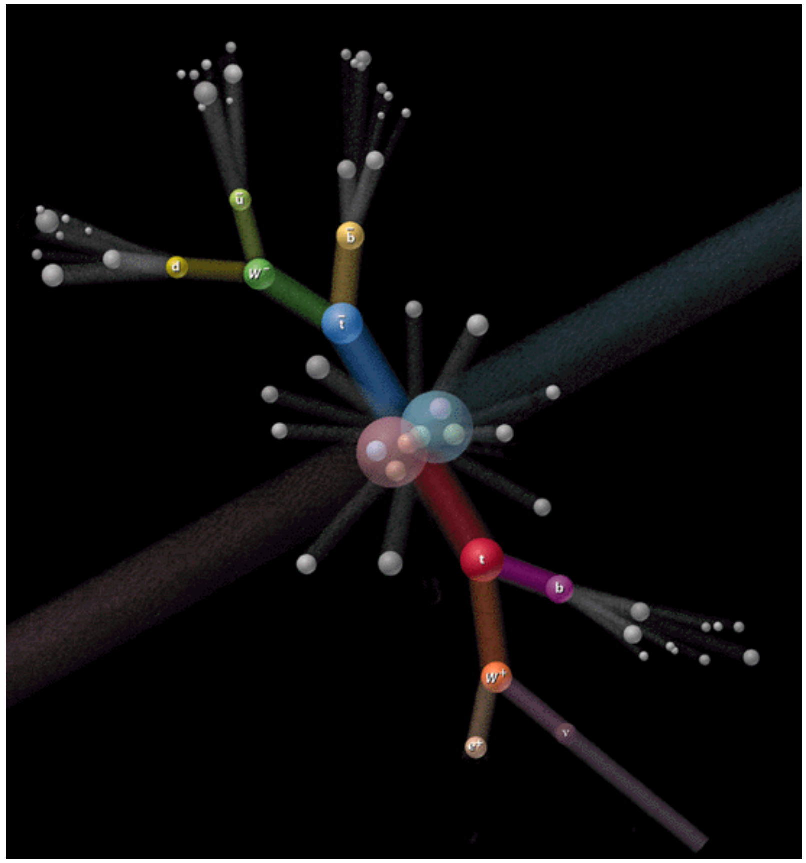
Fundamental Particles, Fundamental Questions



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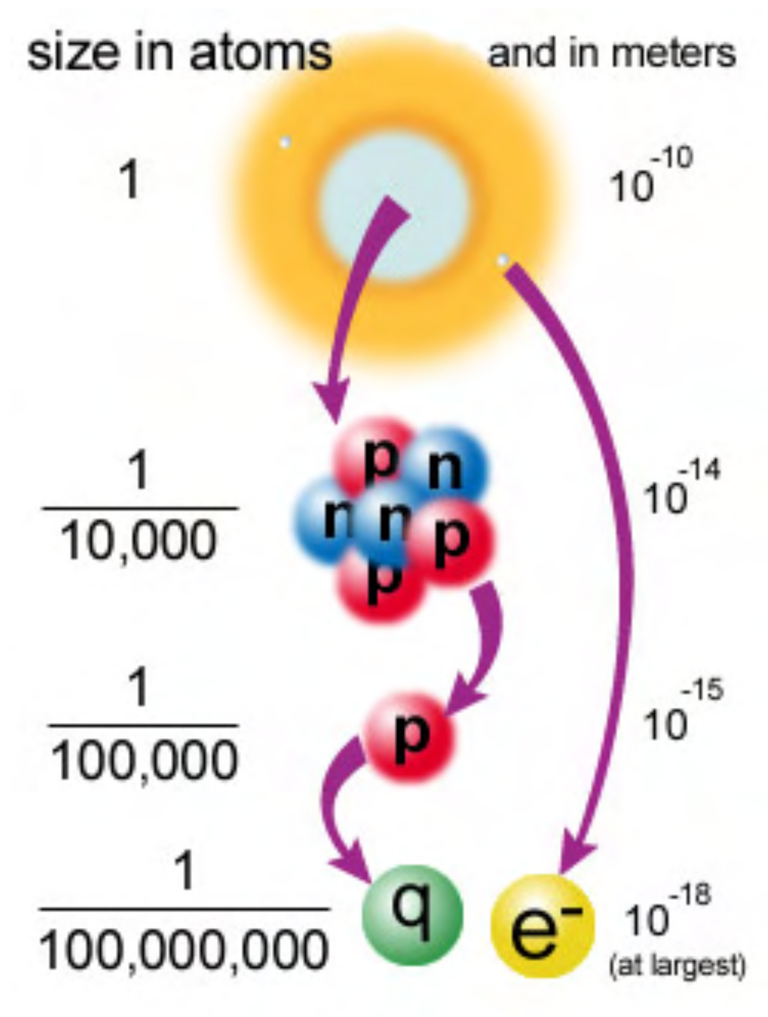
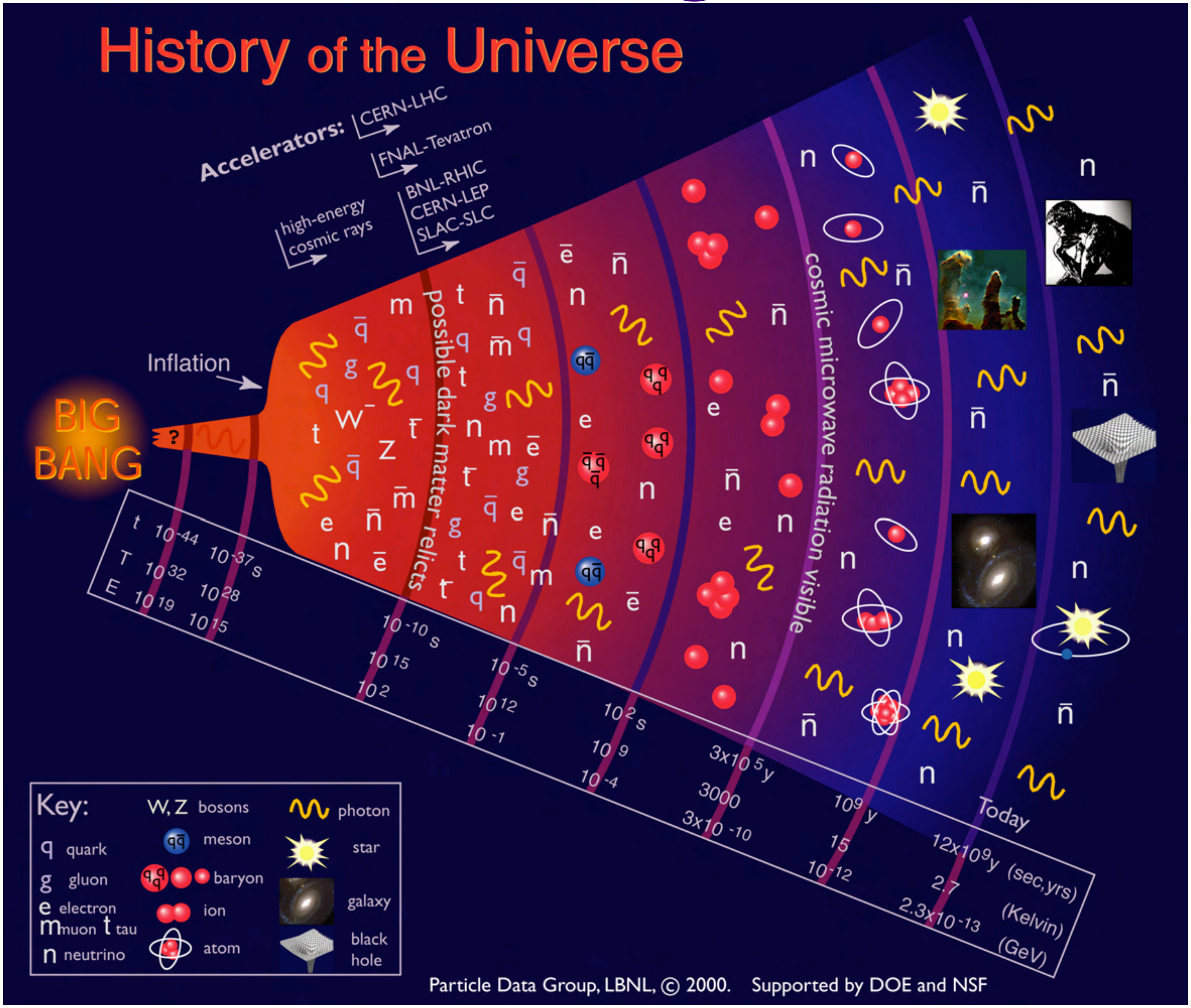
The smallest pieces of matter…

