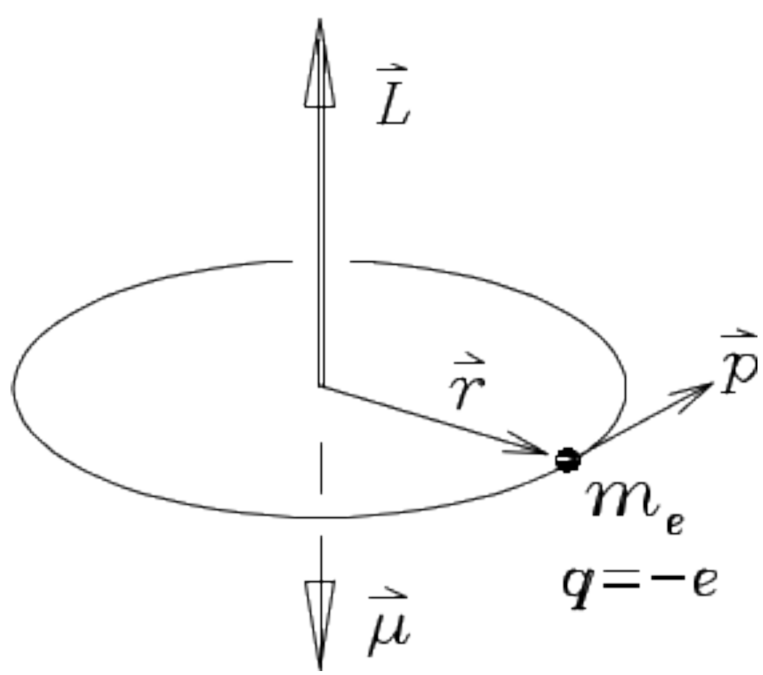
ELEMENTARY PARTICLES

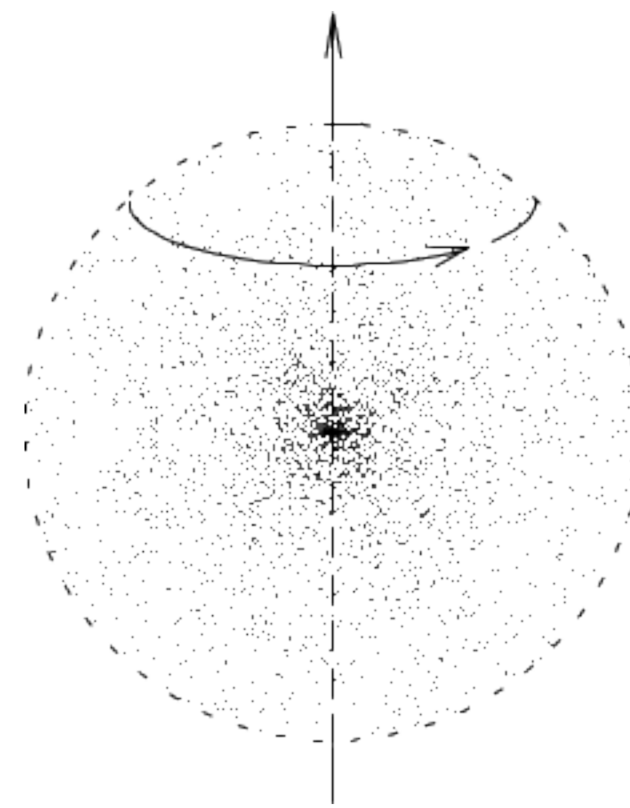
The Dreams that Stuff is Made Of

An historical introduction *ca*. 1975
by *Jess H. Brewer*

Spin

Orbital angular momentum $\boldsymbol{L}$ (left) of a charged electron implies a magnetic moment $\boldsymbol{\mu}$ in the opposite direction.





The same electron *at rest* (right) has **intrinsic** angular momentum (spin) $|\boldsymbol{S}| = \frac{1}{2}\hbar$ and $\boldsymbol{\mu}$: imagine (incorrectly) charged bits of mass collapsing down to a *point particle*.

Leptons:

spin ½ point particles

(*fermions*)

