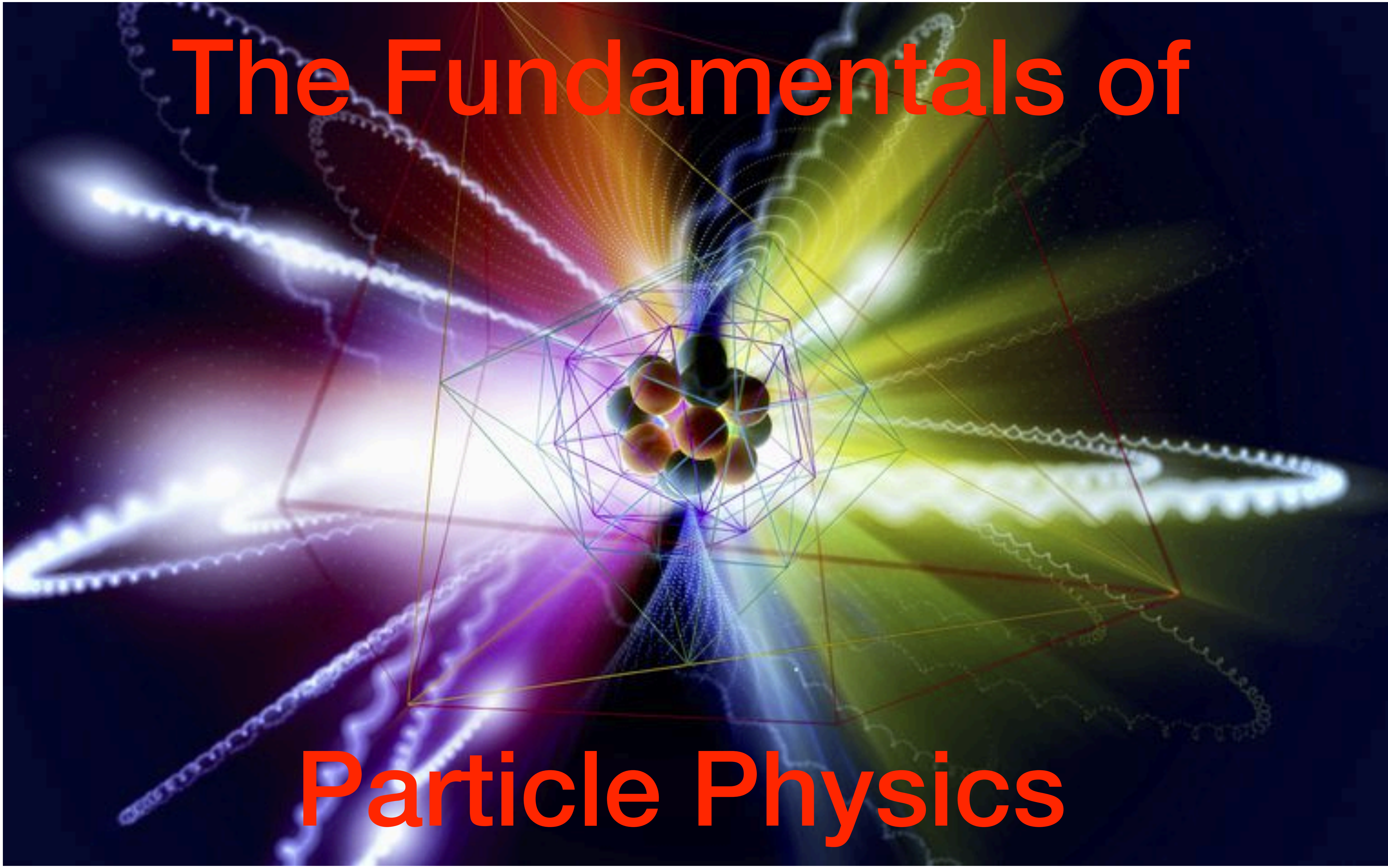
The Fundamentals of Particle Physics



Quarknet High School Teacher’s Workshop

July 1 2019

What is Particle Physics?

- Study of the nature of matter in its most fundamental state i.e. what our Universe is made up of.

- How these fundamental constituents interact with each other to produce the Universe as we see it.

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What exactly does this mean?

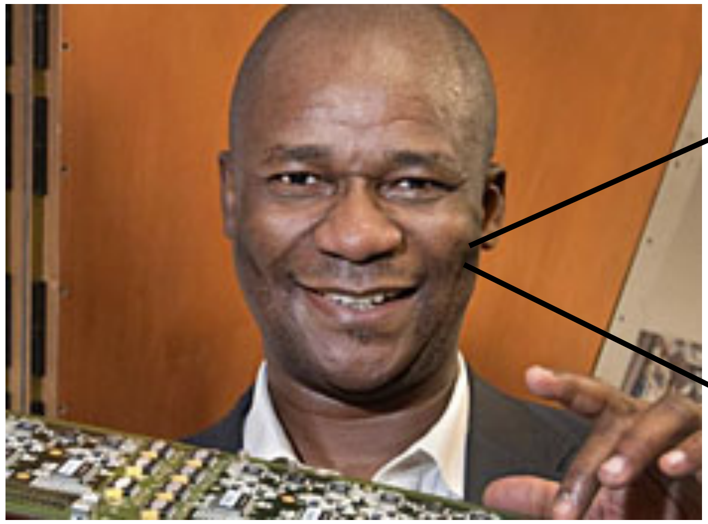
Lets explore this!!!

1m

Lets take Ketevi, the workshop organizer

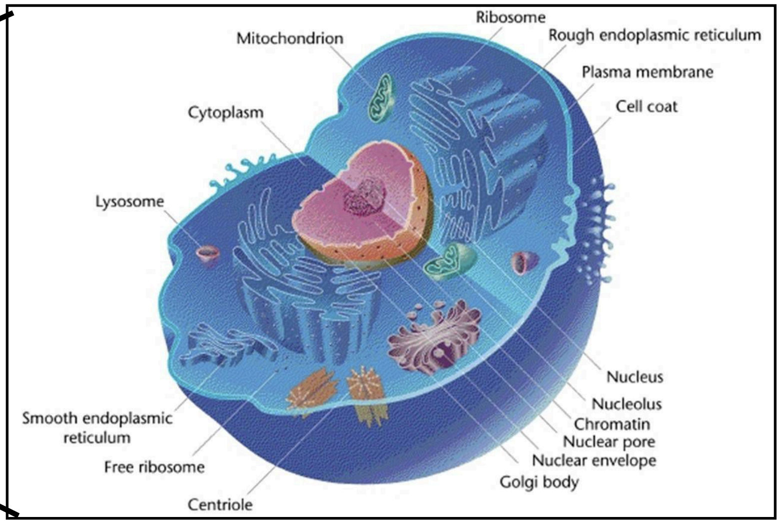
Lets explore this!!!

1m



Lets take Ketevi, the workshop organizer

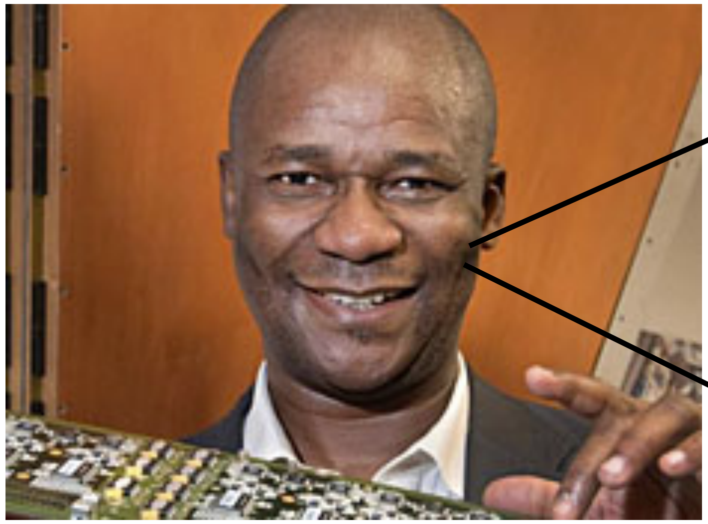
1µm



Ketevi is made up of cells

Lets explore this!!!

1m



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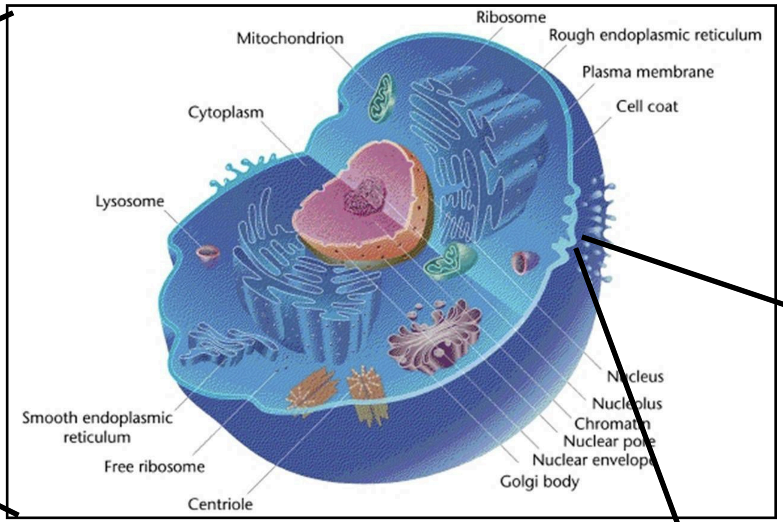

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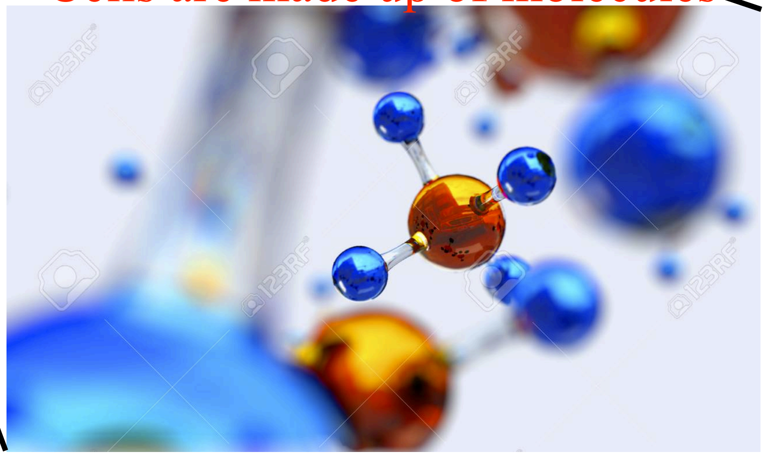
Cells are made up of molecules



1nm

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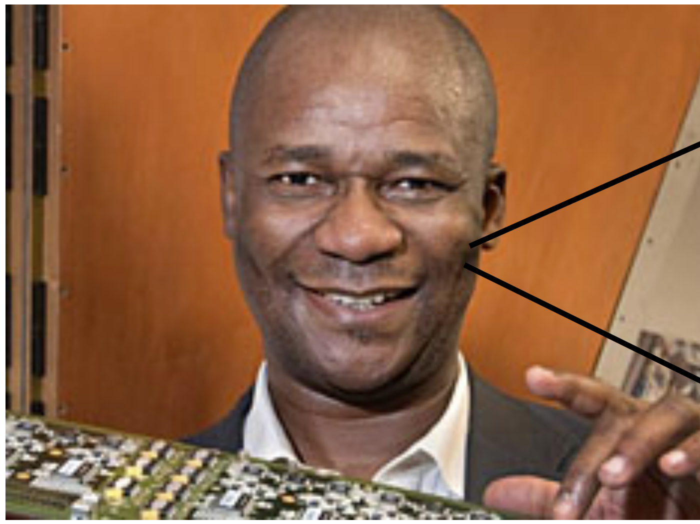

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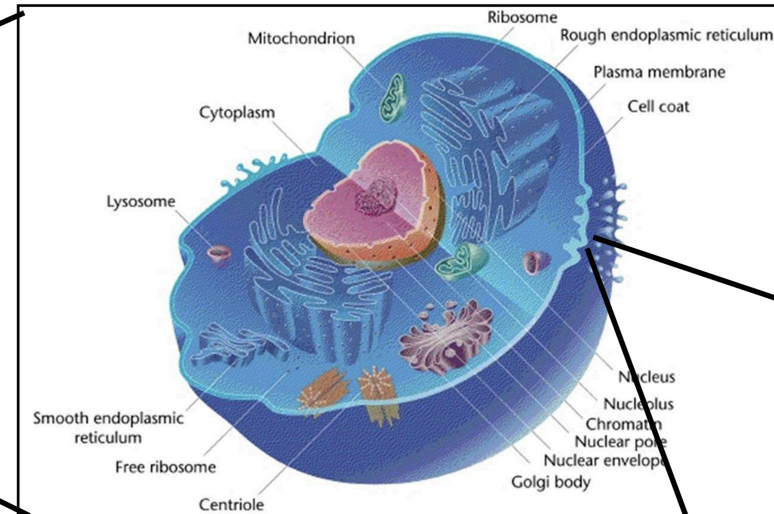

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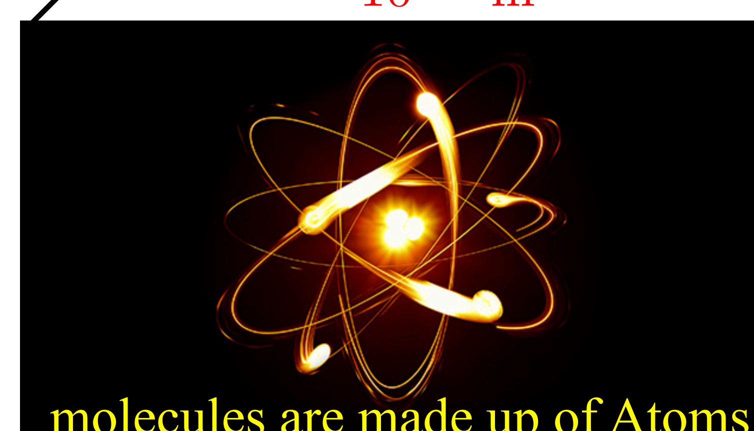
1nm

