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B Physics

Plenary Talk at the Int. Europhysics Conf.
on High Energy Physics Marseille, 1993

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UDK 539.172 M-16

B Physics : Preprint ITEP 92-93/

M.V. Danilov - M., 1993 - 16p.

New results on beauty hadron decays are reviewed. Among the highlights are the observation of the decays $B \to K^* \gamma$ which provides evidence for penguin diagrams and direct observation of time oscillations between B_d^0 and $\bar{B}_d^0$ mesons.

Fig. - 21, ref - 65.

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Introduction

Beauty physics has developed rapidly during the last two years. Partially, progress was achieved because of large data samples collected by CLEO, LEP and CDF. Another and probably even more important reason was progress in experimental techniques. The excellent electromagnetic calorimeter of CLEO allowed them to study effectively many final states with photons. The most remarkable achievement was the observation of the $B \to K^*\gamma$ decay which occurs due to so-called penguin diagrams.

The silicon vertex detectors of the LEP experiments, CDF and SLD finally demonstrated their anticipated power in background rejection. Using vertex information B samples with 80% purity were obtained with a selection efficiency higher than 75%. The effective use of vertex detectors resulted in a drastic improvement in b-lifetime measurements. The accuracy of individual lifetimes of beauty hadrons is in some cases better than 10% and the expected hierarchy started to appear. B^+ lifetime is longer than the Λ_b lifetime at a 3 sigma level.

Another beautiful result obtained through the improvement in vertex detectors is the first observation of time oscillations between B_d^0 and $\bar{B}_d^0$ mesons. This observation raised hopes for reaching quite decent sensitivity to B_s^0 oscillations in the near future.

This paper reviews the recent results on beauty hadron decays. Production of heavy flavours and investigation of Z^0 properties using beauty hadrons are discussed in talks by S.Catani and J.Lefrançois. The theory of heavy quarks is discussed by K.Zalewski. The first three parts of this paper are devoted to b hadron spectroscopy, lifetimes and hadronic decays. The status of the semileptonic $b \to c$ and $b \to u$ transitions is described next. The three last parts are devoted to loop induced processes : $B^0\bar{B}^0$ mixing, $b \to s\gamma$ and $b \to s$ "gluon" transitions.

Spectroscopy

Until recently only the B^0 and B^+ mesons had been reconstructed completely. Evidence for other b-hadrons B^*, B_s, Λ_b came from partial reconstruction and the masses of B_s and Λ_b were not known.

Recently four experiments have reconstructed the B_s meson and measured its mass [1, 2, 3, 4]. Fig.1 shows the event with the decay $B_s^0 \to \psi'\phi \to \mu^+\mu^-K^+K^-$ found by the ALEPH Collaboration [1]. Four tracks form a secondary vertex separated from the interaction point by 4.53 ± 0.14 mm. Both muons are well identified. They penetrated without interaction seven interaction lengths of iron. Their invariant mass (3.692 ± 0.020 GeV) coincides perfectly with the known ψ' mass of 3.685 GeV. Two tracks forming a ϕ-candidate have specific ionization in the TPC in a good agreement with the kaon hypothesis. The K^+K^- invariant mass of 1.0204 ± 0.0008 GeV agrees well with the ϕ mass. The measured B_s mass is 5.3684 ± 0.0056 GeV. The expected background from reflections from B^0 and Λ_b decays was estimated to be less than 0.0003 and 0.00008 events respectively. The combinatorial background above 5 GeV was estimated to be less than 0.006 events at 95% CL.

This single event is so clean, perfect and beautiful that it is possible to claim on its basis alone the observation of a new particle just like in the good old bubble chamber days.

Many other B_s^0 candidates have been observed by ALEPH, DELPHI, OPAL and CDF (see Table 1). However just this one event dominates the measurement of the B_s^0 mass.

CDF observed the largest number of B_s^0 mesons (see Fig.2). However the background is also large. The value of the B_s^0 mass obtained by CDF is about 15 MeV larger than the ALEPH value. Nevertheless the two results are marginally consistent and consistent with the results obtained by OPAL and DELPHI which have larger errors.

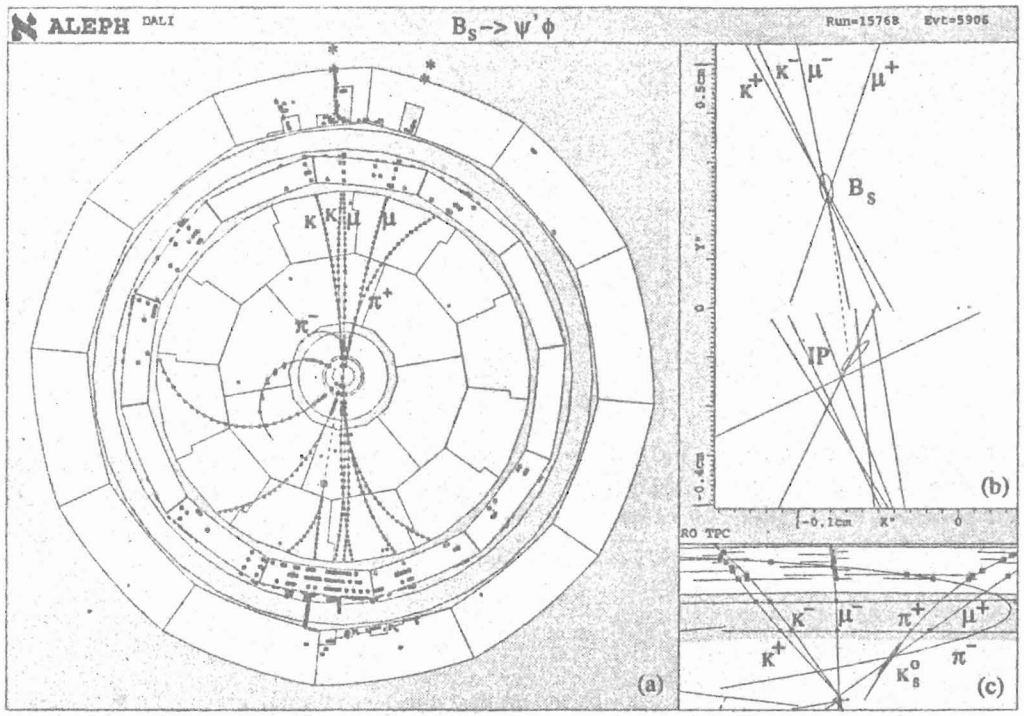

Figure 1: ALEPH event with the decay $B_s^0 \to \psi'\phi \to \mu^+\mu^- K^+K^-$.

Table 1: The B_s^0 mass measurements.

Experiment	$M_{B_s^0}$ [MeV/c^2]
ALEPH (2 events)	$5368.6 \pm 5.6 \pm 1.5$
DELPHI (4 events)	$5357 \pm 12 \pm 8$
OPAL (1 event)	5360 ± 70
CDF (14±4.7 events)	$5383.3 \pm 4.5 \pm 5.0$
Average	5373.2 ± 4.2

The average value of the B_s^0 mass of 5373.2±4.2 MeV agrees reasonably well with the theoretical predictions by Martin [5] ($M_{B_s} = 5374$ MeV) and Kwong and Rosner [6] ($M_{B_s} = 5345 - 5388$ MeV). It is about two standard deviations away from the mass obtained by the CUSB Collaboration [7] from the analysis of the photon spectrum at the $\Upsilon(5S)$.

The OPAL Collaboration observes seven Λ_b candidates in the decay mode $\Lambda_b^0 \to \Lambda_c^+\pi^-$ [8] at a mass of 5620 ± 30 MeV (see Fig.3). The estimated background is only 1±0.5 event. However, being conservative OPAL gives only an upper limit

$$f(b \to \Lambda_b) \cdot B(\Lambda_b \to \Lambda_c{}^+\pi^-) < 5.0 \cdot 10^{-3} \quad @\ 90\% \quad CL.$$

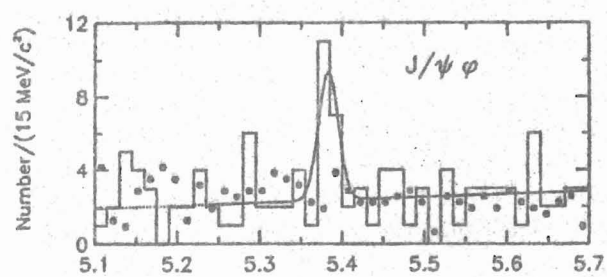

Figure 2: $J/\psi\phi$ invariant mass distribution (CDF).

