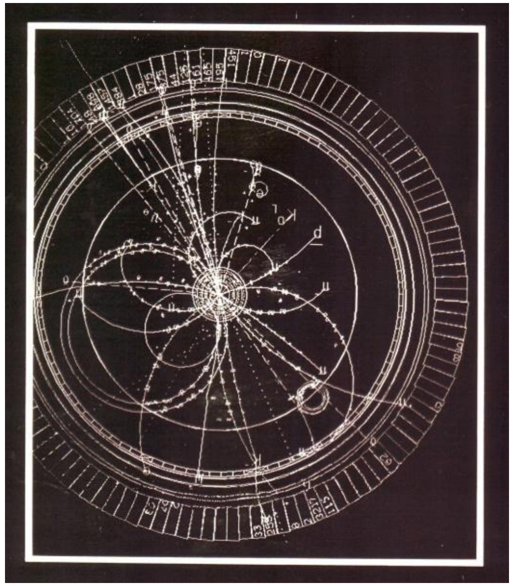
Lecture 15, Anti-matter



Internet, CERN

Standard Model (Theory) : 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

Standard Model (Theory): 4 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

Internal Properties

The conservation of Leptons Rule seems to get **into trouble** when applied to some decay experiments in nature such as :

$$\mu^- \to e^- + \nu_\mu + \blacksquare$$

$$\tau^- \to \mu^- + \nu_\tau + \blacksquare$$

The second neutrino is a **mystery !**

Convinced us of the difference between the electron neutrino and muon neutrino … there must be some property that distinguishes them, even if we cannot measure it.

About reducing Mathematics !

Leon Lederman
Nobel laureate

There is awesome resistance for the system to change. But I think this is a better way to teach physics. Once you reduce the math, physics is harder to teach and may be that’s part of the problem.

How to distinguish them ?

Assignments of lepton numbers.

	Electron-number L_e	Muon-number L_μ	Tau-number L_τ
electron	1	0	0
electron-neutrino	1	0	0
muon	0	1	0
muon-neutrino	0	1	0
tau	0	0	1
tau-neutrino	0	0	1

May be there are some [redacted] that we cannot measure by any familiar means **...**
recall [redacted]
Call this number a Lepton number, L_e, L_μ and L_τ
Like an "internal switch" 1 or 0, for Leptons.
Notice: ... does not distinguish between the lepton and its neutrino (with same generation).

More quantum labels !

(internal properties)

“Internal Switch” in Lepton

Comment !

It is a way of thinking … to keep track.

Physicists call it internal (intrinsic) properties … … like your Spin. … recall States. ~ existing in a thing as a natural or permanent quality. ~essential.

But one would need to be convinced that we are doing something more useful and interesting than just assigning and playing with numbers / labels.

Lepton Number Conservation

Consider the good old equation again $\nu_e + d \rightarrow u + e^-$

By definition all quarks have lepton number 0 (this is reasonable), hence

$$\begin{array}{cccccccc} & \nu_e & + & d & \rightarrow & u & + & e^- \\ L_e & 1 & + & 0 & = & 0 & + & 1 \end{array}$$

Normally particle physicists will need to be convinced that a property (attribute; intrinsic) is "real" and not just only an invention of the mind if :

a) It can be demonstrated that lepton number (in our case) is a conserved quantity in experimental particle reactions.

b) Usage of the say lepton number (in our case) conservation rule helps us to "understand" reactions that we could not comprehend or predict otherwise.

Another Example

Another reaction from nature.

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

$$\begin{array}{ccccccc} L_e & 0 & + & 1 & = & 0 & + & 1 \\ L_\mu & 1 & + & 0 & = & 1 & + & 0 \end{array}$$

Lepton Number Conservation

The total electron number, muon number and tauon number are separately conserved in all reactions.

In the last lecture: Weak force must maintain the number of leptons of each generation. Now we are conserving 3 different lepton numbers.

Mysterious Neutrinos

Now we are ready to discuss this decay reaction from the last lecture.

$$\mu^- \rightarrow e^- + \nu_\mu + \boxed{}$$

What is the problem ?

Let's apply our new rule !

	μ^-	$\rightarrow$	e^-	$+$	ν_μ	$+$	$\nu_?$
L_μ	1	=	0	+	1	+	?
L_e	0	=	1	+	0	+	?

$\Leftarrow$ $L_\mu = 0$

$\Leftarrow$ $L_e = -1$???

For sure muon number must be zero. But the electron number must be –ve 1 (but there is no such thing in our previous scheme !)

Mysterious radioactive decay (Beta)

Recall another odd decay experiment, we've discussed before in the last lecture … here we also try the new rule

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

$$\begin{array}{cccccc} & d & = & u & + & e^- \\ L_e & 0 & \neq & 0 & + & 1 \end{array}$$

The problem can be solved if one postulates …

$$\begin{array}{cccccccc} & d & \to & u & + & e^- & + & \nu_? \\ L_e & 0 & = & 0 & + & \boxed{} & + & \boxed{} \end{array}$$

The presence of the mysterious neutrino above was deduced entirely through trying to conserve Electron Number.

Recall how unknown X Reacts with matter

$$X + p = n + e^{+}$$

Wow ! Worse still, a totally new particle is produced … positive electrical charge equal to that of the proton. It has a mass of the electron and certainly not a proton. (~2000 x the electronic mass)

- Discovery, 1933, Anderson, in cosmic ray experiment. e^{+} is called the positron.

Let us now check the new conservation law … it is ok

$$\begin{array}{ccccccccc} & X & + & p & \rightarrow & n & + & e^{+} \\ L_e & & + & 0 & = & 0 & + & \end{array}$$

Note: By definition, proton and neutron have lepton numbers of 0.

Look at how $\nu_?$ Reacts with matter

$$\nu_? + p = n + e^+$$

Wow ! Worse still, a totally new particle is produced … positive electrical charge equal to that of the proton. It has a mass of the electron and certainly not a proton. (~2000 x the electronic mass)

Discovery, 1933, Anderson, in cosmic ray experiment. e^+ is called the positron.