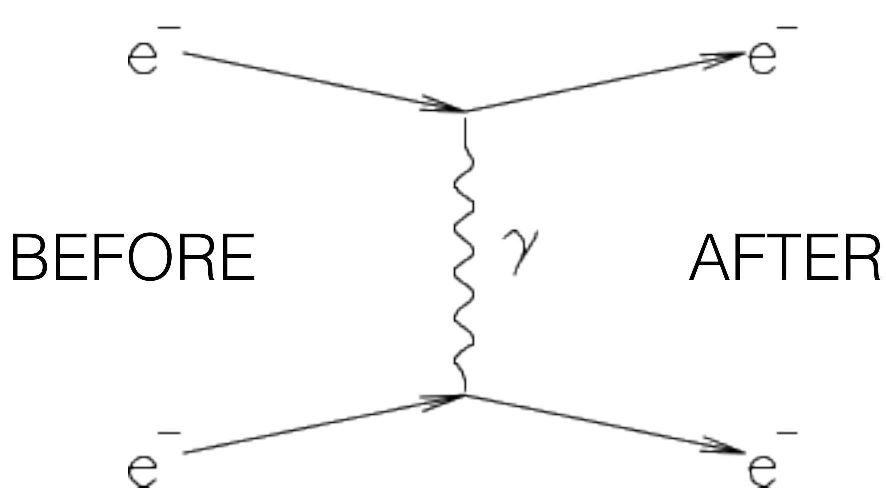
with *only Electroweak* Interactions

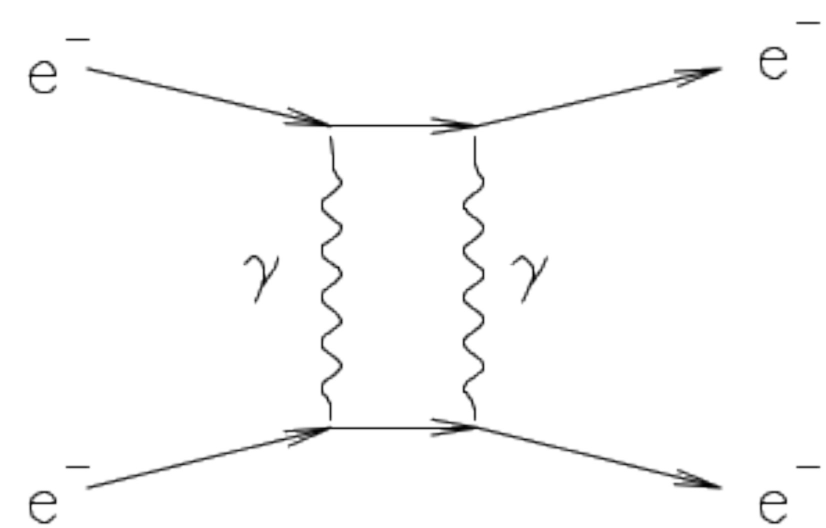
PARTICLE(s)		**Mass** (MeV/c^2)	**Charge** Q/e	**Lifetime** (s)	**Principle Decay Modes**
electron	e	0.511	-1	$> 6 \times 10^{29}$	none
e neutrino	ν_e	$< 1.7 \times 10^{-5}$	0	∞	none
muon	μ	105.66	-1	2.2×10^{-6}	$\mu \to e + \bar{\nu}_e + \nu_\mu$ $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$
μ neutrino	ν_μ	< 0.27	0	∞	none
tau	τ	1784	-1	3.03×10^{-13}	$\tau^- \to (\mu, e)^- + \nu_{(\mu,e)} + \nu_\tau$ $\tau^- \to (\text{hadron})^- + (\text{neutrals}) + \nu_\tau$
τ neutrino	ν_τ	< 35	0	∞	none

Feynman Diagrams:

Rigourous Cartoons

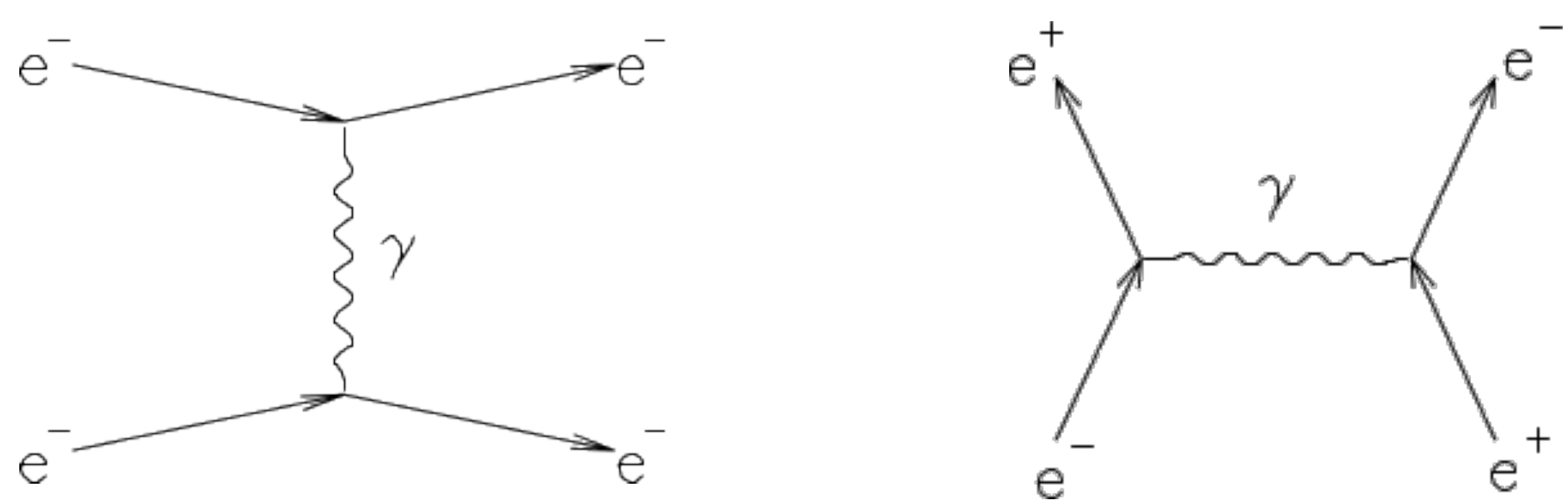
QED Rules: (1) electron lines are unbroken; (2) one photon meets one electron at each vertex; (3) each new vertex adds a factor $\alpha \approx 1/137$.





Perturbation Theory: the "*second-order*" diagram (*right*) is "weaker" than the "*first-order*" diagram (*left*) by a factor of $\alpha^2 \approx 1/19{,}000$. "Third order" is even weaker. So you get it *about right* in one try!

