Introduction

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Particle Physics today:

According to our current understanding the world around us is made of two categories of particles: Leptons and 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 four interactions in to a single 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 successful 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 into 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 . The electron is the lightest of the charged leptons and the τ-lepton the heaviest. Other than the different mass the properties of the different charged leptons are the same. The neutrinos also have different masses but otherwise have the same properties.

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 removes divergences 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, the tau-neutrino in 2000 and finally the Higgs Boson in 2012.

All 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 was discovered by the ATLAS and CMS experiments at the Large Hadron Collider (LHC) 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 was absolutely essential in demonstrating that the standard model is indeed a self consistent theory. In the past ten years ATLAS and CMS have studied the properties of the Higgs Boson and have conclusively proven that the discovered particle is indeed the Higgs Boson as predicted by the Standard Model. According to the Standard Model the Higgs couples to particles that have mass. Consequently since the Higgs is massive it can interact with itself. The interactions of Higgs with itself have not been studied yet and are the topic of future research. Also not predicted by the Standard Model is the mass of the Higgs or any of the other particle masses. Several theories have been proposed which would set upper bounds for the Higgs mass such as Supersymmetry. However, to this day no experimental evidence exist about their existence. Experimental physicists at CERN have planed upgrades to the LHC accelerator and the experiments with the purpose to increase the intensity of the proton beams of the LHC. This will allow the most detailed studies of the Higgs properties. This program is expected to commence in 2029. Further to the future a new accelerator has been proposed at CERN, the Future Circular Collider (FCC), which will have a circumference of about 100 Km and should be able to provide beams whose energy will be far higher than the LHC.

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, since 1998 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. A large number of experiments have been studying this topic throughout the world and more experiments are under construction aiming to measure the masses of the neutrinos as well as other important properties which are expected if the neutrinos have mass.

According to the standard model these particles interact with each other via the four known interactions. However, not all of them interact via all four 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. In quantum field theory, interactions are mediated by particles which are called for this reason mediators. Strong interactions are mediated by eight particles called gluons, g_i , with $i=1,\ 2,\ldots,8$. The mediator of electromagnetic interactions is the photon, γ , and the mediators of the weak interactions are the $W^{\pm}$ and the 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.

Apart from investigations on the origin of mass of the neutrinos or measurements of the Higgs particle properties, one other fundamental question is particle physics today is the question of matter-antimatter asymmetry. In other words why the world is made of particles and not anti-particles. One would have expected that in the early universe particles and antiparticles should have been produced in equal numbers and the question arises as to what happened to the anti-particles. It turns out that there is a theory which predicts this asymmetry but it requires that the combination of charge conjugation (transforms particles to anti-particles) and parity symmetries ($\vec{x}\rightarrow-\vec{x}$), the CP-symmetry, is violated. The standard model of particle physics can accommodate CP-violation but not enough to predict the matter-antimatter asymmetry that we observe in nature. In other words we don't know why the observed universe is made exclusively of matter and this is a question which attracts considerable interest in particle physics today.

