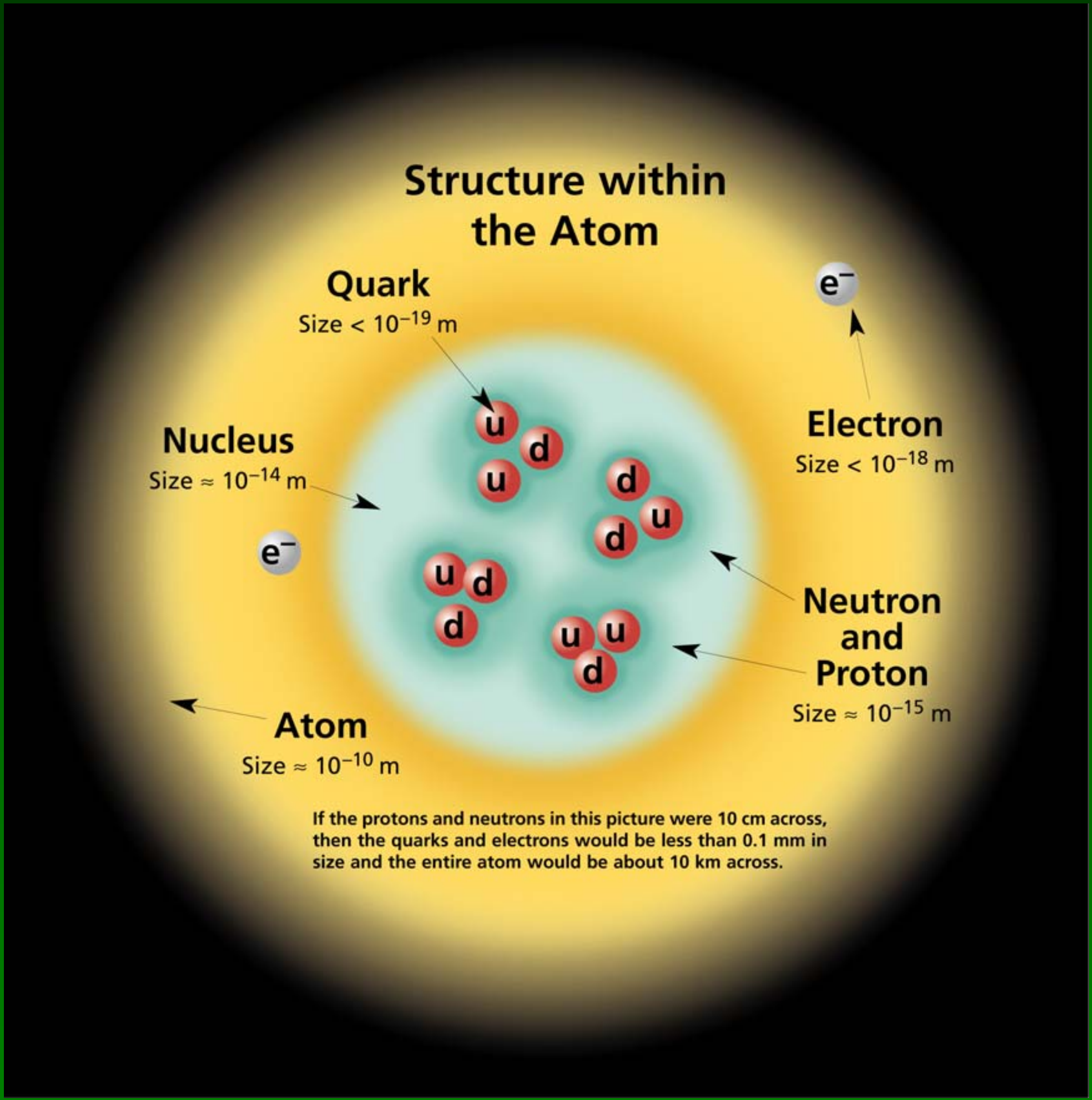
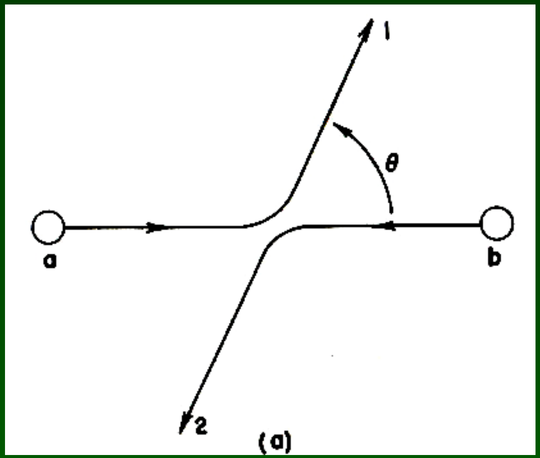
The Building Blocks of Nature