The L3 Collaboration observes B^* production at the Z^0 [9]. The fraction of B^* mesons is quite high:

$$\frac{N_{B^*}}{N_B + N_{B^*}} = 0.82 \pm 0.07 \pm 0.10.$$

Some indications of Ξ_b baryon have been obtained by DELPHI [2] and ALEPH [2] using $\Xi^-\ell^-$ correlations. However the statistical significance of the signals is too low to make conclusions.

An indication of B^{**} meson decaying into $B\pi$ has been obtained by ALEPH [2] at $M_{B^{**}} = 5.61 \pm 0.04 \pm 0.02$ GeV. This decay can be an important source of tagged B mesons. However the statistical significance of the signal is again below 3σ and it needs confirmation.

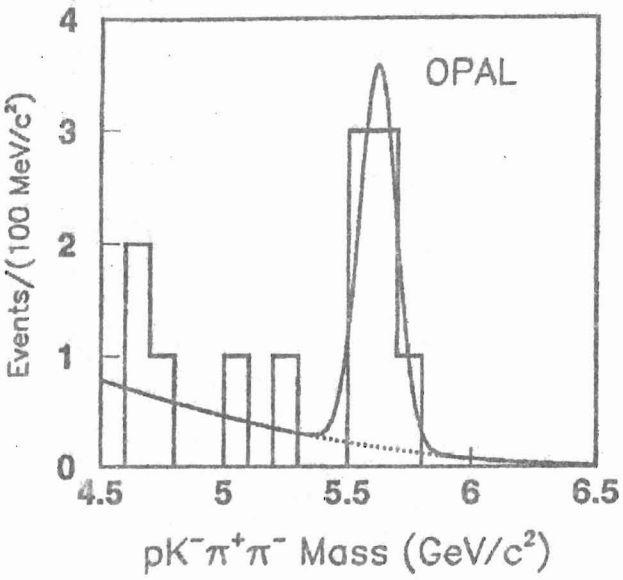

Figure 3: $\Lambda_c^+\pi^-$ invariant mass distribution.

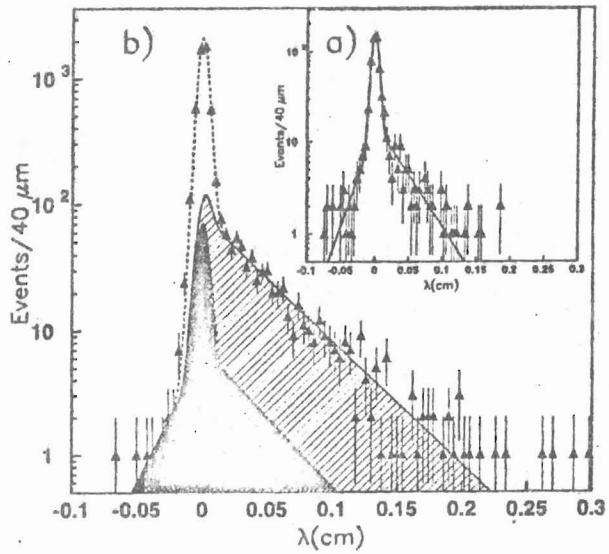

Figure 4: Pseudo-$c\tau$ distribution in J/ψ signal region.

Lifetimes

In the inclusive approach one does not separate different b-hadron species. Therefore this approach gives an average lifetime for b-hadrons weighted by their production fractions and branching ratios for decays into tagging particles (high p_T leptons, J/ψ, etc.). This method has a high efficiency but relies heavily on Monte Carlo simulations for the estimation of non-beauty backgrounds and determination of the b-hadron boost.

Impact parameter measurements are the simplest and most frequently used. Averaging ALEPH, DELPHI, L3, and OPAL results on lepton and hadron impact parameter measurements one gets [10]

$$\langle\tau_b\rangle_{imp.par.} = 1.44 \pm 0.04\ ps$$

where the error includes 0.03 ps of common systematics.

Partial b-hadron reconstruction allows one to measure a distance between the interaction point and the b decay vertex. ALEPH, DELPHI, OPAL, and CDF have measured the decay distance for J/ψ particles. Fig.4 shows the CDF measurement of the pseudo-$c\tau$ distribution for b-hadrons decaying into $J/\psi\ X$ [4]. A beautiful exponential tail is clearly visible. The peak at zero $c\tau$ is due to direct J/ψ production in $p\bar{p}$ collisions which is 6 times larger than the J/ψ yield from b-hadron decays. From this measurement CDF infers a b lifetime of

$$\langle\tau_b\rangle_{J/\psi} = 1.46 \pm 0.06 \pm 0.06\ ps.$$

Averaging LEP and CDF results on b lifetimes using partial reconstruction, which include the DELPHI measurement using generic b-vertices and the ALEPH dipole method measurement, one gets [10]

$$\langle\tau_b\rangle_{\substack{partial\\ reconstruction}} = 1.53 \pm 0.04\ ps.$$

Impact parameter measurements and measurements with partial b-hadron reconstruction need not be identical because of different branching ratios for b-hadron decays into tagging particles. Neglecting a possible difference and averaging the results obtained by the two methods we obtain an inclusive b-hadron lifetime of

$$\langle\tau_b\rangle_{incl} = 1.49 \pm 0.04\ ps.$$

This value is considerably larger than the world average values in 1990 (1.18 ± 0.11 ps [11]) and in 1992 (1.29 ± 0.05 ps [12]). The error now is very small and hopefully the result will not change any more.

It is very interesting to compare lifetimes of different b-hadrons. Contrary to the case of charm particles the expected differencies are small. Theory predicts the following hierarchy

$$\tau_{B^+} > \tau_{B_s^0} \simeq \tau_{B_d^0} > \tau_{\Lambda_b^0}$$

however the difference is expected to be smaller than 10-20%. It is challenge for experiment to observe such small differences.

The straightforward way of lifetime measurements using full b-hadron reconstruction suffers from low efficiency or high background. So far only a few such measurements have been performed. Most measurements use partial reconstruction. B^0 mesons are identified by $D^{(*)-}l^+$ pairs which result from the decays $B^0 \to \bar{D}^-\ell^+\nu$ and $B^0 \to \bar{D}^{*-}\ell^+\nu$.

If a slow π^- from the D^{*-} is lost the B^0 decay imitates B^+ decay. The B^+ sample comes from the decay $B^+ \to \bar{D}^0 \ell^+ \nu$.

B^0 and B^+ samples are contaminated with wrong charges because of semileptonic B-decays into D^{**} or non-resonant $D^{(*)} n\pi$ final states.

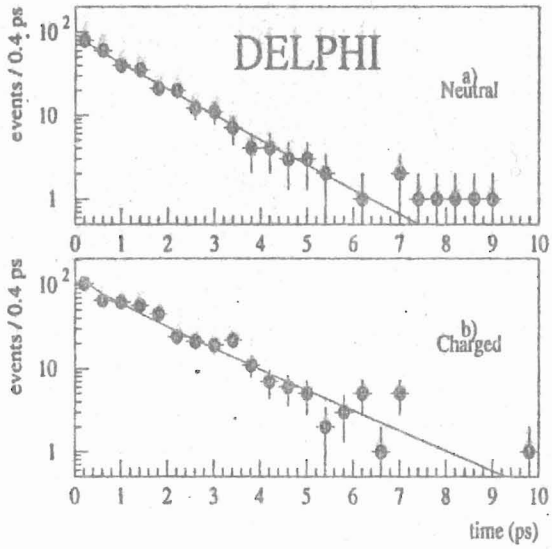

Figure 5: Proper time distribution for neutral (a) and charged (b) b-vertices.

The DELPHI collaboration has measured the decay time distribution for charged and neutral vertices consistent with B-meson decays (see Fig.5). After correction for B_s^0 and Λ_b contributions they extracted B^0 and B^+ lifetimes with quite small errors which are dominated by systematic uncertainties in the determination of the vertex charge.

Results of lifetime measurements for charged and neutral B-mesons are summarized in Tables 2 and 3 [4, 13]. An accuracy of about 7% has been achieved in both cases.

The ratio of B^+ and B^0 lifetimes is slightly larger than unity but consistent with it within errors:

$$\tau_{B^+}/\tau_{B^0} = 1.07^{+0.12}_{-0.11}.$$

This ratio can be also (indirectly) obtained from the ratio of semileptonic branching fractions of B^+ and B^0 mesons. Using different methods to tag the charge of B mesons ARGUS [14, 15] and CLEO [16] obtained

$$\begin{aligned}
\tau_+/\tau_0 &= 1.12 \pm 0.27 \pm 0.34 \quad \text{(ARGUS)}, \\
\tau_+/\tau_0 &= 1.05 \pm 0.16 \pm 0.15 \quad \text{(CLEO)}, \\
f_+\tau_+/f_0\tau_0 &= 1.00 \pm 0.23 \pm 0.14 \quad \text{(ARGUS)}, \\
f_+\tau_+/f_0\tau_0 &= 1.20 \pm 0.16 \pm 0.12 \quad \text{(CLEO)},
\end{aligned}$$

where f_+ and f_0 are the fractions of charged and neutral B mesons in $\Upsilon(4S)$ decays.

