BTeV/C0

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Abstract

The physics goals and techniques of the proposed BTeV experiment at the C0 Tevatron interaction area are summarized, with emphasis on aspects of the experiment that depend on near-beam issues. BTeV aims to carry out a comprehensive study of rare processes (especially CP violation) in charm and beauty decay starting in collider Run II. Vertex detectors will be deployed within a few mm of the beam. Early running may employ a wire target in the beam halo.

1 INTRODUCTION

The BTeV collaboration is proposing to carry out a dedicated heavy-quark collider experiment in the C0 interaction region at the Tevatron. The main goals of BTeV are to search for CP violation, mixing, and rare flavor-changing neutral-current (FCNC) decays of b- and c-quark hadrons at unprecedented levels of sensitivity. Each year of BTeV collision operation is expected to produce $O(10^{11})$ b hadrons and $O(10^{12})$ c hadrons, to be compared with $O(10^5)$ of each available at the e+e- “B Factories” and $O(10^9)$ b events per year at the HERA-B fixed-target experiment. The BTeV spectrometer is being designed to make optimal use of the produced samples, avoiding many of the compromises necessary in general-purpose detectors.

The rationale for sensitive b-quark studies has been discussed extensively [1]-[3]. In a nutshell, the goal is to test thoroughly the Kobayashi-Maskawa (KM) [3] mechanism – the Standard-Model explanation for CP violation – in a regime in which large effects are expected, as opposed to the $O(10^{-3})$ effects observed in the $K^0$ sector [3,4]. The KM model, while compatible with all known experimental evidence, is not unique, and it is appropriate to regard the origin of CP violation as a key unsolved problem of contemporary science. The baryon asymmetry of the universe leads us to think [3] that CP violation beyond that predicted in the KM model should exist [4]. The over-arching question in particle physics today is, what “new physics” underlies the Standard Model? It is possible that $K^0$ CP violation arises in part or even entirely from physics outside the Standard Model, in which case it is the only new-physics signature that has already been observed.

Many experiments now seek to address this topic. The $B$-Factory and HERA-B groups are vying to be the first to observe CP violation in $B$ decay, and the CDF and D0 groups are not far behind. However, it is likely that these efforts, while adequate to observe effects, will not suffice for the thorough investigation that the importance of the topic demands.

High-sensitivity charm studies are complementary to beauty studies. In the Standard Model, CP violation, mixing, and FCNC decays, all relatively large in beauty, are drastically suppressed in charm [5]. Any contribution from new physics will thus stand out dramatically. For example, new physics might be Higgs-like and couple to quark mass [6], or might couple more strongly to “up-type” than “down-type” quarks [7]. In such scenarios, charm has the biggest new-physics signal-to-background ratio of any quark. On the experimental side one has (compared to beauty) large production cross sections, large branching ratios to final states of interest, and straightforward tagging via the $D^{*+} \rightarrow D^0 \pi^+$ decay chain. The experimental approach taken by BTeV, featuring a primary trigger based on the presence of secondary vertices, naturally provides high charm and beauty sensitivity simultaneously. We can thus carry out a “two-pronged assault” on the Standard Model.

2 STANDARD-MODEL CP VIOLATION

2.1 The CKM Quark-Mixing Matrix

The KM mechanism for CP violation invokes a non-zero phase in the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing matrix [1,3].

$$V = \begin{pmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{pmatrix}.$$ 

The matrix $V$ parametrizes the coupling of the $W$ bosons to the quarks in a way that allows the generations to mix. For example, instead of coupling the $u$ quark only to the $d$, $W^+$ emission couples the $u$ to the linear combination

$$V_{ud}|d\rangle + V_{us}|s\rangle + V_{ub}|b\rangle,$$

with similar expressions for the couplings to the $c$ and $t$ quarks. This generation mixing provides an explanation for the observed non-stability of the $s$ and $b$ quarks.

As is well known, for two generations of quarks, the quark mixing matrix is real and has one free parameter, the

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2The Standard Model, while consistent with all established experimental results, has more than twenty free parameters (the lepton masses, quark masses and mixing parameters, coupling constants, Weinberg angle, Higgs mass, etc.) and thus is generally considered to be only an approximation. New physical effect(s) yet to be discovered are presumed to determine the values of these parameters.