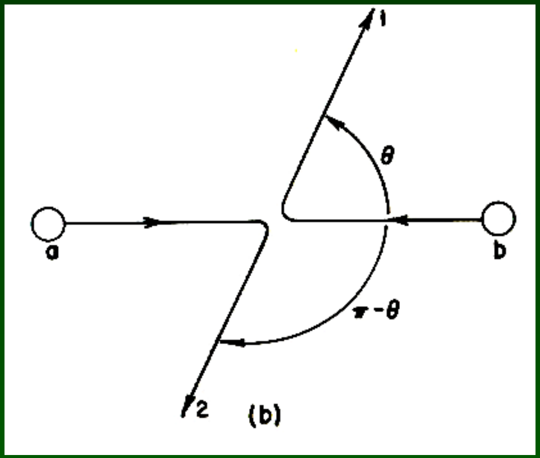
Schematic picture of constituents of an atom, & rough length scales. The size quoted for the nucleus here (10^{-14} m) is too large- a single nucleon has size 10^{-15} m, so even a U nucleus (containing 238 nucleons) is only 5×10^{-15} m across.

Identical Particles: BOSONS & FERMIONS



One possible path for the scattering between 2 particles with a deflection angle θ.

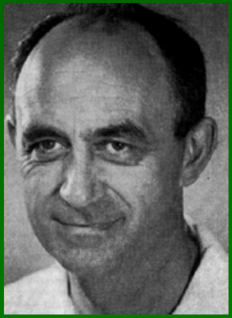
Another amazing result of QM comes because if we have, eg., 2 electrons, then we can't tell them apart- they are 'indistinguishable'. Suppose these 2 particles meet and interact- scattering off each other through some angle θ. Two processes can contribute, in which the deflection angle is either θ or π – θ .



Another path contributing to the same process, assuming the particles are identical.

This means of course that both paths must be included at an equal level. Now suppose we simply EXCHANGE the particles- this would be accomplished by having θ = 0. Now you might think that this means the wave-function doesn't change because the particles are indistinguishable. But this is not true- in fact we only require that

$$|\Psi(1,2)|^2 = |\Psi(2,1)|^2$$



E Fermi
(1901-1954)

S Bose
(1894-1974)

ie., the probabilities are the same, for the 2 wave-functions. We then have 2 choices:

$\Psi(2,1) = +\Psi(1,2)$ **BOSONS**

$\Psi(2,1) = -\Psi(1,2)$ **FERMIONS**

If we add the 2 paths G (θ) & G(π–θ) above we must also use these signs:

$$G = G(\theta) + G(\pi-\theta) \quad \text{or} \quad G = G(\theta) - G(\pi-\theta)$$

FERMIONS → MATTER

The result on the last slide is fundamental to the structure of all matter. Suppose we try & put 2 fermions in the SAME state. These could be 2 localised states, centred on positions $\mathbf{r}_1$ & $\mathbf{r}_2$, and then let $\mathbf{r}_2 \rightarrow \mathbf{r}_1$; or 2 momentum states with momenta $\mathbf{p}_1$ & $\mathbf{p}_2$, with $\mathbf{p}_2 \rightarrow \mathbf{p}_1$. These are indistinguishable particles, so that if we now swap them the equation for fermions on the last page becomes

$$\Psi(1,1) = -\Psi(1,1)$$

which is only valid if

$$\Psi(1,1) = 0$$

(PAULI EXCLUSION PRINCIPLE)

W Pauli (1900-1958)

The Pauli exclusion principle says that the amplitude and the probability for 2 fermions to be in the state is ZERO- one cannot put 2 fermions in the same state.