10^{-10}m



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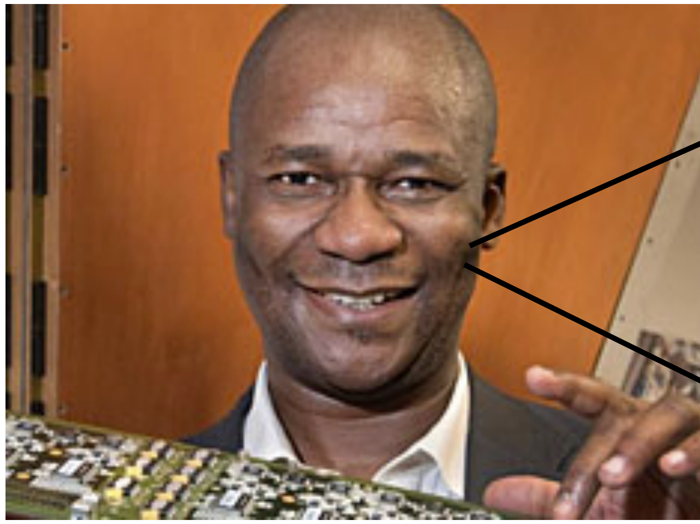

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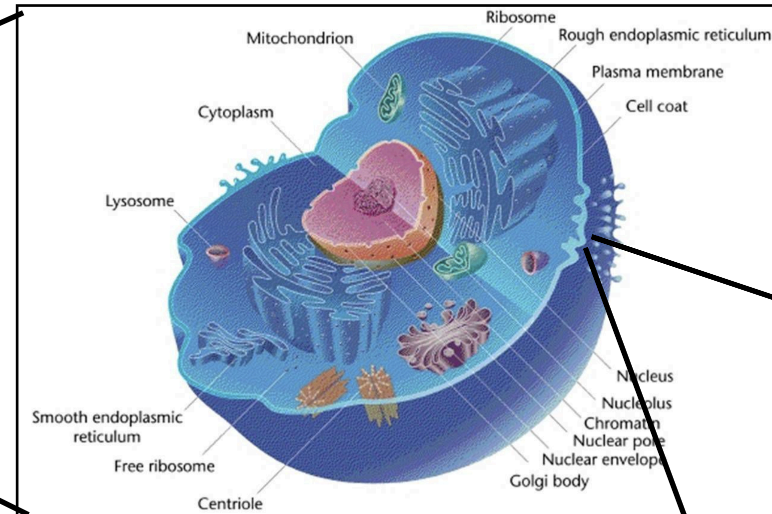
$1\mu m$



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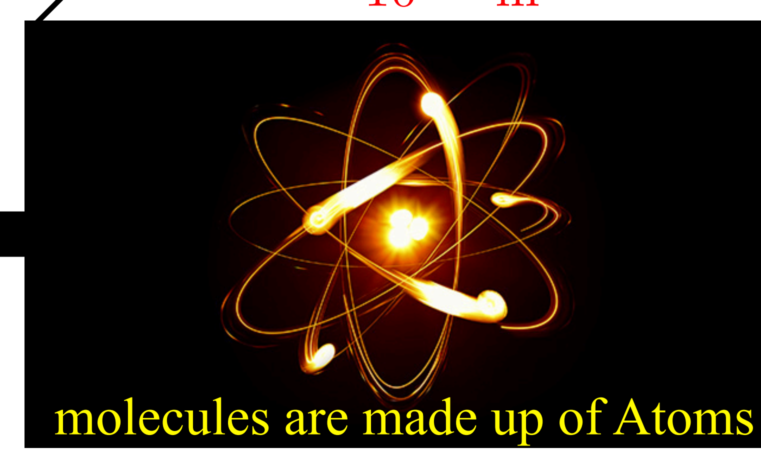
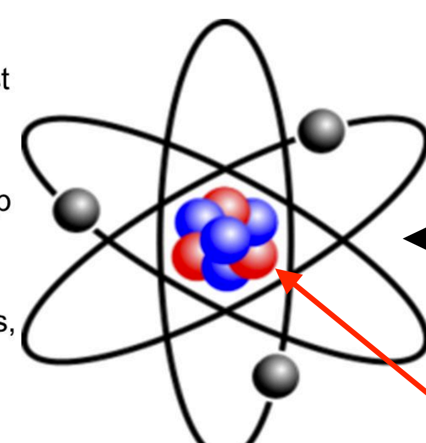


Atoms

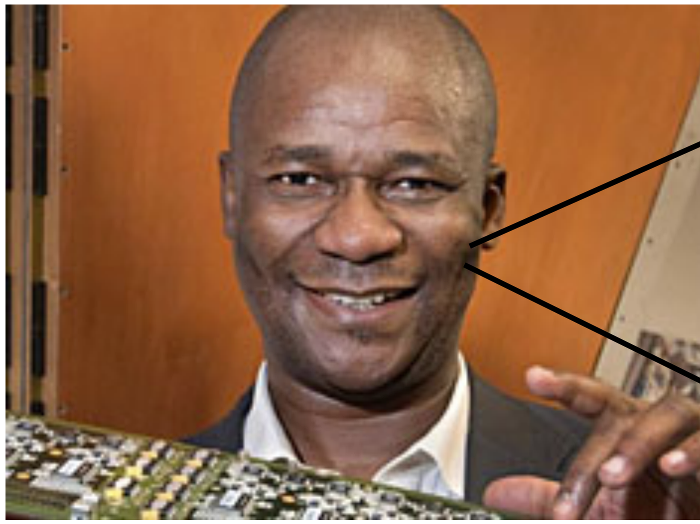
- Atom- The smallest particle that can be called an element.
- All matter is made up of atoms.
- Made up of Protons(+), Neutrons, and Electrons (-)



10^{-14}m

Lets explore this!!!

1m



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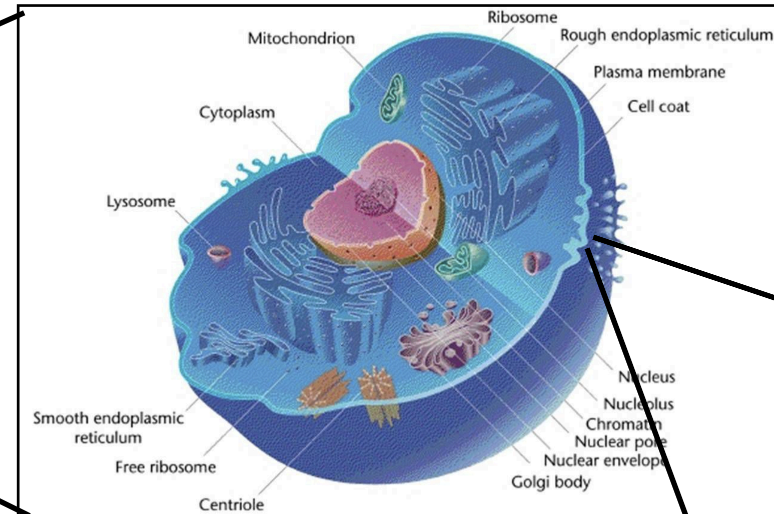
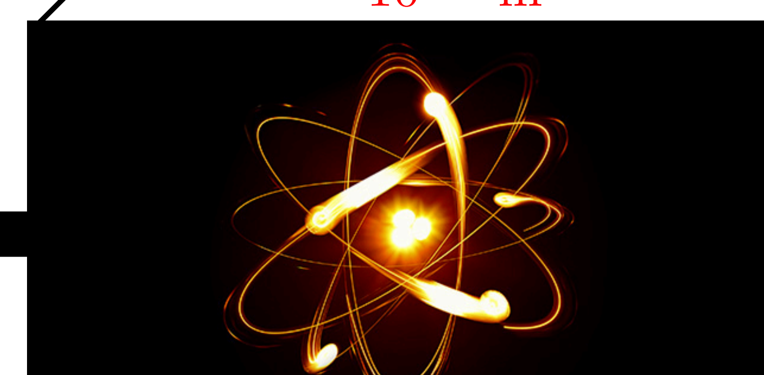


Ketevi is made up of cells

Cells are made up of molecules

1nm

10^{-10}m



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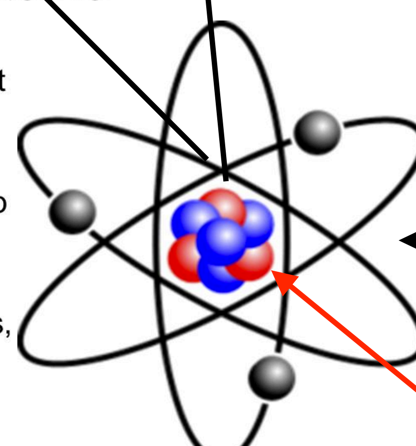
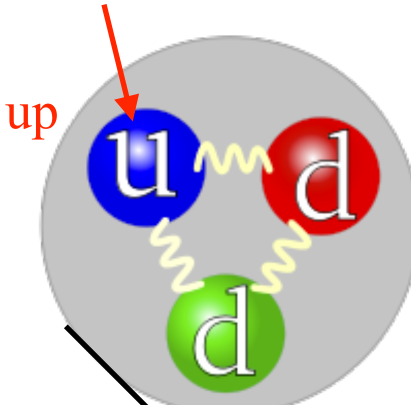


10^{-14}m

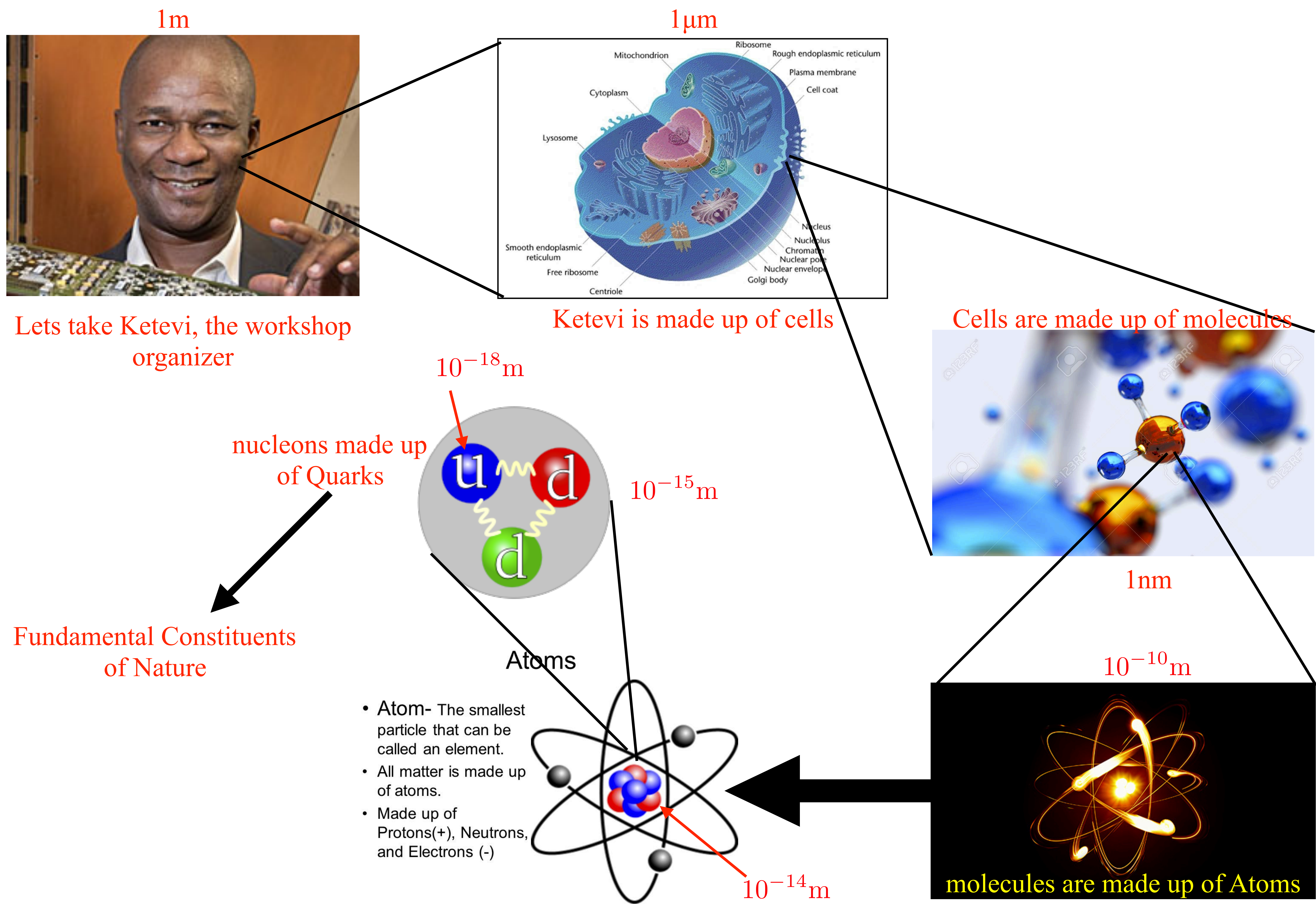
10^{-15}m



nucleons made up of Quarks

10^{-18}m

Lets explore this!!!



