P-827/Add.2

Addendum 2 to the Proposal for a B-Physics Experiment at TEV I: The μBCD

(June 4, 1991)

The BCD Collaboration

Executive Summary

In this Addendum to the μBCD Proposal[1] we examine the capability of the experiment for a topical physics issue: the study of $b \rightarrow u$ transitions by full reconstruction of exclusive decay modes. The μBCD will be very competitive with e^+e^- colliders for this, particularly as B_s decays are more readily studied at a hadron collider. An initial run of 250 nb^{-1} would provide first evidence for prominent modes such as $B_s \rightarrow D_s^- \pi^+$. The richness of the physics results would be very much greater in an exposure of 2.5 pb^{-1} than one of 250 nb^{-1} as many more CKM-suppressed decays modes would become accessible, and over 10,000 exclusive B decays would be reconstructed. In the Appendix we present results of Monte Carlo studies that emphasize the importance for Kaon identification in reconstructing nonleptonic B decays.

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1 Introduction

We summarize the main points in our view of a program leading to the measurement of CP violation in the B-meson system at Fermilab. Supporting details have been presented in our proposal (P-827) of Oct. 8, 1990 and the Addendum of Jan. 7, 1991.

- We understand that a scenario is under consideration in which little support is given to R&D for B physics in the near term, but a call for proposals is made in late 1993 for major collider experiments that might begin data taking in the year 2000. This scenario would result in decisions on the B-physics program at Fermilab being based on information little different than that presently available, which is insufficient to plan for the full success of a large effort. Rather, we feel that expanded R&D efforts towards elements of a major B-physics experiment are needed through 1995, at which time it would be more realistic to commit to the large experiment.

- There are many university and Fermilab physicists not involved with the present collider program that seek a way to prepare now for a future B-physics experiment at the Fermilab collider. We believe the best option for this is an R&D effort with a modest, but Ph.D- and publication-worthy physics program at the C0 intersect. The experiment would emphasize a general study of B-decays with no trigger initially, recording 1000 events/sec, of which one/sec would include a B-$\bar{B}$ pair. This is equivalent to 10^{33} luminosity at an e^+e^- collider. The physics program would include:

    1. Reconstruction of $b \to u$ decays to all-charged final states (considering the tertiary decay products) such as $B^+ \to \rho^0\pi^+$, and $\rho^0 D_s^+$, $B_d^0 \to \pi^+\pi^-$, $\pi^- D_s^+$, and $\rho^0\rho^0$, and $B_s^0 \to K^-\pi^+$, $K^- D_s^+$, and $\rho^0 K_S^0$.
    2. Reconstruction of prominent B_u, B_d, and B_s, decays to all-charged final states, such as $B_u \to \bar{D}^0\pi^+$, $B_d \to D^-\pi^+$ or $\bar{D}^0\rho^0$, and $B_s \to D_s^-\pi^+$ or $\bar{D}^0 K^0$, all of which include Kaons among the tertiary particles.
    3. Measurement of the production cross section of B's as a function of Feynman x, permitting measurement of the gluon structure function at much lower x than is presently accessible.

    The apparatus would incorporate vertexing, Kaon identification, and high-rate data acquisition.

- The above program complements the ongoing CDF program which will concentrate on $B \to J/\psi$ decays at moderate to high P_t.

- Such a program could be initiated without commitment to full-luminosity running with a full detector complement. It is our understanding from Mike Harrison of the Accelerator Division that low-cost, low-luminosity running in C0 is compatible with the present configuration of the Tevatron, but would be best accomplished in short dedicated runs appended to collider runs for CDF and D0.

- A key technical advance needed for a collider B-physics program is a 3-D silicon vertex detector/tracker. To maintain large acceptance over a long luminous region of p-$\bar{p}$ collisions the vertex detector must incorporate interleaved 'disks' and 'barrels.' This is a considerable engineering challenge in view of the simultaneous requirements of mechanical precision and stability, large channel count, and cooling of on-detector electronics.

- R&D towards such a design has been begun under the auspices of T-784 and is encouraging, but not yet definitive. A proof-of principle demonstration of our proposed silicon vertex detector could be made within one year, but requires $150k for assembly tooling, and (at least) an additional full-time physicist and technician at Fermilab.

- At present the only significant laboratory resources devoted to collider vertex detectors are with CDF. Here a 2-D detector will soon be installed with a capability for partial reconstruction of high-P_t B's associated with top-quark decay. We do not believe such a detector will evolve into a capability for full reconstruction of low-P_t B-decays without a major change in the physics focus of CDF.

