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ABSTRACT

The present knowledge of b quark decay and spectroscopy is largely based on data accumulated at e^+e^- colliders, in particular machines operating near threshold for open beauty production. On the other hand, interesting information is coming from Fermilab hadron collider data, thus strengthening the hope that soon it will be possible to exploit the huge cross sections for high energy hadronic b production to explore many different facets of b -flavored hadron phenomenology. The exciting goal of discovering CP violation in B meson decays is stirring a great deal of interest in several laboratories. To this purpose "asymmetric" e^+e^- " B -factories" are being pursued in the United States and in Japan. In addition, dedicated b -experiments at hadron machines may play a significant role in this endeavor. Past achievements and potentials of different approaches will be presented.

1. Introduction

The b -quark was discovered at Fermilab in the Υ bound states in 1977.¹ Since then, the major features of its confined properties (Υ spectroscopy) and decay properties (through B meson decays) have been studied most extensively at e^+e^- colliders, in particular at machines near threshold for open beauty production, CESR at Cornell University and DORIS-II at DESY. The first measurements of B lifetime were made at PEP and PETRA and have been repeated with improved statistical accuracy at LEP and, recently, by the CDF experiment at Fermilab. In particular, very important achievements are experimental data on individual b -flavored hadron lifetimes.^{2,3} These data show the crucial role of precision vertex detectors in b physics.

B decays have been studied at hadron machines too, in particular in collider experiments. The pioneering work was performed at the $S\bar{p}\bar{p}S$ by the UA1 experiment, which measured the production cross section and saw the first in-

Table 1: Facilities for b-quark production operating in the past decade.

Accelerator	Location	$\sqrt{S}(\text{GeV})$	$\sigma_{b\bar{b}}(\text{nb})$	$\sigma_{b\bar{b}}/\sigma_t$	$\langle L \rangle_{\text{day}} (pb^{-1})^\dagger$
CESR	Cornell, USA	10.5	1.15	0.25	11
DORIS	DESY, Germany	10.5	1.15	0.25	0.9
PEP	SLAC, USA	29.0	0.04	0.09	0.3‡
PETRA	DESY, Germany	35.0	0.03	0.09	0.5
TRISTAN	KEK, Japan	55.2	0.013	0.09	0.5
LEP	CERN, Switzerland	90.0	7.0	0.215	0.2
<i>SppS</i>	CERN, Switzerland	630	$\approx 2 \cdot 10^4$	$\approx 3 \cdot 10^{-4}$	0.05
TEV I	Fermilab, USA	1800	$\approx 6 \cdot 10^4$	$\approx 8 \cdot 10^{-4}$	0.13

$^\dagger \langle L \rangle_{\text{day}}$ is defined as the average daily luminosity in most recent runs over a period when the machine was operating regularly. The figures are based on private communications from staff members of the various laboratories and are meant to give an order of magnitude indication of the luminosity capability of the various machines. They may have been evaluated averaging over different periods of time and using slightly different assumptions.

‡ This number is extracted from the MAC integrated luminosity over four years of operation. Subsequently PEP has run for brief periods with higher average luminosity ($1.2 pb^{-1}/\text{day}$).

dications of $B^0 \bar{B}^0$ mixing.⁴ CDF has recently produced interesting data on b physics, studying exclusive decays involving ψ mesons, in particular performing a quite extensive investigation of the $b\bar{b}$ production.⁵ The other experiment now taking data at the Tevatron, D0, has presented preliminary information on the production cross section and mixing.⁶

The data accumulated at the facilities listed in Table 1 have shown the great potential of “beautiful hadrons” as probes of our present understanding of the “Standard Model”.⁷ These achievements have motivated several laboratories to investigate their capabilities for a successful b -physics program.

The first figure of merit which characterizes different facilities is given by the $b\bar{b}$ production cross section. This is certainly a criterion which favors hadronic

Fig. 1 The e^+e^- annihilation cross section.

machines. As an example, the cross section for beauty production measured by UA1, operating at the $S\bar{p}\bar{p}S$, is four orders of magnitude greater than the cross section at the $\Upsilon(4S)$.⁴ Fig. 1 shows the dependence upon the center-of-mass energy of the annihilation cross section at e^+e^- colliders and the regions covered by existing machines. The non-resonant component is proportional to $1/s$.

The fraction of hadronic events which contain a $b\bar{b}$ pair, $\sigma_{b\bar{b}}/\sigma_{tot}$, is not so favorable for hadronic machines, as Table 1 illustrates. This fraction increases with $\sqrt{s}$, where $\sqrt{s}$ is the center-of-mass energy, as $\sigma_{b\bar{b}}$ increases much faster than σ_t . Electron-positron colliders operating at the Υ and Z^0 resonance have a much higher $\sigma_{b\bar{b}}$ and ratio $\sigma_{b\bar{b}}/\sigma_t$ than continuum e^+e^- machines.

Simple topological and kinematical criteria have been developed to enhance the beauty content in the data sample from experiments performed at the $\Upsilon(4S)$. Higher energy e^+e^- colliders and hadronic machines produce boosted b -flavored hadrons, allowing some enrichment of the beauty sample by identifying displaced vertices in the range expected for b decays. The potential of this technique has been clearly shown by the beautiful recent data on individual b -hadron lifetimes, the B_S discovery, and the measurement of the time evolution of $B^0\bar{B}^0$ mixing.

The most exciting investigation in the field of beauty physics is the exploration of the phenomenology of CP violation. This promises to be a rich field which will provide a crucial test of the validity of the Standard Model and deeper insight to the mechanism of CP violation. The importance of this symmetry breaking for the very existence of the universe is paralleled by a paucity of experimental information, limited to measurements performed in the neutral K system. This goal has prompted several studies aimed at designing “ B -factories”, which are expected to achieve the desired statistical accuracy in CP asymmetry measurements within a time scale of a few years. Two B -factories^{8,9} are presently expected to turn on around the end of the decade. An existing hadron facility, Fermilab, is considering a dedicated b physics program with the goal of measuring CP violation and $B_S^0 \bar{B}_S^0$ mixing. There is some interest in installing dedicated beauty spectrometers in the future ultra-high energy pp collider planned at CERN (LHC) either in an interaction region of the collider itself,¹⁰ or in fixed target mode of operation, either with an extracted beam¹¹ or with a gas jet target.¹² In addition, several efforts are presently being pursued to explore the sensitivity to CP violation asymmetries and $B_S^0 \bar{B}_S^0$ mixing of general purpose detectors.^{13,14} At the existing $e - p$ collider HERA, in Hamburg, Germany, a fixed target experiment has been proposed with the same goals.^{15,16} Similar efforts were pursued in connection with the now defunct SSC proton-proton collider.¹⁷⁻¹⁹

2. Threshold e^+e^- machines

The simplicity of the final states studied and the relatively favorable signal to background ratio have allowed the e^+e^- machines at threshold for $b\bar{b}$ production, namely CESR at Cornell and DORIS-II at DESY, to provide a great wealth of data on B meson decay phenomenology. The data sample currently being acquired with the CLEO II detector²⁰ at the CESR collider should total 10^7 $B\bar{B}$ events in a few years. A planned upgrade of the CESR collider in conjunction with an improved detector, CLEO III, will provide a ten-fold increase in the luminosity and will allow precision studies of the main dynamical features of hadronic and semileptonic B decays.

