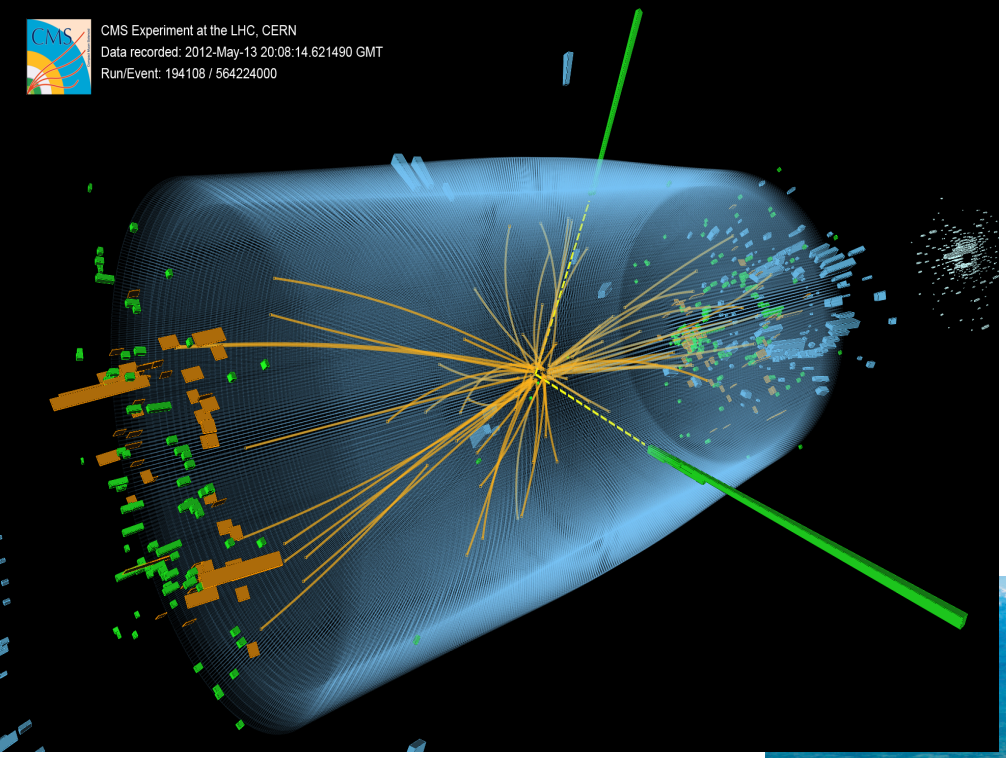
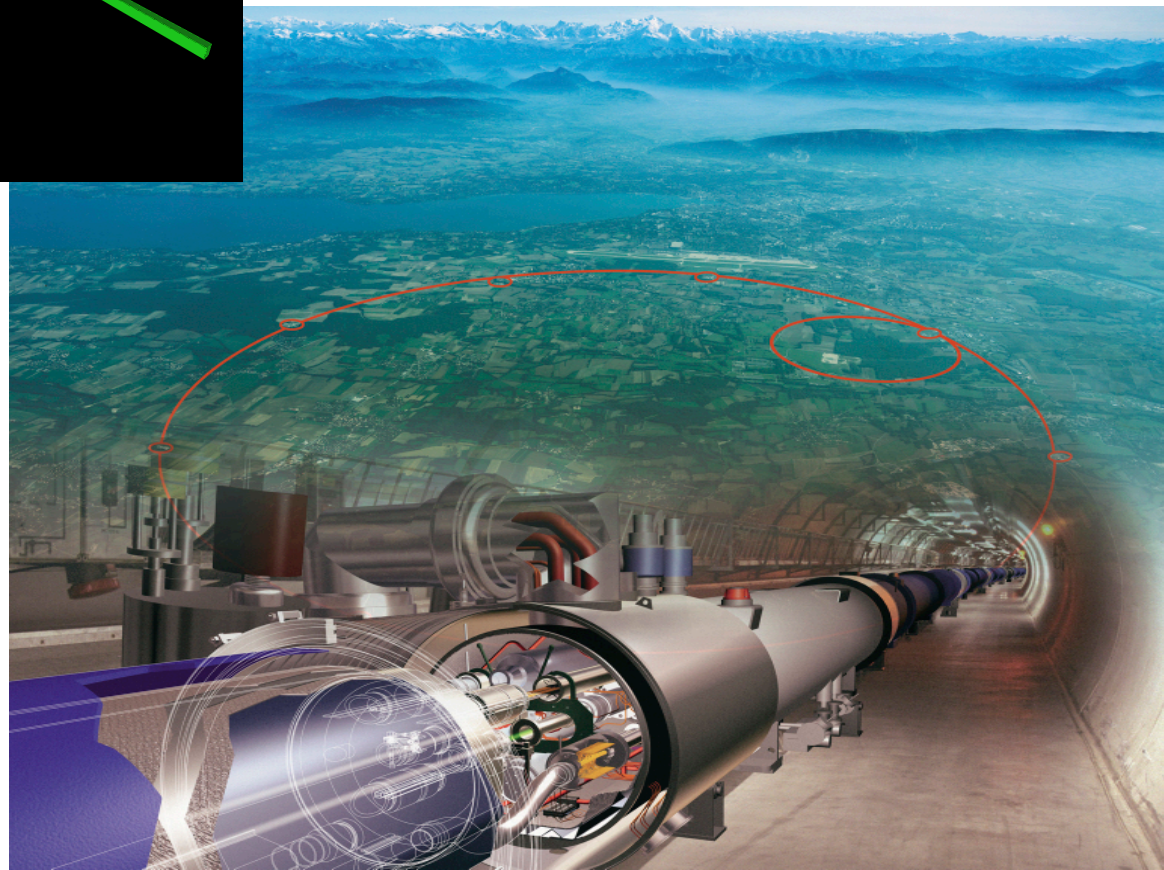


The Hunt for the Higgs Boson

- Why?
- How?
- Future?



Cecilia E. Gerber

University of Illinois-Chicago

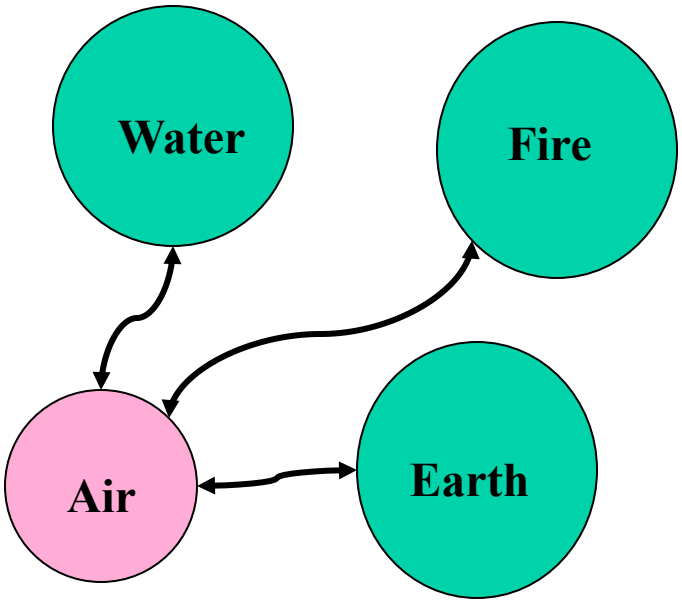


What is the World Made of?

Anaximenes of Miletus (6BC)



ELEMENTARY CONSTITUENTS

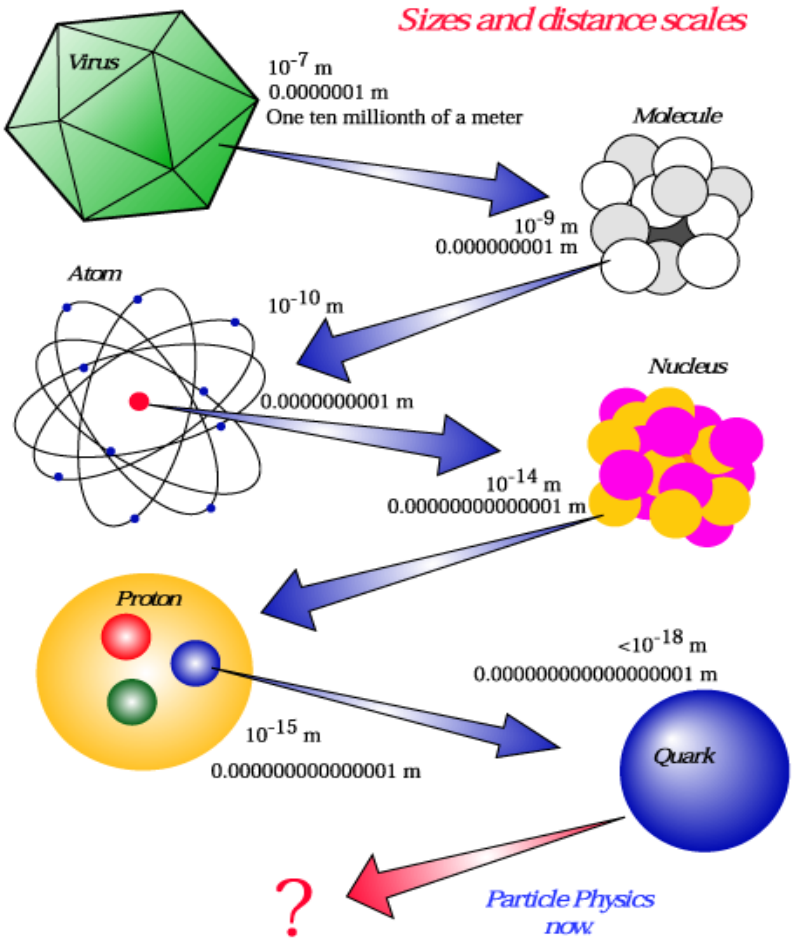


INTERACTIONS

"All forms of Matter are obtained from rarifying Air"

- Simple: few constituents and interactions.
- Wrong: No experimental confirmation.

What is the World made of?

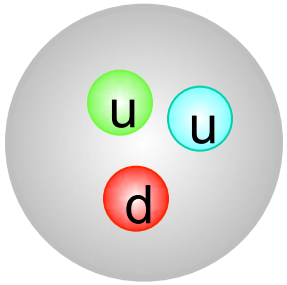


Periodic Table

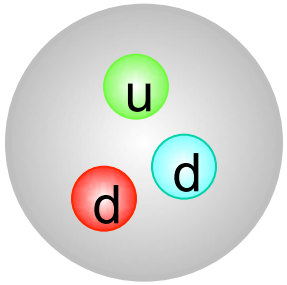
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub						

La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr

All atoms are made of protons, neutrons and electrons



Proton



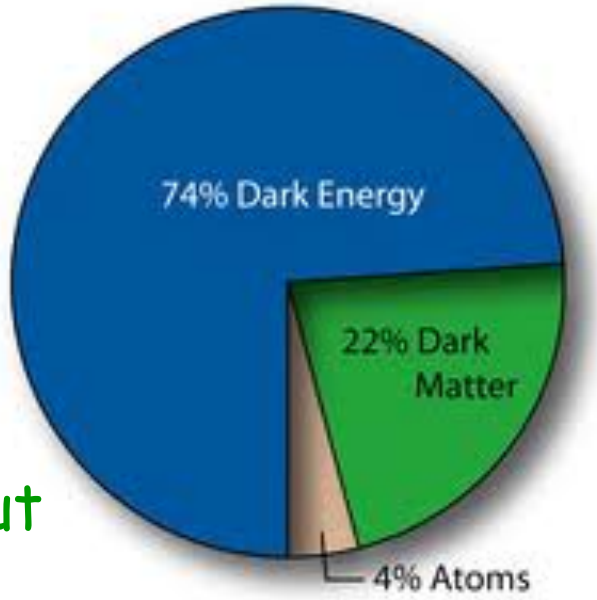
Neutron



Electron

Composition of the Universe

- Baryonic ("Normal") matter: ~ 4.4%
  - Inside stars: ~ 0.6%
  - Outside stars: ~ 3.8%
- Dark matter: ~ 22%
  - Mass that we infer to exist through its gravitational effects but that emits no detectable radiation.
- Dark energy: ~ 74%
  - An unknown form of energy that may be causing the expansion of the universe to accelerate with time.

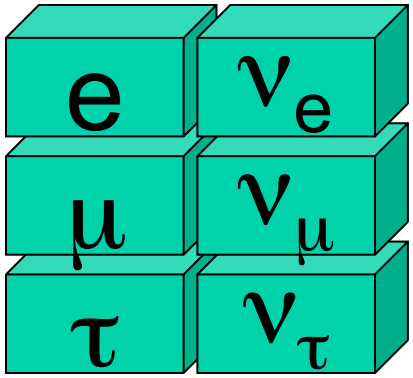


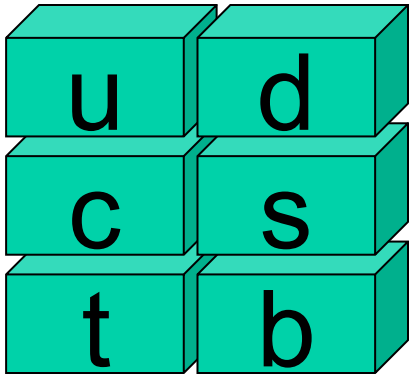
The vast majority of the universe is NOT composed of atoms!

What is the Normal Matter Made of?

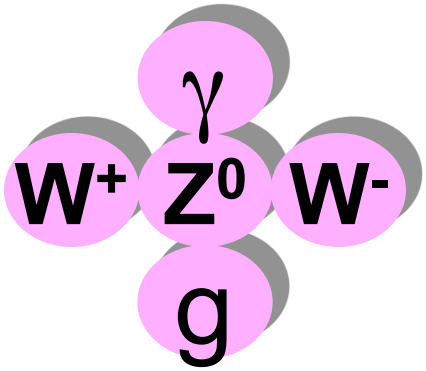
Standard Model (~1970)

ELEMENTARY CONSTITUENTS





INTERACTIONS



Higgs



Strong 1

Electromagnetic 10^{-2}

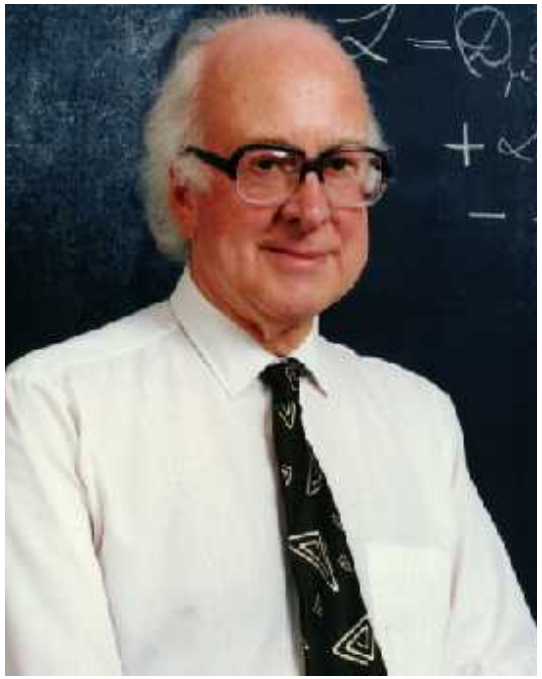
Weak 10^{-6}

Gravity 10^{-40}

The Higgs Boson

- In the simplest form of the SM, all fundamental particles have zero mass.
- However, fundamental particles do have mass. The top quark weighs as much as 170 protons (and is thought to have near-zero size.)
- In 1964, Peter Higgs postulated a physics mechanism which gives all particles their mass.
- This mechanism is a field which permeates the universe.