Crossing Symmetry
& *Time-Reversed Antiparticles*

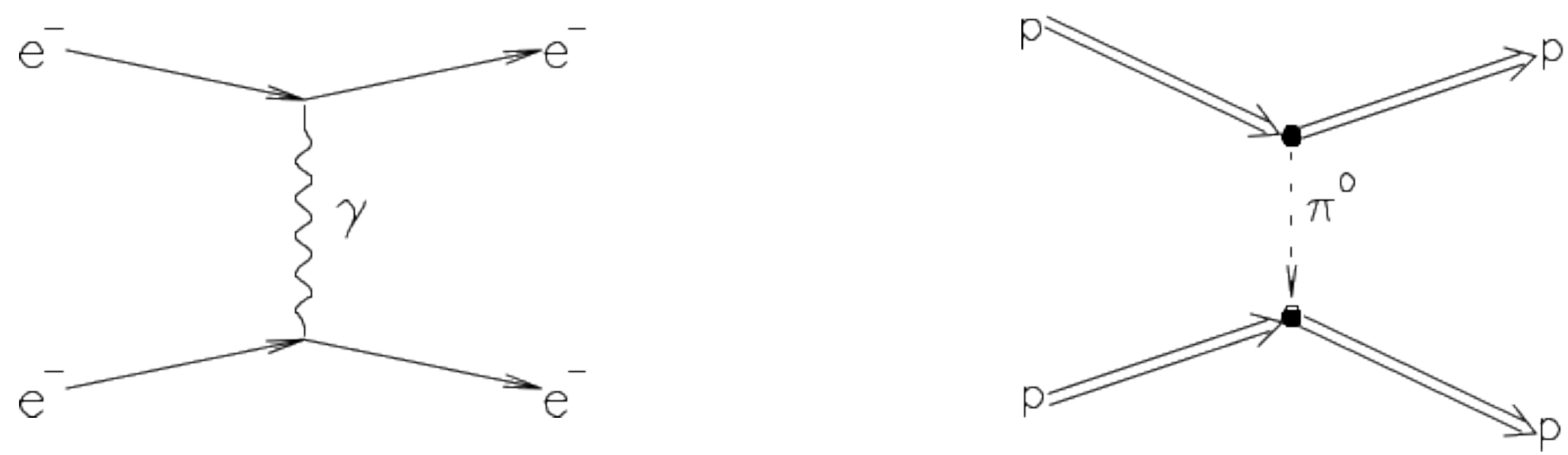


The diagram on the left (two electrons exchanging a photon) is in some sense the *same* as that on the right (an electron-positron *pair* annihilating into a photon which then spontaneously turns into another pair).

An *antiparticle* is always shown *propagating backward in time*. This is (probably) just a math convention.

Virtual Particles:
Embezzling the Energy Bank

Energy is conserved. However… Heisenberg's Uncertainty Principle ($\Delta E \Delta t \geq \frac{1}{2}\hbar$) says that the "*uncertainty*" ΔE in your "energy bank balance" won't be noticed as long as you only *withdraw* it for a very short time Δt.



The *photon* in the QED diagram (left) has no mass, so it doesn't get missed for a long time. Electromagnetism is therefore *long-range*. The *pion* mediating the nuclear force between two protons has an mc^2 of 135 MeV, so it has to be "re-deposited" immediately! Hence the *short range* of the nuclear force. (Lucky us!) — Hideki Yukawa, 1935

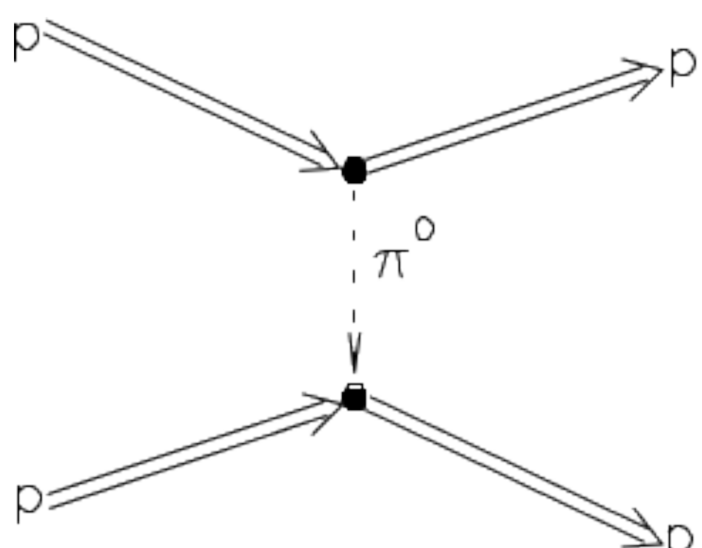
Intermediaries

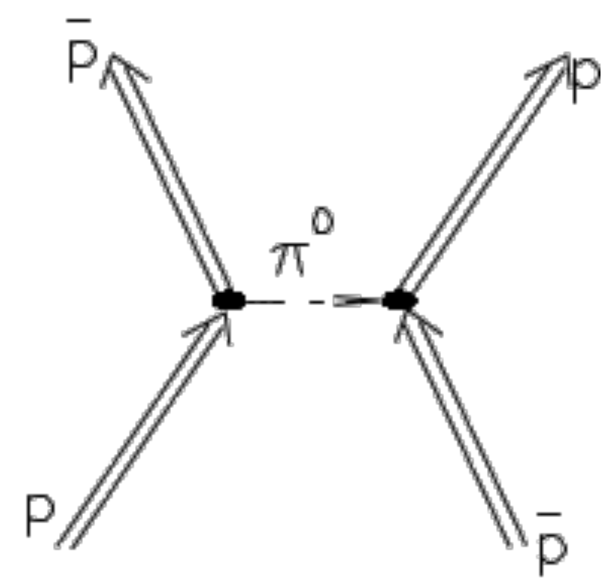
Particle		Mass (GeV/c^2)	Interaction mediated	Lifetime (s)
graviton	(?)	0	*gravity*	stable
photon	γ	0	*electromagnetism*	stable
vector boson	$W^\pm$	80.6	*weak*	2.93×10^{-25}
vector boson	Z^0	91.2	"	2.60×10^{-25}
pion (mainly)	π	0.139	*strong*	$\pi^\pm$: 2.6×10^{-8} π^0 : 8.3×10^{-17}
gluon	g	0?	*superstrong*	?
Higgs boson	H^0	> 24	*ultrastrong*	?
Higgs boson	$H^\pm$	> 35	"	?

Crossing Symmetry
revisited

Left: proton-proton scattering by *single pion exchange*.

