PARTICLE PHYSICS
the quest to understand the fundamental structure of matter

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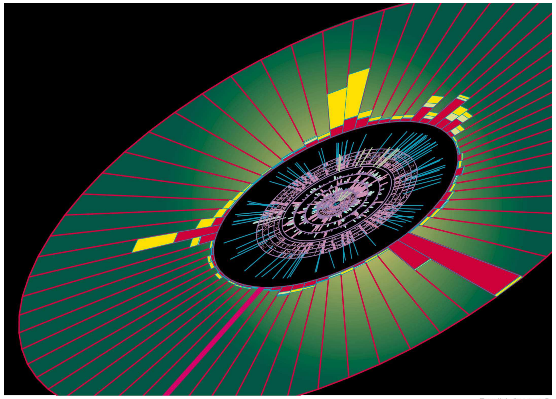
University of Illinois-Chicago

Fermilab Saturday Morning Physics, Fall 2018



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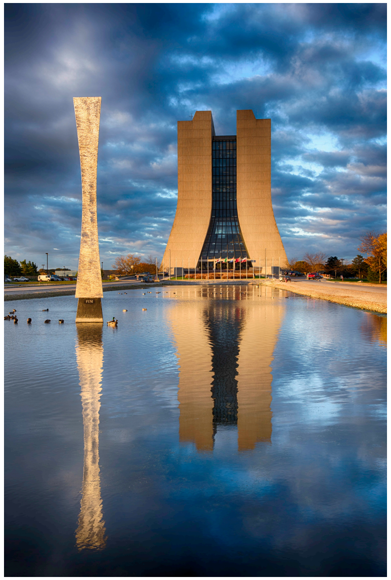


What is the World Made of?

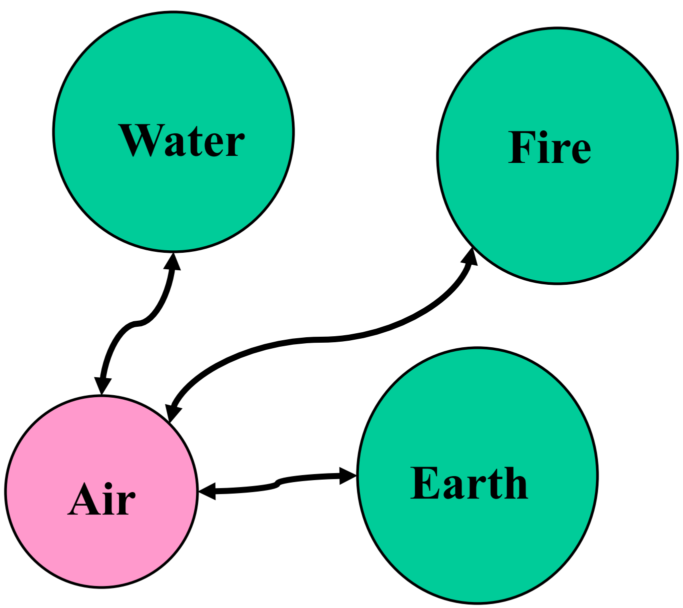
Democritos of Abdera (Greece, 465 BC)

- Introduced the idea that all matter is made of indivisible particles, that he called ATOMS
- Atoms are solid, invisible, indestructible
- Atoms differ in size, shape and arrangement so that
  - Solids are made of small, pointy atoms
  - Liquids are made of large, round atoms
  - Oils are made of fine atoms that can easily slip past each other

What is the World Made of?
What Holds it Together?

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?

Dmitri Mendeleev (1871)

Reihen	Gruppo I. — R^2O	Gruppo II. — RO	Gruppo III. — R^2O^3	Gruppo IV. RH^4 RO^2	Gruppo V. RH^3 R^2O^5	Gruppo VI. RH^2 RO^3	Gruppo VII. RH R^2O^7	Gruppo VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

- Periodic Table of the Elements: tabular arrangement of the Chemical Elements, ordered by their atomic number and recurring chemical properties

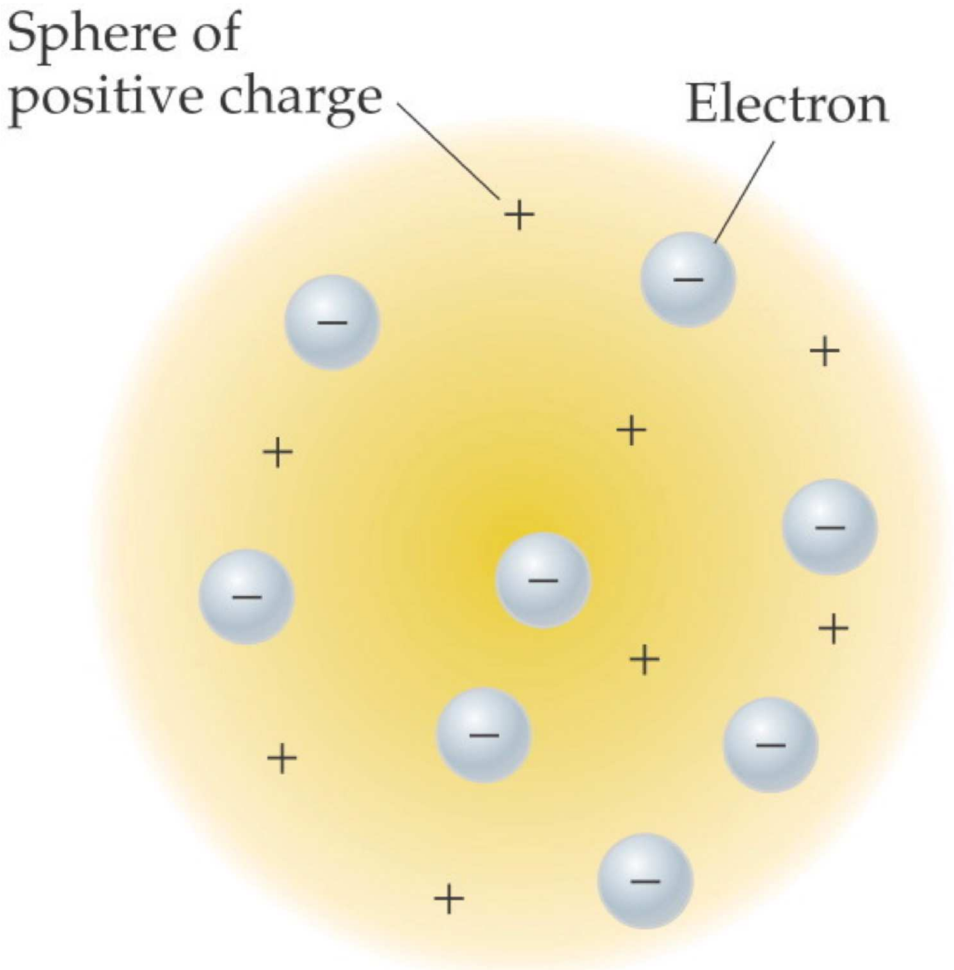
The Discovery of the Electron

J.J.Thomson (1897)

- Advanced the idea that cathode rays were a stream of small pieces of matter. 1906 Nobel Price of Physics

Plum Pudding Model of the Atom

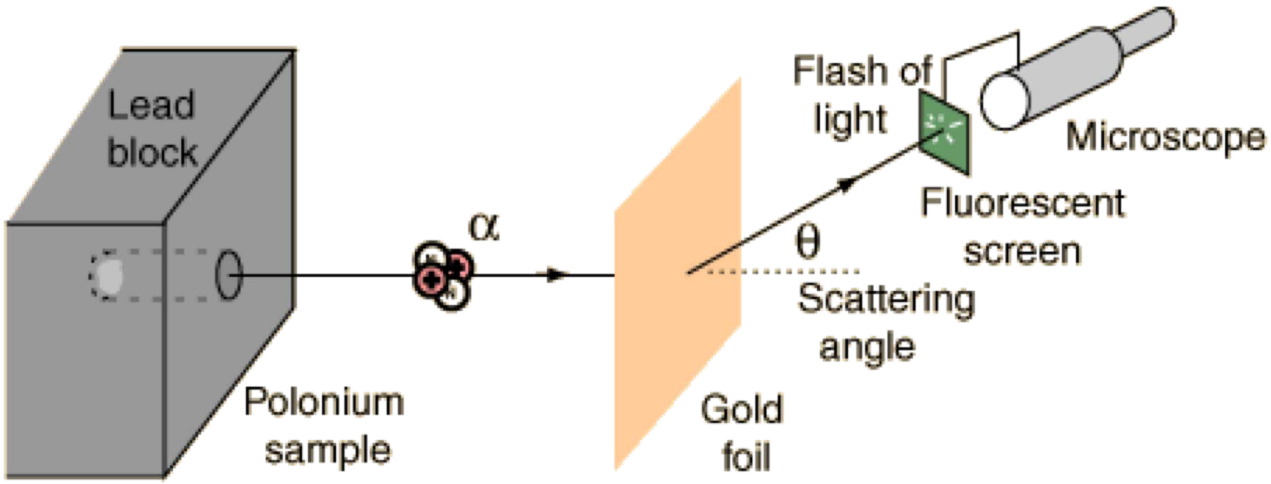
J.J. Thomson (1904)



