Quantum Field Theory: What is a Particle? (Or at least, what I understand of it – so not much).

Quantum field theory (QFT) is a theoretical framework for particle physics. It combines work from classical field theory, special relativity, and quantum mechanics to construct a new model of subatomic particles.

That's nice and all, but a definition really isn't what Meeran was asking for, and is much too complicated for me to understand right now. What I'll do is turn on that fancy academic looking font and adapt the script for the SciSoc I did on the same topic, and BAM! Article.

There are a few things which you need to understand before you're able to define a particle, which ultimately is the goal of this… this. These things are.

- A description of vibrations (simple harmonic oscillators) and waves
- The same as above but considering quantum mechanics. i.e., a description of quantum vibrations and quantum waves
- A field, and like above a quantum field then relativistic quantum field
- And then finally what is a particle (at least according to QFT)

Greeks:

In my talks I spoke initially about the Greeks – specifically Democritus of Abdera. He was that guy who thought that atoms were just uniform, solid, hard, incompressible, indivisible, and indestructible spheres. They thought empty space was where there were none of these sphere things, and in a solid there were an infinite number of these sphery things. He was rather obviously wrong. Moving on: Hooke's Law!

Displacement and Energy of Simple Harmonic Oscillators and Quantum Oscillators:

Displacement of simple harmonic oscillators:

Hooke! You know that man? Yes. Hooke. For some reason a long time ago, he decided that it would be fun to investigate the properties of springs. I suppose, I ought to do the same thing.

Consider an unstretched spring, attached to a wall. The spring is of course smooth and has a mass m attached to the oposite end of the spring. Now imagine you pull the end of the spring a distance of x from it's original equilibrium position. there will be a restoring force, F, which acts oposite to the direction of the extension. The force F is proportional the extension, so you can write $F \propto -x$ or by making it an equality, . Newton told us that $\Sigma F = ma$, so we can substitute that in and arrive at the expression $a = -\frac{k}{m}x$. Anyone who is slightly familiar with simple harmonic motion should know it's conditions, i.e., acceleration is proportional to the negative displacement, which is exactly what we have here! How lovely!

Now, to understand the dynamics of springs, we need to know some theory. We can take Hooke's law and write it as a second order differential equation, which makes it far nicer to look at from a mathematical standpoint. You do this by writing the acceleration as the second derivative of displacement with respect to time, $\frac{d^2x}{dt^2}$. We can put this into our lovely equation we found earlier, and we get $\frac{d^2x}{dt^2} = -\frac{k}{m}x$. This simple equation describes how the displacement of a spring with spring constant k and mass attached m changes with time. Once we've done that, we ask ourselves 'what is the solution?'. Well, I shall tell you! How kind…

So again, imagine you had a spring with mass m on the end, displaced it, and let it move freely. Now imagine that you draw a graph of this, with the displacement on the y-axis and time on the x-axis. You'd recognise a lovely familiar curve! The cosine functions. therefore, we can write the displacement wrt time as proportional to the cosine of t. again writing it as an equality, we get $x(t) = Acos(\omega t)$ where A is the amplitude and omega is the angular frequency (measured in radians per second, i.e., $\omega = \frac{2\pi}{T} = 2\pi f$) hence $x(t) = Acos(2\pi ft)$

So now we have an answer for the displacement function, we ought to check whether it's correct. We can do this by substituting it into the differential equation we found earlier. The second differential of x(t) (acceleration) is $-\omega^2 A\, cos(\omega t) = -\omega^2 x(t)$. You can equate the two sides to find that $\omega = \sqrt{\frac{k}{m}}$ is the condition for our differential equation we found earlier to be correct.

From this you can simply find out the frequency and time period of harmonic oscillators, namely $f = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$ and $T = 2\pi\sqrt{\frac{m}{k}}$.

