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b Quark Physics with 2×10^9 Z Bosons

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Abstract

It has been suggested to realize a factory for 10^9 Z^0 through a linear e^+e^- collider with polarized beams. Very likely the relevant CP studies for B mesons will already have been performed at the B factories by that time, hence GIGA-Z will be a third generation b physics experiment. Yet such a facility would provide us with unique opportunities in the domain of beauty physics that would be of essential significance even in 2010: (1) Production and decay of polarized beauty baryons; (2) searching for and probing transitions driven by $b \to q\nu\bar{\nu}$; (3) detailed and comprehensive studies of inclusive semileptonic B_s decays.

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1 GIGA-Z vs. its competition: LHC-b/BTeV and BELLE/BaBar

A high-luminosity linear collider running on the Z^0 resonance offers intriguing and even unique possibilities for b quark physics. Assuming a sample of 2×10^9 Z^0 bosons produced per year at such a facility, one would end up with about 6×10^8 b or $\bar{b}$ quarks produced in a relatively clean environment. Furthermore, the option of polarized beams would create exciting capabilities for polarization studies and greatly improved b-flavour tagging.

Given the time scales of the linear collider projects b physics studies at GIGA-Z would be a third generation experiment. Thus in evaluating the b-physics potential of this possibility one has to compare it to the capabilities of dedicated second generation b physics experiments LHC-b and BTeV at hadronic colliders and the extension of the first generation experiments BELLE and BaBar running with significantly increased luminosities of possibly $10^{35} s^{-1} cm^{-2}$. We refer to the latter as BELLEII/BaBarII; if it is realized, GIGA-Z would not add anything new to most measurements of B_d and B_u decays (some possible exceptions are stated below). On the other hand we consider it very unlikely that BELLEII/BaBarII would ever spend quality time above the $\Upsilon(4S)$ to study B_s, let alone Λ_b decays.

The comparison with the potential of LHC-b and BTeV is less straightforward. The number of b quarks produced at GIGA-Z has to be compared with 10^{12} to 10^{13} b quarks produced at hadronic collider experiments [1]. However this large number is contained in a enormous background, the signal-to-noise being typically $S/N \approx 5 \times 10^{-3}$ which has to be compared to $S/N \approx 0.21$ at GIGA-Z. Another advantage of GIGA-Z over LHC-b / BTeV is the efficiency of the flavour tag, i.e. of discriminating between b and $\bar{b}$. Using polarized beams at GIGA-Z will result in substantial forward-backward asymmetry for the b quarks which will make flavour tagging relatively easy. Typically one can expect an efficiency $\times$ purity of about 60% at GIGA-Z due to the forward backward asymmetry and the cleaner environment, while the corresponding number at the hadronic fixed target experiments is typically a factor of ten lower, i.e. about 6%. A more detailed discussion can be found in [2].

In both GIGA-Z as well as at LHC-b / BTeV all beauty hadrons are accessible. In order to estimate the production rate for each species one may use the numbers obtained at LEP or theoretical estimates. The relevant numbers are listed in table 1.

mode	b branching ratio	mode	b branching ratio
$b \to B_u$	40%	$b \to B_d$	40%
$b \to B_s$	10%	$b \to \Lambda_b$	10%
$b \to B^{**}$	$\approx 25\%$	$b \to B_c$	$\approx 10^{-3} - 10^{-4}$
$b \to (bcq)$	$\sim 10^{-5}$		

Table 1: b quark branching fractions, taken from [3], except the ones for B_c and (bcq) which are from [4].

Precise data on CP violation are one of the major goals at the presently running B factories and of next generation b physics experiments at hadron machines. Some of these experiments are designed to provide a good measurement of CP asymmetries in B decays and thus it is very likely that at the time of GIGA-Z CP violation will be well studied. Even with the advantage in tagging efficiency and signal-to-noise ratio at GIGA-Z the huge statistics at the hadronic collider experiments will win, at least in the standard modes used for the CP violation analyses. We shall give a summary of the relevant numbers in the next subsection.

Yet we want to point out that the GIGA-Z option would provide a truly complementary program by addressing three topics within b physics that are of fundamental importance for the comprehensive b physics program that is being undertaken worldwide, yet cannot be addressed adequately at other existing or planned facilities and therefore will be highly topical even in 2010.

Those topics are:

1. Polarized beams will produce a huge sample of highly polarized beauty baryons whose weak decays can be analyzed. In this way a determination of the handedness of a quark transition becomes feasible.

2. The quark level transition

$$b \to q + \nu\bar{\nu} \tag{1}$$

could well be affected significantly by New Physics in ways quite different from $b \to q + l^+l^-$ [7]. Searching for $b \to q\nu\bar{\nu}$ in hadronic colliders appears a hopeless enterprise, and even for a $\Upsilon(4S)$ experiment it poses quite a challenge.