2.1 Cross section and final states in the region between $\Upsilon(4S)$ and $\Upsilon(5S)$

Fig. 2 shows the hadronic cross section as measured by the CLEO²¹ experiment in an energy scan performed in 1984. Consistent results were obtained by the CUSB experiment²² which took data simultaneously at the North Interaction Region at CESR. Results from a subsequent measurement performed by CLEO²³ of the hadronic and $B\bar{B}^* + B^*\bar{B}$ cross section in the energy region just

Fig. 2 The hadronic cross section in the region of the $\Upsilon(4S)$ to $\Upsilon(6S)$ resonances. The latest measurements⁸ of $\sigma_{B\bar{B}^*}$ at threshold are included. The last $\sigma_{B\bar{B}^*}$ point includes some $B^*\bar{B}^*$ component.

above threshold for $B\bar{B}^* + B^*\bar{B}$ production are included in Fig. 2.

Potential models, which have been able to describe successfully²⁴⁻²⁶ the confined properties of heavy quarkonia, have been applied to the energy region above open flavor threshold with less success. In order to understand the possible reasons and the physics implications of these shortcomings, it is useful to review the steps involved in the calculation and the major approximations adopted. The physical observables, such as hadronic cross section, resonance total width, resonance electronic width etc., are calculated from the eigenvalues of a mass matrix whose imaginary part is given by the coupling of the various states to specific decay channels. The initial states which are allowed to be mixed by the decay sector are the eigenstates of the strong interaction Hamiltonian for heavy quarkonia. The number of the states which are allowed to mix is finite and is generally

restricted to the first seven S-wave resonances and five or, in some cases, six D-wave resonances. Other orbital angular momentum states are not considered because they do not couple to the virtual photon neither directly nor via mixing to the S states.

The decay sector is composed of the quasi two-body channels accessible at the energies characteristic of the various resonances. The approximation of using a subset of $b\bar{b}$ wavefunctions with the nS or n'D quantum numbers may be a limiting feature of some of these calculations. For example, an exotic $b\bar{b}g$ component²⁷ may be located just above threshold for open flavor production. A model adding this component to the coupled channel sector,²⁸ generally referred to as the Hybrid Quark Model (HQM), appears to reconcile several features of the decays of Υ resonances above flavor threshold, in particular the unexplained broad 'bump' in the hadronic cross section between the $\Upsilon(4S)$ and $\Upsilon(5S)$ region. In addition, this model explains in a natural way the low value of Γ_{ee} of the $\Upsilon(4S)$, which is roughly 30 % lower than potential model predictions,^{29,30} as the $b\bar{b}g$ states does not couple to e^+e^- . Some authors³¹ have re-examined the HQM model and predicted some measurable consequences of an exotic component in the $\Upsilon(4S)$ wavefunction, most notably the presence of a quasi monochromatic photon of energy of the order of 4-5 GeV as a signature of colored $b\bar{b}$ pair. So far, no experimental evidence for these high momentum photons has been found.^{32,33} There is some reluctance to accept the HQM as a valid explanation of the data without direct measurement of some observable associated with the $b\bar{b}g$ state. The recent scan performed at CESR²³ finds that the $B\bar{B}^* + B^*\bar{B}$ final state does not saturate the hadronic cross section and that the residual hadronic cross section has a semileptonic rate which is consistent with a $B\bar{B}X$ final state, where X is a light hadronic state, for instance a π . Note that a source of hadronic cross section neglected in all these models is a three-body component of the decay sector in addition to the quasi two body channels which are assumed to be dominant. For instance, non resonant $B\bar{B}\pi$ could constitute a non negligible component of the cross section in this energy region.

Another issue on which we can derive only limited guidance from theory is whether resonances with mass above threshold are decaying 100% to open flavor final states. The Zweig (or OZI) rule dictates that channels which do not contain open beauty are heavily suppressed.³⁴ On the other hand, it has been argued³⁵ that apparently OZI forbidden final states can be accessed through an intermediate OZI allowed state with non negligible branching ratio, in analogy with the process $\phi \rightarrow \rho\pi$, interpreted as $\phi \rightarrow K^+K^- \rightarrow \rho\pi$. At the $\Upsilon(4S)$ energy, experimental upper limits can be derived from the charged particle momentum spectra, (3.8%-13% at 90% C.L.).³⁶ An indication of a non $B\bar{B}$ component of the $\Upsilon(4S)$ resonance,^{37,38} based on the detection of ψ 's with a momentum too

high to be compatible with their coming from B decay, stirred new interest in this issue. However, CLEO II data have shown that these ψ 's can be explained as coming from the continuum.³⁹ It must be kept in mind that this measurement does not rule out the possibility of some non $B\bar{B}$ decays of the $\Upsilon(4S)$.

A related parameter is the composition of the $\Upsilon(4S)$, namely the ratio between the charged and neutral B component of the final state:

$$\frac{f_-}{f_0} = \frac{\Upsilon(4S) \rightarrow B^- B^+}{\Upsilon(4S) \rightarrow \bar{B}^0 B^0}. \quad (1)$$

The best estimate is⁴⁰

$$\frac{f_-}{f_0} = 1.03 \pm 0.20. \quad (2)$$

Several factors affect this ratio, sometimes with contrasting effects. The simplest assumption,⁴¹ is that the decay width ratio of charged and neutral B 's are proportional to a p^3 phase space ratio, where p is the B momentum. This phase space is characteristic of pairs of mesons produced in P-wave relative angular momentum. It was soon argued²⁸ that this assumption is valid for small p , but does not hold when the decay amplitudes are rapidly oscillating functions of the momentum of the final state mesons, as the one for $\Upsilon(4S)$ decaying into $B\bar{B}$ mesons.

Even for equal B^- and $\bar{B}^0$ masses there is a Coulomb correction⁴² to the cross section for charged $B^- B^+$ production which can be quite sizable near threshold. In particular, assuming pointlike mesons, an 18% enhancement for charged B mesons production would be expected in $\Upsilon(4S)$ decays. However this effect may be highly suppressed⁴³ when the actual size of the mesons is taken into account. According to Ref. 43 the 18% enhancement can become up to a 3% suppression when form factor effects are considered. This is because the B momentum at this center-of-mass energy is close to a node in the decay amplitude of the $\Upsilon(4S)$. A systematic study⁴⁴ of combined Coulomb corrections and form factor effects as a function of the charged and neutral B meson masses has shown that they must be measured with high precision before a reliable prediction for the ratio between charged and neutral B production cross sections can be made.

