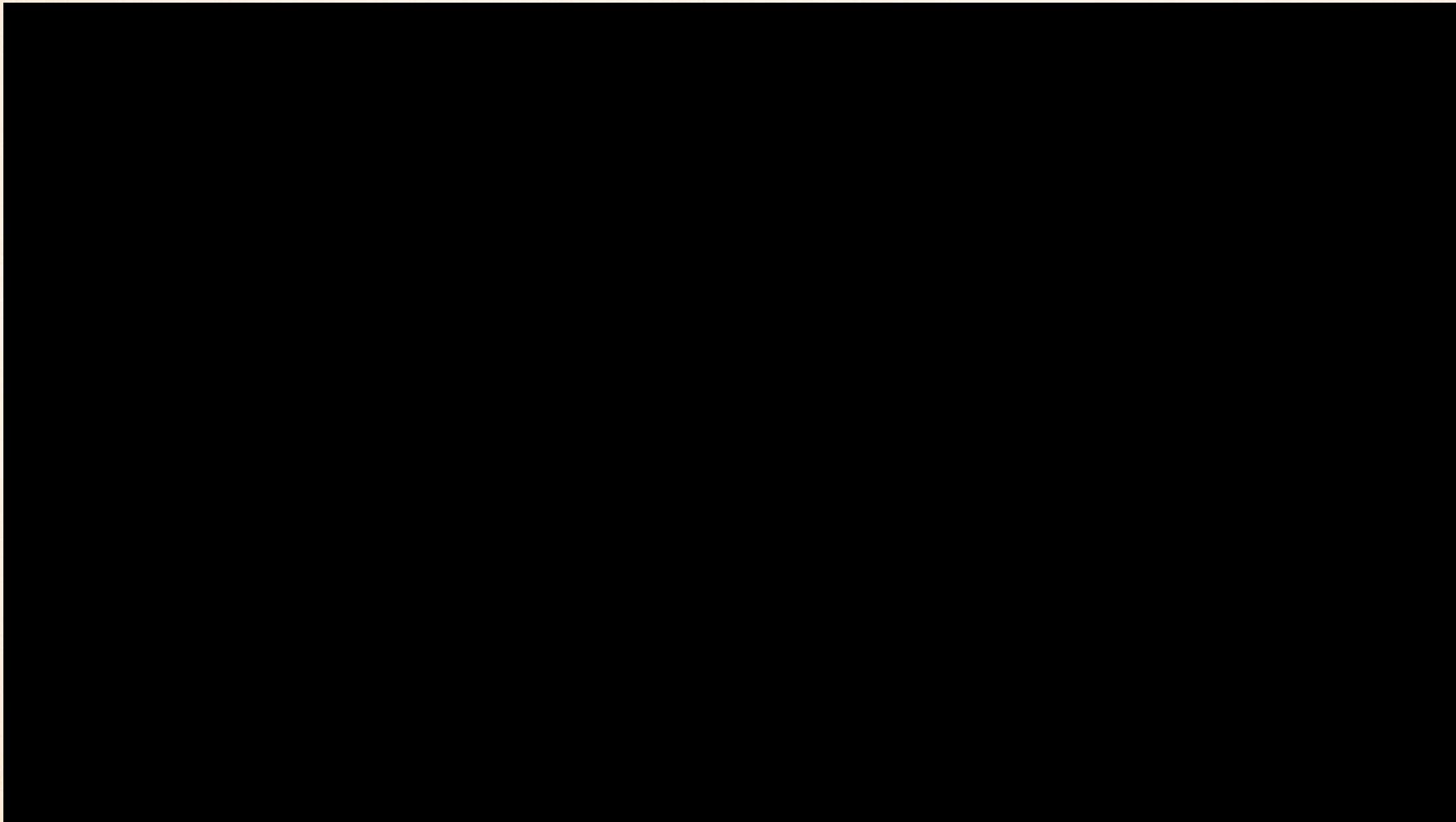
“Yesterday's discovery, today's calibration,
tomorrow's background”



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 **force 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

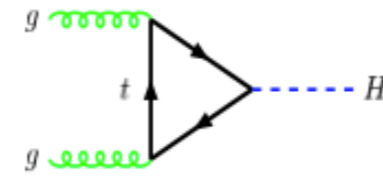
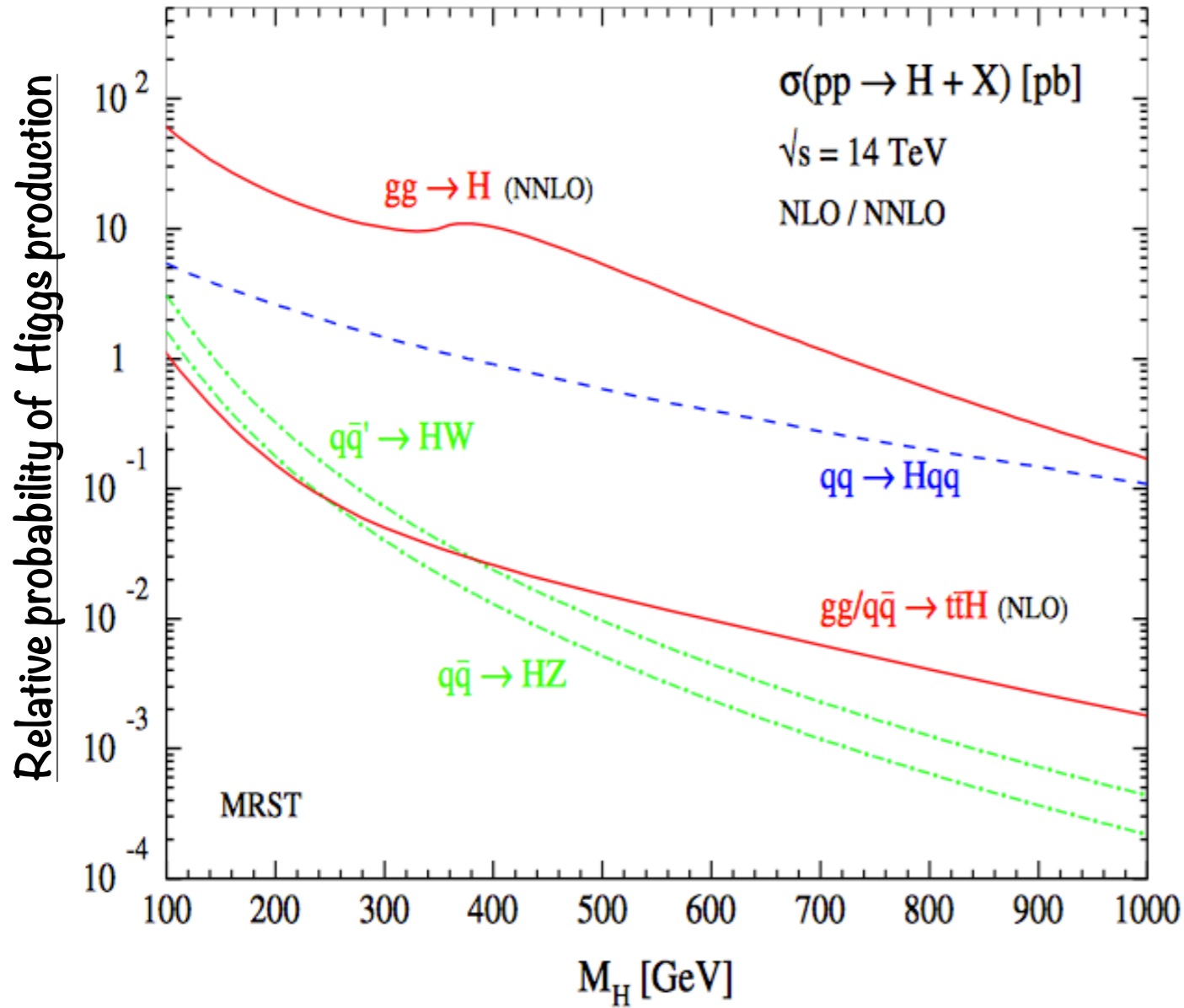
July 4th, 2012: ATLAS and CMS observe a particle consistent with the Higgs boson



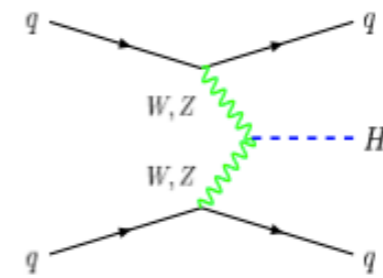
July 4th, 2012: ATLAS and CMS submit Higgs-search papers

Higgs Production

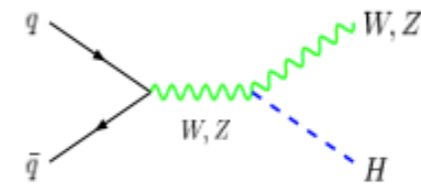
affectionately known as...



