REVIEW OF EXPERIMENTAL RESULTS ON ELECTROWEAK
PENGUIN DECAYS OF $b$ QUARK

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ABSTRACT
Status of experimental measurements of $b \rightarrow s(d)\gamma$, $b \rightarrow s l^+ l^-$, and $b \rightarrow s \nu \bar{\nu}$ is reviewed. Future prospects are discussed.

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1 Importance of electroweak penguin decays of $b$ quark

Flavor Changing Neutral Currents (FCNC) are forbidden to first order in the Standard Model. Second order loop diagrams (see Fig. 1), known as penguin and box diagrams, can generate effective FCNC which lead to $b \rightarrow s$ and $b \rightarrow d$ transitions. Exchange of virtual top quark dominates the loop decays: $b \rightarrow t \rightarrow s(d)$. Since the CKM matrix element $|V_{tb}|$ is very close to unity, rates for the loop decays of $b$ quark are sensitive to $|V_{ts}|$ ($|V_{td}|$) which will be very difficult to measure in the direct decays of the top quark. Complementary information on $|V_{ts}|$ and $|V_{td}|$ can be obtained from $B_s - \bar{B}_s$ and $B^0 - \bar{B}^0$ mixing.

Since the Standard Model loops involve the heaviest particles we know to date ($t, W, Z^0$), rates for these processes are very sensitive to possible exchange of non-standard objects like charged Higgs and other supersymmetric particles. Therefore, measurements of these processes constitute the most sensitive low energy probes for certain high energy extensions of the Standard Model.

Strange quarks can also decay through loop processes, $s \rightarrow t \rightarrow d$. Rate for these decays is, however, strongly suppressed compared to the loop decays of $b$ quark by unfavorable CKM elements ($|V_{ts} \cdot V_{td}|^2/|V_{tb} \cdot V_{ts}|^2 \sim |V_{td}|^2 \sim 10^{-4}$). Consequently, all loop decays of $s$ quark but $s \rightarrow d \nu \bar{\nu}$ are overwhelmed by long distance effects. Rare kaon experiments may soon reach sensitivity needed to detect $s \rightarrow d \nu \bar{\nu}$ decays.

A hard gluon can also be emitted from the penguin loop. Even though the inclusive rate for such decays is expected to be much higher than for the electroweak penguins, many final states emerging from $b \rightarrow s(d)g$ can also be produced by tree level $b \rightarrow u$ decays. Therefore, the inclusive rate is ill defined both theoretically (interference) and experimentally (no common signature). Some exclusive final states uniquely identify $b \rightarrow sg$ decays, but they occur at much smaller rate than inclusive decays. Also, the theoretical interpretation of the data is clouded by unknown hadronization probabilities.

![Figure 1: Electroweak penguin and box diagrams.](image-url)
2 Electromagnetic penguins

2.1 Exclusive $b \to s \gamma$ decays

Existence of the loop decays was first confirmed experimentally by observation of electromagnetic penguin in the exclusive mode of $B \to K^* \gamma$ by CLEO-II at CESR. The initial observation was based on $1.5 \cdot 10^6 e^+ e^- \to \Upsilon(4S) \to BB$ events. The $K^*$ is the lightest hadron which can be produced by $b \to s \gamma$. Exclusive $B$ decay reconstruction at the $\Upsilon(4S)$ has a very small background thanks to the beam energy constraint: $E_B = E_{beam}$. The detection efficiency for the $K^{*0} \gamma \to K^+ \pi^- \gamma$ mode is $22\%$ in CLEO-II.

An updated analysis based on larger statistics ($2.6 \cdot 10^6 BB$ events in 2.4 $fb^{-1}$ of integrated luminosity) and an improved analysis techniques were presented at the Warsaw conference.\footnote{Averaged over various charge modes: $\mathcal{B}(B \to K^* \gamma) = (4.2 \pm 0.8 \pm 0.6) \cdot 10^{-5}$.