PLAY

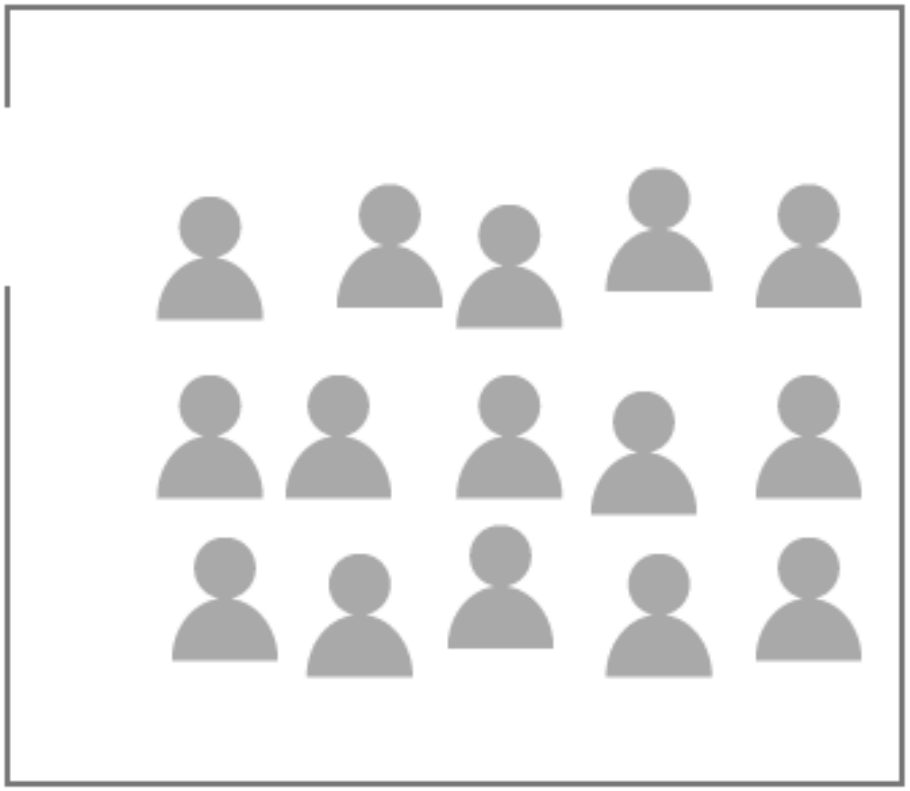


If this postulate is correct, then one of the signatures is a particle, called the *Higgs Boson.*

The Higgs Boson Explained

Former British science minister, William Waldegrave, offered a prize in 1993 for the best lay explanation of the Higgs boson. Professor David Miller, of University College, London, won the prize with the following analogy.

The Higgs Explained (1)



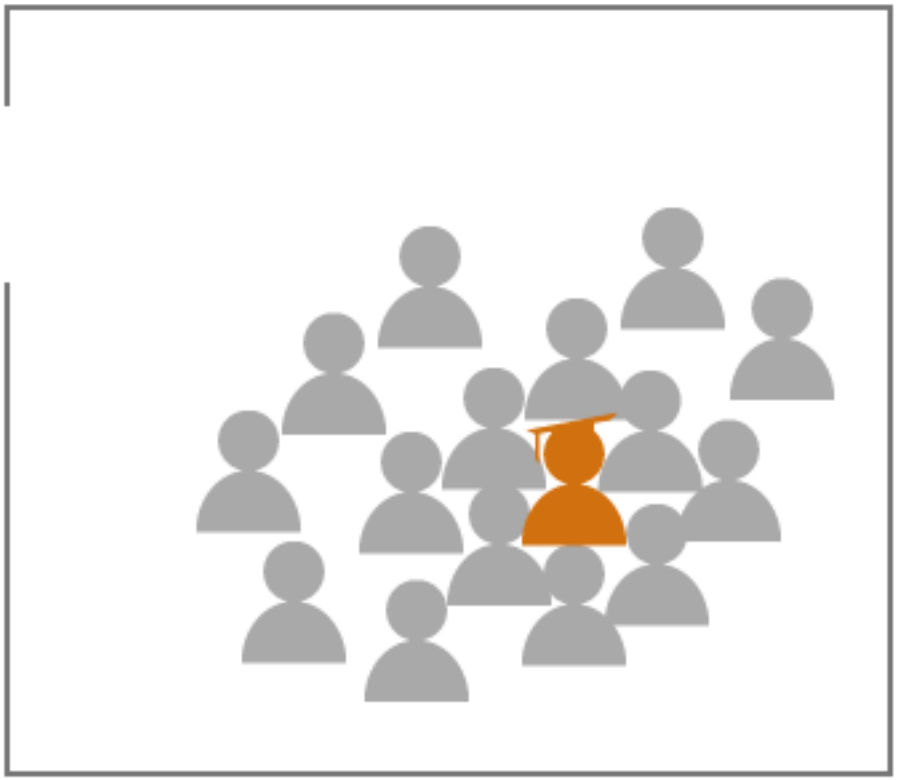
The "Higgs field" is shown here as a room of physicists chatting among themselves.

The Higgs Explained (2)



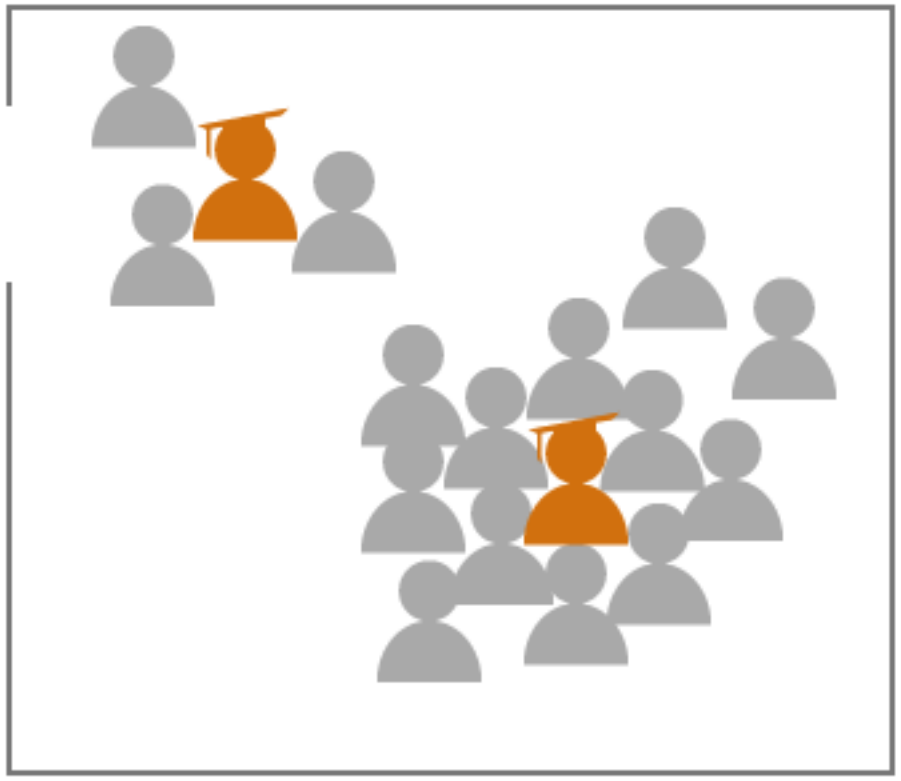
A well-known scientist walks into the room and causes a bit of a stir - attracting admirers with each step and interacting strongly with them - signing autographs and stopping to chat.

The Higgs Explained (3)



As she becomes surrounded by admiring fans, she finds it harder to move across the room - in this analogy, she acquires mass due to the "field" of fans, with each fan acting like a single Higgs boson.

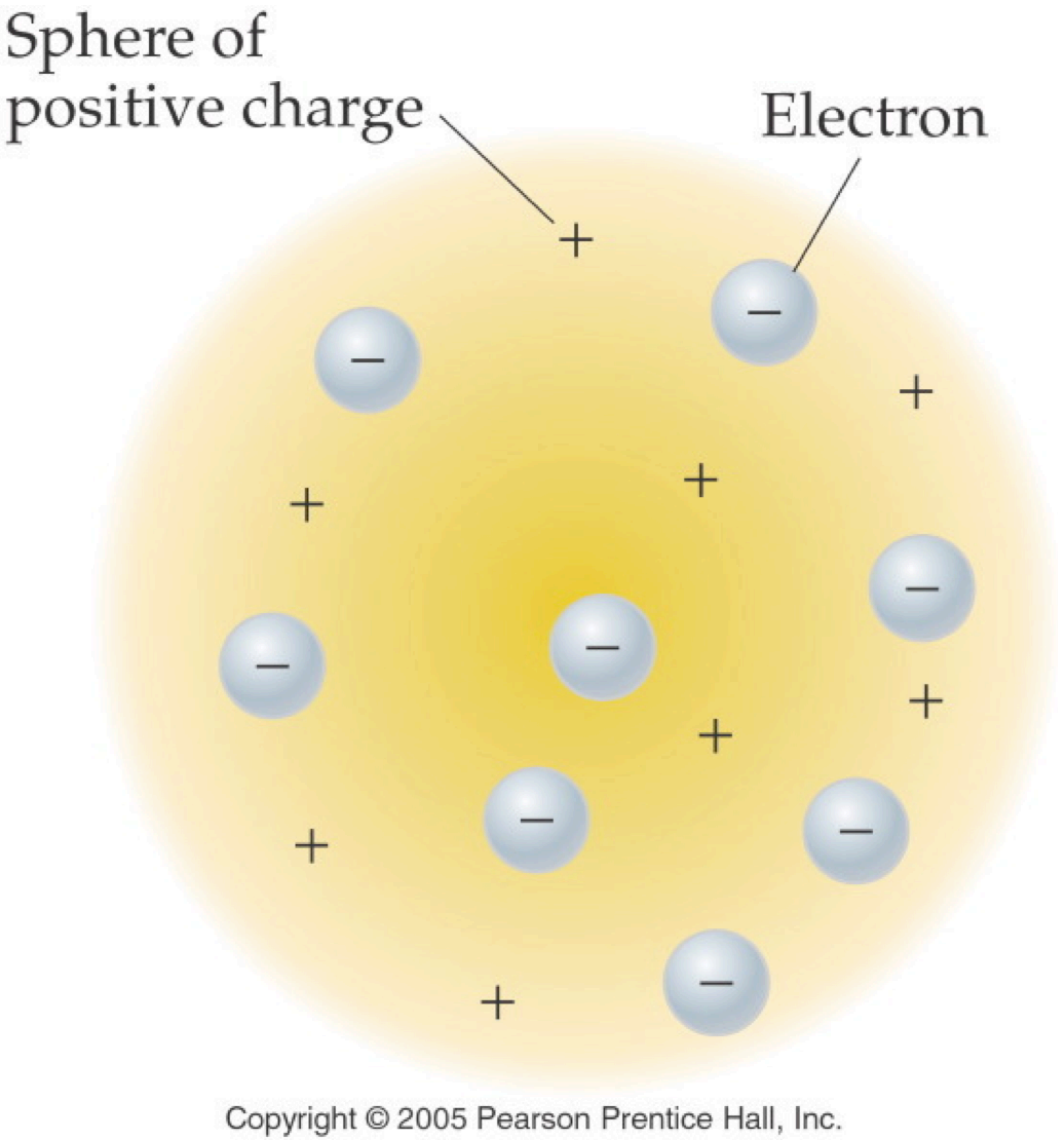
The Higgs Explained (4)



Source: Cern/UCL

If a less popular scientist enters the room, only a small crowd gathers, with no-one clamoring for attention. He finds it easier to move across the room - by analogy, his interaction with the bosons is lower, and so he has a lower mass.

Experimental Methods



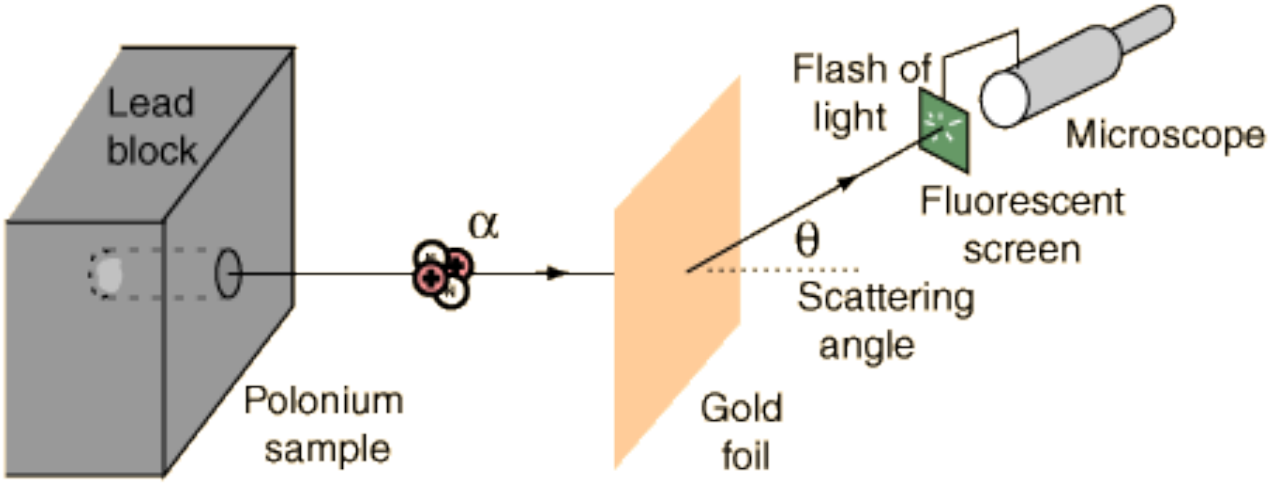
Copyright © 2005 Pearson Prentice Hall, Inc.

1897 Thomson discovered the electron and formulated the plum-pudding model for the atom



Rutherford Scattering

Alpha particles were allowed to strike a thin gold foil. Surprisingly, alpha particles were found at large deflection angles and ~1 in 8000 were even found to be back-scattered.

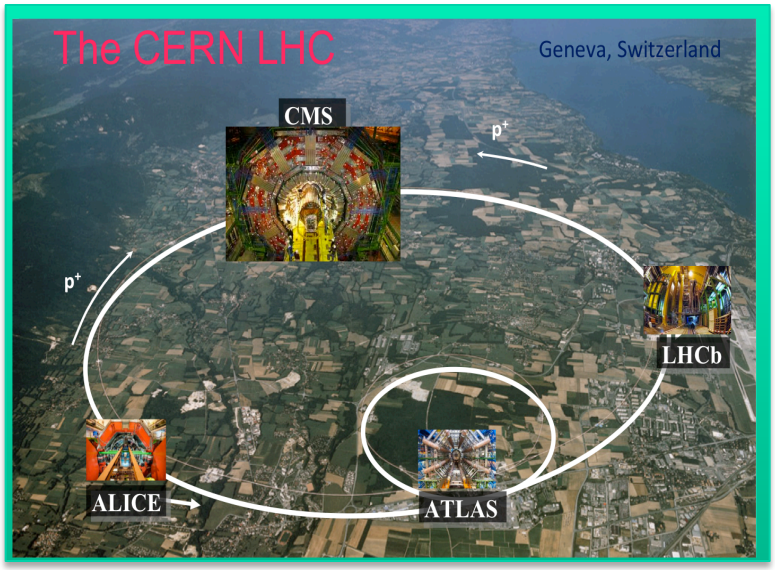


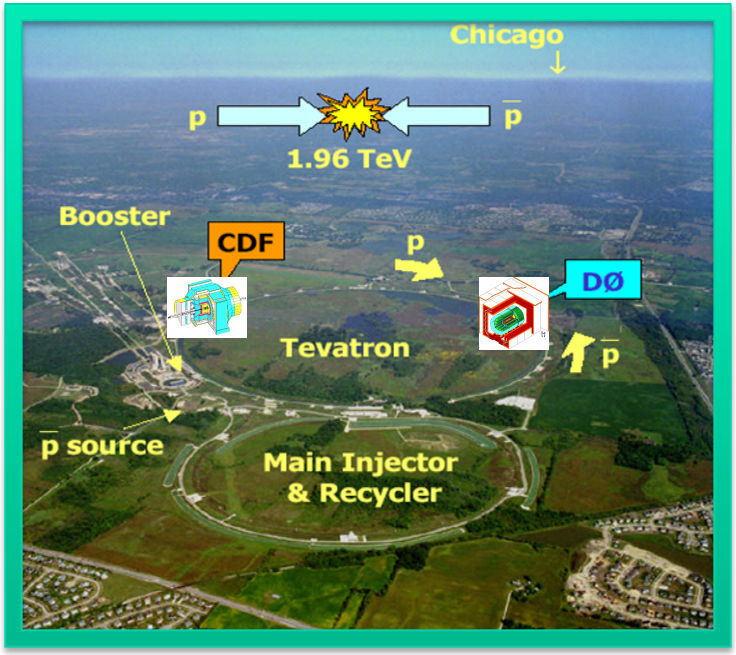
This experiment showed that the positive matter in atoms was concentrated in an incredibly small volume (10^{-13}cm) and gave birth to the idea of the nuclear atom.

