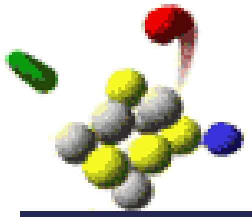
The Standard Model



Particles

(An Introduction) *a particle physics nomenclature*

Galileo’s Relativity (Newtonian space & time)

Einstein’s Special Relativity (space-time)

Einstein’s General Relativity (geometry)

Einstein’s Photoelectric Effect (Planck)

(“Einstein’s quarrels” with Bohr)

Heisenberg, Born, Jordon, Schrodinger, Bell

... several other weird Quantum Phenomena

Edifice of Particle Physics Theory :

... weave Quantum Mechanics with

Special Relativity ... Quantum Field Theory

Particle Physics For Dummies.

Some reminders for our GEM

The Inner Atom


Astronomie et Physique Appliquée

Atomic and nuclear physics

Sir William Crookes 1855 Using some of the first vacuum tubes, Crookes produced cathode rays from negatively charged heated metals in a vacuum.

Julius Plücker 1858 Plücker showed that cathode rays bend under the influence of a magnetic field, suggesting that they are charged in some way rather than electromagnetic waves.

Dmitri Mendeleev 1871 Mendeleev was the first to publish a Periodic table of the elements based on the pattern of their physical and chemical properties. Some elements had not been discovered – Mendeleev left gaps in the table to allow for this. These gaps were subsequently filled as new elements were discovered in the next 15 years.

George Johnson Stoney 1874 Stoney introduced the term 'electron' and estimated the charge on it as 10^{-20} C – very close to the modern value of 1.6×10^{-19} C.

Johann Jakob Balmer 1885 Balmer discovered a simple formula describing the spectrum of light emitted by the hydrogen atom.

Jean-Baptiste Perrin 1895 By deflecting cathode rays with a magnetic field, Perrin showed that negative charge collects where the rays impact.

Wilhelm Konrad Röntgen 1895 Röntgen accidentally discovered X-rays. Three months later an American named Eddie McCarthy became the first person to have a broken bone (his arm) set with their help.

Joesph John Thomson 1897 Using magnetic and electric fields, Thomson was able to measure the mass: charge ratio for cathode rays, showing that they are in fact negatively charged particles – electrons.

Max Planck 1900 Planck announced that atoms can emit light only at certain frquencies, the first step towards quantum theory.

1904 Thomson proposed the 'plum pudding' model of the atom, of electrons embedded in a sphere of positive charge.

Albert Einstein 1905 In order to explain the ejection of electrons from metals by light (the **photoelectric effect**), Einstein proposed that light may behave as a particle as well as a wave.

Charles Barkla 1906 Barkla discovered that each element has a characeristic X-ray spectrum.

◄**Hans Geiger and Ernst Marsden 1909** Using thin metal foils, Geiger and Marsden obtained evidence for the nuclear model of the atom.

Robert Millikan 1909 Millikan measured the charge on the electron and showed that this is the smallest unit of charge that exists.

Ernest Rutherford 1911 The Manchester Literary and Philosophical Society heard a paper from Rutherford, in which he described his nuclear model of the atom.

Niels Bohr 1913 Bohr proposed a model for the electrons in the atom in which the electrons are found in orbits. This model was based on the work of Balmer, combined with quantum theory arising from Planck's work.

1914 Rutherford discovered the proton as a constituent of the nucleus.

Francis William Aston 1918 Building the first mass spectrometer, Aston showed that there are different forms of the same element, now called **isotopes**.

William Draper Harkins 1920 If the nucleus contained only protons it would be too light. In an attempt to account for this missing mass, Harkins proposed the existence of the **neutron**, a neutral particle.

Louis-Victor de Broglie 1923 de Broglie proposed that electrons may behave as waves as well as particles – the theory of **wave-particle duality**.

Erwin Schrödinger 1926 The first paper on **wave mechanics** was published by Schrödinger, in which the electron in atoms was modelled as a wave rather than as a particle.

Clinton Davisson and **George Paget Thomson 1927** Working independently, Davisson and Thomson showed that electrons may be diffracted by a crystal, thus showing that they have wave-like properties.

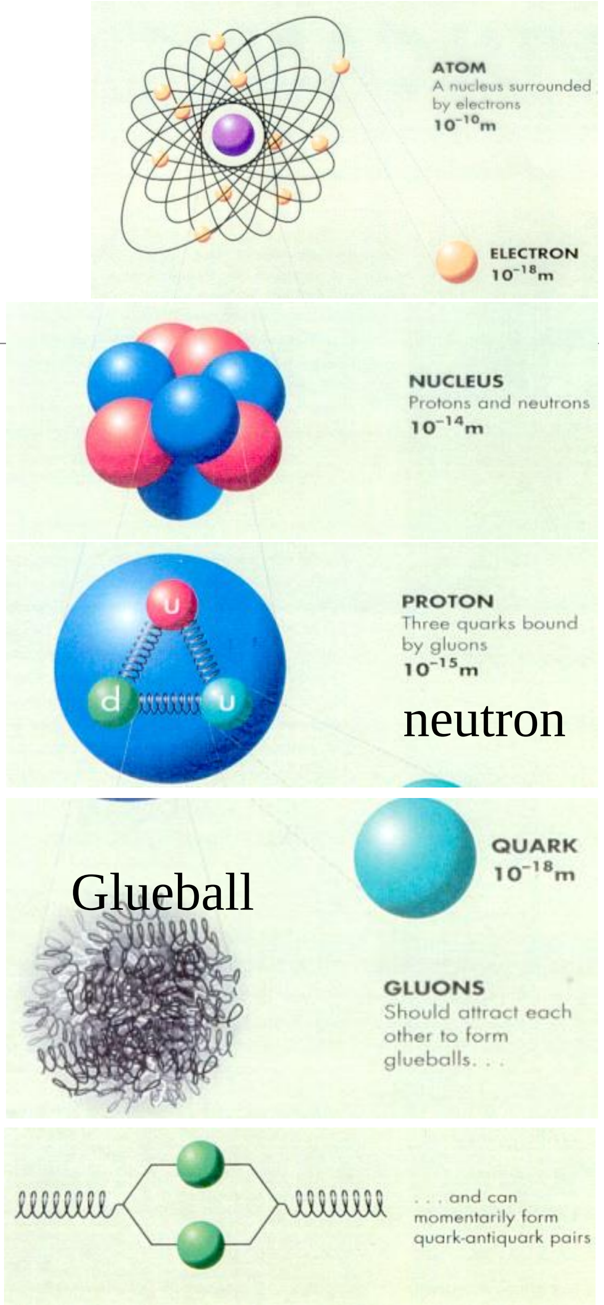
Werner Heisenberg 1927 Heisenberg proposed his **uncertainty principle** – there are inevitable uncertainties introduced in measuring two variables such as position and momentum.

James Chadwick 1932 Chadwick discovered the neutron.

Figure 6.1.9 The unravelling of the structure of the atom

French Singapore Institute

Particle Physics For Dummies.



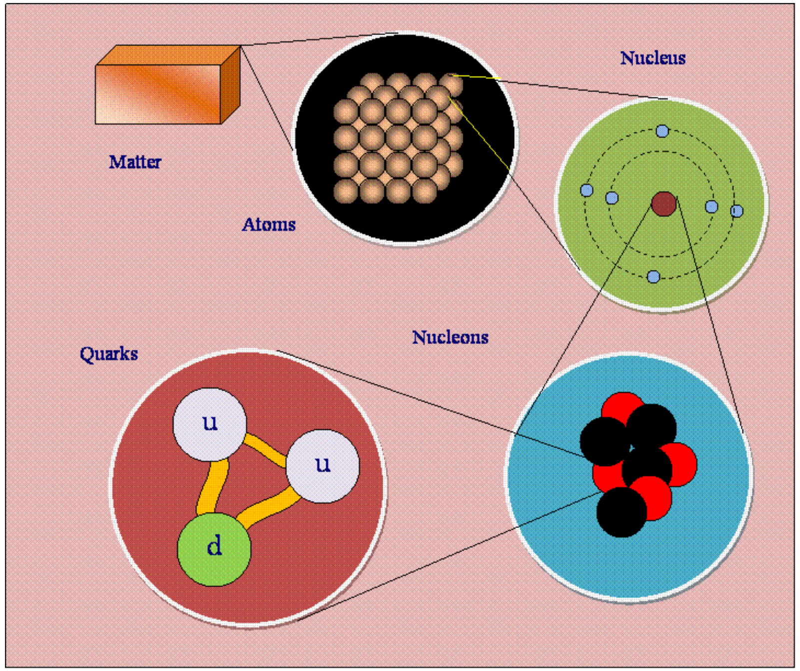
A Socratic question ?

Why protons and protons may stick together ?

What about neutrons and neutrons ?

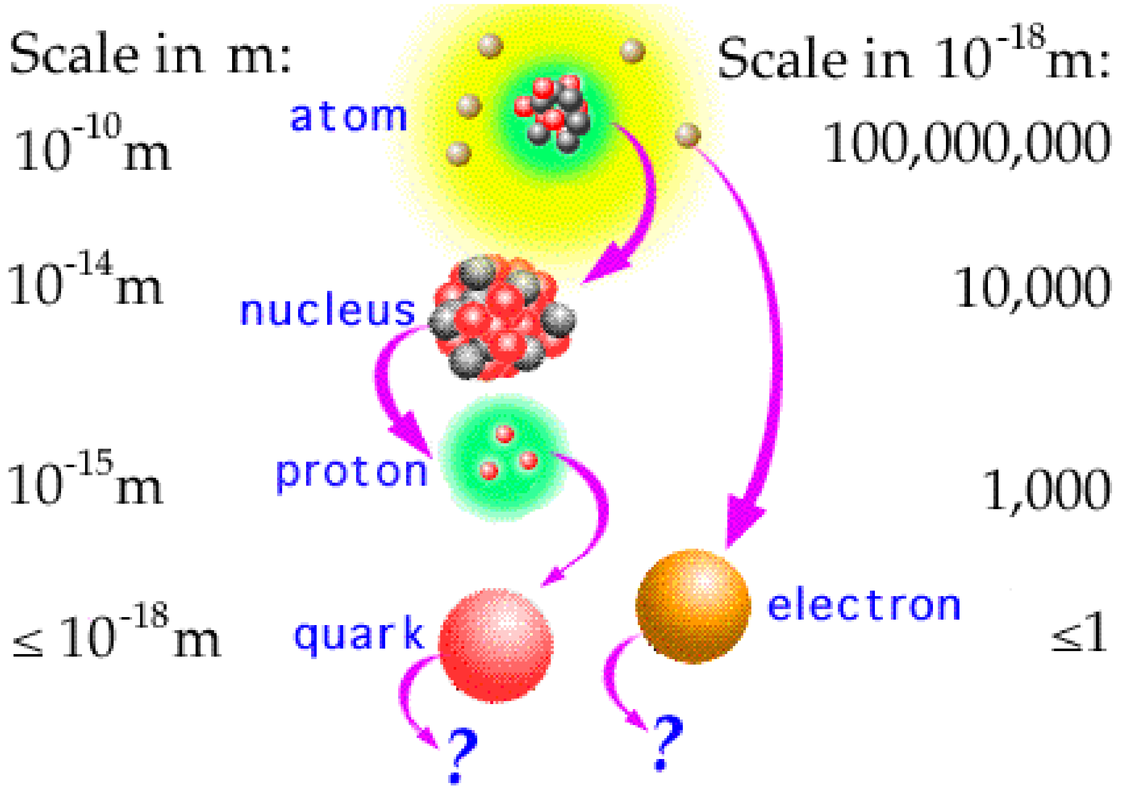
Scales of Nature

Reductionism



A hundred thousand protons, if they would lined up in a row, would stretch only across one atom !

