Introduction: Phenomenological and Experimental Review of $X(3872)$

Escalation in the number of fundamental particles during 1940’s provided a strong challenge to the intellectual minds to create a model which can categorize these observed states, explain their properties along with the prediction of new states. Fermi and Yang, in 1949, thought of describing all the resonances as proton-neutron bound states, and Sakata extended this model to include newly discovered strange quark in 1956. Later on Gell-Mann and Zweig independently develop what we know today as the “Constituent Quark Model (CQM)”. CQM remains a valid effective theory for classifying hadrons (Mesons $[q\bar{q}]$ and Baryons $[qqq]$), even after the introduction of heavy quarks ($c$, $b$, $t$). However, recently discovered states seem not to fit into the conventional mesons and baryons model: in particular, their internal structure seems to be different from conventional $[q\bar{q}]$ and $[qqq]$. From first principle tetraquark, pentaquark, mesonic molecules, hybrid states and glueballs are also allowed because Quantum Chromodynamics (QCD) is non-abelian in nature. Since none of these states have been observed for a long time after the theories were first published (around mid-1960s), it was chosen to label every non-basic state (except $[q\bar{q}]$ and $[qqq]$) as “exotic” state. Great excitement in hadron spectroscopy has come from the recent discovery of a whole host of unexpected states by the meson factories (specifically $B$-
CHAPTER 1. INTRODUCTION: PHENOMENOLOGICAL AND EXPERIMENTAL REVIEW OF $X(3872)$

factories), Belle and BaBar. These new states are called “charmonium-like states”, not because they naturally fit into the spectrum of charmonium states, but because they seem to always decay into final states containing a charm quark and an anticharm quark.

The $X(3872)$, is such charmonium-like “exotic” state, was discovered by the Belle experiment (KEK, Japan) in 2003. It has attracted much theoretical and experimental interest because its properties don’t match any expected state of charmonium spectroscopy and is a strong candidate for exotic states, which further opened the possibilities to more “exotic” interpretations. In this Chapter, we will first briefly review the concepts of the Standard Model (SM) and the Quark Model, with particular emphasis on the $c\bar{c}$ meson. The proposed theoretical models and known experimental facts on the $X(3872)$ will also be given in detail.

1.1 Standard Model

The Standard Model of particle physics is a Quantum Field Theory (QFT) describing the fundamental interactions between elementary particles. These basic interactions are Electromagnetic interaction, Weak interaction and Strong interaction. Gravitational force is not included in the SM. As it is insignificant at the level of particle physics, or at least at energies currently accessible in the laboratory.

The gauge symmetry group of the SM is $SU(3)_C \times SU(2)_L \times U(1)_Y$. $SU(3)_C$ is the symmetry group describing the strong (color) interactions, whereas $SU(2)_L \times U(1)_Y$ represents the symmetry group of the electro-weak sector describing the weak and electromagnetic interactions. The particle content of the model may be broadly classified in terms of two groups, namely the fundamental fermions (spin $\frac{1}{2}$) and the gauge vector bosons (spin 1). The fundamental fermions are in turn subdivided into two parallel classes of particles called quarks and leptons. There are three generations of quarks \{1$^{\text{st}}$ generation: [up ($u$), down ($d$)], 2$^{\text{nd}}$ generation: [charm ($c$), strange ($s$)], 3$^{\text{rd}}$ generation: [top ($t$) and bottom or beauty ($b$)]\}, with each type of quark exhibiting a further internal degree of freedom called color. A quark can take one of
the three colors (green, red, blue), while an antiquark takes an anticolor. The strongly interacting particles, actually observed in nature, are composites of the quarks and are collectively referred to as hadrons. Again, the hadrons are further classified as being either mesons or baryons. Table 1.1 list the known quarks as described by the SM. The leptons also come in three different families or generations and include: the electron, the muon, the tau and their corresponding neutrinos. Table 1.2 list the known leptons as described in the SM. The forces between above stated elementary particles are mediated by the gauge vector bosons. There are two basic theories which describe these interactions.

### Table 1.1: Properties of Quarks in the SM [1].

<table>
<thead>
<tr>
<th>Quark Flavor</th>
<th>Quark Charge</th>
<th>Quark Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>+2/3</td>
<td>2.3^{+0.7}_{-0.5} (in MeV/c^2)</td>
</tr>
<tr>
<td>Down</td>
<td>−1/3</td>
<td>4.8^{+0.5}_{-0.3} (in MeV/c^2)</td>
</tr>
<tr>
<td>Charm</td>
<td>+2/3</td>
<td>1275 ± 25 (in MeV/c^2)</td>
</tr>
<tr>
<td>Strange</td>
<td>−1/3</td>
<td>95 ± 5 (in MeV/c^2)</td>
</tr>
<tr>
<td>Top</td>
<td>+2/3</td>
<td>173.21 ± 0.87 (in GeV/c^2)</td>
</tr>
<tr>
<td>Bottom</td>
<td>−1/3</td>
<td>4.18 ± 0.03 (in GeV/c^2)</td>
</tr>
</tbody>
</table>

### Table 1.2: Properties of Leptons in the SM [1].

<table>
<thead>
<tr>
<th>Lepton</th>
<th>Charge</th>
<th>Lepton Mass (MeV/c^2) (central Value)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ν_e</td>
<td>0</td>
<td>&lt; 2.0 × 10^{-6}</td>
</tr>
<tr>
<td>e</td>
<td>−1</td>
<td>0.511</td>
</tr>
<tr>
<td>ν_μ</td>
<td>0</td>
<td>&lt; 0.19</td>
</tr>
<tr>
<td>μ</td>
<td>−1</td>
<td>105.66</td>
</tr>
<tr>
<td>ν_τ</td>
<td>0</td>
<td>&lt; 18.2</td>
</tr>
<tr>
<td>τ</td>
<td>−1</td>
<td>1776.82</td>
</tr>
</tbody>
</table>

### 1.1.1 Quantum Chromodynamics

Quantum chromodynamics is the theory of strong or nuclear interactions. This interaction is fundamental one, which describes the interactions between quarks and
gluons. The strong or nuclear interaction between quarks and gluons is described in terms of the gauge particles of $SU(3)_C$. These gauge vector bosons are $3^2 - 1 = 8$ in number and are called gluons. Gluons carry both a color and an anticolor. The $SU(3)_C$ symmetry of the color interaction is believed to be exact, so gluons are massless particles. However, the non-abelian nature of the color symmetry allows for these gluons to interact among themselves as well as mediate the strong nuclear force between the quarks. Theory of this sector is referred to as QCD [2]. Since no free quarks have ever been observed, it is postulated that only color-singlet states (the composite hadrons) can exist in nature. It is believed that QCD implies this requirement, known as color confinement. The color confinement principle requires hadrons to be colourless. The strength of the strong interaction is quantified in terms of the strong interaction coupling constant, $\alpha_s$. Unlike the situation in Quantum Electrodynamics (QED), which is an abelian gauge field theory, an important consequence of the non-abelian nature of QCD is that $\alpha_s$ actually decreases with decreasing distance between strongly interacting partons (a generic term used to refer collectively to the quarks and gluons). This color anti-screening effect is called asymptotic freedom.

