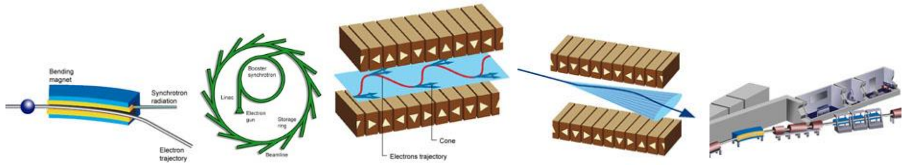
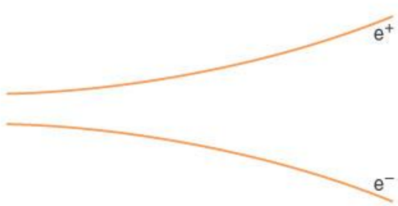


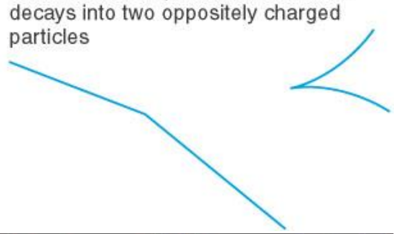
(a) Fast particles make a thin curved track

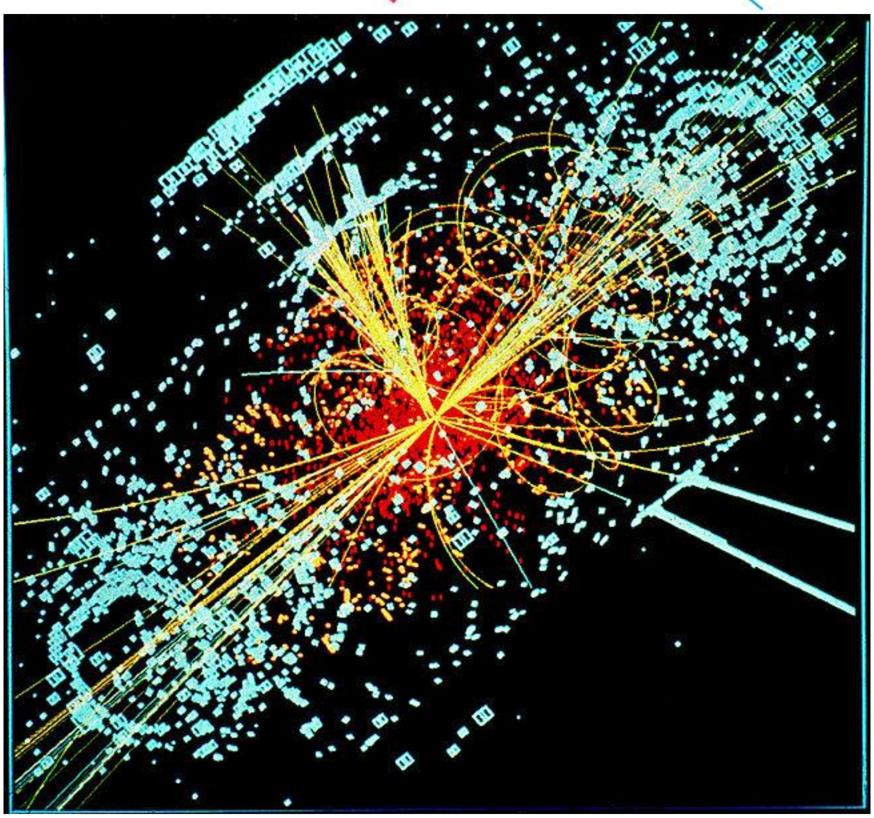


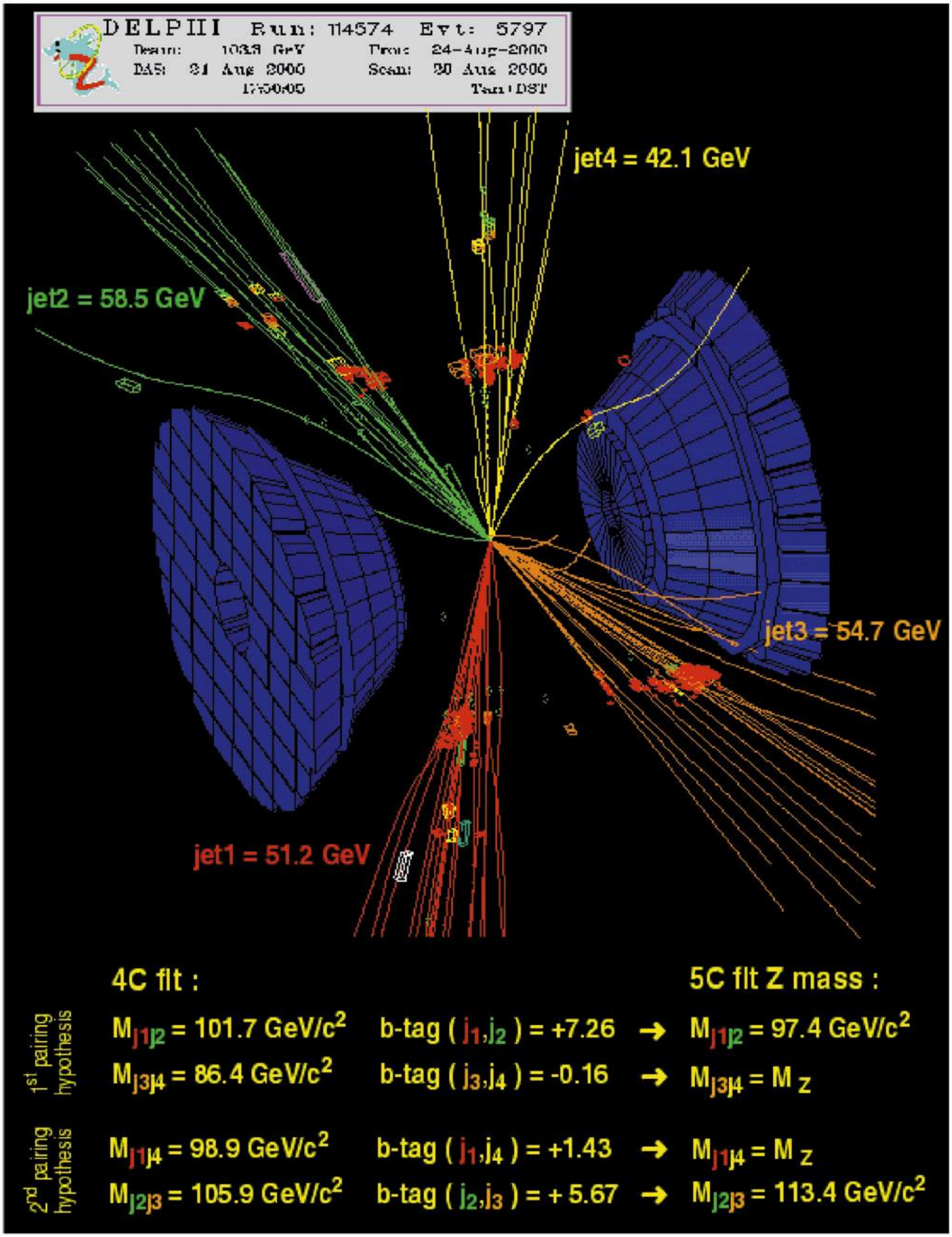
(b) Slow particles or massive particles cause more ionisation in a shorter distance and hence thicker tracks

(c) Particles lose kinetic energy through ionising collisions, so track gets more curved and thicker

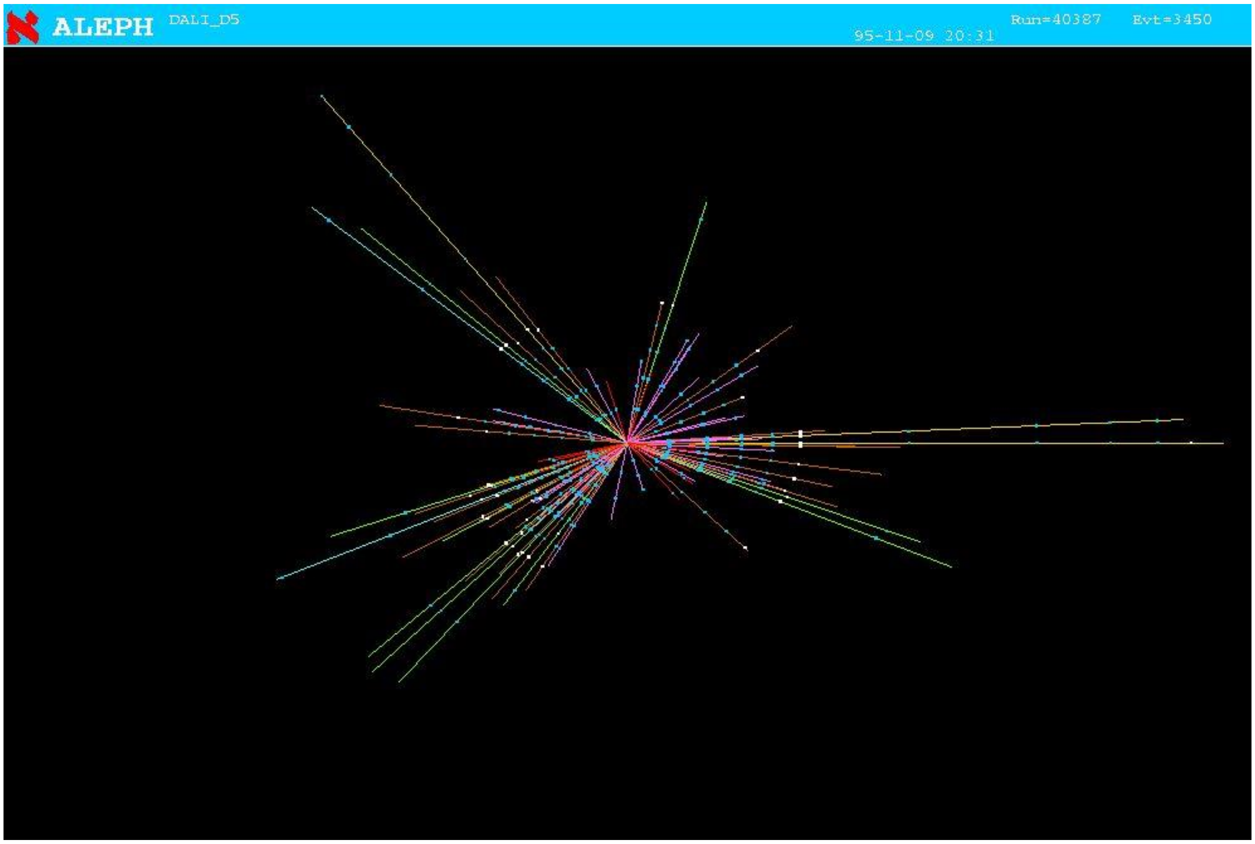
(d) A decay into a charged particle and a massive neutral particle, which itself decays into two oppositely charged particles