Electrons were embedded in a positively charged atom like plums in a pudding

Rutherford Scattering

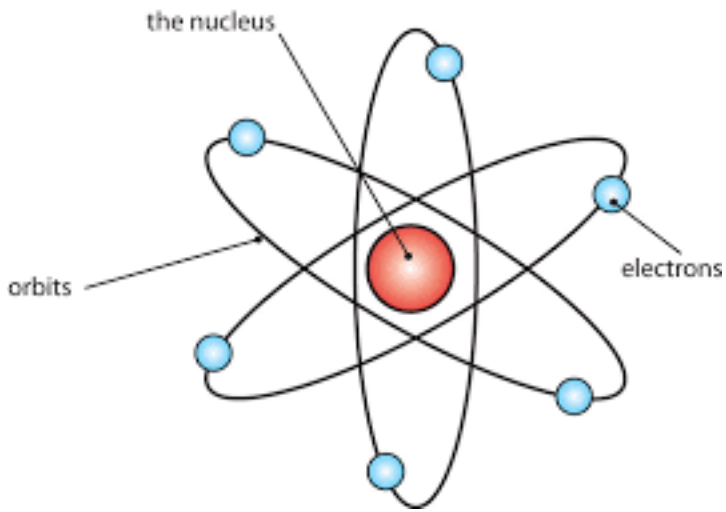
Alpha particles were allowed to strike a thin gold foil. Surprisingly, alpha particles were found at large deflection angles and ~1 in 8000 were even found to be back-scattered



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

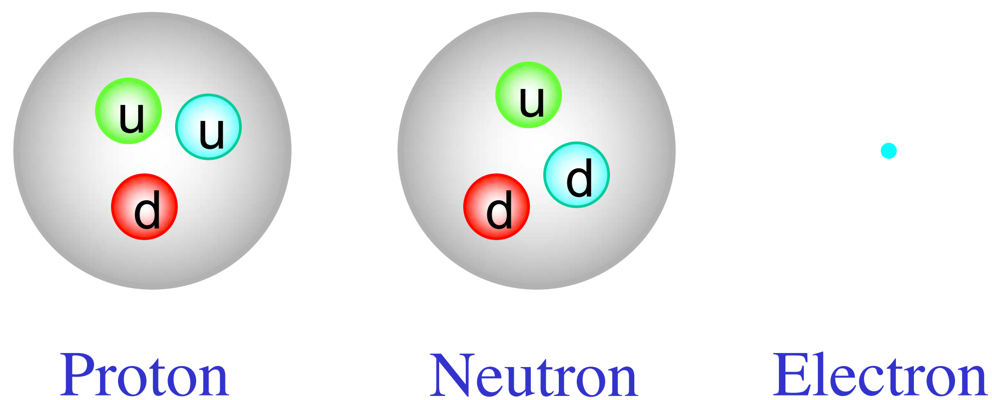
Planeraty Model of the Atom

Ernest Rutherford (1911)



Atoms are made up of a central positive charge surrounded by a cloud of orbiting electrons

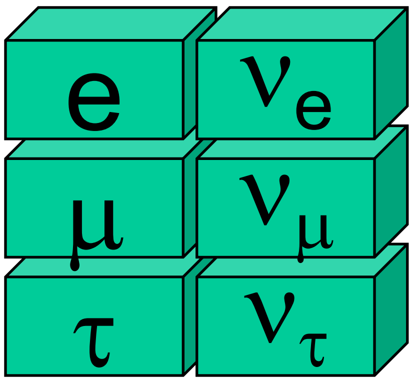
We now know that atoms are made of protons, neutrons and electrons; protons and neutrons are made of quarks & that the atomic atom is governed by quantum mechanics

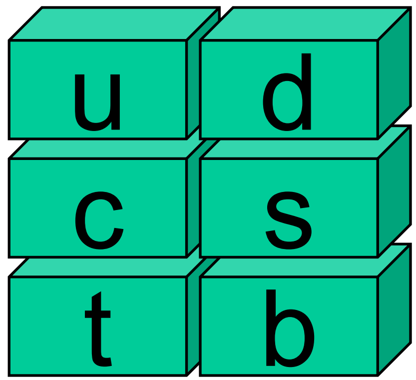


What is the World Made of?
What Holds it Together?

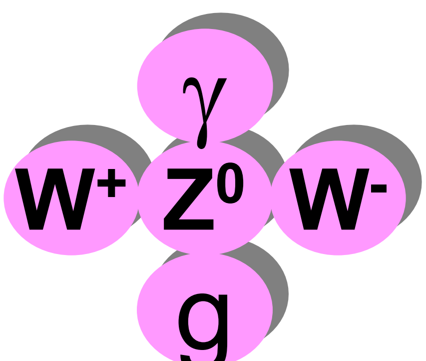
Standard Model (~1970)

ELEMENTARY CONSTITUENTS





INTERACTIONS

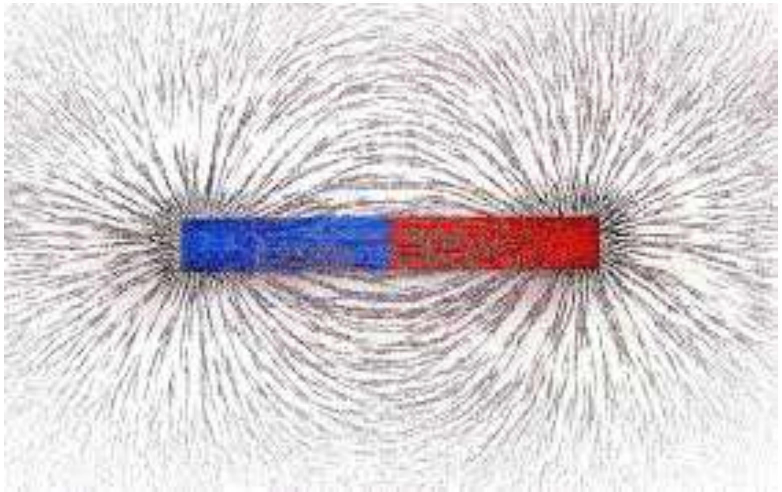


Higgs

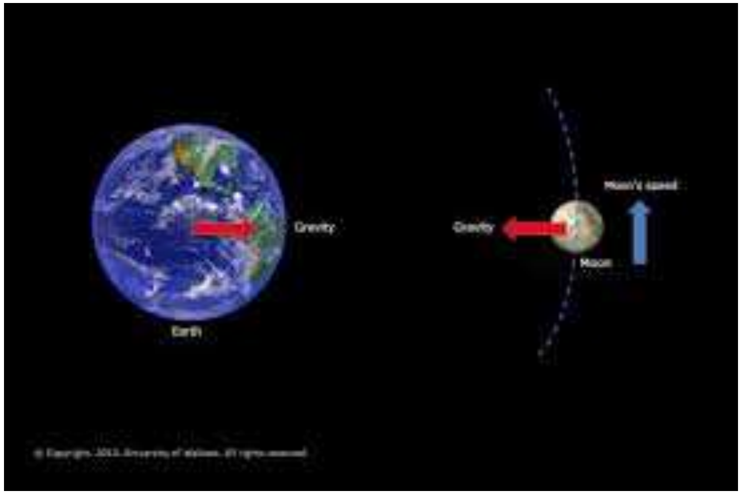
Strong	1
Electromagnetic	10^{-2}
Weak	10^{-6}
Gravity	10^{-40}

How do Matter Particles Interact?

- Particles interact without touching!

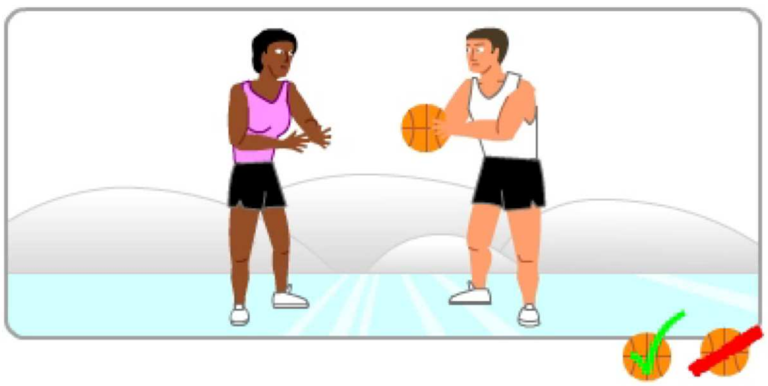


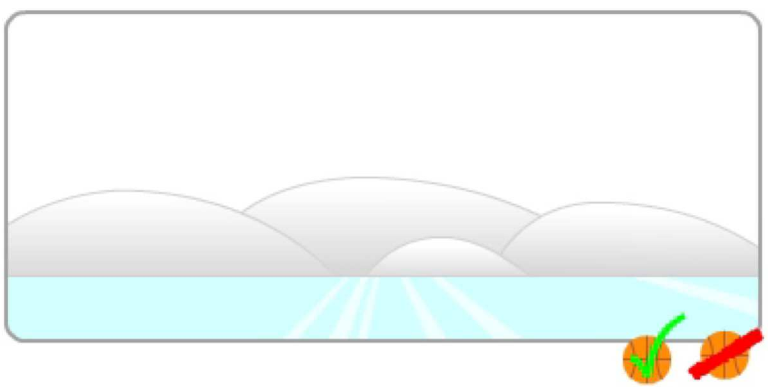
Iron filings “feel” the presence of a magnet



Earth attracts the Moon.

The Unseen Effect





- Even though we cannot see the basketball, we see the effect throwing it has on the two people.

- All interactions which affect matter particles are due to the exchange of force carrier particles

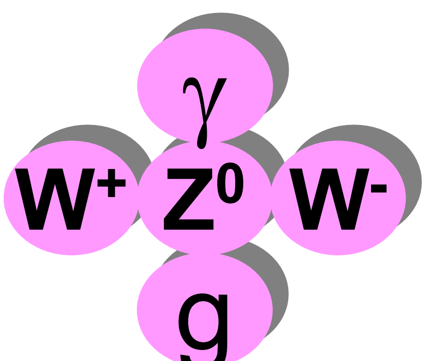
- What we think of as forces, are the effects of the force carrier particles on matter particles

What is the World Made of? What Holds it Together?

