An Electromagnetic Calorimeter for BTeV[1]

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Abstract

BTeV is a dedicated b and charm physics experiment planned to run at the Fermilab Tevatron. The goal of the experiment is to make precise measurements of all the CKM angles in order to determine whether the Standard Model explanation of $\mathcal{CP}$ Violation and mixing is correct or whether new physics is required. To achieve this goal it will be desirable to reconstruct a number of b hadron decay modes involving photons, both singly and from π^0 decay. I will describe the present status of the BTeV Electromagnetic Calorimeter where, in order to attain the physics goals and to satisfy the constraints imposed by running in a hadron collider environment, we have chosen to use Lead Tungstate crystals with phototube readout.

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[1] Invited talk presented at *Beauty '99 - The* 6th *International Conference on B Physics at Hadron Machines*, Bled, Slovenia, June, 1999.

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1 Introduction

BTeV is the proposed experiment at the Fermilab Tevatron dedicated to studying $\mathcal{CP}$ Violation in the b system [1, 2]. To extract the b hadron signals from the large backgrounds at a $p\bar{p}$ collider requires, at a minimum, vertexing in the lowest level trigger and superb particle identification. The ability to reconstruct photons, and, hence, π^0's, with good resolution would also greatly enhance a detector for performing $\mathcal{CP}$ Violation studies. For example, the best proposed method at present for measuring the angle α involves performing a Dalitz plot analysis of the $\pi^+\pi^-\pi^0$ final state in flavour-tagged B^0 decays [3]. Further, there are many channels involving single photons which are interesting and inaccessible to experiments at e^+e^- colliders tuned to the $\Upsilon(4S)$. For example, the ratio of the $B_s \to \phi\gamma$ to $B_s \to K^{*0}\gamma$ branching fractions is probably better, from an experimental point of view, than $\mathcal{BR}(B \to \rho\gamma)/\mathcal{BR}(B \to K^*\gamma)$ to extract $|V_{td}/V_{ts}|$ since the ϕ is a much narrower resonance than the ρ thereby allowing for tighter mass cuts and better rejection of combinatorial background. A sensitive test for new physics proposed by Silva and Wolfenstein[4] (following Aleksan, Kayser, and London[5]) involves relations between the angle χ (called ϵ in [4]), given by;

$$\chi = arg\left(-\frac{V_{cs}^* V_{cb}}{V_{ts}^* V_{tb}}\right)$$

and the standard angles γ and β. The angle χ can be measured using, for example, the $\mathcal{CP}$ eigenstate $B_s \to J/\psi\eta'$, $\eta' \to \rho\gamma$.

These are just a few examples of how the ability to reconstruct final states containing photons can add enormously to the potential of BTeV. The questions are whether there is a detector technology which can: survive the high radiation environment, handle the rate and occupancy, obtain sufficient angular and energy resolution, and allow the extraction of signals in the face of significant combinatorial backgrounds. This paper describes how a baseline technology was chosen and how the parameters of the calorimeter were derived.

2 Calorimeter Design Issues

There are number of constraints, both geometric and due to the physics processes of interest, which set the parameters of a useful calorimeter for BTeV. The area available for a calorimeter is located about 7 m from the nominal interaction point and extends about 1 m. The distance of the beam from the floor is 2.5 m. A transverse dimension of about 4 m by 4 m (i.e., out to a polar angle of about 300 mrad) matches the acceptance of the upstream spectrometer.

Greater than ∼97% of minimum bias photons have a p_T less than 1 GeV. Photons from b hadron decays tend to be somewhat stiffer although only in “two-body” electromagnetic decays, like $B \to K^*\gamma$, does a cut on p_T clearly improve the significance of the signal. Photons from b hadron decays range in energy from about 1 to 60 GeV.