Table 2: The τ_{B^+} measurements.

Experiment	τ_{B^+} [ps]
ALEPH'91 D-lepton	$1.47^{+0.22+0.15}_{-0.19-0.14}$
DELPHI'91 D-lepton	$1.30^{+0.33}_{-0.29} \pm 0.16$
DELPHI'91 Vtx.charge	$1.56 \pm 0.19 \pm 0.13$
OPAL'91 D-lepton	$1.51^{+0.30+0.12}_{-0.28-0.14}$
ALEPH'91+92 Exclusive	$1.77^{+0.45}_{-0.34} \pm 0.14$
DELPHI'91+92 Vtx.charge	$1.81^{+0.12}_{-0.12} \pm 0.19$
OPAL'91+92 D-lepton	$1.66^{+0.12+0.11}_{-0.20-0.12}$
Average LEP	$1.63^{+0.13}_{-0.12}$
CDF	$1.63 \pm 0.21 \pm 0.16$
Average	$1.636^{+0.12}_{-0.11}$

The B_s^0 lifetime is measured using $D_s^- \ell^+$ and $\phi\ell^+$ correlations. For the Λ_b baryon $\Lambda_c \ell^+$ or $\Lambda\ell^+$ correlations are used. As an example a b-baryon decay length obtained by OPAL using $\Lambda\ell$ correlations [17] is shown in Fig.6.

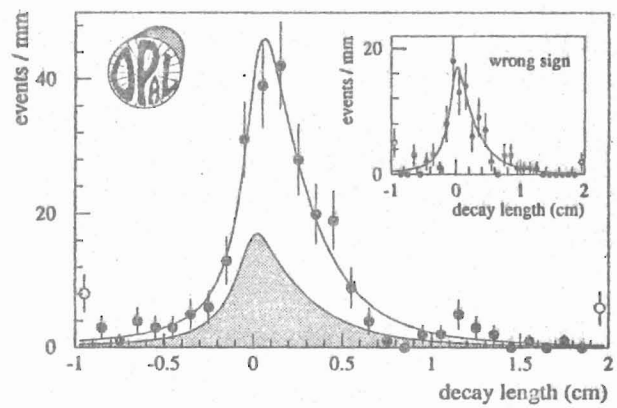

Figure 6: b baryon decay length distribution.

Fig.7 shows individual lifetimes for different b-hadrons. Even for B_s^0 and Λ_b an accuracy of about 15% has been reached.

The expected hierarchy of lifetimes starts to appear – the lifetime of B^+ is larger than the lifetime of Λ_b at a three sigma level:

$$\tau_{B^+} - \tau_{\Lambda_b} = 0.64 \pm 0.20\ ps$$

Further improvement in the accuracy of b-hadron lifetime measurements is expected soon.

Table 3: The τ_{B^0} measurements.

Experiment	τ_{B^0} [ps]
ALEPH'91 D-lepton	$1.52^{+0.20+0.07}_{-0.18-0.13}$
DELPHI'91 D-lepton	$1.17^{+0.29}_{-0.23} \pm 0.16$
DELPHI'91 Vtx.charge	$1.55 \pm 0.25 \pm 0.18$
OPAL'91 D-lepton	$1.51^{+0.24+0.12}_{-0.23-0.14}$
ALEPH'91+92 Exclusive	$1.19^{+0.43}_{-0.29} \pm 0.14$
DELPHI'91+92 Vtx.charge	$1.37 \pm 0.15 \pm 0.21$
OPAL'91+92 D-lepton	$1.63^{+0.14+0.10}_{-0.14-0.11}$
Average LEP	1.47 ± 0.11
CDF	$1.54 \pm 0.22 \pm 0.10$
Average	1.48 ± 0.10

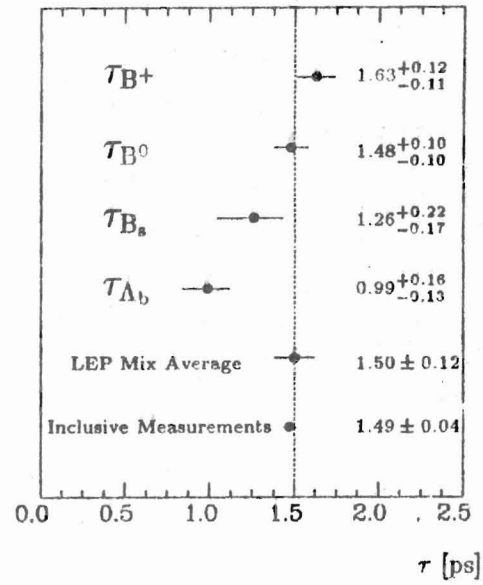

Figure 7: b-hadron lifetimes.

Nonleptonic Decays

Studies of nonleptonic B decays provide important information on the interplay of weak and strong interactions and help to develop quantitative theoretical descriptions of it. The b quark is much heavier than the c quark. Therefore the spectator model[18], the heavy quark effective theory [19] and many other theoretical approaches are expected to work better for beauty than for charm.

Table 4: Branching ratios for two body B meson decays.

	Mode	Branching Ration [%]
$\bar{B}^0 \to$	$D^{*+}\pi^-$	$0.27 \pm 0.04 \pm 0.04 \pm 0.01$
	$D^{*+}\rho^-$	$0.74 \pm 0.11 \pm 0.14 \pm 0.03$
	$D^+\pi^-$	$0.22 \pm 0.03 \pm 0.02 \pm 0.03$
	$D^+\rho^-$	$0.62 \pm 0.08 \pm 0.08 \pm 0.09$
$B^- \to$	$D^{*0}\pi^-$	$0.50 \pm 0.06 \pm 0.07 \pm 0.04$
	$D^{*0}\rho^-$	$1.41 \pm 0.19 \pm 0.30 \pm 0.11$
	$D^0\pi^-$	$0.47 \pm 0.03 \pm 0.05 \pm 0.02$
	$D^0\rho^-$	$1.07 \pm 0.10 \pm 0.16 \pm 0.04$

In particular a factorization approach which was quite successful for charm particles should work even better for beauty particles. In the most developed realization of this approach [20] two-body decays of B(D) mesons depend only on two amplitudes, a_1 and a_2, which correspond to diagrams with so-called external and internal W emission (see Fig.8).

B^0 decays into $D^{(*)-}\pi^+$ or $D^{(*)-}\rho^+$ are determined by one diagram only and branching ratios are proportional to $|a_1|^2$. Two diagrams interfere in the case of analogous B^- decays and branching ratios are proportional to $|a_1 + a_2|^2$.

New CLEO measurements of B-decays into $D^{(*)-}\pi$ and $D^{(*)}\rho$ are given in Table 4[21].

The average ratio of the corresponding branching ratios for neutral and charged B-mesons is smaller than unity [21] :

$$\langle r_b \rangle = \frac{Br(B^0 \to D^{(*)-}\pi^+(\rho^+))}{Br(B^+ \to D^{(*)0}\pi^+(\rho^+))} = 0.62 \pm 0.1.$$

This shows that a_2 is positive and interference is constructive. For D mesons the analogous ratio is considerably larger than unity:

$$\langle r_c \rangle = \frac{Br(D^0 \to K^{(*)-}\pi^+(\rho^+))}{Br(D^+ \to \bar{K}^{(*)0}\pi^+(\rho^+))} = 3.4 \pm 0.5$$

From the fit to the measured B meson branching ratios CLEO obtains [21] $a_1 = 0.98 \pm 0.16$ and $a_2 = 0.25 \pm 0.14$. In principle a_1 and a_2 can be calculated within QCD. Experimental measurements of them should be useful for development of theory.

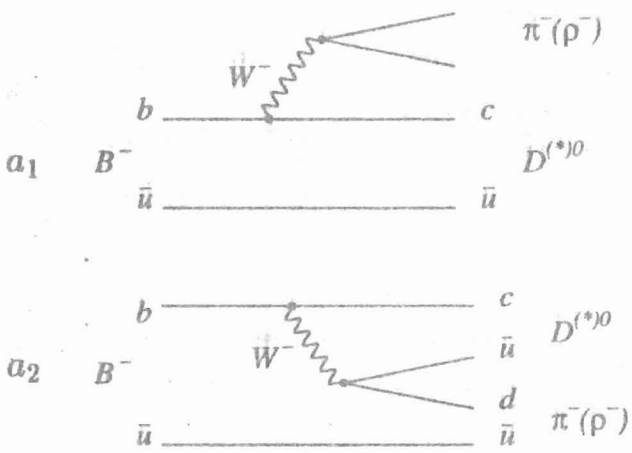

Figure 8: Feynman diagrams for two body B meson decays.