- A schedule for our proposed R&D/physics program for the 90's is

  1. Bench-top and test beam demonstrations of the 3-D vertex detector and compact RICH counter through 1992.
  2. Installation of prototype segments of the vertex detector and RICH counter in C0 at the end of the 1993 collider run.
  3. An initial physics run of the μBCD detector in C0 for the 1995 collider run at a luminosity of 2.5×10^{28} cm^{-2}sec^{-1}.
  4. A run of the μBCD in 1996 at a luminosity of 2.5×10^{29} cm^{-2}sec^{-1} (see Sec. 2 below).
  5. Installation of the μBCD detector as the inner detector of CDF or D0 for a full-luminosity run in 1997. The physics goal would be a study of B_s mixing.
  6. Construction of a dedicated B-physics experiment through $\sim$ 1999, leading to a measurement of CP violation.

- For consideration by the PAC in June 1991 we seek:

  1. Funds and staff support to complete the R&D program of T-784, with emphasis on a proof-of-principle demonstration of the method of construction of a 4π, 3-D silicon vertex detector.
  2. A recommendation that the successful completion of T-784 be followed by the μBCD program.

2 Sensitivity of the μBCD to Nonleptonic B Decays

In this Section we estimate the sensitivity of the μBCD to several classes of B decays that would be fully reconstructed by the measurement of all-charged final states. Such results will overlap with those emerging from e^+e^- colliders in the coming years. A particular advantage of the μBCD is its access to B_s (and B_c and B-baryon) decays, as a precursor to studies of B_s mixing, and of CP violation in both the B_d and B_s systems.

We find below that in a run of 2.5 pb^{-1} the μBCD would reconstruct significant samples of a large variety of CKM-suppressed $b \to u$ nonleptonic transitions, would provide a first sample of baryonic final states, and have very large samples of reconstructed $b \to c$ transitions. Such a run would follow an initial run of 1/10 the integrated luminosity, in which prominent $b \to c$ transitions of the B_s meson and a few of the most prominent $b \to u$ transitions would be observed.

For the studies described below we suppose the μBCD consists of an initial configuration of a silicon vertex detector with interleaved disks and (three) barrel layers between radii of 2 and 10 cm, followed by 16 layers of straw tubes between 10 and 20 cm. The tracking detectors are then surrounded by a compact RICH counter that can perform π/K separation up to 4 GeV/c. The detector is inside a 1.5-Tesla solenoid magnet. The accuracy of the momentum measurement is limited by multiple scattering, and yields an invariant-mass resolution for B decays of about 100-125 MeV/c^2 (prior to use of constrained-fitting procedures that utilize knowledge of the vertex position, and possible intermediate masses in the decay chain).

A superconducting magnet coil that is 10-cm thick and operates at 3 Tesla would provide three times better mass resolution than a conventional coil as assumed.

The rates given below are for a run of 10^7 sec at a luminosity of 10^{29} $\text{cm}^{-2}\text{sec}^{-1}$, during which the interaction rate is 10^4/sec and every tenth event is written to tape. This supposes that an online software trigger has been developed following the experience of a first run with no trigger. There would then be 10 B-$\bar{B}$ events/sec, and hence 10^8 B-$\bar{B}$ events on tape.

2.1 $b \to u$ and $b \to c$ Transitions with $W \to u\bar{d}$

A physics topic that is accessible to the μBCD is the reconstruction of exclusive B decays involving the CKM-suppressed $b \to u$ transition. Evidence for these transitions has been given by CLEO[2] in analyses of the lepton spectra of semileptonic B decays, but no exclusive decays have been reconstructed to date. Indeed from the rate estimates given below, it will be a considerable challenge for any detector to have a significant sample of fully reconstructed $b \to u$ decays by the mid 1990's.

The most prominent $b \to u$ transitions arise from Graphs I and II of Fig. 1. In Table 1 below we list several such transitions that will be accessible to the μBCD. We first restrict our attention to decays to two mesons that (if not long-lived) then decay to all-charged grand-daughters with high probability.

For comparison we list in Table 2 the decays that are the analogs to those in Table 1 but with a $b \to c$ transition.

We see that the only two-body $b \to u$ modes that are expected to have a reasonable rate are the pure Graph-I transitions $B_d \to \pi^+\pi^-$, and $B_s \to \pi^+K^-$. From Monte Carlo

