A survey of new physics searches at BESIII

The Standard Model (SM) of particle physics successfully describes the observed matter constituents and their interactions. The discovery of the Higgs boson is a confirmation of the correctness of its present posture. However, there are many compelling reasons to believe that the SM is an effective theory valid up to some energy scale above which the new physics phenomena is expected to be observed. Searching for discrepancies with the SM is the first priority of the present day of experimental and theoretical investigations. Complementary to direct searches at highest possible energy, the indirect searches of the new physics phenomena are possible at low-energies through virtual processes using the data of high intensity e^+e^- collider flavour physics experiments, such BESIII experiment. The most promising areas under investigation regard rare and forbidden symmetry violating processes, search for exotic states, and anomalous magnetic moment of the muon $(g-2)_\mu$. A large amount of the datasets, collected by the BESIII detector at various energy points in the tau-charm region, allows a unique opportunity to explore the possibility of such kind of new physics searches. BESIII has already published a number of papers related to the new physics using existing data, including 1.3 billion J/ψ events. The BESIII has recently collected additional 9 billion J/ψ events that may provide either a clear signature of the new physics or exclude a large fraction of the parameters of the new physics models.

In order to promote the study of new physics searches, BESIII organizes every year a "New Physics Workshop" that provides an ideal venue for both theorists and experimentalists to discuss the latest results and developments in the area of the new physics, and to come up with the new research ideas which can be completed at BESIII. Some other details about the aforementioned topics are given below:

Forbidden process: Some processes that can be allowed by space-time symmetries, but forbidden by the SM are called forbidden processes. Some important forbidden processes are listed below:

1. Lepton flavour violating (LFV) process: The LFV processes are possible due to finite neutrino mass ($m_\nu \neq 0$), but essentially forbidden. The branching fractions of these decays are predicted to be negligible small, but the contribution of new physics, such as SUSY grand unified theories, SUSY with a right-handed neutrino etc., may enhance the branching fractions of these processes up to the level of current experimental sensitivity. As the LFV in the neutral lepton sector has already been established after the discovery of neutrino oscillations, its detection in the charged lepton sector would be a clear indication of the new physics. BESIII has set one of the more stringent upper limits of $\mathscr{B}(J/\psi \to e\mu) < 1.6 \times 10^{-7}$ at $90\,\%$ confidence level (CL) using 225 million J/ψ events. BESII placed upper bounds on $\mathscr{B}(J/\psi \to \mu\tau) < 2 \times 10^{-6}$ and $\mathscr{B}(J/\psi \to e\tau) < 8.3 \times 10^{-6}$. The limits on these decays can be improved by the BESIII using 10 billion of J/ψ events.

2. Lepton number violating (LNV) processes: Many extensions of the new physics models, such as Higgs extensions, leptoquarks etc., include the possibility of LNV processes. The LNV decays of charged D mesons can be induced by the existence of Majorana neutrinos and are sensitive to neutrino masses and lepton mixing. The branching fraction of such an LNV process depends on the on- and off-shell contributions of the Majorana neutrino masses. BESIII has recently reported upper limits on $D \to hee$ $(h = K, \pi)$ up to the level of 10^{-6} using 2.93 fb^{-1} $\psi(3770)$ data with a single tag technique.

3. Baryon number violating (BNV) processes: The BNV processes can proceed according to the first condition of Sakharov. Many other theoretical models could have BNV processes, such as Georgi-Glashow GUT model, which include the possibility of X and Y bosons having charges 4/3 and 1/3 that couple quarks and leptons and thus BNV and LNV. The following baryon number violating processes with different selection rules are experimentally interested: 1) for proton decay, e.g. $p \to e^+\pi^0, \bar{\nu}K^0,$ etc., and 2) $\Delta(B-L) = 2$ for neutrino antineutrino $(N - \overline{N})$ oscillation. If the $N - \overline{N}$ oscillation exists, then the $\Lambda - \overline{\Lambda}$ may also exist as originally proposed by K. B. Luke. The probability of $\Lambda - \overline{\Lambda}$ oscillation in the presence of a static magnetic field is defined as, $\mathscr{P}(\overline{\Lambda}, t) = \dfrac{\delta m^2_{\Lambda\overline{\Lambda}}}{\delta m^2_{\Lambda\overline{\Lambda}} + (\Delta E)^2} \sin^2(\sqrt{\delta m^2_{\Lambda\overline{\Lambda}} + (\Delta E)^2} \,.\, t)$, where $\delta m_{\Lambda\overline{\Lambda}}$ is the $\Delta B = 2$ transition mass between Λ and $\overline{\Lambda}$, and $\Delta E = -\bar{\mu}_\Lambda \,.\, \overline{B}$ is the energy split due to external magnetic field (here $\bar{\mu}_\Lambda$ is magnetic moment of Λ). In the absence of magnetic field, $\Delta E = 0$ and probability of $\Lambda - \overline{\Lambda}$ becomes as, $\mathscr{P}(\overline{\Lambda}, t) = \sin^2(\delta m_{\Lambda\overline{\Lambda}} \,.\, t)$. There are two ongoing analyses about $\Lambda - \overline{\Lambda}$ oscillation via $J/\psi \to \Lambda\Lambda$ and $J/\psi \to pK^-\overline{\Lambda}$ decays at BESIII with 1.3 billion J/ψ events, where Λ baryon is reconstructed by $p\pi$ in the final state. These analyses will be updated very soon using 10 billion J/ψ data of the BESIII experiment.