The mean number of photons per event is around thirty so combinatorics is a serious issue. Mass resolution is a powerful tool to reduce the effect of combinatorial backgrounds. In order to understand the required energy resolution, we performed an analysis of $B \to K^*\gamma$ using generator level quantities smeared by simple resolution functions. Events are generated using `Pythia 5.7` and `Jetset 7.4`[6] and the heavy quark states are then decayed using the CLEO Monte Carlo program `QQ`[7]. The the photon transverse position was calculated assuming a Gaussian of width $\Delta X/\sqrt{12}$ where ΔX is the transverse dimension of a detector “block” (taken as the same in x and y). The reconstructed photon energy was smeared according to:

$$\frac{\sigma_E}{E} = \sqrt{\frac{a^2}{E} + b^2} = \frac{a}{\sqrt{E}} \oplus b$$

where a and b are the so-called “stochastic” and “constant” terms, respectively. Charged tracks used in the analysis were the result of the full offline fit. The resulting $K^*\gamma$ mass resolution for various combinations of stochastic and constant terms is given in Table 1.

The annual radiation dose is estimated to be 60 KGrays at a radius of about 14 cm (20 mr). The dose falls off like a power of the radius to the 2.3 power from 20 cm on out so the detector needs to be radiation hard towards the middle and radiation tolerant on the outside. At 20 mr, the detectors nearest the beam will receive doses that are a quarter of those expected at the LHC (at greater radius but much higher luminosity and energy).

a (%)	b (%)	Mass Resolution* (MeV/c^2)
3.0	1.0	54
2.5		48
2.0		49
1.5		49
3.0	0.75	46
2.5		50
2.0		42
1.5		39
3.0	0.55	45
2.5		41
2.0		44
1.5		40
3.0	0.25	41
2.5		45
2.0		40
1.5		36

Table 1: $B \to K^*\gamma$ final state mass resolution as a function of the stochastic and constant terms in a parameterized Electromagnetic Calorimeter energy resolution function. The statistical accuracy in the mass resolution due to the size of the Monte Carlo sample is 2-3 MeV/c^2.

The initial design criteria for the calorimeter are summarized in Table 2.

3 GEANT Study of Lead Tungstate Crystals

A calorimeter composed of lead tungstate ($PbWO_4$) crystals has characteristics which best match the criteria articulated in the previous section. The properties of $PbWO_4$ are given in Table 3.

To get more quantitative information specific to BTeV, an array of 24.7×24.7 mm^2 array of blocks with normally incident photons (distributed over the crystal faces) of energies 2.5 to 80 GeV was simulated using GEANT[8]. It was found that a crystal length of 220 to 230 mm is optimal. The contribution

Property	Value
Maximum length	1 meter
Angular Resolution	1 mr at 700 cm
Energy resolution: Stochastic Term Constant Term	 1-3% 0.55-0.75%
Minimum angle	10-20 mr at 700 cm
Maximum angle	200-300 mr
Length	25 radiation lengths
Pulse pair resolution	must be able to associate pulse height to individual beam crossings with low pile up
Radiation hardness	Annual radiation dose of 60 KGrays @ 14 cm radius (20 mrad)

Table 2: Design Criteria for an Electromagnetic Calorimeter in BTeV

from "leakage" was found to be: $\sigma_E/E = 1.08\%/\sqrt{E} \oplus 0.2\%$ for E in GeV. The "transverse leakage" component of this (using 5×5 clustering) was $0.7\%/\sqrt{E}$. Since the BTeV crystals will not be in a magnetic field, they can be read out with photomultiplier tubes with a relatively low number of stages. The photon statistics term for BTeV, assuming 7 photoelectrons/MeV into phototubes, is expected to be $1.2\%/\sqrt{E}$. This compares to $2.3\%/\sqrt{E}$ for CMS where they have a lower number of photoelectrons expected into their APD's. Further, assuming a constant term of 0.55%, as does CMS (KTeV achieved 0.45%), we would expect an energy resolution in BTeV of:

$$\frac{\sigma_E}{E} = \sqrt{\frac{(1.1^2 + 1.2^2)}{E} + (0.55)^2} = \frac{1.6\%}{\sqrt{E}} \oplus 0.55\%$$

To be conservative, the physics simulations discussed in the next session were done using 2.5% rather than 1.6%.

