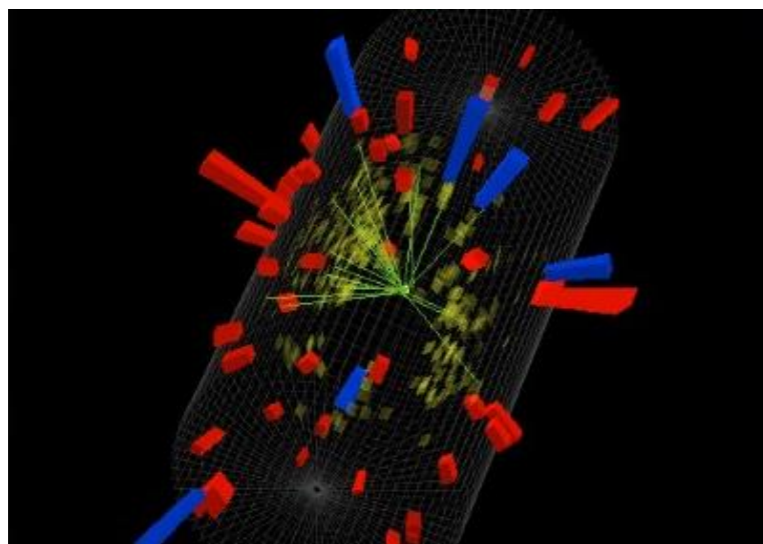
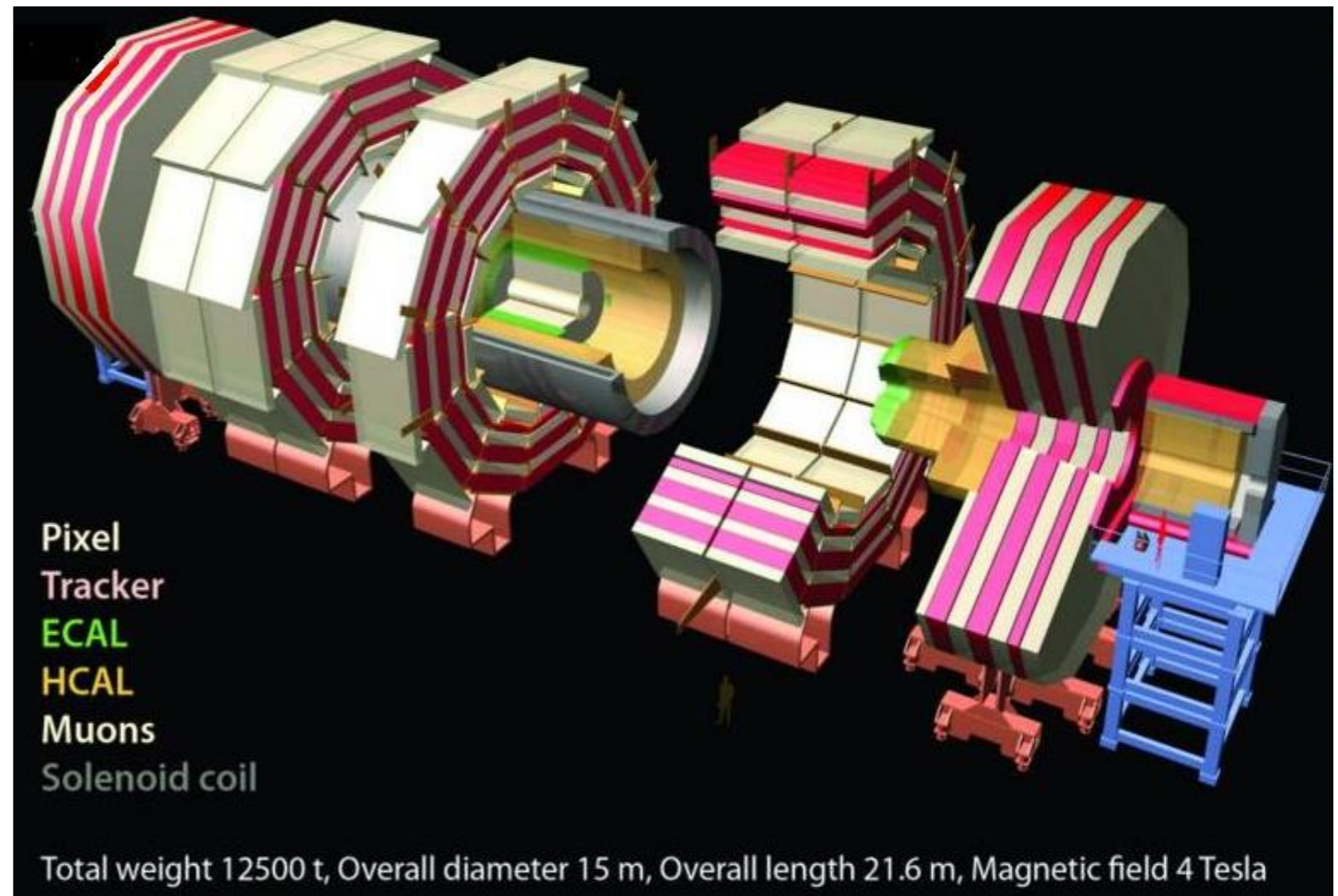
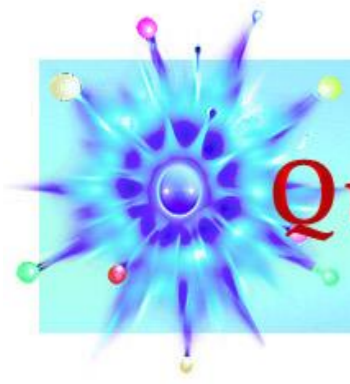




CMS WZH Masterclass





QuarkNet

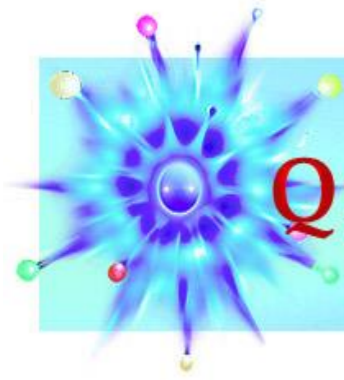
The LHC and New Physics

It's a time of exciting new discoveries in particle physics!

At CERN, the LHC successfully completed Run I

*at 8 TeV of collision energy, confirming that the measurements correspond well to the **Standard Model** and then finding the Higgs boson. The LHC is now into Run II at an amazing 13 TeV and the task is to look for new phenomena...and we are off to a great start.*





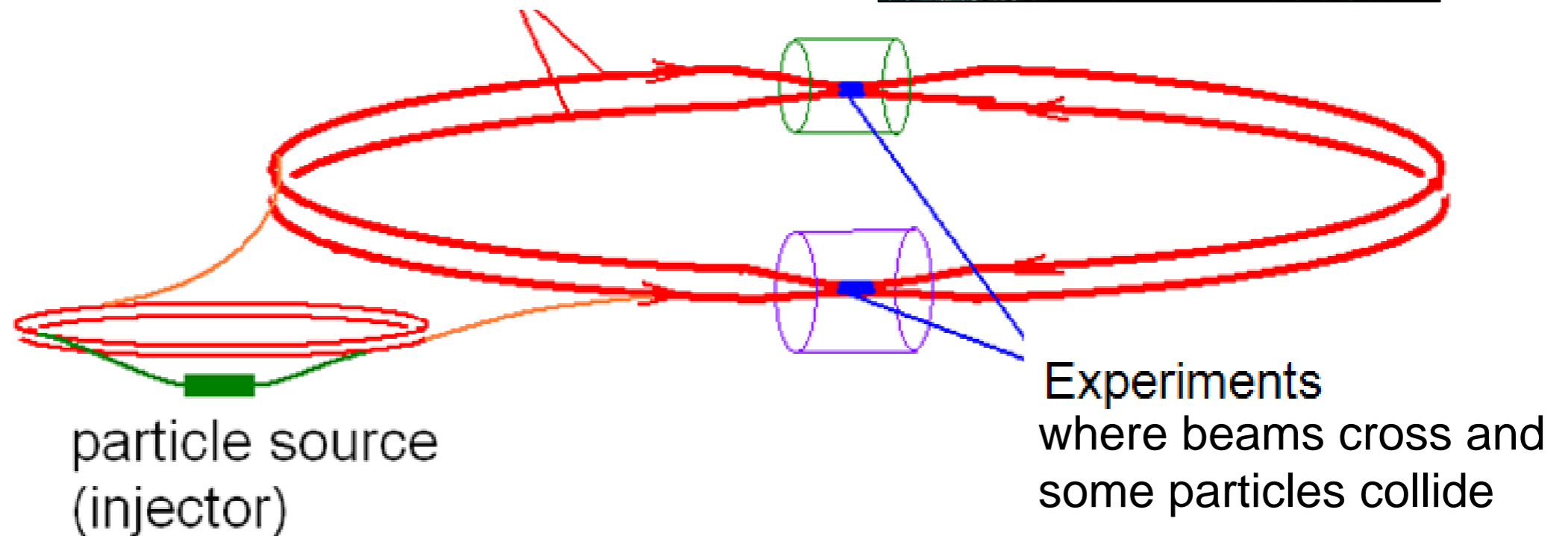
QuarkNet

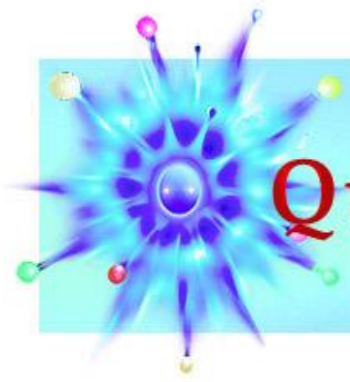
The LHC and New Physics

The LHC is buried ~100 m below the surface near the Swiss-French border.



beams accelerated in large rings
(27 km circumference at CERN)