1.1.2 Electro-Weak Theory

The electro-weak sector of the SM is referred to as the Glashow-Weinberg-Salam (GWS) Model (in honor of the main architects of the theory) [3]. It is a gauge theory that unites the weak and electromagnetic interactions. The gauge symmetry group $SU(2)_L \times U(1)_Y$ requires $2^2 - 1 + (1^2) = 4$ massless gauge vector bosons. However, in order to describe weak interactions phenomenology, it is required that the vector bosons mediating this force acquire a non-zero mass. This is accomplished through the process of spontaneous symmetry breaking [4], which is implemented via the so-called Higgs mechanism [5]. The Higgs mechanism requires the introduction of scalar field. By allowing the scalar field to acquire a non-zero vacuum expectation value, 3 of the 4 gauge vector bosons acquire a mass and these are identified with the $W^+, W^-$ (mediating charged-current weak interactions), and the $Z^0$ (mediating the neutral-current weak interactions). The remaining massless gauge vector boson is identified
1.1. STANDARD MODEL

with the photon, $A$ (mediating the electromagnetic interactions). There remains one neutral scalar field which is called the Higgs Boson and recently observed by CMS [6,7] and ATLAS [8]. Table 1.3 presents a summary of the gauge vector bosons involved in the SM, known interactions of quarks and leptons.

Table 1.3: Properties of SM interactions and forces mediating bosons.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Acts on</th>
<th>Particle</th>
<th>Gauge vector bosons with their masses (GeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak</td>
<td>Flavor</td>
<td>Quarks, Leptons</td>
<td>$W^\pm$: 80.385 ± 0.015,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>$Z$: 91.1876 ± 0.0021</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>Electric charge</td>
<td>Charged particles</td>
<td>$\gamma$: &lt; 1.0 × 10⁻²⁷</td>
</tr>
<tr>
<td>Strong</td>
<td>Color charge</td>
<td>Quarks, Gluons</td>
<td>Gluons: 0</td>
</tr>
</tbody>
</table>

Although the SM successfully describes many aspects of high energy interactions, but still it is not complete. The model contains a large number (17) of free parameters. Further, the SM itself does not unite the strong interactions with the weak and electromagnetic in the same way that the Glashow-Weinberg-Salam model has united the weak and electromagnetic forces. There have been many attempts to unite all these forces to make Grand Unified Theory (GUT) [9]. In this sense, the SM is viewed as the low energy manifestation of the other fundamental theory which should take over at higher energies (i.e. shorter distances).

1.1.3 Discrete Symmetries

Symmetries play an important role in the SM. For each continuous symmetry, there is a corresponding conserved quantity. In the SM of particle physics, there are three related discrete symmetries.

**Parity (P):** Parity flips the sign of all spatial coordinates. In a three dimensional space, it is described as $P(x, y, z) \rightarrow (-x, -y, -z)$.

**Charge Conjugation (C):** This type of symmetry replaces each particle by its corresponding antiparticle.
CHAPTER 1. INTRODUCTION: PHENOMENOLOGICAL AND EXPERIMENTAL REVIEW OF X(3872)

Time Reversal (T): The time reversal operator leaves the spatial direction unchanged, but reverses the momentum and angular momentum. Time invariance implies that the physics does not change if the direction of time is made to run backwards instead of forward.

Among the above three discrete symmetries, charge conjugation has been known to be violated from the beginning because people found no left-handed anti-neutrinos, which are the charge conjugate partners for the left-handed neutrinos.

Parity conservation, on the contrary, was believed to be one of the fundamental conservation laws along with conservation of energy and momentum. This concept changed in 1957, when the study of beta decay of Cobalt-60 nuclei experiment, carried out by a group led by Chien-Shiung Wu, demonstrated conclusively that the parity symmetry is violated [10]. They found that when a specific nucleus was placed in a magnetic field, electrons from the beta decay were preferentially emitted in the direction opposite to that of the aligned angular momentum of the nucleus. Under the Parity transformation, however, it would look like the electrons prefer to be aligned with angular momentum, since the Parity transformation flips the direction of the electron but not that of the angular momentum. As a result, parity is not conserved.

Although charge conjugation and parity are violated separately, the symmetry of a quantum-mechanical system can still be restored if the combined symmetry CP remains unbroken. For example, a left handed neutrino, under the CP transformation will be turned into a right handed anti-neutrino, which exists. Therefore CP symmetry was proposed in 1957 by Lev Landau as the true symmetry between matter and antimatter.

Until 1964, it was thought that the combination CP was a valid symmetry of the universe. That year, Christenson, Cronin, Fitch, and Turlay observed the decay of the long-lived neutral K meson to pair of pions as well as three pions and thus concluding that CP symmetry is violated in the kaon system [11]. Now after B-factory data analysis, a large number of CP violation processes in B-meson system have been observed [1], which occurred by weak interactions.
Although $C, P$ and $CP$ are proven to be broken symmetries, the product $CPT$ is firmly believed to be conserved till now. It is fundamental property of the Quantum Field Theory.

1.2 The Quark Model

Quarks are confined within composite particles called hadrons and bound by the strong interaction field. The quark model is a classification scheme for hadrons in terms of their valence quarks. Mainly there are two common types of hadrons: Baryons and Mesons.

1.2.1 Baryons

Baryons are composed of three quarks having unit baryon number. Their antiparticles are antibaryon having baryon number opposite to the previous one. Proton ($p$), neutron ($n$), lambda ($\Lambda$) etc. are examples of baryons.

1.2.2 Mesons

Mesons are composed of a quark-antiquark pair and thus have zero baryon number. Each meson has a corresponding antimeson, where quarks are replaced by their corresponding antiquarks and vice-versa. For example, the $B^0$ particle is a bottom meson, composed of a down quark ($d$) and a bottom antiquark ($\bar{b}$). Similarly, the $B^+$ meson is composed of an up quark ($u$) and a bottom antiquark ($\bar{b}$). The $D^{*0}$ and the $D^0$ are charmed mesons both composed of a charm quark ($c$) and an up antiquark ($\bar{u}$). Other particles which appear in this thesis, such as kaons and pions, are also mesons and composed of the lighter quarks ($u$, $d$ and $s$ quarks).

