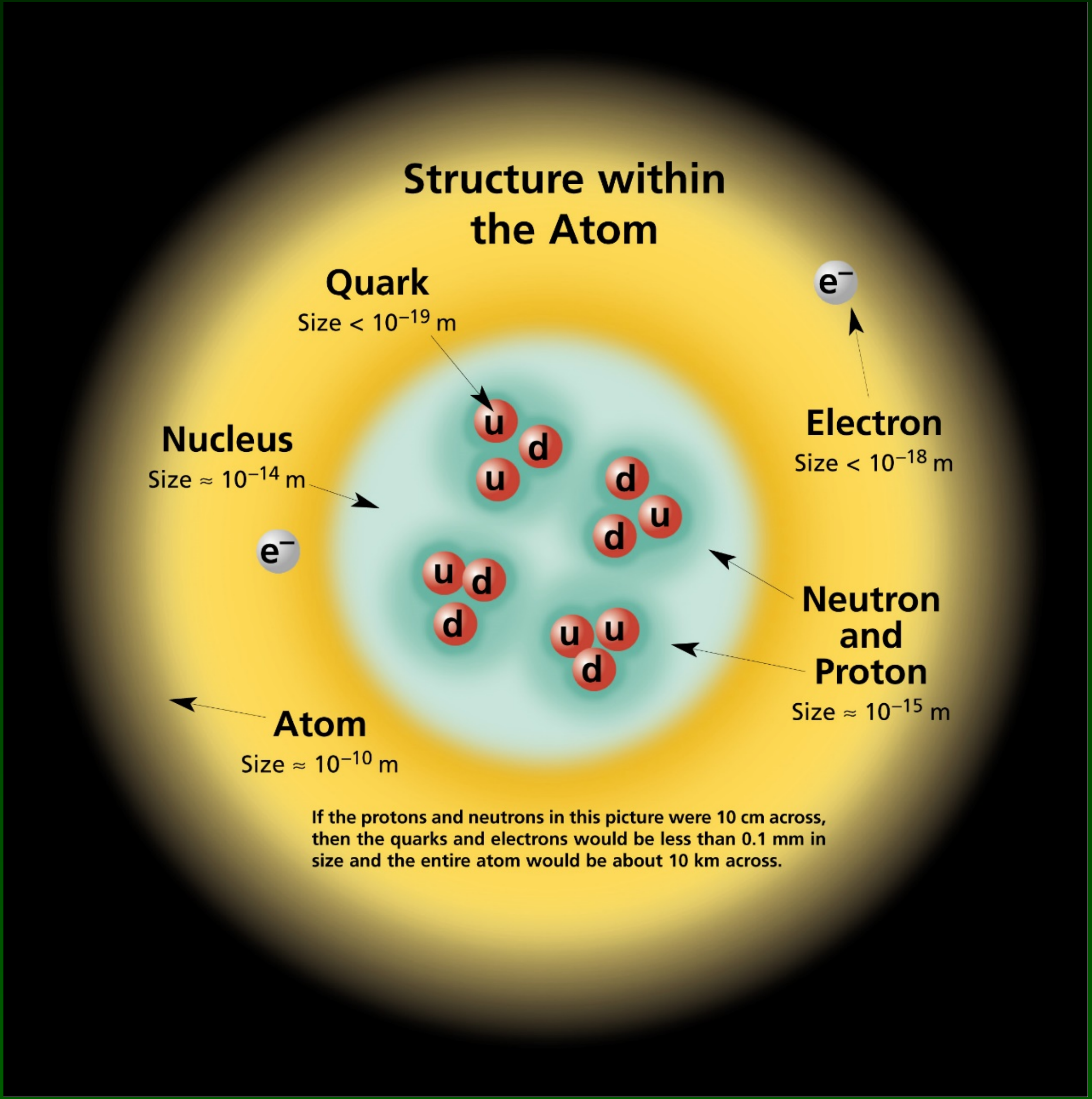
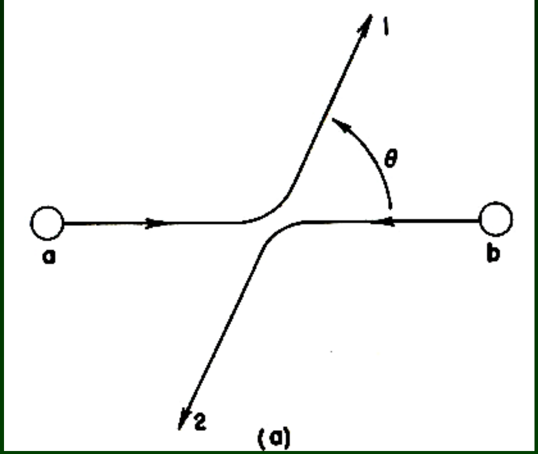
The Building Blocks of Nature



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 x 10^{-15} m across.

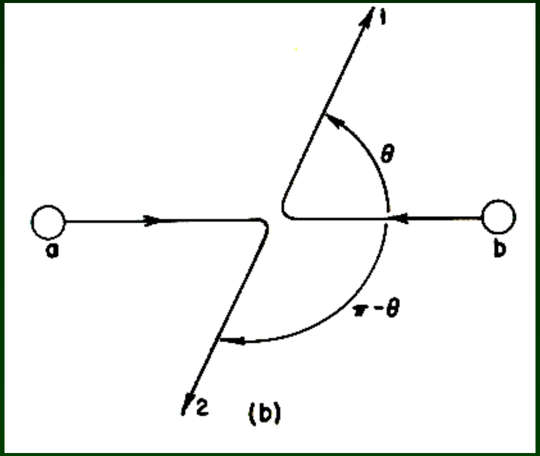
Identical Particles: BOSONS & FERMIONS



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.

