<u>What is the Higgs boson and why was its discovery so important?</u>

Introduction:

Nicknamed the “God particle” by Leon Lederman, the Higgs boson captured the world’s attention – it was a media sensation, and its discovery is one of the greatest of the 21st century.

Particles gain their mass from the Higgs field – the fundamental field associated with the Higgs boson; a particle proposed by Professor Peter Higgs which was discovered on July 4th in 2012 at the Large Hadron Collider at CERN.

Not only does the discovery of the Higgs boson give us a deeper understanding of our universe, but many societal benefits have come as a result of the technology developed during the discovery of this fundamental particle. In addition to this, the Higgs boson could be used as a tool for future discovery and could play a key role in detecting dark matter, amongst other things.

Literature Review:

Professor Peter Higgs

In 1964, Peter Higgs proposed that there was an energy field, now referred to as the Higgs field, that permeated the entire Universe. He proposed this field since no one could understand why some subatomic particles had a great deal of mass, while others had little, and some (e.g. photons) had none. This proposed field would interact with the subatomic particles and would give them their mass. Very massive particles would interact a lot with the field, while massless particles wouldn’t interact with the field at all.

In addition to Peter Higgs, many other scientists contributed to both the theory behind the Higgs boson and its experimental discovery. These include François Englert and Robert Brout, as well as many working at ATLAS at the time of the Higgs’s discovery.

For this essay, industry professionals Victoria Martin and Paul Kirk have been interviewed and their insights are quoted throughout.

Victoria Martin

Victoria Martin is a professor at the University of Edinburgh, currently interested in understanding more about the Higgs boson and its relationship to other fundamental particles. Martin works on the ATLAS experiment at the Large Hadron Collider at CERN – which is the world's largest particle collider, where the Higgs boson was discovered, and has given valuable insights, through an interview held on the 16th of August 2024, which are reported on in this essay.

Paul Kirk

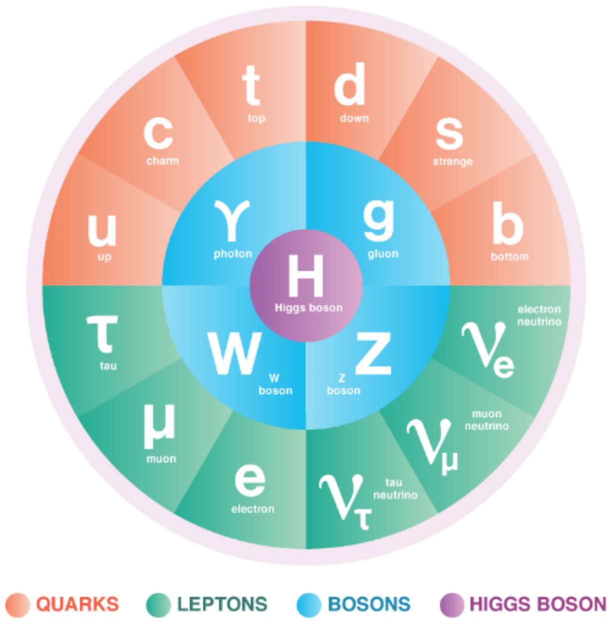
Paul Kirk works at Ørsted Wind Energy, which has been named the world's most sustainable energy developer for 5 years in a row, as a consent manager. He is responsible for managing an operational portfolio of wind farms and ensuring all activities are undertaken in compliance. The company's values and goals align with CERN's, and both strive towards a greener and more sustainable world. Kirk was interviewed on the 23rd of August 2024.

What is the Higgs boson?

Standard Model of Particle Physics:

To understand the impact of the Higgs boson we must first grasp the Standard Model of Particle Physics, which is scientists' best current model of the building blocks of our universe. It includes quarks (which make up protons and neutrons), leptons (fundamental particles which cannot be broken down further), bosons (force carrying particles), and finally the Higgs boson. This can be seen in Figure 1 overleaf.