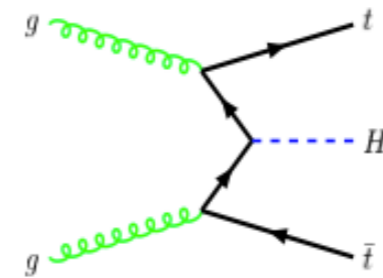
gg fusion



WZ fusion

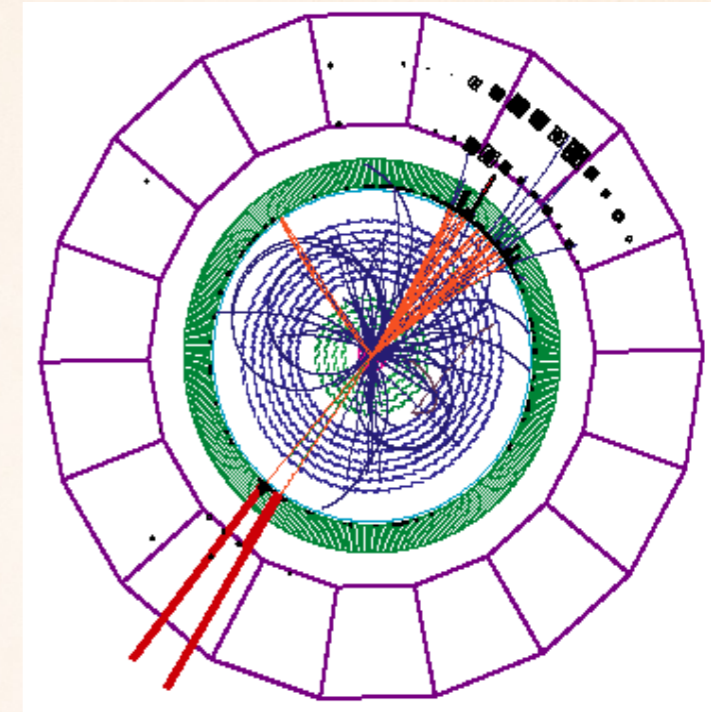
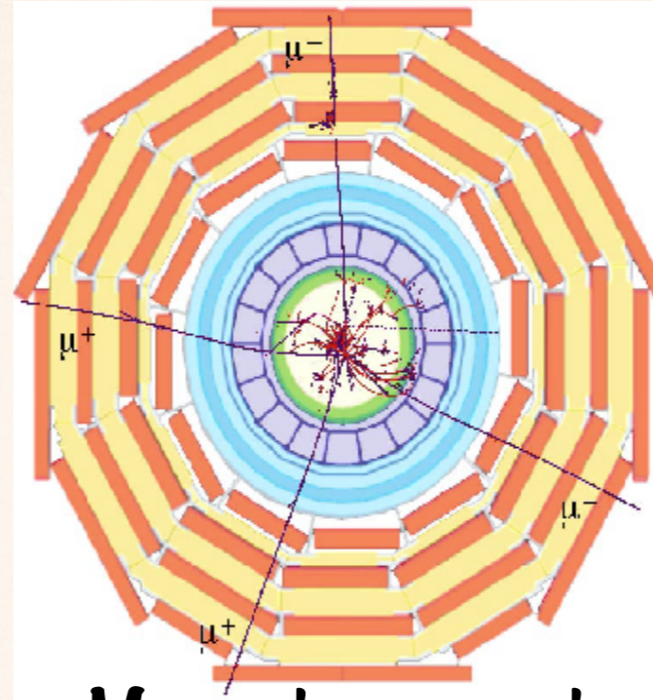
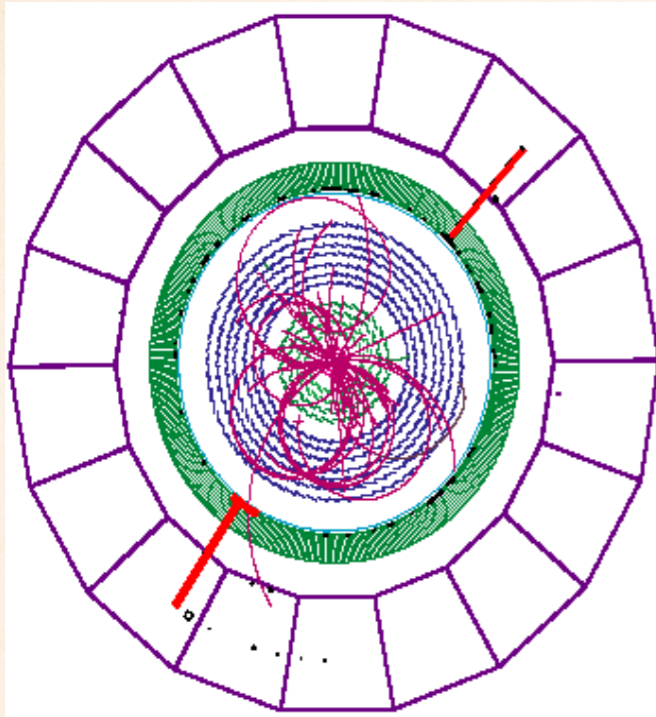