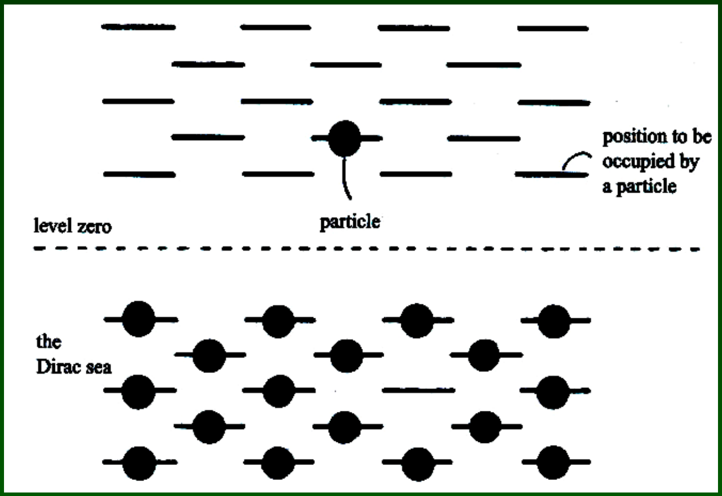
This result is what stops matter collapsing – what makes it 'material' in the first place. Without the exclusion principle, we could put many atoms on top of each other- putting them all in the same state.

All matter is made from elementary fermions. There are various kinds of fermionic particle in Nature, including electrons, protons, neutrons, and a host of other more exotic particles to be discussed in the following slides. The fundamental definition of matter, sought since the Greeks, is thus to be found in the very abstract properties of individual quantum states.

On the other hand bosons LIKE to be in the same state- we see very shortly what this leads to….

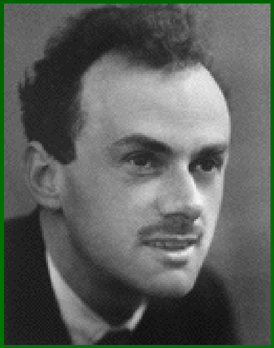
PARTICLES & ANTI-PARTICLES

At the beginning of the 1930's, 3 basic fermionic particles were known- the -ve charged electron, called e^-, the +ve charged proton, called p^+, and the newly discovered neutron, called **n**. The proton & neutron live in the nucleus, and have a mass some 1850 times larger than the electron's.

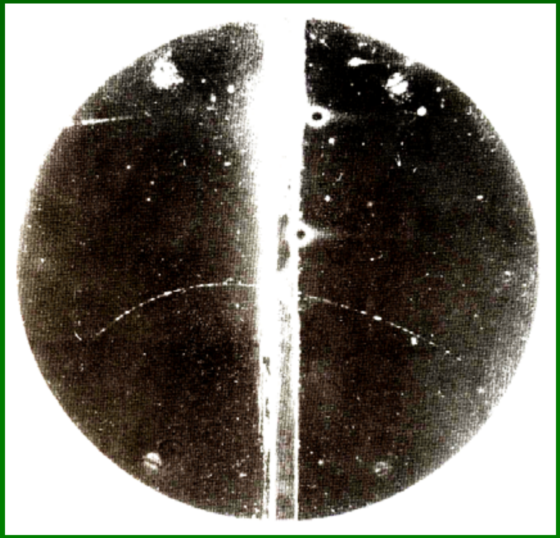


The Dirac vacuum, with 1 electron excited out, leaving a positron (the empty state).

However a remarkable theoretical result fundamentally changed this picture. P.A.M. Dirac, in 1931, reconciled Einstein's special relativity with quantum mechanics, but with a startling result- all particles must have an 'anti-particle', with the same mass but opposite charge. It turns out we can imagine the 'vacuum' or ground state is actually a 'Dirac sea' of quantum states, all occupied. Exciting the system to higher levels is equivalent to kicking particles out of the Dirac sea, leaving empty states behind- these are the anti-particles! We never see the vacuum- only the excited particles and anti-particles.



PAM Dirac (1902-1984)



The discovery of the positron (C. Anderson, 1932), identified by its track.