Standard Model (~1970)

	Weak	Electromagnetic	Strong
	(Electroweak)		
Carried by	W^+ W^- Z^0	Photon	Gluon
Acts on	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

INTERACTIONS



Higgs

Strong 1

Electromagnetic 10^{-2}

Weak 10^{-6}

Color Charge

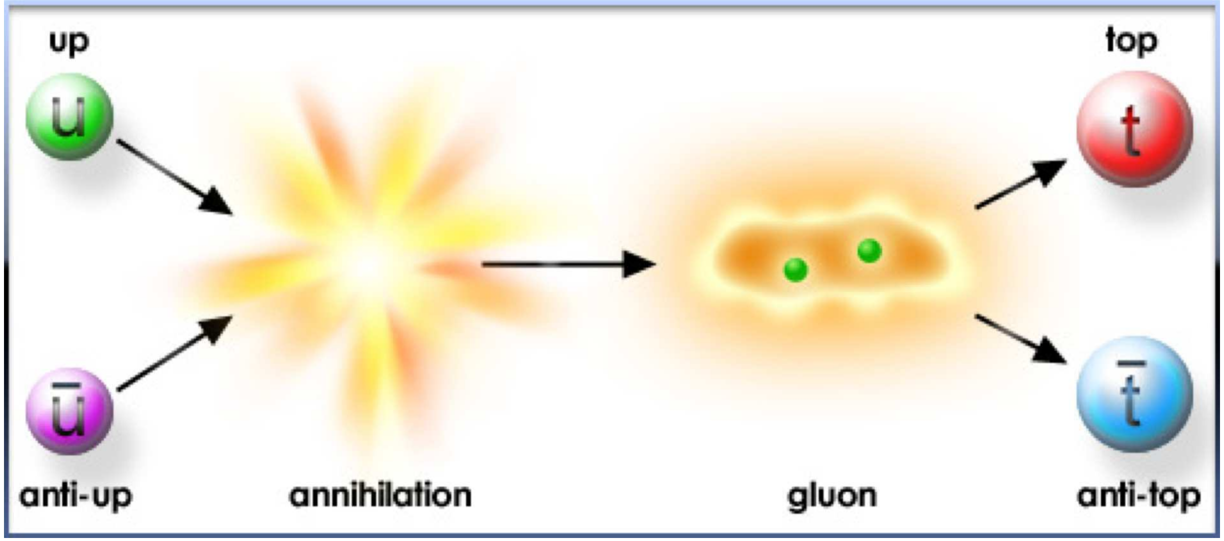
- Quarks and gluons are color-charged particles.
- Quarks constantly change their color charges as they exchange gluons with other quarks.
- This exchange creates a very strong color force field that binds the quarks together.

Color-charged particles cannot be found individually. The color-charged quarks are confined in groups with other quarks. These composites are color neutral.

"Color charge" has nothing to do with the visible colors, it is just a convenient naming convention for a mathematical system

Matter and Antimatter

- For every type of matter particle we've found, there also exists a corresponding antimatter particle, or antiparticle.
- Antiparticles look and behave just like their corresponding matter particles, except they have opposite electric charges.
- Gravity affects matter and antimatter the same way because gravity is not a charged property and a matter particle has the same mass as its antiparticle.

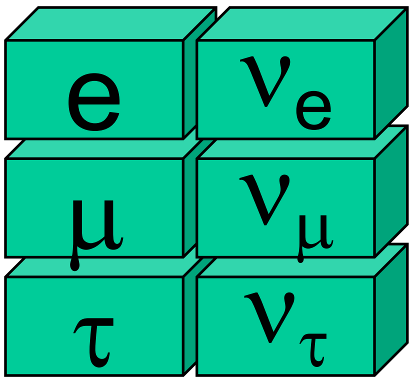


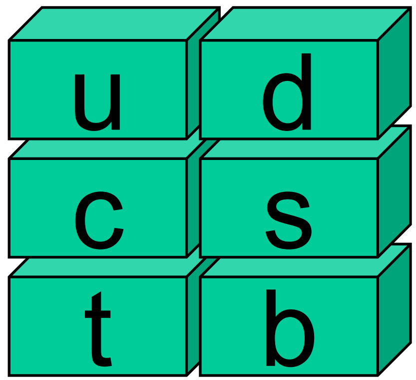
When a matter particle and antimatter particle meet, they annihilate into energy!

What is the World Made of?
What Holds it Together?

Standard Model (~1970)

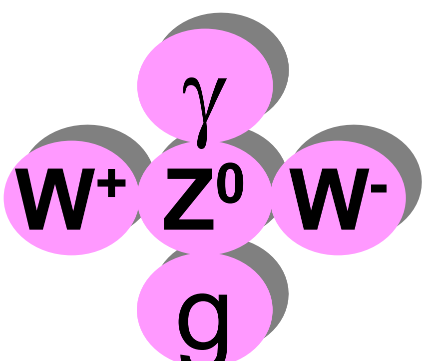
ELEMENTARY CONSTITUENTS





Strong	1
Electromagnetic	10^{-2}
Weak	10^{-6}
Gravity	10^{-40}

INTERACTIONS



Higgs

The Higgs Boson

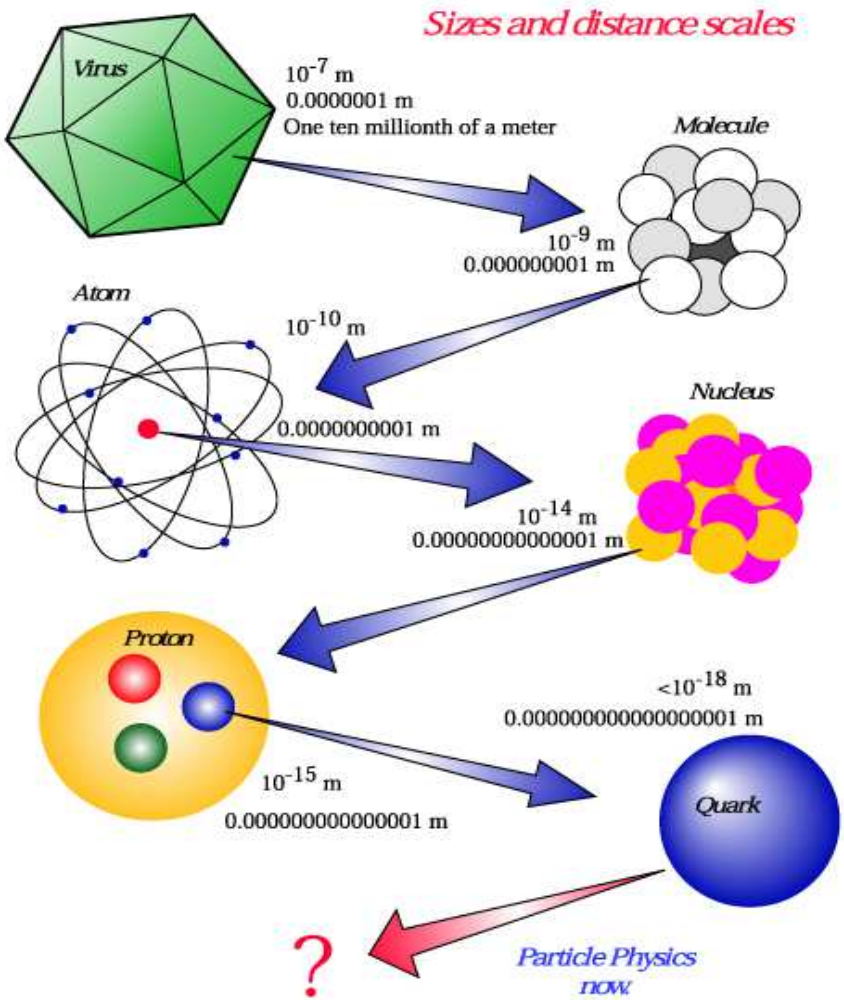
- In the simplest form of the SM, all fundamental particles have zero mass
- However, fundamental particles do have mass. The top quark weighs as much as 170 protons (and is thought to have near-zero size)
- During the 1960's, Peter Higgs and François Englert postulated a physics mechanism which gives all particles their mass
- This mechanism is a field which permeates the universe

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

The Higgs Boson - Explained

Experimental Methods

The World's Meterstick

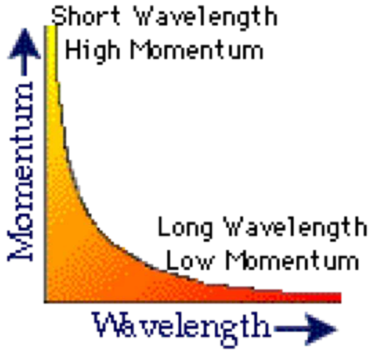


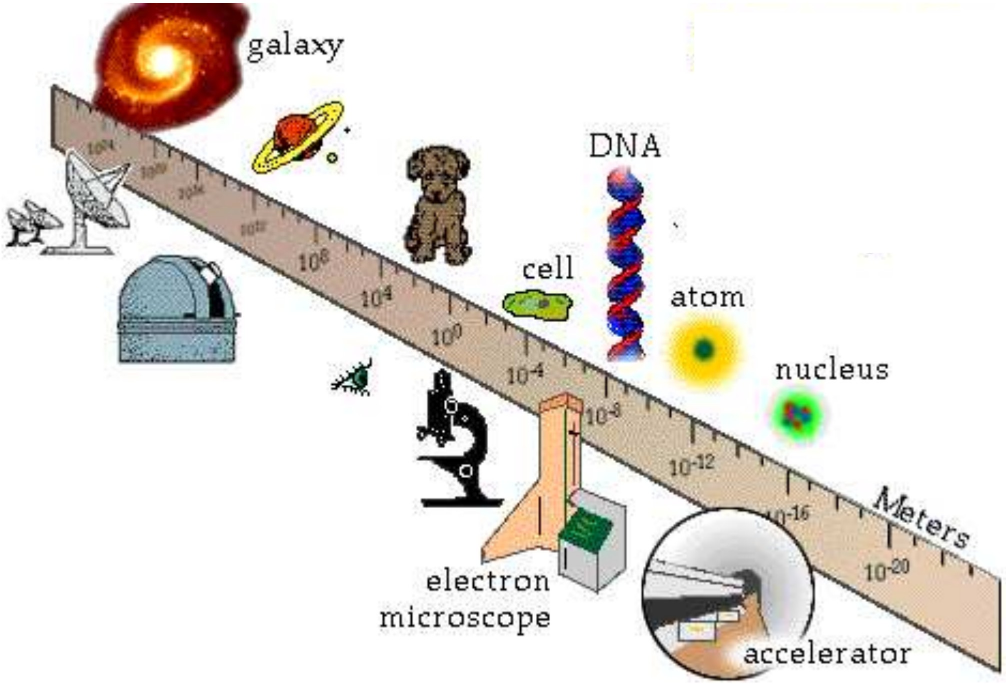
Our model for the ATOM indivisible, fundamental, elementary building block of matter has changed over time as we develop more powerful instruments