Let us now check the new conservation law … it is ok

$$\begin{array}{ccccccccc} & \nu_? & + & p & \rightarrow & n & + & e^+ \\ L_e & & + & 0 & = & 0 & + & - \end{array}$$

Note: By definition, proton and neutron have lepton numbers of 0.

Positron & Mystery Neutrino

What have we done ?

It seems we have introduced a new generation(type) of leptons.

We now call the mysterious neutrino … electron antineutrino … the symbol is $\bar{\nu}_e$

Rewrite the muon decay in full (with new symbol)

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

Is there also a neutrino with $L_\mu = -1$? Yes of course, absolutely in nature !

$$\tau \rightarrow \mu^- + \nu_\tau + \bar{\nu}_\mu$$

More Epistemic Learning ?

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

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

$$\nu_e + \begin{pmatrix} d \\ d \\ u \end{pmatrix} \to \begin{pmatrix} u \\ d \\ u \end{pmatrix} + e^- \longleftrightarrow \nu_e + d \to u + e^-$$

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

The usual radioactivity decay ! $n \to p + e^- + \bar{\nu}_e$

Switching sides you get antiparticle !

Some more “anti” terminology !

What happens when muon anti-neutrino reacts with matter ?

$$\bar{\nu}_\mu + p \rightarrow n + \mu^+$$

As expected, there is a new particle produced which is exactly the same as the muon, but with a positive charge … anti-muon.

6 more leptons

The extended lepton families.

	1st generation	2nd generation	3rd generation
lepton number $= +1$	$\begin{bmatrix} e^- \\ \nu_e \end{bmatrix}$	$\begin{bmatrix} \mu^- \\ \nu_\mu \end{bmatrix}$	$\begin{bmatrix} \tau^- \\ \nu_\tau \end{bmatrix}$
lepton number $= -1$	$\begin{bmatrix} e^+ \\ \bar{\nu}_e \end{bmatrix}$	$\begin{bmatrix} \mu^+ \\ \bar{\nu}_\mu \end{bmatrix}$	$\begin{bmatrix} \tau^+ \\ \bar{\nu}_\tau \end{bmatrix}$

Anti-leptons:

lepton number = -1

Charges: Reversed

Can we do the same (quantum labels)

for quarks ?

Anti-quarks

We have been quite successful, perhaps we extend the idea to quarks by introducing 3 quark numbers also … just like the lepton numbers.

The internal property we will use is baryon number, B. All quarks have baryon number = 1/3 and all leptons have baryon number = 0.

Oh dear !

What is a baryon ? Why not call it quark number ? Also why not call it baryon fraction since it is 1/3 ?

Conservation of Baryon number

In all reactions the total baryon number of the particles before the reaction must be the same as the total baryon number after the reaction.

The extended quark families.

	1st generation	2nd generation	3rd generation
baryon number $= +\frac{1}{3}$	$\begin{bmatrix} \mathrm{u} \\ \mathrm{d} \end{bmatrix}$	$\begin{bmatrix} \mathrm{c} \\ \mathrm{s} \end{bmatrix}$	$\begin{bmatrix} \mathrm{t} \\ \mathrm{b} \end{bmatrix}$
baryon number $= -\frac{1}{3}$	$\begin{bmatrix} \bar{\mathrm{u}} \\ \bar{\mathrm{d}} \end{bmatrix}$	$\begin{bmatrix} \bar{\mathrm{c}} \\ \bar{\mathrm{s}} \end{bmatrix}$	$\begin{bmatrix} \bar{\mathrm{t}} \\ \bar{\mathrm{b}} \end{bmatrix}$

Anti-quarks:
Baryon # = - 1/3
Charges: Reversed

Examples : $antiproton = \bar{u}\bar{u}\bar{d}$ What is the charge ?

$antineutron = \bar{u}\bar{d}\bar{d}$ What is the charge ?

Do we have a theory

… for anti-matter ?

$$H\Psi(r,t) = E\Psi(r,t)$$

Recall what Equation is this ?

$$-\frac{\hbar^2}{2m}\nabla^2\Psi(r,t) + V\Psi(r,t) = i\hbar\frac{\partial}{\partial t}\Psi(r,t)$$

The Schrodinger Equation !

Nature of Anti-matter

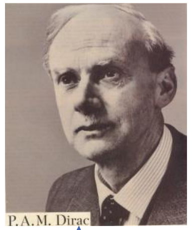
$$H\psi = E\psi$$

1st Hint in 1928.

Any theory that is consistent with relativity must contain both particles and antiparticles … look for a Schrödinger equation equivalent.

$$(-i\vec{\alpha}\bullet\vec{\nabla} + \beta m)\psi = E\psi$$

Recall from Secondary school $ax^2 + bx + c = 0$



Dirac found an equation : the Analogy : $a\psi^2+b\psi+c=0$

One solution describe the electron wonderfully but the other is a particle with the same mass but opposite electrical charge. He thought that it may be a proton.

If it is not the proton, what could it be ?

Solved 1933, Anderson found the antiparticle … "particle seems to turn the wrong way in a magnetic field", Dirac unknowingly predicted the existence of antimatter.

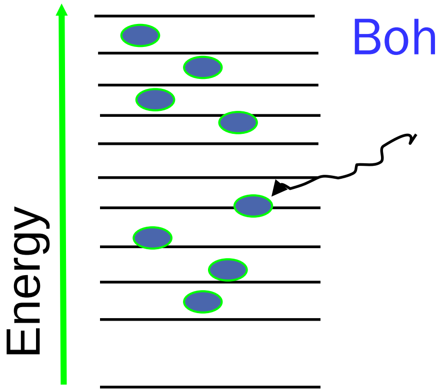
Comments on Anti-matter

$$H\psi = E\psi$$

Antimatter is remarkably rare in the Universe.

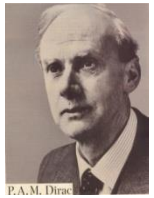
The Problem : Why the Universe does not consist of equal amounts of matter and antimatter ?

If there is a large amount of antimatter in the universe then it must be hidden somewhere.

