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A short history of the smallest

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Abstract. This paper tells the story of the Standard Model of particle physics. That starts in the 1930s with the idea of the pion and then traces its roots from an embryonic quark theory to its contemporary form. Early scepticism towards the quark model dissolved as it elegantly elucidated baryon and meson structures, and helped to uncover the intricacies of the weak and strong interactions. The Δ++ particle's existence demanded the introduction of 'colour' charge, giving birth to Quantum Chromodynamics. Successive discoveries of heavy quarks, heavy leptons and their corresponding neutrinos fortified the Standard Model. The verification of the existence of gluons, the discovery of the W and Z bosons, and - finally - the Higgs boson are considered triumphs of the theory. However, despite its success, the model has inadequacies, notably with regard to dark matter and energy, but also in explaining the very origin of its many free parameters. New ideas and discoveries are needed to help solve these mysteries.

1. The traffic light of particle physics history

As one delves into the captivating saga of particle physics, its history can be viewed through the lens of a traffic signal. Initially there is the "red" phase, a stop-and-observe stage brimming with both exhilaration and bewilderment. This leads into the "yellow" phase, a time when understanding grows and things start to become clearer. Next this rolls into the "green" phase, which represents the last forty years. During this time a vast amount of knowledge has been gathered. There have been some major breakthroughs, but these game-changing discoveries do not come along as often as they used to. Nevertheless the optimism is retained that another dynamic phase, reminiscent of the first two, is on the horizon.

The narrative begins in 1935 (figure 1), closely following the remarkable discovery of the neutron and the pioneering use of cosmic rays. By the dawn of the 1950s the landscape of the field had been dramatically reshaped by the advent of cyclotrons, synchrotrons and colliders, and these have since remained at the forefront of the field. Yet the analysis of particle collisions would be impossible without some form of detection mechanism.

The early days saw the cloud chamber fill this role, only to be succeeded by a host of other devices such as emulsion detectors, spark chambers, bubble chambers and proportional chambers. In the modern era these once standalone technologies have been assimilated and refined into large-scale detectors. Each of these detectors represents a distillation of previous technologies, melding their unique capabilities into a more sophisticated whole.

2. Excitement and confusion

The story unfolds when scientists began to grapple with the nucleus's enigmatic makeup: a dense gathering of protons and neutrons. The crux of the matter lay in understanding the strong binding force between these particles. Conventional wisdom dictated by the understanding of electric charges suggests that two positively charged protons should repel each other, not hold together in a tight knit. Thus, the search for a binding "glue" began.

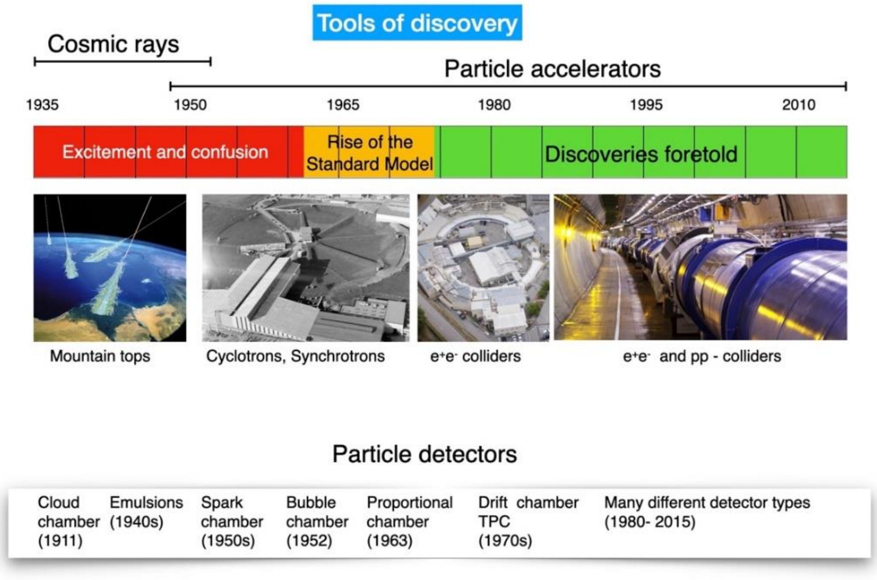


Figure 1. The "traffic light" history of particle physics along with the development of tools for experimentation.

In 1932 Hideki Yukawa proposed that this glue was an exchange particle – the pion. This was modelled after our understanding of the atom, where the electromagnetic interaction is facilitated by a particle known as the photon, an excitation of the electromagnetic field. Drawing an analogy, Yukawa postulated that a similar strong interaction, mediated by the pion, might hold the nucleons (protons and neutrons) together.