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must satisfy constraints from and the lengths of its sides are consistent. In addition it prove that the triangle is indeed closed, suuring enough of the mixing and asymmetry parameters to uniquely large in beauty decays.

CP dependence on the CKM phase (whose sign changes under is compared to that for the Cabibbo angle[11]. Being unitary, for three quark generations the matrix depends on only four independent parameters, including one non-trivial phase[8]. Certain decays can occur via more than one Feynman diagram in such a way that the interference term between the diagrams contains this phase. When the decay width for such a reaction is compared to that for the CP-conjugate reaction, the dependence on the CKM phase (whose sign changes under CP) can result in a CP asymmetry, e.g.

\[ A \equiv \frac{\Gamma(B \to f) - \Gamma(B^\to \bar{f})}{\Gamma(B \to f) + \Gamma(B^\to \bar{f})} \neq 0, \]

which will depend on the decay time if the interference involves \(B\overline{B}\) mixing.

The unitarity of the CKM matrix further implies that the product of any two of its rows or columns be zero. One such relationship is

\[ V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0. \]

This relationship constrains mixing rates and CP asymmetries in various decays of beauty hadrons. Since it states that three complex numbers sum to zero, it can be visualized as defining a triangle in the complex plane (Fig. 1). Because (unlike the case in the \(K^0\) and charm sectors) the sides of this triangle are all roughly similar in length (Fig. 2), the angles are expected to be large. Since the angles determine the CP asymmetries, these should be uniquely large in beauty decays.

### 2.2 Studying the Unitarity Triangle

The task of verifying the KM model then reduces to measuring enough of the mixing and asymmetry parameters to prove that the triangle is indeed closed, i.e. that its angles and the lengths of its sides are consistent. In addition it must satisfy constraints from CP violation in the \(K^0\) sector (Fig. 3). Ideally one would make enough different measurements to verify that all decays constrained by the unitarity triangle satisfy the constraints. This task is made difficult by the small branching ratios for interesting \(B\)-hadron final states (e.g. \(1.7 \times 10^{-5}\) for \(B_d \to J/\psi K_S \to \mu^+\mu^-\pi^+\pi^-\)), thus a large \(b\bar{b}\) production cross section is required. Since \(\sigma_{bb} \sim 100\) \(\mu b\) at \(\sqrt{s} = 2\) TeV, the Tevatron collider is a natural venue for such studies.

The angle \(\beta\) can be determined from the CP asymmetry in \(B_d \to J/\psi K_S\) with essentially no theoretical uncertainty. Since this mode also has a clean experimental signature in the \(J/\psi \to \text{dileptons}\) decay and (compared to other modes with large expected CP asymmetries) a relatively large branching ratio, it is sometimes called the "golden" mode for \(B\) CP violation. Its CP asymmetry is expected[3] to be ~0.5 in the Standard Model and is likely to be measured by 2002 in the next round of experiments.

The other two angles of the unitarity triangle are considerably harder to determine. It is often stated that \(\alpha\) is measured in \(B_d \to \pi^+\pi^-\). The measurement suffers from significant drawbacks. First, the branching ratio is small (< \(1.5 \times 10^{-5}\) at 90% C.L. [3]) and has yet to be definitively established. Second, the larger branching ratio observed for \(B_d \to K^+\pi^-\) imposes stringent experimental requirements on hadron identification and mass resolution to allow adequate suppression of \(K\pi\) background, and also implies a significant contribution to \(BR(B_d \to \pi^+\pi^-)\) from penguin diagrams, whose CP asymmetry is difficult to relate to CKM angles. Nevertheless, the measurement of the CP asymmetry in \(B_d \to \pi^+\pi^-\) will be an important step forward and will furnish a significant constraint on models of CP violation.