If a particle and anti-particle meet, they mutually annihilate, with the excess energy emitted as bosons- in the case of an electron and anti-electron, as high-energy photons (actually gamma rays).

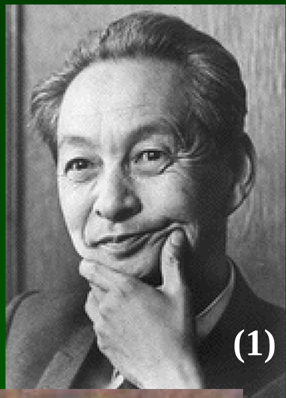
BOSONS → FORCES

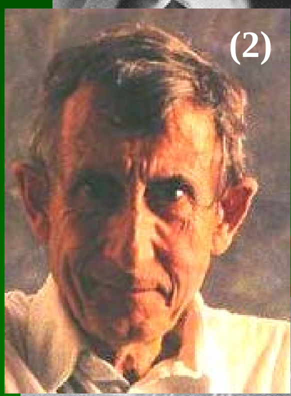
We have seen that the elementary quantum of EM radiation – of the EM field – is the photon, which is a boson. The exchange of photons between charged particles like electrons is, in a quantum theory, what causes the electric and magnetic forces between them.

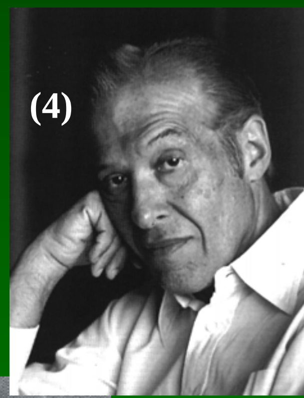
To give a proper mathematical quantum theory of the combined system of electrons & photons – what is called 'Quantum Electrodynamics', or 'QED' – turned out to be very difficult – it was finally accomplished in the period 1946-1951, with the key contributions made by the 4 theorists shown at left.

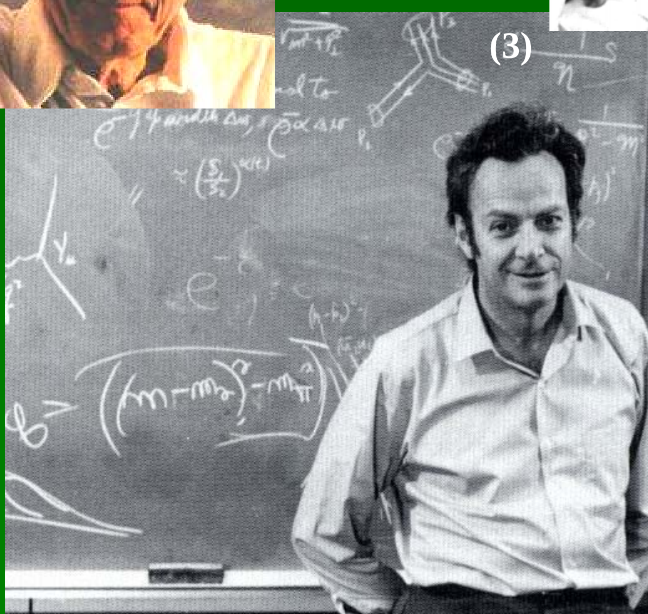
The resulting theory was very important, because it provided a blueprint for all theories of interacting fermion and boson fields – what came to be called 'Quantum Field Theory'. *Its most distinctive feature is the 'Feynman diagram'.*

Particle physics since then– until recently - has been an elaboration of quantum field theory to cover a large variety of fermionic particles interacting via various bosonic fields. We now turn to this story....

