Workshop on the CKM Unitarity Triangle, IPPP Durham, April 2003

CKM Reach at Hadronic Colliders

U Egede*

Imperial College London, London SW7 2AZ, United Kingdom.

The analysis of the CKM parameters will take a leap forward when the hadronic B factories receive their first data. I describe the challenges faced by B-physics at hadronic colliders and the expected reach in specific channels for the LHCb, BTeV, ATLAS and CMS experiments.

1 Introduction

With the hadronic B factories currently under construction or in the design phase B physics will enter a new era. The LHCb, BTeV, ATLAS and CMS experiments all have a time scale for B physics from 2007 onwards. The aim of the experiments is to gain a comprehensive understanding of the CKM matrix for discovering physics beyond the Standard Model. The much larger statistics and the access to B_s decays will allow to many cross checks of CP violation that are not possible at the current B factories.

By 2007 the current e^+e^- B factories will have collected samples of the order of 10^9 B-meson decays. This, combined with the data from the Tevatron will give a precision on the value of the CKM angle β of $\sigma(\sin 2\beta) = O(10^{-2})$ which is close to the systematic uncertainty from penguin pollution in the channel $B \to J/\psi K^0_s$. At the same time the anticipated measurement of B_s mixing will improve the value of $|V_{td}|/|V_{ts}|$ from the partial cancellation of the B_d and B_s form factors. The anticipated improvement in the measurement of the apex of the unitarity triangle between today [1] and 2007 is shown in figure 1.

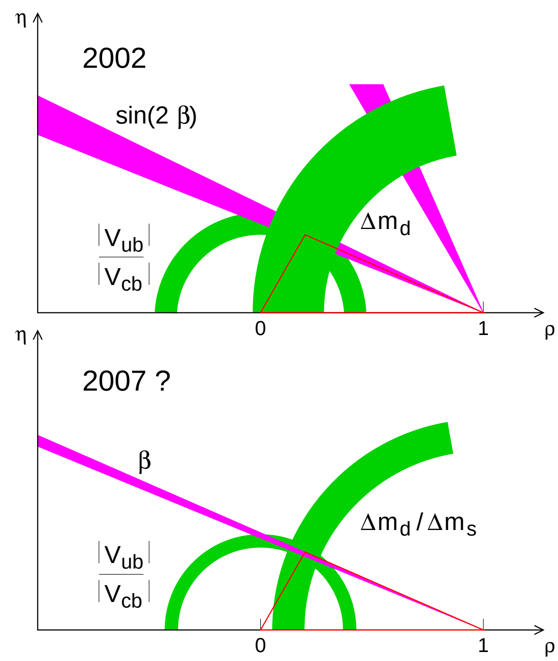

Figure 1. The anticipated improvement in three key measurements of the unitarity triangle between 2002 and 2007.

In table 1 the experimental conditions for the different experiments are summarised and compared to a conceptual design for a future e^+e^- B factory. Several points are worth further comments:

- At a hadron collider the ratio between the $b\overline{b}$ cross section and the total inelastic cross section is very small. The ratio improves as the centre of mass energy increases thus giving the LHC experiments an initial advantage compared to BTeV running at a lower CM energy. It should also be noted that there are significant uncertainties in the $b\overline{b}$ cross section at the LHC energy.

- The large production of B_s, Λ_b and B_c will open up entirely new areas of B physics where the present data samples are very limited.

- LHCb will tune its luminosity to a level where most recorded events will have a single interaction. BTeV's strategy is instead to cope with multiple events in a single bunch crossing by spreading them out across a larger vertex region where the individual primary vertices can be clearly identified.

- The ATLAS and CMS experiments do not have B physics as their primary goal and will as such have a much lower trigger bandwidth dedicated to B physics.

2 Detector layout

For most studies of CP violation in B-meson decays we need to identify the flavour of the B-meson at production time. The dominant contribution to this flavour tagging

*On behalf of the LHCb collaboration.