1.2.3 Quarkonium

A flavorless meson composed of a heavy quark and its own antiquark is called a quarkonium. So quarkonia are mesons with hidden flavor. It is called a bottomonium
CHAPTER 1. INTRODUCTION: PHENOMENOLOGICAL AND EXPERIMENTAL REVIEW OF $X(3872)$

if it is a $b\bar{b}$ meson, such as the $\Upsilon(4S)$ produced at Belle; or a charmonium if it is a $c\bar{c}$ meson like the $J/\psi$, $\psi(2S)$ etc. Charmonium states have masses around 3 GeV/$c^2$, while the bottomonium states have masses around 10 GeV/$c^2$. The toponium doesn’t exist, because the top quark is so heavy that it decays before the formation of a bound state.

1.3 Charmonium

First charmonium state was discovered in November 1974, when two experimental groups at SLAC and Brookhaven announced almost simultaneously the observation of a new narrow resonance, called $J/\psi$ [12]. This was followed very shortly by the discovery of another narrow state by the SLAC group, which was called $\psi'$ [13], which is radial excitation of $J/\psi$. These two resonances were interpreted as bound states of a new quark, called charm ($c$) quark and its antiquark ($\bar{c}$), whose existence had been predicted several years before to account for the non existence of strangeness changing neutral currents [14]. Since then charmonium has proven to be a powerful tool for the understanding the strong interactions.

Heavy quark combinations such as the charm-anticharm (called charmonium) is in particular interesting, as they can be treated (a) as non-relativistic systems and (b) perturbatively due to $m_Q \gg \Lambda_{QCD}$, where $\Lambda_{QCD} \approx 200$ MeV is the QCD scale.

Charmed quarks are heavy ($m_c \approx 1.3$ GeV/$c^2$), so the motion of the charm quark inside the bound states is slow, $v^2 \approx 0.3$, where $v$ is the relative velocity between the $c$ and $\bar{c}$. Thus charmonium system can be approximately considered as a non-relativistic bound state. The potential has two terms for short distance (1st term represents asymptotic freedom) and long distance (2nd represents confinement) [15].

$$V(r) = -\frac{4\alpha_s}{3} \frac{1}{r} + kr. \quad (11)$$

The above simplest form of potential model does not include spin dependent central potential. Here first term is coulomb like potential which is due to single gluon exchange. This term is very similar to the Coulomb term in QED potentials e.g.
positronium or the hydrogen atom, except that here the coupling constant is given by $\alpha_s$ instead of $\alpha_{em}$. Second term is for confinement of quarks within hadrons, which is because of non-abelian nature of QCD and it is completely absent in QED. Here parameters like $\alpha_s$ and $k$ can be determined from fit to data. Using the above potential, charmonium spectrum is quite well reproduced (predicted $\psi''$ state). The non-relativistic treatment only describe feature of charmonium levels (without resolving the fine splitting between states with the same $L$ and $S$ quantum numbers but different $J$, and the hyperfine splitting between the spin-triplet and spin-singlet states).

If we include spin-dependent interaction term in Equation 1.1, then the total potential will become:

$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr + \frac{32\pi \alpha_s}{9m_c^2} \tilde{\delta}_s(r) \vec{S}_c \cdot \vec{S}_{\bar{c}} + \frac{1}{m_c^2} \left( \frac{2\alpha_s}{r^3} - \frac{k}{2r} \right) \vec{L} \vec{S} + \frac{1}{m_c^2} \left( \frac{4\alpha_s}{r^3} \left( \frac{3\vec{S}_c \cdot \vec{r} \cdot \vec{S}_{\bar{c}}}{r^2} - \vec{S}_c \cdot \vec{S}_{\bar{c}} \right) \right). \tag{1.2}$$

Here the spin-spin term gives the spin-singlet splitting, while spin-orbit and the tensor terms describe the fine structure of states. and $\tilde{\delta}_s(r) = \left( \sigma / \sqrt{\pi} \right)^3 e^{-\sigma^2 r^2}$ and $(\alpha_s, k, m_c, \sigma)$ can be determined by fitting the spectrum [16].

After only including a Gaussian-smeared contact hyperfine interaction in the zeroth-order potential in non-relativistic potential in Equation 1.1, the central potential becomes

$$V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr + \frac{32\pi \alpha_s}{9m_c^2} \tilde{\delta}_s(r) \vec{S}_c \cdot \vec{S}_{\bar{c}}. \tag{1.3}$$

The Godfrey-Isgur model is a “relativized” extension of the non-relativistic model. This model assumes a relativistic dispersion relation for the quark kinetic energy, a QCD motivated running coupling $[\alpha_s(r)]$, a flavor-dependent potential smearing parameter $\sigma$, and replaces factors of quark mass with quark kinetic energy [17]. The Hamiltonian consists of a relativistic kinetic term and a generalised quark-antiquark
potential

\[ H = H_0 + V_{qq}(\vec{p}, \vec{r}). \]  

(1.4)

where

\[ H_0 = \sqrt{\vec{p}_q^2 + m_q^2} + \sqrt{\vec{p}_{\bar{q}}^2 + m_{\bar{q}}^2}. \]  

(1.5)

Just as in the non-relativistic model, the quark-antiquark potential \( V_{qq}(\vec{p}, \vec{r}) \) assumed here incorporates the Lorentz vector one gluon exchange interaction at short distances and a Lorentz scalar linear confining interaction. To first order in \((v_q/c)^2\), \( V_{qq}(\vec{p}, \vec{r}) \) reduces to the standard non-relativistic result given by Equation 1.3 [with \( \alpha_s \) replaced by a running coupling, \( \alpha_s(r) \)]. One important aspect of this model is that it gives reasonably accurate results of the spectrum for all quark flavors \( u, d, s, c, b \), whereas the non-relativistic model is only fitted to \( c\bar{c} \) system.

### 1.3.1 Charmonium Production

Charmonium states are produced in a variety of ways at \( e^+e^- \) colliders. The earlier studies of charmonium spectroscopy were performed almost exclusively at \( e^+e^- \) colliders. In these experiments \( e^+e^- \) annihilation proceeds primarily through an intermediate virtual photon, creating a bound \( c\bar{c} \) state. Other production mechanisms include \( B \)-meson decay, two virtual photon production (photon-photon fusion), initial state radiation and double charmonium production.