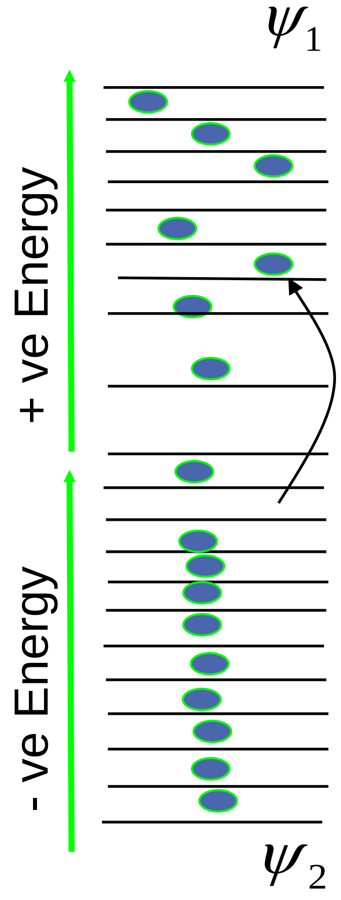


Bohr's Theory

$$(-i\vec{\alpha}\bullet\vec{\nabla}+\beta m)\psi = E\psi$$



Dirac's Theory : A vacancy or a hole in the negative energy sea acts like an electron with a positive charge i.e. a positron



$$-\frac{\hbar^2}{2m}\nabla^2\Psi(r,t)+V\Psi(r,t)=i\hbar\frac{\partial}{\partial t}\Psi(r,t)$$

Notice: the –ve energies are filled up fully with electrons.

Comments on Anti-matter

$H\psi = E\psi$

1st Hint in 1928.

Any theory that is consistent with relativity must contain both particles and antiparticles … the Schrodinger equation equivalent.

$$\begin{pmatrix} \psi_{1Su} \\ \psi_{1Sd} \end{pmatrix}$$

Note 1:

Dirac's one equation seems to describe 2 particles

Note 2 :

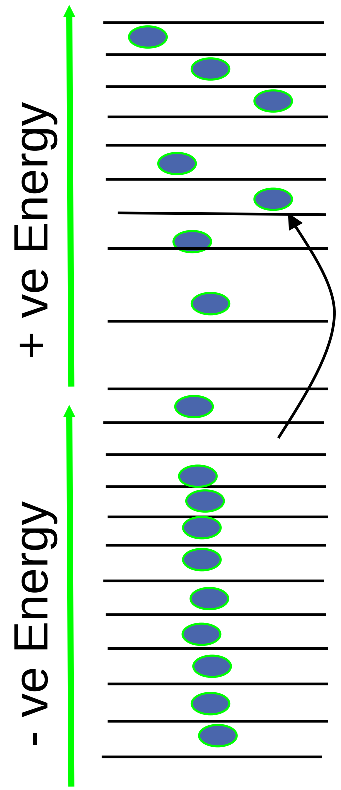
In fact, more than 2 … infinite sea of particles … annihilation … infinite sea of energy

Note 3: Another bonus :

Spin came out naturally from solving Dirac equation … it means it came about when marrying Quantum Mechanics with Special Relativity.

You now know why he is my Hero !

$$\begin{pmatrix} \psi_{2Su} \\ \psi_{2Sd} \end{pmatrix}$$



Annihilation Reactions

One science friction fact is true !

Matter and antimatter will destroy each other if they meet.

Particle physicists regularly collide small amounts of matter and antimatter together, because of the high energies. New particles that may be produced in such a reaction (collisions, scattering or interactions)

A favorite Collision called annihilation: $e^+ + e^- \rightarrow$? ? ? … energy … matter