	LHC	BTeV	Super *BABAR*
Beam type	p-p	p-$\overline{p}$	e^+e^-
Status	Construction	Pending finance	Concept
$\sqrt{s}$	14 TeV	2 TeV	10.58 GeV
$\sigma_{b\overline{b}}$	500 μb	100 μb	1.1 nb
$\sigma_{c\overline{c}}$	3.5 mb	1 mb	1.3 nb
$\sigma_{\text{inclusive}}$	80 mb	60 mb	
$B^+/B_d/B_s/\Lambda_b$ mixture	40/40/12/8	40/40/12/8	50/50/0/0
Bunch separation	25 ns	132/396 ns	
Size of collision region	5.3 cm	30 cm	

	LHCb	ATLAS/CMS	BTeV	Super *BABAR*
Pseudorapidity coverage	2.1–5.3	-2.5–2.5	2.1–5.3	
$\mathcal{L}$ [cm^{-2}s^{-1}]	2×10^{32}	$10^{33}(10^{34})$	2×10^{32}	10^{36}
$< n >$ per bunch crossing	0.5	2 (20)	1.6/4.8	
$n_{b\overline{b}}$ per 10^7 s	10^{12}	$5 \times 10^{12(13)}$	2×10^{11}	10^{10}

Table 1. A comparison of the beam parameters and detector coverage for the hadronic B factories and a comparison with a conceptual future e^+e^- collider.

is through identification of particles from the decay of the other B-hadron created in the event. Hence the detector needs to be designed such that a significant part of the produced pairs of B-hadrons both end up within the detector acceptance. The most cost effective solution to this is to make a detector that sits as much in the forward region as technology allows. As both B-hadrons tend to be boosted in the same direction there is no synergetic effect from covering both forward regions. This leads to the design of the LHCb and BTeV detectors as single-armed forward spectrometers.

The overall design of the LHCb detector is shown in figure 2. The most essential parts of the detector are: the trigger system which reduces the rate of events going to mass storage to an acceptable level; the vertex detector which provides the trigger with secondary vertex identification and the physics with the ability to resolve B_s oscillations; and the particle identification system which provides the essential pion-kaon separation required for *CP* violation studies.

2.1 Trigger

The single most demanding task for the hadronic B physics experiments will be the trigger. The combination of a cross section minimum bias which is orders of magnitude larger than the b cross section, with the rare B decays which are of interest requires a sophisticated trigger that can suppress rates by many orders of magnitude. With a rate of around 10^{12} B-hadrons produced in a year the trigger also have to be selective. This is a completely different situation to current e^+e^- colliders where all B decays are recorded.

There are three main elements that allow identification of events with a B-hadron:

- Large transverse energy or momenta with respect to the beam axis. This is simply an indicator of a high mass particle decaying.
- Vertices which are displaced from the primary vertex. This takes advantage of the long lifetime of B-hadrons compared to other hadrons produced (K_s^0 and Λ live for much longer and do not interfere with the trigger).
- High energy leptons either from semi-leptonic B-decays or in pairs from B-hadrons with a J/ψ in the decay chain. This will also be the trigger for rare $B \to mupm$ decays.

The trigger strategy for LHCb and BTeV are in many ways quite different.

In LHCb the aim of the first trigger level is to identify events with particles of high transverse energy or momentum with respect to the beam axis. The high p_T and E_T arises from the decay of high mass objects and thus favours B-hadrons to the background events with lower mass hadrons. In addition these are the type of B mesons events that the final selection of events for physics analysis favour. At the next trigger level secondary vertices are identified by placing cuts on the significance of the impact parameter for tracks with respect to the identified primary vertex. The last trigger identify more specific classes of B-decays using the results of the online reconstruction.

On the other hand the aim of the BTeV trigger is to identify all B-hadron events and write them to tape. This is done by identifying secondary vertices by placing cuts on the significance of the impact parameter for tracks with respect to the identified primary vertex at the full 7.6 MHz rate of the beam crossings and then at the next trigger level perform full secondary vertex reconstruction. The procedure will intentionally also identify many charm events which