Higgs-Strahlung

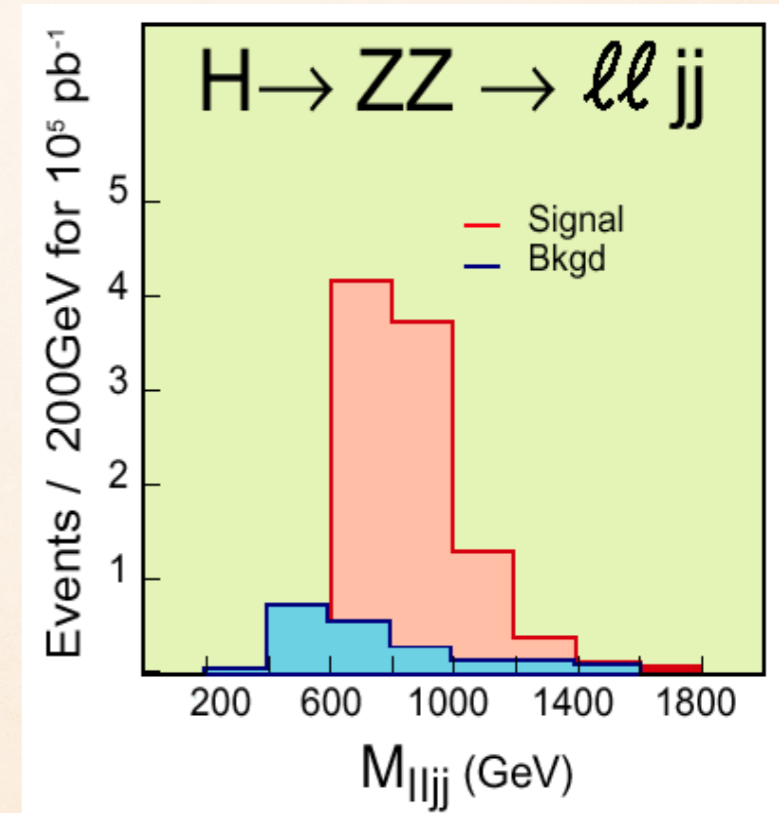
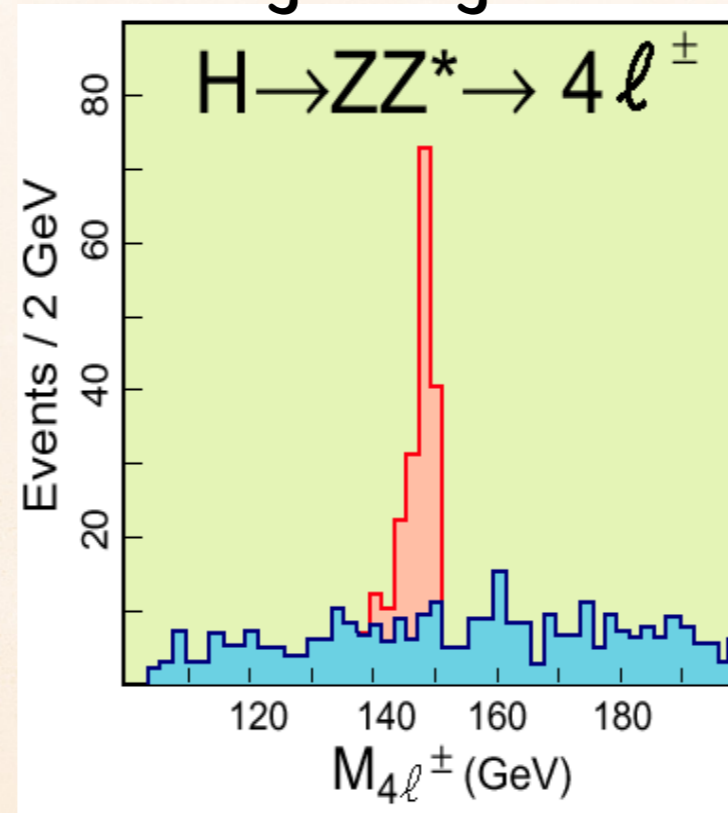
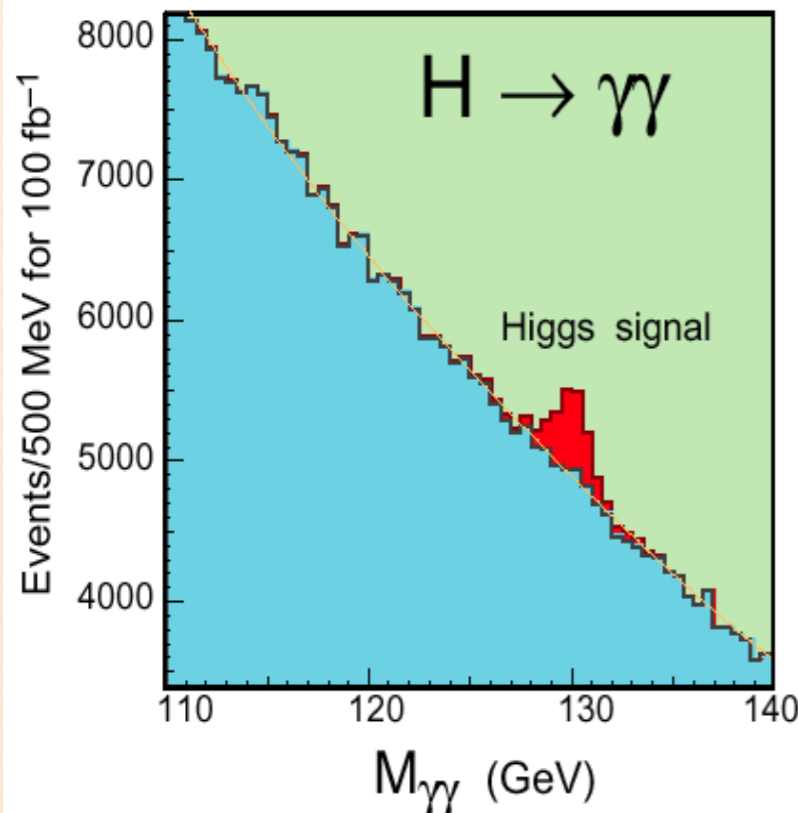