To study the probability of overlaps (i.e., where the clusters from two photons from a π^0 are indistinguishable from a single photon cluster), we calculated the second-moment of the energy distribution, S_2, defined as

$$S_2 = \frac{\sum_i \left(\overrightarrow{R}_i - \overrightarrow{R}_0\right)^2 \cdot E_i}{\sum_i E_i}$$

Property	Value
Density (gm/cm^3)	8.28
Radiation Length (cm)	0.89
Interaction Length (cm)	22.4
Moliere Radius (cm)	2.19
Light Decay Time (ns):	5(39%)
	15(60%)
	100(1%)
Refractive Index	2.30
Maximum of emission (nm)	440
Temperature Coefficient (%/^{o}C)	-2
Light output/NaI(Tl) (%)	1.3
Light output (pe/MeV into a 2" PMT)	10

Table 3: Properties of $PbWO_4$

where $\overrightarrow{R}_i$ is the position vector to the center of each individual crystal in the cluster, $\overrightarrow{R}_0$ is the energy weighted position vector of the entire cluster, and E_i is the energy deposited in each crystal. Clusters are easily separable up to 60 GeV as seen in Figure 1. This is quantified in Table 4.

Energy (GeV)	π^o to γ fake rate (%)	γ to π^o fake rate (%)
60	2.9	0.8
70	1.3	2.9
80	4.2	5.9
90	13.9	16.0
100	38.5	30.7

Table 4: Neutral Particle Fake Rates for 90% Efficiency

Position resolution was calculated using

$$Xcl = \frac{\sum_{i=1}^{5} x_i \cdot E_i}{\sum_{i=1}^{5} E_i}$$

where E_i was the energy reconstructed in each crystal, x_i was the center of each crystal, and the sum extended two crystals in the direction of $-x$ from the highest energy crystal to two crystals in the $+x$ direction. The same