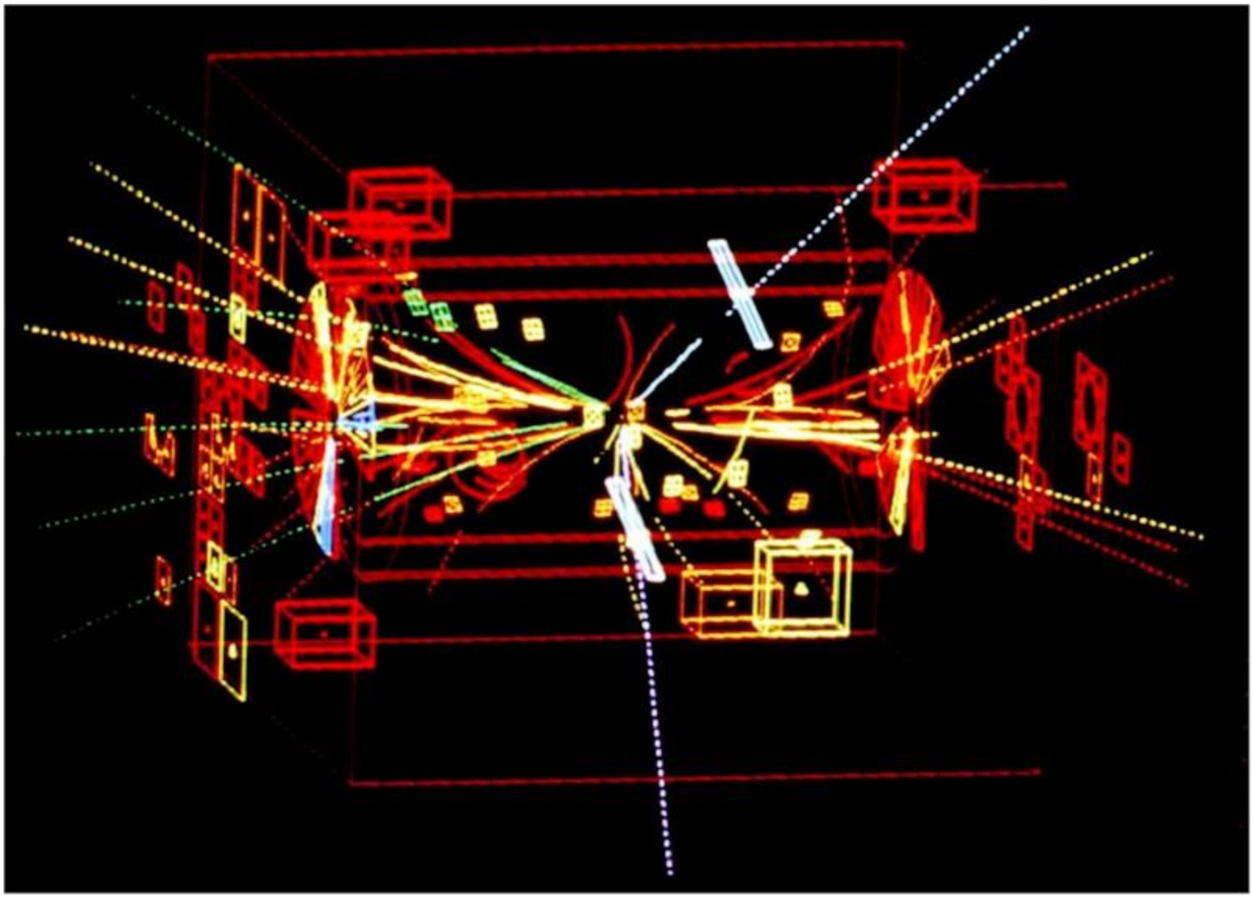


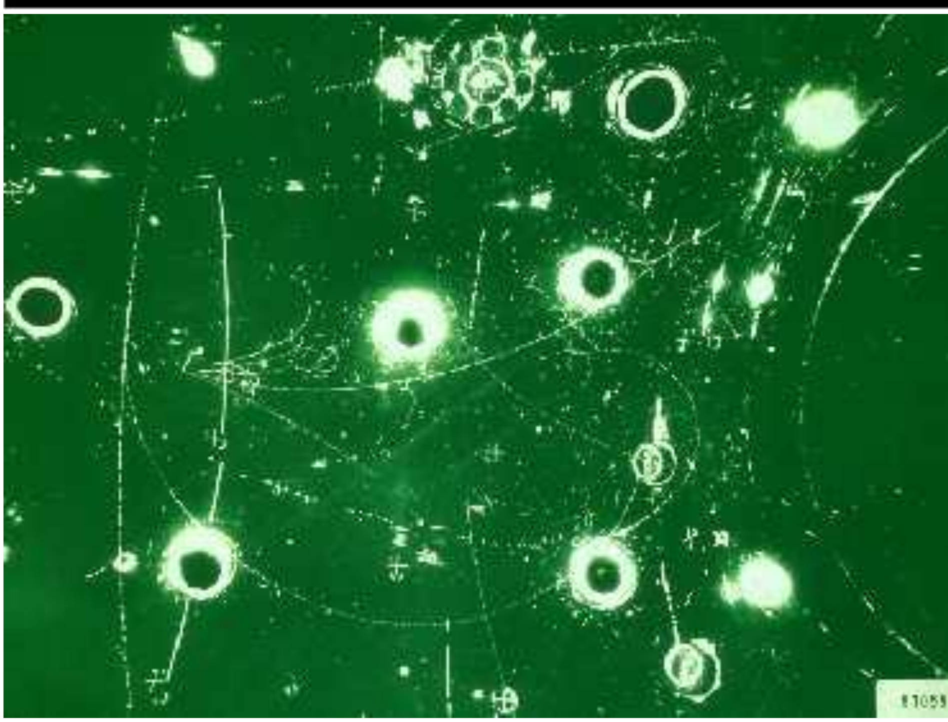


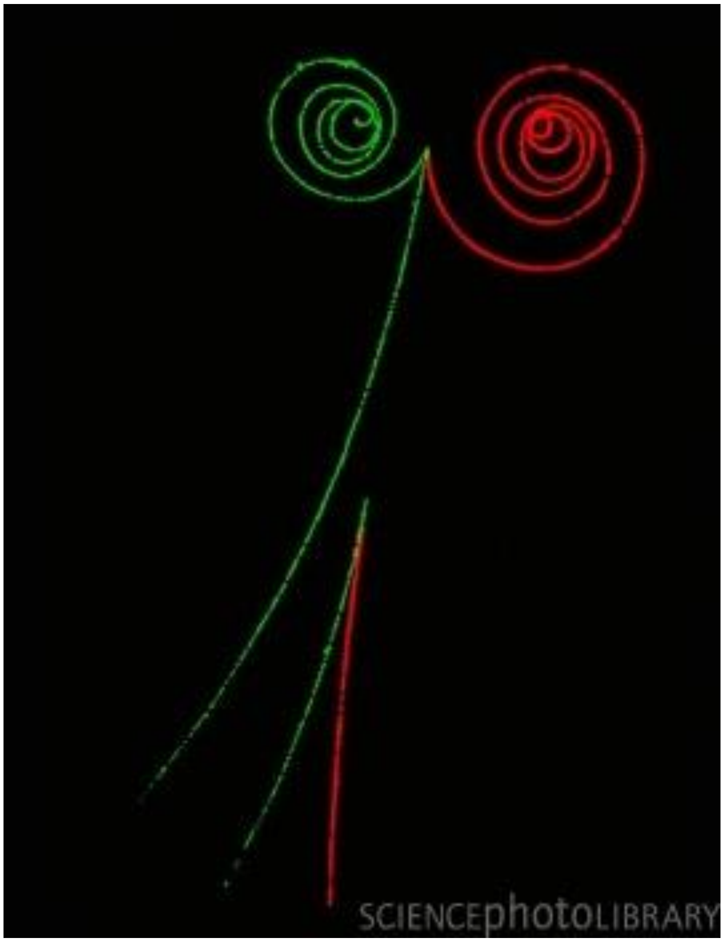


DELPHI Run: 114574 Evt: 5797
jet4 = 42.1 GeV
jet2 = 58.5 GeV
jet3 = 54.7 GeV
jet1 = 51.2 GeV
4C fit :
5C fit Z mass :
1st pairing hypothesis
M j1j2 = 101.7 GeV/c2 b-tag (j1,j2) = +7.26 → M j1j2 = 97.4 GeV/c2
M j3j4 = 86.4 GeV/c2 b-tag (j3,j4) = -0.16 → M j3j4 = M Z
2nd pairing hypothesis
M j1j4 = 98.9 GeV/c2 b-tag (j1,j4) = +1.43 → M j1j4 = M Z
M j2j3 = 105.9 GeV/c2 b-tag (j2,j3) = + 5.67 → M j2j3 = 113.4 GeV/c2