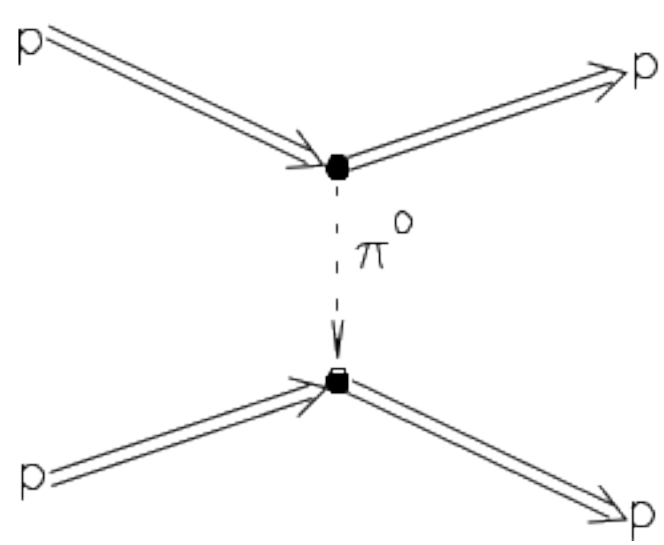
Right: proton-antiproton annihilation into a *virtual* pion → $p + \bar{p}$

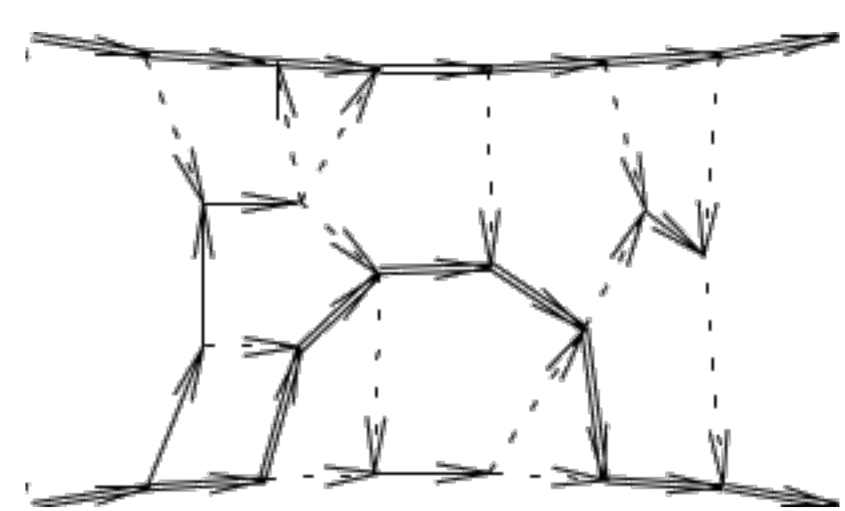




Strong Interactions:
Perturbation Theory "Fails"

Each strong *vertex* has a strength of ≈ 1, so single pion exchange (left) has ≈ the *same* amplitude as the complicated diagram on the right.





This stalled calculations for years and spawned Chew's *S*-matrix theory (which inspired Capra) until *QCD* resurrected Perturbation Theory. [later….]

Interactions

PARTICLE(s)		Gravity	Super-weak	Weak	Electro-magnetic	Strong	Super-strong	Ultra-strong
gravitons		* * *						
photons	γ	yes	?	no	* * *	no	no	no
neutrinos	ν_e, ν_μ, ν_τ	yes	?	yes	no	no	no	no
leptons	e, μ, τ	yes	?	yes	yes	no	no	no
mesons	$\pi, K, \ldots$	yes	?	yes	yes	yes	no	no
baryons	$p, n, \Lambda, \ldots$	yes	?	yes	yes	yes	no	no
neutral kaons	$K^0, \bar{K}^0$	yes	yes	yes	yes	yes	no	no
vector bosons	W, Z	yes	?	* * *	yes	no	no	no
quarks	u, d, s, c, b, t	yes	?	yes	yes	no	yes	no
gluons	g	yes					* * *	
(hypothetical)	T, V	yes						yes
Higgs bosons	H	yes	?					* * *
Relative strength		10^{-40}	?	10^{-4}	$\frac{1}{137}$	1	10-100	$> 10^{10}$?

Hadrons:

strongly interacting particles

MESONS

Name		Mass (MeV/c²)	Lifetime (s)	Spin $\mathcal{J}^{\mathcal{P}}$ [$\hbar$]	Charge $\mathcal{Q}/e$	Isospin $\mathcal{I}$	Strangeness $\mathcal{S}$
MESONS:							
pion	π	139	$\pi^{\pm}$: 2.6×10 8 π^0 : 8.3×10^{-17}	0^-	$-1, 0, +1$	1	0
kaon	K	495	$K^{\pm}$: 1.2×10^{-8} K^0 : ambiguous	0^-	$-1, 0, +1$	$\frac{1}{2}$	K^0, K^+ : $+1$ $\bar{K}^0, K$: -1
eta	η	549	8.9×10^{-15}	0^-	0	0	0
rho	ρ	770	4.3×10^{-24}	1^-	$-1, 0, +1$	1	0
omega	ω	783	6.58×10 23	1	0	0	0
phi	ϕ	1020	1.6×10^{-22}	0^-	0	0	0
	K^*	892	1.33×10^{-23}	1^-	$-1, 0, +1$	$\frac{1}{2}$	K^{*0}, K^{*+} : $+1$ $\bar{K}^{*0}, K^{*-}$: -1
	⋮	⋮	⋮	⋮	⋮	⋮	⋮