Current status of the searches for the forbidden processes at BESIII: Though there are many ongoing analyses related to the forbidden processes, but till now only a few of them are finalised. The progress of most of the analyses is slow either due to a disagreement between data and MC or poor understanding of the backgrounds. The same kind of problem is also expected to be appeared in the full J/ψ data sample.

Rare processes: These processes have very small transition rates predicted by the SM. These processes can be classified as,

A) Flavor changing neutral current (FCNC) processes: The flavour changing neutral current (FCNC) processes, such as $D^0 \to \gamma\gamma, D^0 \to he^+e^-$ etc., in charm sector are highly suppressed by the Glashow-Iliopoulos-Maiani (GIM) mechanism due to absence of high mass down-type quarks. These processes can proceed via $c \to u$ transition.The FCNC D decays are very rare and beyond the scope of any running or planned experiments. However, the contributions of long-distance and new physics may enhance the branching fractions up to the level of current experimental sensitivity. BESIII has recently set the upper bounds on $\mathscr{B}(D^+ \to h^+e^+e^-)$ and $\mathscr{B}(D^0 \to \gamma\gamma)$ up to level of $10^{-6} - 10^{-7}$ and 10^{-6}, respectively.

B) Weak decays of charmonium: The decays of $\psi(nS)$ below the open-charm threshold can proceed via intermediate virtual photons and gluons in electromagnetic and strong interactions, respectively, by $c\bar{c}$ annihilation. As the J/ψ particle, lying just below the open charm threshold, can't decay to a pair of charmed mesons. But, it can decay into a single charmed meson via the weak Cabibbo-favoured ($c \to s$) or Caboibbo-suppressed ($c \to d$) transitions, where a virtual $W^{\pm}$ emits either $l^{\pm}\nu_l$ ($l = e, \mu, \tau$) or a hadronic resonance in the final state. The branching fractions of J/ψ inclusive weak decays are estimated to be up to the level of 10^{-10}. But, several new physics models, such as the top-color model, the minimum supersymmetric Standard Model (MSSM), allow the $\psi(nS)$ flavour-changing processes to be occurred with branching fraction around 10^{-6}. The BESIII has searched for rare decays $J/\psi \to D_s^- \rho^+$, $J/\psi \to D^0 K^{*0}$ and $J/\psi \to D_s^- e^+ \nu / D_s^* \to e^+ \nu$ with null results. A similar searches including other J/ψ weak decay were performed by the BESII experiment with the null results. The experimental upper limits of these J/ψ decays are still above the SM predictions. At present, there are many BESIII ongoing analyses related to this topic.

C) Highly suppressed E. M. decays of quarkonium: The highly suppressed E.M decay of quarkonium states, such as $J/\psi \to \phi/\eta_c e^+ e^-$, $\eta' \to \eta/\pi^0 e^+ e^-$ etc., can proceed via one or two virtual photons. In $\eta' \to \eta/\pi^0 e^+ e^-$ decays, the processes occurred with one and two virtual photons are known as C violating and C conserved processes, respectively. The branching fractions of these decays are expected to be up to the level of 10^{-9} in the framework of the SM. Observations of these decays with the large branching fractions in compared to the SM predictions would be a clear indication of the new physics. At present, there are many ongoing analyses on these topics at BESIII using the data samples collected at J/ψ and $\psi(3686)$ resonances.

Current status of the searches for rare decays at BESIII: The analysis techniques of most of the BESIII analyses are already well established. BESIII has also submitted/published the results related to this topic with null results. A few rare decay processes are expected to be observed using 10 billion J/ψ data of the BESIII experiment.

