Overview of Key BESIII Physics Opportunities

Roy A. Briere, Daniel Cronin-Hennessey

November 11, 2011

Abstract

In this letter we review the BESIII experiment, its current operational status and its primary physics goals. We give some details on the open-charm physics program that is of primary interest to the U.S. contingent of the BESIII collaboration and that directly impacts physics in the scope of the Intensity Frontier. The main point is that BESIII has access to key measurements which were statistics-limited at CLEO-c coupled with a proven ability to increase our statistics by an order of magnitude. The U.S. member institutions include Carnegie Mellon University, University of Hawaii, Indiana University, University of Minnesota and University of Rochester.

1 Introduction

The BESIII experiment at BEPCII in Beijing is designed to provide a comprehensive world-class physics program in the charm threshold region [1]. Currently in operation, BESIII has already accumulated the world's largest data samples of e^+e^- collisions at center-of-mass energies of J/ψ, ψ' and $\psi(3770)$. Primary open-charm physics goals of this program include precision tests of Lattice QCD, precision extraction of CKM matrix elements, improved constraints on D decay phases and enhanced discovery potential for rare exotic D decays. Similar physics goals will be pursued for the D_s meson. BESIII will also provide a precision R scan in the charm region, the world's most precise τ mass measurement and novel investigations of recently discovered charm resonances (XYZ states). In addition to the open charm contributions BESIII has a unique window into charmonium spectroscopy and unprecedented sensitivity to exotic QCD states (e.g., glue-balls and hybrids).

The BEPCII machine is a two-ring e^+e^- collider operating in the $3-4$ GeV energy region. A major component of the BEPCII upgrade was conversion to a two-ring machine, which allows it to overcome one of the key limitations (beam-beam interactions) of the CESR-c machine used for CLEO-c. The accelerator is designed to provide a peak instantaneous luminosity of 10^{33} cm^{-2} s^{-1}, which translates into about 10 billion J/ψ and of order 30 million $D\bar{D}$ pairs per running year (typically 5-6 months of HEP running). BEPCII achieved 65% of peak luminosity during the 2011 $\psi(3770)$ data-taking, almost 10 times CESR-c's prior world-record in this energy regime.

BESIII is a general-purpose state-of-the-art collider detector located at the BEPCII accelerator. The BESIII drift chamber provides precision momentum resolution (0.5% at 1 GeV/c) as well as strong particle identification using specific ionization. The high-acceptance CsI crystal calorimeter provides an energy resolution of 2.5% and position resolution of 6 mm for electromagnetic showers at 1 GeV. Particle identification is greatly enhanced by both the time-of-flight system and muon identification system. Full details can be found in Ref. [2].

Operating since mid-2008, BEPCII has made steady progress toward the design luminosity goals. In the first physics year (2009), samples of J/ψ (226 million) and ψ' (106 million) were taken, in each case about four times the world's largest prior dataset. Analysis topics include precision charmonium spectroscopy, including studies of the $h_c, \eta_c, \eta_c', \chi_{cJ}$, and a broad light hadron physics program including glueball and hybrid searches. Light hadron work from $J/\psi \to ggg$ hadronization is complimentary to tagged-photon work such as that planned for the GLUE-x experiment of the Hall-D project at Jefferson Lab.

The charmonium samples helped us understand our new detector, and we next moved on data-taking runs for precision studies of "open-charm" $D_{(s)}$ mesons. In 2010 and about 2/3 of the 2011 run, 2.9 fb^{-1} at the $\psi(3770)$ were accumulated, about 3.5 times CLEO-c's total. This resonance decays to $D^0\bar{D}^0$ and D^+D^-, analogous to the perhaps more familiar $\Upsilon(4S)$ state used for B physics. In the rest of 2011 running, we took more than 400 pb^{-1} at 4010 MeV, for studies of XYZ spectroscopy and D_s physics from $D_s^+D_s^-$ pairs. A high-statistics scan of the $\psi(3770)$ line-shape was also obtained.

Future running plans include a return to charmonium (2012), then data-taking at 4170 MeV for D_s physics with $D_s^*D_s$ pairs (2013; the same energy used at CLEO-c). Eventual datasets for both D and D_s should be an order of magnitude or more than CLEO-c. Improved precision in the τ mass will also be obtained with a short run next year, making use of a precision beam-energy measurement system.

The open charm data make possible the most precise $D_{(s)}$ decay branching fraction measurements. Of particular interests to our groups are the $D_{(s)}$ leptonic decays that provide access to the $D_{(s)}$ decay constants and the semileptonic branching fractions and $q^2 = M^2_{e\nu}$ distributions which provide access to $D_{(s)}$ form factors. These will be used to confront current and future high precision Lattice QCD predictions.

2 Open Charm ($D_{(s)}$ meson) Physics

The study of open charm meson decays is a key part of precision tests of CKM physics, with the goal of finding New Physics in inconsistencies or disagreements with Standard Model expectations. There are excellent opportunities to confront modern Lattice QCD (LQCD) calculations and to make phase measurements unique to charm at threshold. Both aspects impact existing and future measurements in $B_{(s)}$ physics.

Measurements of charm at threshold are characterized by several unique advantages. First, the production of pairs of $D_{(s)}$ mesons allows for tagging techniques that allow extraction of absolute branching fractions independent of knowledge of the number of $D\bar{D}$ pairs produced. One can also infer the four-momentum of a single missing neutrino with very good resolution, using energy-momentum conservation in events where all other particles are measured. The slow D mesons at threshold also lead to enhanced kinematic separation of signals and backgrounds involving particle mis-identification (e.g., $K - \pi$ swaps) or missing particles. Finally, the quantum coherence of $D^0\bar{D}^0$ meson pairs allows for several unique analyses as detailed below.

CLEO-c results were statistics-limited for most of the high-profile measurements, the exception being golden-mode branching fractions for the D^0, D^+. BESIII already has about 2.9 fb^{-1} at the $\psi(3770)$ compared to 0.8 fb^{-1} for CLEO-c. By matching CLEO-c's systematic uncertainty control, significant advances in precision can already be made with the higher statistics in hand now.

BESIII plans to take $D_s^*D_s$ data at 4170 MeV in 2013. CLEO-c has 0.6 fb^{-1} at this energy; we should be able to accumulate $2 - 3$ fb^{-1} in our first run. More $\psi(3770)$ data will also be taken in the future. This is a valuable contribution to precision flavor physics in its own right, and also a stepping stone to potential future charm threshold efforts at a "super-B" facility.

2.1 Decay Constants

The branching fraction of $D_{(s)} \to \ell\nu$ is proportional to $f^2_{D_{(s)}}$. The D_s case is easier to measure for several reasons: it is Cabibbo-allowed, and the larger mass means that $\tau\nu$ modes are useful (τ leptons are found via $\tau \to \pi\nu, e\nu\nu, \rho\nu$). This has allowed BaBar and Belle to obtain results for the D_s decay constant; however, they are a bit poorer than CLEO-c statistically, and have noticeably larger systematic uncertainties.

On the other hand, precision on f_D has only been possible at threshold. Testing LQCD in charm will help to validate calculations of $f_{B_{(s)}}$ necessary to control theoretical errors which currently limit the utility of *existing* measurements of $\Delta m_d, \Delta m_s$ in the B^0, B^0_s systems. The decay $B^+ \to \tau\nu$ allows some access to f_B, though statistical precision is lacking, and systematic control may be difficult. Note, however, that f_{B_s} is purely in the realm of LQCD. The charm sector, with *experimental* access to both f_D and f_{D_s}, allows tests of the accuracy of LQCD in predicting $SU(3)$-breaking effects.

With the full CLEO-c dataset, both decay constants are statistics-limited [3, 4]:
$f_D = (205.8 \pm 8.5 \pm 2.5)$ MeV, $f_{D_s} = (259.0 \pm 6.2 \pm 3.0)$ MeV
BESIII statistics are certainly valuable to reduce these errors. And in the not-too-distant future, LQCD calculations may be able to attain sub-percent accuracy.

2.2 Form Factors

Semi-leptonic decays are described by a current-current Lagrangian, where the structure of the hadronic current enters into the branching fraction prediction via the square of a hadronic form-factor. This form-factor is a function of only $q^2 = M^2_{e\nu}$, and charm decays provide access to both the $D \to K, D \to \pi$ form factors via $D \to K^-e^+\nu, D \to \pi^-e^+\nu$ decays. B factory determinations of $|V_{ub}|$ are limited by the theoretical precision on the related $B \to \pi$ hadronic form-factor. Theoretical mastery of the form-factor will allow us to better use existing exclusive $B \to \pi\ell\nu$ branching fraction results. As with decay constants, there are results from B factories, but they are not very competitive in precision.

Recent theoretical work has provided model-independent series parameterizations of the form factors[6]. In one such fit, CLEO-c's full-dataset result for the $\pi\ell\nu$ form-factor at $q^2 = 0$ is [5]: $f_+(0)|V_{cd}| = 0.152 \pm 0.05 \pm 0.01$, clearly very statistics-limited.

Ratios of decay constant and form-factor results may be used to cancel out CKM matrix elements to construct pure tests of LQCD.

2.3 Absolute Branching Fractions

The golden-mode branching fractions for $D^0 \to K^-\pi^+$ and $D^+ \to K^-\pi^+\pi^+$ are systematics-limited [7] but, given their importance, an independent cross-check is desirable. On the other hand, CLEO-c's best published (half-dataset) result for $D^+_s \to K^+K^-\pi^+$ is still statistics-limited [8]: $\mathcal{B}(D^+_s \to K^+K^-\pi^+) = (5.50 \pm 0.23 \pm 0.16)\%$

2.4 Quantum Correlations and Phases

The process $e^+e^- \to \gamma^* \to \psi(3770) \to D^0\bar{D}^0$ leads to a C-odd initial state which corresponds to neutral D mesons produced in the coherent state $(D^0\bar{D}^0 - \bar{D}^0 D^0)\sqrt{2}$. This coherence may be exploited in a variety of ways.

One quantity accessible at the $\psi(3770)$ is the strong $K\pi$ scattering phase shift, $\delta_{K\pi}$. D mixing results using the $D^0 \to K^-\pi^+$ mode measure not the familiar x, y parameters describing mixing, but rather altered quantities x', y'. The primed quantities are related to the un-primed ones by a rotation through the angle $\delta_{K\pi}$. An analysis based on about 1/3 of the CLEO-c data currently provides the best knowledge of the $K\pi$ phase [9] $\delta_{K\pi} = (22^{+11+9}_{-12-11})^\circ$; BESIII should be able to improve on this. It will be necessary to study systematic issues more carefully with the higher statistics, or else trade statistics for better systematic stability.

Another useful type of study makes use of CP-tagged Dalitz plots. That is, we can separately study the Dalitz plots of the two different $D^0 \pm \bar{D}^0$ states. By comparing them, one can measure the strong phase analogs to $\delta_{K\pi}$ across a 3-body Dalitz plot. This input is useful in reducing systematic uncertainties on determinations of γ using $B \to DK$ decays. In fact, several LHCb collaborators joined CLEO-c near the end of the experiment for the expressed purpose of performing these analyses. Some of these physicists are currently in contact with BESIII, working to maintain interest in such results and to help identify opportunities for useful interactions, including input on priorities and the details of how results are presented.

2.5 Rare D Decays

A primary goal of the heavy flavor community is discovering a deeper theory of flavor. At the *energy frontier*, one may be able to directly produce new particles relevant to this quest. But experiments under the umbrella of the *intensity frontier* also have promse, via precision and rare decay measurements that are sensitive to virtual contributions of new particles. Such an approach is viable due to the reliability in calculating standard model contributions. Furthermore, rare and precision measurements often have a mass reach well beyond that of direct searches. There is no guarantee that new physics associated with flavor will appear at the same scale as the Higgs, and therefore experiments that probe for new virtual contributions are complimentary to direct searches.

One of the hallmarks of the standard model is the absence of Flavor Changing Neutral Currents (FCNC) at tree level. However, these often appear at the loop level and are thus useful probes for new intermediate particles, given clear standard model predictions. As a probe of new physics, the charm sector is particularly interesting due to the effectiveness of GIM suppression for charm decays. The predicted short-distance contributions of the standard model for FCNC in charm are well beyond the sensitivity of current experiments. The possible new physics scenarios that would allow large FCNC include supersymmetry, extended degrees of freedom and strong dynamics (e.g., top condensates); these are reviewed in Ref. [10]. Thus an unambiguous observation in the charm sector could signal new physics and would help constrain the successor to the standard model as well as provide a better understanding of flavor.

There are number of interesting modes with either flavor violation or $c \to u$ transitions. The charm production rates at hadron colliders and B factories exceed those at charm threshold machines. However, higher multiplicity final states, modes with invisible energy and modes with final state photons benefit from the high purity and kinematic constraints that threshold experiments can deliver. Such examples include $D \to V\gamma$, $D \to X\ell\ell'$, and $D \to X\nu\bar{\nu}$ (V is a vector meson, and X represents hadron states).

Among di-lepton modes, those that violate lepton flavor or number (e.g., $e\mu$, l^+l^+) provide unambiguous evidence for new physics. We expect that the currently running BESIII experiment will improve the previous CLEO-c limits by factors of order three to ten (depending on how background-free a given modes is). The same-flavor di-lepton modes and vector-photon modes are complicated by standard model long-distance contributions. However, in the case of the leptons, rates with the lepton-pair mass cut away from resonance contributions still provide access to new physics.

BESIII will also improve the observations and limits of the vector-gamma modes. In order to disentangle the long distance contributions, one needs to compare the relative rates of several vector-photon modes ($K^*\gamma$, $\rho\gamma$ and $\omega\gamma$, for example). The long distance rates are of the order 10^{-6}, which is within the range of BESIII's sensitivity. The current $K^*\gamma$ measurement is on the high side of predictions, so more precisely confronting SM predictions is an important goal. BESIII will improve this measurement and has the reach to see currently unobserved vector-gamma states. Finally, there is one mode, $D \to \gamma\gamma$, for which the long-distance contributions are suppressed by 2 orders of magnitude (to the level of 10^{-8}). An observation by BESIII would indicate new physics and this mode will be a priority target for the BESIII experiment.

3 Other Physics

We now give a very brief overview of selected portions of the rest of the BESIII physics question.

3.1 Tau Mass

A short run at $\tau\tau$ threshold will lead to an improved value of the τ lepton mass, useful in studies of weak decays and universality. This analysis will take advantage of a new precision beam-energy measurement system. The current world average precision is ± 0.16 MeV; the total error on the single best measrment is about twice as large. BESIII is aiming for $\pm 0.05 \pm 0.05$ MeV, or about four times better than the previous best experiment.

3.2 Charmonium

Direct production of the $J^{PC} = 1^{--}$ $J/\psi, \psi'$ states allows for precision studies of charmonium spectroscopy. Radiative and pionic decays of these provide excellent access to the $h_c, \eta_c, \eta_c', \chi_{cJ}$ states in particular.

BEPCII also provides the opportunity to see if any of the broader $c\bar{c}$ resonant structures exhibit transitions to the plethora of poorly-understood "XYZ" states.

3.3 Light Hadronic Physics

The processes $e^+e^- \to c\bar{c} \to ggg, gg\gamma \to hadrons$ provide access to a rich panoply of light hadron physics. As an example, the radiative decay acts like a broad scan for glueball states, since the photon energy constrains the gg mass. Decays of χ_{cJ} states provide access to initial states with different J^{PC} quantum numbers.

In general, the contributions of BESIII have good synergy and complementarity with the GLUE-x experiment of the Hall-D project at Jefferson Lab.

3.4 *R* Scans

BEPCII has always envisioned energy scans as part of its portfolio. The main interest is to precisely determine R_{had} vs. energy. Improved values will have an impact on radiative corrections to $g-2$ and the running of coupling constants. Detailed scanning of resonance shapes is also possible, and in fact has already stated with the $\psi(3770)$ as noted above.

4 Conclusion

BESIII has been running at record luminosity for several years, accumulating the world's largest dataset at several energies. The most recent runs have concentrated on data for precision studies in the weak-flavor physics of open-charm mesons. These results form an integral part of the communities weak-flavor physics effort at the intensity frontier, and in particular have good synergy with $B_{(s)}$ physics and Lattice QCD. Many other interesting physics topics are also investigated in parallel.

The US groups are small but effective, and are an excellent investment considering the physics potential of BESIII. In particular, it is clear that the larger data samples will be able to improve on the already world-class results from CLEO-c.

References

[1] *Physics at BESIII*, D. M. Asner *et al*, arXiv:0809.1869v1 [hep-ex].

[2] *Design and Construction of the BESIII Detector*, M. Ablikim *et al*, Nucl. Instr. Meth. **A614**, 345 (2010).

[3] *Precision measurement of* $\mathcal{B}(D^+ \to \mu^+\nu)$ *and the pseudoscalar decay constant* f_{D^+}, B. I. Eisenstein *et al*, Phys. Rev. **D78**, 052003 (2008).

[4] *Measurement of* $\mathcal{B}(D_s^+ \to \ell^+\nu)$ *and the decay constant* $f_{D_s^+}$ *from 600* pb^{-1} *of* e^+e^- *annihilation data near 4170 MeV*, J. P. Alexander *et al*, Phys. Rev. **D79**, 052001 (2009); *Improved measurement of absolute branching fraction of* $D_s^+ \to \tau^+\nu_\tau$, P. U. E. Onyisi *et al*, Phys. Rev. **D79**, 052002 (2009); *Measurement of the pseudoscalar decay constant* $f_{D_s^+}$ *using* $D_s^+ \to \tau^+\nu, \tau^+ \to \rho^+\bar{\nu}$ *decays*, P. Naik *et al*, Phys. Rev. **D80**, 124004 (2009).

[5] *Improved measurements of D meson semileptonic decays to* π *and K mesons*, D. Besson *et al*, Phys. Rev. **D80**, 032005 (2009).

[6] *Comment on form-factor shape and extraction of* $|V_{ub}|$ *from* $B \to \pi\ell\nu$, Thomas Becher and Richard J. Hill, Phys. Lett. **B633**, 61 (2006).

[7] *Measurement of absolute hadronic branching fractions of D mesons and* $e^+e^- \to D\bar{D}$ *cross sections at the* $\psi(3770)$, S. Dobbs *et al*, Phys. Rev. **D76**, 112001 (2007).

[8] *Absolute Measurement of Hadronic Branching Fractions of the* D_s^+ *Meson*, J. P. Alexander *et al*, Phys. Rev. Lett. **100**, 161804 (2008).

[9] *Determination of the Strong Phase in* $D^0 \to K^+\pi^-$ *Using Quantum-Correlated Measurements*, J. L. Rosner *et al*, Phys. Rev. Lett. **100**, 221801 (2008); *Determination of the* $D^0 \to K^+\pi^-$ *relative strong phase using quantum-correlated measurements in* $e^+e^- \to D^0\bar{D}^0$ *at CLEO*, D. M. Asner *et al*, Phys. Rev. **D78**, 012001 (2008).

[10] *Rare charm decays in the standard model and beyond*, G. Burdman, E. Golowich, J. Hewett and S. Pakvasa, Phys. Rev. **D66**, 014009(2002) and references therein.