New precise measurements of charm branching ratios which were reported at this Conference [21, 22] improve the accuracy in estimates of charm yield in B meson decays. Using $BR(D^0 \to K^-\pi^+) = 3.80 \pm 0.13\%$, $BR(D^+ \to K^-\pi^+\pi^+) = 9.0 \pm 0.8\%$ and $BR(D_s^+ \to \phi\pi^+) = 3.7 \pm 0.9$ [23] we get Table 5.

Table 5: Charm yield in B decays.

Decay mode	BR [%]	
	ARGUS	CLEO
$B \to D^+ X$	$23.2 \pm 3.0 \pm 5.0$	$22.4 \pm 1.4 \pm 3.2$
$B \to D^0 X$	$51.1 \pm 4.0 \pm 6.6$	$60.8 \pm 2.4 \pm 2.7$
$B \to D_s^+ X$	7.8 ± 2.6	8.3 ± 2.0
$B \to$ "Λ_c" X	6.8 ± 0.6	6.7 ± 1.3
$B \to$ "$c\bar{c}$" X	$4 \cdot (1.07 \pm 0.27)$	$4 \cdot (1.10 \pm 0.09)$
Σ	93.2 ± 10.0	102.6 ± 5.7

The measured charm yield is somewhat smaller than the $1.1 - 1.2$ charm quarks per B decay predicted by the parton model. However, errors are still large and disagreement is not significant.

Semileptonic Decays

Inclusive semileptonic decays are the simplest for theoretical analysis and experimental measurements. However, theory and experiment do not agree. Recent experimental results on semileptonic branching ratios for b-hadrons are summarized in Table 6 [24]. The average semileptonic branching ratio is smaller than 11% while the parton model predicts values between 12% and 14% [18]. Recently corrections to the parton model prediction have been calculated using QCD [25]. They reduce slightly the parton model value but can not bring it into agreement with experiment.

Table 6: Inclusive semileptonic branching fraction of b hadrons.

Experiment	B_{sl}[%]
ARGUS	$10.2 \pm 0.4 \pm 0.2$
ARGUS$_{MI}$	$9.7 \pm 0.5 \pm 0.4$
CLEO	$10.65 \pm 0.05 \pm 0.33$
CUSB	$10.0 \pm 0.4 \pm 0.3$
CB	$12.0 \pm 0.5 \pm 0.7$
ALEPH	$11.4 \pm 0.3 \pm 0.4$
DELPHI	$9.7 \pm 0.4 \pm 0.7$
L3	$11.9 \pm 0.1 \pm 0.4$ $11.7 \pm 0.5 \pm 0.4$
OPAL	$10.5 \pm 0.6 \pm 0.5$
Average LEP	11.0 ± 0.5

However, all experimental results have one drawback. The low energy part of the lepton spectrum is dominated by background from secondary leptons from charm decays. Therefore, only the high energy part is effectively used for the determination of the semileptonic branching ratio. Extrapolation to low momenta is usually done using theoretical models [26, 27]. Such extrapolation can underestimate a contribution from soft leptons and hence to be responsible for the discrepancy.

The ARGUS Collaboration developed a method of secondary lepton suppression. This allowed them to measure the primary lepton spectrum in almost the full energy range and to determine the semileptonic branching ratio in a model independent way [28, 29, 30].

Background from cascade leptons can be considerably reduced by tags from the second B meson in $e^+e^- \to \Upsilon(4S) \to B\bar{B}$ events. Using electrons and muons in the momentum interval between 1.4 GeV/c and 2.3 GeV/c as tags the cascade background is identified by its charge sign. Electrons with a like-sign lepton tag are mainly cascade electrons, and those with an opposite-sign lepton tag are mainly primary. The main corrections arise from $B\bar{B}$ oscillations and from

events where both leptons originate from the same B meson. The first of these corrections is well known, and the latter can be determined experimentally from the distribution of the angle between the two leptons.

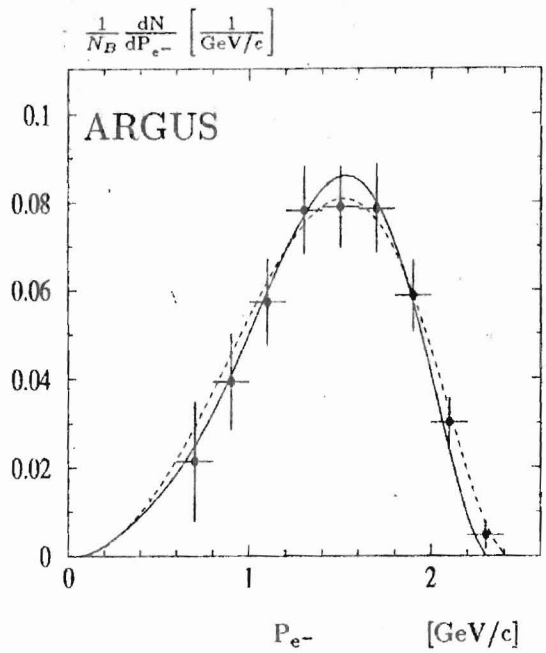

Figure 9: Primary electron spectrum in B decays. Parton and form factor model fits are shown by the solid and dashed lines respectively.

Fig. 9 shows direct lepton spectrum obtained by ARGUS using B tagging with leptons from the second B decay. Extrapolation to lepton momenta below 600 MeV constitutes a correction of only $(5.7 \pm 1.0)\%$. Therefore, the measurement gives essentially model-independent result $BR(B \to e\nu X) = 9.6 \pm 0.5 \pm 0.4\%$ which increases to

$$BR(B \to e\nu X) = 9.7 \pm 0.5 \pm 0.4\%$$

if one adds D and D^* tags. The shape of the spectrum is well described by theoretical models. There is no increase at low momenta which could explain the lepton deficit "problem".

The secondary decay fraction

$$BR(B \to \bar{D} \to e^-) = 7.9 \pm 0.8 \pm 1.0\%$$

is somewhat smaller than expected $(9.8 \pm 1.4\%)$ but consistent with expectations within errors.

Several authors have discussed the possibility that a large charged Higgs contribution in $B \to \tau\nu X$ could explain the small semileptonic branching ratios of B mesons [31]. This possibility is ruled out by the ALEPH measurement [32]

$$BR(B \to \tau\nu X) = 2.76 \pm 0.47 \pm 0.43\%,$$

which agrees perfectly with the Standard Model (SM) prediction of $2.8 \pm 0.3\%$.

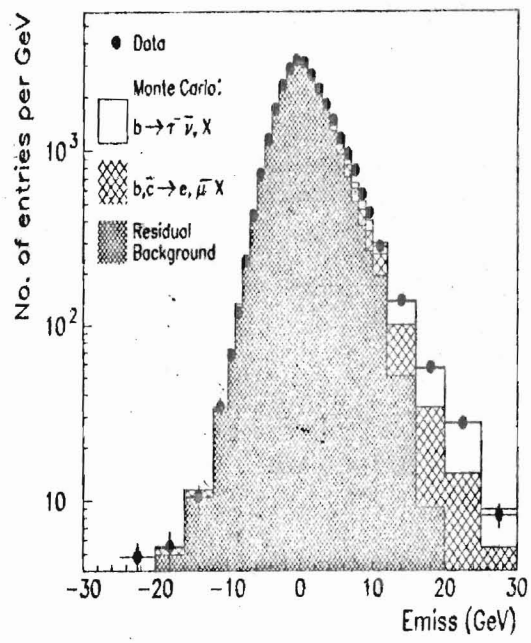

Figure 10: Missing energy distribution in tagged b events without leptons.

The ALEPH result is based on the observation of events with large missing energy and no leptons (see Fig.10). It can be used to exclude a large region in the parameter space of two Higgs doublet models [31, 32]: $\tan\beta < 0.4 \cdot M_H/(1\ \mathrm{GeV})$.