- **Nuclear physics** and **particle physics** study the smallest known building blocks of the physical universe -- and the interactions between them.
- The focus is on single particles or small groups of particles, not the billions of atoms or molecules making up an entire planet or star.



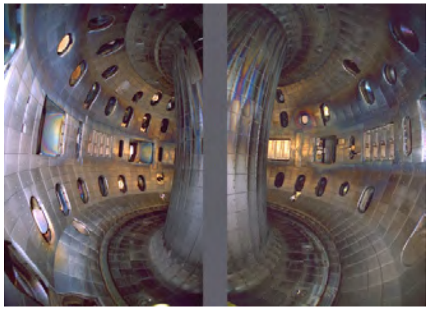
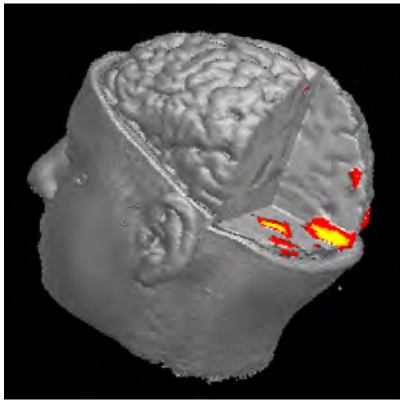
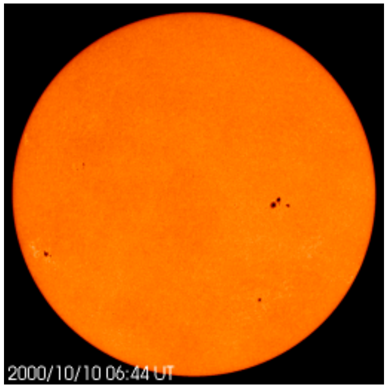
particleadventure.org

… and their large effects …



… affect us all.

- History: alchemy, atomic weapons
- Astronomy: sunshine, "metals", cosmology
- Medicine: PET, MRI, chemotherapy
- Household: smoke detectors, radon
- Computers: the World-Wide Web
- Archaeology & Earth Sciences: dating

