Introduction

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Particle Physics today:

According to our current understanding the world around us is made of two categories of particles: The leptons and the quarks. Quarks and leptons interact with each other via four interactions: the electromagnetic, the strong and weak nuclear interactions and gravity. It has been the goal of particle physics since Maxwell and Einstein to unify these 4 interactions in to one unified theory. This is due to our belief that the underlying laws of nature are simpler than what we actually observe in the world around us with perhaps fewer elementary particles and interactions. To this day two experimentally tested unified theories exist: Maxwell's electromagnetism and the Standard Model of particle physics.

The most complete unified theory available is the Standard Model of particle physics which *quasi*-unifies the electromagnetic with the weak and strong interactions in to a single model albeit with 18 free parameters to be measured by the experiment. To this day no successful quantum theory of gravity exists and no theory has been proposed that can unify gravity with the other three interactions.

The lepton sector of the standard model consists of three generations of leptons:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix} \quad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}$$

Each generation consists of a massive charged lepton, l^-, with its neutral and lighter neutrino partner ν_l. At the time that the standard model was developed there was no experimental evidence that the neutrinos had mass. Hence, the standard model assumed them massless. However, by now we know that the neutrinos do have mass and understanding how do they acquire their mass is one of the hottest subjects both in experimental and theoretical particle physics today.

Quarks form also three generations in the standard model also with increasing mass:

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} t \\ b \end{pmatrix}$$

They are commonly referred to as up, down, charm, strange, top and bottom.

It is not known why the number of quark generations is equal to the number of lepton generations although the fact that they are is indeed helpful in Quantum Field Theory calculations. It is also not yet known why each generation of particles be it leptons or quarks is heavier than the other and why the heaviest of them, the top quark, is many orders of magnitude heavier than the lightest of them the neutrinos. Discovering all these particles took over one century starting with the discovery of the electron in 1897 by Thomson and going up to the relatively recent discoveries of the top quark in 1995 and the tau-neutrino in 2000.

All but one of the particles predicted/incorporated in the standard model have been observed by the experiment. Shown in Fig. 1 are the discovery dates for each particle. Not all of them are considered to be elementary. The Higgs particle has not yet been discovered and its discovery is the focus of the experiments at the Large Hadron Collider at CERN in Geneva. The Higgs plays a pivotal role in the standard model because according to the standard model it is responsible of giving mass to all other massive particles. Hence, proof for its existence is absolutely essential to prove that the standard model is indeed a self consistent theory.

According to the standard model these particles interact with each other via the four known interactions. However, not all of them interact via all 4 interactions. Particles which have charge interact via the electromagnetic interaction and massive particles interact also via gravity. Gravity is much weaker than the other three interactions and can be ignored in particle physics calculations involving realistic beam energies in the laboratory. All quarks carry the 'charge' of the strong interactions which is called colour and therefore interact via the strong interaction. Both leptons and quarks interact via the weak interaction because they also carry weak charges. In quantum field theory interactions are mediated by particles which are called for this reason mediators. Strong interactions are mediated eight particles called the gluons, $\mathbf{g_i}$**.** The mediator of electromagnetic interactions is the photon, γ , and the mediators of the weak interactions are the $\boldsymbol{W}^{\pm}$ and the $\boldsymbol{Z^0}$. All these mediators are spin one particles (vectors). The various particles of the Standard Model along with their basic properties are shown in Table 1. The properties of the 4 interactions and their mediators are shown in Table 2.

Particle Type	Particle Symbol	Charge	Strong Force	Electromagnetic Force	Weak Force
Up-type Quark	u,c,t	+2/3	Y	Y	Y
Down-type Quark	d,s,b	-1/2	Y	Y	Y
Charged Lepton	e^- , μ^-, τ^-	-1	N	Y	Y
Neutral Lepton	ν_e, ν_μ, ν_τ	0	N	N	Y
Higgs	H^0	0	N	N	Y