Hadron Colliders = Discovery Machines

CERN LHC: pp

- 2010 $\sqrt{s}$=7 TeV, 36pb^{-1}
- 2011 $\sqrt{s}$=7 TeV, 5fb^{-1}
- 2012 $\sqrt{s}$=8 TeV, 20fb^{-1}
- Upgrade to 14 TeV in 2015

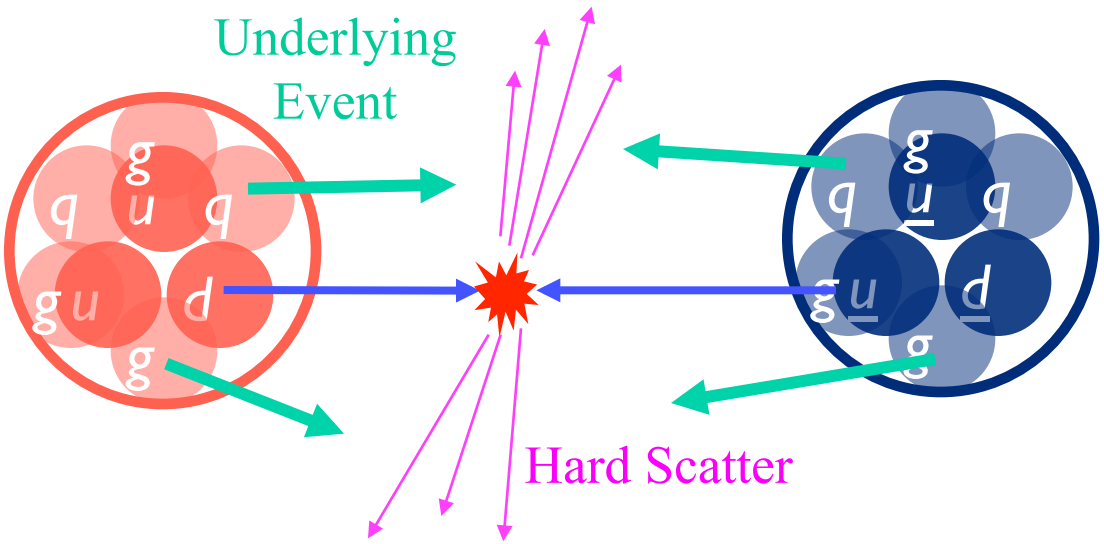


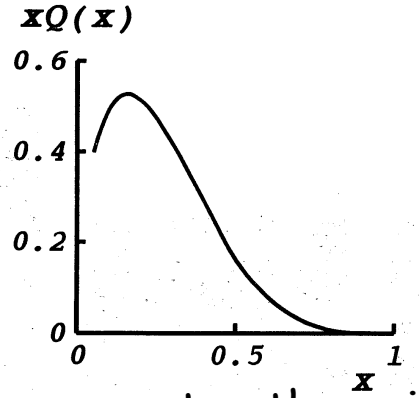


Fermilab Tevatron: p anti-p

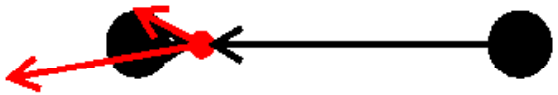
- 1992-96 $\sqrt{s}$=1.8TeV, 100pb^{-1}
- 2001-11 $\sqrt{s}$=1.96TeV, 10fb^{-1}
- Stopped operating Sep 30, 2011

Hadron-Hadron collisions in a nutshell

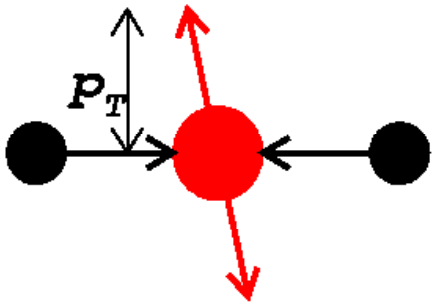




For every proton there is a probability that a single parton carries a fraction "x" of the proton momentum

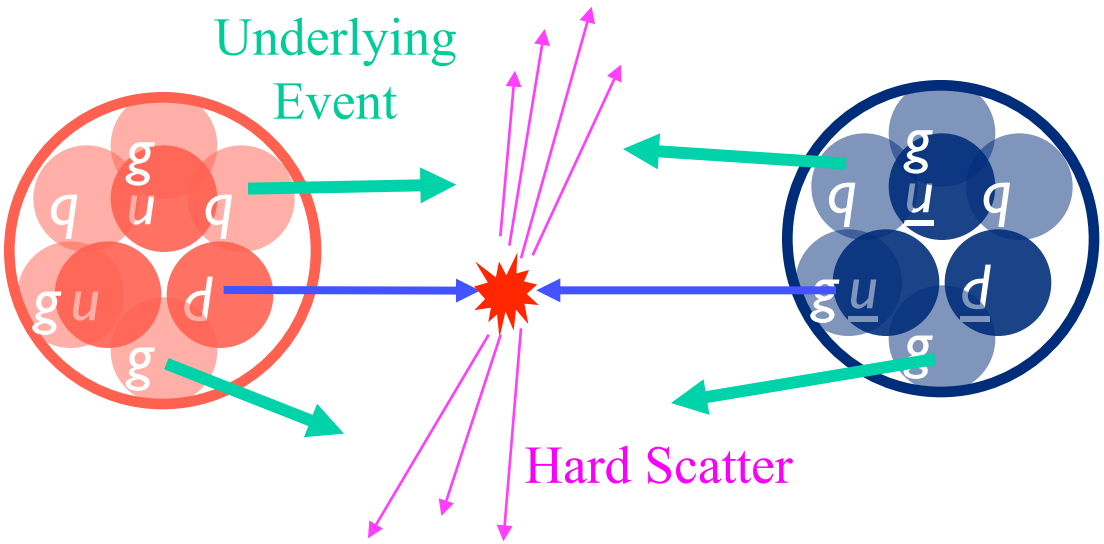


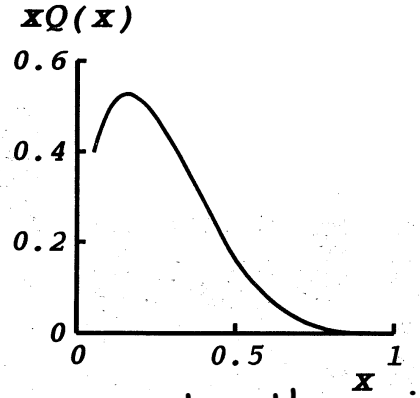
Small x, products boosted along beam direction



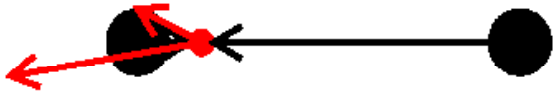
Large x, can create massive objects that decay to secondaries with large momentum component transverse to the beam ➔ Good way of telling that a hard collision occurred.

Hadron-Hadron collisions in a nutshell

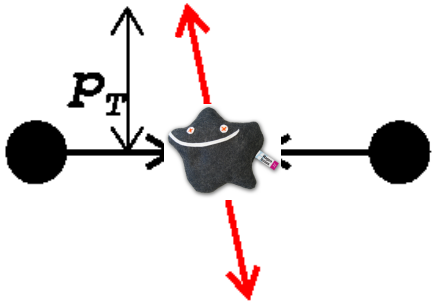




For every proton there is a probability that a single parton carries a fraction "x" of the proton momentum

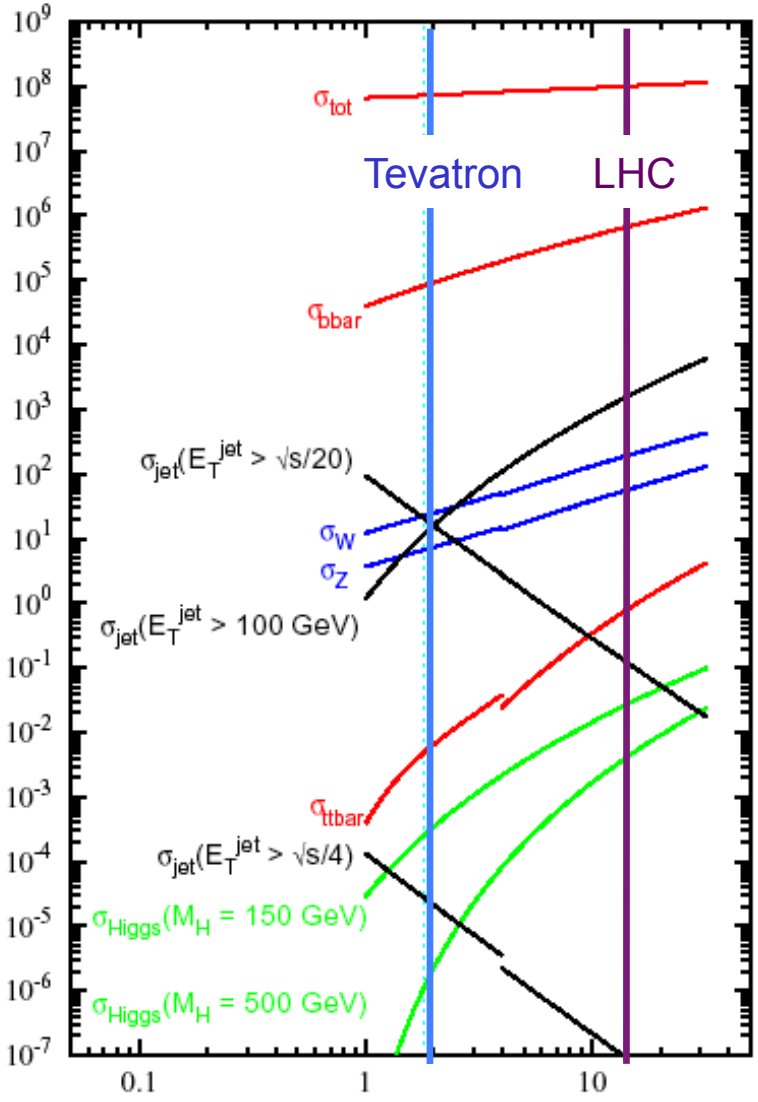


Small x, products boosted along beam direction



Large x, can create massive objects that decay to secondaries with large momentum component transverse to the beam ➔ Good way of telling that a hard collision occurred.

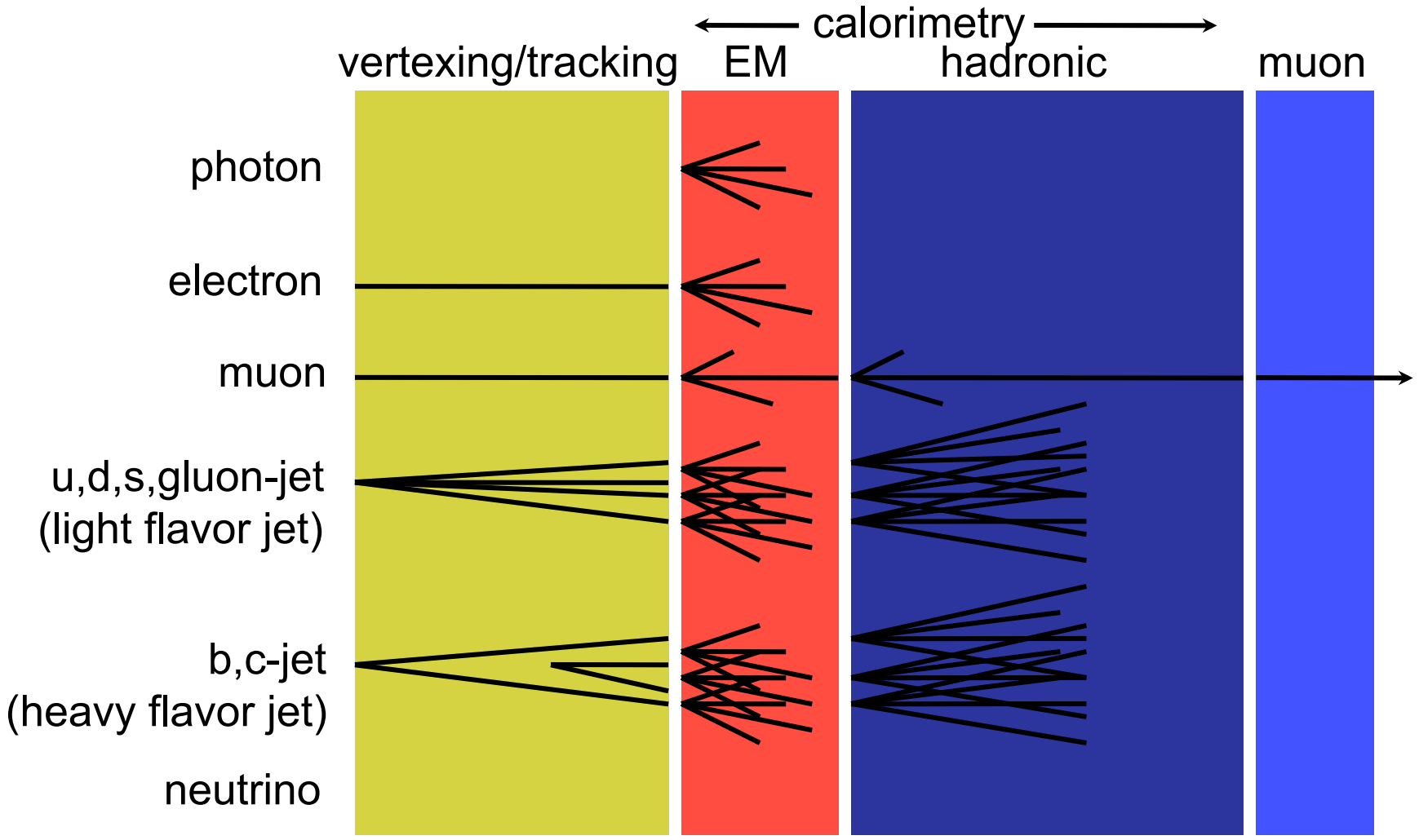
Hadronic Cross Sections

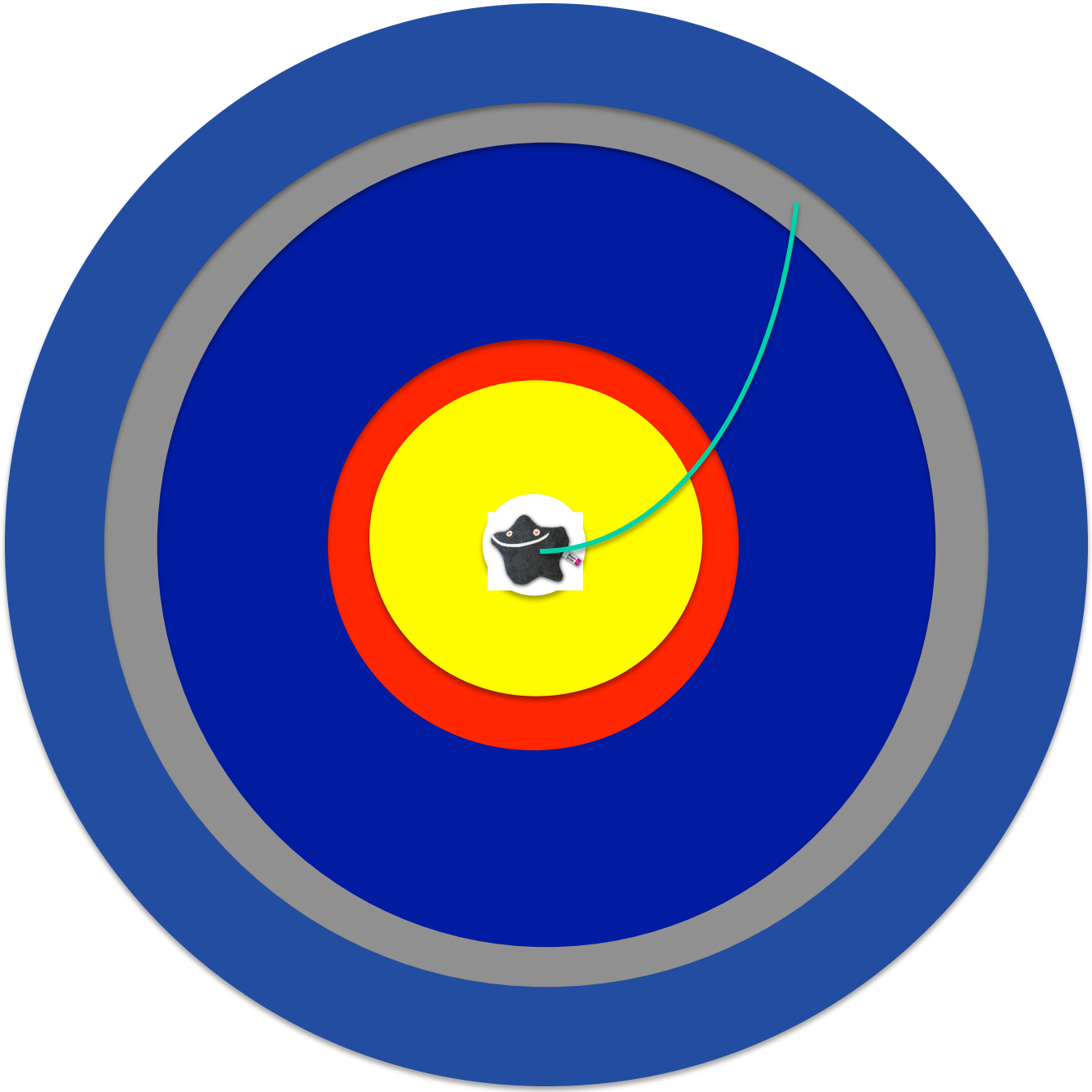


- Production Cross Sections span 12-13 orders of magnitude
  - Only 1 Higgs Boson produced every few billion collisions at the LHC
  - Collision rate overwhelmed by mundane processes
  - Background discrimination and modeling crucial



