Boson Ideas to Do:

1. What is a Boson?
    a. Spin
    b. Properties
    c. Interactions
2. How do they it fit into the Standard Model?
3. Feynmann Diagrams
    a. Explanation on reading them.
    b. What do they describe?
    c. How are they useful?
4. Virtual Particles
    a. What are they?
    b. How do they relate to bosons?
5. Higg's Mechanism
    a. How does it give bosons mass?
6. Different Quantum Mechanics Theories in relation to bosons.
    a. Quantum Field Theory (QFT)
        i. What is it?
        ii. Prospects of being correct
        iii. Prediction capabilities
    b. String Theory
        i. What is it?
        ii. Prospects of being correct
        iii. Prediction capabilities
7. Unifying QFT and General Relativity
    a. Why is it necessary?
    b. Gravitons
    c. How does general relativity break down at small scales?
    d. What would a unifying theory look like?

1. What is a boson?

The boson is a group of fundamental particles that are integral to our understanding of quantum mechanics. It is a group of subatomic particles that are responsible for the interactions between other subatomic particles known as fermions. An unlimited number of bosons can occupy the same quantum state unlike fermions. Fermions are the subatomic particles that make up the matter in the universe. "Bosons (named for the 20th-century Indian

physicist Satyendra Nath Bose) include the particles responsible for all the interactions between this matter" (Watson, 2013, Page 1). The fundamental forces of our universe such as the electromagnetic force, the strong force and the weak force all have bosons that carry their force. For example, the photon is the carrier of the electromagnetic force, the gluon is the carrier of the strong force, and the W&Z bosons are the carriers of the weak force, these are called the vector bosons or gauge bosons. A gauge boson is the quanta of a gauge field according to QFT. A boson is a subatomic particle which has a spin of a whole number. This spin is a multiple of a constant known as the reduced Planck constant also known as $\hbar$ (hbar). This reduced Planck constant has a value of 1.0546 x 10^{-34} joule seconds (J s), which is the Planck constant divided by 2π. The spin of an elementary particle refers to its intrinsic angular momentum. The main difference between bosons and fermions is their spin which gives the particles different properties. While bosons have a spin of a whole number including zero, fermions have spin of multiples of a half ($\frac{1}{2}, \frac{3}{2}, \frac{5}{2}$ ...). The four vector bosons have a spin of 1. A theorized boson known as the graviton is the supposed carrier of the gravitational force. The graviton is theorized to have an integer spin of 2. Unlike the four vector bosons the graviton has never been proven to exist and currently exists only in theory. Also, unlike the other four bosons, the graviton is known as a tensor boson. This is discussed further in section 7. Unlike the other bosons, the Higgs boson is known as a scalar boson and has a spin of 0. The Higgs boson is the quantised manifestation of the Higgs field, which gives other fundamental particles mass through their interactions with this field. This is discussed further in section 5.

2. What is the Standard Model of particle physics?

The Standard Model of particle physics describes three of the four fundamental forces (all but gravity) and classify all known elementary particles. The Standard Model is an example of a quantum field theory and uses fields to describe the interactions of different elementary particles via mediation of the gauge fields and their respective gauge bosons and a scalar field known as the Higgs field and its respective scalar boson known as the Higgs boson. The Standard Model is built upon the gauge symmetries of QFT and is defined by the built-in symmetries SU(3) x SU(2) x U(1). Where U(1) is the gauge symmetry that is inherently similar to electromagnetism. SU(2) is the gauge symmetry that leads to the interactions of the weak field. SU(3) is the gauge symmetry that leads to the interactions of the strong field. These symmetries arise from the ability to distort the wave function in such a manner that it does not affect the fundamental laws of the universe.