Energy of simple harmonic oscillator:

Next, let's try to work out the energy of our harmonic oscillator. To find the total energy, we can sum the potential energy ($\frac{1}{2}kx^2$) and the kinetic energy ($\frac{1}{2}mv^2$):

$E_T = E_K + E_P = \frac{1}{2}mv^2 + \frac{1}{2}kx^2 = \frac{1}{2}m\left(\frac{dx}{dt}\right)^2 + \frac{1}{2}kx^2 = \frac{1}{2}m\omega^2 A^2 sin^2(\omega t) + \frac{1}{2}kA^2 cos^2(\omega t)$ and since $k = m\omega^2$, $E_T = \frac{1}{2}m\omega^2 A^2[sin^2(\omega t) + cos^2(\omega t)] = \frac{1}{2}m\omega^2 A^2 = 2\pi^2 f^2 A^2 m$ i.e. $E_T \propto f^2 A^2$

. We just found that the energy of a classical harmonic oscillator, $E_T = 2\pi^2 f^2 A^2 m$. This shows that the energy of this oscillator is proportional the frequency squared multiplied by the amplitude squared. Nice!

Quantum Oscillators:

One of the largest changes to modern physics started during the early 20th century. Previously, people believed that energy was on a continuous spectrum, however Max Planck suggested that rather than it being a continues quantity, it was rather discrete. He suggested that in an oscillating system with frequancy f, the energy could only ever take integer multiples of f times Planck's constant. i.e., $E_n = nhf$. In the case of a quantum framework, n refers to the number of 'quanta of oscillation' in the system. Adding more quantum increases the total energy of the system, for example increasing n by one (adding on more quanta) causes the total energy to increase by hf.

This was a pretty big deal. Not only did this have profound consequences for quantum physics, but it also helped solve the ultraviolet catastrophe, and was used by Einstein to explain photoelectric emission. That's nice and all, but how does it apply to our nice simple harmonic oscillator? Well, it dictates that the system can no longer have any amplitude, however it can be allowed to have certain discrete values for its amplitude.

To see this in action, we can combine the total energy of a classical oscillator with Planck's expression for the quantum energy. When equating these ($nhf = 2\pi^2 f^2 A^2 m$), we can see that the amplitude of the quantum oscillator, $A = \frac{1}{2\pi}\sqrt{\frac{2nh}{mf}}$. Therefore, we see that, dependant on the integer values of n, both the energy and amplitude of a quantum oscillator can only take certain discrete values.

It's important to note that, though this all has a lot of implications on small scales, you won't notice this in real life. if you imagine a 100 g mass oscillating at a frequency of 1Hz, the difference between each allowed amplitude will be 1.8×10^{-17}. that's ten million times smaller than the diameter of an atom, so I don't think you'll be noticing it… to us at least, the system seems to be continued since the system is (comparatively) so large.

At the moment, we haven't considered the full story. In a way, we've minorly (extremely majorly) simplified the problem. We still have the lovely uncertainty principle to consider! Yay! Going a bit further, we can rewrite the kinetic energy in terms of momentum.

According to the uncertainty principle, as you have all most likely heard, there's a fundamental limit on how accurately you're able to know the position and momentum of a system. This inherent, unavoidable uncertainty is denoted with the famous expression $\Delta x \Delta P \geq \frac{\hbar}{2}$. Where $\hbar$ is the reduced Planck constant ($\hbar = \frac{h}{2\pi}$).

For our oscillating system, if Δx represents the uncertainty in the position of the spring, and ΔP represents the uncertainty in the momentum of the spring. According to classical physics, if the spring was at rest and unextended, then the uncertainty in both the location and momentum of the spring Is zero. Therefore, the total energy of the spring must be zero as shown by the total energy expression at the top by setting p and x equal to zero. However, according to the uncertainty principle, it's not possible for either the Δx nor ΔP to be zero, therefore there is always an inherent quantum motion of the spring, somewhat causing it to jitter around, even when unextended and at rest (in the classical terms).

