Conservation Laws
For every conservation of some quantity, this is equivalent to an invariance under some transformation.
Invariance under space displacement leads to (and from) conservation of linear momentum.
Invariance under time displacement leads to conservation of energy.
Invariance under spatial rotation displacement leads to conservation of angular momentum.
Lorentz transformation ←→ invariant mass.

1. "Old" conservation law"
Angular Momentum
For particles, the total angular momentum equals the orbital and spin angular momentum. $\underline{J} = \underline{L} + \underline{S}$.
Spin of a proton or a neutron is $\frac{1}{2}$ (nuclear shell model).
Spin of the electron is also $\frac{1}{2}$ which comes from the atomic shell model.
Spin of a photon is 1 – this comes from dipole transitions.
The spin of a particle is equal to the spin of the equivalent anti-particle.

(1) Beta Decay:
$n \to p + e^- + \overline{\nu_e}$
Here, all particle have spin ½ - this lead to the first deduction of the neutrino (1/2 != 1). Therefore all fermions.
(2) There is a very rare decay of a Pion (0.01% probability). $\pi^+ \to e^+ + \nu_e$.
$\pi^- \to e^- + \overline{\nu_e}$. So the spin of $\pi^\pm$ must be integer. → Boson.
$\pi^0 \to 2\gamma$. So the spin of π^0 is also integer → boson.
(3) μ is very similar to the electron. → imply that the spin of the μ is also ½ → also a femion. This is confirmed by a measurement of its' gyromagnetic ratio (its' magnetic dipole moment divided by its' spin).
(4) Common π decay (99.99%): $\pi^+ \to \mu^+ + \nu_\mu$, $\pi^- \to \mu^- + \overline{\nu_\mu}$.
So spin of the ν_μ and $\overline{\nu_\mu}$ have the same spin as electron neutrinos, and is ½ integer (fermions).

2. "New" conservation laws
Start off with Leptons.
Fact a) $n \to p + e^- + \overline{\nu_e}$. Can take a beam of neutrons, produce large amounts of neutrinos, and see what happens. $\overline{\nu_e} + p \to n + e^+$. But $\overline{\nu_e} + p \to n + \mu^+$ should surely happen? This has never been observed.

Fact b) $\pi^- \to \mu^- + \overline{\nu_\mu}$. You can take a beam of pions, hence get neutinos. Send these into a target → $\overline{\nu_\mu} + p \to \mu^+ + \ldots$. You may expect $\overline{\nu_\mu} + p \to e^+$, but this will never happen.

This leads to the deduction that ν produced with e give electrons, never μ's.
Conversely ν produced with μ give μ, never electrons.
So there are two different kinds of neutrinos, ν_e and ν_μ, as well as their antiparticles.
We now also have a Tau, which has ν_τ.
So we have three kinds of neutrinos, plus their antiparticles.

Fact c) You would expect the $\mu^+ \to e^+ + \overline{\nu_\mu} + \nu_e$. This is seen. You could have expected $\mu^+ \to e^+ + \gamma$. This never happens.
The deduction from this is that e-type, μ-type and τ-type particles must be separately conserved.
Implementation:
e-type particles are given an electron lepton number $L_e = \pm 1$.
μ-type particles are given an muon lepton number $L_\mu = \pm 1$.
τ-type particles are given an Tau lepton number $L_\tau = \pm 1$.
All non-leptons (all hadrons and all force bosons) have $L_e = L_\mu = L_\tau = 0$.

	L_e	L_m	L_τ
e^-	+1	0	0
e^+	-1	0	0
ν_e	+1	0	0
$\overline{\nu_e}$	-1	0	0
μ^-	0	+1	0
τ^-	0	0	+1

Each lepton number L_e, L_μ, L_τ is separately conserved. Watch out for neutrino oscillations.

Baryons
Baryons (qqq) have $B = +1$.
Anti-Baryons $(\overline{qqq})$ have $B = -1$
Mesons $q\overline{q}$ have $B = 0$.
Leptons and force bosons have no quarks, so $B = 0$
q has $B = {}^1\!/_3$, $\overline{q}$ has $B = -{}^1\!/_3$.
B is totally conserved in all interactions. Watch out for GUTs. This is a theory that tries to combine strong with other interactions. If true, then the proton will decay. If so, then baryon number is violated. However this has not been proved.
$p + p \to \overline{p} + p + p + p$.