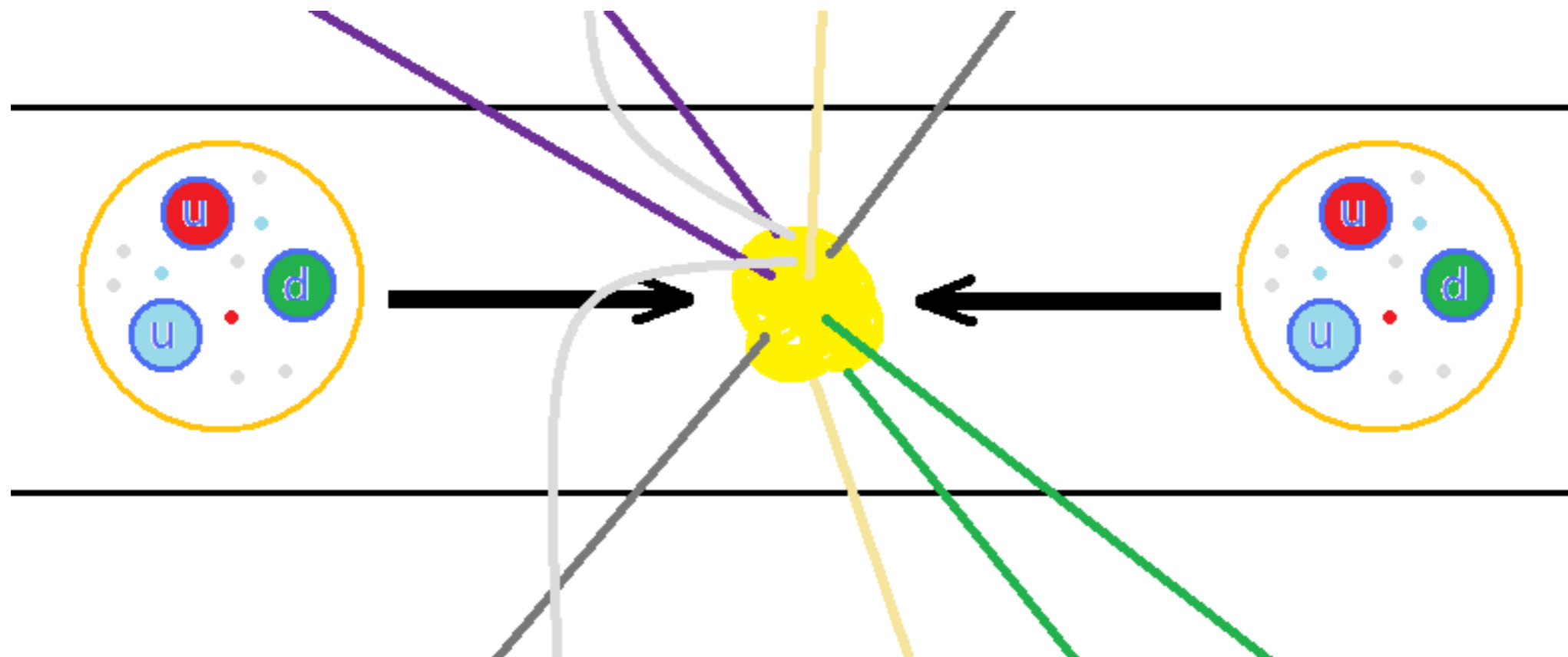
QuarkNet

Energy & Particle Mass

We will look at Run I, in which proton energy is 4 TeV*.

- The total collision energy is $2 \times 4 \text{ TeV} = 8 \text{ TeV}$.
- But each particle inside a proton shares only a portion.
- So a newly created particle's mass **must be** smaller than the total energy.

**In Run II, this was increased to 6.5 GeV!*



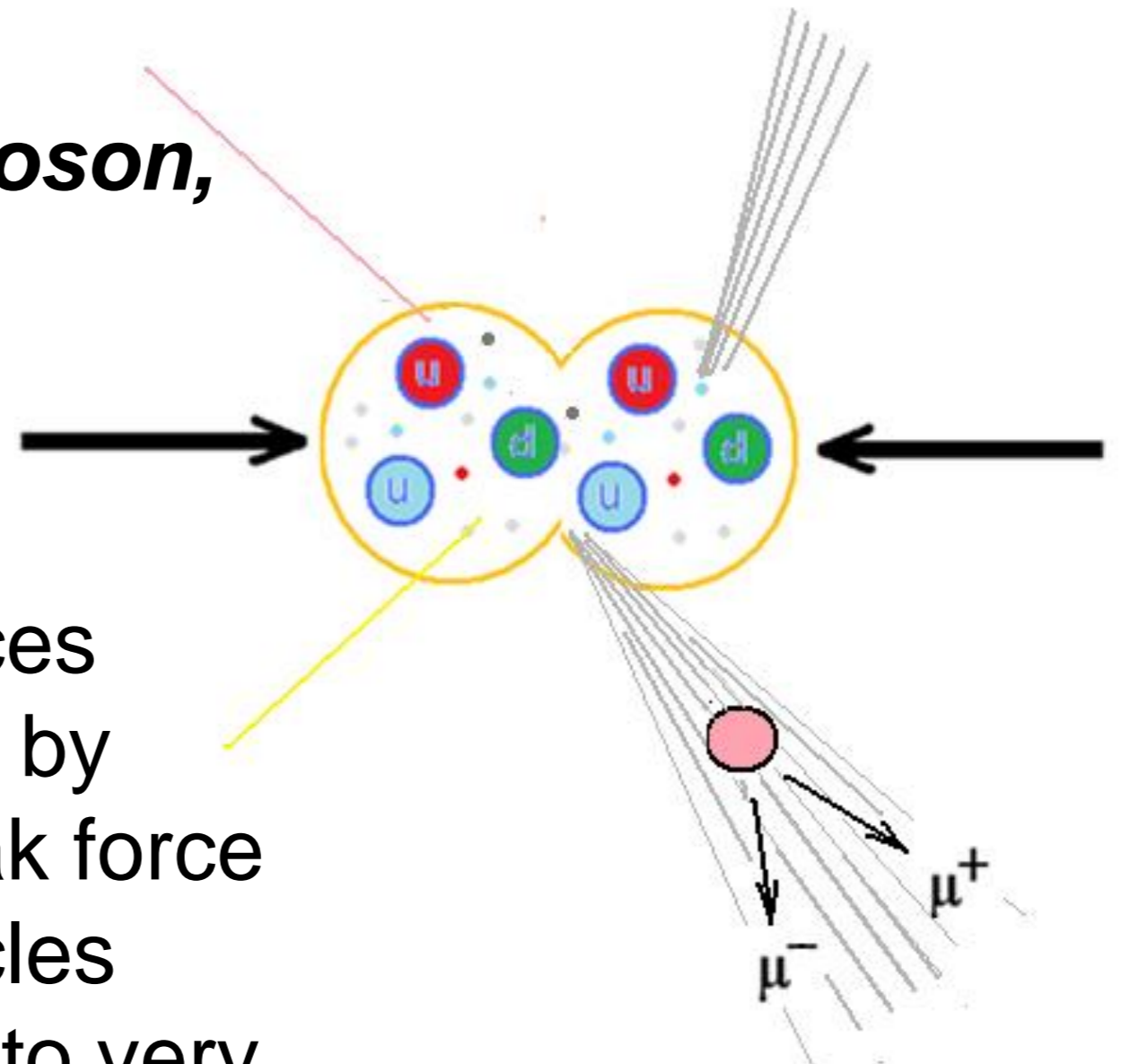


W and Z Particles

We are looking for the mediators of the ***weak interaction***:

- electrically charged **W^+ boson**,
- the negative **W^- boson**,
- the neutral **Z boson**.

Unlike electromagnetic forces carried over long distances by massless photons, the weak force is carried by massive particles which restricts interactions to very tiny distances.



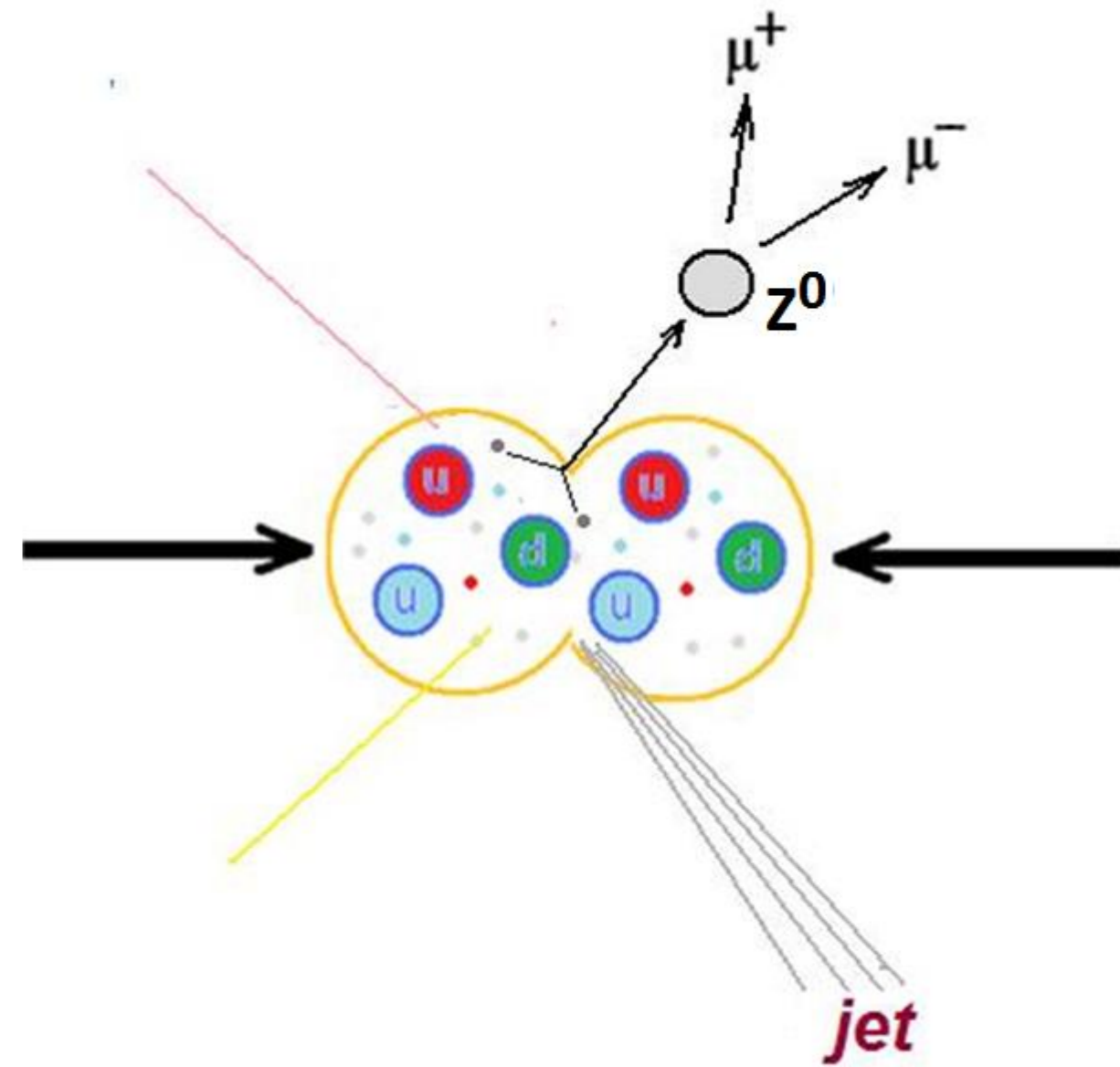


W and Z Particles

The W bosons are responsible for radioactivity by transforming a proton into a neutron, or the reverse.

Z bosons are similarly exchanged but do not change electric charge.

Collisions of sufficient energy can create W and Z or other particles.