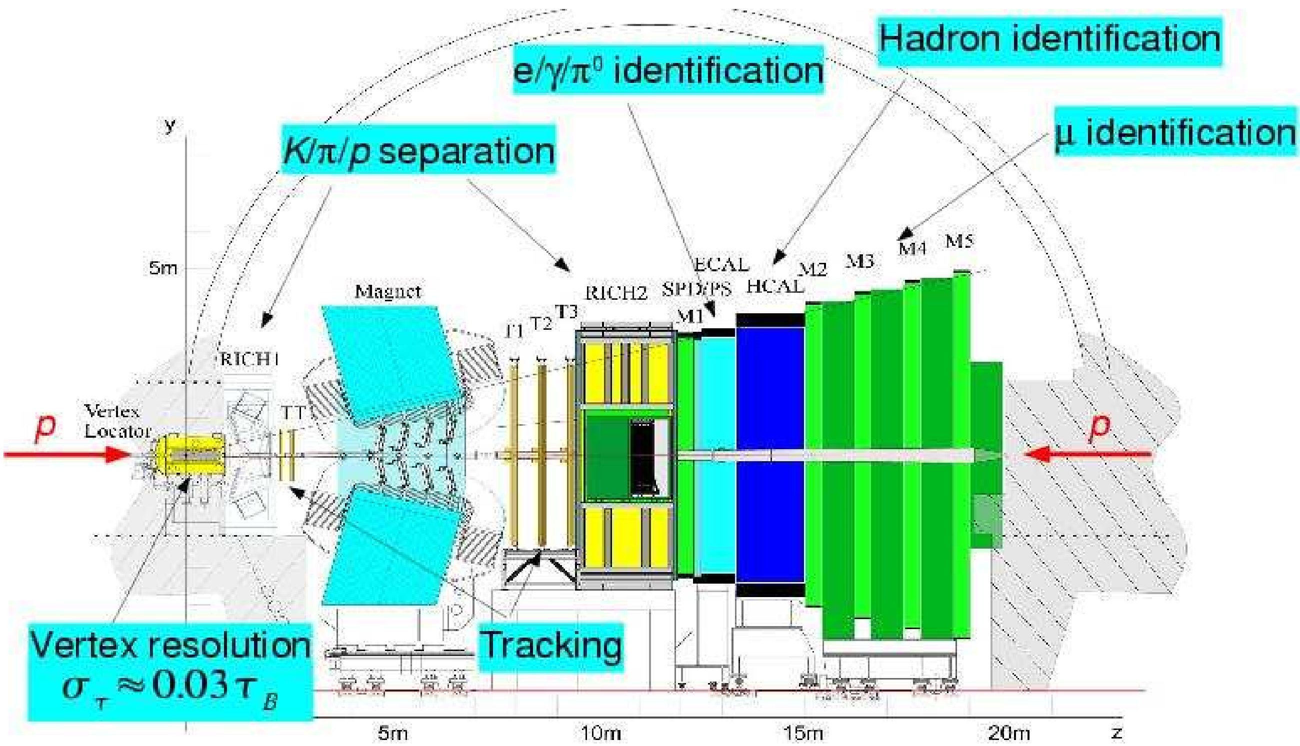

Figure 2. The design of the LHCb detector. The collision point for the protons is within the vertex detector to the left in this drawing.

are predicted to take up 50% of the rate of events going to tape. We show a summary and comparison of the LHCb and BTeV triggers in table 2.

The trigger for ATLAS and CMS is much tighter as only a 10 Hz output rate is allocated for B physics in the first three years of low-luminosity running for the two experiments. Both experiments rely on a single muon of high p_T to trigger at the first level. The identification of muon pairs from either $B \to J/\psi X$ decays or rare two-body decays to a pair of muons form the majority of the trigger. A summary of the trigger is given in table 3.

More details can be found in the talks of M. Ferro-Luzzi [2], L. Moroni [3] and A. Starodumov [4] at this workshop.

trigger type	LHCb	BTeV
High p_T, high E_T	10 MHz	
Impact parameter	1 MHz	7.6 MHz
Decay topology		80 kHz
Physics algorithms	40 kHz	
To mass storage	200 Hz	4 kHz

Table 2. A simplified comparison of the trigger levels at LHCb and BTeV. The 10 MHz ingoing rate for LHCb corresponds to the rate of bunch crossings with a visible interaction. In addition to what is given above both experiments have a dedicated first level trigger for events with one or two high p_T muons.

Trigger type	ATLAS	CMS
Muon trigger	40 MHz	40 MHz
$J/\psi \to \ell^+\ell^-$, $D_s^+ \to \phi\pi^+$	20 kHz	
Physics algorithms	1 kHz	4 kHz
To mass storage	10 Hz	10 Hz

Table 3. A simplified comparison of the B physics trigger levels at ATLAS and CMS.