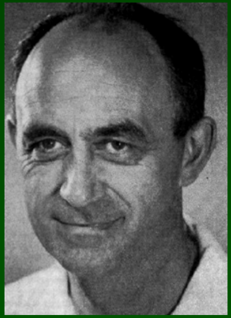
Two processes can contribute, in which the deflection angle is either θ or $\pi - \theta$.



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 $\theta = 0$. 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:

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

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)

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.

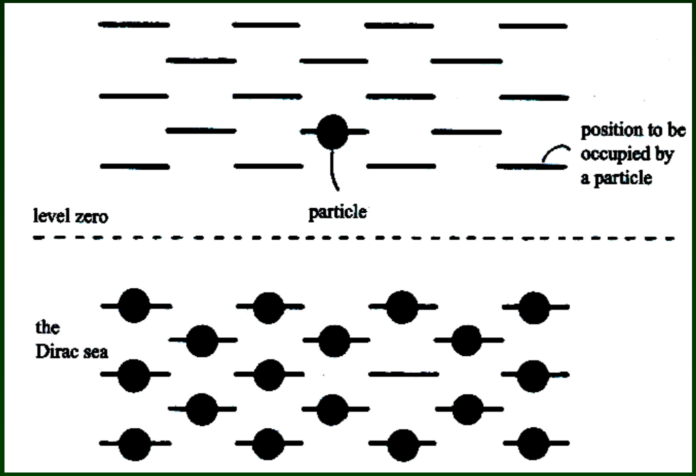
W Pauli (1900-1958)

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….

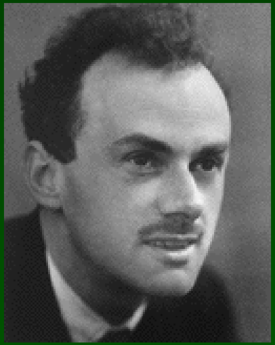
PARTICLES & ANTI-PARTICLES

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 ~ 1850 times larger than the electron's.

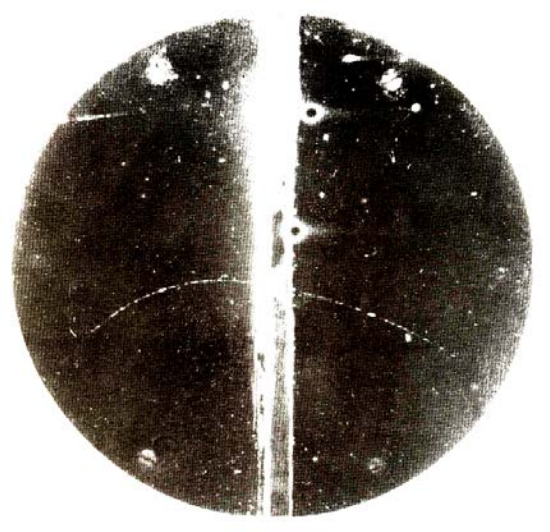


The Dirac vacuum, with 1 electron excited out, leaving a positron (the empty state).

However a key 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)

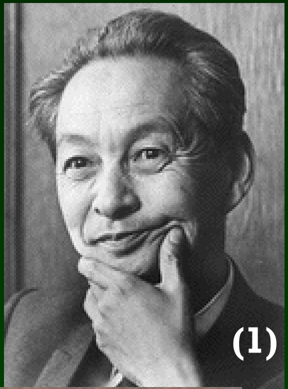


The discovery of the positron (C. Anderson, 1932), identified by its track.

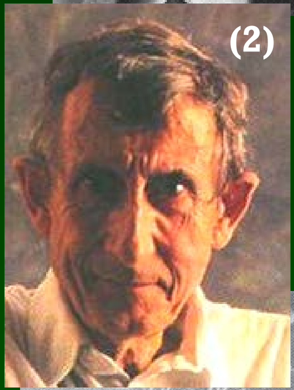
If a particle and anti-particle meet, they mutually annihilate, with the excess energy emitted as bosons- in the case of an electron and anti-electron, as high-energy photons (actually gamma rays).

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.



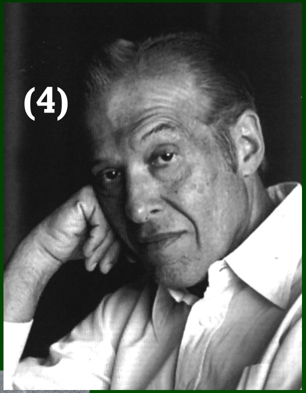
(1)



(2)

The founders of QED:

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



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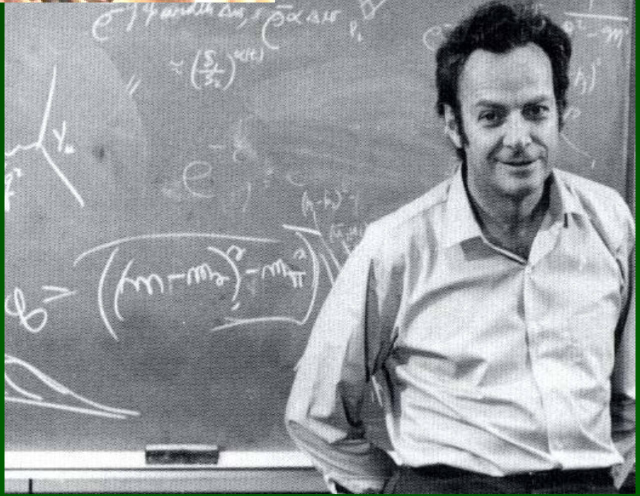
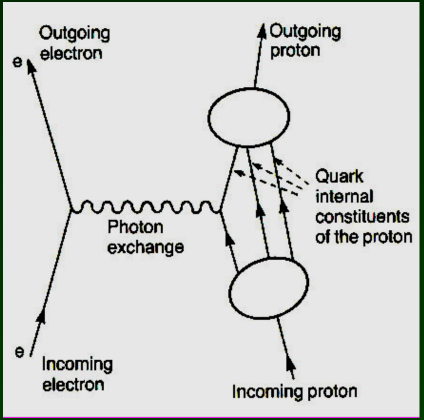