Table 1: *The elementary particles of the Standard Model.*

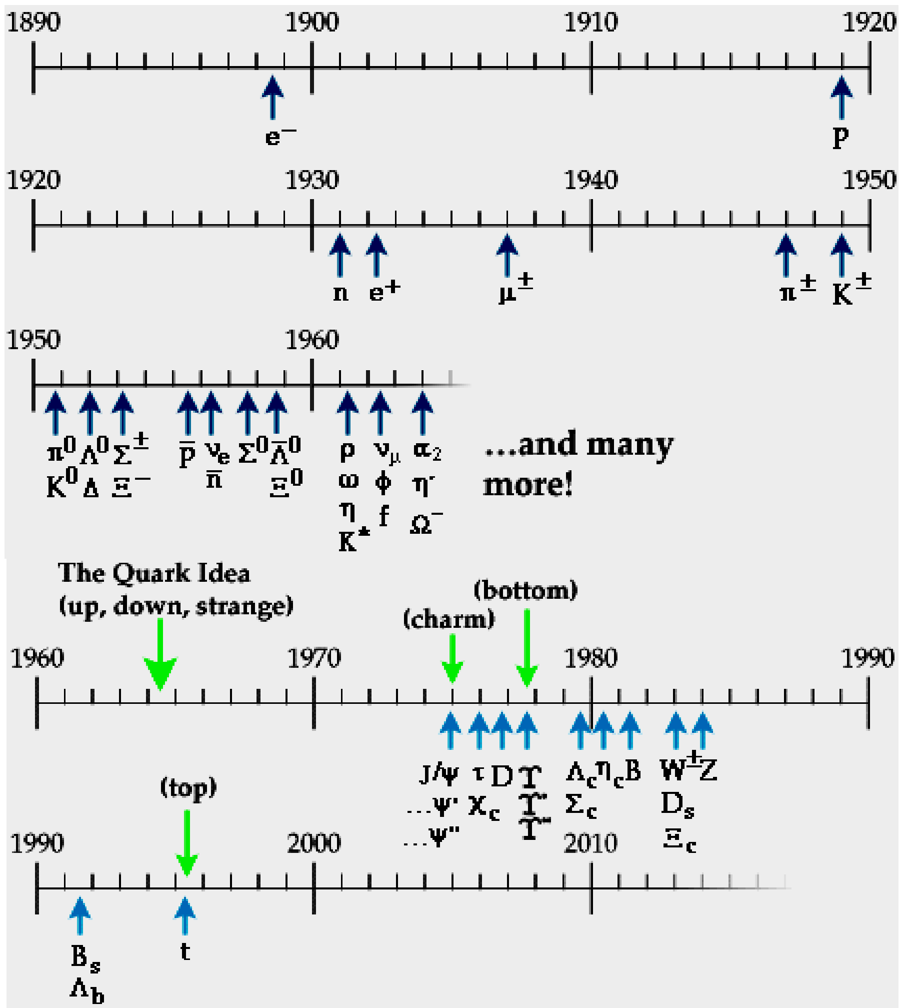

Figure 1: *The discovery dates of the most important particles in nature. Evidently progress was slow in the early dates of particle physics. Later on progress came in bursts separated by quiet periods of preparation for then next brake-through.*

Interaction	Gravity	E+M	Weak	Strong
Quantum	Graviton	γ	$W^{\pm}$ Z^0	g (eight)
Spin-Parity	2^+	1^-	$1^-,1^+$	1^-
Mass	0	0	~80,90 GeV	0
Range	∞	∞	10^{-18} m	$\leq 10^{-15}$ m
Couplings	$G_N = 6.7\,10^{-39} \times \frac{\hbar c}{(GeV/c^2)^2}$	$1/137$	$G_F = 1.166\,10^{-5}\, GeV^{-2} \times (\hbar c)^3$	10^{-1}-10^0
Typical Cross-section	NA	10^{-33} m^2	10^{-44} m^2	10^{-30} m^2
Typical lifetime	NA	10^{-20} sec	10^{-8} sec	10^{-23} sec

Table 2: *The properties of the four known interaction and their corresponding mediators.*

Units used in Particle Physics:

Most of the calculations done in particle physics use a system where: $\hbar = c = 1$. Unit systems use mass, length and time as their basic units from which all other units can be defined. However, by introducing the two equations above we are only left with one independent unit which in particle physics we take it to be GeV. Hence, all quantities will be expressed as a function GeV. In other words mass is given in GeV, length in GeV^{-1} and time in GeV. When one converts from MKSA to this systems it is useful to remember that:

$$\hbar c = \mathbf{0.1973}\, GeV\ fm \quad \text{where} \quad \mathbf{1}\, fm = \mathbf{10^{-15}}\, m$$