Mostly empty Space !



A Socratic question ?

Why is solid matter solid if it is mostly empty space ?

Micro-particles !

micro-matter

Fundamental Particles of Matter

Only 12 particles : We can make all forms of matter.

Lepton Table

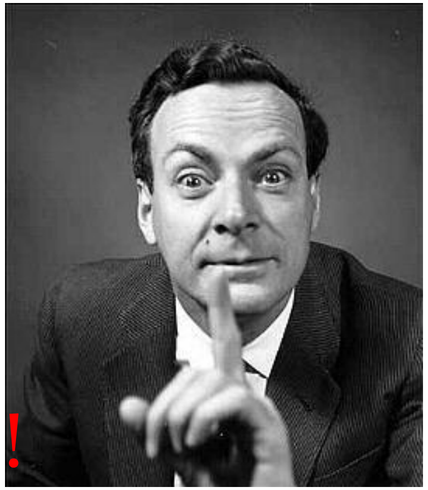
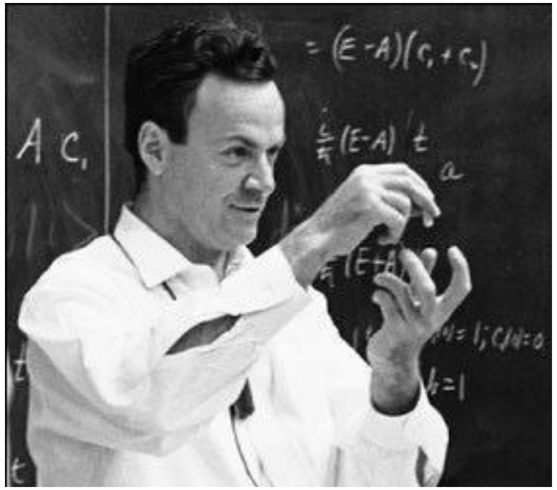
Name	Symbol	Mass in Units of Electron Mass	Electric Charge in Units of Proton Charge
ELECTRON	e^-	1	-1
ELECTRON NEUTRINO	ν_e	LESS THAN 0.00012	0
MUON	μ^-	207	-1
MUON NEUTRINO	ν_μ	LESS THAN 1.1	0
TAUON	τ^-	3491	-1
TAU NEUTRINO	ν_τ	LESS THAN 500	0

Quark Table

	Name	Symbol	Approximate Mass in Units of the Electron's Mass	Electric Charge in Units of Proton Charge
	UP	u	2	⅔
	DOWN	d	6	−⅓
	STRANGE	s	200	−⅓
	CHARM	c	3000	⅔
Beauty	BOTTOM	b	9000	−⅓
Truth	TOP	t	?	⅔

Last to be discovered

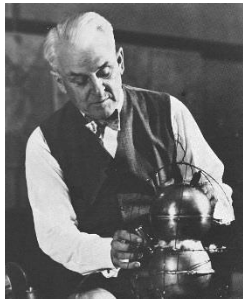
Motto : Shut up and Calculate !


Put-on Theory !

Parton Theory !

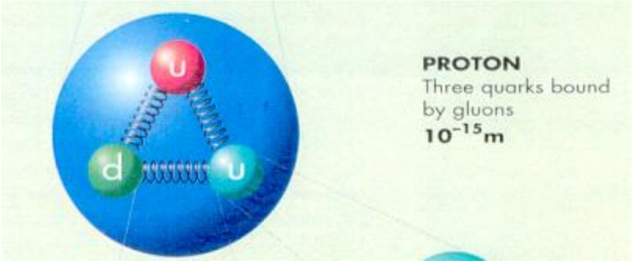
Proton & Neutron Charges



Millikan

$$p = u + u + d$$

$$n = u + d + d$$



$$p\,(uud) = C_u + C_u + C_d = 1$$

$$n\,(udd) = C_u + C_d + C_d = 0$$

What are the Charges of the up and down quarks ? $C_u = +\frac{2}{3}$ $C_d = -\frac{1}{3}$

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TAU NEUTRINO	ν_τ	LESS THAN 500	0

Quark Table

	Name	Symbol	Approximate Mass in Units of the Electron's Mass	Electric Charge in Units of Proton Charge
	UP	u	2	2/3
	DOWN	d	6	-1/3
	STRANGE	s	200	-1/3
	CHARM	c	3000	2/3
Beauty	BOTTOM	b	9000	-1/3
Truth	TOP	t	?	2/3

Last to be discovered

Fundamental Particles of Matter

George Zweig

Gell Mann

James Joyce’s **Finnegan's Wake**:
"Three **quarks** for Muster Mark!"

Generations !

… of fundamental particles …

3 Lepton Generations

Rabi

Who ordered that ? Should be fined.

I tell you, you will not get out until you have paid the last lepton. Luke 12:59 NIV

Lepton Table

Name	Symbol	Mass in Units of Electron Mass	Electric Charge in Units of Proton Charge
ELECTRON	e^-	1	-1
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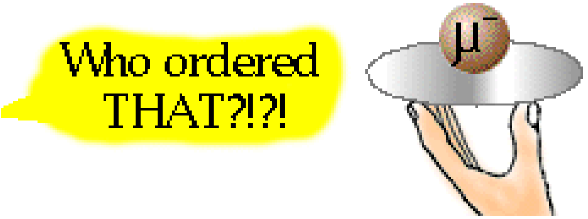
TAUON	τ^-	3491	-1
TAU NEUTRINO	ν_τ	LESS THAN 500	0

Muon and Tauon are allowed to decay into particles. The electron is a stable object. Leptons are accompanied by electrically neutral neutrinos.

Question : Why are there equal numbers of quarks and leptons ?
Answer :   We do not know !



3 Quark Generations

Notes:

In the order of discovery and masses.

4 were discovered in High Energy Labs (Colliders).

Quark Table

Name	Symbol	Approximate Mass in Units of the Electron's Mass	Electric Charge in Units of Proton Charge
UP	u	2	⅔
DOWN	d	6	-⅓
STRANGE	s	200	-⅓
CHARM	c	3000	⅔
BOTTOM	b	9000	-⅓
TOP	t	?	⅔

A Socratic question ?

How can a particle have mass and yet no size, charge and yet no size, spin and yet no size ?

… how can it exist and have no size ?

What about Forces ?

What are Fundamental Forces ?

Consider some types of forces below:

Gravity

Friction

Tension

Electromagnetic

Vander Waals

Centripetal (Pseudo)

...

What about Fundamental Forces ?

Interactions

The 4 Fundamental Forces

Gravity Force	(long range)
Electromagnetic Force	(long range)
Strong Nuclear Force	($\sim 10^{-15}$m, short range)
Weak Nuclear Force	($\sim 10^{-17}$m, short range)
Atom is	$\sim 10^{-10}$ m in diameter

Is there a 5th force ? Or why only 4 ?

Answer is : We still do not know !

The Strong Forces (Nuclear)

Strong force only acts between quarks.

- Quarks feel the strong force, leptons do not.
- Both quarks and leptons “feel” the other 3 forces.

- The leptons do not bind together to form particles.
- The strong force between quarks means that they can only bind (attractive) together to form particles.

How come we never “see” a quark ?

What about gluons ?

The Weak Force (Nuclear)

We have experienced radioactivity before.

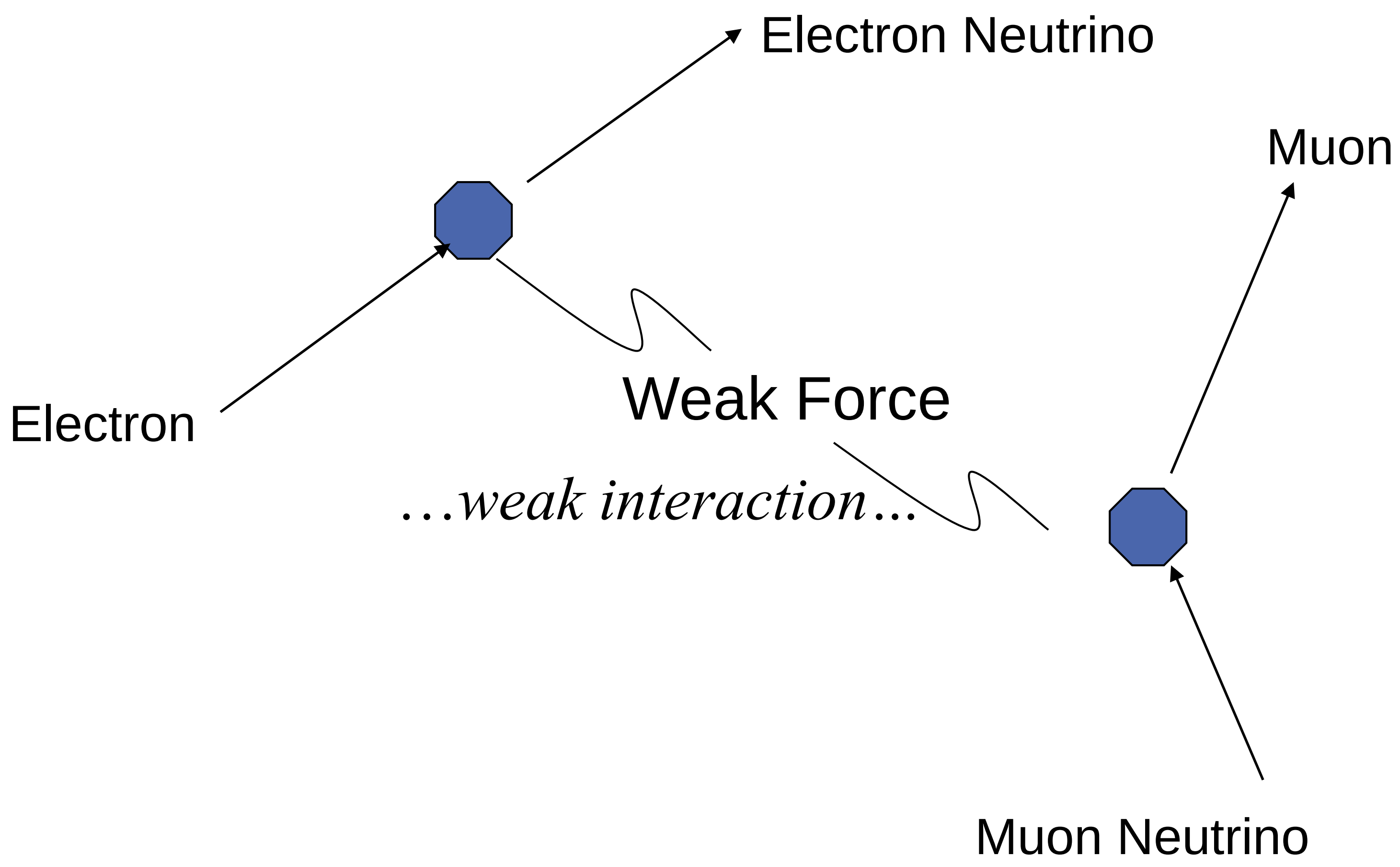
The most difficult of the fundamental forces to describe.