Fig. 3 illustrates this sensitivity, which is very dramatic when $m_{B^0} > m_{B^-}$ due to the kinematical suppression of $B^0 \bar{B}^0$ relative to $B^+ B^-$. The measured values of the $\bar{B}^0 - B^-$ mass difference is $0.41 \pm 0.25 \pm 0.19$ MeV.⁴⁵

The knowledge of the branching ratios $\Upsilon(4S) \rightarrow B^0 \bar{B}^0 (B^+ B^-)$ is a crucial element, together with a high statistics data sample, for a precision measurement of exclusive branching ratios. Similarly, the knowledge of the B_S content of

Fig. 3 Branching ratio $(\Upsilon(4S) \rightarrow (B^+ B^-))/(\Upsilon(4S) \rightarrow (B^0 \bar{B}^0))$ as a function of the energy W in the resonance region. Curve a) was calculated assuming $m_{B^-} = m_{B^0} = 5.278$ GeV/c, curve b) was calculated assuming $m_{B^-} = m_{B^0} = 5.280$ GeV/c, Curve c) was calculated assuming $m_{B^-} = 5.278$ GeV/c, $m_{B^0} = 5.280$ GeV/c. Curves are the ratio of modulus square of decay amplitudes weighted by corresponding phase space factors and are taken from Ref. 44.

the $\Upsilon(5S)$ and its vicinity has important experimental implication, as it will determine the capabilities of threshold e^+e^- machines for B_S physics. In addition, a detailed study of the final states composition of the complex region above the $\Upsilon(4S)$ can provide some guidance in our understanding of QCD phenomenology in non-perturbative regimes.

2.2 Topological and kinematical cuts for beauty enhancement

The dominant source of background events is the $q\bar{q}$ continuum, which has

Fig. 4 R_2 for events containing a D^{*+} candidate for $\Upsilon(4S)$ (after continuum subtraction) and for scaled continuum.

a cross section approximately three times higher than $b\bar{b}$ at the $\Upsilon(4S)$, the local maximum of $\sigma_{b\bar{b}}$ in this energy region.

The natural way to enhance the signal to background ratio in inclusive and semi-inclusive measurements is to take advantage of the different topology of $B\bar{B}$ and continuum events. The former are rather spherical, as the B mesons are produced with relatively low momentum (≈ 300 MeV/c) and therefore their decay topology is not very different from the one in their rest frame. On the other hand, continuum events have a jet-like structure, with particles concentrated in two relatively narrow back-to-back cones. The CLEO II detector²⁰ is the first detector to feature a high quality electromagnetic calorimeter together with an excellent charged particle tracking system with a large solid angle coverage. Therefore it has the capability to reconstruct a large fraction of the particles produced in e^+e^- collisions and consequently it can determine the event topology very precisely.

As a consequence, it can exploit this selection technique very effectively.

Several variables have been identified to provide a measure of the spherical nature of the events. One of these, frequently used in CLEO and ARGUS analyses, is the R_2 variable defined as H_2/H_0 , where H_k is the k Fox–Wolfram moment, defined as:

$$H_k = \frac{1}{s} \sum_i^N \sum_j^N [|\vec{p}_i| \cdot |\vec{p}_j| P_k(\cos\phi_{ij})] \quad (3)$$

where N is the number of particles, s is the square of the center-of-mass energy, $P_k(\cos\phi_{ij})$ is the Legendre polynomial of order k and ϕ_{ij} is the angle between the vector momenta of the i and j particles. R_2 is equal to 1 for jetlike events and to 0 for perfectly spherical events. Fig. 4 shows an example of continuum and $B\bar{B}$ R_2 distributions obtained from CLEO data taken at a center-of-mass energy below $b\bar{b}$ threshold and from continuum subtracted $\Upsilon(4S)$ data.

An alternative approach can be used in the study of exclusive or semi-exclusive decays, where at least one of the B decay products is fully reconstructed. The alignment of a daughter of the candidate B is calculated with respect to an axis which describes the global orientation of the tracks assigned to the recoiling B . For instance, an event directionality variable widely used is the sphericity axis, calculated by minimizing the quantity:

$$S = \frac{3}{2} \frac{\sum_j^N |\vec{p}_{j\perp}|^2}{\sum_j^N |\vec{p}_j|^2}. \quad (4)$$

Jetlike events have maximal alignment between any decay product and sphericity axis defined by the either jet, whereas spherical events exhibit no correlation between any global axis and individual particle direction. Fig. 5 shows an example of this approach applied to events containing a D^{*+} .

In exclusive decays taking place at the $\Upsilon(4S)$ and vicinity, we can use the simplicity of the final state to apply kinematical constraints which reject both continuum and combinatorial background, with an efficiency dependent upon the complexity of the final state considered and the momentum resolution of the experimental apparatus.

The $B\bar{B}$ state comes from the decay of a resonance at rest into a particle and its antiparticle: therefore the sum of the energies of the B decay products must be equal to the beam energy. In the CLEO II data sample, the resolution in ΔE varies from 8 to 46 MeV depending upon the B decay mode.⁴⁶ This excellent energy resolution allows to select specific final states with no contamination from decays involving extra particles.

Fig. 5 Comparison between cosine of the angle of sphericity axis and D^{*+} momentum for (a) continuum data and (b) $B\bar{B}$ Monte Carlo.

The rms spread of the beam energy is of the order of 2.5 MeV at CESR and 6 MeV at DORIS-II. It can be seen that it is highly advantageous to calculate the invariant mass of the candidate decay products with the relationship:

$$M = \sqrt{E_b^2 - (\sum_i^N \vec{p}_i)^2}. \quad (5)$$

The invariant mass calculated with Eq. (5), commonly known as “beam constrained mass”, is characterized by a resolution smaller by roughly a factor of 10 than the one obtained by calculating the total energy from the individual reconstructed energies. In addition, at the $\Upsilon(4S)$, B mesons are produced in a P-wave state, so their angular distribution is $\sin^2\theta$, where θ is the angle between the reconstructed B meson and the beam axis. In contrast, final states not coming

from a real B decay are produced by chance combination of tracks and usually have an isotropic distribution. In addition, more complex criteria based on a combination of variables optimized to discriminate between continuum and $B\bar{B}$ have been used.⁴⁷

2.3 Accomplishments and near term goals of threshold e^+e^- machines

Threshold e^+e^- machines have contributed a great wealth of information about B meson decays. Fully reconstructed exclusive final states have led to the discovery of B mesons.⁴⁸ In addition, the study of exclusive semileptonic decays together with the measurement of τ_B performed at higher energy e^+e^- machines and at Fermilab are the basis of a rather precise evaluation of $|V_{cb}|$.⁴⁰ The discovery of neutral $B^0\bar{B}^0$ mixing^{49,50} renewed the theoretical interest in strategies to measure CP violation in B decays and the measured mixing parameter $x = \Delta M/\Gamma$ is related to the CKM matrix element $|V_{td}|$. The original evidence of non-zero $|V_{ub}|$ ^{51,52} has been confirmed with improved accuracy by the new CLEO data.⁵³ In addition, the high statistics data sample currently being accumulated already allows to exploit tagged B 's to obtain physics observables like the individual charged and neutral B meson semileptonic decays.⁵⁴ Great progress has also been made on the the experimental investigation of hadronic B decay phenomenology.⁴⁵ Evidence for electromagnetic 'penguin' diagrams has been found,⁵⁵ in the rare decay $B \rightarrow K^*\gamma$, and a signal in the sum of $\bar{B}^0 \rightarrow \pi - \pi^+$ and $\bar{B}^0 \rightarrow K^- \pi^+$ channel has been reconstructed.⁴⁷ More detailed knowledge on other rare decays may be forthcoming and provide a sensitive probe to several features of the Standard Model.