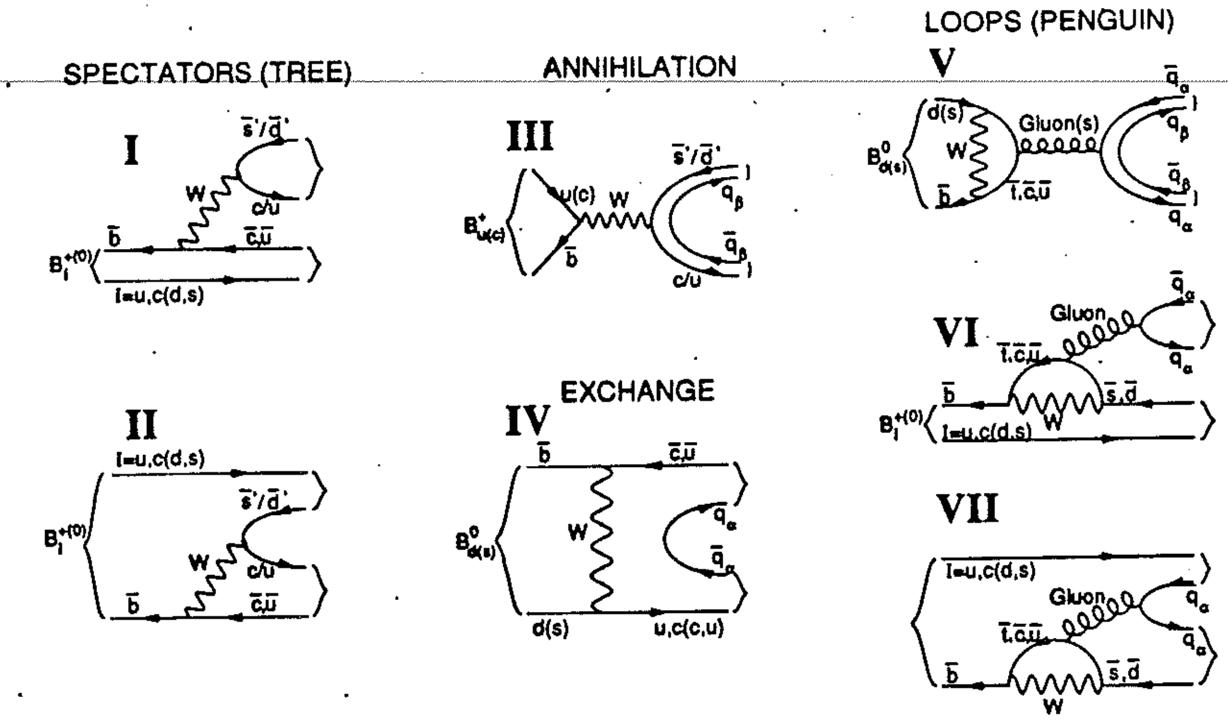

Figure 1: Seven graphs for the nonleptonic decays of B mesons. The dashed lines are W bosons; gluons are not shown.

simulations of the effectiveness of a vertex detector in isolating secondary vertices,[4] we conclude that the $\pi^-\pi^+$ and $K^-\pi^+$ modes will have the poorest signal-to-noise of any all-charged B decay. Because the μBCD has limited tracking length, its mass resolution for these modes is about 5 times worse than assumed in those studies. Previously we estimated[4] that the signal-to-noise would be about 1/1. Hence for the μBCD we might expect a signal-to-noise of only about 1/5. Then, for example, the $\pi^+\pi^-$ signal would be above a background of about 1100 events, so the background subtraction would produce a signal of 218 ± 36 events.

In addition, there may be a background of 35 or so events in the $\pi^+\pi^-$ mode due to $B_s^0 \to \pi^+K^-$ in which the Kaon has momentum greater than 4 Gev/c. For such events the Kaon cannot be identified in the RICH counter. Then if the Kaon is called a pion there is a significant probability that the event satisfies a hypothesis of $B_d^0 \to \pi^+\pi^-$, leading to the background just mentioned.

We note that corresponding to any two body mode $B \to XY$, the four-body mode $B \to XY\pi^+\pi^-$ in which a charged-pion pair emerges from the sea will have an equal or even slightly larger branching fraction. The four-body decays, in which all four tracks emanate from the same secondary vertex, offer several advantages to the data analysis:

- Better mass resolution.
- Better particle ID, as the tracks are softer.
- Much better signal-to-noise in the vertex algorithm.

Table 1: Estimated rates for $b \to u$ decays with $W \to u\bar{d}$ to all-charged final states. The model estimates are from Bauer, Stech, and Wirbel[3] with $a_1 = 1.0$, $a_2 = -0.2$, $|V_{cb}| = 0.05$, and $|V_{ub}/V_{cb}| = 0.1$. The 'Acceptance' is the product of (the fraction of events who tracks satisfy the geometric and momentum cuts) and (the branching fraction of the daughter mesons to all-charged grand-daughters). The cuts are $|\eta| < 2.5$, $P_t > 0.3$ GeV/c, and for Kaons only, $P < 4$ GeV/c. The number of 'Events' is for an exposure of 2.5 pb^{-1}, corresponding to a run of 10^7 sec at a luminosity of 2.5×10^{29} cm^{-2}sec^{-1}. We suppose the various B mesons are produced in the proportions $B_u : B_d : B_s = 0.375 : 0.375 : 0.25$. The number of 'Events' in this and subsequent rate estimates includes a factor of 1/3 for reconstruction and vertexing efficiency. The mass resolution is limited by multiple scattering, according to $\sigma_P/P \approx \sqrt{(0.03)^2 + (0.004P_t)^2}$.