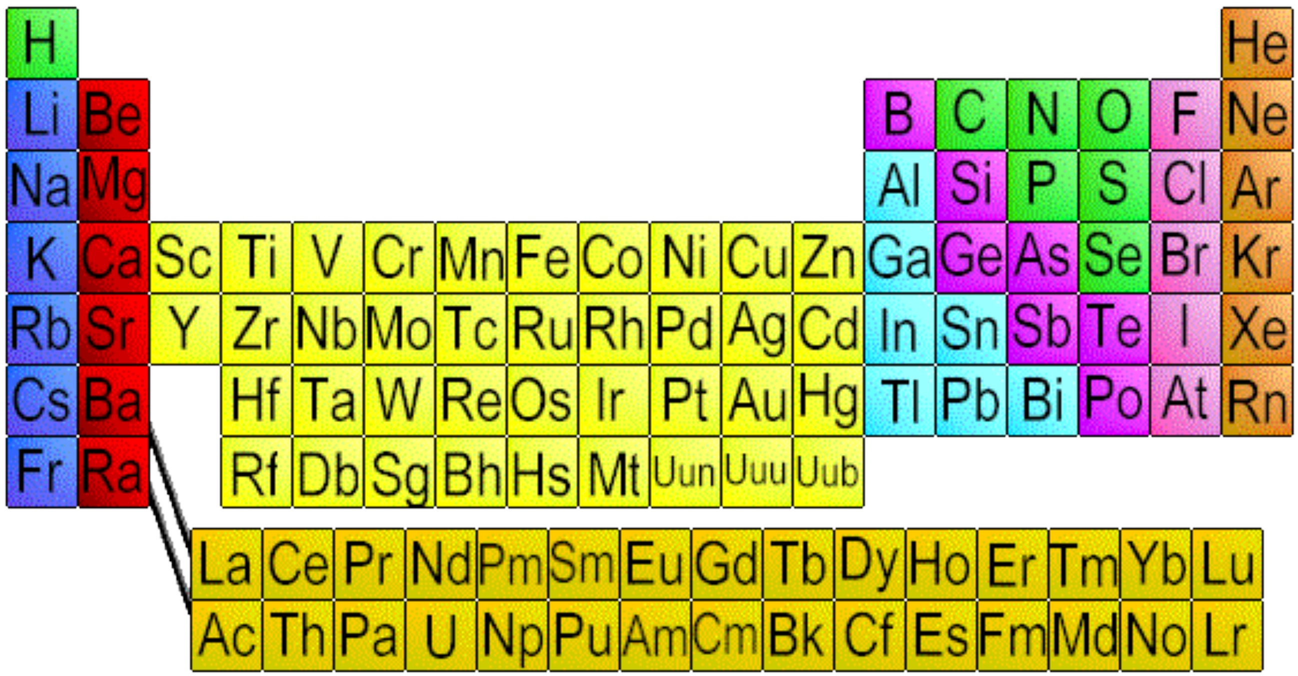

Atoms

Classifying the composition of objects at the atomic level is now a familiar process.

This ring, for example, is made up of only 2 kinds of atoms: gold (**Au**) and carbon (**C**)

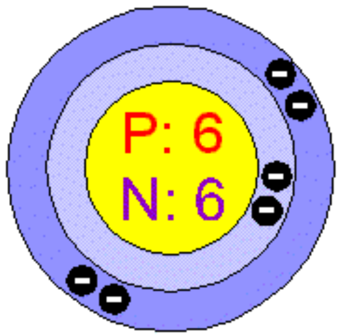
Periodic table

The periodic table lists about 114 atoms with distinct properties: mass, crystal structure, melting point…



The range and pattern of properties reflects: the internal structure of the atoms.

Inside Atoms: neutrons, protons, electrons



Carbon (C)

Atomic number Z=6

(number of protons)

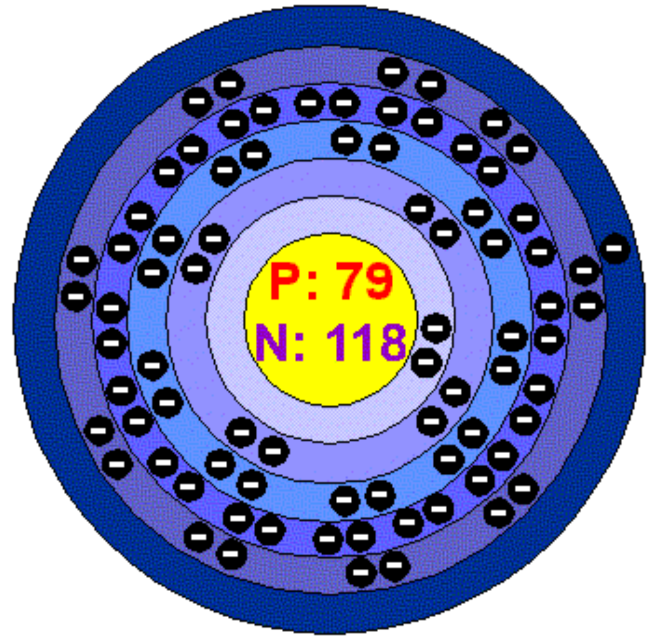
Mass number A=12

(number of protons + neutrons)

electrons = # protons

(count them!)

(atom is electrically neutral)



Gold (Au)

Atomic number Z = 79

Mass number A = 197

#electrons = # protons

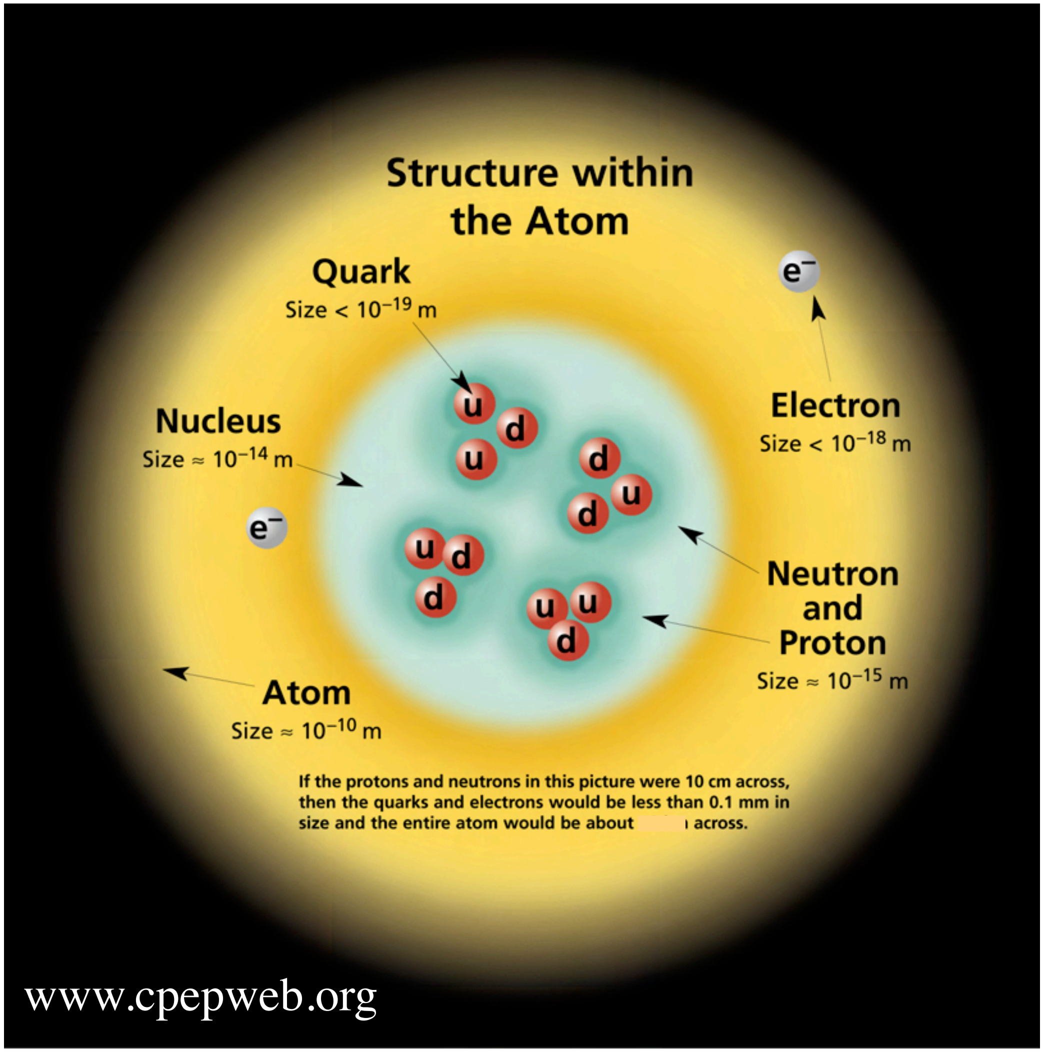
(trust me!)