Why ?

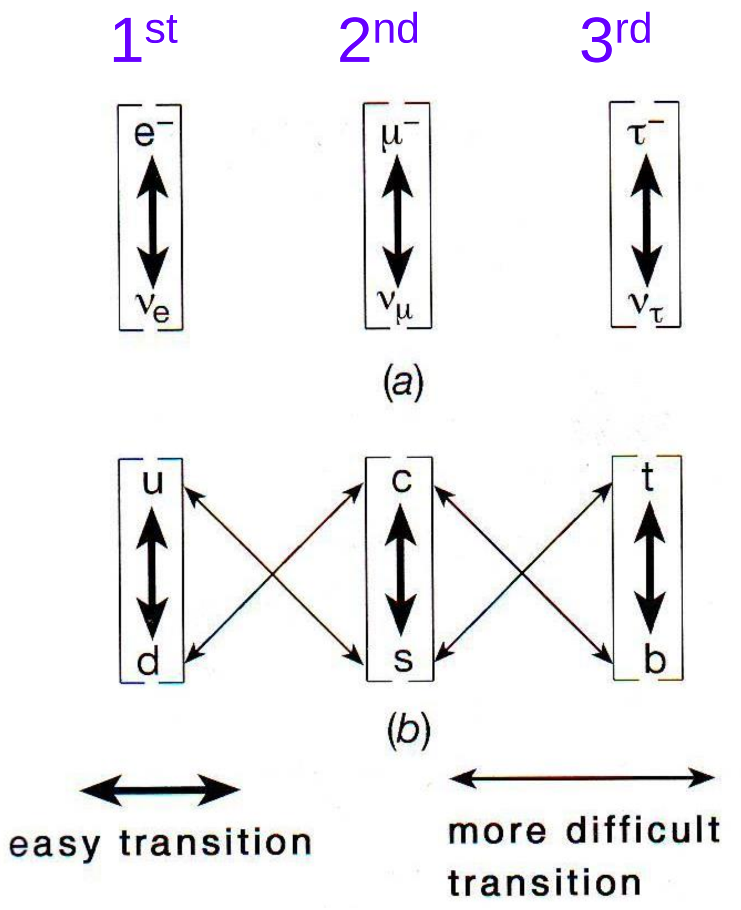
The categories of attractive and repulsive ideas do not fit the weak force description.

This is because it changes particles from one type to another.

The Weak Force



The Weak Force (Interactions)

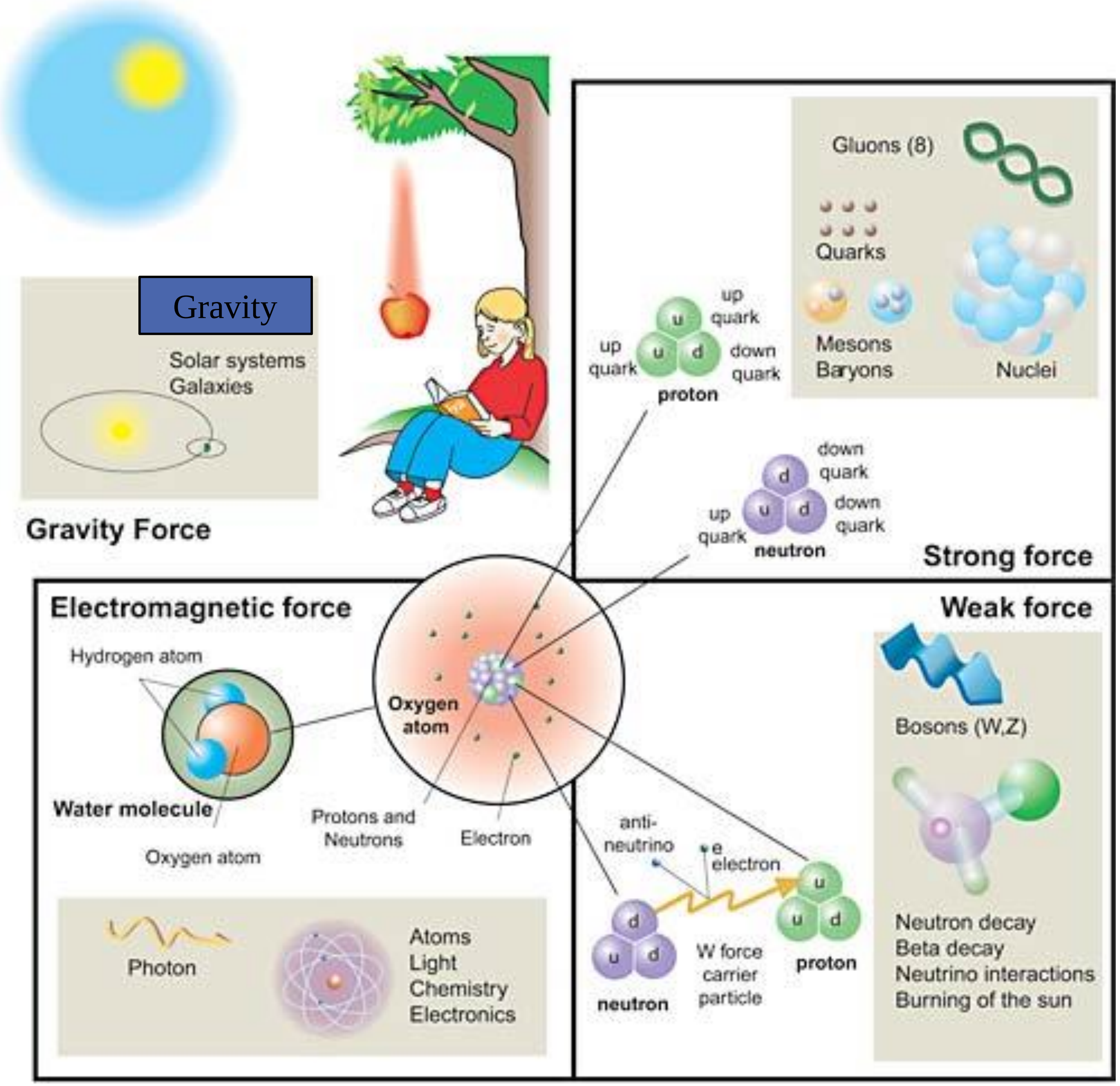


Generations

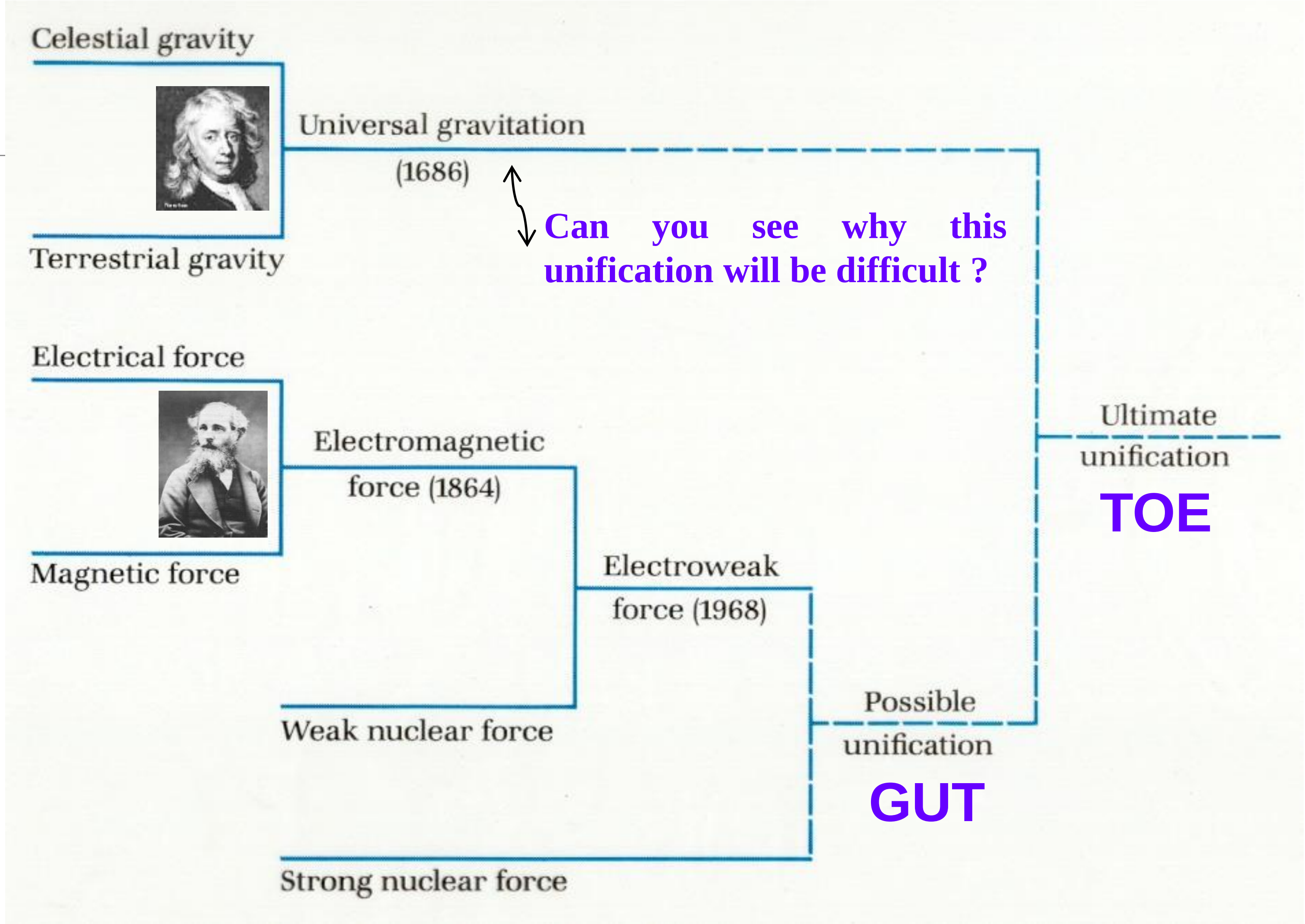
Leptons

Quarks

Summary of Fundamental Interactions (Forces)



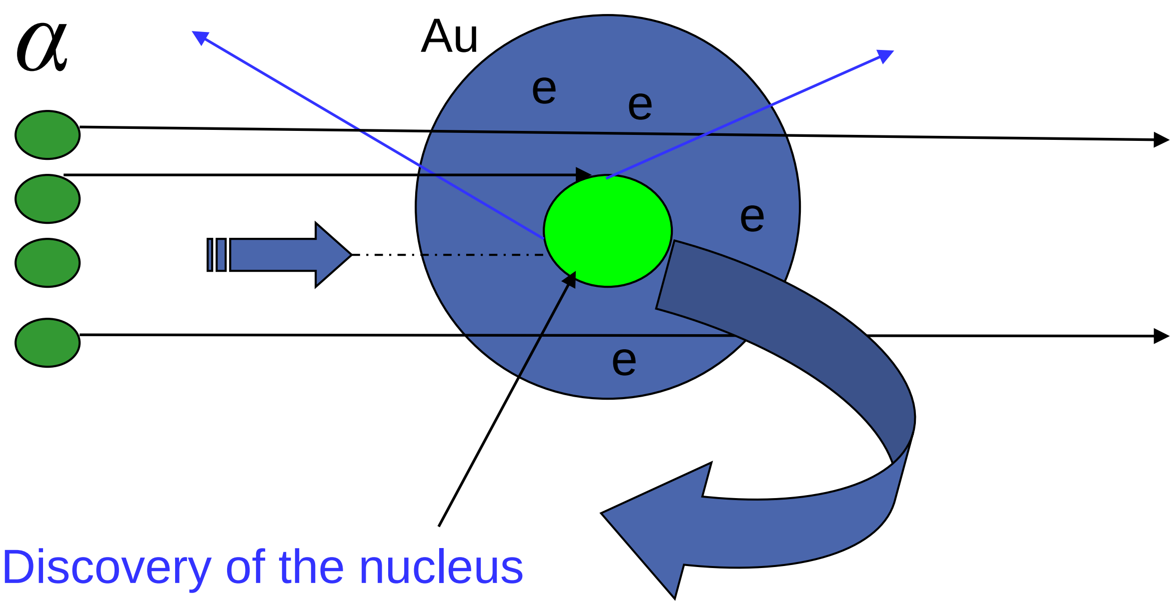
Summary of 4 Fundamental Interactions (Forces)



Particle Physics For Dummies.