Search for exotic state: These are pure new physics phenomena and not described by the SM of particle physics. The searches of the exotic states can be classified into following two categories:

1) Search for new resonances: Many astrophysical observations strongly suggest the existence of dark matter which amounts about 25% of the total universe. The nature of the dark matter is still mysterious and its existence can only be inferred via the gravitation effects. Many models beyond the SM introduce several light weak interacting degrees of freedoms that couple to the SM particles via either Higgs, vector, Axion or Neutrino portals. The neutrino portal can be best explored at neutrino facility experiments. The rest of the other portals can be experimentally explored using the data of high intensity electron-positron collider experiments. The other details about these portals are given below:

A) Light Higgs boson: The light Higgs boson is predicted by many models beyond the SM including Next-to-Minimal Supersymmetric Standard Model (NMSSM). The Higgs sector of the NMSSM contains seven Higgs boson, among them there is a CP-odd light boson (A^0) whose mass is expected to be few GeV. Such a low-mass Higgs boson can be accessible via radiative decays of quarkonium states, such as J/ψ and $\Upsilon(1S)$ mesons. The coupling of the Higgs field to the down-type (up-type) quark-pair is directly proportional to $\tan\beta$ ($\cot\beta$), where $\tan\beta$ is a standard SUSY parameter. The branching fractions of $J/\psi \to \gamma A^0$ and $\Upsilon(1S) \to \gamma A^0$ decays are expected to be up to the level of 10^{-9} and 10^{-7}, respectively. BaBar, BESIII, CMS and BELLE experiments have explored the possibility of the Higgs boson decaying to either a fermion-pair or invisible final state particles and reported the null results only so far. The current best experimental limits on the product branching fraction $\mathscr{B}(J/\psi \to \gamma A^0) \times \mathscr{B}(A^0 \to \mu^+\mu^0)$, which vary in the range of $(2.8 - 495.3) \times 10^{-8}$ for $0.212 \leq m_{A0} \leq 3.0$ GeV/c^2 and produced using 225 million J/ψ data of BESIII experiment, is still an order of magnitude above the theoretical prediction. About 40 times more statistics of the BESIII J/ψ data may provide an opportunity to exclude all the parameters of the new physics models related to the light Higgs boson.

Current status of light Higgs boson searches at BESIII: Analysis techniques related to this topic are well established for both visible and invisible decays (ongoing analysis) of a light Higgs boson. The search for di-muon decays of a light Higgs boson can be performed once again using 10 billion J/ψ data-set. A dedicated study of single photon trigger may also provide an opportunity of exploring the possibility of the invisible decays of light Higgs using this data-set. Searches for a light Higgs boson decaying to di-photon, still not explored by any collider experiment, and hadronic final states via $J/\psi \to \gamma A^0$ can also be performed using this data-set.

B) Axion-like particle: An Axion-like particle (a) is a hypothetical pseudo-scalar particle that can couple to SM gauge boson via the so called Axion portal. These particles are introduced by the spontaneous breaking of the Peccei-Quinn symmetry, which is one of the most attractive solutions of the strong CP problem of the QCD. While the parameters of the Axions are related to QCD, the coupling and the mass of the ALPs are taken to be independent and can appear in a variety of extensions to the SM. The simplest search for an ALP at BESIII can be possible via it's coupling to photons as, $\mathscr{L} \supset \frac{g_{a\gamma\gamma}}{8}\epsilon\mu\nu\alpha\beta F^{\mu\nu}F^{\alpha\beta}a$. The search for an Axion-like particle at BESIII can be performed via ALP-strahlung ($e^+e^- \to \gamma a$) and the photon fusion ($e^+e^- \to e^+e^-a$) processes. The search for an axion-like particle can also be explored via radiative decays of quarkonium states $J/\psi \to \gamma a$. The branching fraction of $J/\psi \to \gamma a$ can be computed as, $\mathscr{B}(J/\psi \to \gamma a) = \frac{1}{8\pi\alpha}g^2_{a\gamma\gamma}m^2_c\mathscr{B}(J/\psi \to e^+e^-)$. The large data-set collected by the BESIII experiments at J/ψ and $\psi(3686)$ provide a unique opportunity to explore the possibility of the Axion-like particles. One of the possible difficulties could arise how to select two best photons for $a \to \gamma\gamma$ reconstruction. One of the easiest ways would be to combine all the three possible combinations of di-photon invariant mass spectrum, and then search for a narrow resonance of ‘a’ signal.

Current status of the searches of an axion-like particle at BESIII: The searches for Axion-like particles are neither yet explored by the BESIII experiment nor any other e^+e^- collider experiments. The BELLEII has a dedicated program on the searches for this kind of new particle.