Accelerators: the ultimate microscope

- All particles have wave properties
- We need to use particles with short wavelengths to get detailed information about small things

- A particle's momentum and its wavelength are inversely related

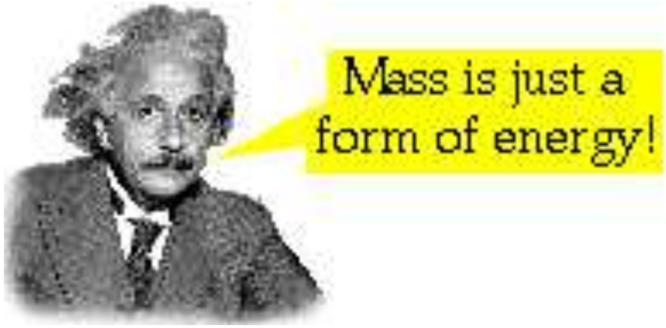


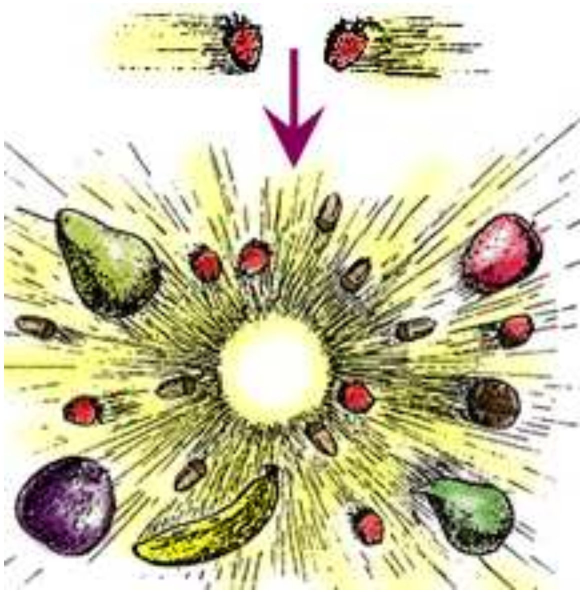


We use particle accelerators to increase the momentum of the probing particle, thus decreasing its wavelength

Energy-Mass Conversion

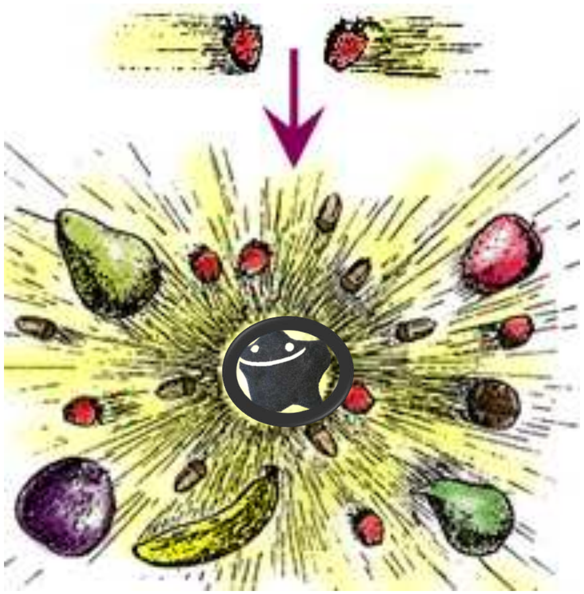
- How can we study massive, unstable particles, such as the top quark or the Higgs Boson?
- We can use Albert Einstein's famous equation $E=mc^2$ and a particle accelerator!





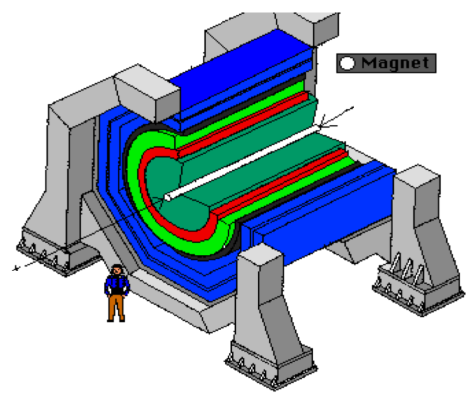
Accelerate low-mass particles to close to the speed of light & convert all that kinetic energy into new massive unstable particles to study their properties

The Event

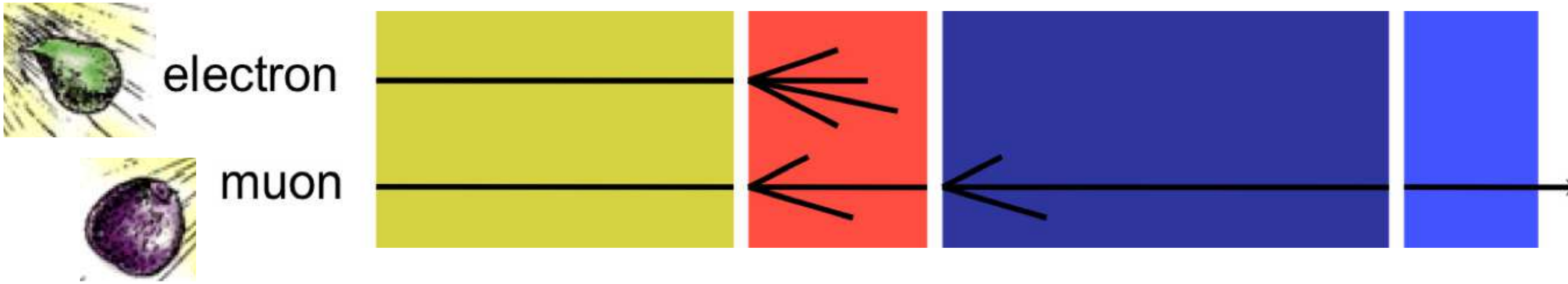


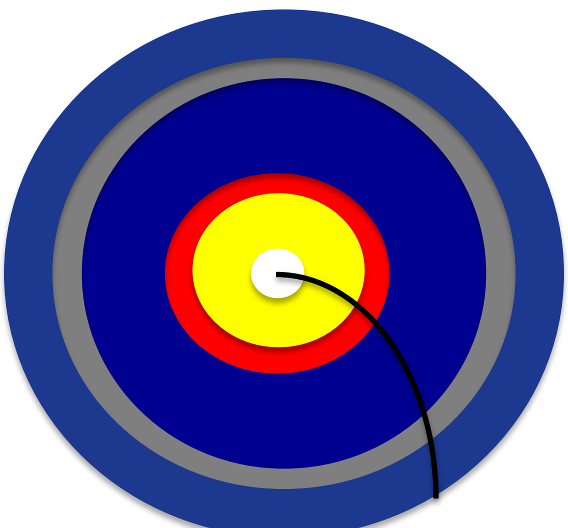
- Each collision between accelerated particles is called an EVENT
- Many particles are created in an event
- Most decay immediately into new stable particles

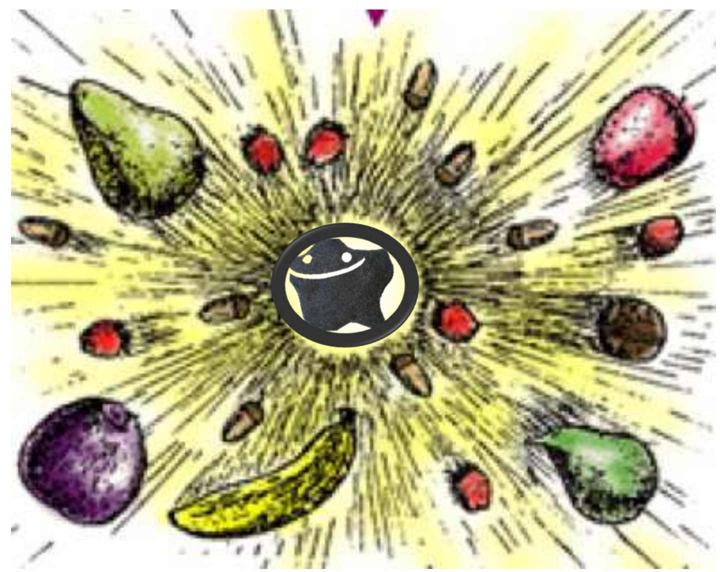
- To look for these various decay products, we use multi-component detectors
- Each component is used to measure the energy of the decay products and to distinguish different particle types
- With all these information we can learn about the particle created in the collision and check if they agree with the theory being tested



Schematic Particle ID







How a Higgs Boson Decays

- Higgs bosons decay to other particles immediately after they are produced. Each possible way is called a decay channel