(3)

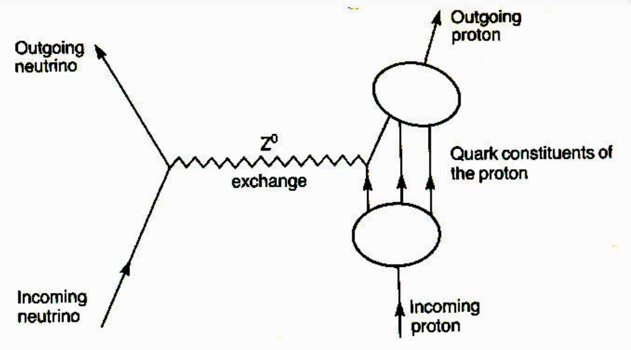
To give a proper mathematical quantum theory of the combined system of electrons & photons – what is called ‘Quantum Electrodynamics’, or ‘QED’ – turned out to be very difficult – it was finally accomplished in the period 1946-1951, with the key contributions made by the 4 theorists shown at left.



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

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….

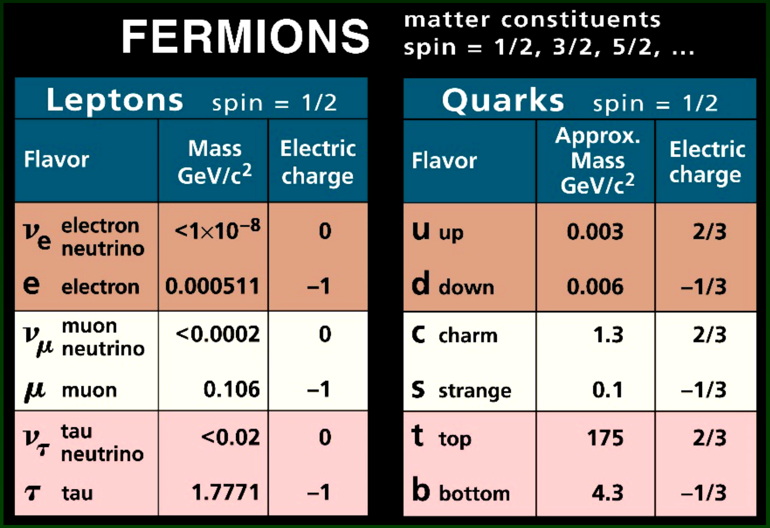


Proton-neutrino scattering (Z^0 exchange)

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, ...

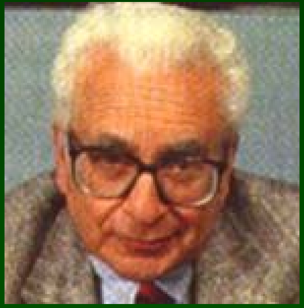
Leptons spin = 1/2

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

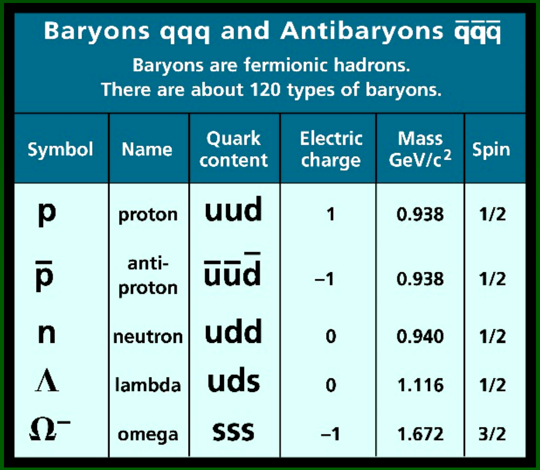
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

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).



M Gell-Mann (1929-)

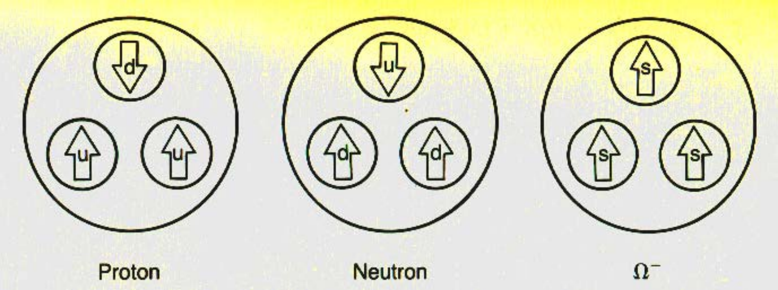
Physical particles like baryons are 'colourless'- made from 3 quarks, one of each colour. Many baryons can be made with different triplets of quarks.



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

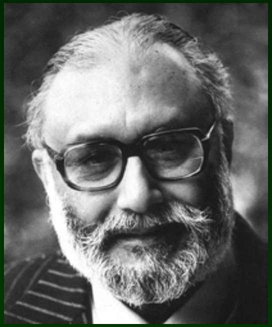
Baryons are fermionic hadrons.
There are about 120 types of baryons.