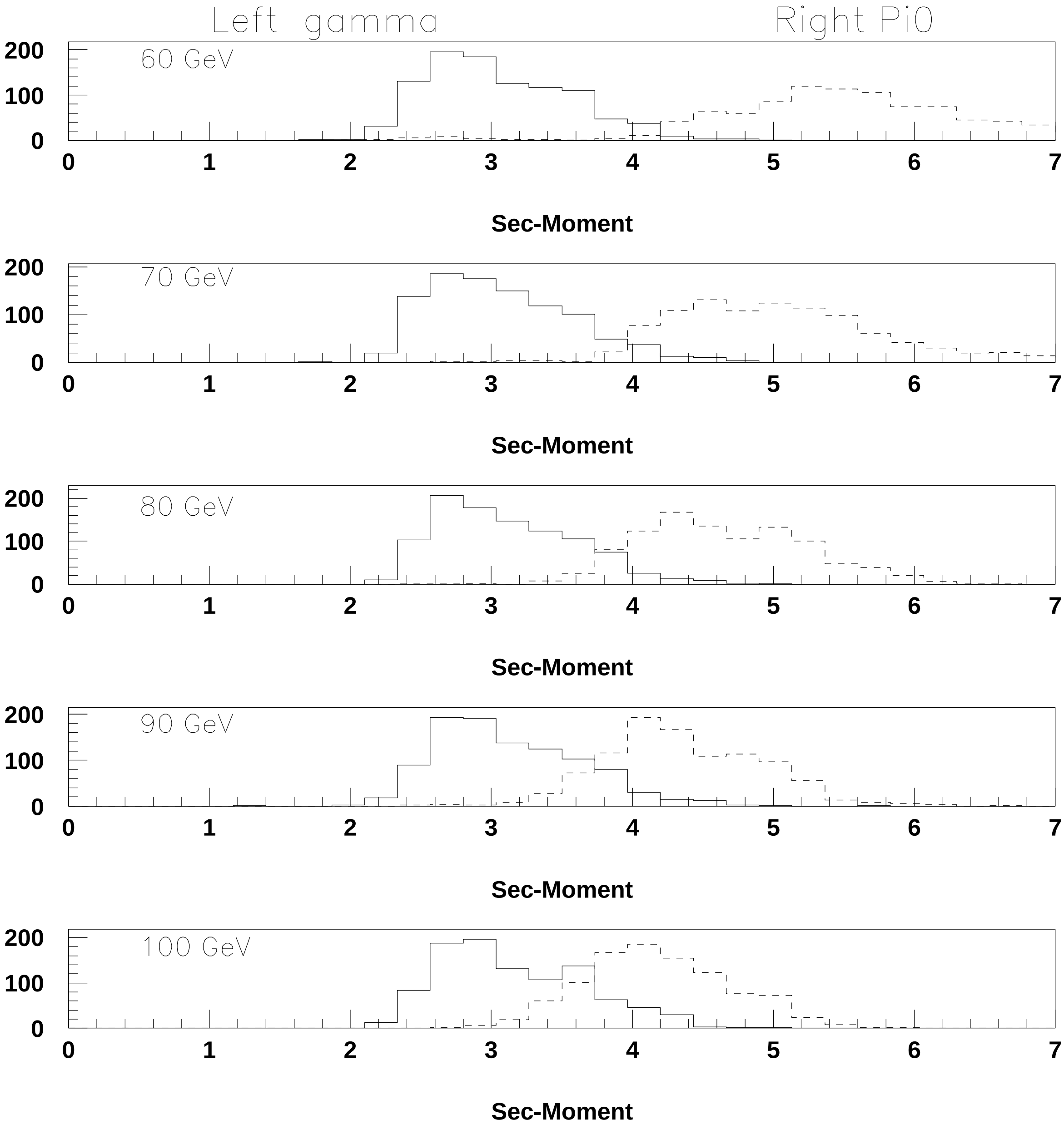

Figure 1: Second-moment energy distribution, S_2, for γ's and π^o's, as derived using GEANT and 4 photoelectrons/MeV.

was done for the other transverse dimension (call it y). The rms position resolution as a function of energy, shown in Figure 2, is described well by $\sigma_x = 3526\mu\text{m}/\sqrt{E} \oplus 217\mu\text{m}$. This is considerably better resolution than was used in the study discussed in the next section where it was assumed the position resolution was just the crystal transverse dimension divided by $\sqrt{12}$, i.e., $\sigma_x \equiv \sigma_y = (24.7\ \text{mm})/\sqrt{12} = 7100\ \mu\text{m}$.

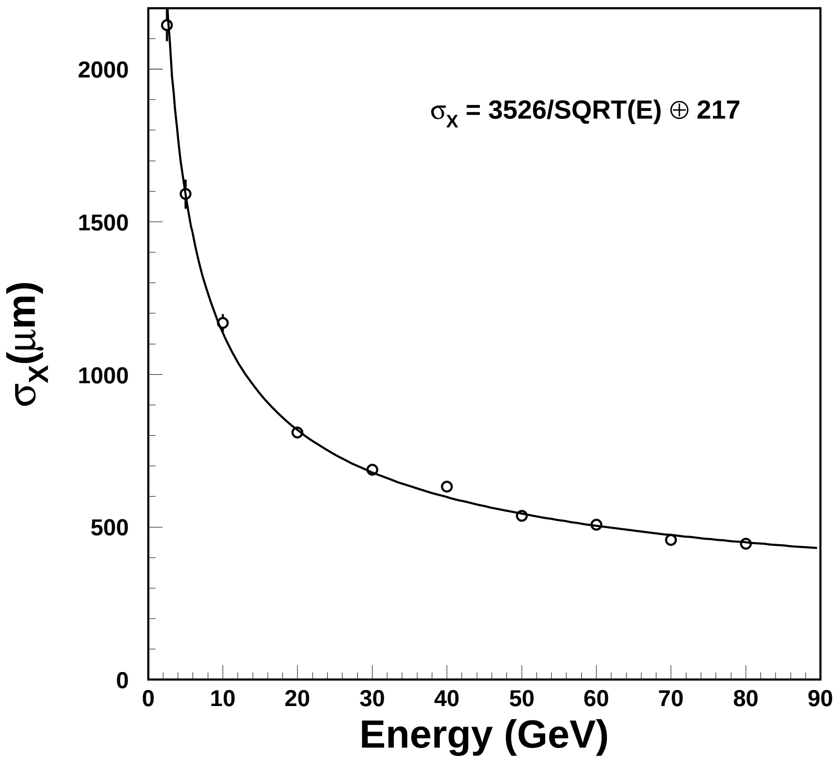

Figure 2: The expected r.m.s. position resolution for photons as a function of energy.

