Physics Potential of a High-luminosity J/ψ Factory

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Abstract

We examine the scientific opportunities offered by a dedicated "J/ψ factory" comprising an e^+e^- collider equipped with a polarized e^- beam and a monochromator that reduces the center-of-mass energy spread of the colliding beams. Such a facility, which would have budget implications that are similar to those of the Fermilab muon program, would produce $\mathcal{O}(10^{13})$ J/ψ events per Snowmass year and support tests of discrete symmetries in hyperon decays and investigations of QCD confinement with unprecedented precision. While the main emphasis of this study is on searches for new sources of CP-violation in hyperon decays with sensitivities that reach the Standard Model expectations, such a facility would additionally provide unique opportunities for sensitive studies of the spectroscopy and decay properties of glueball and QCD-hybrid mesons. Polarized e^- beam operation with $E_{\rm cm}$ just above the $2m_\tau$ threshold would support a search for CP violation in $\tau^- \to \pi^-\pi^0\nu$ decays with unique sensitivity. Operation at the ψ' peak would enable unique probes of the Dark Sector via invisible decays of the J/ψ and other light mesons.

Keywords: Hyperons, CP violation, rare decays, glueball & QCD-hybrid spectroscopy, τ decays

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Introduction

In contrast to K-meson and B-meson systems, where CP violations have been extensively investigated, CP violations in hyperon decays have never been observed. A consequence of CP symmetry in Λ decay is that $\alpha_- = -\alpha_+$, where α_- (α_+) is the up-down asymmetry parameter for $\Lambda \to p\pi^-$ ($\bar{\Lambda} \to \bar{p}\pi^+$) decay. Any deviation of the CP asymmetry parameter $A_{CP} \equiv (\alpha_- + \alpha_+)/(\alpha_- - \alpha_+)$ from zero would be an unambiguous signal for CP violation. Conservative estimates of standard model (SM) induced CPV in Λ decay via the Kobayashi-Maskawa mechanism are in the $|A_{CP}| \simeq (1 \sim 5) \times 10^{-5}$ range [1, 2]. A measurement of $|A_{CP}|$ that is above this range would be a sign of new, beyond-the-SM (BSM) physics.

Agreement between SM calculated and measured values of ϵ'/ϵ [3] restricts the possible level of non-SM CP violations for parity-changing decay processes of s-quarks to be below the 6×10^{-5} level [4], but allows for asymmetries as large as $\mathcal{O}(10^{-3})$ in parity-conserving processes that can be observed in hyperon decays, such as $\Lambda \to p\pi^-$ and $\Xi^- \to \Lambda\pi^-$ [5].

The best current experimental upper limit for the Λ hyperon's A_{CP} parameter[1] is $|A_{CP}| < 2.4 \times 10^{-2}$ (90% CL) from a BESIII analyisis of 420K fully reconstructed $J/\psi \to \Lambda(\to p\pi^-)\bar{\Lambda}(\to \bar{p}\pi^+)$ events with negligible background [7] in a 1.3 B J/ψ event sample. This result superceded an earlier result $|A_{CP}| < 4.0 \times 10^{-2}$ that was based on 96K $p\bar{p} \to \Lambda\bar{\Lambda}$ events [8]. Recently BESIII increased their J/ψ data sample to 10 B events. Analyses that are currently underway that using this expanded data set plus Λ (& $\bar{\Lambda}$) hyperons produced from $\Xi \to \Lambda\pi$ decays are expected to improve the sensitivity to the $\sim 2 \times 10^{-3}$ level [9].

However, this anticipated more stringent limit from BESIII will barely touch the upper end of the new physics possibilities discussed in ref. [5], and is two orders-of-magnitude above the level expected for SM sources of CPV. Thus, a search for a new-physics source of CPV in hyperon decays has considerable reach, and this motivates the exploration of techniques that significantly improve on the BESIII sensitivity.

