# Introduction to Particle Physics

## From lens of an experimentalist

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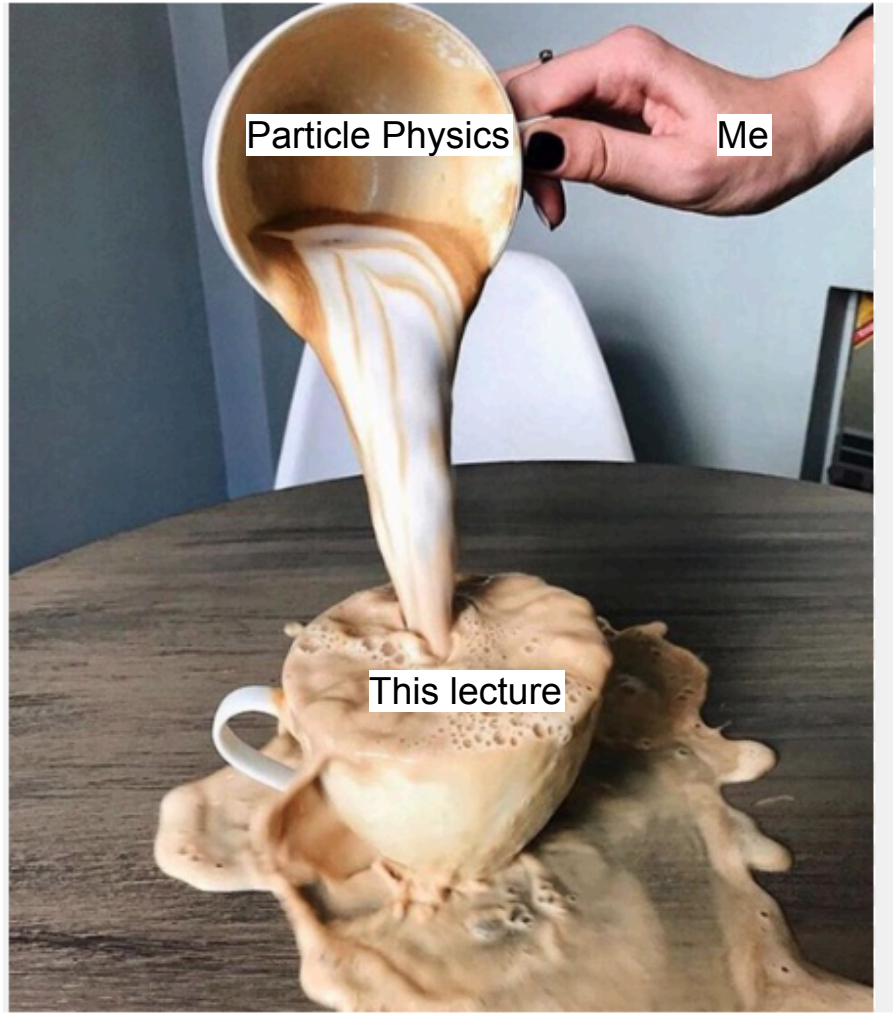
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

# Outline

There is a lot one could cover within this topic




- Introduction & Theory
- Motivation
- Experimental Particle Physics
- Collider Physics

# Follow closely, there will be quiz questions —> correct answers?

# Introduction & Theory

# What is particle physics?

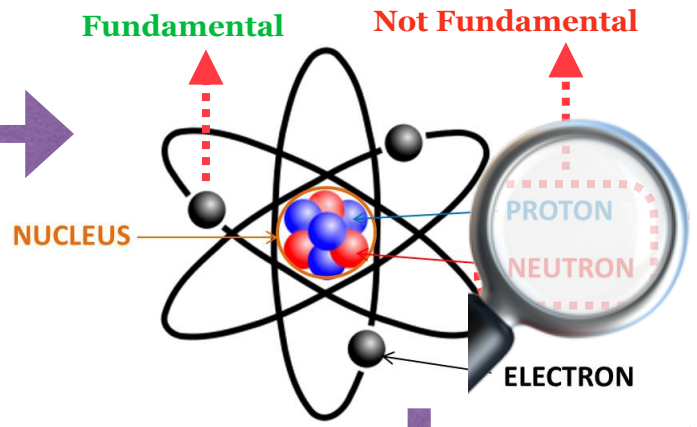
A field of physics that tries to understand the fundamental nature of the universe

In other words, what is the smallest building blocks of nature?

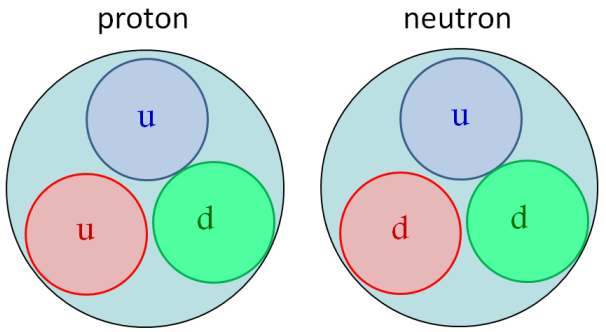
# What is particle physics?

H.S. Science

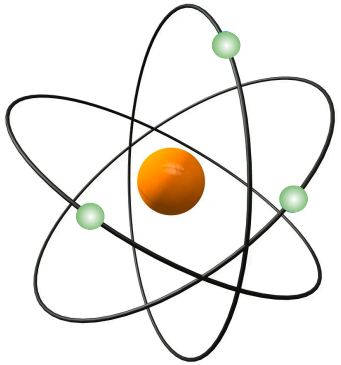
Atom, the building blocks of matter

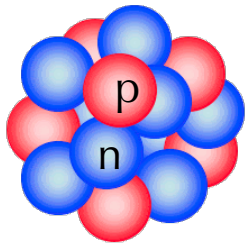



Quarks the building blocks

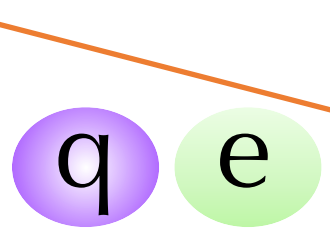


# The scale of fundamental interaction

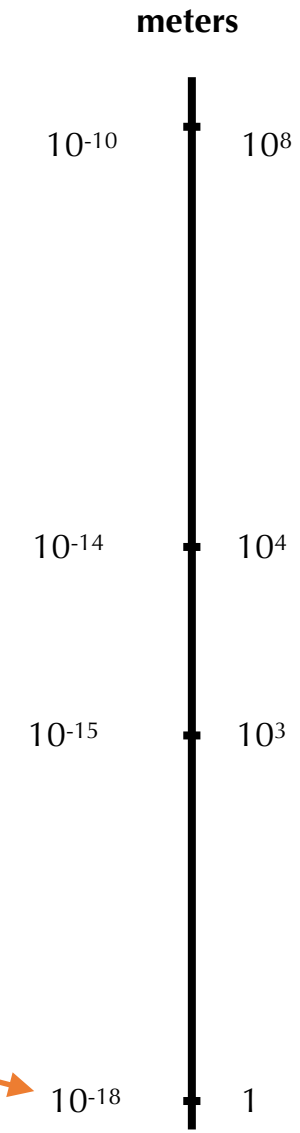








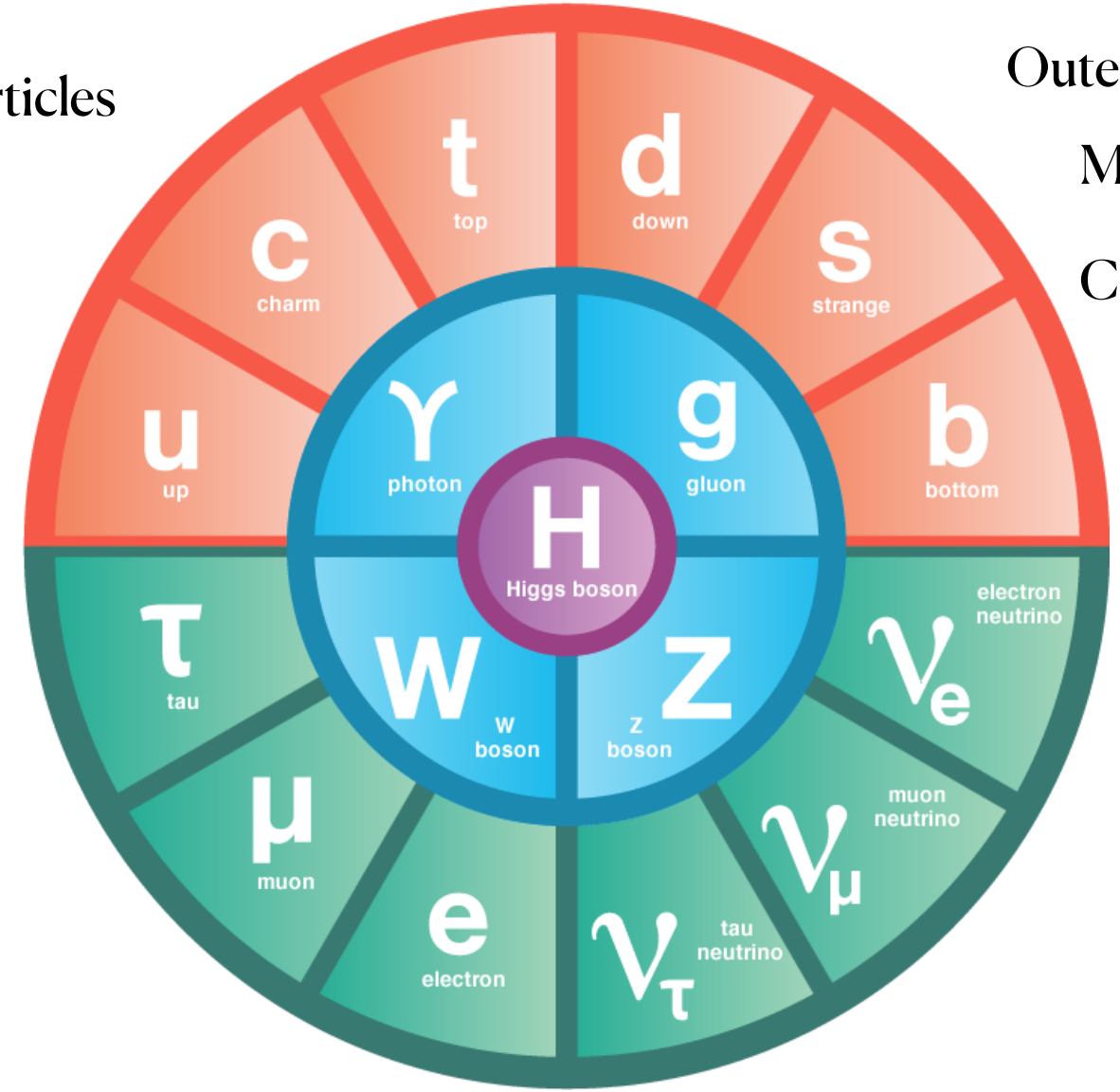

Scale we are concerned about






# Our Current Understanding of Fundamental Nature of Universe

17 known fundamental particles




Outer layer: matter particle

Medium layer: force carrier

Center particle: Higgs Boson

Most recently discovered, very special

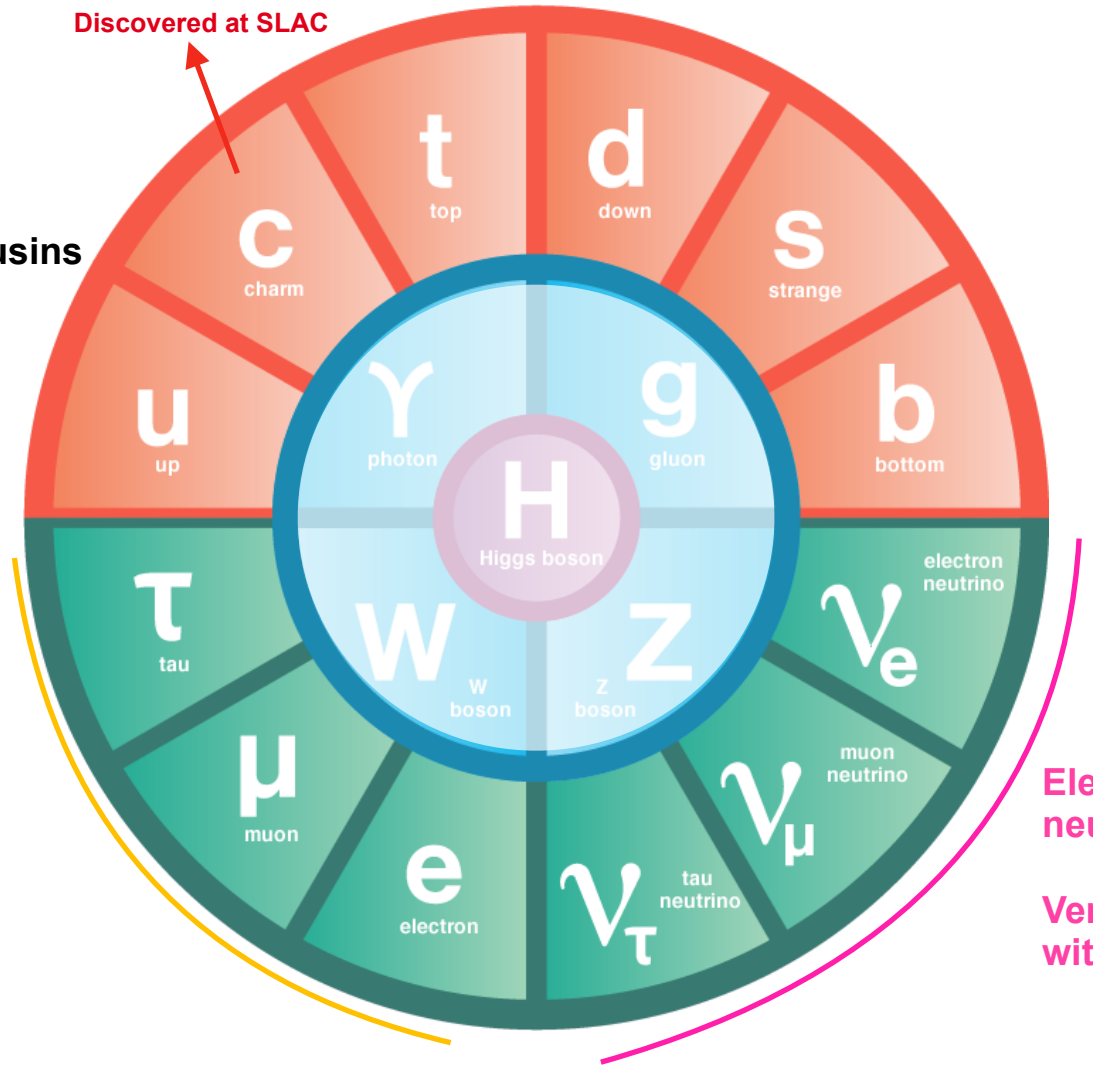
# Matter Particle: The Fermions

Matter component of visible universe (stars, galaxies, you, me…)

## Top half Quarks:

**Up & down makes proton/neutrons**

**Charm, strange, top & bottom heavier cousins**




## Bottom half Leptons:

**Electrons & heavier cousins muons, tau**

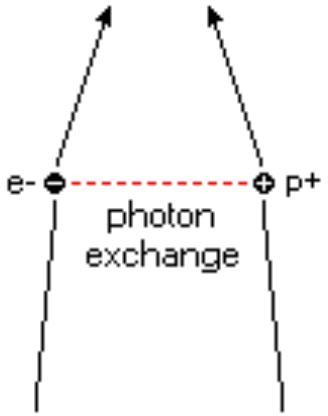
**Electron-neutrino, muon-neutrino, tau-neutrino**

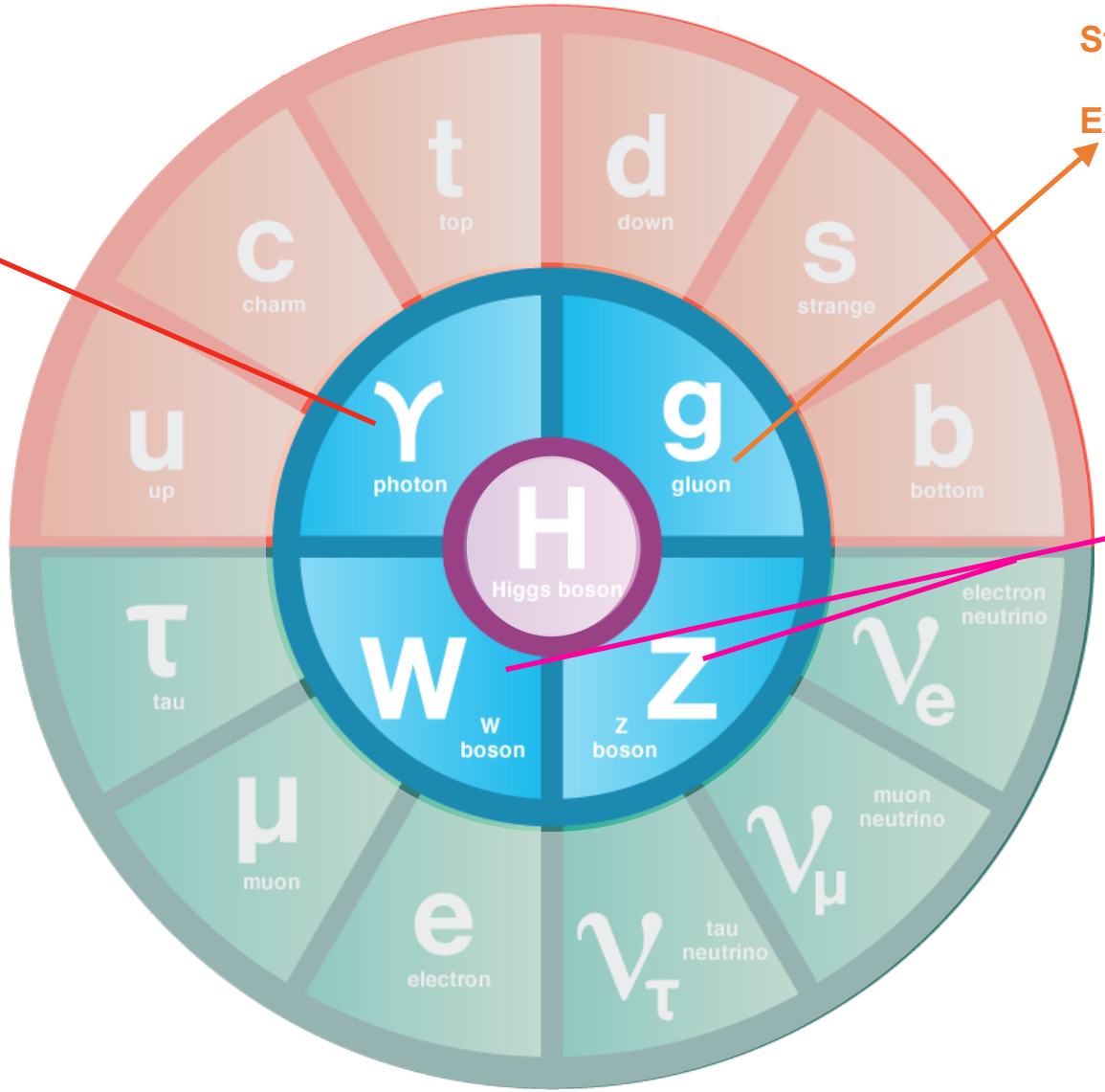
**Very light passes through entire earth without interacting**