Higgs $\rightarrow b + \bar{b}$	(b quark and its antiquark)
Higgs $\rightarrow \tau^{+} + \tau^{-}$	(τ lepton and its antiparticle)
Higgs $\rightarrow \gamma + \gamma$	(two photons, also called gammas)
Higgs $\rightarrow W^{+} + W^{-}$	(W boson and its antiparticle)
Higgs $\rightarrow Z^{0} + Z^{0}$	(Two Z bosons)

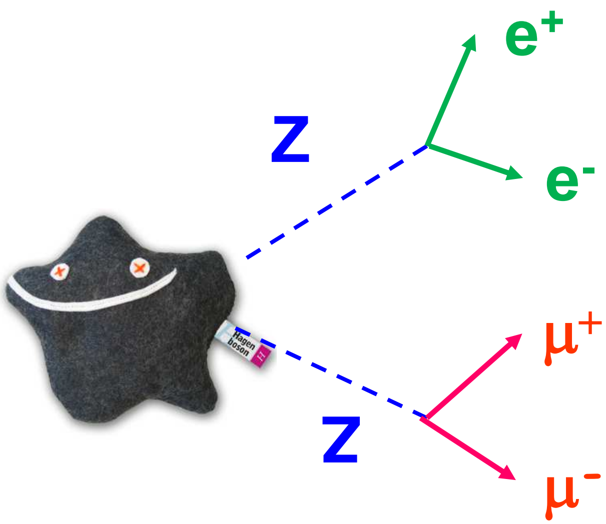
- The $b\bar{b}$ decay channel is the most common. But many other processes can also produce these particles
- We say that the $b\bar{b}$ decay channel has a large background
- The best channel to look for the Higgs is ZZ

Easy to Detect Higgs to ZZ

- Both the Higgs and the Z bosons decay immediately after being produced
- We only see the electrons and muons in our detectors
- The 4 possible combinations are

$$H \rightarrow Z + Z^* \rightarrow e^+ + e^- + e^+ + e^-$$
$$H \rightarrow Z + Z^* \rightarrow e^+ + e^- + \mu^+ + \mu^-$$
$$H \rightarrow Z + Z^* \rightarrow \mu^+ + \mu^- + e^+ + e^-$$
$$H \rightarrow Z + Z^* \rightarrow \mu^+ + \mu^- + \mu^+ + \mu^-$$

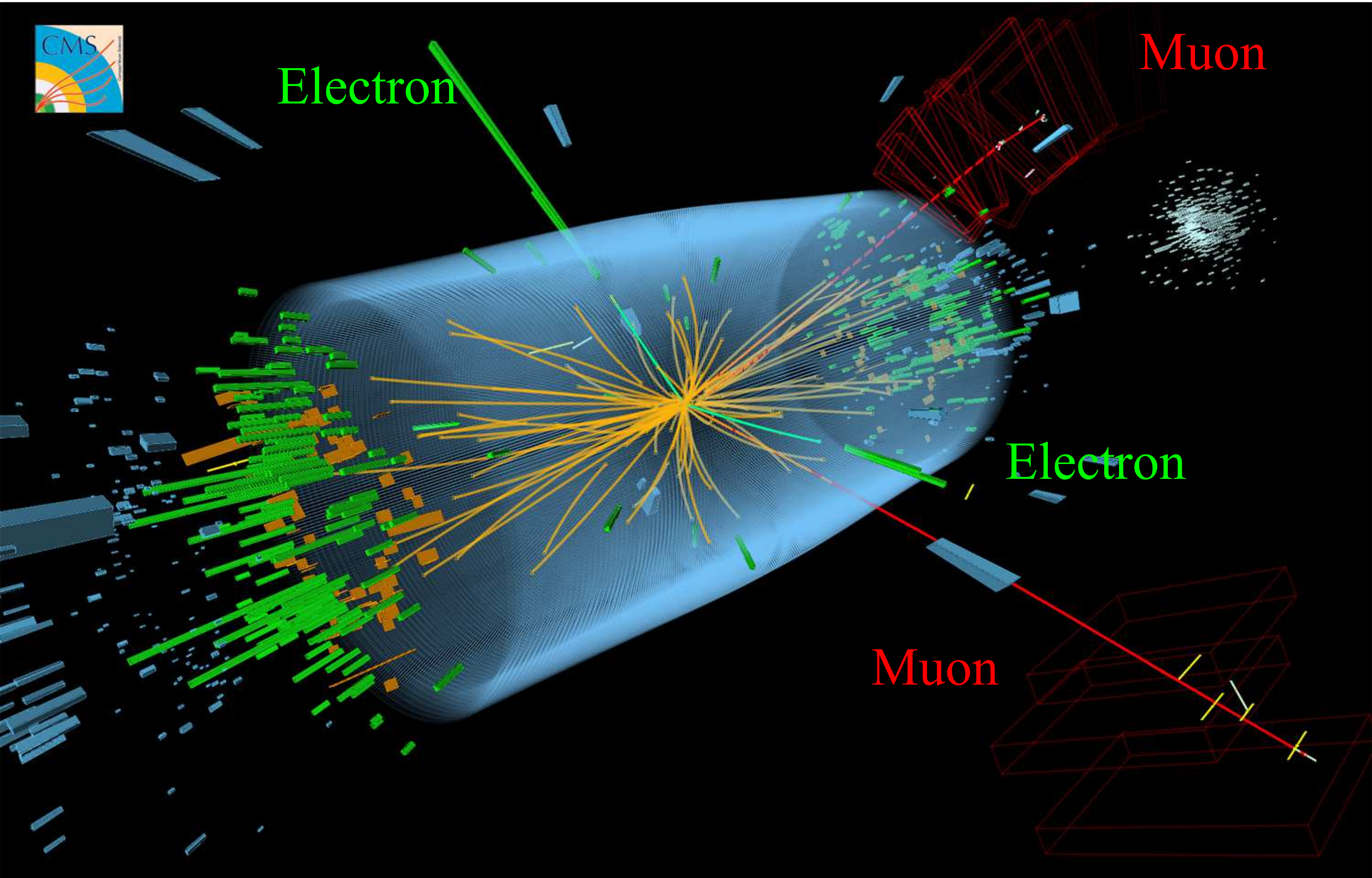
- Need to look for events with 4 muons, or 4 electrons, or 2 muons and 2 electrons



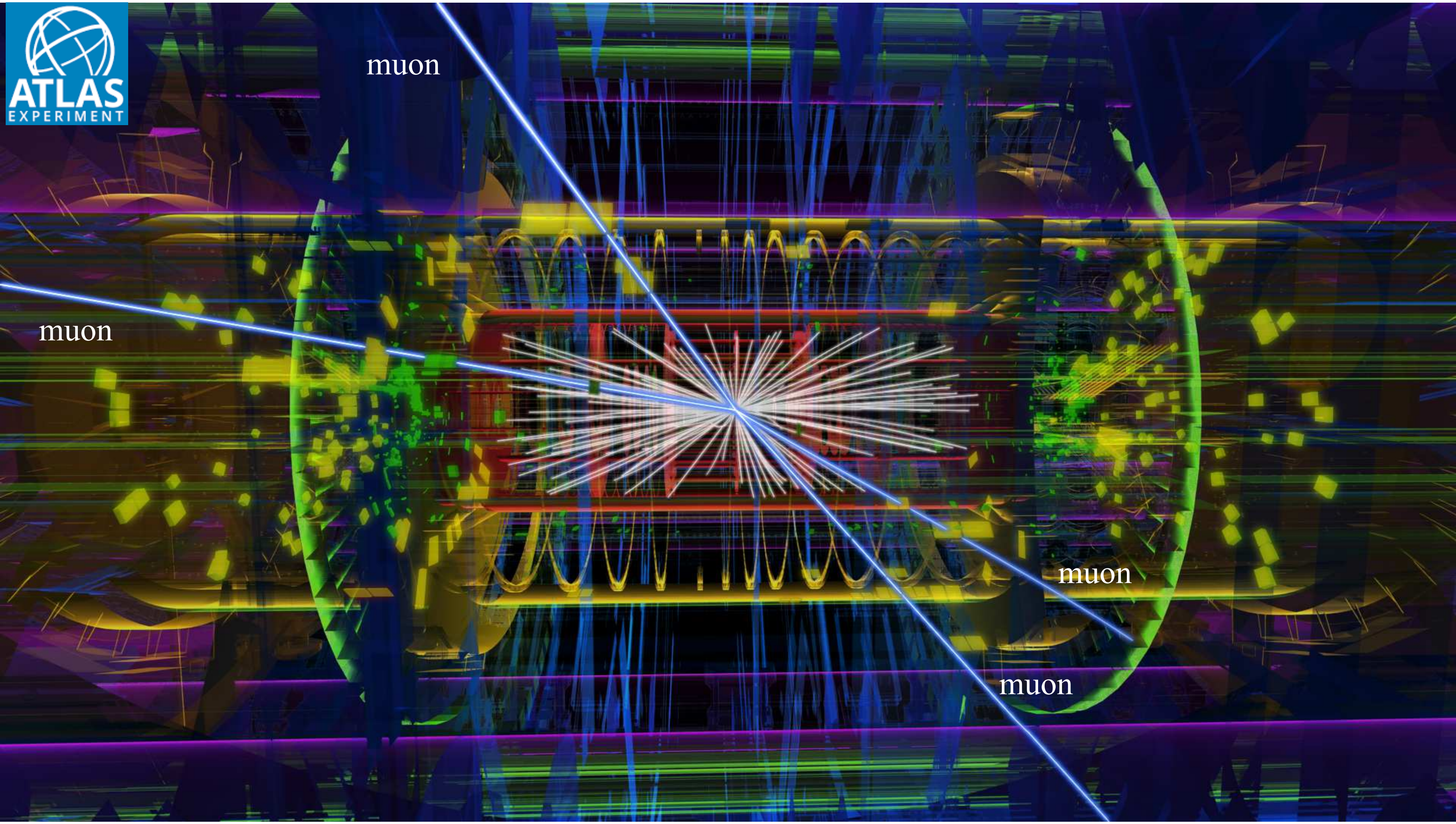
The mass of the Higgs boson can be calculated combing the mass and energy of the decay products (electrons and muons)