Of course theories require the concrete validation of experiments. When researchers turned to cosmic rays in their hunt for the elusive pion, initial efforts proved fruitless. Eventually, however, they found something that closely resembled it; a particle in the 100 MeV region (particle physicists do have a fondness for electron volts with a proton mass for reference weighing in at about 1 GeV) – the muon. This enigmatic muon was exceedingly penetrating, capable of traversing metres of material. This characteristic disqualified it from being the sought-after pion, which should interact strongly with nuclei and not be as penetrating. As a result the muon was viewed as a kind of heavy electron that operated independently. When the muon was first discovered the physicist Isidor Rabi famously joked, "*Who ordered that particle?*" In truth scientists are still grappling with the muon's role in the grand scheme of things. Its discovery, however, was a messenger of the rich tapestry of particles yet to be discovered.

A decade later the elusive pion finally made its debut again through cosmic rays. Cecil Powell was at the helm of the experiment, noticing peculiar tracks in the emulsions that spanned several hundred microns (figure 2). By scanning these tracks it became evident that an unknown particle was decaying into another, which subsequently decayed into a third - a process now recognised as a pion-muon-electron decay. This unknown particle closely matched the criteria for a pion: it had a mass of 140 MeV, a notably brief lifetime (although lengthy in nuclear terms), and its sequential decay into a muon and then an electron implied an intricate link between these particles. However, piecing together how this intricate dance of decay occurred presented a new challenge for the physicists of the time.

As the narrative of particle physics continued, the plot only thickened. Within the confines of cloud and bubble chambers, scientists observed intriguing phenomena: particles that propagated without leaving a trace only to decay into pions or particles that morphed into a proton and a pion - quite a puzzling spectacle. Thus, the concept of "strangeness" was born. These peculiar particles earned the nickname "strange," reflecting the contrast between their manner of creation and their subsequent decay, which occurred within mere billionths of a second. This strangeness appeared to be an innate characteristic of matter, yet its true nature remained enigmatic.

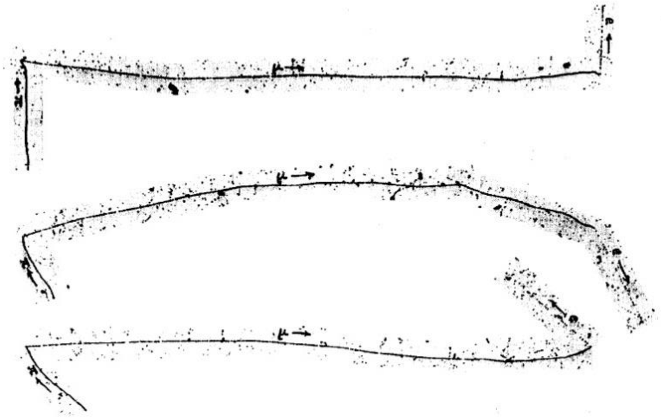


Figure 2. The image shows the particle tracks in the emulsion that proved the existence of the pion and its decay.

Rafael Armenteros added another twist to the tale in 1952 with the discovery that particles could possess not just one, but two units of strangeness. This implied that they could decay into strange particles themselves. The particle bearing this new attribute was baptised Xi, also known as the hyperon particle.

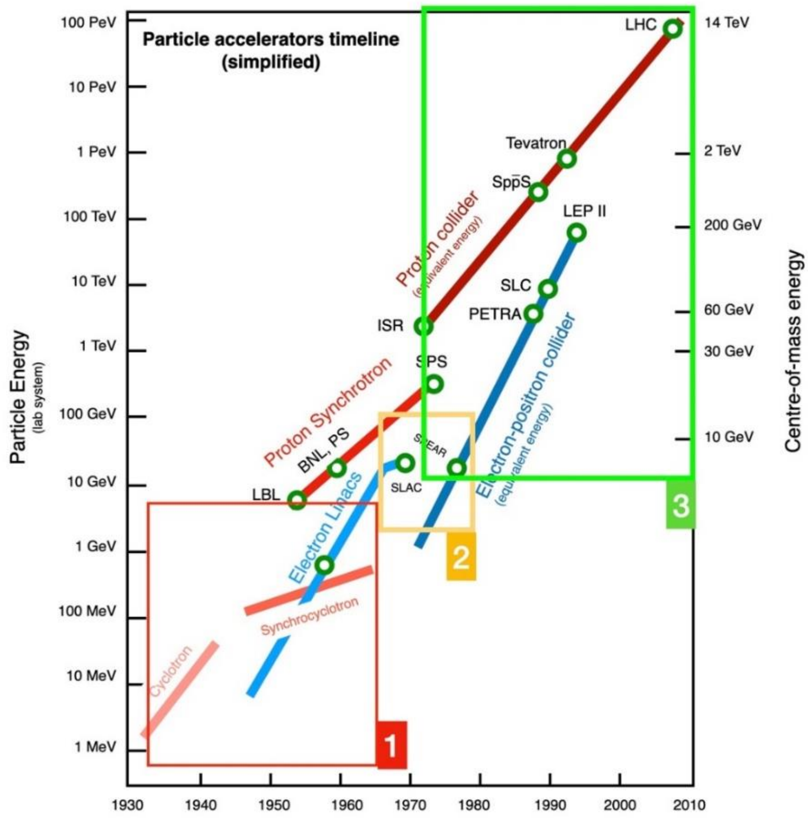


Figure 3. Overview about the energy and the operation time of the most important accelerators and colliders in the history of particle physics.