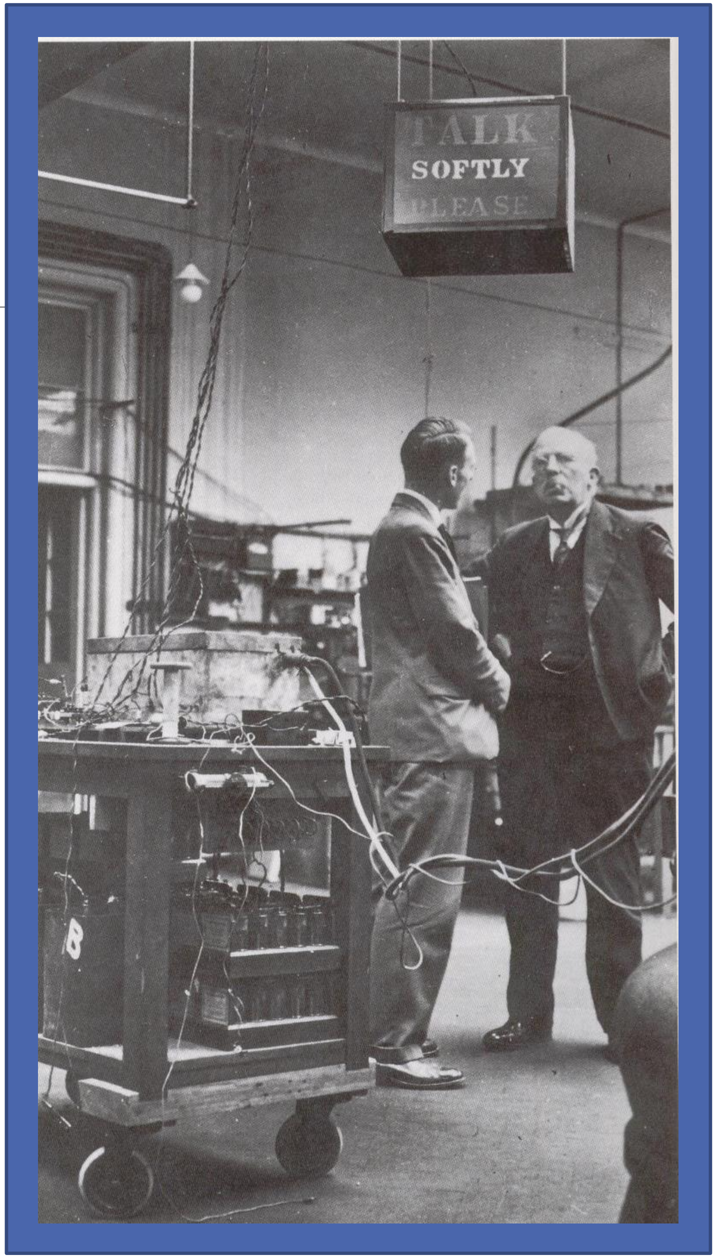
How do we know so much of micro-stuff ?

Rutherford, 1911



Discovery of the nucleus

Also theorize the existence of neutrons.



Succeeded J. J. Thomson

"*In science there is only physics; all the rest is stamp collecting*."

Big “toys”

for high energy particle physicists !

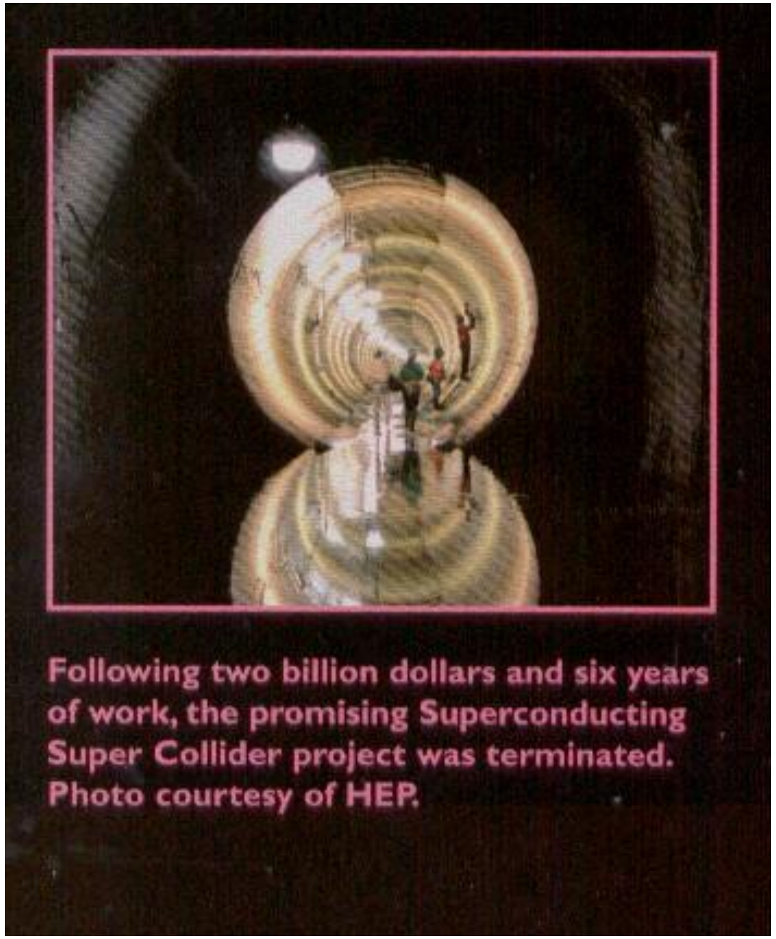
Demised of SCSC (SSC) !

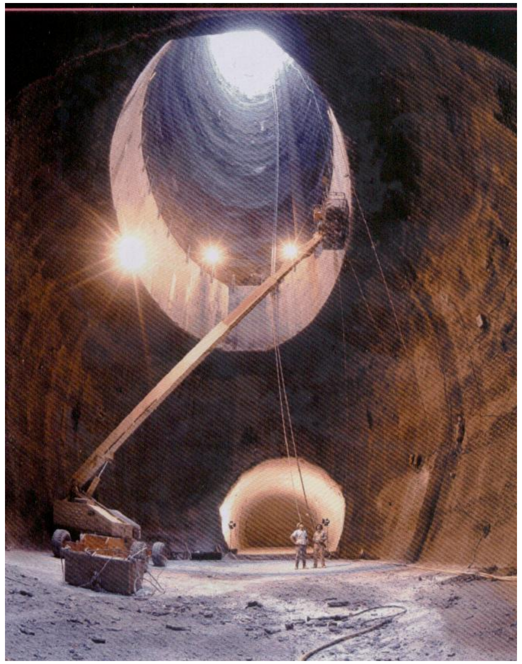
Big Toys

for Physicists

Ring circumference was 87.1 kilometers (54.1 mi) with an energy of 20 TeV per proton (total 40 TeV)

Cancelled in 1993



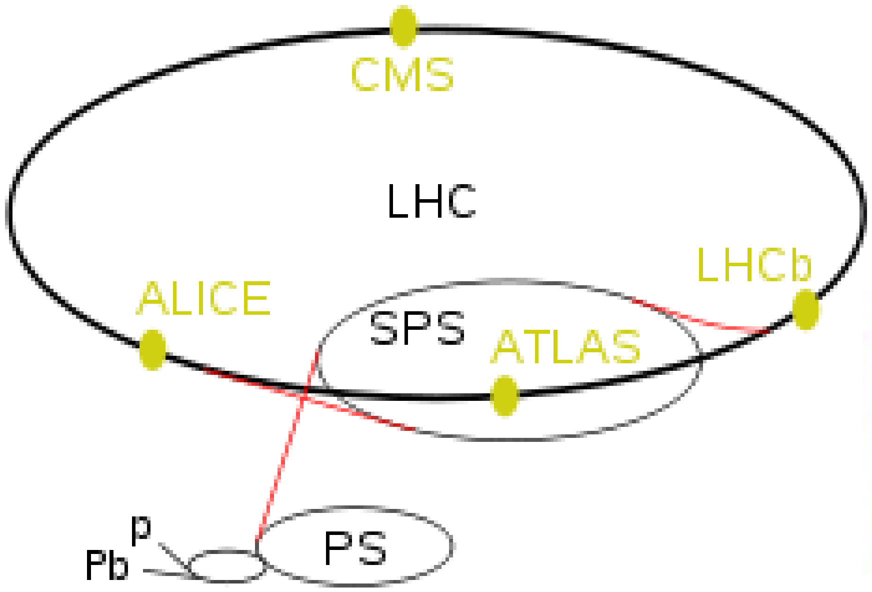


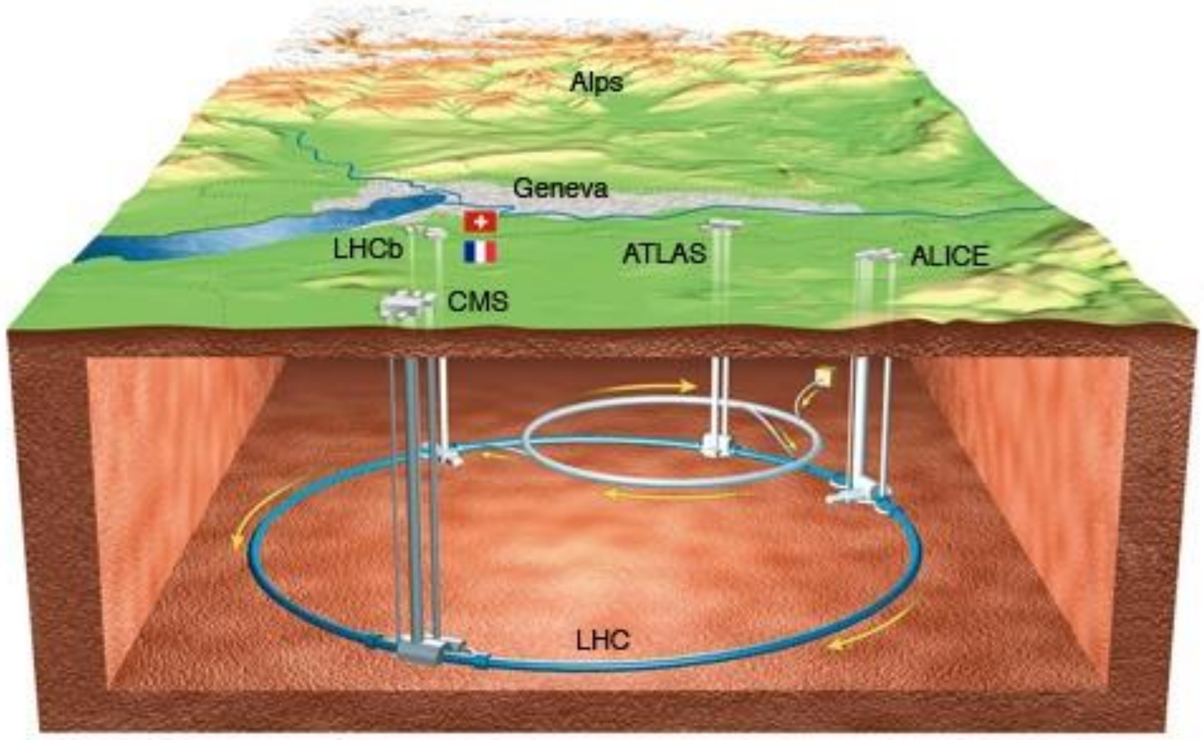
May have used more money just to fill this tunnel !