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^-

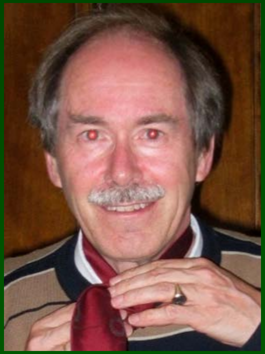
QUANTUM FIELD THEORY pushed to the Limit


A Salam
(1926-1996)

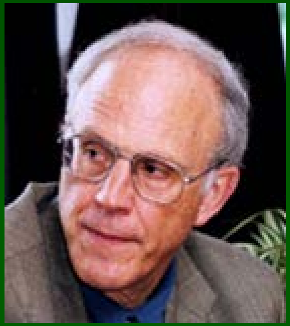

S Weinberg
(1933-)

The underlying framework of modern particle physics is quantum field theory – a hierarchy of fields which will ultimately be unified into one 'master field'. This dream, deriving originally from Einstein (who however wanted a *classical* unified field theory, not a quantum one), made huge progress from 1967-77. First came the unification of the weak & EM forces into an 'electroweak' field theory (Salam & Weinberg. 1967).

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 viable, and with his supervisor Veltman showed how to do calculations with it. The next step, taken in unpublished work by 't Hooft in 1972 & in papers by Gross & Wilczek, and Politzer in 1973, was to incorporate the strong interactions. Quarks interacting via 'gluons' had the remarkable feature of 'asymptotic freedom' – the attractive force between the quarks does not decrease as they separate, and so it needs an infinite energy to separate them (as they separate, a string of 'quark/anti-quark pairs' is produced, and this costs energy proportional to the length of the string).


Gerard 't Hooft
(1947-)

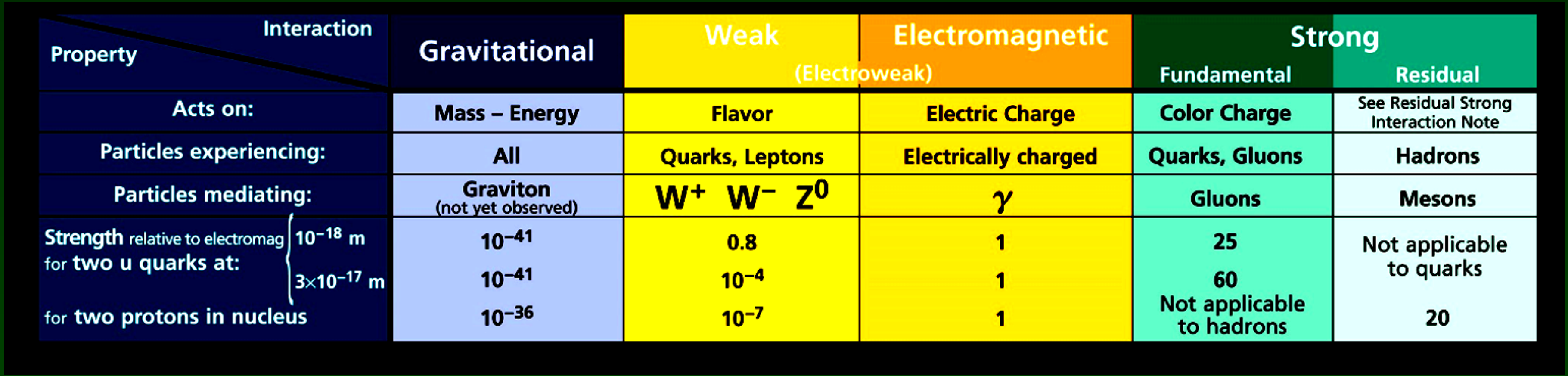
This set of basic ideas was quickly assembled into a unified theory of weak, strong, and EM fields, now called the *'Standard Model'.* This theory has been tested in many ways in the last 30 yrs – most predictions have been verified (except for that of the Higgs boson, not yet found).


David Gross (1941-)


Frank Wilczek (1951-)

FUNDAMENTAL INTERACTIONS

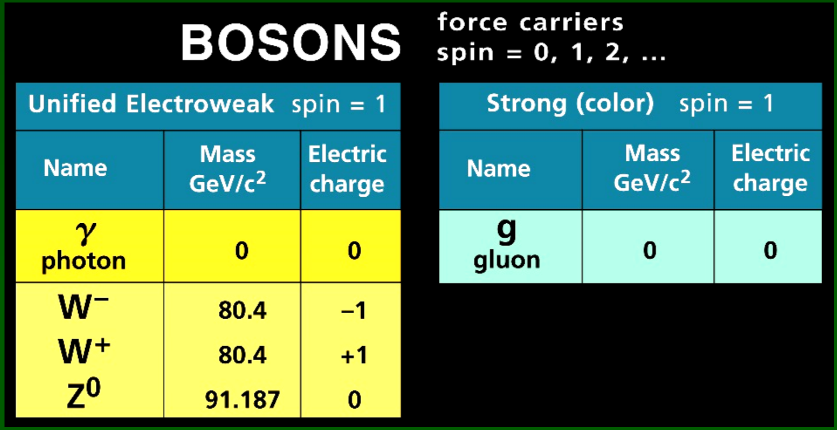
All interactions in Nature are mediated by BOSONS – which CAN exist in the same state:



Property \ Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	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
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