3. Continuum e^+e^- machines and the Z^0 resonance

The advantage of e^+e^- machines operating at higher energies is the boost which allows a better separation of the decay vertices of charm and beauty hadrons. Before the advent of Z^0 machines, continuum machines ran at a center of mass energy ≈ 29 GeV at PEP and 30 GeV at PETRA and subsequently at 50 GeV at TRISTAN. LEP, operating at the center-of-mass energy in the region of the Z^0 mass, is presently collecting a sizeable data sample (about 200,000 $b\bar{b}$ pairs for each experiment in the results presented at the 1993 summer conferences).² This will allow high precision studies of b hadron spectroscopy and lifetimes.

3.1 Cross section in high energy e^+e^- colliders

The Z^0 resonance is the most favorable operating point for high energy e^+e^-

colliders because $\sigma_{b\bar{b}}$ is more than hundred times higher than for continuum energies below and the fraction of b events is more than twice as large.⁵⁶⁻⁵⁹

3.2 Techniques to enhance the beauty content of the data sample

One method to enrich selectively the beauty sample is based on the use of lepton tags.⁵⁶ The study of the lepton momentum distribution from various sources indicates that events with high transverse momentum[†] leptons come almost exclusively from b decays. Fig. 6 summarizes the various sources of leptons and the corresponding transverse momentum distributions. This technique provides a high purity sample at the price of using only a fraction of beauty events, as the semileptonic branching fraction is only 20% and the momentum cut further reduces the fraction of events accepted.

An alternative approach has been pursued at PETRA, with the goal to enrich the statistical significance of the beauty sample at the price of some systematic uncertainty associated with higher model dependence in the efficiency and background estimates.⁶⁰ This selection method is based on topological criteria conceptually similar to the ones discussed for threshold machines, but with a machinery which is much less intuitive. The underlying idea is again the spherical spatial distribution of the b decay products in its rest frame. A sphericity product $s_1 \times s_2$ is defined by dividing the event into two halves, through a plane orthogonal to the jet axis. The sphericities s_1 and s_2 of particles belonging to the two different hemispheres are then calculated separately in the rest frame of a nominal b moving with $\beta = 0.74$. The product $s_1 \times s_2$ is used to discriminate $b\bar{b}$ sample from lower mass $q\bar{q}$ primary jets. Fig. 7 shows the b purity of the selected sample as a function of the $s_1 \times s_2$ cut. The TASSO collaboration chose a value of $s_1 \times s_2 \geq 0.18$ as an optimum cut, with a 35% efficiency for $b\bar{b}$ events and a b purity of $(29.4 \pm 1.2)\%$ ⁶⁰

All the experiments at LEP are presently equipped with high resolution silicon vertex detectors⁶¹⁻⁶³ which allow them to disentangle complex decay topologies as shown in Fig. 8. Therefore requirements of tracks with significant impact parameter relative to the primary event vertex or of a well identified displaced vertex are the most important beauty tags in these experiments.

An alternative way to identify b -jets,² which is widely used also at hadron machines, is the observation of ψ decays into two leptons, (e^+e^- or $\mu^+\mu^-$). This tag is not completely pure because ψ are produced also directly in Z^0 decays. Theoretical predictions^{64,65} would suggest that the background from $Z^0 \rightarrow c\bar{c}\psi$

[†] The transverse momenta are measured with respect to the jet axis which approximates the direction of the heavy quark.

Fig. 6 Transverse momentum distribution of leptons from different source in e^+e^- collisions at 29 GeV (from Ref. 56).

and $Z^0 \rightarrow q\bar{q}\psi$ should be below 1%. An experimental confirmation is important in order to use this tag in high precision studies.

3.3 Achievements and near term goals of high energy e^+e^- colliders

The main implication of the high boost characterizing B mesons produced at these machines is the magnified laboratory decay distance due to the Lorentz dilation factor $\gamma\beta$. At a center-of-mass energy of 29 GeV the B meson mean decay length is approximately $860 \mu\text{m}$, and at the Z^0 center-of-mass energy it is $2710 \mu\text{m}$, to be contrasted with $27 \mu\text{m}$ at the $\Upsilon(4S)$ center-of-mass energy. Not surprisingly, the main achievement of the continuum colliders has been the measurement of the B lifetime, averaged over the species produced at the respective energies. Much more precise measurements were performed by the LEP

Fig. 7 b purity of selected sample as a function of $s_1 \times s_2$ cut (from Ref. 60).

experiments and by the CDF experiment at Fermilab.² In addition, individual lifetimes have been measured not only for the $\bar{B}^0$ and B^- but also for the B_S and Λ_b .⁶⁶ The B_S meson has been seen for the first time at LEP⁶⁷ and evidence for Λ_b through Λ_c -lepton correlations has been obtained. Time dependent flavor oscillations in the B^0 system have been measured.⁶⁶

In the future we may expect higher samples of fully reconstructed B decays, with consequently better determination of individual b -flavored hadron lifetimes and more detailed mapping of heavier b -meson and baryon spectroscopy.

4. Hadron Machines

The most appealing feature of hadron machines as tools to study beauty physics is their very high cross section for $b\bar{b}$ production. On the other hand, beauty events are a minuscule fraction of the overall event rate. The signal to background ratio favors present collider experiments with respect to their fixed target counterparts by a few orders of magnitude. In both cases the challenge is to devise a trigger system selective enough suppress by several orders of magnitudes the recording of background events, mostly produced in generic inelastic collisions, to prevent them from saturating the data acquisition system.

The consequence of these difficulties is that so far experiments performed at hadronic machines have not been able to take full advantage of the very high

Fig. 8 $B_S \rightarrow D_S \pi$ event (ALEPH) showing the silicon vertex detector crucial role in identifying b jets.

production cross section relative to e^+e^- facilities. Only a handful of beauty events have been seen at fixed target experiments.⁶⁸⁻⁷⁰ The higher signal to background ratio has enabled collider experiments to be more successful in investigating beauty decays. The pioneering exploration of b physics in a hadron collider environment performed by UA1 at the CERN Sp $\bar{p}$ S^{71,72} has been continued successfully by the CDF experiment at Fermilab.⁵ The addition of a high precision vertex detector has enhanced its b physics capabilities in several respects. The other experiment presently operating at the Tevatron, D0, has some preliminary data on b -physics too⁶ and it may explore some features which are more suited to its hermetic muon coverage.