Decay Mode	Branching Fraction		Acceptance	Events	Mass Res. (MeV/c^2)
$B_u^+ \to \rho^0\pi^+$	$0.05(a_1 + 2.01a_2)^2 \lvert V_{ub}/V_{cb}\rvert^2$	1.8×10^{-6}	0.49	23	109
$B_d^0 \to \pi^-\pi^+$	$0.14a_1^2 \lvert V_{ub}/V_{cb}\rvert^2$	1.4×10^{-5}	0.63	218	126
$B_d^0 \to \pi^-\pi^+\pi^-\pi^+$	$0.14a_1^2 \lvert V_{ub}/V_{cb}\rvert^2$	1.4×10^{-5}	0.36	129	92
$B_d^0 \to \rho^0\rho^0$	$0.16a_2^2 \lvert V_{ub}/V_{cb}\rvert^2$	6.5×10^{-7}	0.35	6	92
$B_s^0 \to K^-\pi^+$	$0.14a_1^2 \lvert V_{ub}/V_{cb}\rvert^2$	1.4×10^{-5}	0.24	56	124
$B_s^0 \to K^-\pi^+\pi^-\pi^+$	$0.14a_1^2 \lvert V_{ub}/V_{cb}\rvert^2$	1.4×10^{-5}	0.31	73	88
$B_s^0 \to \rho^0 K_S^0$	$0.16a_2^2 \lvert V_{ub}/V_{cb}\rvert^2$	6.5×10^{-7}	0.17	2	94

Here we only give as examples the four-body modes $B_d \to \pi^+\pi^-\pi^+\pi^-$, and $B_s \to \pi^+K^-\pi^+\pi^-$, as listed in Table 1. A study of backgrounds in the four-body modes due to misreconstructed events is reported in Sec. 3.1 below, where these are found to be small. As a consequence the statistical significance of the signal in these four-body will be greater than for the corresponding two-body modes.

Thus it is in these four-body modes that the μBCD will provide the cleanest measurement of the $b \to u$ transition.

Table 2 indicates that sizable signals will be available for the Graph-I decays with $b \to c$ transitions. The mode $B_s \to D_s^-\pi^+$ is particularly important in that this mode is the chief candidate for a study of B_s mixing, in which the B_s decay must be self-tagging as to whether a B_s or $\bar{B}_s$ decayed. For the B_c, the μBCD will mainly be sensitive to the decay $B_c \to B_s\pi^+$ in which the charm quark decays before the bottom quark.

Table 2: Estimated rates for $b \to c$ decays with $W \to u\bar{d}$ to all-charged final states that are the analogs of the decays in Table 1. The low 'Acceptance' reflects the low probability that the various D mesons decays to all-charged grand-daughters. For the B_c^+ mode we suppose that the production rate of these mesons is 1/10 that of B_u^+.

Decay Mode	Branching Fraction		Acceptance	Events	Mass Res. (MeV/c^2)
$B_u^+ \to \bar{D}^0\pi^+$	$0.40(a_1 + 0.75a_2)^2$	2.9×10^{-3}	0.017	1220	88
$B_d^0 \to D^-\pi^+$	$0.40a_1^2$	4.0×10^{-3}	0.017	1680	89
$B_d^0 \to \bar{D}^0\rho^0$	$0.06a_2^2$	2.4×10^{-5}	0.013	8	75
$B_s^0 \to D_s^-\pi^+$	$0.40a_1^2$	4.0×10^{-3}	0.027	1780	94
$B_s^0 \to \bar{D}^0K_S^0$	$0.06a_2^2$	2.4×10^{-5}	0.006	2	78
$B_c^+ \to B_s^0\pi^+$	$0.05 \times 4 \times 10^{-3}$	2×10^{-4}	0.012	7	97

2.2 $b \to u$ and $b \to c$ Transitions with $W \to c\bar{s}$

Another class of nonleptonic decays accessible to the μBCD is that in which the virtual W decays to a $c\bar{s}$ combination. This emerges as a D_s^+ with fair probability, which can then be detected via its all-charged decay modes, which total about 1.5%. Tables 3 and 4 give estimates of branching ratios and rates for several such modes in which there are Graph-I transitions of $b \to u$ and $b \to c$, respectively.

Table 3: Estimated rates for $b \to u$ decays with all-charged final states in which the virtual W boson decays to $c\bar{s}$. The branching ratios are taken as $|V_{ub}/V_{cb}|^2$ times those for the corresponding $b \to c$ transition in Table 4. For the B_d and B_s modes we require $P < 4$ GeV/c to avoid confusing the two decays due to lack of particle ID.

Decay Mode	Branching Fraction		Acceptance	Events	Mass Res. (MeV/c^2)
$B_u^+ \to \rho^0 D_s^+$	$0.6a_1^2\,|V_{ub}/V_{cb}|^2$	6×10^{-5}	0.023	33	74
$B_d^0 \to \pi^- D_s^+$	$0.6a_1^2\,|V_{ub}/V_{cb}|^2$	6×10^{-5}	0.025	36	91
$B_s^0 \to K^- D_s^+$	$0.6a_1^2\,|V_{ub}/V_{cb}|^2$	6×10^{-5}	0.012	13	86

Table 4: Estimated rates for $b \rightarrow c$ decays with all-charged final states in which the virtual W boson decays to $c\bar{s}$. The branching ratios are from Ref. [3].