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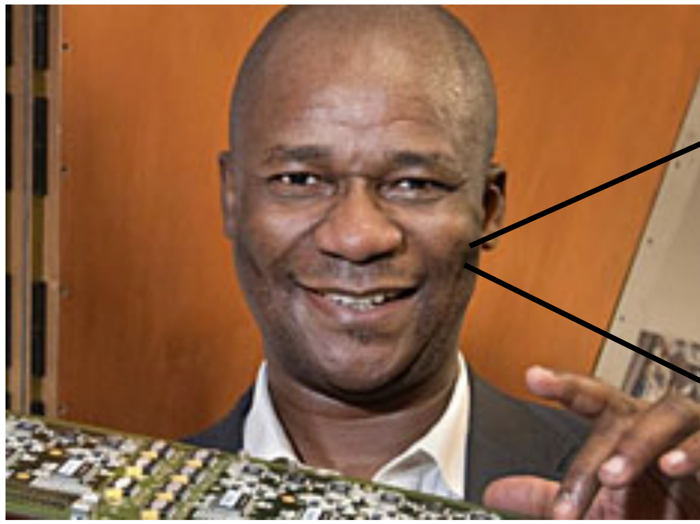

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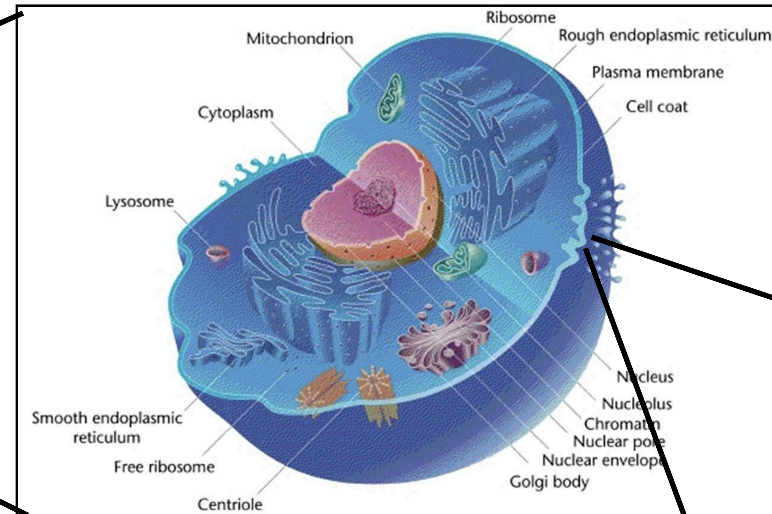

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Cells are made up of molecules

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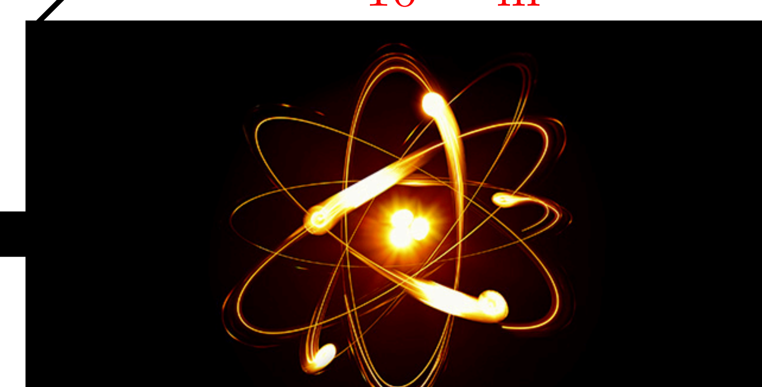

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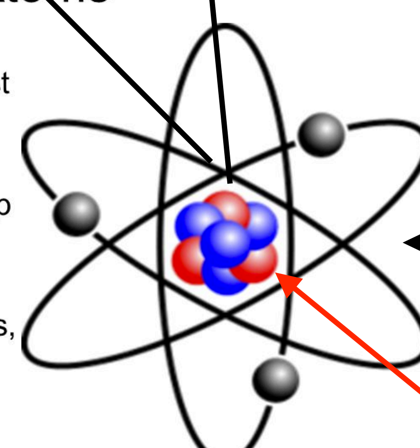
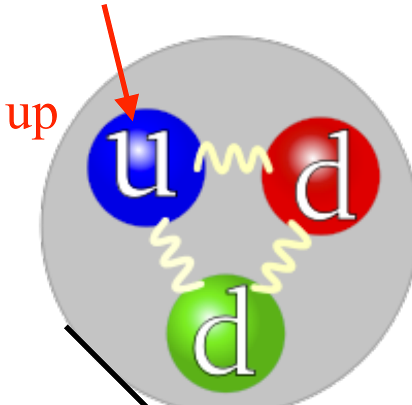


10^{-14}m

10^{-15}m

10^{-18}m



nucleons made up of Quarks

Fundamental Constituents of Nature

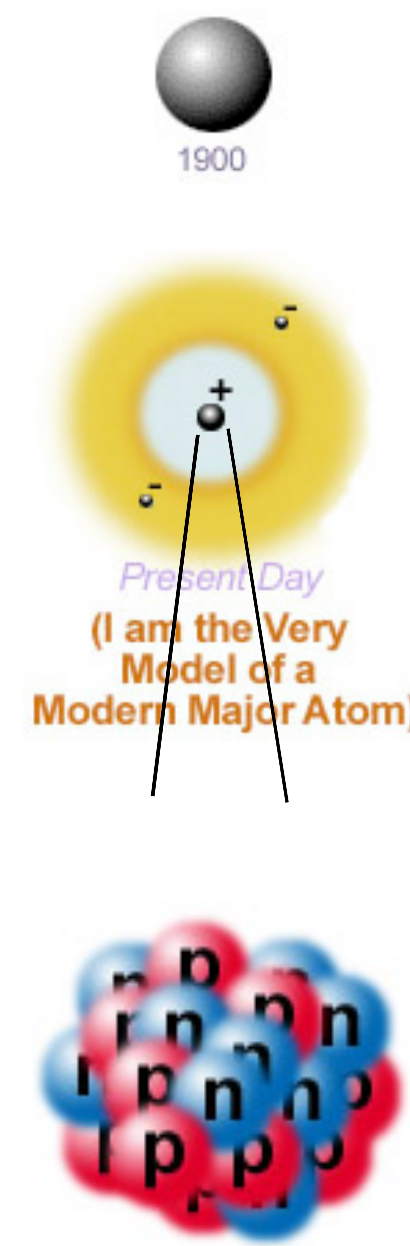
Standard Model of Particle Physics

Very Brief History

400 B.C - Greek philosopher Democritus postulates smallest constituent of nature to be atom.

"atomos" meaning "not to be cut" or Fundamental

Beginning of 20th century - The Democritus model of a fundamental atom was investigated further through scattering experiments.



1897 - JJ. Thompson discovers Electron in Cathode Ray experiment.

1917 - 1920 - Ernst Rutherford discovers and names Proton as existing inside atomic nucleus.

1932 - James Chadwick discovers neutral particle called Neutron inside atom.

Scattering experiments were the precursors of the high energy collider experiments we see today

Very Brief History continued

1930's - Enrico Fermi proposed very small particle called Neutrino to explain β decay spectrum.

1940's - Hideki Yukawa proposed that Meson particle must be responsible for holding nucleus together.

- It was later found that actually Mesons are bound states of quarks and Gluons are responsible for holding nucleus together.

1950-90's - Invention of more sophisticated particle accelerators meant the discovery of many particles we call the "particle zoo". Some of these were Fundamental particles

Fast forward

2012 - Highest energy particle accelerator at Cern, found the last particle in the Higgs Boson.

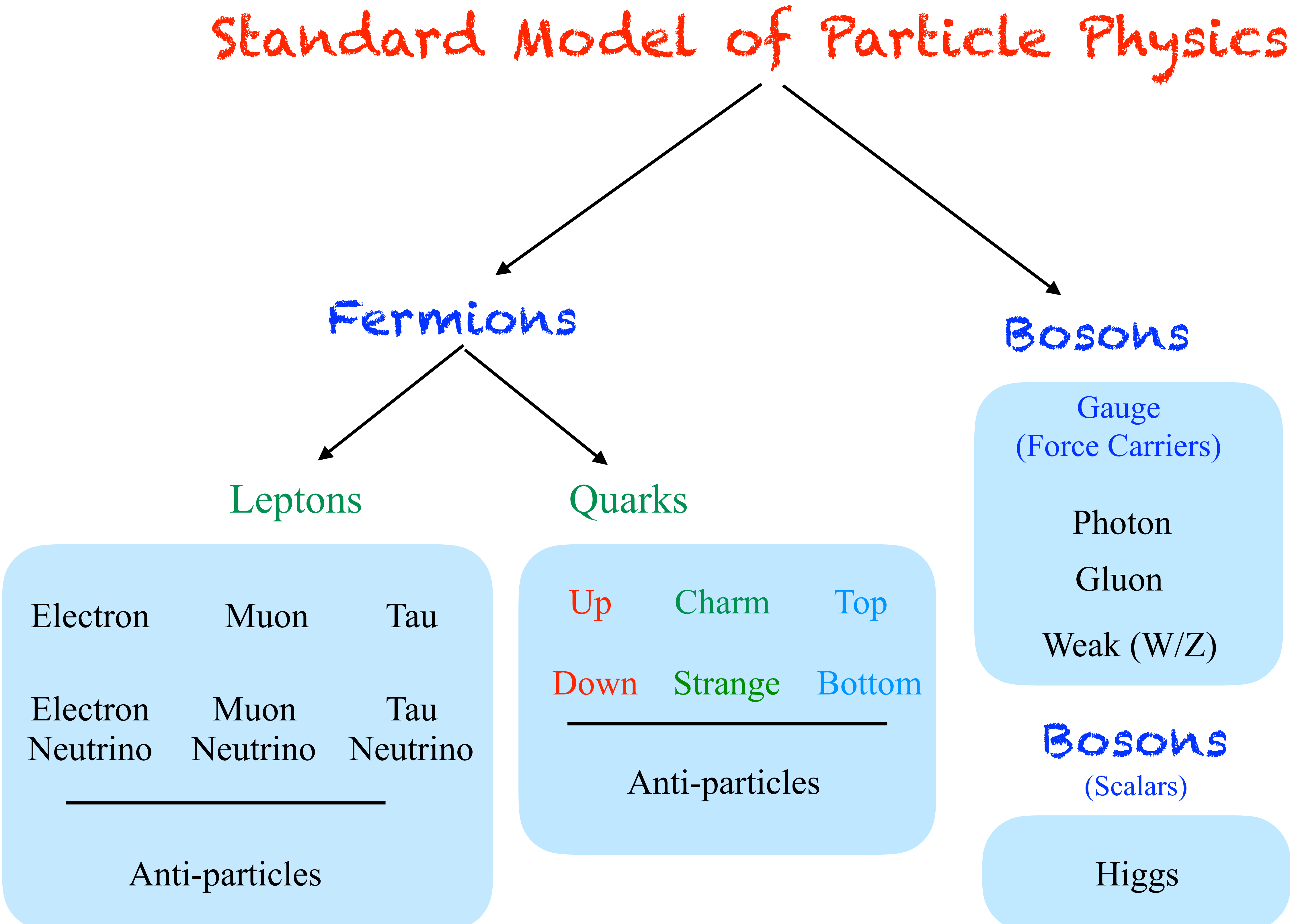
This leads us to the Standard Model of Particle Physics

Standard Model of Particle Physics

- Model used to classify and explain the fundamental particles and their interactions.

- Like a periodic table of elements, but for particle physicists.

- One of the most successful theories created so far.



Standard Model of Particle Physics
Fermions
Bosons
Leptons
Quarks
Electron
Muon
Tau
Electron Neutrino
Muon Neutrino
Tau Neutrino
Anti-particles
Up
Charm
Top
Down
Strange
Bottom
Anti-particles
Gauge (Force Carriers)
Photon
Gluon
Weak (W/Z)
Bosons
(Scalars)
Higgs

Particles classifications:

We may classify particles primarily using their spin and their charge.

Spin - value of intrinsic angular momentum assigned to all particles.

Charge - intrinsic property of a particle and determines how it responds when placed in a presence of a certain force. not specific to *electric charge*

In Standard Model:

Fermions: spin = 1/2 ⟶ Leptons: Integer charges, e.g.1e

Quarks: Fractional charges, e.g. 2/3e

Gauge Bosons: spin = 1

Scalar Boson: spin = 0

Anti-particles look and behave like their corresponding matter particles, but have opposite charge.

Another form of classification is through particle **masses.**

Nature of particles is best explained using Quantum Field Theory and Relativity.

- Particles are so small that classical physics fails
- Particles move so fast that special relativity provides best tools to explain their properties

To explain the energy, momenta and masses of particles we use

energy-momentum relation:

$$E^2 = (mc^2)^2 + (pc)^2$$

e.g. particles at rest i.e. no momentum has energy

$$E = mc^2$$

Einstein's famous equation

Energy of a particle is measured in electron volts (eV) $1\text{eV} = 1.6 \times 10^{-19}\text{J}$

Particle Physicists are lazy!!!! ⟶ Natural Units: c = 1

Natural units allow us to easily convert energy into mass and momentum i.e.

$$E^2 = m^2 + p^2$$

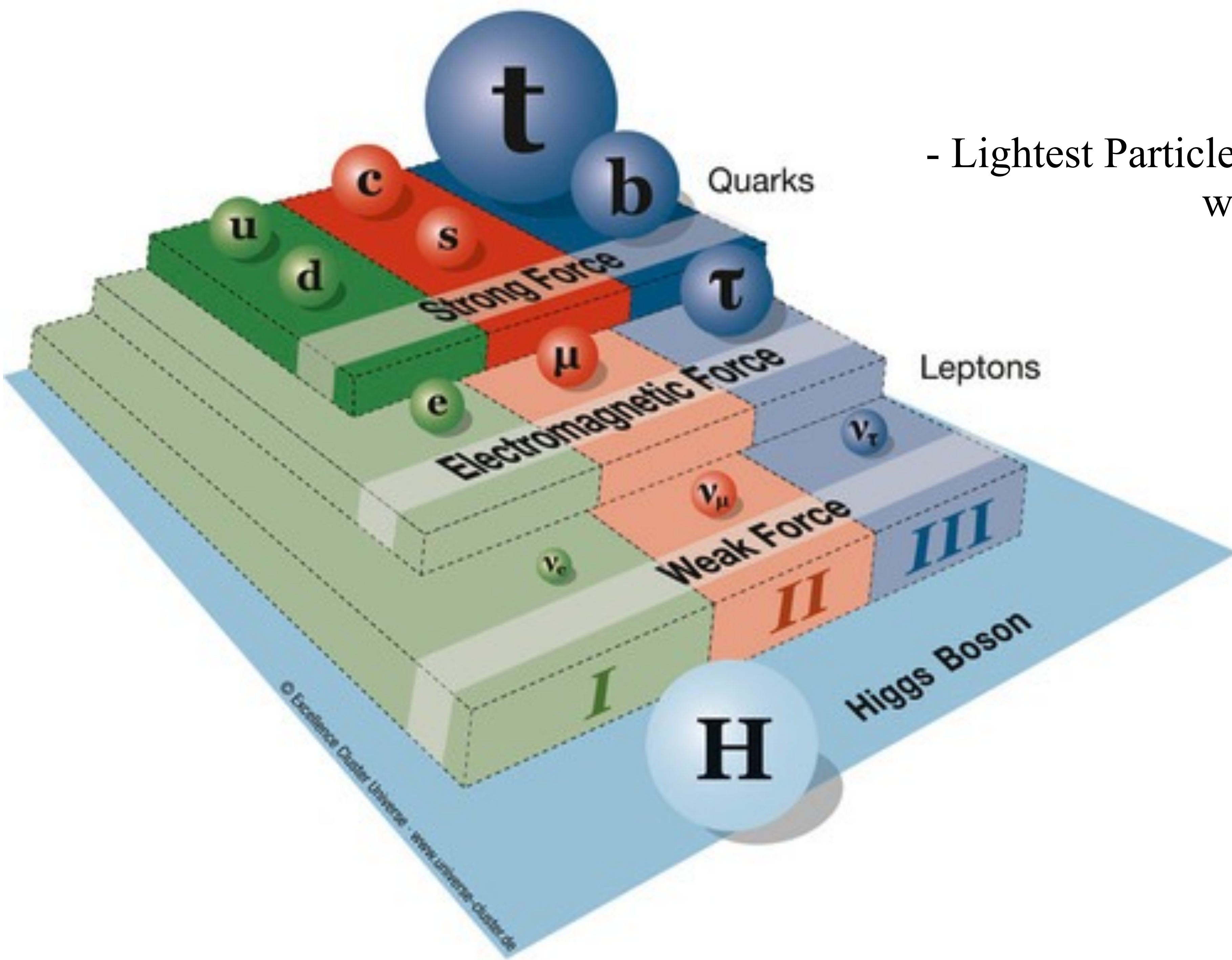
Thus units of Energy, Mass & Momentum are written in some variation of eV

Mega, Giga or Tera - electron volts (MeV, GeV or TeV)

e.g. Mass of the electron is 0.511 MeV which is very very small

With all these in mind the Standard Model can be shown as:

STANDARD MODEL OF ELEMENTARY PARTICLES



- Top quark is heaviest with m = 173 GeV

- Higgs Boson is 2nd heaviest with m = 126 GeV

…

…

- Lightest Particles in SM are Photon and Gluon with m = 0 GeV

How do these particles interact with each other to form the world we see?