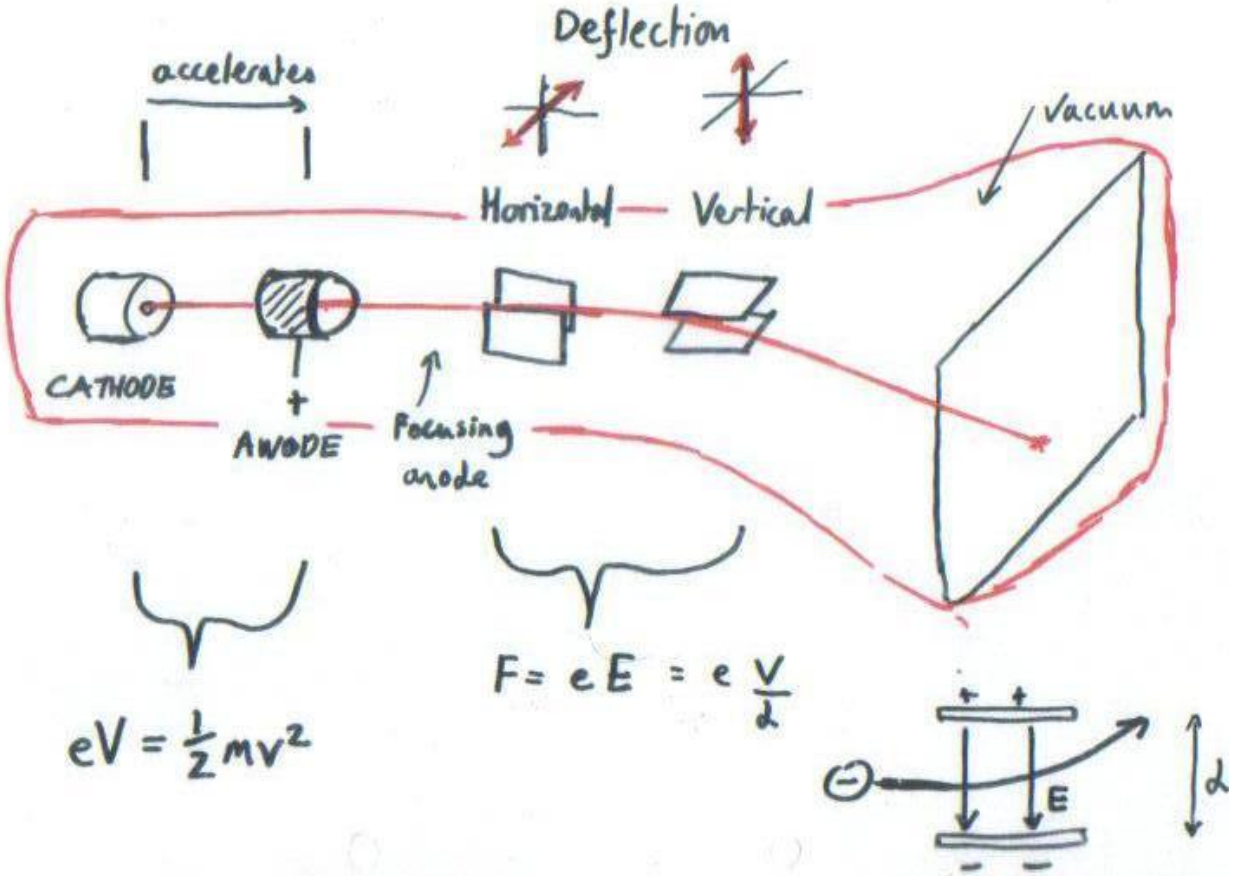

ALEPH
DALI_D5
Run=40387 Evt=3450
95-11-09 20:31



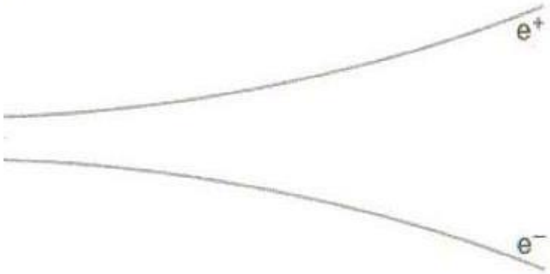



SCIENCEphotoLIBRARY

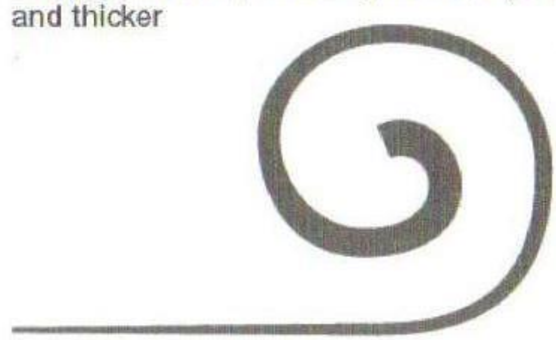
THE CATHODE RAY TUBE



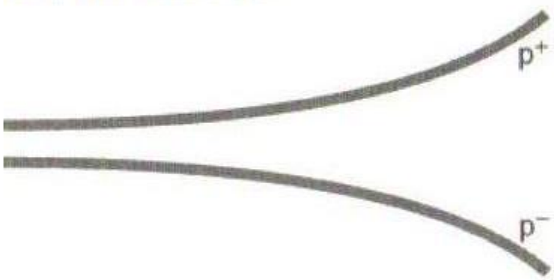
(a) Fast particles make a thin curved track



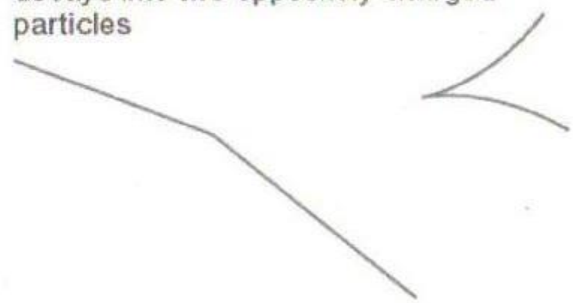
(c) Particles lose kinetic energy through ionising collisions, so track gets more curved and thicker



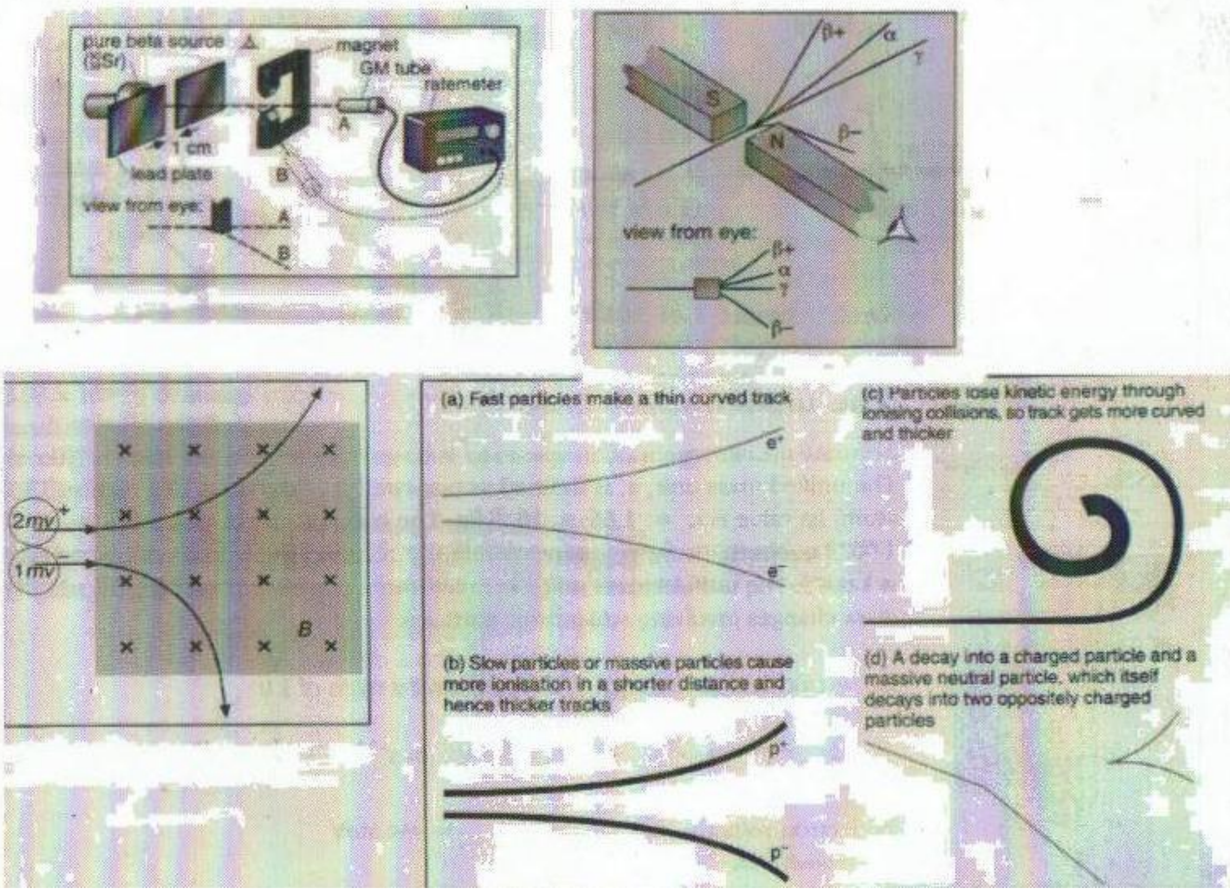
(b) Slow particles or massive particles cause more ionisation in a shorter distance and hence thicker tracks



(d) A decay into a charged particle and a massive neutral particle, which itself decays into two oppositely charged particles



magnetic deflection.JPG



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$ Baryons are fermionic hadrons. These are a few of the many types of baryons.					
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

BOSONS

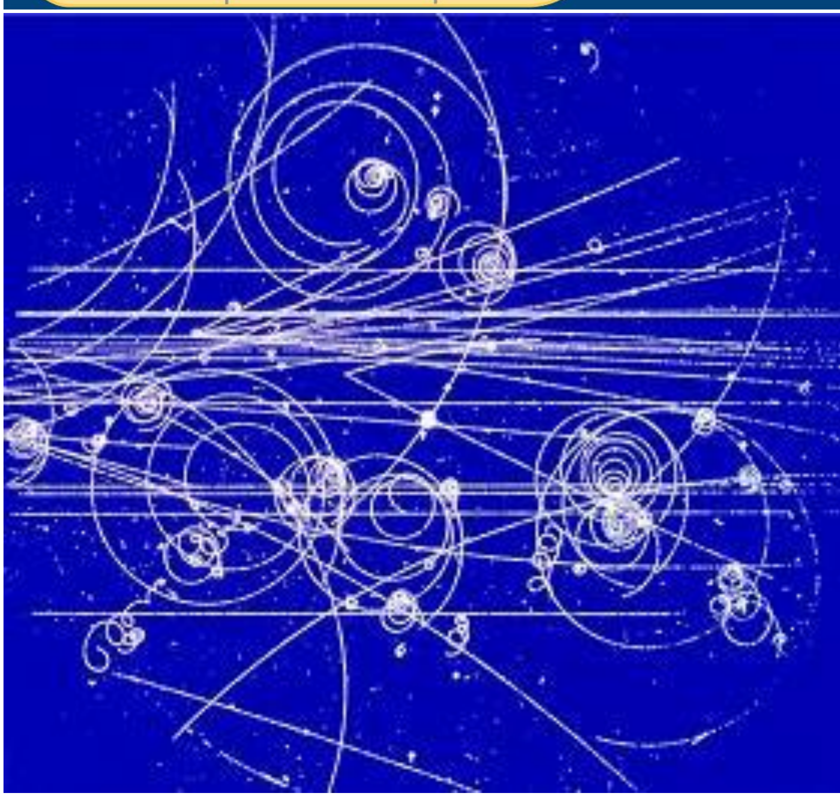
force carriers
spin = 0, 1, 2, …

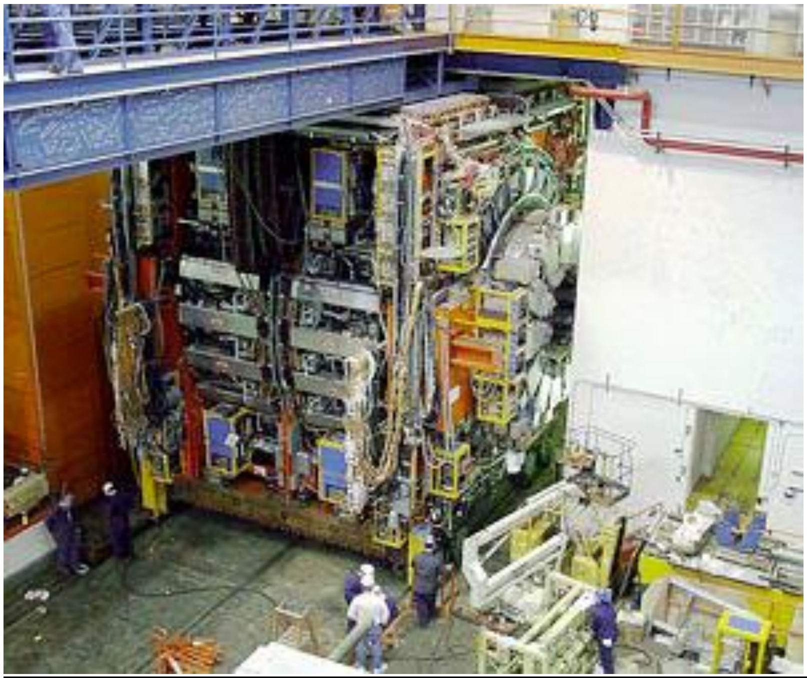
Unified Electroweak spin = 1

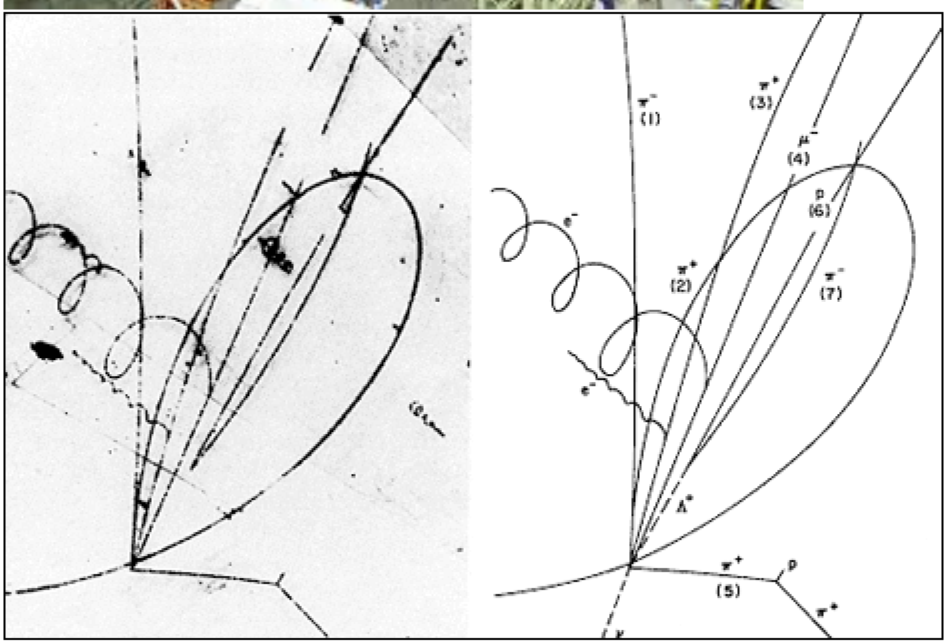
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