# Force Carriers: Bosons

## Force carriers

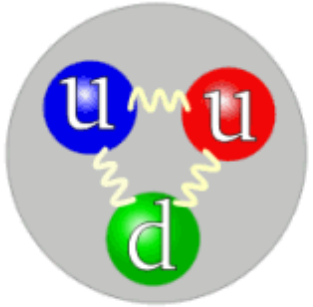
**Electromagnetic force**



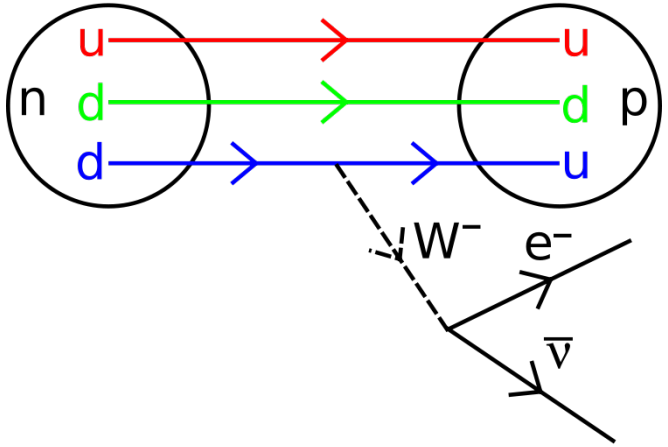

**Strong force: between quarks**

**Example: binds proton/neutrons**




**Weak force:**

**Example: radioactivity**



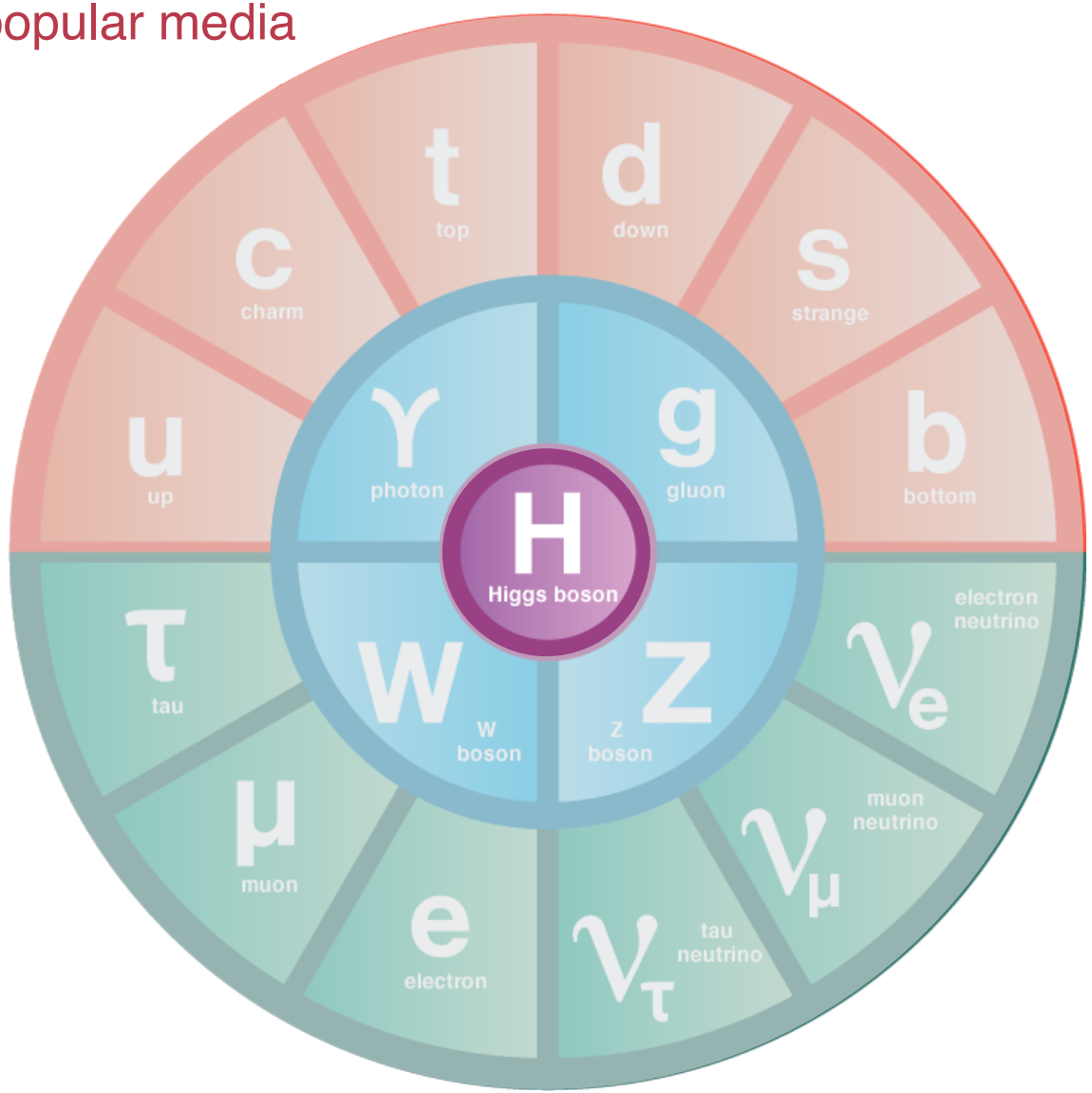
# The Higgs

## Known as god particle in popular media

**Most recently discovered**

**A central role**

**Gives mass**




JULY 4 2012


The New York Times

Oil Backed Up, Iranians Put It On Idled Ships

ROMNEY NOW SAYS HEALTH MANDATE BY OBAMA IS A TAX

Physicists Find Elusive Particle Seen as Key to Universe

2013

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François Englert

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Peter W. Higgs

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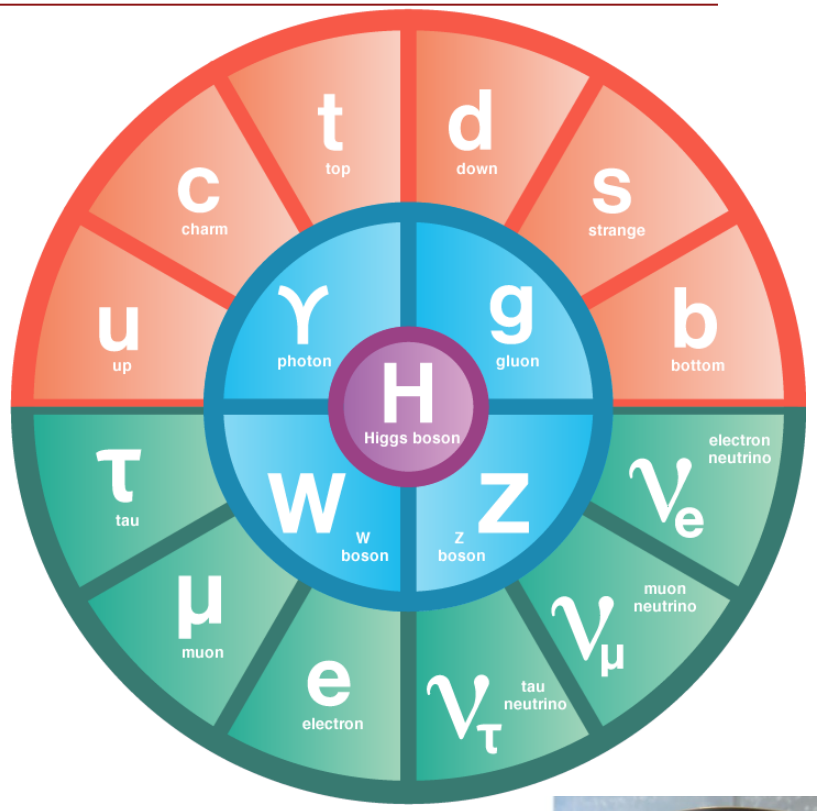
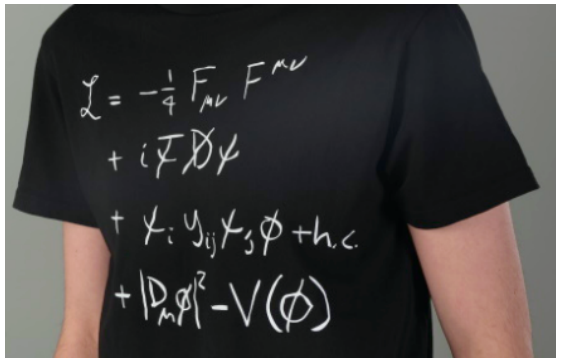
# Theory of Our Current Understanding

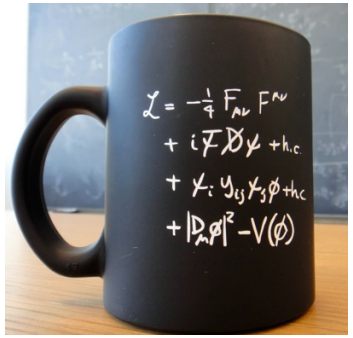
## The Standard Model

A theoretical framework describing all known fundamental particles & their interactions