In the paper Gaillard, M.K., Grannis, P.D. and Sciulli, F.J., 1999. The standard model of particle physics. Reviews of Modern Physics. The authors describe the interactions of electrically charged particles as the exchange of quanta of the electromagnetic field called photons. These photons are massless and thus explain the long range of the electromagnetic force. The photon is described by QED (quantum electrodynamics). The authors also state that the strong force is mediated via the exchange of gluons between quarks that carry a quantum number of charge. This charge is referred to as colour by physicists. Since gluons possess this colour charge, they couple to one another. The colour force between two coloured particles increases in strength as the distance increases. Thus, quarks and gluons cannot appear as free particles and only exist inside composite particles known as hadrons. An example of a hadron is a proton. They state that the weak force is mediated by the charged W bosons and the neutral Z boson. These bosons are responsible for the radioactivity of matter. The W and Z bosons have mass with the Z boson being the heaviest. This mass is acquired via the interactions of the weak field with the Higgs field. Since these bosons interact with the Higgs field they cannot propagate at the speed of light. $W^{\pm}$ bosons only interact with left-handed particles and right-handed antiparticles. The Z boson can interact with both left-handed particles and right-handed antiparticles. Left-handedness of fermions is when the spin orientation is opposite to the direction of motion. The authors explain that the W and Z bosons and the photon are grouped together and collectively mediate electroweak interactions.

Currently, the Standard Model does not explain gravitational interactions, although the theoretical particle known as the graviton, if proven to exist, could unite the Standard Model and Einstein's theory of general relativity.

$$L = -{}^{1}/_{4}\, F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + hc + \overline{\psi_i}y_{ij}\psi_j\phi + hc + |D\mu\phi|^2 - \mathrm{V}\,(\phi)$$

The Standard Model Lagrangian is the overall equation used to describe the elementary particles of the Standard Model and their interactions with one another. The Standard Model Lagrangian is a Lagrangian density rather than a full Lagrangian. It includes all the gauge symmetries the Standard Model is built upon. The Standard Model Langrangian does not explain dark energy or the matter-antimatter imbalance of the universe but is used to model the behaviour and interactions of elementary particles with a high degree of accuracy.

5. The Higg's Mechanism

Originally when the fundamental theory of the Standard Model was formulated. The bosons of the weak force were theorised to be massless. Later, experiments showed that the $W^{\pm}$ and Z bosons were massive. This accounts for the short range of the weak force. Peter Higgs proposed the idea that another field was interacting with the respective fields of the fermions and the W and Z bosons giving them mass. If the Higgs boson could be found it would imply the existence of the Higgs field. The Higgs boson was discovered in CERN by the LHC in 2012 by two experiments simultaneously, ATLAS and CMS. This proved Higgs' Theory to be correct and he was awarded the Nobel Prize in Physics in 2013.

How does the Higgs mechanism give particles mass?

The Higgs field has what is called a "Mexican Hat" potential. This is where the lowest energy state is not centred around the point in which the field strength is zero. This is called a non-zero vacuum expectation value. Oscillations in this field can occur in different directions. It can oscillate up and down a valley moving closer and further from the point in which the field strength is zero. This oscillation is the Higgs boson. Another oscillation can occur radially around the point where the field strength is zero and it occurs in the lowest energy state. This oscillation gives rise to a Nambu-Goldstone boson. This boson is massless and is not a gauge boson since the location in the potential represents a different field state.

This Nambu-Goldstone boson is "eaten" by the U(1) symmetry in the U(1) x SU(2) symmetries.

> Spontaneous breaking of gauge symmetry was introduced into particle physics in 1964 by Englert and Brout, followed independently by Higgs and subsequently by Guralnik, Hagen and Kibble. They demonstrated how one could dispose simultaneously of two unwanted massless bosons, a spinless Nambu–Goldstone boson and a gauge boson of an exact local symmetry, by combining them into a single massive vector boson in a fully relativistic theory. The two polarisation states of a massless vector boson

> are combined with the single degree of freedom of a spin-zero particle to yield the three degrees of freedom of a massive spin-one particle. (Ellis, J., Gaillard, M.K. and Nanopoulos, D.V., 2016. A historical profile of the Higgs boson. *The standard theory of particle physics*, pp.255-274.)