The LEP experiments looked for these decays in $e^+ e^- \to Z^0 \to b\bar{b}$ but were not able to observe the signal due to an insufficient number of $b\bar{b}$ pairs. Hadronic colliders provide production rates superior to the ones achievable in $e^+ e^-$ collisions. The CDF experiment at Tevatron has attempted to observe $B^0 \to K^{*0} \gamma$ decays\footnote{An integrated luminosity of $23.34 \, pb^{-1}$ was obtained yielding $7 \cdot 10^8 p\bar{p} \to b\bar{b}X$ events produced in the central region ($|\eta| < 1$). The trigger required a high $P_t$ photon ($> 10$ GeV) associated with two charged tracks ($P_t > 2$ GeV, $\Delta \phi < 18^\circ$). Large backgrounds from non-$b\bar{b}$ events are suppressed in the off-line analysis by requiring a detached $B$ decay vertex and large impact parameters at the primary vertex of the $K^+ \pi^-$ candidates. Unfortunately the resultant experimental detection efficiency is extremely low ($\sim 0.0001\%$) and no signals are observed by CDF. The upper limit set by CDF, $\mathcal{B}(B^0 \rightarrow K^{*0} \gamma) = < 22 \cdot 10^{-5}$ (at 90% C.L.), is a factor of four away from the branching ratio measured by CLEO. Using the similar analysis, CDF also sets 90% C.L. limit: $\mathcal{B}(B_s \rightarrow \phi \gamma) = < 39 \cdot 10^{-5}$, which is only slightly looser than the limit previously obtained by ALEPH $< 29 \cdot 10^{-5}$.\footnote{To estimate number of $b\bar{b}$ pairs and reconstruction efficiencies for the CDF measurements, I use $\sigma(p\bar{p} \to b\bar{b}X) = 30 \mu b$ for $|\eta| < 1$.}} by implementing dedicated “penguin trigger”. An integrated luminosity of $23.34 \, pb^{-1}$ was obtained yielding $7 \cdot 10^8 p\bar{p} \to b\bar{b}X$ events produced in the central region ($|\eta| < 1$). The trigger required a high $P_t$ photon ($> 10$ GeV) associated with two charged tracks ($P_t > 2$ GeV, $\Delta \phi < 18^\circ$). Large backgrounds from non-$b\bar{b}$ events are suppressed in the off-line analysis by requiring a detached $B$ decay vertex and large impact parameters at the primary vertex of the $K^+ \pi^-$ candidates. Unfortunately the resultant experimental detection efficiency is extremely low ($\sim 0.0001\%$) and no signals are observed by CDF. The upper limit set by CDF, $\mathcal{B}(B^0 \rightarrow K^{*0} \gamma) = < 22 \cdot 10^{-5}$ (at 90% C.L.), is a factor of four away from the branching ratio measured by CLEO. Using the similar analysis, CDF also sets 90% C.L. limit: $\mathcal{B}(B_s \rightarrow \phi \gamma) = < 39 \cdot 10^{-5}$, which is only slightly looser than the limit previously obtained by ALEPH $< 29 \cdot 10^{-5}$.

2.2 Search for exclusive $b \to d \gamma$ decays

Detection of $b \to d \gamma$ is difficult because the rates are suppressed by $|V_{td}|^2/|V_{ts}|^2 \sim 10^{-2} - 10^{-1}$. Rejection of the dominant background from $b \to s \gamma$ decays requires a good particle identification, except for the simplest exclusive final states in which kinematic cuts alone are very effective. CLEO-II searched for
$B \rightarrow (\rho, \omega) \gamma$ decays. No evidence for the signal was found due to lack of sufficient experimental statistics ($2.6 \cdot 10^6 \bar{B}B$ pairs). The following upper limits were set (90% C.L.): $\mathcal{B}(B^0 \rightarrow \rho^0 \gamma) = < 3.9 \cdot 10^{-5}$, $\mathcal{B}(B^0 \rightarrow \omega \gamma) = < 1.3 \cdot 10^{-5}$, and $\mathcal{B}(B^- \rightarrow \rho^- \gamma) = < 1.1 \cdot 10^{-5}$. The ratio $\mathcal{B}(B \rightarrow (\rho, \omega) \gamma)/\mathcal{B}(B \rightarrow K^* \gamma)$ can be used to determine $|V_{td}|^2/|V_{ts}|^2$ after corrections for the phase space and $SU(3)$–flavor symmetry breaking effects. Unfortunately the latter are somewhat model dependent. Long Distance interactions may further complicate the analysis.