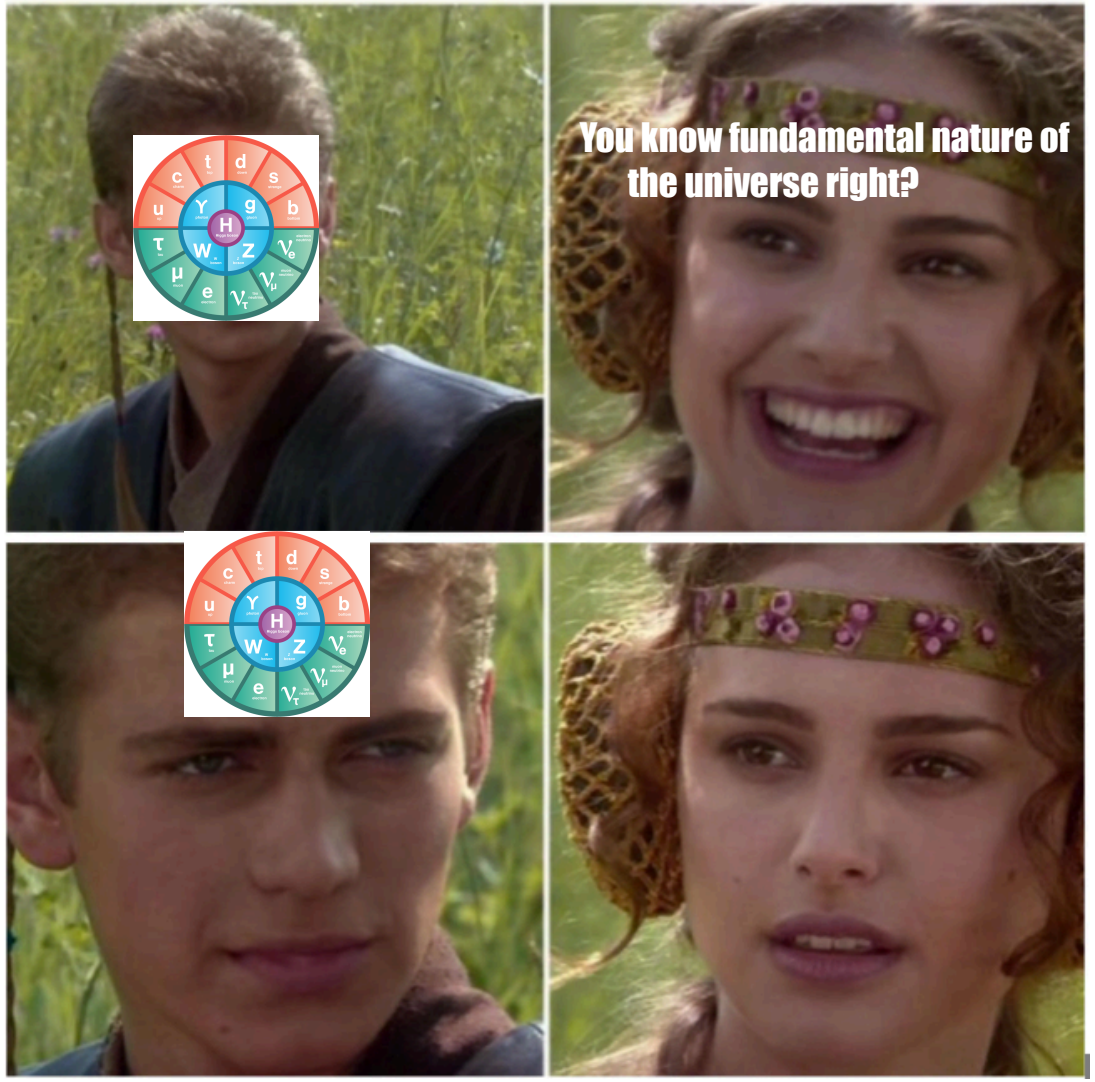
Periodic table of particle physics





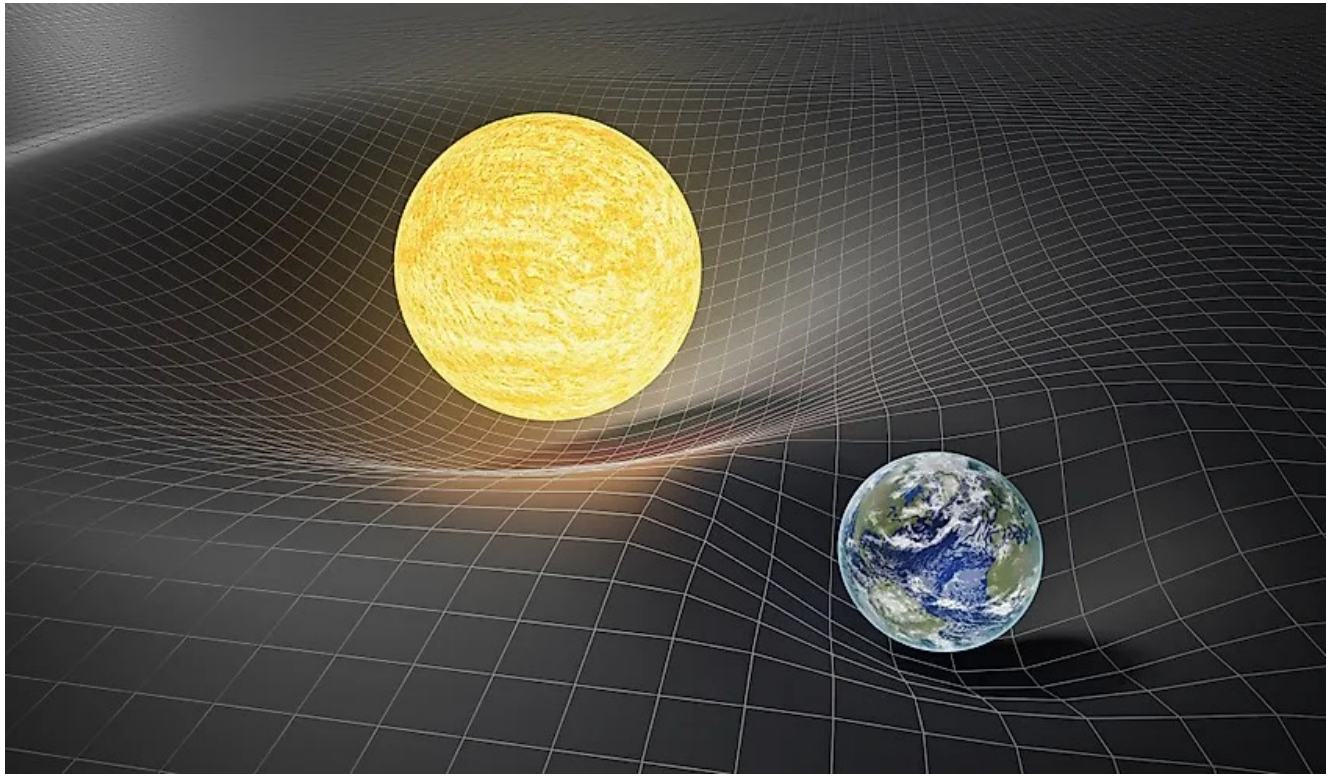
# Motivation



# Out Limited Understanding of the Universe

## Limitation of The Standard Model

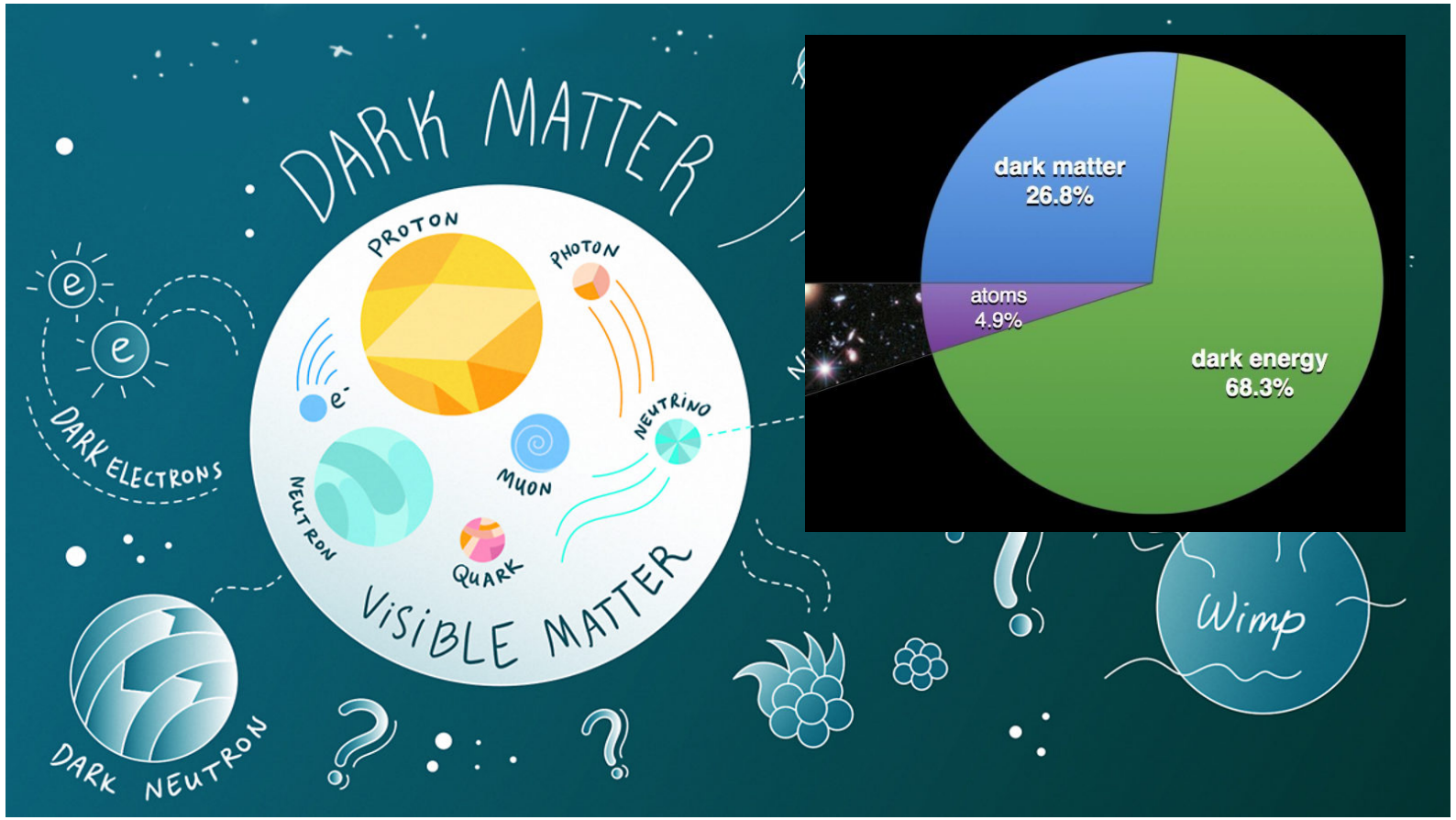
I. Where is gravity, the fourth fundamental force?



# Out Limited Understanding of the Universe

## Limitation of The Standard Model

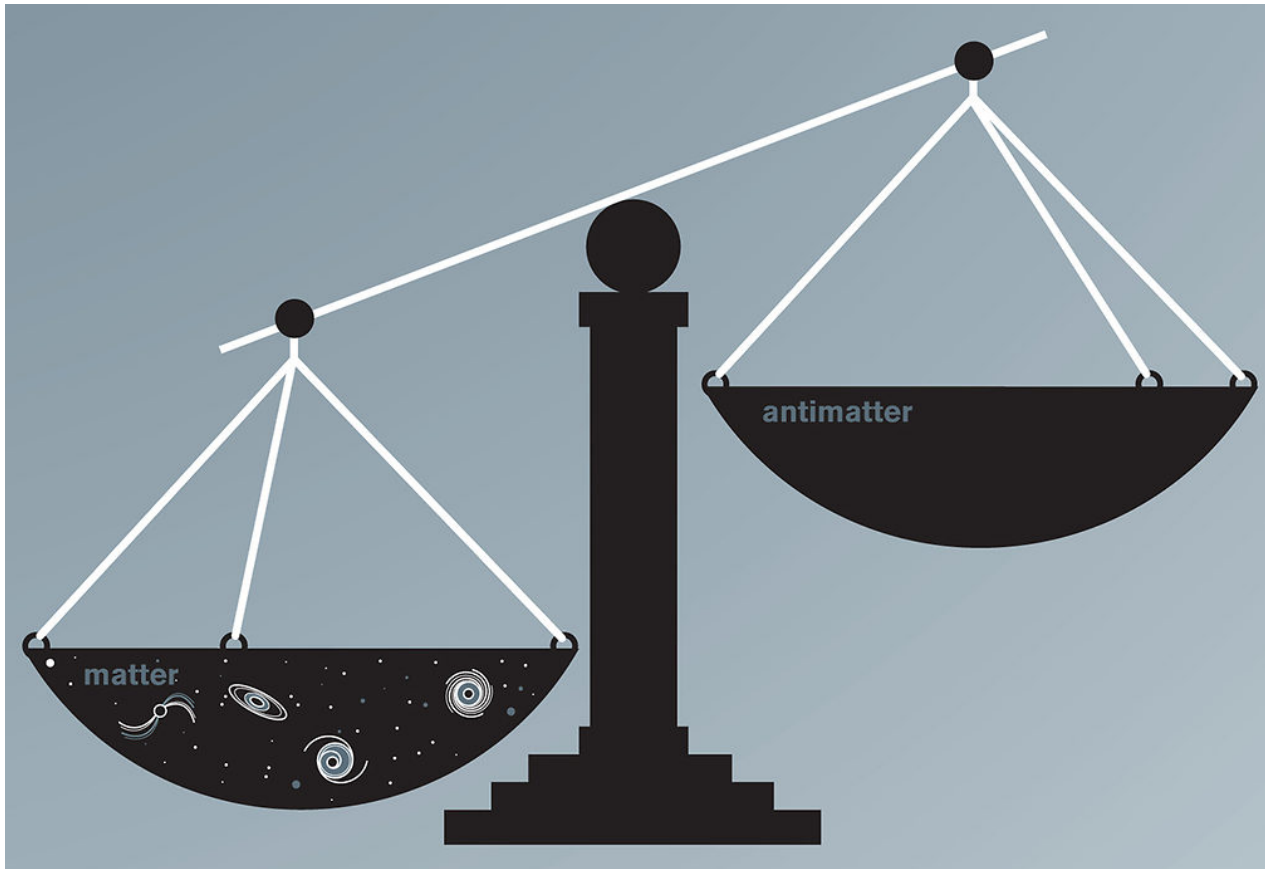
II. Nature of dark matter?



# Out Limited Understanding of the Universe

## Limitation of The Standard Model

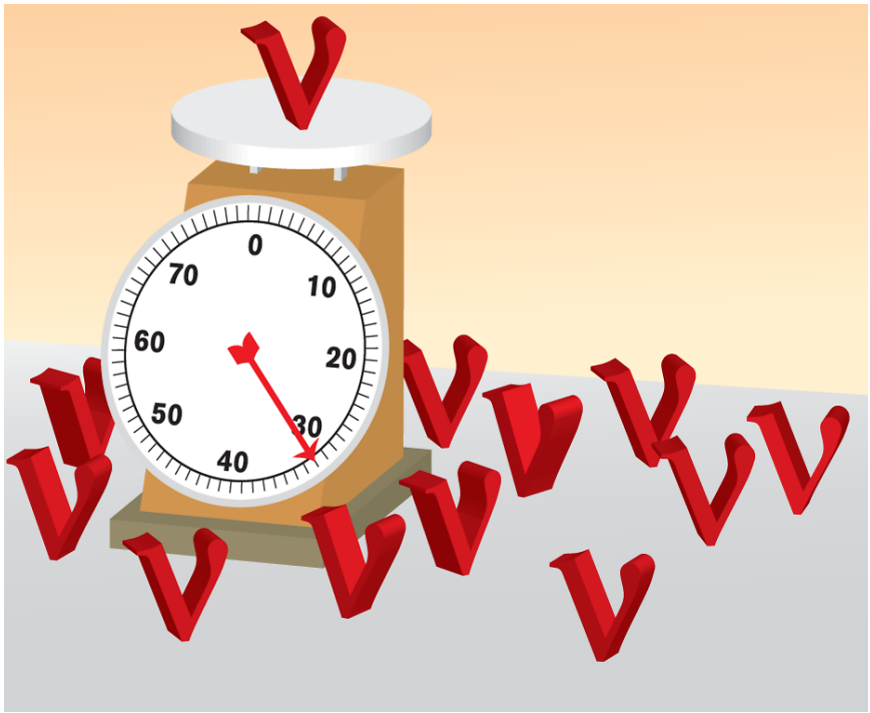
III. Why more matter than antimatter?



# Out Limited Understanding of the Universe

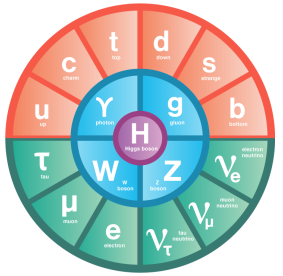
## Limitation of The Standard Model

IV. Origin of Neutrino masses?



# Summarizing Our Current Understanding

**We know 17 fundamental particles**




**Standard Model, a theoretical framework gives description of this particle & how they interact**

**There are certain observations the theory can't describe → our understanding is incomplete**

- **We want to understand what we don't within the Standard Model**

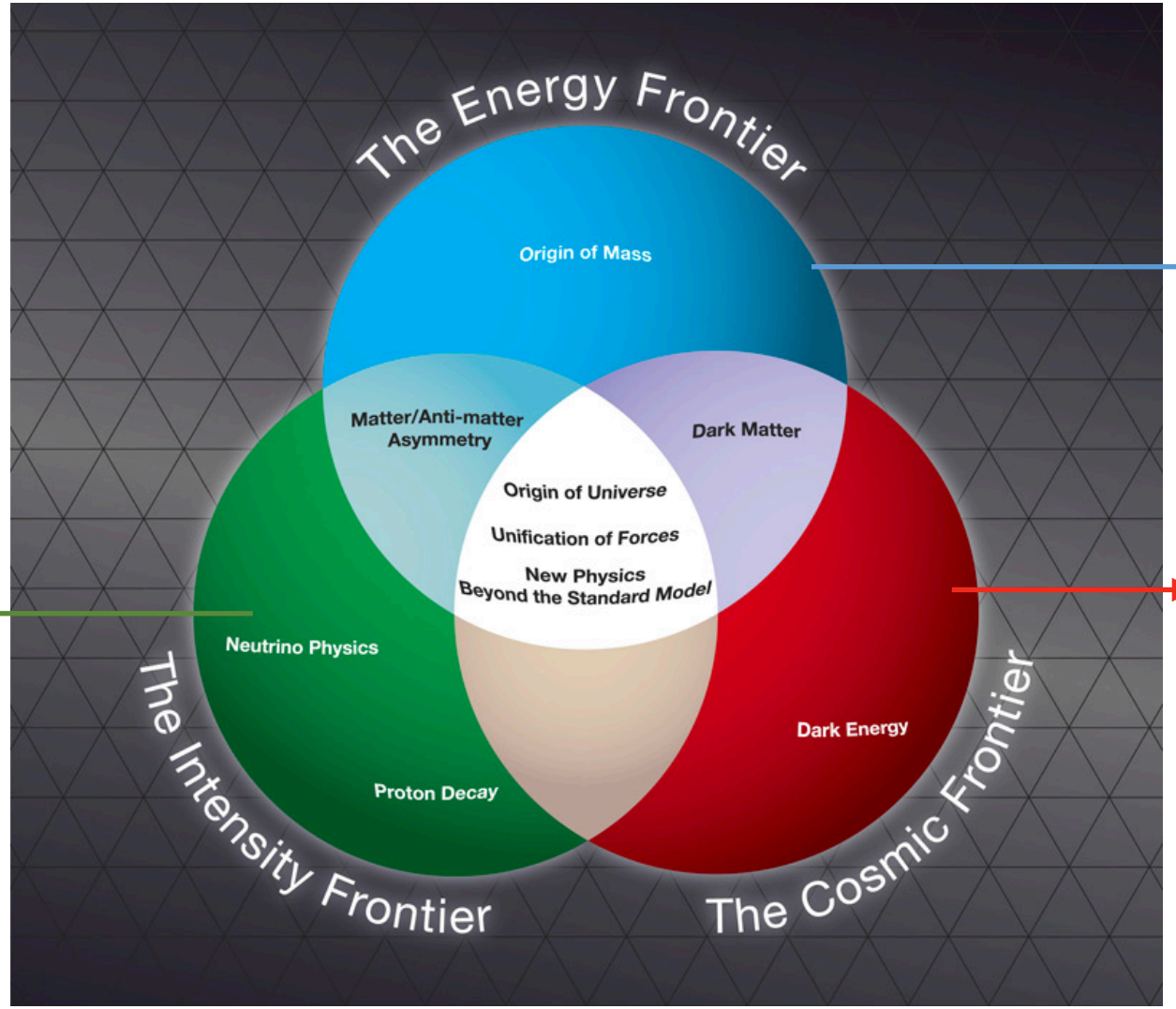
**And**

- **Look for new particles & interactions**

**Scope of experimental particle physics research**

# Experimental Particle Physics

# Particle Physics Today




High energy colliders

Example: LHC

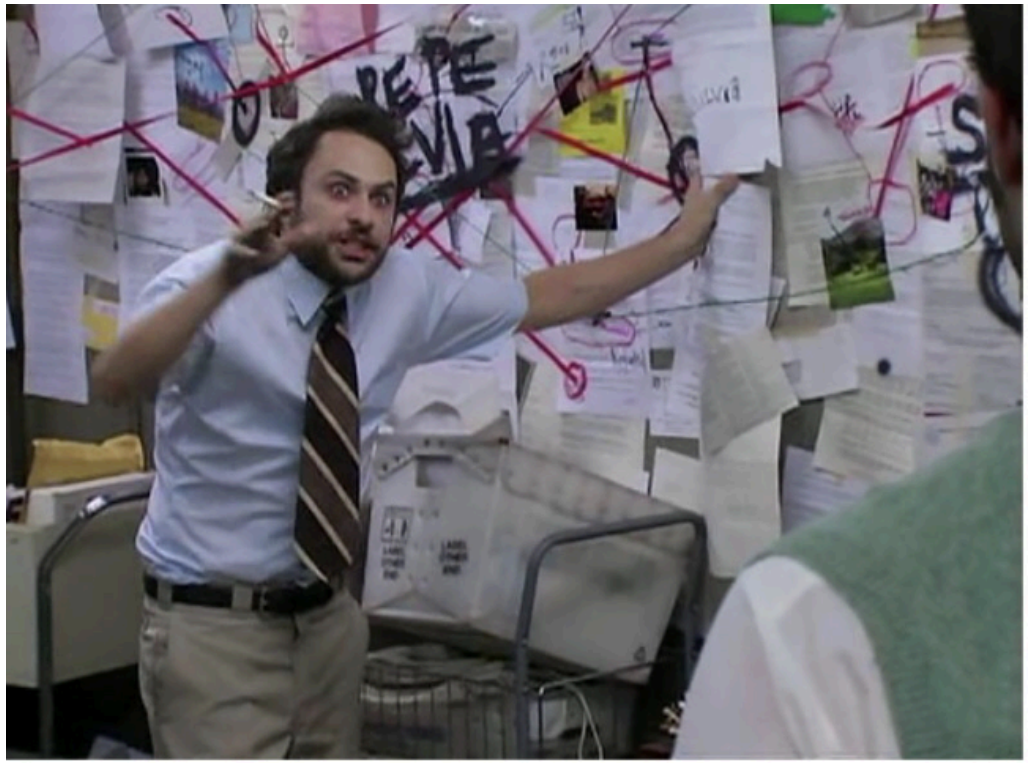
Experiments directly looking for dark matter, survey of dark energy

Example: LSST, LZ

Rare processes

Example: neutrino experiments like DUNE

# Collider Physics



# Why call colliders?

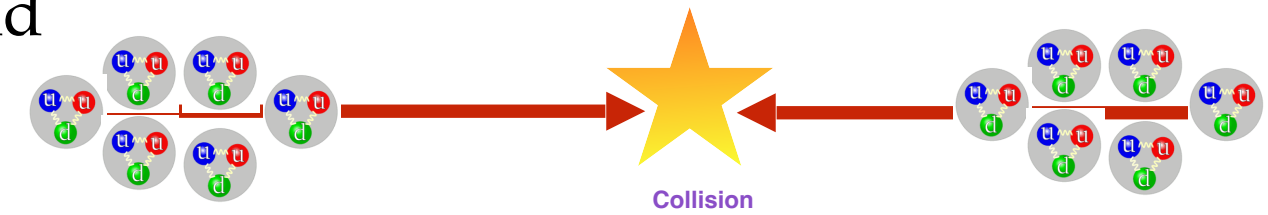

**Collides particles at high energies, look for a new type of particle or interaction in data**

Not present in Standard Model

# Large Hadron Collider (LHC)

## World's most powerful accelerator

- 27km circumference, 100m underground
- Collides bunches of protons at very high energies at different interaction points




# How Does Particle Accelerator Work?

## First order: Electric & Magnetic Field

Lorentz Force

$$\overline{F(t)} = q\left(\underbrace{\overline{E(t)}}_{F_E} + \underbrace{\overline{v(t)} \otimes \overline{B(t)}}_{F_B}\right)$$

$F_B$: Control direction of beam & collision

$F_E$: Accelerates particle to very high energies

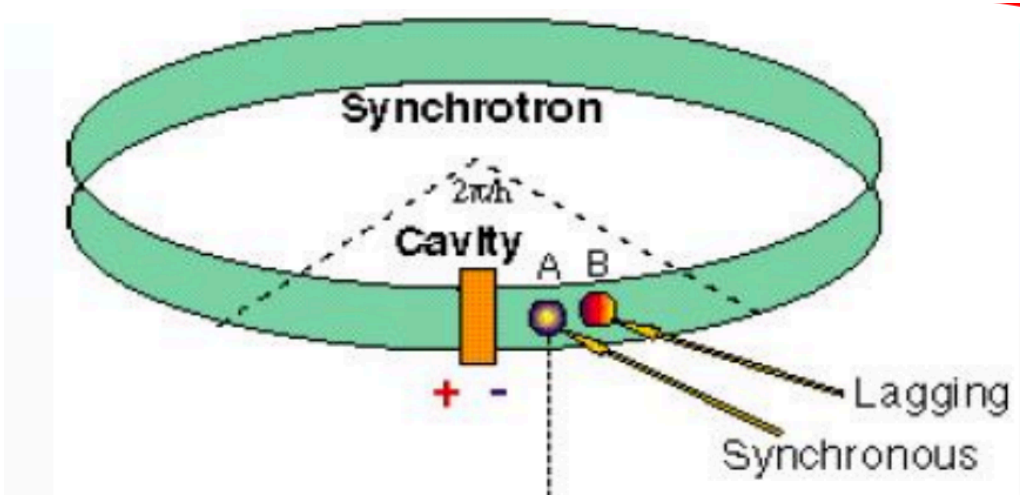
# How Does Particle Accelerator Work?