$$E^2 = p^2c^2 + m^2c^4$$

$H \to ZZ \to e^+e^- \mu^+\mu^-$ Candidate



$H \rightarrow ZZ \rightarrow \mu^+\mu^- \mu^+\mu^-$ Candidate

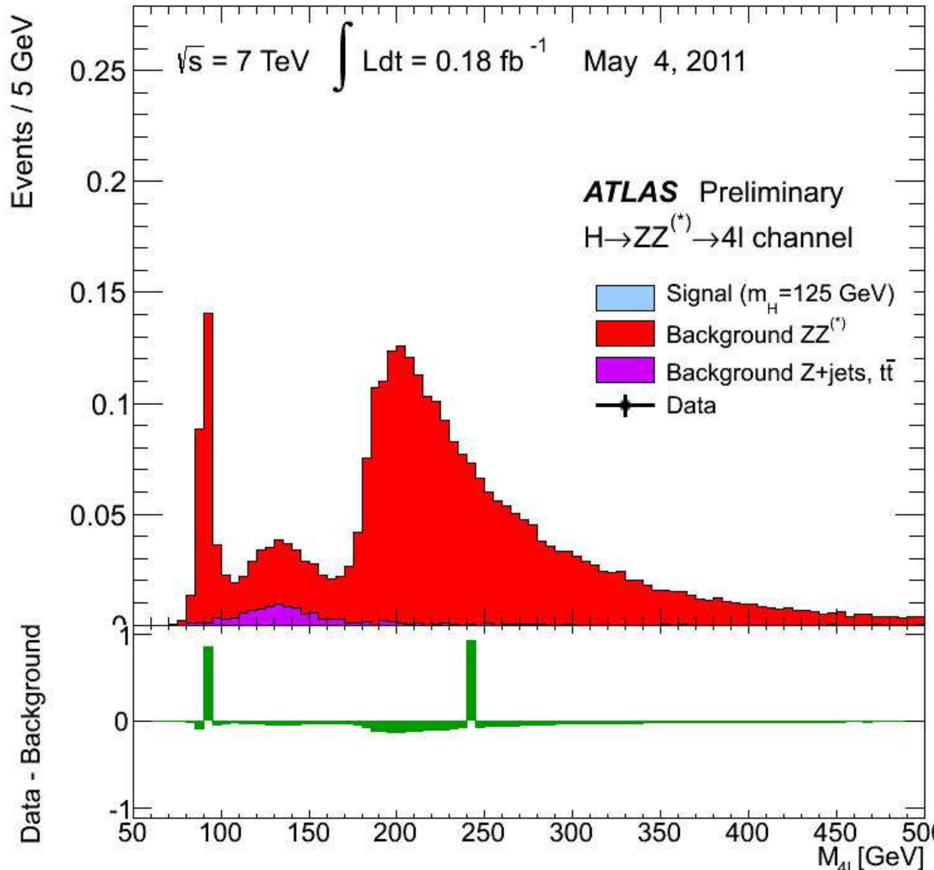


The Mass Histogram

$$e^+ + e^- + e^+ + e^-$$
$$e^+ + e^- + \mu^+ + \mu^-$$
$$\mu^+ + \mu^- + e^+ + e^-$$
$$\mu^+ + \mu^- + \mu^+ + \mu^-$$

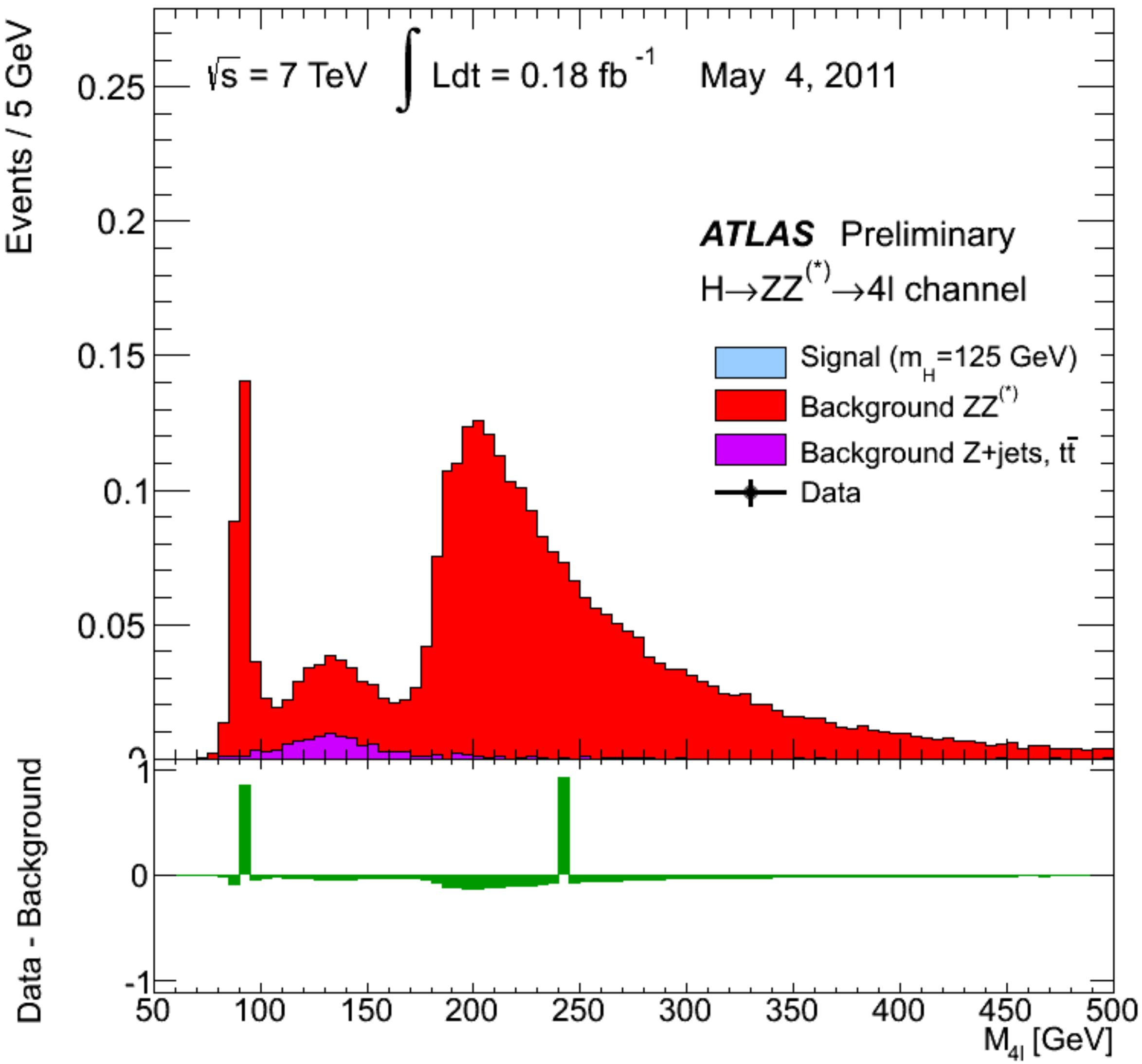
$$E^2 = p^2c^2 + m^2c^4$$

- The four possible decay product combinations could come from the decay of a Higgs boson or from the decay of other processes (background)
- Need to look at a large number of events and plot the number of times each value of the mass occurs