From the present experimental limits CLEO obtains: $|V_{td}|^2/|V_{ts}|^2 < 0.45 - 0.56$, where the range indicates the uncertainty in the theoretical factors.

With more data and improved particle identification devices $b \rightarrow d \gamma$ may be observed by the next generation of $e^+e^- \rightarrow \Upsilon(4S)$ experiments.

Another way to determine $|V_{td}|^2/|V_{ts}|^2$ is to use a ratio of $B^0 - \bar{B}^0$ and $B_s - \bar{B}_s$ mixing. While $B^0 - \bar{B}^0$ mixing is already well measured by various experiments, only lower bounds on $B_s - \bar{B}_s$ mixing have been set. Measurement of $B_s - \bar{B}_s$ mixing is likely to require a dedicated experiment at hadronic collider with excellent time resolution and robust triggering, like BTeV proposed for the Tevatron, and LHC-B proposed for the LHC.

### 2.3 Significance of inclusive measurements

The measured rate for exclusive mode of $B \rightarrow K^* \gamma$ is in the ball-park of the Standard Model predictions. Quantitative tests of the Standard Model with rates measured for exclusive channels are severely handicapped by our inability to calculate hadronization probabilities from the first principles of the theory. Predictions of phenomenological models for $K^*$ fraction in $b \rightarrow s \gamma$ decays ($R_{K^*} = \mathcal{B}(B \rightarrow K^* \gamma)/\mathcal{B}(b \rightarrow s \gamma)$) vary in a wide range ($1 - 40\%$). One should notice however, significant improvements in recent lattice-QCD calculations in this area.

Fortunately, when summed over all possible final states hadronization probabilities drop out and inclusively measured rate should reflect the short distance interactions which can be accurately predicted using the effective Hamiltonian of the Standard Model. The first non-perturbative correction is expected to be of second order in the expansion over $\Lambda_{QCD}/m_b$, thus it should be small thanks to the heavy $b$ quark mass. Next-to-leading order perturbative calculations have been recently completed for the $b \rightarrow s \gamma$. Assuming unitarity of the CKM matrix to constrain $|V_{ts}|$ the Standard Model predicts $\mathcal{B}(b \rightarrow s \gamma) = (3.5 \pm 0.3) \cdot 10^{-4}$. 

4
2.4 Measurement of inclusive $b \to s \gamma$ by CLEO

When reconstructing simple exclusive final states like $B \to K^* \gamma, K^* \to K\pi$, backgrounds are usually low due to the tight kinematic constraints (here: constraints to the $B$ and $K^*$ masses, and to the beam energy). Inclusive measurements are more challenging and they are often background limited.

The main background limitation in CLEO comes from continuum production of lighter quarks $e^+ e^- \to q \bar{q}$, $q = d, u, s, c$. These backgrounds can be reliably subtracted using data taken below the $e^+ e^- \to B\bar{B}$ threshold. However, statistical fluctuations in the background level can easily swamp the signal unless the backgrounds are efficiently suppressed. Backgrounds from $B$ decays are less serious since $b \to s \gamma$ decays are quasi-two-body and produce higher energy photons ($E_\gamma \sim m_b/2$) than photons from usual decay modes.