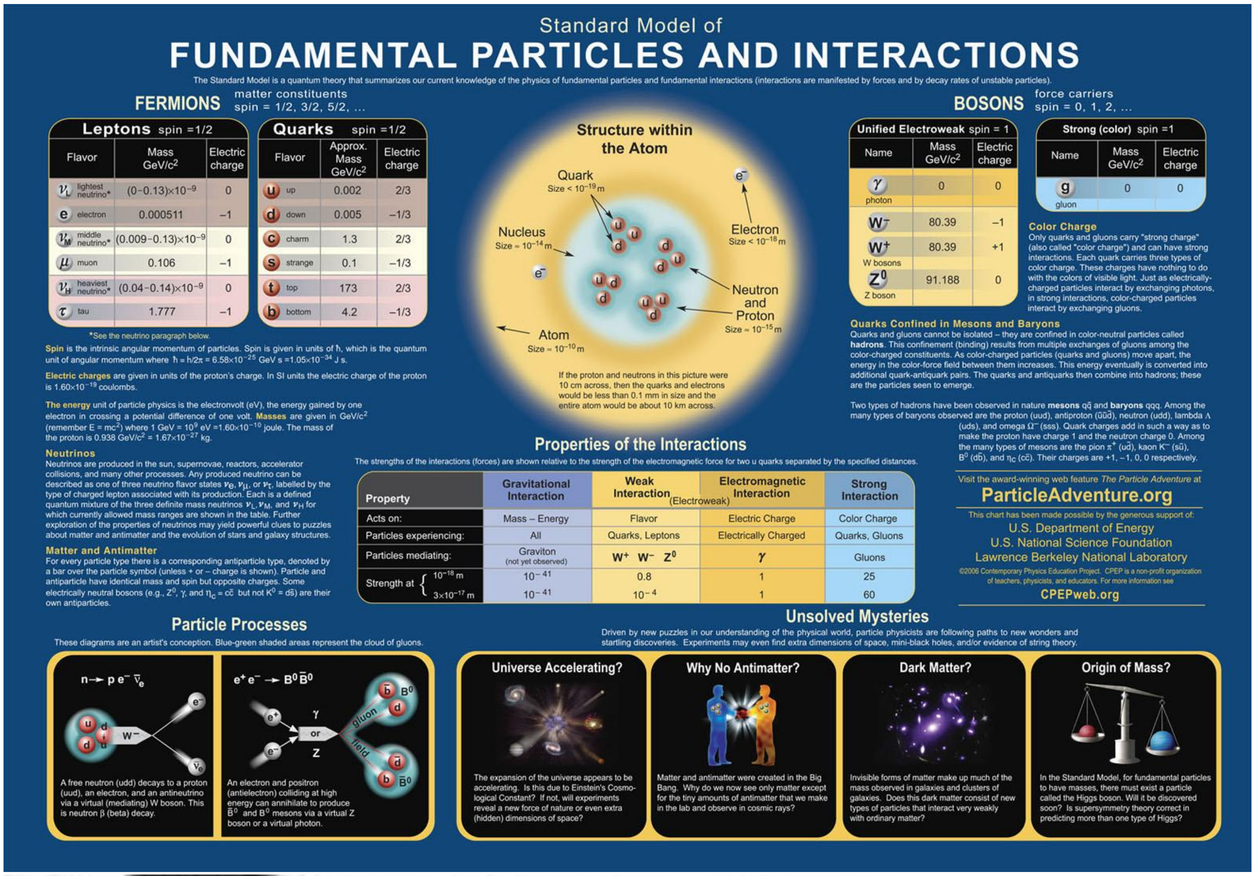
Strong (color) spin =1

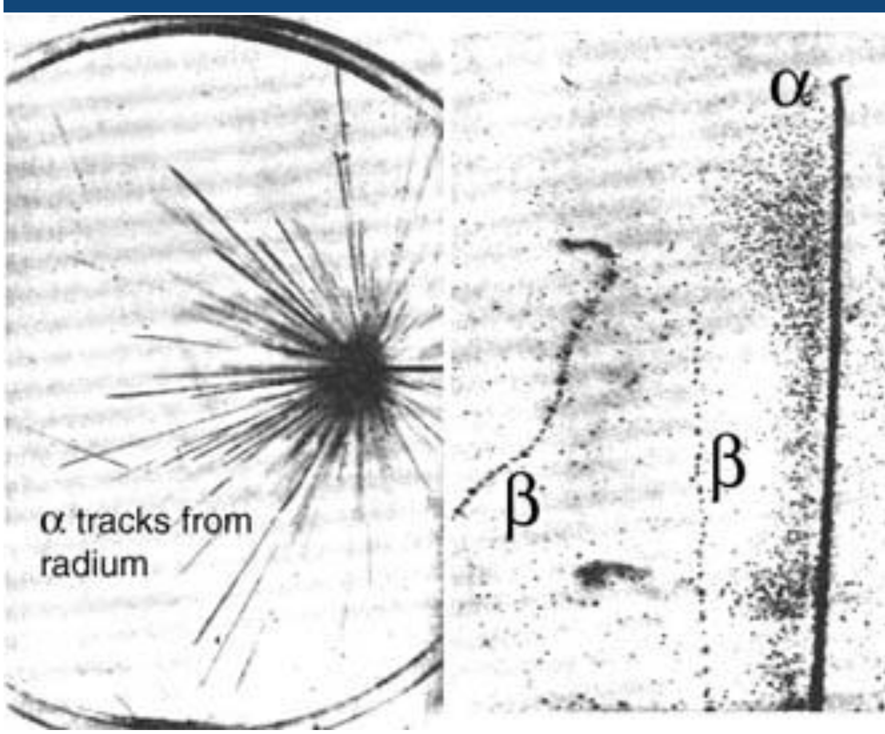
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

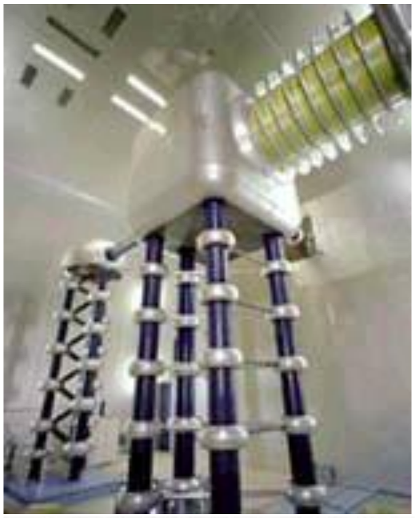





π^- (1)
π^+ (3)
μ^- (4)
p (6)
e^-
π^+ (2)
π^- (7)
e^-
Λ^+
π^+ (5)
p
π^+
ν


Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...
Leptons spin =1/2
Flavor | Mass GeV/c2 | Electric charge
ν_L lightest neutrino* | $(0-0.13)\times10^{-9}$ | 0
e electron | 0.000511 | –1
ν_M middle neutrino* | $(0.009-0.13)\times10^{-9}$ | 0
μ muon | 0.106 | –1
ν_H heaviest neutrino* | $(0.04-0.14)\times10^{-9}$ | 0
τ tau | 1.777 | –1
Quarks spin =1/2
Flavor | Approx. Mass GeV/c2 | Electric charge
u up | 0.002 | 2/3
d down | 0.005 | –1/3
c charm | 1.3 | 2/3
s strange | 0.1 | –1/3
t top | 173 | 2/3
b bottom | 4.2 | –1/3
*See the neutrino paragraph below.
Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $=1.05\times10^{-34}$ J s.
Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.
The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c2 (remember $E = mc^2$) where 1 GeV = 10^9 eV $=1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c2 = 1.67×10^{-27} kg.
Neutrinos
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states ν_e, ν_μ, or ν_τ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos ν_L, ν_M, and ν_H for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.
Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$ but not $K^0 = d\bar{s}$) are their own antiparticles.
Structure within the Atom
Quark Size < 10^{-19} m
Nucleus Size ≈ 10^{-14} m
Electron Size < 10^{-18} m
Neutron and Proton Size ≈ 10^{-15} m
Atom Size ≈ 10^{-10} m
If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
BOSONS force carriers spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Name | Mass GeV/c2 | Electric charge
γ photon | 0 | 0
W^- | 80.39 | –1
W^+ W bosons | 80.39 | +1
Z^0 Z boson | 91.188 | 0
Strong (color) spin =1
Name | Mass GeV/c2 | Electric charge
g gluon | 0 | 0
Color Charge
Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.
Quarks Confined in Mesons and Baryons
Quarks and gluons cannot be isolated – they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.
Two types of hadrons have been observed in nature mesons $q\bar{q}$ and baryons qqq. Among the many types of baryons observed are the proton (uud), antiproton ($\bar{u}\bar{u}\bar{d}$), neutron (udd), lambda Λ (uds), and omega Ω^- (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π^+ ($u\bar{d}$), kaon K^- ($s\bar{u}$), B^0 ($d\bar{b}$), and η_c ($c\bar{c}$). Their charges are +1, –1, 0, 0 respectively.
Properties of the Interactions
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.
Property | Gravitational Interaction | Weak Interaction (Electroweak) | Electromagnetic Interaction | Strong Interaction
Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge
Particles experiencing: | All | Quarks, Leptons | Electrically Charged | Quarks, Gluons
Particles mediating: | Graviton (not yet observed) | W^+ W^- Z^0 | γ | Gluons
Strength at 10^{-18} m | 10^{-41} | 0.8 | 1 | 25
Strength at 3×10^{-17} m | 10^{-41} | 10^{-4} | 1 | 60
Visit the award-winning web feature The Particle Adventure at
ParticleAdventure.org
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
©2006 Contemporary Physics Education Project. CPEP is a non-profit organization of teachers, physicists, and educators. For more information see
CPEPweb.org
Particle Processes
These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.
$n \rightarrow p\, e^- \bar{\nu}_e$
A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.
$e^+ e^- \rightarrow B^0 \bar{B}^0$
γ or Z
gluon field
An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.
Unsolved Mysteries
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.
Universe Accelerating?
The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?
Why No Antimatter?
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?
Dark Matter?
Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?
Origin of Mass?
In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?


α tracks from radium
α
β
β



"Colorless"

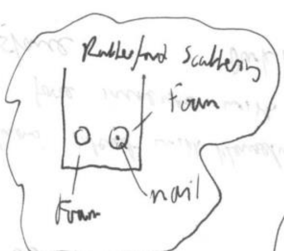
Colour — r, g, b } All the same but combine differently?

r + g + b = white

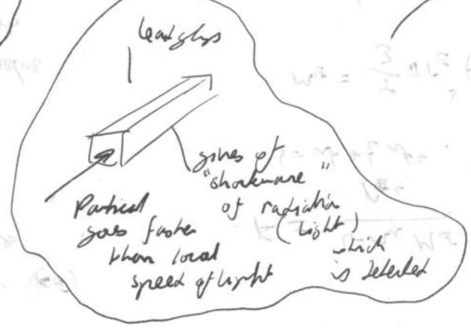
↳ Combining 2 ano to become white?! or black.

red + antired = black

How do we know a ~~particle~~ quark has colour?