Various methods of determining \(\gamma\) have been discussed and have various advantages and drawbacks. A promising method appears to be comparison of branching ratios for \(B^+ \to D^0 K^+\) and \(B^- \to \overline{D}^0 K^-\) [3]. Both of these can occur via two processes that interfere, namely \(B^+ \to D^0 K^+, \overline{D}^0 \to K^+\pi^-\) and \(B^+ \to D^0 K^+, D^0 \to K^+\pi^-\) (and charge-conjugates). Since the first proceeds via \(b \to u\) conversion while the second includes a doubly Cabibbo-suppressed \(D^0\) decay, both are highly suppressed.
processes, leading to the favorable situation where the interference between them can have a relatively large effect (of order unity) on branching ratios. On the other hand, the branching ratios for these modes are expected to be $O(10^{-6})$. Another method is via the mixing-induced $CP$ asymmetry in $B_s(B_c) \to D_s^{\pm} K^\mp$; this measurement will require excellent decay-time resolution given the rapid expected $B_s/B_c$-mixing oscillations.

We see that a complete test of the KM model will require very large $B$ samples. Only hadroproduction can supply such large numbers of events. Furthermore, since several of the decay modes of primary interest are to all-hadronic final states, a significant physics penalty is paid if the typical $B$ trigger, requiring high-$p_t$ leptons from semileptonic or $B \to J/\psi$ decays, is employed. We are thus led to the BTeV strategy: a first-level trigger based on decay-vertex reconstruction.

BTeV’s sensitivity has been estimated [15] as $\pm 0.04$ in $\sin 2\beta$ and (ignoring penguin contributions) $\pm 0.1$ in $\sin 2\alpha$. These are for one year of running at the nominal luminosity of $5 \times 10^{30}$ cm$^{-2}$s$^{-1}$. We are investigating our sensitivity to $\gamma$ and also the possibility of running at higher luminosity.

3 NON-STANDARD-MODEL $CP$ VIOLATION

A variety of extensions to the Standard Model (SM) have been considered in which $CP$-violating phases can arise elsewhere than in the CKM matrix. Possible non-Standard sources for $CP$ violation include additional Higgs doublets, non-minimal supersymmetry, massive $W$'s with right-handed couplings (“left-right-symmetric” models), leptoquarks, a fourth generation, etc. [3, 16]. Such mechanisms could be responsible for all or part of $K^0$ $CP$ violation.

These models have various attractive features. For example, an enlarged Higgs sector is a relatively natural and straightforward extension of the SM, especially since we know of no reason (other than Occam’s Razor!) why, assuming Nature opted to implement the Higgs mechanism, she should have stopped after only one physical Higgs boson. Left-right-symmetric models are appealing in that they provide a unified explanation for both parity and $CP$ violation. And in such extensions of the SM, the CKM phase could be exactly zero, perhaps due to some yet-to-be-determined symmetry principle – a less arbitrary scenario than the SM, in which the value of the CKM phase is a free parameter.

Typically these alternative models for $CP$ violation lack the distinctive feature of the SM that $CP$ asymmetries are largest in the $B$ sector. Many of them can lead to $CP$ violation in charm decay at the $10^{-3}$ to $10^{-2}$ level and have the additional distinctive signatures of large flavor-changing neutral currents or mixing in charm. While direct $CP$ violation at the $10^{-3}$ level in Cabibbo-suppressed charm decays is a prediction of the Standard Model [17], its observation in Cabibbo-favored or doubly Cabibbo-suppressed decays would constitute unambiguous evidence for new physics, as would the observation of indirect $CP$ violation in charm.

![Figure 3: Sketch of BTeV Spectrometer.](image-url)

At the levels discussed in the literature, such effects could be detectable in BTeV, which could reconstruct $10^8$ to $10^9$ charm decays, but more simulation is required to assess backgrounds and systematics [18].

4 THE BTEV SPECTROMETER

The proposed BTeV spectrometer (shown schematically in Fig. 3) covers the forward and backward regions at the new C0 Tevatron interaction area. The instrumented angular range is $0.01 \leq |\tan \theta| \leq 0.3$. Monte Carlo simulation shows that such coverage includes ~50% of all $B$ and $D$ decays.