Schematic Particle ID





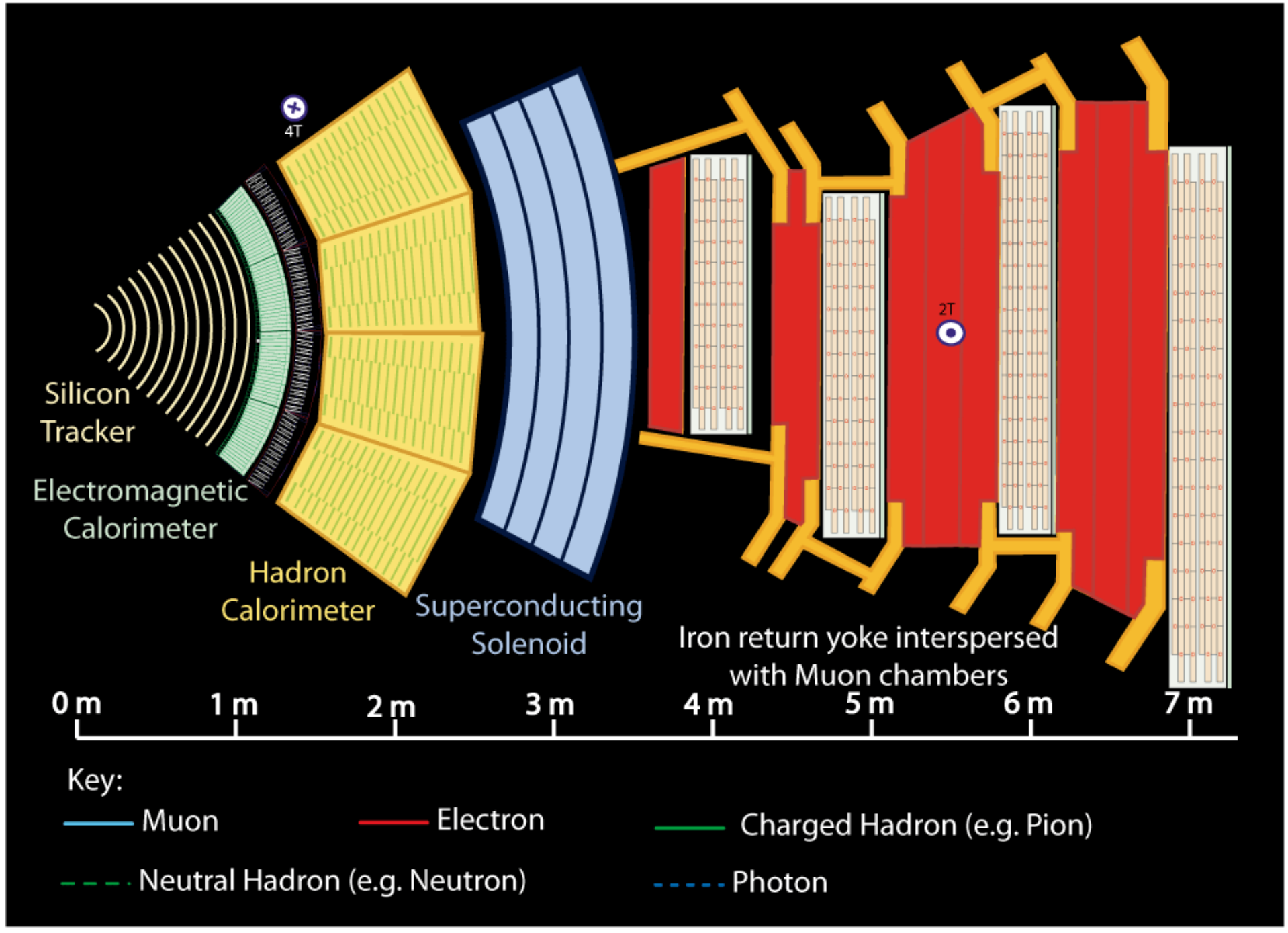
Tracking

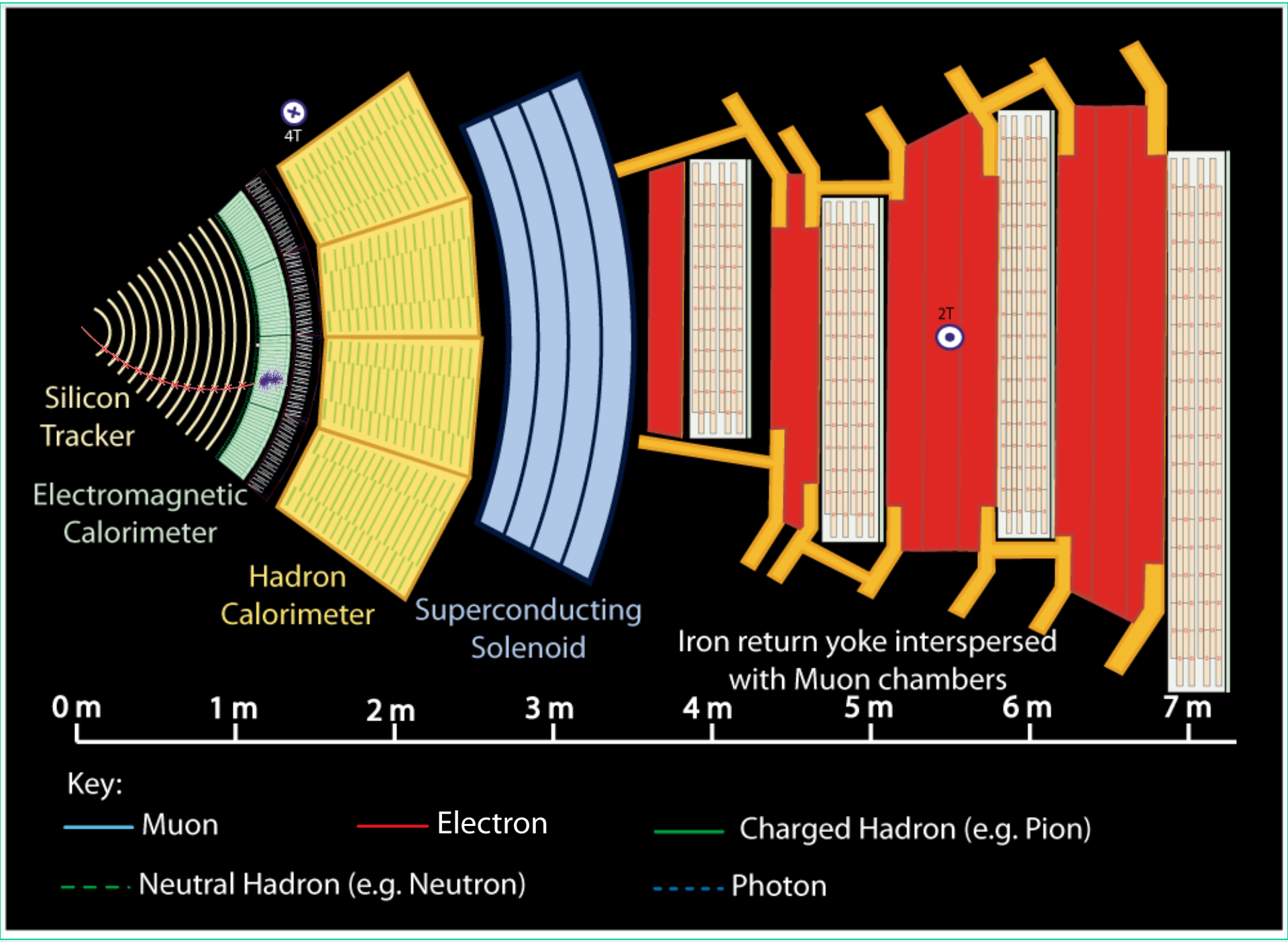
EM Calorimeter

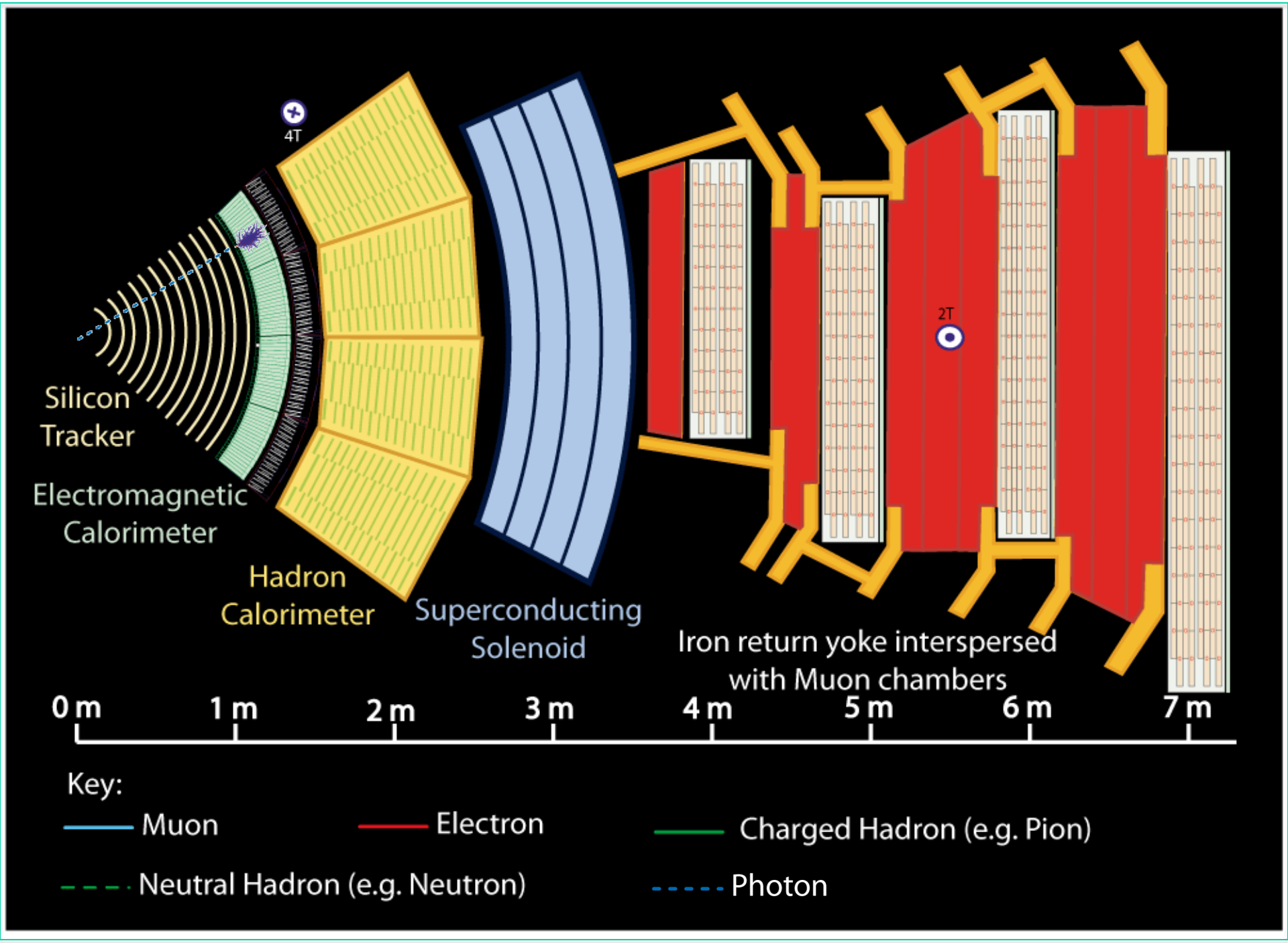
Had Calorimeter

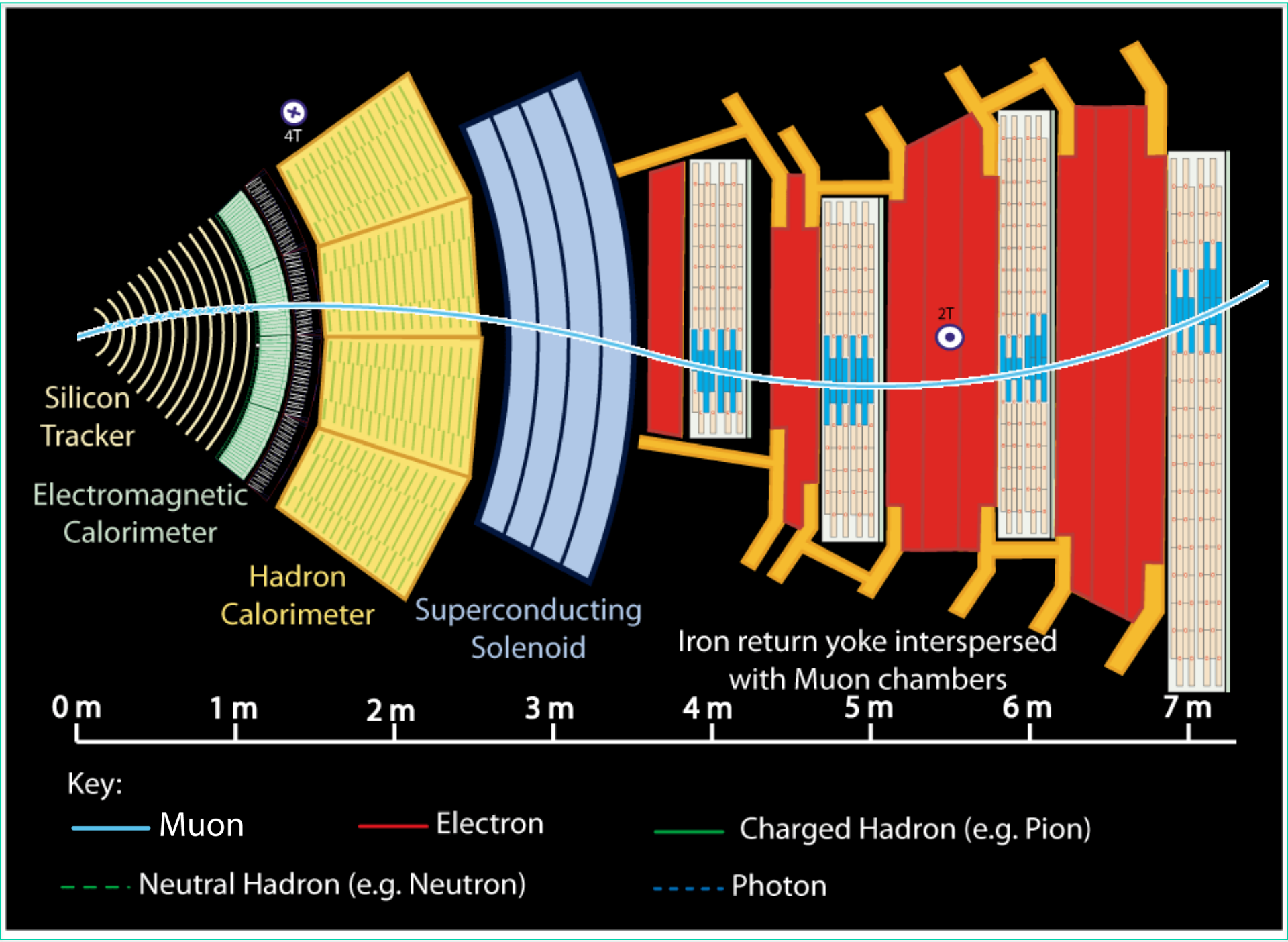
Muon

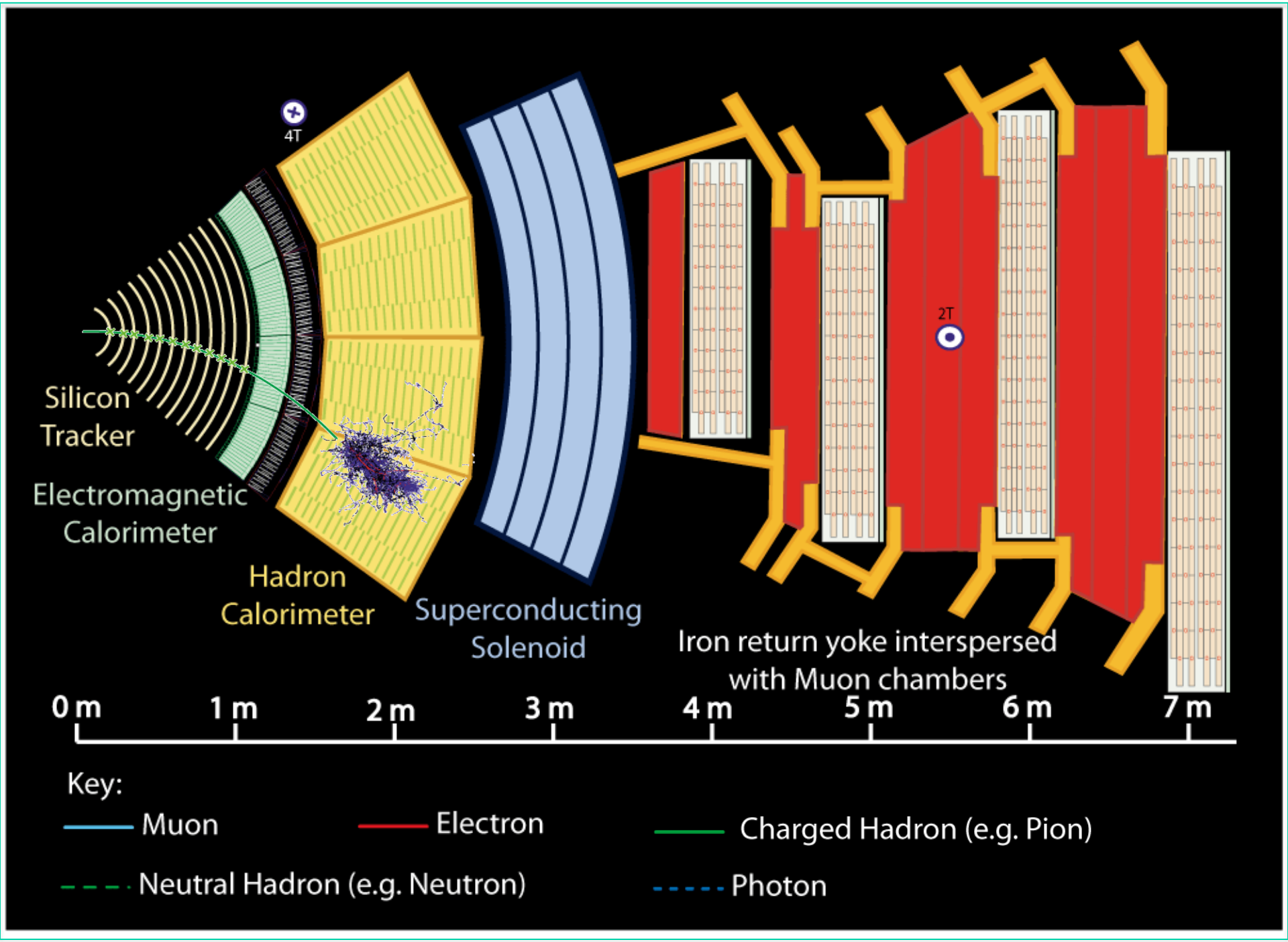
Magnet

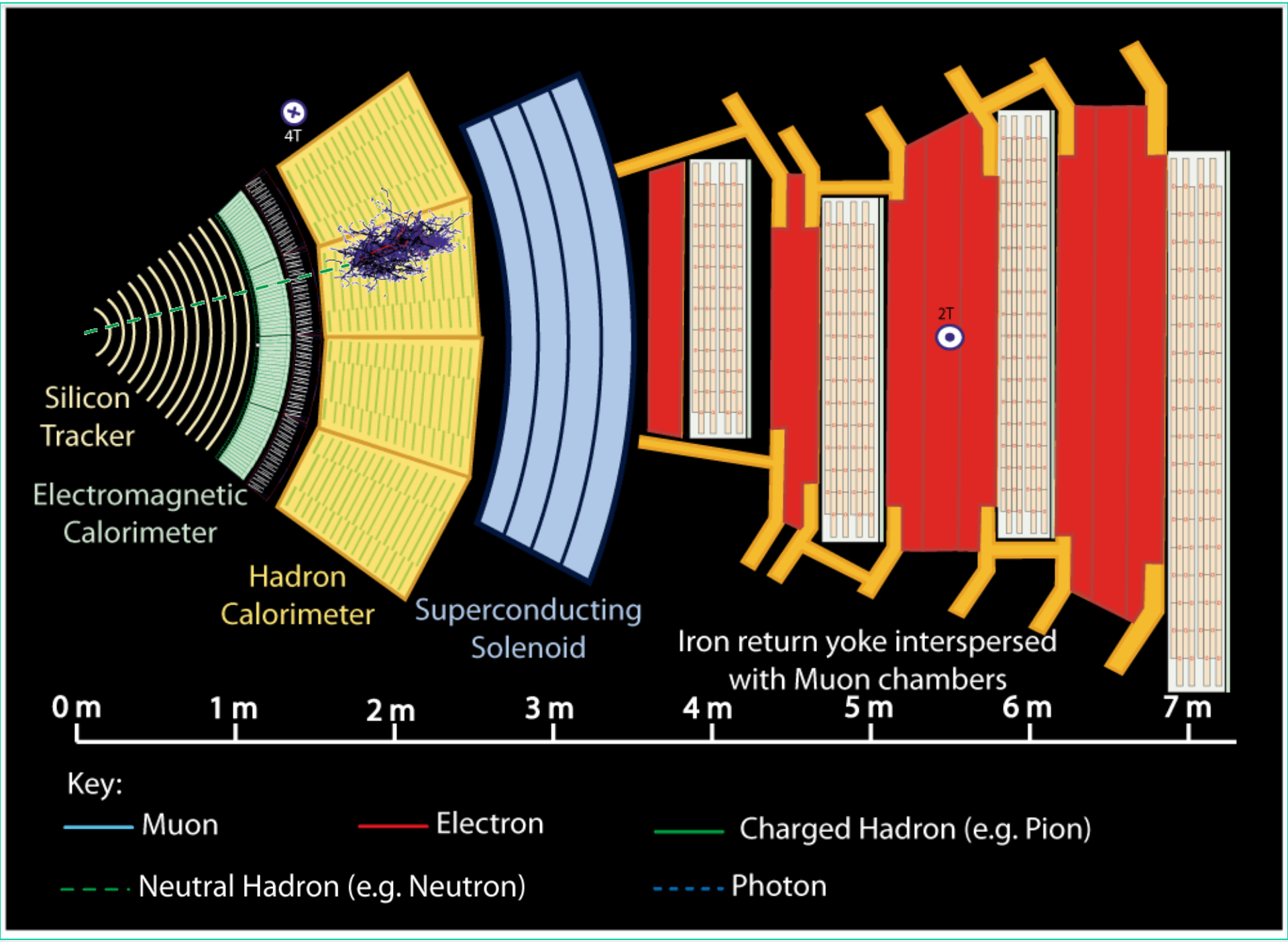

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

