HERA-B: Physics Potential and Prospects

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Abstract

HERA-B is a hadroproduction experiment located at DESY in Hamburg, Germany. The experiment produces $B$ mesons and baryons by inserting thin wire targets into the halo of the proton beam circulating in the HERA storage ring. The $B$ decays are studied to search for evidence of $CP$ violation and constrain the angle $\beta$ and possibly $\gamma$ and $\alpha$ of the CKM unitarity triangle. The experiment also produces $B_s$ mesons; these decays are studied to measure or constrain the mass difference $\Delta m_s$ and width difference $\Delta \Gamma_s$ between the two $B^0_s$/$\overline{B}^0_s$ mass eigenstates. Finally, the large number of $B$‘s produced allows HERA-B to search for rare and forbidden decays such as $B \to K^{(*)}\ell_1^+\ell_2^-$. The experiment is scheduled to begin running in early 2000.

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1 Introduction

HERA-B is a hadroproduction experiment that produces $b$ mesons and baryons by colliding protons circulating in the HERA proton storage ring with fixed wire targets. The nominal interaction rate is 40 MHz. Downstream of the targets are the following detectors: a silicon-strip vertex detector used to reconstruct decay vertices; a large-aperture ($250 \times 160$ mrad$^2$) dipole magnet and thirteen drift chamber stations used to measure momentum; a Ring-Image Čerenkov counter (RICH) used to identify pions, kaons, and protons; an electromagnetic calorimeter used to measure electron and photon energies; and a set of gas ionization chambers interleaved with iron plates used to identify muons. More details about these detectors can be found in the HERA-B Technical Design Report [1].

Two main triggers are used for the experiment: a dilepton trigger and a high-$p_T$ trigger. The former identifies electron and muon pairs based on hits in the electromagnetic calorimeter or muon chambers. The hit positions are used as seeds for a Kalman-filter tracking algorithm which searches regions in wire tracking chambers for corresponding hits. When hits in several successive chambers are found, a track is reconstructed. For events with two or more tracks, the invariant mass of all opposite-sign track pairs ($m_{\ell^+\ell^-}$) is calculated and events with $m_{\ell^+\ell^-}$ above a threshold are passed. The threshold is chosen to efficiently select $J/\psi \rightarrow \ell^+\ell^-$ decays. The high-$p_T$ trigger works in the same manner except that hits in a set of pad chambers located within the magnet determine the track seeds used by the Kalman filter. The hit patterns that initiate a trigger correspond to tracks that have high transverse momentum ($p_T$) with respect to the beam. The mass threshold used for the high-$p_T$ trigger is chosen to efficiently select $B^0 \rightarrow \pi^+\pi^-$, $B^0 \rightarrow K^+\pi^-$, and $B^0_s \rightarrow K^+K^-$ decays.\footnote{Charge-conjugate modes are included unless otherwise noted.}

Events that pass either the dilepton or high-$p_T$ trigger are input to a second-level trigger running in a “farm” of dedicated processors. This trigger projects the two dilepton or high-$p_T$ tracks into the silicon vertex detector, finds corresponding hits on silicon strips, and uses these hits to reconstruct silicon-based tracks. These silicon tracks are well-measured and are required to form a vertex some distance downstream of the nearest target wire.