t-tbar fusion

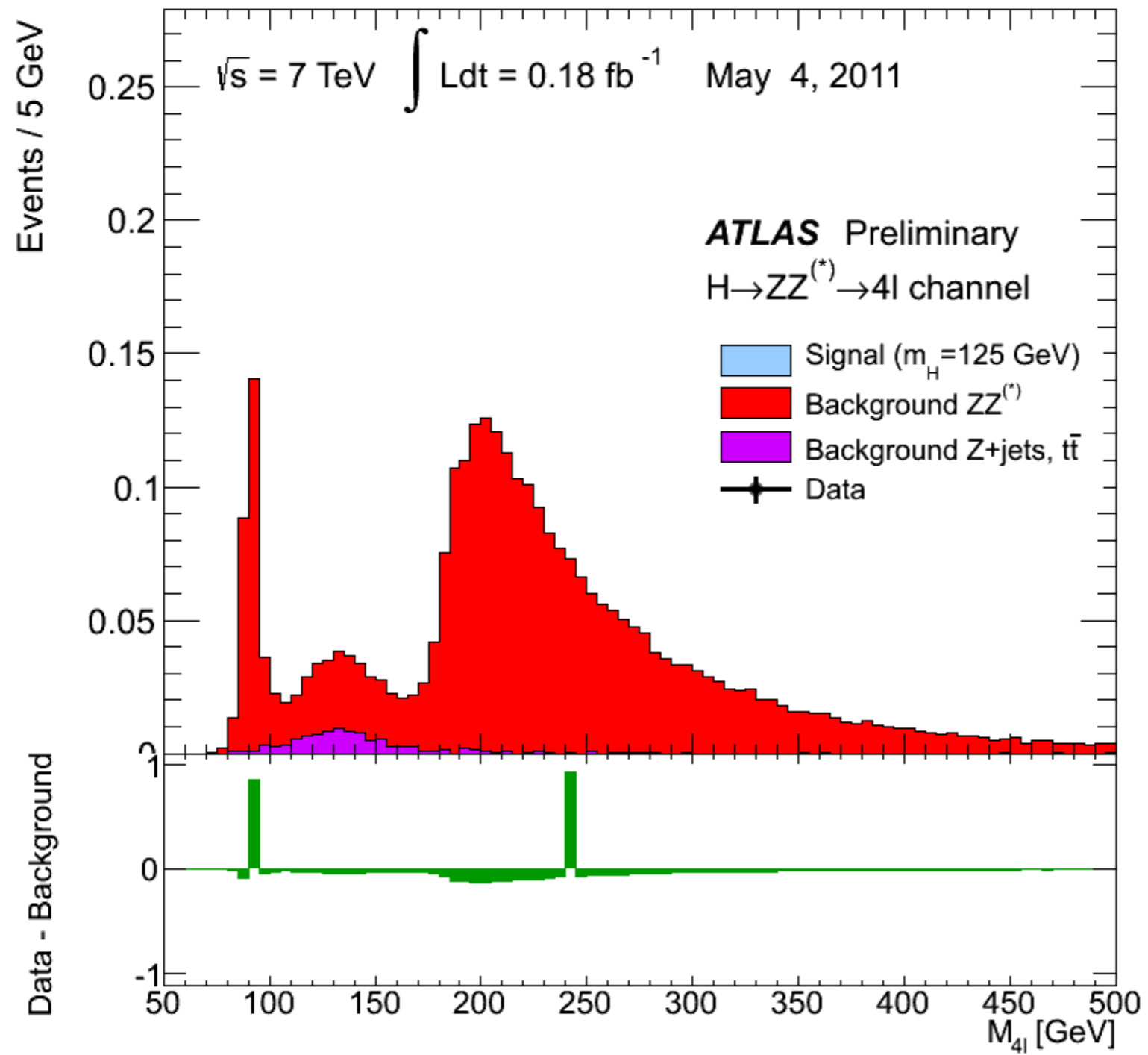
Observing the Higgs boson



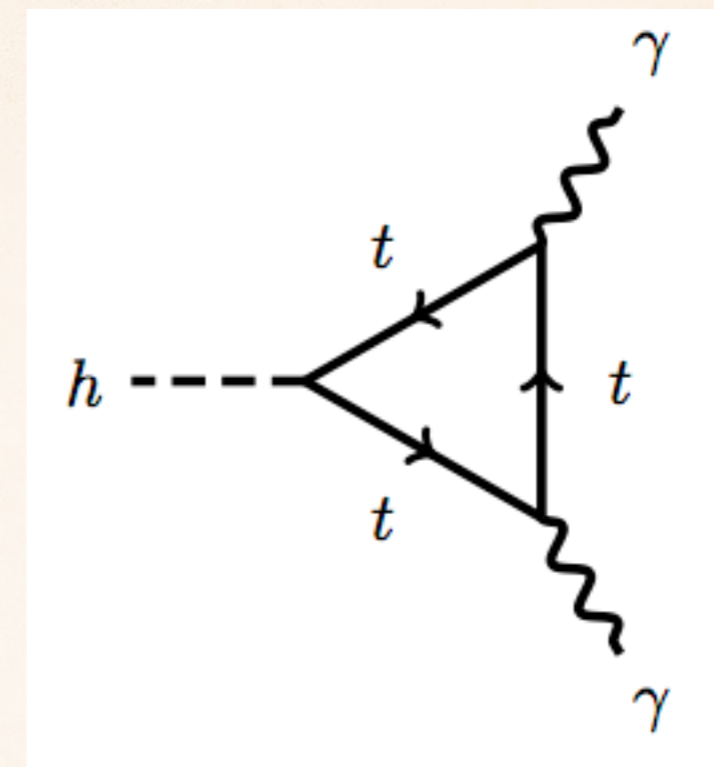
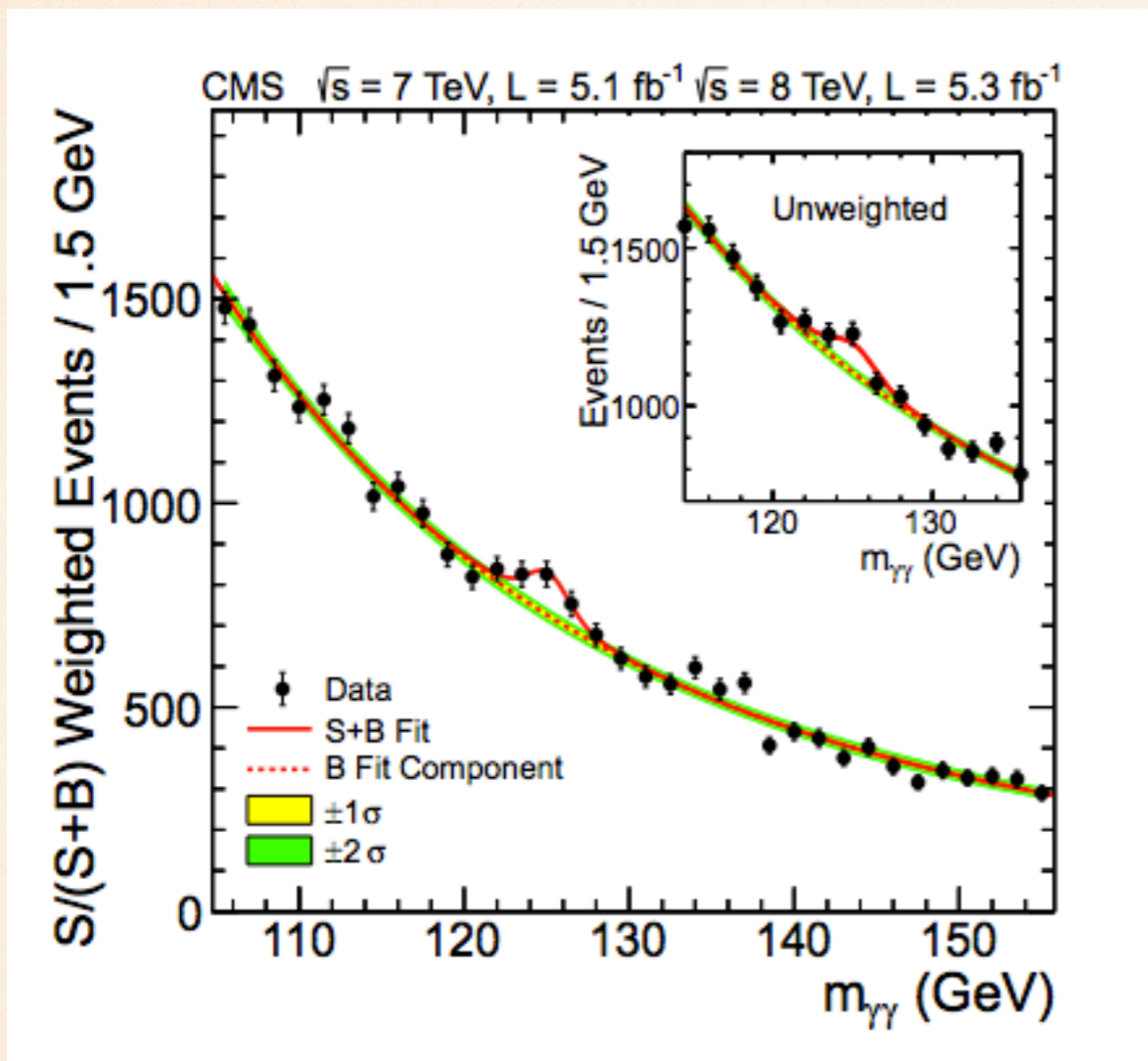
Many decay modes