LHC : Large Hadron Collider

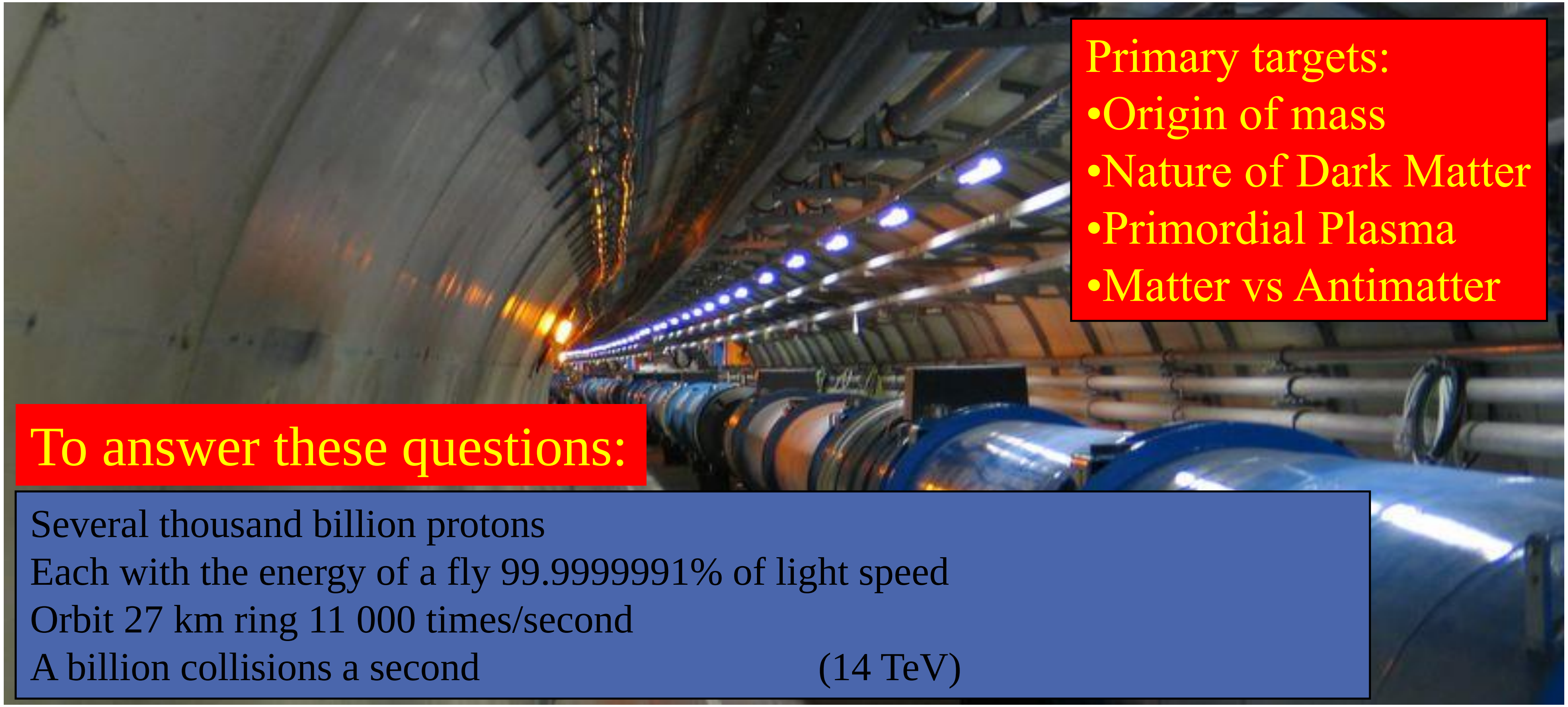
European **O**rganization (**C**ouncil) for Nuclear Research
LHC : 4 Major Facilities

LHC : Large Hadron Collider





The Large **Hadron** Collider (LHC)

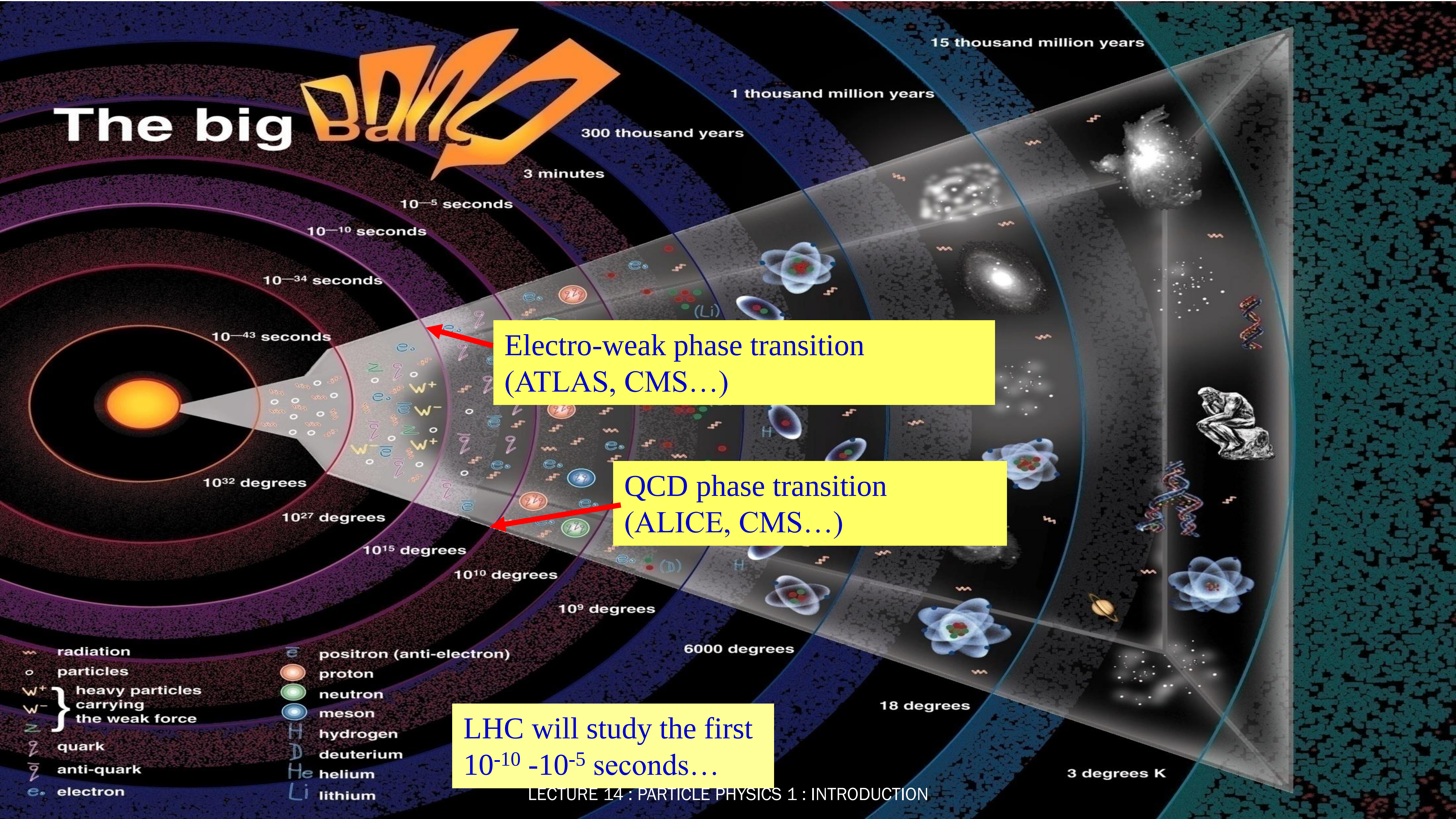


Primary targets:

- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

To answer these questions:

Several thousand billion protons
Each with the energy of a fly 99.9999991% of light speed
Orbit 27 km ring 11 000 times/second
A billion collisions a second (14 TeV)

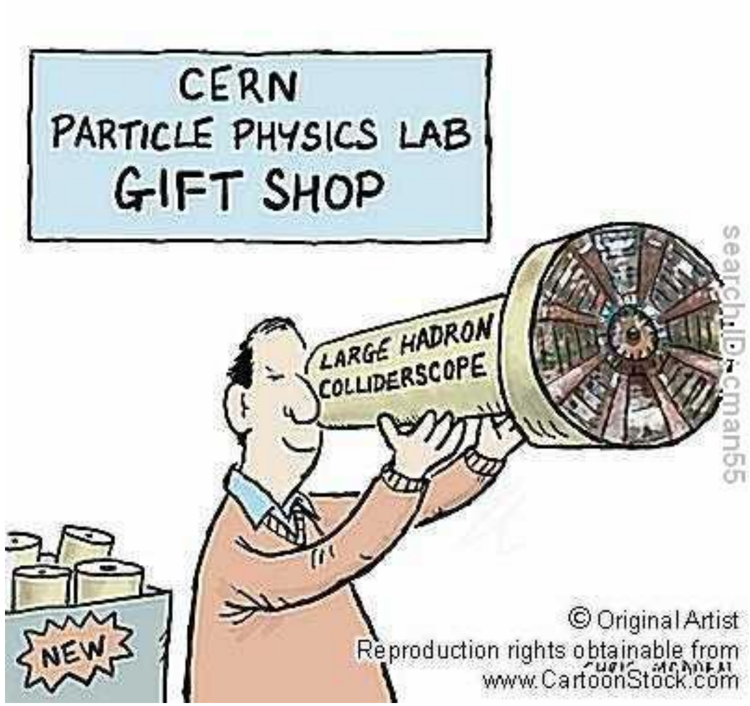


Electro-weak phase transition (ATLAS, CMS…)

QCD phase transition (ALICE, CMS…)

LHC will study the first 10^{-10} -10^{-5} seconds…

“Big Toys”