- **\( e^+e^- \) Annihilation or Direct formation**

  In \( e^+e^- \) annihilations, direct charmonium production is allowed only for states with the quantum numbers \( J^{PC} = 1^{--} \), namely the \( J/\psi, \psi', \psi(3770) \) etc. shown in Figure 1.1(a). Precise measurements of the masses and widths of these states can be obtained from the energy of the electron and positron beams, which are known with good accuracy. All other states can be produced by radiative decays of the \( J^{PC} = 1^{--} \) resonances.

\[ e^+e^- \rightarrow \psi(2S) \rightarrow \gamma + X. \]  

(1.6)
1.3. CHARMONIUM

- **B-meson decay**

Charmonium states can be produced at the B-factories in the color suppressed decays of the B-meson shown in Figure 1.1(b). The large data samples available at the B-factories make this a promising approach for the study of known states, as well as the discovery of new resonances: X(3872), X(3940), Y(3940), Z(4430)$^+$ etc. are recent examples which illustrate well the discovery potential of the B-factories in the field of charmonium physics. The decays of the B-meson provide a clean production environment for charmonium production and states of any quantum number can be formed. The small production rates can be overcome by restricting the study to specific exclusive final states, to take advantage of variables like: the B-meson mass, beam energy constraints etc. Decay modes under search in this thesis are propagated through this mode of production. e.g. $B^0 \to \psi'K^+\pi^-$, $B^0 \to X(3872)K^+\pi^-$, $B^+ \to \psi'K_S^0\pi^+$, $B^+ \to X(3872)K_S^0\pi^+$, $B^+ \to \psi'K^+\pi^0$ and $B^+ \to X(3872)K^+\pi^0$ decay modes.\(^1\) We will exploit these decay modes in order to study the production of $X(3872)$ in $B \to X(3872)K\pi$ decays.

- **Photon-photon ($\gamma\gamma$) fusion**

Electron-positron annihilations at higher energies can produce the $J$-even ($0^{--}, 0^{++}, 2^{-+}$ and $2^{++}$) charmonium and charmonium-like states through two virtual photons via the process:

$$e^+e^- \to e^+e^- + (c\bar{c}).$$

as shown in Figure 1.1(c). The production rate in this case decreases by a factor $\alpha^2$ from the rate for a single photon, where $\alpha$ is the fine structure constant. The $(c\bar{c})$ state is usually identified by its hadronic decays. The cross section for process in Equation 1.7 scales linearly with the $\gamma\gamma$ partial width of the $(c\bar{c})$ state being studied [18]:

$$\sigma(e^+e^- \to e^+e^- (c\bar{c})) = \int d^5L(\alpha_i)\sigma(\gamma\gamma \to (c\bar{c})).$$

\(^1\)Conjugate modes are also included in all analyses unless stated explicitly.
CHAPTER 1. INTRODUCTION: PHENOMENOLOGICAL AND EXPERIMENTAL REVIEW OF $X(3872)$

![Figure 1.1: Charmonium production diagrams at $e^+e^-$ colliders.](image)

(a) $e^+e^-$ annihilation, (b) $B$-meson decay, (c) Photon-photon fusion, (d) Initial state radiation, (e) Double charmonium production.

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12
1.3. CHARMONIUM

where $L(\alpha_i)$ is the luminosity function expressed in the variable $\alpha_i$ (for example, the four momenta of the outgoing leptons), and the two-photon cross section $\sigma(\gamma\gamma \rightarrow (c\bar{c}))$ is given (in natural units $\hbar = c = 1$) by:

$$\sigma(\gamma\gamma \rightarrow (c\bar{c})) = 8\pi\frac{2J + 1}{M}\frac{\Gamma\gamma}{(s - M^2)^2 + M^2 \Gamma^2}\frac{M\Gamma}{F(q_1^2, q_2^2)}.$$  (1.9)

Here $J$, $M$ and $\Gamma$ are the spin, mass and total width of the $c\bar{c}$ state under study, respectively; $s$ is the center-of-mass energy of the colliding photon system; $\Gamma_{\gamma\gamma}$ is the two-photon partial width of the $c\bar{c}$ state; $q_1$ and $q_2$ are the four-momenta of the virtual photons and $F(q_1^2, q_2^2)$ is the factor describing the evolution of the cross section. e.g. $\gamma\gamma \rightarrow \eta_c(2S)$ or $\gamma\gamma \rightarrow Z(3930)$.

- Initial state radiation (ISR) or Radiative return

In this process either the electron or the positron radiates a photon before the annihilation as shown in Figure 1.1(d), thereby lowering the effective CM energy. Only $J^{PC} = 1^{--}$ states can be produced in ISR. This process allows a large mass range to be explored and is very useful for the measurement of $R$,

$$R = \frac{\sigma(e^+e^- \rightarrow hadrons)}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}.$$  (1.10)

and for the search of new vector states. e.g. $e^+e^- \rightarrow \gamma_{ISR}Y(4260) \rightarrow J/\psi\pi^+\pi^-$. 

- Double charmonium production

The production of double charmonium states in $e^+e^-$ annihilation as shown in Figure 1.1(e) was discovered by Belle Collaboration from a sample of data collected near the $\Upsilon(4S)$ resonance at a CM energy $\sqrt{s} = 10.6$ GeV, by studying the recoil momentum spectrum of the $J/\psi\eta_c$ [19]. The collaboration also found evidence for $J/\psi\chi_{c0}$ and $J/\psi\eta_c'$ production. With Belle data study [20], the $e^+e^- \rightarrow J/\psi c\bar{c}$ cross section measured in a model independent way comes out to be $(0.74 \pm 0.08 \pm 0.09)$pb. For the second charmonium with the mass below the open charm threshold, this fraction is $(16 \pm 3)$% [20]. Despite the small cross section value, these studies are possible, thanks to the high luminosity $B$-factories era. We can reconstruct one of two charmonium (e.g. $J/\psi$),
CHAPTER 1. INTRODUCTION: PHENOMENOLOGICAL AND EXPERIMENTAL REVIEW OF $X(3872)$

to observe the process of pair production. The second state can be seen in the spectrum of masses recoiling against the reconstructed ones, $M_{\text{rec}}(J/\psi) = \sqrt{(E_{CM} - E_{J/\psi}^*)^2 - (p_{J/\psi}^*)^2}$, where $E_{J/\psi}^*$ and $p_{J/\psi}^*$ are the energy and momentum of $J/\psi$. In the process of charmonium pair production in the $e^+e^-$ annihilation, the final charmonium states have opposite charge parities. It was experimentally found that either scalar mesons with the quantum number $J^{PC} = 0^{++}(\chi_{c0})$ or pseudoscalar mesons with $J^{PC} = 0^{--} [\eta_c$ and $\eta_c(2S)]$ are produced together with $J/\psi$. The $J^{PC} = 1^{++}(\chi_{c1})$ and $J^{PC} = 2^{++}(\chi_{c2})$ are not seen. This could indicate that this process favors the production of $J = 0$ states over those with $J = 1$ and higher [21].