The B meson semileptonic width depends on CKM matrix elements V_{cb} and V_{ub}:

$$\Gamma^b_{sl} = \frac{BR^b_{sl}}{\tau_b} = \frac{G_F m_b^5}{192\pi^3}\left(\gamma_{cb}|V_{cb}|^2 + \gamma_{ub}|V_{ub}|^2\right).$$

Since $|V_{ub}|$ is much smaller than $|V_{cb}|$ the latter can be calculated using measurements of BR_{sl} and τ_b :

$$|V_{cb}| = 0.042 \pm 0.001 \pm 0.004.$$

The error is dominated by the uncertainty in m_b and in γ_{cb} which are model dependent.

$|V_{cb}|$ can be also estimated using exclusive semileptonic decays. The results are similar to the inclusive approach [33] but model dependent.

Heavy quark effective theory allows a model independent determination of $|V_{cb}|$ from the measurements of $B \to D^*\ell\nu$ at maximum q^2 [34, 35, 19]. Unfortunately experimental data at this point are not accurate enough (see Fig.11) and extrapolation from the whole phase space is performed. The heavy quark effective

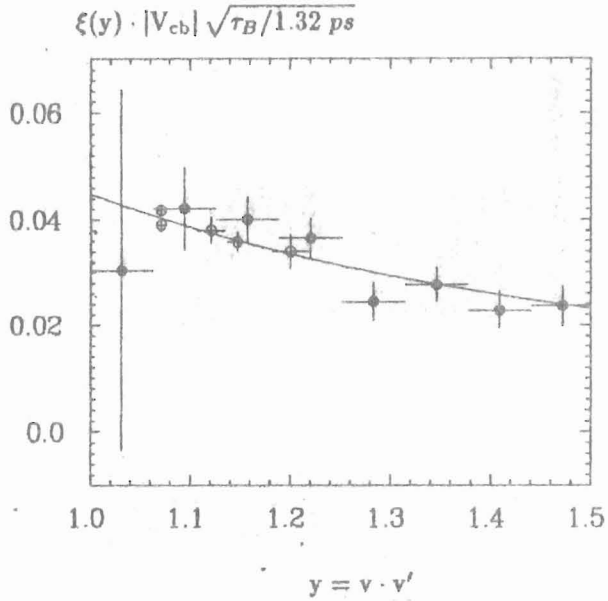

Figure 11: The Isgur-Wise function multiplied by $|V_{cb}|\sqrt{\tau_B/1.32\ ps}$. Filled circles show ARGUS results on the decay $B^0 \to D^{*-}\ell^+\nu$. Other points show results of the lattice calculations.

theory predicts that all semileptonic B decays into D^* and D are described by V_{cb} and a single universal form-factor, the so-called Isgur-Wise function $\xi(y)$, where $y = v \cdot v'$ is a product of B and $D^{(*)}$ four-velocities. Theory does not fix the shape of the Isgur-Wise function. Usually it is taken from models and this leads to a model dependence of the results.

Using a linear parametrization of the Isgur-Wise function for fitting ARGUS data in the decays $B^0 \to D^{*-}\ell^+\nu$ and $B^+ \to \bar{D}^{*0}\ell^+\nu$ [36, 37] we obtain

$$|V_{cb}| = 0.042 \pm 0.005 \quad \text{and}$$
$$|V_{cb}| = 0.040 \pm 0.007$$

respectively. It is hard to estimate the model dependence but different parametrization of the Isgur-Wise function change the result by about 10% [37]. From the analogous analysis of the decay $B^0 \to D^{*-}\ell^+\nu$ CLEO presented similar results [38] :

$$|V_{cb}| = 0.036 \pm 0.004 \pm 0.004.$$

Last year's attempts to fix theoretically the shape of the Isgur-Wise function [39] have not been successful [40]. There has been a progress in lattice calculations of the Isgur-Wise function [41] as illustrated in Fig.11. However, the greatest hope for a reduction in the model dependence of V_{cb} determination lies with the expected improvement in experimental data.

Charmless Semileptonic Decays

Measurements of the CKM matrix element $|V_{ub}|$ are very important for constraining the theory of weak interactions. In particular, a non-zero value is essential for the Kobayashi-Maskawa explanation of the origin of CP violation.

In 1989 ARGUS [42] and CLEO [43] obtained the first evidence for charmless semileptonic decays by observing leptons with momenta above the endpoint for $b \to c\ell\nu$ transitions. ARGUS also observed [44] a completely reconstructed event with $\bar{B}^0 \to \pi^+\mu^-\bar{\nu}$. Using a parton model [26] for extrapolation to the whole momentum interval CLEO and ARGUS obtained:

$$|V_{ub}/V_{cl}| = 0.12 \pm 0.014^1 \quad \text{(CLEO)},$$
$$|V_{ub}/V_{cb}| = 0.11 \pm 0.012 \quad \text{(ARGUS)}.$$

One should remember that errors on $|V_{ub}/V_{cb}|$ are not gaussian and moreover there is a large model dependence of at least a factor of two.

Using their new detector the CLEO Collaboration has performed a new measurement of charmless semileptonic decays [45]. They used two approaches with "soft" and "strict" cuts. In the first approach the continuum contribution is suppressed by rejecting jet-like events with the Fox-Wolfram parameter $R_2 > 0.3$. The efficiency of this requirement for $b \to u\ell\nu$ transitions is found by Monte Carlo studies to be 72%.

The CLEO II detector is hermetic enough to detect missing momentum $\vec{p}_{mis}$ due to ν emission in semileptonic decays. Therefore, in the second approach with "strict" cuts CLEO requires a missing momentum larger than 1 GeV/c in the hemisphere opposite to the lepton. This approach is very close to the method used by ARGUS [42, 44]. In addition CLEO required very small values of R_2 : $R_2 < 0.2$. By these requirements continuum background is suppressed by a factor of 70 while efficiency remains as high as 38%.

Fig.12 shows the lepton spectra obtained with the two approaches. In both cases a clear excess is visible above the contribution from $b \to c\ell\nu$ transitions and the continuum background.

Using the observed excess in the momentum interval 2.4 – 2.6 GeV/c and a parton model [26] for the extrapolation to the full momentum range CLEO obtains:

$$|V_{ub}/V_{cb}| = 0.073^{+0.010}_{-0.011} \quad \text{("strict" cuts)}$$
$$|V_{ub}/V_{cb}| = 0.082^{+0.011}_{-0.012} \quad \text{("soft" cuts)}.$$

[1] We quote here the CLEO measurement in the momentum interval 2.4 – 2.6 GeV/c, which can be compared with the new CLEO results.

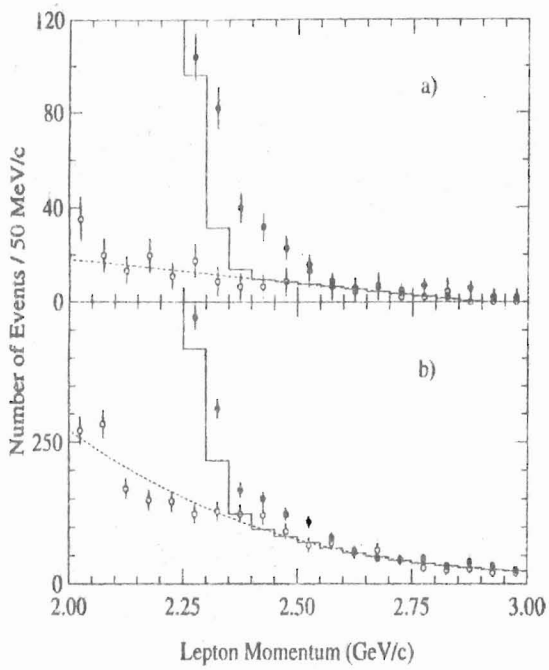

Figure 12: Lepton momentum spectrum measured by CLEO after the (a) "strict" and (b) "soft" cuts. The filled and open points are the $\Upsilon(4S)$ and scaled continuum data. The solid curves show the predicted $b \to c\ell\nu$ contribution. The dashed curves are fits of continuum data.

As a final value CLEO quotes:

$$|V_{ub}/V_{cb}| = 0.076 \pm 0.008.$$

This result is larger than the value $|V_{ub}/V_{cb}| = 0.062 \pm 0.018$ presented by CLEO at the Dallas Conference [46]. Since the measured rate is proportional to $|V_{ub}|^2$ the new $|V_{ub}/V_{cb}|$ value corresponds to about a 50% larger rate. The new CLEO value is twice smaller (in rate) than the first CLEO [43] and ARGUS [42, 44] results. However, within errors results are consistent (the difference is about two standard deviations) and it is possible to average them. This leads to the value

$$|V_{ub}/V_{cb}| = 0.082 \pm 0.007,$$

which is dominated by the new CLEO result.