Decay Mode	Branching Fraction		Acceptance	Events	Mass Res. (MeV/c^2)
$B_u^+ \rightarrow \bar{D}^0 D_s^+$	$0.6a_1^2$	6×10^{-3}	0.0002	30	79
$B_d^0 \rightarrow D^- D_s^+$	$0.6a_1^2$	6×10^{-3}	0.0012	178	64
$B_s^0 \rightarrow D_s^- D_s^+$	$0.6a_1^2$	6×10^{-3}	0.0009	89	63

2.3 $b \rightarrow c$ Transitions with $W \rightarrow u\bar{s}$

The μBCD will have sensitivity to some CKM-suppressed transitions in which the virtual W decays to a $u\bar{s}$. The rates for this will be high enough only for Graph-I transitions with $b \rightarrow c$. Table 5 gives estimates of branching ratios and rates for three such modes.

Table 5: Estimated rates for $b \rightarrow c$ decays with all-charged final states in which the virtual W boson decays to $u\bar{s}$. The branching ratios are from Ref. [3].

Decay Mode	Branching Fraction		Acceptance	Events	Mass Res. (MeV/c^2)
$B_u^+ \rightarrow \bar{D}^0 K^+$	$0.03(a_1 + 0.46a_2)^2$	2.7×10^{-4}	0.010	66	88
$B_d^0 \rightarrow D^- K^+$	$0.03a_1^2$	3.0×10^{-4}	0.011	73	89
$B_s^0 \rightarrow D_s^- K^+$	$0.03a_1^2$	3.0×10^{-4}	0.014	69	94

Note that the B_s can decay to both $D_s^+ K^-$ (via a $b \rightarrow u$ transition along with $W \rightarrow c\bar{s}$, Table 3) and to $D_s^- K^+$ (via a $b \rightarrow c$ transition along with $W \rightarrow u\bar{s}$, Table 5). Furthermore, the branching ratios are comparable. Since the $b \rightarrow u$ transition involves a CP-violating phase, the interference between B_s and $\bar{B}_s$ to $D_s K$ will offer another method of probing CP violation.

2.4 B Decays to Baryons

The RICH counter of the μBCD will be able to effect K/p separation for momenta above 2 GeV/c. This permits a study of B decays to final states containing baryons, should the branching fractions be large enough. The report of ARGUS[5] of an observation of $B^+ \rightarrow p\bar{p}\pi^+$ and $B_d^0 \rightarrow p\bar{p}\pi^+\pi^-$ each with a branching fraction of 6×10^{-4} was not confirmed by CLEO.[6] Theoretical estimates of baryonic branching ratios are not yet definitive; one recent estimate[7] for exclusive two-body decays is that the largest branch to a CKM-favored state is about 8×10^{-4}, compared to an early conjecture[8] of 1%.

Tables 6 and 7 give estimates of branching ratios and rates for $b \to u$, and $b \to c$ transitions to baryonic final states, respectively.

Table 6: Estimated rates for $b \to u$ decays with baryonic all-charged final states. The branching ratios are from Ref. [7], and are very rough.

Decay Mode	Branching Fraction	Acceptance	Events	Mass Res. (MeV/c^2)
$B_u^+ \to p\bar{p}\pi^+$	6×10^{-6}	0.26	40	85
$B_d^0 \to p\bar{p}$	6×10^{-6}	0.42	63	107
$B_s^0 \to \Lambda\bar{p}\pi^+$	6×10^{-6}	0.05	7	80

Table 7: Estimated rates for $b \to c$ decays with baryonic all-charged final states. The branching ratios are from Ref. [7], and are very rough.

Decay Mode	Branching Fraction	Acceptance	Events	Mass Res. (MeV/c^2)
$B_u^+ \to p\bar{\Lambda}_c\pi^+$	8×10^{-4}	0.010	198	59
$B_d^0 \to p\bar{\Lambda}_c$	8×10^{-4}	0.013	257	74
$B_s^0 \to \Lambda\bar{\Lambda}_c\pi^+$	8×10^{-4}	0.002	26	58

3 Appendix: Particle ID *vs.* Mass Resolution

In designing an experiment to reconstruct all-charged decay modes of B's the question arises as to the relative importance of the vertex detector, the tracking system, and particle ID. CDF has shown that a signal for $B \to J/\psi X$ events can be obtained with a good tracking system and lepton ID, but no vertex detector or Kaon identification. The premise of the μBCD is that reconstruction of low-P_t nonleptonic B decays will require a vertex detector. Here we consider whether the second most important item is tracking (mass resolution) or Kaon ID.