Strangeness

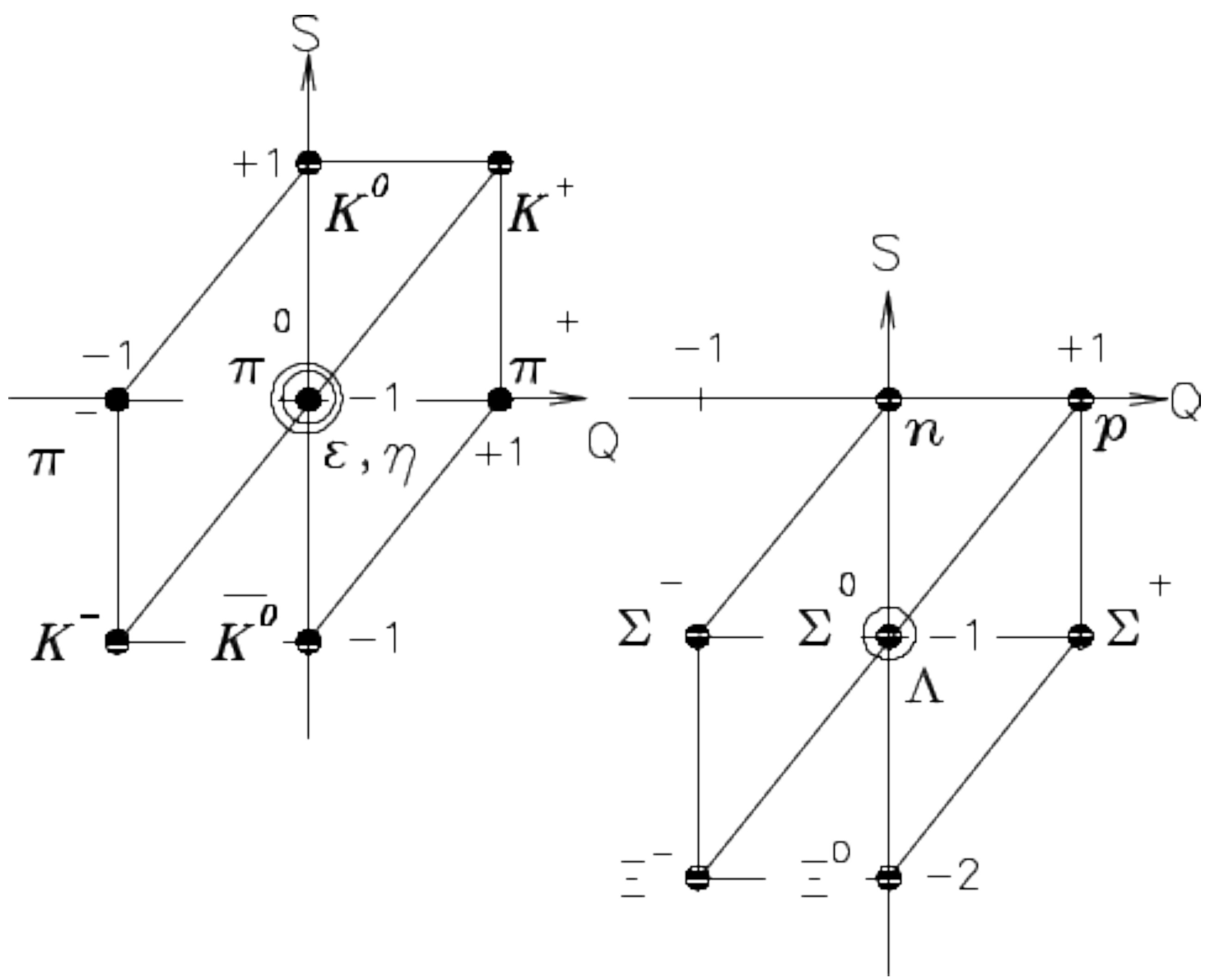
As accelerators reached higher energies, they could create heavier (and more exotic) particles, like the K^0 meson, or *kaon*, which was thought at first to be just an excited state of the *pion*. But there was a problem: with mc^2 of over 400 MeV, the neutral kaon should decay almost instantly to two pions. Instead it is remarkably *stable*. Usually such behaviour is indicative of a *conserved quantity* that the decay would violate. What could this strange quantity *be*? In wry frustration, people decided to call it ***strangeness*** ($\mathcal{S}$). Whatever it is, kaons have it; pions don't — and while the *strong* interaction *conserves* $\mathcal{S}$, the *weak* interaction (which governs K^0 decay) does not.