At this point it might be important to define some fundamental building blocks of the SM.

In particle physics we usually rely on Group theory when setting up fundamental interactions.

For instance, in nature there are 4 fundamental forces:

- *Electromagnetic force*
- *Weak force*
- *Strong force*
- *Gravitational force*

SM interactions are based on the following gauge group based :

$$SU(3)_c \times SU(2)_w \times U(1)_Y$$

Strong Force

Weak Force

contains Electromagnetic Force

Fundamental forces and their carriers

Electromagnetism (QED)	**Photon (γ) exchange**
Strong interactions (QCD)	**Gluon (g) exchange**
Weak interactions	**W and Z bosons exchange**
Gravitational interactions	**Graviton (G) exchange ?**

- Photon mediates electromagnetic interactions i.e the reason we can see each other is because there is a group of photons bouncing back and forth between us at the speed of light.

- Strong force is mediated by the Gluon particle. Strong force is responsible for quark confinement i.e. why the protons/neutrons and in the end atoms stick together to form us and the world around us.

- W/Z bosons mediate the weak force which is responsible mostly for radioactive decay and other nuclear processes. Weak force is also mostly how neutrinos interact with other matter.

- Gravity is postulated to be mediated by a hypothetical Graviton and is not part of the SM.

Which forces act on which matter particles?

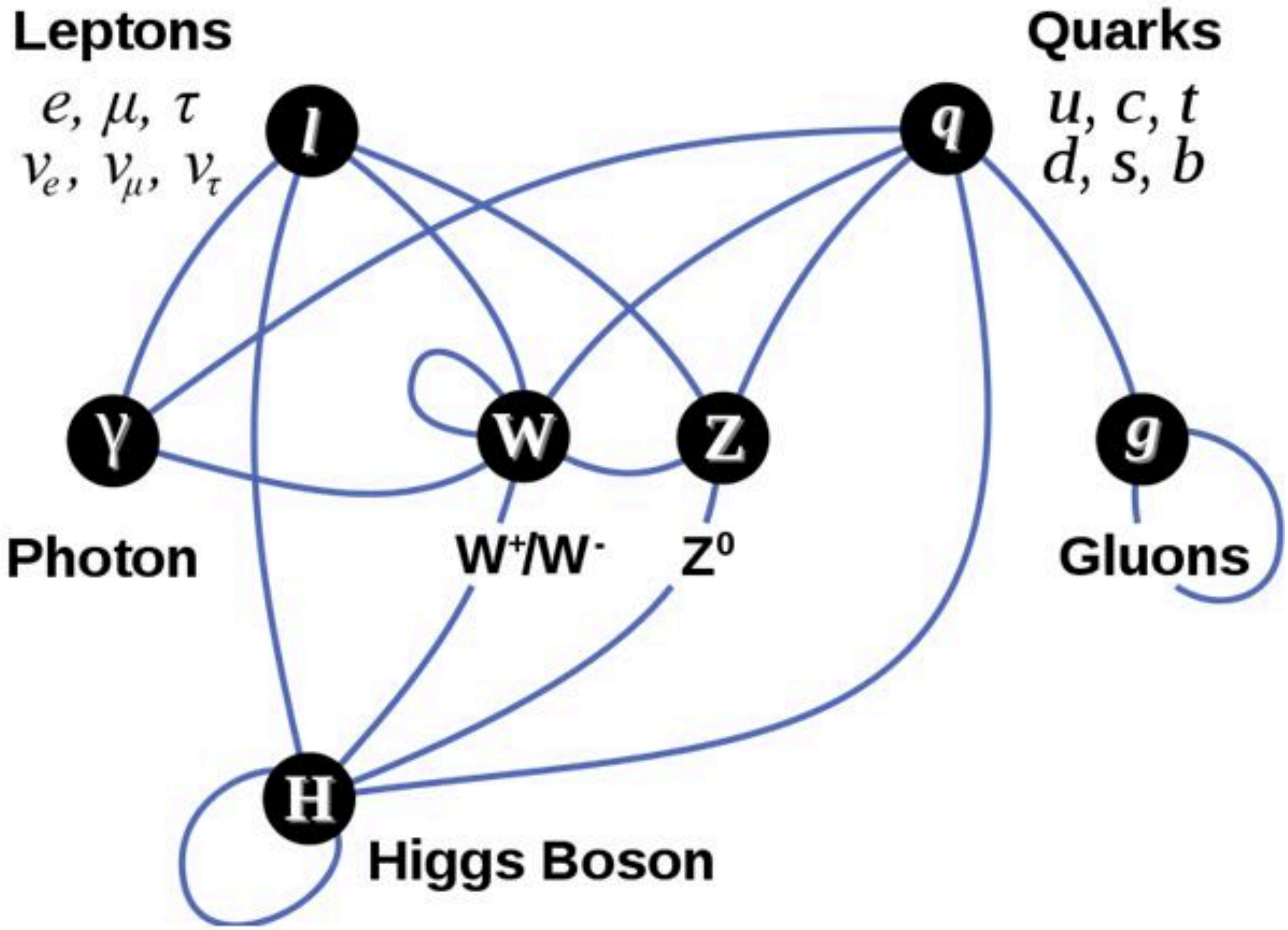
- EM forces acts on all fermions as long as they have charge i.e. it acts on charged leptons and all quarks.

- Weak force acts on all leptons and all quarks.

- Strong force only acts on quarks.

	Weak	EM	Strong
Quarks	✔	✔	✔
Charged leptons	✔	✔	✖
Neutral leptons (neutrinos)	✔	✖	✖

Which forces act on which matter particles?



Some properties of the matter particles

Charge Q of particle is defined as $Q = I_3 + Y/2$

- I_3: 3rd component of isospin, quantum number of strong interactions
- Y: Hypercharge which we mentioned before

Quarks:

Family of quark	Charge (Q)	Hypercharge (Y)	Isospin (I_3)
u, c, t	**+2/3**	**+1/3**	**+1/2**
d, s, b	**-1/3**	**+1/3**	**-1/2**

Fractional charges of quarks means they can form bound states to create Baryons and Mesons with integer charge.

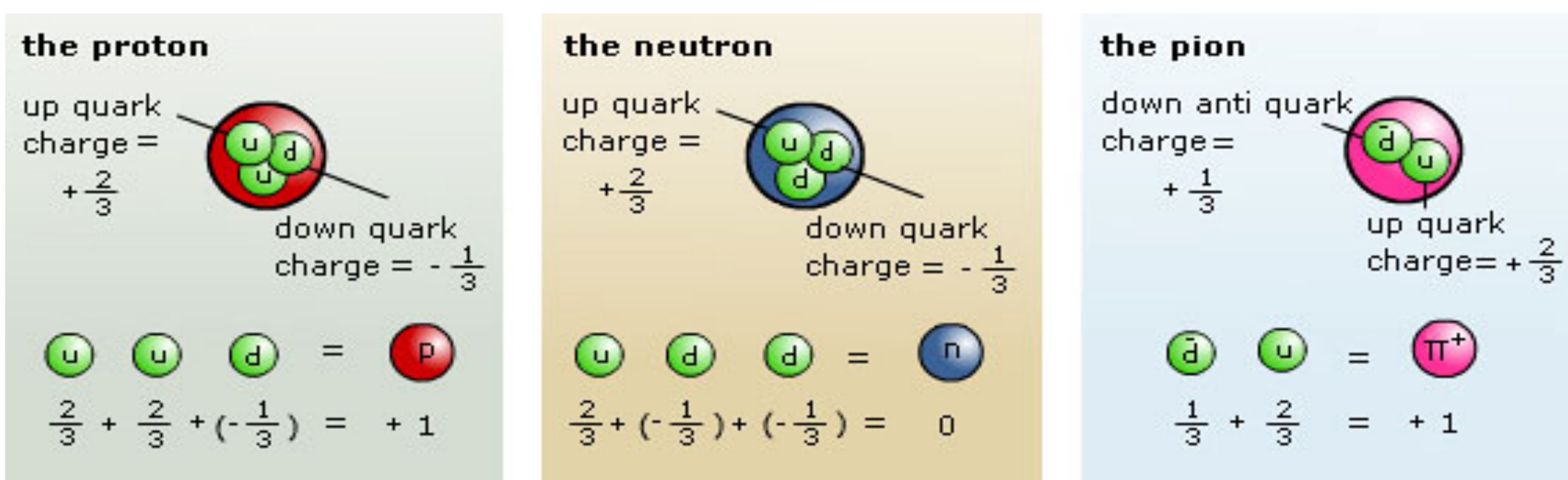
Quarks continued:

Baryons are bound states of 3 quarks of the form (qqq)

qqq	Q	Bar.
uuu	2	Δ^{++}
uud	1	Δ^{+}
udd	0	Δ^{0}
ddd	-1	Δ^{-}
uus	1	Σ^{*+}
uds	0	Σ^{*0}
dds	-1	Σ^{*-}
uss	0	Ξ^{*0}
dss	-1	Ξ^{*0}
sss	-1	Ω^{-}

Mesons are bound states of 2 quarks of the form (q qbar)

qqbar	Q	Mes.
uubar	0	π^{0}
udbar	1	π^{+}
ubar d	-1	π^{-}
ddbar	0	η
uus	1	K^{+}
uds	0	K^{0}
dds	-1	K^{-}
uss	0	K^{0}
dss	-1	η'



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uus	1	[illegible]
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dds	-1	[illegible]
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[illegible]	[illegible]	K^{0}
[illegible]	[illegible]	K^{-}
uss	0	K^{0}
dss	-1	η'

These form part of the particle zoo

Interesting fact: One of these baryons - J/Psi particle - was discovered here at BNL in 1976 by the Alpha Magnetic Spectrometer experiment.

Samuel Ting, PI on the experiment shared a Nobel Prize for the discovery.

Leptons :

Family of lepton	Charge (Q)	Hypercharge (Y)	Isospin (I_3)
e, μ, τ	**-1**	**-1/2**	**-1/2**
ν_e, ν_μ, ν_τ	**0**	**-1**	**+1/2**

- Leptons already have integer charge so its harder to naturally form bound states.

- Neutrinos were initially thought to have zero mass, however recently observations of neutrinos coming from the Sun and atmosphere showed that they oscillate.

- Oscillate meaning they change from one state to the other as they propagate

If they oscillate, they must have mass - more on this During Dr. Mary Bishai's talk.

Ok so what about the Higgs particle?

- Higgs is a very important particle because it is responsible for the SM particle masses through its interactions with these particles.

- best way to explain this is to use another piece of machinery commonly used in particle physics.

Lagrangian - Equation used to map out particle interactions

General Lagrangian term contains

$$\mathcal{L} \supset \bar{\psi} D^{\mu} \gamma_{\mu} \psi + m \bar{\psi}_L \psi_R + (D^{\mu} \phi)^{\dagger} D_{\mu} \phi + y \phi \bar{\psi}_L \psi_R$$

Kinetic term fermion interactions with Bosons

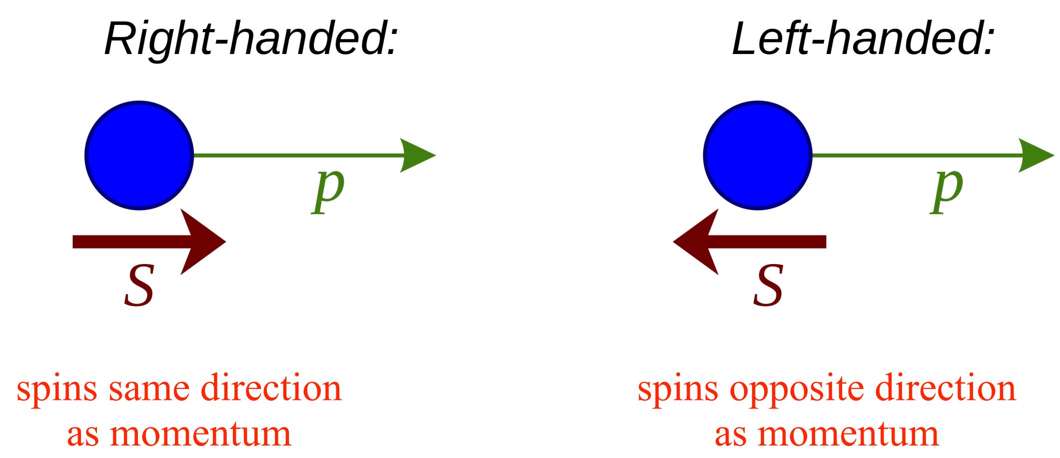
Fermion mass term

Scalar interaction with Bosons

Yukawa term interaction of scalar with fermions

- In order for a particle to have mass, it must be chiral, i.e. have a right handed and left handed components.