Mesons
e.g. π.
$\pi^0 \to 2\gamma$ (98.8%)
Therefore mesons are not conserved. Therefore no special quantum numbers, and no special conservation laws.

Particle	**Mass**	**Decay**	**Notes**

γ	$\gamma < 6\times10^{-17} eV$	Stable	no lighter particle to decay to.
ν	$\nu_e < 3eV$ $\nu_\mu < 190 KeV$ $\nu_\tau < 18.2 MeV$ (in essence, no mass)	Stable	no lighter particle to decay to and conserve the lepton number.
$e^\pm$	$0.5 MeV$	Stable	No lighter particle to decay to and conserve lepton number and charge.
μ	$100 MeV$	$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu$, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$	Can decay to the lighter $e^\pm$, but to conserve lepton numbers we need neutrinos. Hence only weak interaction, which s slow.
$\pi^\pm$	$140 MeV$	$\pi^+ \to \mu^+ + \nu_\mu \quad 3\times10^{-8} s$ $\pi^- \to \mu^- + \bar{\nu}_\mu \quad 3\times10^{-8} s$	Need the neutrinos to conserve the lepton number, theferore weak.
π^0	$140 MeV$	$\pi^0 \to 2\gamma$	No Q to conserve. No B, L_e or L_μ to conserve. Can't go by the strong force. Therefore no lighter hadron. Therefore must be EM.
p	$1000 MeV$	Stable	No lighter particle to conserve B
N	$1000 MeV$	$n \to p + e^- + \bar{\nu}_e$ 900s	Need ν to conserve L_e, therefore weak. Very slow because very small Q value.

Force	**Speed**	**Time**
Strong	Fast	$10^{-23} s$
EM	Medium	$10^{-16} s$
Weak	Slow	$10^{-6} \to 10^{-10} s$

Strangeness
This is the first of several partially conserved quantum numbers.
1947 Rochester & Butler (Manchester)
Clound chamdre in cosmic rays. After the lead plate in the middle, there is a small gap indicating a neutral particle, then there are two charged particles coming from this – one positive, one negative.

These were called "V" events of the types $K^0 \to \pi^+ + \pi^-$ and $\Lambda^0 \to p + \pi^-$. Λ^0 has a mass of 1.1GeV, and was the first observation of any particle with a mass greater than the mass of the proton or neutron.
After this time, accelerators were invented allowing us to control the times, places and energies of particle collisions.

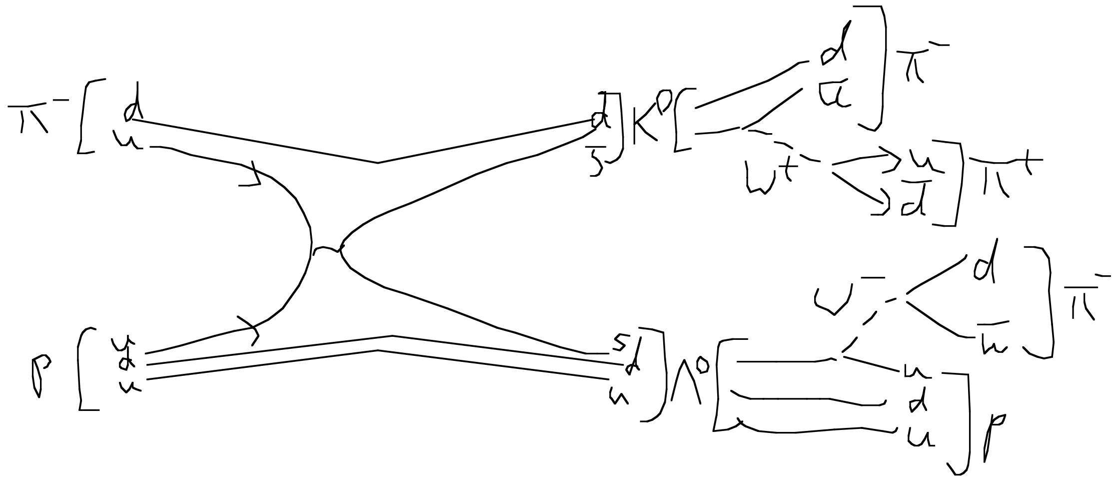
Neutral particle produced by interaction in the lead. Production rate meant that it must be by the strong interaction – any other, and the decay would not happen fast enough and the particles wouldn't be seen.
Hence it would be expected that the particle would decay through the strong force, so it should decay in 10^{-23} seconds. This time comes from the distance the particle travels (for the strong interaction, this is around $10^{-15}m$)., and the maximum speed it can travel at (speed of light). However, in this case the distance between the lead and the interaction is at least a few mm. So even if the particle decayed right at the edge of the lead, it could not possibly be due to the strong force. The decay must be slow – it must be by the weak interaction.