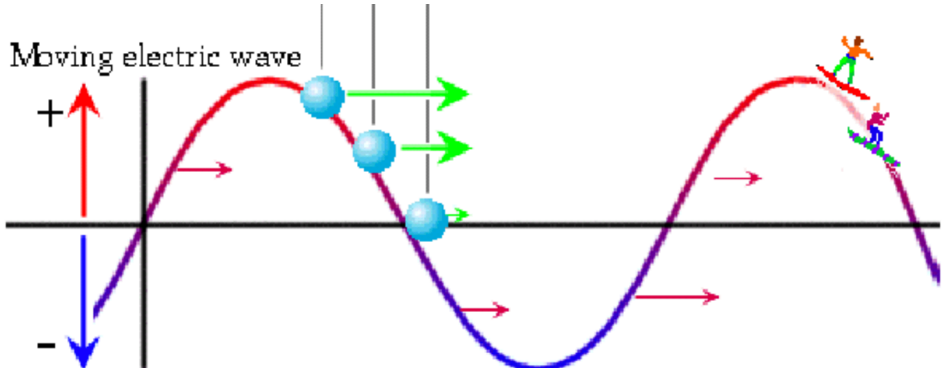
## First order: Electric & Magnetic Field

Lorentz Force → $\overrightarrow{F(t)} = q\left(\overrightarrow{E(t)} + \overrightarrow{v(t)} \otimes \overrightarrow{B(t)}\right)$

$F_E$ $F_B$

- **Synchrotron**
  - Accelerator cavity has oscillating field, particle at different x/y position gets different energy
    - Slow particle gets extra energy, creating bunches of particles
  - Dipole magnet bends particle
  - Quadrupole magnet used for collisions



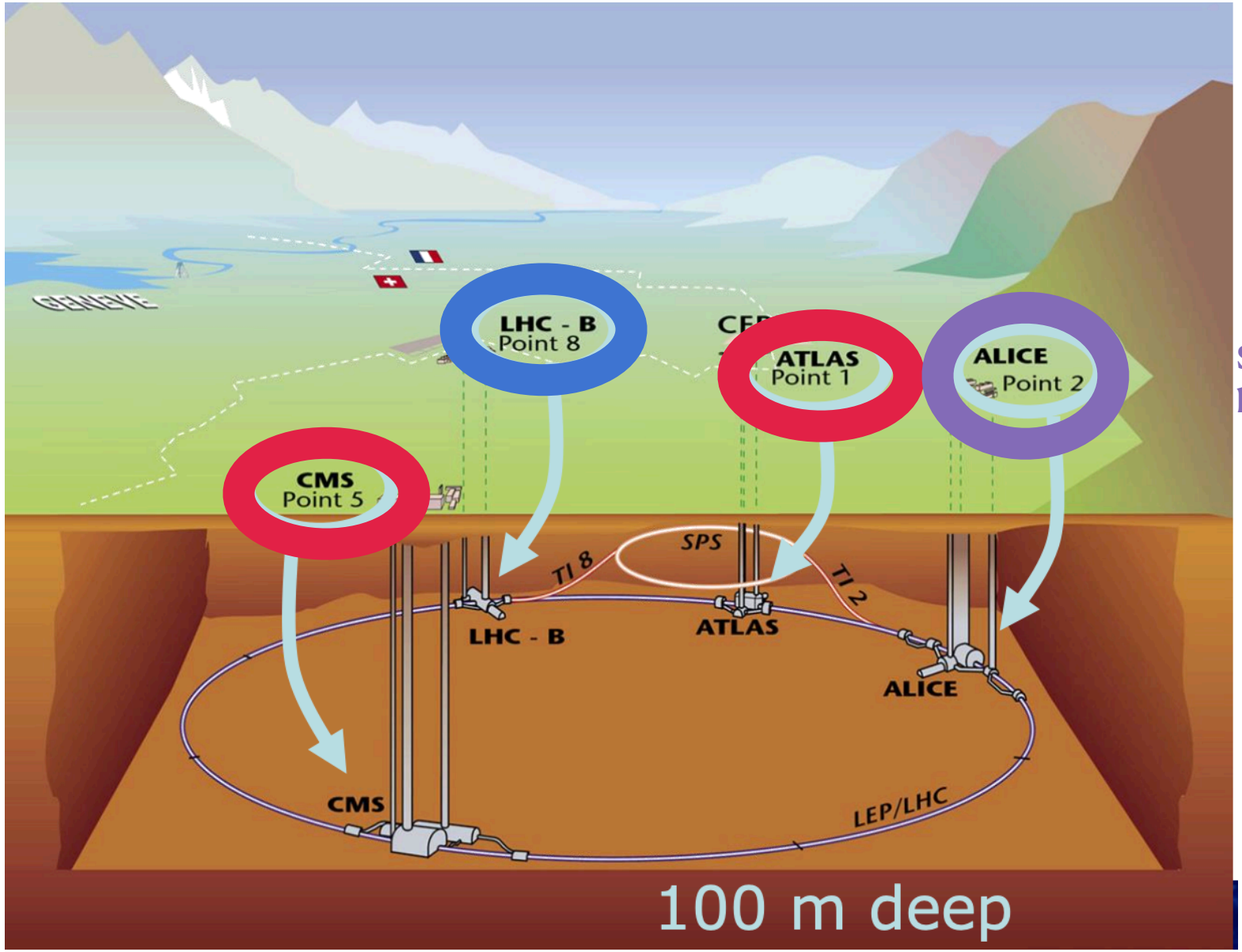



# LHC

# Collision Points & Experiments

**Goal:**

**Study SM particles & search for new phenomena beyond SM**



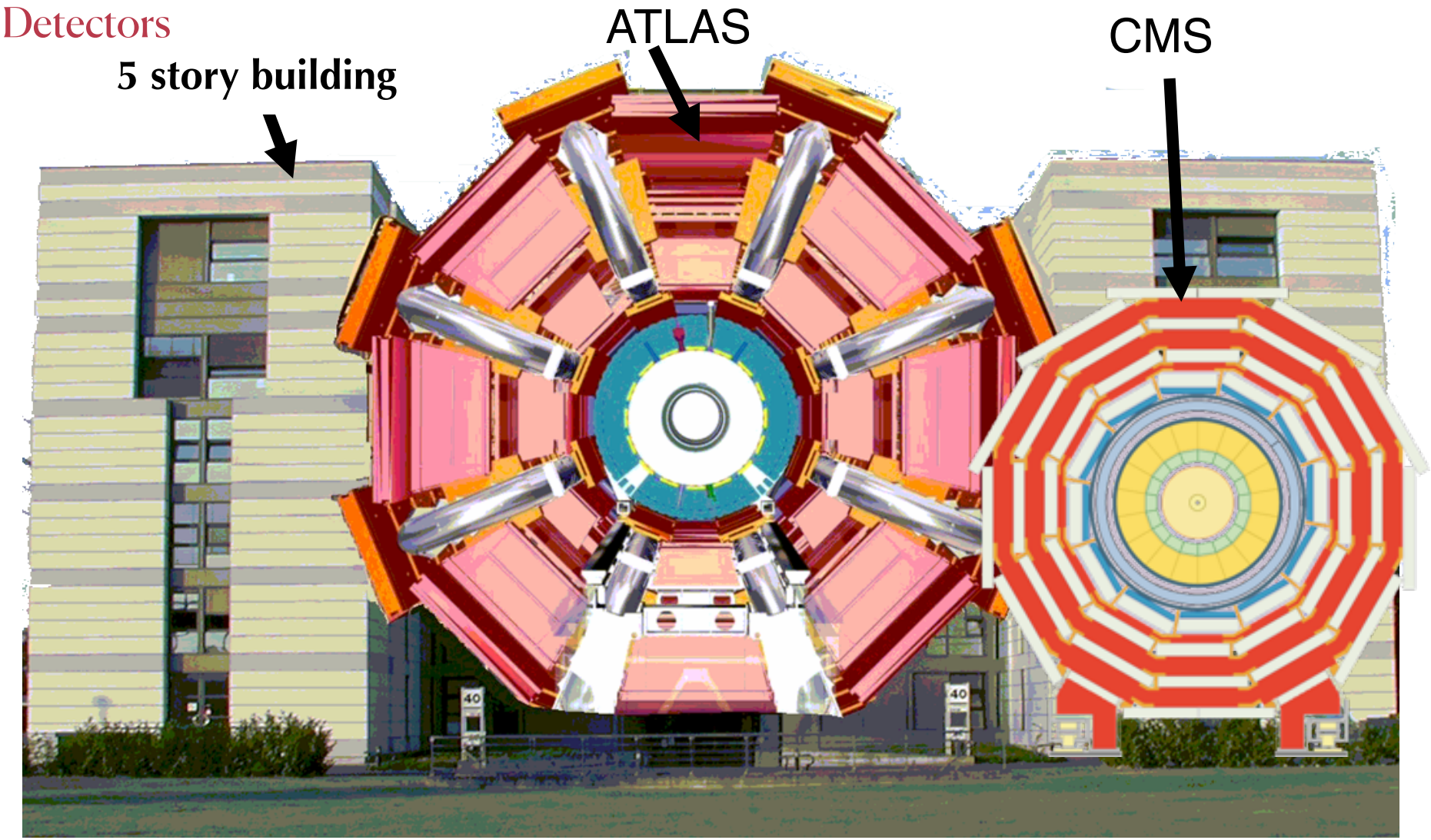

**Physics of b-quark**

**Strong interaction using heavy ion**

# General Purpose Experiment

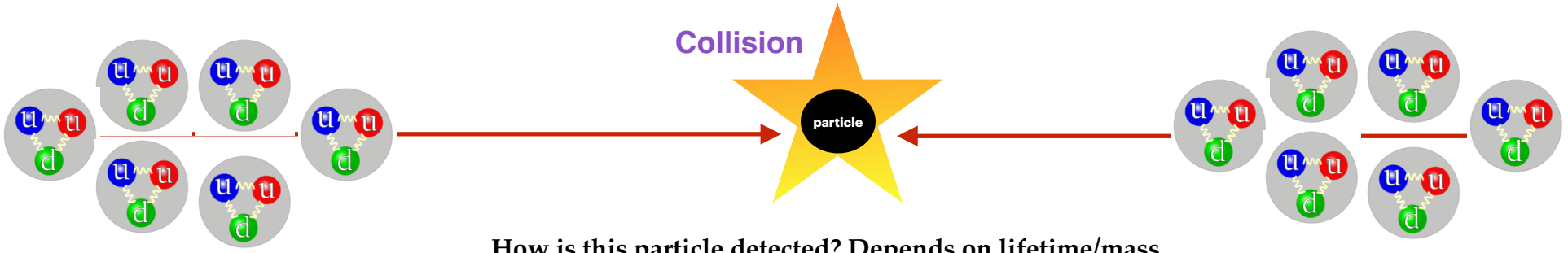
## ATLAS & CMS Detectors

**General multipurpose experiment**



1 GeV ~= $10^{-27}$ Kg

# Fundamentals of Particle Reconstruction

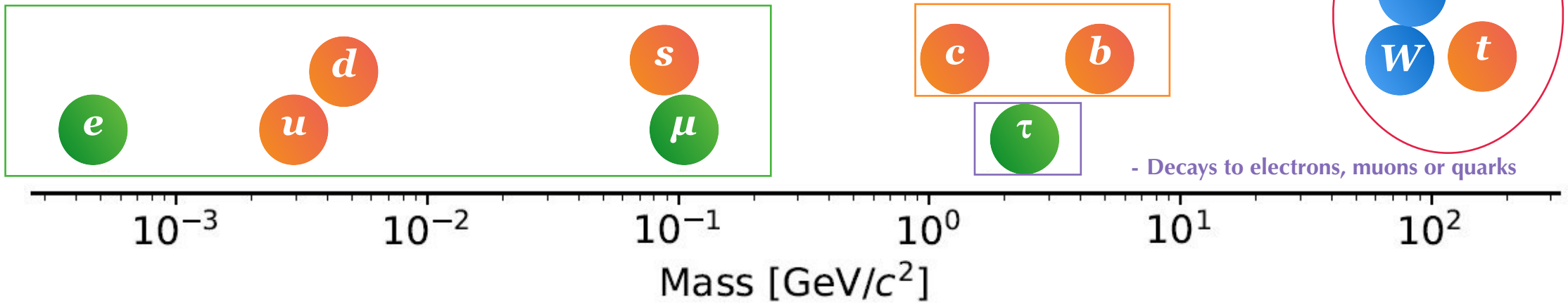



- Heavy particles decays instantaneously (<$10^{-21}$ secs)
- can only be detected in terms of final decay products

**How is this particle detected? Depends on lifetime/mass**

- Relatively longer lifetimes (~$10^{-12/-13}$ secs)
- Decays to either leptons or lighter quarks

- Stable particles that interact with various layers of the detector

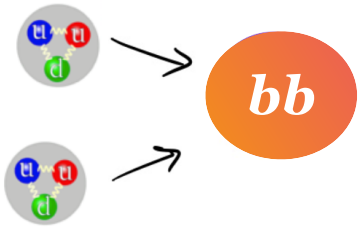



- Neutrinos are undetectable in ATLAS

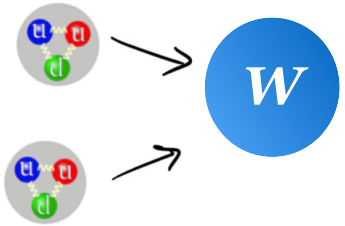
- Photons (gluons) massless stable, interact similar to electrons (lighter quarks)

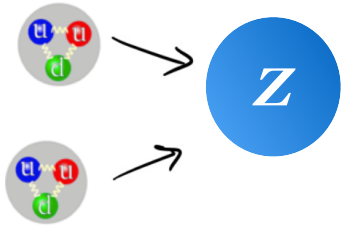
# So How do we detect particle like Higgs?

## Game of probability



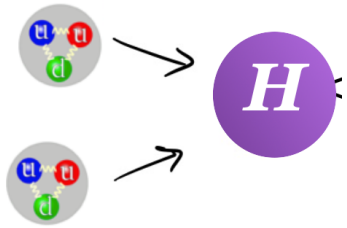

bottom + anti bottom 1 in ~5




W 1 in ~10,000

Z 1 in ~ 100,000

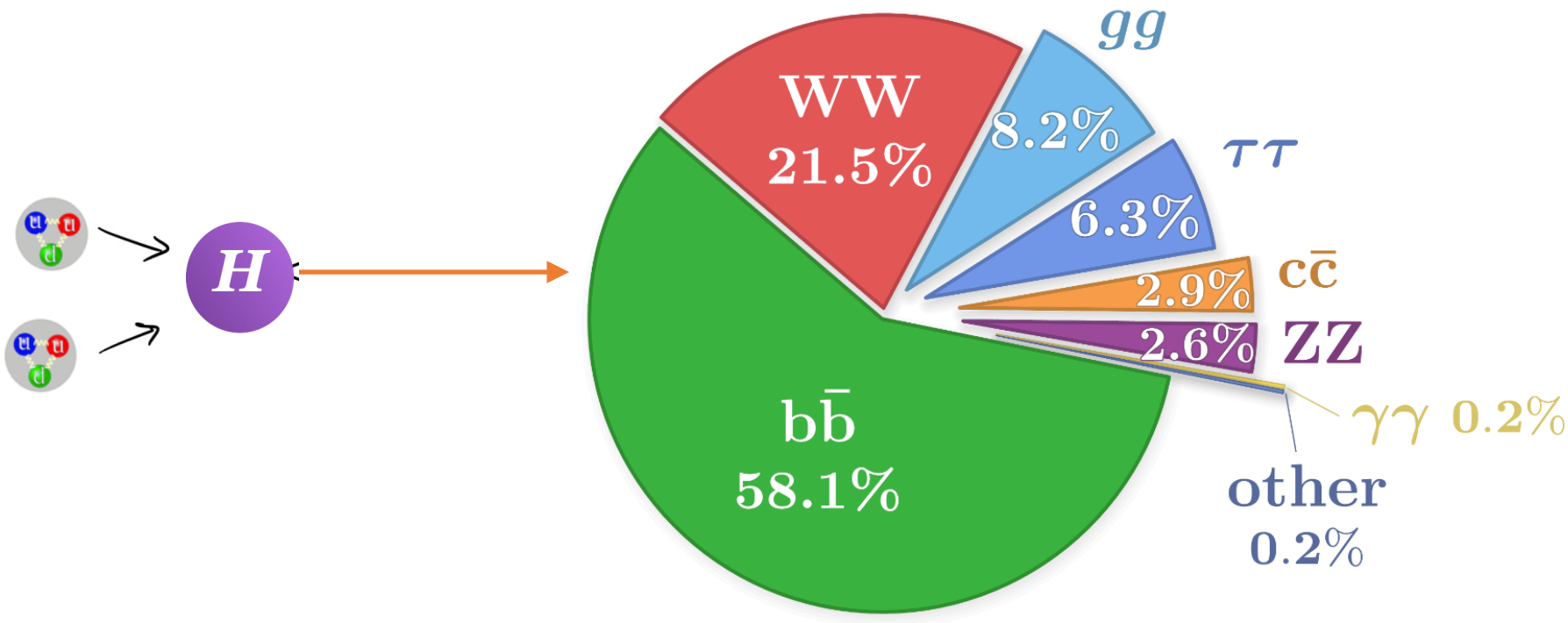



**H** **1 in a billion**

**In other words, 1 Higgs in ~1.5 million collisions**

# So How do we detect particle like Higgs?

But all heavy particle decay instantaneously!