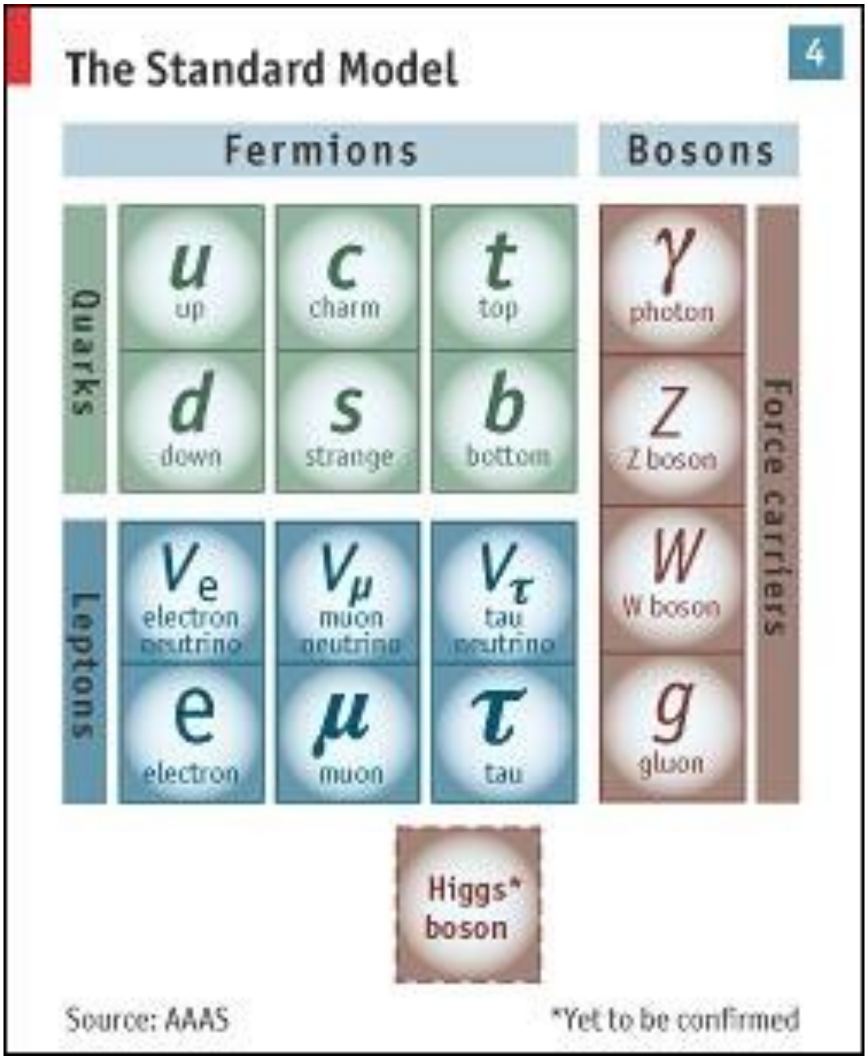


gluon — Force becomes stronger with distance.

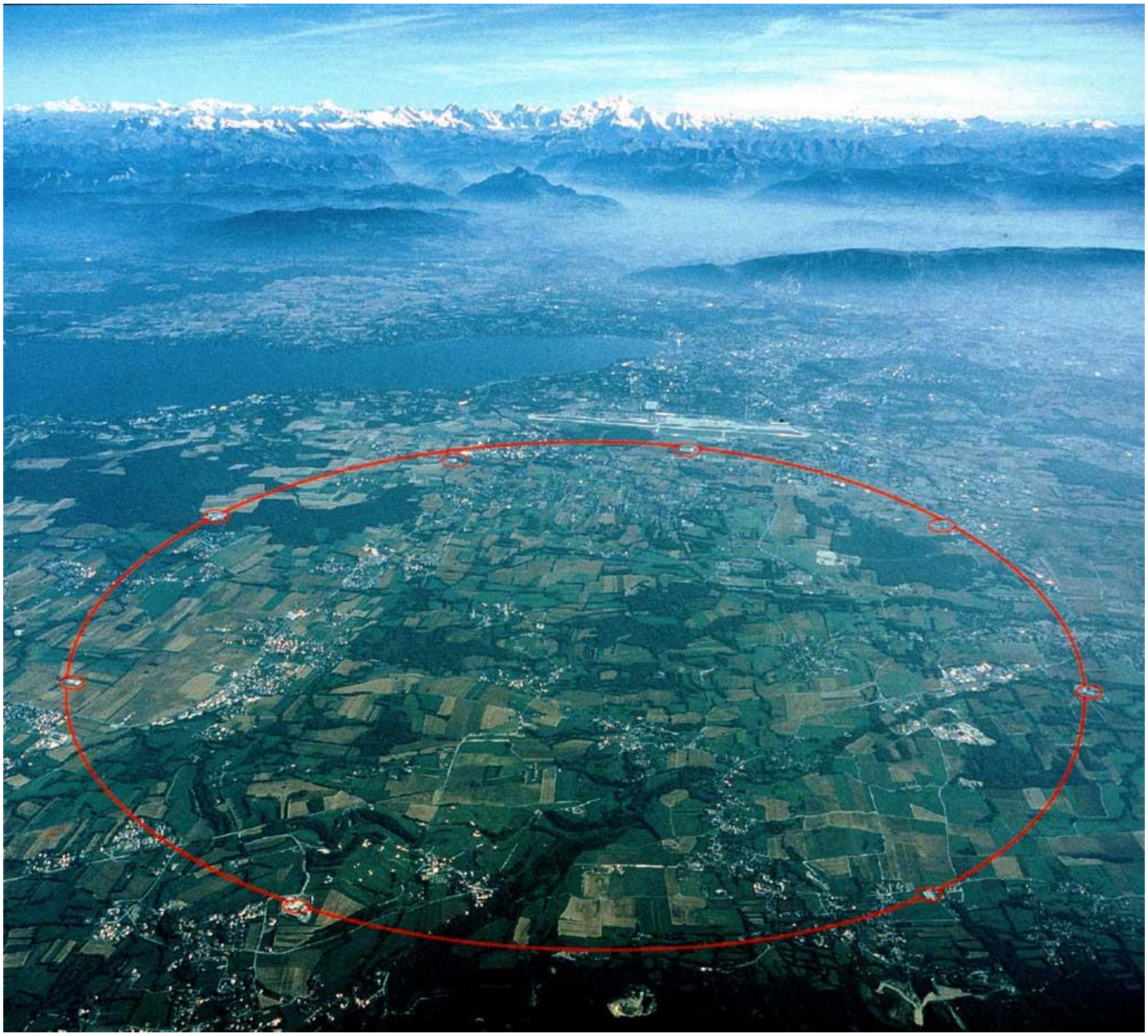


Quantum field Theory ⟹ symmetry groups SU(3) x SU(2) x U(1) ⟹ Standard model

even though perfect symmetry with quarks + leptons exists there are 3 times as many interactions with quarks suggesting that each quark comes in 3 colours

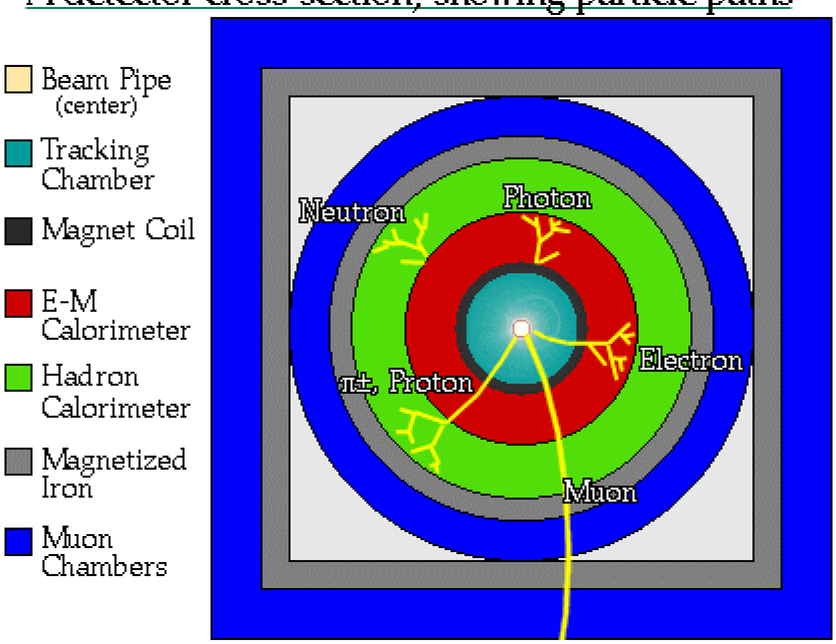


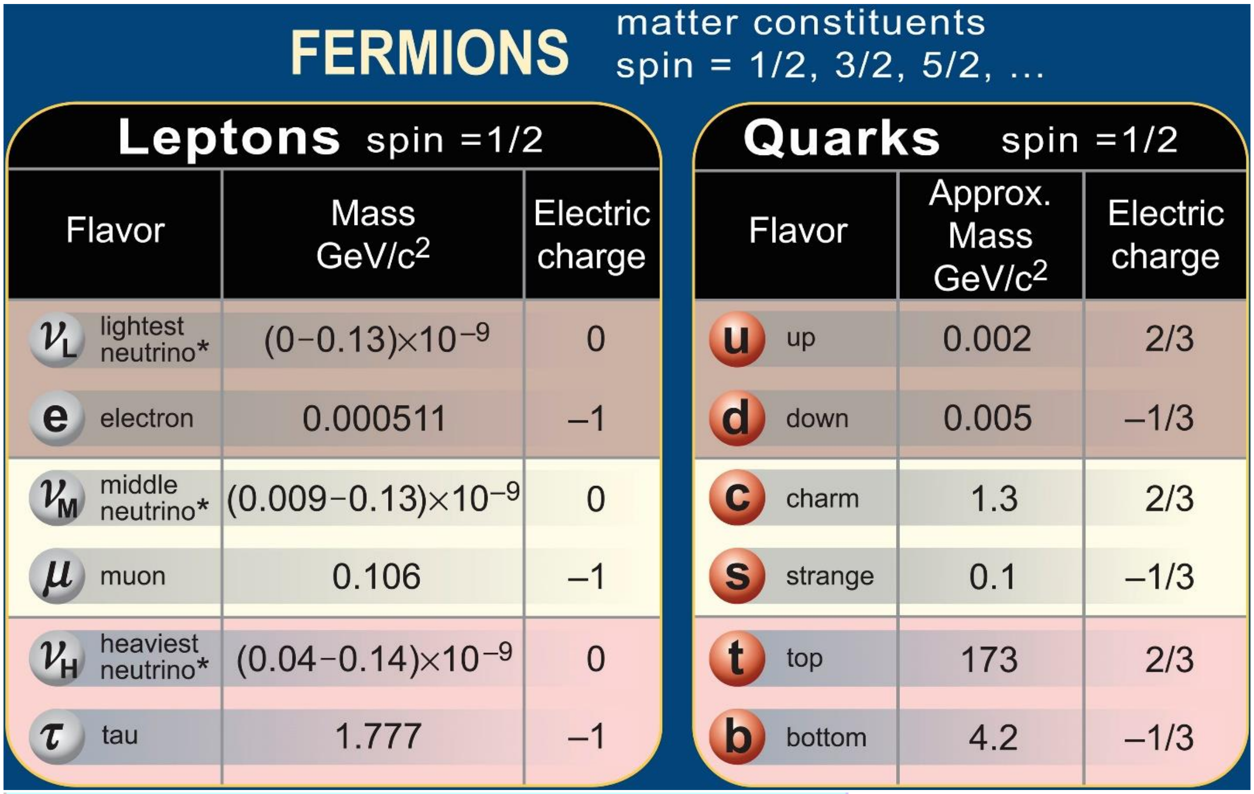
The Standard Model
4
Fermions
Bosons
Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
V_e
electron neutrino
V_μ
muon neutrino
V_τ
tau neutrino
e
electron
μ
muon
τ
tau
γ
photon
Z
Z boson
W
W boson
g
gluon
Force carriers
Higgs* boson
Source: AAAS
*Yet to be confirmed



PHYSICS AT THE FARM:
Discovery of the Muon.