Lifetimes expected for K^0 and Λ^0 are $\sim 10^{-23}s$ by the strong force, but are actually $10^{-8} \to 10^{-10}$ or 10^{-10} respectively. (two lifetimes for K^0 as there are two types – short and long. This is not important.)

Principle of Associated Production 1953 Gell-Mam
These "strange" particles have a quantum number called "strangeness". Always produced in pairs with $S = +1$ and $S = -1$ - no net strangeness. Strong production process.
Decay separately with each decay having $\Delta S = 1$ only via the weak interaction, which is the only reaction where strangeness is not conserved.

With the Quark model (1964) (u, d, s)
By convention:
K^0 has $S = +1$ and is a Meson $\left(d\,\overline{s}\right)$
Λ^0 has $S = -1$ and is a Baryon $\left(u\,d\,s\right)$.
So:
s quark has $S = -1$, $Q = -\frac{1}{3}$, $B = \frac{1}{3}$.
$\overline{s}$ quark has $S = +1$, $Q = +\frac{1}{3}$, $B = -\frac{1}{3}$.
S is an additive quantum number.
All other quarks have $S = 0$.
All leptons have no quarks, so $S = 0$.

$\pi^- + p \to K^0 + \Lambda^0$



At mid-point.
$s\bar{s}$ produced.
No net s produced.
($\Delta s = 0$: strong.

At later reactions: $\Delta S = 1$. W involved. Therefore Weak decay.

Strangeness conserved in strong and EM reactions, but not in weak interactions.

Isospin
This is a partly-conserved quantum number. It can also be called isotropic or isobaric spin. The symbol is I, although some older ones call it T . It has similar properties with angular momentum spin quantum number, hence the "spin".

It is due to the charge indedendance of the strong interaction. It is due to the energy levels in mirror nuclei, such as ${}^7_3Li$ and ${}^7_4Be$, which are identical in energy levels (one has 3 protons 4 neutrons, the other 4 protons 3 neutrons). $\pi^+ + p$ and $\pi^- + n$ cross-sections are identical (apart from resonance).
→ neutrons and protons are the "same" particle as far as the strong interaction is concerned. We will call them two states of the nucleon.

We can have both proton and neutron in the same energy state with parallel spins. As these are Fermions, and they obey the Fermi exclusion principle, because you can have them in the same state you need a distinguishing quantum number. Obviously, they do have a differing feature – the charge – but instead of using this we invent a new quantum number, called Isospin.
Here
$I_3 = +\frac{1}{2}$ for the Proton
$I_3 = -\frac{1}{2}$ for the neutron.
I_3 is the third component of Isospin I. This is the third projection of the Isospin – an equivalent in angular momentum would be L_z, the projection onto the z-axis. But here we have Isospin space, not standard space, hence the numbered axis.

Now go down to the Quark level. We know that the proton is uud, and the neutron udd. So we can deduce:

u quark: $I_3 = +\frac{1}{3}$
d quark: $I_3 = -\frac{1}{2}$.
Their overall Isospin $I = \frac{1}{2}$
$I_3 = 0$ for all other quarks.
Note that I_3 is algebraically addible, and I is vectorially additive.
Isospin is the appropriate quantum number for up and down quarks. It corresponds to strangeness for the strange quark.

By analogy with ordinary angular momentum spin S, the number of states with angular momentum $S = 2s+1$.
→ Isospin number of substates in Isospin multiplet (i.e. the number of particles with the same I but different I_3) $= 2I+1$.
e.g. proton, neutron:
$I_s = +\frac{1}{2}, -\frac{1}{2}$
$I = \frac{1}{2}$
$2I+1=2$ i.e. proton and neutron.