CERN
PARTICLE PHYSICS LAB
GIFT SHOP
LARGE HADRON COLLIDERSCOPE
NEW
searchID: cman55
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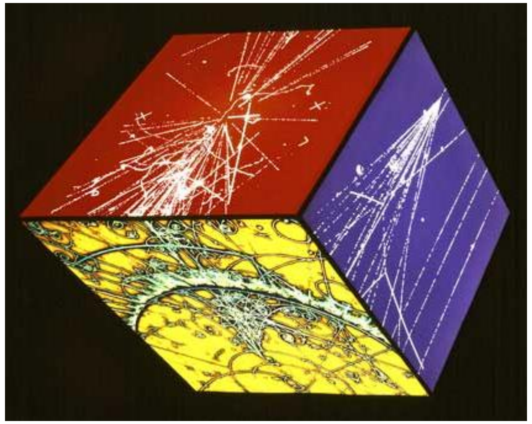
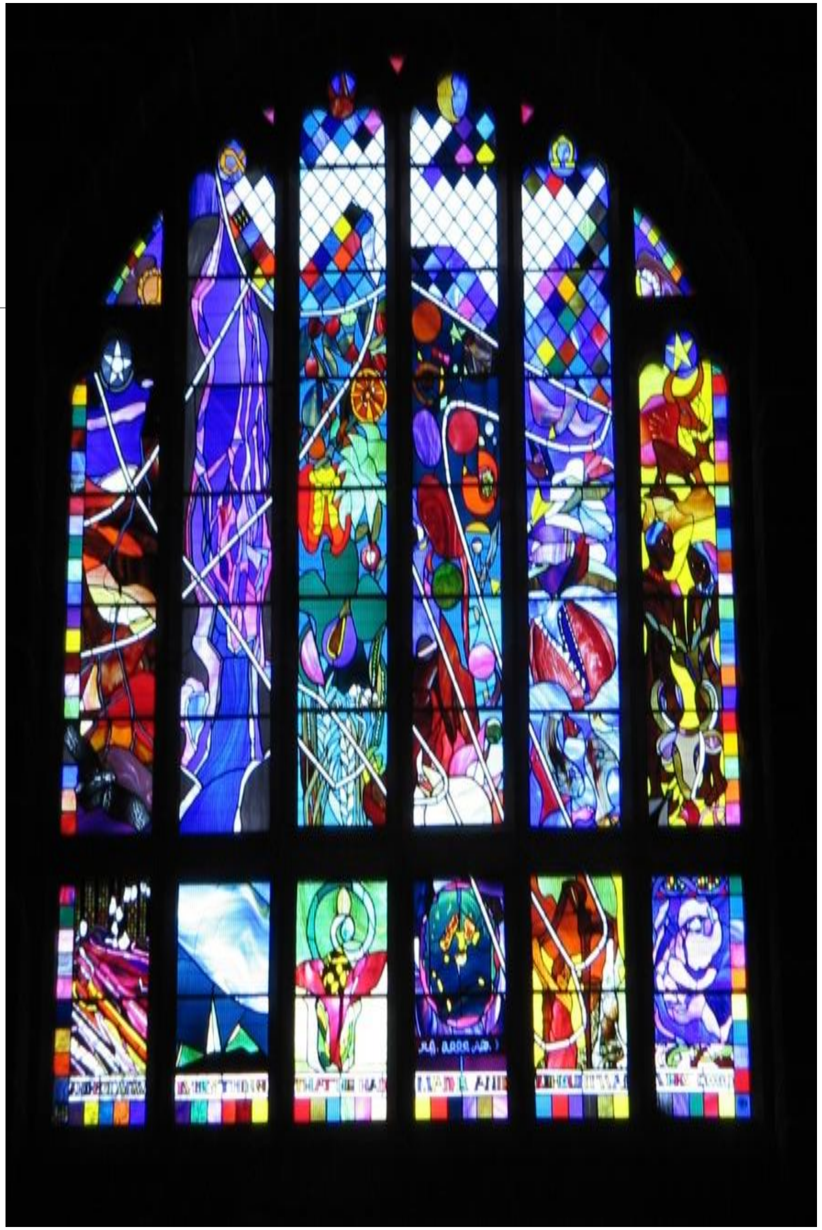
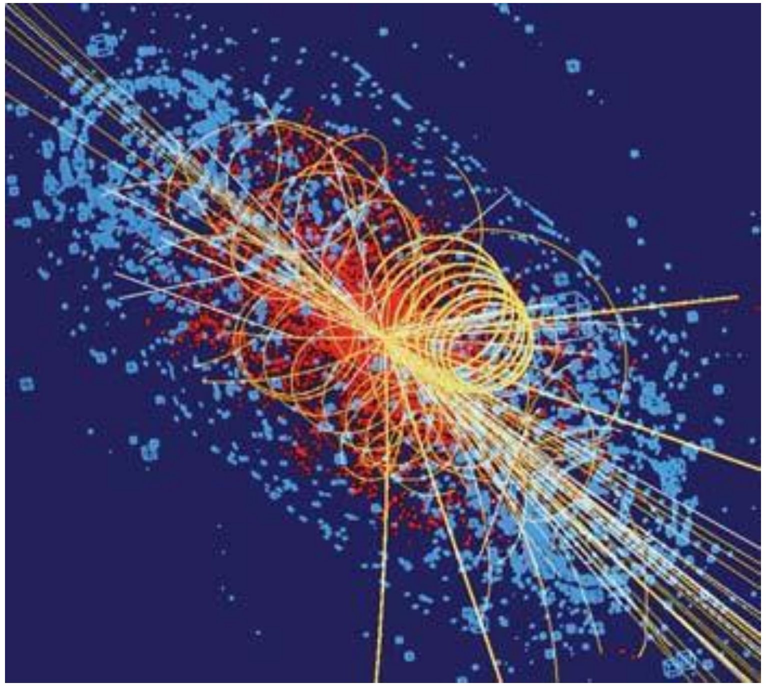


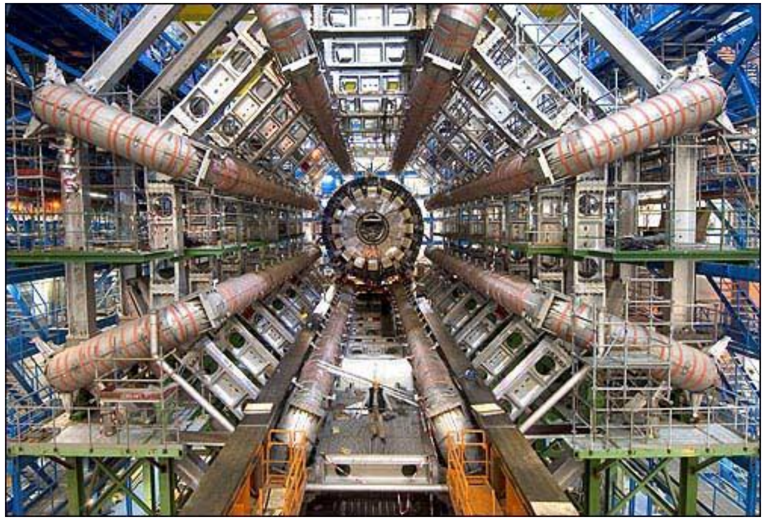


LHC Detectors & their Missions

Detector	Full Name	Mission
ATLAS	A Toroidal LHC ApparatuS	General Purpose (including searching for the Higgs boson and supersymmetry) e.g. Squarks, Selectron
CMS	Compact Muon Solenoid	General Purpose (including searching for the Higgs boson and supersymmetry)
ALICE	A Large Ion Collider Experiment	Creating quark-gluon plasma
LHCb	Large Hadron Collider beauty	Searching for CP violation in B particle decay
LHCf	Large Hadron Collider forward	Testing cosmic ray detection devices
TO TEM	TOTal Elastic & diffractive cross section Measurement	High precision measurements of protons

ATLAS A Toroidal LHC ApparatuS





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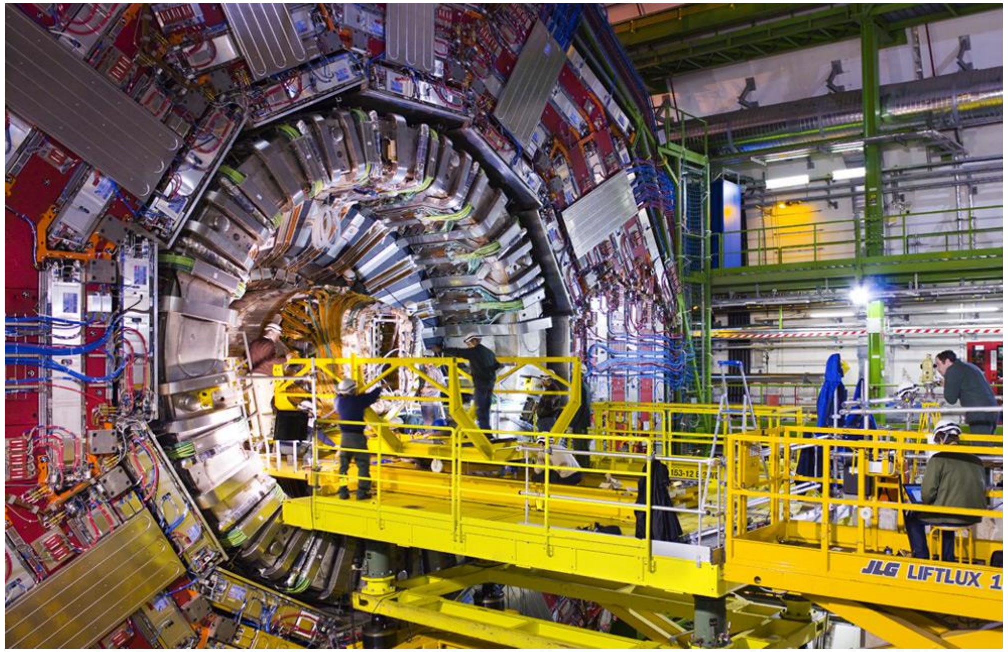
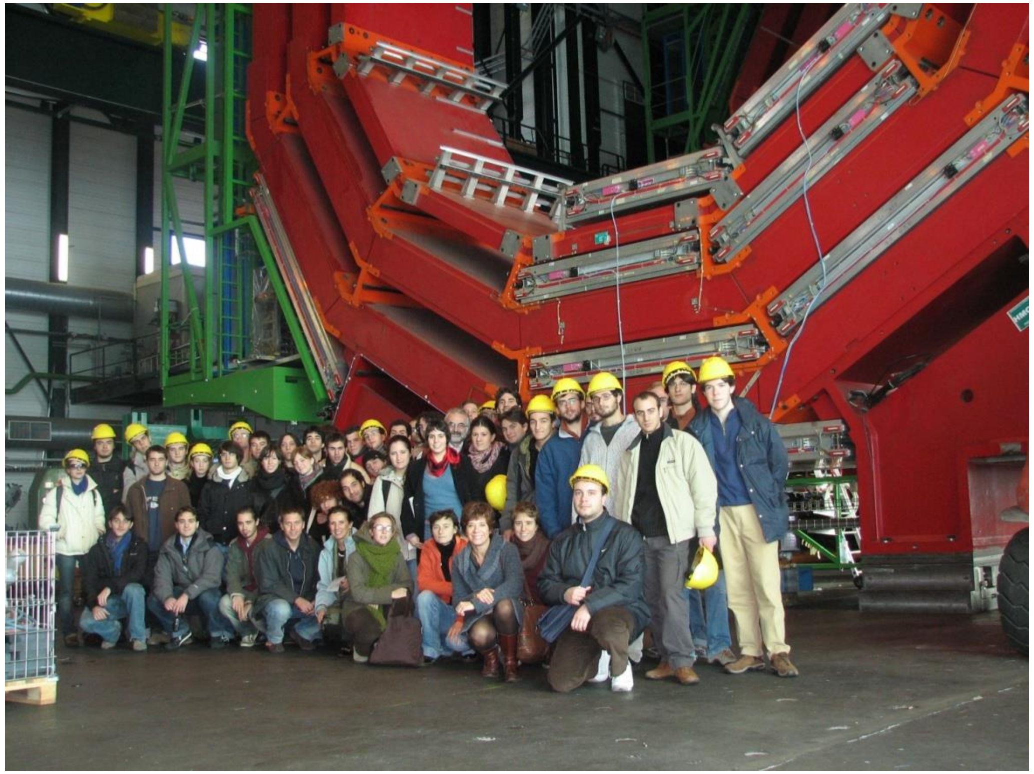
CMS Compact Muon Solenoid