1.3.2 Charmonium Decays

Following are different ways through which charmonium can change its state:

(1) **Annihilation**: Annihilation of $c\bar{c}$ to leptons via photon is shown in Figure 1.2. It is generally suppressed for bound state. But decay to leptons is a clean experimental signal.

\[ \psi' \rightarrow e^+e^-, \ J/\psi \rightarrow \mu^+\mu^- \]

![Figure 1.2: Annihilation of $c\bar{c}$](image)

(2) **Strong Decay**: Charmonium states below the open charm threshold decay via intermediate photons or gluons which are produced by the annihilation of $c\bar{c}$ pair. These type of decays are OZI violating but flavor conserving. Suppression of this
1.3. CHARMONIUM

type of decays leads to (relatively) long lifetime and hence narrow width of $J/\psi$ and $\psi'$.

e.g. $J/\psi(1^3S_1)$ or $\psi' \rightarrow ggg \rightarrow \text{hadrons}$

$J/\psi(1^3S_1)$ or $\psi' \rightarrow \text{virtual } \gamma \rightarrow \text{hadrons}$

$J/\psi(1^3S_1)$ or $\psi' \rightarrow \text{virtual } \gamma \rightarrow \text{leptons}$

$J/\psi(1^3S_1)$ or $\psi' \rightarrow \gamma gg \rightarrow \text{hadrons}$

or Creation of one or more light $q\bar{q}$ pairs from vacuum to form light mesons.

e.g. $\psi(3770) \rightarrow \omega \pi^0$

$\psi(4160) \rightarrow \phi \pi^+ \pi^-$

$\psi(3770) \rightarrow \pi^+ \pi^- \pi^0$

These type of decays are shown in Figure 1.3.

Figure 1.3: Strong decay of charmonium states.

(3) Electromagnetic or Radiative Decay: Radiative decay of charmonium is shown in Figure 1.4 e.g. $J/\psi \rightarrow \gamma \eta_c(1S)$, $\psi(4040) \rightarrow \chi_{c1}\gamma$

These type of decays are competitive and often most accessible transitions.

(4) Weak Decay: Weak decays of one or both heavy quarks, e.g.

- $J/\psi \rightarrow D_s^- \nu_c$ or $\bar{D}_d e^+ \nu_e$ where $D_s$ ($D_d$) decay mode is Cabbibo-favored (Cabbibo-suppressed).

- $J/\psi \rightarrow \bar{D}^0 e^+ e^-.$

Feynman diagrams are shown in Figure 1.5.


1.3.3 Charmonium Spectroscopy

The $c\bar{c}$ system of two fermions is very much similar to the hydrogen atom. So it can be characterized with the same quantum numbers as that of hydrogen atom: $n$, $L$, $S$ and $J$ respectively the radial quantum number, the orbital quantum number, total spin and total angular momentum. Charmonium spectroscopy is an ideal place for
1.3. CHARMONIUM

studying the dynamics of QCD in the interplay of perturbative and non-perturbative QCD regime. Now, almost forty years after the discovery of $J/\psi$, charmonium physics continues to be an exciting and interesting field of research because of discoveries of new states and the exploitation of the $B$-factories which are rich source of charmonium and charmonium-like states. This field has grown very quickly, as exotic states continue to be found at the rate of about one or two new ones every year. Many thanks to $B$-factories for this achievement. Charmonium spectrum for well established, experimentally found and predicted charmonium and charmonium-like states is shown in Figure 1.6 with $J^{PC}$ of each state known till now. The charmonium states follow a pre-defined nomenclature. States with even $J$ and $PC = ++$ are called $\eta_c(nL)$, states with odd $J$ and $+-$ as $PC$ are called $h_c(nL)$ states, states with

Figure 1.6: Charmonium spectrum for known, predicted and experimentally established charmonium and charmonium-like states.
CHAPTER 1. INTRODUCTION: PHENOMENOLOGICAL AND EXPERIMENTAL REVIEW OF $X(3872)$

PC as $++$ are called $\chi_{cJ}(nL)$ and with $PC = --$ are called $\psi(nL)$ states except lowest $\psi$ state which is known as $J/\psi$ due to historical reasons. The spectrum consists of many narrow states below the threshold of $D^0\bar{D}^0$ (3.729 GeV/$c^2$) for open charm and several states above threshold, some of them wide (because they decay to $D^0\bar{D}^0$), some of them still narrow, because their decay to open charm is forbidden by some conservation rule. All predicted charmonium states below the $D^0\bar{D}^0$ threshold have been observed in experiment. While above this threshold, experimental information on the charmonium states is rather limited.

1.4 Charmonium-Like “Exotic” States

In recent years, new particle states have been found (like $X(3872)$, $Z(4430)^+$ etc.) which resembles like charmonium but seem to have different properties from that of conventional charmonium states. They come under the category of charmonium-like “exotic” states. These exotic states can be broadly classified with following models:

1.4.1 Multiquark

Multiquark model includes two types of states: Tetraquark (colorless combination of 4 quarks), pentaquark (colorless combination of 5 quarks). Below is the explanation of these two types of categories:

**Tetraquark** model assumes two quark-antiquark pairs. There have been no confirmed reports of a tetraquark state to date, although $\sigma(600)$, $f_0(980)$ and $a_0(980)$ states are considered by some authors to be a $J^{PC} = 0^{++}$ light tetraquark state [22]. The $B$-factories recently observed two very narrow states, the $D_{sJ}(2317)^{\pm\mp}$ and $D_{sJ}(2460)^{\pm\mp}$ [23, 24], which have also been interpreted as tetraquark states.

**Pentaquark** model assumes four quark and one antiquark or we can say baryon+a meson (a color-neutral). In 2003, the LEPS Collaboration [25] reported evidence for the $\Theta^+$, a $udud\bar{s}$ pentaquark candidate with a mass of 1540±10 MeV/$c^2$, $\Gamma < 25$ MeV and a statistical significance of 4.6$\sigma$. The $\Theta^+$ was then confirmed by ten experimental papers with significances ranging from 3 to 7$\sigma$ including CLAS Collaboration [26].
1.4. CHARMONIUM-LIKE “EXOTIC” STATES

But in a high-statistics repeat of their own measurement, CLAS Collaboration found that their earlier observation of Θ⁺ was false and no evidence for the existence of the pentaquark exists [27]. However, it was not seen by the B-factories and other high-energy experiments. Because of these non-confirmations, it is doubted that Θ⁺ really exists [28]. We end up this with a quote from PDG’08 summarizing the saga of the pentaquark: “The whole story - the discoveries themselves, the tidal wave of papers by theorists and phenomenologists that followed, and the eventual ‘undiscovery’ - is a curious episode in the history of science.”