To measure $CP$ violation, HERA-B measures the proper time distributions $d\Gamma(B^0 \rightarrow f)/dt$ and $d\Gamma(\bar{B}^0 \rightarrow f)/dt$ and constructs the asymmetry parameter $A_{CP}(t) = (d\Gamma/dt - d\bar{\Gamma}/dt)/(d\Gamma/dt + d\bar{\Gamma}/dt)$. For the final state
\[ J/\psi K^0_S, \]
\[ A_{CP}(t) = -D_T D_M \sin(2\beta) \sin(xt), \quad (1) \]
where \( D_T \) is a “dilution” factor arising from mistagging the \( B^0 \) or \( \bar{B}^0 \) flavor of the decay, \( D_M \) is a dilution factor caused by tagging signatures from neutral \( B \) mesons which oscillate before they decay, \( \beta \) is the interior angle of the CKM unitarity triangle, \( x \) is the \( B^0_\star \bar{B}^0_\star \) mixing parameter \( \Delta m/\Gamma \), and \( t \) is the decay time in units of \( B \) lifetime. Alternatively, HERA-B can count the total number of decays (corrected for acceptance) and construct the ratio of partial widths \( A_{CP} = (\Gamma - \bar{\Gamma})/(\Gamma + \bar{\Gamma}). \) This quantity equals 
\[-D_T D_M \sin(2\beta) \xi(t_0), \]
where \( \xi(t) = [\sin(xt) + x \cos(xt)]/(1 + x^2) \) and \( t_0 \) is the minimum value of decay time that a decay vertex must satisfy. Such a requirement is necessary to sufficiently reduce backgrounds.

The proton interactions at HERA-B lead to a production asymmetry between \( B^0 \) and \( \bar{B}^0 \) of a few percent; this must be measured and corrected for in order to detect a \( CP \) asymmetry. The correction is made by constructing the ratios
\[ R = \left( \frac{N_{B \to f}}{\varepsilon_f} \right) \left( \frac{\varepsilon_n}{N_{B \to n}} \right) \quad \text{and} \quad \bar{R} = \left( \frac{N_{\bar{B} \to f}}{\varepsilon_f} \right) \left( \frac{\varepsilon_{\bar{n}}}{N_{\bar{B} \to \bar{n}}} \right), \]
where \( N_{B \to n} \) and \( N_{\bar{B} \to \bar{n}} \) are the numbers of \( B^0 \) and \( \bar{B}^0 \) decays to a (copious) channel not exhibiting \( CP \) violation, e.g., \( B^0 \to J/\psi K^0_\star \to \ell^+\ell^-K^+\pi^- \). The ratio \((R - \bar{R})/(R + \bar{R})\) then equals \((\Gamma - \bar{\Gamma})/(\Gamma + \bar{\Gamma})\).

For \( N_{B \to n} \gg N_{B \to f} \), the uncertainty on \( \sin(2\beta) \) is:
\[ \Delta \sin(2\beta) \approx \frac{1}{\xi(t_0) D_M D_T \varepsilon_{tag}} \frac{1}{\sqrt{\varepsilon_{tag} N_B}} \sqrt{\frac{S + B}{S}}, \quad (2) \]
where \( N_B \) is the number of \( B^0 \to J/\psi K^0_\star \) candidates, \( S \) is the number of true signal events, \( B \) is the number of background events, and \( \varepsilon_{tag} \) is the tagging efficiency. The factor \( D_T \varepsilon_{tag} \) indicates the performance of the tagging method. There are four methods to be used in HERA-B to tag the flavor of the decaying \( B^0 \) or \( \bar{B}^0 \):

1. the charge of a lepton with \( p_T > 5 \text{ (0.8)} \text{ GeV}/c \) that originates from the semileptonic decay of the other \( b \) hadron in the event;
2. the charge of a kaon with \( 5 < p < 50 \text{ GeV}/c \) that originates from the \( b \to D \to K^\pm \) decay of the other \( b \) hadron in the event;
the “jet charge” defined by:

\[ Q_{\text{jet}} = \sum_i q_i |\vec{p}_i \cdot \hat{a}| / \sum_i |\vec{p}_i \cdot \hat{a}|, \]  

(3)

where \( \hat{a} \) is the direction vector of the \( B \) candidate as defined by the positions of the interaction and decay vertices, and \( i \) runs over all tracks in the decay vertex;

4. the “same-side” tag, which is the charge of a track within a small \( \eta-\phi \) cone around the \( B^0 \) momentum vector which has minimum \( p_T \) relative to the combined (\( B^0 + \) track) momentum vector.

