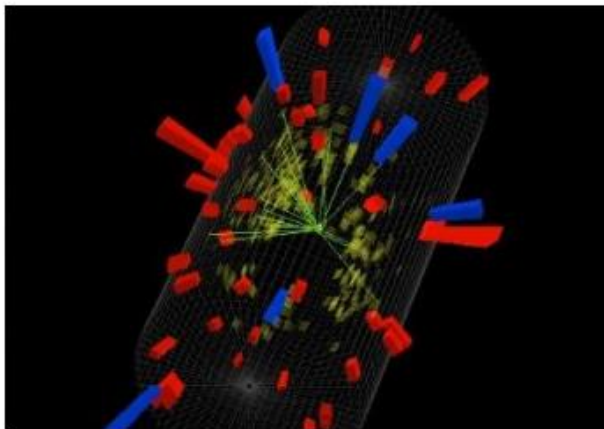
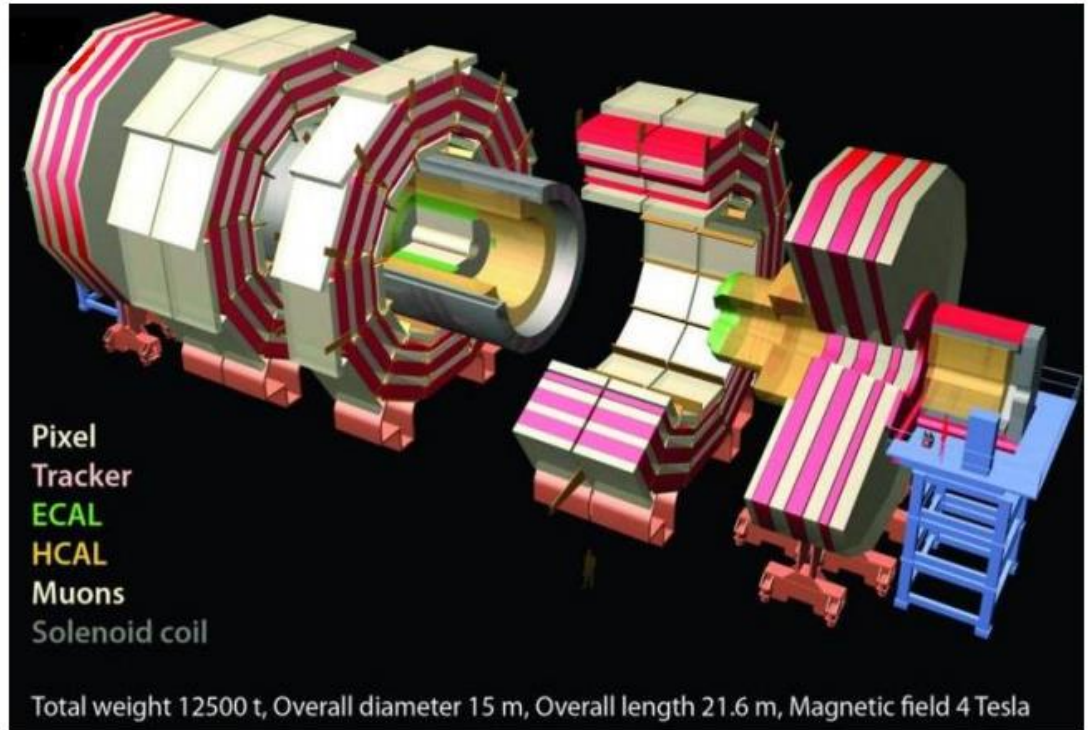


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# CMS WZH Masterclass



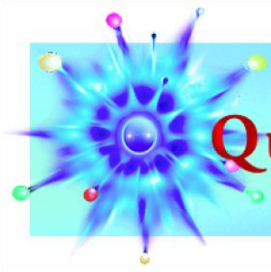
INTERNATIONAL  
**MASTERCLASSES**  
hands on particle physics



Fermilab



UNIVERSITY OF  
NOTRE DAME

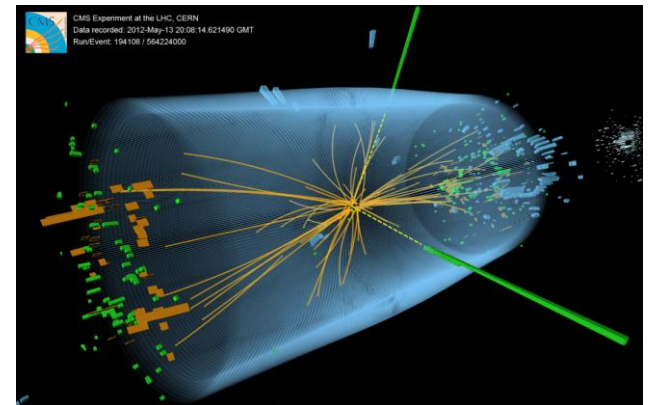


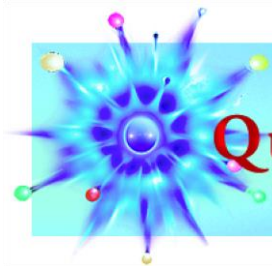
QuarkNet

# The LHC and the new physics

*It is a time of exciting new discoveries in particle physics.*

*The Large Hadron Collider at CERN has been operating for almost 10 years and had not only shed new light on the Standard Model but discovered new particles, including the cornerstone **Higgs boson**.*



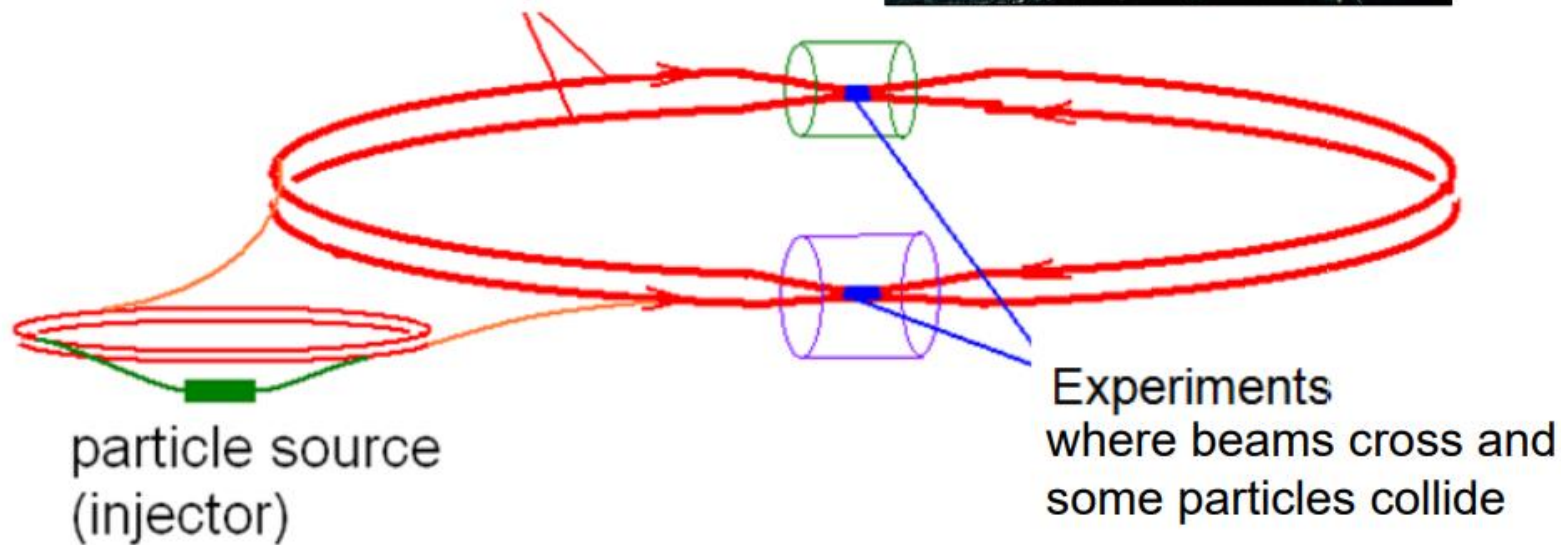


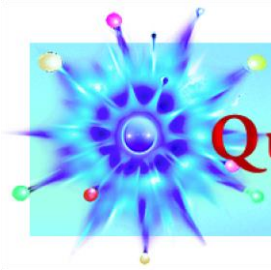
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# The LHC and the new physics

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

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





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# The LHC and the new physics

## Generic Design

Cylinders wrapped around the beam pipe

From inner to outer . . .