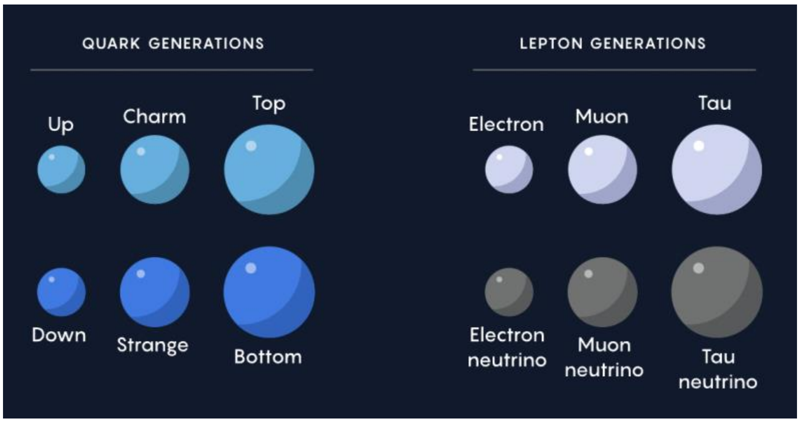
Figure 1 – The Standard Model (Riesselmann, n.d.)



Each boson, seen in blue, acts as a different force carrier. The photon carries the Electromagnetic Force (responsible for generating visible light and the rest of the electromagnetic spectrum), the gluon carries the Strong Nuclear Force (which holds positively charged particles close together in the nucleus), and the W & Z bosons carry the Weak Nuclear Force (which is involved in radioactive decay).

Three progressively heavier, but in other ways identical, versions of each type of matter particle (ie quarks and leptons) exist. This is made clear in Figure 2.

Figure 2 – Quark and Lepton generations (Natalie Wolchover, 2020)



While Figure 2 shows Top and Bottom quarks, and the Tau and Tau neutrino as *physically* bigger than other quarks and leptons, this is simply a visual representation to aid in understanding the difference in mass – in reality they are roughly the same size, and it is the Higgs boson that causes this difference in mass – a phenomenon which we will come into shortly.

To further demonstrate the difference in mass, see the third column (mass, measured in MeV/c^2 - mega electron volts/the speed of light squared, coming from the famous equation $E = mc^2$) of Figure 3 below.

Figure 3 – the six quark flavours and their properties (Rwanda Basic Education Board, n.d.)

Quarks	Flavor	mass (MeV/c^2)	Rest energy (MeV)	Charge Q	spin ($\hbar$)	Baryon number	Strange-ness
u	up	5	360	$+\frac{2}{3}e$	½	$\frac{1}{3}$	0
d	down	7	360	$-\frac{1}{3}e$	½	$\frac{1}{3}$	0
c	charmed	1500	1500	$-\frac{1}{3}e$	½	$\frac{1}{3}$	+1
s	strange	150 000	540	$+\frac{2}{3}e$	½	$\frac{1}{3}$	-1
t	top	176000 ± 13000	1 7 3 000	$-\frac{1}{3}e$	½	$\frac{1}{3}$	+1
b	bottom	4.8 G	5 000	$+\frac{2}{3}e$	½	$\frac{1}{3}$	-1

As seen above in Figure 1, the Higgs boson is in the very centre. It is a fundamental particle associated with the Higgs field – a field which gives mass to other fundamental particles, including quarks and leptons. (Riesselmann, n.d.) This is what causes the difference in mass in Figure 3.

Unlike the bosons described above, the Higgs is not a force mediator, instead, interactions with the Higgs boson and the associated Higgs field give rise to the Higgs mechanism which gives particles their mass – we will look at this in more depth in the next section.

The Higgs; Boson, Field, and Mechanism:

The Higgs boson is a unique fundamental particle – the only one that exists with zero spin, no electric charge and no strong force interaction. (ATLAS, n.d.) It has a mass of approximately 125GeV/c^2, making it the 2^{nd} most massive particle in the Standard Model.

In the media, we often hear solely about the Higgs boson, however the Higgs boson is simply the smallest part of the Higgs field. The Higgs field – which gives subatomic particles their mass – is made up of countless individual Higgs bosons.

As a particle, for example an electron, moves through space it constantly interacts with Higgs bosons – causing excitations of the Higgs field. These interactions slow down the electron, and this is what is meant by 'mass'. (Natalie Wolchover, 2020)

Essentially, the more that a sub-atomic particle interacts with the Higgs field, the more mass it has. For example, a top quark (the heaviest of the subatomic particles, depicted in Figure 1 and 2) is heavier than an electron – by about 350,000 times! As aforementioned, the top quark is not bigger, only heavier, and the top quark and electron are actually around the same size. Meanwhile, massless particles, such as photons, do not interact with the Higgs field at all.