CLEO used two complementary approaches to suppress the continuum background. In one approach only the photon among $b \to s \gamma$ decay products was explicitly reconstructed. Topological differences between $B\bar{B}$ events (spherical - since $B$ mesons almost at rest at $\Upsilon(4S)$) and $e^+ e^- \to q \bar{q}$ events (two jets) were used for the background suppression. For the best sensitivity all shape variables where combined using a neural net technique. The signal amplitude was extracted using a one parameter fit to the neural net output variable, with the signal shape and the $B\bar{B}$ backgrounds taken from Monte Carlo simulation, and the continuum background subtracted using the below $\Upsilon(4S)$ data. In the second approach, all products of the $b \to s \gamma$ decay were reconstructed as in exclusive reconstruction. Thus, the constraints to the $B$ mass and to the beam energy could be used. The final state was only loosely restricted to contain a kaon candidate (a charged track consistent with $K^\pm$ by $dE/dx$ and ToF, or a $K^0_s \to \pi^+\pi^-$ candidate) and $1-4$ pions (including at most one $\pi^0 \to \gamma\gamma$). The photon energy spectra measured by CLEO with these two methods in a sample of $2.2 \cdot 10^8$ $B\bar{B}$ events are shown in Fig. 2. The first method has rather large continuum background but also high signal efficiency (32%). The second method is very good in suppressing continuum background, but the signal efficiency is much smaller (9%). Sensitivity of these two approaches is nearly equal, and the measurements of signal amplitudes are only slightly correlated. By combining these two methods together, CLEO-II measured $B(b \to s \gamma) = (2.32 \pm 0.57 \pm 0.35) \cdot 10^{-4}$ in agreement with the Standard Model expectations.

Combining the inclusive and the exclusive measurements, CLEO-II determines $R_{K^*} = (18.1 \pm 6.8)$% in agreement with some phenomenological estimates and the recent QCD calculations on lattice.
Figure 2: Inclusive $E_\gamma$ spectra in the CLEO-II $b \to s \gamma$ measurement obtained with the event-shape analysis (left) and with the inclusive $B-$reconstruction (right). (a) $\Upsilon(4S)$ data (solid histogram), scaled below $\Upsilon(4S)$ data (dashed histogram) plus estimated $\Upsilon(4S)$ backgrounds (squares). (b) Background-subtracted data (points) and Monte Carlo prediction for the shape of the $b \to s \gamma$ signal (solid curve).

Figure 3: Inclusive $E_\gamma^*$ spectrum in the ALEPH $b \to s \gamma$ measurement. On the left: data (points) and total estimated background (solid histogram). On the right: background-subtracted data (points) and Monte Carlo prediction for the shape of the $b \to s \gamma$ signal (solid curve).
2.5 Measurement of inclusive \( b \to s \gamma \) by ALEPH

Even though \( e^+ e^- \to b \bar{b} \) cross-section is larger at \( Z^0 \) than at \( \Upsilon(4S) \), high luminosity is more difficult to obtain at higher \( e^+ e^- \) collision energies. Thus, \( b \bar{b} \) samples obtained by the LEP experiments are smaller than the one accumulated at CESR. Preliminary analysis by ALEPH is based on \( 0.6 \cdot 10^6 b \bar{b} \) pairs. The other disadvantage for experiments at \( Z^0 \) is a loss of the beam energy constraint, since \( b \) quark produces not only a \( B \) meson, but also a few fragmentation particles. In addition to \( B^- \) and \( B^0 \), also \( B_s \) and \( b- \)baryons are produced. On the other hand the \( Z^0 \) environment offers important advantages too. Produced \( b \) quarks are highly relativistic, thus decay products from two \( B \) mesons separate into two back-to-back hemispheres reducing reconstruction ambiguities. Even more important; average decay length of \( B \) meson is by two orders of magnitude larger than in CLEO (2600 \( \mu m \) vs. 30 \( \mu m \)). Therefore at the \( Z^0 \), detached vertex cuts are a powerful suppression tool against the light quark backgrounds.