**Remember Z, W, tau, b-quark, c-quark all decay**

# How do we really detect Higgs?

Based on final state particles!

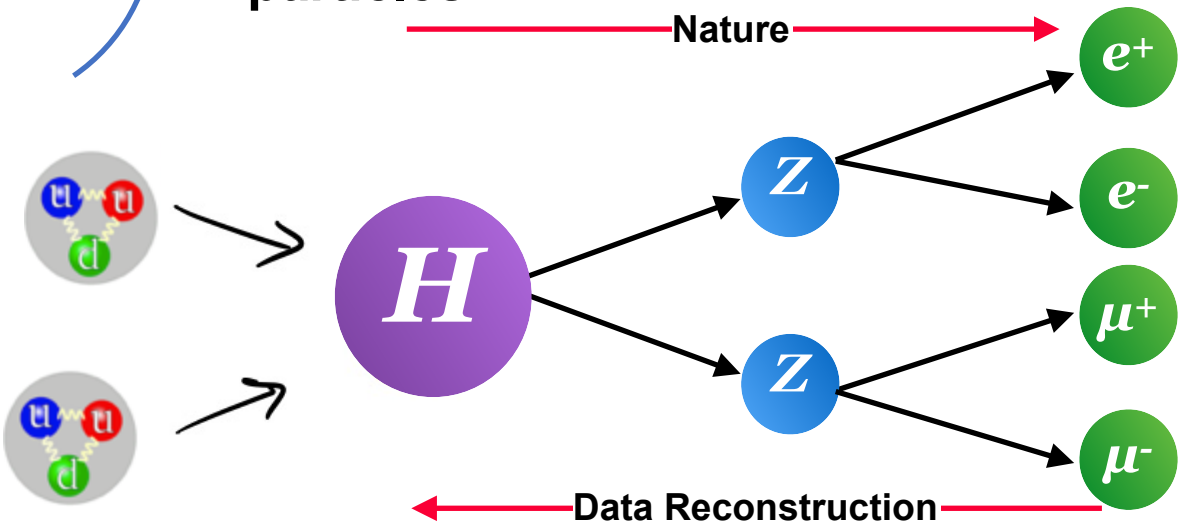
**Final state particle —> stable particles that interact with our detectors**

We only have handful

- **Electrons**
- **Photons**
- **Lighter quarks**
- **Gluons**
- **Muons**

**Our detectors are designed to measure properties of these particles**

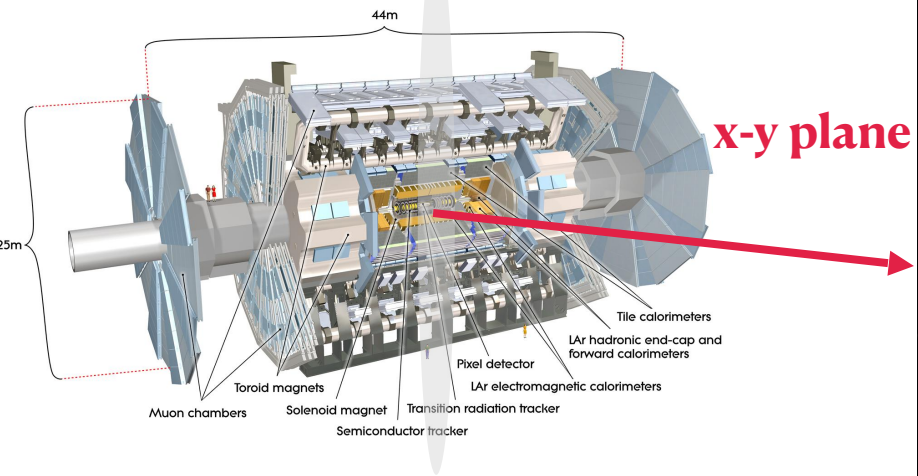
**We measure properties of these, identify the parent particle & measure its properties**