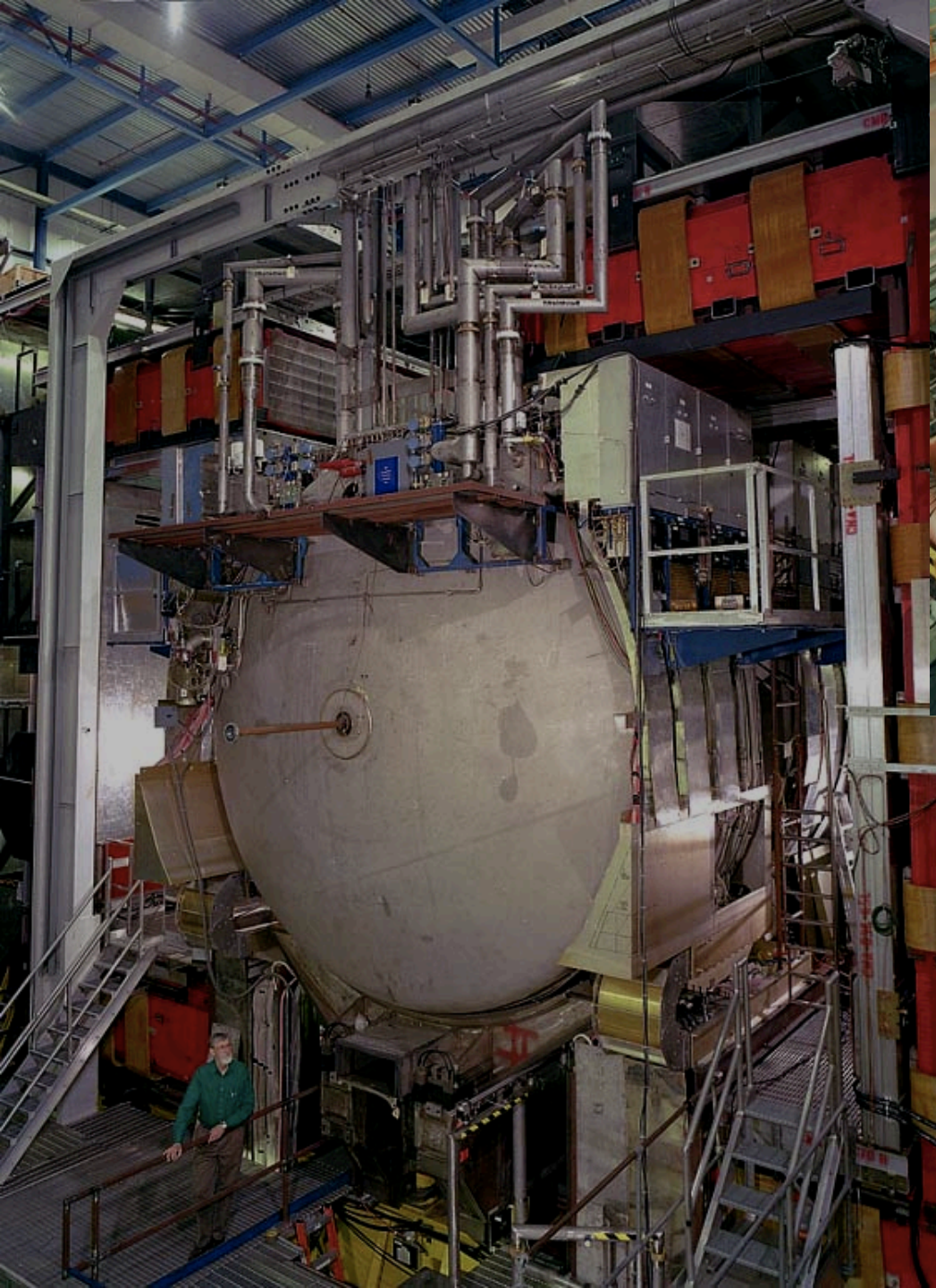

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

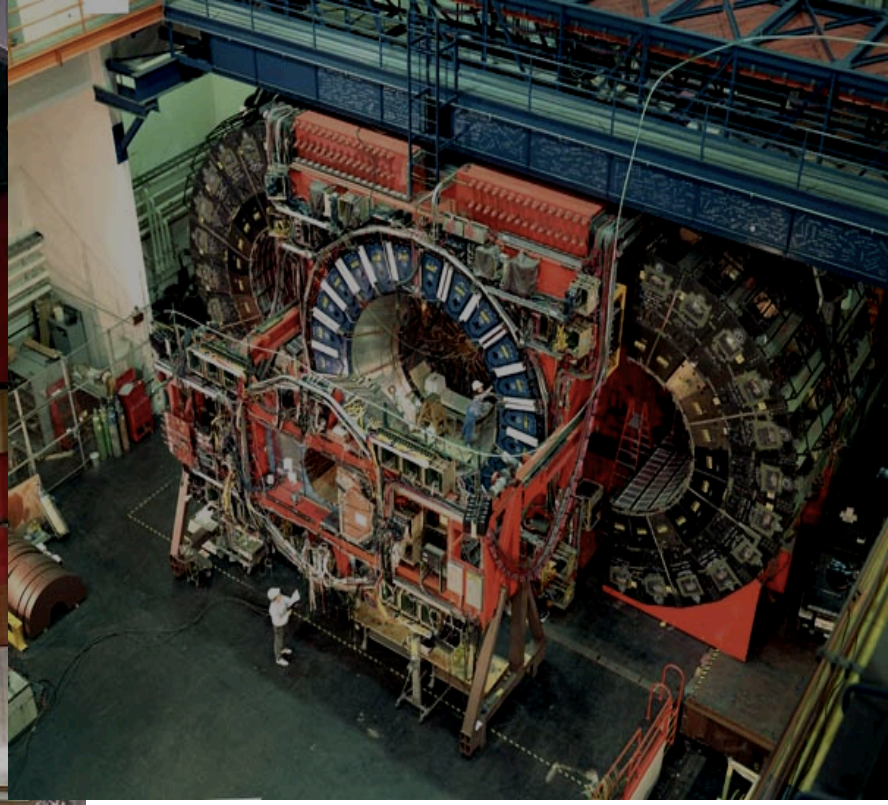

4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon


4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon






Canon
EOS
ELAN
Canon
EOS
ELAN

The LHC Detectors



CMS

21 m long, 15 m high, 15 m wide.