2.2 Particle identification

To make hadronic final states useful for *CP* violation studies it is required that we can distinguish pions and kaons very well. A good example is for the $B_s \to D_s^{\mp}K^{\pm}$ decay to be used for the extraction of the angle γ. The decay $B_s \to D_s^- \pi^+$ is expected to have a branching fraction 15 times larger than the kaon decay thus drowning the $B_s \to D_s^{\mp}K^{\pm}$ signal without any particle identification. In figure 3 we illustrate the particle identification capability of LHCb to isolate the $B_s \to D_s^{\mp}K^{\pm}$ signal. For the two-body B meson decays the kaon-pion separation is also essential for the extraction of the angle γ from the individual measurements of $B_d \to \pi^+\pi^-$ and $B_s \to K^+K^-$ decays.

Both LHCb and BTeV use Ring Imaging Cherenkov (RICH) detectors for pion and kaon identification. For a given radiator the effective momentum range is limited from below by the onset of Cherenkov radiation for the pions and from above when the kaon Cherenkov angle saturates causing the rings created by kaons and pions to have the same radius. This means that

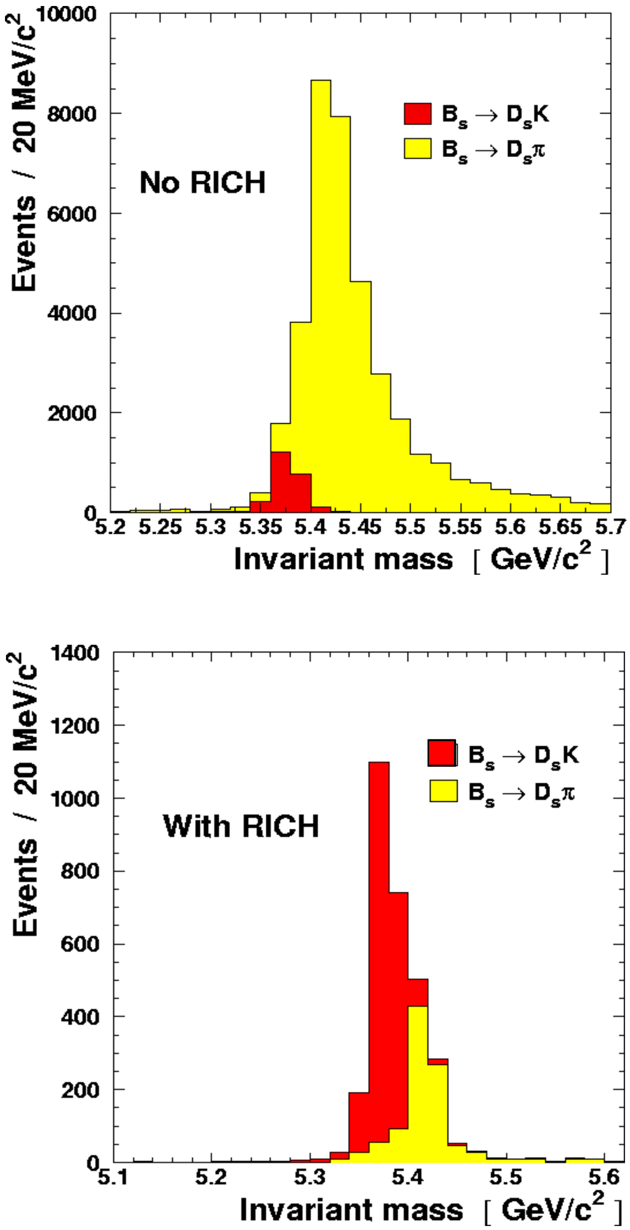

Figure 3. Without particle identification from the Cherenkov detectors in a simulation from LHCb (top) the $B_s \to D_s^{\mp} K^{\pm}$ signal is drowned by the $B_s \to D_s^{-} \pi^{+}$ decay. With particle identification (bottom), the signal is dominant compared to the background.

more than one radiator is required. ATLAS and CMS have a very limited ability for kaon-pion separation.

Kaon identification is one of the dominant sources for flavour tagging. This can either be through identifying the charge of a kaon from the decay of the other B created in the event or for the tagging of B_s decays from the decay $B_s^{**} \to B_s K^+$. In addition to kaon-pion separation it is important to reduce the contamination of the kaon tagging sample with protons. The LHCb experiment use an aerogel radiator with refractive index of 1.03 in addition to the two gas radiators to provide kaon and proton separation down to around 2 GeV/c.

3 Physics reach

The aim of giving numbers for the physics reach before the start-up of experiments is to assure that the detector design is able to give the promised results in a selection of channels that are thought to be representative of the physics that will be of interest in 2007 and beyond. In the same spirit we will here only give a few examples of the physics that can be addressed at the future B factories. No attempt has been made to be comprehensive. The numbers in this section are from [5–8] and later conference updates.