ALEPH looks for inclusive \( b \to s \gamma \) decays by combining a high energy photon cluster with other particles in the same hemisphere to match the \( B \) meson mass within the experimental resolution. The energy of \( B \) candidates \( (E_B) \) is required to be large, since on average \( B \) meson carries about 70\% of the beam energy. Up to 8 particles are allowed in addition to the photon, including charged tracks, \( \pi^0 \)'s detected in the electromagnetic calorimeter, and \( K_L^0 \) detected in the hadronic calorimeter. To reduce confusion from the fragmentation pions, the charged tracks included in the \( B \) meson combination must miss the primary interaction point. Once the \( B \) candidate is created, the photon energy can be boosted to the \( B \) rest frame \( (E^*_\gamma) \) where the signal photons are quasi-monochromatic: \( E^*_\gamma \sim m_b/2 \). Further background suppression is achieved by requiring a detached vertex in the opposite hemisphere.

The selected data are fit in various bins of \( E^*_\gamma \), \( E_B \), and vertex detachment in the opposite hemisphere allowing for three contributions: signal, final state radiation background, and all other backgrounds. The shapes of these contributions are fixed from the Monte Carlo simulations while normalizations are allowed to float. Fig. shows the results of the fit in a function of \( E^*_\gamma \) for the tighter cuts on the other two variables. The total reconstruction efficiency \((\sim 12\%)\) is similar to the one obtained by CLEO in their inclusive \( B \) reconstruction. In spite of four times smaller \( b \bar{b} \) statistics, ALEPH is able to observe a significant inclusive signal. This should be attributed to the better background suppression by the vertex cuts. The rate measured by ALEPH, \( \mathcal{B}(b \to s \gamma) = (3.29 \pm 0.71 \pm 0.68) \cdot 10^{-4} \), is consistent with the CLEO measurement and the Standard Model predictions.
The other LEP experiments were not able to see $b \rightarrow s \gamma$ signal and set upper limits consistent with the CLEO and ALEPH measurements:

- **DELPHI**: $< 5.4 \cdot 10^{-4}$,
- **L3**: $< 12 \cdot 10^{-4}$ (90% C.L.)

### 2.6 Theoretical implications of the inclusive measurements

Combining the CLEO measurement with the preliminary ALEPH result and dividing by the Standard Model predictions Ali obtains:

$$\left| \frac{V_{ts}^*}{V_{tb}} \right| = 0.84 \pm 0.09 \text{(experiment)} \pm 0.04 \text{(theory)}$$

consistent with the unitarity constraint:

$$\left| \frac{V_{ts}^*}{V_{tb}} \right| \approx |V_{cs}| = 1.01 \pm 0.18$$

Using the measured values to eliminate $V_{tb}$ and $V_{cb}$, Ali extracts from the $b \rightarrow s \gamma$ measurements:

$$|V_{ts}| = 0.033 \pm 0.007$$

The agreement between the measured and the Standard Model rates (including the CKM matrix unitarity) leaves a little room for non-standard contributions. Meaningful constraints on many extensions of the Standard Model can be obtained as discussed by J. Hewett at this conference.

### 2.7 Future prospects

The theoretical uncertainties in the predictions for the inclusive $b \rightarrow s \gamma$ rate are smaller than the present experimental errors, calling for improved measurements. The CLEO experiment has more than doubled their data sample since the first measurement of the inclusive $b \rightarrow s \gamma$ rate, and it still accumulates the data. The data analysis is under progress. No more data is expected at the $Z^0$ peak at LEP. In the future, $\Upsilon(4S) B$-factories at CESR (CLEO-III experiment), PEP-II (BaBar experiment) and KEK-B (Belle experiment) will produce very large samples of $b \rightarrow s \gamma$ events with smaller backgrounds thanks to the improved particle identification (all three experiments) and some $B$ vertex capability (PEP-II and KEK-B). Photon energy spectrum should be measured with a good accuracy. Detection of $b \rightarrow d \gamma$ via inclusive $B$ reconstruction may not be out of question. Potential of future hadronic collider experiments for electromagnetic penguins has not been explored. The CDF has made the first step in this direction as discussed in section 2.1.
detected in an electromagnetic calorimeter yield too much background, use of converted photons which can be pointed to a detached $B$ vertex should be investigated.