3. With the CP asymmetries being functions of the moduli of the CKM parameters one attempts to extract the latter from CP insensitive rates as precisely as possible to infer the size of the former. $|V(cb)|$ and $|V(ub)|$ are determined in semileptonic B decays. Yet there is one source of potentially considerable uncertainties in the values thus obtained, namely limitations to the validity of quark-hadron duality, of which at present little is known for certain. Detailed comparisons of semileptonic B_s and $B_{u,d}$ decays would be of invaluable help in this respect.

In the following subsections we shall elaborate on the points raised above.

2 Standard Model CP Violation

The first task is to measure the three angles that are usually referred to as $\phi_1 = \beta$, $\phi_2 = \alpha$ and $\phi_3 = \gamma$ [3].

BELLE and BaBar expect to measure $\sin(2\beta)$ from the CP asymmetry in the 'golden' mode $B_d \to \psi K_S$ (and related ones) with an uncertainty of about 8%; it should be reduced significantly by BELLEII/BaBarII. Since this mode is relatively easy to detect even with large backgrounds, the high statistics at LHC-b and BTeV are very likely to win over GIGA-Z. Indeed, the precision achieved at LHC-b is expected to be $\sigma(\sin 2\beta) \approx 1.5\%$, and similar for BTeV.

The angle α can be determined from CP asymmetries in $B \to \pi's$. However the observable asymmetries are significantly or even severely affected by hadronic uncertainties. One way which has been studied in some detail is to measure the branching ratio for all $B \to \pi\pi$ modes together with the asymmetry in $B_d \to \pi^+\pi^-$: α can then be obtained through an isospin analyis of the two pion final state [5]. Yet the channel $B_d \to \pi^0\pi^0$ is estimated to have a tiny branching ratio; furthermore, it is very hard to identify at LHC-b / BTeV. In [1] the prospects of extracting α at LHC-b have been considered on the basis of $B \to \pi^+\pi^-$ only, assuming that the penguin contribution to these decays are known; based on this an uncertainty $\sigma(\alpha) \sim 3° - 10°$, (depending on the value of α) could be achieved. BTeV on the other hand will rely on a

Mode	branching ratio	number of events
$\Lambda_b \to \Lambda_c \ell \bar{\nu}_\ell$	8×10^{-2}	4.7×10^6
$\Lambda_b \to p \ell \bar{\nu}_\ell$	8×10^{-4}	4.7×10^4
$\Lambda_b \to X_s \gamma$	2.7×10^{-4}	11000
$\Lambda_b \to \Lambda \gamma$	3.7×10^{-5}	1400
$\Lambda_b \to \Lambda \ell \ell$	1.2×10^{-6}	50

Table 2: Expected numbers of events for Λ_b decays, based on the standard model estimates

detailed analysis of the Dalitz plot for $B \to 3\pi$. The cleaner environment for both BELLEII/BaBarII as well as GIGA-Z should make the measurement of $B_d \to \pi^0\pi^0$ easier. For the case of GIGA-Z a first discussion on this can be found in [2]; however, a detailed study of $B_d \to \pi^0\pi^0$ at GIGA-Z has not yet been performd.

Determining γ at the first generation experiments will be extremely difficult, since the B_s states are not accessible. It is expected that at LHC-b/BTeV one can determine γ through a combination of methods with an uncertainty of $\sigma(\gamma) \sim 6° - 14°$ depending on the B_s mixing parameter and strong phases. Furthermore the Cabibbo suppressed angle often referred to as χ can be measured through the CP asymmetry in $B_s \to \psi\eta, \psi\phi$. A signal beyond the expected value for the asymmetry of about 2% would reveal the presence of New Physics. The sensitivity of LHC-b/BTeV should reach the CKM level. With most of the relevant modes suffering from small branching ratios, yet possessing clear signatures, we do not see how GIGA-Z could be competitive with LHC-b/BTeV.

There are actually six KM unitarity triangles rather than one with angles of order unity, λ^2 and λ^4. Ultimately one wants to measure as many of them as possible; yet again no case can be made that GIGA-Z could in general overcome its intrinsic disadvantage in statistics relative to LHC-b/BTeV.

3 Weak Decays of Polarized Beauty Baryons

A fundamentally unique feature of GIGA-Z would be the availability of polarized beams. They would yield polarized beauty quarks which in turn give rise to highly polarized beauty baryons through fragmentation in about 10% of the events which still represents a huge number. This opens up a whole new field of dynamical information one can deduce from their weak decays. The existence of initial state polarization in Λ_b decays allows to analyze the chirality of the quark coupling *directly*; it also leads to a whole new program of studying observables revealing direct CP violation.