Properties of nucleons

Name	Mass	Electric Charge
Proton	1 GeV	+1
Neutron	1^+ GeV	0

- Units:
  - **The electric charge of an electron is -1 in these units.**
  - **Mass units are "billion electron volts" where 1 eV is a typical energy spacing of atomic electron energy levels**.
- Question: Why are the masses nearly the same but the electric charges so different?

Further layers of substructure:



u quark:
electric charge = 2/3

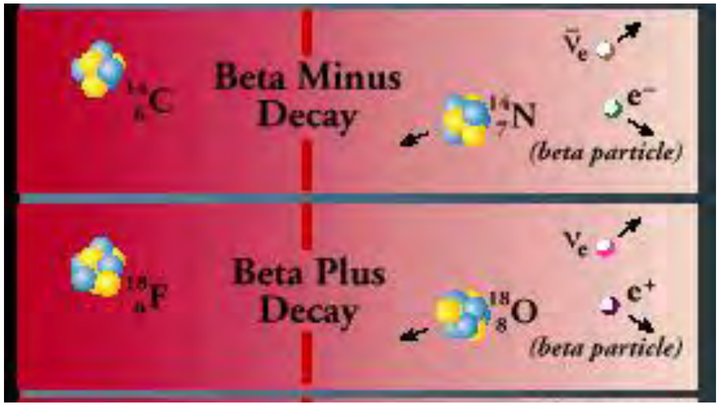
d quark:
electric charge = -1/3

Proton = **uud**
electric charge = 1

Neutron = **udd**
electric charge = 0

If each proton were 10 cm across, each quark would be .01 mm in size and the whole atom would be: 10 km wide.

Introducing the neutrino



Another subatomic particle, the **neutrino**, plays a crucial role in radioactive decays like

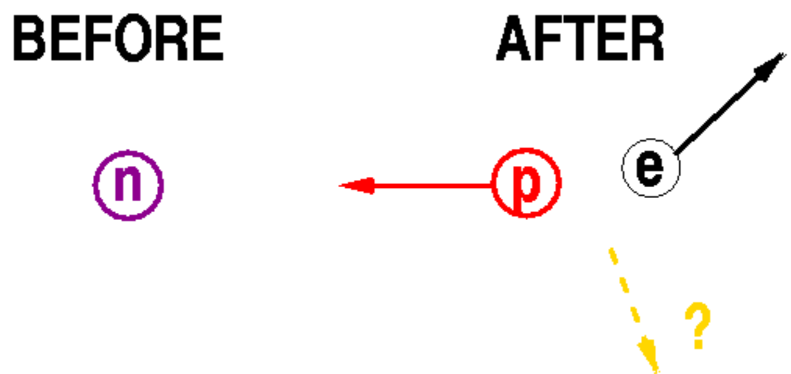
$n \rightarrow p^+ + e^- + \bar{\nu}_e$

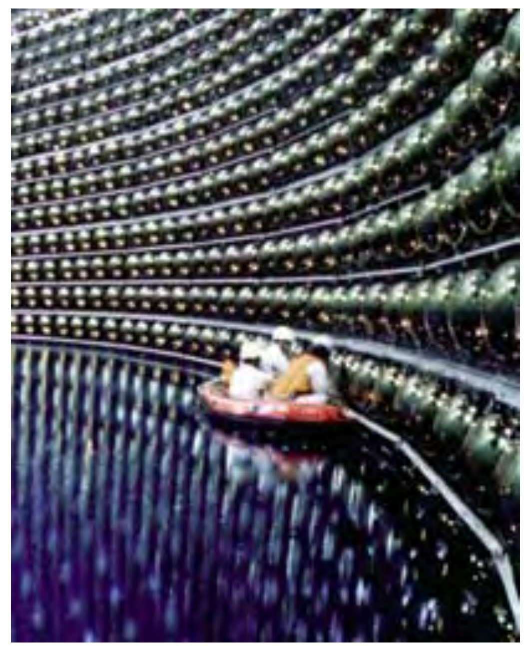
The ν_e (electron-neutrino) is closely related to the electron but has strikingly different properties.

Name	Mass	Electric Charge
electron	0.0005 GeV	-1
electron-neutrino	< 0.00000001 GeV	0

How to detect neutrinos?

- Their existence was inferred by Pauli in 1930. E.g., without **neutrinos**, radioactive decays would not conserve energy or momentum.
- The 2002 Physics Nobel prize to Davis & Koshiba was for detecting **neutrinos** emitted by fusion in our sun.





www.nobel.se/physics/laureates/2002/press.html

Exotic Matter Particles

Other subatomic matter particles are heavier copies of those which make up ordinary atoms (u, d, e, v_e)

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

Sub-atomic interactions

- **Two familiar kinds of interactions are**
  - **gravity (masses attract one another)**
  - **electromagnetism (same-sign electric charges repel, opposite-sign charges attract)**

More exotic phenomena hint at new interactions peculiar to the subatomic world:

- **What binds protons together into nuclei ?**

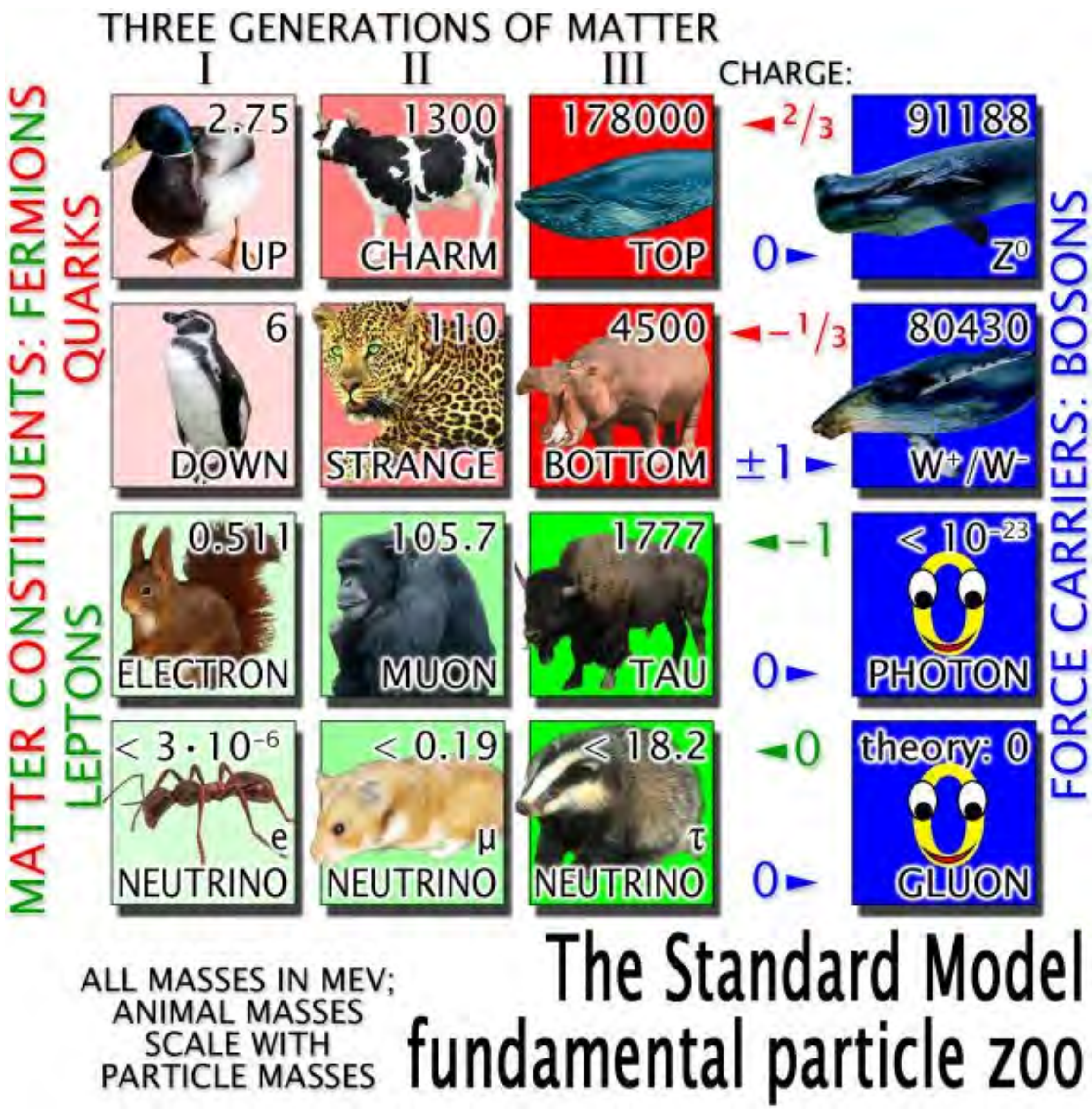
  Must be a force strong enough to overcome repulsion due to protons' electric charge

- **What causes radioactive decays of nuclei ?**

  Must be a force weak enough to allow most atoms to be stable (long-lived).

Force	Strength	Carrier	Physical effect
Strong nuclear	1	Gluons	Binds nuclei
Electromagnetic	.001	Photon	Light, electricity
Weak nuclear	.00001	Z^0, W^+, W^-	Radioactivity
Gravity	10^{-38}	Graviton?	Gravitation

Subatomic particles interact by exchanging integer-spin "boson" particles. The varied interactions correspond to exchange of bosons with different characteristics.



e4.physik.uni-dortmund.de/bin/view/ATLAS/Bildergalerie

Mass Mysteries

Broken Mass Symmetries:

Flavor

Why do fermions with the same charge have different masses?

Electroweak

Why are the W & Z bosons heavy while the photon is massless?

Higgs Mechanism

The Standard Model of particle physics postulates a particle called the Higgs boson, whose interactions give rise to all mass:

- During an earlier epoch of our universe, all the known elementary particles were massless.
- The Higgs boson triggered a phase transition (as when water freezes into ice) which caused all particles interacting with the Higgs boson to become massive.
- **The W and Z bosons and the fermions are massive because they interact with the Higgs boson.**
- The photon and gluon remain massless because they do not interact directly with the Higgs boson.

A variety of masses:

The Higgs field would form a uniform background within the universe. Each particle would interact with the Higgs boson to a different degree.