3 Searches for $b \rightarrow s l^+ l^-$

3.1 Theoretical expectations

The $b \rightarrow s l^+ l^-$ decay rate is expected in the Standard Model to be nearly two orders of magnitude lower than the rate for $b \rightarrow s \gamma$ decays. Nevertheless, the $b \rightarrow s l^+ l^-$ process has received considerable attention since it offers a deeper insight into the effective hamiltonian describing FCNC processes in $B$ decays. While $b \rightarrow s \gamma$ is only sensitive to the absolute value of the $C_7$ Wilson coefficient in the effective hamiltonian, $b \rightarrow s l^+ l^-$ is also sensitive to the sign of $C_7$ and to the $C_9$ and $C_{10}$ coefficients, where the relative contributions vary with $l^+ l^-$ mass. These three coefficients are related to three different processes contributing to $b \rightarrow s l^+ l^-$: $b \rightarrow s(\gamma \rightarrow l^+ l^-)$, $b \rightarrow s(Z^0 \rightarrow l^+ l^-)$, and box diagram (see Fig. 1). Processes beyond the Standard Model can alter both the magnitude and the sign of the Wilson coefficients.

3.2 Searches in exclusive modes

The simplest allowed final states are $B \rightarrow K l^+ l^-$, and $B \rightarrow K^* l^+ l^-$ ($B \rightarrow K \gamma$ is forbidden by the angular momentum conservation). Each of them is expected to constitute $\sim 10\%$ of the total $b \rightarrow s l^+ l^-$ rate. The most sensitive searches for these decays were performed by CDF and CLEO-II experiments.

The CDF search [25] is based on $17.8 \text{ pb}^{-1}$ of data ($\sim 5 \times 10^8 \bar{b}b$ pairs for $|\eta| < 1$) and di-muon trigger. The backgrounds are suppressed by transverse momentum cuts ($P_T(\mu) > 2, 2.5 \text{ GeV}$, $P_T(K^{(*)}) > 2 \text{ GeV}$, $P_T(B) > 6 \text{ GeV}$), detached vertex cut ($c\tau(B) > 100 \mu m$), isolation requirement and $B$ mass cut. The resulting di-muon mass distributions are shown in Fig. 4. The signals due to long distance interactions $B \rightarrow K^{(*)} \psi(l)$ are observed. Since the branching ratios for these decays were previously measured by the other experiments, CDF used these signals for normalization. Reconstruction efficiencies are roughly 0.13% for the $K$, and 0.07% for the $K^*$ modes. A few events observed outside the $\psi$ and $\psi'$ bands are consistent with the background estimates. The following upper limits are set: $\mathcal{B}(B^- \rightarrow K^- \mu^+ \mu^-) < 1.0 \times 10^{-5}$ and $\mathcal{B}(B^0 \rightarrow K^{*0} \mu^+ \mu^-) < 2.5 \times 10^{-5}$ (90 % C.L.).

The CLEO-II experiment searched for these decays in a sample of $b\bar{b}$ pairs by two orders of magnitude smaller ($\sim 2.2 \times 10^6 B\bar{B}$) than in the CDF analysis, though with efficiencies larger also by two orders of magnitude ($\sim 15\%$...
for $K$ and $\sim 5\%$ for $K^*$), and suitably low backgrounds. Thus, by this strange coincidence the sensitivity of the CDF and of the CLEO-II experiments were very similar. In addition to the limits in the di-muon mode, $\mathcal{B}(B^- \to K^- \mu^+\mu^-) < 0.9 \cdot 10^{-5}$ and $\mathcal{B}(B^0 \to K^{*0} \mu^+\mu^-) < 3.1 \cdot 10^{-5}$, CLEO also set the limits using di-electrons: $\mathcal{B}(B^- \to K^- e^+e^-) < 1.2 \cdot 10^{-5}$ and $\mathcal{B}(B^0 \to K^{*0} e^+e^-) < 1.6 \cdot 10^{-5}$.