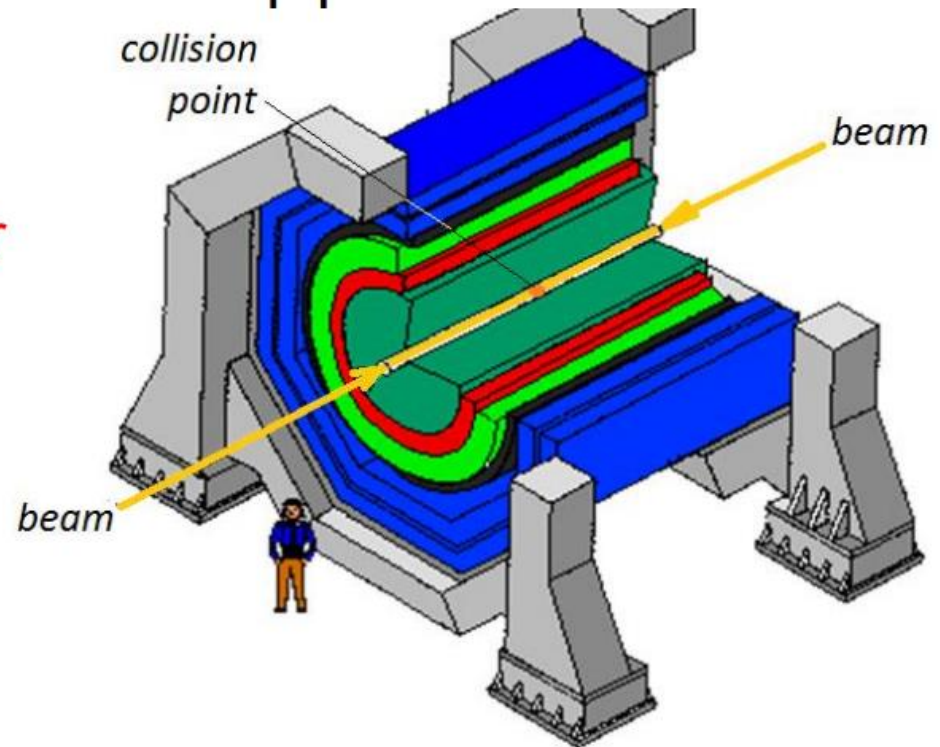
Tracking

Electromagnetic calorimeter

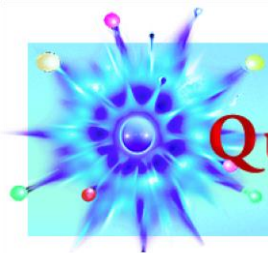
Hadronic calorimeter

Magnet\*

Muon chamber

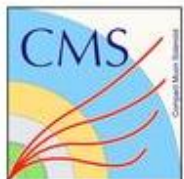


\* *location of magnet depends on specific detector design*



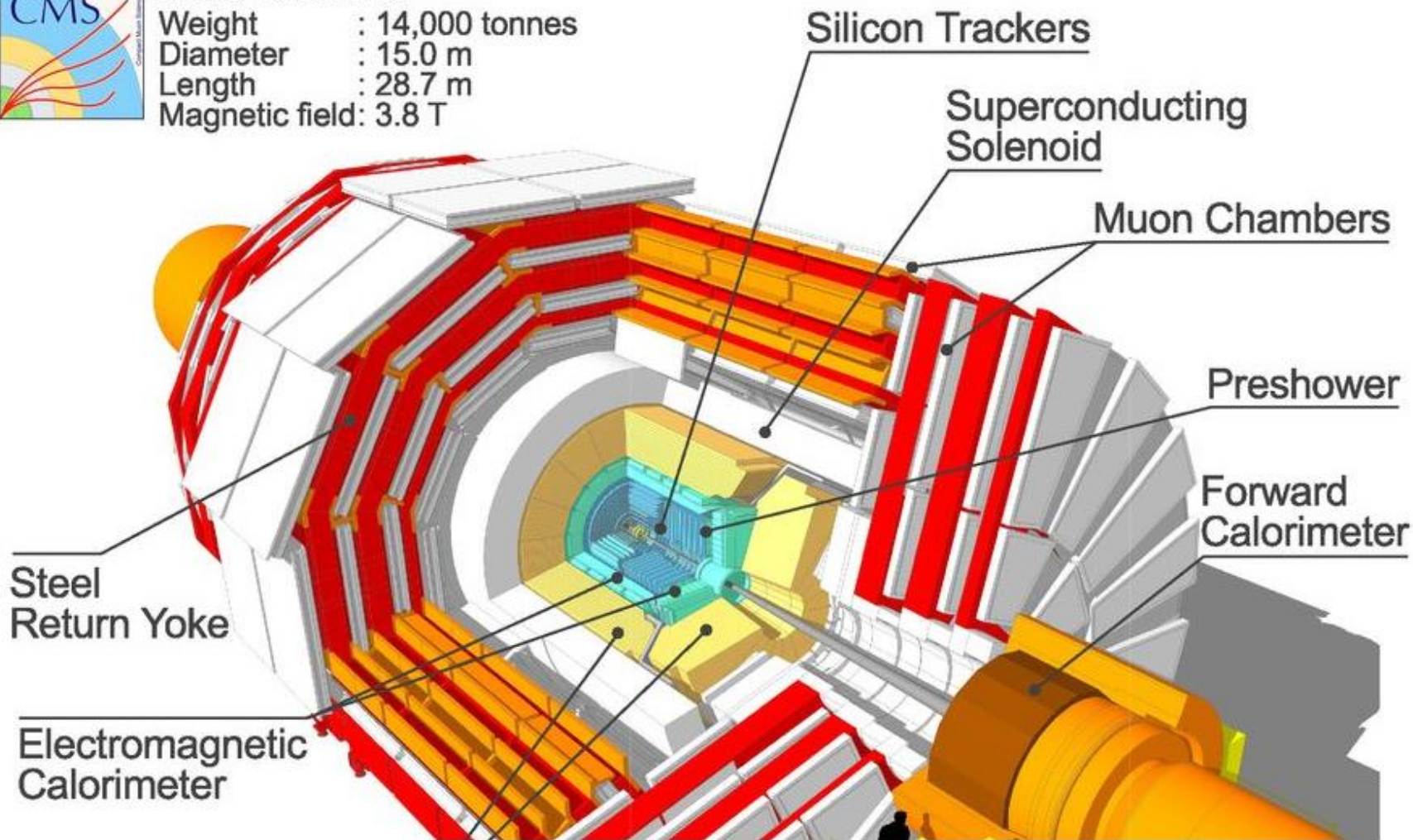
QuarkNet

# The Compact Muon Solenoid (CMS)

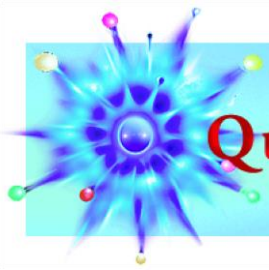


## CMS Detector

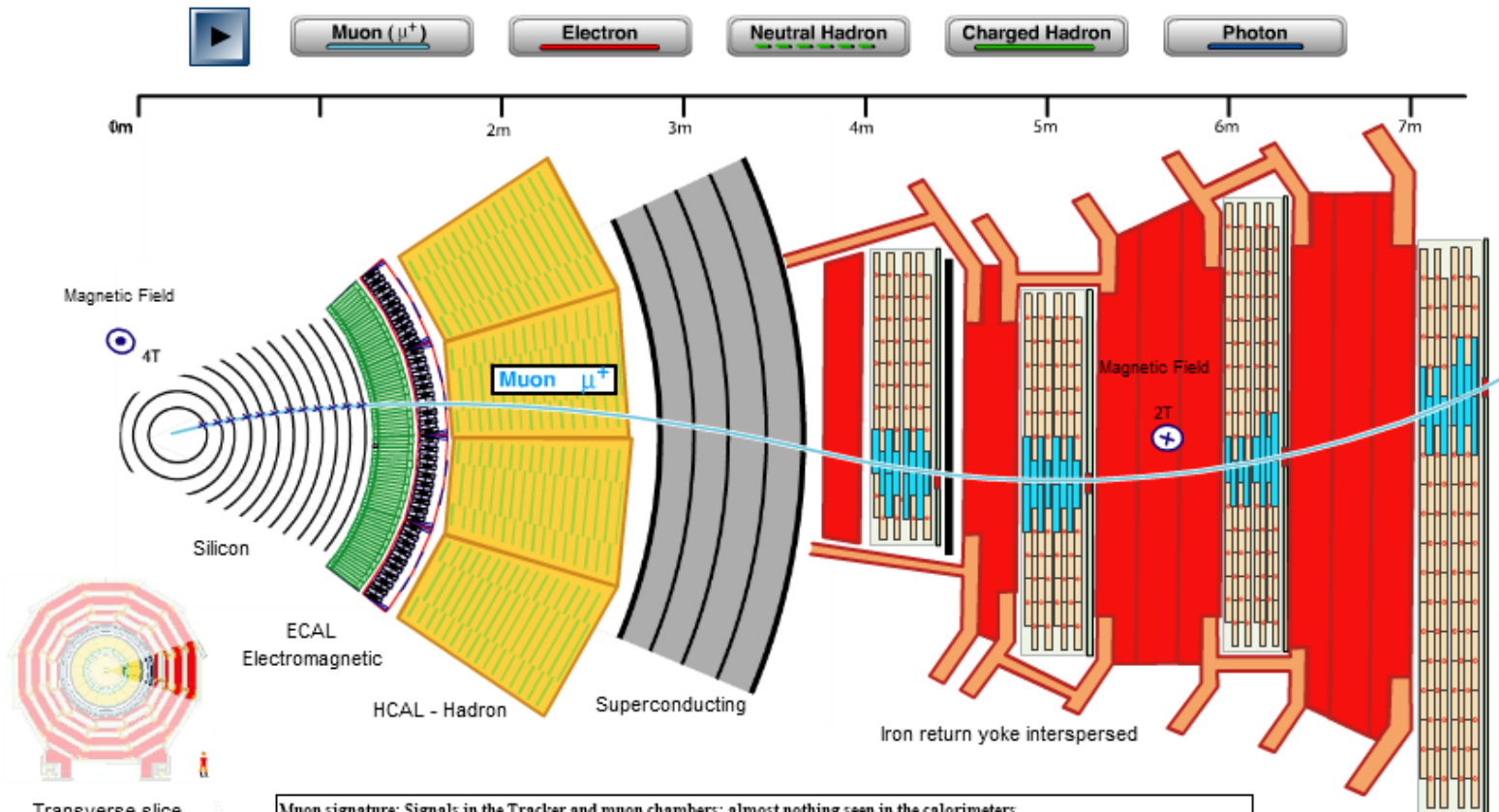
Weight : 14,000 tonnes  