This discovery was made at the crossroads between the cosmic era and the particle physics era. During this flurry of confusion, the collisions instigated had centre-of-mass energies roughly two-three times the proton mass. As physics experiments ventured into higher energy collisions (figure 3), the understanding of particle physics advanced at an accelerated pace.

3. Discovering particles

So, what exactly does a particle physicist do? In essence their work centres around accelerating particles, such as protons or electrons, to extreme speeds and then directing these particles to collide with a target, which could be anything from a block of metal to a hydrogen cell or even with a counter-rotating particle beam. The ensuing collision produces an array of phenomena for observation, in particular the production of several new particles.

One intriguing outcome is the decay of newly produced particles into two separate entities. Scientists can measure the momentum and charge of the resultant particles, their scattering angle and other characteristics to discern fundamental properties. A common practice involves plotting their so-called invariant mass, revealing distinct peaks referred to as resonances (figure 4). These resonances offer crucial insights into the complex world of particle interactions.

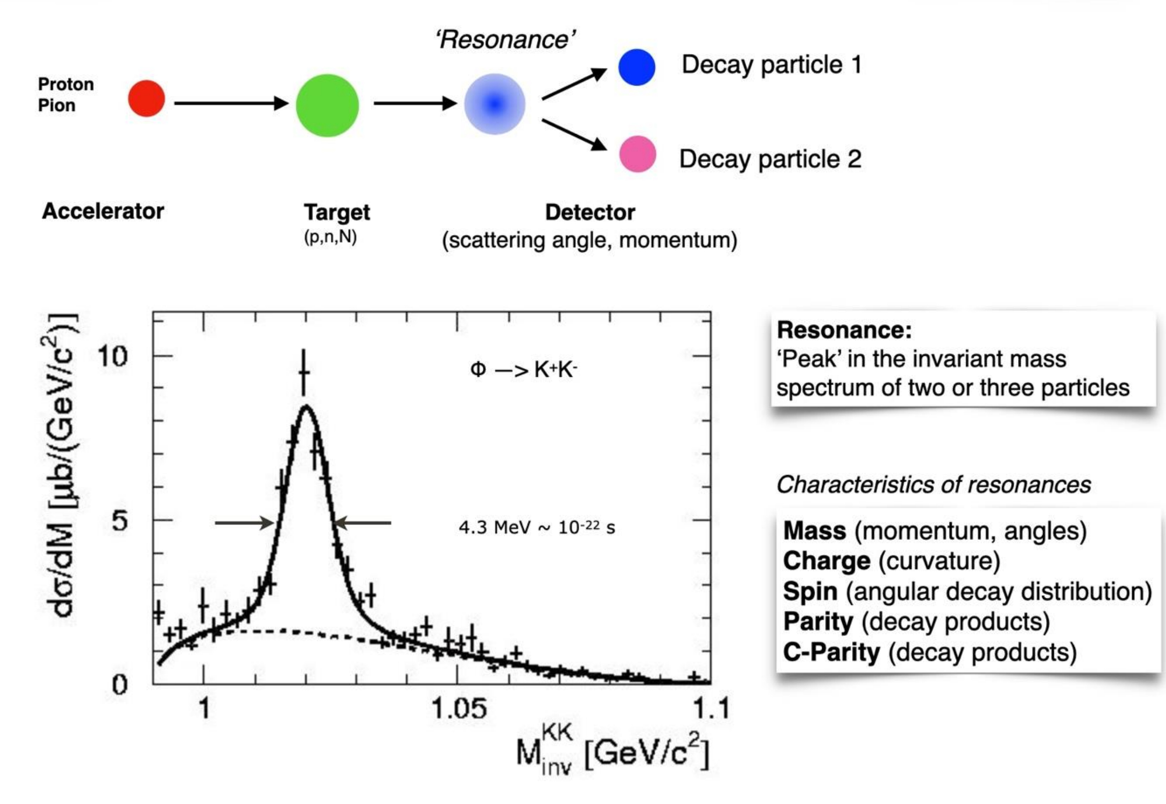


Figure 4. How a "resonance" shows up as a peak in the invariant mass spectrum of two decay particles.

Diving into the intricacies of particle physics it is found that the width of these resonances has a close relationship with the lifetime of the particle, a correlation mediated by the Heisenberg Uncertainty Principle. From these resonance widths it is inferred that the particle exists for an incredibly short time, approximately 10^{-22} seconds - a timescale unattainable by conventional measurement techniques.

The following years witnessed the discovery of numerous resonances using particle accelerators. Each of these particles presented its own set of unique properties for scrutiny: mass, charge, spin and two symmetry-related aspects – parity ("P") and charge ("C")-parity.