Done at CERN, LEP: Large Electron-Positron Collider

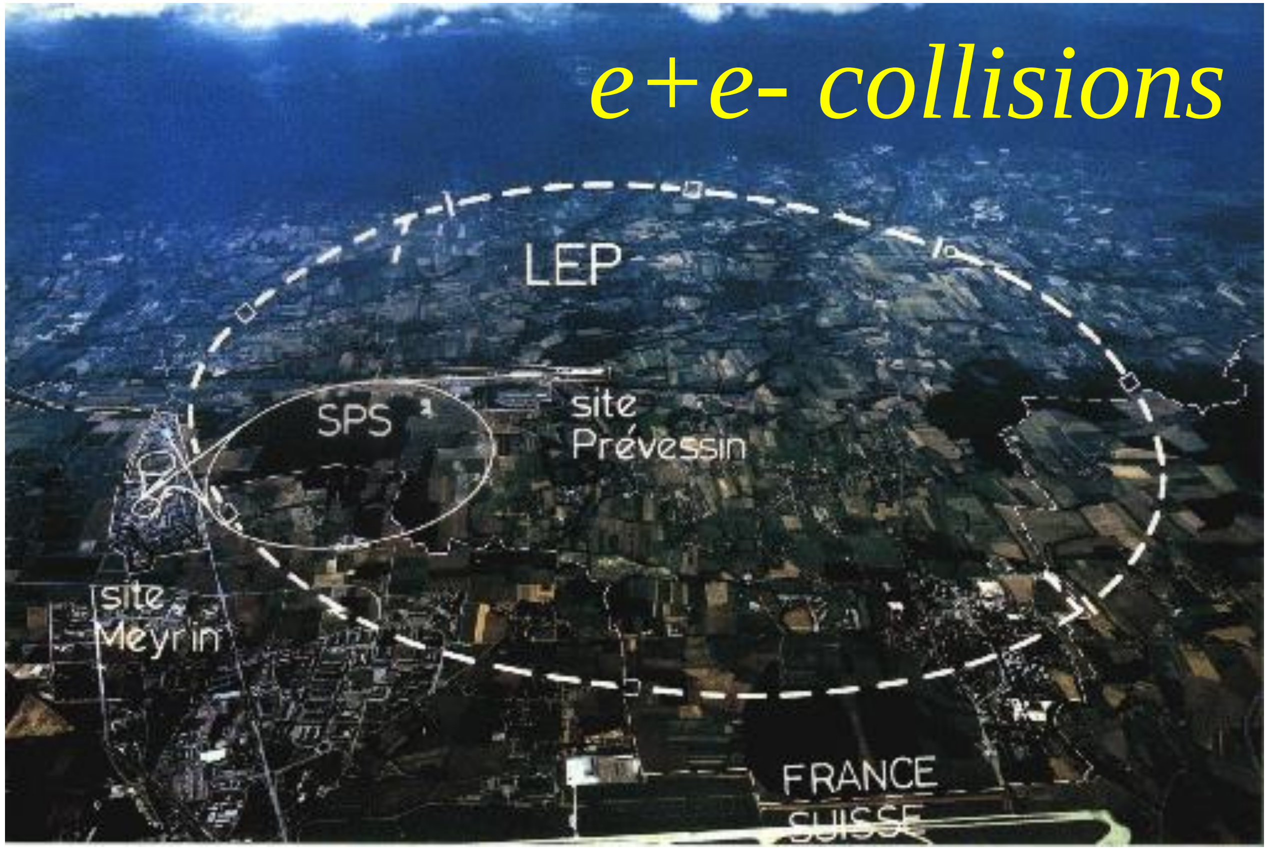
PET Scan

Anti-particles are not science fiction any more

Antimatter is becoming increasingly common in medical technology. One technique, called **Positron Emission Tomography (PET scan),** follows the flow of a positron-emitting fluid through the body. Wherever an antimatter positron encounters a normal-matter electron, the pair annihilates and produces particles whose trajectories trace back to the point of annihilation, allowing a computer to reconstruct the shape of structures in the body.

https://www.technology.org/2015/03/02/antimatter-in-practice-protons-in-the-pet-scanner/

Large Electron-Positron Collider



LHC (Large Hadron Collider … proton-proton … pp scattering) is sitting on the old LEP (Large Electron-Positron Collider … e+e- scattering)

European organization (**C**ouncil) for **N**uclear **R**esearch

Features of e^+e^- Annihilation

All energies of e^+ and e^- simply scatter off each other … nothing happens.

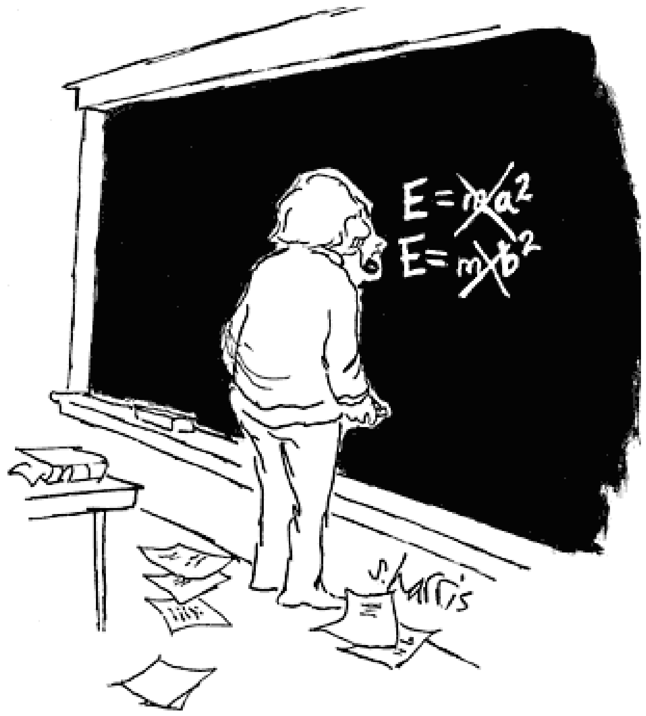
If e^+ and e^- move slowly, then they can go into orbit round each other producing a "Bohr like" atom called positronium (like a binary system). This system is unstable.

At higher energy, we may get $e^+ + e^- \longrightarrow \mu^+ + \mu^-$

At even higher energy, we've $e^+ + e^- \longrightarrow \tau^+ + \tau^-$

Higher energy still, messy "jet events".