Theorists Robert Brout, François Englert, and Peter Higgs made the proposal of the Brout-Englert-Higgs mechanism which gives a mass to particles when they interact with the "Higgs field", which pervades the universe. The BEH Mechanism is a type of superconductivity which occurs when all of space is filled with a sea of charged particles and this mechanism is simply what occurs when particles, for example the W and Z bosons, interact with the Higgs field. (CERN, n.d.)

The Higgs' Discovery:

"The Higgs boson was the only fundamental particle predicted by the Standard Model that had not yet been seen by experiments when the LHC started." (CERN, n.d.) Soon after the LHC started (10th September 2008), only 4 years later in fact, the Higgs boson was discovered. The Higgs boson was detected both by the LHC and the Compact Muon Solenoid (CMS), however in this essay we will focus on how the LHC discovered it. Higgs bosons only exist in high-energy conditions. The LHC creates these conditions by accelerating protons close to the speed of light and smashing them together, creating a stream of particles that decay into lighter particles.

The Higgs boson has a half-life of 1.6×10^{-22} seconds (meaning that it decays by half every 1.6×10^{-22} seconds) and is therefore too quick to be spotted. However, it could be identified by noticing the particle decays that came as a result of the Higgs boson's interactions – ones that indicated a particle with no spin, and matched the theoretical predictions made by Peter Higgs and others. (Lea, 2024) The production can be seen below in Figure 5.

Figure 4 – a computer simulation of a proton-proton collision like that at the LHC indicated the discovery of the Higgs boson (Lea, 2022)

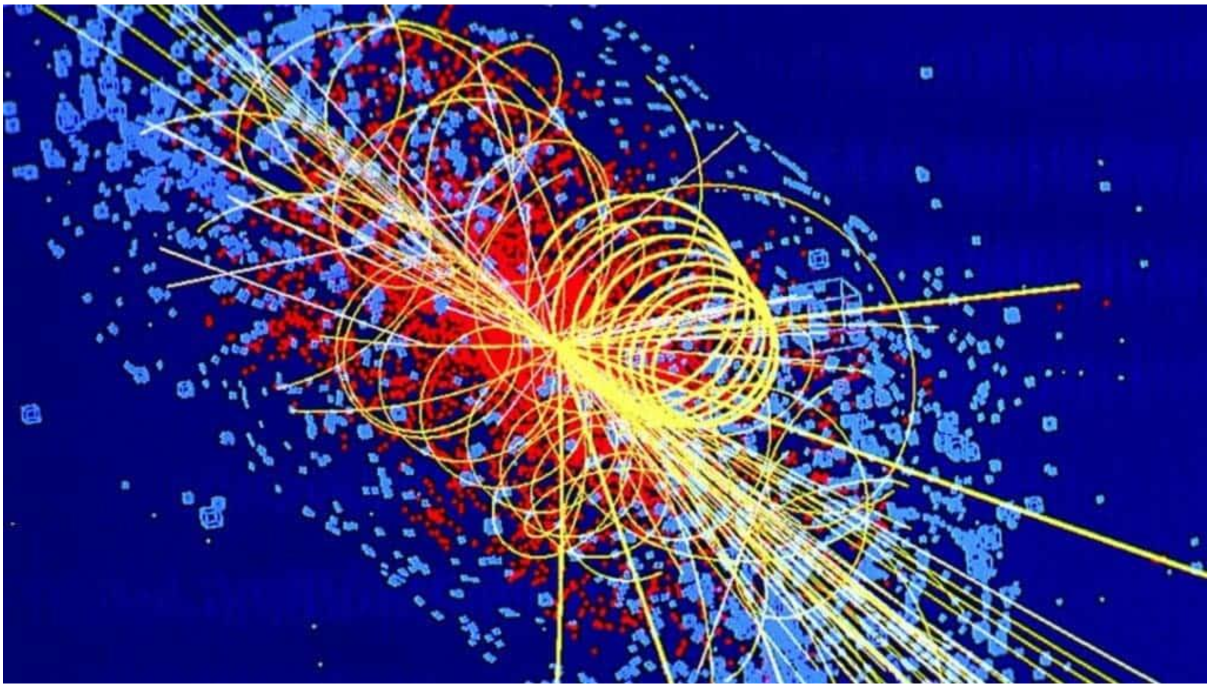
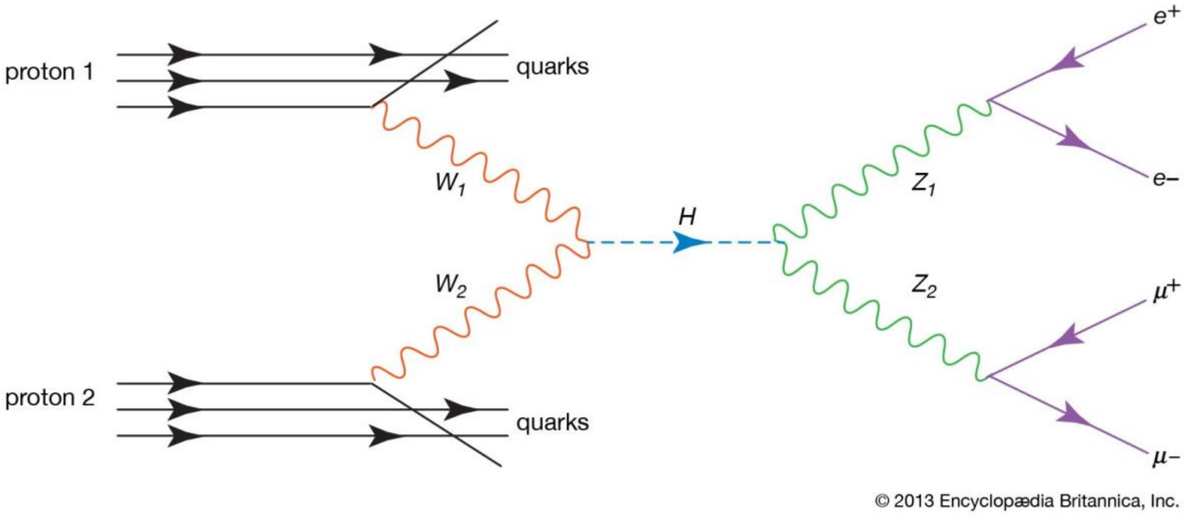