A detector cross-section, showing particle paths





FERMIONS

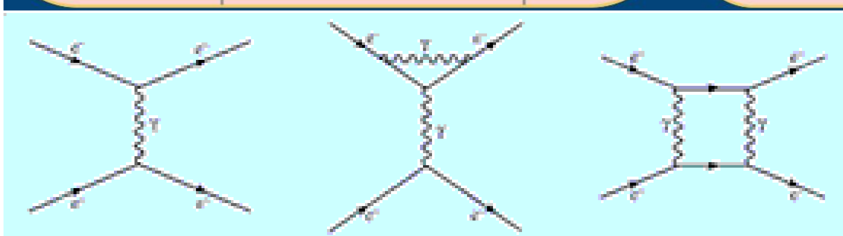
matter constituents
spin = 1/2, 3/2, 5/2, ...

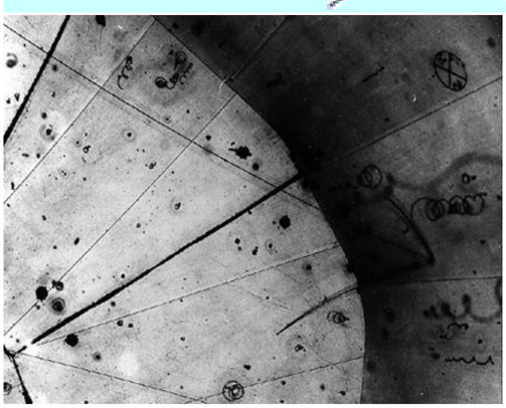
Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

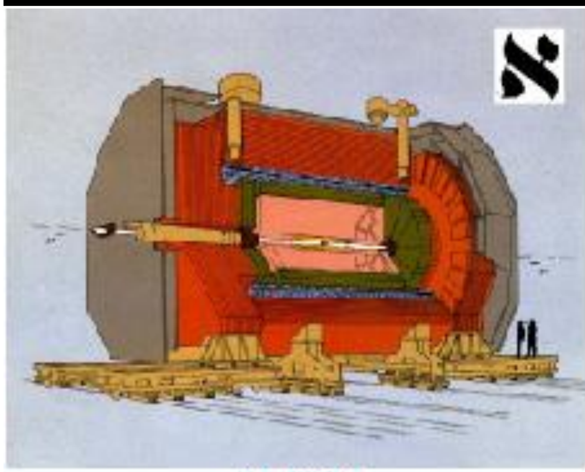
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3



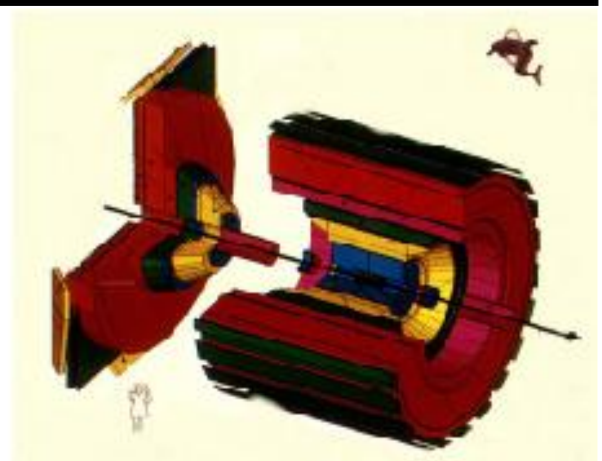


PROPERTIES OF THE INTERACTIONS

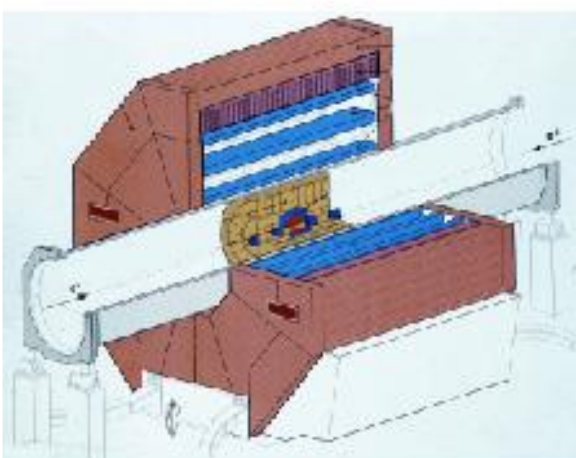
Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20



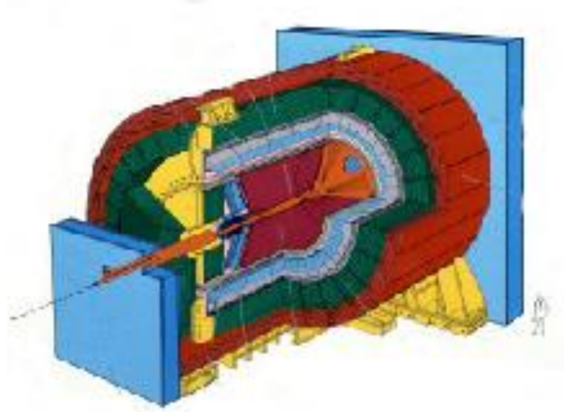
ALEPH



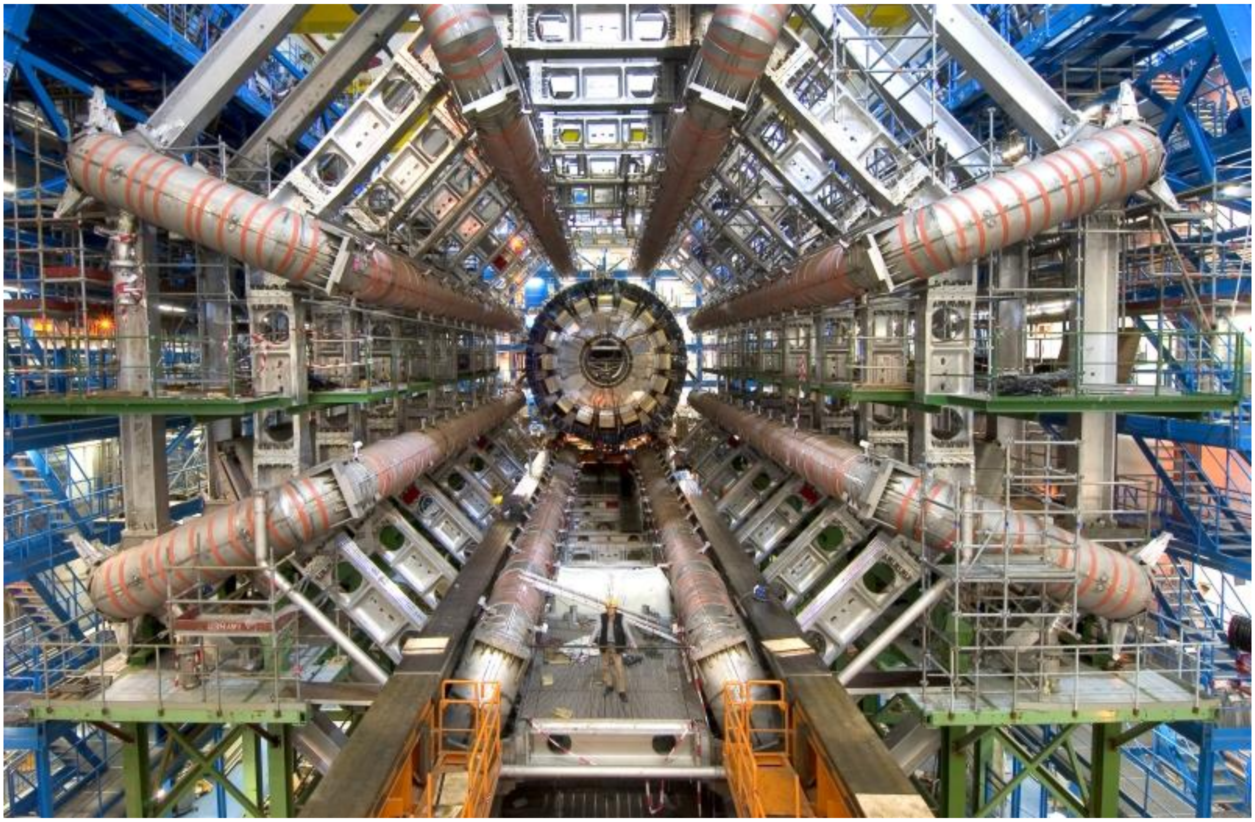
DELPHI



L3



OPAL



Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

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

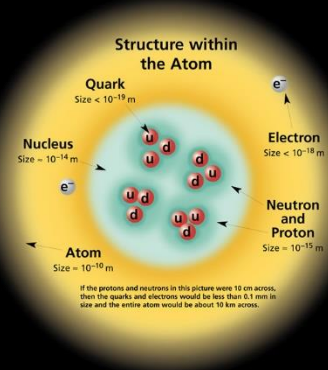
Quarks spin = 1/2

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

Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq **and Antibaryons** $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons. There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons. There are about 140 types of mesons.

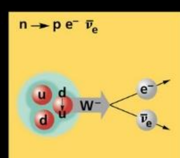
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

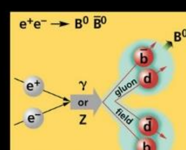
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

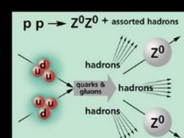
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at **http://ParticleAdventure.org**