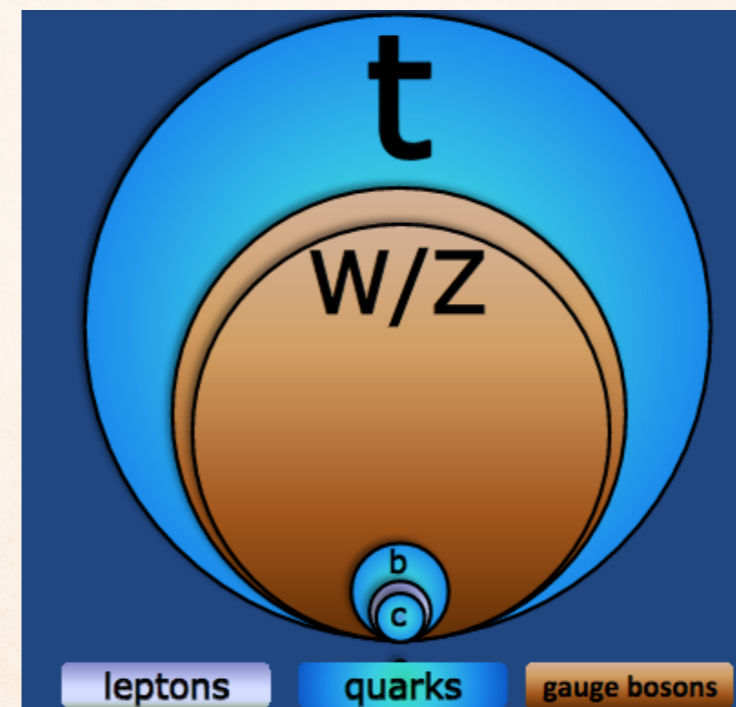
Higgs boson discovery



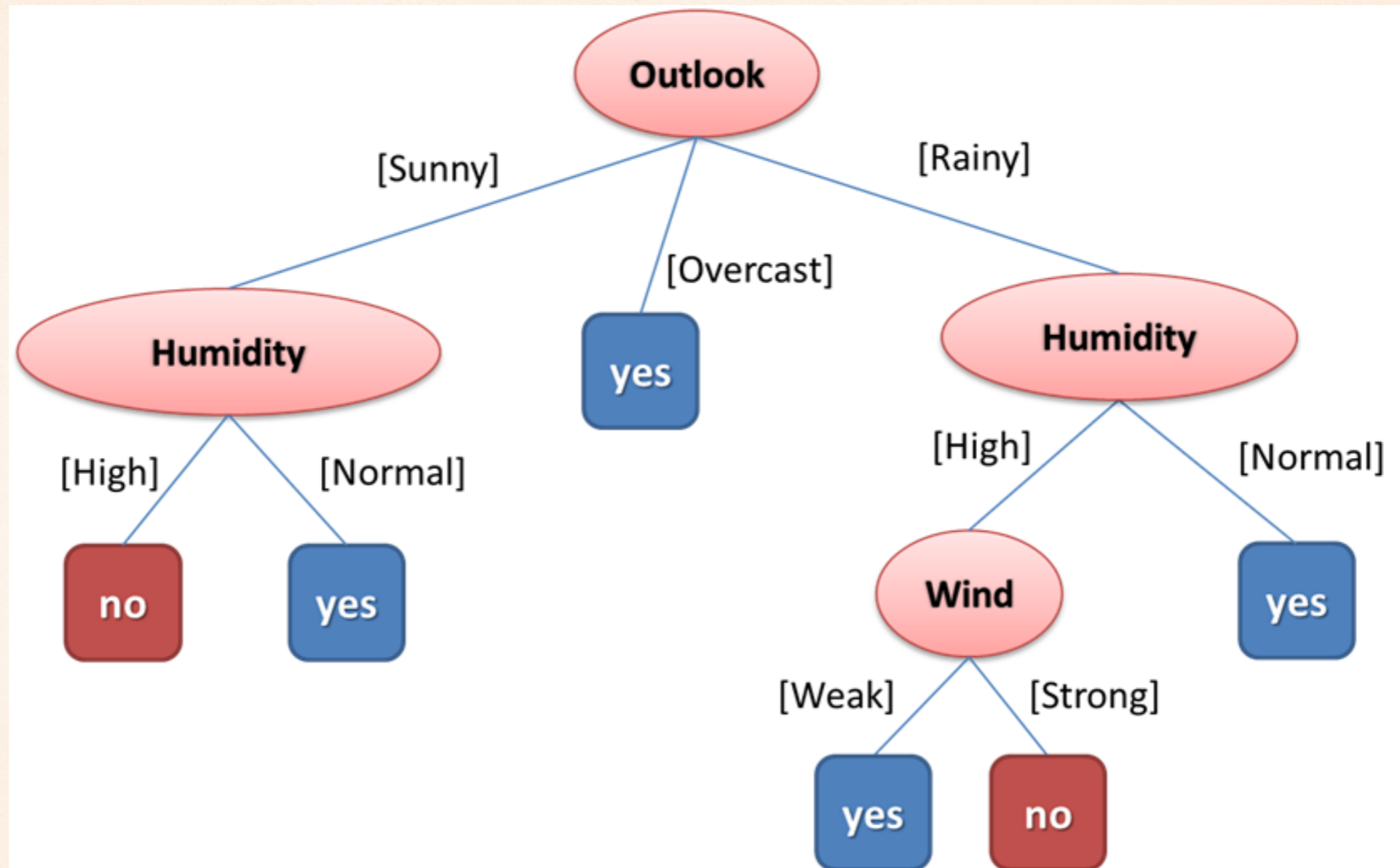
What's next: Understand the relationship between the top and the Higgs



Higgs \rightarrow largest coupling with the top

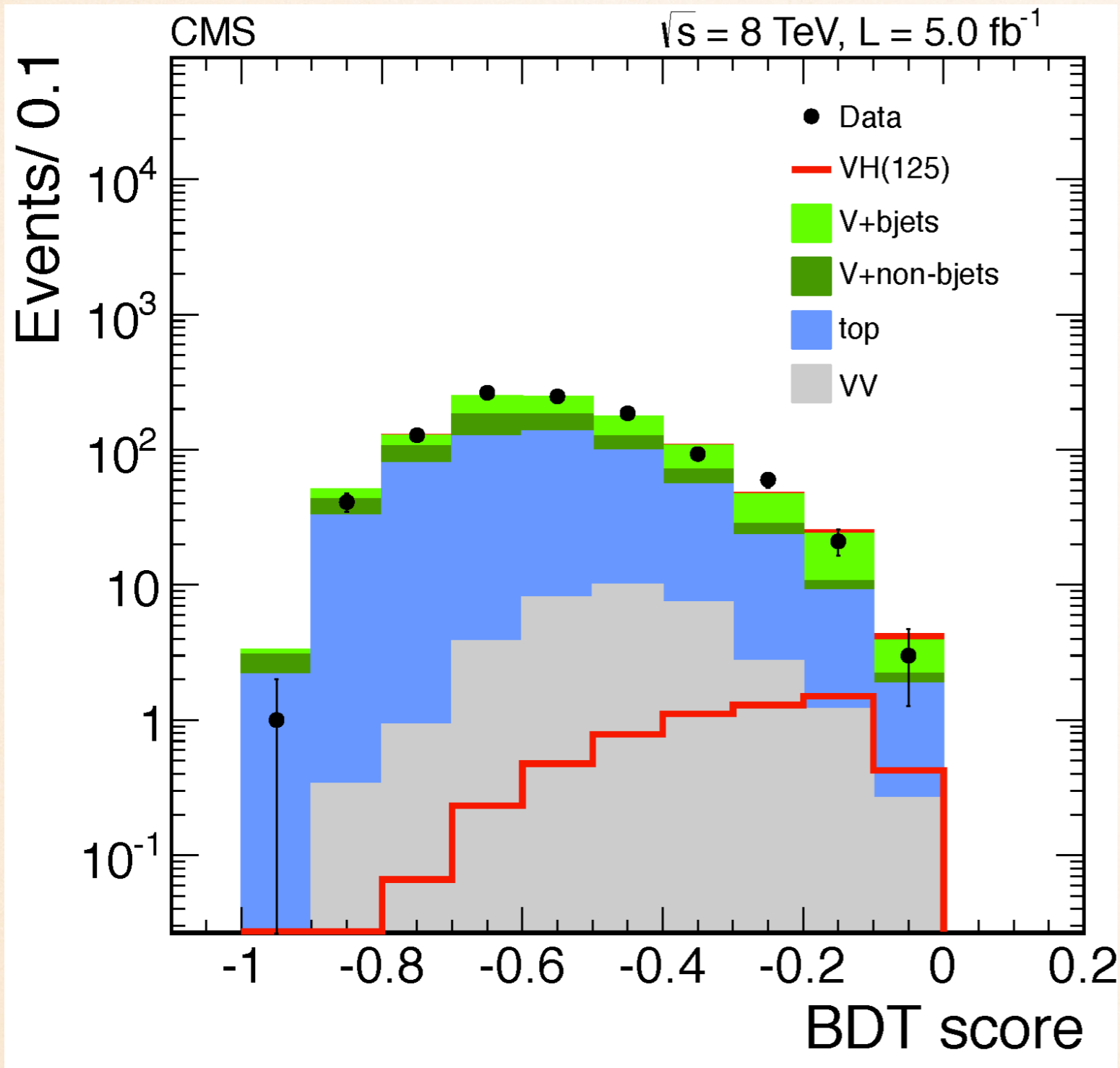


What's next: Use machine learning to probe further



Ask enough questions to fully characterize weather

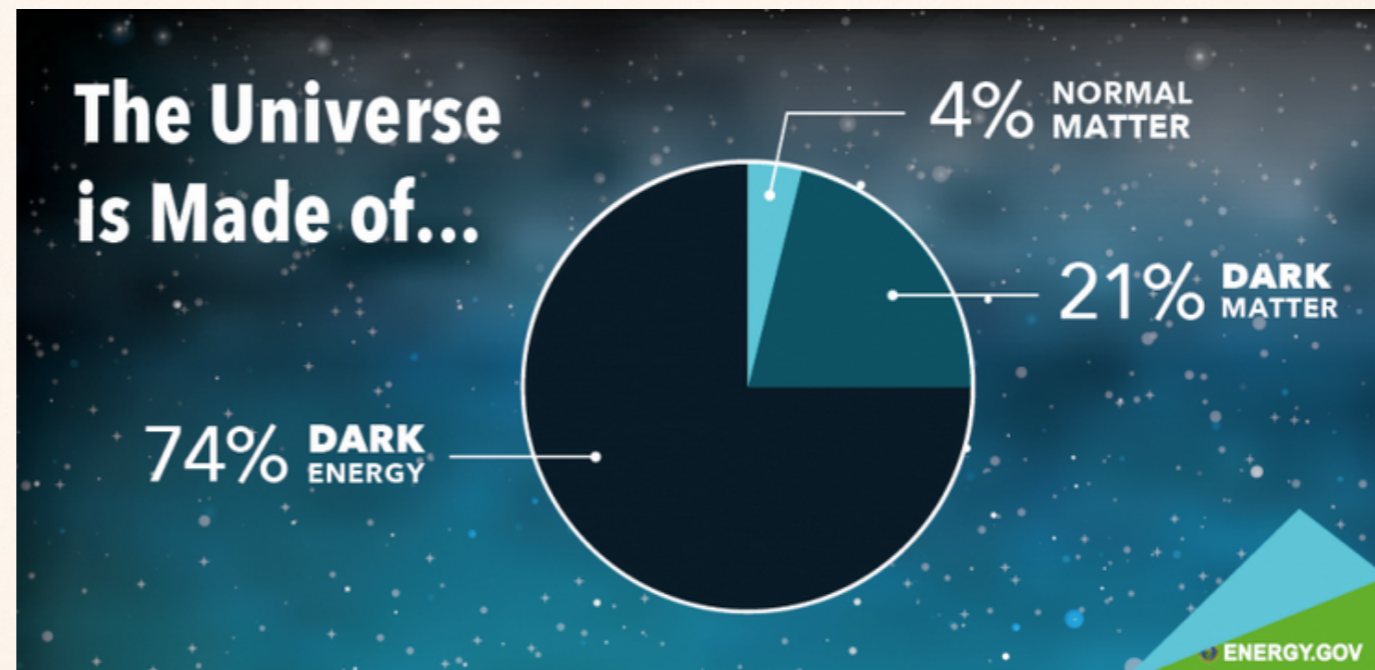
What's next: Use machine learning to probe further