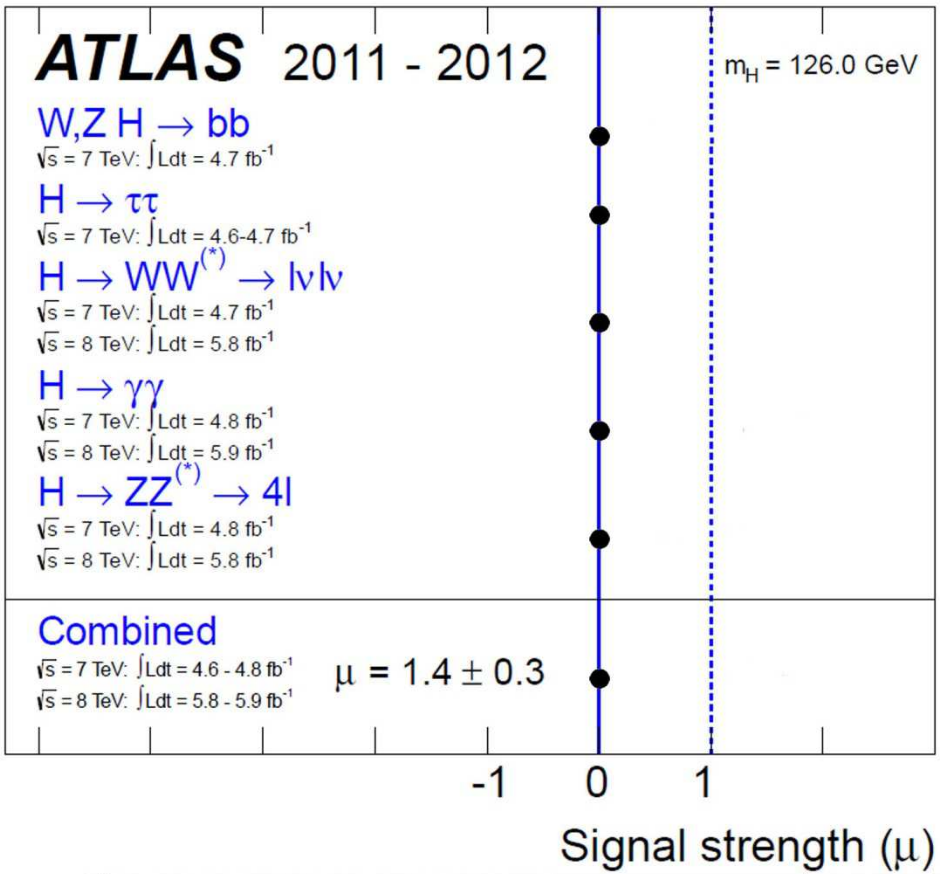


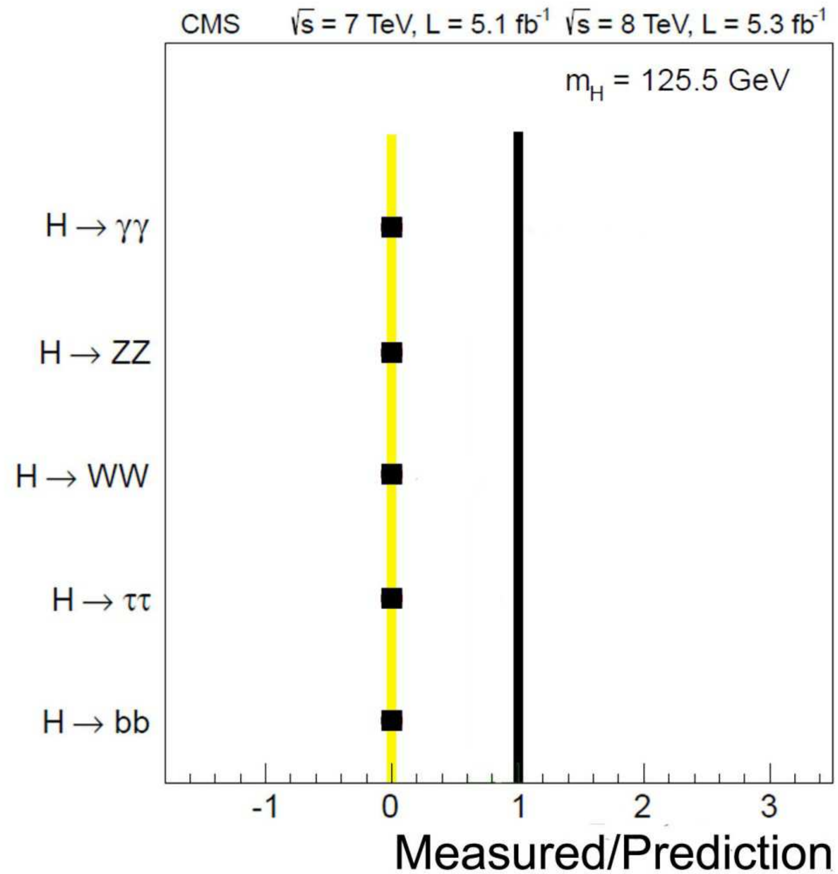
Predicted Background: number of 4 lepton events we expect to occur from decays not involving a Higgs boson