1905
Einstein made 8 attempts
1934
The great, Planck



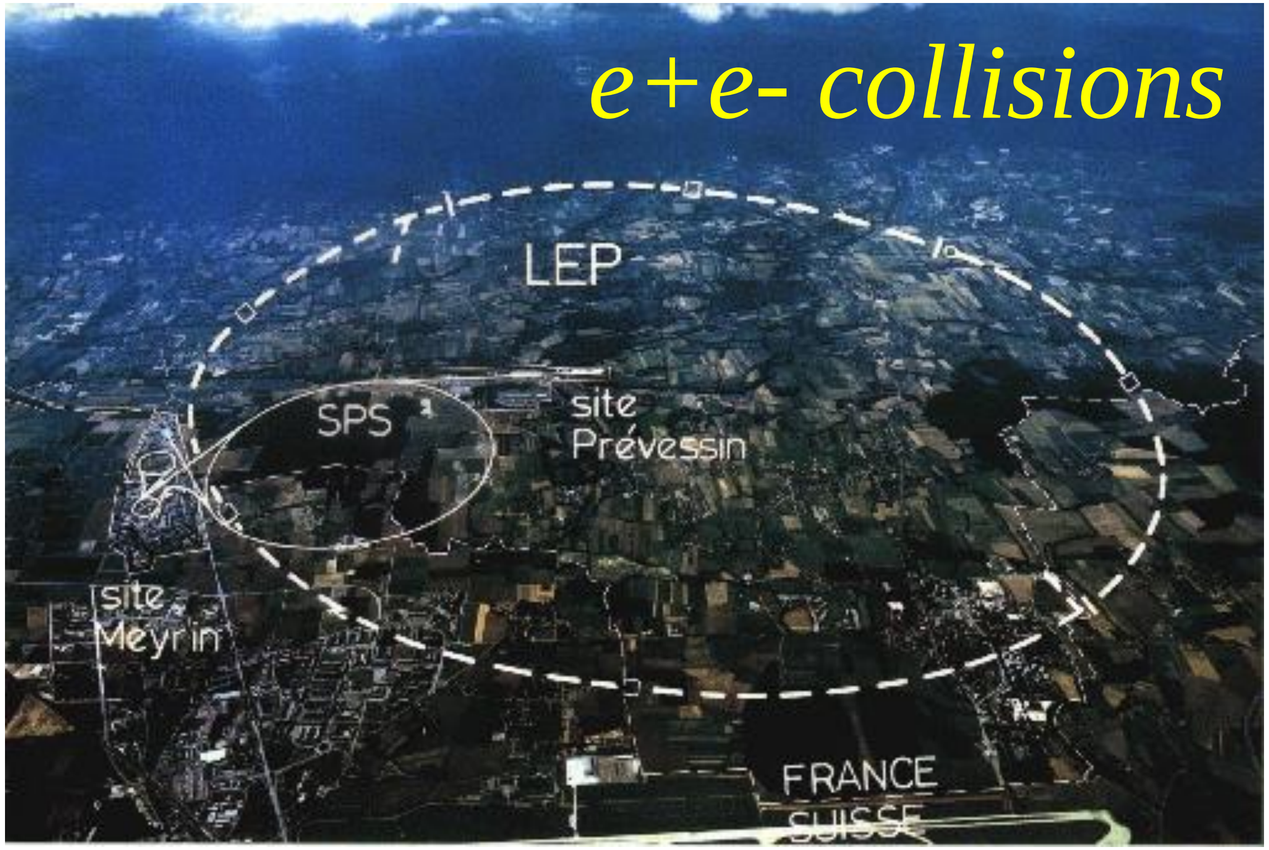
Recall

$$E = m_0 c^2$$

$$E^2 \neq \left(m_o c^2\right)^2$$

$$E^2 = (m_0 c^2)^2 + \left(pc\right)^2$$

Large Electron-Positron Collider



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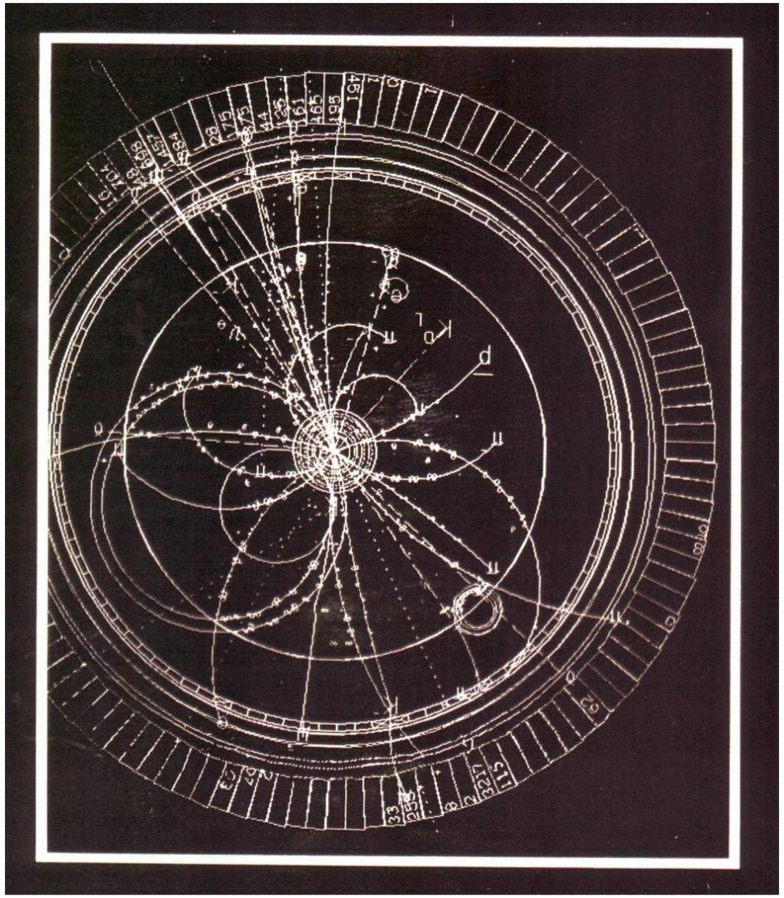
What are jet events ?



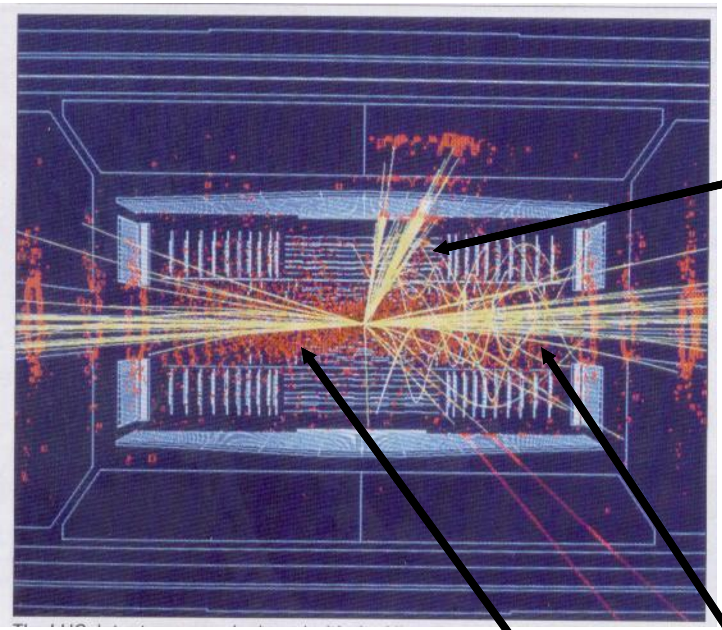
They are not clean and nice as the lepton reactions.

In fact, as energy thresholds increases, more and more particles are produced … mostly mesons.

Note : when e^+ and e^- react together, the initial combination of particles is such that the electrical charge, lepton number and baryon number all total to zero.

This allows the reaction to produce almost anything, provided the combination adds to zero again.

Annihilation Jet Reactions



Sometimes there is a 3rd jet … manifestation gluons

Quark Jets, eventually materialized to hadrons, baryons, mesons

CERN : European Center (Council) for Nuclear Research

Matter & Antimatter : Comments

The materialization of particles and antiparticles is a consequence of the $E = mc^2$.

