We present a selection of recent results from the BESIII collaboration, including both charmonium and $D$ meson physics. We first discuss the observation of a charged, charmonium-like state, the $Z_c(3900)$. Conventional charmonium topics include a search for lepton flavor violation, studies of $\chi_{cJ} \to \gamma\gamma$ decays, and mass and width determinations for the $h_c$, $\eta_c(1S)$, and $\eta_c(2S)$. We finish with results on the decay constant $f_D$ from $D^+ \to \mu^+ \nu$ and on form-factors in $D^0 \to K^- e^+ \nu, \pi^- e^+ \nu$.

1Work supported in part by US DOE DE-FG02-91ER40682.
1 Introduction

The BESIII experiment at the BEPCII collider has accumulated the world’s largest datasets at charm threshold. Results discussed here are based on samples of 225 million $J/\psi$ decays, 106 million $\psi(3686)$ decays, and 2.9 fb$^{-1}$ at the $\psi(3770)$. These datasets are approximately 4x, 4x, and 3.5x, respectively, compared to the previous best and represent the first iteration of our charmonium and $D$ meson programs.

In addition to the core physics summarized above, BESIII is able to do additional physics at other energies, including but not limited to $R_{had}$ energy scans and precision $\tau$ mass measurements. Indeed, we will start this presentation with our most surprising result, based on a fraction of our 2013 data taken at a center-of-mass energy corresponding to the $Y(4260)$ state.

2 $Z_c(3900)$: An Exotic Charged State?

The Belle collaboration recently observed two exotic charged bottomonium-like states, the $Z_b(10610)$ and $Z_b(10650)$[1]. These states were observed in the $\Upsilon(nS)\pi^\pm$ and the $h_b(mS)\pi^\pm$ mass spectra in the decays $\Upsilon(5S) \rightarrow \Upsilon(nS)\pi^+\pi^-$ and $\Upsilon(5S) \rightarrow h_b(mS)\pi^+\pi^-$ (here, $n = 1, 2, 3$ and $m = 1, 2$).

BESIII recently accumulated a 0.525 fb$^{-1}$ dataset at a center-of-mass energy of 4260 MeV. While studying the $J/\psi\pi^+\pi^-$ final state, a well-known decay mode of the $Y(4260)$, a new structure was observed in our $J/\psi\pi^\pm$ mass spectra[2].

In Fig. 1 we display both the $J/\psi\pi^+$ and $J/\psi\pi^-$ mass distributions. We observe two similar peaks in each plot. Studies of Monte-Carlo samples show that the lower-mass peak is a reflection of the higher-mass peak. This is due to the fact that the Dalitz plot of $M^2(J/\psi\pi^+)$ vs. $M^2(J/\psi\pi^-)$ is a rather narrow elongated band. We also note significant structure in the $\pi^+\pi^-$ mass, but find that this can be modeled with only a few amplitudes without leading to significant changes in the $J/\psi\pi^\pm$ mass distributions as compared to phase space; see Fig. 1. In addition to occurring in both $J/\psi\pi^+$ and $J/\psi\pi^-$, the $Z_c$ peak also occurs with both $e^+e^-$ and $\mu^+\mu^-$ decays of the $J/\psi$, and with both the low-mass and high-mass lobes of the $\pi^+\pi^-$ mass distribution.

In subsequent analysis, we make a single $J/\psi\pi^\pm$ mass plot, choosing the higher of the two masses, and fit this distribution to study the new peak. Results are shown in Fig. 2. The fit includes an $S$-wave Breit-Wigner convolved with our Monte-Carlo-determined resolution on top of a four-parameter background. We note that phase-space Monte-Carlo events, shown as a dashed line, have a shape very similar to this empirical background.

The parameters of the resonant term extracted from this fit are:

$$M = (3899.0 \pm 3.6 \pm 4.9) \text{ MeV}/c^2 \quad \Gamma = (46 \pm 10 \pm 20) \text{ MeV}.$$
Figure 1: Plots of $J/\psi \pi^+\pi^-$ events. Right: The $J/\psi \pi^+$ mass; center: the $J/\psi \pi^-$ mass; left: the $\pi^+\pi^-$ mass. In each plot, the points are data, the green filled histogram is background estimated from $J/\psi$ sidebands, the red dashed line is a Monte-Carlo simulation including $f_0(980)$, $\sigma(500)$, and non-resonant terms in the di-pion mass, and the magenta line is $Z_c(3900)\pi^\pm$ Monte-Carlo.

Figure 2: Left: Dalitz plot of $J/\psi \pi^+\pi^-$ events. Note the $Z_c$-related vertical bands and the horizontal variations vs. the $\pi\pi$ mass. Right: A plot of the larger of the $J/\psi \pi^\pm$ masses, fit to a $Z_c(3900)$ resonance term and an empirical background (only slightly different from phase space).
We also determine the fraction of $J/\psi \pi^+ \pi^-$ events that are in the $Z_c$ peak to be $(21.5 \pm 3.3 \pm 7.5)\%$.

Similar results confirming our observations have been presented by Belle$^3$ and Northwestern University$^4$.

3 Selected Charmonium Results

At $e^+e^-$ colliders, one can directly produce states with $J^{PC} = 1^{--}$. Specifically, these are the $^3S_1$ state of charmonium (in the usual $2S+1L_J$ spectroscopic notation), including for example the $J/\psi$ and $\psi(3686)$ ("$\psi'$"). Decays of these directly-produced states allow access to other charmonia such as the $\chi_{cJ}$, $h_c$, and $\eta_c$, which are the $^3P_0,^1P_1$, and $^1S_0$ states, respectively.

In the following section, we give examples of some analyses involving these states, based on our first data samples from 2009.

3.1 A Limit on $J/\psi \to e\mu$

At current sensitivities, lepton flavor violation is negligible in the Standard Model due to the very small neutrino masses. We perform a search for the flavor-violating decay $J/\psi \to e\mu$ in order to constrain models with new physics.

This analysis is based on a sample of 225 million $J/\psi$ decays. We select two-track events with a back-to-back topology and veto on photons to remove radiative QED events. Electron identification requires a large value of the ratio of calorimeter energy to track momentum, $E/p$, with the muon detector used as a veto. Muon identification requires a small $E/p$ and a penetrating track in the muon detector. Our final signal variables are the total energy (calculated from the momenta and masses) and net three-momentum of the two detected particles.

We find four candidates, with an expected background of $4.75 \pm 1.09$ determined from Monte-Carlo simulations. This yields a limit of:

$$B(J/\psi \to e\mu) < 1.5 \times 10^{-7}.$$  

This represents more than a factor of seven improvement over the best prior limit.

Many other rare decays are accessible at BESIII, and we now have about five times more $J/\psi$ decays in our total data sample.

3.2 A Study of $\chi_{c0,2} \to \gamma\gamma$

Our large sample of 106 million $\psi(3686)$ decays allows for precision studies of $\chi_{c2} \to \gamma\gamma$ decays$^6$. We look for events with three photons and no tracks, arising from
\( \psi(3686) \to \gamma_1 \chi_{cJ} \); \( \chi_{cJ} \to \gamma_2 \gamma_3 \). We identify the \( \chi_{cJ} \) states via the energy of the transition photon, \( \gamma_1 \), which has better resolution than the \( \gamma_2 \gamma_3 \) invariant mass.

The transition lines are shown in Fig. 3; note that the \( J = 1 \) transition is forbidden. Also displayed is the \( E_{\gamma_1} \) lineshape we use, as extracted using a very high-purity sample (99.2\%) of hadronic decays of the \( \chi_{cJ} \).

![Figure 3](image)

**Figure 3:** Left: The \( E_{\gamma_1} \) distribution, showing transition lines from the \( \chi_{c2}, \chi_{c0} \). The data points are fit to a solid line which includes signal peaks above the red dashed background shape; fit residuals are displayed below. Right: Lineshape extracted from data, via \( \psi' \to \gamma_1 \chi_{cJ}; \chi_{cJ} \to K^+ K^- \).

We obtain the branching ratios:

\[
\mathcal{B}(\chi_{c0} \to \gamma \gamma) = (2.24 \pm 0.19 \pm 0.12 \pm 0.08) \times 10^{-4}
\]
\[
\mathcal{B}(\chi_{c2} \to \gamma \gamma) = (3.21 \pm 0.18 \pm 0.17 \pm 0.13) \times 10^{-4}
\]

where the errors are from statistics, internal systematics, and PDG inputs[7] on needed branching fractions and widths. We also extract the ratio of widths:

\[
R = \frac{\Gamma_{2 \to \gamma \gamma}}{\Gamma_{0 \to \gamma \gamma}} = (0.271 \pm 0.029 \pm 0.013 \pm 0.027) .
\]

The expected ratio is \( 4/15 \simeq 0.27 \).

Finally, we perform the first helicity analysis for the \( J = 2 \) decay. We find that the ratio of helicity 0 to helicity 2 is

\[
f_{0/2} = 0.00 \pm 0.02 \pm 0.02
\]
demonstrating the dominance of the helicity-2 process, as predicted by theory.
3.3 Masses and Widths of the $h_c$ and $\eta_c$

This analyses uses the decay chain $\psi(3686) \rightarrow \pi^0 h_c, h_c \rightarrow \gamma \eta_c$ to study lineshapes of both the $h_c$ and $\eta_c$[8]. The $\eta_c$ is reconstructed in sixteen exclusive channels. In fact, for five of the sixteen $\eta_c$ modes, we also report the first measurement of the branching fraction. The radiated $\pi^0$ is also detected, and this results in very clean peaks for both states, as shown in Figs. 4 and 5.

Figure 4: Left: Sum of sixteen exclusive $\eta_c$ decay modes, with a fit including a peak from $\psi(3686)$ decays to the same final states and combinatorial background, in addition to the $\eta_c$ peak. Right: A background-subtracted plot of the same data.

Figure 5: The $h_c$ peak obtained via the $\pi^0$ recoil mass.

We obtain the most precise $h_c$ mass and width to date:

\[ M(h_c) = (3525.31 \pm 0.11 \pm 0.14) \text{ MeV/c}^2 \quad \Gamma(h_c) = (0.70 \pm 0.28 \pm 0.22) \text{ MeV} . \]

The $\eta_c$ results, are also quite precise:

\[ M(\eta_c) = (2984.49 \pm 1.16 \pm 0.52) \text{ MeV/c}^2 \quad \Gamma(\eta_c) = (36.4 \pm 3.2 \pm 1.7) \text{ MeV} . \]
While there are more precise width results available, the precision on the mass is similar to the best previous measurements[7]. Those results have some tension with each other; ours favors a mass toward the higher end of their range. Furthermore, our $\eta_c$ measurements benefit from having highly suppressed interference effects due to our technique; this may be the best method with larger datasets in the future.

3.4 Mass and Width of the $\eta_c(2S)$

BESIII has made the first observation of the $M1$ transition $\psi(3686) \rightarrow \gamma \eta_c(2S)[9]$. We reconstruct the $\eta_c(2S)$ in the $K_S K^\pm \pi^\mp, K^+ K^- \pi^0$ modes and also detect the 48 MeV transition photon. A 4C kinematic fit enforcing four-momentum conservation is performed for both channels, and a 5C fit is also done for the mode with a $\pi^0$ where that particle’s mass is the fifth constraint. As seen in Fig. 6 backgrounds from $\chi_{cJ}$ and $\psi(3686)$ decays are substantial, but a signal for the suppressed $M1$ transition is nonetheless evident.

![Figure 6: Invariant mass of $K_S K^\pm \pi^\mp$ (left) and $K^+ K^- \pi^0$ (right); the $\eta_c(2S)$ peaks are near 3.64 GeV. The many component curves are detailed in the caption.](image)

We extract the $\eta_c(2S)$ parameters:

$$M(\eta_c(2S)) = (3637.6 \pm 2.9 \pm 1.6) \text{ MeV}/c^2 \quad \Gamma(\eta_c(2S)) = (16.9 \pm 6.4 \pm 4.8) \text{ MeV}.$$  

These are comparable in precision to the current PDG world averages[7] of $(3637 \pm 4)$ MeV/$c^2$ and $(14 \pm 7)$ MeV, respectively.

4 Preliminary Precision Charm Results

BESIII has a sample of 2.9 fb$^{-1}$ of $\psi(3770)$ data; this resonance dominantly decays to $D^0 D^0$ and $D^+ D^-$ pairs. At the peak, the total $D \bar{D}$ cross-section is about 6.6 nb. We
note that there is insufficient energy for any additional hadrons; in particular, $D\overline{D}\pi$ is kinematically forbidden.

A key to many analyses is the use of “$D$ tagging”; this refers to full reconstruction of one $D$ or $\overline{D}$ meson in a fully hadronic final state. Examples of modes used include $D^0 \rightarrow K^-\pi^+$ and $D^+ \rightarrow K^-\pi^+\pi^+$.

There are two key variables characterizing tags. The beam-constrained mass, 
\[ m_{bc} = \sqrt{E_{bm}^2 - p_{cand}^2}, \]
is based on momentum conservation. Here, $E_{bm}$ is the beam energy and $p_{cand}$ is the $D$ candidate momentum (summed from the decay daughters).

The energy difference, 
\[ \Delta E = E_{cand} - E_{bm}, \]
tests for energy conservation; here, $E_{cand}$ is the $D$ candidate energy. Unlike $m_{bc}$, it depends on particle identification since charged daughter rest-masses are needed to calculate energies from track momenta.

Use of tagging provides many advantages. First, it removes most backgrounds from continuum ($u\bar{u}, d\bar{d}, s\bar{s}$ light-quark pair) events. Second, it constrains the kinematics of the other $D$. Specifically, it gives the vector direction of the momentum; the magnitude is known a-priori from energy-momentum conservation. And this constraint allows one to infer the four-vector of an unobserved neutrino in the decay of the $D$ opposite the tag as long as all other decay products are detected. It is the last feature that is key to the two analyses discussed below.

The branching ratios and efficiencies of the hadronic $D$ ($\overline{D}$) tagging modes largely cancel when studying the other “signal” $\overline{D}$ ($D$), since we measure the ratio of the tag plus signal yield to the tag only yield.

In addition to the results presented here, work is in progress on many other topics. These include the strong $K\pi$ phase, quantum coherence measurements of modes including $K_S\pi^+\pi^-$, the $D^0\overline{D}^0$ oscillation parameter $y$, rate asymmetries in $D \rightarrow K_{L,S}\pi\pi$, the non-$DD$ cross-section at the $\psi(3770)$, and more.

### 4.1 The Decay Constant $f_D$

We now present BESIII’s precise determination of the pseudoscalar decay constant $f_D$ from the decay $D^+ \rightarrow \mu\nu$[10]. This Cabibbo-suppressed $D^+$ mode has only been measured at $D\overline{D}$ threshold. On the other hand, $D_s^+ \rightarrow \mu\nu$ has been measured both at threshold and at $B$ factory energies; a submitted Belle result[11] is currently the world’s best.

The decay rate is proportional $f_D^2$, which may be thought of as characterizing the probability that the $c$ and $\overline{d}$ quark overlap such that they may annihilate into a virtual $W^+$ boson. Other necessary external inputs include $V_{cd}$ and $\tau_{D^+}$; in particular:

\[ \Gamma(D^+ \rightarrow \mu\nu) = \frac{G_F^2}{8\pi} f_D^2 |V_{cd}|^2 m_\mu^2 m_{D^+}^2 \left(1 - \frac{m_\mu^2}{m_{D^+}^2}\right). \]

$D^+D^-$ events are tagged with nine $D^+$ decay modes: $K^-\pi^+\pi^+$, $K^-\pi^+\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-\pi^-$, $K_S\pi^+$, $K_S\pi^+\pi^0$, $K_S\pi^+\pi^-\pi^-$, $K_SK^+$, $K^+K^-\pi^+$, and $\pi^+\pi^+\pi^-$. We
require exactly one track in addition to the tag, with the correct charge. We veto any unused high-energy (> 300 MeV) EM calorimeter showers not matched to a track. This is especially effective in reducing $D^+ \to \pi^+\pi^0$ background, which is important since $m_n^2$ is comparable to our $MM^2$ resolution.

Our final signal variable is $MM^2 = E_{miss}^2 - p_{miss}^2$, where the missing four-momentum is obtained by subtracting the $D$ tag and signal $\mu$ momenta from the known initial-state four-vector. This quantity will peak at zero when only a neutrino was omitted from our kinematic calculations. Our data is presented in Fig. 7, where a remarkably clean signal peak is evident.

We observe a signal of $377.3 \pm 20.6 \pm 2.6$ events above a background of 47.7 events.
From this signal, we extract:

\[ B(D^+ \to \mu \nu) = (3.74 \pm 0.21 \pm 0.06) \times 10^{-4} \]

\[ f_D = (203.01 \pm 5.72 \pm 1.97) \text{ MeV} \]

This is more precise than the previous best measurement of \( f_D = (205.8 \pm 8.5 \pm 2.5) \) MeV, based on 818 pb\(^{-1}\) from CLEO-c\(^{[12]}\). It is in agreement with recent lattice QCD calculations; see, for example, the summary in Ref. \(^{[10]}\). Note that the measurement is still statistics-limited; we expect that BESIII will take more data in the future in order to further improve this important result.

4.2 \( D \) Semileptonic Form-Factors

BESIII has extracted the form-factors \( f_{\pi,K}(q^2) \) from the semileptonic decays \( D^0 \to K^-e^+\nu,\pi^-e^+\nu \)^\(^{[13]}\). Here, \( q^2 = m_{\ell\nu}^2 \) and these form factors describe the effects of meson structure in the decay, relative to idealized free-quark decay. In particular, the partial decay rate for \( D^0 \to \pi^-e^+\nu \) is given by:

\[ \frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{ud}|^2 p_\pi^3 |f_{\pi}(q^2)|^2 \]

and a similar expression for \( D^0 \to K^-e^+\nu \).

The four tag modes \( K^-\pi^+, K^-\pi^+\pi^0, K^-\pi^+\pi^+\pi^- \) and \( K^-\pi^+\pi^0\pi^0 \) are used. Particle identification is important for both the \( D \) tag and the semileptonic “signal” \( D \). However, there is actually excellent kinematic separation between the Cabibbo-allowed \( K\ell\nu \) mode and the ten-times rarer Cabibbo-suppressed \( \pi\ell\nu \) mode. This is in marked contrast to older analyses based on \( D^* \) tagging with higher-energy \( D \) mesons. With the very large luminosities of \( B \) factories, it is now possible to use a full-event reconstruction tagging technique, which is far superior to the older \( D^* \) tagging, but still has higher backgrounds than analyses from charm threshold.

We require exactly two oppositely-charged tracks in addition to our hadronic \( D \) tag, with the correct electron charge. Electron identification is based on \( E/p \), while \( K-\pi \) separation employs time-of-flight and \( dE/dx \). We veto any unused high-energy (> 250 MeV) EM calorimeter showers not matched to a track. Our final signal variable is \( U = E_{\text{miss}} - p_{\text{miss}} \); the “miss” quantities, representing the unobserved neutrino, are analogous to those in the previous analysis. For signal, \( U \) peaks at zero and is similar to a missing-mass-squared. Fits to the \( U \) distributions in Fig. \(^8\) lead to the branching fraction results shown in Table \(^1\).
Figure 8: $U = E_{\text{miss}} - p_{\text{miss}}$ distributions (GeV) for $D^0 \rightarrow K^- e^+ \nu$ (left), $D^0 \rightarrow \pi^- e^+ \nu$ (right). The blue total fit curve is the sum of a green signal shape and a red background term.

Figure 9: Extracted form factors, $f(q^2)$, for $D^0 \rightarrow K^- e^+ \nu$ (left), $D^0 \rightarrow \pi^- e^+ \nu$ (right). The data points are compared to Lattice predictions (red) bracketed by one-sigma error bands (blue).

Table 1: Preliminary BESIII branching fractions and PDG 2012 world averages[7].

| Mode                  | BESIII BF (%) | PDG BF (%) |
|-----------------------|---------------|------------|
| $D^0 \rightarrow K^- e^+ \nu$ | 3.542 ± 0.030 ± 0.067 | 3.55 ± 0.04 |
| $D^0 \rightarrow \pi^- e^+ \nu$ | 0.288 ± 0.008 ± 0.005 | 0.289 ± 0.008 |

Table 2: Preliminary BESIII form-factor results. For brevity, only results from the three-parameter series fit are shown.

| Mode                  | $f_+(0)|V_{cs(d)}|$ | $r_1$          | $r_2$          |
|-----------------------|-----------------|----------------|----------------|
| $D^0 \rightarrow K^- e^+ \nu$ | 0.729 ± 0.008 ± 0.007 | -2.179 ± 0.355 ± 0.053 | 4.359 ± 8.927 ± 1.103 |
| $D^0 \rightarrow \pi^- e^+ \nu$ | 0.144 ± 0.005 ± 0.002 | -2.728 ± 0.482 ± 0.076 | 4.194 ± 3.122 ± 0.448 |
For the form-factor analysis, we divide the data into bins of $q^2$ to determine values of $d\Gamma/dq^2$ integrated over these bins. We note that our $q^2$ resolution is excellent and the smearing effects, which we do include, are modest. The extracted form factors are shown in Fig. 9 along with a representative lattice QCD calculation\cite{14}. We have not attempted to update the comparison to lattice QCD made at the original presentation of BESIII results at CHARM2012; in the future, we will compare final BESIII results to all updated LQCD results. Numerical values of our form factor fit results are given in Table 2 for the three-parameter version of the popular series expansion\cite{15} prescription for parameterizing the form factor. The results for other fits are available in Ref. 13.

All results except for the $K\nu$ branching fraction are still statistics-limited. The present results were obtained with about one-third of the full 2.9 fb$^{-1}$ sample; an update to the full dataset is expected soon.

5 Conclusions

We have presented a selection of results broadly spanning charm physics, including the discovery a possible new exotic state, studies of several conventional charmonium states, and first results from a precision $D$ physics program.

Now five years from our first collisions, BESIII has established a broad and successful program in charm physics. Recently, in 2012, even larger samples have been accumulated at the $J/\psi$ and $\psi(3686)$; total samples are now about 1.2 billion and 0.35 billion decays, respectively. Furthermore, our 2013 dataset includes more data near 4260 MeV, and also a large sample at the $Y(4360)$. This and future running will sustain a vibrant physics program for many more years to come.

ACKNOWLEDGEMENTS

We thank our BEPCII colleagues for the excellent luminosity and our BESIII collaborators for their many efforts culminating in the physics results presented herein.

References

[1] Belle Collaboration, A. Bondar et al., Phys. Rev. Lett. 108, 122001 (2012).
[2] BESIII Collaboration, M. Ablikim et al., Phys. Rev. Lett. 110, 252001 (2013).
[3] Belle Collaboration, Z.Q. Liu et al, Phys. Rev. Lett. 110, 252002 (2013).
[4] T. Xiao et al, arXiv:1304.3036.
[5] BESIII Collaboration, M. Ablikim et al., Phys. Rev. D87, 112007 (2013).

[6] BESIII Collaboration, M. Ablikim et al., Phys. Rev. D85, 112008 (2012).

[7] J. Beringer et al, (Particle Data Group), Phys. Rev. D86, 010001 (2012).

[8] BESIII Collaboration, M. Ablikim et al., Phys. Rev. D86, 092009 (2012).

[9] BESIII Collaboration, M. Ablikim et al., Phys. Rev. Lett. 109, 042003 (2012).

[10] G. Rong, arXiv:1209.0085, contribution to the proceedings of The 5th International Workshop on Charm Physics (Charm 2012).

[11] Belle Collaboration, A. Zupanc et al, arXiv:1307.6240, submitted to JHEP.

[12] CLEO Collaboration, B.I. Eisenstein et al, Phys. Rev. Lett. 78, 052003 (2009).

[13] C. Liu, arXiv:1207.1171, contribution to the proceedings of The 5th International Workshop on Charm Physics (Charm 2012).

[14] Jon A. Bailey et al (for the Fermilab-MILC Collaboration), arXiv:1111.5471

[15] T. Becher and R.J. Hill, Phys. Lett. B633, 61 (2006).