The path to $\delta \mathbf{A_{CP}} < 10^{-4}$

The statistical sensitivity for hyperon CP asymmetry parameter measurements goes as $\left[\mathcal{P}^{Y}_{\rm rms}\sqrt{N_{\rm evts}}\right]^{-1}$, where $\mathcal{P}^{Y}_{\rm rms}$ is the rms polarization of the hyperon. To improve on the BESIII A_{CP} sensitivity of 2×10^{-3} that is expected for the full 10 B J/ψ event data sample, to the $< 10^{-4}$ level requires at least a twentyfold increase in $\mathcal{P}^{\Lambda}_{\rm rms}\sqrt{N_{\rm evts}}$. We propose to achieve this by increasing $\mathcal{P}^{\Lambda}_{\rm rms}$ with a polarized e^- beam and increasing $N_{\rm evts}$ by a combination of a luminosity increase and a reduction in the c.m. energy spread of the colliding beams. (Here we limit discussion to $\Lambda\bar{\Lambda}$ measurements; similar results obtain for $\Xi\bar{\Xi}$ & $\Sigma\bar{\Sigma}$.)

e^- beam polarization: BESIII Λ measurements, which are done with unpolarized e^- and e^+ beams, were only possible because of the $\cos\theta$-dependent polarization of the Λ and $\bar{\Lambda}$ produced by a non-zero complex phase difference, $\Delta\Phi$, between the $A_{\frac{1}{2}\frac{1}{2}}$ and $A_{\frac{1}{2}-\frac{1}{2}}$ helicity amplitudes for the $J/\psi \to \Lambda\bar{\Lambda}$ process [10]. BESIII measured this to be $\Delta\Phi = (42.4 \pm 0.8)^\circ$ [7] and the corresponding rms polarization is $\mathcal{P}^{\Lambda}_{\rm rms} \simeq 0.15$ (solid black curve in Fig. 1a). If the e^- beam has an 80% longitudinal polarization, the Λ hyperon's rms polarization will increase approximately four-fold to $\mathcal{P}^{\Lambda}_{\rm rms} \simeq 0.6$ (dotted blue curve in Fig. 1a), which is equivalent to a factor of 16 gain in $N_{\rm evts}$. Another huge advantage of a polarized e^- beam is that throughout the measurement period the polarization can be reversed or set to zero, with no changes to the beam conditions, thereby providing a powerful tool for understanding and controling systematics. Thus, the e^- beam polarization is an essential feature of our evaluation.

Higher Luminosity: BEPCII is the highest luminosity e^+e^- collider to operate in the τ-charm threshold energy region and typically produces 1 B events/month at the J/ψ peak. However, the BEPCII design is optimized for $E_{\rm cm} = 3.77$ GeV, where the instantaneous luminosity is 10^{33}cm^{-2}s^{-1}; at $E_{\rm cm} = m_{J/\psi}c^2 = 3.097$ GeV the luminosity is a factor of $2.5 \sim 3$ lower. An e^+e^- collider based on BEPCII technology but optimized for the J/ψ would have at least double BESIII's J/ψ event rate. SuperKEKB is developing

[1] HyperCP limited the combination of CP parameters in the $\Xi \to \Lambda\pi$, $\Lambda \to p\pi$ chain to $|A^{\Lambda}_{CP} + A^{\Xi^-}_{CP}| < 2 \times 10^{-3}$ [6].

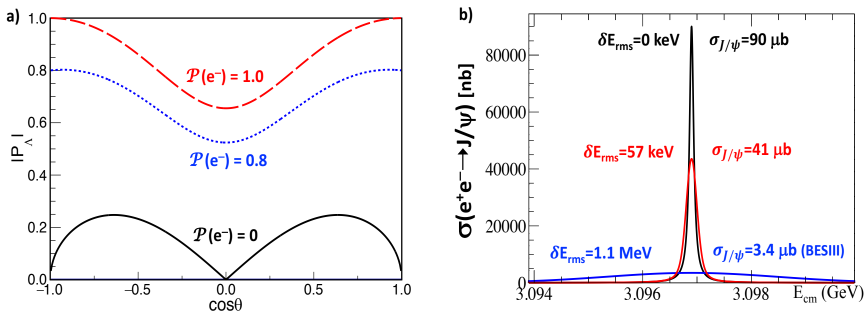

FIG. 1: **a)** The production angle dependence of the absolute value of the Λ polarization for $\mathcal{P}(e^-) = 0$ (solid black), $\mathcal{P}(e^-) = 0.8$ (dotted blue) and $\mathcal{P}(e^-) = 1.0$ (dashed red). **b)** The J/ψ line shape for different values of $\delta E_{\rm rms}$.