We can work out an expression for the total uncertainty in the energy of the system by substituting Δx and ΔP into the expression we had earlier ($\Delta E \geq \frac{\hbar^2}{8m\Delta x^2} + \frac{1}{2}m\omega^2\Delta x^2$). To minimise the uncertainty, we differentiate ΔE wrt Δx and set it equal to zero. i.e., $\frac{d(\Delta E)}{d(\Delta x)} = -\frac{\hbar^2}{4m(\Delta x)^3} + m\omega^2\Delta x = 0$ which gives us the relationship for the position uncertainty, $\Delta x = \sqrt{\frac{\hbar}{2m\omega}}$. How delightful!

By taking this result and substituting it back into the energy uncertainty relationship and simplifying, we find $\Delta E \geq \frac{1}{2}hf$. This therefore implies that the minimum energy of a harmonic quantum oscillator is equal to $\frac{1}{2}hf$. This minimum quantum energy, called the zero point energy, is a super important result in QM! For our model, we therefore need to change the Planck's quantum energy expression s.t. the minimum energy instead of being 0 is $\frac{1}{2}hf$./ by factoring in this zero point energy, we find that the total energy of a quantum oscillator, $E_n = \left(n + \frac{1}{2}\right)hf$. Importantly, the energy required to add one quantum of oscillation is still hf as was before.

So after doing all of that, we're going to ignore it! Generally, this shift is so small that it doesn't need to be considered, however it is actually very important and lies at the centre of a very large unsolved mystery, the *cosmological constant problem*.

Displacement and Energy of Waves and Quantum Waves:

Displacement of Waves:

Now that we've looked at all of those oscillator things, it's time to consider some waves. As from A level physics, a wave can be considered as a propagating disturbance – a way of transferring energy and information without transferring matter. In classical physics, waves are categorised as either mechanical or electromagnetic. The main difference is that mechanical ones require a medium to travel though, however electromagnetic waves don't.

The displacement of a wave in the y direction can be described as a function of displacement in the x direction and time, t using this handy expression $y(x,t) = A\cos(kx - \omega t)$. In this expression, k is the wave number and describes the special frequency of the wave, $k = \frac{2\pi}{\lambda}$.

Note if we consider a fixed value of x, the displacement equation reduces to the displacement function of an SHO – like this, you can consider a wave as a series of coupled harmonic oscillators.

Similarly, to earlier with the displacement function for a harmonic oscillator being the solution to a differential equation, the displacement function for a wave propagating through space is also a solution to a differential equation – the wave equation ($\frac{\partial^2 y}{\partial t^2} = v^2 \frac{\partial^2 y}{\partial x^2}$). The wave equation is a second order partial differential equation for both space and time derivatives and contains information about the velocity of the wave too.

Just like earlier, we can test that our function for the displacement of a wave in the y direction $y(x,t)$ is a solution by substitution. By differentiating $y(x,t)$ twice wrt time and space respectively, we find that $\frac{\partial^2 y}{\partial t^2} = -\omega^2 y(x,t)$ and $\frac{\partial^2 y}{\partial x^2} = -k^2 y(x,t)$. By combining the two, we get the expression $\omega^2 = v^2 k^2$ which reduces to $v = f\lambda$. A coincidence? No, but it is nice to see such a famous equation popping up.

It's relatively important to note that for any system, the wave equation products that wall waves must travel at the same speed, (in this case v). From what we will now call the constraint equation for class 0 waves ($v = f\lambda$) (a class zero wave is one which follows the wave equation $\frac{\partial^2 y}{\partial t^2} = v^2 \frac{\partial^2 y}{\partial x^2}$)