The first three methods have been studied extensively using a Monte Carlo simulation, and their expected efficiencies, dilution factors, and overall factors \( D_M D_T \sqrt{\varepsilon_{\text{tag}}} \) are listed in Table 1.

| Method                                      | \( \varepsilon_{\text{tag}} \) | \( D_M D_T \) | \( D_M D_T \sqrt{\varepsilon_{\text{tag}}} \) |
|---------------------------------------------|-------------------------------|----------------|----------------------------------|
| \( p_T (p_T) > 5 \) (0.8) GeV/c            | 0.15                          | 0.53           | 0.20                             |
| 5 < \( p_K \) < 50 GeV/c                   | 0.48                          | 0.29           | 0.20                             |
| \( \sum q_i |\vec{p}_i \cdot \hat{a}| / \sum |\vec{p}_i \cdot \hat{a}| \) | 0.99                          | 0.12           | 0.12                             |
| All combined:                               |                               |                | 0.29                             |

Table 1: The expected efficiencies, dilution factors \( D_M D_T \), and overall factors \( D_M D_T \sqrt{\varepsilon_{\text{tag}}} \) for three tagging methods to be used in HERA-B.

## 2 Measurement of \( \sin(2\beta) \) and \( \sin(2\alpha) \)

To estimate the precision with which HERA-B can measure \( \sin(2\beta) \) using \( B^0 \to J/\psi K^0_S \) decays, we insert values for all parameters into Eq. (2). These values are listed in Table 2; the resultant uncertainty is \( \Delta \sin(2\beta) = 0.17 \) in one year of running. The precision with which HERA-B can measure \( \sin(2\alpha) \) using \( B^0 \to \pi^+\pi^- \) decays is also estimated using Eq. (2); inserting values for the parameters (see Table 3) gives \( \Delta \sin(2\alpha) = 0.36 \) in three years of running. This estimate does not include theoretical uncertainty, which
is discussed below. The branching fraction for $B^0 \to \pi^+\pi^-$ is taken to be $0.47 \times 10^{-5}$, and the signal-to-background ratio is taken to be one. Both estimates above include a lifetime cut on the decay vertex of $0.5\tau_B$, which is approximately 10 times the expected resolution in the vertex $z$ position. The precision obtained for $\sin(2\beta)$ would be a significant improvement over the current result from CDF; the precision obtained for $\sin(2\alpha)$ would constrain this parameter to a range much smaller than that allowed by current data.

|                |       |
|----------------|-------|
| $\sigma_{\bar{b}b}$ | 12 nb |
| $\sigma_{inel}$    | 13 mb |
| $\sigma_{\bar{b}b}/\sigma_{inel}$ | $9.2 \cdot 10^{-7}$ |
| interaction rate   | 40 MHz|
| $\bar{b}b$ rate    | 37 Hz |
| fraction reconstructed as $B^0 \to J/\psi K^0_S$ | $3.8 \cdot 10^{-6}$ |
| (for $f(\bar{b}b \to B^0 X) \simeq 0.7$) |       |
| reconstructed $B^0 \to J/\psi K^0_S$ per $10^7$ s | 1400  |
| statistical factor $1/\xi(\tau_B)$ | 1.5   |
| $\langle 1/D_M \rangle$ mixing of tagging $B$ | 1.2   |
| $\ell + K + \sum q_i$ tagging factor $(D_T\sqrt{\epsilon_{tag}})^{-1}$ | 3.5   |
| $\Delta \sin(2\beta)$ after $10^7$ s | 0.17  |

Table 2: The expected uncertainty in $\sin(2\beta)$ after one year of running.