1.4.2 Charmonium Hybrid

QCD suggests far richer spectrum of hadrons so called exotic hadrons such as hybrid mesons (q̅qg). These are composed of color-octet quark-antiquark pair and an excited gluon. Hybrids and mesons can have common $J^{PC}$ quantum numbers. But hybrids have additional gluonic degrees of freedom so they can have exotic quantum numbers (e.g. $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$ etc.) which are not accessible for mesons. Heavy quarkonium hybrids have been studied using constituent gluon model [29], the flux tube model [30], the quasi-gluon model [31] and lattice QCD [32–37]. These studies broadly agree that heavy hybrids should exist in the same mass range as heavy quarkonia, suggesting that some of the XYZ states could be heavy hybrids.

1.4.3 Near-Threshold Enhancement

Due to the proximity of the $X(3872)$ mass to the $D^0\bar{D}^{*0}$ threshold, another possible scenario is that the $X(3872)$ is actually has cusp effect in the amplitude at the threshold. This effect would lead to a bump in the cross-section slightly above the threshold and also it affects kinematic distributions. The possible thresholds include the $DD^*$, $D^*D^*$, $DD_1$ and $D^*D_1$ at $E_{CM} \approx 3872, 4020, 4287$ and $4430$ MeV, respectively. $S$-wave ($L = 0$) scattering dominates the cross section at the threshold, however in few cases, higher waves also become important. States in a relative $S$-wave with little relative momentum (which lives long on the time scale of strong interactions) will
have enough time to exchange pions and interact \[38\]. Molecular state is possible due to binding which is possible (via an attractive $\pi$ exchange which could occurs through couplings such as $D \leftrightarrow D^*\pi^0$). It should be noted that there could also be a repulsive interaction which arises due to some strong interaction effects and it can result in a virtual state above threshold. Thus, near the kinematical threshold there can be a structure in the cross section which may or may not be a resonance. In addition, if there are $c\bar{c}$ states which are near a threshold, they can interact with the threshold and will result in a mass shift of both the $c\bar{c}$ resonance and the threshold-related enhancement. These effects could be quite significant in the observed cross section, particularly of the $c\bar{c}$ states close to the threshold \[38, 39\].

### 1.4.4 Glueballs

Glueballs contain only valence gluons and no quarks. Theoretical calculations show that glueballs could exist at energy ranges accessible to current colliders. However they are extremely difficult to identify because they mix with ordinary meson states. So far they have not been observed and identified with certainty; one possible candidate is the $f_J(1710)$ \[40\].

### 1.5 Review of “Exotic” $X(3872)$ State

In 2003, the Belle Collaboration reported a narrow resonance in the $(J/\psi\pi^+\pi^-)$ mass spectrum in exclusive $B^\pm \to J/\psi\pi^+\pi^-K^\pm$ decay mode \[41\] with a mass of $3872.0 \pm 0.6 \pm 0.5$ MeV/$c^2$ shown in Figure 1.7. This announcement was very surprising because it was soon realised that the apparent quantum numbers, mass, quark content and decay patterns of this new state, called $X(3872)$, were not compatible with a standard charmonium state interpretation. Later on this state was also confirmed independently by many other experimental Collaborations like CDF \[42\], D0 \[43\], BaBar \[44\] and recently by LHCb \[45\] and CMS \[46\] experiments at LHC. Investigation of the nature of this state has received immense phenomenological and experimental attention. Among the “exotic” states, the $X(3872)$ is the only one ob-
1.5. REVIEW OF “EXOTIC” X(3872) STATE

Figure 1.7: Observation of X(3872), in left plot with experimental data (peak around 0.78 GeV/c²) as compared to right plot in Monte Carlo.

erved in number of decay modes like: \( X(3872) \rightarrow J/\psi \pi^+\pi^- \) [41, 47], \( X(3872) \rightarrow \gamma J/\psi \) [48, 49], \( X(3872) \rightarrow \gamma \psi' \) [49, 50], \( X(3872) \rightarrow J/\psi \omega (\rightarrow \pi^+\pi^-\pi^0) \) [51, 52], \( X(3872) \rightarrow D^0 \bar{D}^0 \pi^0 \) [53–55], and \( X(3872) \rightarrow D^0 \bar{D}^0 \gamma \) [44, 55].

An surprising property of the X(3872) is isospin violation. It was found that in the decay \( X(3872) \rightarrow J/\psi \pi^+\pi^- \), the invariant mass of \( \pi^+\pi^- \) peaks at the mass of the \( \rho^0 \) meson with \( \rho \) and \( J/\psi \) in a relative S-wave. This is because it is found that dipion in \( X(3872) \) have been coming from \( \rho \) meson [56, 57]. The \( \rho^0 \) carries isospin \( I=1 \), but the initial state (if assumed to be a pure \( c\bar{c} \) state) has \( I=0 \) (as it would not contain any \( u \) or \( d \) valence quarks). One of the mechanisms to induce isospin violation is the \( u/d \) quark mass difference in strong interaction. However, as the mass difference is small, the effect should be very small, consistent with the measured branching fractions. Another possible mechanism to induce isospin violation is the \( u/d \) quark charge difference in electromagnetic interactions (EM). Isospin should only be conserved in strong interaction, but not in EM interaction. Thus one of the possible explanations might be, that the decay \( X(3872) \rightarrow J/\psi \rho (\rightarrow \pi^+\pi^-) \) is proceeding via EM interaction, i.e. the \( \rho \) might not be created by sea quarks or by gluons coupling, but by
a virtual photon. On the other hand, the decay mode \( X(3872) \rightarrow J/\psi \omega (\rightarrow \pi^+\pi^-\pi^0) \) is isospin conserving decay mode. But ratio of branching fractions of above decay modes estimated by Belle [51] and BaBar [52] are:

\[
\frac{B(X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi)}{B(X(3872) \rightarrow \pi^+\pi^- J/\psi)} = 1.0 \pm 0.4(\text{stat.}) \pm 0.3(\text{syst.}) \quad \text{(Belle)}. \tag{1.11}
\]

\[
\frac{B(X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi)}{B(X(3872) \rightarrow \pi^+\pi^- J/\psi)} = 0.8 \pm 0.3 \quad \text{(BABAR)}. \tag{1.12}
\]

Since above two branching fractions \( B(X(3872) \rightarrow \pi^+\pi^-\pi^0 J/\psi) \) and \( B(X(3872) \rightarrow \pi^+\pi^- J/\psi) \) are comparable, so this indicates that isospin mixing occurs at large scale.

Earlier \( X(3872) \) was thought to be a normal charmonium state [58]. The absence of a strong signal in the \( \chi_{cJ}\gamma \) [59] decay channel disagree with potential model expectations for a conventional charmonium state.

Another possible interpretations for the \( X(3872) \) nature include \( P \)- or \( D \)- wave charmonium, a tetraquark, a loosely bound molecule \( (D^0\bar{D}^{*0}) \) or molecule \( (D^0\bar{D}^{*0}) + \text{charmonium (cc)} \) mixture.