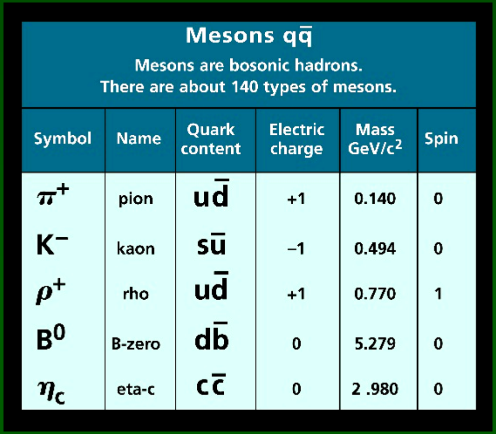
BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/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



Mesons $q\bar{q}$

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

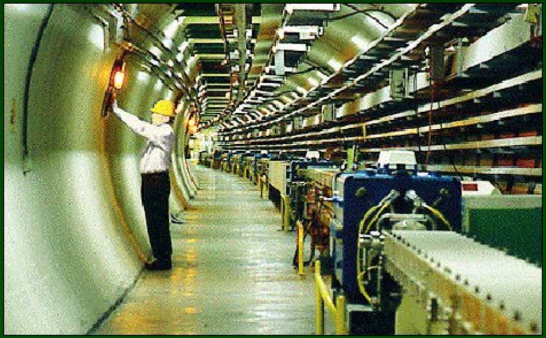
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	−1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

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

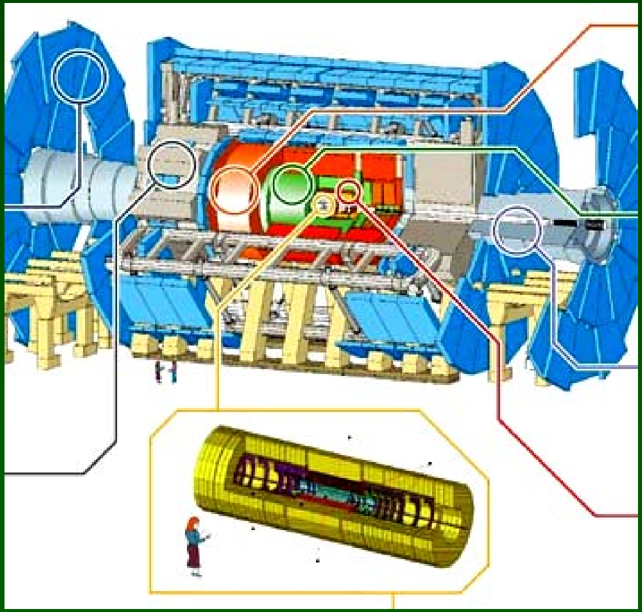
EXPERIMENTS in PARTICLE PHYSICS

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.

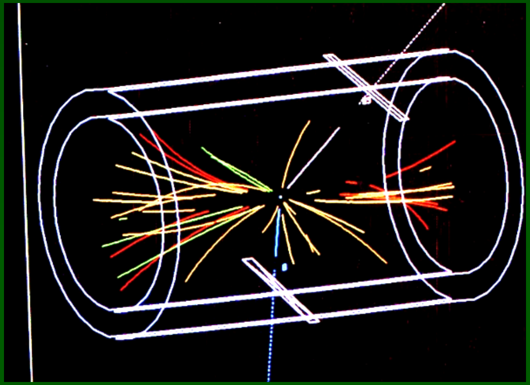
ABOVE: Fermilab- aerial view



Inside the LHC ring (CERN)



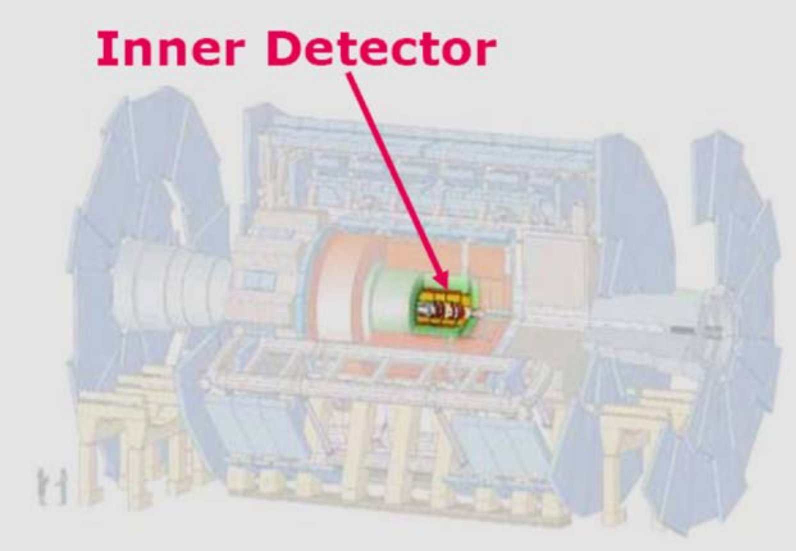
The 'ATLAS' detector (CERN)



$p^+ - p^-$ 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.