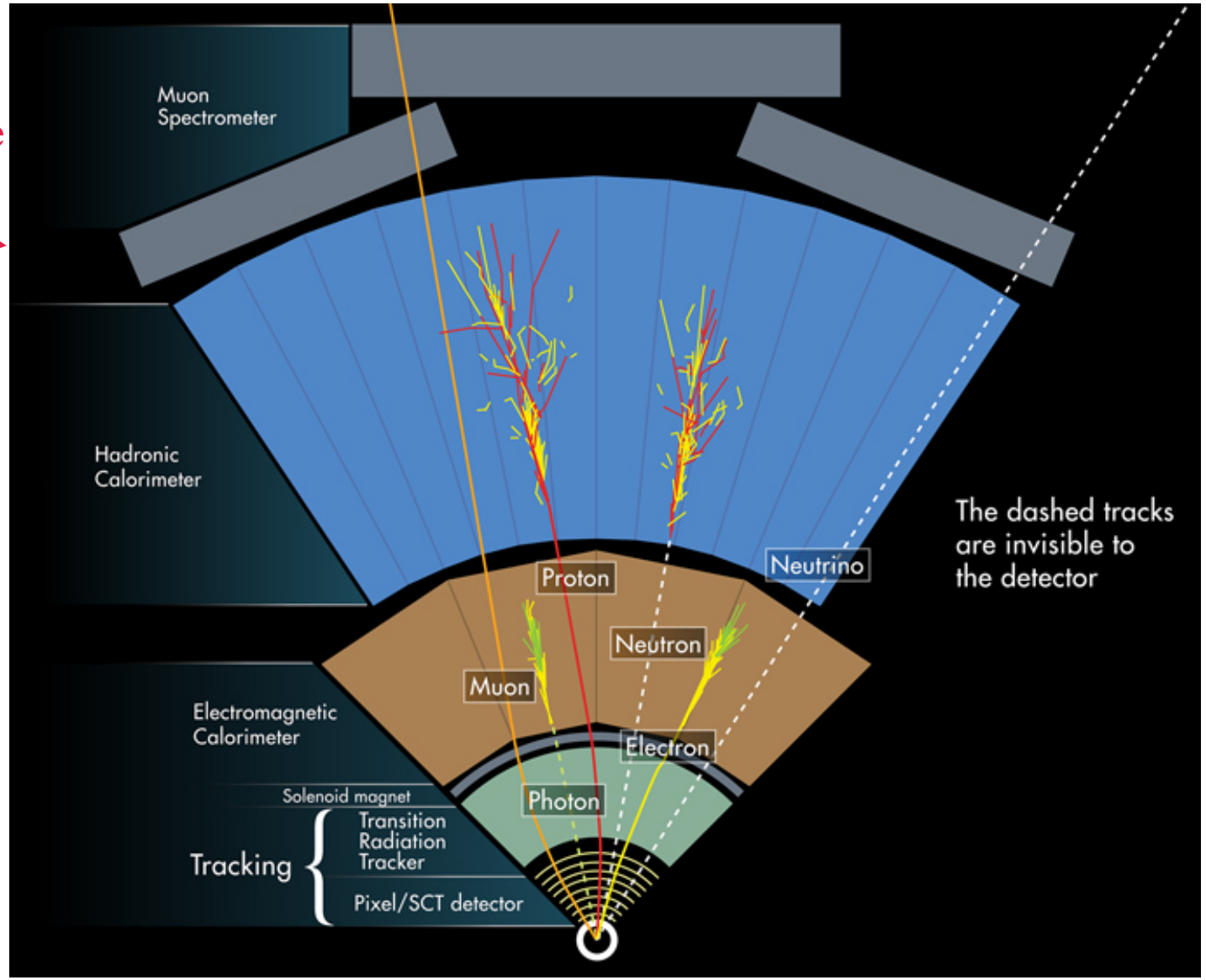

**We look for Higgs in the final state that has 2electron & 2muon**

# How does detector detect final state particles?

Combining information from various sub-detectors designed to do different things

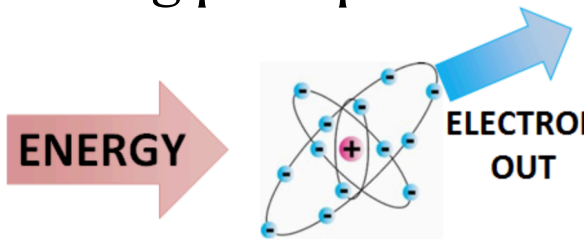


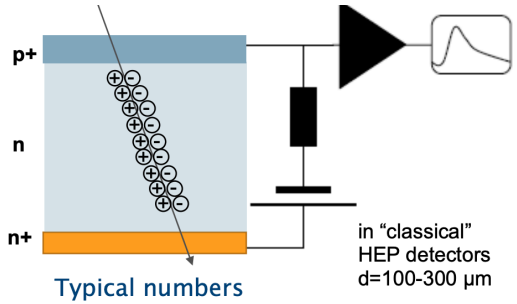

x-y plane

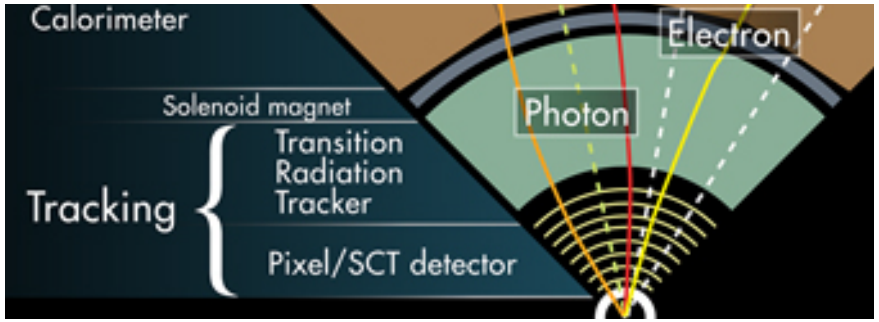


# Tracking Detectors

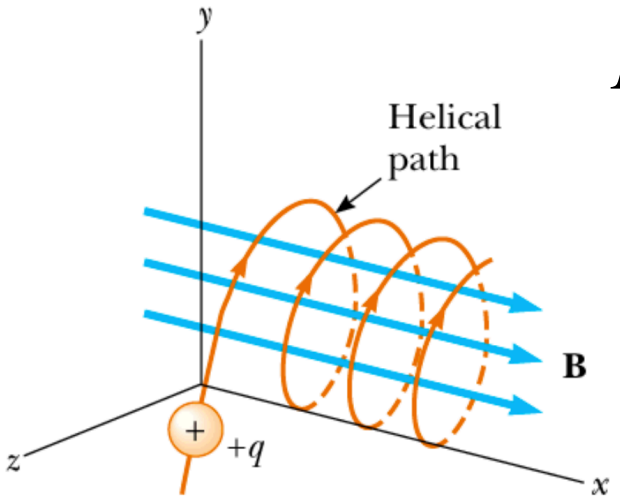
- Ionization working principle



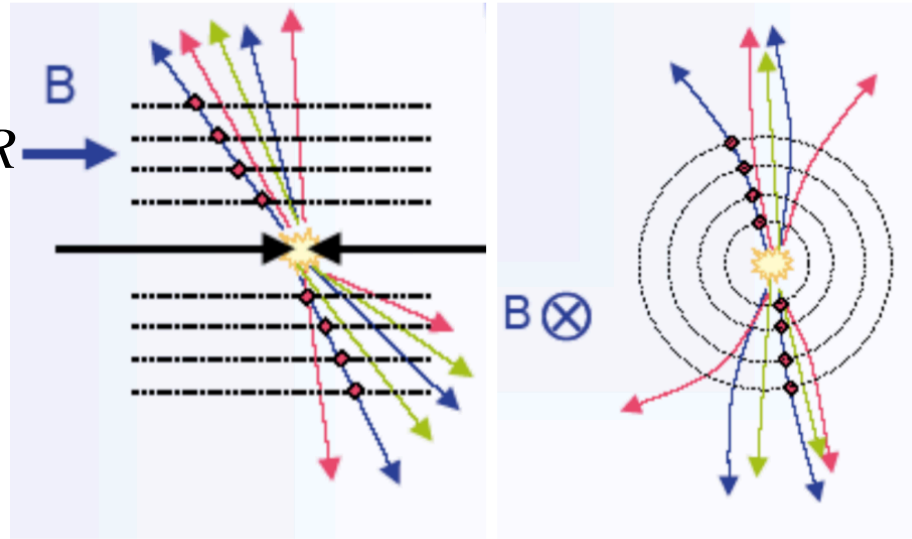




A charged particle inside magnetic field, Lorentz force



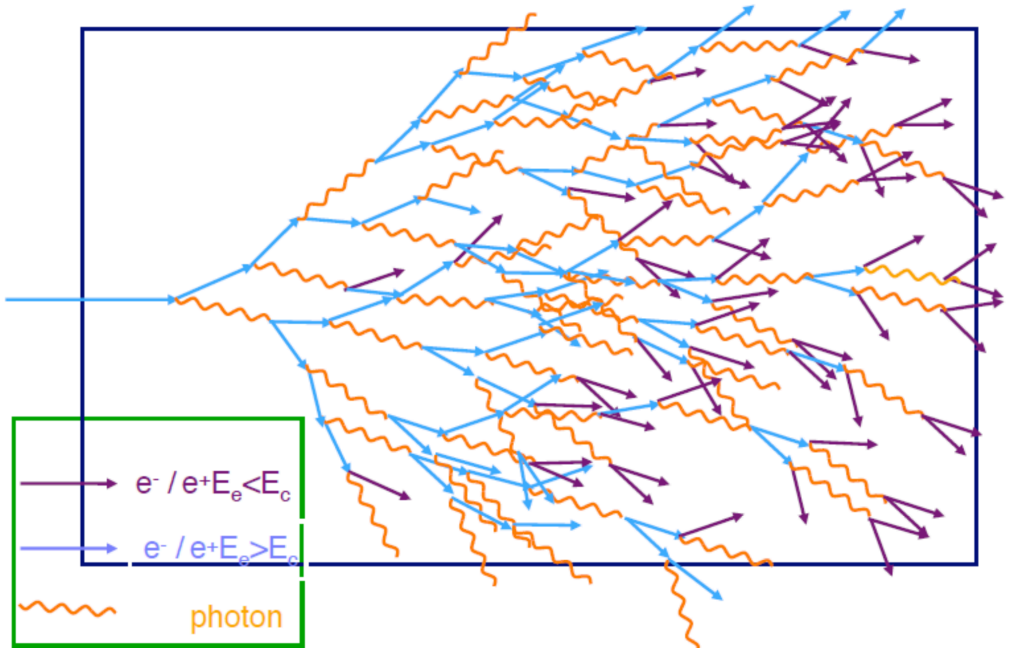

$$F = Bqv = \frac{mv^2}{R} \rightarrow p = BqR$$



# Calorimeters

## Energy Absorption: aka stop particles entirely

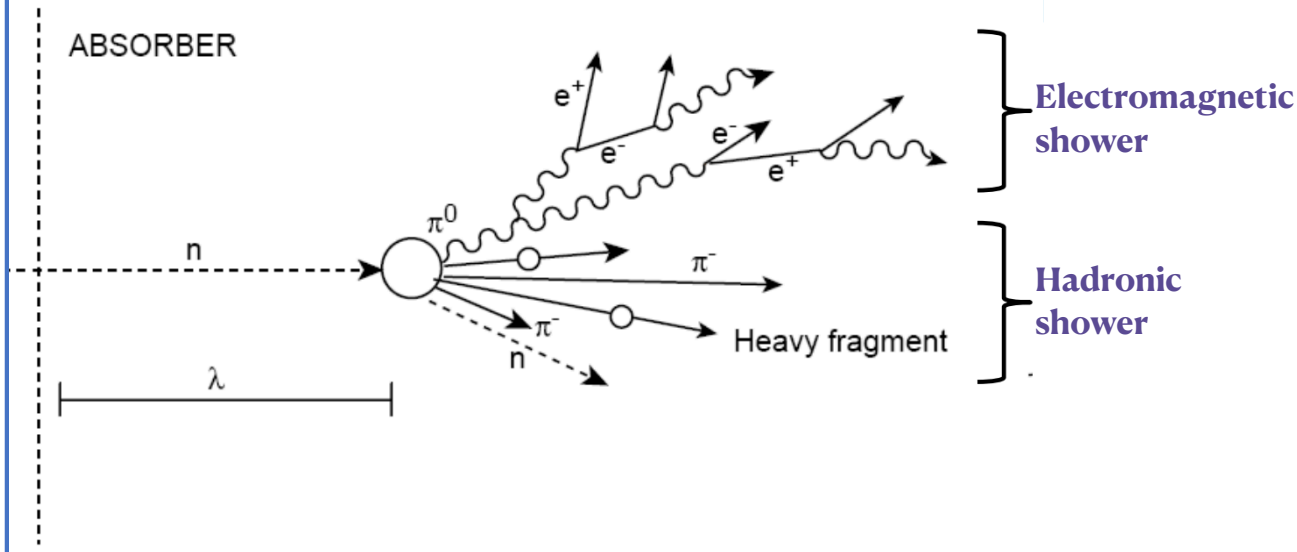
Electromagnetic Calorimeter




Electron & photon creates shower

Good calorimeter absorbs all the particles from the shower

Hadronic Calorimeter



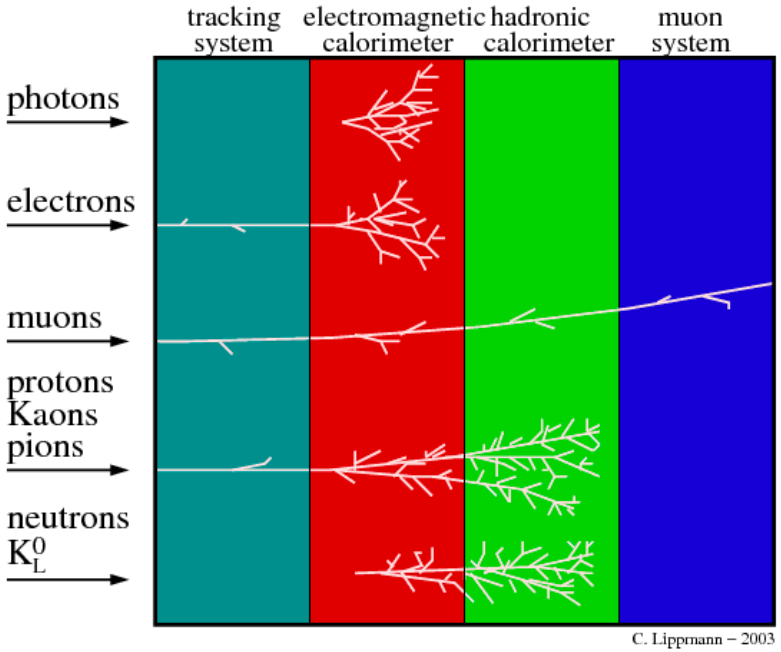

Similar Principle just different showering

# Muon Spectrometer

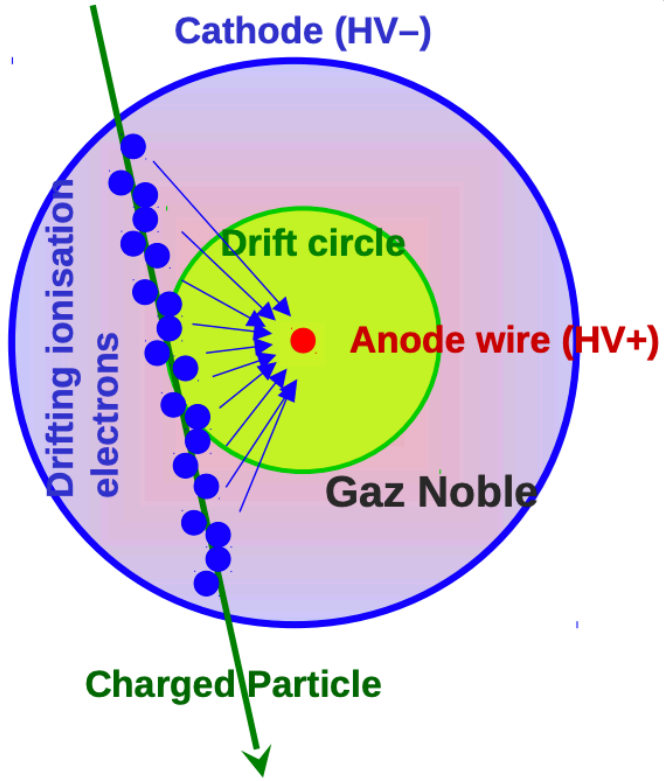
**Goal: measure momentum of muons**

- Similar principle as tracking detectors, track muon's momentum

**Muons go through all layers of the ATLAS detector, we can't stop them, only measure momentum**

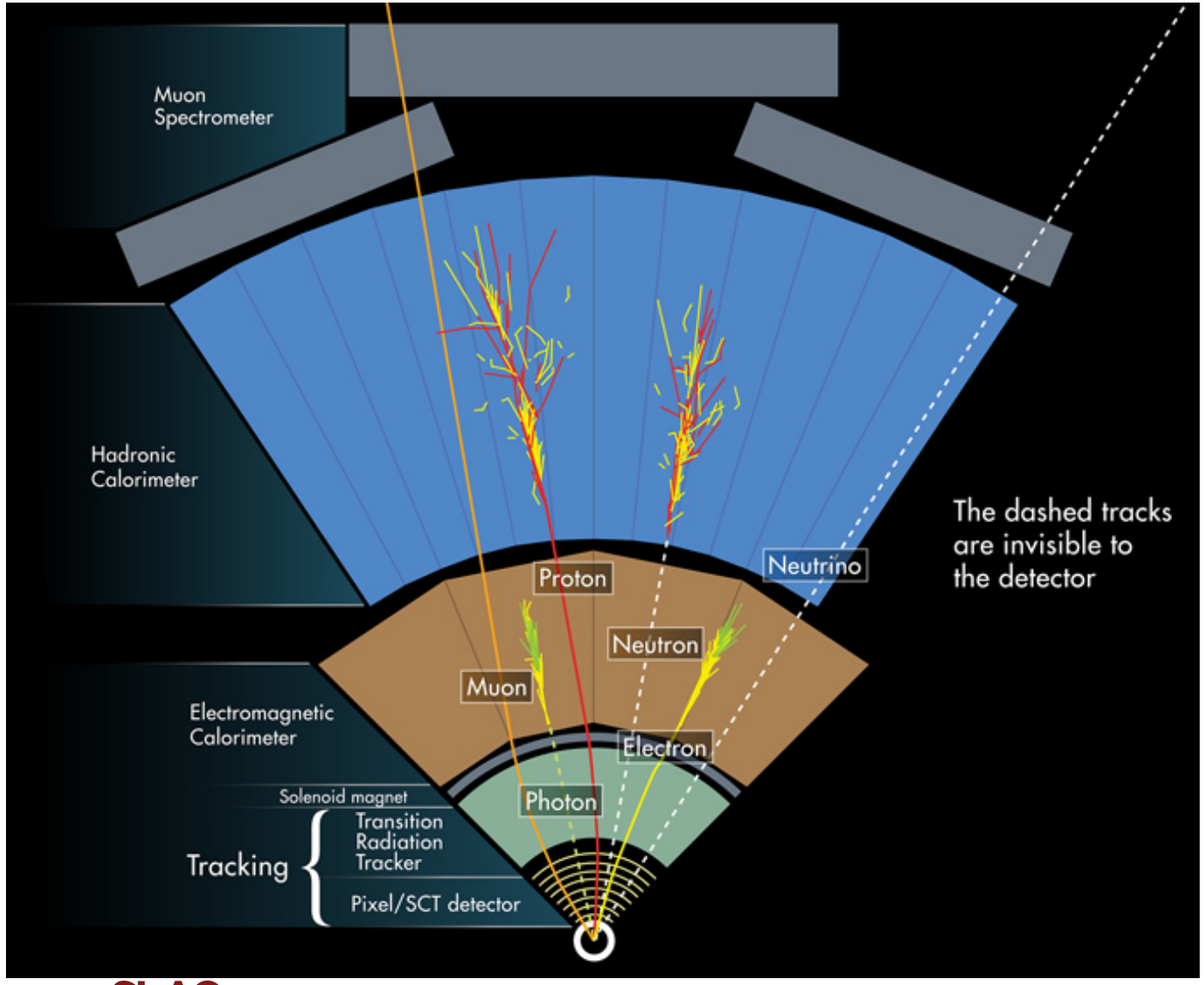


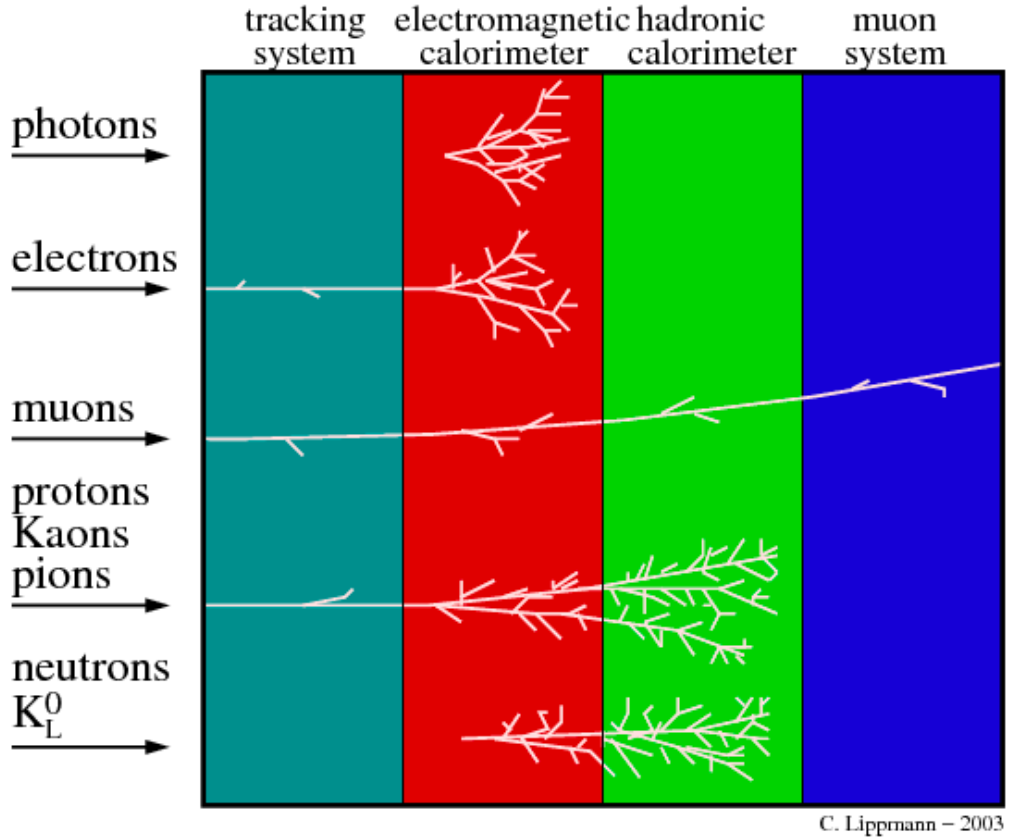

Muons, most precisely measured objects in ATLAS



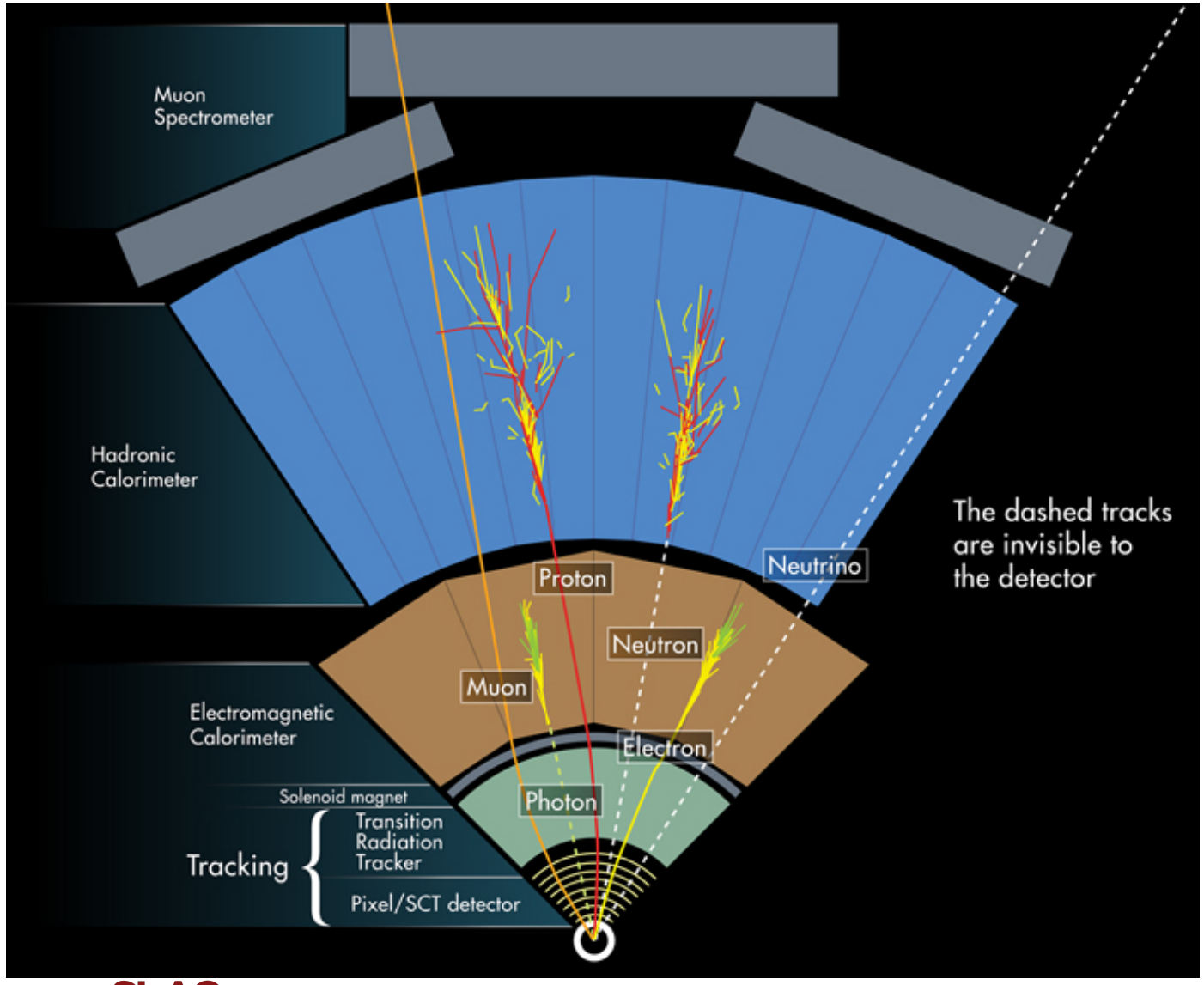

Charged particle: Muon

# Putting it all together—> the ATLAS Detector



# Putting it all together—> the ATLAS Detector




**Tracking detectors**:

- Goal is to track trajectory of charged particles
- You want light tracking detector, ionization

**Electromagnetic calorimeters**:

- Goal measure energy of electrons/photons
- You want it dense and deep enough to stop them entirely

**Hadronic Calorimenters**

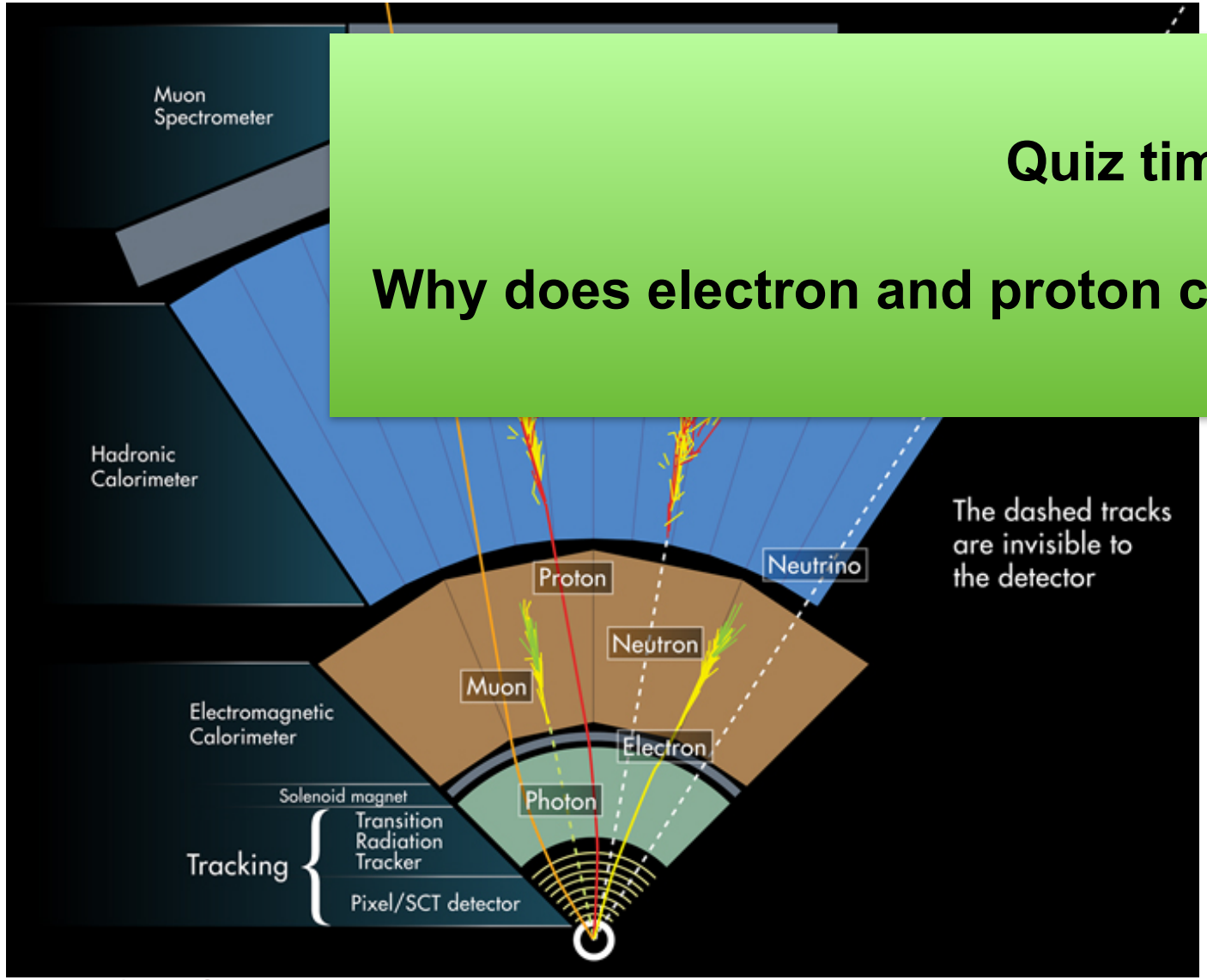
- Measure energy of all hadrons (pion, kaon , proton, neutron)
  - Up, down, strange quarks and gluons

**Muon Spectrometer**

- Goal measure the momentum precisely
- Ionization

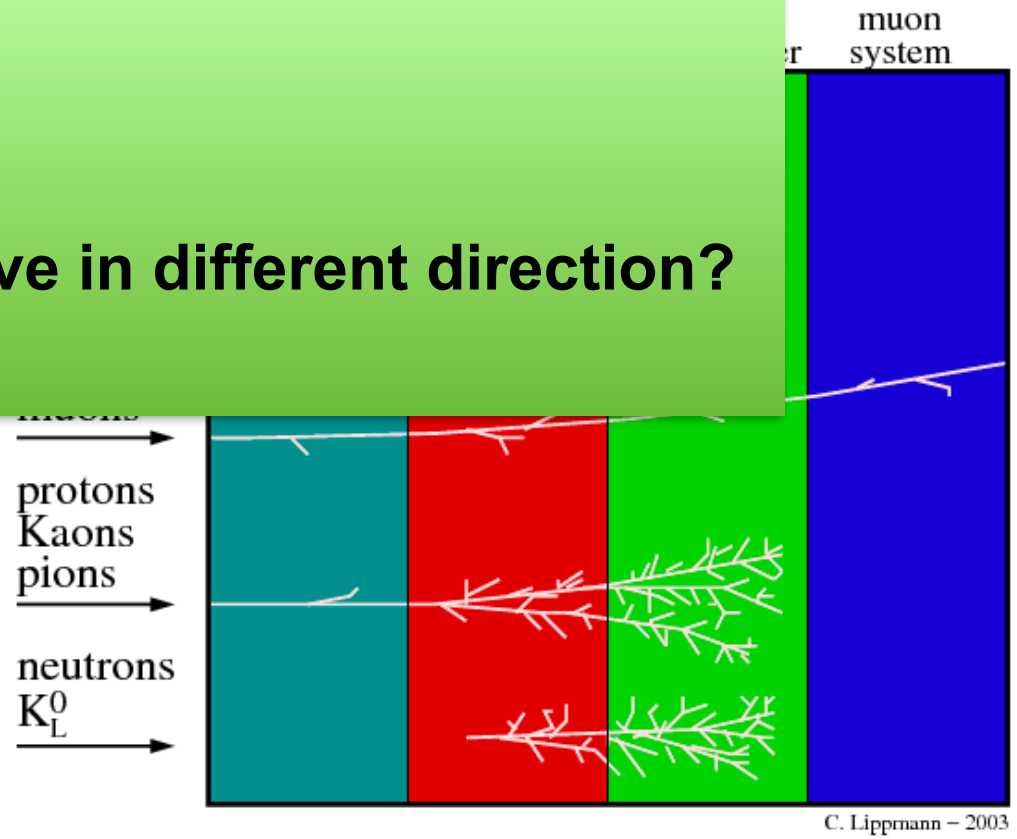
& the magnetic field!!