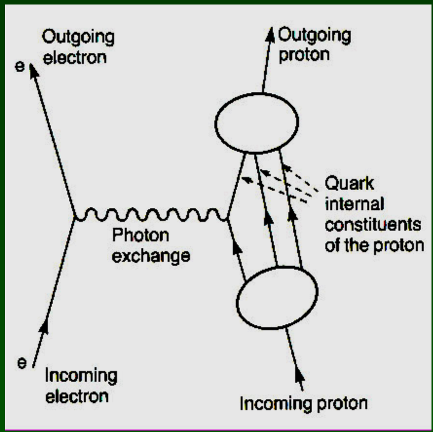




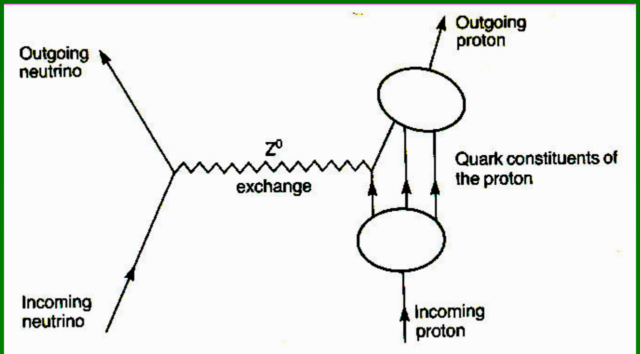




The founders of QED:
(1) S Tomonaga (1906-1979)
(2) FJ Dyson (1923-)
(3) RP Feynman (1920-1987)
(4) J Schwinger (1918-1994)



TOP: Scattering between a proton (3 quarks) and an electron, via photon exchange



Proton-neutrino scattering (Z^0 exchange)

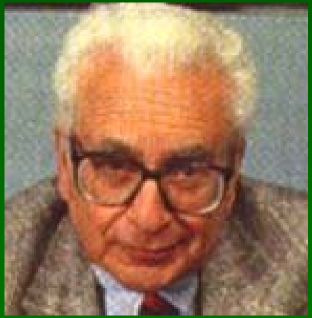
CONSTITUENTS of MATTER

Matter is made from fermions- and it is the Pauli principle, preventing these from overlapping, that gives matter its volume and structure. We now know of many fermions, but at the most basic level yet established, they are made from QUARKS and LEPTONS.

The quarks come in 18 varieties, which are given funny names- one has 3 "colours" (red,blue, green), and then 6 flavours. Heavy fermionic particles (protons, neutrons, mesons, etc.) are made from combinations of quarks. Quarks were first postulated by Gell-Mann and Zweig.

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

Leptons spin = 1/2			Quarks spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge	Flavor	Approx. Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0	u up	0.003	2/3
e electron	0.000511	−1	d down	0.006	−1/3
ν_μ muon neutrino	<0.0002	0	c charm	1.3	2/3
μ muon	0.106	−1	s strange	0.1	−1/3
ν_τ tau neutrino	<0.02	0	t top	175	2/3
τ tau	1.7771	−1	b bottom	4.3	−1/3



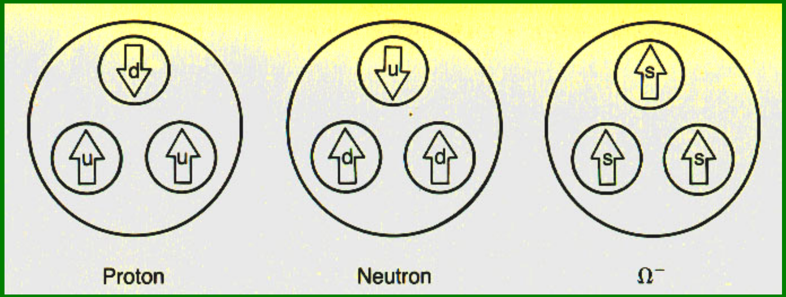
M Gell-Mann (1929-)

The light fermions are called leptons- also shown above. Note the leptons are ordinary spin-1/2 fermions with charge 1 or 0 (in units of electric charge), but the quarks have charges in units of 1/3 of an electron charge. The quarks can never appear freely- if we try to pull them apart, the force binding them gets even stronger (one has to create more massive particles).

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

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

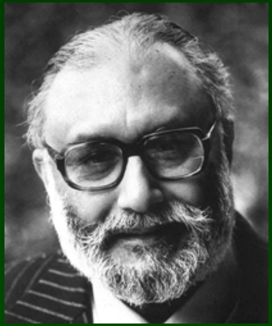
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	−1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	−1	1.672	3/2



Quark composition of p, n, and Ω^-

Physical particles like baryons are 'colourless'- made from 3 quarks, one of each colour. Many baryons can be made with different triplets of quarks.