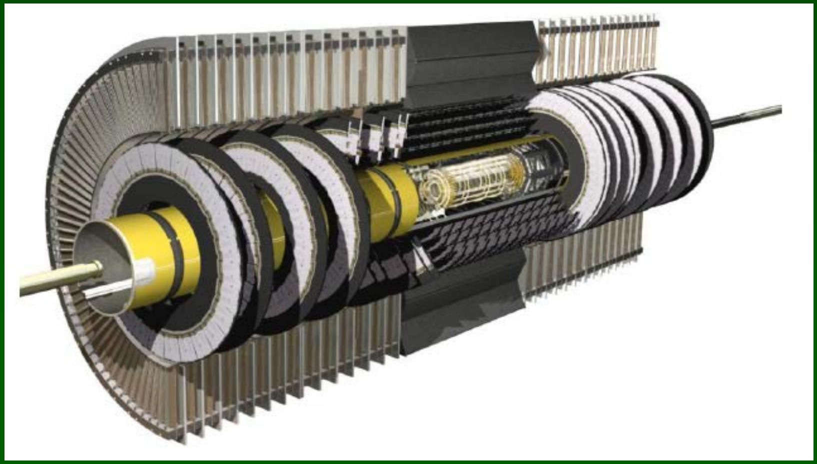
Inside a High-Energy Experiment: The LHC-ATLAS experiment



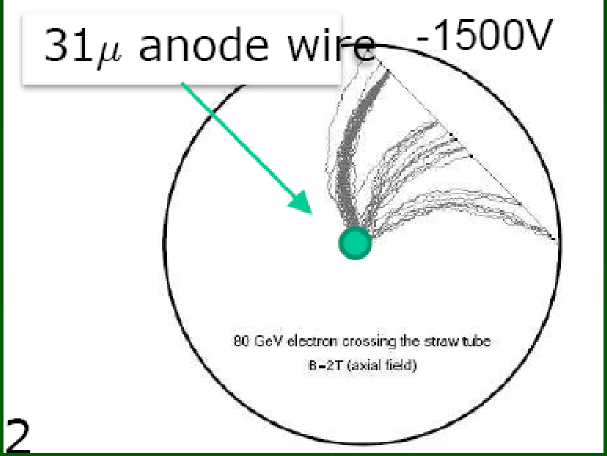
Site of the inner detector inside the ATLAS expt.

Let's take a look inside one of these experiments. For the last 10 yrs the huge ATLAS experiment, along with others, has been under construction at CERN in Geneva, as part of the LHC (Large Hadron Collider).

The ATLAS experiment, shown on the last page, is huge: 44 m long, 22 m in diameter, and weighing 7,000 tons. Let us now look at just one small detector in the inner core of this (see below). This particular detector weighs 4.7 tons. It is packed with 300,000 individual 'straws', of diameter 1/15 mm (a thick human hair). Each of these straws is a sophisticated 'Geiger counter'– style detector, in which an avalanche of electrons discharges if a fast particle passes through it – see cross section below right. ATLAS begins running in May 2008: 2 TB of data per second will then emerge from it for the next 10 yrs. Physicists are already planning the next expt.



The inner detector in the ATLAS experiment.



Cross-section of one of the 'straws

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’.

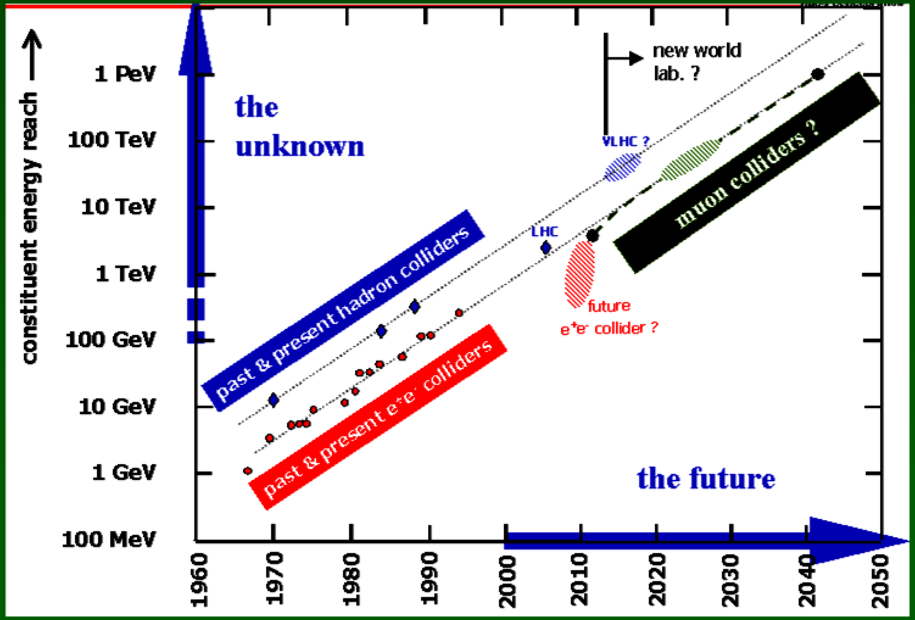
REDUCTIONISM: Crudely, the belief that Nature can be understood in a sort of ‘lego’ approach, with fundamental building blocks, so that everything can be understood if one knows these blocks and the forces between them.

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

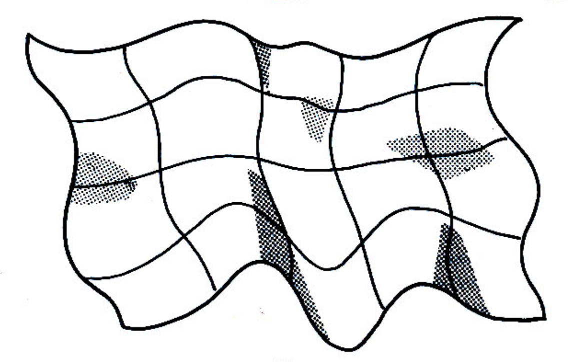
(i) The difficulty in quantizing gravity, which may be solvable by string theory. However There are problems with the string approach, & many (eg. ‘t Hooft, Penrose) feel that a different approach is necessary at or beyond the Planck scale – one which may supercede quantum field theory.

(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.