Diameter : 15.0 m  
Length : 28.7 m  
Magnetic field: 3.8 T



[Let's take a closer look at the real thing.](#)



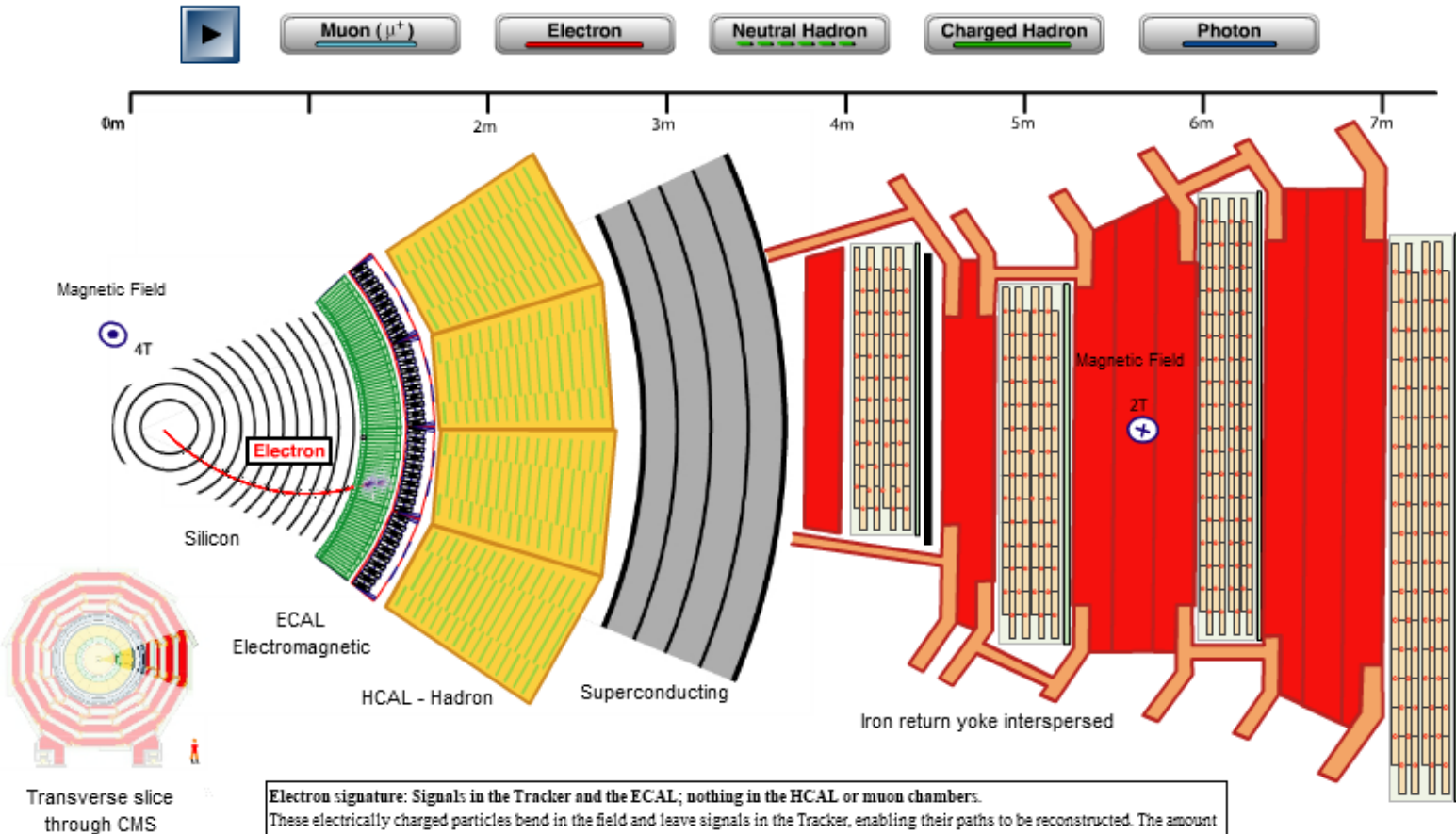
### Transverse Slice of the Compact Muon Solenoid (CMS) Detector



**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.

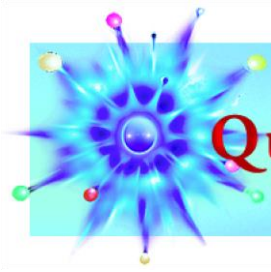
D. Barney, CERN, 2004

## 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  $0.3\alpha B$ , 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.