Dirac Mass



- The Higgs couples to fermions through Yukawa interaction and to gauge bosons through the kinetic term

$$(D^\mu \phi)^\dagger D_\mu \phi$$

After the process of electroweak symmetry breaking the scalar is written

$$\phi = \frac{v + h}{\sqrt{2}}$$

vacuum expectation value of the scalar

Higgs scalar

Plugging back into the previous Lagrangian means

Plugging ϕ into the Lagrangian

$$\mathcal{L} \supset \bar{\psi} D^{\mu} \gamma_{\mu} \psi + m \bar{\psi}_L \psi_R + (D^{\mu} \phi)^{\dagger} D_{\mu} \phi + y \phi \bar{\psi}_L \psi_R$$

We get, for interactions with fermions

$$\mathcal{L} \supset \frac{yv}{\sqrt{2}} \bar{\psi}_L \psi_R + \frac{y}{\sqrt{2}} h \bar{\psi}_L \psi_R$$

Thus the fermion mass is $m_{\psi} = \frac{yv}{\sqrt{2}}$

Determined experimentally

so top quark mass is $m_t = \frac{y_t v}{\sqrt{2}}$

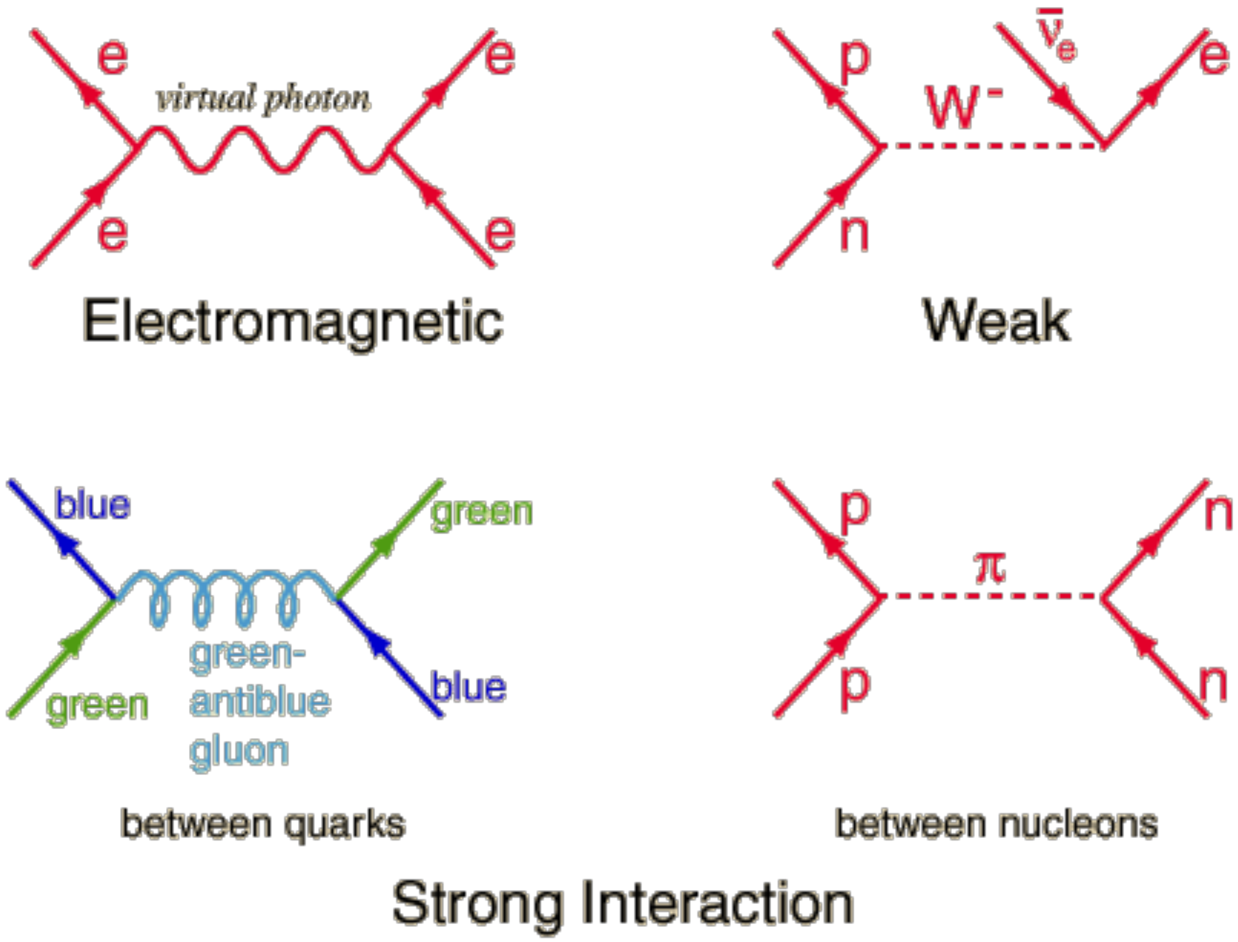
Boson masses come from the scalar kinetic term

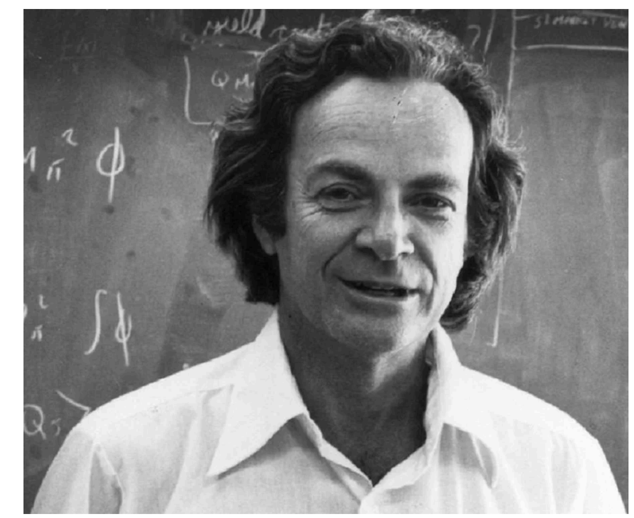
I realize I may have confused you so early on a Monday Morning

This is how we theoretically explain where particle masses come from.

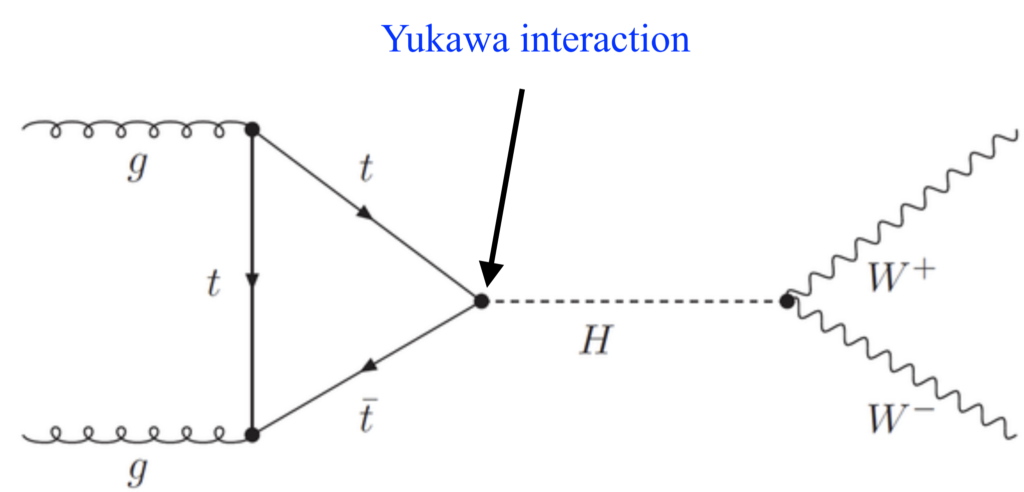
Particle masses are actually determined experimentally, more about this later.

Further tools used by particle physicists to quantify particle interactions are ***Feynman Diagrams***.





Richard Feynman
Nobel Prize 1965

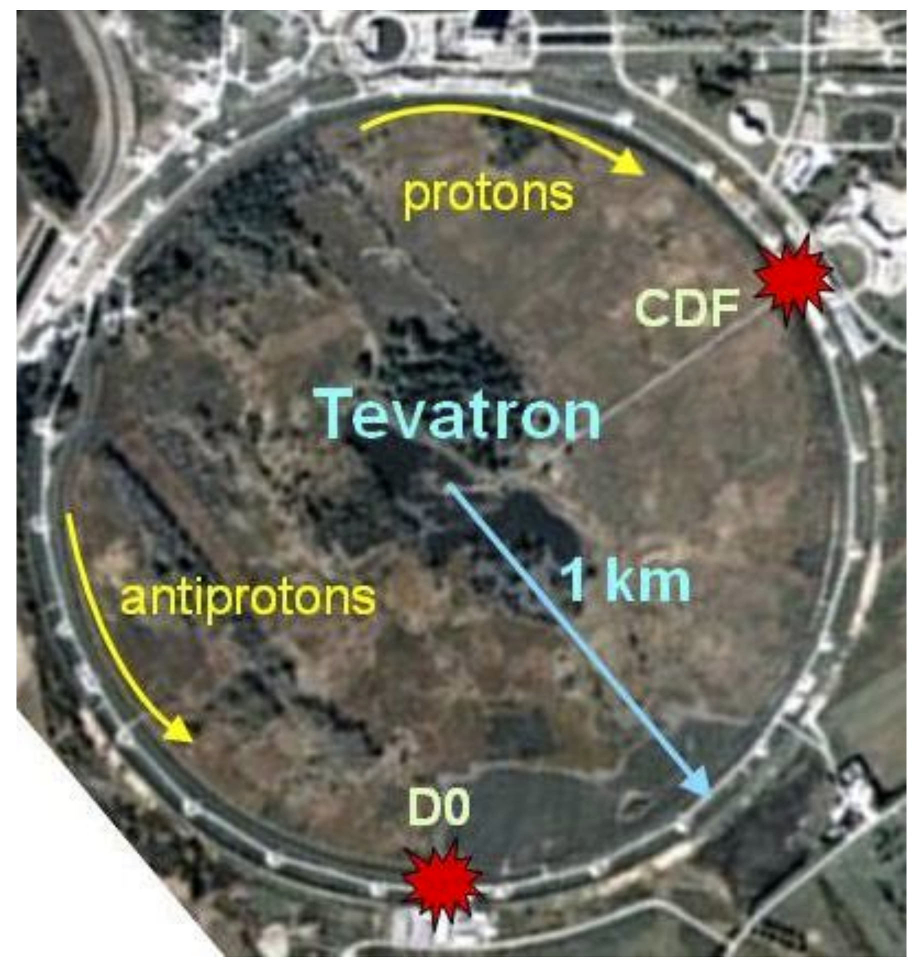


How are the particles found in Experiments?

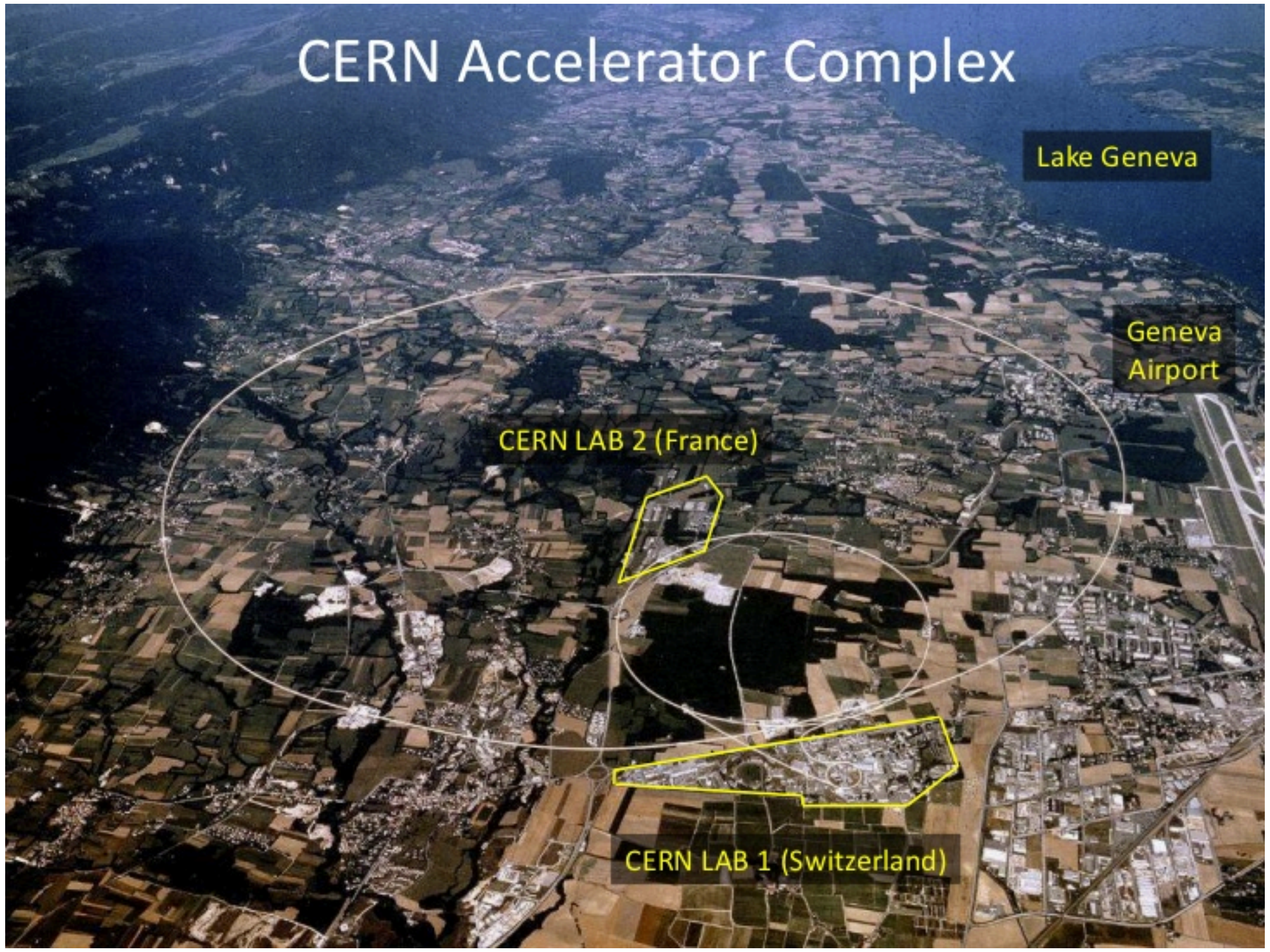
Many of these particles were found in high energy collider experiments

e.g.