In analysing $b \to s\gamma$ in a generic way one has to keep in mind that there are actually two transition operators, namely

$$b_R \to s_L\gamma \ , \ b_L \to s_R\gamma \ . \tag{2}$$

While the second one is highly suppressed in the SM (by $\mathcal{O}(m_s/m_b)$) they could be of comparable size in New Physics scenarios:

$$\text{Standard Model}: \quad b_R \to q_L \quad \gg \quad b_L \to q_R \tag{3}$$

$$\text{New Physics}: \quad b_R \to q_L \quad \sim \quad b_L \to q_R \tag{4}$$

While the decays of mesons realistically cannot distinguish between these two transitions, those of baryons can. An study of the Λ polarization in the decay $\Lambda_b \to \Lambda\gamma$ with polarized Λ_b would probe the SM prediction (3). Such a study should be quite feasible with the expected sample size, see Table (2). A significant non-vanishing contribution of $b_L \to s_R\gamma$ would signal the intervention of New Physics. One can actually undertake an *inclusive* polarization study of $\Lambda_b \to \Lambda\gamma + X$ with large statistics; the clean environment of GIGA-Z is of course crucial here. Corresponding studies can be performed with $\Lambda_b \to l^+l^-X$ with smaller statistics.

Semileptonic decays of polarized Λ_b allow to test the $V - A$ character of b quarks with unprecedented accuracy.

The next step is to search for CP asymmetries in the *spectra* of semileptonic decays. Since such asymmetries require the intervention of New Physics, one has a better chance in $b \to u$ than $b \to c$ transitions and in those that involve the suppressed chirality state; i.e., one would compare

$$\Lambda_b \to l^-(p+X)_{\text{no charm}} \quad vs. \quad \bar{\Lambda}_b \to l^+(\bar{p}+X)_{\text{no charm}} \tag{5}$$

for polarized Λ_b's.

In final states with at least three particles – $\Lambda_b \to ABC$ – one can also form T-odd correlations like

$$C_T \equiv \langle \vec{\sigma}_{\Lambda_b} \cdot (\vec{p}_A \times \vec{p}_B) \rangle \tag{6}$$

with $\vec{p}_{A[B]}$ denoting the momenta of A and B, respectively, and $\vec{\sigma}_{\Lambda_b}$ the Λ_b polarization. $C_T \neq 0$ can be due to T violation – or final state interactions. This ambiguity can be resolved by observing the CP conjugate process $\bar{\Lambda}_b \to \bar{A}\bar{B}\bar{C}$ and the analoguous observable $\bar{C}_T$: if one finds

$$C_T \neq \bar{C}_T \ , \tag{7}$$

then one has uncovered CP violation of the direct variety. Since these effects are typically quite suppressed in the Standard Model, such studies represent largely a search for New Physics. They can be performed in nonleptonic modes

$$\Lambda_b^0 \to \Lambda_c^+ \pi^- \pi^0, p\pi^-\pi^0, \Lambda K^+ \pi^- \tag{8}$$

as well as in semileptonic channels containing a τ lepton, since the effect is proportional to the lepton mass [6]:

$$\Lambda_b^0 \to \Lambda_c^+ \tau^- \nu, p\tau^- \nu \tag{9}$$

In passing we would like to note that analogous studies can be performed with polarized *charm* baryons.

4 $B \to X_q \nu\bar{\nu}$

A measurement of this mode is impossible at the hadronic machines due to large backgrounds. Aside from the cleaner environment, a Z^0 factory has one important intrinsic advantage here, namely that the b quarks are produced into different hemispheres. This hemispheric separation and the simplicity of the underlying event would provide powerful tools in searching and actually measuring such transitions. This is also illustrated by the fact that the present bound was deduced at LEPI:

$$\mathrm{BR}(B \to X_s \nu\bar{\nu}) \leq 7.7 \cdot 10^{-4} \quad \mathrm{ALEPH} \tag{10}$$

In table 3 we collect the standard model expectations [7, 10] for decays of the type $b \to s\nu\bar{\nu}$.

New Physics can affect $b \to q l^+ l^-$ and $b \to q\nu\bar{\nu}$ in quite different ways for various reasons [10]. Of course, $b \to q\nu\bar{\nu}$ provides hardly a spectacular signature. Therefore searching for such modes in the environment of a

Mode	branching ratio	number of events
$B \to X_s \nu \bar{\nu}$	4×10^{-5}	19000
$B \to K \nu \bar{\nu}$	2.4×10^{-6}	1150
$B \to K^* \nu \bar{\nu}$	5×10^{-6}	2400

Table 3: Expected numbers of events for $b \to s \nu \bar{\nu}$ decays, based on standard model estimates. A sum over the neutrino species is understood. The numbers are from [8] for the inclusive and from [9] for the exclusive decays.

hadronic collider appears quite hopeless. In an e^+e^- threshold machine such transitions could be found only at the cost of reconstructing one B more or less fully.