Compared to the “central-geometry” case (e.g. CDF and D0), this “forward-geometry” configuration accepts relatively high-momentum particles (see Fig. 4). It also leads to an advantageous vertex-detector arrangement, consisting of detector planes inside the vacuum pipe oriented perpendicular to the beam (Fig. 5), allowing substantially better reconstruction of decay proper time. Another key advantage of forward geometry is the feasibility of effective hadron identification. Because QCD mechanisms of $bb$ production yield quark pairs that are closely correlated in rapidity ($|y_b - y_{\bar{b}}| \lesssim 1$), there is little disadvantage in omitting the small-rapidity region: when the decay products of one $B$ hadron are detected in the forward (or backward) region, decay products of the second (“tagging”) $B$ have a high probability to be detected there also.

In addition to large acceptance, the apparatus must have high interaction-rate capability, an efficient trigger for heavy-quark decays, high-speed and high-capacity data acquisition, good mass and vertex resolution, and good particle identification. Of these requirements, the most challenging are the trigger and the particle identification. We intend to trigger primarily on the presence of a decay vertex separated from the primary vertex [19]. To reduce occupancy and facilitate vertex reconstruction at trigger level 1, pixel detectors will be used for vertex reconstruction. For efficient, reliable, and compact particle identification, we will build a ring-imaging Cherenkov counter. In other respects the spectrometer will resemble existing large-aperture heavy-quark experiments; see Refs. [15, 20] for more detailed discussions.

5 NEAR-BEAM ISSUES IN BTEV
5.1 Size of vertex-detector beam gap

A key point in the reconstruction of decay vertices in forward geometry is the dependence of the impact-parameter resolution on the transverse distance of the vertex detectors from the beam [21]. This is illustrated in Fig. 6. For sufficiently fine pixel resolution, the impact-parameter resolution will typically be dominated by multiple coulomb scattering in the first detector plane that the particle encounters. The effective r.m.s. scattering angle $\delta \theta_y$ in the $y$-$z$ view for a charged particle of momentum $p$ traversing a detector of thickness $X$ and radiation length $X_0$ is [22] 

$$\delta \theta_y \approx 0.015 \frac{\text{GeV}}{p} \sqrt{\frac{X}{X_0}}.$$ 

(The thickness $X$ of course must include substrate, readout electronics, and RF shielding.) If the particle encounters the first detector at a longitudinal distance $z$ from the vertex and transverse distance $y$ from the beam, the scattering contribution to impact-parameter resolution is 

$$\delta y \approx z \delta \theta_y \approx y \left( 0.015 \frac{\text{GeV}}{p_y} \sqrt{\frac{X}{X_0}} \right). \quad (1)$$ 

A similar equation holds for the $x$-$z$ view, where $\delta x$ also depends on $p_y$ since the beam gap is assumed to be in $y$.

We see that the impact-parameter error is proportional to the transverse distance of the track from the beam at the first measurement plane encountered by the particle. To minimize the scattering contribution, it is thus important to keep the beam gap as small as possible. The other parameters appearing in Eq. 1 are less subject to control by the experimenter: the distribution of $p_y$ is determined by the mass and production and decay dynamics of the particle to be studied, and $X/X_0$ is fixed by signal/noise, mechanical support, and cooling issues. Furthermore, the dependence on $X/X_0$ is as the square root, so while thickness should be minimized, it is difficult to make a big impact in this way.

Fig. 7 shows the dependence of the proper-time resolution on the size of the beam gap for simulated $B_s \rightarrow J/\psi K^*$ events. (The time resolution in this mode is an indicator of physics reach for studies of $B_s$ mixing, a challenging measurement in $b$ physics.) As the half-gap $y_{\text{min}}$
is decreased from 9 mm to 3 mm, the r.m.s. resolution improves by about a factor of 2. In addition, since cuts on vertex separation must be made in order to suppress background, the number of events in the final sample increases by more than a factor of 2. This indicates the substantial improvement in physics reach that is possible if the vertex detectors can be moved closer to the beam. With the nominal 6 mm half-gap, the reach in $x_s$ (the parameter that relates the $B_s$ mixing rate to its decay rate) is about 40, i.e. if $x_s = 40$ we expect to obtain a 5-standard-deviation signal for $B_s$ mixing in about one year of running at $\mathcal{L} = 5 \times 10^{34}$ cm$^{-2}$s$^{-1}$. This should be compared with the Standard-Model prediction $x_s < 60$ and the current experimental lower limit $x_s > 15$.