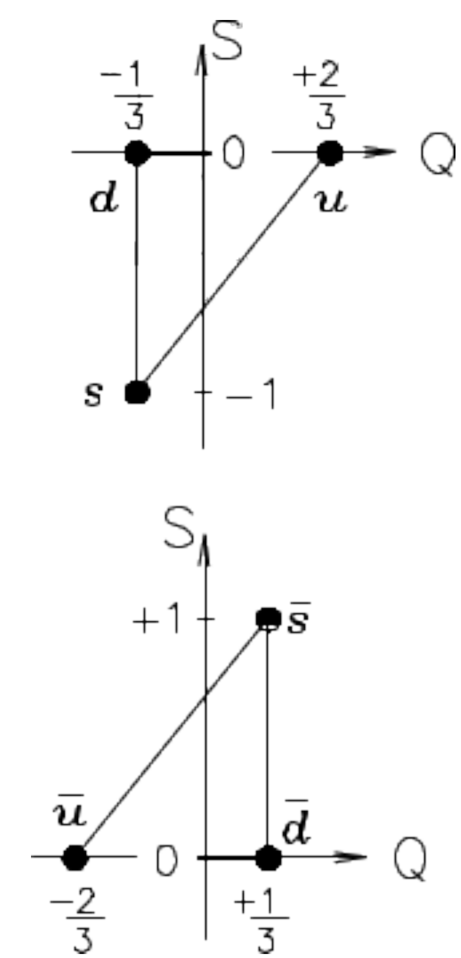
More Hadrons

BARYONS

Name		Mass (MeV/c²)	Lifetime (s)	Spin $\mathcal{J}^{\mathcal{P}}$ [$\hbar$]	Charge $\mathcal{Q}/e$	Isospin $\mathcal{I}$	Strangeness $\mathcal{S}$
BARYONS:							
nucleon	N	938	proton (p) : ∞ neutron (n) : 920	$\frac{1}{2}^+$	$0, +1$	$\frac{1}{2}$	0
lambda	Λ	1116	2.6×10^{-10}	$\frac{1}{2}^+$	0	0	-1
sigma	Σ	1190	$\Sigma^{\pm} :\approx 10^{\;\;10}$ $\Sigma^0 :< 10^{-14}$	$\frac{1}{2}^+$	$-1, 0, +1$	1	-1
cascade	Ξ	1320	$\approx 2 \times 10^{-10}$	$\frac{1}{2}^+$	$-1, 0$	$\frac{1}{2}$	-2
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$
delta	Δ	1232	5×10^{-24}	$\frac{3}{2}^+$	$-1, 0, +1, +2$	$\frac{3}{2}$	0
	Σ^*	1383	1.6×10^{-23}	$\frac{3}{2}^+$	$-1, 0, +1$	1	-1
	Ξ^*	1530	6.6×10^{-23}	$\frac{3}{2}^+$	$-1, 0$	$\frac{1}{2}$	-2
Omega	Ω	1672	$1.3 \times 10^{\;\;10}$	$\frac{3}{2}^+$	-1	0	-3
	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

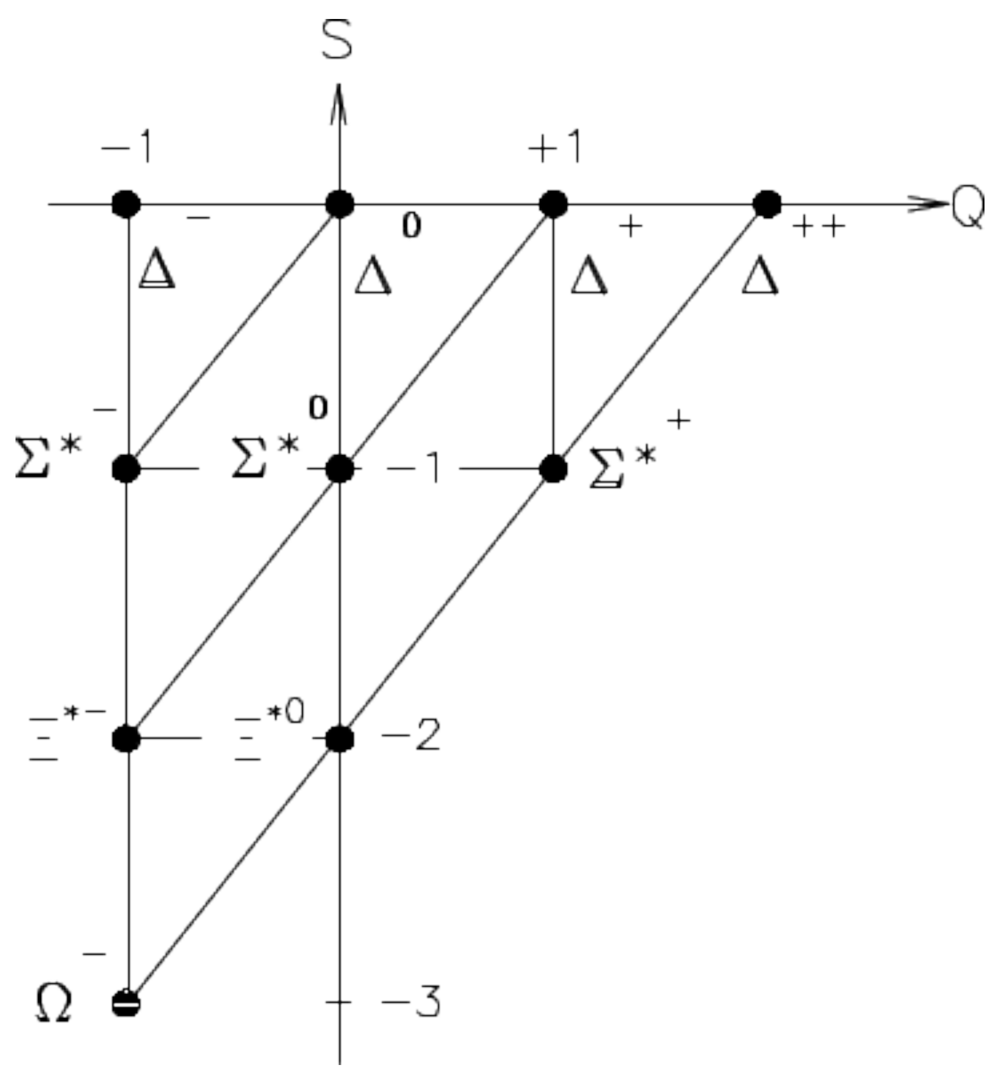
SU(3), the Eightfold Way & **Quarks**





I spin, ***U*** spin, ***V*** spin: they're all spins… but *why* "spin"?