The 1950s brought to light a particularly noteworthy discovery: a particle (called "Delta") resembling a proton, but heavier by about 300 MeV. This particle exhibited four distinct charge states: doublepositive, single-positive, neutral and negative. The significance of this discovery was not immediately apparent, yet it would later play a crucial role in our understanding of particle physics.

By 1960 the catalogue of known baryons and mesons had swelled to almost a hundred. There were the mesons - intermediate in size or mass - and the baryons - more massive than a proton or a neutron. Within these categories particles exhibited a diverse array of properties: spin, parity, charge parity and more. This prompted questions about the fundamental structure of nature. Were all these particles with their various properties elementary?

In the 1960s the true nature of these particles remained elusive even to the most eminent physicists. Lev Landau famously expressed the sense of helplessness, lamenting that "*theory is helpless... in dealing with strong interactions*", while Freeman Dyson predicted that "*the correct theory will not be found in the next 100 years*". The predicament was reminiscent of Dmitry Mendeleev trying to decipher the Periodic Table: what guiding principle could help classify these myriad particles? Furthermore, drawing parallels to the inquiries of J.J. Thomson and Ernest Rutherford, physicists pondered the internal structure of these particles. Could these particles just be tiny structureless entities?

4. Rise of the Standard Model

The period spanning 1962 to 1974 marked a pivotal era in particle physics, bearing echoes of the 1920s when quantum theory was initially unravelled. This transformative period was set into motion by Murray Gell-Mann and Yuval Ne'eman. These insightful physicists discerned an underlying order amidst the apparent chaos. They observed that the multitude of discovered particles could be organised based on their shared spin and parity characteristics.

This led to the creation of innovative diagrams, featuring charge on one axis and strangeness on the other. This schematic representation provided a structured view of the particle world, shedding light on how these numerous particles related to one another. In many ways this step mirrored the development of the Periodic Table in chemistry, introducing an organising principle that brought clarity to the intricate landscape of particle physics.

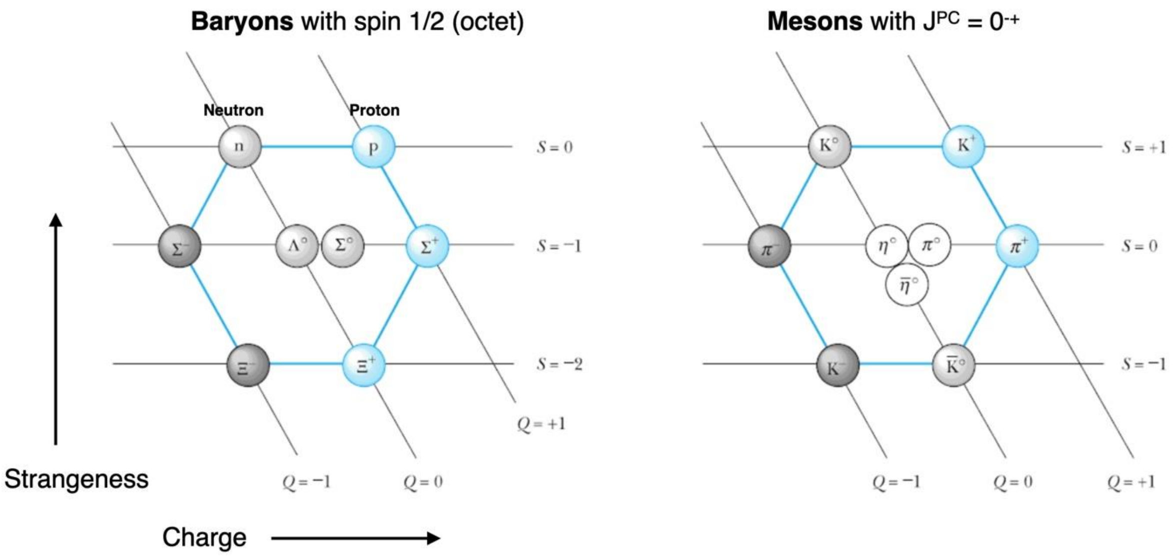


Figure 5. Classification of baryons and mesons according to the SU(3) model.

From these diagrams (figure 5) it became apparent that particles known as mesons formed a structure known as an octet comprising eight related particles plus one that seemed distinctly separate. Similarly particles known as baryons could also be arranged into octets and notably into more complex decuplet structures, further illustrating the underlying symmetry and order in the particle world. The investigators began to realise that there was a deeper symmetry at play, which was related to SU(3) - the special unitary group of rank 3. While the introduction of group theory helped to bring order, this approach was initially regarded more as a mathematical convenience than a reflection of physical reality.

Gell-Mann and Ne'eman's model made one prediction that was particularly striking: it suggested the existence of a particle with triple strangeness as part of the baryon decuplet with spin 3/2. This was a tangible prediction from the SU(3) model. Sure enough in 1964 a particle fitting this description was discovered at Brookhaven National Laboratory, exhibiting precisely the properties predicted by the model. This discovery spurred physicists to contemplate the possibility of a physical reality underlying the mathematical model.

Subsequently Gell-Mann and George Zweig independently proposed a new ground-breaking idea: the "generators" of the SU(3) symmetry are actually real particles, baptised "*quark*s" by Gell-Mann (while Zweig called them "*aces*"). They suggested that mesons were made of a quark and an anti-quark. Baryons were bound states of three quarks with the proton, for instance, composed of two quarks of the type "up" and one quark of type "down". The types of quarks posited at this stage were the up quark, down quark and strange quark (to explain mesons and baryons with "strangeness").

Intriguingly these quarks would not carry integer electric charges, as one might expect, but fractional charges of +2/3 or -1/3. This unexpected fractional charge proved a stumbling block for many physicists, given the lack of evidence for any particle with a fractional charge and the fact that a free quark had never been observed. Yet this innovative idea went a long way towards explaining a multitude of phenomena in particle physics.

The model that was put forth in 1964 was intriguing but was met with a degree of scepticism. Mesons in this model consisted of a quark and an antiquark pair. With three types of quarks - up, down and strange - and their corresponding anti-quarks, nine distinctive combinations emerged for each combination of spin, parity and C-parity. Impressively these combinations accounted for all the different types of mesons observed up to that point.

The turning point when this model transformed from being a plausible theory to a robust explanation can be traced back to a sequence of significant experiments. As early as 1956 Robert Hofstadter at Stanford had put a linear accelerator to use much like an electron microscope, although with an incredibly short wavelength - roughly equivalent to the size of a proton. Scattering these electrons off a proton, Hofstadter observed that the proton had a finite radius; the proton's scattering was characteristic of a diffused sphere, not a point particle, with a radius of about one femtometre.

Fast-forwarding to 1967 another team at Stanford, composed of Richard Taylor, Jerome Kendall and Henry Friedmann, pushed Hofstadter's experiment further. They used electrons accelerated to 20 GeV, yielding a wavelength about a hundred times smaller than Hofstadter's. Their results were astonishing: the "deep inelastic" electron scattering indicated the presence of exactly three hard, point-like particles inside the proton. This ground-breaking experiment provided an explicit image of the proton's structure, strongly endorsing the quark model.

To complete the narrative it is necessary to look back to 1958. At that time Richard Feynman and Murray Gell-Mann were examining particles decaying through the weak interaction and made a remarkable observation: the decay of a muon - often referred to as the 'heavy electron' - and that of a neutron occurred at quite a similar rate. They concluded that there must be a symmetry between the muon, a weakly interacting particle and the neutron, which is a strongly interacting particle.

Around the same time Sheldon Glashow proposed a new concept that reshaped our understanding of the weak interaction. Glashow proposed that the weak interaction is transmitted by so-called W bosons, which act as carriers of this force. To account for the weak interaction's aptly named 'weakness', these W bosons needed to have a significantly large mass. However, an enigma persisted: existing theory at that time did not offer a way of explaining how these carrier particles could attain such substantial mass. The concept of the Higgs boson emerged from this fundamental issue in the theoretical landscape of particle physics.

The solution came in the form of spontaneous symmetry breaking, an idea pioneered by Yoichiro Nambu. A few years later François Englert and Robert Brout, working independently of Peter Higgs, proposed the existence of a universal field that permeated all of space. This field, they suggested, interacts with the W bosons, endowing them with their substantial mass via the process of spontaneous symmetry breaking.

Peter Higgs added a significant detail to this idea. He suggested that this universal field should possess an excitation that would manifest as a massive particle. This particle, named in his honour, came to be known as the 'Higgs' boson, serving as a tangible testament to the existence of the eponymous Higgs field.

In 1967 Sheldon Glashow, Abdus Salam and Steven Weinberg synthesised this idea with other developments in the field. They suggested that electromagnetic and weak interactions - the forces responsible for muon and neutron decays, respectively - were just two sides of the same coin, a manifestation of the same fundamental interaction. This interaction was elegantly described by the gauge groups SU(2)xU(1).

They also postulated the existence of the Z^o boson, a heavy counterpart to the photon, along with the two other intermediate (“W”) vector bosons. These four particles were believed to mediate both the electromagnetic and the weak interactions at low energies. At extremely high energies beyond a few hundred GeV, the two interactions were said to converge into a single fundamental interaction. Importantly Weinberg introduced the concept of the Higgs field as a mechanism to account for the hefty masses of these bosons, a prediction that was yet to be confirmed experimentally at that time.

In an influential paper from 1970 Glashow, John Iliopoulos and Luciano Maiani articulated a new concept that suggested an innate symmetry between leptons - which include electrons, muons and their associated neutrinos - and the then-known quarks: up, down and strange. They proposed that quarks and leptons are linked through what is now understood as “weak charges”. This proposition anticipated the existence of a fourth quark (called “charm”), a prediction that was later vindicated through the discovery of the J/psi particle, which turned out to be a bound state of a charm and an anti-charm quark.

This significant discovery was accomplished simultaneously by two different teams, led by Samuel Ting and Burton Richter, who were conducting proton-proton collisions (at Brookhaven) and electron-positron collisions (at Stanford) respectively. Both groups made their findings public on the same day. What set the J/psi particle apart was its astonishingly “long” lifetime of around 10^{-20} seconds in stark contrast to the expected 10^{-23} seconds. This observation marked a significant leap forward in our understanding of particle physics.

5. Colour charge

The question of what keeps quarks bound within a proton was a significant one during this period. The existing understanding of electromagnetism and the weak interaction seemed insufficient in explaining the strong interaction, which was believed to occur between protons and neutrons. However, a closer examination suggested that the strong interaction was occurring between quarks, while a residual interaction akin to Van der Waals forces occurred between the protons and neutrons.

This led to the consideration of the Δ^{++} particle, a seemingly aberrant example that could not be reconciled with the quark model. Its existence demanded the presence of three identical up quarks, each with spins aligned in the same direction, resulting in an S-wave or zero angular momentum state. This arrangement, however, went against the Pauli Exclusion Principle and the very existence of Δ^{++} appeared to be in violation of this cardinal rule.

The first part of the solution came in 1964 when Moo Young Han, Yoichiro Nambu, and Oscar Greenberg proposed the introduction of an unseen quantum number, which they dubbed 'colour'. In their model, combining the three different colours would yield a 'white' or colour neutral state. Despite being labelled by Richard Feynman as a classic case of poor physicist terminology, the colour concept found traction. This idea that colour was a new kind of charge, a strong charge, became instrumental. Theorists Harald Fritzsch and Gell-Mann expanded upon this concept, proposing a model that mirrored the Weinberg-Salam theory, which formed the groundwork of Quantum Chromodynamics (QCD). The three different colour charges in their model constituted a SU(3) gauge group.

This gave birth to the idea of the gluon, a massless exchange particle similar to the photon except that it had the ability to change the colour of a quark. Thus, it had two indices and could interact with itself, a stark difference from the neutral photon. The interactions between gluons led to a rather peculiar phenomenon: as two quarks were pulled apart, the gluon field between them would intensify to such an extent that it would eventually break, producing a new quark-antiquark pair from the vacuum. Furthermore, when quarks were brought extremely close at high energy collisions, these 'strings' or gluons ceased to play a role, a phenomenon known as asymptotic freedom. Hence, the interaction strength of the strong interaction changes with energy. Later the "running coupling constant" of this theory has been verified with high precision over numerous orders of magnitude, testifying to its robustness.

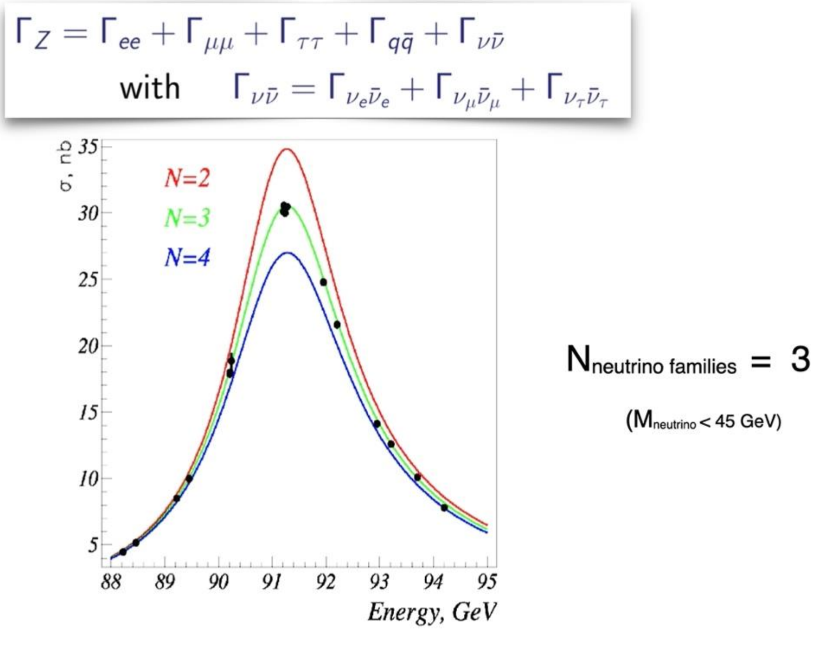
6. Discoveries foretold

The quark model gradually gained widespread acceptance, transforming from a hypothesis to a theory that provided comprehensive and precise explanations for the observations in particle physics. With the four quarks (up, down, strange and charm), four leptons (electron, muon and their neutrinos) and their interaction fields, the Standard Model of physics was nearing completion. Yet the confirmation of the gluon and the source of mass for these particles were still outstanding.

Unexpectedly the discovery of a new lepton, the "tau" in 1975 posed an intriguing turn of events. The presence of this heavier lepton together with the lepton-hadron symmetry pointed towards the existence of a new family of quarks (baptised "top" and "bottom") and leptons (the "tau" and its neutrino). The discovery of a resonance in the electron-positron scattering at Fermilab in 1977, identified as a bound state of a bottom and anti-bottom quark, marked the beginning of the third quark family.

At the Deutsches Elektronen-Synchrotron (DESY) in Germany a crucial discovery concerning the existence of gluons was made in the late 1970s. Through a series of experiments using electron-positron collisions scientists were able to indirectly observe the presence of gluons, the carrier particles of the strong force, through the analysis of distinct jet-like patterns of hadrons.

By 1983 CERN's proton-antiproton collider was functional, enabling the production of W and Z bosons. The subsequent accelerator, LEP was operational by 1991, producing electron-positron collisions around 90 GeV. This facilitated precise measurements of the resonance shape of the Z^o boson, which is sensitive to the number of families of elementary particles (figure 6). The results conclusively showed that only the curve for three families of quarks and leptons matched the data.



$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{q\bar{q}} + \Gamma_{\nu\bar{\nu}}$$
$$\text{with} \quad \Gamma_{\nu\bar{\nu}} = \Gamma_{\nu_e\bar{\nu}_e} + \Gamma_{\nu_\mu\bar{\nu}_\mu} + \Gamma_{\nu_\tau\bar{\nu}_\tau}$$

Figure 6. The image shows the shape of the Z^0 boson resonance and its relation to the number of quark families.

Following the discovery of the tau neutrino at Fermilab in 2000 the stage was set for one of the most ground-breaking discoveries in particle physics - the Higgs boson.

This elusive particle, integral to the Higgs field that imparts mass to other particles, was detected at the Large Hadron Collider in 2012 at CERN, and its discovery required an incredibly rigorous process of data collection and analysis. Over a span of two years the ATLAS and CMS experiments analysed roughly ten quadrillion proton-proton collisions with their detectors observing tens of millions of collisions events per second. Buried within this mountain of data was the tell-tale sign of the Higgs boson – a small surplus of events (figure 7) that amidst a much larger backdrop of other interactions hinted at the particle's presence.