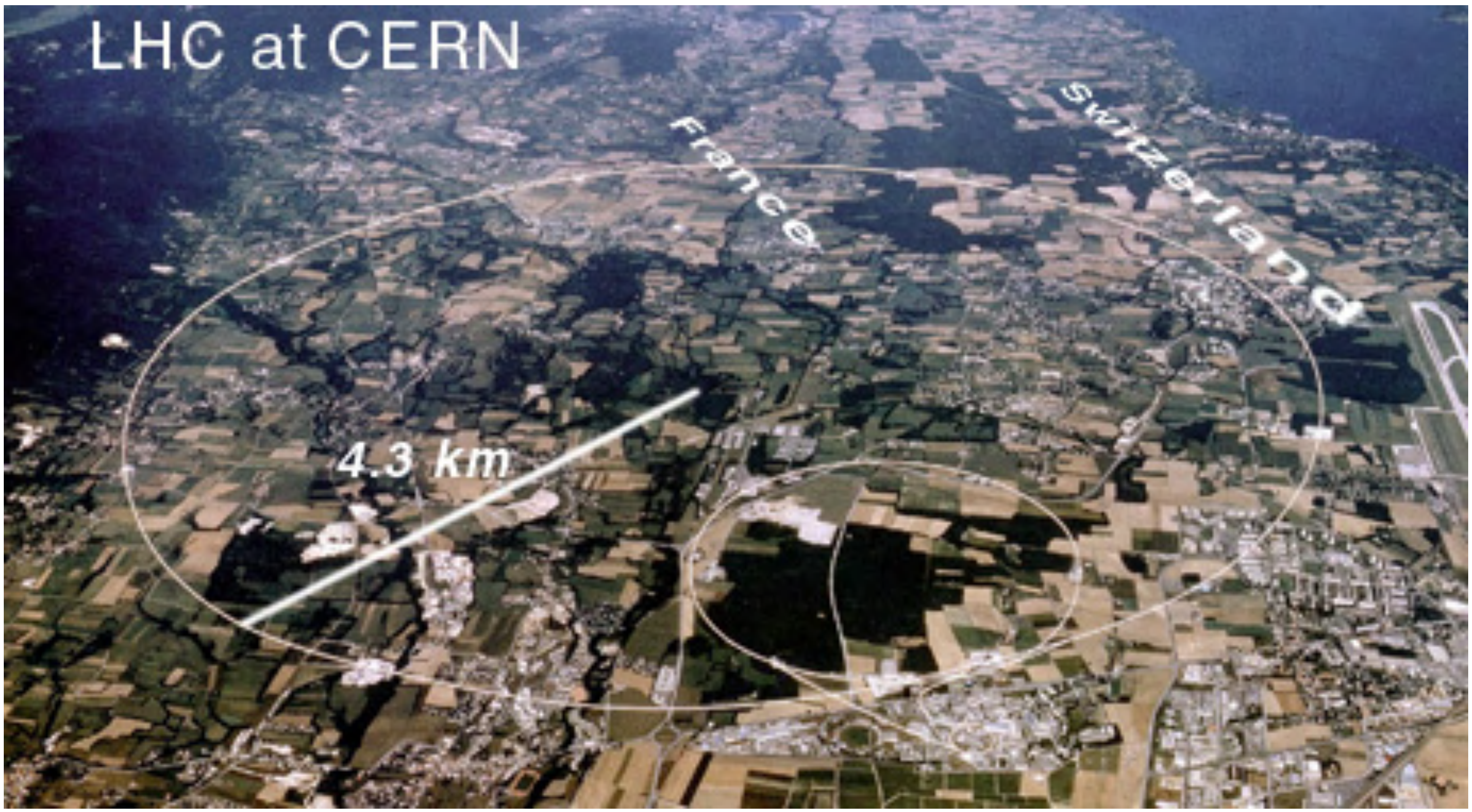
The more strongly a particle interacted with the Higgs, the more mass it would gain and the more inertia it would display

Where is the Higgs Boson?

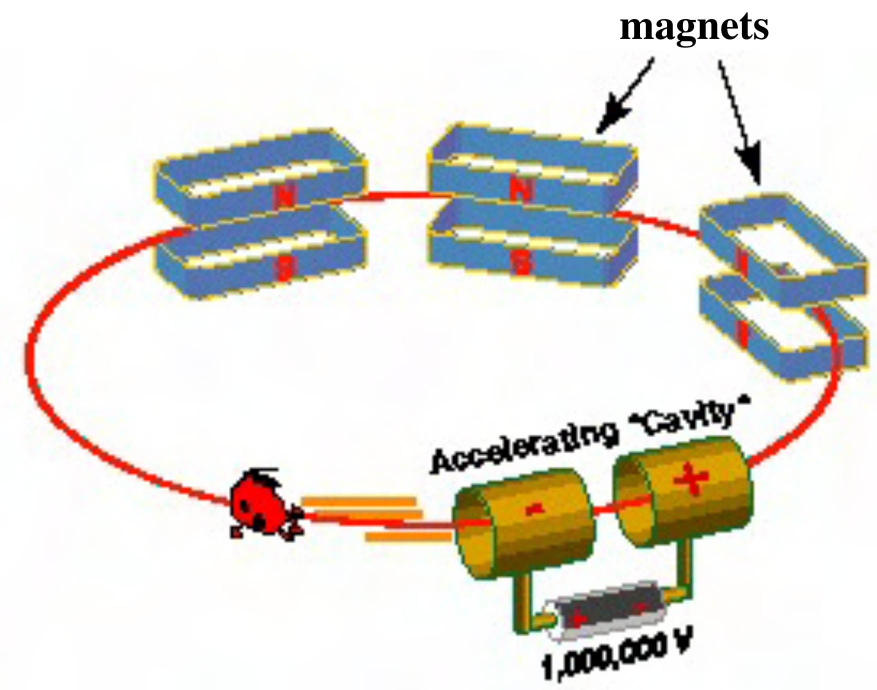
- If this theory of the origin of mass is true, experiment should be able to detect the Higgs boson.
- The Standard Model does not predict how heavy the Higgs boson is, but it does predict how strongly it interacts with all the known particles. For fermions, the interaction is proportional to mass: $\lambda_f = \frac{m_f}{175\mathrm{GeV}}$
- When elementary particles collide, the energy released in the collision can re-coalesce as one or more elementary particles… and the produced particles could include a Higgs.
- Experiments observing protons collide can create and study Higgs bosons.

Producing Elementary Particles

Causing particle collisions powerful enough to produce a Higgs boson requires an enormous and powerful particle accelerator: the **Large Hadron Collider** (LHC), which started up last fall.



Acceleration & Steering



Protons are accelerated and collided in LHC. Two beams or protons travel in opposite directions.

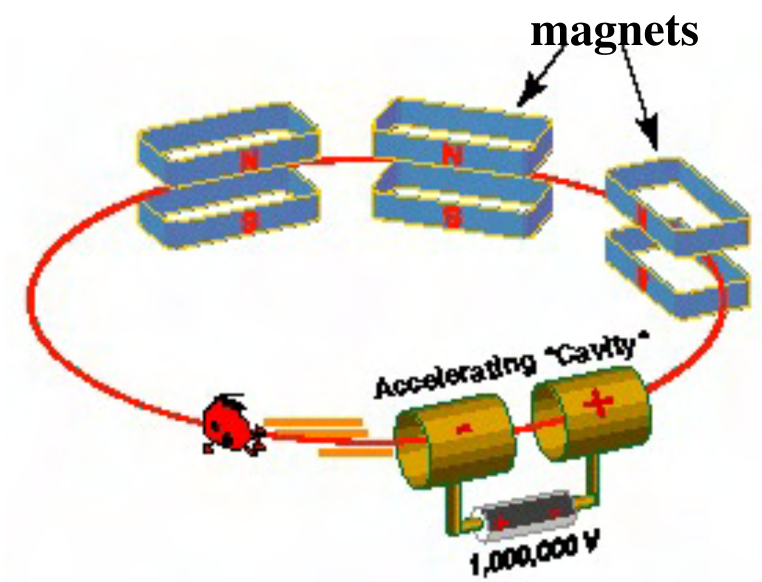
Electric fields accelerate the protons because:

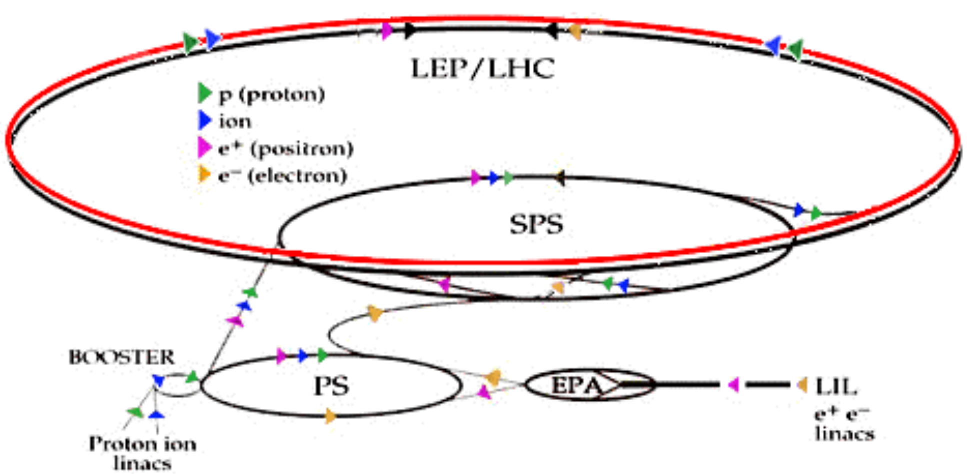
- like charges repel and unlike charges attract each other
- $\vec{F}_{elec} = q\vec{E}$

Magnetic fields steer the beams:

- since charged particles move in circles when exposed to magnetic fields
- $\vec{F}_{mag} = q\vec{v} \times \vec{B}$

Designing an Accelerator





Equating the magnetic force to the centripetal force

$$qvB = \frac{mv^2}{r}$$

tells us the size of the ring required for a given proton beam speed

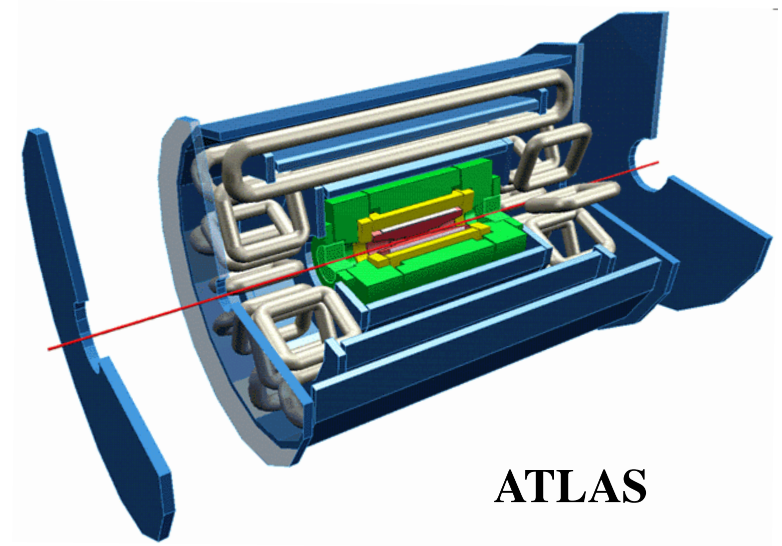
$$r = \frac{mv}{qB}$$

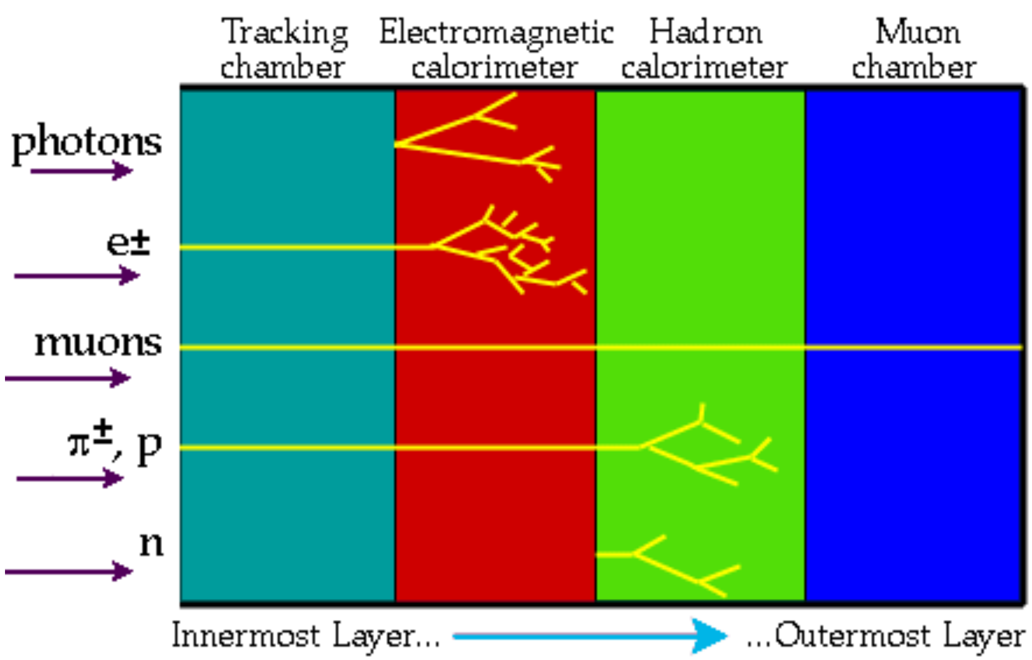
and the timing of the oscillating electric field

$$f = \frac{v}{2\pi r} = \frac{qB}{2\pi m}$$

Detection

At four places around the LHC ring, protons from the two counter-rotating beams will collide.