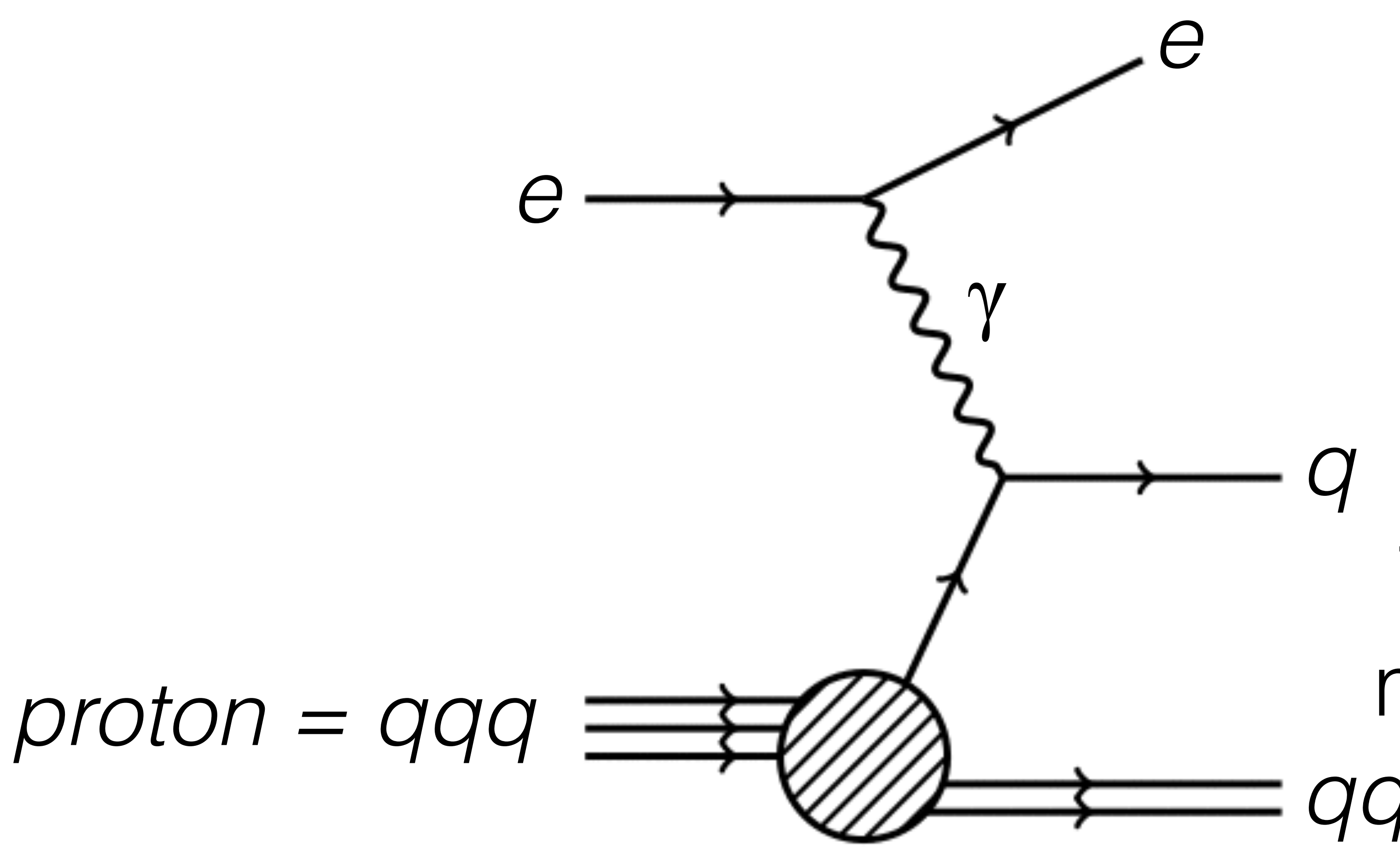
The Omega-minus



The Ω^- (strangeness –3) was *predicted* **before** it was *seen*.

This convinced everyone that SU(3) was “real”.

Deep **I**nelastic **E**lectron **S**cattering

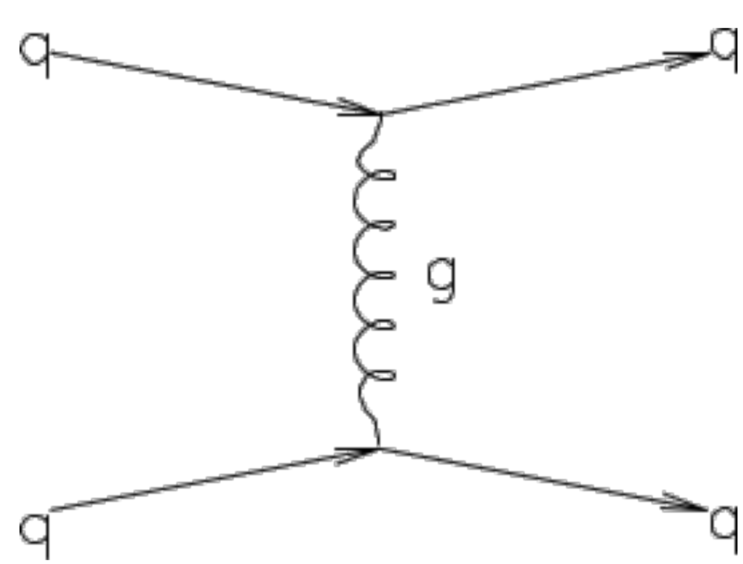


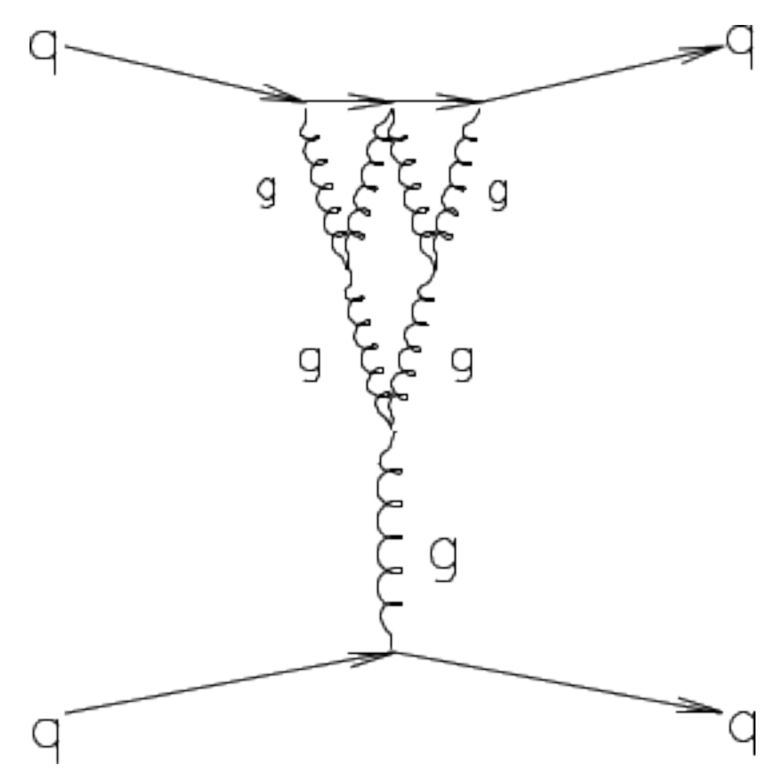
These 3 quarks must recombine.