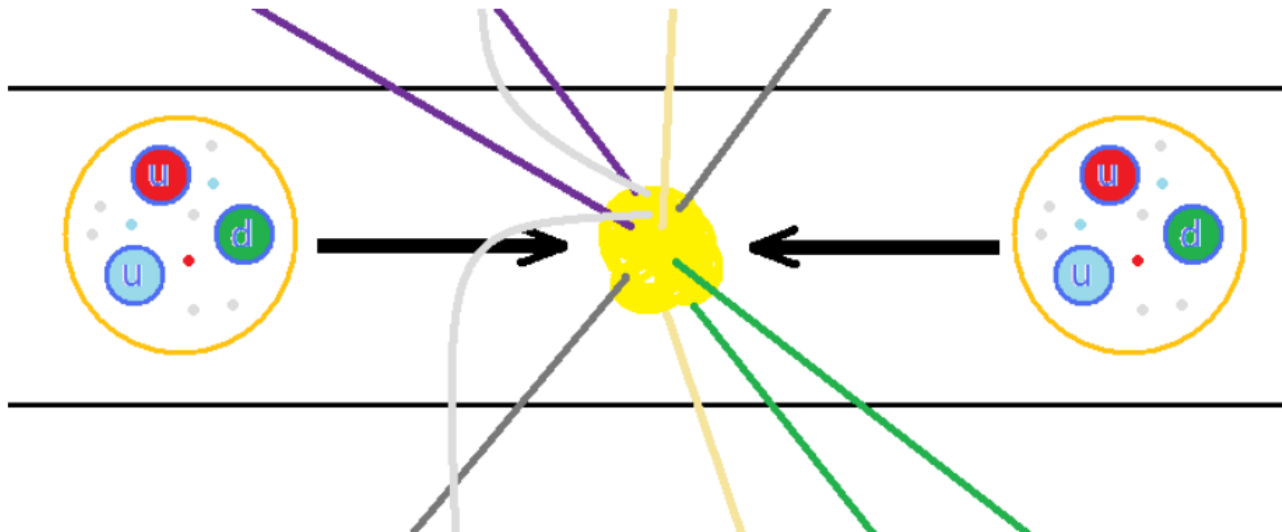


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# Protons collide inside CMS

The LHC accelerates protons to as much as 6500 times the energy equivalent of their mass. The protons circulate in opposite directions and collide in the center of CMS.

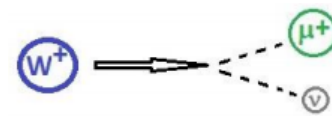
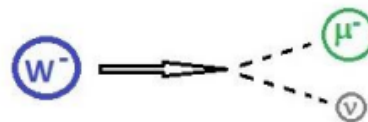
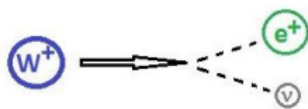
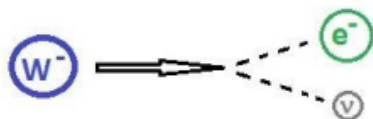
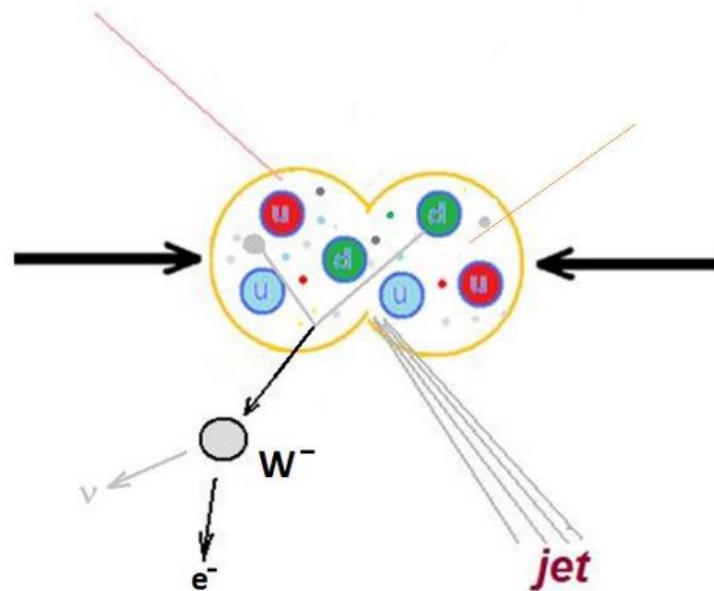
But protons are not just particles: they are more like bags of quarks and gluons. When they collide, *anything* can happen. And we are looking something specific.





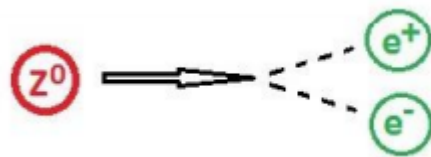
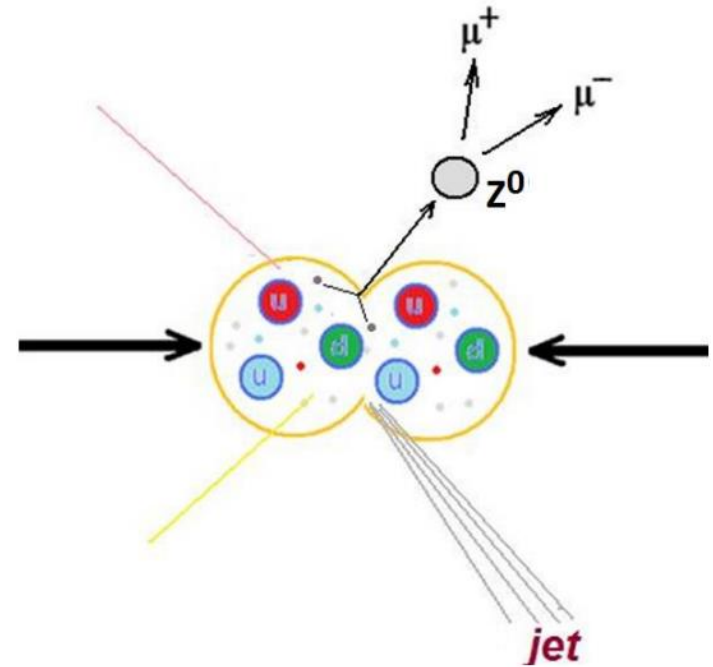
The + or – charged W boson enables radioactive decay by transforming neutrons into protons.

It decays into a neutrino and another lepton. Since CMS cannot detect the neutrino directly, we can call this a one-lepton event.