Use of different theoretical models for extrapolation of the lepton momentum spectrum leads to $|V_{ub}/V_{cb}|$ values between 0.06 and 0.11 [45]. Taking this spread as a rough measure of the systematic uncertainty we finally get

$$|V_{ub}/V_{cb}| = 0.08 \pm 0.02.$$

So far there has been no convincing measurement of exclusive charmless semileptonic decays. The best upper limits have been obtained by CLEO [47]:

$$\begin{array}{lll} BR(B \to \rho^0 \ell\nu) & < (1.6 - 2.7) \cdot 10^{-4} & @\ 90\%\ CL \\ BR(B \to \pi\ell\nu) & < 1.4 \cdot 10^{-4} & @\ 90\%\ CL, \end{array}$$

where the range of values is due to the model dependence of the detection efficiencies. These limits correspond to upper limits on $|V_{ub}/V_{cb}|$ of $0.08 - 0.13$ which are close to the value obtained from inclusive measurements.

Smaller values of $|V_{ub}/V_{cb}|$ and $|V_{cb}|$ lead to better lower bounds on m_t from the CP violation parameter ε_k [48] (see Fig.13).

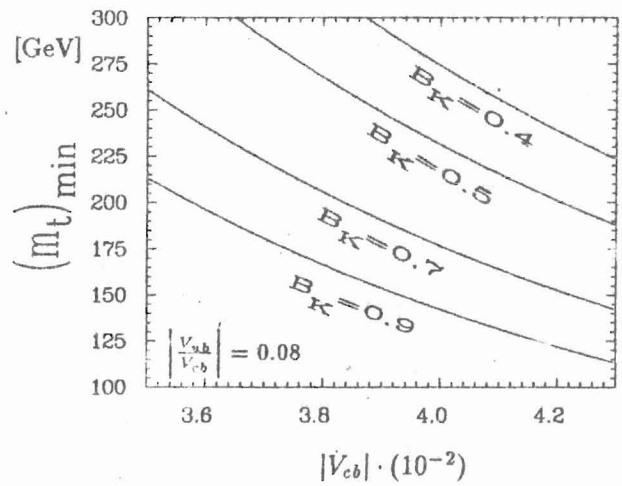

Figure 13: Lower bounds on m_t from ε_K.

$B\bar{B}$ Oscillations

Many new measurements of $B^0\bar{B}^0$ mixing have been reported at this conference.

CLEO presented a high statistics measurement of dileptons [49]. They observed 184.5 ± 30 like-sign dileptons which corresponds to

$$\chi_d = 0.157 \pm 0.016 \pm 0.018^{+0.028}_{-0.021}.$$

The last and the largest error is due to the uncertainty in the lifetimes of charged and neutral B mesons and their production fractions in $\Upsilon(4S)$ decays since

$$\chi_d = \frac{N_{\ell^\pm\ell^\pm}}{N_{\ell\ell}} \left(1 + \frac{f_+}{f_0}\left(\frac{\tau_+}{\tau_0}\right)^2\right).$$

By tagging one neutral B meson with a semileptonic decay into D^* ARGUS [14] and CLEO [49] have managed to reduce this error considerably. In order to keep the efficiency reasonable only a slow pion from

the D^* and a lepton were required. Counting the numbers of like-sign and unlike-sign dileptons in such events ARGUS and CLEO obtained

$$\chi_d = 0.155 \pm 0.046 \pm 0.039 \quad \text{and}$$
$$\chi_d = 0.149 \pm 0.023 \pm 0.019 \pm 0.010$$

respectively. One should remember that this method is highly correlated with the usual dilepton method and therefore the results should not be averaged.

For the first time oscillations between B_d^0 and $\bar{B}_d^0$ mesons have been observed directly by ALEPH [50, 51] and DELPHI [51].

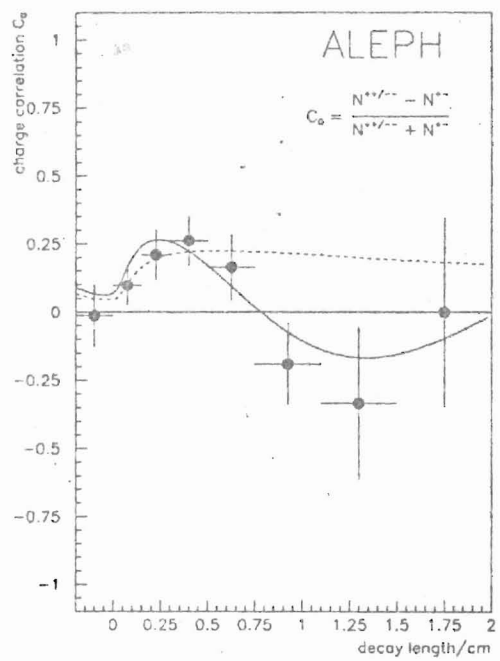

Figure 14: Difference between the fractions of like-sign and unlike-sign $D^*\ell$ pairs.

ALEPH observed time oscillations by measuring the decay length distribution in $D^*\ell$ and dilepton events. In the first method $B^0\bar{B}^0$ oscillations lead to unlike-sign pairs $D^{*\pm}\ell^{\mp}$. Unfortunately the D^* vertex can not be measured precisely. Instead the decay length distribution of D^0 mesons was measured for like-sign and unlike-sign $D^*\ell$ pairs versus the decay length. Fig.14 shows the normalized difference between number of like- and unlike-sign $D^*\ell$ pairs versus the decay length. Data show obvious oscillation curve which corresponds to the oscillation frequency

$$\Delta m_d = (3.44^{+0.65+0.26}_{-0.70-0.20}) \cdot 10^{-4}\ \text{eV/c}^2.$$

Using $\tau_{B_d^0} = 1.44 \pm 0.15\ ps$ ALEPH gets

$$x_d = \frac{\Delta m_d}{\Gamma_d} = 0.75^{+0.15+0.08}_{-0.14-0.05}.$$

In the second method ALEPH measures the proper time distribution for B decay vertices in events with dileptons. First the charmed particle decay vertex is reconstructed on each side of the event, and then the inferred charm track is vertexed with the lepton to give the b decay point. The fraction of like-sign leptons versus the proper time of the B candidate is shown in Fig.15.

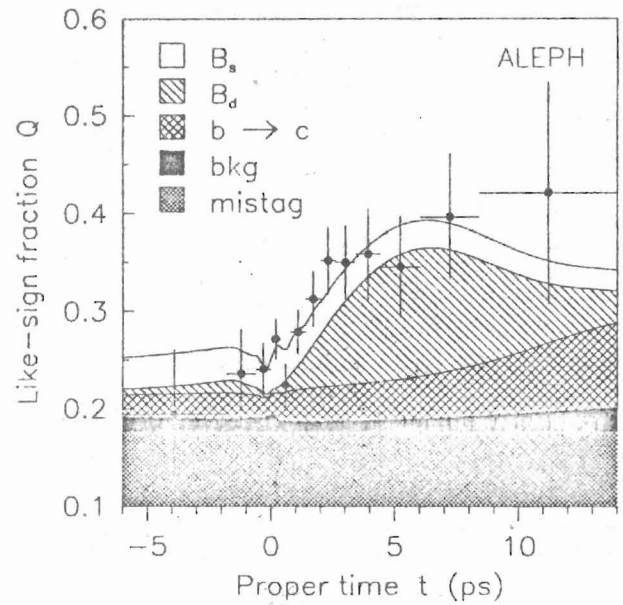

Figure 15: Like-sign fraction of dileptons with the contributions from various sources of dileptons indicated.

The beautiful oscillation curve is seen on top of various backgrounds. Since both B_d^0 and B_s^0 decay semileptonically the measured time distribution is sensitive to both Δm_d and Δm_s. Assuming infinite frequency of B_s oscillations ALEPH gets from the fit

$$\Delta m_d = 0.53^{+0.07+0.11}_{-0.06-0.10}\ ps^{-1},$$

which corresponds to

$$x_d = \frac{\Delta m_d}{\Gamma_d} = 0.76 \pm 0.10 \pm 0.16.$$

If Δm_s is allowed to vary the fit prefers large values of Δm_s without changing the other parameters much. A sensitivity to Δm_s of about a few ps^{-1} is indicated by the fit. However, ALEPH does not quote number as studies of systematic uncertainties are unfinished.