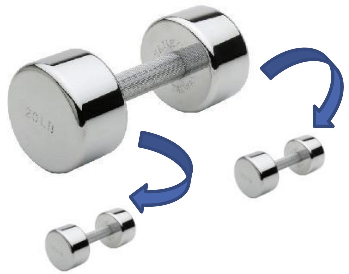
So annihilation experiments between matter and antimatter can lead to the production of new matter and antimatter provided they are produced in equal amounts and provided there is enough energy in the reaction.

Seems to imply an essential symmetry between them.

If there are equal quantities of matter and antimatter, then where are all the antimatter?

The creation of the Universe would violate our conservation laws, unless equal amounts of matter and antimatter are produced … a fundamental cosmological problem.

Quarks combine to Hadrons



Quark Masses (read with a pinch of salt)

The masses of the quarks (in GeV/c^2).

Charge	1st generation	2nd generation	3rd generation
+2/3	up 0.33	charm 1.58	top 175[1]
−1/3	down ~0.33	strange 0.47	bottom 4.58

We expect : down quark is slightly more massive than the up quark. Why ?

It is impossible to calculate how much of the mass of a proton, say, is due to the masses of the quarks inside and how much is due to the interaction energies (gluons) between the quarks.

We believe that it is (theoretically) impossible to isolate an individual quark (or antiquark) … Quark confinement !

Get angry with me !

Even more quantum labels !

Properties of Hadrons

Internal Properties of quarks

The quark flavour numbers.

Not quark numbers

Quark	U	D	C	S	T	B
up	1	0	0	0	0	0
down	0	−1	0	0	0	0
charm	0	0	1	0	0	0
strange	0	0	0	−1	0	0
top	0	0	0	0	1	0
bottom	0	0	0	0	0	−1

1974

1977

1994/95

The flavour numbers belong to each quark, not to each generation as in the case of the leptons. There is also no common flavour number to the u and d quarks, What about anti-quarks ? Do they have flavour numbers also?

Strong Force (Interaction)

The strong force exists only between quarks. The leptons do not feel the strong force.

HEP says that the strong force is flavour independent.

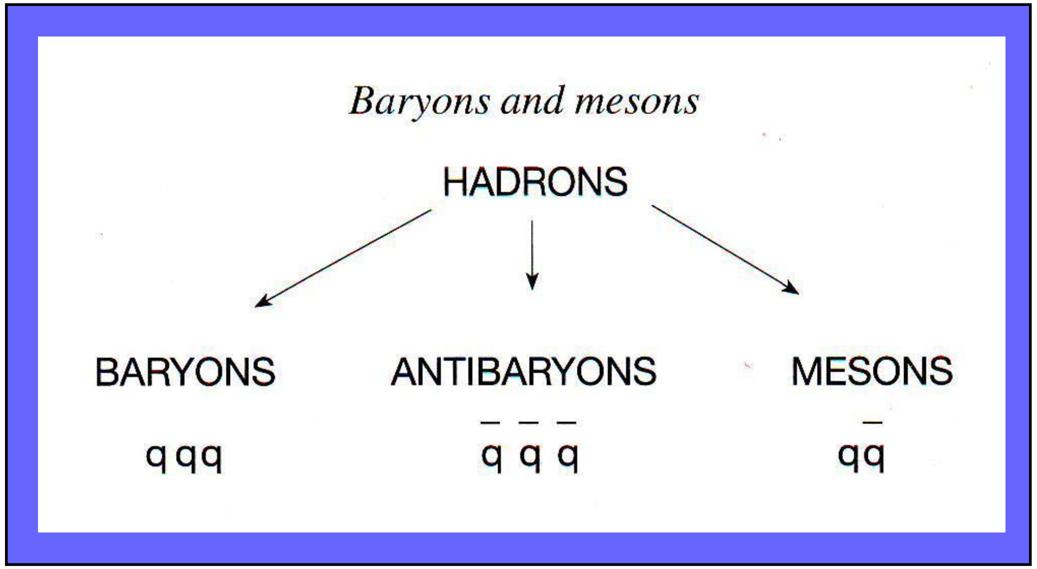
The strong force ensures that quarks and antiquarks can only stick in groups of

$3q$(baryons) or $2q$(mesons) [collectively called hadrons]

$$qqq \text{ or } \bar{q}\bar{q}\bar{q} \qquad q\bar{q} \text{ or } \bar{q}q$$

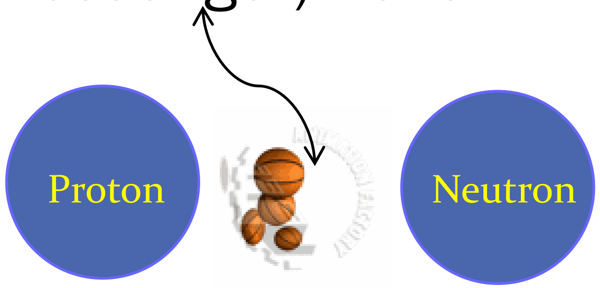
Baryons and Mesons

The hadron family tree



Mesons was 1st proposed for interaction between nucleons … mesons so called intermediate mass between electron and protons. … similar idea comes from photons in E & M.

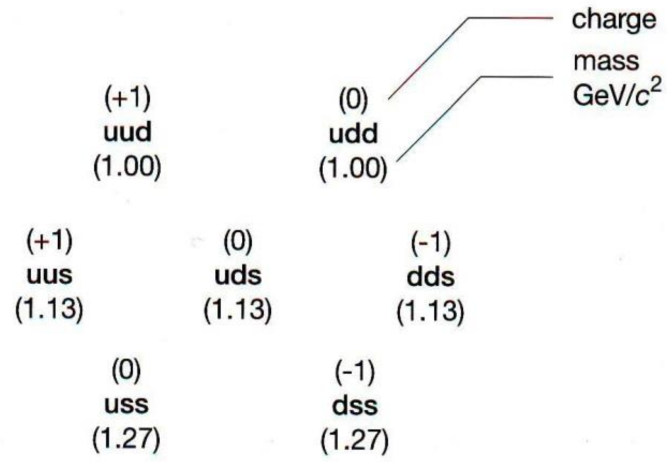
Historical, where did Mesons come from … (messenger) Balls