4 Preliminary Physics Study with the Baseline Calorimeter

As a first attempt to understand whether it is possible to extract signals at all with such a device several decay channels were analysed, with the most thoroughly examined being $B^0 \to K^{*0}\gamma$. The full detector was simulated using `MCFast v4_2`[9], a fast Monte Carlo package developed by the Fermilab Computing Division for detector design studies. The MCFast showering/calorimetry package[10] deposits energy in the detector elements based on parameterized shower shapes and not on individual particle tracking. The program executes much faster than a GEANT simulation but represents the energy deposition in detectors quite well and has been shown to be consistent with GEANT over the range of energies relevant to BTeV.

The $\mathcal{BR}(B^0 \to K^{*0}\gamma)$ was taken to be 4×10^{-5} while the background to the analysis was assumed to be $B \to K^* + X$ decays paired with random "real" photons. The charged track selection involved selecting a "good" vertex separated from the primary with a significance of greater than 3 standard deviations. There is not a shower reconstruction package as yet for BTeV so rudimentary shower reconstruction was performed. This involved utilizing the generated photon impact point at the calorimeter as the seed position for deciding on a set of blocks to use for calculating shower energy. No shower was used which had a charged track pointing to it.

Two selection criteria were crucial in greatly reducing the combinatorial background. Only showers having a transverse momentum relative to the beam axis greater than 1 GeV/c were selected. This kept 85% of the signal and eliminated 97% of the background. A very powerful cut involved balancing the momentum of the photon transverse to the to the B direction, determined as the line connecting the primary and $K\pi$ vertices, against the similarly defined transverse momentum of the K^{*0} candidate. Clearly, a real $K^{*0}\gamma$ combination has no net momentum transverse to the B^0 direction. This cut is more generally useful than for just this analysis while it is only in "two-body" electromagnetic B decays, like $B^0 \to K^{*0}\gamma$ that the cut on photon p_T relative to the beam axis is efficient.

The total efficiency of all analysis cuts was found to be 1.3% which, with the assumed branching fraction, translates into about 24,000 reconstructed events per year. The signal to background is estimated to be around 1:1.

The resulting signal is shown in Figure 3. The B mass resolution, using a single Gaussian, was found to be 49 MeV/c^2. One background which was studied in somewhat more detail is that due to $B \to K^{*0}\pi^0$ decays where one of the photons from the π^0 is not reconstructed. The result of running events containing a $B \to K^{*0}\pi^0$ decay through the $B^0 \to K^{*0}\gamma$ analysis is also shown in Figure 3. This background is not negligible but is not so large as to threaten our ability to see the signal. Since no attempt was made to suppress this particular background (e.g., no effort was made to explicitly identify and eliminate photons deemed to have come from a π^0) and since the relative normalization is based on the PDG branching fraction for $K^*\gamma$ and the PDG upper limit for $K^{*0}\pi^0$, the number of events in Figure 3 from $B \to K^{*0}\pi^0$ decays is probably much larger than will finally be the case.

Results from an analysis of $B^0 \to \rho\pi$ decays using the baseline detector are encouraging but still too preliminary to say just how feasible this will be in BTeV.

5 Conclusions

To completely and exhaustively probe the CKM picture of $\mathcal{CP}$ Violation requires a high rate experiment with the capability of reconstructing final states including single photons and π^0's. Examples of such decays are $B^0 \to \rho\pi$ and $B_s \to J/\psi\eta'$.

BTeV has a prototype Electromagnetic Calorimeter design which incorporates $PbWO_4$ crystals with phototube readout. We have benefited from R&D done by CMS who showed that $PbWO_4$ is a viable calorimeter technology. BTeV has an advantage over CMS in that the Calorimeter is not in a strong magnetic field. Hence the signals can be read out using phototubes leading to larger photoelectron yields and better resolution. The radiation dose is also less than that sustained by the CMS calorimeter. Detailed simulations indicate that it is possible to reconstruct final states including neutrals, like $B^0 \to K^{*0}\gamma$, with good efficiency and signal to background. The simulations used quite conservative estimates for the energy and spatial resolution of the calorimeter. There are still a number of R&D issues to address with regard to the phototubes and the readout chip itself. There are no outstanding technology questions, however, and we have moved more into the stage of setting milestones and working out the details of implementation.