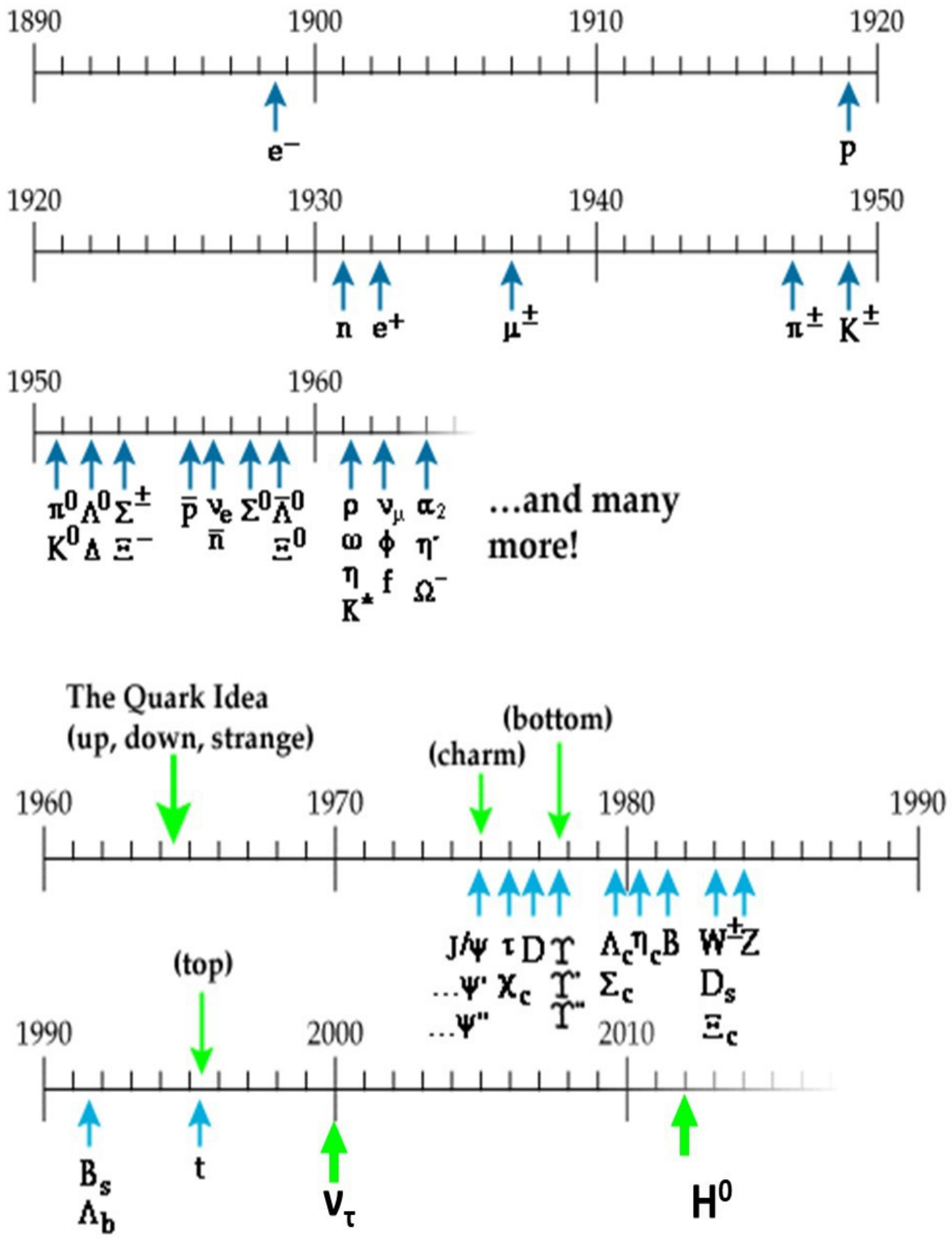

Figure 1: *The discovery dates of the most important particles in nature. Evidently progress was slow in the early dates of particle physics. Later on progress came in bursts separated by quiet periods of preparation for then next brake-through.*

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	-1/3	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.*

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^{-1}. When one converts from MKSA to this systems it is useful to remember that:

$$\hbar c = 0.1973\, GeV\ fm$$

where $1\, fm = 10^{-15}\, m$.

The cross-section unit in particle physics is: $1\, Barn = 10^{-28}\, m^2$ It is then easy to show that:

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

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 and Occhialini.

Example 2: In table 2 the coupling constant which measures the strength of the weak interaction is given by $G_F = 1.16610^{-5}\,GeV^{-2} \times (\hbar c)^3$ which in units of $\hbar = c = 1$ is given by $G_F = 1.16610^{-5}\,GeV^{-2}$. 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 and gravitons if they exist must be 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,

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

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

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

(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:

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

and it is called the Plank length.