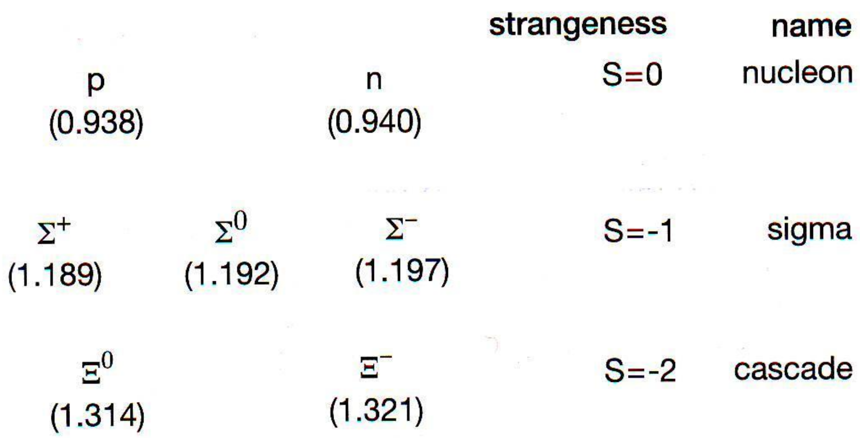
Yukawa

1949 Nobel Prize

Baryon Families

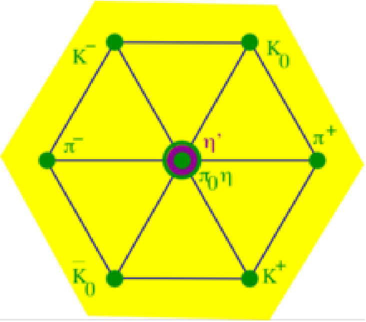


Quark combinations (predicted particle masses in GeV/c^2).



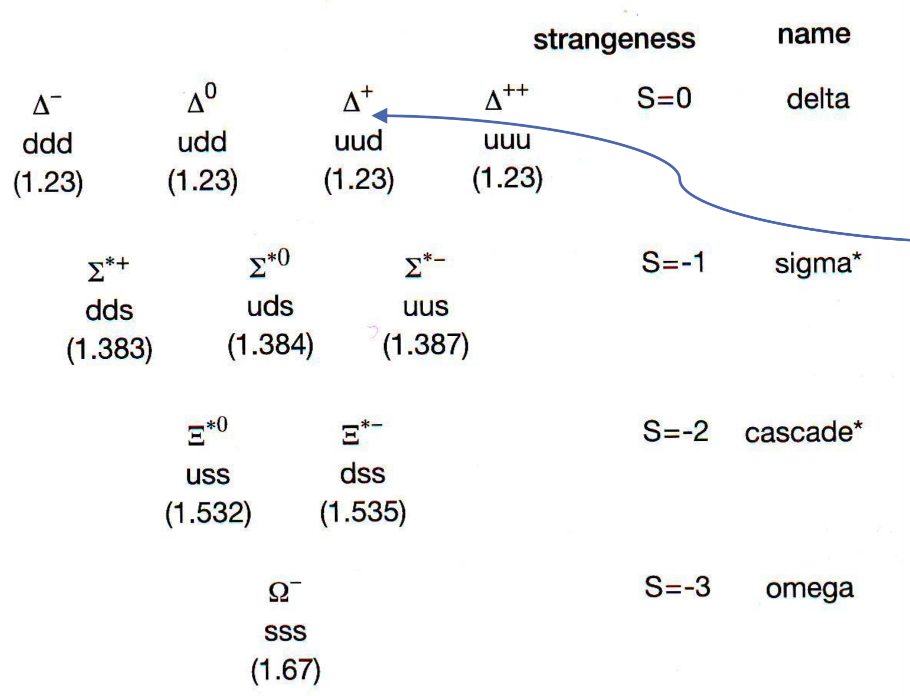
A baryon weight diagram (particle masses in GeV/c^2).

Weighted diagrams … The Eightfold Way



Only for u, d, s … the diagrams get more complicated when one add c, t, and b.

Higher Baryon Families



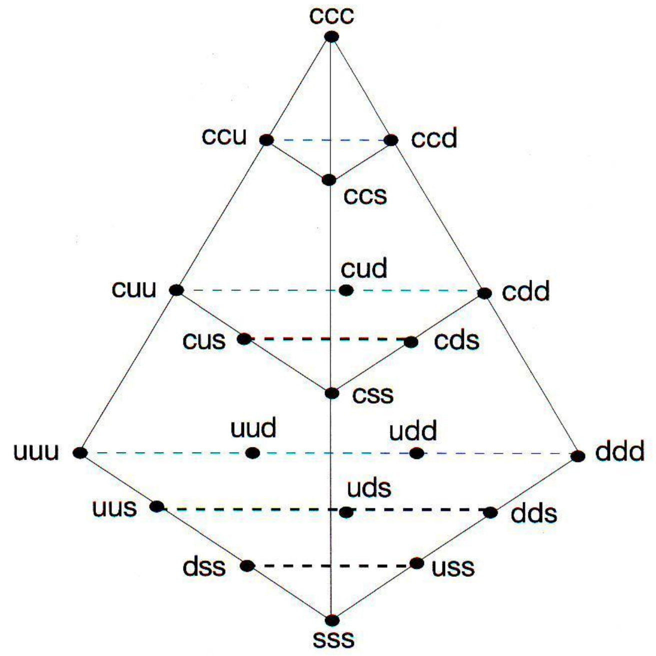
The higher mass baryons.

Why not proton ?

Charmless

Notice **higher versions of proton and neutrons**

A Charming Decuplet



A charming extension to the baryon decuplet.

Meson Families

	(0) $d\bar{s}$ (0.80)	(+1) $u\bar{s}$ (0.80)
(-1) $d\bar{u}$ (0.66)	(0) $u\bar{u}$ $d\bar{d}$ $s\bar{s}$ (0.66/0.94)	(+1) $u\bar{d}$ (0.66)
	(-1) $s\bar{u}$ (0.80)	(0) $s\bar{d}$ (0.80)

Meson quark combinations.