Search for a unified field theory- STRING THEORY



Quantum gravity theory tries to quantize the fluctuating geometry of spacetime

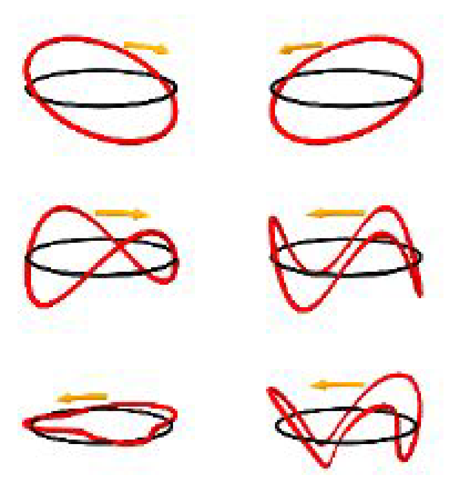
Arguably the most important problem in modern physics is how to unify the standard model (ie., the strong, weak, & EM forces) with gravity. The basic problem is that (i) the fields corresponding to the first 3 forces can be 'quantized' (producing all the boson excitations we have seen), but (ii) if we 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 naively 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 (2015) 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. article excitations (electrons, photons, quarks) are oscillation modes of s strings. 4-d spacetime is the 'unwrapped' part of this.

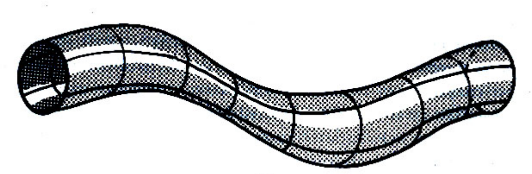
Even without a final theory, it is easy to see that unification can only happen at the Planck length scale of 10^{-35} m, or at energies of 10^{29} eV. Thus the theory cannot be tested *directly* except at energies 10^{16} times greater than modern accelerators- *this will never happen*.

For this reason – and because there is currently a vast number (10^{500}) of candidate theories – there seems little hope that string theory will produce a viable framework for the description of our world.



Schematic depiction of the some possible oscillation modes of a string

A string; magnified view below

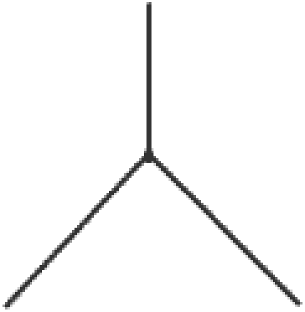


String Theory II: Quantum Geometry

Clearly it is not possible to draw the different kinds of possible 11-dimensional geometry. Various attempts have been made to depict some features of these. In the same way, eg., as one can imagine tying a 2-d tune into complicated knots in 3-d space, one can make incredibly complex wrapped up geometries in 11-d space – one example is shown in schematic & very over-simplified form at right.

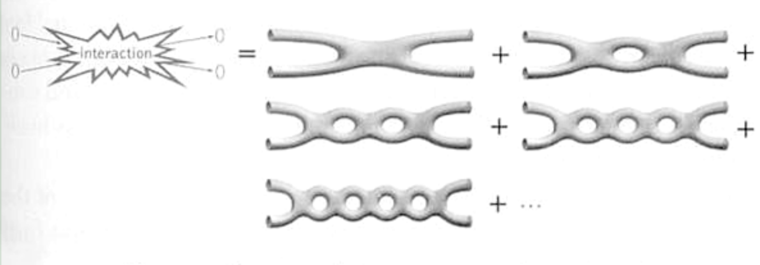
The 'Calabi-Yau' geometry

Any process whatsoever in physics, involving any kind of particle & also gravity, is supposed to be representable in string theory as a complex quantum geometry.The basic idea is shown at left – at the top we see 1 particle dividing into two, shown first as a Feynman diagram and then as a string geometry. Below this we see the collision between 2 particles, which is a sum of different string amplitudes – each of the pictures represents a different quantum amplitude.In the same way spacetime, when examined at a very fine lengthscale, is a wildly fluctuating quantum geometry ('spacetime foam').

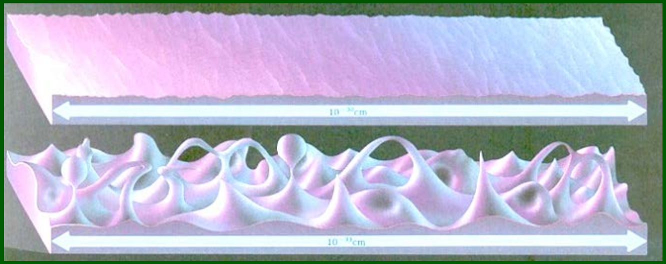


particle decay

Particle decay as a string process



Particle scattering as a sum of string processes



Spacetime examined on a coarse-grained scale (top) and at the Planck scale (below)

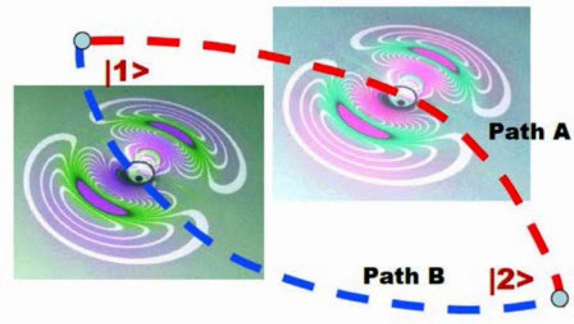
Search for a theory of QUANTUM GRAVITY

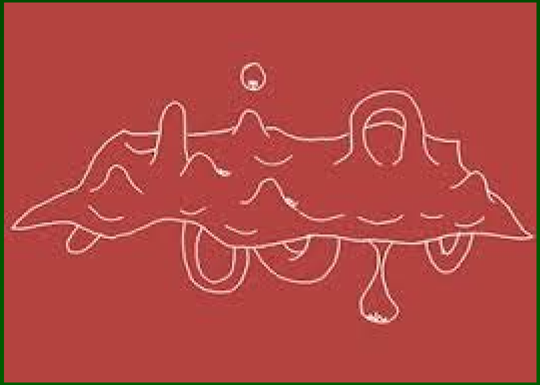
If we pull back a little from the wild ideas in string theory, we can make progress. Some of the most exciting ideas in physics have come from attempts to find a compromise between QM and gravity. There have been 2 main developments:

(1) SPACETIME as a QUANTUM FIELD

Suppose we really do take seriously the idea that spacetime is a field like any other. Then, if we also want to make it quantum mechanical - ie., to make spacetime a QUANTUM FIELD – we have to sum over all possible spacetimes – all are possible.

If taken seriously this idea leads to very strange conclusions. Suppose, eg., we do a 2-slit experiment in the usual way but now with a non-negligible mass. Then in the 2 branches of the superposition, spacetime is different – the mass, carrying the spacetime distortion with it, then distorts spacetime differently along each path. But what does this mean – that we are in a superposition of different universes with different spacetimes?





A strongly fluctuating surface

If so, then we would have some pretty strange possible 'paths' for the universe – where wormholes appear 'out of nowhere', and all sorts of strange configurations can appear (the 2-d analogy is at left).

Many have nevertheless tried to put together such theories, with interesting results – most notably the idea of 'inflation' (according to which the entire universe appeared in a single tunneling event).

A wormhole appears

Others have argued that this is all silly, and that QM itself must break down because of gravity – if true, this really would be a revolution.

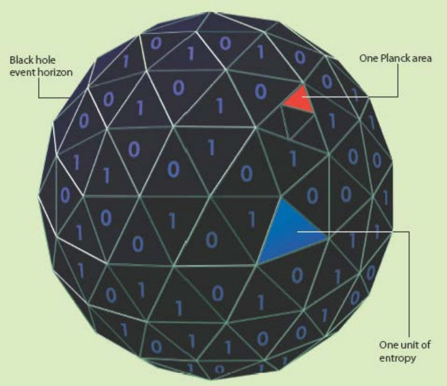
(2) QUANTUM FIELDs in CURVED SPACETIME

A less radical idea is to see what happens to ordinary quantum fields like the EM field and its photon excitations, when they are in a very strongly curved spacetime (ie., in a very strong gravitational field). This led to several major discoveries:

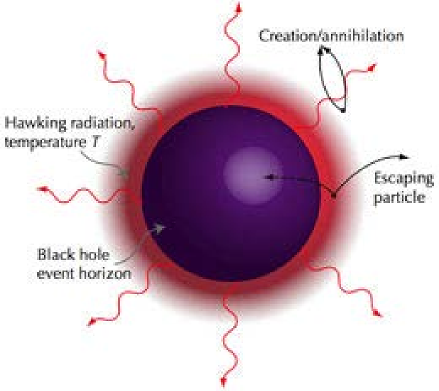
Hawking Radiation & Black Hole Entropy: According to Einstein's theory of spacetime and gravity, nothing inside the event horizon of a black hole can escape. But is this true if we treat matter or radiation near a black hole as quantum fields (still, however, treating spacetime itself classically)?

In 1973 Hawking showed that in such a theory

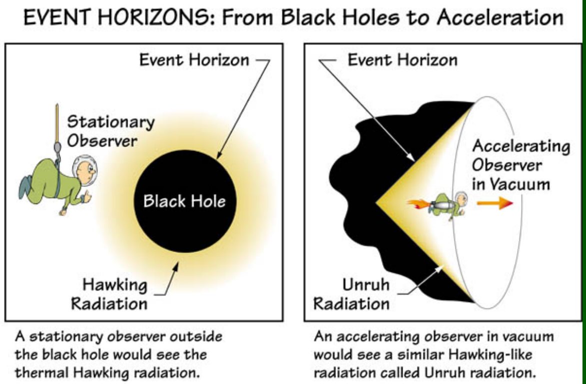
- **A black hole has a huge entropy (ie., contains a huge amount of info), proportional to the area of its event horizon – so much that black holes contain ~ 10^{16} times more entropy than the rest of the universe!**
- **The strong spacetime curvature destabilizes the quantum fields, and creates excitations (photons, electrons, etc) from the vacuum. Some of these are radiated away – black holes radiate at the 'Hawking temperature' T_H, slowly losing mass, & eventually they radiate to nothing.**



Imagining the info of black hole On event horizon, represented as binary code of 1's and 0's.



Hawking radn from black hole



A stationary observer outside the black hole would see the thermal Hawking radiation.

An accelerating observer in vacuum would see a similar Hawking-like radiation called Unruh radiation.

Comparison between Hawking & Unruh Radiation – relating strong spacetime curvature to strong acceleration

Hawking noted that this led to a paradox: where did all the info go? He argued it disappeared – so that QM must break down around black holes. 40 yrs later we are still arguing over this 'black hole info paradox'.

Unruh Radiation: If an object is accelerated in a vacuum, it will feel like it is in a bath of radiation at the 'Unruh temperature' T_U. This 'Unruh effect' is closely related to Hawking's effect.

The net result of all this work? Tantalizing results – but no theory of quantum gravity yet. Thus...

THE BIGGEST PROBLEM IN PHYSICS IS STILL UNSOLVED