Consider the following modified wave equation with a linear term in y added on the end. (this shall be used to describe class 1 waves). $\frac{\partial^2 y}{\partial t^2} - v^2 \frac{\partial^2 y}{\partial x^2} = -(2\pi\chi)^2 y$. Hopefully, the reasoning behind this should become clear soon. To find out what's happening when we do this, we can substitute the function $y(x,t)$ into our fancy new wave equation. From that, we obtain the expression $\omega^2 - k^2 v^2 = 4\pi^2\chi^2$. Substituting in definitions for ω and k, we arrive at this; $f^2 - \frac{v^2}{\lambda^2} = \chi^2$. Rearranging for f, we get $f = \sqrt{\frac{v^2}{\lambda^2} + \chi^2}$. This should make sense, right? when we set chi (χ) equal to zero, we retain the original wave equation for class 0 waves, and more importantly the original constraint equation for those kinds of waves, $v = f\lambda$. However if χ is non-zero, a new constraint on f appears; $f \geq \chi$ since $\frac{v}{\lambda} \geq 0$. In other fore nice works, χ represents the minimum possible frequency of the wave. i.e., by adding and modifying the wave equation with a linear term in y, $-(2\pi\chi)^2 y$, we put a lower limit on the frequency of the wave permitted by the equation. From now on, we can write the modified wave equation explicitly in terms of the minimum frequency f_{min} instead of χ.

Energy of Waves:

To continue our journey, next let's try and calculate the energy of a wave. In order to do this, consider a rope of mass per unit length μ which has a series of transverse waves sent down it. We'll focus on a very small length of the rope, with length in the x direction of dx. Because the wave is transverse, the displacement of the rope will always be at 90 degrees to the direction of wave propagation. Therefore, the small section of the rope will move upwards and downwards in the y direction, but not change in the x direction. We can consider the velocity in the y direction of the rope to be v_y. The kinetic energy within this section of rope can easily be calculated. It can be writen by $dE_K = \frac{1}{2} dm v_y^2$ which can further be simplified (?) to $dE_K = \frac{1}{2}\mu A^2\omega^2 \sin^2(kx - \omega t)dx$

To calculate the total energy, obviously you also need to consider the potential energy. This can be done by again considering a small section of the rope. The potential energy can be calculated as the work done as the rope stretches. Therefore dE_P equals the force times the extension. If dx represents the length of the unstretched rope, then the extension of the rope can be approximated as the difference between ds and dx. Therefore, we achieve the expression $dE_P = T(ds - dx)$ where T is the tension acting on the small section of rope. Furthermore, this can be writen as $T(\sqrt{dx^2 + dy^2} - dx)$. By taking out a factor of dx from the square root, we get $dE_P = Tdx\left(\left(1 - \left(\frac{dy}{dx}\right)^2\right)^{\frac{1}{2}} - 1\right)$. Since the section of rope is small, you can preform a binomial expansion on the square root to remove it from the equation. The square root from the previous equation can be approximated as $1 + \frac{1}{2}\left(\frac{dy}{dx}\right)^2 + \cdots$ where higher orcer terms than $\left(\frac{dy}{dx}\right)^2$ can be ignored since they're so small. After doing all of this, you're finally able to write the potential energy of the section of the rope as $dE_P = \frac{1}{2}T\left(\frac{dy}{dx}\right)^2 dx$. Again, substituting in the wave expression $y(x,t)$ we used earlier, the potential energy can be writen as $dE_p = \frac{1}{2}Tk^2A^2\, sin^2(kx - \omega t)\, dx$. Perfect!

So finally, we can sum the potential and kinetic energies to get the total energy in the small section of rope $dE = \mu\omega^2A^2\, sin^2(kx - \omega t)\, dx$. Note this is only in the length dx, so to calculate the distance for a whole wavelength, you integrate dE between 0 and λ, however you don't only integrate this – naturally you need to integrate it like a pro! After integrating, you find $E_\lambda = \frac{1}{2}\mu\omega^2A^2\lambda$ and as always, we substitute definitions of ω and λ to get $E_\lambda = 2\pi^2f^2A^2\mu$. Interestingly, you can note that the energy contained within a wavelength of a wave is proportional to the product of the frequency squared and the amplified squared, as was the case earlier with our simple harmonic oscillator. of course, this isn't only valid for ropes. It holds true for all waves regardless the medium through which they travel. After that, the obvious question to consider is 'if harmonic oscillators and waves obey the same relationship, is the same true when quantum mechanics is taken into consideration?'