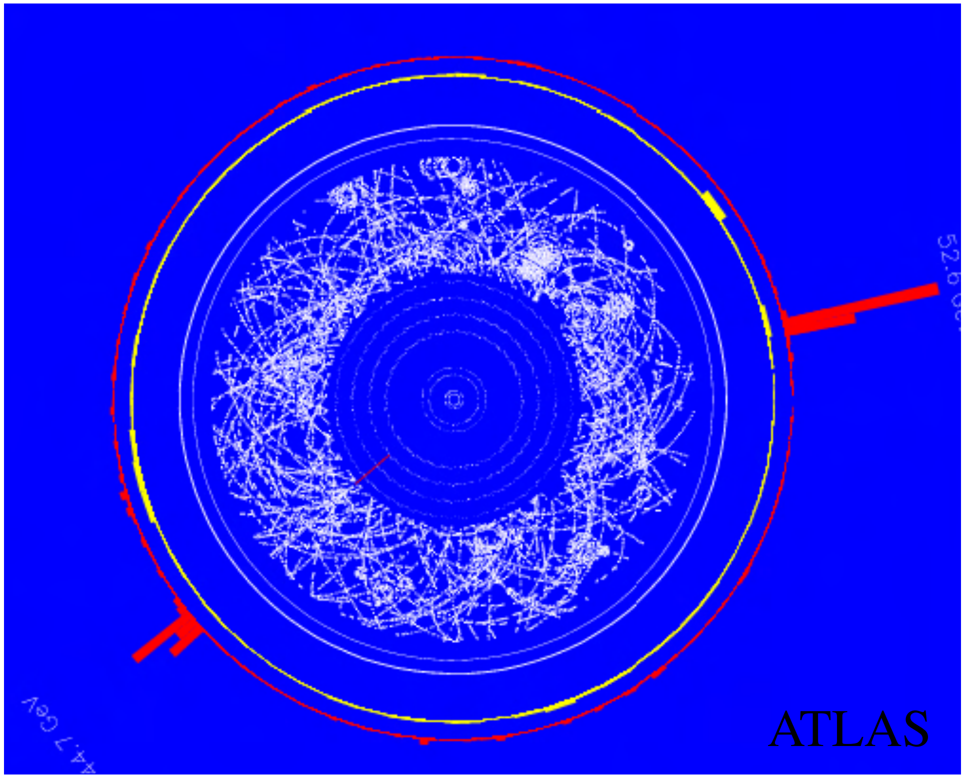




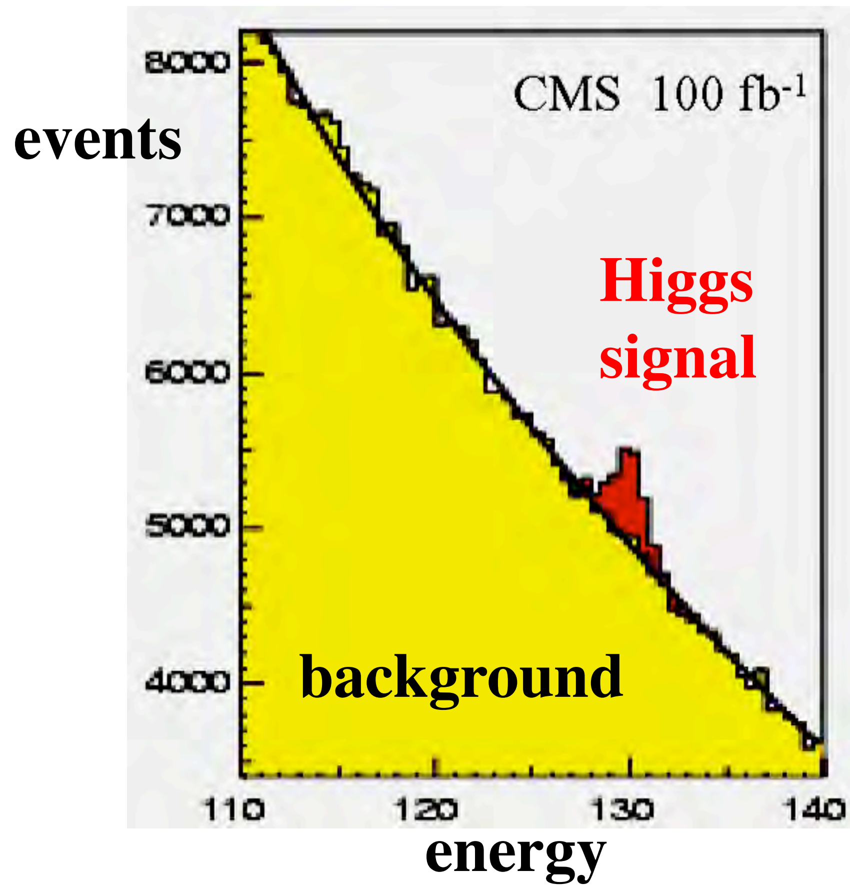
The collision energy condenses into particles (e^-, p, π…)

Layered detectors surrounding the collision point are sensitive to the passage of various energetic particles.

Higgs Detection: $H \rightarrow \gamma\gamma$

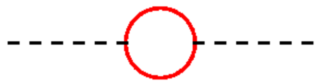
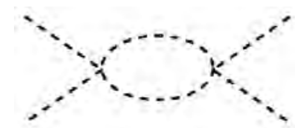


A Higgs decaying to 2 energetic photons would be a striking event in the LHC detectors.



The combined energies of the signal photons would cluster at the mass of the Higgs boson. In contrast, background events include photon pairs with a variety of energies.

Fundamental questions

- How accurate is the Standard Model of the origin of mass? e.g., in the SM, the Higgs boson is fundamental (not made of any smaller particles).
- Could the Higgs boson be composite?
  - Several **theoretical points** argue in this direction:
  - Higgs mass  and self-interaction 
- What would a composite Higgs be made of?
  - **Top quarks?** Might explain why top is so heavy!
  - **An entirely new type of fermions?** Might require a new force!
- If the Higgs is composite, how can we tell?
  - A composite Higgs could cause **processes which are rare** in the SM to occur more frequently.
  - A composite Higgs might be part of a **larger family of particles**, analogous to the many states composed of quarks (**p**, **n**, **π**…)

Conclusions

Several layers of subatomic structure have been revealed in the millennia since the "particle quest" began.

Many questions about the fundamental particles and forces - and the origins of their masses - remain.

The joint efforts of theoretical and experimental particle physicists will begin providing answers in this decade as the LHC data emerges.