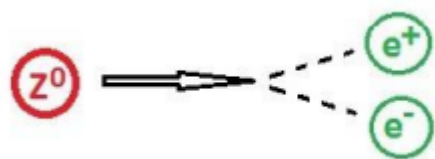
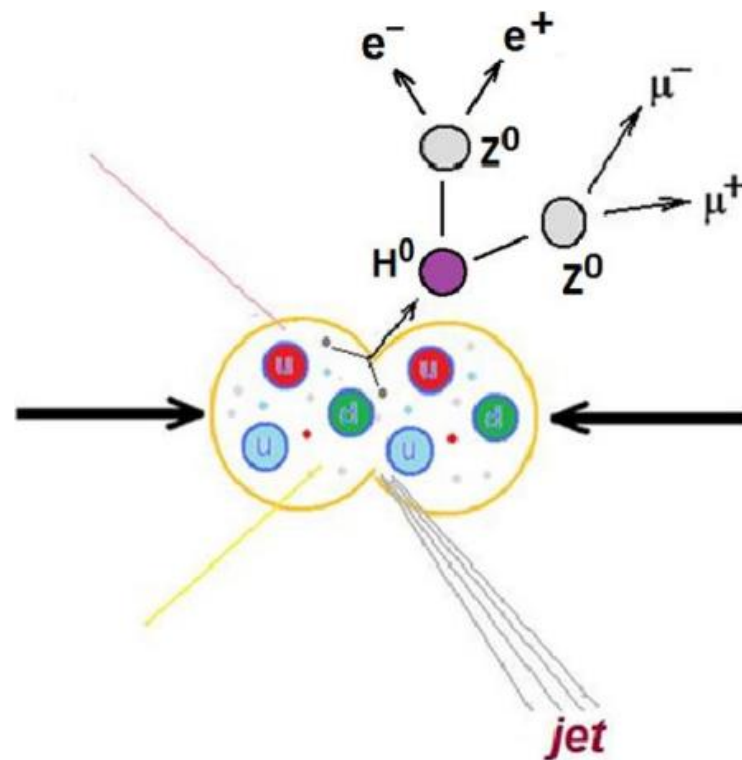
The Z boson is a neutral cousin of the W. It enables the “weak neutral current”.

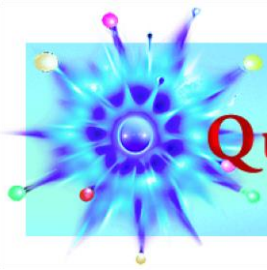
It decays into two leptons of the same type but opposite charge – electron and positron or muon and antimuon. It has other decay paths but we are not looking for these.



The Higgs boson is an expression of the field that gives other particles mass.

One decay mode of the Higgs is into two Z bosons, which themselves promptly decay. Thus we can get 2 muons and 2 electrons or 4 muons or 4 electrons.

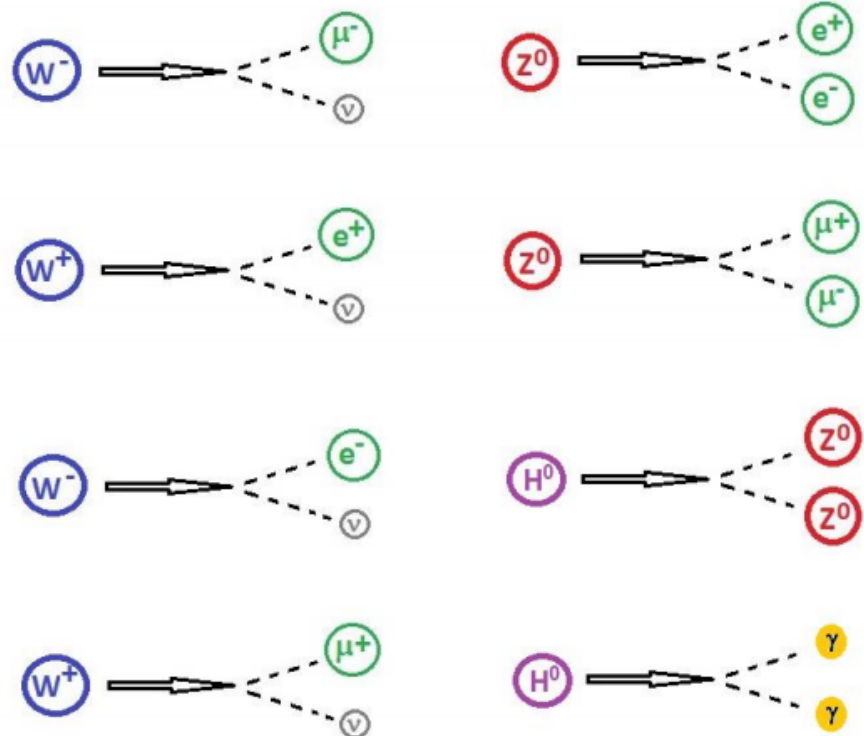




Because bosons only travel a tiny distance before decaying, CMS does not “see” them directly.

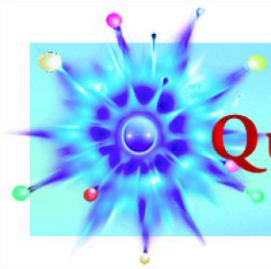
CMS *can* detect :

- electrons
- muons
- photons



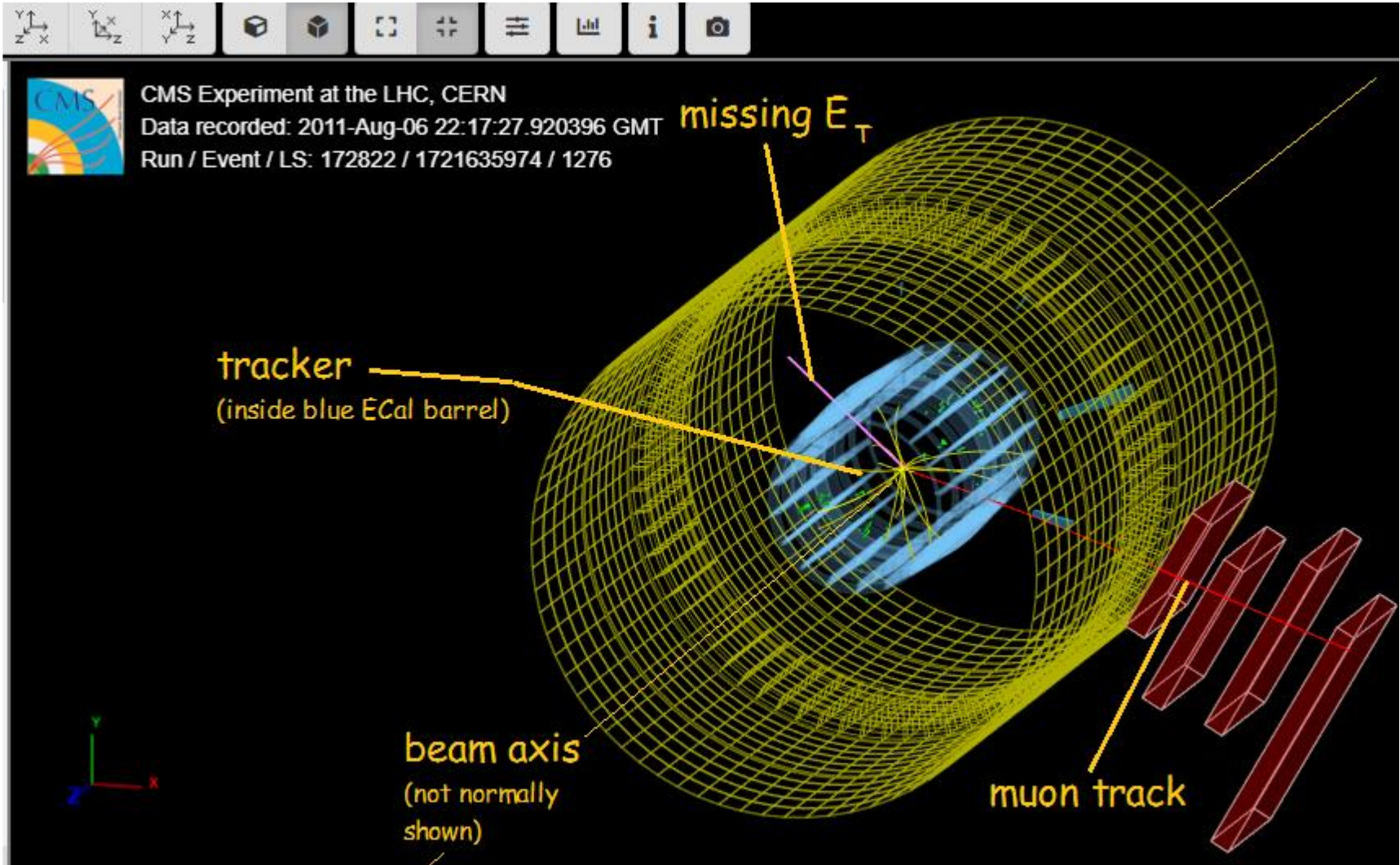
CMS can infer:

- neutrinos from “missing energy”



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# iSpy event display for CMS

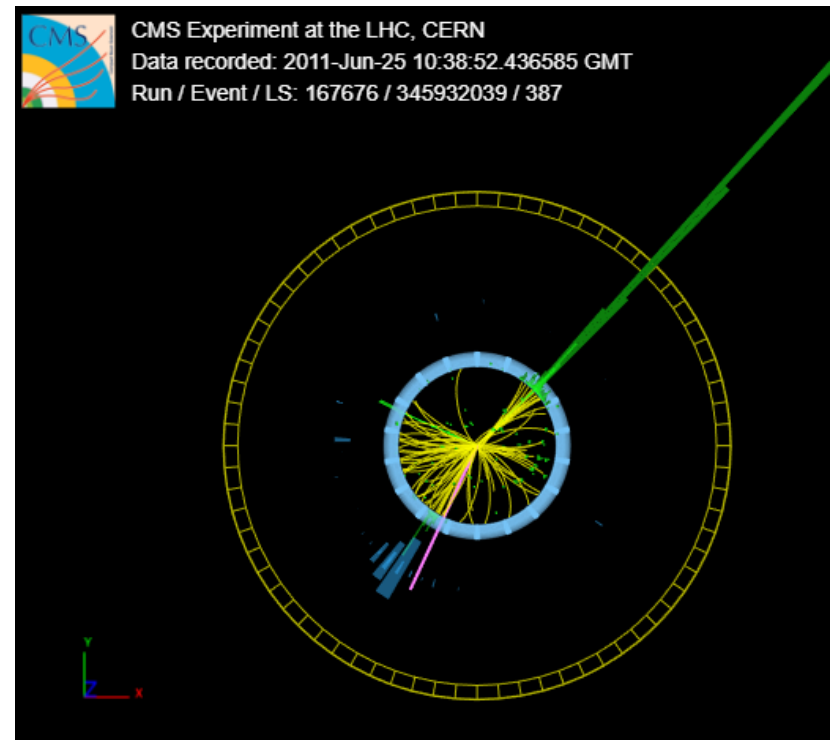
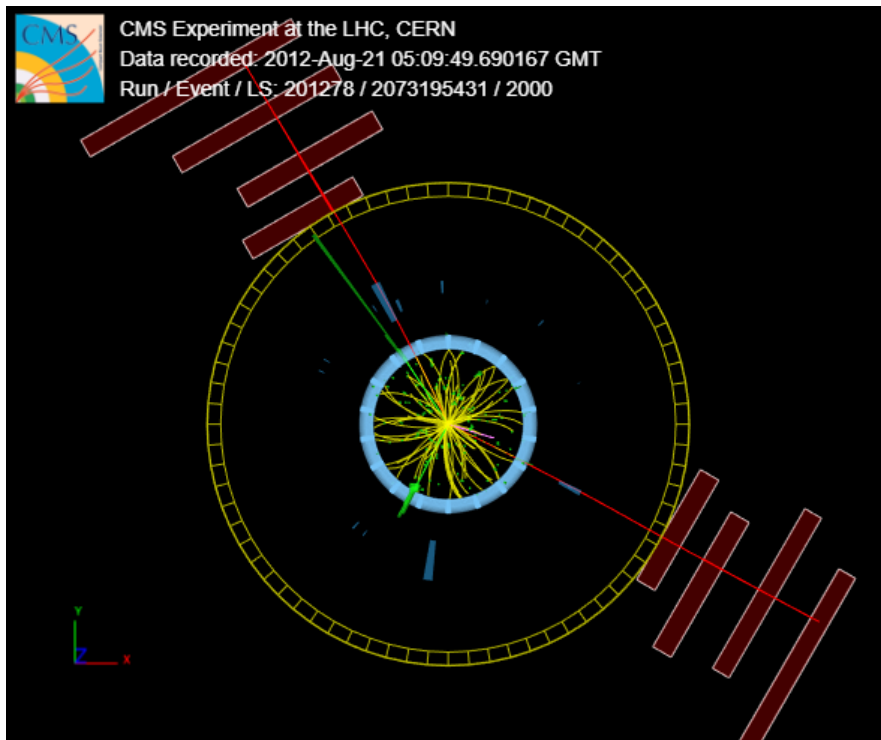


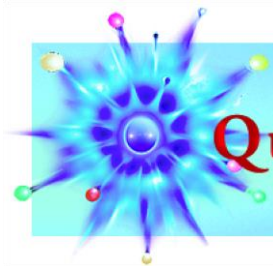


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# 1, 2, or 4 leptons?

Which of these events is 1-, 2-, or 4-lepton? Which flavors of leptons? What else do you see?

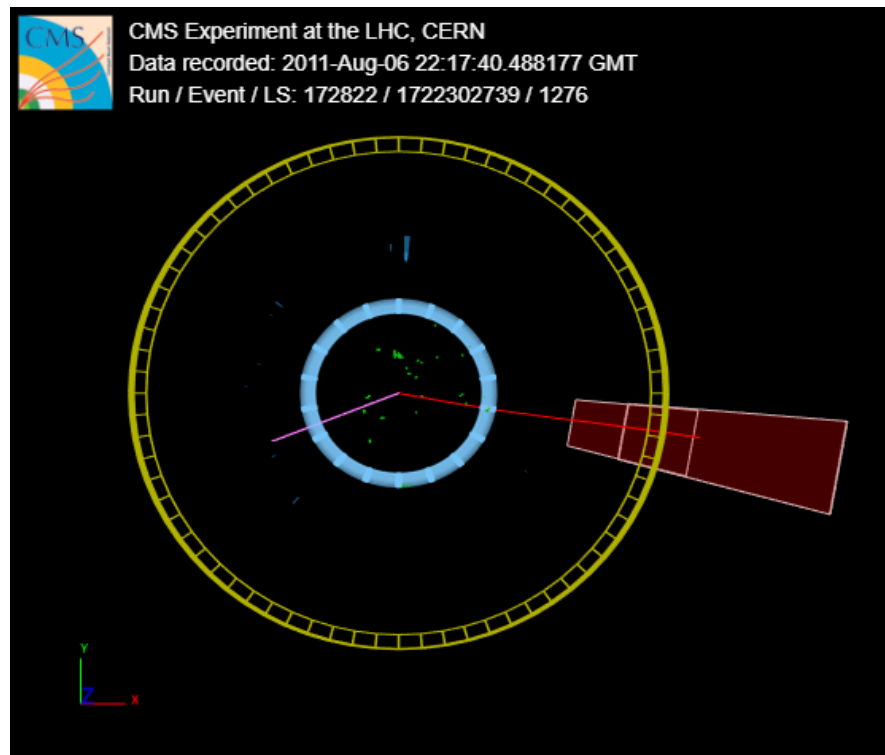
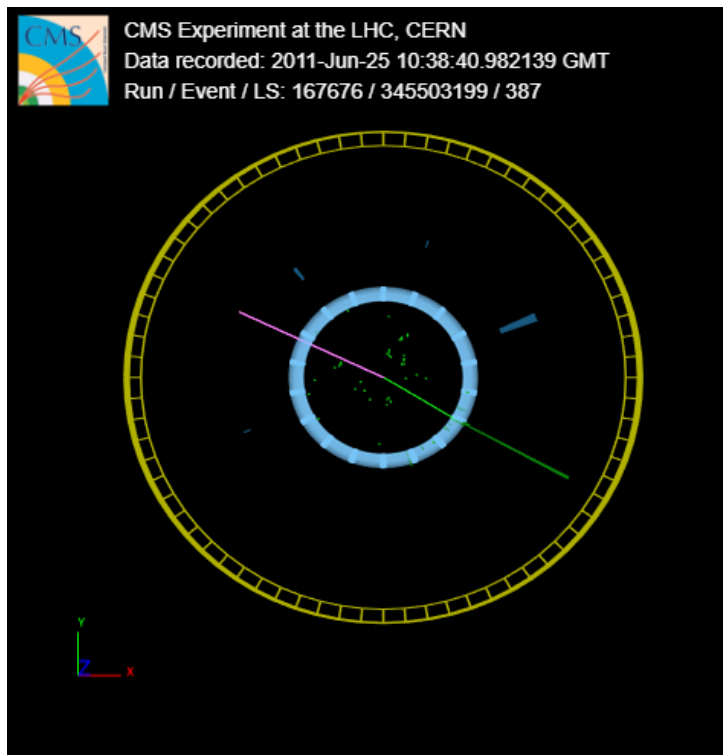