The cross-section unit in particle physics is: $\mathbf{1}\, Barn = \mathbf{10^{-28}}\, m^2$

It is then easy to show that:

- $\mathbf{1\, Kgr = 5.6\, 10^{26}\, GeV}$
- $\mathbf{1\, Gev^{-2} = 0.389\, mb}$
- $\mathbf{1\, m = 5.068\, 10^{15}\, GeV^{-1}}$
- $\mathbf{1\, sec = 1.5\, 10^{24}\, GeV^{-1}}$

Three examples are presented next which illustrate the use of this unit system:

Example 1: Scattering experiments have shown in the past that the radius of a nucleon is approximately $r_0 \approx 1.4\,fm$. Yukawa considered this to be the range of the interaction which holds the nucleon together. He then assumed that this interaction is mediated by a particle and was able to calculate the mass of this particle. Here is how he did it:

The mass of the mediating particle in GeV can be calculated from the interaction range as follows:

$$m \approx \frac{\hbar c}{r_0} = \frac{197.3\,MeV\;fm}{r_0} = \frac{197.3\,MeV\;fm}{1.4\,fm} = 140\,MeV$$

So by doing that he predicted the mass of the particle called pion, π , which in some models in the past has been used as the mediator of the strong interactions. This particle was eventually discovered in the late 40s at Bristol by Powell.

Example 2: In table 2 the coupling constant which measures the strength of the weak interaction is given by $G_F = 1.166\,10^{-5}\,GeV^{-2} \times (\hbar c)^3$ which in units of $\hbar = c = 1$ is given by $G_F = 1.166\,10^{-5}\,GeV^{-2}$. This can be used to compute the scale and the range of the weak interactions as follows:

The scale of the weak interaction is then given by:

$$\mu_W \sim \frac{1}{\sqrt{G_F}} \sim 10^2\,GeV \; .$$

From this the range of the weak interaction can be estimated using:

$$\lambda = \frac{\hbar c}{\mu_w} = \frac{0.1973\,GeV\;fm}{10^2\,GeV} \sim 10^{-18}\,m$$

Example 3: As discussed during class gravity is a very different interaction and this can be demonstrated also by computing the scale of gravity with similar arguments. The range of gravity is of course infinite since gravitons are massless.

The strength of the gravitational interaction is given by Newton's constant which is:

$$G_N = 6.67\,10^{-11}\,m^3\,Kgr^{-1}\,sec^{-2} = 6.67\,10^{-11}\,Jule\,m\,Kgr^{-2} \quad \text{(I1)}$$

However,

$$\mathbf{1}\,\boldsymbol{Jule} \;=\; \frac{\mathbf{1}\,\boldsymbol{eV}}{\mathbf{1.6\,10^{-19}}} \qquad \text{(I2)}$$

$$\mathbf{1}\,\boldsymbol{m} \;=\; \frac{\hbar\,\boldsymbol{c}\times\mathbf{10^{15}}}{\mathbf{0.1973}}\boldsymbol{GeV}^{-1} \qquad \text{(I3)}$$

$$\mathbf{1}\,\boldsymbol{Kgr}=\mathbf{5.6\,10^{26}}\frac{\boldsymbol{GeV}}{\boldsymbol{c}^2} \qquad \text{(I4)}$$

(I1)(I2)(I3)(I4) $\Rightarrow \; G_N \;\simeq\; 6.7\,10^{-39}\dfrac{\hbar\,c}{(GeV/c^2)^2}$

As before $\hbar \;=\; c \;=\; 1$ $\Rightarrow \; G_N \;\simeq\; 6.7\,10^{-39}\dfrac{1}{(GeV/c^2)^2}$

We then translate this to the scale of gravity:

$$\mu_G \;\sim\; \frac{1}{\sqrt{G_N}} \;\sim\; 10^{19}\,GeV$$

which is usually referred as Plank mass. This is interpreted to be the energy scale where Quantum Gravity effects become important. The length at which this happens can be estimated as:

$$\lambda \;=\; \frac{\hbar\,c}{10^{19}\,GeV} \;\sim\; 10^{-33}\,cm$$