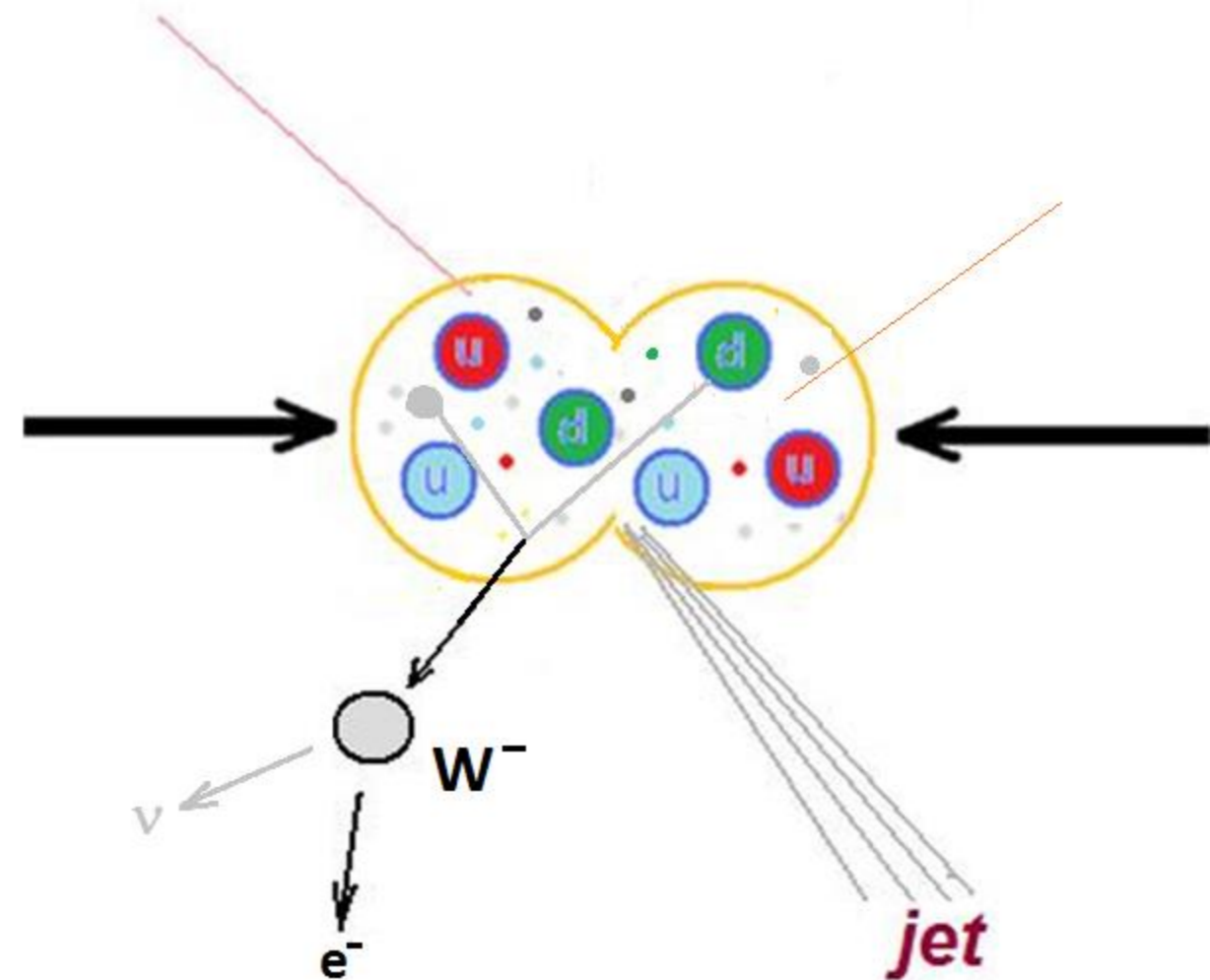


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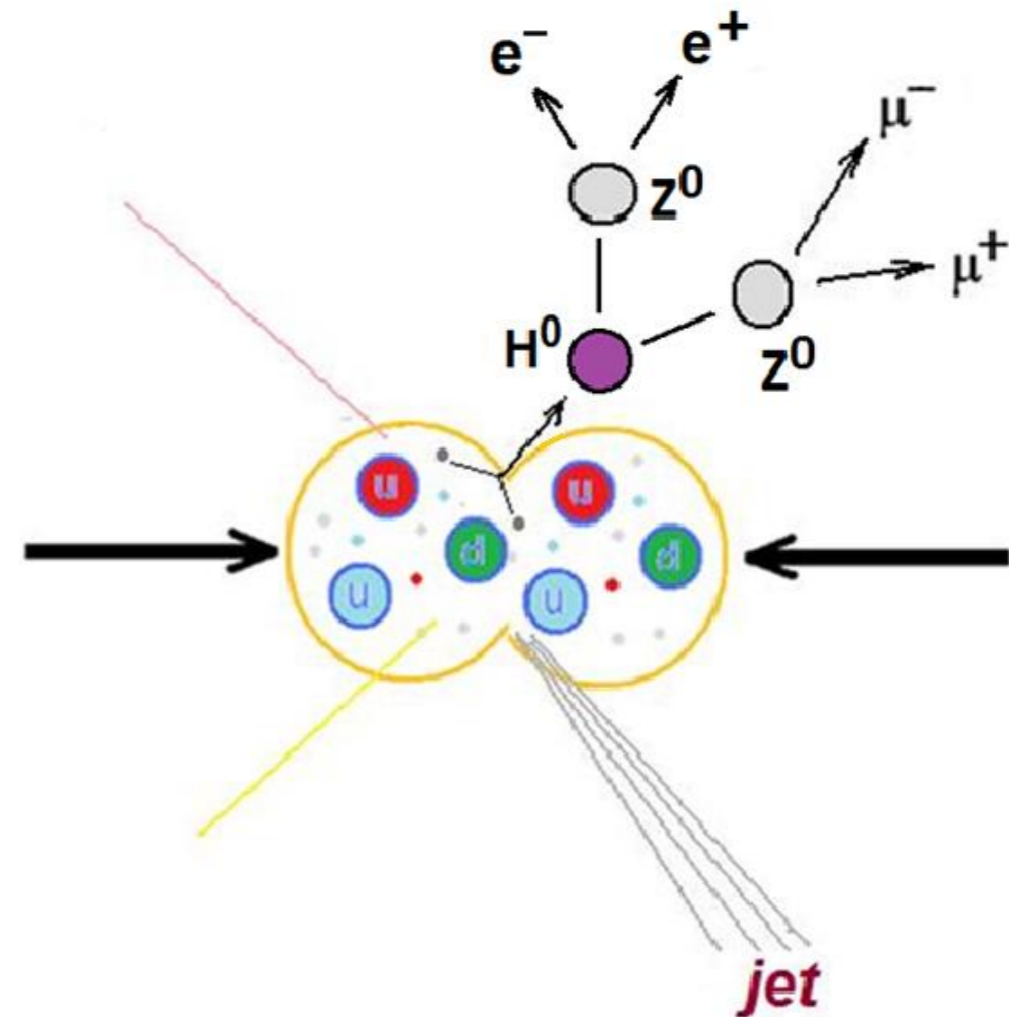




Higgs Particles

The Higgs boson was discovered by CMS and ATLAS and announced on July 4, 2012.

This long-sought particle is part of the “Higgs mechanism” that accounts for other particle having mass.