# Putting it all together—> the ATLAS Detector

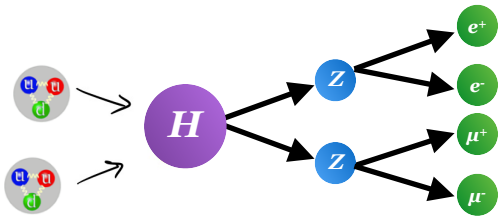


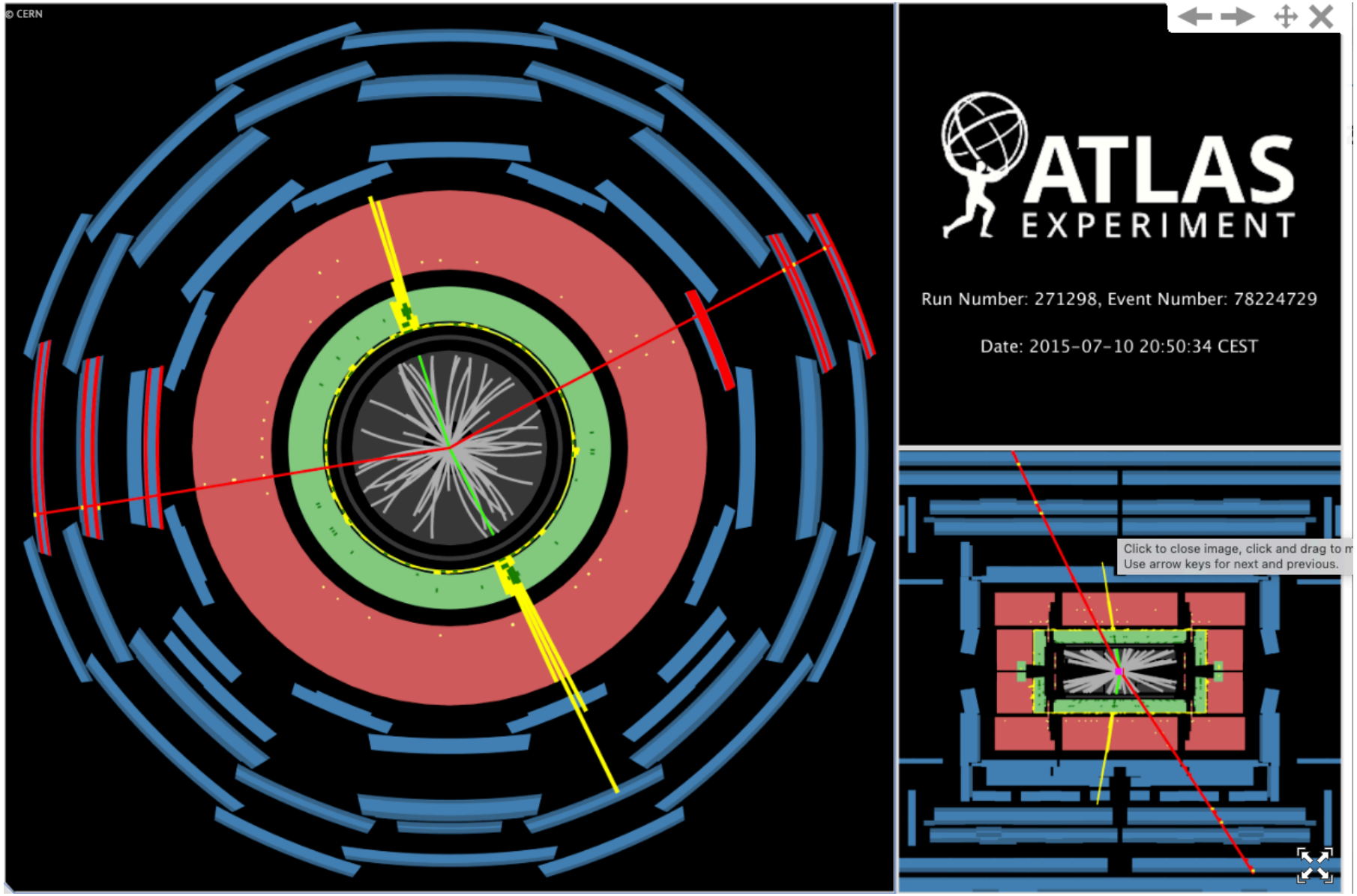

**Quiz time:**

**Why does electron and proton curve in different direction?**

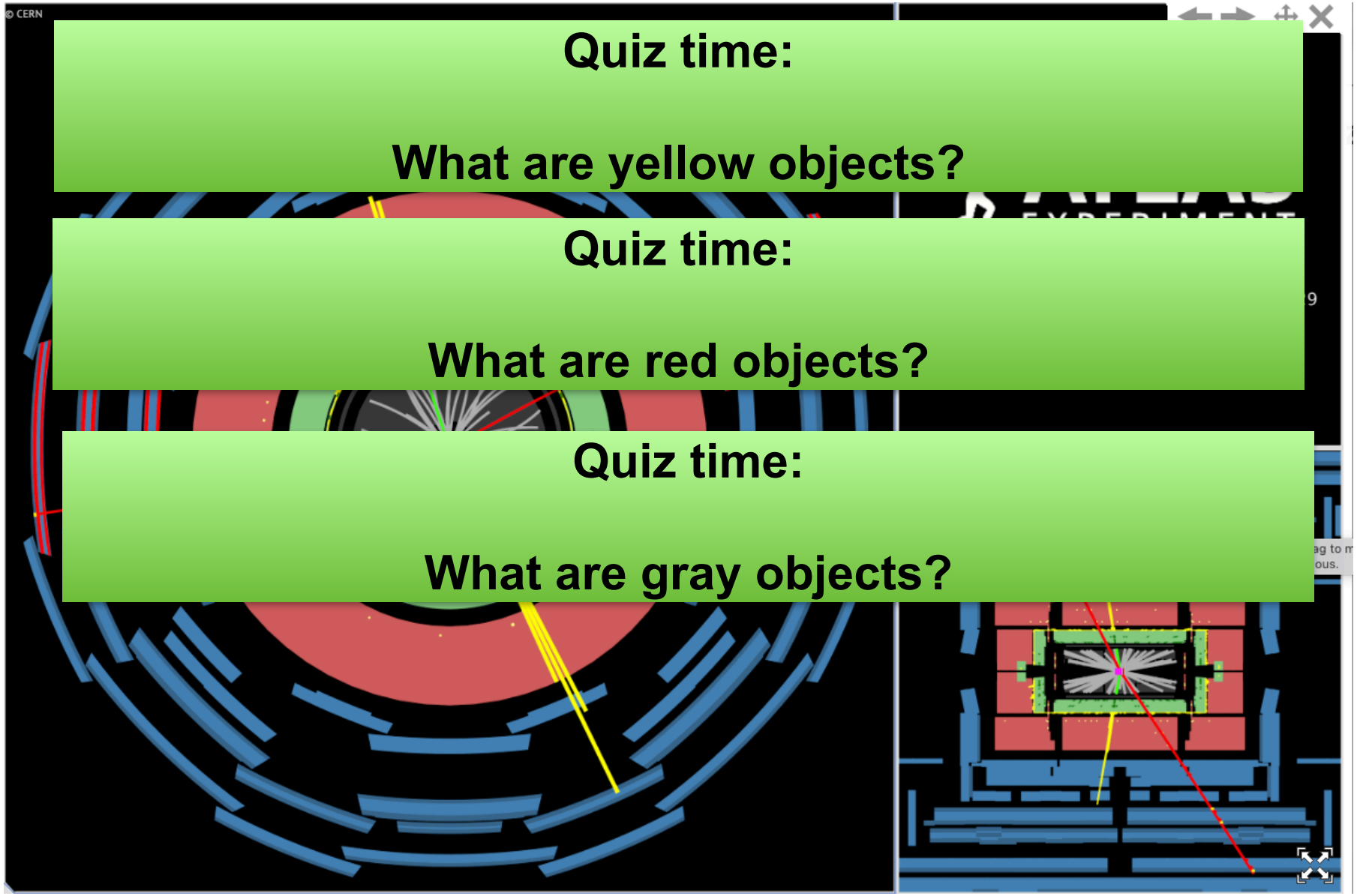


# Higgs in a detector

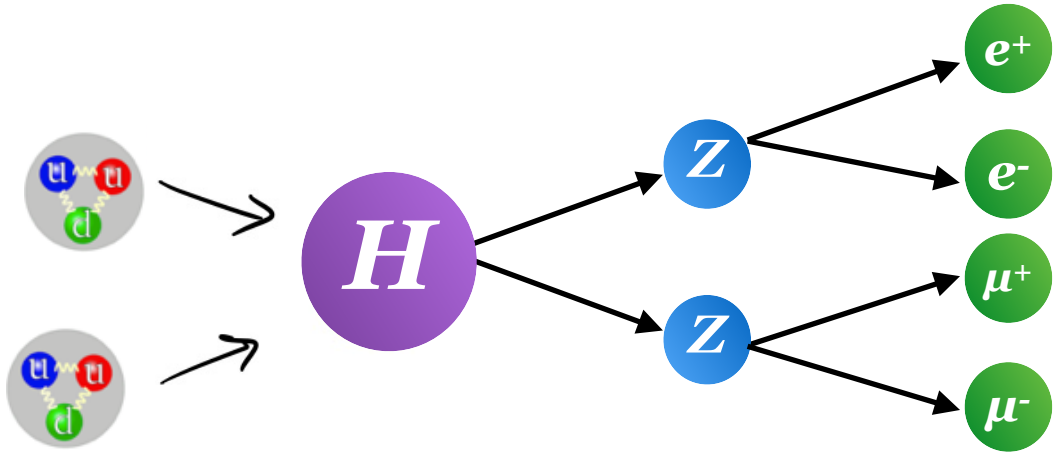


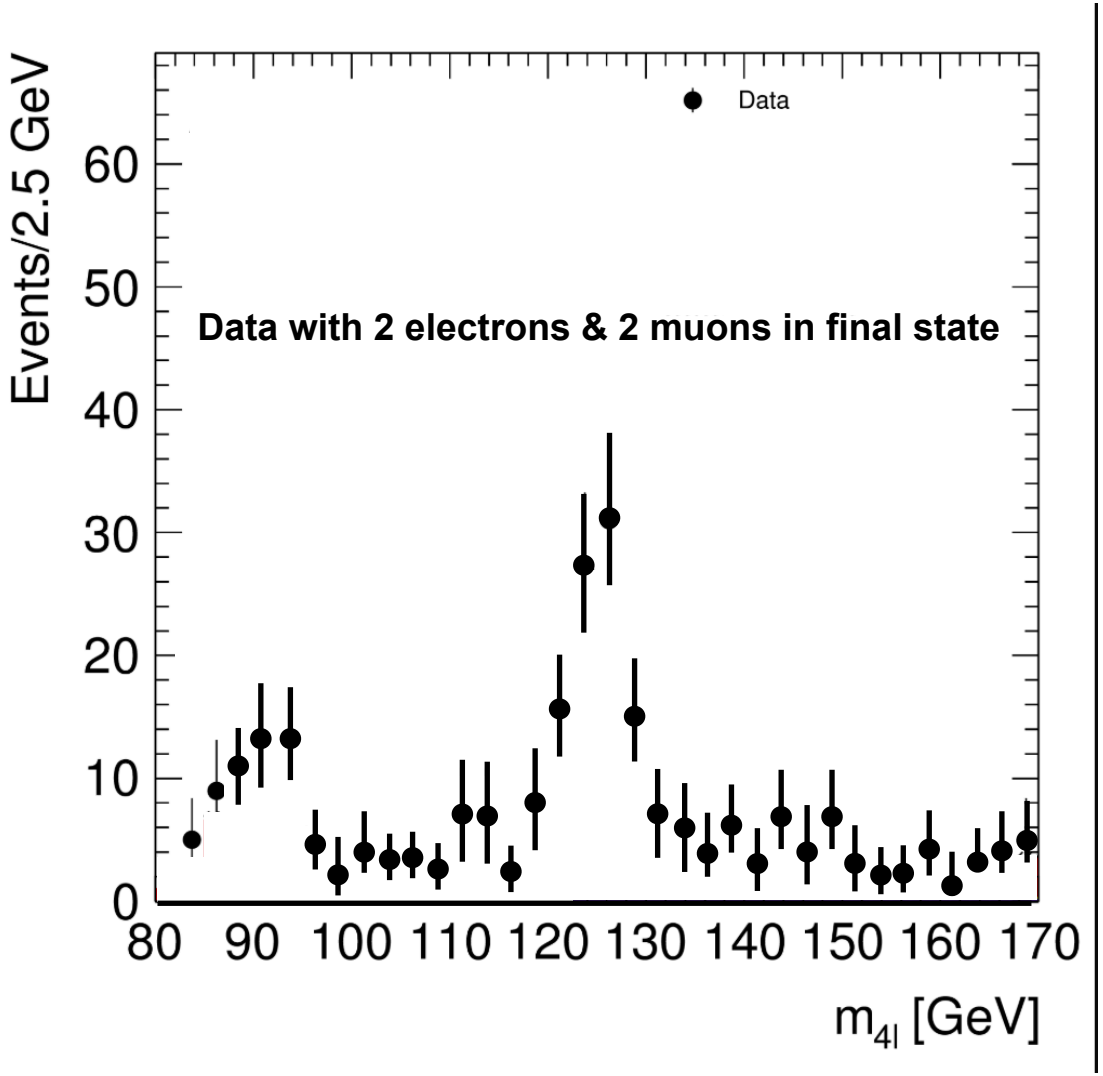
# Higgs in a detector



# Higgs Hunting




How do we know this is Higgs?

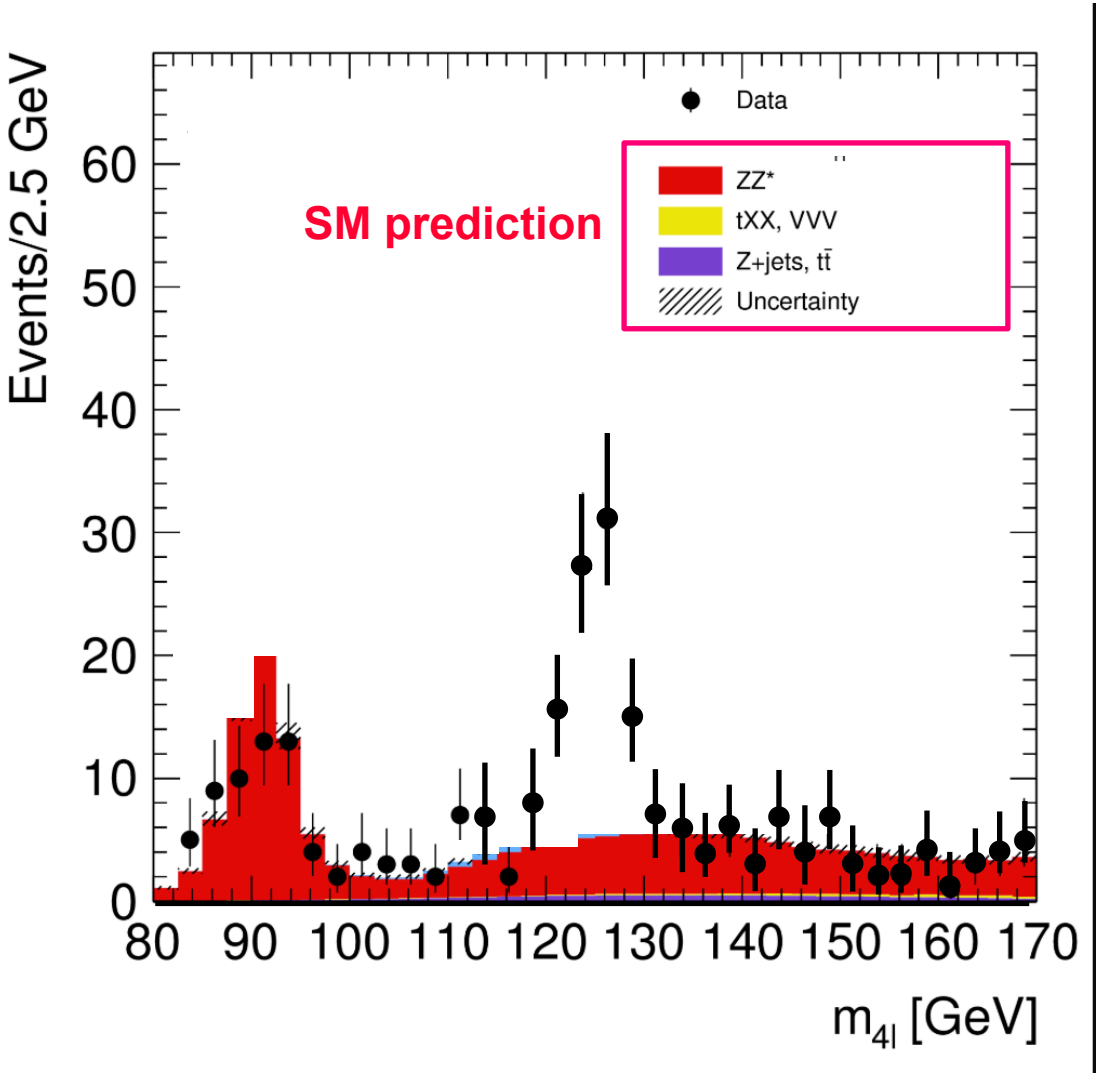


# Power of Statistics & Theory Prediction

## Hypothesis Testing

**Null hypothesis ($H_o$): there is no Higgs boson in data**

Does data match this prediction?