The DELPHI collaboration analysed time dependence of high p_T ($p_T > 1$ GeV/c) like-sign dileptons. The B lifetime is estimated using the lepton impact parameter. The accuracy of such an estimate is only about 70% but this is sufficient for a measurement of $B_d^0\bar{B}_d^0$ oscillations. Fig.16 shows the time dependence

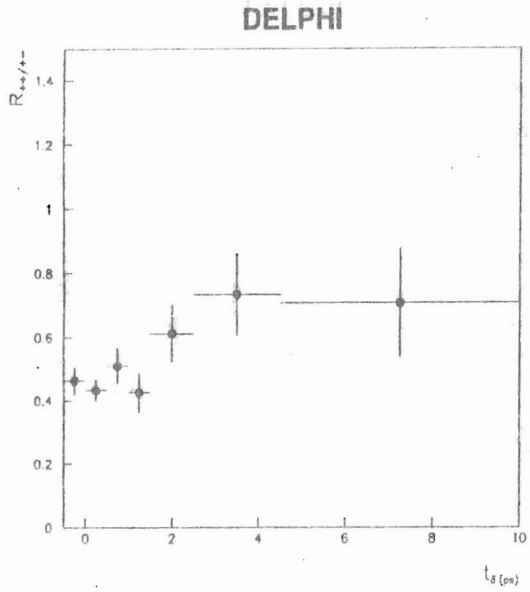

Figure 16: Ratio of the numbers of like-sign and unlike-sign dileptons.

of $r_d = N(\ell^+\ell^+ + \ell^-\ell^-)/N(\ell^+\ell^-)$. It increases from 0.45 ± 0.02 for $t < 2\ ps$ to 0.66 ± 0.06 for $t > 2\ ps$. From this measurement DELPHI obtains

$$x_d = 0.65^{+0.30}_{-0.20} \pm 0.11.$$

The direct measurements of $B^0_d \bar{B}^0_d$ oscillations agree perfectly with time integrated measurements by ARGUS and CLEO ($x_d = 0.69 \pm 0.09$). Averaging all results on x_d we get

$$x_d = 0.71 \pm 0.07.$$

Assuming 110 GeV/c^2 $< m_t <$ 200 GeV/c^2 and 175 MeV $< \sqrt{f_B^2 B} <$ 255 MeV one gets [52]:

$$0.005 < |V_{td}| < 0.012.$$

Measurements of $B\bar{B}$ mixing at high energies are summarized in Table 7[53]. The accuracy has improved considerably during the last years. New methods have been tried such as jet-charge lepton correlations. The results are consistent with $\chi_s \approx 0.5$ predicted by the Standard Model. However sensitivity of the time integrated measurements to $B^0_s \bar{B}^0_s$ mixing is very limited. The available data lead only to a lower limit $\chi_s > 0.22$ at 90% CL which depends on fractions of B^0_d and B^0_s mesons (assumed here to be 0.375 and 0.15 correspondingly).

Table 7: $B\bar{B}$ mixing at high energies.

Experiment	x
MAC	$0.21^{+0.29}_{-0.18}$
MARK II	$0.17^{+0.15}_{-0.08}$
CDF	$0.176 \pm 0.031 \pm 0.032$
UA1	$0.148 \pm 0.029 \pm 0.017$
L3	$0.118 \pm 0.012 \pm 0.010$
ALEPH	$0.105 \pm 0.009 \pm 0.010$
DELPHI	$0.121 \pm 0.015 \pm 0.007$
DELPHI global	0.160 ± 0.030
OPAL global	$0.143 \pm 0.022 \pm 0.007$
ALEPH global	$0.114 \pm 0.014 \pm 0.008$
D0	$0.14 \pm 0.03 \pm 0.06$
Average	0.121 ± 0.010

Evidence for Penguins: Observation of $B \to K^*\gamma$

So-called penguin diagrams have been invented long time ago [54] and their importance for B decays has been noted [55]. The radiative process $b \to s\gamma$ (see Fig.17) provides the cleanest signature for penguin diagrams. The branching ratio for $b \to s\gamma$ is expected to be in the range $(2-4) \times 10^{-4}$ in the SM with QCD corrections [56]. The fraction of $b \to s\gamma$ decays that hadronize to $K^*(892)\gamma$ is predicted less reliably to be in the range from 5% to 40% [57].

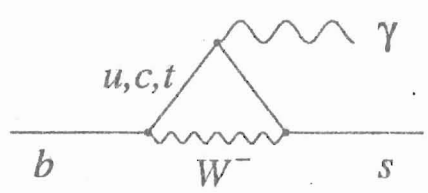

Figure 17: Penguin diagram for $b \to s\gamma$. The photon may be radiated from any of the four lines.

Recently CLEO has observed the decay $B \to K^*\gamma$ [58]. The dominant experimental problem is to separate $B \to K^*\gamma$ decays from large background from continuum processes with and without initial state radiation (ISR) of photons. CLEO suppresses this background with a series of event shape cuts.

The $q\bar{q}$ background is suppressed by rejection of events with two-jet topology (with $R_2 > 0.5$) and requirement of a large normalized momentum transverse to the photon direction ($0.25 < S_\perp < 0.6$).

To further suppress the ISR background CLEO considers variables in the rest frame of the e^+e^- following the radiation of the high energy photon (the primed frame). In this frame they require $R'_2 < 0.3$, where R'_2 is evaluated excluding the photon, and $|\cos\theta'| > 0.5$, where θ' is the angle between the photon and thrust axis of the rest of the event.

B candidates are required to have energy close to the beam energy, $|\Delta E| = |E_{beam} - E_{K^*\gamma}| < 90$ MeV (2.2σ). For candidates passing this cut, photon energy is scaled to obtain $\Delta E = 0$ and then the $K^*\gamma$ mass is computed. The resulting mass distribution (see Fig.18) has a peak at the B mass.

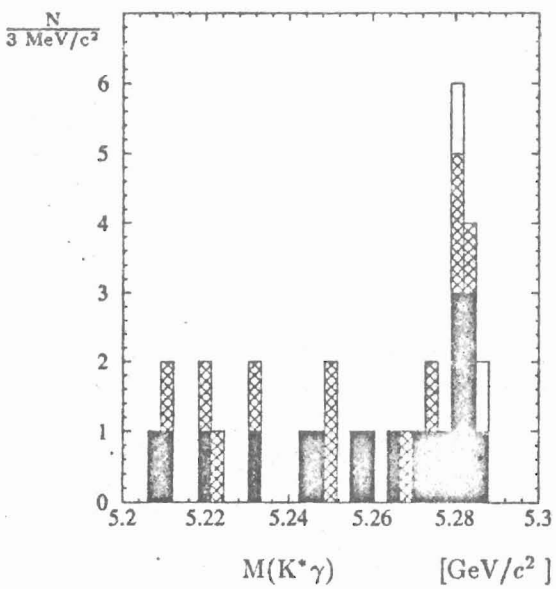

Figure 18: The mass distribution for $K^{*0}\gamma$ (black histogram) and $K^{*-}\gamma$.

Continuum background is estimated using ΔE and mass sidebands. For the three final states, $K^-\pi^+\gamma$, $K^0_s\pi^-\gamma$ and $K^-\pi^0\gamma$ it is found to be 1.1 ± 0.2, 0.05 ± 0.03 and 0.8 ± 0.3 events, respectively. It is also checked that distribution of variables inside the cuts for events in the B mass peak is inconsistent with that expected for continuum events. The the probability of the observed peak to be the background fluctuation is smaller than 10^{-8}.

After background subtraction there are 6.6 ± 2.8 and 4.1 ± 2.3 signal events in $K^{*0}\gamma$ and $K^{*-}\gamma$ final states, respectively. This corresponds to

$$BR(B^- \to K^{*-}\gamma) = (5.7 \pm 3.1 \pm 1.1) \times 10^{-5}$$
$$BR(B^0 \to K^{*0}\gamma) = (4.0 \pm 1.7 \pm 0.8) \times 10^{-5}.$$

The average value is

$$BR(B \to K^*\gamma) = (4.5 \pm 1.5 \pm 0.9) \times 10^{-5}.$$

In the search for inclusive $b \to s\gamma$ transitions CLEO uses similar event shape variables ($R_2, S_\perp, R'_2, \cos\theta'$) in order to suppress background. However, even after background suppression by a factor of 470 (!) it dominates the signal region in the photon energy spectrum. In the signal region between 2.2 GeV/c and 2.7 GeV/c CLEO observes an excess of 69 ± 43 photons after background subtraction. This excess is not statistically significant and leads to the upper limit of

$$BR(b \to s\gamma) < 5.4 \cdot 10^{-4} \quad @\ 95\%\ \mathrm{CL},$$

which is very close to the SM predictions.