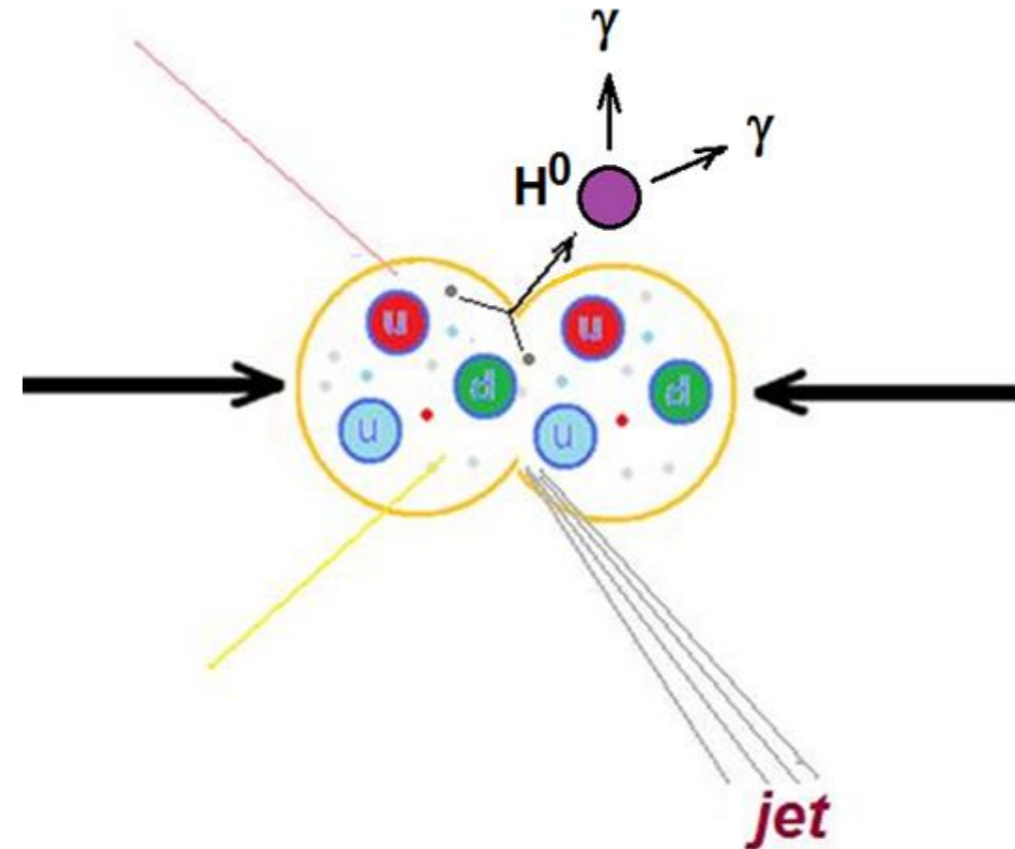




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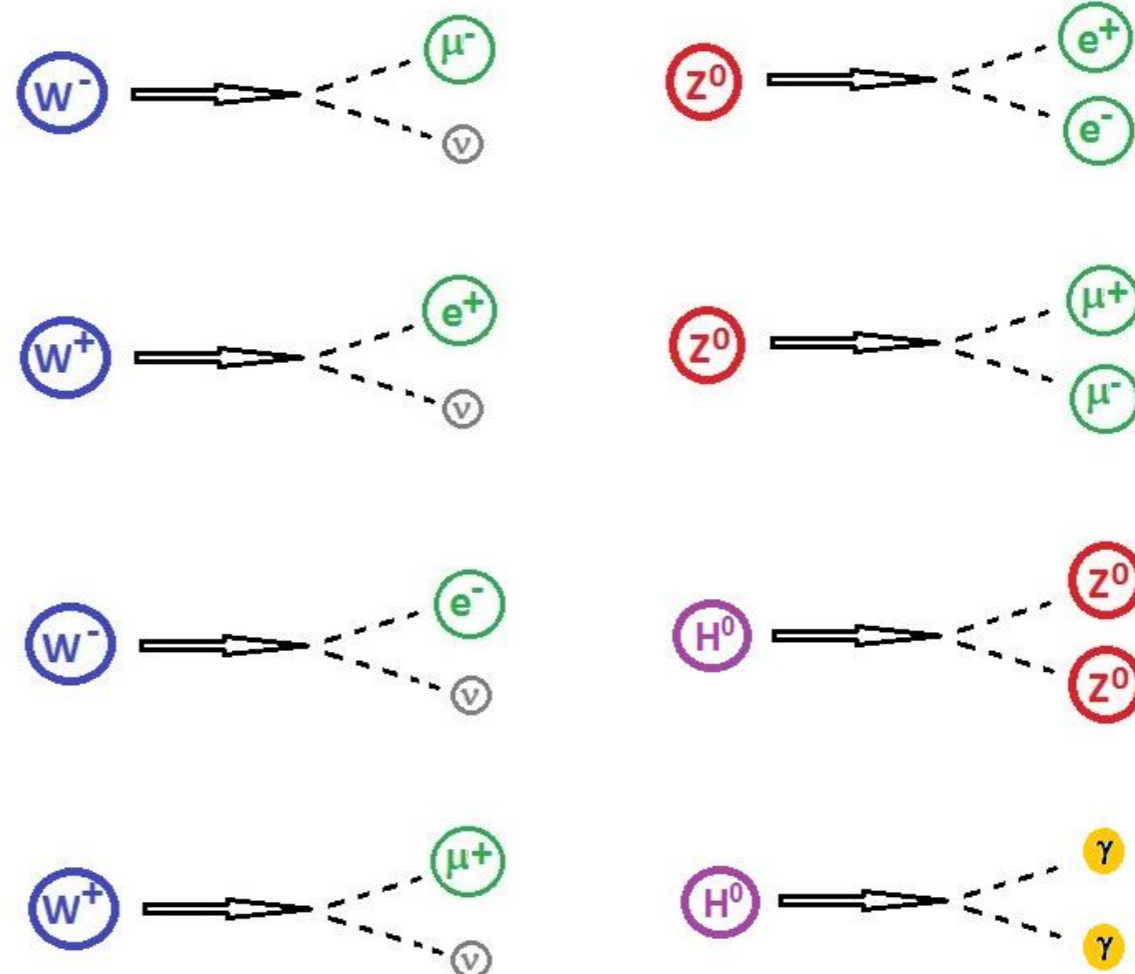


W and Z Decays

Because bosons only travel a tiny distance before decaying, CMS does not “see” them directly.

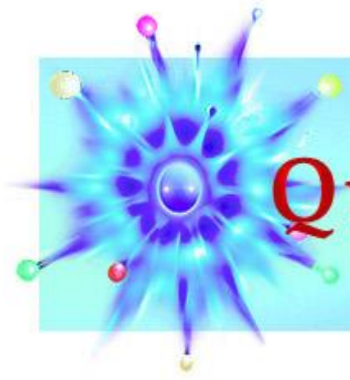
CMS *can* detect :

- electrons
- muons
- photons



CMS can infer:

- neutrinos from “missing energy”



QuarkNet

iSpy-webgl

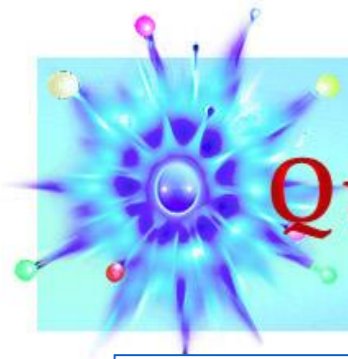
The screenshot displays the iSpy-webgl interface. On the left is a 'Detector' panel with a list of components and checkboxes:

- Tracker Barrels
- Tracker Endcaps
- ECAL Barrel
- ECAL Endcap (+)
- ECAL Endcap (-)
- HCAL Barrel
- HCAL Endcaps
- HCAL Outer
- HCAL Forward (+)
- HCAL Forward (-)
- Drift Tubes
- Cathode Strip Chambers

The main 3D view shows a detector structure with several labeled features:

- event display controls**: A toolbar at the top of the interface.
- event vertex (near collision)**: A red dot at the center of the detector.
- missing energy**: A pinkish-purple energy flow originating from the vertex.
- energy deposit**: A green energy flow originating from the vertex.
- electron track**: A blue track originating from the vertex.
- beamline**: A red and green coordinate system at the bottom left.

Legend at the bottom: **ECAL=blue wireframe HCAL=yellow wireframe tracker inside ECAL**



QuarkNet

Recording event data

CIMA
CMS Instrument for Masterclass Analysis

Choose your Masterclass

test
Test2
31Jan2015

Choose your location

Buffalo
MexicoCity
Quito

Choose your group

6
7
8
9
10

Choose the date of your masterclass, the institute, and your dataset.

Find your dataset.

Record parent particles and decay modes.

Back Events Table (Group 1) Mass Histogram (TT1) Results (TT1) ➔ Event Display

Masterclass: TestTables-Feb2017
location: TT1
Group: 1

Instructions (also available as screencast):

- For each event, identify the final state and select a primary state candidate.
 - For Higgs or Zoo candidate, no final state is chosen
 - If you cannot decide between W+ and W-, choose W instead
- If you think the final state is a neutral particle (like a Z), but you don't know its exact type, select NP for "neutral particle." Find its mass from the Event Display and enter it.
- Once you have selected everything, click "Submit".

In case of an error, double clicking the data line will reload it; you can then try it again.

Select Event

Event index:

Event number: 1-10

final state

Electron

Muon (μ)

primary state candidate

W⁻ NP Higgs

W⁺ W Zoo

NP Mass: GeV/c²

Event index	Event number	Chosen Values	Mass
9	1-9	Z, μ	mu
8	1-8	e, W ⁺	
7	1-7	μ , Z	95
6	1-6	μ , Z	NaN
5	1-5	e, Z	NaN
4	1-4	μ , W ⁺	
3	1-3	μ , W ⁺	
2	1-2	e, W ⁻	
1	1-1	e, W ⁺	



Recording event data

Mass Histogram and Results pages

Back Events Table Mass Histogram Results

Masterclass: 31Jan2015
location: MexicoCity

Group	Muon	Electron	W	W-	W+	Z	Higgs	Zoo	Total
1	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0



Total:

Muon	Electron	W	W-	W+	Z	Higgs	Zoo	Sum	amu	W+W-
9	9	3	1	3	11	2	3	23	1	3



Detector Design

Generic Design

Cylinders wrapped around the beam pipe

From inner to outer . . .