Time Evolution of Higgs Boson Data



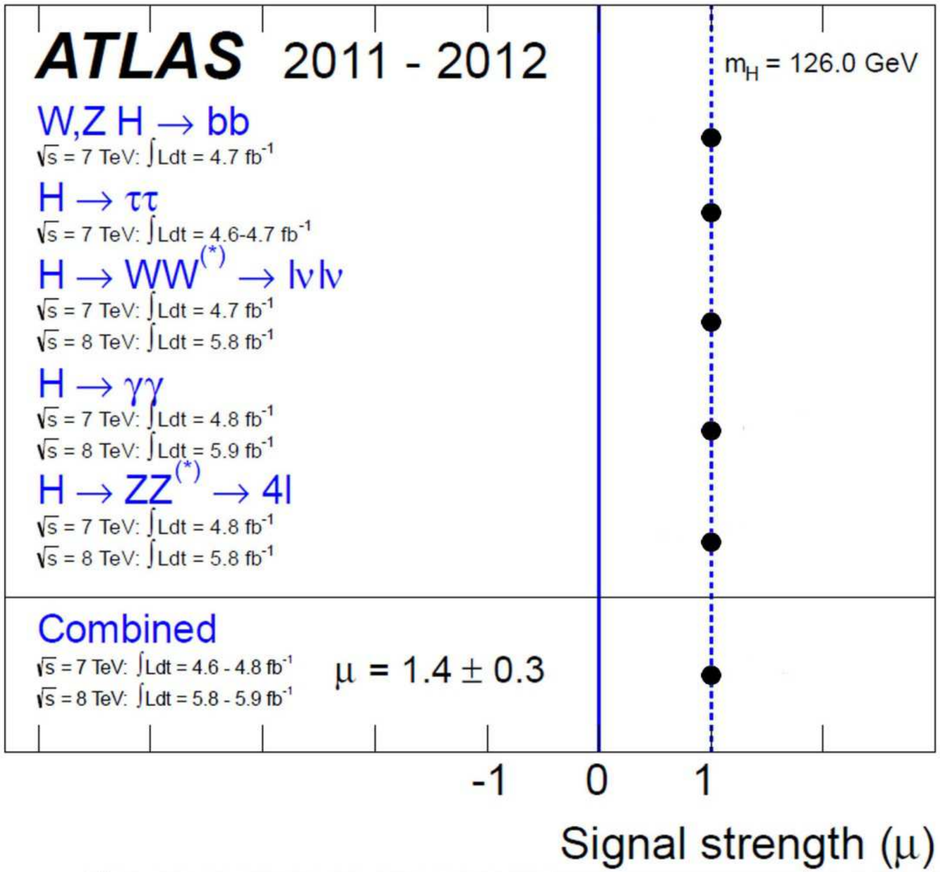
Results if no Higgs

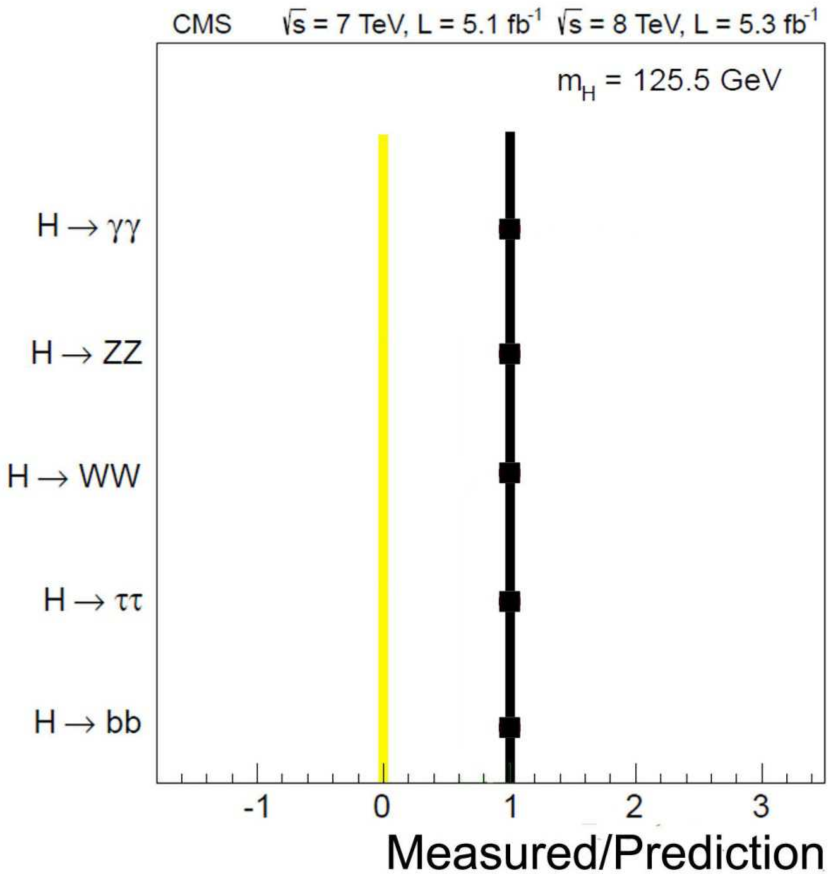




Ratio of Measurement to Standard Model Prediction

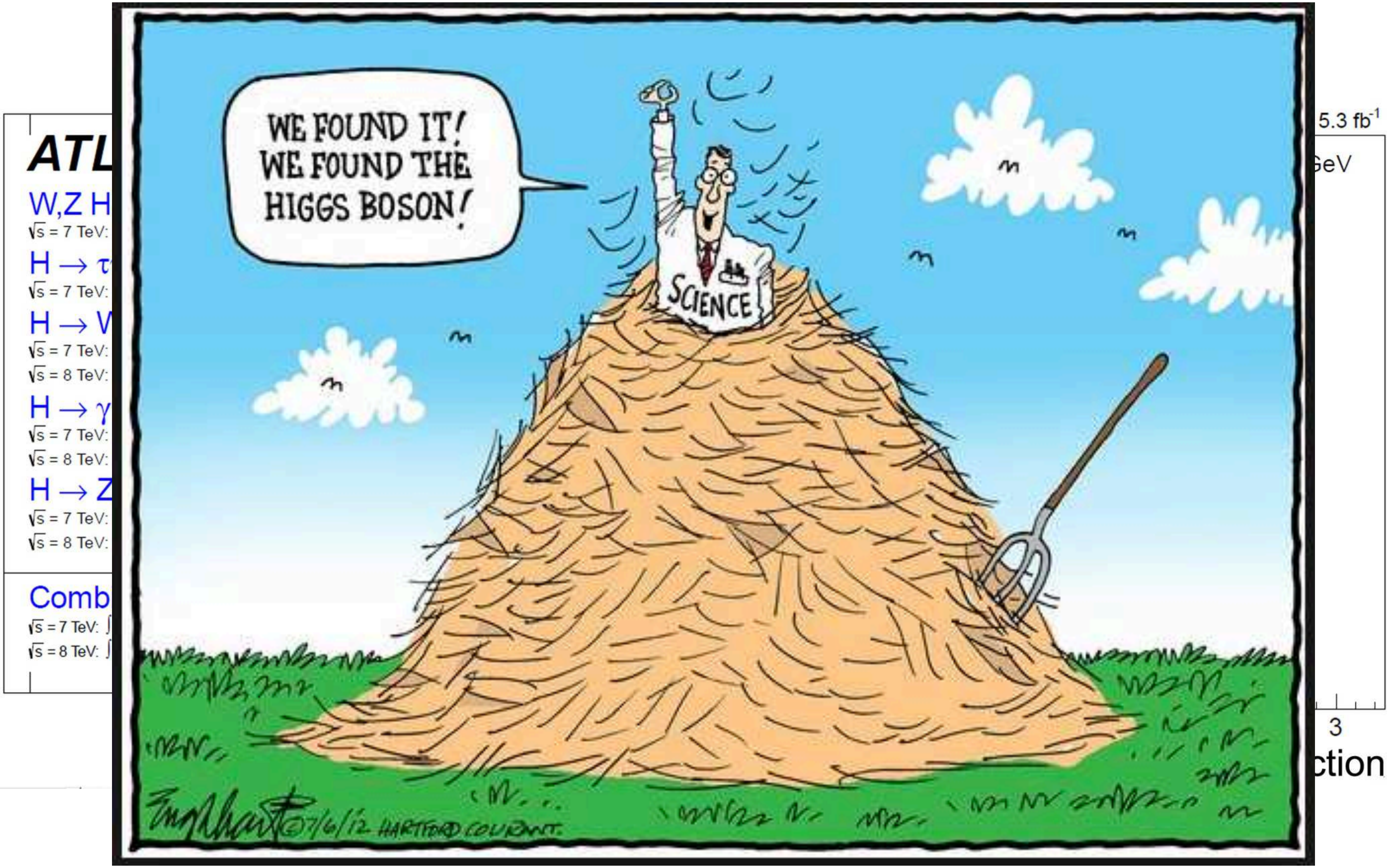
Results with Higgs





Ratio of Measurement to Standard Model Prediction

July 2012 Results



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

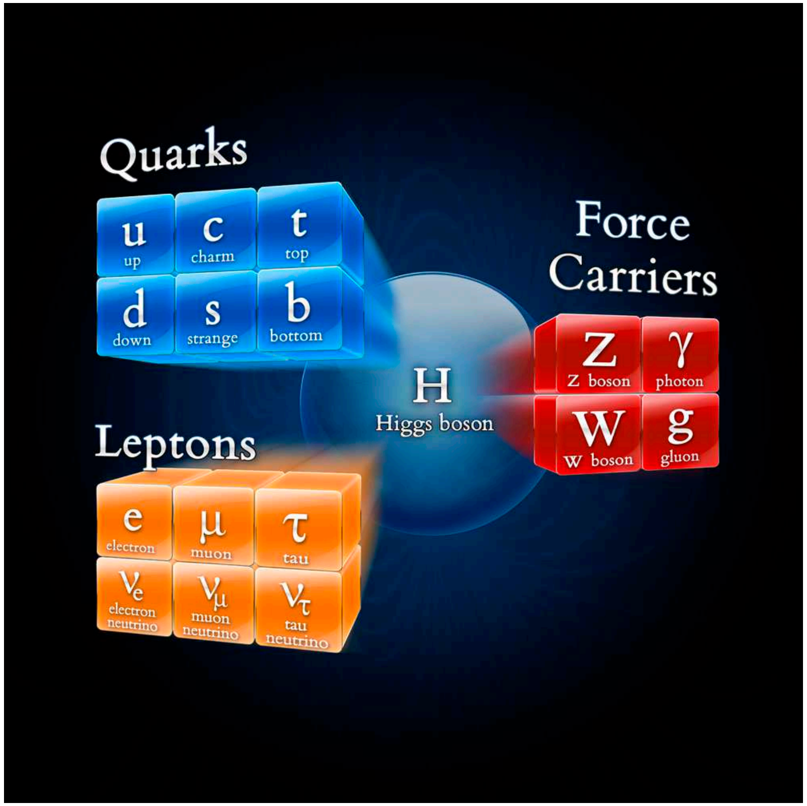
• electron	1897	Thomson	1906 Nobel Prize
• e-neutrino	1956	Reactor	1995 Nobel Prize
• muon	1937	Cosmic Rays	
• mu-neutrino	1962	BNL	1988 Nobel Prize
• tau	1976	SLAC	1995 Nobel Prize
• tau-neutrino	2000	Fermilab	First direct evidence

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 Fermilab	
Force Carriers	•Photon	1905	Planck/Einstein	1918/1921 Nobel Prizes
	• Gluon	1979	DESY	
	• W/Z	1983	CERN	1984 Nobel Prize
	•Higgs Boson	2012	CERN	2013 Nobel Prize

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

Summary of what we have learnt

- The building blocks of matter are quarks and leptons
- There are force carrier particles associated with each force
- The Higgs mechanism is responsible for the mass of the particles



The Standard Model is the most complete explanation of the fundamental particles and interactions to date

Why are we not satisfied?

- Why are there exactly three generations of quarks and leptons?
- Are quarks and leptons actually fundamental, or made up of even more fundamental particles?
- Why can't the Standard Model predict a particle's mass?
- How come neutrinos have mass?

- Why do we observe matter and almost no antimatter if we believe there is a symmetry between the two in the universe?
- What is this "dark matter" that we can't see that has visible gravitational effects in the cosmos?

- How does gravity fit into all of this?

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 continues to take data at a higher center of mass energy
  - What will we find?

Compositeness

Dark Matter?

ergy?

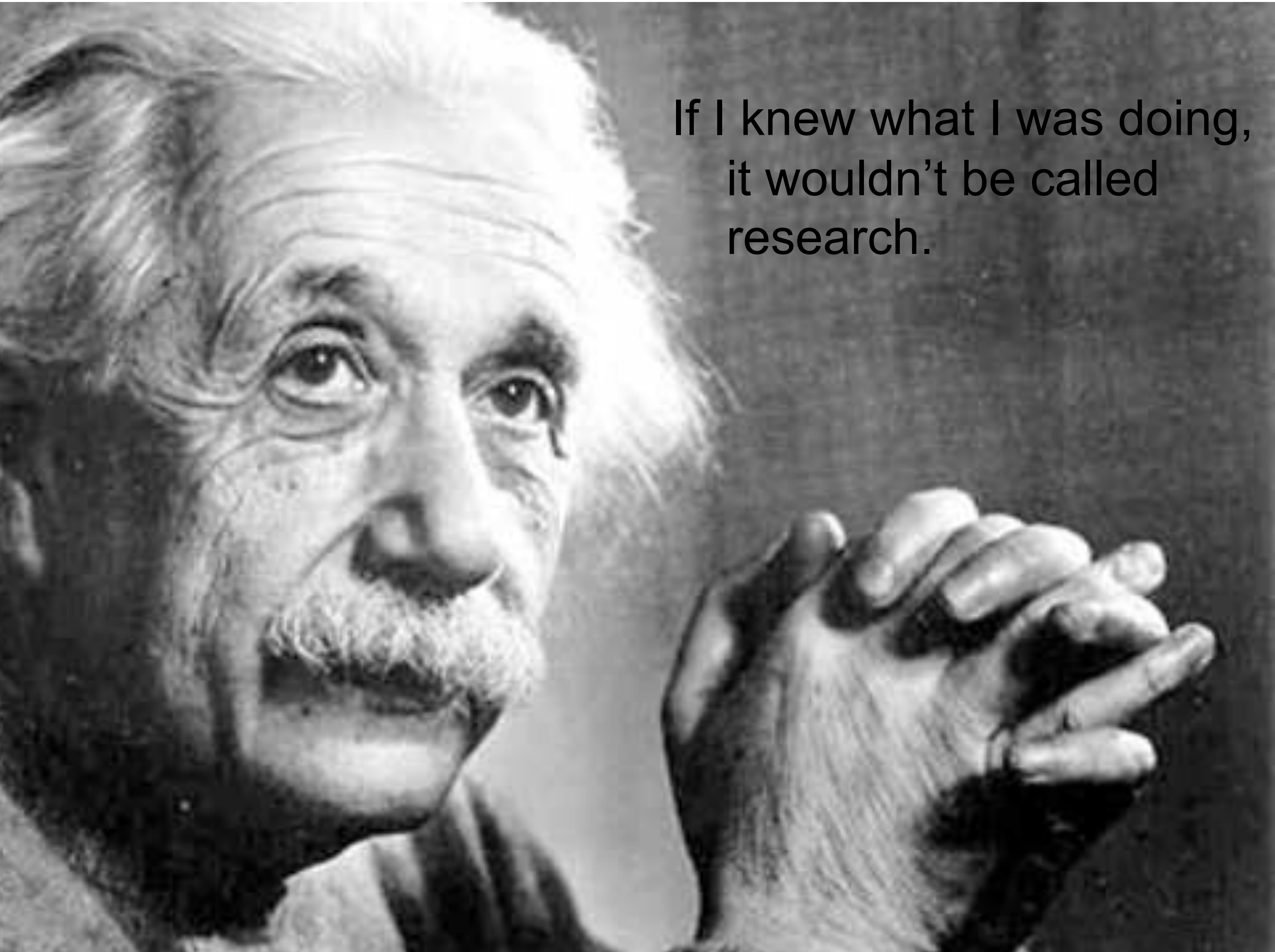
S

Black

W'? Z'?

Extra di ensions?

Something totally unexpected?


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

Credits

- The CMS and ATLAS collaborations
- Fermi National Accelerator Laboratory
- CERN
- The Particle Adventure – Lawrence Berkeley National Lab