Quantum Waves:

As was said earlier, since a wave is nothing but a series of simple harmonic oscillators, it would follow that the properties of a quantum wave are extremely similar to those of a quantum oscillator as found earlier. Specifically, we would expect the energy of a quantum wave to be expressed using Planck's constant multiplied by the frequency as shown earlier with the zero point energy, $E_n = \left(n + \frac{1}{2}\right) hf$ where n is the number of quanta of oscillation contained in the wave.

So… let's do that! Consider a long wave of length L meters, with wavelength λ. Obviously, it will have $\frac{L}{\lambda}$ crests. Because of this, you're able to write the energy in the wave within that specified region of length L using the equation $E_L = E_\lambda \left(\frac{L}{\lambda}\right) = 2\pi^2 f^2 A^2 \mu \left(\frac{L}{\lambda}\right)$. Since we're considering a large wave, we can approximate this equal to nhf as for a large system as said earlier, the zero point energy (the $\frac{1}{2} hf$) can be ignored. So after all of that, rearranging the earlier expression for the amplitude A, we get the equation A $\approx \frac{1}{2\pi}\sqrt{\frac{2nh\lambda}{fL\mu}}$. This shows that the allowed values of A must be proportional to the square root of n, and the energy must obviously also be proportional to n.

So, for a quick summary of all of that information:

Class 0 waves, relating to the unmodified wave equation ($\frac{\partial^2 y}{\partial t^2} - v^2 \frac{\partial^2 y}{\partial x^2} = 0$) have the constraint equation $v = f\lambda$

For class 0 waves, the frequency can be anything therefore the energy of the wave can take any value, implying that a quantum of this wave also takes any energy instead of discrete energy levels. This means if you have a super small amount of energy avaiblae for the system, it's still possible to make a quantum of this kind of wave assuming the frequency is low enough since $E = hf$

Class 1 waves, relating to the modified wave equation ($\frac{\partial^2 y}{\partial t^2} - v^2 \frac{\partial^2 y}{\partial x^2} = -(2\pi\chi)^2 y$) have the constraint equation $f = \sqrt{\frac{v^2}{\lambda^2} + f_{min}^2} \geq f_{min}$

For class 1 waves, with quantum mechanics taken into consideration, a lower bound is placed on the frequency which in turn places a lower bound on the energy that a quantum of this type of wave can have. Particularly, we see that $E_{min} = hf_{min}$. In extension, it shows that if the energy available is less than f_{mim}, then you're unable to make a single quantum of this wave.

Fields, Quantum Fields and Quantum Relativistic Fields:

We've actually been dealing with fields for a while (if anyone has actually been reading this). You know that function y which we had earlier? Well, $y(x, t)$ *is* a field!

Fields. According to the google, a field is a physical quantity, represented by a number or another tensor, that has a value for each point in space and time. (Yes, I copied that directly. No, I shall not be referencing it.) This is a perfectly correct definition, but... kind of scary, so here is a nice and non-scary one! It's a function of space and time where each point has a related equation of motion which describes how the function changes with time. There are a few different kinds.

Vector and Scalar Fields:

Scalar fields are ones where each point in space has a number or attribute assigned to it. Consider the example where you measure the temperature for every square centimetre in a room with a hot metal rod in the middle. You could then draw a temperature field of this, by assigning a number to every point in this room. To make it easier to see, you can also add a colour gradient! Quite impressive.

Another important kind of field is a vector one. This is where both a number and direction are assigned to each point in space. An example of this is maybe the electric field, or possibly a wind one. They can be drawn where each point has an arrow corresponding to it. The direction of the arrow noting… the direction, and the size denoting the magnitude. This field would update around if something in the field were to change (for example a charge moving).