At GIGA-Z the statistics will be high enough to make such searches a meaningful enterprise. As can be seen from table 2 one can expect a few times 10^3 events in exclusive channels and about 10^4 inclusively, based on the standard model rates.

5 Semileptonic B_s Decays

One of the motivations for extracting reliable values for the CKM parameters $|V(cb)|$, $|V(ub)|$ etc. is to infer predictions for various CP asymmetries in B decays that are as precise as possible. $|V(cb)|$ and $|V(ub)|$ are determined in semileptonic B decays through observables in exclusive as well as inclusive modes.

The most reliable values for $|V(cb)|$ have been derived from the total semileptonic width of B mesons and from the rate of $B \to l\nu D^*$ at zero recoil, and the two values agree in a nontrivial fashion; the theoretical uncertainties are estimated to be around 5%. They might be reduced for $|V(cb)|$ from $\Gamma_{SL}(B)$ to about 2% with similar progress concerning $B \to l\nu D^*$ less likely.

The situation is much less satisfactory with respect to $|V(ub)|$: its determinations so far have a sizeable model dependence with little theoretical control. There is thus little guidance in the theoretical error estimate, but a realistic estimate assuming some theoretical progress is a theoretical uncertainty of about $(10 - 15)\%$.

Certainly after BELLEI/BaBarI – if not before – the theoretical treatment will become the limiting factor.

However on top of that there could conceivably be another significant source of a systematic uncertainty: quark-hadron duality or duality for short which underlies almost all applications of the $1/m_Q$ expansions cannot be an identity. There is a large body of folkloric or circumstantial evidence that duality is a useful and meaningful concept in particular for semileptonic transitions. Yet for a full evaluation of the comprehensive data on beauty physics as they will exist in 2010 it is essential to know with *tested* confidence whether limitations to duality in semileptonic transitions arise on the 10%, the 5% or the 1% level. It is quite unlikely that this question can be answered by theoretical means alone. A much more realistic way is to proceed like one does in dealing with experimental systematic uncertainties: undertake to extract the same quantity in systematically different way and compare the results.

More specifically one can perform an "independent" extraction of $|V_{cb}|$ in B_s decays. This could be done through measuring $\Gamma_{SL}(B_s)$. Secondly, one could determine the rate for $B_s \to l\nu D_s^*$, extrapolate to zero recoil and extract $|V(cb)F_{B_s \to D_s^*}(0)|$. Note that the Heavy Quark Expansion yields

$$|F_{B_s \to D_s^*}(0)| \simeq |F_{B \to D^*}(0)| \tag{11}$$

up to $SU(3)$ breaking corrections, which can be estimated.

Extracting $|V(cb)|$ separately from B_d and B_u decays is an important cross check on experimental systematic uncertainties, but in all likelihood it could *not* reveal duality violations. For the physical origin of those would be the 'accidental' presence of a nearby hadronic resonance with appropriate quantum numbers; up to small isopin breakings it would affect equally $B_d \to l\nu X_c$ and $B_u \to l\nu X_c$, but not $B_s \to l\nu X_c$; likewise a resonance affecting B_s transitions would have no impact on $B_{u,d}$ channels. If the same value emerged for $|V(cb)|$ in both cases, we would truly have established theoretical control in this case at least. If not, we would not know which of the values is the correct one, but we would be aware of a serious problem.

Duality violation could exhibit a different pattern in $B \to l\nu X_u$ channels. Here a detailed comparison of B_d and B_u modes is called for also theoretically: on one hand one expects a difference in the endpoint region of B_d and B_u semileptonic decays [11], and on the other hand hadronic resonances could affect $B_d \to l\nu X_u$ and $B_u \to l\nu X_u$ quite differently. Yet even so, $B_s \to l\nu X_u$, both inclusively and exclusively, would provide crucial cross checks.

6 Summary

A GIGA-Z facility could not be realized before 2010 at the earliest. We certainly hope and fully anticipate that the usually discussed CP studies in the beauty hadron sector will have been performed with considerable accuracy by that time or soon thereafter. Observing the same reactions in the GIGA-Z environment might turn out to serve some purpose still – but that is *not* the motivation we are suggesting in this note.

Our emphasis is on GIGA-Z providing us with novel and unique tools to probe for the presence of New Physics in the beauty sector: on one hand one can study the weak decays of polarized beauty baryons and $B \to \nu\bar{\nu}X$ transitions; on the other hand one can perform detailed analyses of in particular B_s decays to cross check systematic uncertainties in our extractions of $|V(cb)|$ and $|V(ub)|$ which form the basis of the CKM predictions for the asymmetries already observed.

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