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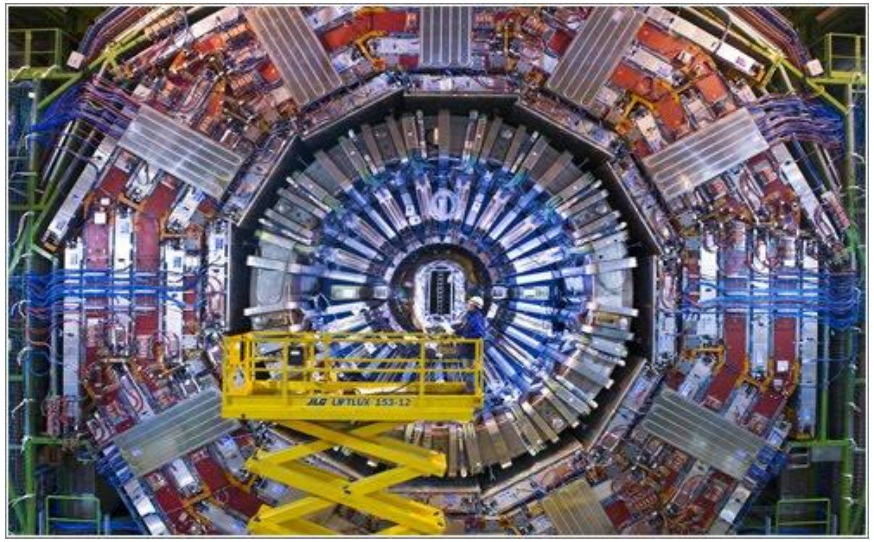
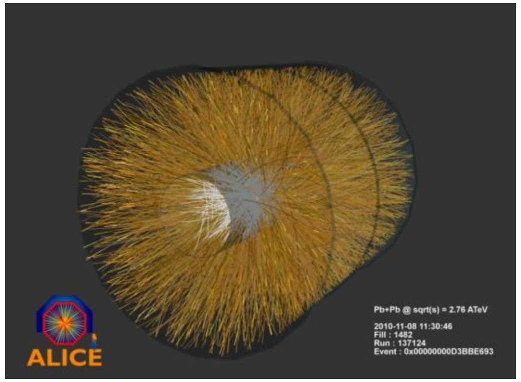
ALICE A Large Ion Collider Experiment





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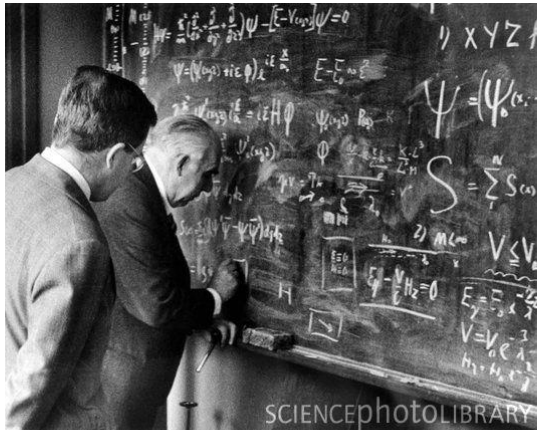
LHC-b


LHCb
the collaboration in photos
LHC beauty – an experiment at the Large Hadron Collider

3 groups of HEP Physicists

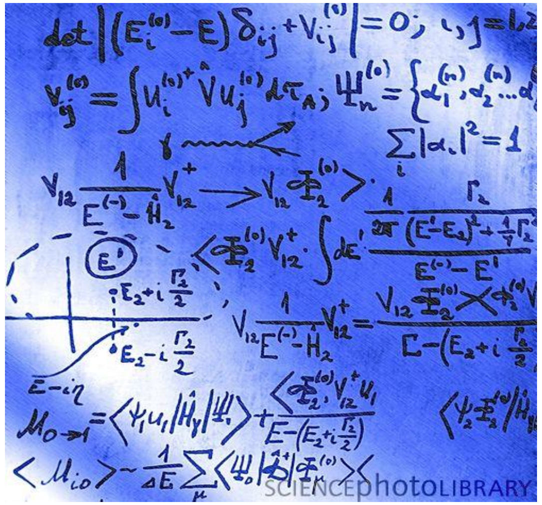


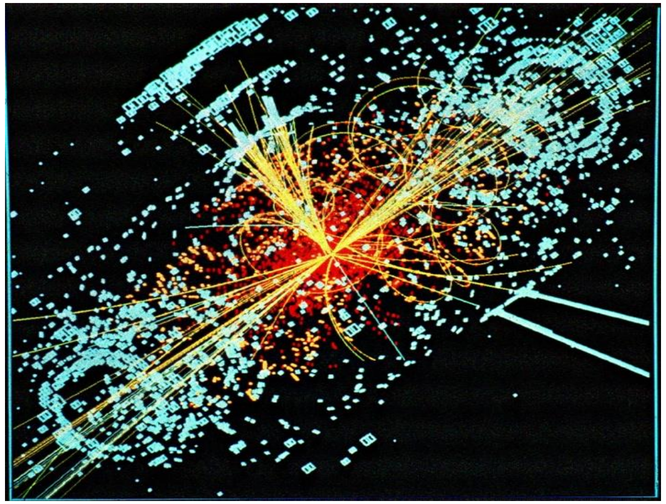
Theorists

(fundamental theory)

Phenomenologists

(build models from data)

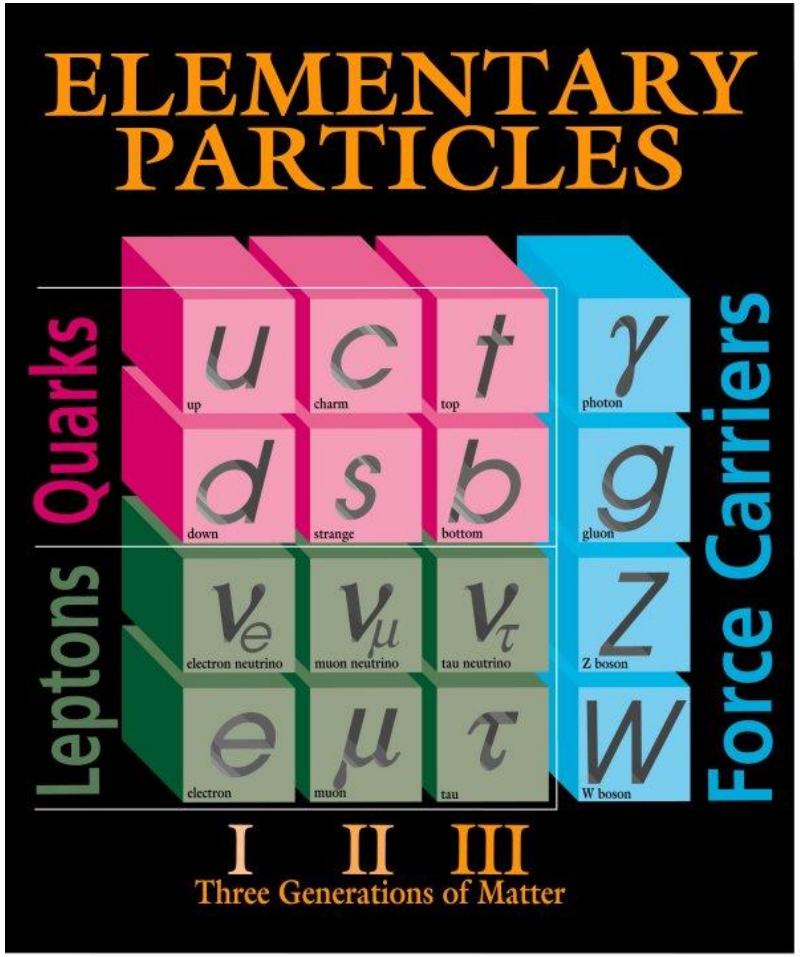


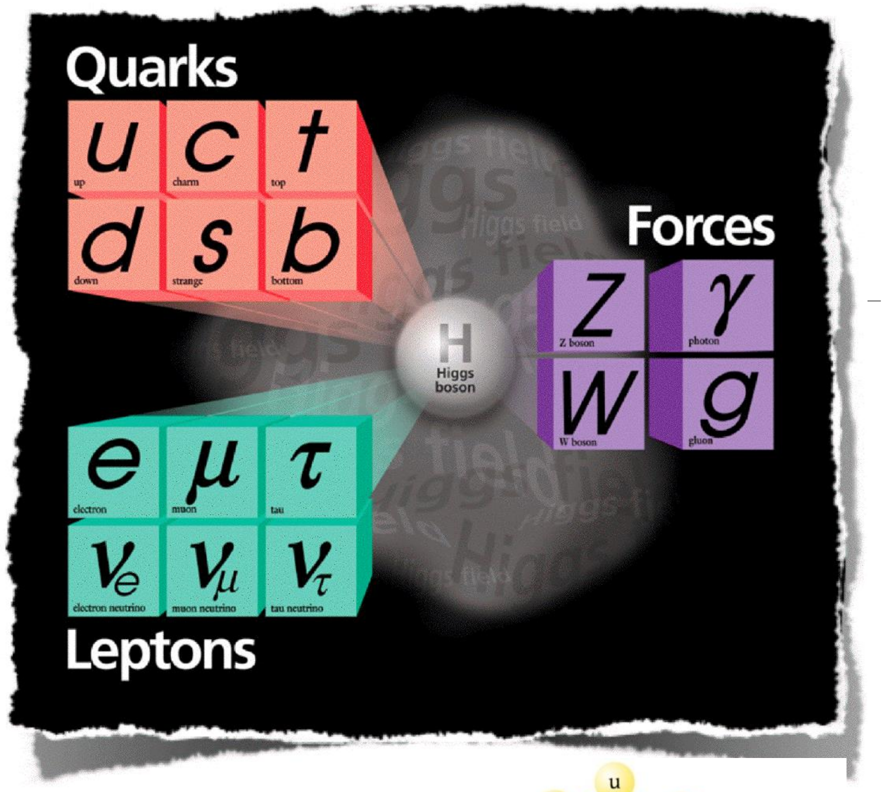


Experimentalists

(throw questions to nature : data)

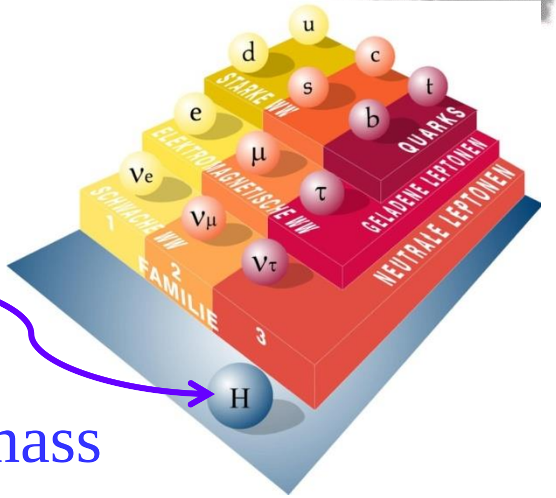
Summary





Only 12
matter particles

Higgs give particles mass



The Lepton

Particle physics can seem like a very unreal topic which examines rare and insignificant sounding small objects.