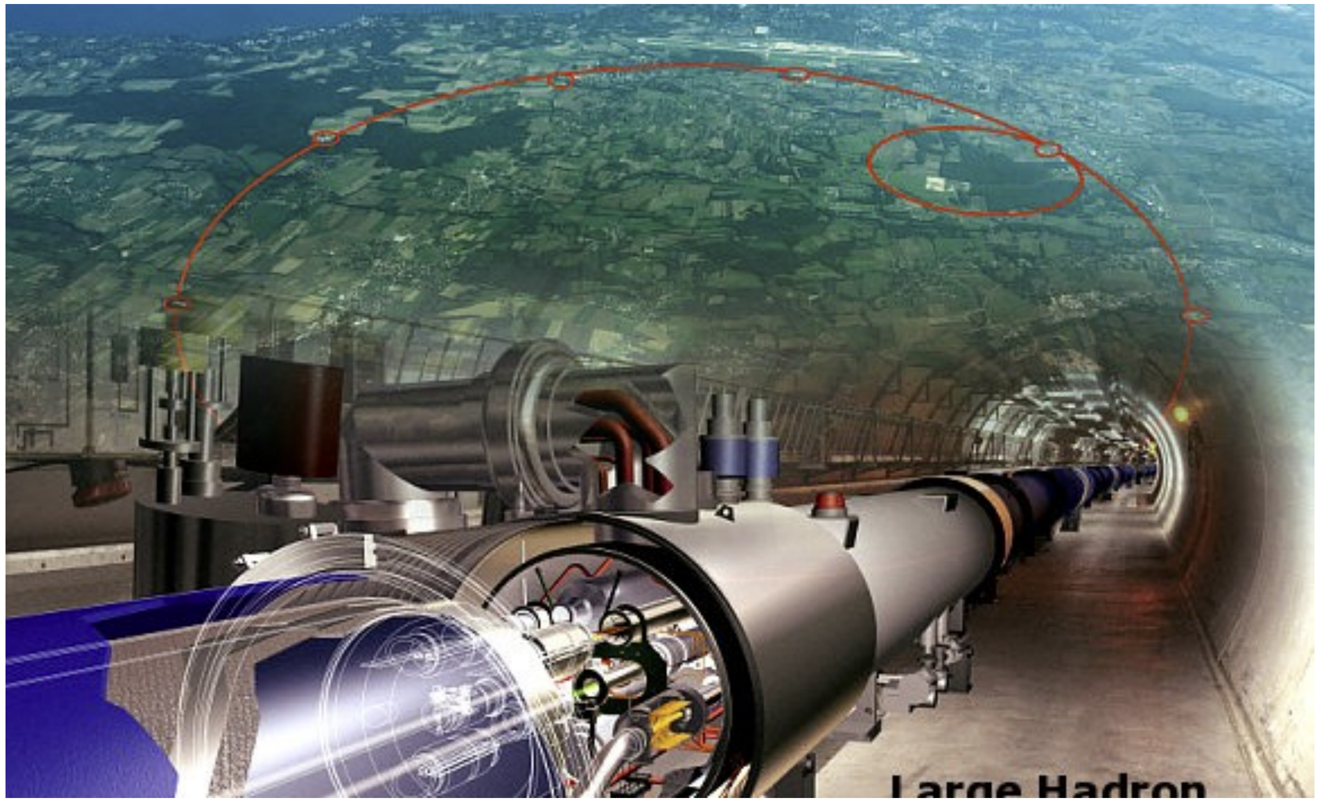
Tevatron Collider at Fermilab near Chicago



Large Hadron Collider at Cern in Switzerland



Tunnel & beam pip, Deep underground



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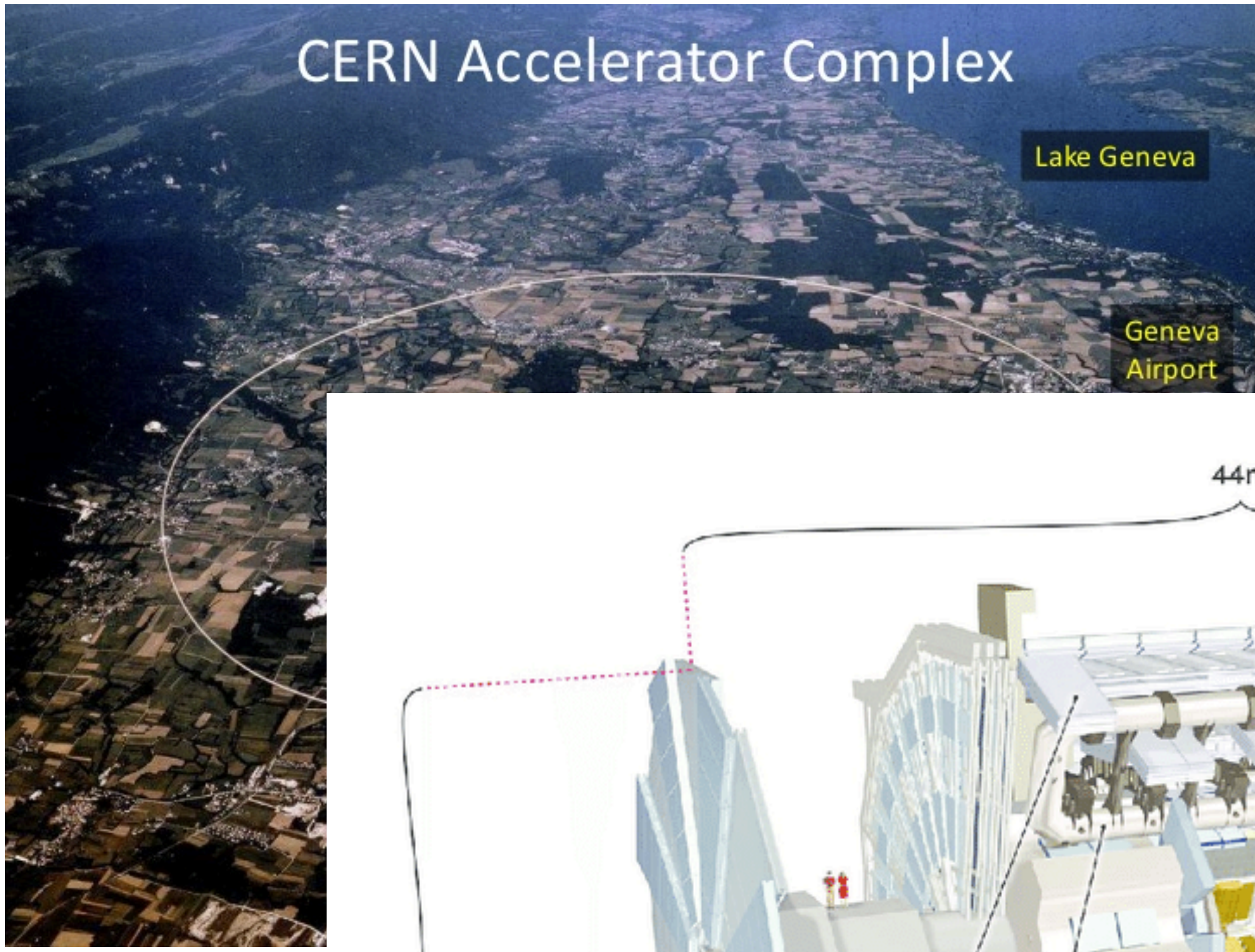
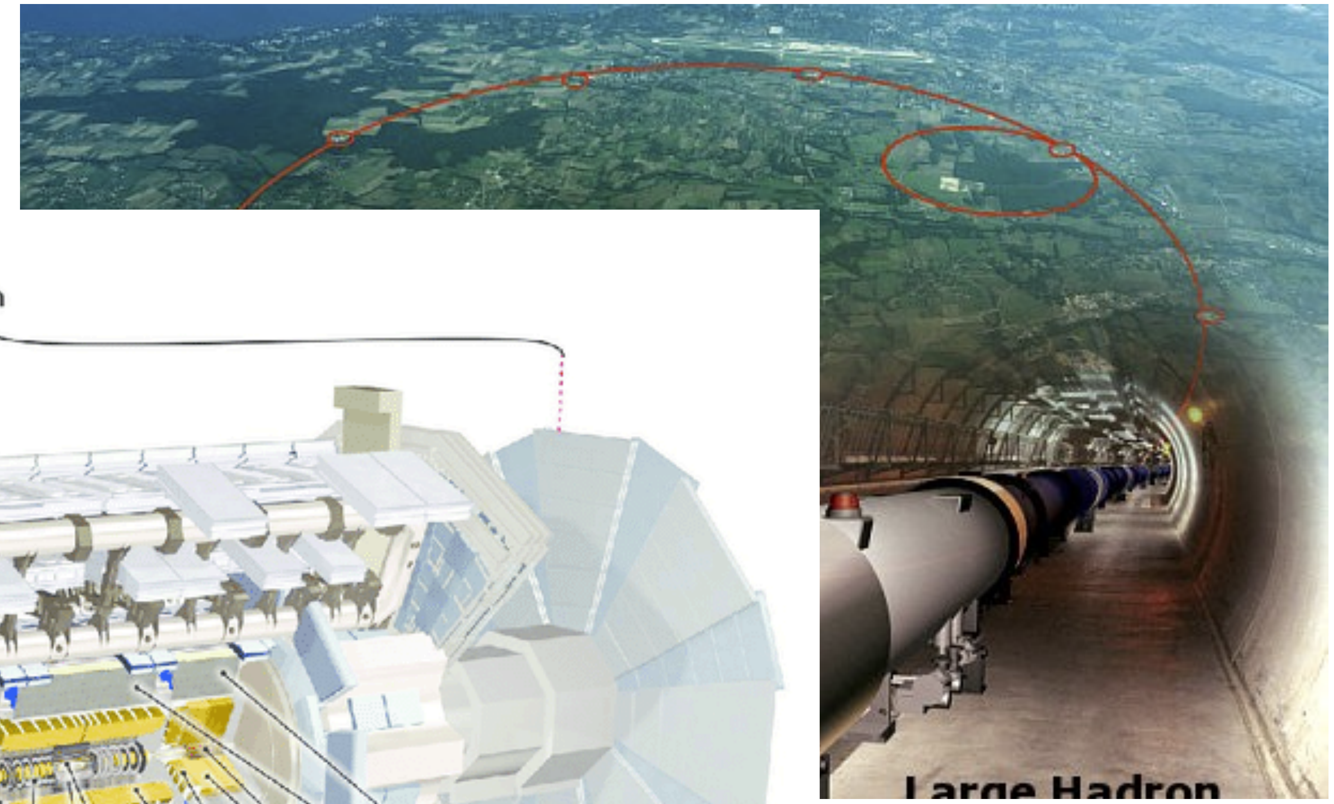
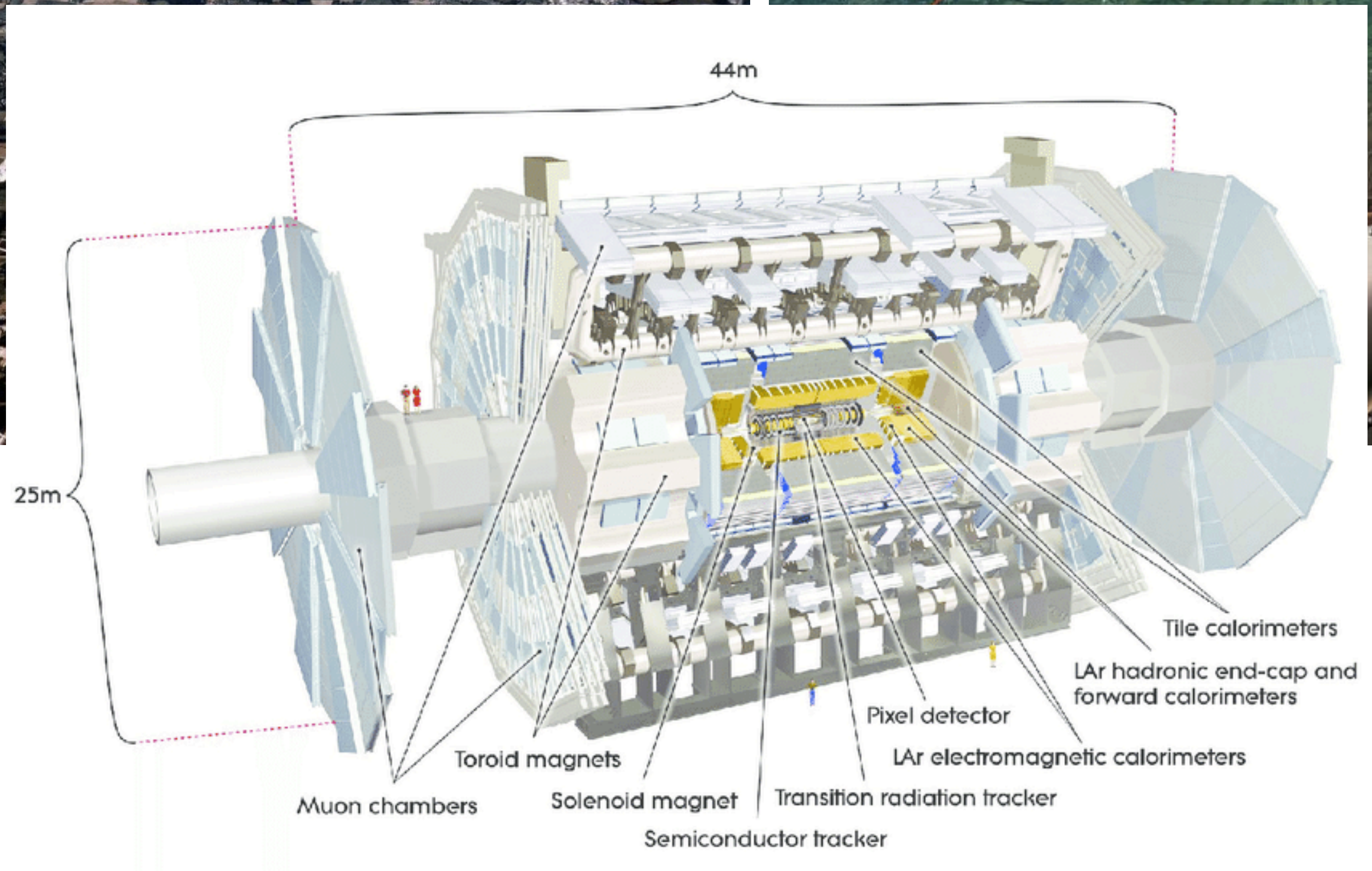