Given a functioning vertex detector that isolates charged B-decay products from the rest of the event, the remaining data-analysis issue is the suppression of misreconstructed B decays. The problem arises due to missing tracks (photons, or charged tracks that fail the acceptance cuts), and due to misidentified charged tracks.

Based on Monte Carlo simulations described below, the more serious problem is potential misidentification of π's and K's that allow B_d modes to be confused with B_s modes, or modes with missing neutrals to be falsely claimed as all-charged modes. From this we infer that Kaon identification is more critical than precision mass resolution, although clearly both would be desirable.

Our studies are divided in two parts. In the first we assume Kaon identification, but the mass resolution is that for the μBCD, as indicated in Tables 1 and 2. In the second we suppose there is no Kaon identification, but the mass resolution is that of the present CDF.

3.1 Good Hadron Identification

For our first study we simulated the production and decay of 2×10^5 B mesons using ISAJET with B-decay branching fractions according to a model of Bjorken.[9] We suppose that all charged pions and Kaons are correctly identified, and look for cases in which a decay with missing tracks reconstructs to within 2σ of a B mass, where $\sigma \approx 125$ MeV/c^2 as for the μBCD.

Of the 2×10^5 simulated decays, only 3 were potentially misreconstructed as any of the 5 modes listed in Table 1, and in fact it was only the mode $B_d \to \pi^+\pi^-\pi^+\pi^-$ that had the 4 background events. These events were due to D^* decays in which the soft pion or photon was lost. However, among the observed charged tracks a subset reconstruct to the D mass. This background can be eliminated by a mass cut on the D.

In a separate simulation of $B_d \to \pi^+\pi^-\pi^+\pi^-$ decays according to four-body phase space, as might arise from a $b \to u$ transition, we found that in 31% of the decays a combination of either two or three of the pions satisfied a D-meson mass hypothesis accidentally when using the mass resolution of the μBCD. Thus the price of eliminating the misreconstructed events is a 31% loss of efficiency in the $B \to 4\pi$ mode. With the mass resolution of CDF, which is about 5 times better than μBCD, the loss would be only 6%.

3.2 Good Mass Resolution

In this section we show that if the B-decay products have been successfully isolated from the rest of the event (by a vertex detector) then all-charged modes can be reconstructed correctly with good probability without hardware particle identification. However, misidentifications of decays with neutrals, and confusions between the B_d and B_s are shown to be so severe that particle identification is warranted. Of course, there is extensive experience in the community that particle identification is vital when background tracks are present in the sample.

For our study we used the sample of 10^5 B-$\bar{B}$ pairs generated by ISAJET as described in the previous subsection. We suppose that the accuracy of the momentum measurement of the charged tracks is

$$\frac{\sigma_P}{P} = \sqrt{(0.004)^2 + (0.0015P_t)^2}.$$

This is a good approximation to the resolution currently achieved in CDF, and reproduces their mass resolution of 17 MeV/c^2 for $J/\psi \rightarrow \mu^+\mu^-$ decays with $P_t > 2$ GeV/c for the muons, and $P_t > 4$ Gev/c for the J/ψ.

We begin with the charged meson B_u. Among the sample of 10^5 B decays were 133 examples of $B_u \rightarrow$ all-charged tracks. In the absence of hadron identification we supposed that each track could be either a pion or a Kaon. For an n-body decay there are then 2^n different hypotheses as to the identity of the tracks. For each of these we calculated the invariant mass, using track momenta smeared according to the above prescription.

- The hypothesis with reconstructed mass closest to the known mass of the B_u was taken as the 'correct' one.

In 76% of the cases this analysis actually provided the proper particle identification. Some details are given in Table 8. At this stage we ignore the possibility that the decay includes separated vertices due to cascade D- or K-meson decays.

Table 8: The numbers of $B_u \rightarrow$ all-charged decays for which the correct particle identification was obtained by examining which hypothesis yielded the best invariant mass. Also shown are the numbers of correct identifications when the 'plausibility' cut, described in the text, is applied as well.

n_{track}	Correct ID Via Best Mass	Plausibility Cut	Total Events
3	3	1	4
5	12	2	21
7	25	11	38
9	33	18	38
11	23	14	27
13	5	4	5
all	101	50	133

The results of Table 8 are very encouraging, but they were obtained with the knowledge that the set of tracks to be studied was the proper one. In practice we will not have this knowledge. For example, most B decays contains neutrals that cannot be associated with the charged tracks by the vertex detector. Most likely we will have to consider the neutrals as missing. The remaining charged tracks that fit to a secondary vertex are then (incorrectly) presented as candidates for an all-charged decay of the B. With the correct particle identification of these tracks, their combined invariant mass would be less than the B

mass by at least M_π and the event could be rejected. However, without particle identification, hypotheses in which pions are called Kaons lead to larger invariant masses and might by accident coincide with the B mass.