12 500 tonnes (as heavy as the Eiffel tower)

500 M CHF (Material)

4300 physicists from 41 nations

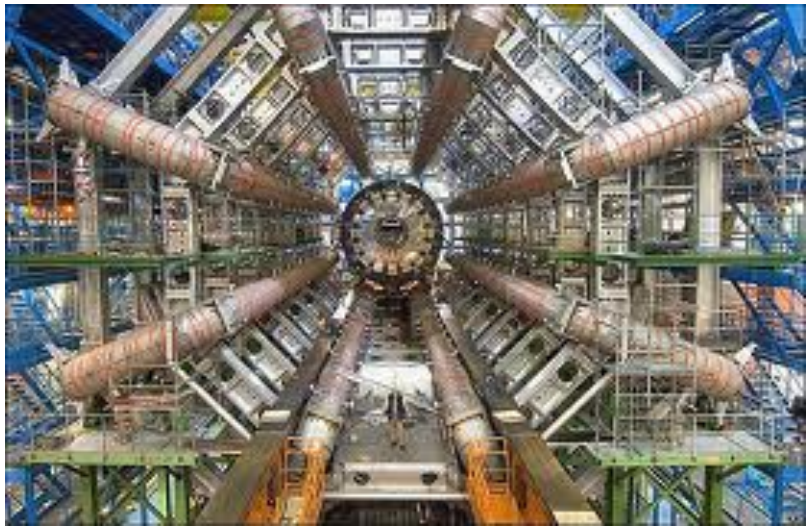
ATLAS

46 m long, 25 m high, 25 m wide

7000 tonnes

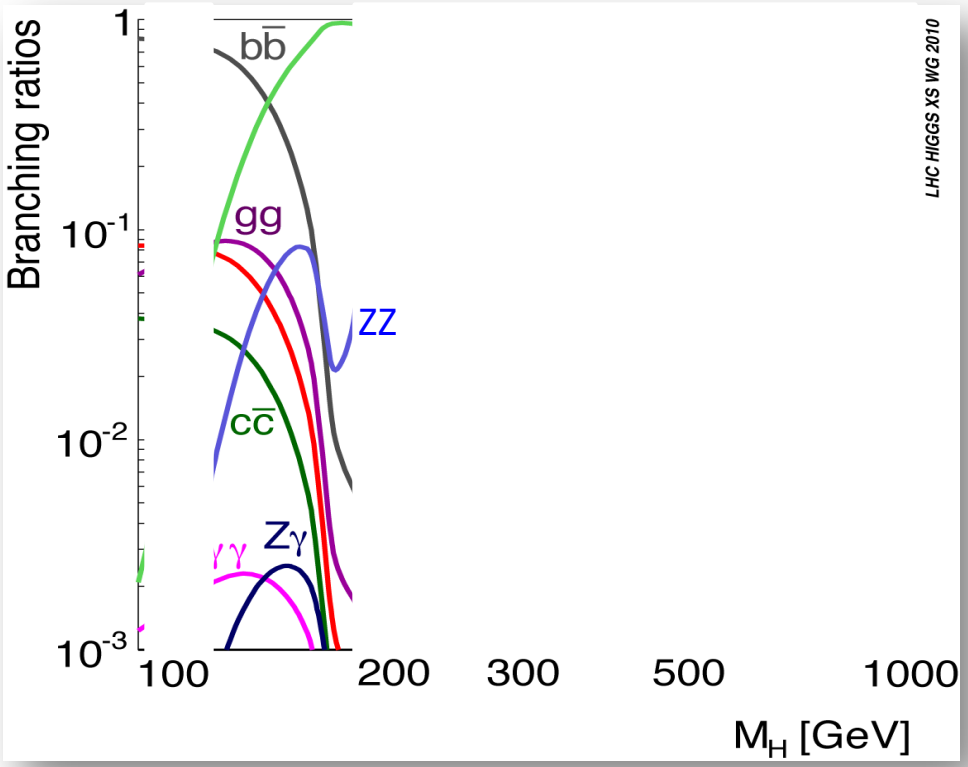
500M CHF (Material)

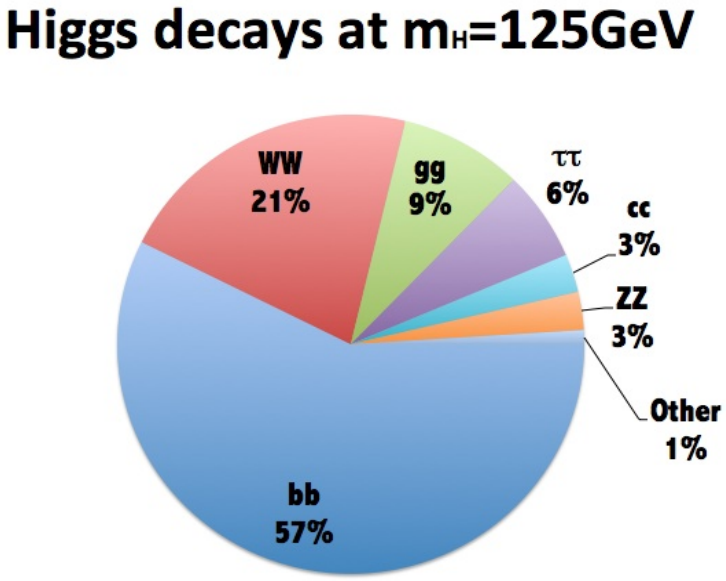
3000 physicists from 38 nations



How a Higgs boson decays

Decay modes depend on mass

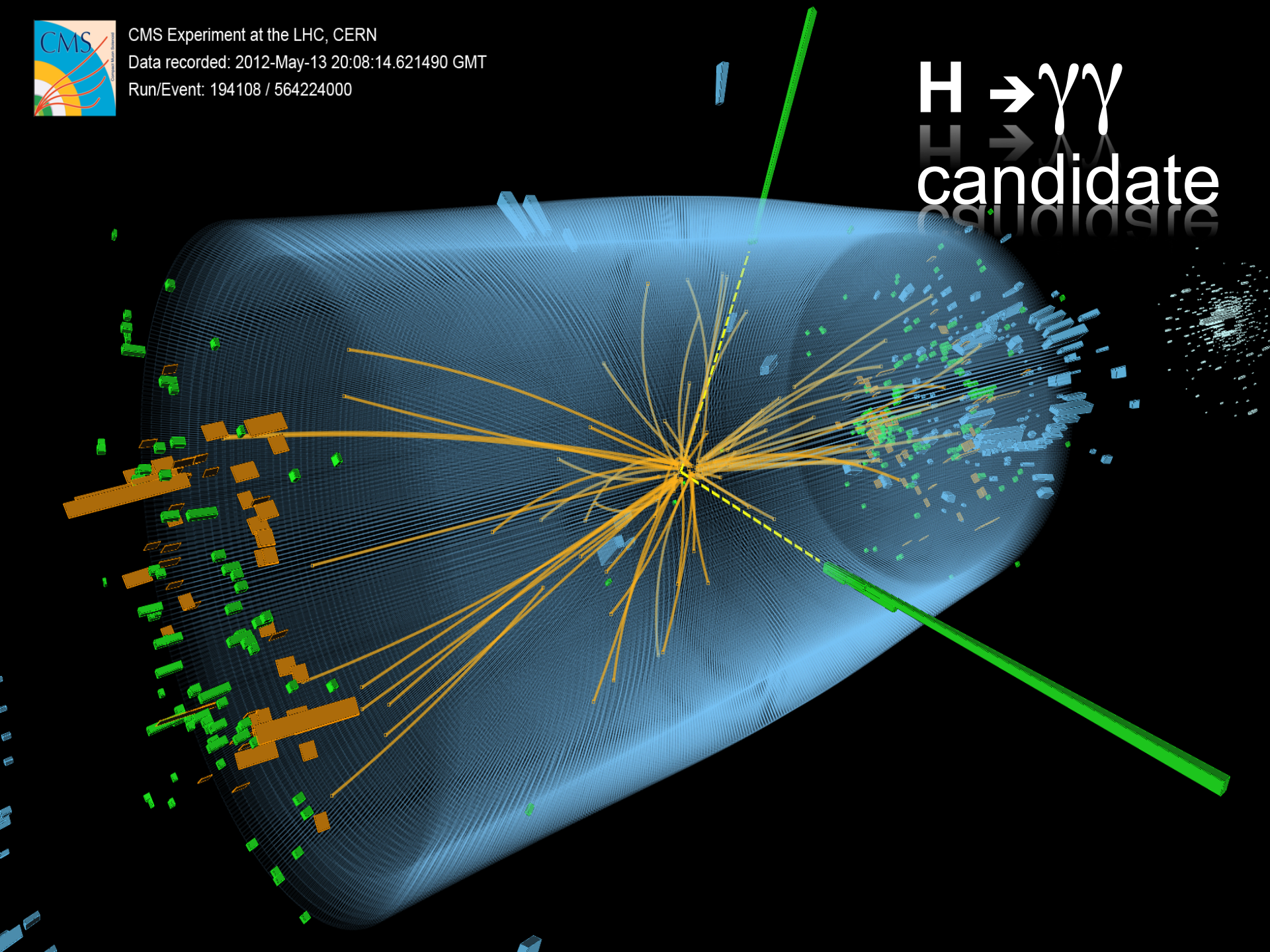




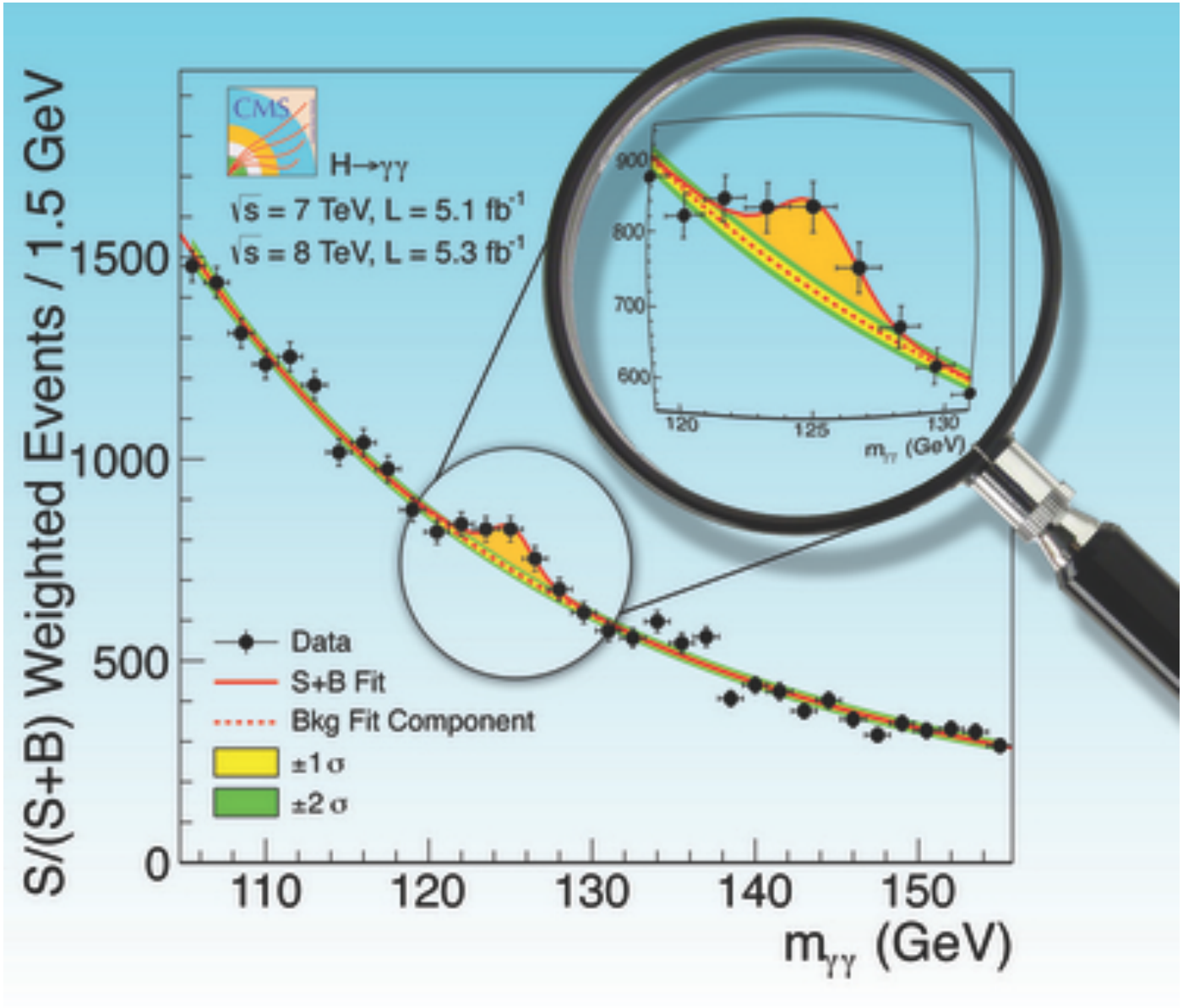
Best bets:

H → γγ & H → ZZ → 4 lep.

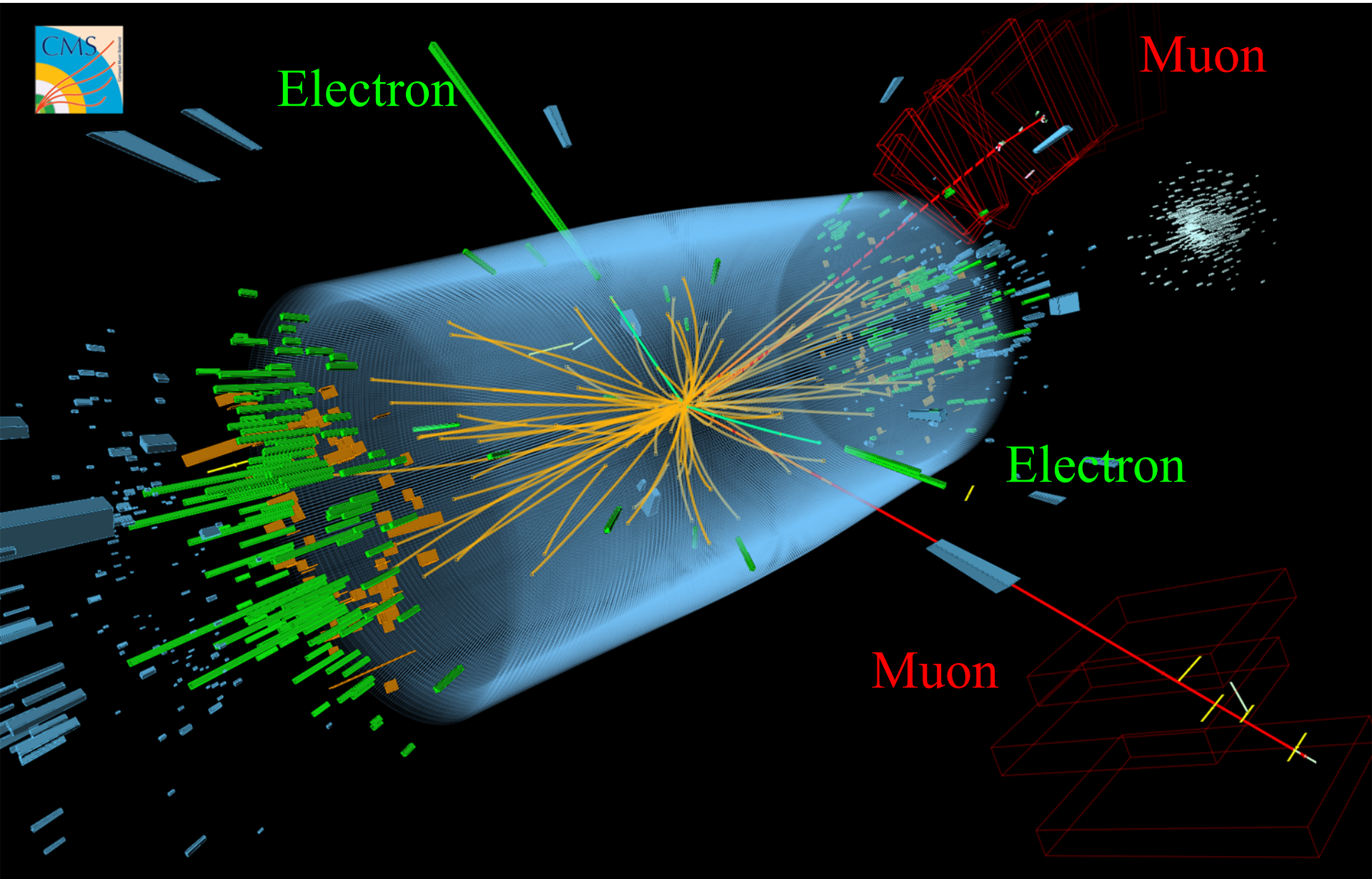
Allow for reconstruction of invariant mass and observation of Higgs "bump" above falling non-resonant background.


CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000
H → γγ
candidate

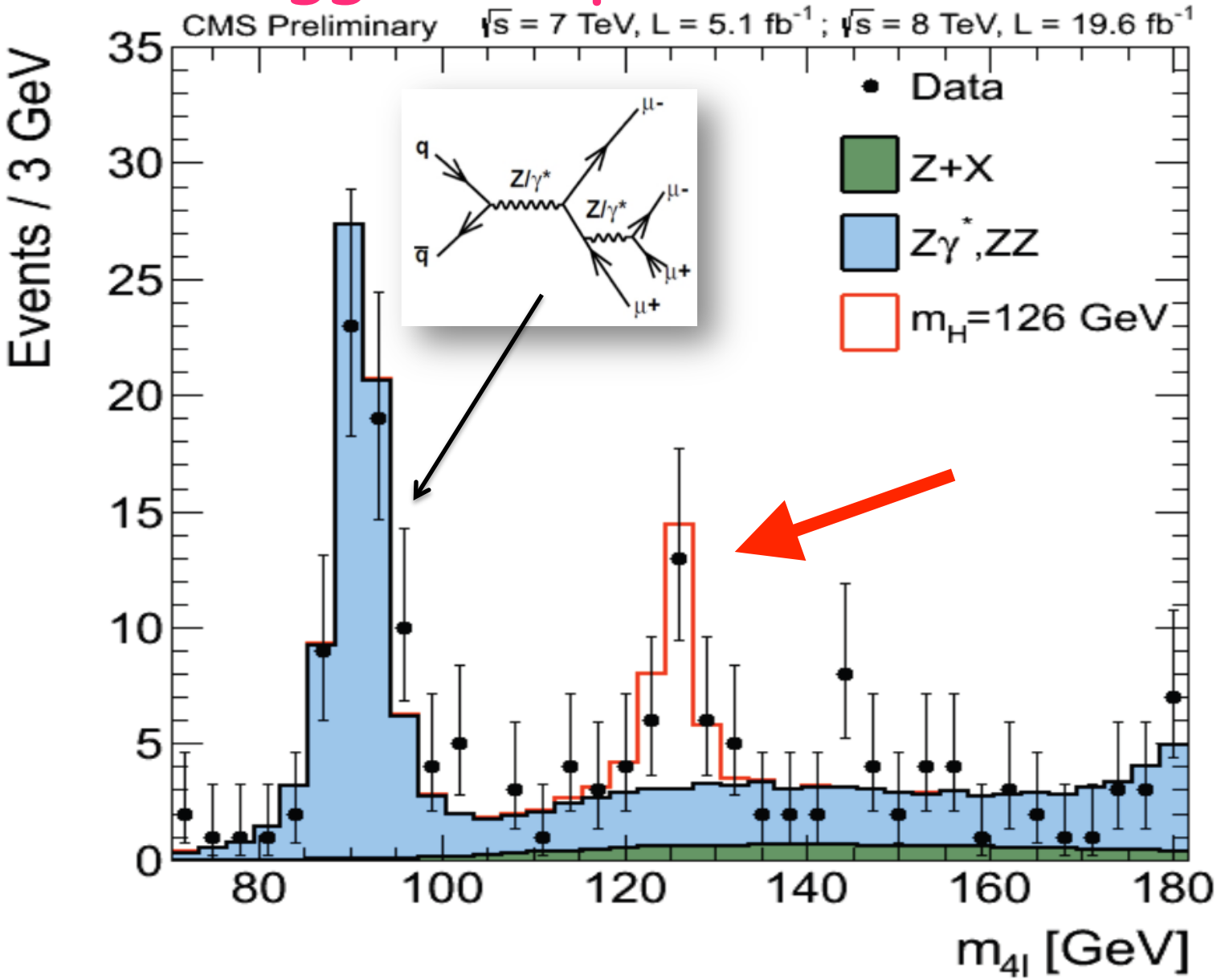
Higgs bump: photons



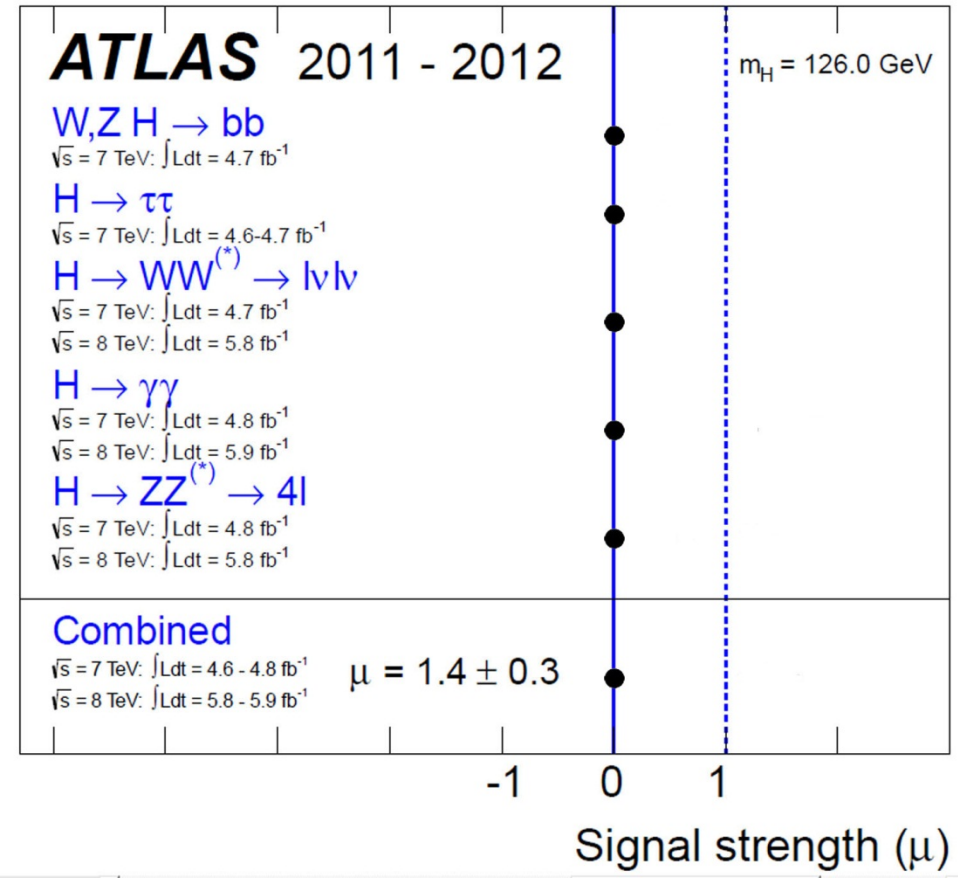
$H \rightarrow ZZ \rightarrow 4$ leptons Candidate

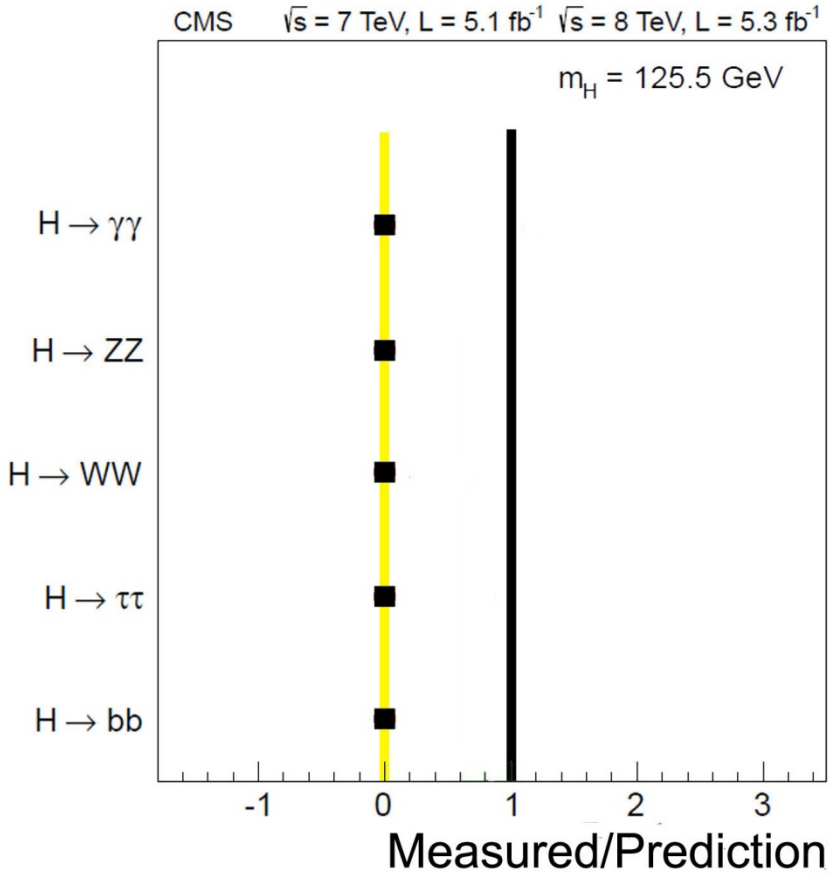


Higgs bump: Z bosons

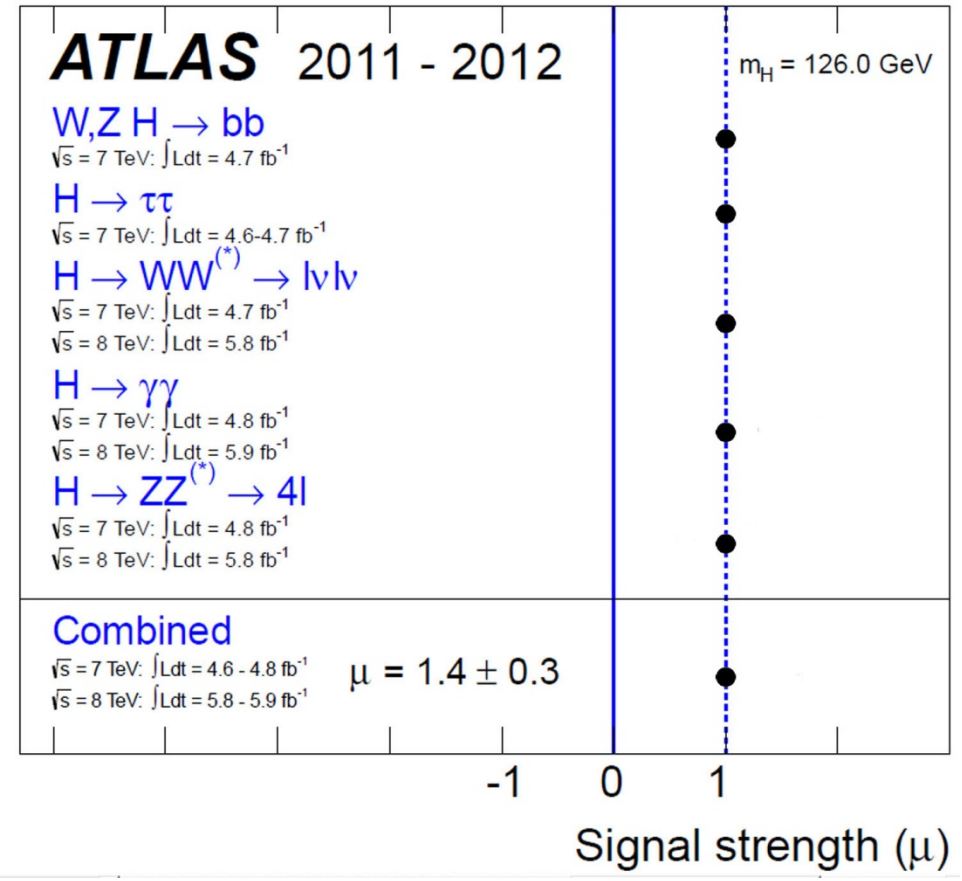


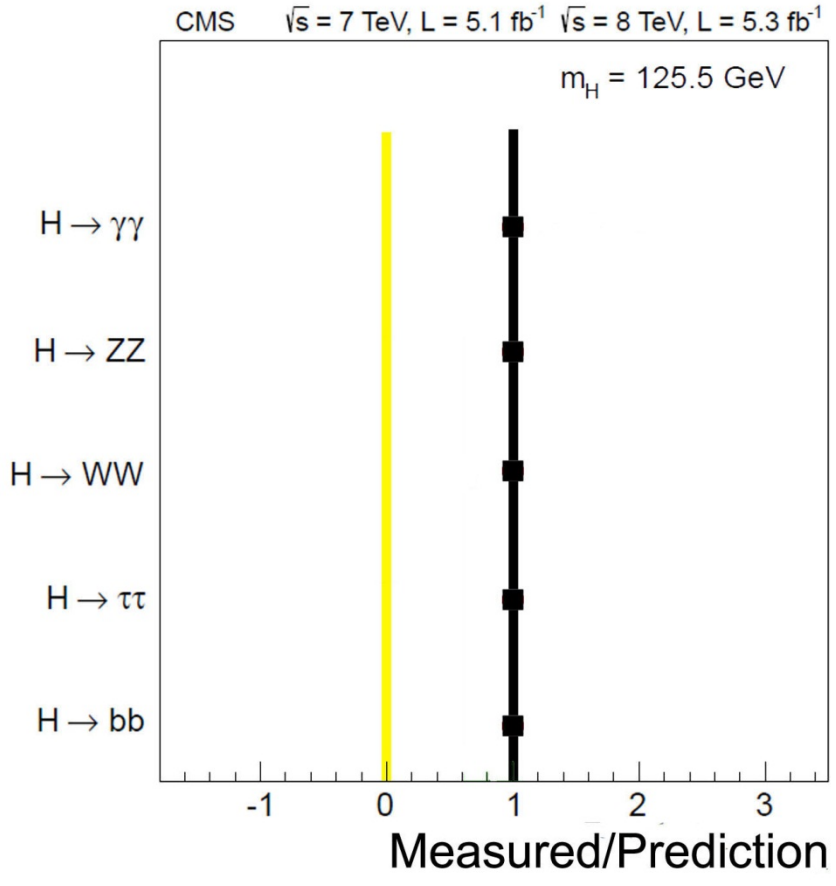
Results if no Higgs





Results with Higgs

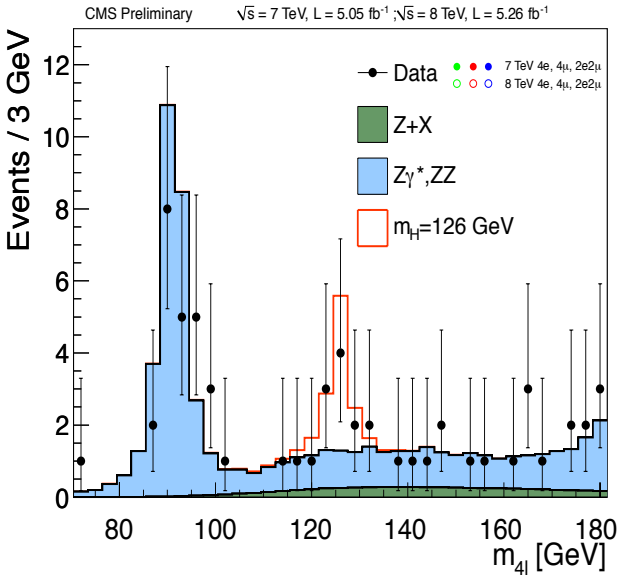




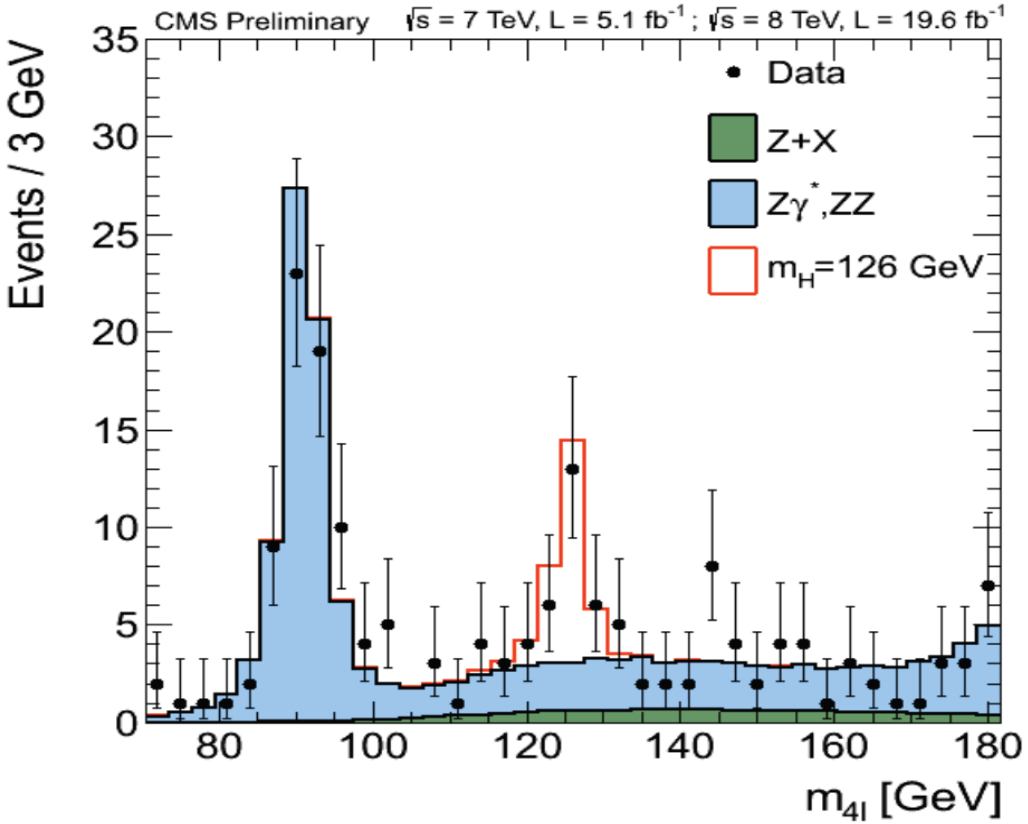
July 2012 Results



Then vs Now (2.5 times as much data)