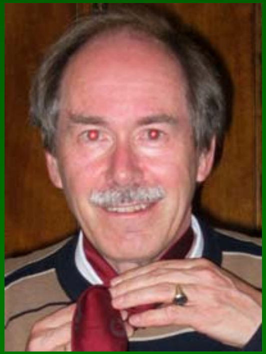
QUANTUM FIELD THEORY pushed to the Limit



A Salam (1926-1996)

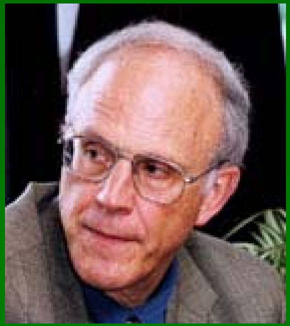
S Weinberg (1933-)

The underlying framework of all these theories of modern particle physics is quantum field theory – the idea of a hierarchy of fields which will ultimately be unified into one very complicated 'master field'. This dream, which derives originally from Einstein (who however was interested in a ***classical*** unified field theory, not a quantum one), made huge progress in the period 1967-77. First came the unification in 1967 of the weak and EM forces into an 'electroweak' field theory, by Salam & Weinberg. This theory was thought to be inconsistent (technically, to be 'non-renormalisable') & was ignored until 1970, when 't Hooft, then a student, showed that it was indeed a viable theory, and he & his supervisor Veltman showed how to do calculations with it. The next step, taken in an unpublished work by 't Hooft in 1972 & in papers by Gross & Wilczek, and Politzer in 1973, was to address the strong interactions. It was found that a field theory of quarks interacting via 'gluons' had a remarkable feature which was called 'asymptotic freedom' – the attractive force between the quarks does not decrease as they separate, and so it would take an infinite energy to separate them (in fact, as they separate a string of 'quark/anti-quark pairs' is produced, and this costs energy proportional to the length of the string). Instead the quarks stay very close to each other where they can behave much like a gas of free particles.



Gerard 't Hooft (1947-)

This set of basic ideas was quickly assembled into a unified theory of the weak, strong, and EM fields, now called the *'Standard Model'.* This theory has been tested in many ways since its inception 30 yrs ago – not only does it work quantitatively, but most have predictions have been verified (the most important outstanding prediction being that of the Higgs boson, not yet found).



David Gross (1941-)

Frank Wilczek (1951-)

On the next page a more detailed picture is given of how these 3 interactions are unified, and the particles or quanta that are associated with this unified set of boson fields. This theoretical framework is a remarkable and very powerful extension of QED to a much broader quantum field theory of 'elementary particles'.

FUNDAMENTAL INTERACTIONS

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

The fundamental bosons are divided into 4 classes- these bosons cause interactions between fermions, and give rise to 4 fundamental forces in Nature- the strong, weak, electromagnetic, and gravitational interactions.

At very high energies things change. All interactions (with their associated particles), except the gravitational one, merge into a single complex field described by the 'standard model'. To unify gravity with this is a fundamental unsolved problem

BOSONS

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

Unified Electroweak spin = 1		
Name	Mass GeV/c²	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/c²	Electric charge
g gluon	0	0

Mesons $q\bar{q}$

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

Symbol	Name	Quark content	Electric charge	Mass GeV/c²	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

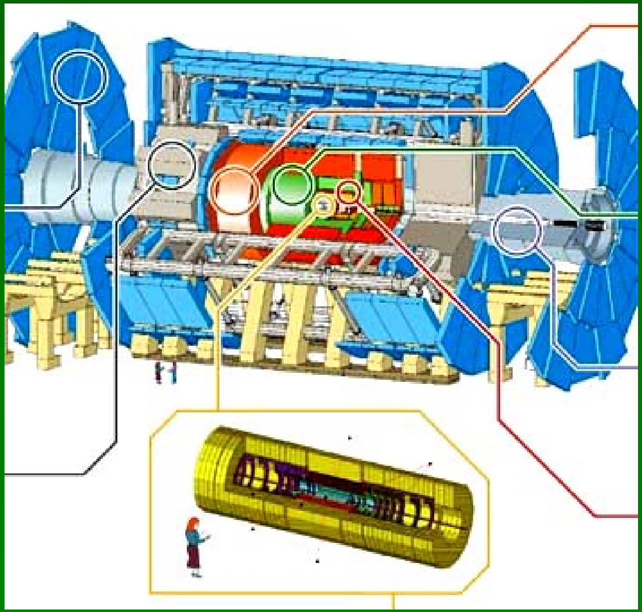
Note the strong interaction between quarks is mediated by gluons, but gluons (& mesons) are quark pairs.