"For everything that's lovely is/But a brief, dreamy, kind delight." - 'Never Give All the Heart', W. B. Yeats

Only for 3 light quarks … similarly it gets more complicated when charm, truth (top) and beauty (bottom) are added.

Nonet

			strangeness	family name
K^0 (0.498)		K^+ (0.494)	S=+1	kaons
π^- (0.140)	$\pi^0/\eta/\eta'$ (0.135/0.547/0.958)	π^+ (0.140)	S=0	pions/eta
K^- (0.494)		$\bar{K}^0$ (0.498)	S=-1	kaons

The meson nonet.

Review Internal Properties, Quarks

Comments !

To label various hadrons by the internal properties of the quarks that they contain.

Example :

Any hadron that contains a strange quark is called a strange particle and given a value of the internal property S. So the S value tells us how many strange quarks it contains.

Try :

charge

What is the quark content for D^0 meson which has C quantum label = +1?

It must be $(c\bar{u})$. Note : there may be other solutions but why this ?

Properties of Hadrons (Quantum labels)

Internal Properties of quarks

The quark flavour numbers.

Not quark numbers

Quark	U	D	C	S	T	B
up	1	0	0	0	0	0
down	0	−1	0	0	0	0
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strange	0	0	0	−1	0	0
top	0	0	0	0	1	0
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Only 12 particles : We can make all forms of matter.

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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	$2/3$
DOWN	d	6	$-1/3$
STRANGE	s	200	$-1/3$
CHARM	c	3000	$2/3$
BOTTOM	b	9000	$-1/3$
TOP	t	?	$2/3$

Beauty

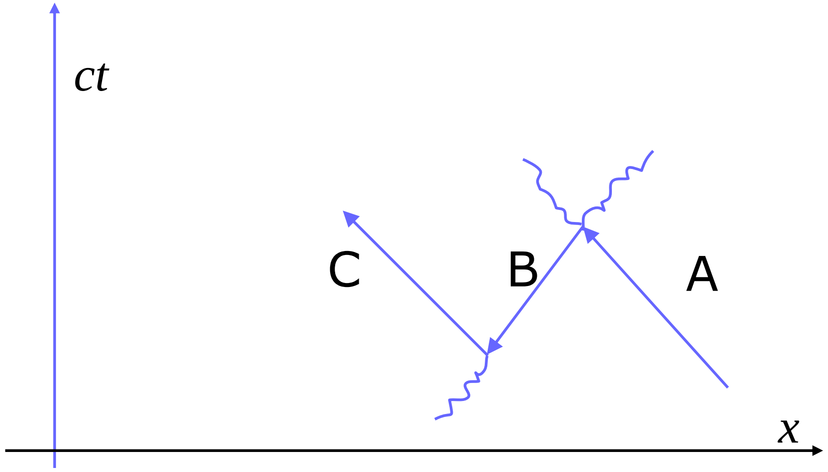
Truth

Last to be discovered

A Socratic thought ...

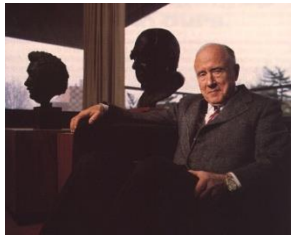
to think about !

If you see one you see All !



Recall: Space-time diagram and world lines of micro particles.

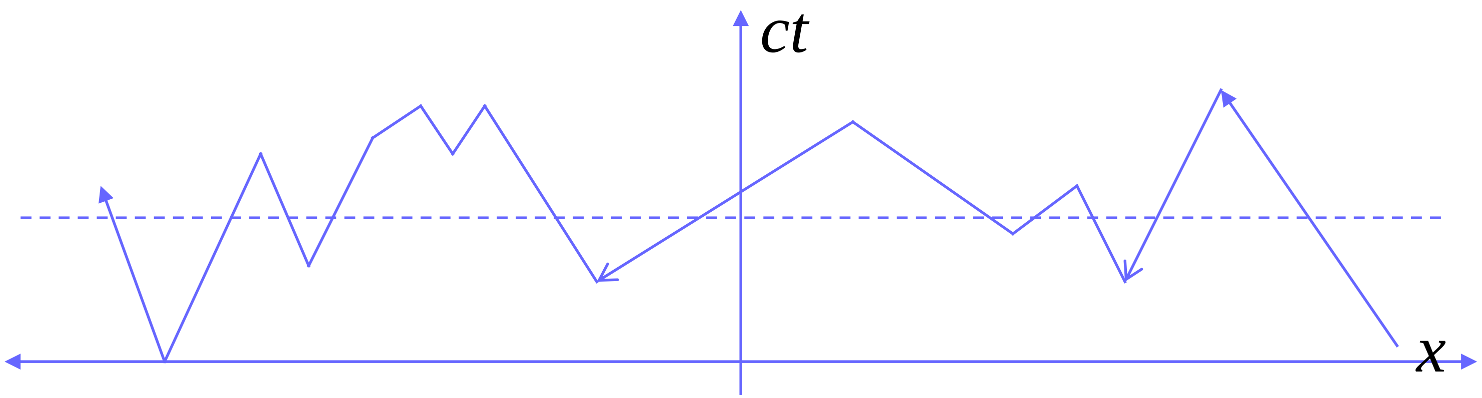
Notice: how do we represent an antiparticle ? ?



Richard Feynman and John Wheeler suggested that instead of viewing this diagram as representing 2 electrons and 1 positron, we can perceive it as representing a single particle that travels forward in time as electron A, travels backward in time as position B (may then moves forward in time again as electron C)

Feynman, 1965 and Wheeler

So there is only one electron in the Universe !



The electron would have a complicated world line, sometimes going forward in time, sometimes backward. When it was going forward in time it would be an electron, when it was going backward in time it would be a positron ... but there would be only one electron. This provides a nice explanation of why electrons have the same charge. Weak point: there appears to be many more electrons (e^-) than positrons (e^+) in the universe.

All the best !

The more success the quantum theory has, the sillier it looks.

A. Einstein

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

Standard Model (12 + $\overline{12}$ particles)

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

Thank you

… for taking this module