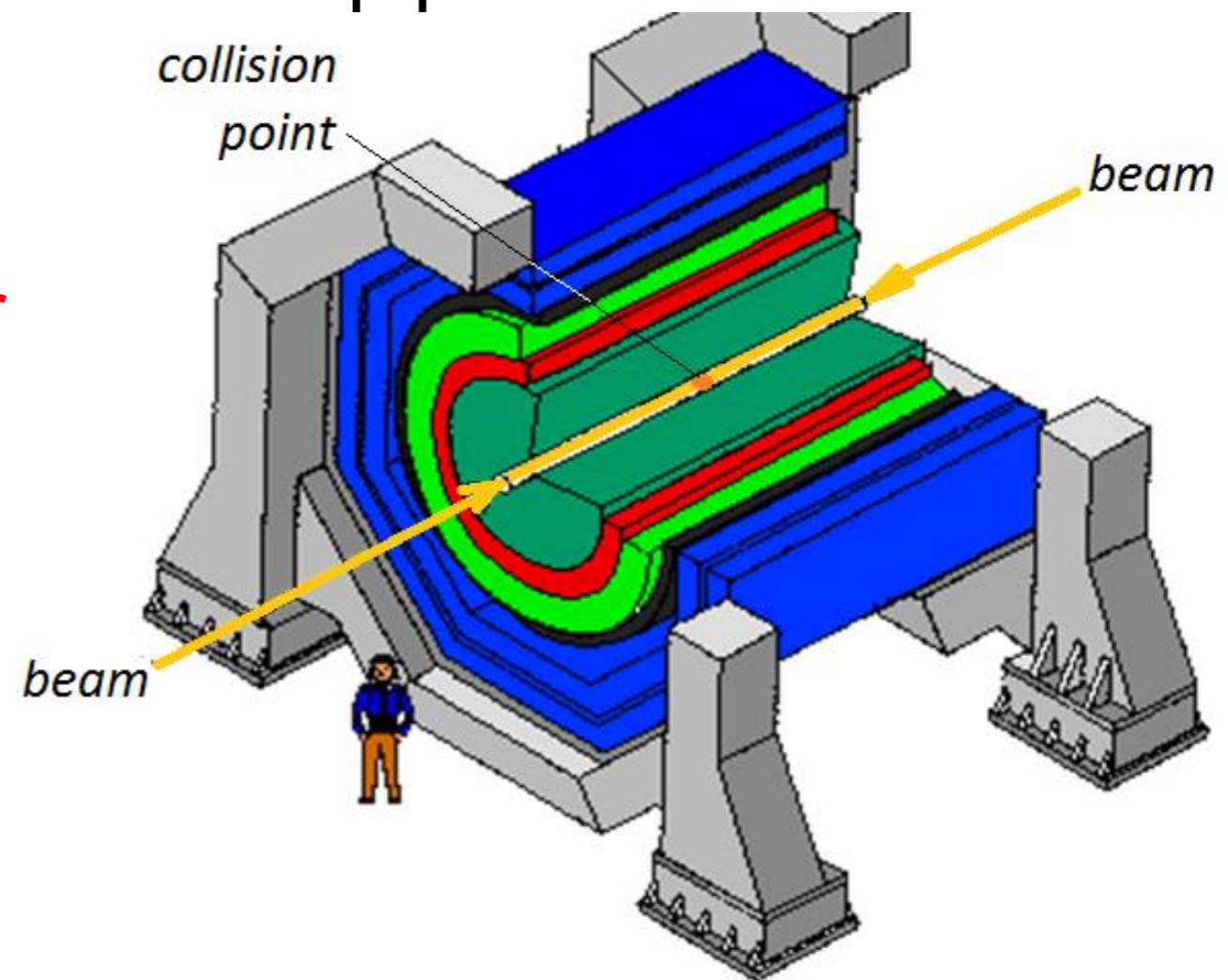
Tracking

Electromagnetic calorimeter

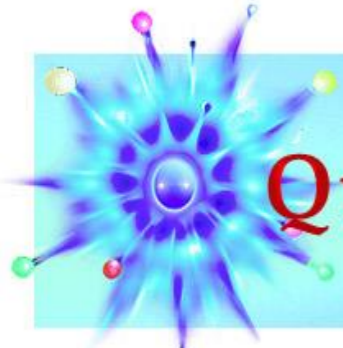
Hadronic calorimeter

Magnet*

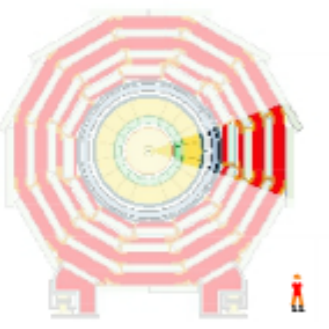
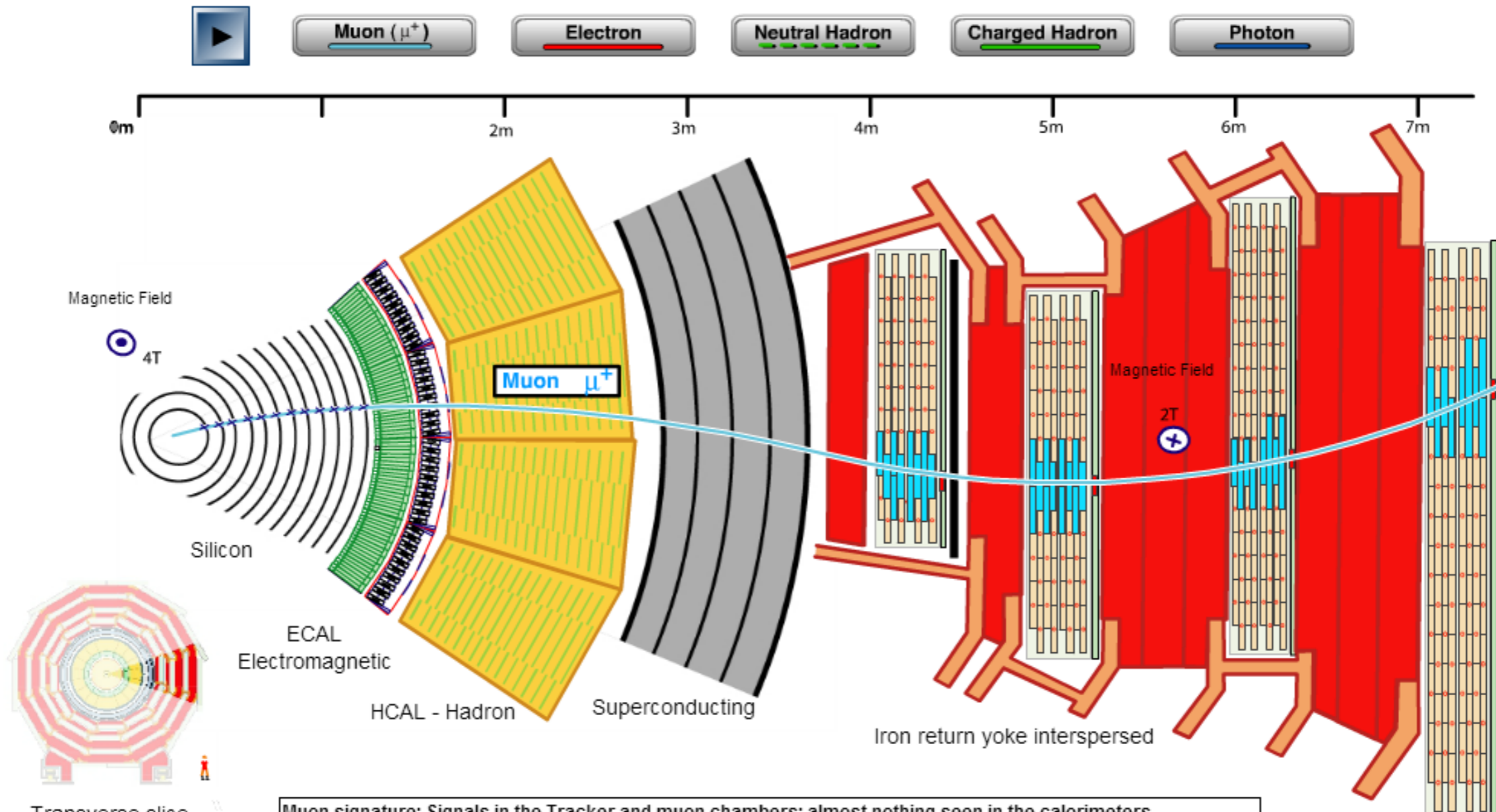
Muon chamber



* *location of magnet depends on specific detector design*



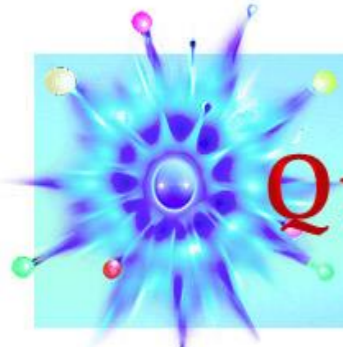
Transverse Slice of the Compact Muon Solenoid (CMS) Detector



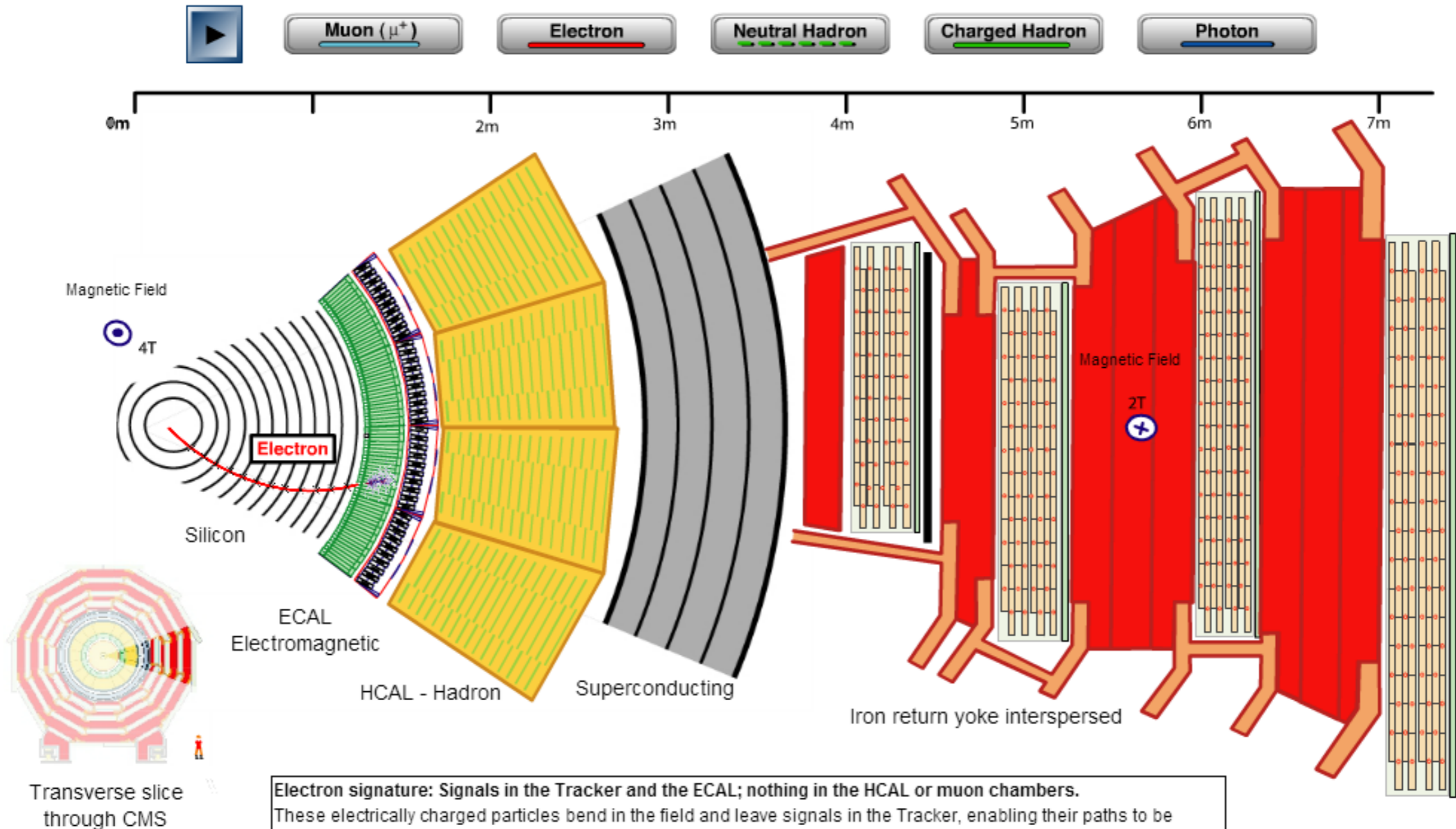
Transverse slice through CMS

Muon signature: Signals in the Tracker and muon chambers; almost nothing seen in the calorimeters. Muons are perhaps the easiest particles to identify in CMS: no other charged particle traverses the whole detector. Being charged, they are bent by the field in one direction inside the solenoid and in the opposite direction outside. As muons can only arise from the decay of something heavier their presence signifies that something potentially interesting has happened.