Some other examples of ordinary fields, describing ordinary stuff (all class 0 fields) include arrangement of atoms in a magnet, speed of the wind, temperature field, weight of water on a river and many, many more. For each of *these* fields, there is a medium. The field is not to be confused with the medium (seems rich me saying 'not confused' given that this is the most confusing article thing I've ever read, and I'm the one who wrote it…) In these cases, the field merely describes and characterises one of the many properties of the relevant medium.

Quantum Fields and Relativistic Quantum Fields:

Note: I feel like I didn't explain this well enough, and I can't really be bothered to look to see where I should fit it in, so I'll do it here. The difference between an ordinary field and a relativistic field. An ordinary field has a medium. All of the ones covered above, the wind and temperature field all have mediums. Soon (literally next paragraph), we will see a field with no medium (spoiler, the EM field). *This* is a relativistic field since there is no medium. Reiterating, relativistic fields do not describe a property of some ordinary physical medium that is made from anything resembling ordinary matter. As far as we know experimentally, they don't describe the property of anything at all. These fields (relativistic ones), as far as we know, are among the fundamental elements of the universe. That is a fine however very important distinction which as I said I didn't at all make clear.

Maxwell decided to combine the wave equation with his (not his?) electricity and magnetism equations. After doing some fancy (scary) maths, he got this equation; $\frac{\partial^2 \vec{E}}{\partial t^2} - c^2 \frac{\partial^2 \vec{E}}{\partial x^2} = 0$ where $c = \frac{1}{\sqrt{\mu_0 \varepsilon_0}} = 3.0 \times 10^8\ ms^{-1}$. Hopefully this should look pretty familiar. It's the same as the wave equation, but with the electric field instead of $y(x, t)$. This nice equation predicted that the speed of an electromagnetic wave should be 3,000,000 ms^{-1}. Remarkably, this result matched the recently (then – not now) measured speed of light to a much high accuracy. This led people (physics people presumably) to believe that light itself was an electromagnetic wave!

Of course, people went around asking mean and horrible questions which I'm sure Sam Caschetto would be answer with ease – relating of course to special relativity. (Going on a bit of a tangent here). They asked, 'relative to which frame of reference is it measured to be this speed', and Einstein came along with the *RADICAL* theory of special relativity to answer it saying all observers measure the same speed of light, irrespective of their frames of reference. This of course means that different observers measure the actual passage of time differently according to the relative speed with which they travel. Furthermore, Einstein predicted that light, and all electromagnetic waves, are able to travel through a perfect vacuum with *no medium* (woahhhhhhhhhhh) to support them. Because of these features, you can describe EM waves as a 'self-propagating ripple in an underlying relativistic field, namely the electromagnetic field' (more on that later, maybe if I remember).

So, having just looked at the electromagnetic field, and seeing that that is a class 0 wave with no medium, you might ask the question (which I've been asking myself for much, much, much time); what's the difference between the class 0 and class 1 wave equations? Well I *think* that maybe I possibly can probably hopefully answer that question now. First though, I'll ask you a question: what is light? Well you might say a photon, and that would be correct. A photon, a *massless* particle (that massless bit is important, so don't forget it). Now we've got that massless thing out of the way, I can answer the question which I asked myself (?) (about the difference between class 0 and 1 wave equations).

(Answering that now!). The EM field isn't the only kind of relativistic field. There are two main kinds. These refer to the unmodified (class 0) and modified (class 1) wave equations we looked at earlier ($\frac{\partial^2 \Psi}{\partial t^2} - c^2 \frac{\partial^2 \Psi}{\partial^2 x} = 0$ and $\frac{\partial^2 \Psi}{\partial t^2} - c^2 \frac{\partial^2 \Psi}{\partial^2 x} = -(2\pi f_{min})^2 \Psi$ respectively, where Ψ is a relativistic field, dependant on space and position ($\Psi(x,t)$). Both of these relativistic wave equations describe waves which carry information and energy without a physical medium for the wave to pass through. Surprisingly, as far as we (they) can tell at least, it's possible for these relativistic fields to be one of the truly fundamental pieces of the universe. Back to the question at hand…