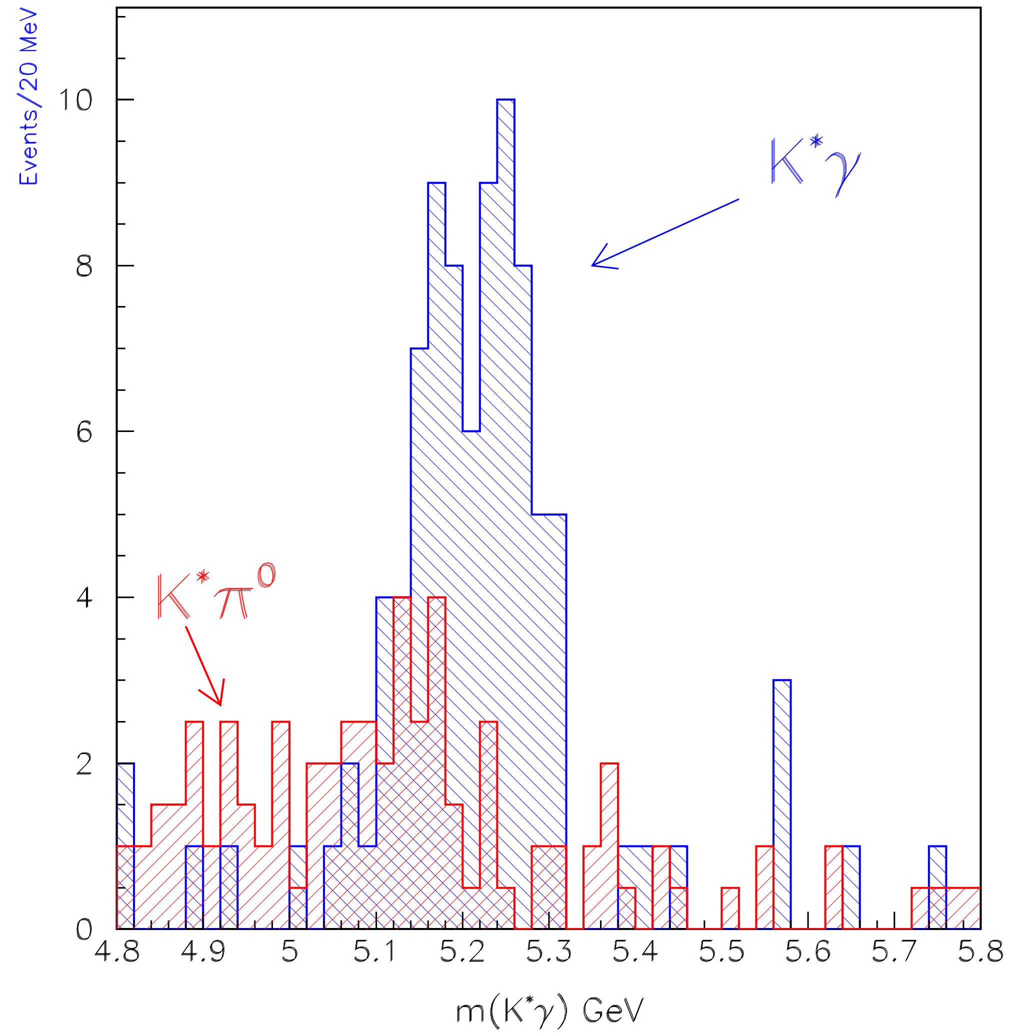

Figure 3: The $K^+\pi^-\gamma$ invariant mass spectrum for $B^0 \to K^{*0}\gamma$ and $B^0 \to K^{*0}\pi^0$ events. The relative normalization of the two samples is explained in the text.

A high quality Electromagnetic Calorimeter adds enormously to the ability of BTeV to do what we really want – discover where the new physics beyond the CKM picture of $\mathcal{CP}$ Violation is lurking!

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