EXPERIMENTS in PARTICLE PHYSICS

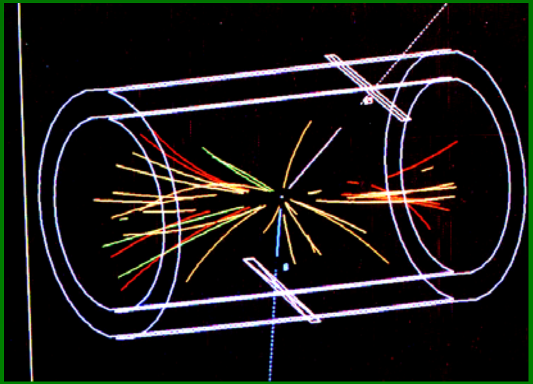
The pattern for experimental research on the building blocks of Nature was set by Rutherford, and has hardly varied since- one smashes things together at high energy, to see what comes out. The energy per particle in such experiments has now reached the TeV (10^{12} eV) level. By comparison, the ionisation energy of a H atom (the energy required to strip the electron off it) is 13.6 eV; & the energy in Rutherford scattering experiments is ~ 1 MeV (10^6 eV). The modern experiments are huge and very expensive- they are done either in CERN (Geneva) or Fermilab (Chicago). Particles are accelerated in huge underground rings, guided by giant magnets.

ABOVE: Fermilab- aerial view

Inside the LHC ring (CERN)



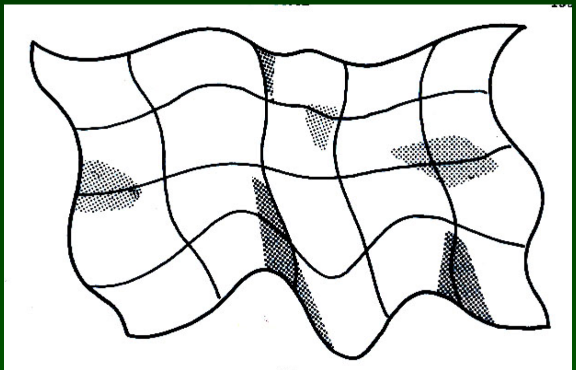
The 'ATLAS' detector (CERN)



p^+ - p^- scattering (CERN)

The result of these particle smashing expts is observed by sensitive detectors. A lot of modern technology (including the world wide web), has come from this work.

Search for a unified field theory- STRING THEORY



Quantum gravity theory tries to quantize the fluctuating geometry of spacetime

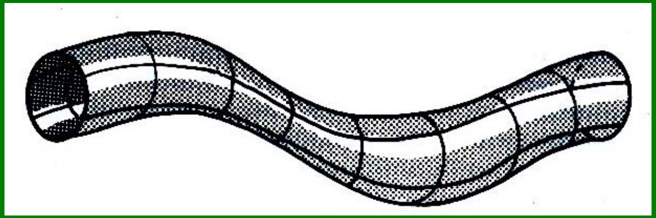
Arguably the most important problem in modern physics is how to unify the standard model (ie., the strong, weak, & EM forces) with gravity. The basic problem is that (i) the fields corresponding to thefirst 3 forces can be 'quantized' (producing all the boson excitations we have seen), but (ii) if we try and quantize gravity, we get nonsense- interactions between quantized gravity waves ('gravitons') are infinite.

The current attempt to solve this problem is called string theory (sometimes rather stupidly called the 'TOE', for 'Theory of Everything'). This theory began over 30 years ago with attempts to control the infinities in quantum gravity.