Another Weird Topic !

What Standard Model (fundamental particle physics theory)

… says about fundamental forces ?

… it turns out …

4 Fundamental Forces (Interactions)

Forces (Interactions) 	Force Messengers Bosons (integer Spins)	Matter Fermions (1/2 Integer Spins)
Gravity	Graviton (massless) Geometry ?	All matter that have mass No charges
Electromagnetic (E+M~ light)	Photon (massless)	All charged matter 2 charges +ve or –ve
Strong	Gluons (massless) 3 colours, (R, G, B)	Quarks 3 Charges u, d, s, c, t, b (R, G, B)
Weak	W^+, W^-, Z^0 (3 Massive bosons)	Quarks, 6 flavours Leptons, 6 flavours

… the Lepton …
more on neutrinos

Where to find Leptons ?

Leptons, unlike quarks, may exist as separate individual objects.

1st generation	2nd generation	3rd generation
Electron Found in atoms Electric currents Radioactivity	Muon Produced at upper atmosphere by cosmic rays	Tau So far only in the labs Not naturally occuring
Electron neutrino Radioactivity Atomic reactors Nuclear Reaction in the Sun	Muon Neutrino Produced by atomic reactors Produced at upper atmosphere by cosmic rays	Tau neutrino So far only in the labs Not naturally occuring

Fortunately, neutrinos interact with matter so rarely that even a huge number passing through us does no harm to us.

The Leptons (M_p= proton mass)

1st generation	2nd generation	3rd generation
electron	muon	tau
$5.45 \times 10^{-4} M_p$ (5.11×10^{-4} GeV/c^2)	$0.113 M_p$ (0.106 GeV/c^2)	$1.90 M_p$ (1.78 GeV/c^2)
electron-neutrino	muon-neutrino	tau-neutrino
$2\text{–}3 \times 10^{-9} M_p$ ($\sim$2–3 eV/c^2)	$< 1.8 \times 10^{-4} M_p$ ($<$ 170 heV/c^2)	$1.9 \times 10^{-2} M_p$ ($<$ 18.2 MeV/c^2)

Charges

- 1e

Zero

Stable particle $\quad$ 2.19×10^{-6}s $\quad$ 3.3×10^{-13}s

$\sim 10^{12}$ electron-neutrinos pass through our bodies every second.

What are Neutrinos ?

Our theories do not predict the masses of neutrinos !

Recently, neutrinos have extremely small but non zero (finite masses).

Need a block of lead ninety thousand million million metres thick.

So Neutrinos interact weakly and rarely.

~10^{12} electron-neutrinos pass through our bodies every second.

How do we study (unknown) neutrinos ?

Aspects of Neutrino Reaction

Consider the characteristic reaction again but more deeply

$$X_{unknown} + n \to p + e^{-}$$

Evidently, inside the neutron, the following fundamental reaction has taken place.

$$X_{unknown} + d \to u + e^{-}$$

This is the basic reaction that has been triggered by the weak force. Notice that it only involves one of the quarks within the original neutron. The other 2 quarks are unaffected.

Neutrino reactions with matter

Consider this characteristic (Famous) reaction

$$\nu_e + n \rightarrow p + e^-$$

If the neutron in the above is part of the nucleus of an atom, then the reaction will transform the nucleus.

$$\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^-$$

The electron produced by the reaction would be moving quickly to be captured by the Argon nucleus.

A Rule:

Charge conservation !

Aspects of Neutrino Reaction

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Aspects of Neutrino Reaction

Look more closely at the charges

$$\begin{array}{lccccccc} & \nu_e & + & d & \rightarrow & u & + & e^- \\ charges & 0 & & -\frac{1}{3} & & +\frac{2}{3} & & -1 \end{array}$$

What can we learn ?

Conservation of Electrical Charge

In any reaction the total charge of all the particles entering the reaction (collision or scattering) must be the same as the total charge of all the particles after the reaction.

A good practice is to check this rule 1st in every reaction one studies.

Muon neutrinos & Electron neutrinos

Again consider this characteristic (famous) reaction

$$\nu_{\mu} + n \rightarrow p + \mu^{-}$$

Again more closely $$\nu_{\mu} + d \rightarrow u + \mu^{-}$$

Note: charge is also conserved. Muon is 200 times more massive than the electron. The Muon neutrino has never produced an electron and electron-neutrino has never produced a muon.

- So weak force acts within the lepton generations.

Neutrinos verified

Wolfgang Pauli postulated it in 1932

Confirmed in 1950 in atomic reactors

Also muon is established in 1950… surfaced in 1929 in cosmic ray experiments.

Question in everyone's mind ?

Nobody was able to tell if the muon-neutrino and the electron-neutrino were different particles.

(Exclusion Principle)

not Principal !

Consider The Reverse Reaction of

$$\nu_e + {}^{37}_{17}Cl \rightarrow {}^{37}_{18}Ar + e^-$$

More neutrino reactions

Consider the reverse process by swallowing one of its electrons:

$$^{37}_{18}Ar + e^- \rightarrow ^{37}_{17}Cl + \nu_e$$

This process is called K capture.

The electron that triggers the reaction comes from the lowest energy state of the orbital electrons …

The electron can be “swallowed” by one of the protons in the nucleus turning it into a neutron … weak force at work.

$$\nu_e + ^{37}_{17}Cl \rightarrow ^{37}_{18}Ar + e^-$$

At the quark level (Lepton Generation Conservation)

Recall: this electron is swallowed by one of the protons in the nucleus turning it into a neutron.

$$\begin{array}{cccccc} u & + & e^- & \rightarrow & d & + & \nu_e \\ \frac{2}{3} & & -1 & & -\frac{1}{3} & & 0 \end{array}$$

The member of the first generation that was present before the reaction, the electron, has to be replaced by another member of the first generation after the reaction… in this case is electron-neutrino.

What can we learn now ? Lepton Generation Conservation

In any reaction, the total number of particles from each lepton generation must be the same before and after the reaction.

Another example :

$$\nu_\mu + e^- \rightarrow \mu^- + \nu_e$$

Another Rule:
Lepton Generation conservation !

An Odd Situation

Beta Radioactivity (decay) we learn from Junior College

$$n \rightarrow p + e^-$$

At the quark level there is a more fundamental reaction taking place

$$\begin{pmatrix} d \\ d \\ u \end{pmatrix} \rightarrow \begin{pmatrix} u \\ u \\ d \end{pmatrix} + e^- \quad \Longrightarrow \quad \begin{pmatrix} d \\ d \\ u \end{pmatrix} \rightarrow \begin{pmatrix} u \\ d \\ u \end{pmatrix} + e^- \quad \Longrightarrow \quad d \rightarrow u + e^-$$

RHS: an electron has appeared. Either the rule is violated or we have not yet found out how to apply the rule consistently.

Tau and Muon raise Another Mystery

But people observed the following decay events in nature :

$$\begin{array}{cccccccccc} \mu^- & \rightarrow & e^- & + & \nu_\mu & + & \nu_? \\ \tau^- & \rightarrow & \mu^- & + & \nu_\tau & + & \nu_? \end{array}$$

What is hard to understand is the presence of a second neutrino among the decay products ...

This reaction does not conserve leptons ?

How can we be sure ?

Is there something wrong with the rules laid down ?

Who ordered that ?

Rabi

Recall :

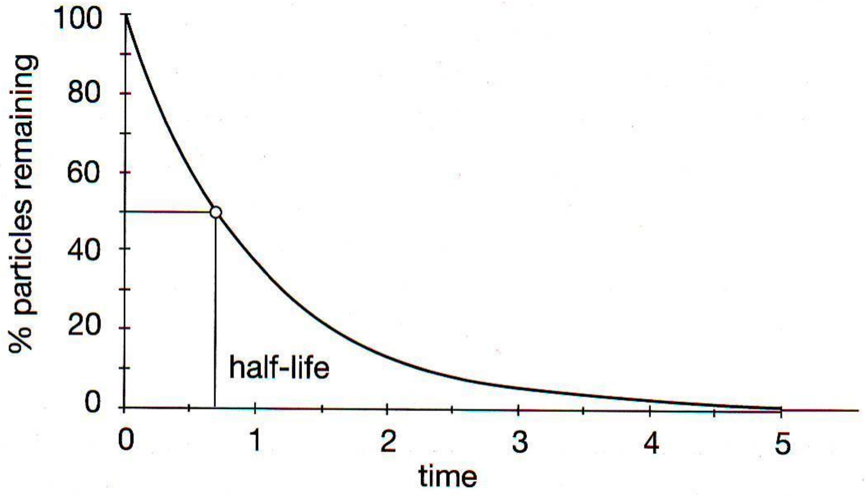
Cosmic rays are streams of charged particles that hit the earth.

75% of the cosmic rays counted at sea level are muons.

Protons from the sun strike in the atmosphere causing reactions that produce muons.

A comment on random decays ?

Why half life ? Leptons



The decay of particles.

The particles produced by the decay did not exit before the decay took place.

The decay process **is not like a 'bag' splitting open** to release the electron & neutrino held inside.

Recall the photon from the atom.

"A watched pot never boils"

Muon lifetimes : 2.19703 (0.0004) x 10^{-6} sec.

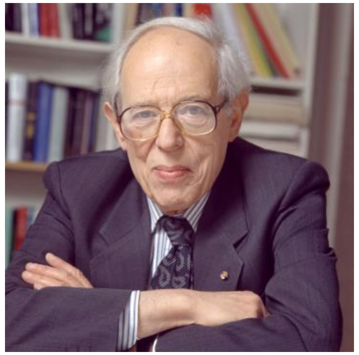
Tau mass is ~17 times of muon and life times is 3.3(0.4) x 10^{-13} sec.

Physics at its best !

"It was a wonderful mess at that time. Wonderful ! Just great ! It was so confusing … physics at its best when everything is confused and you know something important lies around the corner".

Recalled by Abraham Pais

Einstein's Biographer



4 Fundamental Forces (Interactions)

Forces (Interactions) 	Force Messengers Bosons (integer Spins)	Matter Fermions (1/2 Integer Spins)
Gravity	Graviton (massless) Geometry ?	All matter that have mass No charges
Electromagnetic (E+M~ light)	Photon (massless)	All charged matter 2 charges +ve or –ve
Strong	Gluons (massless) 3 colours, (R, G, B)	Quarks 3 Charges u, d, s, c, t, b (R, G, B)
Weak	W^+, W^-, Z^0 (3 Massive bosons)	Quarks, 6 flavours Leptons, 6 flavours