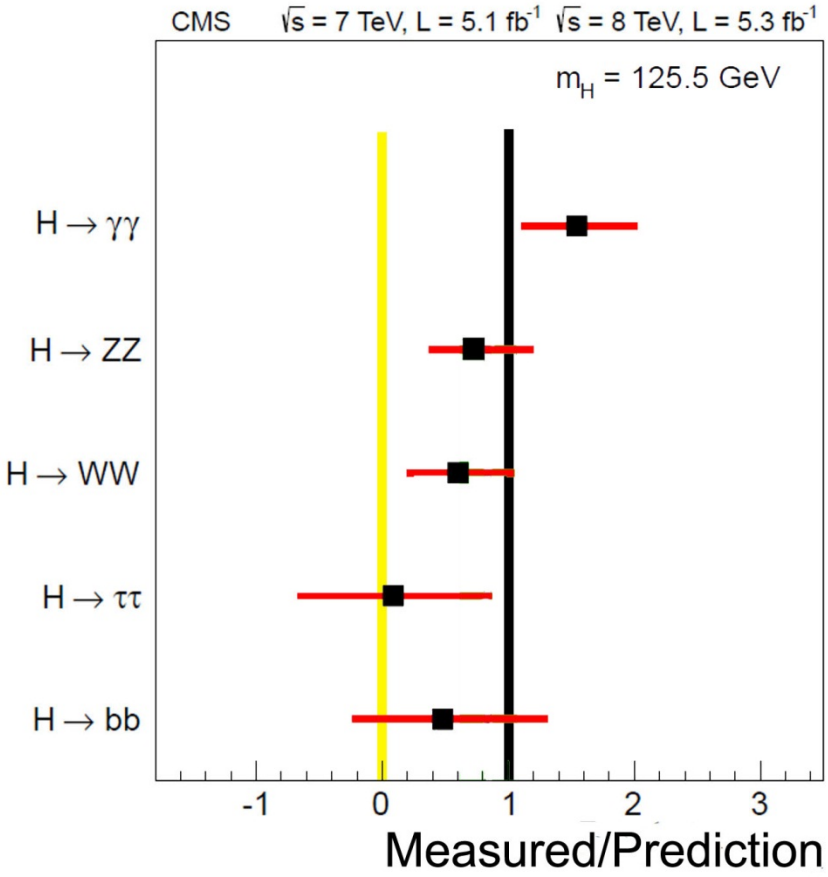


July 2012

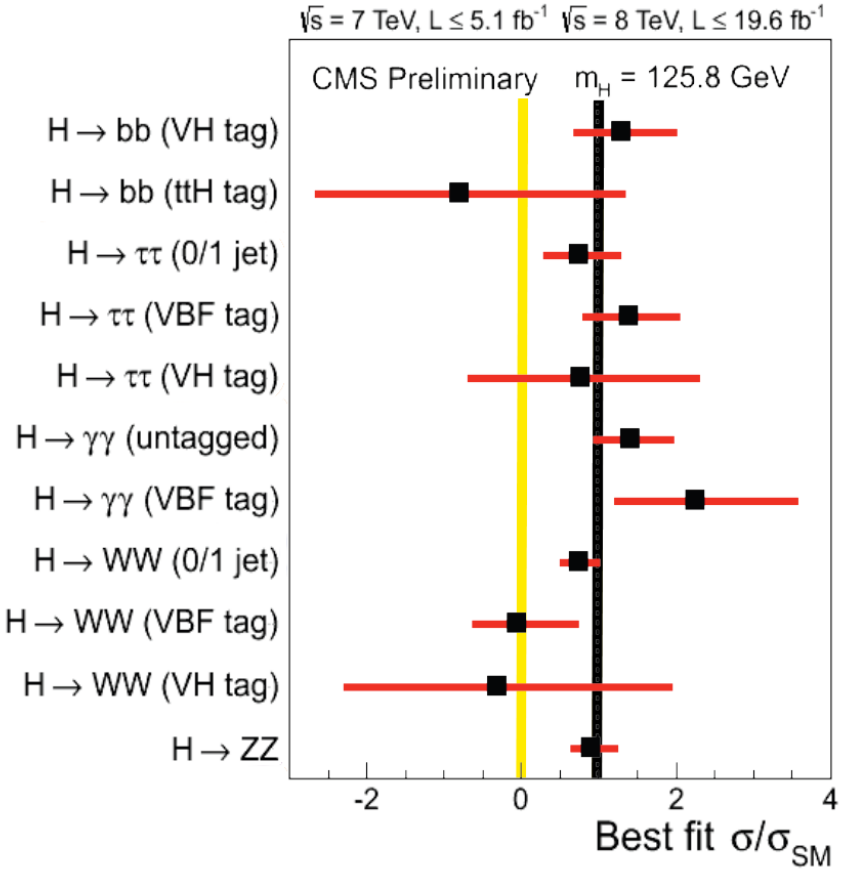


Now

Then vs Now (CMS only, but ATLAS results similar)



July 2012



Now



Tuesday, October 8
4:45 AM Chicago time.

The Nobel Prize in Physics 2013



Photo: A. Mahmoud

François Englert



Photo: A. Mahmoud

Peter W. Higgs

The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs ***"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"***

Worldwide discoveries that led to the Standard Model

LEPTONS

• electron	1897	Thomson	1906 Nobel Prize
• e-neutrino	1956	Reactor	1995 Nobel Prize
• muon	1937	Cosmic Rays	
• mu-neutrino	1962	BNL	1988 Nobel Prize
• tau	1976	SLAC	1995 Nobel Prize
• tau-neutrino	2000	Fermilab	First direct evidence

QUARKS

• up/down	1968	SLAC	1990 Nobel Prize
• strange	1964	BNL	1980 Nobel Prize
• charm	1974	SLAC/BNL	1976 Nobel Prize
• bottom	1977	Fermilab	
• Top	1995	D0/CDF	

Force Carriers

•Photon	1905	Planck/Einstein	1918/1921 Nobel Prizes
• Gluon	1979	DESY	
• W/Z	1983	CERN	1984 Nobel Prize

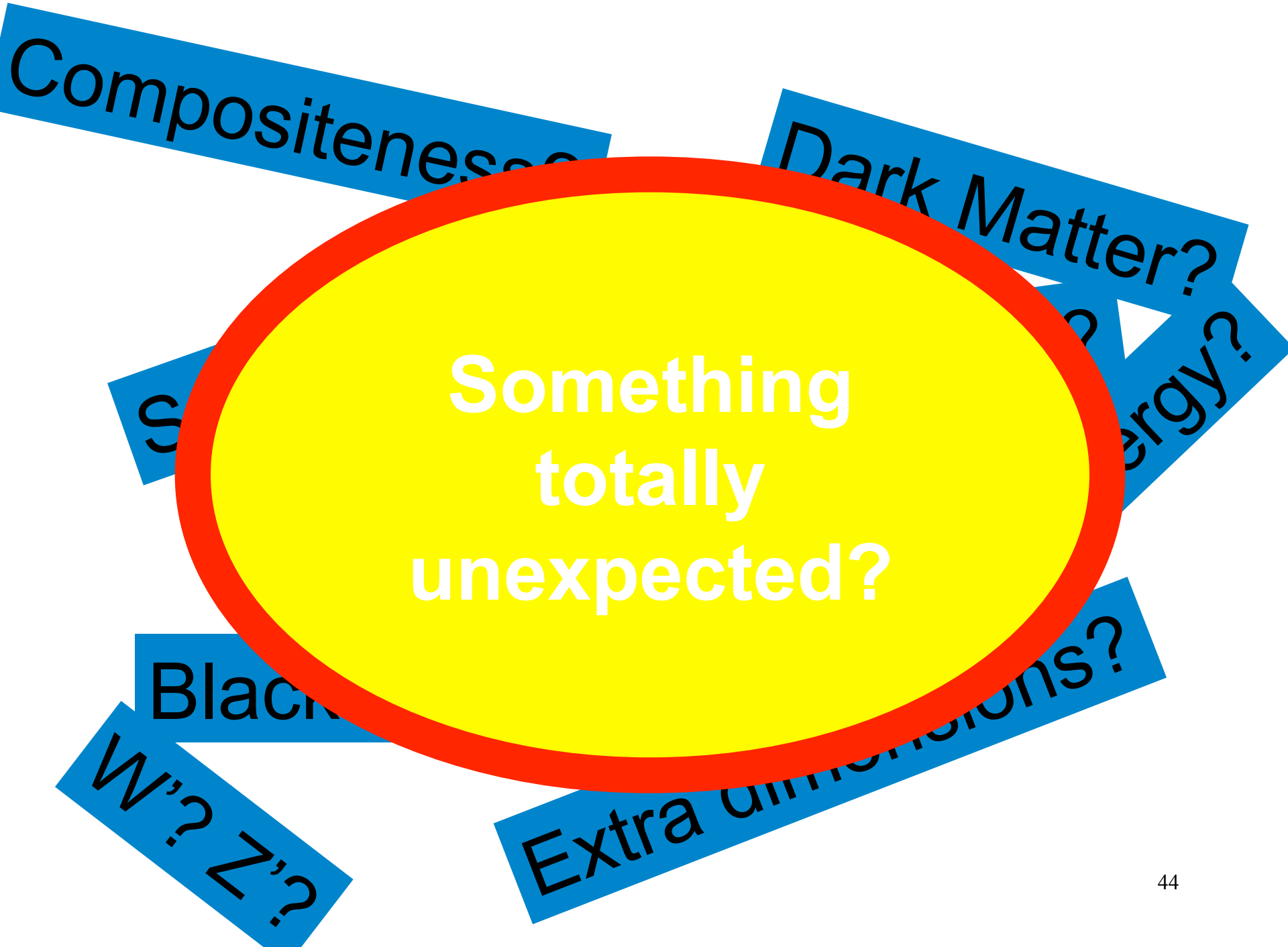
THEORY & TECHNOLOGY (for particle detectors) also recognized with Nobel Prizes.

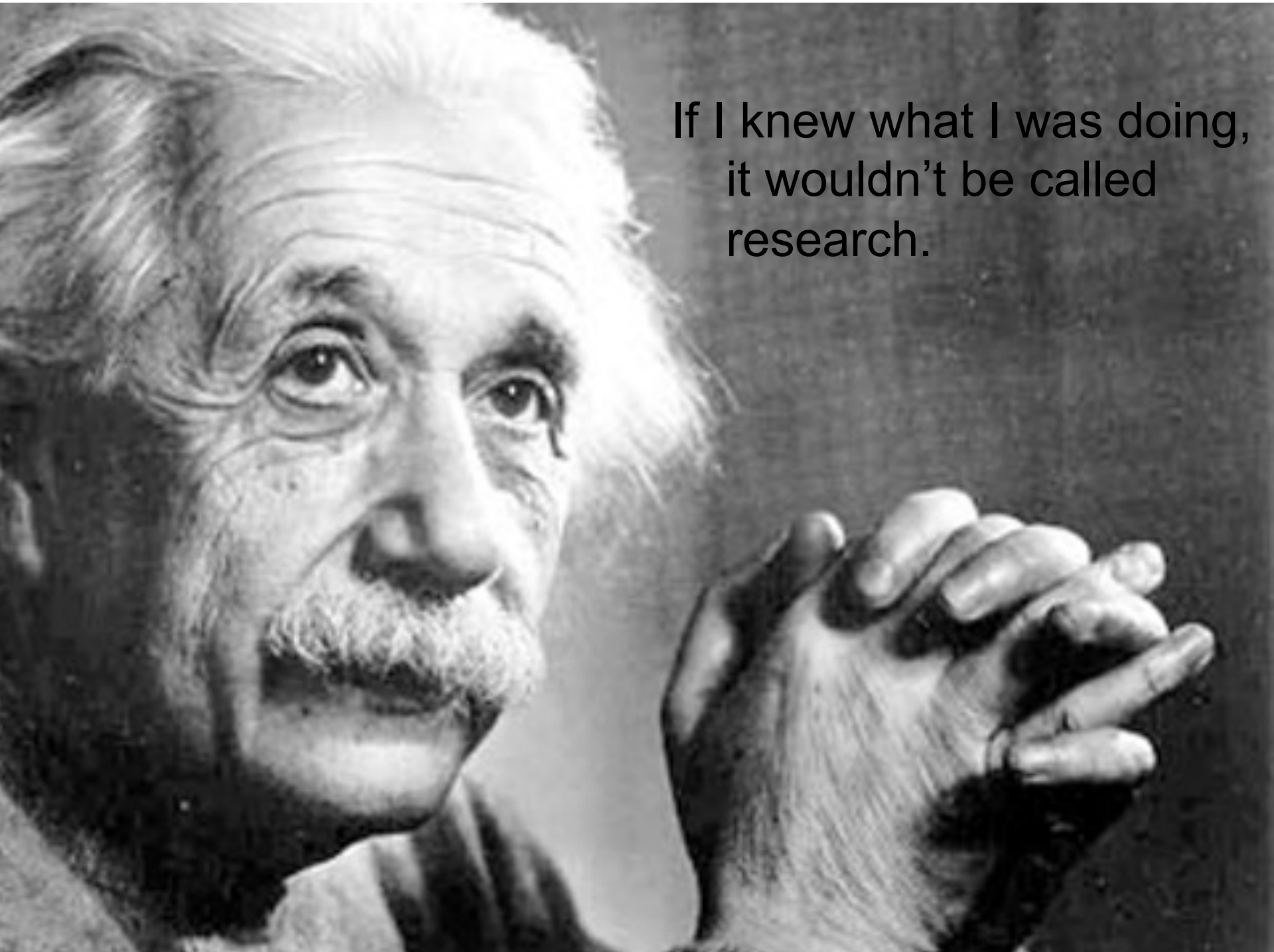
Is this the end of the story?



While possible, this rock formation is not likely to arise in nature
(Credit: Fermi Today 11/15/13)

- "Fine tuning" refers to extreme cancellations in a proposed explanation for something.
- The Standard Model is finely tuned in several ways, but the most significant is the fact that it does not explain why gravity is so much weaker than the other forces.
  - The SM is likely not wrong, but incomplete.
- LHC will resume operations in 2015 at a higher center of mass energy
  - What will we find?


Compositeness?
Dark Matter?
Something totally unexpected?
Extra dimensions?
W’? Z’?


If I knew what I was doing,
it wouldn't be called
research.