Figure 5 – the Higgs boson production (Sutton, 2024)



<u>Why was the discovery of the Higgs boson so important?</u>

This section will look at what we've discovered so far as a result of the Higgs boson, how the discovery of the Higgs boson has helped the general society, and what discoveries could be made as a result of this one.

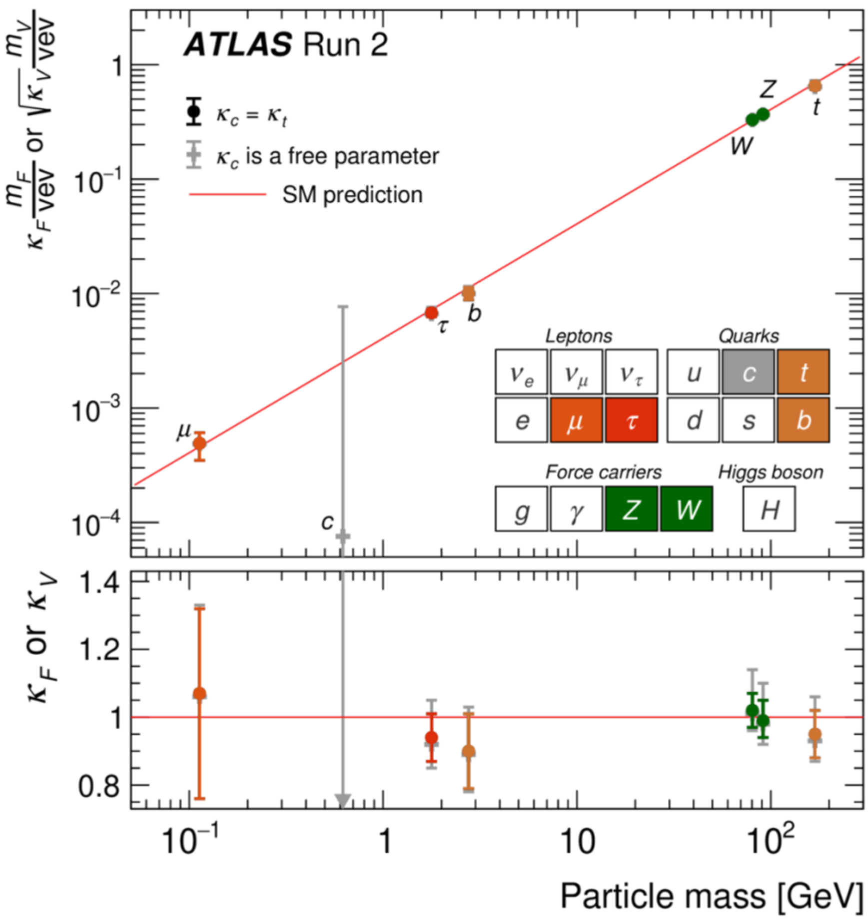
Higgs boson's interactions:

Since its discovery in 2012, it doesn't come as a surprise that countless discoveries have been made coming out of it – in particular from its interactions with other particles. In our interview, Professor Victoria Martin stated: "The way the Higgs boson interacts with the other particles is fundamentally different from the way anything else interacts, and that's because the Higgs boson doesn't have any spin… that makes it interact differently than all of the other particles so it's kind of like a whole new force that we didn't know about before… it's really opening out a whole set of new things that we can look at."

Through analysing the production and decay of the Higgs boson, it has been confirmed that the fundamental particle interacts with bosons and fermions (subatomic particles which have a half-integral spin, e.g. protons and neutrons, unlike bosons which have integer spin values). This confirms the prediction by the Standard Model, seen in Figure 1, which is that particles gain their mass via the Higgs field. (ATLAS, n.d.)

Additionally, since the discovery, interaction strengths (also referred to as couplings, or coupling strengths) with the Higgs boson and other particles have been measured to see whether they match the predictions made by the theory. As expected, the stronger the coupling the heavier the particle as it would interact more with the Higgs field. Figure 6 shows the Higgs boson coupling strength against the particle mass.

Figure 6 – parameter proportional to Higgs boson coupling strength (on the vertical axis) against the particle mass (horizontal axis) (ATLAS, n.d.)



After looking at couplings with bosons such as the W and Z boson, scientists moved on to measure the strengths of interaction with matter particles. In 2016, it was discovered that the Higgs boson can decay into pairs of tau leptons.

Moving back to Higgs production and decay, in 2018, the Higgs boson production from two top quarks was found and so was the Higgs boson decay into bottom quarks. (CERN, 2022)

Clearly, many interactions have been discovered, however there are many more to come, which will be covered in the section after next.

How has Higgs helped humanity?

The route to the discovery of the Higgs boson has brought about many benefits for society. After speaking to both Victoria Martin and Paul Kirk, it was evident that the advantages that have come as a result of this discovery are countless. In Kirk's words, "Discovering the Higgs boson has pushed the limits of what we can do to find a particle" and this has led to many advances to everyday life, healthcare, and a more sustainable planet.

"I believe science should be, and is, now part of our culture" – Victoria Martin remarked during our interview – "But it [CERN] also does bring benefits to people's everyday life, whether they are involved in science or not, everybody in the countries that invest in CERN do feel the benefit of CERN."

Famously, Tim Berners-Lee invented the world wide web in 1989 while working at CERN. This was developed in order for scientists to communicate and share their findings and CERN didn't charge those utilising this, which has now revolutionised the way in which people communicate. This is one of many breakthroughs as a result of the development of the LHC which lead to the discovery of the Higgs boson.

Victoria Martin discussed that within the LHC, when colliding two protons together, there are two apertures that the protons go through, and they suck all of the air out – using an excellent vacuum. This vacuum needs to be incredibly strong as we don't want protons colliding with any air molecules in the process of acceleration. CERN had to develop brand new vacuum technology in order to make this work and this same vacuum technology has now been applied to solar panels as they also need a vacuum layer between the different layers collecting sunlight. These solar panels have now been installed on the roof of Geneva airport meaning the airport can generate its own electricity.

When asked about the benefits that the Higgs boson brings to general society, Paul Kirk mentioned: touch screens that were heavily contributed towards when CERN were trying to create an interface when using particle accelerators, healthcare benefits – in particular accelerated technology being used for cancer treatment including hadron and electron therapy, and computing infrastructure that CERN have developed is now being used for monitoring air pollution which links to Kirk's role at Ørsted.