Mass(y?) particles: These are related to the class 1 wave equation $\frac{\partial^2 \Psi}{\partial t^2} - c^2 \frac{\partial^2 \Psi}{\partial^2 x} = -(2\pi f_{min})^2 \Psi$ (again, where Ψ is a relativistic field). This wave equation has the constraint equation $f^2 = \frac{c^2}{\lambda^2} + f_{min}^2$. This constraint equation is very important. Multiplying each term by Planck's constant squared, you get

$$h^2 f^2 = \left(\frac{hc}{\lambda}\right)^2 + h^2 f_{min}^2$$

This equation looks extremely similar. It should (but probably won't) remind you of the energy momentum relationship

$$E^2 = p^2c^2 + (mc^2)^2$$

By this, it is tempting to equate terms.

- By equation the second terms terms you get $p^2c^2 = \left(\frac{hc}{\lambda}\right)^2$, which shows the de Broglie relationship $\lambda = \frac{h}{p}$

- And by equating the last terms, you get $(mc^2)^2 = h^2 f_{min}^2$ which implies $m = \frac{hf_{min}}{c^2}$. This is very important also! It shows that what we would consider mass is actually the smallest energy of a relativistic quantum field divided by the speed of light squared! Swell!

Massless particles: These are related to the class 0 wave equation $\frac{\partial^2 \Psi}{\partial t^2} - c^2 \frac{\partial^2 \Psi}{\partial^2 x} = 0$. This wave equation has no constraint on the frequancy, so there is no minimum frequency as in $f_{min} = 0$ therefore $m = 0$. Hence this related to massless particles (this is what you'd expect. It explains why photons, which are quanta of the EM field have no mass as said earlier (further backed up since light is perfectly modelled by the modified wave equation)).

As the constraint equation we got from class 0 was $f = \frac{c}{\lambda}$, we can again multiply by Planck's constant as we did earlier and do some things… (getting $hf = \frac{hc}{\lambda}$)

- This $hf = E = \frac{hc}{\lambda}$ should also look pretty familiar – it's the famous (apparently) relationship which is used to describe the photoelectric effect.
- If we set $m = 0$ in the energy momentum relationship, we get $E^2 = p^2c^2$ which leads to $E = pc$ – the familiar energy-momentum relationship for massless particles! That's convenient.

The answer to the actual damn question: (damn isnt a swear word, right?)

Well after all of that absolutely lovely maths and not maths, I think we're finally in a position to understand what a particle is according to quantum field theory. It should hopefully (but probably not since I'm so bad at explaining things) be relatively obvious at this point – we've already looked at what a photon is, and I just spend much time talking about mass and massless particles. The 'simple' definition is what lies right at the heart of the standard model. Within this nice standard model, it's the relativistic quantum fields which are the truly fundamental, and only the quanta of these relativistic quantum fields which are the particles themselves (so the particles =/= fundamental! (Someone should probably change the name from fundamental particle to something less false – like normal particle or something)).

Again, a particle is only the smallest possible vibration/ripple (a quanta) of a relativistic quantum field, with particles of mass satisfying the class 1 equation, with massless particles satisfying the class 0 equation

For example, the smallest vibration in the electron field is called an electron, a quanta of the electromagnetic field is called a photon, and the same is true for quarks, bosons, fermions, and all other fundamental particles. In the end, every single fundamental particle in existence is just a ripple in a more fundamental underlying relativistic quantum field. Noice! I'm going for a snooze.

Final Word Thing:

This is a nice and simple version of stuff; things in the real world are far more complicated and less nice. There are these dodgy things called path integrals which I haven't touched, and **much** less hand-wavey ways of dealing with QFT like Feynman diagrams and much, much more, but hopefully I've done a good enough job at explaining what a particle is.. maybe… :thumbsup: