The Significance of the Discovered Tetraquarks and Pentaquarks at the LHCb: Where Do We Go From There?

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In recent years, the Large Hadron Collider beauty (LHCb) collaboration at CERN has made significant breakthroughs in the field of exotic hadrons, most notably with the discovery of a pair of open charm tetraquarks and a strange pentaquark in 2022. These discoveries challenge the conventional understanding of hadron structures as described by the Standard Model (SM), offering a glimpse into the complexities of quantum chromodynamics (QCD) beyond the well-established mesons and baryons. This review provides a comprehensive overview of the groundbreaking discoveries of the strange pentaquark and the pair of open charm tetraquarks, delving into the essential background of the Standard Model, the experimental setups, and methodologies employed in collider experiments like those at the Large Hadron Collider (LHC), along with details of the data analysis techniques that led to the identification of these exotic states. Additionally, we discuss the implications of these findings, and the next generation of experiments they may inspire.

1 Introduction

Particle physics is a domain of science that provides us with knowledge about the fundamental building blocks of the universe and their interactions and decays.

Many groundbreaking discoveries in particle physics have contributed to our profound understanding of the world. It started with Thomson's misguided theory of the structure of an atom resembling a plum pudding model, where the electrons were the "chips" embedded in the positively charged "cookie dough"[1]. It was proven to be wrong by Rutherford's gold foil experiment, which discovered the positively charged nucleus made up of positively charged protons and neutral neutrons[2]. This helped us understand the basic structure of an atom.

The long-awaited discovery of the Higgs Boson particle was achieved in 2012[3]. The existence of this fundamental particle provided us with insights into how matter around us acquires mass—that is, through the Higgs field associated with the Higgs Boson. It remains as one of the greatest discoveries in particle physics and is a sign of how far we have come to understand the fundamental building blocks of matter and their interactions.

The continual development of the technological equipment, such as the particle accelerators and detectors, drives the surges in new discoveries and the domain of particle physics.

Recent discoveries of new particles and their properties have contributed to our understanding of the Standard Model[4].

One such discovery occurred at the LHCb experiment in 2022, where researchers discovered a new pair of tetraquarks and the first ever strange pentaquark: a major scientific breakthrough for our understanding of the quantum model of particles[5]

Made up of four and five quarks, respectively, the tetraquarks and pentaquarks are called 'exotic hadrons' that depart from the traditional pairs and triplets found in mesons and baryons. These findings provide valuable insight into the strong nuclear force and the Standard Model.

A thorough discussion of these discoveries is instrumental in understanding how far we have come and how far we can go. This Literature Review will discuss the discovery of the pentaquark and the pair of tetraquarks at the LHCb at CERN, Geneva, and what it means for the future of particle physics.

2 Methodology

The primary methodologies for this literature review will include analyzing various sources and criteria essential for understanding the details of the discovery and summarizing its key points. Specifically, a range of sources, including CERN's official press announcement regarding the discovery, peer-reviewed academic papers, CERN documents, and other relevant research materials, will be analyzed to provide a comprehensive perspective.

3 Theoretical Background

3.1 Particle Physics

3.1.1 The Standard Model

The Standard Model (SM) of particle physics, as shown in Figure. 1., is a theoretical framework proposed to describe the particles and interactions within our universe. It has been tremendously successful in predicting many of the discoveries of

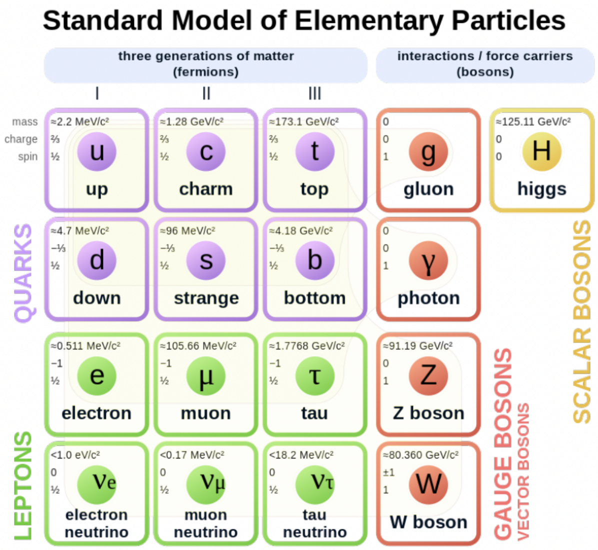

Fig. 1 Standard Model of Elementary Particles[11].

the modern physics. It includes the quarks and leptons, together with the Higgs Boson and the three existing fundamental interactions: the weak force, the strong force, and the electromagnetic force.

Introduced more than 100 years, after the discovery of the electron in 1897[6], the complete Standard Model of particle physics took a long time to build. Fueled by the discovery of quarks in the 1970s, and subsequently by the top quark in 1995[7], tau neutrino in 2000[8], and the Higgs Boson in 2012[9], SM has only increased in terms of its credibility.

It is widely regarded as one of the most accurate representations of the subatomic world to date. An interactive model of it can be seen in Ref.[10]

3.1.2 The Standard Model in Lagragian Form

The Lagrangian form of the Standard Model is an equation that describes all possible interactions and the forces mediating the particles within the SM. It offers a mathematical framework for the quantum field theory by describing particles and their interactions through underlying fields. The Lagrangian is one of the simplest and most concise representations, despite appearances[12].

The entire Lagragian form can be seen in Figure. 2. and has been divided into 5 sections, each explaining different aspects of the model. It introduces the three fundamental interaction forces—the strong, weak, and electromagnetic forces—and their corresponding mediating particles—the gluons, the W and Z bosons, and photons respectively.

Section 1 of the equation focuses on particles known as gluons, that have been represented by the letter ‘g’ and are massless. They carry the strong force, which is an interaction force that

1
$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2}ig_s^2(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu$$

2
$$-\partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+\phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4}g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \frac{1}{2}g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac{1}{2}ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - g^1 s_w^2 A_\mu A_\mu\phi^+\phi^-$$

3
$$-\bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\frac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + (\bar{d}^\lambda_j\gamma^\mu(1 - \frac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1+\gamma^5)u^\lambda_j)]$$

4
$$+\frac{ig}{2\sqrt{2}}\frac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1-\gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1+\gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j] - \frac{g}{2}\frac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j)$$

5
$$+\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2}\bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Fig. 2 The Standard Model written in Lagrangian form.[12]

mediates the hadrons, particles made up of quarks such as protons and neutrons, by interacting amongst themselves. They have a property called color charge which is a quantum number analogous to the electric charge but with three possible "colors", red, green, and blue, and their anticolors, antired, antigreen, antiblue. The color property has no relation to the colors we see in the usual sense and is just a classification used to differentiate between particles. It is a property fundamental to the theory Quantum Chromodynamics (QCD) and can be read more about in Ref.[13].

Section 2, which is almost half of this equation, explains interactions between particles known as bosons, particularly, the W and Z bosons. They carry the weak force and mediate all particle interactions. They help massive matter particles decay into less massive matter particles. The recently discovered Higgs boson, represented by the letter 'H,' interacts differently and is discussed in Section 3. Also, photons, massless particles denoted by the letter 'A' carry the electromagnetic force, mediating all electromagnetic interactions between charged particles. Unlike the gluons, the W and Z bosons have a mass, which is equivalent of 80 and 90 times the mass of a proton. Their mass originates from the interaction with the Higgs field, which has its minimum at a non-zero value. When particles like the W and Z bosons interact with it, they gain mass because they must align with this energy state to remain stable. This process is a fundamental example of spontaneous symmetry breaking[14]. Since the Higgs does not have an electric or color charge, it does not interact with the gluons and photons, thus leaving them massless.

Section 3 describes the interaction of elementary particles via the weak force. This equation indicates how matter particles come in three generations with different masses, the lightest ones being first generation, and heaviest being the third. It also includes the basic interactions between the Higgs field that contributes to the mass of elementary particles.

Section 4 and 5, include the virtual particles known as 'ghosts' which help simplify the mathematical framework. In a path integral formalism, a standard method in modern quantum field theory, ghosts allow for a mathematically consistent computations within QCD.The ghost particles are never part of the initial or final states of an interaction and are used to streamline the formulation in the Lagragian model.

The Lagragian model represents particular symmetry groups, fundamental interactions, and describe particle properties, such as mass, charge and spin. The relationships described in the model have no fundamental explanation for their interactions; they are simply presented as mathematical expressions that have been justified through experiments, but research is still ongoing to resolve any contradictions. For example, in section 3, it is assumed that neutrinos, weak, neutral, subatomic particles, are massless. There is no consistent way to introduce mass for neutrinos into the equations due to symmetry constraints. Therefore, they are assumed to be massless, as most interactions satisfy these constraints.

However, recent discoveries suggest that neutrinos do have a small mass that may require new considerations for their interactions and modifications beyond the Standard Model.

3.1.3 Introducing Quarks

Scientists discovered quarks while trying to understand the structure of an atom. After the initial discovery of electrons and the nucleus, came the subsequent recognition of the nuclear building blocks: protons and neutrons.

Eventually, scientists realised that nucleons are further subdivided into quarks. Quarks are elementary particles, or in other words, the smallest building blocks of the universe. Two physicists, Murray Gell-Mann and George Zweig first proposed their existence in 1964[15].

Quarks contain fractional negative and positive charges in terms of electron charge measured in a unit called electron-Volt (eV). They are classified in terms of flavors: up, down, top, bottom, strange, and charm. The up, top, and charm quarks have a charge of $\frac{+2}{3}e$, whereas the down, strange, and bottom quarks have a charge of $\frac{-1}{3}e$.

Additionally, quarks are also characterized according to their mass. Lighter quarks include the up, down, and strange quarks; heavier ones include the top, bottom, and charm quarks. As can be seen in Table.1., the top quark has the largest mass and is almost 175 times heavier than a proton.

The quarks' masses are measured in units of $\frac{\text{MeV}}{c^2}$ (Mega-electron Volts per the square of the speed of light) through Einstein's famous equation, the conservation of mass and energy equation, $E = mc^2$, where E is the energy in MeV, c is the speed of light, and m is the mass. Since energy and mass are related by this equation, quark mass can be expressed in terms of energy.

To remain consistent with standard physics notation, mass is typically given in $\frac{\text{MeV}}{c^2}$. However, it's important to note that using MeV as a unit of mass is also acceptable, as it is a convention in official research papers and other calculations to keep the unit of c² implicit. Therefore, even when the mass of a particle is given in MeV, it essentially implies $\frac{\text{MeV}}{c^2}$.

Table.1., gives a visual structure of the properties of quarks including their symbol, mass, and charge.

To maintain consistency with the established conventions, this paper will use the symbols for the quarks instead of their full names, such as u for the up quark, d for the down quark, and so on.

The mass of quarks is a fundamental feature that contributes to various phenomena, including particle decays, which will be further discussed.

Quarks, as the building blocks, combine to form particles such as protons and neutrons, which are made up of three quarks each. Specifically, protons are made of two up and one down quarks (uud), and neutrons are made of one up and two down

Table 1 A classification of quarks according to their symbol, charge, and mass. Mass is measured in MeV/c^2, where $1\,\mathrm{MeV}/c^2 = 10^6\,\mathrm{eV}/c^2$.

Quarks	Symbol	Charge	Mass ($\frac{\mathrm{MeV}}{c^2}$)
Up	u	$\frac{+2}{3}e$	5
Down	d	$\frac{-1}{3}e$	5
Top	t	$\frac{+2}{3}e$	173000
Bottom	b	$\frac{-1}{3}e$	4500
Strange	s	$\frac{-1}{3}e$	100
Charm	c	$\frac{+2}{3}e$	1300

quarks (udd). Quarks usually combine in groups of twos and threes to form particles such as these, known as hadrons.

3.1.4 Antiparticles

Every particle in this universe has its antiparticle.

When a particle meets an antiparticle, they annihilate each other, which is consistent with the conservation of energy and mass, $E = mc^2$. It means that the object's mass can be measured as a form of its energy. For example, electrons and positrons annihilate each other to form photons which is essentially a quantum of energy.

Antiparticles share many of the same properties as their corresponding particle, such as mass; however, the one difference remains that antiparticles have an opposite charge than their partner particles.

For example, an electron is a particle with a -1 charge. Its antiparticle, however, the positron, has the same mass but an opposite charge of +1.

These antiparticles also include antiquarks. Apart from the six flavors of quarks, another six flavors of antiquarks also exist with the same mass but opposite charge. For example, an up quark (u), which has a charge of $\frac{+2}{3}$ has an antiparticle called an antiup quark ($\bar{u}$), which has an opposite charge of $\frac{-2}{3}$. An overbar notation is used to indicate an antiparticle, so an antiup quark which is written as $\bar{u}$ (u-bar).

One of the unsolved mysteries of modern physics is the imbalance between matter and antimatter in our universe. Although an equal number of both should have been produced from the Big Bang energy, our very existence is evidence that more matter than antimatter exists in the universe.

3.1.5 Hadrons

Hadrons are particles built from a combination of quarks. They are subdivided into two categories: baryons and mesons. Baryons are composed of three quarks, the protons (uud) and neutrons (udd) being the two most well-known examples. Mesons are composed of a quark and an antiquark, such as the pion ($u\bar{d}$) and kaon ($u\bar{s}$). In addition to these mesons and baryons, other exotic hadrons, such as tetraquarks and pentaquarks, exist. We will be discussing these particles in further detail later in the paper.

Hadrons interact through the three fundamental forces, the strong, the weak, and the electromagnetic. The strong nuclear force mediated through gluons is of particular interest for this paper. Gluons interact both with the quarks and with themselves by the exchange of the "color" property. It confines the quarks into hadron and makes them temporarily stable. This is explained by the concept of asymptotic freedom, a property of QCD [16]. At small distances (high energies), the strong force weakens, and gluons and quarks have little to no interaction between them. However, when the quarks in a hadron are pulled apart, the distance between them increases (lower energies), causing the strong force to strengthen. The gluons, which mediate the strong force, then push the quarks closer together at these larger distances, thus confining them within the hadron. This behavior allows physicists to make more precise predictions about particle interactions at small distances, where calculations are simpler, compared to the more complex calculations at larger distances. Baryons generally experience stronger interactions due to the presence of more quarks and a more complex color charge distribution compared to mesons.

The strong force is, as the name suggests, stronger than the weak force. In the context of hadrons, the two forces are part of very different processes. The strong force, as mentioned, keeps the hadron temporarily stable through confinement, whereas the weak force mediates its decay processes. In other words, the strong force maintains hadron stability, and the weak force triggers their decay.

3.1.6 Leptons

In contrast to hadrons, leptons are particles that are not made of quarks. They are so-called fundamental particles, like the quarks, meaning they are indivisible into smaller components. A few examples include electrons (e) and muons (μ). These particles do not undergo decay processes.

Unlike hadrons, the leptons are not affected by the strong force; rather, they interact only via the weak and electromagnetic force. Since leptons do not have a color property, they aren't affected by this force Gluons and photons are massless, whereas the W and Z bosons mediate have masses of 80 and 90 times the mass of a proton, respectively. Leptons can be both charged and neutral. A few examples of charged leptons include the electrons, muons [17], and taus [18], while the neutral leptons include neutrinos.

Figure. 3. provides a visual summary of the classifications of hadrons and leptons, alongside their interactions and their categorization in terms of spin. The fermions include baryons from the hadron family and leptons, while bosons include the mesons from the hadron family as well as photons, gluons, Higgs Boson, and the W and Z bosons. Further details regarding spin, and distinction between fermions and bosons, are discussed in later sections

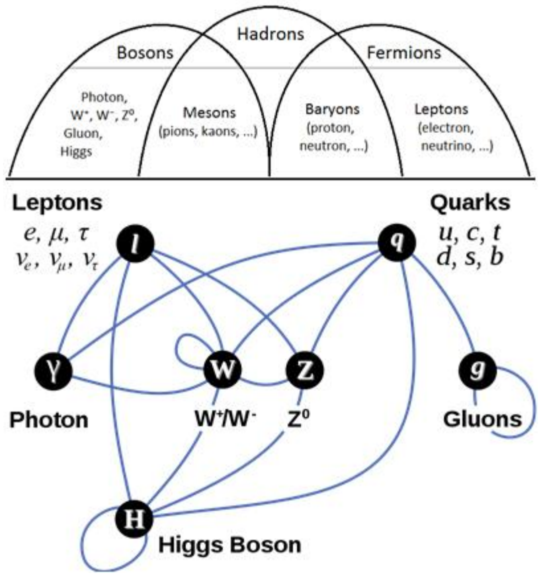

Fig. 3 Classification of the elementary subatomic particles and their interactions [19].

3.1.7 Differences Between Hadrons and Leptons

Here are the key differences between hadrons and leptons: Hadrons are composed of quarks that can be in combination of threes (baryon) or twos (mesons), whereas leptons are particles that are indivisible into smaller components. Hadrons are mediated by the three fundamental forces, the strong, the weak, and the electromagnetic, whereas leptons only interact through the weak and electromagnetic force.

Electromagnetic force is stronger in its interaction with the hadrons as opposed to the leptons. This is because the leptons can carry either one unit of electric charge, or remain neutral, whereas hadronic particles can have higher electric charges. the stronger the charge of a particle, the greater the electromagnetic force it experiences.

The weak force interacts differently with the hadrons as opposed to the leptons. This is because the weak force mediates the unstable hadron decays, whereas leptons act as the decay products.

To sum it up, particles exist either as fundamental building blocks (leptons, interaction bosons) or as composite particles which are bound states of quarks (hadrons). Apart from the hadrons and leptons, there is another way to classify these particles: in terms of their isospin and hypercharge.

3.1.8 Isospin and Hypercharge Multiplets

All particles are characterized by their isospin and hypercharge, approximate symmetries relating them to one another. For example, the proton has a mass of $938.27\frac{\mathrm{MeV}}{c^2}$, and the neutron has a mass of $939.47\frac{\mathrm{MeV}}{c^2}$. This similarity in their masses suggest that there is an underlying fundamental connection between these two particles. In fact, proton and neutron share the same hypercharge but have different isospins. Particles connected via restricted values of the isospin and hypercharge are grouped into so-called multiplets. An example of a multiplet is shown in Figure. 4.

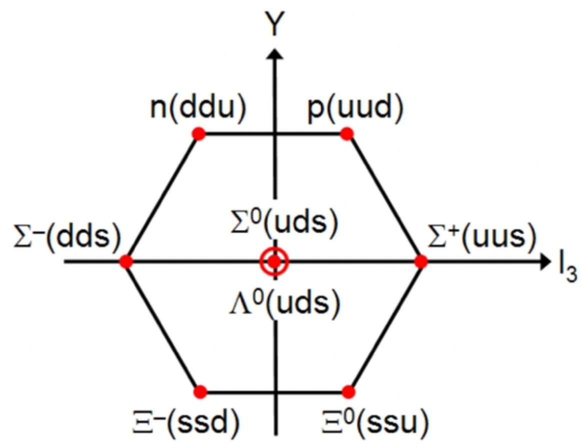

Fig. 4 An example of a multiplet where the x-axis is the isospin and the y-axis the hypercharge [20].

As shown in the Figure. 4., protons and neutrons belong to the same multiplet as the sigma, lambda and xi baryons.

Members of the same multiplet can transform into each other under a symmetry transformation. For example, the proton has an isospin number $\frac{1}{2}$, and the neutron has an isospin number $\frac{-1}{2}$. They can thus transform into one another by a rotation in isospin space.

The theory was first suggested along with the discovery of quarks by Physicist George Zweig [21]. He proposed a model in which hadrons (like protons and neutrons) were composed of fundamental particles, which he called "aces" which were later renamed as "quarks". He discussed how the strong interaction force has a symmetry- the isospin symmetry.

3.1.9 Fermions and bosons

Particles can also be categorized based on another internal symmetry- the spin. Although the analogy is not exact, the spin behaves in many ways like the more commonly observed angular momentum in classical mechanics. The two categories include the fermions and bosons.

Fermions are particles with $\frac{1}{2}$ integer spin values. Among them are baryons, such as protons and neutrons, and leptons. Bosons are particles with whole integer spins. These include the Higgs Boson (0 spin) and the photons, gluons, mesons, W and Z bosons (1 spin).

More about the properties of individual fermions and bosons can be read in section 2.2 of Ref. [22].

3.1.10 Decays

The most important step in understanding a particle's quark composition and formation process is analyzing its decay products.

Particles such as hadrons disintegrate into smaller components when they become unstable. This instability arises from the presence of heavier quarks or too great overall mass of the hadron. Above a certain mass threshold, hadrons lack the necessary energy to remain stable and hold all their constituents together. For example, the top quark is 175 times heavier than a proton, and accordingly has a much shorter predicted lifetime of about 5×10^{-25} second.

For this reason, it is also impossible for us to observe particles such as pentaquarks and tetraquarks naturally in our surroundings. They require huge amounts of energy to create, which can only be achieved under experimental conditions provided or under cosmological conditions, such as the Big Bang.

Decay processes are imperative to get an insight into a particle's nature. In the case of the discovery of the pentaquark, a decay of the B meson particle helped confirm its presence.

3.1.11 Unusual properties of the strange and charm quarks

To understand LHCb's 2022 discovery, it is essential to understand its unusual nature, related to the presence of strange and charm quarks.

Exotic hadrons, especially pentaquarks, are only ever formed through a combination of the lighter quarks, which require less energy to remain stable and allow detection. However, LHCb discovered its first-ever pentaquark with a strange (s) quark content. These formations are rare and require a lot of energy to develop. A formation of not only a heavy configuration, with five quarks, but also with one of these quarks being heavy itself, pushes forward the boundaries of experimental particle physics.

Additionally, the pair of tetraquarks observed were so-called 'open-charm'. Charm quarks usually form hadrons with a $c\bar{c}$ combination- the charm quark always has its anti-charm partner. However, the quark content of these newly found tetraquarks included a charm quark without its corresponding charm anti-quark and hence are referred to as 'open-charm' tetraquarks. As it is a first ever tetraquark with such a property, it is important in understanding the unusual properties of how the heavier quarks interact in forming exotic hadrons.

3.2 Collider Physics

3.2.1 General Information About Colliders

All the particles discussed so far were discovered by different types of particle accelerators.

Particle accelerators use electromagnetic fields to move particles at very high speeds and energies while containing them in beams that are later used for collider experiments.

Collider experiments are where the particle decays and their intermediate byproducts can be detected and analyzed. Modern particle colliders help us research the properties of these particles[23].

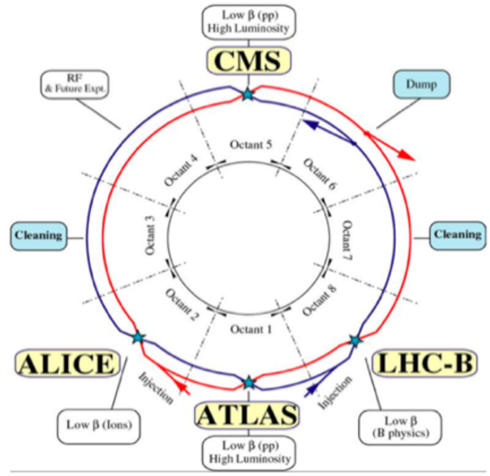

Fig. 5 Collider rings and detectors at the LHC[23].

3.2.2 Modern High Energy Particle Colliders

All beam collisions happen at the center-of-mass (CM) frame, where the total momentum of the colliding particles is zero. This means that no energy is lost to the surroundings during the experiment. In other words, the CM frames coincide with the lab frames to obtain the highest possible energy of particle collisions and ensure the kinetic energy of these particles is fully available for new particle creation and the study of interactions. Various types of colliders, such as the ring and linear colliders, are used for experiments.

3.2.3 Ring Colliders

Ring colliders, as the name suggests, are in the shape of a ring. They have two beams circulating in opposing directions around a roughly circular pipe. The places where the two beams meet allow for collisions that can be observed through the detectors.

A structure of the ring collider can be seen in Figure. 5. It is a schematic view of the LHC ring at CERN, Geneva along with a division of all the experiment groups such as ATLAS, CMS, LHCb.

Ring colliders allow for multiple collision points in an experiment and are relatively compact. However, the energy of the charge particles they accelerate is limited, due to severe energy loss to radiation. For this reason, linear colliders are used in very high energy electron-positron collisions.

3.2.4 Large Hadron Collider (LHC)

The focus of this research paper is the LHC as compared to other colliders since that is where the tetraquark and pentaquark discovery took place. It is a type of ring collider as seen in Figure. 5. previously.

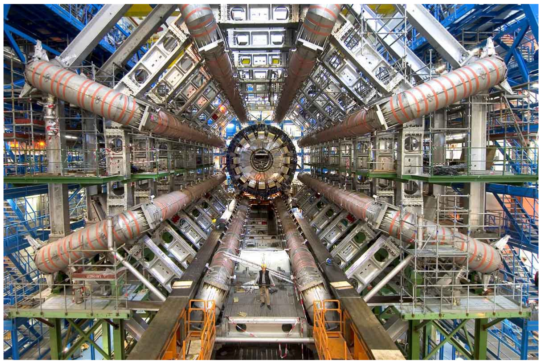

Fig. 6 The CMS detector at CERN[24].

The LHC is used for proton-proton collisions and allows for a study of composite particles such as hadrons as their byproduct. A picture of the CMS detector at CERN, a general-purpose detector, can be seen in Figure. 6. CMS measurements played a key role in informing the analysis of the pentaquark and tetraquarks discovery at LHCb.

3.2.5 Identifying the Presence of a Particle

Detectors are the components used in colliders to identify and observe the presence of a particle. Sensitive particle detectors are used where the beams in a particle collider meet to measure the product of these collisions and understand the particles present.

The beams are surrounded by detectors in the following order, starting from the inside towards the outside.

- **VX (vertexing) and TR (tracking)** - These detectors measure the tracks of charged particles passing through them (VX allows identification of b and sometimes c quarks)[25].

- **ECAL (electromagnetic calorimeter)** - It captures and measures the energies of electrons and particles which interact primarily electromagnetically. Usually made from a dense material, it forces the passing particle to deposit its energy in a form of a so-called shower. A shower is a chain reaction that occurs which in the case of electromagnetic showers produces secondary electrons, positrons and photons by their interaction with the dense material[5].

- **HCAL (hadronic calorimeter)** - Following a similar principle as ECAL, it captures and measure the energies of hadronic particles. It is optimised towards particles interacting via the strong force[26].

- **MC (muon chamber)** - They measure the passage of muons, which are very difficult to capture in other detectors. MC detects muons by measuring their momentum through the track's curvature (matched to VX and TR)[27].

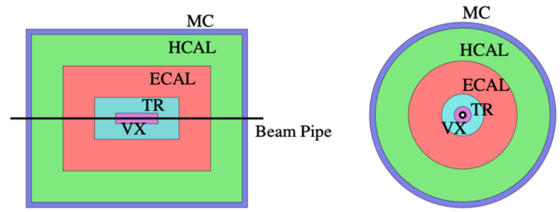

Fig. 7 Side (left) and cross-sectional (right) views of a typical particle detector[28].

- **Scintillator Counters** - Scintillators are instruments that measure the photons emitted by the ionized tracks left by a charged particle.

- **Cherenkov Detectors** - They measure the Cherenkov radiation. When a particle moves through a material at a speed faster than light speed in this medium, the energy it deposits ionises the atoms of the medium. Their deionisation produces a characteristic blue glow called the Cherenkov radiation[23].

All these detectors together combine to help understand particle collisions and products formed in the collider experiments. Shown in Figure. 7. is a cartoon model of a typical modern particle detector. It is roughly cylindrical around the beam. Its side view (on the left) and cross- section (on the right) visualize their relative placements. To further understand the complete process of the consecutive particle interactions and decays, a full reconstruction of particle decay processes must be done via the analysis of the data gathered.

3.2.6 Identification of Particles at LHC

The data from particle detectors requires graphical analysis and mathematical modelling. Additional information about the collision can be obtained by the secondary detectors like the Scintillator counters and Cherenkov detectors that help understand properties of the particles and narrow down their identity.

3.2.7 Invariant Mass Identification

One way to identify a particle is through the concept of invariant mass.

The invariant mass is a property that remains the same no matter how fast or in what direction a particle is moving.

If a particle were to decay into several other particles, the mass of the initial particle could be calculated as a sum of its decay particles' masses. This is provided that there are no other background particles or massless particles such as photons released in the process.

For instance, the Z boson is a particle that decays into a pair of muons- $(\mu+, \mu)$. The mass of the two muons can be calculated via the detectors from their energies and momenta. When plotting their masses, the peak indicates the invariant

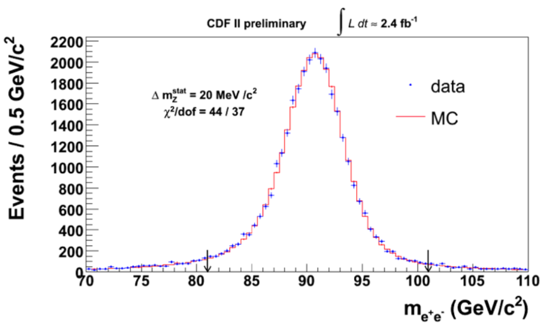

Fig. 8 Distribution of $\mu+\mu-$ events with respect to the dimuon invariant mass [23].

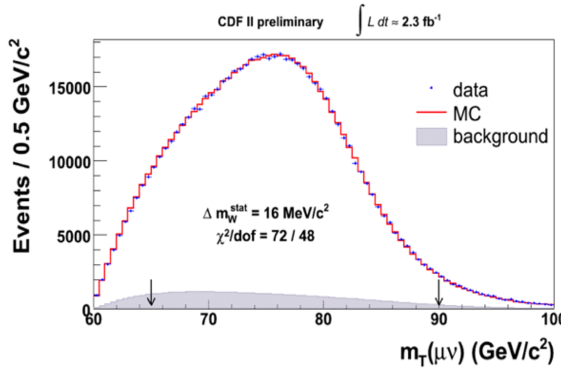

Fig. 9 Distribution of $W \to \mu\nu$ events with the transverse mass [23].

mass. In the case of a Z boson, it is about 92GeV, as seen in Figure. 8.

This process is called the Drell-Yan Process and can be used to identify other particles, such as the Higgs Boson. The invariant mass is hence an important concept in particle identification.

3.2.8 Transverse Mass Identification

Invariant mass cannot always be used to identify particles. This is because during a decay process there may be massless particles which are not taken into consideration through the invariant mass. Hence, we use another concept- the transverse mass.

The transverse mass is a concept used to calculate the "missing energy" which is present due to the massless or undetected particle in a decay.

For example, W bosons are produced through proton collisions and decay instantaneously. Common decay product for the W boson includes a charged lepton (like a muon or electron) and a neutrino.

Neutrinos do not interact with most particle detectors and cannot be measured in experiments. Hence, the energy and momentum of the charged lepton are compared with the missing neutrino to identify if the initial particle was the W boson.

The transverse mass is plotted in a similar way to the invariant mass. Here, the mass of the W boson is found via identifying the steepest ascent of the transverse mass of its decay products, as shown in Figure. 9.

3.2.9 Identifying top quarks

The top quarks are very heavy particles and require special attention during the particle detection.

The top quarks are mainly produced in $t\bar{t}$ pairs during the high energy proton collisions. Subsequently, they decay via the weak interaction, producing W bosons and bottom quarks. The reconstruction of top quarks takes place through hadronic channels (W bosons are identified), leptons + jets channels (where lepton, transverse energy and b-tagged jets are present), and dilepton channels (two lepton channels are analysed).

More about the reconstruction and identification of top quarks can be read in Ref. [29]

3.2.10 Dalitz Plot

The Dalitz Plot is a technique created to study complex particle decays with many constituents. It involves plotting the squares of the invariant masses of two pairs of decay products on a graph. These decay products are formed as a result of the decay of an unstable particle, such as a negatively charged B meson, into its lighter constituents, such as the J/ψ (J-psi) meson. The specific decay products depend on the nature of the initial particle and the forces involved and can be used to understand the intermediate states formed in the decay process.

Each point in the plot corresponds to a specific combination of the invariant masses of the decay products, providing insights into the dynamics of the decay process and the resonances involved.

Usually, the plot would show a uniform spread, which correspond to no resonance, which is not necessarily a typical feature in all decays. When intermediate particles briefly form during the decay, non-uniform features like vertical or horizontal bands are indicated as their intermediate resonances. They indicate which pairs of particles undergo an intermediate "resonance" before further decaying or interacting with the detector.

Crucial for the formation of the pentaquark was the process of the negative charged B meson decay. In this case, the negatively charged B meson ($b\bar{u}$) decays into a J/ψ meson ($c\bar{c}$), an antiproton ($\bar{p}$, and a Λ baryon (uds). In this case, a Dalitz plot can be made by the squares of invariant masses of the $J/\psi\bar{p}$ and the $J/\psi\Lambda$. As seen in Figure. 10., a Dalitz plot of this decay suggests that there is in fact the presence of an intermediate state as indicated by the presence of the horizontal and vertical bands.

3.2.11 Phase Space Analysis (phsp)

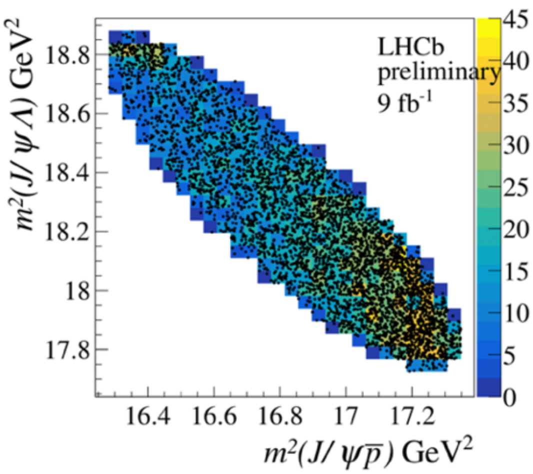

Fig. 10 A dalitz plot of the B meson decay [30].

Particle formation and decay can occur in various ways. Phase space is a mathematical concept that can be used in a phase space analysis, an experimental tool, to determine which particle formation is favored most in a decay process.

The phase space represents all possible ways a particle can decay, showcasing a range of momentum and energy states for the decay products. Phase space analysis helps interpret the distribution of these states, providing insights into the most likely particle formation in the decay. If there is no favored formation, the phase is usually flat-shaped in all possible graphs.

3.2.12 Amplitude analysis

The amplitude analysis is a complex mathematical framework that examines all possible interactions and contributions in a given region of particle energy.

In classical physics, amplitude refers to the maximum displacement or intensity of a wave from its equilibrium position. It is directly related to the energy carried by the wave, with larger amplitudes corresponding to greater energy.

In quantum mechanics, amplitude refers to a complex number associated with the probability of a system's state or outcome. The probabilities for specific decay channels can be calculated as the squared magnitude of the total sum of amplitudes, considered as complex numbers.

Amplitude analysis is related to the wave-particle duality of a quantum particle and depends on the concept of constructive and destructive interference. This interference can modify the amplitude of a decay process, sometimes amplifying certain channels while suppressing others. By accounting for these interferences, amplitude analysis provides a richer understanding of how particles behave in quantum systems. It captures the multiple interaction channels and how they may interfere with one another, providing insights into the fundamental nature of the interactions governing particle decays [31].

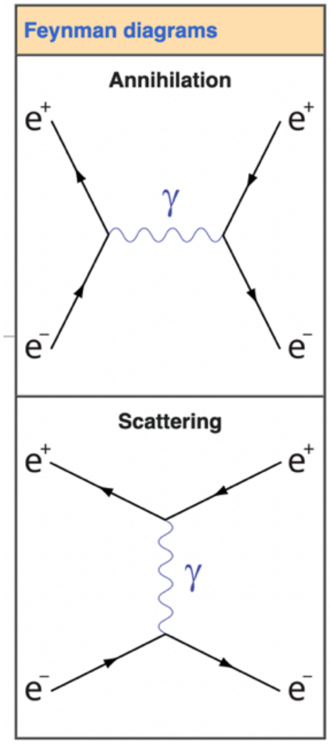

Fig. 11 The two Feynman diagrams that showcase the two ways an electron and positron can interact [33].

The experimental data can be used to analyze the underlying interactions by fitting the predicted behavior of the particles in the amplitude analysis to the measured data. This is achieved by adjusting certain parameters to best match the observed distribution of particles. Various sophisticated fitting methods are employed, such as the helicity formalism, which is particularly effective in analyzing spin-dependent processes. An example of this is the amplitude analysis used in studying the pentaquark's behavior, where the helicity formalism helped to understand the maximum likelihood fit [32].

There are many ways that channels may interfere. A simple example describing two of these processes can be seen through the Bhabha scattering [33], which describes the interaction between an electron and a positron.

$$e^+e^- \to e^-e^+$$

This process can be understood through two main Feynman diagrams, which depict different pathways of interaction between the particles: a scattering process and an annihilation process, as illustrated in Figure 11. These two processes can interfere, leading to subtle effects in the observed scattering cross-section.

Bhabha scattering has been used as a luminosity monitor in a number of e+e- collider physics experiments. The accurate measurement of luminosity is necessary for accurate measurements of cross sections. Computing the cross-section allows us to measure the width of the area, which is inversely proportional to the decay time of a decay process. Overall, the amplitude analysis provides a crucial framework for extracting detailed insights into particle interactions and advancing our understanding of a decay process.

3.2.13 Resonances

Some particles cannot be detected directly in a detector, like the neutrinos. Hence, indirect methods are used to understand the particle interaction in terms of its resonance.

Resonance occurs when an object is subjected to an oscillating force close to its natural frequency. When the two frequencies match, the amplitude of oscillations increases, leading to higher the interaction probability and the formation of the peaks at specific energies. Resonance essentially corresponds to a particle.

One of the indirect methods used include the cross-section concept. According to this, a probability that two elementary particles interact with each other is calculated. The graph shows an area that represents the likelihood of an interaction occurring, highlighting the specific energy at which resonance takes place. At this energy, the interaction probability increases significantly due to the formation of an excited state in the system. This results in a resonance peak in the cross-section curve when plotted against energy, which can be used to calculate the mass and width of the involved excited states. This provides insights into the particles involved in the interaction, helping to identify the nature of the resonant states formed during the decay process.

A peak is observed instead of a single value because the mass-energy equivalence indicates that most of the signal corresponds to the actual mass. However, signals at lower and higher masses are also observed, and these variations are accommodated by a difference in energy that is distributed to other constituents in the decay process.

These readings allow to calculate the lifetime of a particle through the width of the peak. A larger width indicates a faster decay process.

3.2.14 Statistical Significance

The statistical significance quantifies how likely the features in the data are to be attributed to the physical signal or just the background noise.

Typically, a value of greater than 5 standard deviations, or 5-sigma, is satisfactory to announce the formation of a new particle. In particle physics, sigma is the general threshold used to claim a discovery, often discussed with a link to confidence level. A 5-sigma result corresponds to a confidence level of approximately 99.99994%, indicating a highly significant result with an extremely low probability of being due to random chance.

This threshold is chosen in particle physics due to its precise quantitative measure and is a widely understood way to express the certainty of a measurement. Unlike confidence level which can be more subjective, sigma provides a concrete numerical value[34].

3.2.15 Signal yield and purity

The signal yield of a decay refers to the number of times this decay process was detected in the experiment in total.

The signal purity refers to the number of times a particular decay occurs in the process as compared to the total. A higher signal purity means that the decay was measured with minimum background noise (disturbance due to unrelated particles) and allows for precise data analysis.

3.2.16 Statistical and systematic uncertainty

Statistical uncertainty refers to a variation in measured readings due to the limited number of data points collected and number of events observed. Most data points are plotted with a 'line of best fit' which refers to an average of those data points on a graph. Because of this averaging, there are some data points that may deviate from the average leading to a statistical uncertainty in the value.

Systematic uncertainty refers to uncertainties that may arise due to the imperfection in the precision of machinery, such as the detectors. Specifically, when measuring small energy readings from interactions between specified particles, the uncertainty is higher due to the increased likelihood of error.

Additionally, quantum fluctuations are another factor that contribute to uncertainty. There is a fundamental limitation in measuring a quantum particle, which can be explained by Heisenberg's uncertainty principle. According to this principle, the position and momentum of a particle cannot be measured simultaneously with high precision. This is not a restriction due to the imprecision of the experimental measurement apparatus but an inherent reservation that prevents obtaining perfect measurements[35].

Due to these factors, there were statistical and systematic uncertainties in the measurement of the mass and width of the pentaquark and tetraquarks. The data related to each particle discovery are provided in the respective sections.

3.2.17 Confirming the discovery of a new particle

Many analyses are done to understand if a detected particle is, in fact, a new particle. collider data first goes through all the analyses mentioned so far to gain insights into the potential particle's properties, such as its mass, charge, velocity, energy, and momentum.

Furthermore, the events leading up to its formation are repeated multiple times to understand their different aspects Discovering exotic particles such as tetraquarks and pentaquarks can often be confused with the structure of hadronic molecules. For example, tetraquark-like bound states of two mesons can

Fig. 12 LHC at CERN[36].

imitate an actual particle with four quarks bound together. This means the tetraquark is not a new particle since it is made up of already existing particles. If the tetraquarks were to form through four quarks in a compact model (bound all together), they would be considered as new particles.

Therefore, when discovering exotic hadrons, it is important to understand whether the given particle is in a hadronic molecule or a compact state.

There were many experiments done to understand and confirm the new exotic particles discovered at LHC. More information on how this was done will be discussed in the discovery section.

3.2.18 LHC at CERN

CERN, the European Organization for Nuclear Research, is one of the most renowned particle accelerator centers in the world. Located near Geneva, Switzerland, it is a hub of innovation and discovery in the field of high energy physics.

It is known for having the world's largest particle accelerator- the LHC. Figure. 12. shows a layout of how big the LHC at CERN is. It spans the border of France-Switzerland near Geneva and is about 27 Kilometers (17 miles) in circumference. This vast scale allows particles to be accelerated to near the speed of light for the high-energy collisions which are necessary to observe and analyze particle interactions. It is located 100m underground to ensure the accuracy and reliability of its experiments, particularly when it comes to minimizing the impact of cosmic rays, high-energy particles that travel through space from distant galaxies, that could affect the readings taken by their detectors. These experimental conditions are crucial for any observation and analyses that takes place at the LHC, including the discovery of the pentquark and tetraquarks.

The groundbreaking discovery of the Higgs Boson particle took place at CERN's LHC in 2012. Since then, they have been making new discoveries including those of exotic particles. There are several major experiments at the LHC at CERN including the ATLAS, CMS, LHCb, and ALICE. Each of these collaborations are designed to study different aspects of particle

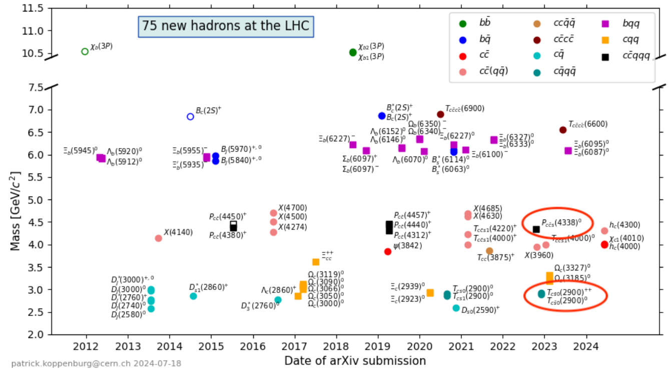

Fig. 13 The ATLAS, CMS, and LHCb collaboration has discovered these hadrons so far- the hadrons of this particular discovery have been highlighted[39].

physics.

To learn more about CERN and its discoveries, refer to Ref.[37].

To understand the discovery, LHCb will be the main point of this discussion. LHCb (Large Hadron Collider beauty) focuses specifically on studying the bottom quark (also known as the beauty quark), hence the name.

The LHCb collaboration has provided valuable data regarding rare decays that were previously undetected and have played a crucial role in advancing our understanding of particle physics.

We will be focusing on one of their discoveries that took place in 2022- the discovery of the three new exotic particles- the pentaquarks and the pair of tetraquarks.

4 LHCb discovers three new exotic particles

While it was observed how hadrons usually form in groups of twos and threes, very rarely are they formed in groups of fours and fives. In fact, it is only in the past 20 years that we have managed to observe and confirm the existence of these exotic hadrons.

So far, 75 hadrons have been discovered at the LHC, of which 67 have been found by LHCb. A visual representation of the hadron family discovered so far is included in Figure. 13. As shown, the pentaquark and pair of tetraquarks marked in red are the main subject of this review. In 2022, the first pentaquark with a strange (s) quark content and the first pair of tetraquarks with open-charm quarks were discovered. These exotic hadrons are significant in understanding how quarks combine.

The original announcement of this discovery by the LHCb can be read in Ref.[38].

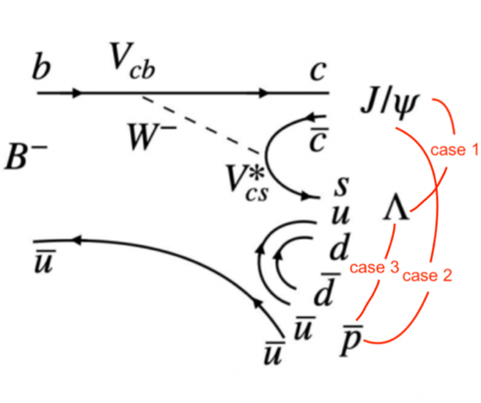

Fig. 14 Possible combination of quarks hypothesized to have formed the pentaquark through the negative B meson decay[40].

5 The First Ever Strange Pentaquark

5.1 About the Pentaquarks

The pentaquark discovered is composed of a charm, anticharm, up, down and strange quarks ($c\bar{c}uds$).

5.2 Decay Process

This pentaquark was discovered as a decay of the negatively charged B meson which is made of a bottom quark and an up antiquark ($b\bar{u}$). It was observed as a part of a $J/\psi\Lambda$ resonance in the following decay

$$B^- \to J/\psi\Lambda\bar{p}$$

The advantage of studying the B meson was that it decayed into multiple products which allowed for a good resolution of the invariant mass (the mass of a particle before it decayed) and a high signal purity. This led to a narrow resonant structure where the observed peak of the particles' interaction was sharp and well-defined and easily distinguishable.

When the decay of these B mesons was first observed, it was hypothesized that the pentaquark formed could include a combination of the $J/\psi\Lambda$, $J/\psi\bar{p}$, or $\Lambda\bar{p}$ particles. Figure. 14. shows the decay of the B meson and the possible ways in which these quarks could combine to form the pentaquark.

5.3 Phsp Analysis

To analyze which particle formation was favored most, a phase space (phsp) analysis at CMS (a Compact Muon Solenoid which is a general-purpose detector at the LHC) was done. However, this analysis failed to point towards one possible outcome as all graphs showcased an inconsistent flat phsp indicating that any of these decays was equally likely to happen. The phsp analysis at the CMS can be seen in Figure. 15. The mass projections that are seen could be described due to the presence of a K^* (excited resonances of kaon particles).

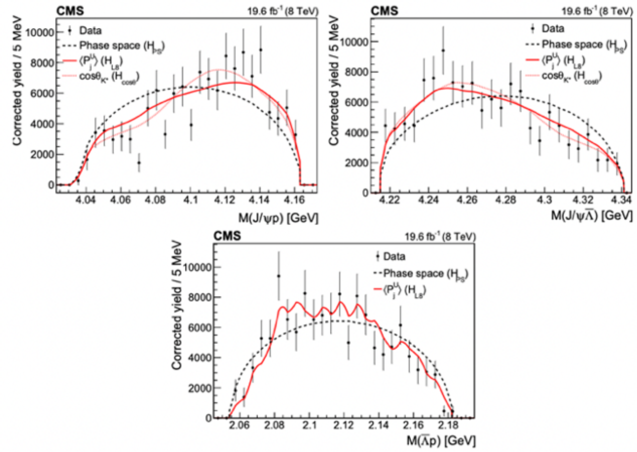

Fig. 15 the phsp analysis of the pentaquark particle with three possible cases of its formation[40].

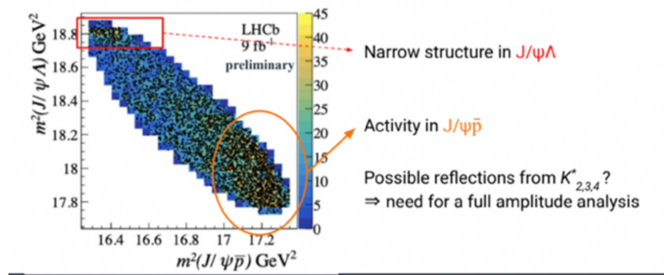

Fig. 16 The Dalitz Plot analysis of the pentaquark particle[40].

5.4 Dalitz Plot

Following this, LHCb analysed the full dataset of the $B^- \to J/\psi\Lambda\bar{p}$ signal candidates. A Dalitz plot analysis led to further queries. A picture of this Dalitz plot is shown in Figure. 16. (taken from the CERN seminar documents)

The graph refers to the narrow structure in the $J/\psi\Lambda$ region and a higher activity in the $J/\psi\bar{p}$ region which indicated no conclusion as to which decay channel is the main contributor.

The LHCb collaboration concluded that these readings observed might not be directly due to new or unknown particles, but rather could be reflections or indirect effects of the known K* meson. Hence, a full amplitude analysis was suggested.

5.5 Amplitude Analysis

The amplitude analysis with K^* showed peaks with $J/\psi\Lambda$ and $J/\psi\Lambda$, but had no obvious contribution in the $\bar{p}\Lambda$ distribution.

Similar studies of the model with $J/\psi\Lambda$ resonance were done which eventually showcased compatible results with the $J/\psi\Lambda$.

Hence, the pentaquark was determined to consist of a combination of the quarks from the J/ψ particles ($c\bar{c}$) and Λ (uds) partcles.

5.6 A Summary of the Experimental Findings

The negatively charged B meson was measured to have a mass of 5279.44MeV with a statistical uncertainty of 0.05MeV. A fit model was determined using a 1000 toy experiments to lead to the systematic uncertainty value of 0.07MeV. This pentaquark candidate is named $P\psi s\Lambda(4338)$. With a strange quark content of $c\bar{c}uds$, this was the first pentaquark to have a spin parity $\frac{-1}{2}$

According to the official CERN announcement of the discovery in Ref.[40], the pentaquark, $P\psi s\Lambda(4338)$, has a mass of 4338.2MeV with a statistical uncertainty of 0.7MeV and a systematic uncertainty of 0.4MeV and has a width of 7.0MeV with a statistical uncertainty of 1.2MeV and a systematic uncertainty of 1.3MeV. Table. 2. gives a systematic summary of these measurements.

However, there still remains a question whether this particle is indeed a compact particle or hadronic molecule. Many peaks close to the meson-baryon molecule threshold favor the molecular interpretation. Although, this cannot be discriminated from the data, LHCb plans on observing this decay process in s-wave. This refers to a specific type of particle interaction wherein, particles involved have zero angular momentum and collide head-on with no orbital rotations. This could help analyze further measurements of its detailed decay modes, energy dependence of its production cross-sections, and its interactions with other particles which should allow to answer the question regarding its nature.

Table 2 The Mass and Width of the pentaquark candidate, $P\psi s\Lambda(4338)$. The first uncertainty is statistical and second is systematic.

Particle	Mass (MeV)	Width (MeV)
$P\psi s\Lambda(4338)$	$4338.2 \pm 0.7 \pm 0.4$	$7.0 \pm 1.2 \pm 1.3$

6 The First Pair of Open-Charm Tetraquarks

6.1 About the Tetraquarks

The tetraquark candidates discovered at the LHCb have been observed in several B meson decays. The first one is a tetraquark with a quark content of $c\bar{s}u\bar{d}$, and is doubly electrically charged. The other consists of $c\bar{s}\bar{u}d$ quarks and is its neutral counterpart. The tetraquarks were observed in a joined analysis of the decay processes from the decay processes of positively charged and neutral B mesons.

The quark content of these two tetraquarks includes a charm quark without its corresponding charm antiquark and is hence referred to as an open-charm tetraquark. They are the first instance of a pair of tetraquarks that have been observed and are presumed to be a part of the same isospin multiplet.

$$T^{a}_{c\bar{s}0}(2900)^{++} \rightarrow D_s^+\pi^+ \text{ in } B^+ \rightarrow \bar{D}^- D_s^+ \pi^+$$
$$T^{a}_{c\bar{s}0}(2900)^{0} \rightarrow D_s^+\pi^- \text{ in } B^0 \rightarrow \bar{D}^0 D_s^+ \pi^-$$

Fig. 17 Figure. 17. the decay processes of the two tetraquarks- the doubly charged tetraquark and neutral tetraquark, respectively[40].

The decay processes of the two tetraquarks are as shown in equations (1) and (2) of Figure. 17. Equation (1) refers to the doubly charged tetraquark, and Equation (2) refers to the neutral tetraquark. They are further explained in their respective sections.

6.2 Doubly charged Tetraquarks

The B^+ meson decays into a negatively charged D anti-meson ($\bar{D}^-$) with a quark content of $c\bar{d}$, a positively charged strange D meson (D_s^+) with a quark content of $c\bar{s}$, and a positively charged pion (π^+) with a quark content $u\bar{d}$. In the intermediate state of this decay, the doubly charged tetraquarks are formed with the positively charged strange D meson and the positively charged pion.

The full dataset for these two decays was taken in Run 1 and Run 2. These Runs refer to the distinct periods of data collection during which experiments were conducted at the LHC. Run 1 refers to the initial phase of data taking at the LHC, which started in 2010 and ran until early 2013 and Run 2 refers to data collected from mid-2015 through the end of 2018. In the decay of the B^+ mesons, the signal yield was 3751. The purity of this event was 95.2%. This showcases that the detected signal was high as compared to the background events.

The Dalitz plot is presented in Figure. 18. The Dalitz plot of the two decay products, in the case of the doubly charged tetraquarks, shows a clear vertical band at $6GeV^2$ and a faint horizontal band at $8.5GeV^2$ that indicate the presence of this tetraquark candidate.

6.3 Neutral Tetraquarks

Similarly, in the case of neutral tetraquarks, they are formed in the intermediate state of the B^0 meson decays. The B^0 decays into a D anti-meson ($\bar{D}^0$) with a quark content of $\bar{c}u$, a positively charged strange D meson (D_s^+) with a quark content of $c\bar{s}$, and a negatively charged pion (π^-) with a quark content $\bar{u}d$. The neutral tetraquark consists of the positively charged strange D meson and negatively charged pion.

The signal yield for the neutral tetraquark was measured to be 4008 with a purity of 90.7%. Again, a Dalitz plot of the constituent particles of the tetraquark candidate affirm its presence

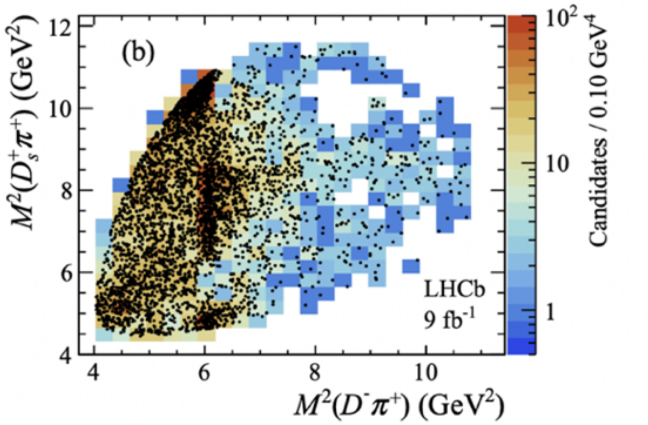

Fig. 18 Figure. 18. A Dalitz plot of the doubly charged tetraquark[41].

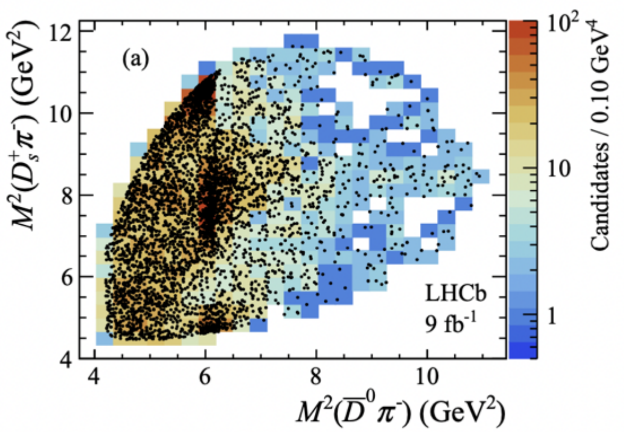

Fig. 19 A dalitz plot of the neutral tetraquark[41].

with a clear vertical band at 6GeV2 and a faint horizontal band at 8.5GeV^2. this can be seen in Figure. 19. below.

6.4 Joined amplitude analysis

Additionally, a joint amplitude analysis was done due to the presence of possible multiplets in the two decays as indicated by their similar masses. This analysis revealed common parameters between the two channels. LHCb used the strategy of comparing their resonances with the D^{**} mesons and then added the $D_s\pi$ to look for potential partners of these tetraquarks.

6.5 A Summary of the Experimental Findings

According to LHCb collaboration's paper regarding the amplitude analysis of the two tetraquark decays in Ref.[41], The doubly charged tetraquark and the neutral tetraquark candidates are named $T^a_{c\bar{s}0}(2900)^{++}$ and $T^a_{c\bar{s}0}(2900)^0$ respectively. The $T^a_{c\bar{s}0}(2900)^{++}$ has a quark content of $c\bar{s}u\bar{d}$ and the $T^a_{c\bar{s}0}(2900)^0$ has a quark content of $c\bar{s}\bar{u}d$. Both states are found to have spin-parity 0+, and their resonant characteristics are similar, suggesting that they belong to an isospin triplet.

The $T^a_{c\bar{s}0}(2900)^{++}$ has a mass of 2.935GeV with a statistical uncertainty of 0.021GeV and a systematic uncertainty of 0.013GeV, and a width of 0.143GeV with a statistical uncertainty of 0.038GeV and a systematic uncertainty of 0.025GeV. The $T^a_{c\bar{s}0}(2900)^0$ has a mass of 2.879GeV with a statistical uncertainty of 0.017GeV and a systematic uncertainty of 0.018GeV, and a width of 0.153GeV with a statistical uncertainty of 0.028GeV and a systematic uncertainty of 0.020GeV. Table. 3. gives a systematic summary of these measurements.

With the ongoing data collection, there are prospects for discovering other particles that could fit this multiplet, like one made of a positively charged strange D meson and a neutral pion. The theoretical understanding of the isospin structure allows for a more directed search for new particles fitting the multiplet.

Table 3 Table. 3. The Masses and Widths of the tetraquark candidates, $T^a_{c\bar{s}0}(2900)^{++}$ and $T^a_{c\bar{s}0}(2900)^0$. The first uncertainty is statistical and second is systematic.

Particle	Mass (GeV)	Width (GeV)
$T^a_{c\bar{s}0}(2900)^{++}$	$2.935 \pm 0.021 \pm 0.013$	$0.143 \pm 0.038 \pm 0.025$
$T^a_{c\bar{s}0}(2900)^0$	$2.879 \pm 0.017 \pm 0.018$	$0.153 \pm 0.028 \pm 0.020$

7 Outlook

7.1 LHCb's future plans

LHCb's objective now is to further study these tetraquarks and pentaquarks and understand their properties.

As mentioned earlier, the nature of the pentaquark, particularly whether it is a compact particle or a hadronic molecule, could be explored with further investigation into its decay process in s-wave, examination of cross-sections, and interactions with other particles.

Additionally, the ongoing data collection for the tetraquarks presents exciting prospects for discovering additional particles that could complete the predicted multiplet, such as those formed from a positively charged strange D meson and a neutral pion. Theoretical insights into the isospin structure could offer a more targeted approach to uncovering new particles within this multiplet.

The pentaquark is not just any new particle," said LHCb spokesperson Guy Wilkinson. "It represents a way to aggregate quarks, namely the fundamental constituents of ordinary protons and neutrons, in a pattern that has never been observed before in over fifty years of experimental searches. Studying its properties may allow us to understand better how ordinary matter, the protons and neutrons from which we're all made, is constituted."

LHCb is now boosting its data to a new level and detector and collider upgrades are under way. Many new hadronic particles are expected to be discovered and explored in the coming runs.

7.2 Beyond the Standard Model

This discovery of new exotic particles pushes the boundary of the Standard Model[42]. It is an indication of the numerous possibilities in the ever-growing hadron list and a sign of the technological progress accompanying the discoveries.

While the Standard Model is a powerful tool into understanding the fundamental constituents and their interactions, it fails to take into consideration certain phenomenon that limit our understanding in the world of not only particle physics, but also astrophysics. For example, the elusive nature of dark matter, the surprisingly low mass of the Higgs Boson, and the perplexing characteristics of neutrino masses. Various theoretical interpretations have been proposed to address these gaps in our understanding, including concepts like Supersymmetry (SUSY), Weakly Interacting Massive Particles (WIMPs), and other hypotheses[43]. This discovery helps us gain insights into certain unexplained theories, such as the matter antimatter asymmetry.

One of the famous concepts that is yet to be explained is the matter-antimatter imbalance. Every particle has a corresponding antiparticle, meaning all existing particles should be annihilated with their corresponding antiparticle. However, the very existence of our planet Earth indicates that there is more matter than antimatter. The theory is that during the Big Bang, there must have been an imbalance in the number of particles and antiparticles, which caused the prevalence of matter around us.

A more in depth understanding of how the quarks and antiquarks combine, for instance withing the tetra and pentaquarks, can be a further step towards answering this unsolved problem.

7.3 Understanding the Early Universe

Briefly after the Big Bang theory, quarks could freely roam around without being confined into specific structures (for approximately for one-millionth of a second). The entire universe consisted of a highly energetic quark-gluon plasma.

As the universe started cooling down, the quarks assembled into composite particle. Since the energy available for the particle formation was still very high, the exotic hadrons, tetra- and pentaquarks among them, must have proliferated the early universe.

Our understanding of these discovered particles is effectively a lens into the conditions of the early universe and the origins of the physical principles of matter and its interactions.

8 Conclusion

This paper discussed the Standard Model of particle physics and collider physics to provide relevant theoretical background for the discovery that took place at the LHCb CERN in 2022. It focuses on the characteristics of the strange pentaquark ($c\bar{c}uds$) and the pair of open-charm tetraquarks ($c\bar{s}u\bar{d}$ and $c\bar{s}\bar{u}d$) as part of the discovery, along with an analysis of the process that led to their identification. The strange pentaquark contains a strange quark, which is one of the heavier quarks not typically found in pentaquark formations, while the pair of tetraquarks features open-charm quarks, both of which are unique properties that are discussed to understand the significance of these particles. This discovery is an important milestone in the progress of high-energy physics and, in particular, the ways in which exotic hadrons can be formed. It may help us gain insights into theories concerning the early universe and the matter-antimatter imbalance.

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