D. Barney, CERN, 2004

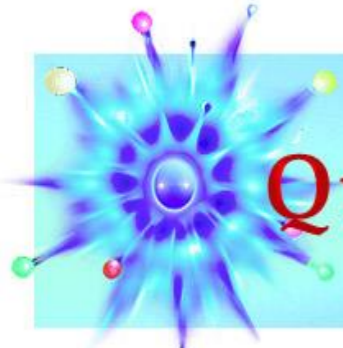


Transverse Slice of the Compact Muon Solenoid (CMS) Detector

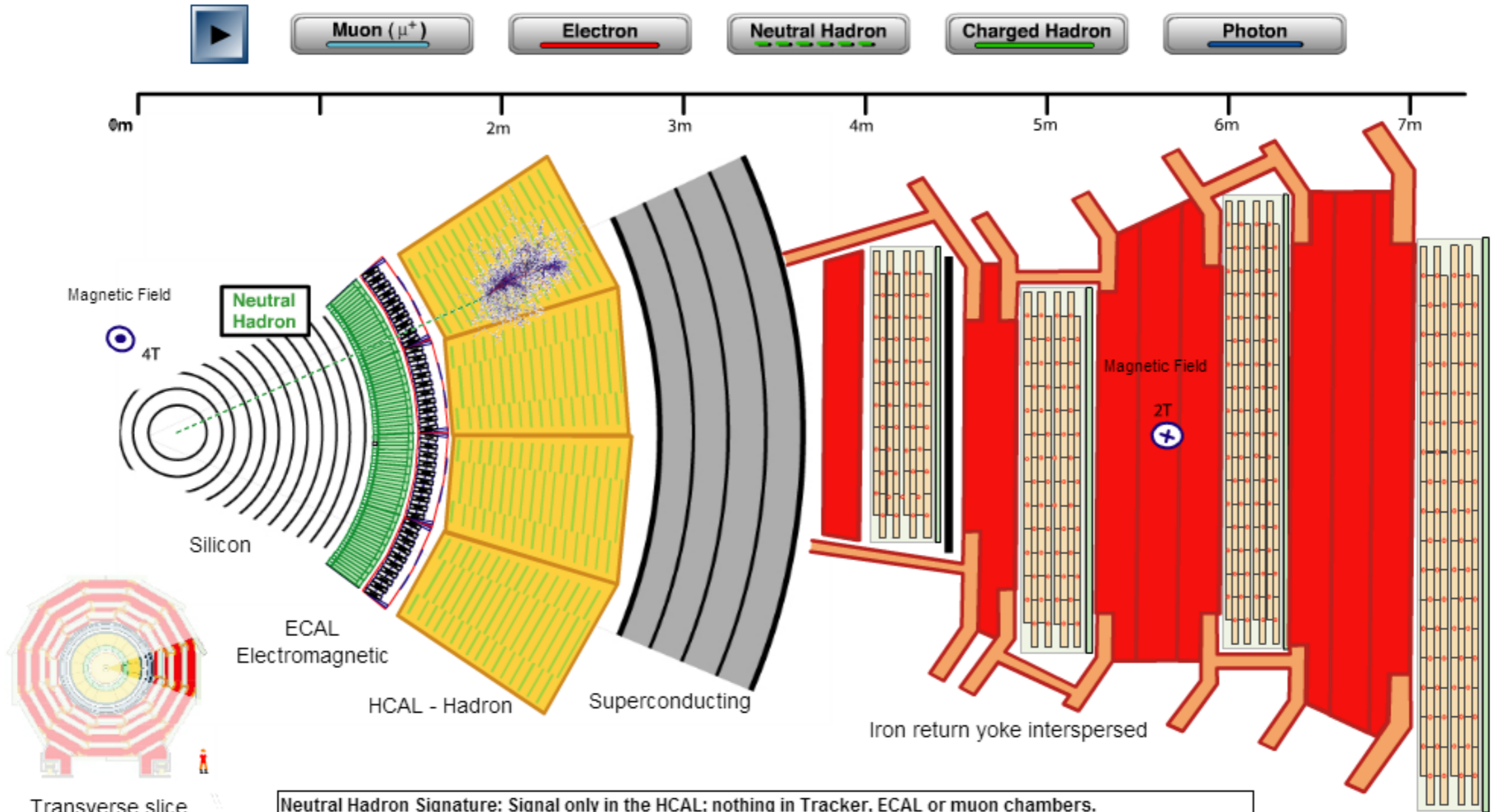


Electron signature: Signals in the Tracker and the ECAL; nothing in the HCAL or muon chambers.
 These electrically charged particles bend in the field and leave signals in the Tracker, enabling their paths to be reconstructed. The amount of bend depends on the momentum they carry, with the radius of curvature, r , being given by the momentum, p , divided by $0.3 \times B$, where B is the magnetic field strength (3.8T in CMS). Electrons are slowed to a stop in the transparent lead tungstate crystals of the ECAL, producing a **shower** of electrons, photons and positrons along the way and depositing their energy in the form of light, which is detected. The amount of light is proportional to the electron energy.

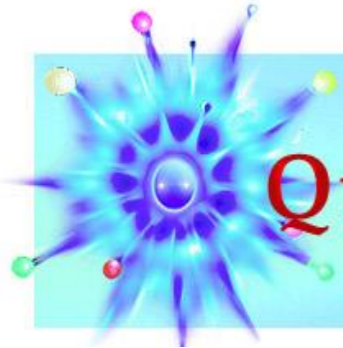
Derived from CMS Detector Slice from CERN



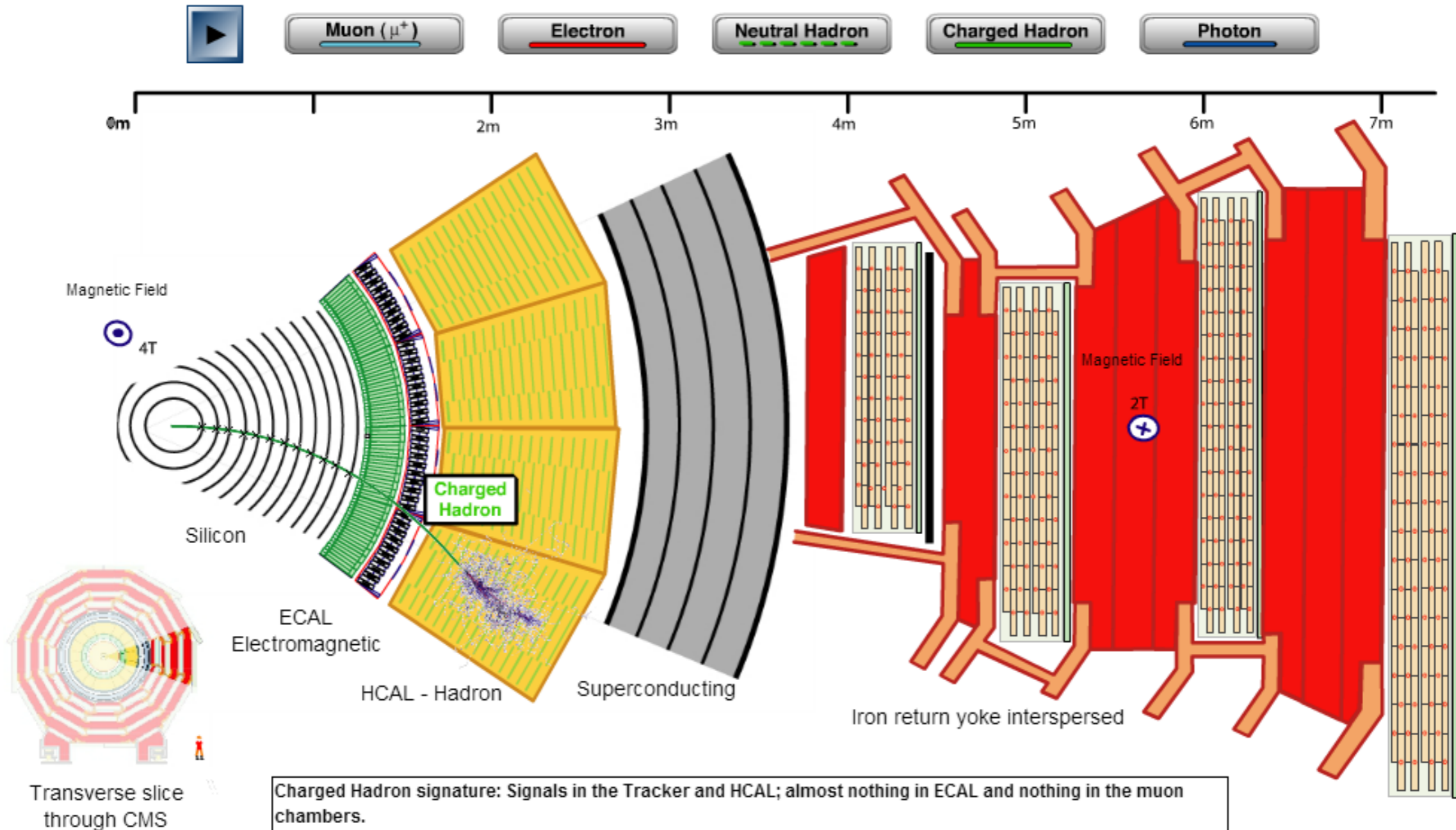
Transverse Slice of the Compact Muon Solenoid (CMS) Detector



Neutral Hadron Signature: Signal only in the HCAL; nothing in Tracker, ECAL or muon chambers.
 Neutral hadrons, such as neutrons, travel straight through the Tracker and ECAL, without being bent by the magnetic field or leaving any signals. Like charged hadrons, they are slowed to a stop in the HCAL, depositing their energy and leaving signals in the form of light in the plastic scintillators. The amount of light is proportional to the energy of the incoming hadron.

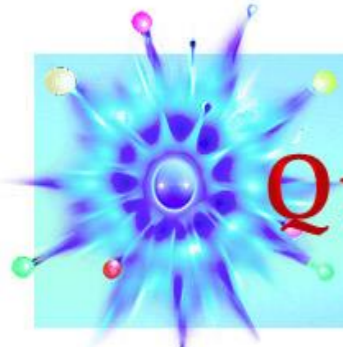


Transverse Slice of the Compact Muon Solenoid (CMS) Detector

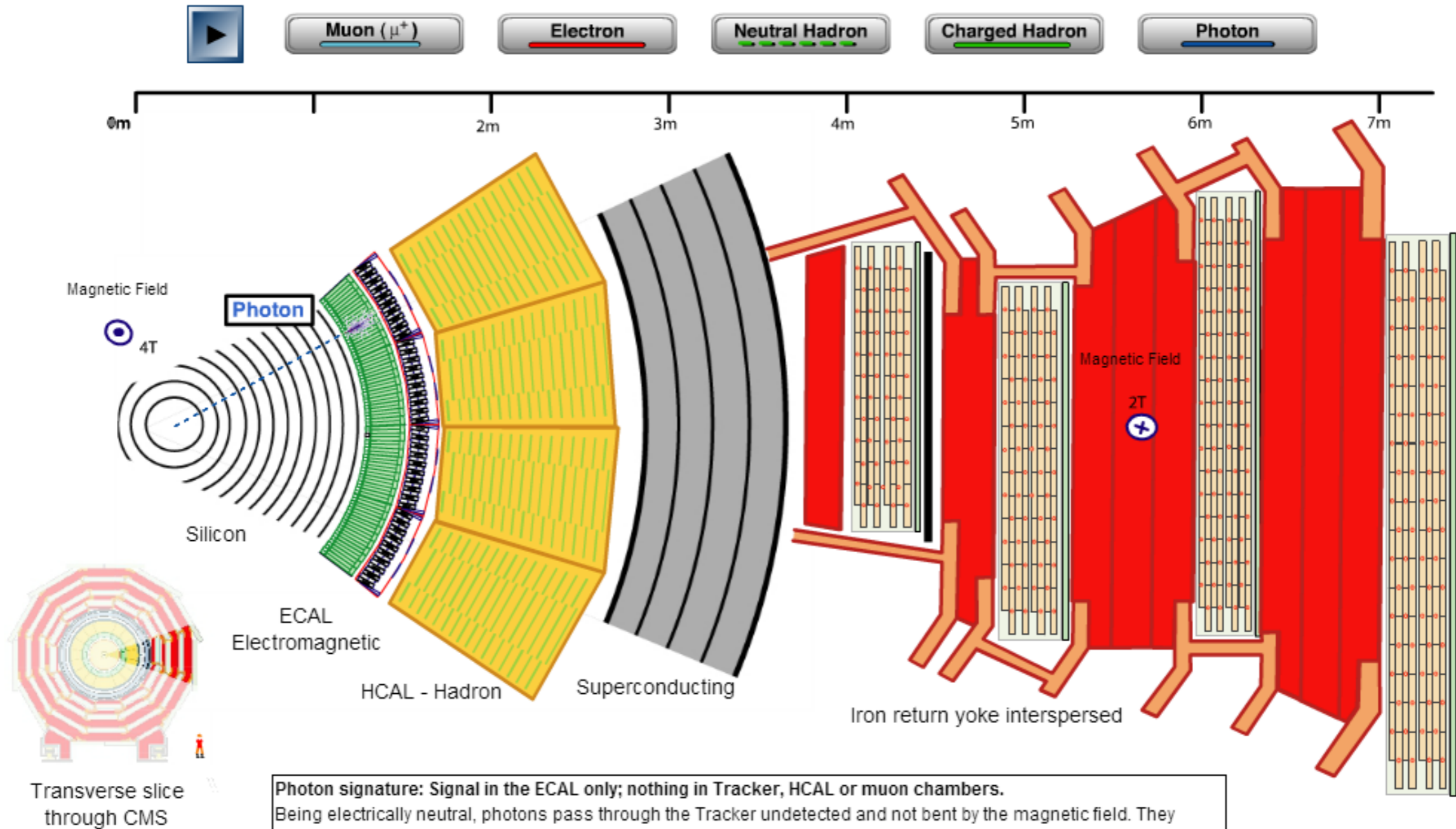


Charged Hadron signature: Signals in the Tracker and HCAL; almost nothing in ECAL and nothing in the muon chambers.