The experimental limits are an order of magnitude away from the Standard Model predictions.

### 3.3 Inclusive searches

The new CLEO analysis looks for inclusive $b \to s l^+l^-$ decays using the inclusive $B$ reconstruction technique previously described for the $b \to s \gamma$ decays (see section 2.4). The obtained di-lepton mass spectra are shown in Fig. 5. Again clear signals for $B \to X_s \psi$ and $B \to X_s \psi'$ are observed. Events outside the $\psi$ and $\psi'$ bands are consistent with the $B\bar{B}$ background estimates (the continuum backgrounds are small). With a sample of $3.3 \cdot 10^6$ $B\bar{B}$ pairs and reconstruction efficiencies around 5%, CLEO sets the 90% C.L. upper limits, $\mathcal{B}(b \to s e^+e^-) < 5.7 \cdot 10^{-5}$ and $\mathcal{B}(b \to s \mu^+\mu^-) < 5.8 \cdot 10^{-5}$ (combined: $\mathcal{B}(b \to s l^+l^-) < 4.2 \cdot 10^{-5}$), which are again an order of magnitude away from the Standard Model predictions. $\mathcal{B}(b \to s e^+e^-) = (0.8 \pm 0.2) \cdot 10^{-5}$ and $\mathcal{B}(b \to s \mu^+\mu^-) = (0.6 \pm 0.1) \cdot 10^{-5}$.

The upper limits on inclusive $b \to s \mu^+\mu^-$ previously presented by the experiments at hadronic colliders appear to be based on overestimated sensitivity. Therefore, they are not included here.

### 3.4 Future prospects

The search for exclusive channels by CLEO-II was statistics limited. An order of magnitude increase in $B\bar{B}$ statistics expected for the CLEO-III phase of the CESR program should put these channels in detectable range. However, measurement of the inclusive rate is questionable since the CLEO-II results are already background limited due to random combinations of leptons from semileptonic $B/D$ decays and of the other particles from two $B$ mesons in the event. Asymmetric $B$ factories at SLAC and KEK may be better suited for

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$b$ The results were obatined by UA1 at SppS and D0 at Tevatron. I have simulated efficiency of the UA1 kinematic cuts with PYTHIA and the modern $b \to s \mu^+\mu^-$ theory and obtained a number by a factor of three lower than the overall efficiency estimated by UA1. Allowing for the trigger and reconstruction losses makes the discrepancy larger. I find the $B\bar{B}$ background subtraction method used by UA1 highly questionable as well. The preliminary result reported by D0 at the Warsaw conference is currently under revision.
Figure 4: Di-muon mass distributions in the CDF search for $b \to s \mu^+ \mu^-$ via exclusive final states $B^+ \to K^+ \mu^+ \mu^-$ (left) and $B^0 \to K^{*0} \mu^+ \mu^-$ (right).

Figure 5: Di-lepton mass distribution in the CLEO-II inclusive search for $b \to s l^+ l^-$. On- (top) and off- (bottom) $\Upsilon(4S)$ data are shown.
suppression of these backgrounds. The interesting physics lies not only in the measurement of total rates, but also in studies of di-lepton mass distribution and forward-backward lepton charge asymmetry. Such studies will require huge experimental statistics which will be very difficult to achieve at $e^+e^-$ colliders. Very large statistics will also be required for detection of any $b \to d l^+l^-$ decays. Thus, more detailed exploration of these decays will be performed at hadronic colliders. Triggering on di-leptons is relatively easy. The upgraded CDF and D0 experiments should be able to observe the exclusive modes during the Main Injector Run at Tevatron. Measurement of the inclusive rate and studies of the differential distributions for di-leptons will likely require good $K/\pi$ separation and excellent vertex resolution. These are attributes of the BTeV and LHC-B experiments.