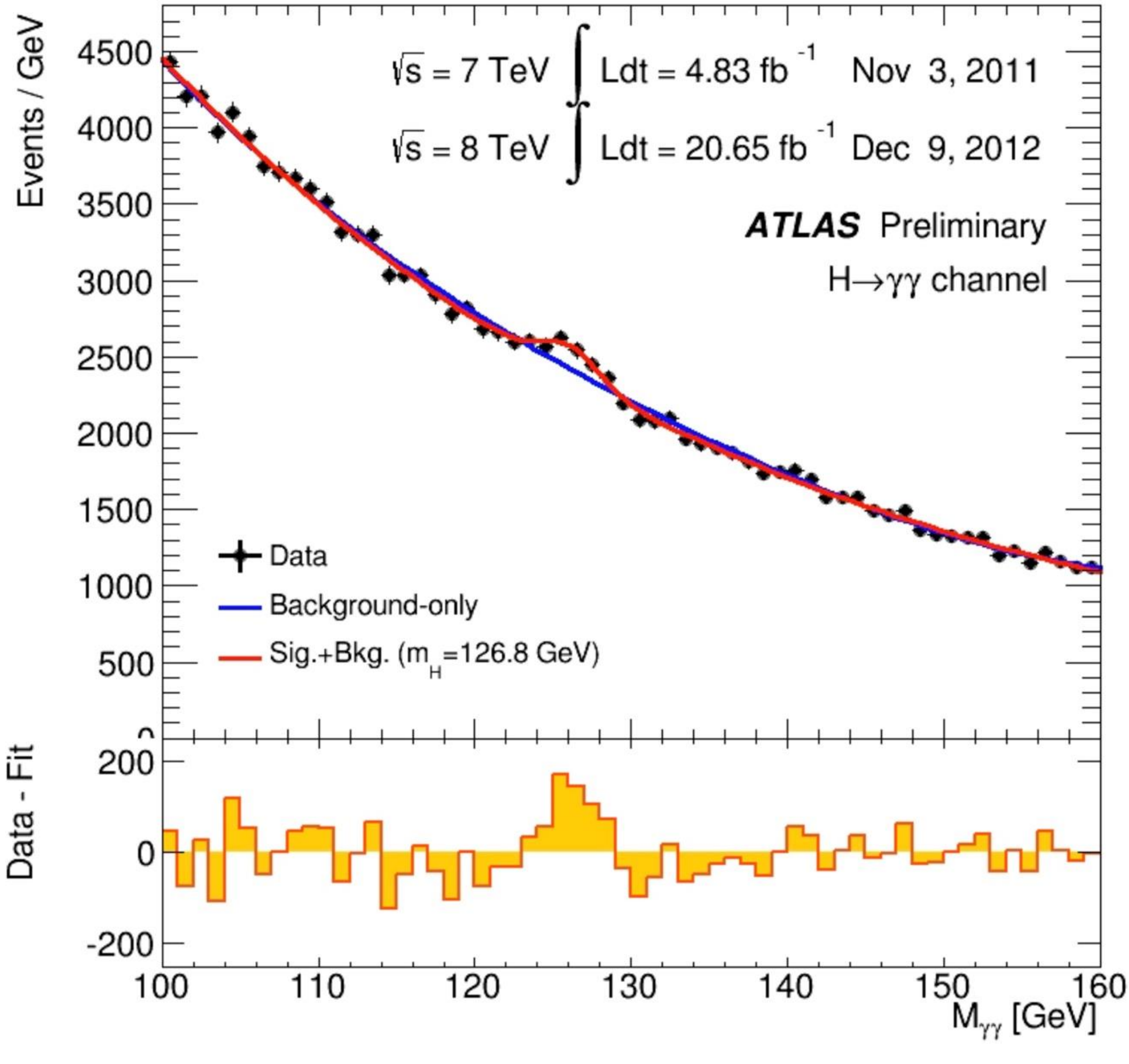


Figure 7. The small peak at a mass of 125 GeV shows the first evidence for the discovery of the Higgs boson.

7. The Standard Model

Today the Standard Model (figure 8) is the best explanation we have for the world of particles around and within us. It has withstood countless tests with experimental outcomes corresponding closely to its predictions, rarely straying beyond two or three standard deviations.

Despite its seeming completeness the Standard Model leaves much to be desired. Curiously although it features three particle families, the constituents of our observable Universe are entirely made up of members from just the first family, leaving one to ponder the need for the remaining families.

Its many arbitrary parameters, including the cryptic values of the quark and lepton masses dictated by the Higgs field, leave a sense of dissatisfaction and a yearning for a deeper, more universal principle that would reveal the true origin of this "recipe".

The existence of phenomena like dark matter and dark energy tell us that the Standard Model in spite of its profound explanatory power cannot provide the final answer to our quest for understanding the Universe.

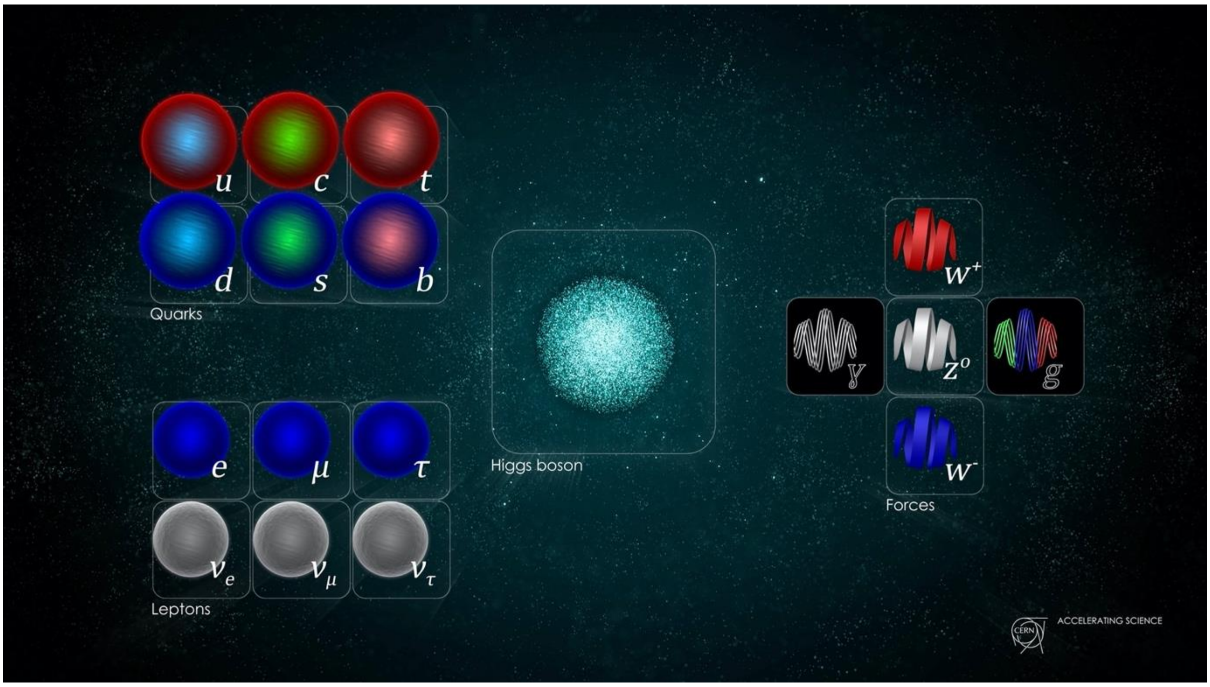


Figure 8. The Standard Model of particle physics.