Very high energy electrons (at SLAC) scatter off individual "*partons*" in a proton. This convinces everyone(?) that "*quarks*" are "real" particles.

Confinement:
No "bare" quarks!

Interactions between quarks are mediated by massless(?) "***gluons***", which (unlike photons) can "branch" to *two* gluons.





As a result, the quark-quark binding force *does not drop off with distance*. The ***work*** done in separating a single quark *grows* until it stores enough energy to make other masses.

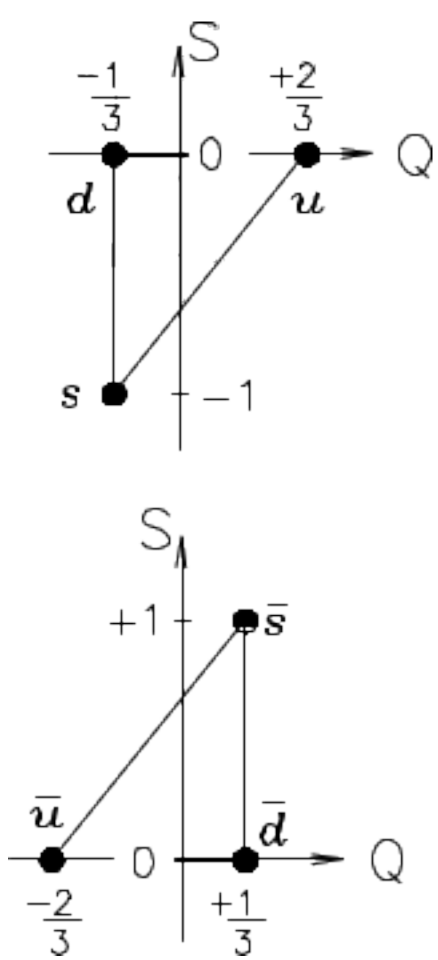
All the Quarks

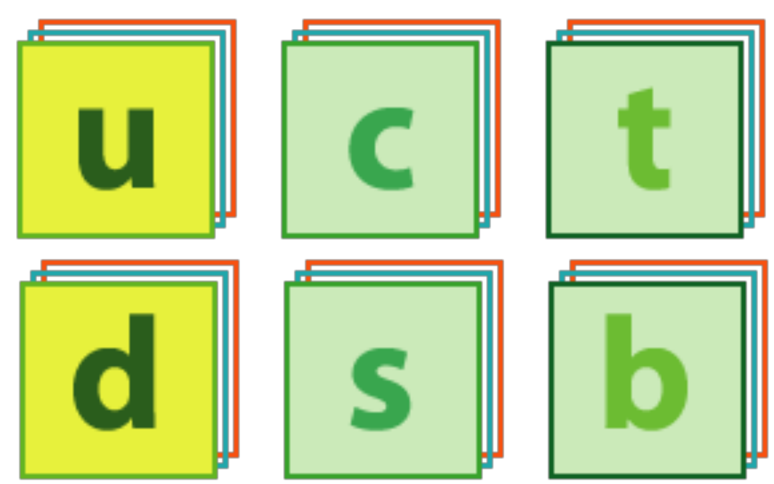
"***Top***" & "***Bottom***" were originally called ***Truth*** & ***Beauty***, but particle physicists got tired of all the wisecracks. There is now solid evidence that *there are no more* "***generations***".

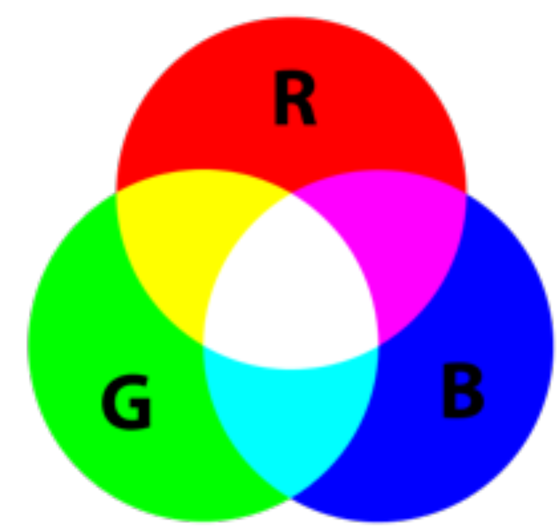
Name		Mass (MeV/c^2)	Lifetime (s)	Spin $\mathcal{J}^{\mathcal{P}}$ [$\hbar$]	Charge $\mathcal{Q}/e$	Isospin $\mathcal{I}$	Strangeness $\mathcal{S}$
"up"	u	411?	∞?	$\frac{1}{2}$	$+\frac{2}{3}$	$\frac{1}{2}$	0
"down"	d	411?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	$\frac{1}{2}$	0
"strange"	s	558?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	0	-1
"charm"	c	$\geq$ 1500?	∞?	$\frac{1}{2}$	$+\frac{2}{3}$	0	0
"bottom"	b	?	∞?	$\frac{1}{2}$	$-\frac{1}{3}$	0	0
"top"	t	?	∞?	$\frac{1}{2}$	$+\frac{2}{3}$	0	0

Quantum **C**hromo**D**ynamics

Each quark (or antiquark) comes in 3 “***colours***” (not really colour — that’s just a mnemonic *metaphor* to remind us that they “add up” to a “colourless" total).







The Standard Model

6 quarks, 6 leptons & all their antiparticles, plus the various force-carrying intermediaries = *all there is!* (**?**)