The cornerstone of b physics in hadron collider experiments has been so far the signature provided by the decay of the ψ meson into two leptons. In addition,

high $p_{\perp}^{\dagger}$ leptons have been used by UA1⁴, CDF⁷³ and D0⁶ to determine the production cross section and average mixing fraction for neutral B 's.

Heavy quarks are produced in hadronic colliders preferentially at small polar angles and this effect is more pronounced as $\sqrt{s}$ increases. A variable related to the polar angle acceptance is the rapidity y defined as:

$$y \equiv \tanh^{-1} \left(\frac{p_z}{E} \right) = \frac{1}{2} \ln \frac{\cos^2 \theta/2 + m^2/(4p^2) + \dots}{\sin^2 \theta/2 + m^2/(4p^2) + \dots} \approx -\ln[\tan(\theta/2)] \equiv \eta \quad (6).$$

where θ is the polar angle with respect to the beam axis and η is the pseudo-rapidity, which for $p \gg m$ and $\theta \gg 1/\gamma$ is approximately equal to y . UA1 and CDF, which have been the richest source of information about B mesons produced in hadronic environment, employ general purpose detectors which have a good acceptance in relatively restricted rapidity regions: UA1 covers the $|y| \leq 1.5$ region and CDF the $|y| \leq 1$ region. This in itself reduces the efficiency for beauty events sizably, as they are produced in a relatively wide rapidity interval. This effect is larger in CDF, where a smaller rapidity coverage corresponds to a wider rapidity range spanned by the produced b 's. On the other hand, it should be noted that restricting attention to the central region avoids the need to disentangle the tracks associated with the process of interest from the debris of forward tracks associated to interactions of the spectator partons. In addition, radiation damage effects to vertex detector elements are less severe in the central region than at very small angles from the beam.

Some new proposals for dedicated spectrometers for beauty physics adopt a complementary philosophy, emphasizing the forward region, where a large fraction of the B mesons are produced. The BCD group⁷⁴ formulated a very ambitious proposal, mostly targeted towards an SSC experiment, advocating a very hermetic detector with a solid angle coverage down to a rapidity of ± 4 , ($\theta \approx 2^\circ$). The COBEX group⁷⁵ chooses to optimize the acceptance in a more limited solid angle, in the θ range between 5–10 mr and 600 mr the forward and backward hemispheres, where most of the B 's are expected to be produced. At the present time several laboratories show great interest in exploring the capabilities of dedicated b experiments and also of general purpose high- p_T detectors. No dedicated b experiment has yet been approved anywhere, but this situation may change in the next few years.

The problem of background rejection is much more severe in fixed target experiments.⁷⁶ The main advantages in fixed target experiments are a simpler detector, lower particle multiplicities and B 's produced with higher boosts.

[†] The z axis corresponds to the beam axis.

4.1 $b\bar{b}$ production cross section at hadron machines

The process of heavy-quark production in hadronic collisions can be calculated in perturbative QCD⁷⁷ according to the standard factorization formula:⁷⁸

$$\sigma(s) = \sum_{i,j} \int dx_1 dx_2 \hat{\sigma}_{ij}(x_1 x_2 s, m^2, \mu^2) F_i^A(x_1, \mu) F_j^B(x_2, \mu) \quad (7)$$

where F_i^A is the density of parton i on hadron A , m is the heavy quark mass, $\sqrt{s}$ is the total center-of-mass energy of the $A + B$ system, and μ appearing in the density functions is the factorization scale, taken to be equal to the renormalization scale of the partonic cross section $\hat{\sigma}_{ij}$. The partonic cross section is given by:

$$\hat{\sigma}_{ij} = \frac{\alpha_s^2(\mu^2)}{m^2} f_{ij} \left(\rho, \frac{\mu^2}{m^2} \right), \quad (8)$$

where $x_1 x_2 s$ is the partonic center-of-mass energy squared and $\rho = 4m^2/x_1 x_2 s$. The dimensionless functions f_{ij} are written as:

$$f_{ij} \left(\rho, \frac{\mu^2}{m^2} \right) = f_{ij}^{(0)}(\rho) + 4\pi\alpha_s(\mu^2) \left[f_{ij}^{(1)}(\rho) + \bar{f}_{ij}^{(1)}(\rho) \ln \frac{\mu^2}{m^2} \right] + O(\alpha_s^2). \quad (9)$$

The explicit value of $f^{(0)}$, $f^{(1)}$ and $\bar{f}^{(1)}$ are given in Ref. 77, where their dependence upon ρ is shown. The $f^{(1)}$ coefficients for gluon-gluon interaction tend to a constant value at large ρ or, equivalently, at small x .

Fig. 9 shows the relevant partonic subprocesses for the Born term (of order $O(\alpha_s^2)$)⁷⁹ and Fig. 10 shows some examples of NLO corrections (of order α_s^3). These corrections to the one-particle inclusive cross section have been computed by two groups^{80,81} and fully agree at the partonic level. Detailed calculations have been performed for $p\bar{p}$ collisions at center-of-mass energies of 0.63 TeV and 1.8 TeV, corresponding to the operating point of the experiments UA1 and CDF respectively. It is very important to establish the agreement between experimental data and theoretical predictions. This will allow to assess the reliability of the perturbative approach. In addition, a good theoretical understanding of hadronic heavy flavor production is essential to study the capabilities of future b experiments both at existing facilities or in future higher energy colliders.

The most intriguing feature of the perturbative QCD results is the large contribution of the α_s^3 term, which would appear to cast some shadow on the validity of the perturbative approach: the K factor, which is defined as the ratio

Fig. 9 Feynman diagrams for heavy quark production in hadronic collisions (order α_s^2).

Fig. 10 Examples of NLO Feynman diagrams for heavy quark production in hadronic collisions (order α_s^3).

between the full result and the first order calculation, is of the order of 2.5 for $m \approx 5$ GeV. There is some theoretical justification of this relatively large correction.⁷⁸ At large value of the ratio $m/\sqrt{s}$ the highest spin pole dominates

the asymptotic behavior. Thus the effect is to be thought of as the contribution of a new channel instead of a perturbative correction, as the center-of-mass energy increases, the non leading order (NLO) term becomes increasingly important or even the dominant term this seems to contradict the validity of the perturbative expansion.