In addition to $B^0 \to J/\psi K^0_S$ and $B^0 \to \pi^+\pi^-$ decays, there are other modes which provide sensitivity to $\sin(2\beta)$ and $\sin(2\alpha)$. These are summarized in Tables 4 and 5. Each table has six columns: the left-most column lists the decay mode of interest; the second column lists the branching fraction for the decay as either measured from data or estimated in Ref. 3. The third column lists the number of $B + \bar{B}$ decays reconstructed per year. This number is obtained by multiplying the branching fraction by the $\bar{b}b$ production rate, the fraction of $\bar{b}b$ pairs which yield a $B$ meson, the factor $10^7$ seconds of running per year, and the estimated HERA-$B$ trigger and reconstruction efficiencies. The fourth column lists the first-level trigger which accepts the decay. The fifth column lists the number of vertices arising from the decay chain and the number of kinematic constraints that can be used to reject background. The sixth column shows a sketch of the decay topology.
Table 3: The expected uncertainty in $\sin(2\alpha)$ after three years of running. For simplicity, we assume the ratio of penguin amplitude to tree amplitude to be very small.

These last two columns indicate the level of background suppression one expects for the decay mode: two or more decay vertices and a large number of kinematic constraints should provide substantial background suppression.

Experimentally, the modes listed in Table 4 are very promising: all have two decay vertices and at least five kinematic constraints. The branching fractions are substantial and indicate that HERA-B should reconstruct $>3000$ of these decays per year. Theoretically, the decays provide a clean measurement of $\sin(2\beta)$: the dominant amplitudes have a single weak phase ($\text{Arg} V_{cs}^* V_{cb}$), and thus direct $CP$ violation is negligible and Eq. (1) has negligible theoretical uncertainty.

The decay modes listed in Table 5 are more challenging: they have only one decay vertex and fewer kinematic constraints. Theoretically, the amplitudes may receive significant contributions from penguin diagrams which have a different weak phase from that of the tree diagram ($\text{Arg} V_{cd}^* V_{cb}$); in this case Eq. (1) also has a $\cos(\alpha t)$ dependence and, in addition, the measured value of $\alpha$ is shifted from the true value by an amount which depends on the unknown ratio of the penguin amplitude to the tree amplitude. This shift can be determined via an isospin analysis [6], but such an analysis requires measuring small branching fractions of difficult-to-reconstruct decay modes.
modes such as $B^+ \to \pi^+\pi^0$ and $B^0 \to \pi^0\pi^0$. Another method [7] to determine $\alpha$ in the presence of penguins uses $SU(3)$ flavor symmetry and the decays $B^0 \to \pi^+\pi^-$, $B^0 \to K^+\pi^-$, and $B^+ \to \pi^+K^0$. Although the last decay will not be measured in HERA-B (it is not selected by the trigger), only the branching fraction is needed and this is expected to be well-measured at CLEO III [8], BaBar [5, 9], and BELLE [10]. The three-body decays $B^0 \to \rho\pi \to \pi^+\pi^-\pi^0$ can also determine $\alpha$ in the presence of penguins via a Dalitz plot analysis [11]; however, the branching fraction for $B^0 \to \rho^0\pi^0$ is probably too low for this method to be useful in HERA-B. The modes $B^0 \to \rho\rho$ which have two vector particles in the final state require an angular analysis to extract $\sin(2\alpha)$, and this in turn requires a relatively large event sample.

3 Measurement of $\sin(2\gamma)$

A number of decay modes have been discussed in the literature which provide sensitivity to the angle $\gamma$, which is the third angle of the CKM unitarity triangle. Some of these modes are listed in Table 6. The first three were proposed by Gronau and Wyler [12]; by measuring their branching fractions and those of their charge conjugates, one can construct two triangles with a common base. The angle between the sides representing the $B^+ \to D^0_{CP}\pi^+$ and $B^- \to D^0_{CP}K^-$ amplitudes is $2\gamma$. Because only tree diagrams contribute to these decays, there is no uncertainty arising from penguin diagrams or final-state rescattering. Unfortunately, the expected branching fraction for $B^- \to D^0K^-$ is too low for HERA-B to make a meaningful measurement. The next three modes were proposed by Dunietz [14] and are analogous to the first three but pertain to $B^0$ decays; their branching fractions are also expected to be too low for HERA-B.