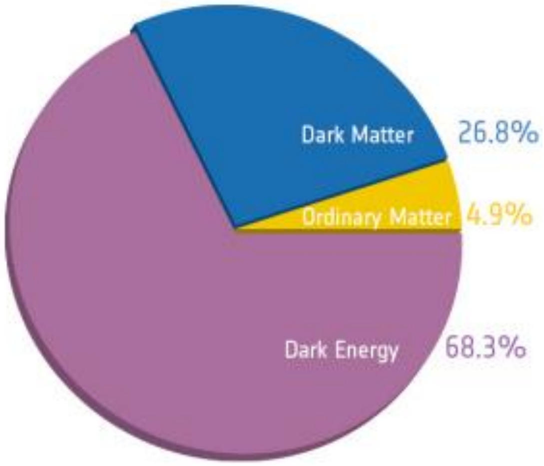
A tool for future discovery:

From dark matter to discovering new particles, we still have much to learn about the Higgs boson and its interactions. "Physicists are not just trying to verify that the properties of the Higgs boson agree with those predicted by the Standard Model – they are also now using the Higgs boson as a tool to search for evidence for new physics!" (ATLAS, n.d.)

Dark matter particles don't interact with electromagnetic radiation or other particles of matter that make up our surroundings. However, due to interactions with gravity, we know that dark matter has mass. Since the Higgs boson explains where mass comes from, many predict it could interact with dark matter.

As seen in Figure 7 overleaf, dark matter makes up around 26.8% of our universe and remains somewhat of a mystery – which is why experiments at the LHC involving the Higgs are vital towards advancing our knowledge.

Figure 7 – The Distribution of Matter and Energy in the Universe (European Space Agency, 2013)



Gian Guidice, who is leader of the theoretical division at CERN stated that: “Since the discovery of the Higgs boson, the field of dark matter has changed completely… our new theoretical ideas have widened our horizons.” (Cooper, 2022)

In an interview with Space.com Victoria Martin stated, "We know that the Higgs boson interacts with everything that is heavy, so if dark matter is a heavy particle, then the Higgs boson should be interacting with it,". This again shows the importance of the Higgs boson as a tool for future discovery. (Cooper, 2022)

In our interview, Martin shared that ATLAS are currently working on discovering whether there is in fact not just one Higgs boson, but rather a family of 5 Higgs bosons. The Higgs boson discovered in 2012 has no spin or charge, however other Higgs bosons could have different characteristics.

While some models such as the one Martin is looking at suggest a family of Higgs with different characteristics, other models suggest there is one type of Higgs that interacts with heavy particles and another that interacts with lighter particles.

“Any additional Higgs that we may discover would indicate that there must be new physics,” Kétévi Assamagan, a physicist at the US Department of Energy’s Brookhaven

National Laboratory, said in an interview with Symmetry magazine. “It could help us explain some of the things that don't necessarily fit in the Standard Model.” Dark matter could be explained by additional Higgs particles, and so could other phenomena such as why there is an imbalance of matter and antimatter in the universe. (Johnson-Groh, 2022)

These further discoveries could be made at the Large Hadron Collider, which is consistently being upgraded and is set to be transformed into a “next-generation High-Luminosity LHC” which will run until 2040. (Johnson-Groh, 2022) However, there are a number of options for future colliders as well – such as the Future Circular Collider which would initially focus on creating lots of Higgs bosons.

Conclusion:

To conclude, the Higgs boson is a mass giving particle which makes up the Higgs field. The Higgs field, which exists in every region of the universe, gives particles their mass via the BEH mechanism.

In essence, the discovery of the Higgs boson is so important because of how greatly it has impacted our knowledge of the Standard Model and our universe. Many theories have been proven correct and questions answered as a result of the discovery and a whole new realm of discoveries are now within our reach thanks to it.

In addition to broadening our scientific knowledge, en route to this discovery humanity has been helped along the way – from the world wide web to improved cancer treatment.

Possibly the greatest part about discovering the Higgs boson is the new possibilities and areas of research we can now look at. In a few years, the title of an essay similar to mine could instead be about the discovery of dark matter thanks to the Higgs, or an enquiry into a family of Higgs bosons.

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