This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

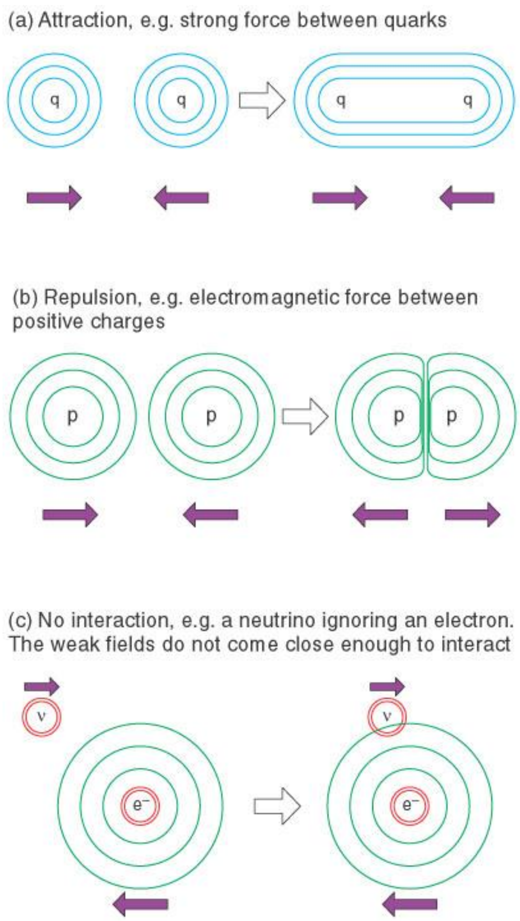
http://CPEPweb.org

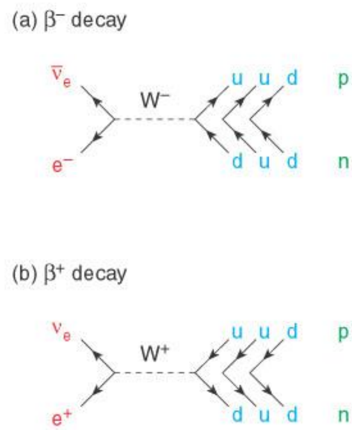
Mesons $q\bar{q}$

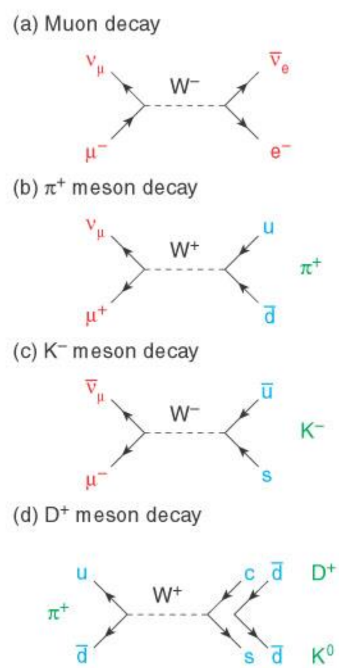
Mesons are bosonic hadrons

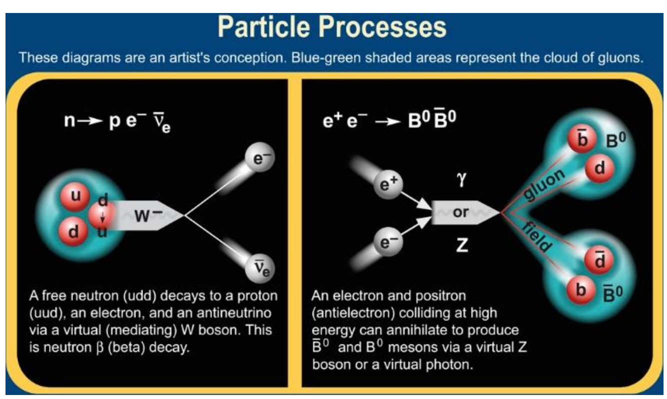
These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u\bar{d}}$	+1	0.140	0
$\mathbf{K^-}$	kaon	$\mathbf{s\bar{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u\bar{d}}$	+1	0.776	1
B^0	B-zero	$\mathbf{d\bar{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c\bar{c}}$	0	2.980	0


(a) Attraction, e.g. strong force between quarks
q
q
q
q
(b) Repulsion, e.g. electromagnetic force between positive charges
p
p
p
p
(c) No interaction, e.g. a neutrino ignoring an electron. The weak fields do not come close enough to interact
ν
e⁻
ν
e⁻


(a) β⁻ decay
ν̄e
e⁻
W⁻
u u d
d u d
p
n
(b) β⁺ decay
νe
e⁺
W⁺
u u d
d u d
p
n

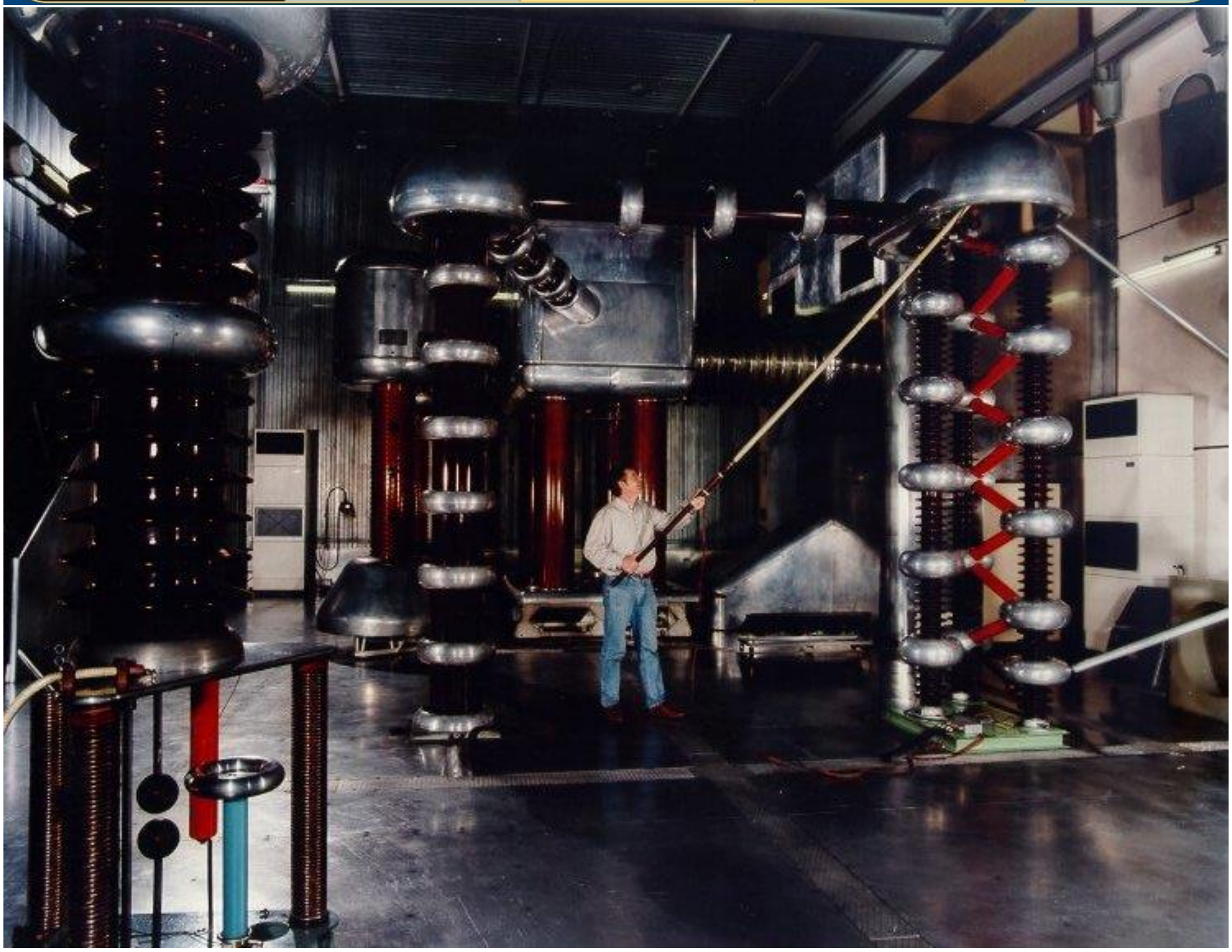

(a) Muon decay
νμ
μ⁻
W⁻
ν̄e
e⁻
(b) π⁺ meson decay
νμ
μ⁺
W⁺
u
d̄
π⁺
(c) K⁻ meson decay
ν̄μ
μ⁻
W⁻
ū
s
K⁻
(d) D⁺ meson decay
u
d̄
π⁺
W⁺
c d̄
s d̄
D⁺
K⁰


Particle Processes
These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.
n → p e⁻ ν̄e
W⁻
A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.
e⁺ e⁻ → B⁰ B̄⁰
γ
or
Z
gluon
field
B⁰
B̄⁰
An electron and positron (antielectron) colliding at high energy can annihilate to produce B̄⁰ and B⁰ mesons via a virtual Z boson or a virtual photon.

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction (Electroweak)	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60



Royal Holloway University of London

The Forces

Four . . . . or one ?

The forces of nature between matter particles (quarks and leptons) arise from the exchange of other 'force carrying' particles called bosons. If a boson is emitted by one quark or lepton and is absorbed by another, then there is a force between the two.

Force	Boson	Source	Relative strength*	Range
gravity	graviton	mass	10^{-39}	infinite
weak	W^+, W^-, Z	weak charge	10^{-5}	10^{-18}m
electromagnetism	photon	charge	10^{-2}	infinite
strong	gluons	colour	1	10^{-15}m

* in the nucleus

Gravity

The weakest force, but responsible for the attraction between astronomical objects. The graviton has not been observed. Felt by all particles.

Strong

Felt by quarks only, this force also holds nuclei together. There are eight different types of gluons carrying different combinations of colour.

Weak

Responsible for radioactive β decay. The force carriers ($W^\pm$, Z bosons) have mass and were discovered at CERN in 1983-4. Felt by all matter particles.

The weak force and electromagnetism are different manifestations of the electroweak force. The mathematical theory of this force predicts the existence of the Higgs boson, responsible for the mass of all objects.

Electromagnetism

Holds atoms together and plays a major role in everyday life. The force carrier is the familiar photon. Electricity and magnetism are simply different manifestations of this force. Felt by all particles except neutrinos, which are uncharged.

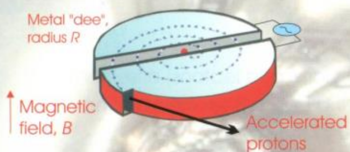
Can all four forces be described as different aspects of a more general theory ?

Background: Simulation of a Higgs event

Particle Accelerators

Cyclotron

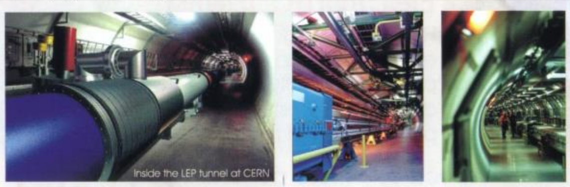
The first circular accelerator was the cyclotron.



Equating forces $mv^2/r = Bev$ and the time for half a turn, $t = \pi r/v$; hence $t = \pi m/eB$. This is independent of radius, so with the correct choice of frequency for the ac voltage protons will be accelerated every time they cross the gap. The final kinetic energy $= (BeR)^2/2m$ and is about 10 MeV for $R = 0.3$ m.

The largest machines

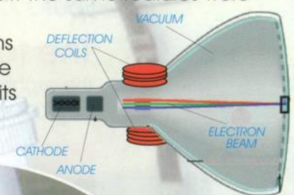
Some of the largest machines ever built accelerate the smallest particles to a speed very close to the speed of light. The equation $E \approx hc/\lambda$ shows that high energy particles have a short wavelength and can therefore probe smaller distances when they collide. In the largest accelerators particles circulate at a fixed radius and the magnetic field is increased as they gain energy.