The amplitudes for $B^0 \to K^+\pi^-$ and $B^0 \to K^-\pi^+$ can be used in conjunction with that for $B^+ \to \pi^+K^0$ (measured at CLEO/BaBar/BELLE) to construct two more triangles and determine $\sin(2\gamma)$. This method [15] requires estimating a color-allowed tree amplitude, and this introduces theoretical uncertainty. However, the branching fraction for $B^0 \to K^+\pi^-$ is large enough for HERA-B to collect a few hundred events per year, and such a sample could provide a first constraint on this angle. It is estimated [16] that

\[ \text{However, if the } D^0 \text{ is detected via a hadronic decay such as } D^0 \to K^-\pi^+, \text{ there is uncertainty arising from interference with a doubly-Cabibbo-suppressed amplitude such as } D^0 \to K^-\pi^+ \text{ – see Ref. [3].} \]
in one year of running, HERA-B could measure a difference in the rates for \( B^0 \to K^+\pi^- \) and \( \overline{B}^0 \to K^-\pi^+ \) with a precision \( \Delta A_{CP}/A_{CP} = 0.08 \) (0.16), for a signal-to-background ratio of unity (0.10).

A bound \( \gamma_0 \) of the form \( 0 < \gamma < \gamma_0 \) or \( \gamma_0 < \gamma < 180^\circ \) which may have less theoretical uncertainty \([17]\) can be obtained from the inclusive measurement \( B(\overline{B}^0 \to K^-\pi^+ + B^0 \to K^+\pi^-) \); however, this bound depends on the ratio \( B(\overline{B}^0 \to K^-\pi^+ + B^0 \to K^+\pi^-)/B(B^+ \to K^0\pi^+ + B^- \to \overline{K}^0\pi^-) \) being less than one, which may not be the case (e.g., see Ref. [2]).

The decay \( \overline{B}^0 \to D^{*-}\pi^- \) is also promising, as the branching fraction is substantial and 2000–3000 of these decays should be reconstructed per year. Because the final state is not a \( CP \) eigenstate, fitting for the decay time dependence yields \( \sin(2\beta + \gamma) \) rather than \( \sin(2\gamma) \), which is advantageous if \( \gamma \) is near 90\(^\circ\) (as possibly indicated by data from CLEO \([2, 18]\)). This decay proceeds via the \( b \to c\bar{u}d \) transition; because all quark flavors in the final state are different, only tree diagrams contribute and there is no theoretical uncertainty arising from penguin diagrams or final-state rescattering. The ultimate success of this method and the others discussed above depends on as-yet-unknown backgrounds.

4 \( B_s^0 \) Physics

In addition to \( B_d \) mesons, HERA-B also produces \( B_s \) mesons; these allow the experiment to measure or constrain parameters of the \( B_s^0-\overline{B_s^0} \) system. For example, the decays \( B_s^0 \to D_s^-\ell^+\nu\ell, B_s^0 \to D^-\pi^+, B_s^0 \to D^-\pi^+\pi^-\pi^+, B_s^0 \to J/\psi K^{*0}, \) and \( B_s^0 \to K^+K^- \) can be used to measure the mass difference \( \Delta m_s \) or decay width difference \( \Delta \Gamma_s \) between the two \( B_s^0/\overline{B_s^0} \) mass eigenstates. The mode \( B_s^0 \to D_s^-K^+ \) (analogous to \( \overline{B}^0 \to D^{*-}\pi^- \), i.e., no penguin contribution) can be used to measure \( 2\phi_M + \gamma \), where \( \phi_M \) is the \( B_s^0/\overline{B_s^0} \) mixing phase (expected to be very small). The mode \( B_s^0 \to J/\psi \phi \) should not exhibit \( CP \) violation at HERA-B’s level of sensitivity \([19]\), and thus observing a \( CP \) asymmetry would indicate physics beyond the Standard Model. For all these modes, the number of events HERA-B expects to reconstruct per year is listed in Table 6. For most modes, the number of reconstructed events is \( >100 \) per year, or \( >300 \) events in three years. Unfortunately, the number of reconstructed \( B_s^0 \to D_s^-K^+ \) decays is too low for HERA-B to constrain \( 2\phi_M + \gamma \); this sample needs to be large in order to resolve the rapid \( B_s^0/\overline{B_s^0} \) oscillations.
The “reach” of HERA-B for measuring the mass difference $\Delta m_s$ has been estimated based on the amplitude fit method of Ref. [20]. This reach is taken to be that value of $\Delta m_s$ in which the quantity $S/N$ (signal to noise ratio) equals 1.645, where $S/N$ is given by:

$$\frac{S}{N} = \sqrt{\frac{n}{2}} f_s (1 - 2\eta)e^{-(\sigma_\tau \Delta m)^2/2}. \quad (4)$$

In this expression, $n$ is the number of $B_s^0$ or $\bar{B}_s^0$ decays reconstructed, $f_s$ is the fraction which are true signal, $\eta$ is the probability of a mistag, and $\sigma_\tau$ is the decay time resolution. Typical values for these parameters are listed in Table 8 and imply that in three years of running, $\Delta m_s$ could be measured or constrained up to values $> 24 \text{ ps}^{-1}$. This is superior to the current world limit $\Delta m_s > 14.3 \text{ (95\% C.L.)} [21]$.

HERA-B can search for CP violation in the $B_s^0$ system by measuring the decay time distribution of $B_s^0 \to K^+K^-$ decays and looking for a deviation from an exponential time dependence. If the time distribution is exponential, then it can be used along with that for $B_s^0 \to D^\pm \pi^\mp$ to determine the width difference $\Delta \Gamma_s [23]$. Since $dN_{KK}/dt = e^{-\Gamma_t t} \equiv e^{-\Gamma_L t}$, and $dN_{D^\pm \pi}/dt \propto e^{-(\Gamma_1 + \Gamma_2)t/2} \cosh(\Delta \Gamma_s/2)t \approx e^{-(\Gamma_1 + \Gamma_2)t/2} \approx e^{-(\Gamma_L + \Gamma_H)t/2}$, $\Gamma_{D^\pm \pi} - \Gamma_{KK} = (\Gamma_L + \Gamma_H)/2 - \Gamma_L = \Delta \Gamma_s/2$. HERA-B expects to reconstruct $\sim 35 B_s^0 \to K^+K^-$ decays per year, and a preliminary study indicates that such a sample could be sensitive to a difference $\Delta \Gamma_s/\Gamma_s \approx 0.18$. This sensitivity is superior to that of the current measurement from CDF [24].

5 Summary

In summary, the physics potential of HERA-B is substantial. We expect the experiment to do well measuring $\sin(2\beta)$, with an expected uncertainty of $\Delta \sin(2\beta) = 0.17$ after one year of running. The experiment can constrain $\sin(2\alpha)$, but this requires a better theoretical understanding of the penguin contribution to this mode. If the penguin contribution were very small, HERA-B could obtain $\Delta \sin(2\alpha) \approx 0.36$ after three years of running for a signal-to-background ratio of unity. The experiment can potentially constrain the angle $\gamma$ via $B^0 \to K^+\pi^-$ and $\bar{B}^0 \to D^{\ast+}\pi^-$ decays; the viability

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4A non-exponential decay time distribution demonstrates interference between the $B_{s,H}$ and $B_{s,L}$ amplitudes to $K^+K^-$; thus there exists an interference term in the rate $|\langle K^+K^-|H|B^0 \rangle|^2$ which changes sign under CP. Such a term is CP violating – see e.g., Ref. [22].
of these methods depends on unknown backgrounds. HERA-B can constrain $\Delta m_s$ to be $> 24 \text{ ps}^{-1}$ in three years of running, which is an improvement over the current world limit of $\Delta m_s > 14.3$ (95% C.L.). HERA-B will also search for rare and forbidden dilepton decays such as $B \to K^{*}\ell^+\ell^-$, $B^0_s \to \phi\ell^+\ell^-$, and $B \to K^{(*)}\mu^+\mu^-$. Finally, HERA-B may find new phenomena such as measurable CP violation in $B^0_s \to J/\psi\phi$ decays.