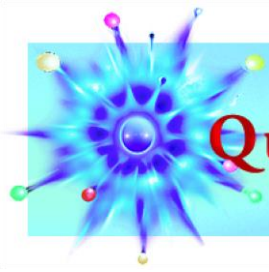


QuarkNet

# 1, 2, or 4 leptons?

**Which of these events is 1-, 2-, or 4-lepton? Which flavors of leptons? What else do you see?**

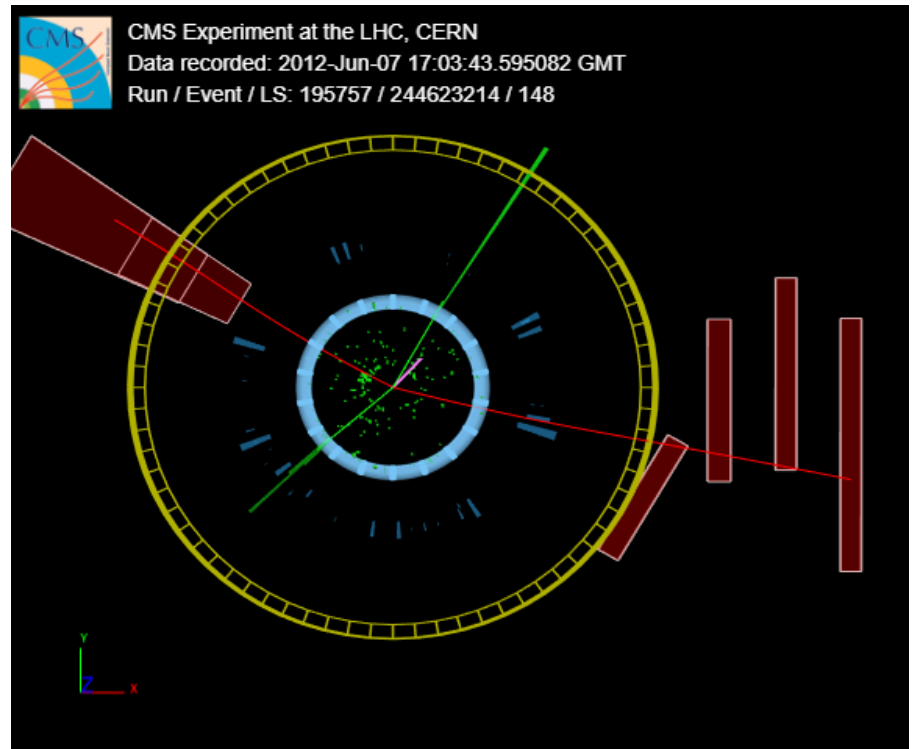
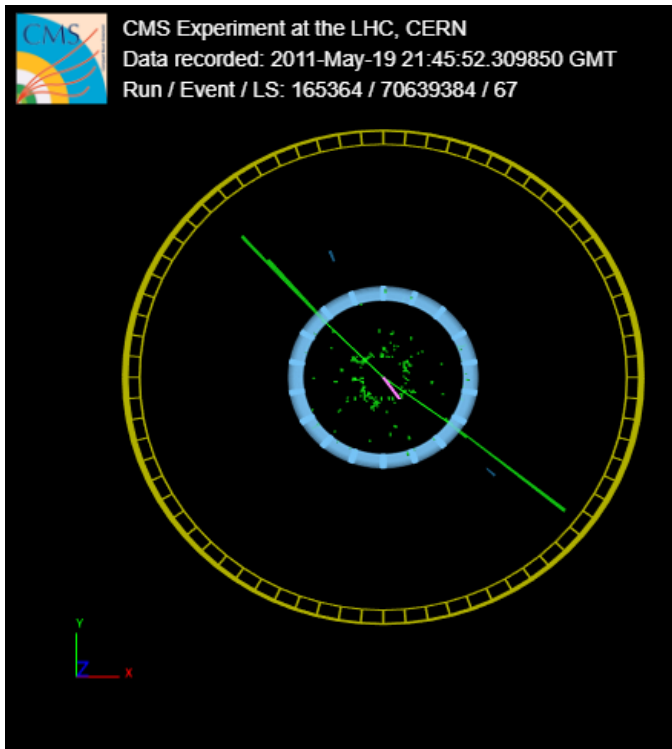