The size of the half-gap is in principle limited from below by two effects: 1) radiation damage in the vertex detectors and 2) creation of backgrounds at the other interaction regions. In practice the first limit will be reached well before the second! For silicon detectors with a 4 mm half-gap, the radiation-damage limit ($\sim 10^{14}$ minimum-ionizing particles/cm$^2$) is reached in $\approx 1$ year of running at $\mathcal{L} = 5 \times 10^{33}$ cm$^{-2}$s$^{-1}$. Development of diamond pixel detectors may allow a smaller gap.

### 5.2 Wire-target running in C0

The commissioning of a third collider interaction region is likely to be a complex process, and simultaneous collider luminosity in all three areas might not be available during the first years of Collider Run II. It has thus been envisaged since the earliest consideration of the C0 program that a significant portion of the early running might be carried out using a wire or pellet target in the halo of the proton or antiproton beam. This could afford an early opportunity for commissioning of detectors. Since it would provide a source of primary interactions localized at a known point or along a known line in space, it could also be invaluable for testing the vertex trigger.

While halo running would be essentially useless for beauty due to the small fixed-target $b$ cross section, surprisingly, the charm reach could be comparable in fixed-target and collider modes. The increase in charm cross section at $\sqrt{s} = 2$ TeV compared to 43 GeV has not been measured but is presumed to be a factor $\gtrsim 10$. However, if only one spectrometer arm is instrumented at first, fixed-target has a factor-of-3 advantage in geometrical acceptance, and a factor $\approx 4$ in cross section can be made up by taking advantage of the target-A dependence of charm production ($\sigma_{\text{inel}} \propto A^1$ vs. $A^{0.71}$ for the total inelastic cross section which limits the interaction rate). Finally, triggering on charm is likely to be considerably more efficient in fixed-target mode, where the moderate $p_t (\lesssim 1$ GeV) of charm decay products stands out more prominently relative to minimum-bias background: in fixed-target a factor $\approx 100$ in background suppression is available before vertex reconstruction, perhaps allowing charm triggering in the short-lifetime regime (proper time $< 1$ ps) crucial to studies of charm mixing in $D^0 \rightarrow$ hadrons and $D^\pm \rightarrow K^\mp \pi^\pm$.

A possible physics advantage of halo running has also been suggested. Biases in charm mixing studies may arise from $b \rightarrow c$ cascade decays. These would be suppressed by two orders of magnitude in fixed-target relative to collider mode, due to the reduced beauty production cross section.

Assuming a 1 MHz rate of inelastic interactions, $> 10^8$ charm decays can be reconstructed per year ($10^7$ s) of fixed-target operation. For example, the rate of $D^0(\bar{D}^0) \rightarrow K^\mp \pi^\pm$ is estimated as

$$n_{D^0(\bar{D}^0)\rightarrow K\pi} = 10^7 s \cdot 10^6 \text{int.}/s \cdot 6.5 \times 10^{-4} A^{0.29} D^0(\bar{D}^0)/\text{int.} \cdot 4\% \cdot 10\%,$$

where the last two factors appearing in Eq. 2 are $BR(D^0 \rightarrow K^- \pi^+) \cdot 4\% \cdot 10\%$ and the product of acceptance and reconstruction efficiency. Other decay modes will increase the total by a factor $\sim 3$. This interaction rate implies $\approx 0.4$ interactions/crossing with 396 ns bunch spacing and $\approx 0.1$ with 132 ns spacing, low enough that $p_t$-based triggers should not be badly affected by pile-up. That a 1 MHz interaction rate is feasible with a halo target follows from the work of the HERA-B collaboration, who have demonstrated 30 MHz with wire targets in the halo of the HERA proton beam. However, the Tevatron scraping and
collimation procedures may need considerable rethinking, since high-rate operation of a halo target requires that the target compete efficiently with the collimators.

6 CONCLUSIONS

If approved, BTeV will be the state-of-the-art charm and beauty experiment in the mid-2000’s period. The near-target compete efficiently with the collimators.

• Minimizing the size of the vertex-detector beam gap will both maximize the number of events satisfying analysis cuts and optimize their vertex resolution.

• Early charm sensitivity at a competitive level may depend on halo targeting.

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