The calculated cross section is affected by the uncertainty in some values in the input parameters like the QCD scale Λ and the heavy quark mass. Ref. 80 performs a detailed study of the sensitivity of the differential cross section to these parameters. In general, the predicted value increases with the assumed value of the QCD scale Λ and decreases if the assumed value of the b quark mass increases. In addition, the structure functions F_i^A are extrapolated from data taken at lower energy and there is some theoretical disagreement on the functional form of their asymptotic behavior at low x .⁸² This uncertainty in the structure function extrapolation has been investigated in great detail.^{83,84} Finally, there is an intrinsic theoretical ambiguity associate with the choice of renormalization and/or factorization scale μ . Cross sections calculated to all the orders in perturbation theory should be independent of the choice in the scale μ .⁸⁵ However if the perturbative expansion is carried over up to order n , different choices of μ will produce different results (of order $\mathcal{O}(\alpha_S^{n+1})$). Renormalization group arguments dictate this dependence to be through logarithms of the ratio between μ and some scale M relevant to the problem. It is obvious that if the ratio μ/M becomes either too small or too big, large logarithmic terms develop and the fixed order calculation becomes meaningless. In our case a natural mass scale is the heavy quark mass itself and it is customary to choose $\mu = \mathcal{O}(m_b)$. Another relevant mass scale is the center-of-mass energy of the colliding system. When this scale is very different than the heavy quark mass produced, divergent logarithmic terms arise and the fixed order calculation becomes quite uncertain.

Fig. 11 compares the results of a perturbative QCD calculation⁸⁶ for the cross section of $\pi N \rightarrow b\bar{b}X$ with data from fixed target experiments.^{68,70} The agreement is fairly good but the paucity of data and the scant statistical accuracy of the measurements is a good indication of the difficulties in studying b physics in fixed target experiments with beams presently available, which will be discussed in more detail below.

Figs. 12 and 13 summarize the information on beauty production from UA1⁷² and CDF.⁸⁷ It can be seen that the UA1 experiment⁷² is in good agreement with the NLO calculation. Note that originally the data seemed to exhibit significant discrepancy with the theoretical predictions⁸⁸ at large p_T^{min} . This is the only experiment which quotes a cross section for $b\bar{b}X$ production extrapolated to the whole range of rapidities and quark transverse momenta allowed by kinematics. The y coverage of UA1, $|y| \leq 1.5$, represents a sizable fraction of the rapidity range spanned by $b\bar{b}$ events, making this extrapolation feasible. The

Fig. 11 Cross section through order α_s^3 for $b\bar{b}$ production in $\pi^- p$ interaction as a function of laboratory momentum. Here $m = 5$ GeV and two choices are made for the evolution scale $Q^2 = m^2$ or $4m^2$ (from Ref. 46).

measured $\sigma_{b\bar{b}}$ is $19 \pm 4.3^{+10.4}_{-6.5} \mu\text{b}$. The first error is associated with the uncertainty in the normalization of the theoretical QCD $p_\perp$ dependence to the data. The second error is evaluated by allowing the theoretical curve for the inclusive b quark production to vary by changing the relevant input parameters (factorization and renormalization mass scale μ , b quark mass m_b and Λ within their uncertainty). These uncertainties affect the extrapolation of the cross section to $p_T^{\text{min}}=0$. In the CDF case, the theoretical curve is an “upper limit” of the value which can be achieved with sensible variations of the input parameters of the calculation described before. The new preliminary data shown at summer conferences (1993), which are somewhat lower than the published data, seem to indicate a marginal agreement with the upper values of the theoretical predictions. In addition, preliminary D0 data seem to be in fairly good agreement with theoretical predictions.⁶ The limited domain of y and $p_\perp$ acceptance makes it difficult to extract a value of the total cross section $\sigma_{b\bar{b}}$ for CDF. The CDF preliminary measurement of $\sigma(b\bar{b}X)$ for $p_T^1 \geq 6.5$ GeV and $p_T^2 \geq 8.75$ GeV for the two b -flavored partons and both of them within the rapidity interval $|y| < 1$ is $(2 \pm 1) \mu\text{b}$,⁸⁹ contrasted with theoretical predictions in the range of $(0.4-1) \mu\text{b}$ for $4.5 < m_b < 5$ GeV, $\sqrt{m_b^2 + p_T^2}/2 < \mu < 2\sqrt{m_b^2 + p_T^2}$ and $160 < \Lambda_4 < 360 \text{ MeV}$. Λ_4 is the QCD scale evaluate for a number of flavors $n_f = 4$ in the $\overline{MS}$ renor-

Fig. 12 The inclusive single b quark cross-section of $|y| < 1.5$ and $p_T > p_T^{\min}$ for $p\bar{p}$ collisions at $\sqrt{S} = 0.63$ TeV (UA1). Also shown is the $\mathcal{O}(\alpha_s^3)$ calculation of Nason, Dawson and Ellis⁸⁰.

Fig. 13 The inclusive single b quark cross-section of $|y| < 1$ and $p_T > p_T^{\min}$ from $p\bar{p}$ collisions at $\sqrt{S} = 1.8$ TeV (CDF). Also shown is the $\mathcal{O}(\alpha_s^3)$ calculation with “extreme values” of the factorization scale $\mu = M_T/4$ and $\Lambda_4 = 275$ MeV.

malization scheme. A study of the experimental information on this parameter, performed by Martin, Stirling and Roberts,⁹⁰ concluded that the best estimate is $\Lambda_4 = 230 \pm 55$ MeV.

Much progress has been made in recent years in probing the validity of the perturbative expansion. On the theoretical side, the dynamics of heavy quark production has been explored more deeply by Mangano, Nason and Ridolfi (MNR),⁸⁵ by investigating correlations between the b and $\bar{b}$ and developing algorithms suitable to evaluate the $b\bar{b}$ production cross section with specific kinematical cuts of any given experiment. Among others, the p_T distribution of the quark-antiquark pair, and the difference in rapidity y , and azimuth ϕ between them have been studied. This provides more stringent tests of the perturbative expansion, and in particular it allows the assessment of the relevance of the “gluon splitting” diagram, where an energetic gluon recoils against a heavy $q\bar{q}$ pair. Note that the first order calculations which are widely used to study the experimental acceptance, especially of future experiments, have an exact correlation of the produced pair: they are characterized by $\Delta\phi = 180^\circ$. On the other hand, “gluon splitting” processes, where a QCD $gg \rightarrow gg$ collision is followed by a branching of one of the gluons into a $Q\bar{Q}$ pair, are peaked at $\Delta\phi=0$, as the quark-antiquark pair recoils coherently against the hard gluon. Depending upon the detailed kinematical cuts and the center-of-mass energy, either of the two processes will be dominant or their interplay will be important.⁸⁷

These predictions have withstood experimental checks. In particular, UA1 has investigated the angular correlations quite thoroughly, both in azimuth ($\Delta\phi$) and in “space angle” ΔR , (defined as $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$). An interesting analysis discussed in Ref. 72 is the approximate experimental identification of the lowest order contribution to the measured cross section identified as “quasi-two-body” (with almost back to back topology in azimuth, namely $\Delta\phi > 150^\circ$) and higher order contributions (the remaining $\Delta\phi$ range). The comparison between the experimental decomposition of the $b\bar{b}$ cross section and the MNR predictions is quite good and indicates that non-perturbative effects do not appear to play a major role in beauty production at this value of $\sqrt{s}$.