In general the strategy for the experiments will be to make several measurements that in independent ways test the Standard Model.

As an example the β measurement from $B_d \to J/\psi K_S^0$ and the measurement of $|V_{td}|/|V_{cb}|$ through B_d mixing are both sensitive to new physics contributions in the B_d loop diagram. On the other hand a measurement of γ from the $B_s \to D_s^{\mp} K^{\pm}$ decays and of $|V_{ub}|/|V_{cb}|$ from the branching fractions of $B_d \to h_u \ell \nu$ and $B_d \to h_c X$ decays only probes processes at the tree level and are as such not expected to be sensitive to new physics.

This means we can form a *standard triangle* from the angle γ and $|V_{ub}|/|V_{cb}|$ measurements and a *new physics triangle* from β and $|V_{td}|/|V_{cb}|$. If these two triangles do not share the same apex we have a sign of new physics. The principle is illustrated in figure 4.

3.1 B_s mixing and the *CP* angle $\delta\gamma$

Within the Standard Model the weak phase ϕ_s in B_s mixing is given by the small value $-2\delta\gamma \equiv -2\lambda^2\eta$. This means that new physics could easily show up as a larger value of *CP* violation in a decay like $B_s \to J/\psi\,\phi$ which is equivalent to the $B_d \to J/\psi K_S^0$ decay for the measurement of the phase 2β in B_d mixing. The good calorimetry of BTeVwill also allow a measurement of ϕ_s in the decay $B_s \to J/\psi\,\eta^{(\prime)}$. The precision in the angle ϕ_s will depend on how fast the oscillation frequency is for B_s mixing but will in general be around 0.02.

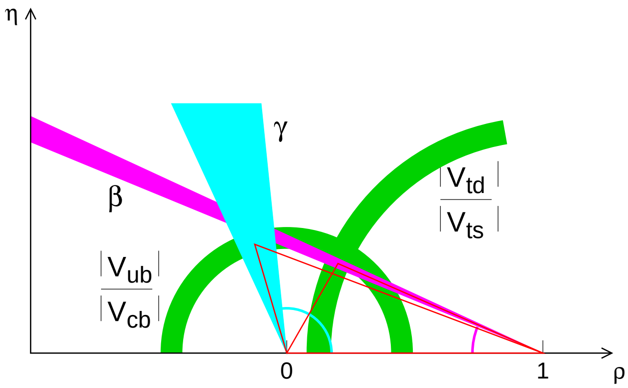

Figure 4. An illustration of how a mismatch is possible between measurements of the unitarity triangle which are sensitive to new physics and measurements which are not.

3.2 Extraction of the angle γ

The extraction of the *CP* angle γ is one of the main purposes for the hadronic B factories. The decay $B_s \to D_s^{\mp} K^{\pm}$ is sensitive to the angle $\phi_s + \gamma$, where the ϕ_s part comes from B_s mixing and the γ part from the phase of V_{ub} in the tree level decay. If new physics contributes to ϕ_s it will be the same contribution as for the direct measurement of ϕ_s and as such will not interfere with a clean measurement of γ from the tree level decay. The decay $B_d \to D^{*\pm}\pi^{\mp}$ is the equivalent decay for B_d but suffers from the problem that one of the interfering decays is doubly-Cabibbo-suppressed with respect to the other; the increased statistics in this channel due to the large branching fraction will more or less cancel the deterioration in sensitivity from the doubly-Cabibbo-suppressed amplitude leading to a similar overall sensitivity to γ.

The angle γ can also be extracted with high precision from a comparison of $B_d \to \pi^+ pim$ and $B_s \to K^+K^-$ [9]. This method is sensitive to new phases introduced in the penguin decays and as such might not measure the Standard Model value of γ. In table 4 we summarise the statistical samples available with one year of data for a γ measurement.

Decay channel	LHCb	BTeV	Possible new phases?
$B_s \to D_s^{\mp} K^{\pm}$	8 k	7.5 k	No
$B_d \to D^{*\pm}\pi^{\mp}$	650 k		No
$B_d \to \pi^+\pi^-$	27 k	15 k	Yes
$B_s \to K^+K^-$	38 k	19 k	

Table 4. The expected statistics in one year at design luiminosity for different channels for the extraction of the angle γ. All have the potential for an accuracy of 10° or better in γ.