4 Searches for $b \to s \nu \bar{\nu}$

The rate for $b \to s \nu \bar{\nu}$ is enhanced compared to the $b \to s l^+l^-$ decays primarily by summing over three neutrino flavors ($b \to s \tau^+\tau^-$ has a small expected rate and will be difficult to detect experimentally). The predicted rate is only a factor of ten lower than for $b \to s \gamma$ (3.8 $\pm$ 0.8) $\cdot$ 10$^{-5}$. In principle, these decays are the cleanest theoretically among all penguin decays. Therefore, measurement of inclusive rate for this process would be of considerable interest. Unfortunately, the neutrinos escape the detection making it difficult for experimentalists to control the backgrounds. So far, only LEP experiments have been able to probe these decays by requiring a very large missing energy in a hemisphere. Semileptonic backgrounds are reduced by eliminating events with identified lepton in the signal hemisphere. Detached vertex in the opposite hemisphere suppresses non-$b\bar{b}$ backgrounds. Missing energy distribution in a $b-$hemisphere obtained by ALEPH in a sample of $\sim 0.5 b\bar{b}$ pairs is shown in Fig. 6. From the lack of excess of events over the semileptonic backgrounds at the highest energy bins, ALEPH obtained: $B(b \to s \nu \bar{\nu}) < 7.7 \cdot 10^{-4}$ at 90% C.L.

Exclusive mode of $B \to K^* \nu \bar{\nu}$ should constitute about 30% of the total rate. DELPHI has set the following upper limits: $B(B^0 \to K^{*0} \nu \bar{\nu}) < 1.0 \cdot 10^{-3}$ and $B(B_s \to \phi \nu \bar{\nu}) < 5.4 \cdot 10^{-3}$ (90% C.L.)

The inclusive limit set by ALEPH is an order of magnitude away from the expected rate. Unfortunately, no more data is expected at the $Z^0$ peak at LEP. Perhaps, $\Upsilon(4S)$ experiments will be able to develop analysis techniques which will probe these decays in the future high statistics data. It is hard to imagine that experiments at hadronic colliders will ever have any sensitivity to these decays.
Figure 6: Missing energy in a hemisphere for the selected $b\bar{b}$ events by ALEPH (points). Shaded histograms show the estimated background distribution. The expected $b \to s\nu\bar{\nu}$ signal shape is indicated by dotted line. The two highest bins are used to set the upper limit.

5 Summary

Among all electroweak penguin processes only $b \to s\gamma$ has been detected experimentally. CLEO-II measured the inclusive rate and the exclusive fraction for $B \to K^*\gamma$, both with about 30% accuracy. Recently, the ALEPH experiment has also observed the inclusive signal with the rate consistent with CLEO. Incremental increase of statistics by CLEO-II experiment will soon allow reduction of experimental errors by up to a factor of 2. In a few years, further improvements are expected by CLEO-III, BaBar and Belle experiments.

Experimental upper limits on all other penguin processes are roughly an order of magnitude away from the Standard Model predictions. Exclusive $b \to d\gamma$ and $b \to s l^+l^-$ decays should be detectable by the next generation of $e^+e^-$ experiments. The latter should also be observable by the central detectors during the Run II of the Tevatron collider. Detailed exploration of $b \to s l^+l^-$ processes (inclusive rate, di-lepton mass distribution, $b \to d l^+l^-$) are likely to require specialized experiments at a hadronic collider with good kaon identification and excellent vertex resolution, like in the proposed BTeV and LHC-B detectors.

The $b \to s\nu\bar{\nu}$ decays are the cleanest theoretically but the hardest experimentally. They may remain undetected for a foreseeable future.
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