The major emphasis in CDF has been the measurement of the inclusive cross section for b quark production with different experimental techniques.⁸⁷ Some preliminary results on the spatial correlations between the quark pair have been reported,⁸⁹ namely the $\Delta\phi$ between electron and muon for dileptons with relatively high invariant mass ($M_{e\mu} > 5\text{GeV}$). The results appear consistent with the MNR predictions (as shown in Fig. 16) modulo a scale factor.

4.2 Techniques for beauty enhancement at hadron colliders

The most formidable problem in hadronic machines is to achieve the capability of selecting beauty events from the background of ‘minimum bias’ events

Fig. 14 Measured $b\bar{b}$ angular distributions for b quark pairs with $p_T > 6$ GeV/c (left) and $p_T > 11$ GeV (p_T identifies the transverse momentum of the higher p_T (anti)-quark. (from UA1). Errors are statistical only. Shown are the distributions for $\Delta\phi$ (azimuth angle) and ΔR ("space angle"). The solid line corresponds to the central value of the MNR predictions and dotted line corresponds to the Monte Carlo used for acceptance evaluation.

and charm events. Two examples will be given to illustrate this problem. Several fixed target experiments which took data in 1993 at Fermilab⁹¹ used a 800 GeV proton beam. At this energy the ratio between $b\bar{b}$ and $c\bar{c}$ production cross section is:

$$\frac{\sigma_{b\bar{b}}}{\sigma_{c\bar{c}}} = 0.3 \times 10^{-3}, \quad (10)$$

where the σ 's are taken from QCD calculations^{78,80} to order α_s^3 and the ratio between $b\bar{b}$ production and total event rate, assuming a hydrogen target, is

$$\frac{\sigma_{b\bar{b}}^H}{\sigma_t^H} = 0.25 \times 10^{-6}. \quad (11)$$

Fig. 15 The single b quark cross section for all rapidities (UA1) and $p_{Tb} > p_{Tb}^{min}$ in $p\bar{p}$ collisions at $\sqrt{s} = 0.63$ TeV. The inclusive cross section is separated into 2-body and 3-body components and compared with the central value of MNR predictions.

Fig. 16 The opening angle between e and μ (CDF) in the transverse plane, MNR predictions are shown with (solid line) and without (dotted line) the requirement of invariant mass $M_{e\mu} > 5$ GeV. The theoretical prediction including the mass cut is normalized to the whole data interval, whereas the prediction excluding this cut is normalized to $\Delta\phi > 80^\circ$.

If higher atomic number A targets are used, this ratio becomes:⁹²

$$\frac{\sigma_{bb}^A}{\sigma_t^A} = \frac{\sigma_{bb}^H}{\sigma_t^H} A^{\alpha(h)-\alpha(T)}, \quad (12)$$

where $\alpha(h)$ gives the relationship between the heavy quark production cross section from a single nucleon target and a target with A nucleons. According to QCD models $\alpha(h)$ is expected to be ≈ 1 . Experimentally it has been found $\alpha(\Upsilon) \approx 0.95$ for Υ production, (α has been measured⁹³ to be 0.962 ± 0.014 for Υ production and 0.948 ± 0.020 for Υ' and Υ'' production). The parameter $\alpha(T)$ relates the total cross section for nucleon–nucleon interaction with the total cross section for proton p on heavy target.

If we assume that the total cross section is proportional to the nucleus surface area, we get $\alpha(T) = 0.67$, in the region of incident proton momentum of 60–280 GeV/c it has been found that $\alpha(T) = 0.72 \pm 0.01$.⁹⁴

At the Tevatron center-of-mass energy (1.8 TeV) the corresponding quantities are

$$\frac{\sigma_{bb}}{\sigma_{c\bar{c}}} = 0.4 \times 10^{-1}, \quad (13)$$

and

$$\frac{\sigma_{bb}}{\sigma_t} = 0.8 \times 10^{-3}. \quad (14)$$

The main advantage of the higher center-of-mass energy at the collider is the much more favorable ratio between σ_{bb} and σ_t or $\sigma_{c\bar{c}}$. In addition, the rapidity and $p_\perp$ distributions for charm and beauty production are different. Therefore the beauty to charm ratio can be higher in some regions of phase space than the integral one. Fig. 17 shows the comparison between the theoretical $p_\perp$ distributions of charm and beauty events at $\sqrt{s} = 1.8$ TeV and Fig. 18 the corresponding comparison for the rapidity distribution. These curves have been obtained by integrating over y or $p_\perp$ the differential cross section $d\sigma/dp_\perp^2 dy$ tabulated in Ref. 80. It should be mentioned as a word of caution that the curves compared come from a perturbative QCD calculation carried out to order α^3 both for charm and beauty production. As the charm quark is lighter, the α^3 term is expected to be higher and to have a stronger μ dependence than in the case of beauty production. In addition, in this case a significant non-perturbative contribution may be expected. Therefore it is very important to get some experimental input on these distributions. It can be seen that charm events span a wider rapidity range and have a softer $p_\perp$ spectrum. On the other hand, the Feynman scaling variable x_F ($x_F \equiv p_\parallel/p_{max}$, where $p_\parallel$ is the momentum along the beam axis and p_{max} is

Fig. 17 $p_{\perp}$ distributions calculated to order α_s^3 for $b\bar{b}$ and $c\bar{c}$ production at $\sqrt{s} = 1.8$ TeV (from Ref. 80).

Fig. 18 Rapidity distributions calculated to order α_s^3 for $b\bar{b}$ and $c\bar{c}$ production at $\sqrt{s} = 1.8$ TeV (from Ref. 80).

the maximum momentum allowed by kinematics) has a broader distribution for charm decays than for beauty, so the charm hadrons produced are likely to have a sizable longitudinal momentum and therefore are characterized by a topology with displaced vertices.

The low values for the ratios $\sigma_{b\bar{b}}/\sigma_{c\bar{c}}$ and $\sigma_{b\bar{b}}/\sigma_t$ discussed above imply that the challenge is to devise trigger strategies selective enough to discard all of the ‘minimum bias’ events and to reduce the fraction of accepted charm events to a value which does not saturate the data logging capabilities. In general, the trigger scheme adopted in experiments at hadron colliders has a hierarchy of criteria with increasing degree of complexity and consequently increasingly slow. At each level the decision time must be adequate to handle the expected event rate in order to have good efficiency. This challenge increases with the luminosity at which the experiment needs to operate. For instance, at the Tevatron, assuming $\sigma_{b\bar{b}} = 60 \mu\text{b}$, $\sigma_{c\bar{c}} = 1,500 \mu\text{b}$ and $\sigma_{tot} = 70 \text{ mb}$, and a luminosity of $2 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$, the corresponding interaction rates are 120 Hz, 3 KHz and 140 KHz. A suppression of the minimum bias events requires an algorithm able to perform its decisions in a few μs at this luminosity, which is the one typical of the 1993 run at Tevatron (and in fact, already below the highest luminosities achieved).⁹⁵ At a projected luminosity of $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, all these rates are scaled upward by a factor of 50 and the challenge to the triggering scheme appears quite obvious. However future pp colliders, like LHC, require triggering schemes and data acquisition systems able to cope with very high interaction rates. This challenge is generating a quite active R&D effort on pipelined front end electronics and fast readout systems⁹⁶ which can benefit future b experiments greatly.