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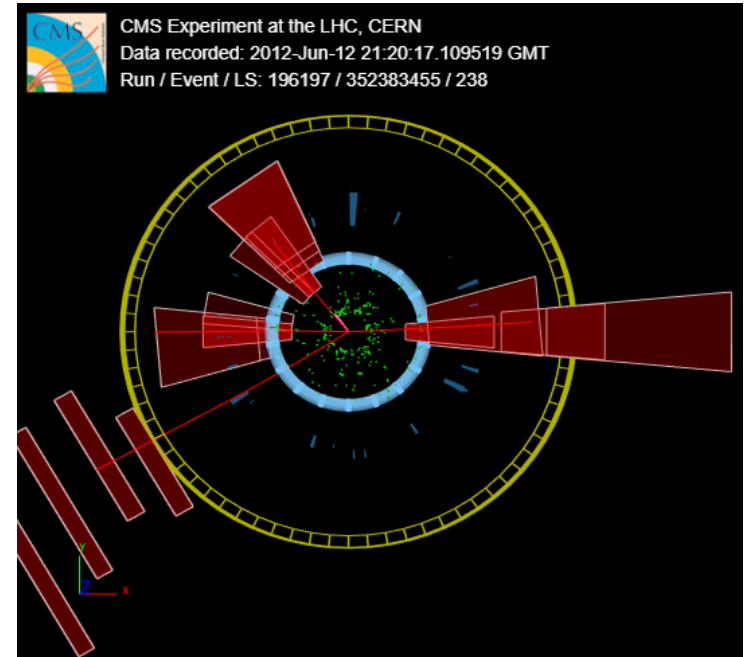
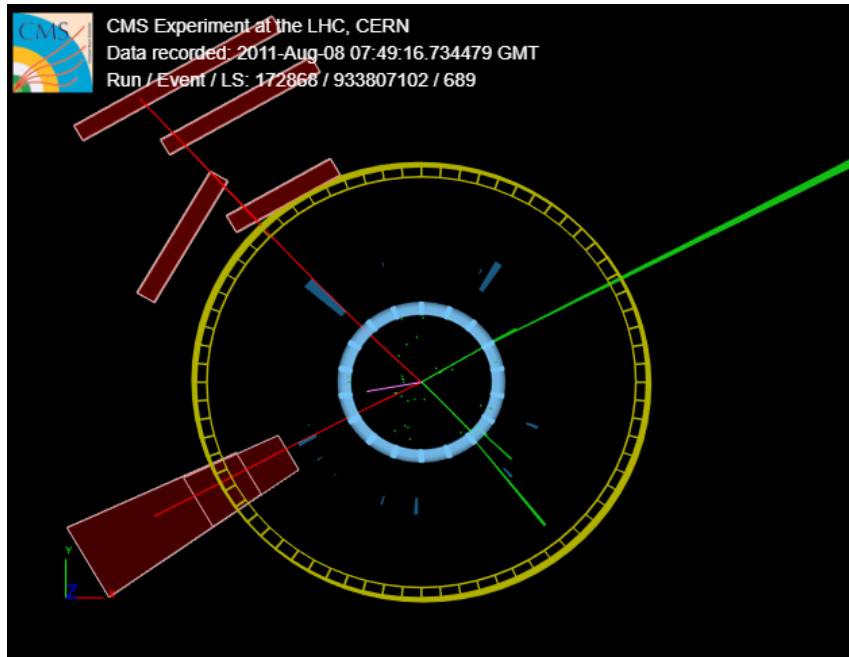
# 1, 2, or 4 leptons?

Which of these events is 1-, 2-, or 4-lepton? Which flavors of leptons? What else do you see?





Which of these events is 1-, 2-, or 4-lepton? Which flavors of leptons? What else do you see?





# CMS Instrument for Masterclass Analysis (CIMA)

## Enter data on each event:

Back Events Table (Group 1) Mass Histogram (Table01) Results (Table01)

→ Event Display

Masterclass: Event01

location: Table01

Group: 1

<b>Select Event</b> Event index: <input type="text" value="14"/> ▾ Event number: 1-14	<b>Final State</b> <input type="radio"/> e ν <input type="radio"/> μ ν <input type="radio"/> e e <input type="radio"/> μ μ <input type="radio"/> 4e <input type="radio"/> 4μ <input type="radio"/> 2e 2μ	<b>Primary State</b> Charged Particle: <input type="radio"/> W <sup>+</sup> <input type="radio"/> W <sup>-</sup> <input type="radio"/> W <sup>±</sup> <input type="radio"/> Neutral Particle (Z, H) <input type="radio"/> Zoo	<b>Enter Mass</b> <input type="text"/> GeV/c <sup>2</sup> <input type="button" value="Next"/>
---	--	---	---

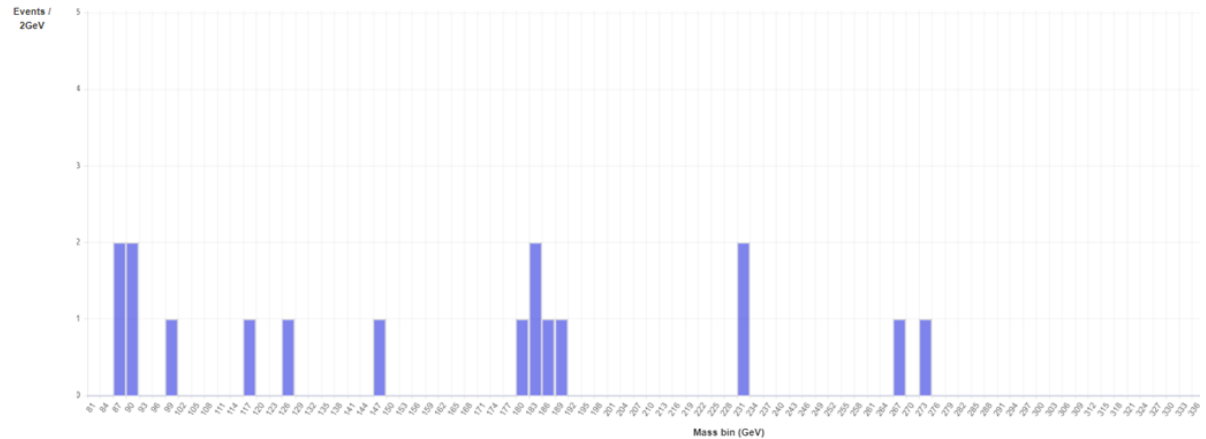
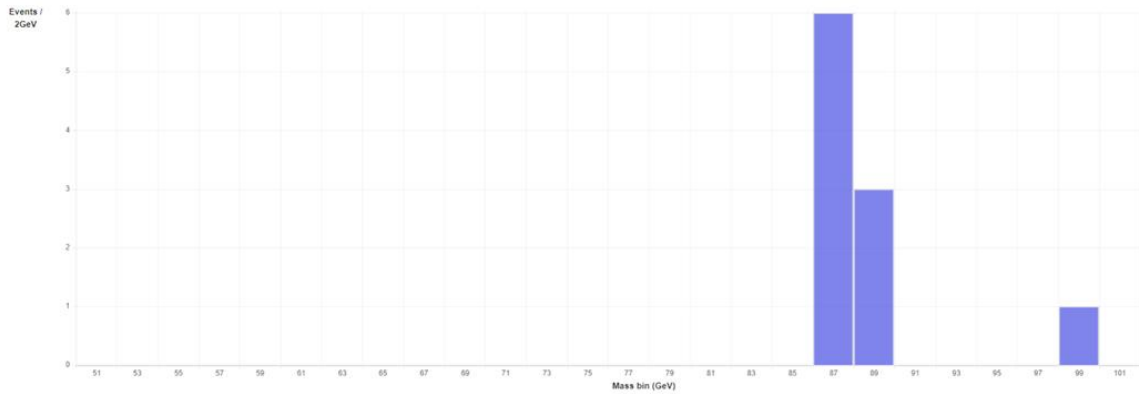
Event index	Event number	Final state	Primary state	Mass
13	1-13	μν	W <sup>±</sup>	



# CMS Instrument for Masterclass Analysis (CIMA)

## CIMA makes mass histograms automatically:

Masterclass: CUA-FIU-WM-6Aug2019  
location: FIU-Aug2019





# CMS Instrument for Masterclass Analysis (CIMA)

## CIMA tabulate data for key ratios:

Back Events Table (Group 21) Mass Histogram (FIU-Aug2019) Results (FIU-Aug2019)

Masterclass: CUA-FIU-WM-6Aug2019  
location: FIU-Aug2019

Group	e	$\mu$	W+	W-	W $\pm$	Neutral	Zoo	Total
21	26	32	21	21	0	13	0	55
22	41	46	24	38	1	16	1	80
23	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0
25	10	12	10	5	0	5	1	21

Total:

Group	e	$\mu$	W+	W-	W $\pm$	Neutral	Zoo	Total
All	77	90	55	64	1	34	2	156

Ratios:

e/ $\mu$	W+/W-
0.92	0.86



“Science is nothing but developed perception, interpreted intent, common sense rounded out and minutely articulated.” *George Santayana*

- Indirect observations and imaginative, critical, logical thinking can lead to reliable and valid inferences.
- Therefore: work together, think (sometimes outside the box), and be critical of each other's results to figure out what is happening.

**Form teams of two. Each team analyzes 100 events.**

**Talk with physicists about interpreting events. Pool results.**