Inside the LEP tunnel at CERN

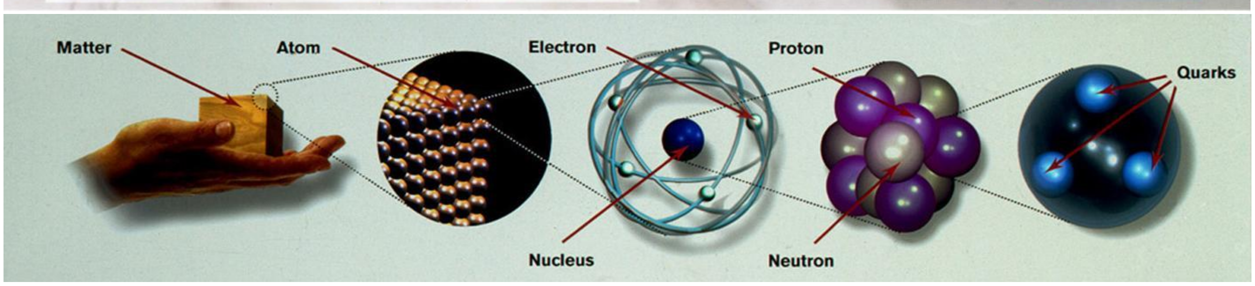
Television set

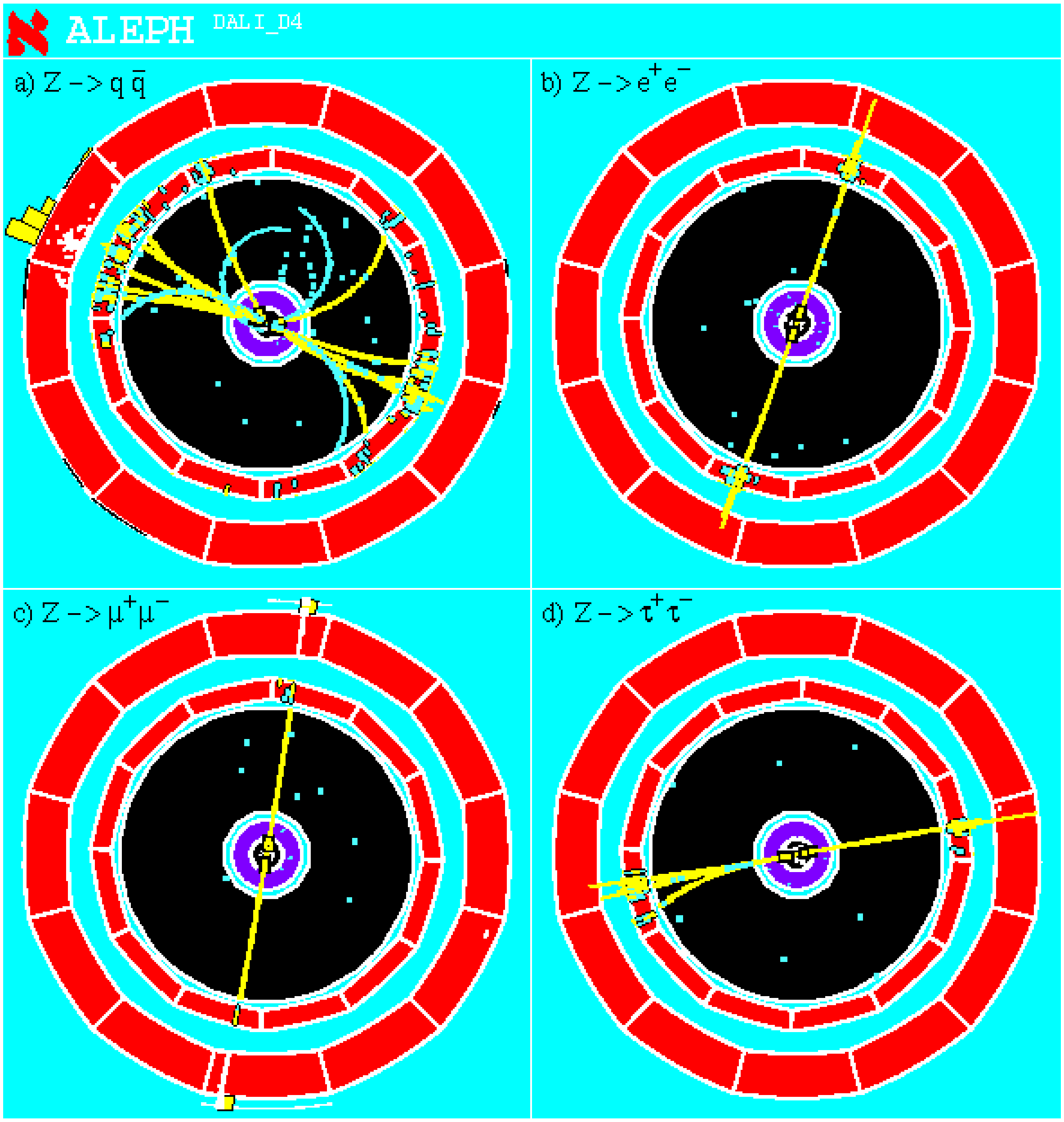
A television set is a particle accelerator in which electrons reach an energy of about 20 keV. The same features were found in the LEP accelerator at CERN. LEP accelerated electrons and positrons to 100 GeV before colliding them. LEP completed its research programme in 2000 and is being replaced by the Large Hadron Collider.



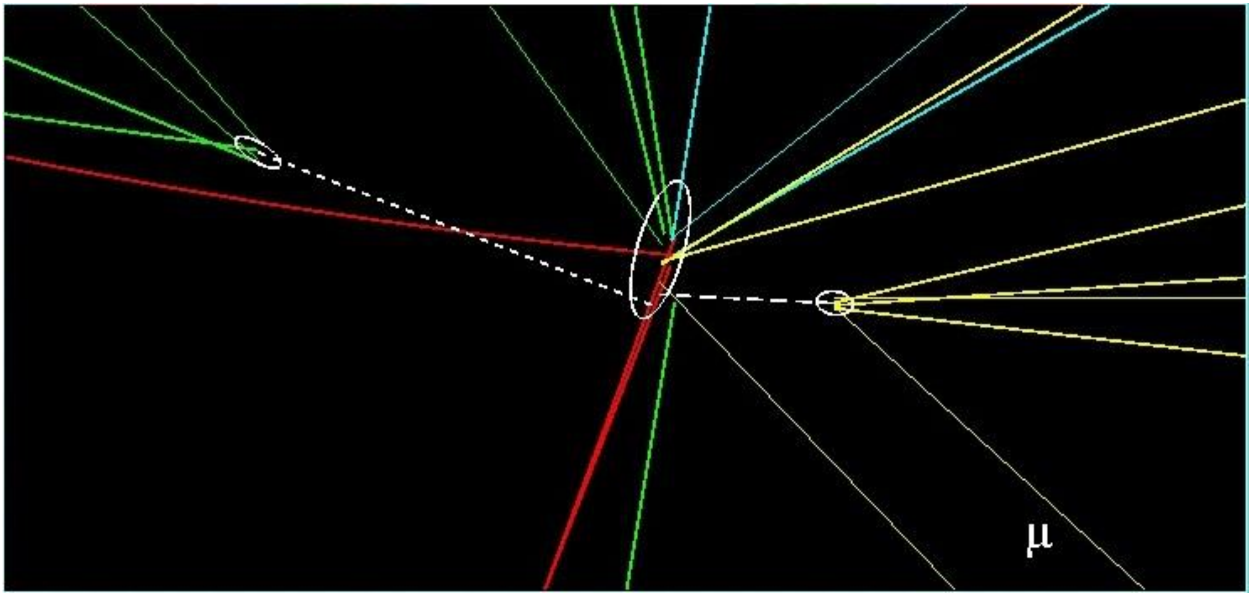
Computer graphic of LHC positioned in the existing LEP tunnel.

Background: Computer graphic of the LHC





ALEPH
DALI_D4
a) Z -> q $\bar{q}$
b) Z -> e^+e^-
c) Z -> $\mu^+\mu^-$
d) Z -> $\tau^+\tau^-$


μ

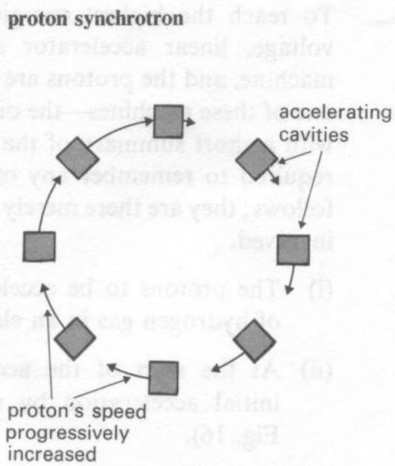


Figure 13 In a proton synchrotron, the protons are repeatedly accelerated by the same cavities.

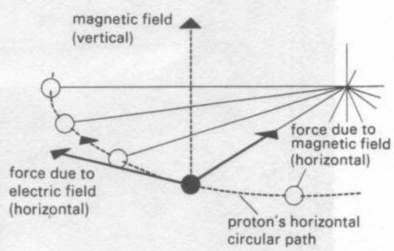
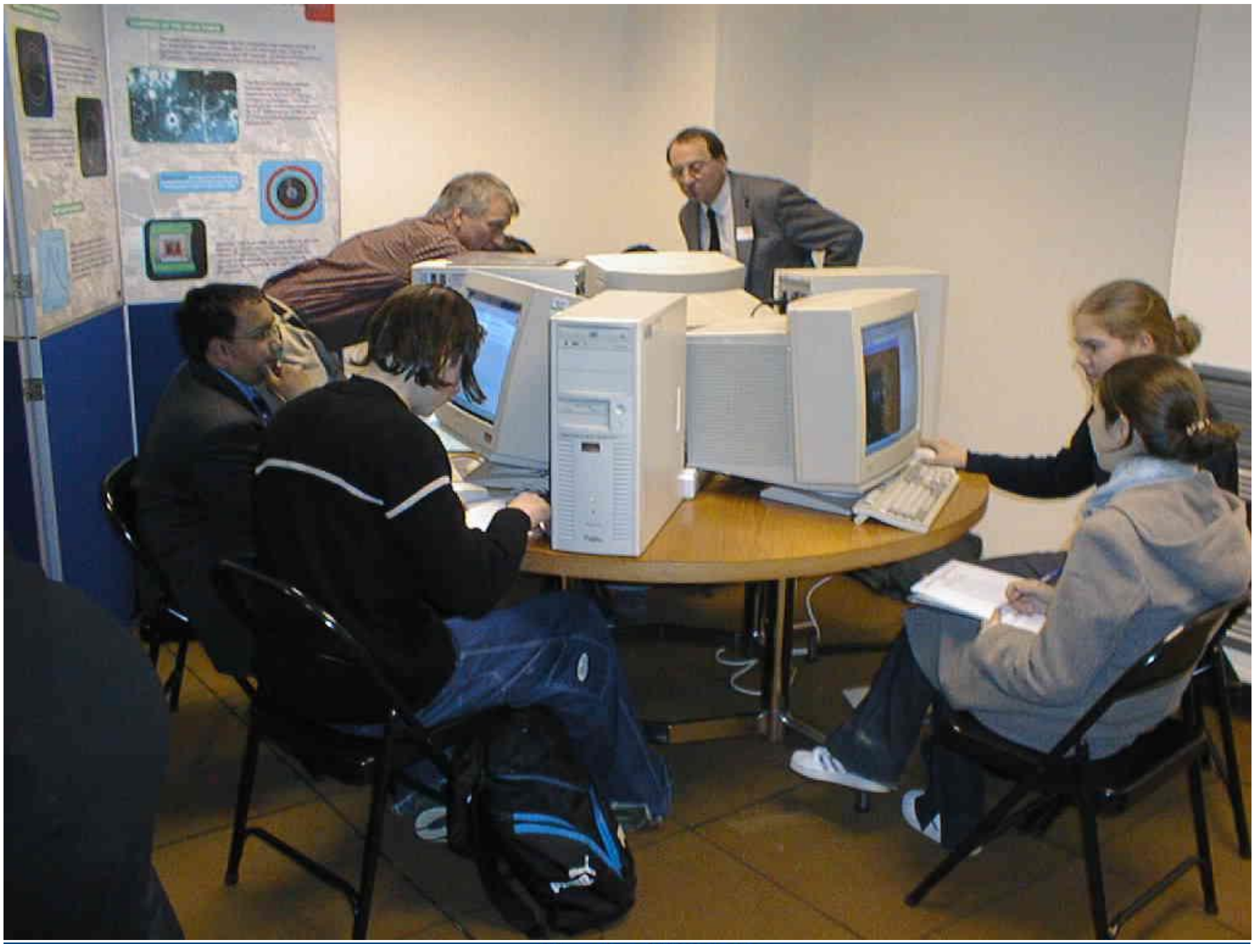


Figure 14 In a synchrotron, the proton is accelerated by electric forces acting tangentially to its circular path. Meanwhile the magnetic field exerts the necessary restraining force directed towards the centre of the circle.

Figure 15 An analogy for a synchrotron.



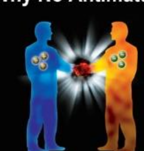
Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?



Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

Origin of Mass?

In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?