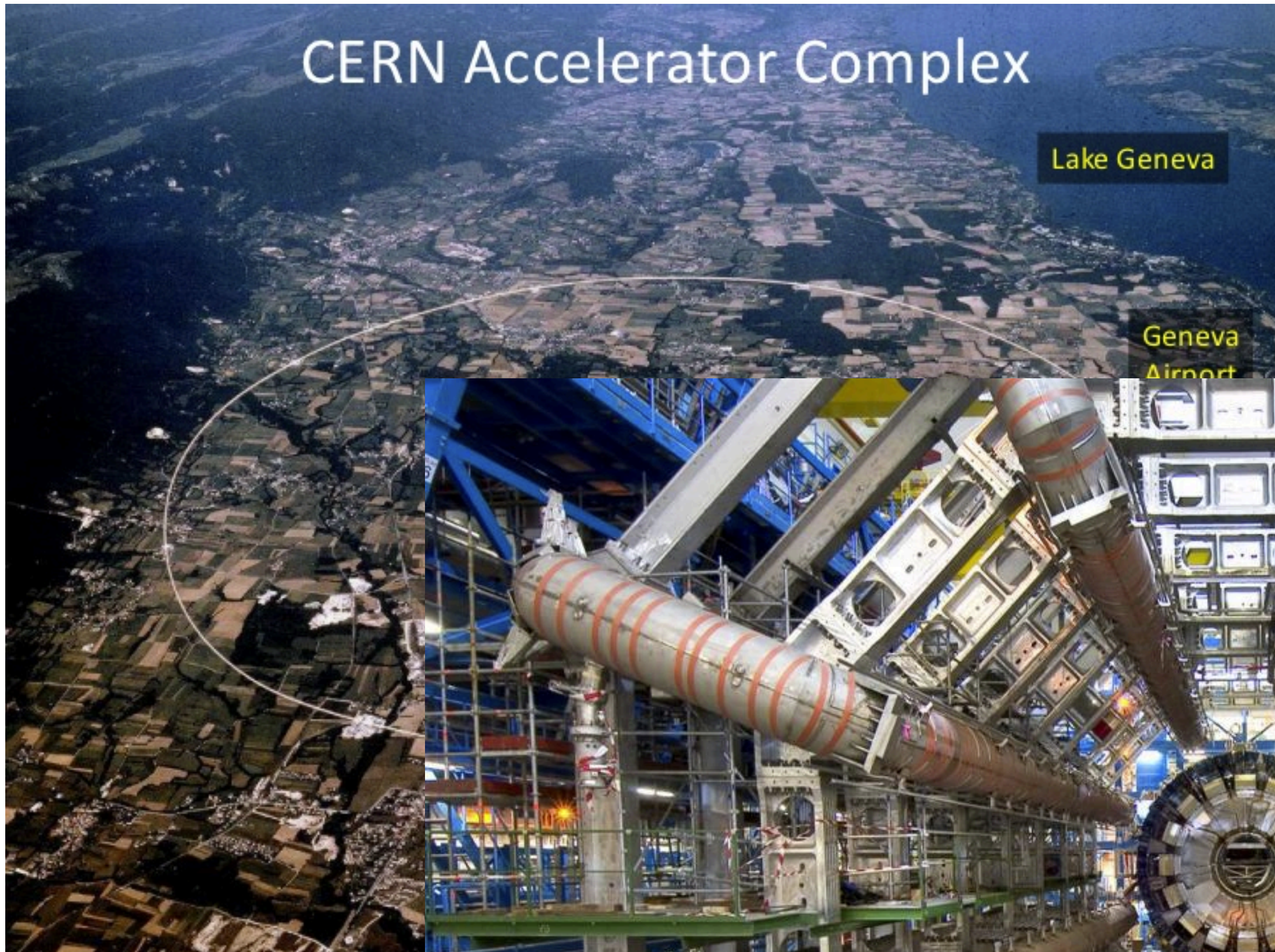
Tunnel & beam pip, Deep
underground





Atlas detector

Large Hadron Collider at Cern in Switzerland



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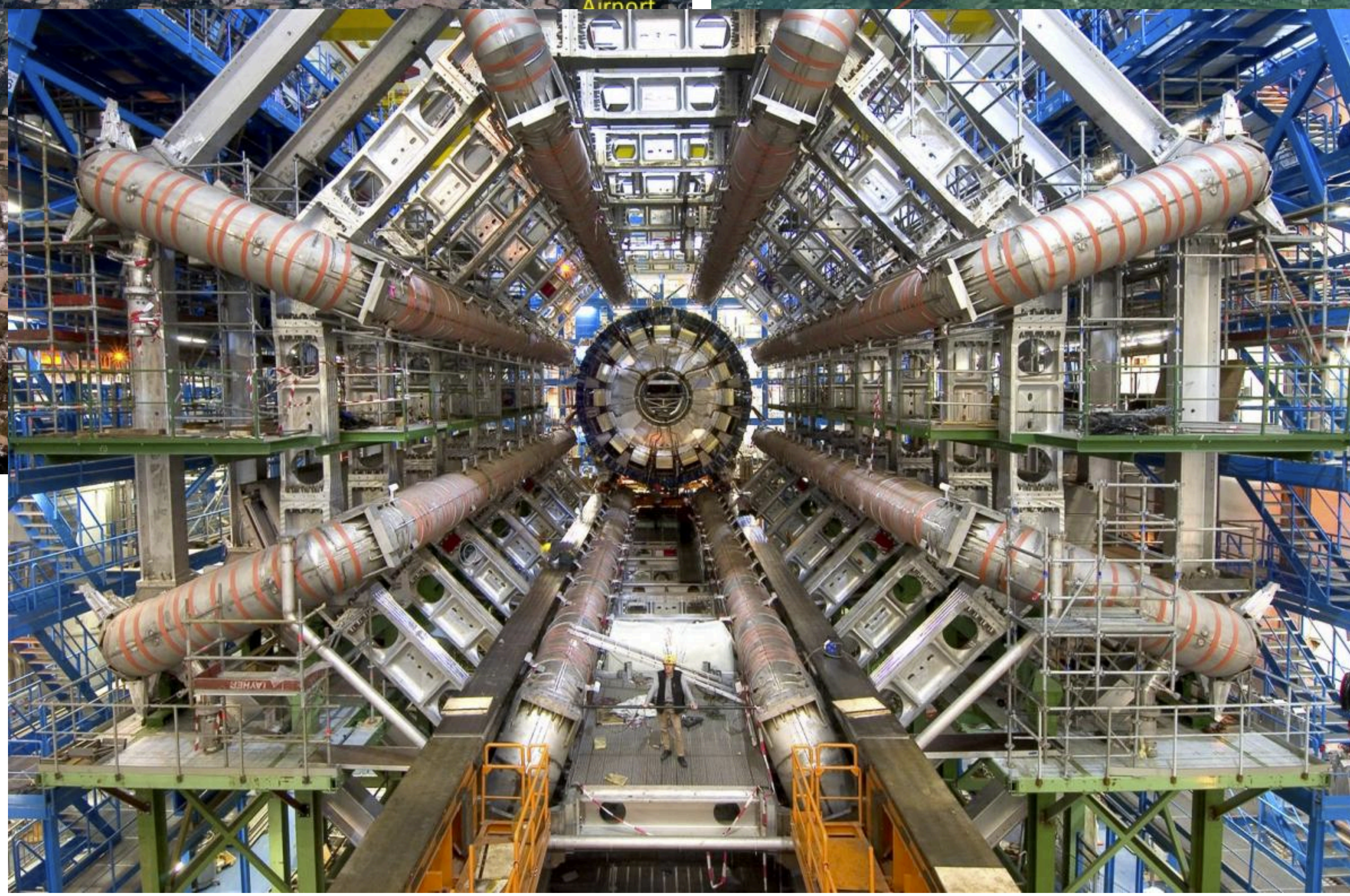
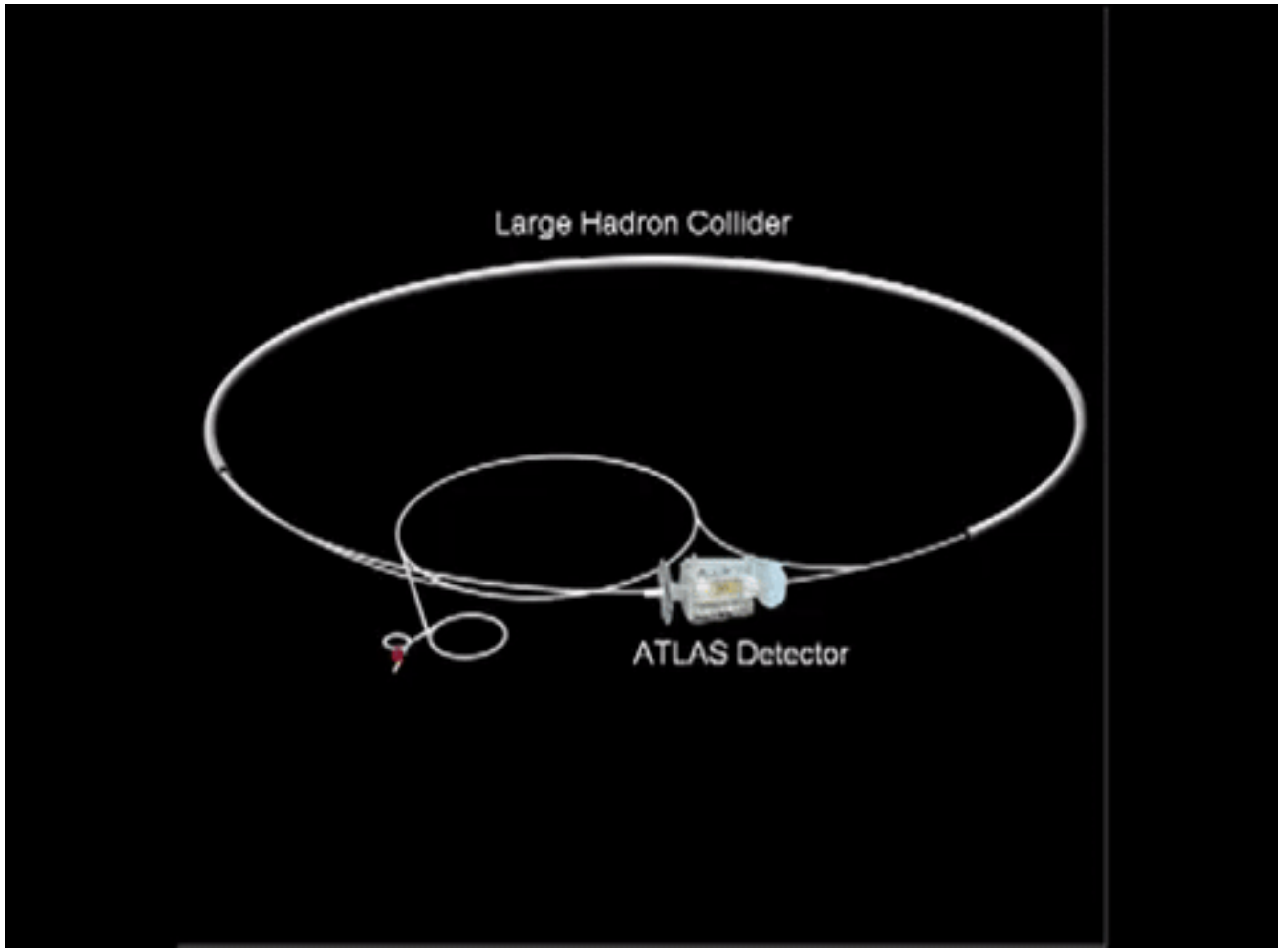
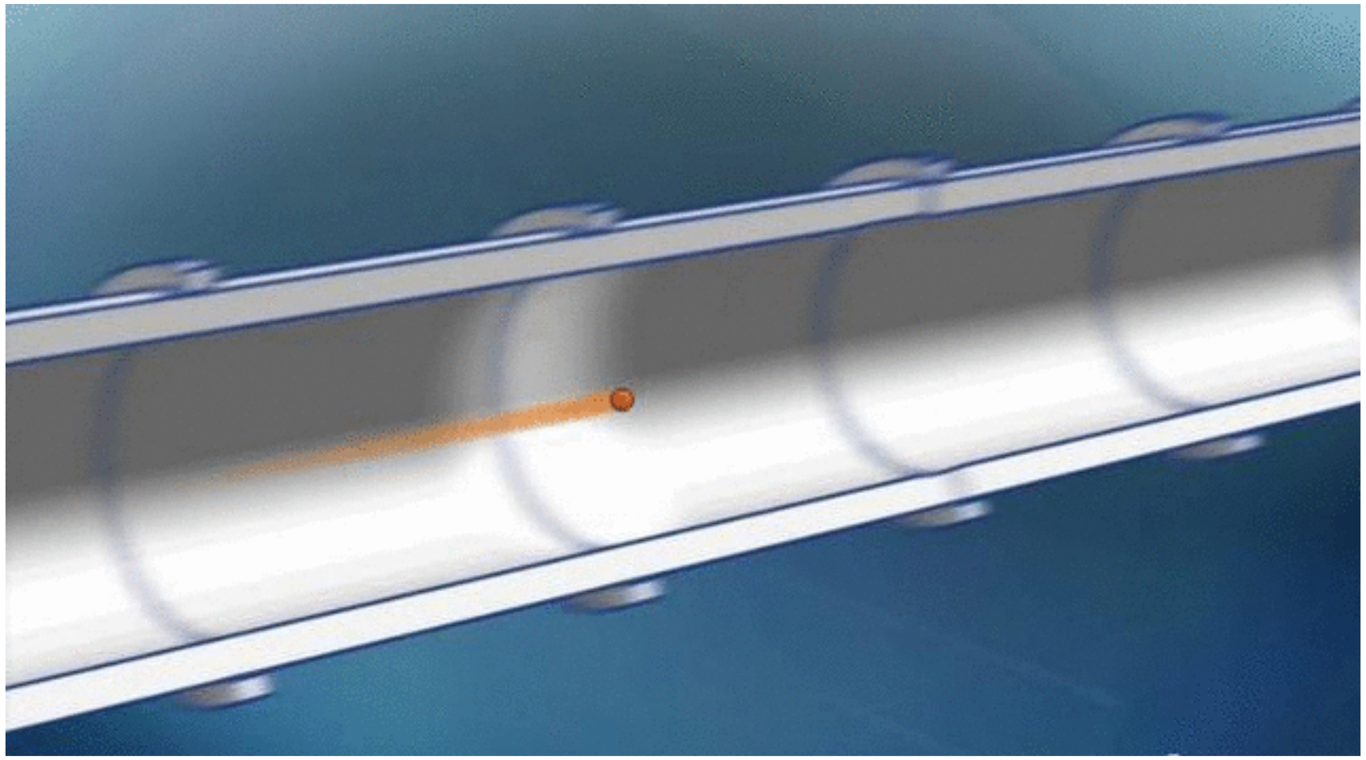


Atlas detector for real real

So how does this all work exactly?