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| Decay mode | BR ($\times 10^{-5}$) | Rec. Evnts per year | Trigger | Vertices/Constraints | Topology |
|------------|-----------------|---------------------|--------|---------------------|----------|
| $B^0 \rightarrow J/\psi K^0_S$ | 3.7 | 1400 | $\mu\mu/ee$ | 2/5 | |
| ($J/\psi \rightarrow \ell^+\ell^-$) |  |  |  |  | |
| ($K^0_S \rightarrow \pi^+\pi^-$) |  |  |  |  | |
| $B^0 \rightarrow J/\psi K^{*0}$ | 1.9 | 700 | $\mu\mu/ee$ | 2/7 | |
| ($J/\psi \rightarrow \ell^+\ell^-$) |  |  |  |  | |
| ($K^{*0} \rightarrow K^0_S\pi^0$) |  |  |  |  | |
| $B^0 \rightarrow \psi' K^0_S$ | 0.87 | 330 | $\mu\mu/ee$ | 2/6 | |
| ($\psi' \rightarrow J/\psi \pi^+\pi^-$) |  |  |  |  | |
| ($J/\psi \rightarrow \ell^+\ell^-$) |  |  |  |  | |
| $B^0 \rightarrow \psi' K^{*0}$ | 0.58 | 220 | $\mu\mu/ee$ | 2/8 | |
| ($\psi' \rightarrow J/\psi \pi^+\pi^-$) |  |  |  |  | |
| ($J/\psi \rightarrow \ell^+\ell^-$) |  |  |  |  | |
| ($K^{*0} \rightarrow K^0_S\pi^0$) |  |  |  |  | |
| $B^0 \rightarrow \chi_{c1} K^0_S$ | 1.1 | 430 | $\mu\mu/ee$ | 2/6 | |
| ($\chi_{c1} \rightarrow J/\psi \gamma$) |  |  |  |  | |
| ($J/\psi \rightarrow \ell^+\ell^-$) |  |  |  |  | |
| $B^0 \rightarrow \chi_{c1} K^{*0}$ | 0.52 | 200 | $\mu\mu/ee$ | 2/8 | |
| ($\chi_{c1} \rightarrow J/\psi \gamma$) |  |  |  |  | |
| ($J/\psi \rightarrow \ell^+\ell^-$) |  |  |  |  | |
| ($K^{*0} \rightarrow K^0_S\pi^0$) |  |  |  |  | |

Table 4: Methods to measure the CKM angle $\beta$ in HERA-B.
| Decay mode    | BR (×10⁻⁵) | Rec. Evnts per year | Trigger | Vertices/Constraints | Topology |
|--------------|-------------|---------------------|---------|----------------------|----------|
| \( B^0 \to \pi^+\pi^- \) | 0.47        | 210                 | high-\( p_T \) | 1/2                  |          |
| \( B^0 \to \pi^-K^+ \)   | 1.4         | 260                 | high-\( p_T \) | 1/2                  |          |
| \( B^0 \to \rho^+\pi^- \) | 4.4         | <1900               | high-\( p_T \) | 1/4                  |          |
| \( B^0 \to \rho^-\pi^+ \) | 1.0         | <420                | high-\( p_T \) | 1/4                  |          |
| \( B^0 \to \rho^0\pi^0 \) | 0.1         | <42                 | high-\( p_T \) | 1/4                  |          |
| \( B^0 \to \rho^+\rho^- \) | 2.9         | ≪1200               | high-\( p_T \) | 1/6                  |          |
| \( B^0 \to \rho^0\rho^0 \) | 0.064       | ≪27                 | high-\( p_T \) | 1/4                  |          |