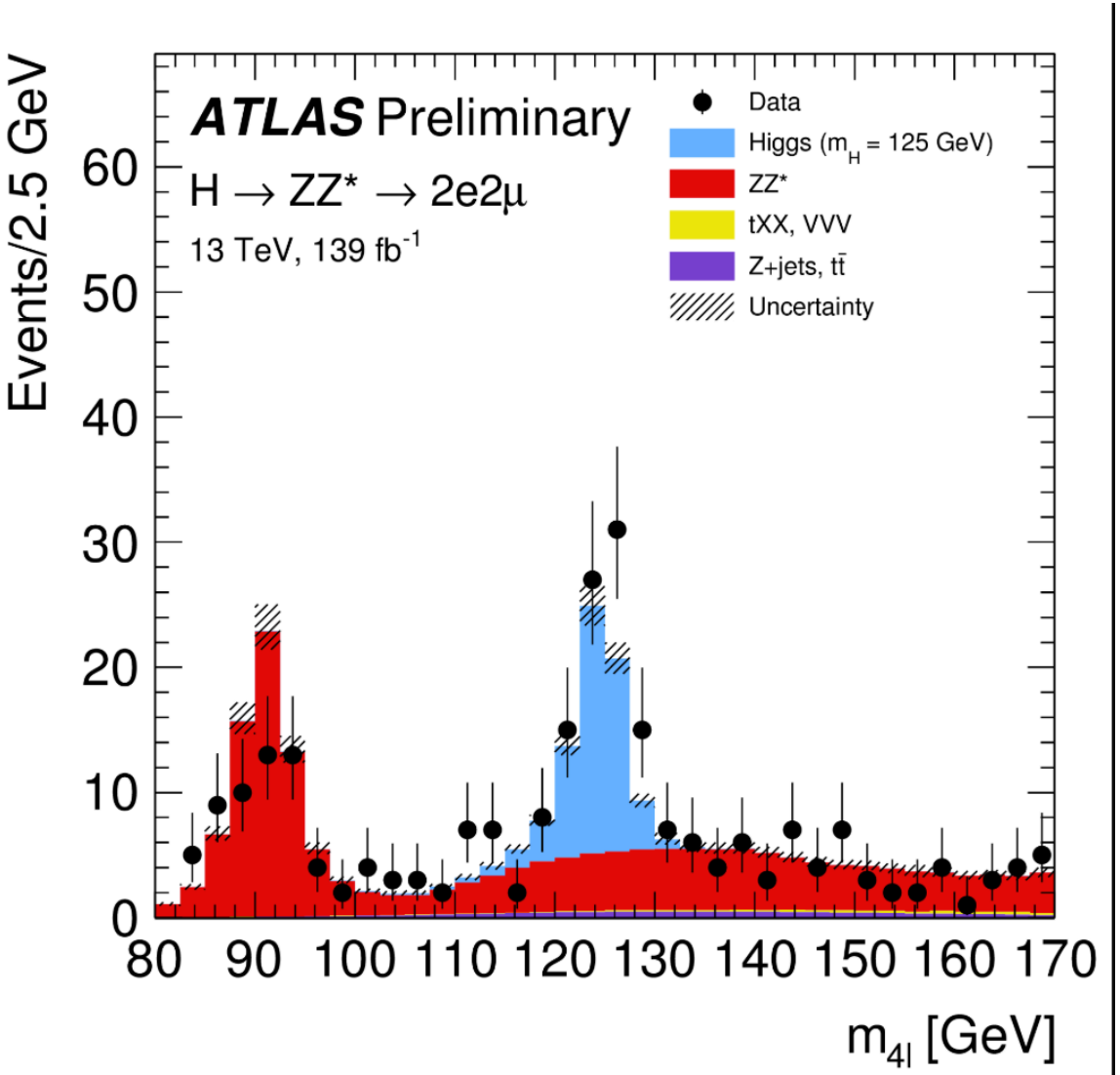


# Power of Statistics & Theory Prediction

## Hypothesis Testing

**Test hypothesis ($H_1$): there is Higgs boson in data**

Looks more likely!!!



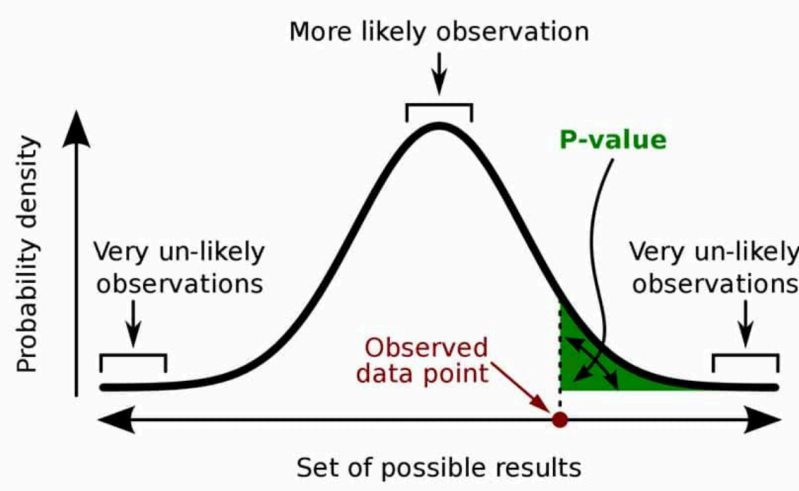
# Quantitative Requirement for Hypothesis testing

## Hypothesis Testing

**Null hypothesis ($H_0$): there is no Higgs boson in data**

**Test hypothesis ($H_1$): there is Higgs boson in data**

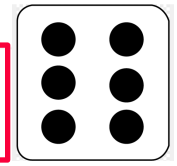
**Fit the data! —> Find p-value**




### Numbers & Terms

| Sigma (σ) | p-value | What it Means |
|---|---|---|
| 1σ | ~32% | Not surprising at all |
| 2σ | ~5% | Happens often by chance |
| 3σ | 0.3% | Interesting hint (often called "evidence") |
| **5σ** | ~0.00003% (1 in 3.5 million) | **Discovery level** — chance of fluke is tiny |

corresponds to getting a 6, 30 times in a row



**This is what we need for discovering a new particle**

# All about the Higgs!

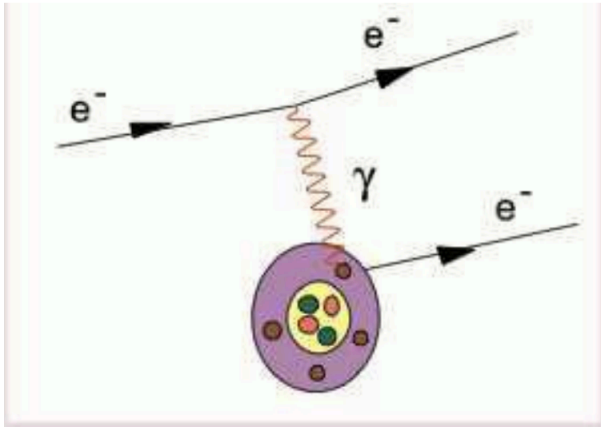
**Currently at the LHC:**

- **We search for new particles directly**
- **We study properties of Standard Model particles**
- **We study Higgs in detail:**
  - **Have measured properties like mass, spin, interactions to other particles**
  - **& will continue to do so!!**

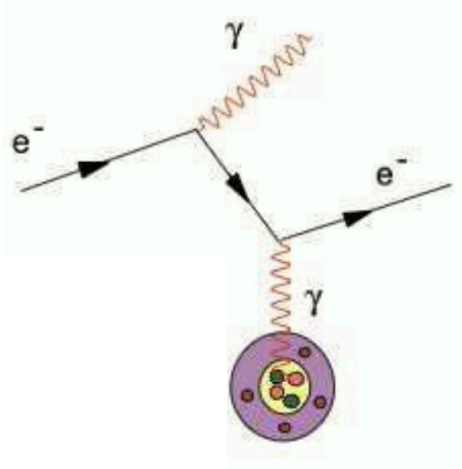
Questions?? ==>

# Both electrons and photons loose energy when interacting with the detector material

## Electrons



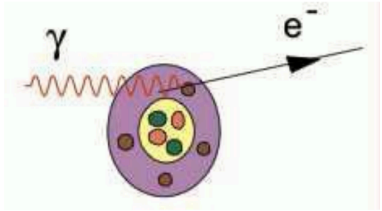

**Ionization,** dominant at low energies




**Bremsstrahlung,** dominant at high energies

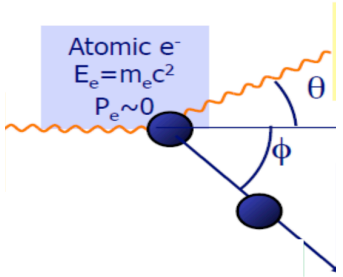
Main mechanism for electron to loose energies in ATLAS/CMS

## Photons



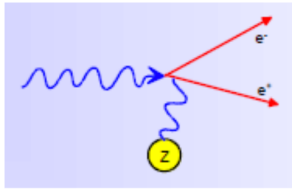

**Photoelectric effect:** dominant at low energy

Completely knocks off electrons from atom




**Compton effect:** dominant at medium energy

knocks off electrons from atom that doesn't absorb photon




**Pair production:** dominant at high energy

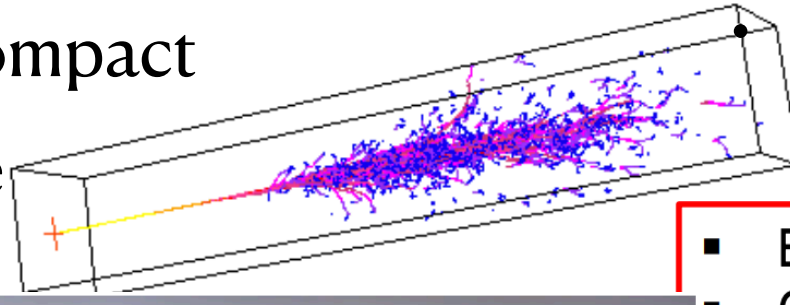
Splits to e+e-

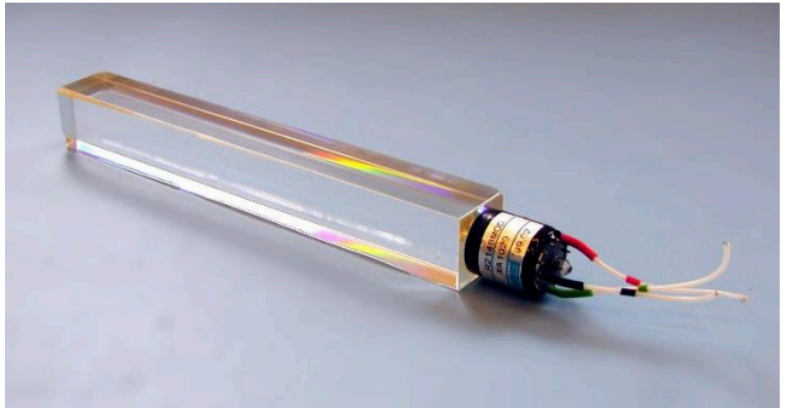
**>1GeV Bremsstrahlung & pair production, main interaction type**

Two types of calorimeter for both electromagnetic & hadronic

**Homogenous**

- All same material, very dense to contain shower
- Example: lead tungstate crystal material for CMS detector
- Best resolution, compact
- But very expensive

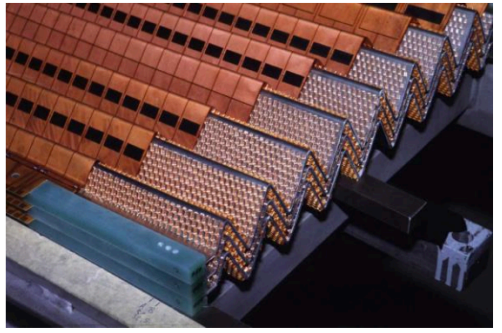


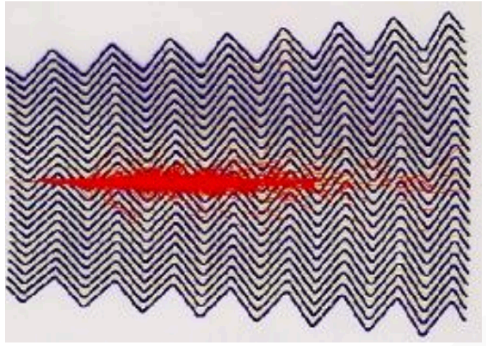


**Sampling**

- Sandwich of high-Z absorber material like lead & low-Z material like gas/liquid

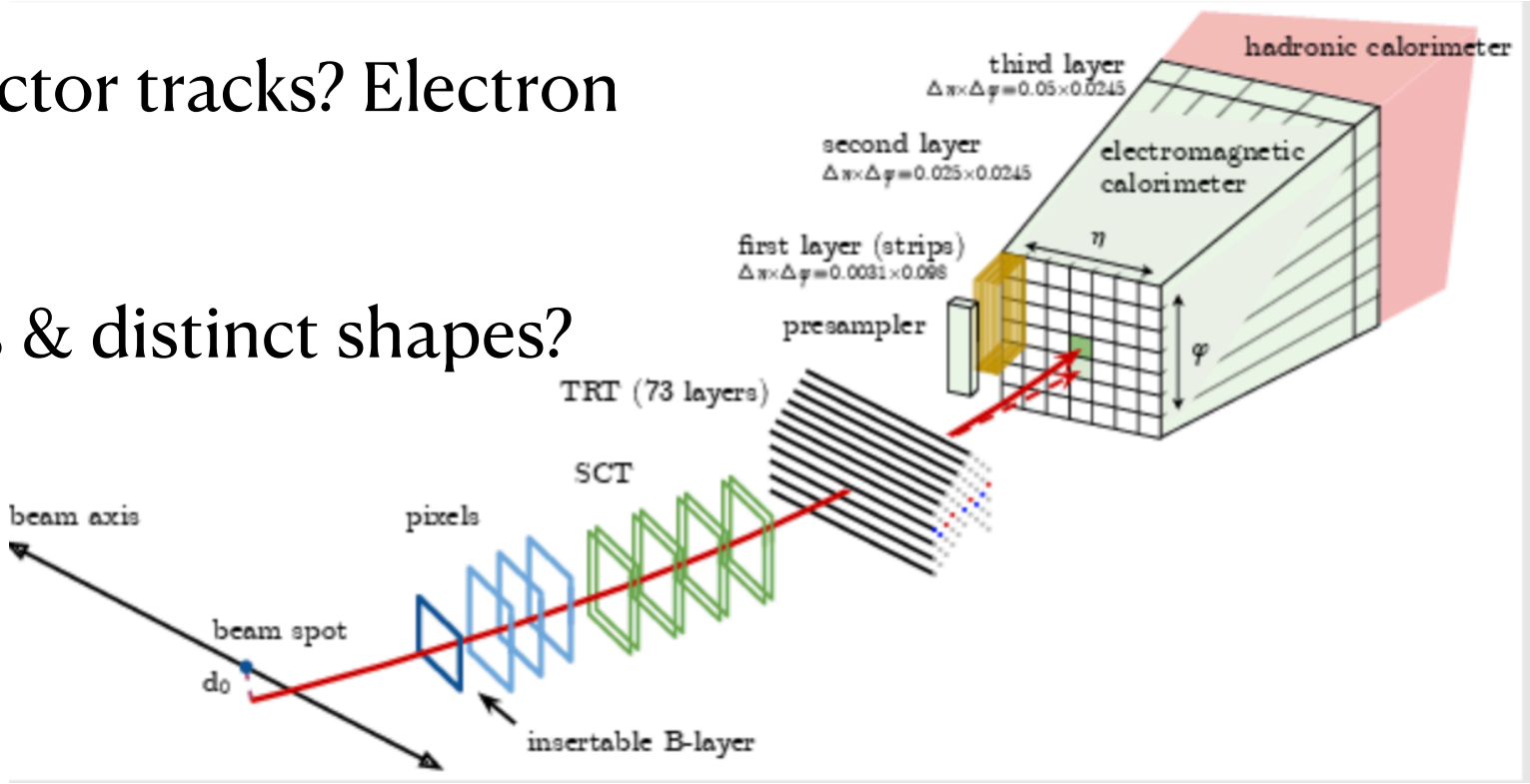
Worse resolution





# Electrons/photons

- Energy deposits in EM calorimeter cells as clusters
- Matches with inner detector tracks? Electron candidate
- No inner detector tracks & distinct shapes? Photon candidate



# Jets

- Energy deposits in hadronic calorimeter cells as clusters, within a radial cone (i.e. delta R)
- Matches with inner detector tracks?
- Machine learning to distinguish heavy flavor jets (b/c)
- Machine learning to distinguish quark vs gluon jets