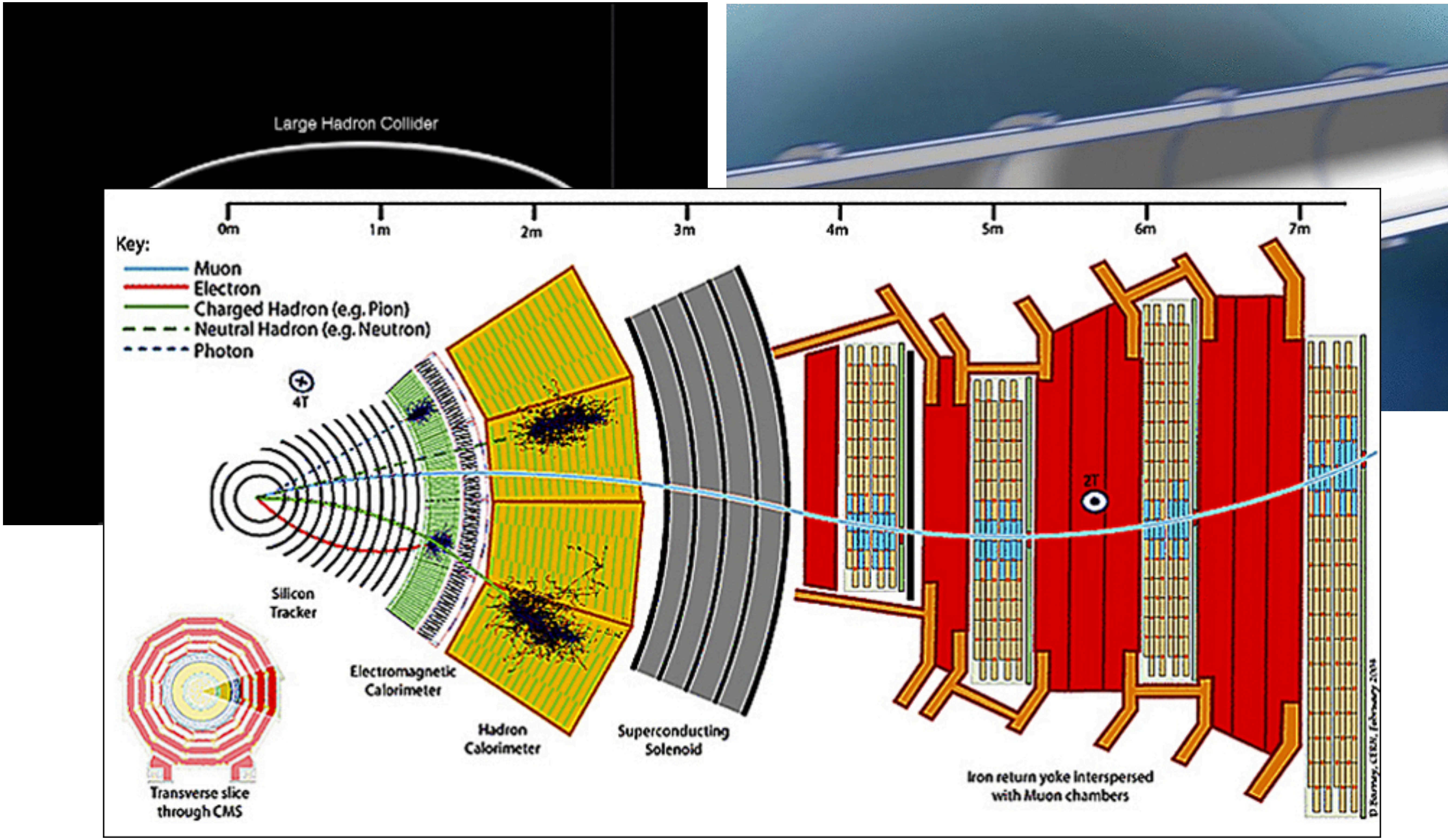




Bunches of protons are accelerated in the beam pipe using highly powered magnets.

Protons collide at high energies in detector into many particles which detected as they interact with the detector.

So how does this all work exactly?

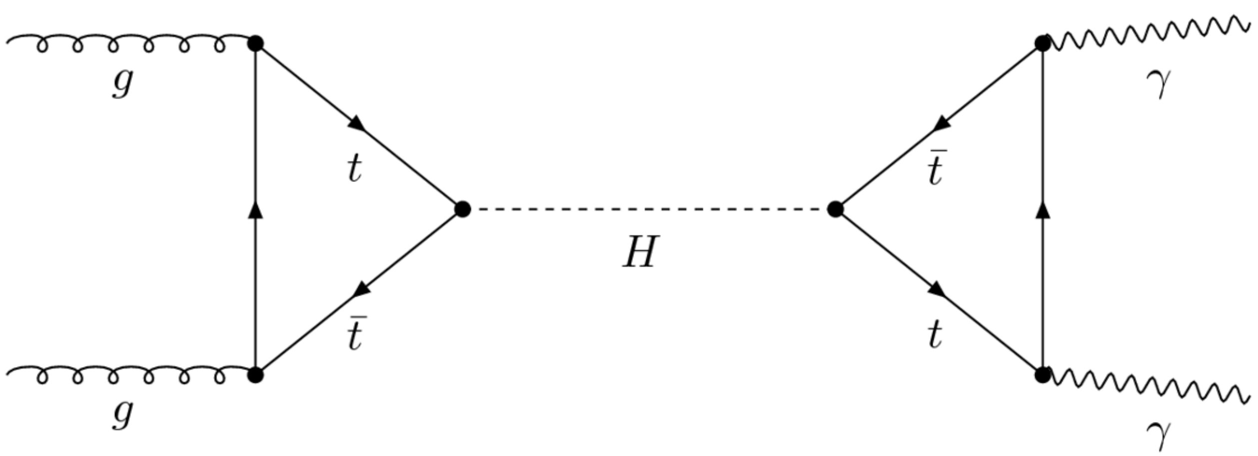


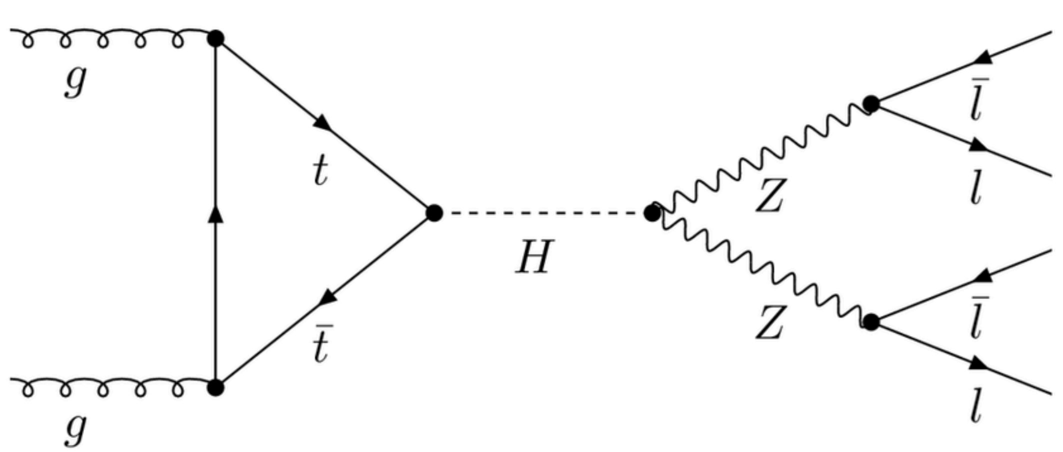
Specific example: how the Higgs was discovered

Higgs was discovered using two main channels:

- Observing two photons coming from the same point

- Observing 4 leptons, 2 pairs, each coming from the same point





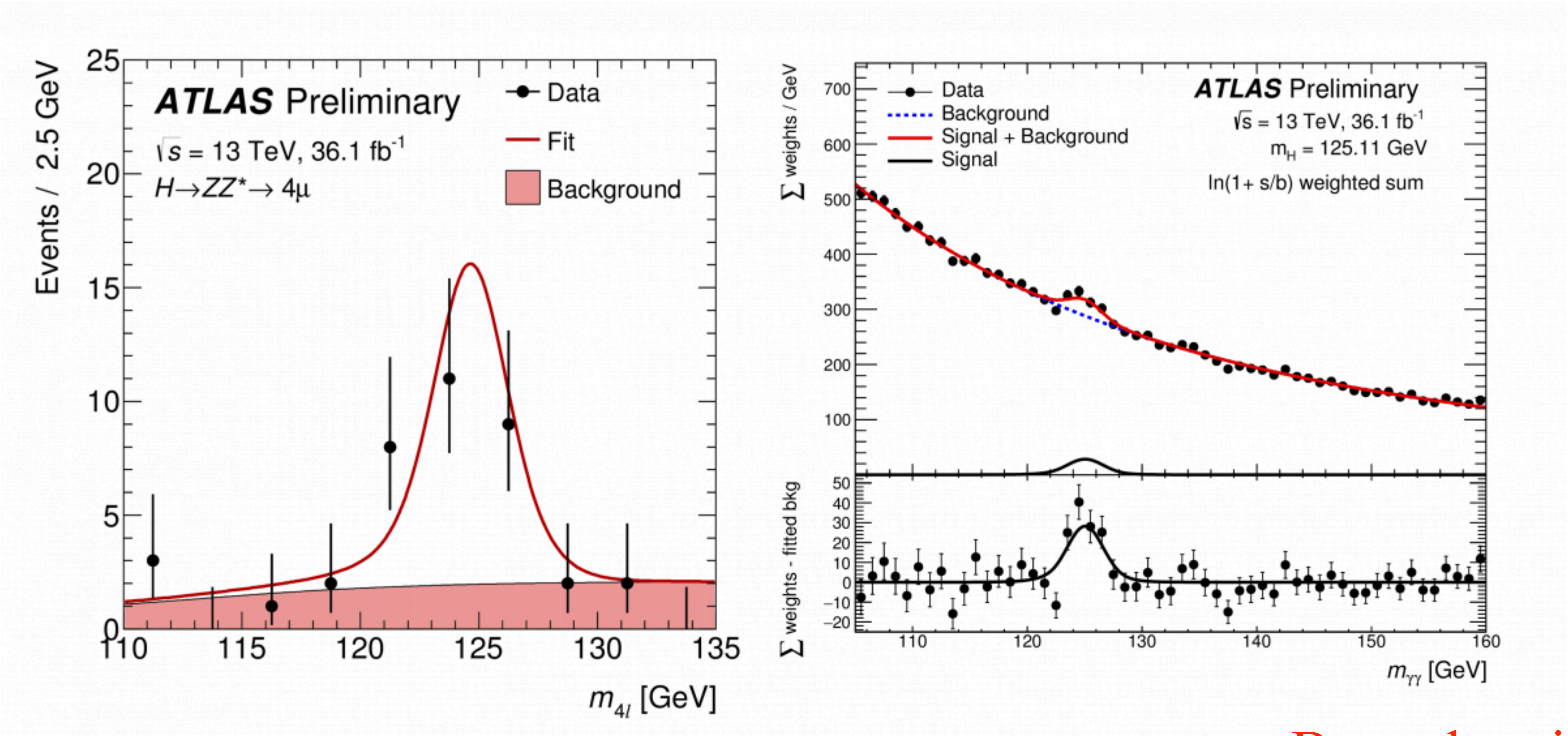
Higgs is produced from proton collisions and then quickly decay into other SM particles which are longer lived.

How does this look to us after data reduction?

To see this process, we use different variables that give us a handle this process.

Also, since there is so much data, this is a statistical process.

One such variable is the invariant mass distribution of the decay products of the Higgs.



Bump hunting

Summary

Particle Physics tells us about the nature and interactions of subatomic particles.

Currently particle physics is best explained by the Standard Model.

SM is one of the most successful theories in nature as it explains a lot of what we see in Nature.

With the discovery of the Higgs in 2012 at the LHC, all SM particles have been discovered.

However, Particle physics is incomplete; we will explore this in the next talk.

Some resources

Particle Physics

http://particleadventure.org/index.html ← Interactive learning for PP
even has a cellphone App

https://quarknet.org/ ← many resources for teachers and students

https://quarknet.org/data-portfolio ← a lot of useful practical PP information

About LHC

https://home.cern/science/accelerators/large-hadron-collider ← Overview of LHC & virtual tour of Cern

http://hypatia.phys.uoa.gr/ReadAbout/ ← ATLAS simulation tool