C) Dark photon: The dark photon (γ') is a new type of force carrier in the simplest scenario of an Abelian $U(1)$ interaction in which the dark matter particles are considered to be charged. A γ' with mass below twice the proton mass can explain the feature of the electron/positron excess observed by the cosmic ray experiments, as well as the presently observed deviation of the anomalous magnetic moment of the muon (a_μ) up to the level of $(3-4)\sigma$ between the measurement and SM prediction. The γ' couples with the SM photon via the kinetic mixing with the SM hyper charge field. The coupling strength between the dark sector and the SM, ϵ, can be parameterised as $\epsilon^2 = \alpha'/\alpha$, where α' and α are the final structure constants in the dark and SM sectors, respectively. A series of experiments, including BESIII, have reported null results in γ' searches, including the a_μ favoured region, and have constrained the ϵ values as a function of γ' mass to be below 10^{-3}. BESIII has recently explored the possibility of γ' in the initial state radiation process $e^+e^- \to \gamma'(\to l^+l^-)\gamma$ $(l = e, \mu)$ (in the mass region of 1.5 - 3.4 GeV/c^2 only), and the electromagnetic Dalitz decays of $J/\psi \to e^+e^-\eta(')$ and have reported so far only the null results. By using the 10 billion of the J/ψ events, the search for dark photon can be performed in radiative decays, such as $J/\psi \to \gamma\gamma'$, and electromagnetic Dalitz decays, such as $\pi^0 \to \gamma\gamma'(\to e^+e^-)$ etc..

Current status and scope of the dark photon searches at BESIII: BESIII has explored the possibility of dark gauge boson using both J/ψ and $\psi(3770)$ data with the null results. The exclusion limits on ϵ that has been set using these BESIII data seem to be worse than the existing experimental sensitivity. However, the searches for the dark photon via radiative decays of psuedoscalar mesons, such as $\pi^0 \to \gamma\gamma'(\to e^+e^-)$, at BESIII may provide better exclusion limits on ϵ in comparison to the existing limits. At BESIII, a large number of pseudo scalar mesons can be selected via either radiative decays J/ψ or $J/\psi \to n(\pi^+\pi^-)\pi^0$ decays.

2) Search for invisible decays of light vector and pseudoscalar mesons: Invisible particles interact so weakly that they are not observable in the particle physics detector. The SM allows only neutrinos to be invisible particles. Quarkonium states ($q\overline{q}$) can annihilate a neutrino-pair via virtual Z^0 boson. These processes are very rare and beyond the reach of current generation of collider experiments. But the contribution of new physics beyond the SM, such as light dark matter, can enhance the branching fraction up to level of current experimental sensitivity. BESIII has performed the searches for invisible decays of light vector and pseudoscalar mesons via $J/\psi \to V\eta(')$ $(V = \omega, \phi)$ decays using 1310.6 and 225 million J/ψ events, respectively., and reported the null results so far. BESIII is also exploring the possibility for invisible decays of Λ and χ_{cJ} mesons using the data at J/ψ and $\psi(3686)$ resonances, respectively. Recently collected 10 billion of J/ψ data may further improve the sensitivity on these new physics searches.

In SM, heavy mesons decays to two neutrinos, such as $D \to \nu\bar{\nu}$ and $B \to \nu\bar{\nu}$, are helicity suppressed. The branching fraction of $D^0 \to \nu\bar{\nu}$ is expected to be upto level of 10^{-30}, but the contribution of several dark matter candidates may enhance the branching fraction $\mathscr{B}(D^0 \to \nu\bar{\nu})$ up to the level of 10^{-15}. Recently, Belle has reported the result from a first search for the D^0 decays to invisible final states using 924 fb^{-1} data collected at and near the $\Upsilon(4S)$ and $\Upsilon(5S)$ resonances. Belle uses a charm tagging in the process $e^+e^- \to c\bar{c} \to D^{(*)}_{tag} X_{frag} D^{*-}_{sig}$ with $\overline{D}^{*-}_{sig} \to \overline{D}^0_{sig}\pi^-_s$ to select an inclusive D^0 sample. A 2D fit to the invariant mass distributions of D^0 and energy residual in the electromagnetic calorimeter E_{ECL} is used to extract the signal yields. No significant signal event is observed, and a 90% C.L. upper limit was set at $\mathscr{B}(D^0 \to \text{invisible}) < 9.4 \times 10^{-5}$. A 2.93 fb^{-1} of the data collected at the $\psi(3770)$ threshold by the BESIII experiment can also be utilised to search for invisible decays of D^0 meson using a double tag technique pioneered by the MARK III collaboration. The double tag sample in which one of the D mesons in $\psi(3770) \to D\overline{D}$ is tagged with its dominant hadronic decay modes and other D meson is allowed to reconstruct with the signal mode of interest can provide a clean environment for the search for invisible decays of D^0 meson.