3.3 Rare decays

The predicted branching fraction from the Standard Model for the $B_d \to \mu^+\mu^-$ decay is around 10^{-10} and for the $B_s \to \mu^+\mu^-$ decay around 4×10^{-9}. As the decays have to be mediated through a loop there is the possibility that particles from new physics will participate and dramatically increase the decay rate. Table 5 summarises the expected number of reconstructed events given the Standard Model decay rate. As it can be seen a measurement of the $B_d \to \mu^+\mu^-$ decay will be marginal even at high luminosity for CMS and ATLAS as there may well be significant background. The background levels are almost impossible to evaluate from simulations due to the very large rejection factors required.

Decay channel	ATLAS	CMS	BTeV	LHCb
$B_d \to \mu^+\mu^-$	14	4.1	3	
$B_s \to \mu^+\mu^-$	27	21	18	30
$B \to K^{*0}\mu^+\mu^-$	2 k	12 k	8 k	13 k

Table 5. The expected reconstructed rate for Standard Model production of rare decays. Statistics are after 3 years at the nominal luminosity for LHCb and BTeV, and 3 years of low luminosity ($\mathcal{L} = 10^{33}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$) for ATLAS and CMS (except $B_d \to \mu^+\mu^-$ which is one year at high luminosity ($\mathcal{L} = 10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$) for ATLAS and CMS).

4 Systematics

In the experiments we need to control everything that can give a flavour asymmetry and fake *CP* violation. There are several penitential sources for a flavour asymmetry:

- Since LHC is a proton-proton machine the angular distributions and relative ratios of the different types of B and $\bar{B}$ hadrons will be different at the percent level which is larger than some of the effects we want to measure.
- The tracking efficiency for positive and negative particles will be different due to the magnetic dipole field (positive and negative particles go through different parts of the detector).
- Particle identification will be different for K^+ and K^- due the the difference in nuclear interaction length.
- The flavour tagging will be different due to asymmetries in both the efficiency and mistag rates.

All these effects should be measured and corrected from analysing the data. Separate control channels should be found for each of the different types of hadrons and care should be taken that there is no expected direct *CP* violation in the control channels.

5 Conclusions

The *B* factories at hadronic colliders will in the future provide statistics of the order of 10^{12} $b\overline{b}$ pairs per year. A sophisticated trigger is required to reduce the background from the much larger production of minimum bias events and to select the specific *B* decays of interest.

The LHCb and BTeV detectors are optimised to cover a wide range of (semi)-leptonic and hadronic decays with high efficiency. The ATLAS and CMS experiments will be competitive in channels with a muon pair in the final state which could be of great interest in the detection of rare *B* decays.

The experiments should together be able to make comprehensive measurements of the *CP* violating effects in the quark sector. Hopefully we will from this see that the single *CP* violating phase of the Standard Model is no longer sufficient to explain all the data and that new phases from New Physics are required.

6 Acknowledgements

I would like to thank the organisers of the workshop for providing a good atmosphere for discussions. Also I would like to thank P. Eerola (ATLAS), F. Palla, A. Starodumov (CMS) and L. Moroni (BTeV) for providing me with information and corrections on the other experiments. Naturally any remaining errors are my responsibility.

References

1. V. Lubicz, Unitarity Triangle Fits in the Standard Model and Sensitivity to New Physics, in *Workshop on the CKM Unitarity Triangle*, IPPP Durham, 2003.
2. M. Ferro-Luzzi, The LHCb trigger strategy and performance, in *Workshop on the CKM Unitarity Triangle*, IPPP Durham, 2003.
3. L. Moroni, BTeV: Strategies and sensitivities, in *Workshop on the CKM Unitarity Triangle*, IPPP Durham, 2003.
4. A. Starodumov, *B* Physics triggers at CMS, in *Workshop on the CKM Unitarity Triangle*, IPPP Durham, 2003.
5. P. Ball *et al.*, (2000), hep-ph/0003238.
6. S. Amato *et al.*, CERN-LHCC **98-004** (1998), LHCb collaboration.
7. G. Y. Drobychev *et al.*, BTeV-doc **316-v3** (2002), BTeV collaboration.
8. G. L. Bayatian *et al.*, CERN-LHCC **2002-028** (2002), CMS collaboration.
9. R. Fleischer, Phys. Lett. **B459**, 306 (1999), hep-ph/9903456.