- 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

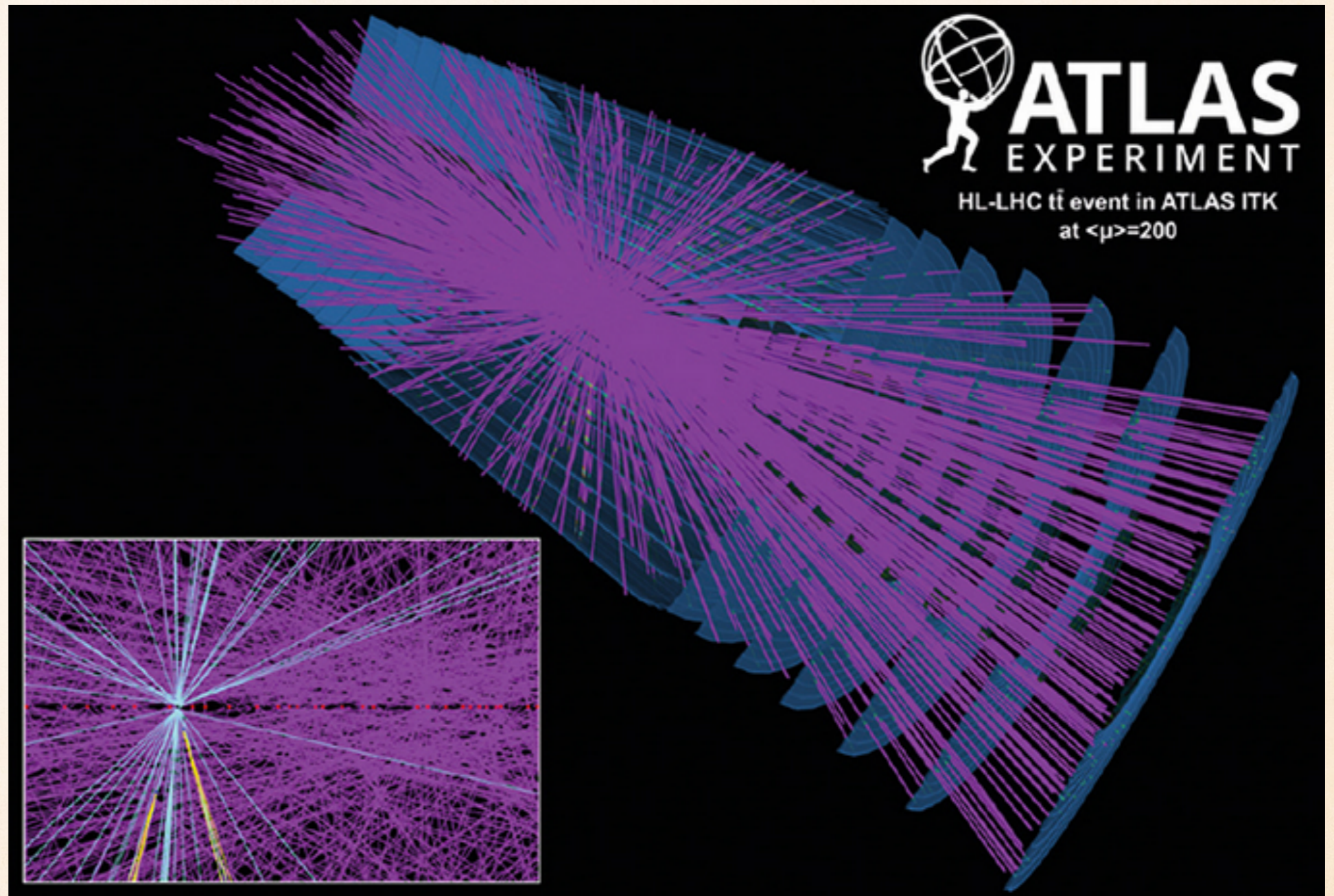


- Where is all the anti matter?
- We haven't included gravity into the mix yet!

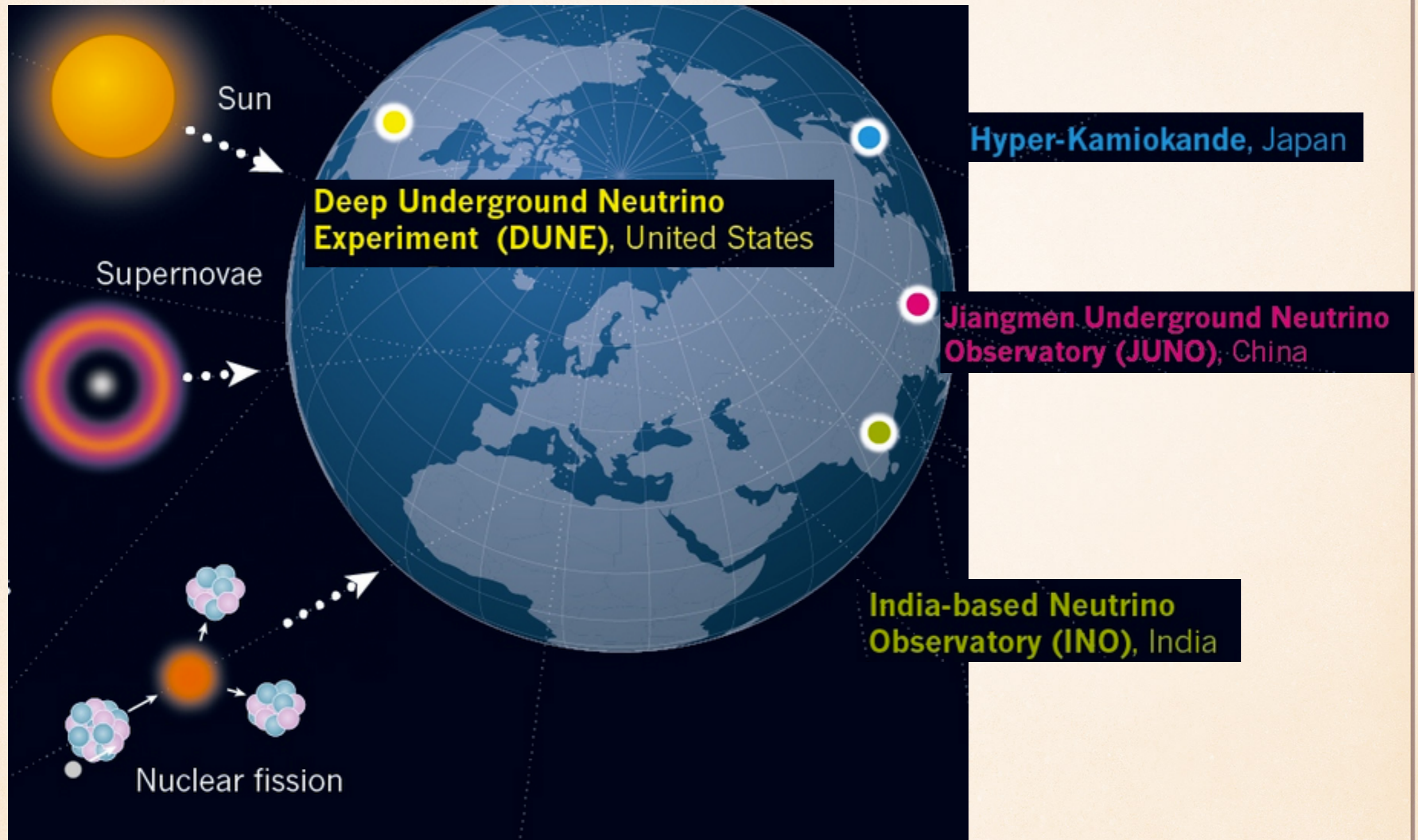


Where do we see ourselves in the next 10 years?