Table 5: Methods to measure the CKM angle \( \alpha \) in HERA-B. A “≪” sign indicates that the trigger and reconstruction efficiencies assumed are optimistic.
| Decay mode                              | BR ($\times 10^{-5}$) | Rec. Events per year | Trigger | Vertices/Topology |
|----------------------------------------|------------------------|----------------------|---------|------------------|
| $B^- \to D^0 K^-$ ($D^0 \to K^- \pi^+$) | 1.5                    | < 650                | high-$p_T$ | 1/4              |
| $B^- \to D^0 K^-$ ($D^0 \to K^+ \pi^-$) | 0.0077                 | < 3                  | high-$p_T$ | 1/4              |
| $B^- \to D^0_K^0 K^-$ ($D^0_{CP} \to K^+ K^-$) | 0.23                   | < 98                 | high-$p_T$ | 1/4              |
|                                          |                        |                      |         |                  |
| $B^0 \to \bar{D}^0 K^{*0}$ ($\bar{D}^0 \to K^- \pi^+$) | 0.023                  | < 10                 | high-$p_T$ | 2/5              |
|                                          |                        |                      |         |                  |
| $B^0 \to D^0 K^{*0}$ ($D^0 \to K^- \pi^+$) | 0.0077                 | < 3                  | high-$p_T$ | 2/5              |
|                                          |                        |                      |         |                  |
| $B^0 \to D^0_{CP} K^{*0}$ ($D^0_{CP} \to K^+ K^-$) | 0.0035                 | < 1.5                | high-$p_T$ | 2/5              |
|                                          |                        |                      |         |                  |
| $B^0 \to \pi^\pm K^{\mp}$             | 1.4                    | 260                  | high-$p_T$ | 1/2              |
| $\bar{B}^0 \to D^{*+} \pi^-$ ($D^{*+} \to D^0 \pi^+$) | 7.4                    | < 3100               | high-$p_T$ | 2/5              |
| $B_{s0}^0 \to \rho^0 K_S^0$             | 0.003                   | $\ll$ 1.5            | high-$p_T$ | 2/5              |

Table 6: Methods to measure the CKM angle $\gamma$ in HERA-B. A “<” sign indicates that the trigger and reconstruction efficiencies assumed are optimistic.
Table 7: $B_s^0$ decay modes to be collected in HERA-B. These modes can be used to measure $\Delta m_s$ and $\Delta \Gamma_s$, to constrain $\sin(2\phi_M + \gamma)$, and to search for new physics. All $D_s^-$ final states are reconstructed via $D_s^- \rightarrow \phi \pi^- \rightarrow K^+K^-\pi^-$ or $D_s^- \rightarrow K^{*0}K^- \rightarrow K^+\pi^-K^-$. A “$<$” sign indicates that the trigger and reconstruction efficiencies assumed are optimistic.
### Table 8: Decay modes to be used to measure or constrain the mass difference $\Delta m_s$, and the lower limits obtained in one, two, and three years of running.

| Decay Mode | $D_s^{(*)}\ell^+\nu$ | $D_s^-\pi^+$ | $J/\psi K^{*0}$ |
|------------|----------------------|---------------|-----------------|
|            | $D_s^-\pi^+\pi^-\pi^+$ |               |                 |
| $n$ (events/yr) | $\sim 900$ | $\sim 400$ | $\sim 100$ |
| $f_s$ (signal fraction) | 0.35 | 0.6 | 0.9 |
| $\eta_{\text{mistag}}$ (prob. of mistag) | 0.24 | 0.33 | 0.33 |
| $\sigma_z$ (vertex resolution) | 600 $\mu$m | 450 $\mu$m | 300 $\mu$m |
| $\sigma_t$ (proper time resolution) | 0.11 ps | 0.081 ps | 0.054 ps |
| $(p_B) \approx 100$ GeV/c |       |       |       |
| $\Delta m_s$ reach in one year | 12 ps$^{-1}$ | 13 ps$^{-1}$ | 14 ps$^{-1}$ |
| $(S/N = 1.645)$ |       |       |       |
| $\Delta m_s$ reach in two years | 14 | 17 | 21 |
| $\Delta m_s$ reach in three years | 15 | 18 | 24 |
| (World limit: $\Delta m_s > 14.3$ @ 95% C.L.) |       |       |       |