In an attempt to reject track sets with missing neutrals we make an additional requirement:

- The hypothesis with invariant mass closest to the B mass is considered valid only if the mass difference is less than two standard deviations.

From the known form of the momentum resolution the error on the invariant mass of a given track set can be estimated for this. With momentum resolution as given above the B-mass resolution is rather good, varying from 17 MeV/c^2 for 3-track decays to only 7 MeV/c^2 for 13-track decays.

However, even using our revised prescription a large number of B_u decays with missing neutrals were claimed to be correctly identified all-charged decays. The numbers of events are summarized in Table 9. In particular we see that events with large numbers of charged tracks are readily misidentified.

Table 9: The numbers of B_u decays with missing neutrals for which an hypothesis as to the identity of the charged tracks led to an all-charged invariant mass within $\pm 2\sigma$ of the B mass. These events would then be incorrectly identified. Also shown are the numbers of decays with missing neutrals that pass the 'plausibility' cut.

n_{track} (charged)	'Correct' ID Via 2-σ Cut	Plausibility Cut	Total Events
3	4	1	2982
5	268	114	5512
7	1448	338	5560
9	2786	161	3497
11	1252	9	1266
13	235	3	237
all	5993	626	19054

On examining the decays with missing neutrals that were mistakenly identified as all-charged decays, we noticed that if an event is misidentified there are often many different ways of doing this all with invariant-mass hypothesis close to the true B mass. On the other hand, in the true all-charged decays typically only the correct particle identification led to a mass close to the B mass. Accordingly we have applied an additional criterion for particle identification:

- When N different hypotheses as to the identity of the charged tracks all lead to invariant masses within $\pm 2\sigma$ of the B mass, we define the 'plausibility' of the identification as $1/N$. Only decays with plausibility > 90% are considered to be identified.

The use of the 'plausibility' cut significantly reduces the number of events with missing neutrals that are mistakenly identified as all-charged decays, as also summarized in Table 9. The effect of applying the plausibility cut to the true all-charged decays is shown in Table 8, where we see that 38% of the all-charged events survive the plausibility cut. Unfortunately, because there are so many more decays with neutrals than all-charged tracks, the number of misidentified decays that pass our cuts is still larger by an order of magnitude than the number of correctly identified all-charged decays.

Thus far we have not taken advantage of the possibility that some of the B-decay products arise from the tertiary decay of a long-lived D or K meson. With a vertex detector that correctly associates these tracks with a separated vertex, additional constraints will be available. Here we estimate the maximum advantage that might be obtained from tertiary vertices by examining the decays $B_u \to D^0+$ all-charged tracks.

We suppose that the D^0 is correctly identified in a separate study, and all that remains is to identify the charged tracks associated with the B-decay vertex. Again we examine the invariant masses of the various particle-ID hypotheses and apply the plausibility cut, with results as shown in Table 10. The tertiary vertex can indeed be very helpful; in contrast to the results of Table 8, we now correctly identify 94% of the B_u decays. Of course, one must factor in the probability that the tertiary vertex is correctly analyzed.

Table 10: The numbers of $B_u \to D^0+$ all-charged decays for which the correct particle identification was obtained by examining which hypothesis yielded the best invariant mass. Here the D^0 has been assumed to have been correctly identified via its decay products which form a separated tertiary vertex.

n_{track} (charged)	Correct ID Via 2-σ Cut	Correct ID Via Plausibility Cut	Total Events
2	25	18	25
4	22	20	23
6	35	35	35
8	11	11	12
10	2	2	3
all	95	86	98

We must also consider those events in which a D^0 is successfully reconstructed at a tertiary vertex, but the tracks from secondary B vertex include neutrals. According to Ref. [9] the situation here is relatively favorable in that a substantial fraction of the decays $B_u \to D^0X$ have X as all-charged. The results of our simulation are shown in Table 11, where we infer that the observation of a tertiary D vertex could raise the signal-to-noise to 2 : 3. However, we would still prefer a signal-to-noise much larger than one.

Table 11: The numbers of $B_u \to D^0 + X$ decays where X includes missing neutrals for which the charged tracks were incorrectly identified as reconstructing to the B mass. The D^0 has been assumed to have been correctly identified via its decay products which form a separated tertiary vertex.

n_{track} (charged)	'Correct' ID Via 2-σ Cut	'Correct' ID Via Plausibility Cut	Total Events
2	24	17	298
4	33	29	261
6	79	64	236
8	50	24	75
10	8	4	9
all	194	138	879

We now turn to the neutral mesons, B_d and B_s. These have masses that differ by only a small amount (the value is not presently known, but was taken as 200 MeV/c^2 in this study). If we have a set of tracks whose total charge is zero associated with a secondary vertex, then we must compare our hypotheses as to the particle ID's with both the B_d and the B_s. We might well have a B_d mistakenly identified as a B_s, or *vice versa.* A measure of the probability of this is given in Tables 12 and 13.