Current status of the searches for the invisible final states at BESIII: Analysis techniques for the searches for the invisible decays of light vector and pseudoscalar mesons via two body decays of J/ψ mesons are well established by the BESIII experiment. BESIII is also trying to explore the possibility of invisible decays of light baryons, such as $\Lambda \to \text{invisible}$. It may also release this year the results related to the decay processes of $J/\psi \to \gamma + \text{invisible}$ and $J/\psi \to \text{invisible}$. However, BESIII still needs to explore the possibility of the invisible decays of invisible decays of Charm mesons, such as $D^0 \to \text{invisible}$.

Measurements of the electromagnetic form factors at BESIII: The electromagnetic transition form factors (TFFs) describe the interaction of hadronic matter with photons. They represent the deviation to the standard point-like predictions of the quantum electrodynamics. Thus, the TFFs also provide the valuable inner structure of the hadrons. Additionally, the TFFs of the light mesons contribute to the hadronic light-by-light (HLBL) corrections to the theoretical determination of the muon anomalous magnetic moment, $a_\mu = (g-2)_\mu$, which provides a low-energy test of the completeness of the SM. Present deviation in experimental and theoretical determination of a_μ is larger than 3σ. This deviation might be a hint of new physics beyond the SM.

Experimentally, the TFFs can be determined in both time and space-like regimes. In the time-like regime, TFFs are measured in Dalitz decays and in the radiative production of pseudo scalar mesons in the e^+e^- annihilation. Both the cases allow to the study the TFFs as a function of single virtuality, which corresponds to the squared di-lepton invariant mass spectrum. The space-like regime can be studied in e^+e^- scattering processes, where each of the beam leptons emits a photon. The two photons fuse to form a hadronic state. This process allows to study meson TFFs at arbitrary space-like virtualities. BESIII has a dedicated program for the measurements of the

TFFs in both space and time-like regions. The preliminary results of the space-like π^0 transition form factor has recently released by the BESIII experiment.

The electromagnetic Dalitz decays of $A \to Bl^+l^-$ can proceed via $A \to \gamma^* B$, where γ^* is a virtual photon converting into a lepton-pair in the final state. The observed di-lepton invariant mass spectrum in these decays deviates from the standard point-like prediction of the quantum electrodynamics due to the internal electromagnetic structure of the decaying meson arising at $A \to B$ transition vertex. The difference is firmly described by the TFF. The Vector Meson Dominance (VMD) model describes the coupling of the virtual photon to the 'A' meson via an intermediate vector meson V in the time-like region, where V is the intermediate resonant contribution of ρ, ω, ϕ and charmonium mesons. Though recent results of the BESIII improve the precision of $J/\psi \to e^+e^-P$ $(P = \pi^0, \eta('))$ and also measure the TFFs of $J/\psi \to e^+e^-P$, but the precision of the TFFs is still limited by large value of the statistical uncertainty. In $J/\psi \to e^+e^-\eta$ Dalitz decay, an evidence of ρ peak is also seen in the di-electron invariant mass dependent TFF data with a significance of 4σ, but the result is not very conclusive due to limited statistics. A high statistic of 10 billion J/ψ data can be utilised to improve the precision on the measurements of the TFFs of $J/\psi \to e^+e^-P$. The EM Dalitz decays can also be utilised to search for a hypothetical dark gauge boson (γ') via either $J/\psi \to \gamma' P$ or $P \to \gamma' P$, where γ' decays to a lepton-pair in the final state. The branching fractions $J/\psi \to \mu^+\mu^-P$ can also be measured for the first time by using the data of the BESIII experiment.

Status of the measurements of the TFFs at BESIII: BESIII has recently measured the π^0 TFF in the space-like regime, and TFFs of $J/\psi \to e^+e^-P$ and $\chi_{cJ} \to \mu^+\mu^-J/\psi$ in the time-like regime. The TFFs of $J/\psi \to e^+e^-P$ are still limited by a large value of the statistical uncertainty that can be improved using 10 billion J/ψ events. The branching fractions of these decays, including $J/\psi \to \mu^+\mu^-P$ decays, can also be updated while taking into account of both resonant contribution of $J/\psi \to V(\to l^+l^-)P$ and non-resonant contribution of $J/\psi \to l^+l^-P$.