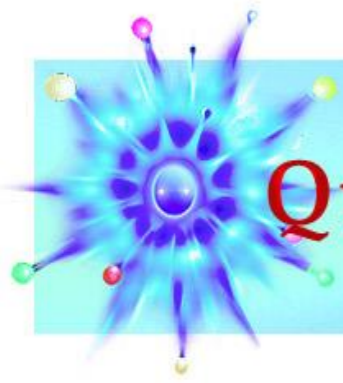
Charged hadrons, such as protons and pi plus or pi minus (made of pairs of quarks), are bent by the magnetic field and travel straight through the ECAL leaving almost no signals. Upon reaching the HCAL they are slowed to a stop by the dense materials, producing showers of secondary particles along the way that in turn produce light in thin layers of plastic scintillator material. The amount of light is proportional to the energy of the incoming hadron.



Transverse Slice of the Compact Muon Solenoid (CMS) Detector



D. Barney, CERN, 2004



QuarkNet

Sketch the tracks in CMS

Web
Version

$(Z^0) \rightarrow \mu^+ \mu^-$

HCAL Outer - just outside solenoid magnet

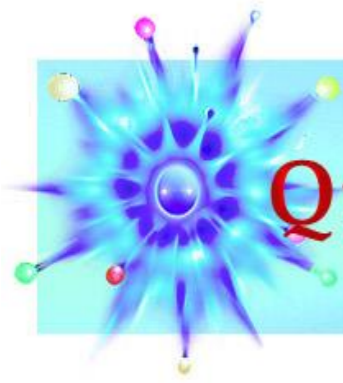
ECAL Barrel

+ particles curve clockwise

- particles curve anti-clockwise

End (x-y) view

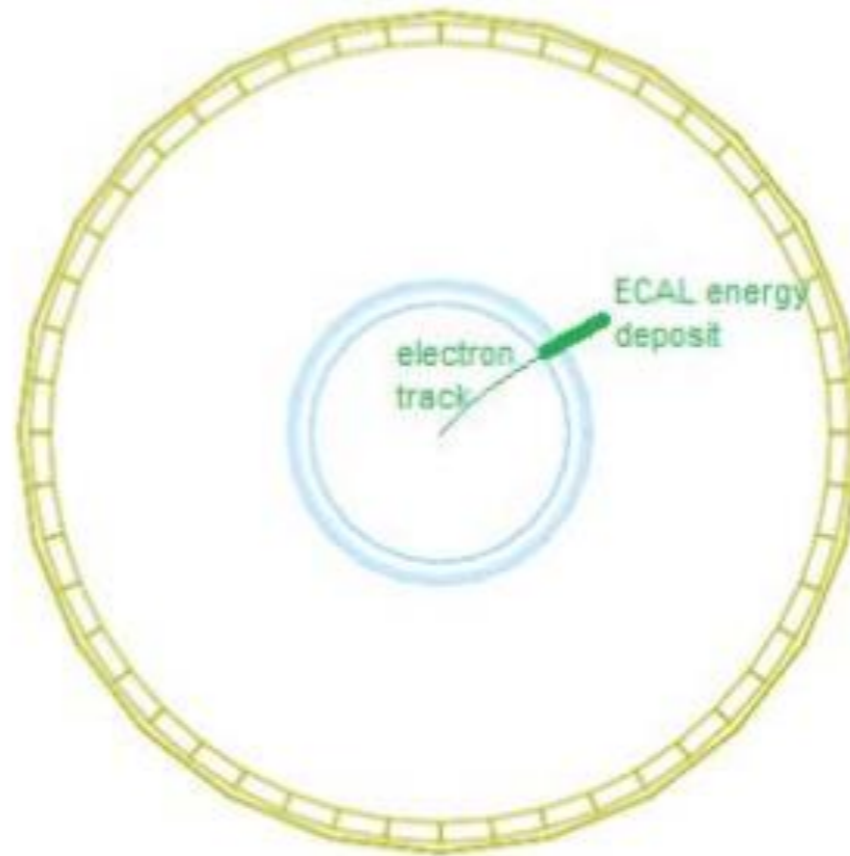
1. Draw a muon (-) going through the detector slice.
2. Draw an antimuon (+) going in the opposite direction.



QuarkNet

Sketch the tracks in CMS

$$(Z^0) \rightarrow e^+ e^-$$

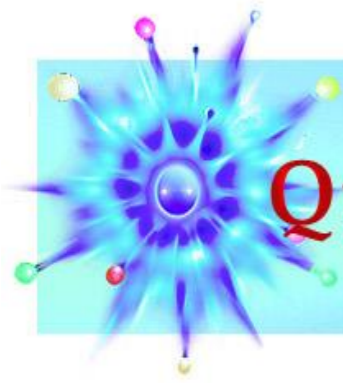


End (x-y) view



- Muon
- Electron
- - - - Missing Et

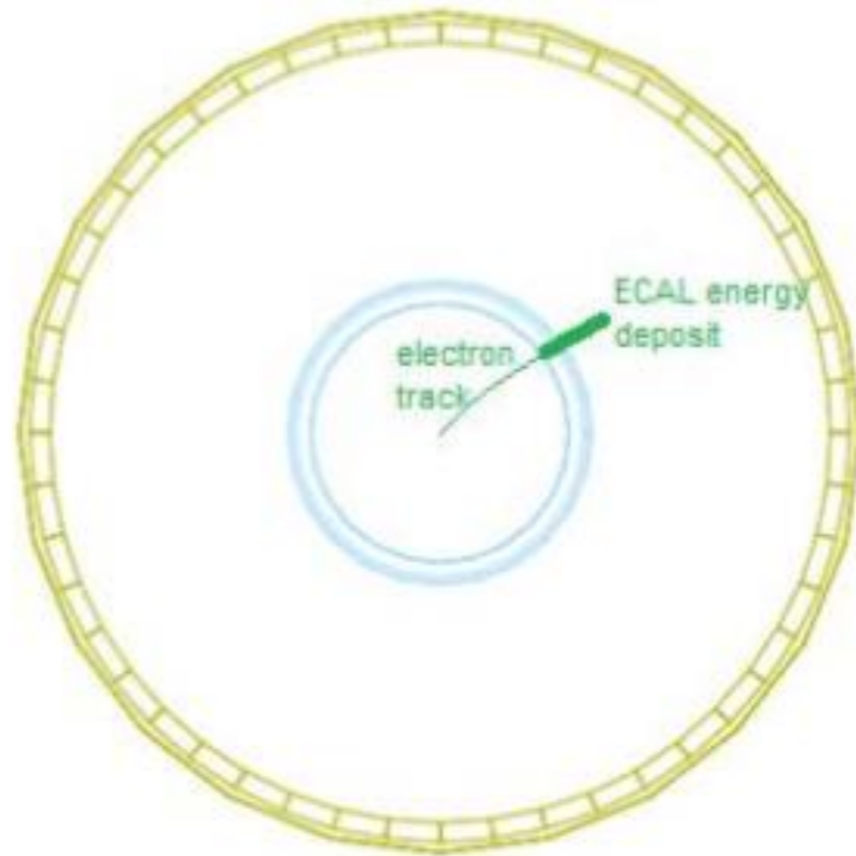
An electron (-) track is already drawn. Add the positron (+) track and energy deposit