The CLEO results on exclusive and inclusive radiative B meson decays provide the first measurement of the CKM matrix element V_{ts} [59]:

$$0.50 < |V_{ts}/V_{cb}| < 1.67.$$

They also provide important constraints on the extensions of the SM. The existence of charged Higgs particles would lead to additional diagrams for the $b \to s\gamma$ transition and change the branching ratio. In the two-Higgs-doublet models the CLEO results allow to exclude $H^\pm$ masses well above the lower bound from the direct searches at LEP [60]. The decay mode $t \to H^+b$ can be also excluded [60]. Obviously such conclusions are extremely important not only for our present knowledge but also for developing a strategy for future searches.

However, in the most interesting version of the two-Higgs-doublet model, the Minimal Supersymmetric Standard Model (MSSM), contributions from other supersymmetric particles ($\tilde{\chi}^-$, $\tilde{\chi}^0$, $\tilde{g}$), can cancel the charged Higgs contribution [61, 62]. The CLEO results on $b \to s\gamma$ transitions exclude a large fraction of possible combinations of parameters in MSSM but do not restrict $m_{H^\pm}$. To a large extent this is due to uncertainty in the SM estimates of $BR(b \to s\gamma)$.

Fig.19 shows the allowed range in the (m_H, $\tan\beta$) plane [62] with the SM constraint

$$2.9 \cdot 10^{-4} < BR(b \to s\gamma) < 4.8 \cdot 10^{-4},$$

which is close to the CLEO constraints. The density of points in Fig.19 is proportional to the fraction of possible solutions left after the use of the constraint on $BR(b \to s\gamma)$. Low m_{H^+} is not excluded and it is still worthwhile to search for the decay $t \to H^+b$.

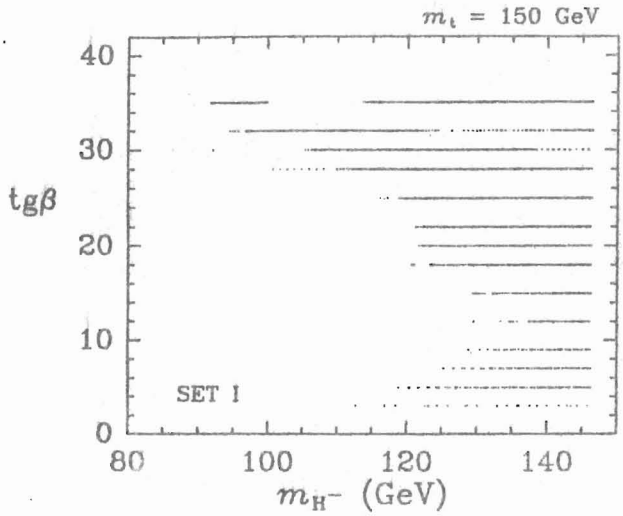

Figure 19: Allowed region in the $(m_H, \tan\beta)$ plane.

Search for $b \to s$ "g" transitions

Penguin diagrams lead also to transitions $b \to sg$, $b \to sgg$, and $b \to sq\bar{q}$ which result in non-leptonic charmless B decays. We will denote such transitions as $b \to s$ "g". These processes are not rare. The SM predicts them at a level of $(1-2)\%$ [63]. Their rate can be further enchanced in the extensions of the SM, for example in SUSY [64]. However it is very hard to detect the $b \to s$ "g" transitions experimentally. The only upper limit on multibody final states comes from the charm counting in B decays and it allows even 20% contribution of charmless hadronic decays.

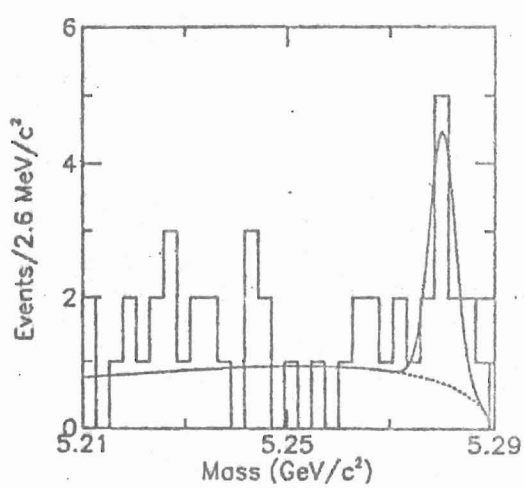

Figure 20: Beam constrained mass. Curves are projections of the multidimensional likelihood fit.

The CLEO Collaboration has searched for two body charmless B decays [65]. They suppress a formidable background using a multidimensional analysis of many variables : the thrust and B meson angles, energy and momentum flow in nine bins around $K\pi$ axis. Fig.20 shows the $K^-\pi^+$ mass distribution obtained by CLEO and the results of the multidimensional analysis. This analysis gives a signal of $13.6^{+4.7}_{-3.9}$ events with a statistical significance of 5.4 standard deviations. The significance drops to 4.2σ if systematic uncertainties are taken into account. Such a significance is not obvious from the mass distribution shown in Fig.20. It is hidden in the likelihood of the multidimensional analysis.

The CLEO II detector can not separate $K^-\pi^+$, $\pi^+\pi^-$, and K^+K^- final states well enough. Therefore all these states can contribute to the peak in Fig.20. Nevertheless, some separation is possible on the basis of ionization energy losses in the drift chamber and the difference in ΔE for different mass hypotheses. It gives $N_{K^-\pi^+} = 6.4^{+3.9}_{-3.1}$, $N_{\pi^+\pi^-} = 7.2^{+4.3}_{-3.5}$, and $N_{K^+K^-} = 0^{+0.8}_{-0.}$. Only the sum of $K^-\pi^+$ and $\pi^+\pi^-$ channels is statistically significant:

$$BR(\bar{B}^0 \to K^-\pi^+ \text{ or } \pi^+\pi^-) = (2.4^{+0.8}_{-0.7} \pm 0.3) \cdot 10^{-5}.$$

It is hard to get information on the total yield of $b \to s$ "g" transitions from the measurements of two-body decays. Therefore ARGUS tried to look for semi-inclusive decays $B \to K(n\pi^\pm)$, where $n = 1$–7[29]. The second B in the event is required to be reconstructed in the semileptonic decay modes $B \to D^{(*)}\ell\nu$. The requirement of a completely reconstructed $\Upsilon(4S)$ decay reduces the continuum background by 3×10^5 times while the tagging efficiency with semileptonic decays remains at about 1% level.

Using this procedure six $K(n\pi^\pm)$ events have been found in the B mass region with a negligible background of 0.14 ± 0.14 events. In five out of six events the $K(n\pi^\pm)$ system contains a charm candidate. The sixth event (see Fig.21) can not be explained as a result of the $b \to c$ transition. In this event the tagging B decays into $D^{*+}\mu^-\nu$ and the second one into $K^+\pi^-$. K^+ and π^- have momenta (2.664 ± 0.035 GeV/c and 2.595 ± 0.030 GeV/c) above the endpoint for $b \to c$ transitions and can not be combined with other particles in the event to form a charm candidate. Unfortunately, like in case of CLEO, it is not possible to exclude a possibility that the actual decay is $B^0 \to \pi^+\pi^-$ although the probability of this is 13 times smaller.

Observation of one event agrees with the expectations calculated for $BR(b \to s$ "g"$) = 2\%$. There is no indication of a very large enhancement of this branching ratio with respect to the SM prediction.

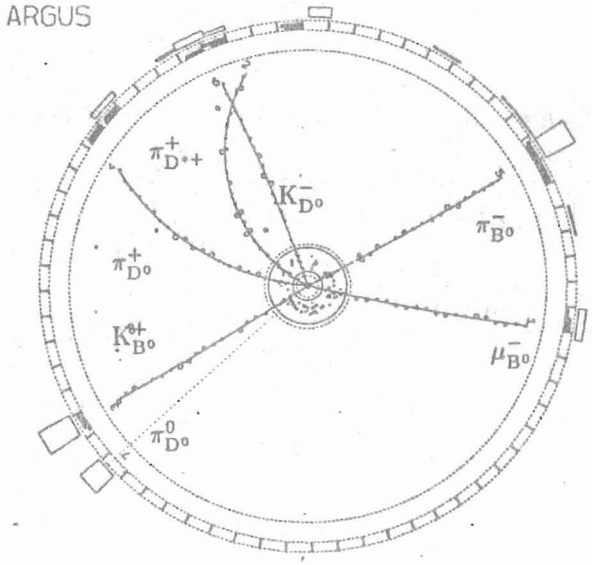

Figure 21: Completely reconstructed event with the decay $B^0 \to K^+\pi^-$ (or $\pi^+\pi^-$).

Acknowledgments

I am especially indebted to I.Belyaev, Yu.Gershtein, P.Saull, D.H.Saxon, S.Semenov, and A.Snizhko for the help in the preparation of this paper. I would like to thank F.Gilman for the support which allowed me to participate in this Conference.

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