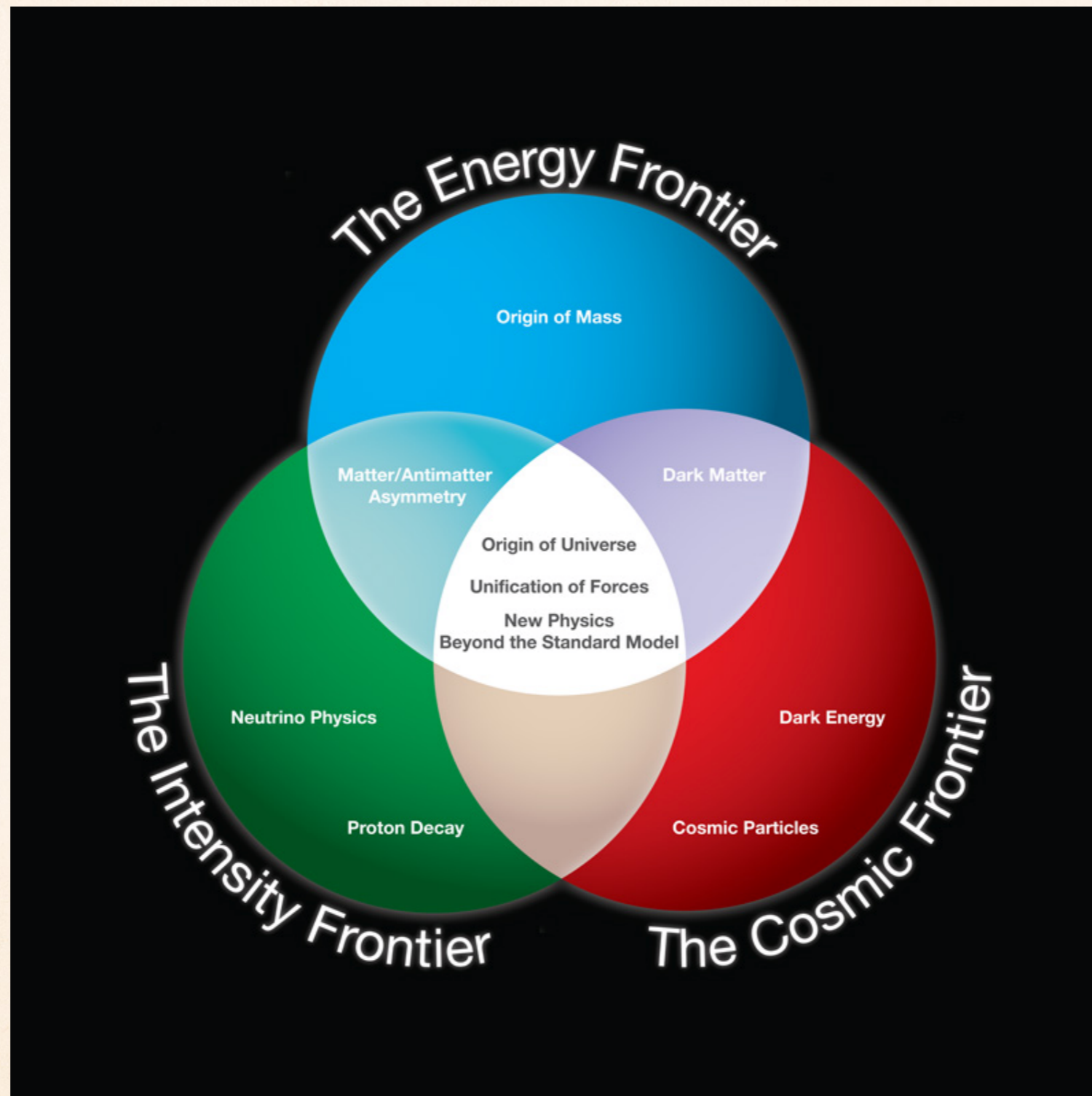
- Plan on collecting at least 15 times more data
- Many technical challenges associated with designing upgraded detectors



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

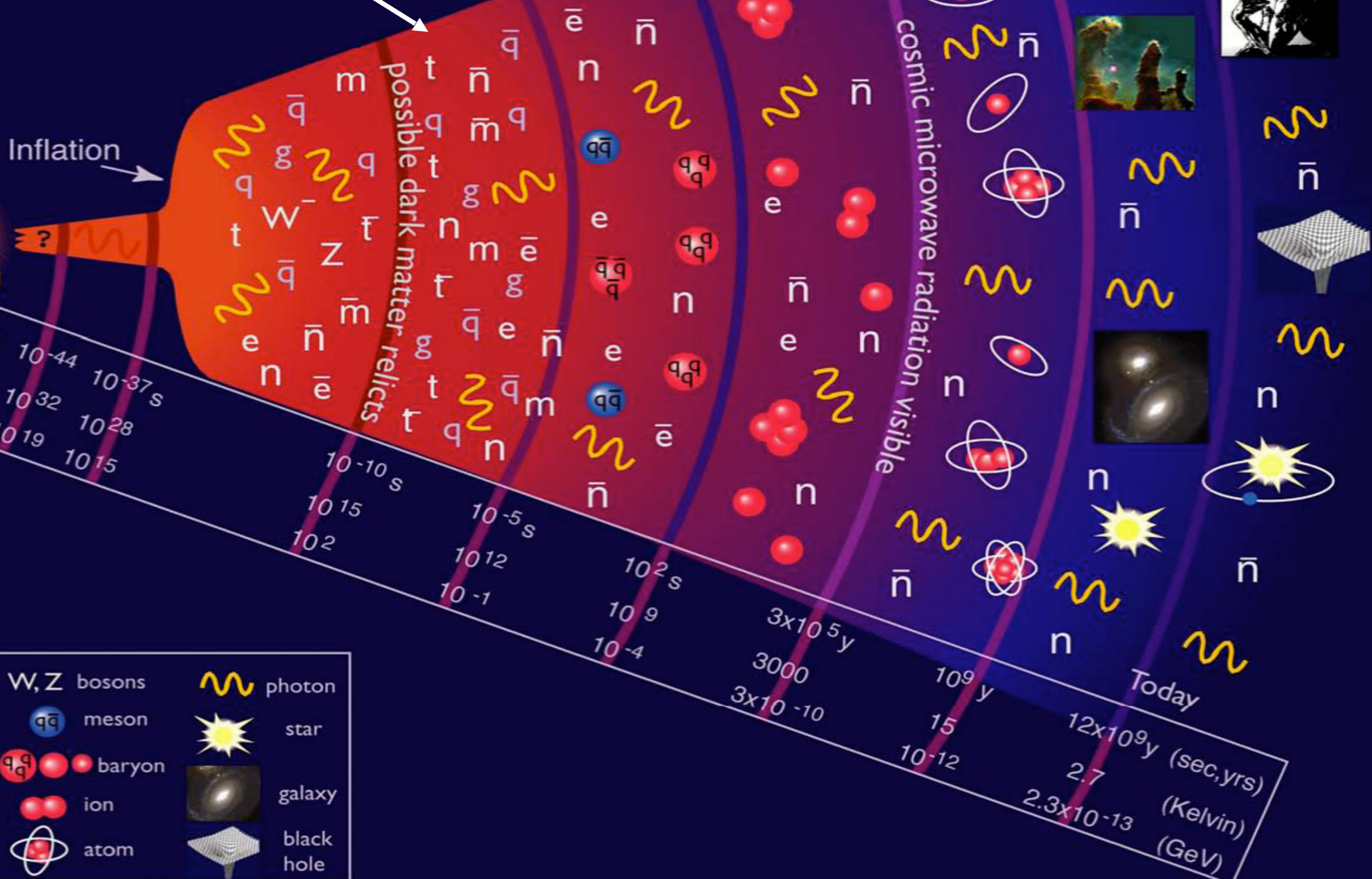
Inflation

t	10^{-44}	10^{-37} s
T	10^{32}	10^{28}
E	10^{19}	10^{15}

	10^{-10} s	10^{-5} s	10^2 s	10^9 y	10^9 y	Today
	10^{15}	10^{12}	10^9	3×10^5 y	15	12×10^9 y (sec,yrs)
	10^2	10^{-1}	10^{-4}	3×10^{-10}	10^{-12}	2.7 (Kelvin)
						2.3×10^{-13} (GeV)

Key:

W,Z bosons		photon	
quark		meson	
gluon		baryon	
electron		ion	
muon		atom	
tau		star	
neutrino		galaxy	
		black hole	

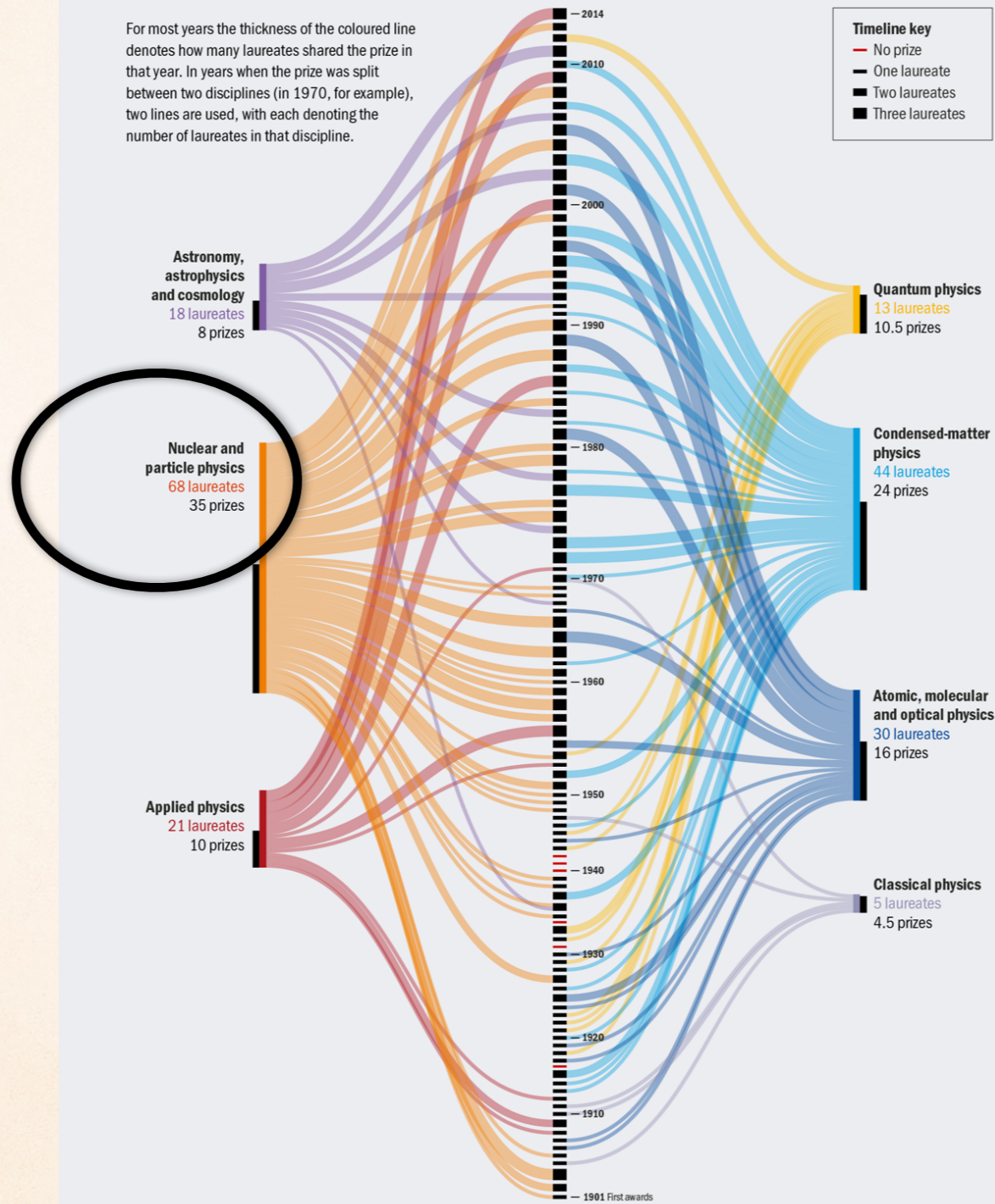


Nobel Prizes

Which physics discipline attracts the most Nobel prizes?

For most years the thickness of the coloured line denotes how many laureates shared the prize in that year. In years when the prize was split between two disciplines (in 1970, for example), two lines are used, with each denoting the number of laureates in that discipline.

Timeline key
 — No prize
 — One laureate
 ■ Two laureates
 ■ Three laureates



Particle
 Physics: 68
 laureates, 35
 prizes!

physicsworld

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References

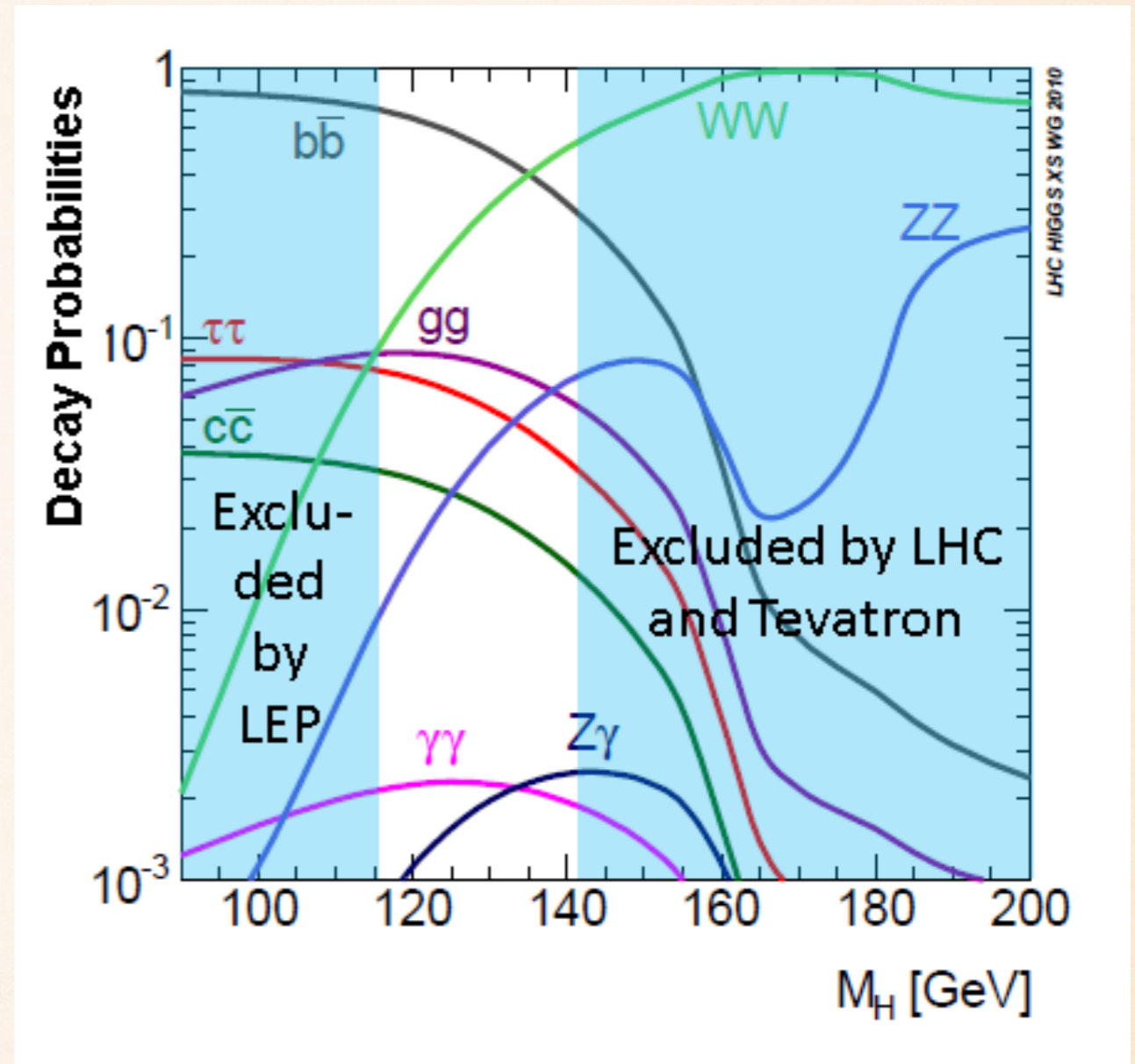
- Used CERN resources
- Used journals like Nature
- Borrowed from talks given by my colleagues: Dave Barney, Joe Incandela

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