When applying the full symmetries of the electroweak interaction or U(1) x SU(2). Three Nambu-Goldstone bosons arise from different oscillations in the potentials of the fields. These Goldstone bosons are "eaten" by the bosons of the electroweak interaction. Since only three Nambu-Goldstone bosons arise from the oscillations and there are four bosons in the electroweak interaction. Only three bosons receive mass from these Goldstone bosons, those bosons being the bosons of the weak force, the $W^{\pm}$ and Z bosons. This explains why the bosons of the weak force are massive. The Higgs field permeates all of space but only fermions and the bosons of the weak force couple to it and thus gain mass.

Although the Higgs mechanism is responsible for the mass of the fundamental particles the majority of the mass of a hadron comes from the energy of the strong force within the hadron holding the quarks together. This means that the majority of the mass in atoms comes from the strong force and not the Higgs mechanism. The Higgs mechanism is still incredibly important as without the Higgs field the electron would be massless and thus the radius of the orbit of the electron around the nucleus would be infinite and the elements of the universe would not exist.

6b. String Theory

What is it?

> String theory replaces point particles by strings, which can be either open or closed (depends on the particular type of particle that is being replaced by the string), whose length, or string length (denoted ls), is approximately 10^{-33}cm. (Wray, K., 2011. An introduction to string theory.)

A brief overview of String Theory is that it is an alternative theory to QFT and aims to describe the same characteristics of Quantum Mechanics in a different and more accurate manner than QFT. It describes the different fundamental particles of the universe as vibrating one dimensional string that exist in multi-dimensional space and oscillate with different frequencies. These strings can be closed loops or open. String Theory requires that there is at least an additional six dimensions or even up to an extra twenty-two dimensions in the universe for the mathematics to work. These different modalities of the strings lead to the different elementary particles and the bosons. It was originally created to describe the strong force that holds a hadron together, but QCD provides a more accurate description of the strong interactions. In general, QFT has a higher degree of accuracy than string theory and is more in line with experimental observations.

Why is string theory attractive?

String Theory has the capability to quantise gravity as it has the ability to predict the existence of a massless spin 2 boson which is the theorized characteristics of the graviton. This is incredibly attractive to physicists as the ability to unify QM with General Relativity would be a massive breakthrough in physics. The issue that QFT has that String Theory over comes is that in QFT when quantising gravity infinities occur which highlight the incompletion of the theory. A common analogy for the issue is, imagine spacetime as the canvas in which the different fields of QFT are painted upon. Together they create a beautiful painting. Imagine then you try to turn the canvas itself into paint, then all of a sudden, the whole painting falls apart. This is the main attractive point to string theory it avoids this complication and has the ability to quantise gravity but in order to do so requires these extra undetectable dimensions.

The main issue with ST:

ST requires that these extra dimensions exist but if they do where are they? Physicists have found no experimental evidence to prove the existence of any extra dimensions other than the four that make up our universe. Advocates of ST came up with solutions to this issue and one of those solutions is compactification. Compactification is that these extra dimensions exist at such a small scale it is impossible to detect them with our current level of technology and if only physicists could examine the universe at an extremely close scale these compacted dimensions would become detectable. This leads to the main problem with ST. ST has the ability to quantise gravity but all the predictions and calculations done with ST are either incorrect or inaccurate. The prediction capability of ST is null in comparison with QFT. QFT currently is the most accurate description of the universe as its predictions and calculations agree with experimental results with a high degree of accuracy.

References:

Watson, G. and Higgs, P, (1998) “*What is a boson?*.”

Gaillard, M.K., Grannis, P.D. and Sciulli, F.J., 1999. The standard model of particle physics. *Reviews of Modern Physics*.

Ellis, J., Gaillard, M.K. and Nanopoulos, D.V., 2016. A historical profile of the Higgs boson. *The standard theory of particle physics*.

Wray, K., 2011. An introduction to string theory.