With two mass hypotheses to be considered for each neutral decay, there are typically so many ways of satisfying one or the other hypothesis that our 'plausibility' cut is of little use. The problem of B_d's being misidentified as B_s's is particularly severe as there will be many more all-charged decays of the B_d than of the B_s.

We have attempted to derive an advantage from the existence of tertiary decays in another manner. The B-decay products may include daughter mesons such as D, J/ψ, ϕ, K_S... that decay in turn. This time we do not suppose that the daughters have separated tertiary vertices, but that their decay products are intermixed with those directly from the B decay. However, we examine subsets of the B-decay tracks for those that reconstruct to the mass of one of the possible daughter mesons. This search is more fruitful if we restrict ourselves to hypotheses for the decay products of the daughters that lead to a B mass when combined with the rest of the tracks from the B decay. Tables 14 and 15 list the fraction of all-charged B_d decays that are thus correctly reconstructed in this manner, and the numbers of misidentified decays when there are missing neutrals. With this approach we only achieve a signal-to-noise of 1 : 4.

While our present study does not exhaust the possibilities of analyses of B decays without explicit particle identification, it indicates that the signal quality will not be high. In view

Table 12: The numbers of $B_d \rightarrow$ all-charged decays for which the correct particle identification was obtained by examining which hypothesis yielded the best invariant mass. Also listed are the numbers of decays for which the 'best' particle-ID hypothesis fitted to the B_s mass.

n_{track}	Correct ID as B_d	Wrong ID as B_s	Total Events
4	169	33	222
6	48	44	105
8	35	40	87
10	23	17	43
12	8	6	15
all	283	140	472

Table 13: The numbers of $B_s \rightarrow$ all-charged decays for which the correct particle identification was obtained by examining which hypothesis yielded the best invariant mass. Also listed are the numbers of decays for which the 'best' particle-ID hypothesis fitted to the B_d mass. The 'plausibility' cut has been applied.

n_{track}	Correct ID as B_s	Wrong ID as B_d	Total Events
4	8	2	11
6	19	2	25
8	17	2	23
10	2	2	4
12	4	2	7
all	50	9	70

of this it appears wise to provide for Kaon identification in the hardware.

4 References

[1] BCD Collaboration, *Proposal for a B-Physics Experiment at TEV I: The μBCD*, submitted to Fermilab (Oct. 8, 1990).

[2] R. Fulton *et al.*, *Observation of B-Meson Semileptonic Decays to Noncharmed Final States*, Phys. Rev. Lett. 64, 16 (1990).

Table 14: The numbers of $B_d \rightarrow$ all-charged decays for which the correct particle identification was obtained by simultaneous fits for the B mass and the mass of a daughter meson. No use is made of a possible tertiary vertex. The column labelled '2-σ Cut' includes all decays for which the correct particle identification leads to B and daughter masses both within 2σ of the true value, whether or not this identification was the 'best.'

$n_{\text{daughters}}$	Correct ID Via 2-σ Cut	Correct ID Via Plausibility Cut	Total Events
2	47	32	47
3	153	112	181
4	162	132	189
5	47	32	65
6	28	12	47
7	18	12	41
8	9	4	29
9	12	9	21
10	6	1	17
11	5	4	6
12	2	0	3
13	2	1	2
all	491	351	648

[3] M. Bauer, B. Stech, and M. Wirbel, *Exclusive Non-Leptonic Decays of D^-, D_s^-, and B-Mesons*, Z. Phys. C **34**, 103 (1987).

[4] BCD Collaboration, *Response to the SSC PAC*, (July 11, 1990).

[5] H. Albrecht *et al.*, *Observation of Charmless B Meson Decays*, Phys. Lett. **209B**, 119 (1988).

[6] C. Bebek *et al.*, *Search for Charmless Decays $B \rightarrow p\bar{p}\pi$ and $p\bar{p}\pi\pi$*, Phys. Rev. Lett. **62**, 8 (1989).

[7] G. Lu *et al.*, *CP-Violation Effects in Some Two-Body Baryonic Decays of B_d^0*, Phys. Lett. **259B**, 169 (1991).

[8] I.I. Bigi, *Remark on Baryonic Decays of B Mesons*, Phys. Lett. **106B**, 510 (1981).

[9] J.D. Bjorken, *Estimates of Decay branching Ratios for Hadrons Containing Charm and Bottom Quarks*, (1986), unpublished.

Table 15: The numbers of $B_d \to X$ decays for which X includes missing neutrals and an incorrect particle identification was obtained by a simultaneous fit for both the B mass and the mass of a daughter meson.

n_{track} (charged)	'Correct' ID Via 2-σ Cut	Plausibility Cut	Total Events
2	3	3	2014
3	14	10	1257
4	196	86	9383
5	366	177	2553
6	2034	563	9565
7	1006	272	2421
8	3248	319	5583
9	791	53	1005
10	850	29	976
11	182	4	186
12	113	0	116
13	19	0	21
all	8822	1516	35080