The predicted and observed charmonium states [60] near the \( X(3872) \) mass are listed in Table 1.4. The predicted masses of \( 2^1P_1 \) and \( 2^3P_1 \) are \( \sim 80 \text{ MeV}/c^2 \) higher than the mass of the \( X(3872) \). The observed \( 2^3P_0 \) mass which is lower than \( 2^3P_1 \) mass is still \( \sim 50 \text{ MeV}/c^2 \) above the \( X(3872) \) mass. The \( 2^3P_0 \) and \( 2^3P_2 \) states have no errors assigned.

<table>
<thead>
<tr>
<th>State</th>
<th>( n^{2S+1}L_J )</th>
<th>( J^{PC} )</th>
<th>Mass (MeV/( c^2 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_c(2P) )</td>
<td>( 2^1P_1 )</td>
<td>1( ^{+} ) −</td>
<td>( \sim 3956 )</td>
</tr>
<tr>
<td>( \chi_{c0}(2P) )</td>
<td>( 2^3P_0 )</td>
<td>0( ^{+} ) ++</td>
<td>( 3918.4 \pm 1.9 )</td>
</tr>
<tr>
<td>( \chi_{c1}(2P) )</td>
<td>( 2^3P_1 )</td>
<td>1( ^{+} ) −</td>
<td>( \sim 3953 )</td>
</tr>
<tr>
<td>( \chi_{c2}(2P) )</td>
<td>( 2^3P_2 )</td>
<td>2( ^{+} ) ++</td>
<td>( 3927.2 \pm 2.6 )</td>
</tr>
<tr>
<td>( \eta_{c2}(1D) )</td>
<td>( 1^1D_2 )</td>
<td>2( ^{−} ) −</td>
<td>( \sim 3837 )</td>
</tr>
<tr>
<td>( \psi_{c1}(1D) )</td>
<td>( 1^3D_1 )</td>
<td>1( ^{−} ) −</td>
<td>( \sim 3819 )</td>
</tr>
<tr>
<td>( \psi_{c2}(1D) )</td>
<td>( 1^3D_2 )</td>
<td>2( ^{−} ) −</td>
<td>( \sim 3838 )</td>
</tr>
<tr>
<td>( \psi_{c3}(1D) )</td>
<td>( 1^3D_3 )</td>
<td>3( ^{−} ) −</td>
<td>( \sim 3849 )</td>
</tr>
</tbody>
</table>
broad widths which are $20 \pm 5$ MeV and $24 \pm 6$ MeV, respectively [1]. However $2^3P_1$ is expected to be narrower. The predicted masses of $1^1D_2$, $1^3D_1$, $1^3D_2$ and $1^3D_3$ are $\sim 30-50$ MeV/$c^2$ lower than the $X(3872)$ state. The singlet $1^1D_2$ ($J^{PC} = 2^{--}$) state could be narrow and is closer in mass to the $X(3872)$ state. Thus exact state can be confirmed after its $J^{PC}$ information. After analyzing angular distributions of $B^+ \to X(3872)K^+$, $X(3872) \to J/\psi \pi^+ \pi^-$, CDF excluded all $J^{PC}$ hypotheses except $2^{-+}$ and $1^{++}$ [47]. Recent analysis carried out by LHCb [61], using five-dimensional angular correlations of $B^+ \to X(3872)K^+$, where $X(3872) \to J/\psi \pi^+ \pi^-$ and $J/\psi \to \mu^+ \mu^-$ suggests $X(3872)$ $J^{PC}$ to be $1^{++}$ and rejects $2^{-+}$ hypothesis with $8.2\sigma$. So this $J^{PC}$ rules out the explanation of the $X(3872)$ as a $\eta_c$ ($1^1D_2$) state. The remaining possibility, $\chi_{c1}$ ($2^3P_1$) charmonium, is disfavored by the $X(3872)$ mass.

Some authors have advanced a QCD-tetraquark [62] interpretation for the $X(3872)$, in which all four quarks interact with each other equally rather than in a bound state of bound states. In this model, a so-called diquark $[cq]$ and antidiquark $[\bar{c}\bar{q}]$ ($q, q' = u$ or $d$) act as composite antiquarks and quarks. In this interpretation, the $X(3872)$ is expected to be accompanied by isospin and $SU(3)$ multiplet partners (charged partners). In particular, the $X(3872)$ is considered an $I_3 = 0$ member of an isospin triplet and charged $I_3 = \pm 1$ partner states (e.g decay via $X^+ \to J/\psi \rho^+$) are expected to be produced at a rate in $B$ decays that is twice that for the neutral $X(3872)$. Both BaBar [63] and Belle [56] Collaborations report negative results for its charged partner and set upper limits on product of branching ratios.

In the same proposed interpretation, two neutral $X(3872)$ states (with orthogonal mixtures of $cu\bar{c}u$ and $cd\bar{c}d$) are expected to exist with mass difference of $\frac{(7+2)}{cos(2\theta)}$ MeV. These two different states might result in different $X(3872)$ mass in the neutral and charged $B$ meson decay modes. But this mass difference estimation by BaBar [44], CDFII [64], Belle [56] reports negative results. Further search for $C$-odd partners by Belle with $B \to J/\psi \eta K$ [65] and $B \to \chi_{c1} \gamma K$ [66] didn’t also match above interpretations. So experimental searches for charged- and $C$-odd partners report negative results. However, since these searches are restricted to states with narrow total widths and the published limits may not apply if the partner states access more decay chan-
nels and are thus broader.

Proximity of its mass to the $D^0\bar{D}^{*0}$ threshold along with its measured decay rates suggests it to be a loosely-bound “molecule” of $D^0$ and $\bar{D}^{*0}$ mesons [67]. In this case, the binding energy $E_b$ would be given by the mass difference $m(X(3872)) - (m(D^{*0})+m(D^0))$. Including the new Belle result, the new world average mass of the $X(3872)$ is $m=3871.69\pm0.17$ MeV [1]. The present value for the sum of the masses is $m(D^0)+m(D^{*0})=3871.84\pm0.28$ MeV [1], Thus, a binding energy of $E_b=-0.15\pm0.33$ MeV can be calculated, which is enormously small.