The modern (2006) string theory has an 11- dimensional quantum 'geometry' with 7 of the dimensions 'wrapped up' very tightly (recall a geometry can be closed or 'compact'), to form 'hypertubes', only 10^{-35} m in diameter, called strings. Particle excitations (electrons, photons, quarks, etc) are wave oscillation modes of strings. 4-dimensional spacetime is the 'unwrapped' part of this.

Even without a final theory, it is easy to see that unification can only happen at the Planck length scale of 10^{-35} m, or at energies of 10^{29} eV. Thus the theory cannot be tested *directly* except at particle energies 10^{16} times greater than modern accelerators- *this will never happen*.

A string; magnified view below



Unified Fields, Renormalisation, & 'REDUCTIONISM'

The success of the programme for the unification of forces/fields has emboldened many in their belief in the quantum field theory/string theory blueprint for the ultimate theory of the material world It has also led to a widespread belief in a philosophical approach to Nature which is sometimes called 'Reductionism'. In physics this is sometimes allied to the idea of 'Renormalisation'.

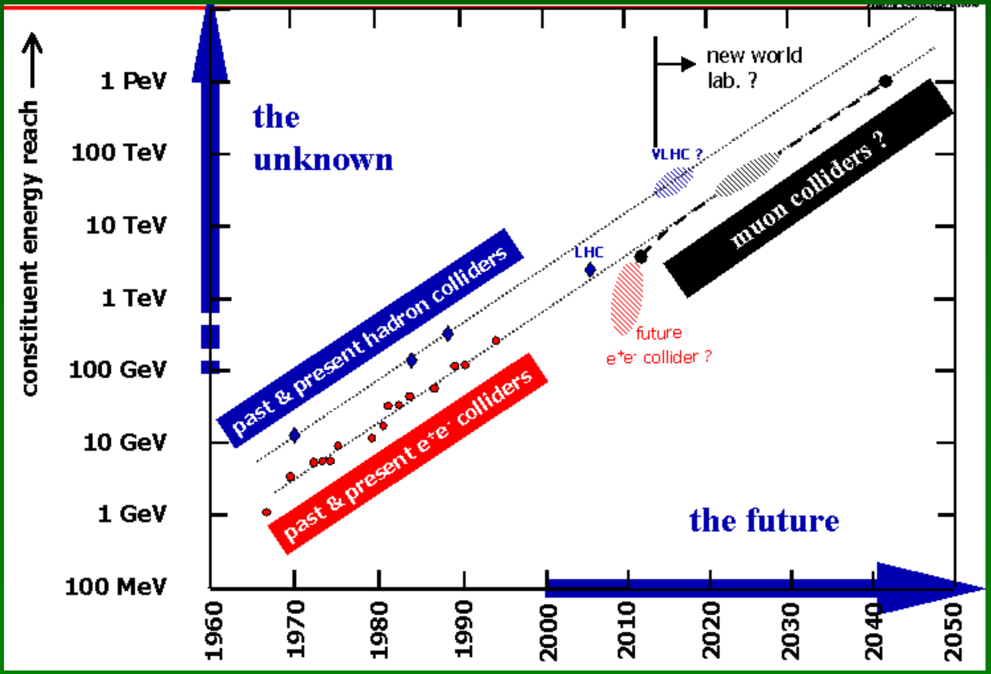
REDUCTIONISM: Crudely, the belief that Nature can be understood in a sort of 'lego' approach, with fundamental building blocks, so that everything can be understood if one knows these blocks and the forces between them.

RENORMALISATION: A technique for producing a low-energy theory (made from large 'lego blocks') from a higher energy one (made from small lego blocks), by averaging over the high-energy degrees of freedom.

The 2 biggest problems facing this approach now are both connected with the extrapolation of present theory to the very high Planck scale energies. They are

(i) The difficulty in quantizing gravity, which may be solvable by string theory. However There are problems with the string approach, & many (eg. 't Hooft, Penrose) feel that a different approach is necessary at or beyond the Planck scale – one which may supercede quantum field theory.

(ii) There is no way on earth to ever do experiments at this scale – despite the optimism of graphs like the one at right.



A 'Livingston plot' showing particle accelerator energies with time.