For the strong interaction only, all $2I+1$ states are degenerate i.e. they have the same energy, i.e. they have the same mass.

For EM interactions, we obviously don't have charge independence. This breaks state degeneracy → mass splitting, therefore $m_n > m_p$. All quantum numbers which are independent of the EM interaction are unaffected by this loss of degeneracy. Therefore all particles within an I multiplet have the same value of these quantum numbers, i.e. the Baryon number.

Because I_3 is algebraically additive, all antiparticles and antiquarks have the opposite I_3 as their opposing particle. They have the same I as the particle.

e.g. the Pion:
π^+ is $u\bar{d}$ → $I_3 = +\frac{1}{2} + \frac{1}{2} = 1$
π^0 is $u\bar{u} / d\bar{d}$ → $I_3 = +\frac{1}{2} - \frac{1}{2} or - \frac{1}{2} + \frac{1}{2} = 0$
π^- is $d\bar{u}$. → $I_3 = -\frac{1}{2} - \frac{1}{2} = 1$.
In total, $I=1$. Therefore $(2I+1)=3$ states within I multiplet. If EM wasn't involved, all particles would have the same mass, and all quantum numbers would be the same between them. Because of EM, there is mass differences. Same as for the nucleon.

Because u has $I_3 = +\frac{1}{2}$, and $Q = +\frac{2}{3}$, and for d $I = -\frac{1}{2}$ and $Q = -\frac{1}{3}$, I_3 is the most positive for states with most positive charge in any I multiplet.

There is obviously some correlation between charge and Isospin – this is a redundancy in the particle system. Proliferation of quantum numbers leads to redundancy and the following constraint – the Gell-Mann – Nisijima Relation.
For Quarks, the charge on the quark is:
$Q_q = \frac{B+S}{2} + I_3$ where all quantum numbers refer to quarks
All of these quantum numbers are algebraically additive, therefore for Hadrons we get:
$Q_H = \frac{B+S}{2} + I_3$ where all quantum numbers refer to the Hadron.
Note for future: extend the quark model → u, d, s, c (charm), b (bottom or beauty), t (top or truth).
$Q = +\frac{2}{3}$ for u $\left(I_3 = +\frac{1}{2}\right)$, c $(C = +1)$, t $(T = +1)$.
$Q = -\frac{1}{3}$ for d $\left(I_3 = -\frac{1}{2}\right)$, s $(S = -1)$, b $(\tilde{B} = -1)$.
All other quarks and leptons have $I_3, S, C, \tilde{B}, T = 0$.
$C, \tilde{B}, T$ behave like S – conserved in strong interaction and EM interaction, but not in weak.

So now:
$Q_q = \frac{B+S+C+\tilde{B}+T}{2} + I_3$ for quarks
$Q_H = \frac{B+S+C+\tilde{B}+T}{2} + I_3$ for Hadrons.
The numerator $(B+S)$, or $\left(B+S+C+\tilde{B}+T\right)$ for extended, are called the Hypercharge, and given the symbol Y.

Isospin Conservation
SI charge independent. I and I_3 conserved.
e.g.:
$\pi^- + p \to \pi^0 + n$
$I : 1 + \frac{1}{2} \to 1 + \frac{1}{2}$
$I_3 : -1 + \frac{1}{2} \to 0 - \frac{1}{2}$
In EM interaction, obviously not charge independent. I is not conserved.
e.g.:
$d + d \to {}^4He + \pi^0$
$I : 0 + 0 \to 0 + 1$
$I_3 : 0 + 0 \to 0 + 0$
→ I is not conserved → cannot be strong interaction. Proceeds by IM interaction so relatively low σ (cross-section).

$$Q = \frac{B+S+C+\tilde{B}+T}{2} + I_3$$

Know that $Q, S, C, \tilde{B}, T$ are all conserved in EM interaction. Therefore I_3 mst also be conserved in EMI.
So I is not conserved, while I_3 is.

$S\left(I, C, \hat{B}, T\right)$ not conserved in weak interaction.
→ I_3 not conserved in weak interaction.

	Strong Interaction	EM	Weak
I	Yes	No	No
I_3	Yes	Yes	No

Now go back and start to generate a model of this all…