QuarkNet

Sketch the tracks in CMS

$$(Z^0) \rightarrow e^+ e^-$$

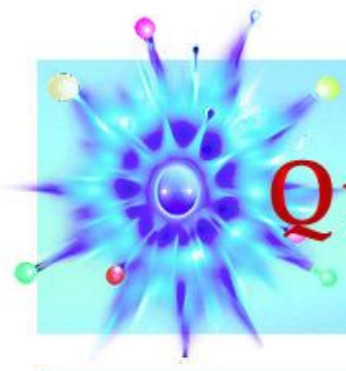


End (x-y) view



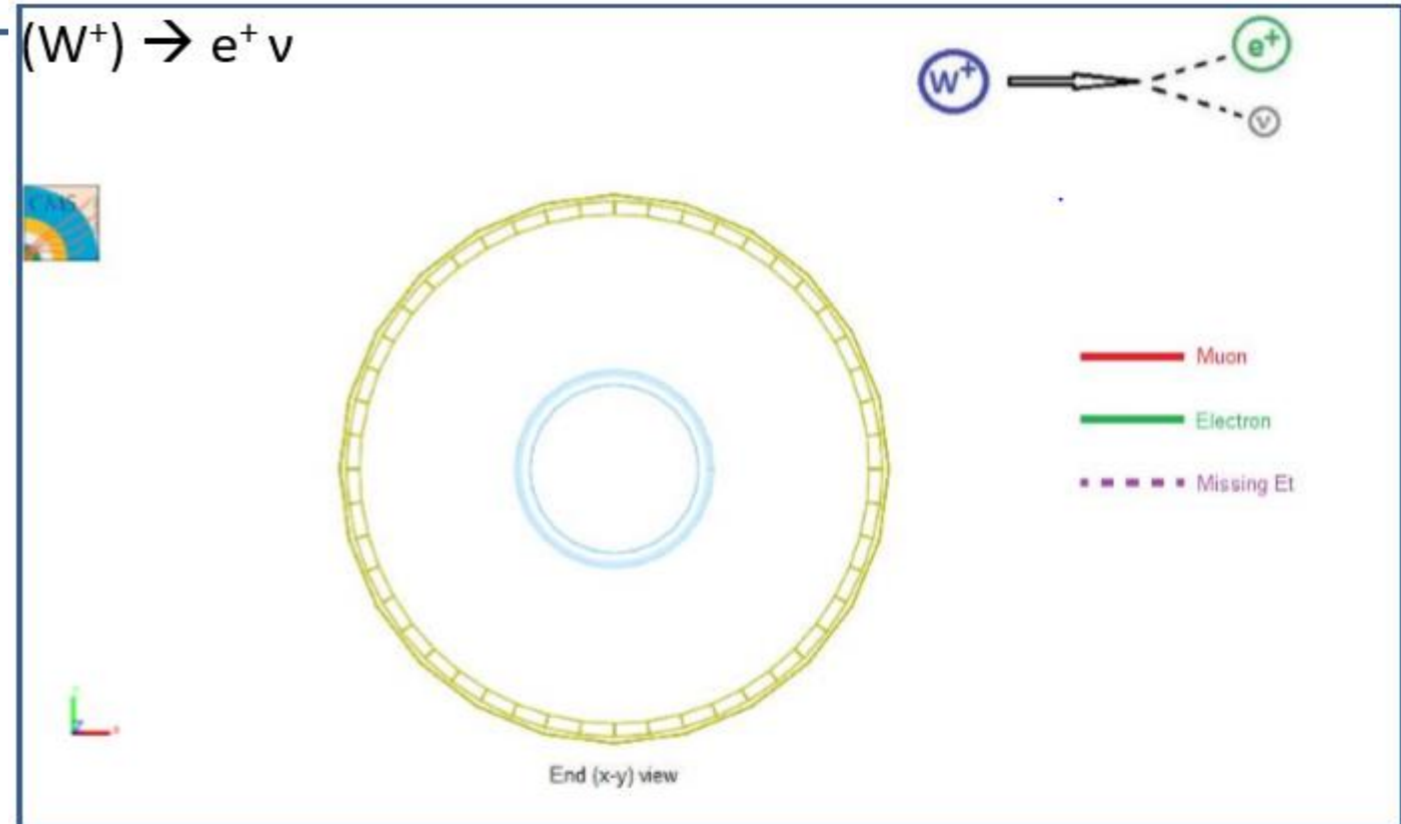
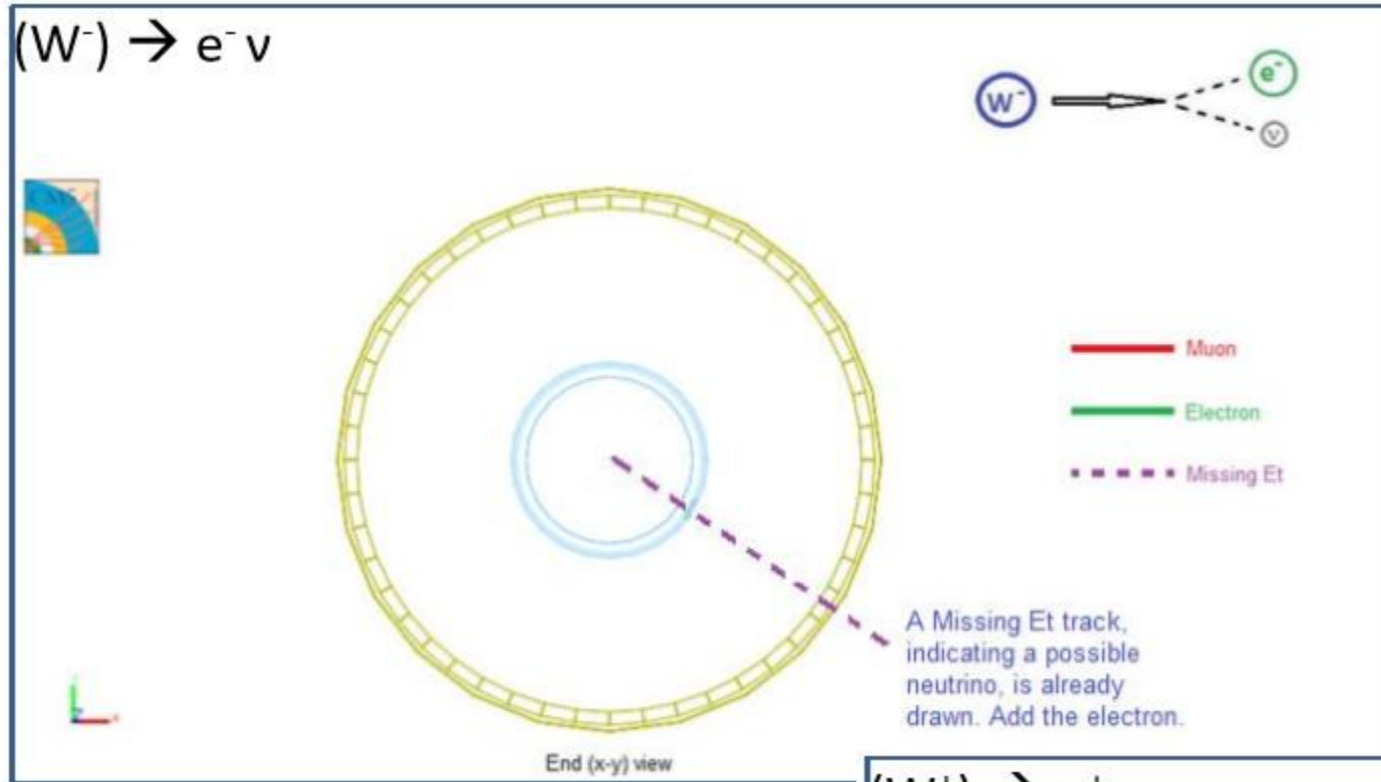
- Muon
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- - - - Missing Et

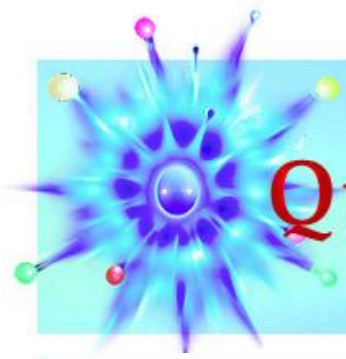
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QuarkNet

Sketch the tracks in CMS

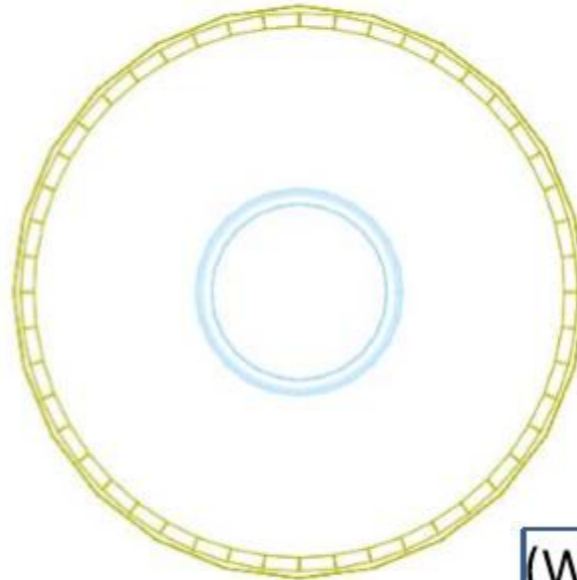




QuarkNet

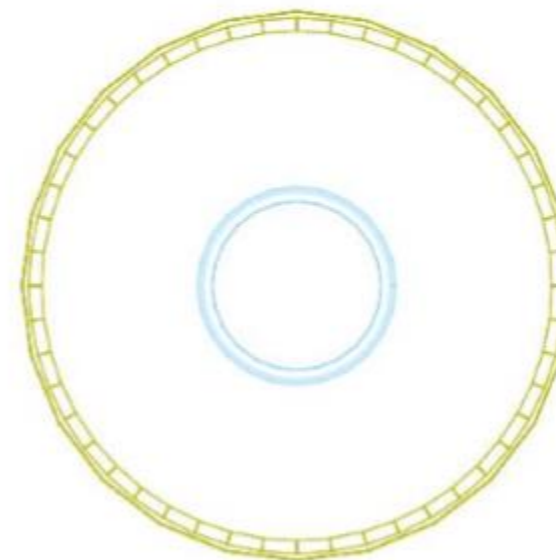
Sketch the tracks in CMS

$(W^+) \rightarrow \mu^+ \nu$

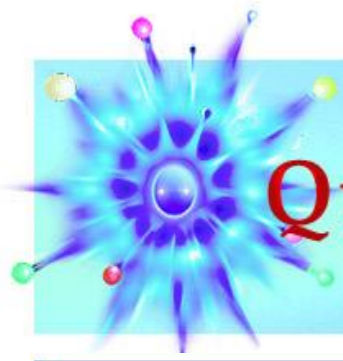


- Muon
- Electron
- - - Missing Et

$(W^-) \rightarrow \mu^- \nu$



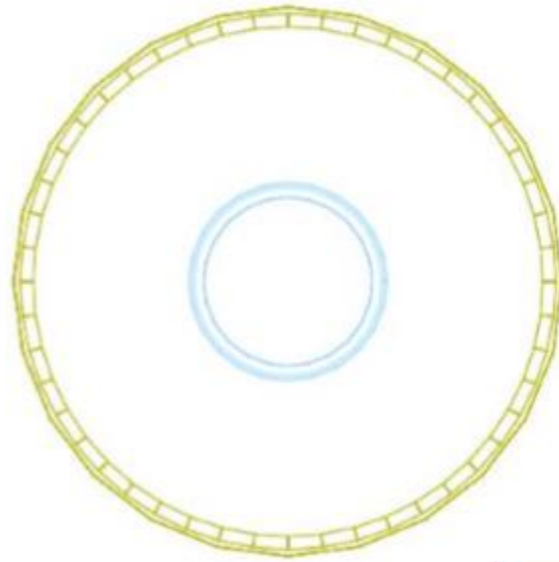
- Muon
- Electron
- - - Missing Et



QuarkNet

Sketch the tracks in CMS

$(H^0) \rightarrow (Z^0 Z^0) \rightarrow 4 \text{ leptons}$

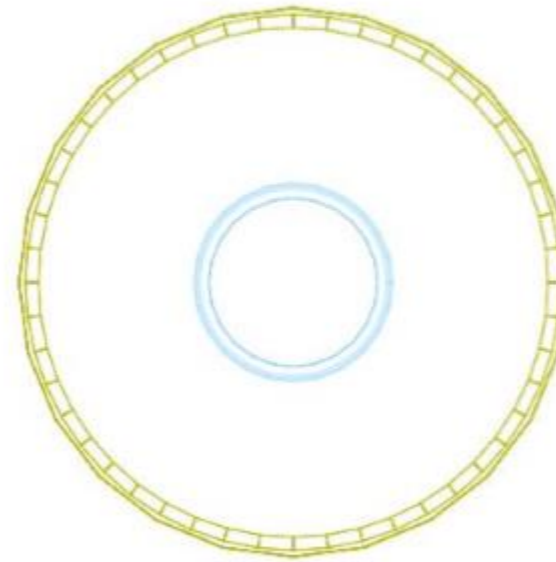


End (x-y) view



- Muon
- Electron
- - - Missing Et

$(H^0) \rightarrow \gamma\gamma$



End (x-y) view



- Muon
- Electron
- - - Missing Et