nanobeam techniques with the goal of producing a factor of 40 luminosity boost over KEKB [11]. Aspects of the SuperKEKB design that are applicable to the J/ψ factory would be incorporated into the J/ψ-factory design with a resultant additional gain in luminosity.

Monochromator scheme: When BEPCII operates at the J/ψ, the c.m. energy spread of the colliding electron and positron beams is $\delta E_{\rm rms} \simeq 1.1$ MeV, and considerably broader than the $\Gamma = 92$ keV J/ψ natural width. The *visible* peak cross section for $e^+e^- \to J/\psi$ at BESIII is $\sigma_{J/\psi} = 3.4\mu$b, a small fraction of its theoretical peak value of $\simeq 90\mu$b (for $\delta E_{\rm rms} = 0$). A monochromator scheme proposed by Zolents [12] introduces momentum dispersion into both beams at the e^+e^- interaction point that is arranged so the low-momentum side of the e^- beam profile intercepts the high energy side of the e^+ beam profile, and vice versa. This can substantially reduce the effective $\delta E_{\rm rms}$ and correspondingly increase the J/ψ production rate; for $\delta E_{\rm rms} = 57$ keV, the cross section is $10\times$higher: $\sigma_{J/\psi} = 41\mu$b (see Fig. 1b).

Other physics with $> 10^{13}$ polarized J$/\psi$ mesons

Although this letter emphasizes the CPV search capabilities of a polarized J/ψ factory, a host of other research programs could be supported by such a facility, most of which would be done simultaneously with the CPV measurements. These include:
i) precision studies of hyperon semileptonic and other rare decays and searches for forbidden decays;
ii) comprehensive studies of QCD in the confinement regime, including the spectra and decay properties of glueballs and QCD-hybrid mesons that are produced in radiative J/ψ decays [13–15];
iii) precise measurements of rare and sensitive searches for forbidden (including C and CP-violating) of the J/ψ and light hadrons such as η, η', ω, and ϕ [16, 17].

Physics opportunities at nearby c.m. energies

Operation at the $\psi(3686)$ (ψ') peak would provide a large, unbiased sample of $\pi\pi$-tagged J/ψ mesons produced via $\psi' \to \pi^+\pi^- J/\psi$ for studies of J/ψ decays to invisible and dark photon final states [18]; similar searches could be done for light mesons using the $\psi' \to \pi\pi J/\psi$; $J/\psi \to \gamma\xi$; $\xi \to invisible$ ($\xi = \pi^0, \eta, \eta', \phi$, etc.) decay sequences. In addition there would be a multi-million event sample of polarized $\Omega^-\bar{\Omega}^+$ pairs [19] for CPV and rare (forbidden) decay measurements (searches), as well as copious transitions to, and decays of, all of the below-open-charm-threshold charmonium levels [20].

Polarized e^- beam operation at a c.m. energy just above the $\tau^+\tau^-$ threshold ($E_{\rm cm} \approx$3.554 GeV) would allow for a sensitive search for CPV in $\tau^- \to \rho^-(\to \pi^-\pi^0)\nu$ decays [21]. Large data samples at this energy would support measurements of the $\mathcal{B}(\tau^- \to K^-\nu)/\mathcal{B}(\tau^- \to \pi^-\nu)$ ratio with sufficient accuracy to extract a Cabibbo-angle (θ_C) value with precision similar to that determined from K-meson decays [22]. A comparison of K-meson and τ-lepton measurements of θ_C would provide a sensitive probe for new BSM physics in the light-quark sector [23].

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