The remaining possibility for $X(3872)$ is molecule + charmonium mixture [67, 68]. This possibility can be checked using radiative decays of $X(3872)$, as these types of decays provide a valuable source of information to understand its nature. Studies of $X(3872) \to \gamma J/\psi$ also helped in establishing +ve $C$-parity of $X(3872)$. This decay mode has been observed by Belle [48] and BaBar [49]. $X(3872) \to \gamma \psi'$ was not observed by Belle [48], but the evidence of same decay mode was reported by BaBar [69] and LHCb [50] with significances $3.5\sigma$ and $4.4\sigma$ respectively. These Collaborations reports the ratio of branching fractions as follows:

LHCb result:

\[ R = \frac{B(X(3872) \to \gamma \psi')}{B(X(3872) \to \gamma J/\psi)} = 2.46 \pm 0.64 \pm 0.29. \tag{1.13} \]

BaBar result:

\[ R = \frac{B(X(3872) \to \gamma \psi')}{B(X(3872) \to \gamma J/\psi)} = 3.4 \pm 1.4. \tag{1.14} \]

Belle Collaboration only set upper limit on $R < 2.1$ at the 90% C.L. as they didn’t observe a significant signal for $X(3872) \to \gamma \psi'$. After considering statistical and systematic uncertainties, this upper limit doesn’t contradict BaBar and LHCb results.

After combining results form Belle, BaBar and LHCb [70], one can have:

\[ \bar{R} = \frac{B(X(3872) \to \gamma \psi')}{B(X(3872) \to \gamma J/\psi)} = 2.31 \pm 0.57. \tag{1.15} \]

This $\bar{R}$ value seems to disfavor the pure $D^0\bar{D}^{*0}$ molecular interpretation of the $X(3872)$, as for pure $D^0\bar{D}^{*0}$, $\bar{R}$ value should be small [$O(10^{-3})$] [71,72]. However, mixing of $D^0\bar{D}^{*0}$ molecule and charmonium could explain this $\bar{R}$ value of $X(3872)$ [50,73].
1.5. REVIEW OF “EXOTIC” \(X(3872)\) STATE

Figure 1.8: Mass measurements of the \(X(3872)\) state. Vertical band shows uncertainty in world average value (3871.69 \(\pm\) 0.17 MeV/\(c^2\)).

Considering the totality of phenomenological and experimental information on the \(X(3872)\) at face value, this resonance seems to be very narrow with upper limit on total width \(\Gamma_{X(3872)} < 1.2\) MeV [56], quantum numbers as \(J^{PC} = 1^{++}\) and current world average mass as 3871.69\(\pm\)0.17 MeV/\(c^2\). Measurements by different experiments on its mass is summarized in Figure 1.8 with vertical band shows uncertainty in world average value. Better understanding of the \(X(3872)\) demands more experimental information and phenomenological insight.

In the present thesis work, we will try to understand in a better way the \(X(3872)\)
CHAPTER 1. INTRODUCTION: PHENOMENOLOGICAL AND EXPERIMENTAL REVIEW OF X(3872)

particle and perform its search in neutral and charged $B \to X(3872)K\pi$ decay modes with $B \to \psi'K\pi$ decays modes as the calibration decay modes.

Figure 1.9: Tree diagram for $B \to \psi'K^*$ decay mode.

Figure 1.10: Tree diagram for $B \to \psi'K\pi$ decay mode.

1.6 Feynman Diagrams for $B \to \psi'K\pi$ decay modes

The $B \to \psi'K^*(\to K\pi)$ and $B \to \psi'K\pi$ (calibration decay modes) are color-suppressed and Cabibbo-favored two body and three body decay modes respectively,
1.7. $B \rightarrow X(3872)K\pi$ Decay Modes and Motivation

which has already been observed and their branching fractions are well measured. In three body decay, this decay mode proceeds via the transition $\bar{b}q \rightarrow \bar{c}\bar{s}u\bar{u}q$ or $\bar{b}q \rightarrow \bar{c}\bar{s}d\bar{d}q$, here $q = u$ or $d$ quark and $u\bar{u}$ or $d\bar{d}$ quark pairs are produced from either sea quarks or from coupling of gluons. Two body penguin proceeds via the transition $\bar{b}q \rightarrow \bar{c}\bar{s}q$, where $q$ can be either $u$ or $d$ quark and $c\bar{c}$ quark pair is produced from either virtual photon or $Z^*$. Tree diagram and penguin diagrams for calibrated decay modes are shown in Figure 1.9 to Figure 1.11.

![Figure 1.11: Penguin diagram for $B \rightarrow \psi'K^*$ decay mode.](image)

1.7 $B \rightarrow X(3872)K\pi$ decay modes and Motivation

Concerned decay mode in this thesis is $B \rightarrow X(3872)K\pi$. Since $X(3872)$ is charmonium-like “exotic” state so one can have almost same Feynman diagrams as that of calibrated decay mode, except $X(3872)$ can have any type of structure (in deep any quark content).

$X(3872)$ state was never observed in three body decay dynamics of $B$-meson before this analysis. So our motive behind this decay mode is to first search for $X(3872)$ in neutral and charged $B \rightarrow X(3872)K\pi$ (three body) decay modes and then to search any resonant structure in background subtracted mass distributions of $M_{X(3872)K}$, $M_{X(3872)\pi}$ and $M_{K\pi}$ for observed $B \rightarrow X(3872)(K\pi)$ decay mode. After doing analy-
sis, it was found that for $X(3872)$ mass region, there is no structure in $M_{X(3872)K}$ and $M_{X(3872)\pi}$ distribution, but a clear structure is observed in $M_{K\pi}$ distribution. And further it is found that resonant $K^*(892)$ is not dominating as compared to $(K\pi)_{NR}$ one for $X(3872)$ mass region, which is not like normal charmonium state behaviour, like $\psi'$, $\chi_{c1}$ mass regions.

1.8 Chapter in Compact

In this Chapter, author has tried to set up an introduction environment for the analysis work carried out in this thesis. Following decay modes are studied in this thesis:

- $B^0 \rightarrow X(3872)K^+\pi^-$
  Our main motive behind this study is to search for $X(3872)$ in $B^0 \rightarrow X(3872)K^+\pi^-$ decay mode as it has not been seen/measured yet. Further binned minimum $\chi^2$ fit is performed to background subtracted $M_{K\pi}$ distribution to separate out resonant and non-resonant components of $K\pi$ mass system. From these studies, we may get some information about the nature of $X(3872)$ particle. For this study, we will take opportunity for utilization of $B^0 \rightarrow \psi'K^+\pi^-$ decay mode (acts as calibration sample).

- $B^+ \rightarrow X(3872)K_S^0\pi^+$ and $B^+ \rightarrow X(3872)K^+\pi^0$ decay modes.
  We have also taken up the search for $X(3872)$ in $B^+ \rightarrow X(3872)K_S^0\pi^+$ and the very preliminary study of $B^+ \rightarrow X(3872)K^+\pi^0$ decay modes. Strategy for searching these decay modes is same as previous one. Calibration modes for above decays modes are $B^+ \rightarrow \psi'K_S^0\pi^+$ and $B^+ \rightarrow \psi'K^+\pi^0$ (only preliminary results) decay modes respectively.