The simplest technique to enhance the beauty content of the recorded data sample is the use of high momentum leptons as a heavy flavor tags. For instance, UA1 used a single μ with $p_{\perp} \geq 10 \text{ GeV}/c$ to extract b production cross section.⁸⁸ CDF used μ ’s with $p_{\perp} \geq 11 \text{ GeV}$ in the 1988-1989 run.⁹⁷ Lower thresholds in single μ trigger can be implemented but may be dominated by background events. The dominant source at low $p_{\perp}$ is constituted by π ’s and K ’s decaying in flight. For instance, UA1 estimates that that 75% of the μ ’s with $p_{\perp}$ of 6 GeV/ c were produced by hadron decays.⁴ Similarly D0 finds that below $p_{\perp}$ of 5 GeV/ c the single μ cross section is dominated by $\pi - K$ decays.⁶ On the other hand, a lower p_T cut-off is quite useful when some other criteria can be added to identify b events. For instance, a lower p_T acceptance for μ ’s is a great benefit for a trigger scheme involving on line reconstruction of ψ mesons. Fig. 19 shows the electron spectrum measured by CDF, together with its relevant components. It can be seen that in the region between 7 GeV and 25 GeV the beauty component of the spectrum appears to be dominant. On the other hand, the estimated cross section for b ’s of $p_{\perp}$ higher than 15 GeV, which corresponds to a lower cut-off in the lepton $p_{\perp}$ of approximately 10 GeV, is roughly a factor of 100 smaller than the total b cross section. Further reduction of the efficiency of this selection criterion is caused by the semileptonic branching fraction and the experimental lepton identification technique. Therefore high $p_{\perp}$ leptons are a rather clean but not very efficient signature for beauty production. A possible generalization of this technique is the requirement of one or a few tracks with high transverse

Fig. 19 Inclusive electron spectrum from CDF.

momentum. Alternatively, a requirement that the total transverse energy E_t be above some threshold may exploit the higher $p_\perp$ of beauty events.

A particle which has a very clear and unique signature is the ψ when it decays into a lepton pair. Event selection criteria based on the identification of a ψ decaying into two μ 's have been successfully employed at UA1 and CDF. The additional constraint provided by the ψ invariant mass allows to lower the $p_\perp$ threshold for the two μ 's. The ψ sample of UA1 requires one μ with $p_T > 2$ GeV and the second μ with $p_T > 3$ GeV.⁹⁸ The CDF ψ sample obtained during the 1992-1993 run does not impose a specific $p_\perp$ cut on the μ 's but the first level trigger selection criteria have an efficiency of 50% for tracks at $p_\perp = 1.8$ GeV/c rising to 90% at $p_\perp = 3.8$ GeV/c. In addition one of the two μ 's must match a charged track reconstructed in the central drift chamber. This requirement has an efficiency of 50% for $p_\perp = 2.7$ GeV rising to 90% for $p_\perp = 3.4$ GeV/c.³ Fixed target experiments claim a very high background rejection by using this trigger strategy.⁷⁶

A technique which has been proposed several years ago⁹⁹ and is receiving increased attention¹⁰⁰ is to use a detached vertex criterion to enhance the beauty content of the event sample. In its simplest form it would just demand the presence of some tracks in the event not pointing to the primary event vertex. Ideally all minimum bias events would be eliminated, while preserving good efficiency for beauty events.⁷⁵ In general this criterion should have very limited rejection for

charm events. However charm decays are characterized by a lower multiplicity and therefore lower vertex reconstruction efficiency. It is important to establish in real system the interplay between this effect and the typical displaced vertex topology to determine the suppression power of a displaced vertex criterion for charm events. The most advanced technological implementation of the detached vertex triggering approach,¹⁰⁰ which takes advantage of fast VLSI technology and massive parallelization of the algorithm, requires roughly $10\mu\text{s}$ to reach a decision. Its present application is in a Level 2 trigger processor, but it could be used in a first level trigger if a sufficiently deep pipeline were feasible. It should be noted that at very high luminosity there is the further complication of multiple interactions which can fake a detached vertex event. In general, at very high luminosities it becomes increasingly difficult to select b events because of the short times available to make a trigger decision. In this case the requirement of a high p_T μ is a very simple and effective addition to the vertex topology trigger.¹⁰¹

Another novel triggering scheme is the “optical impact parameter trigger” originally proposed by Charpak, Giomataris and Ledermann.¹⁰² The principle of this trigger is that the B mesons are produced at some distance from the target and their decay products are emitted at angles slightly higher than the average emission angle of particles from “minimum bias” events. Therefore in principle a solid state radiator (for instance UV grade quartz) shaped like a spherical shell with center corresponding to the target location can be designed in such a way that the Cherenkov light associated with the particles originating from displaced vertices is trapped inside the radiator and collected at the extremities, whereas the light from particles originating from the primary vertex is transmitted. Great care needs to be taken in order to insure that there is no spurious source of light which activates this trigger. Its appeal resides in the fact that it can be very fast and ideally it does not see the high rate background but only the relatively rare signal. On the other hand, quartz is a dense material which adds considerable amount of radiation length which may affect the performance of downstream detector elements adversely. This idea is actively being pursued as one of the b experiment proposals at LHC is planning to use this strategy and test beam results should be available soon.¹⁰³

Fixed target experiments have considered other event selection criteria.⁷⁶ A ‘multiplicity jump’ ΔQ criterion checks for an increase in the number of charged particles detected in a vertex telescope by requiring $\Delta Q \geq \Delta Q_{min}$ and should identify secondary decays in the telescope. Its implementation with silicon strip detectors appeared promising in test beam studies but has not been successful when implemented in an actual experiment due to several technical problems.¹⁰⁴

A new approach is presently being studied, as optical multiplicity jump trigger.¹⁰⁵

An alternative to the three level hierarchy described above is provided by triggering schemes involving the so called “data driven processors”,¹⁰⁶ composed

by a network of independent processing units which perform different operations on the same data, therefore accommodating a high degree of parallelism in a natural way. This approach allows to perform more complex triggering decisions at level one, in a sense merging the traditional level one and two triggers in a single step.

4.3 Accomplishments and near term goals of present hadron machines

In the recent Tevatron run, both CDF and D0 took data. The D0 data on b physics were taken only on a very small run with reduced luminosity, but preliminary results on b production and mixing have been reported.⁶ In this run, CDF had some new features which had a definite impact on its B detection capabilities. In particular, its tracking system was enhanced by the addition of a precision silicon vertex detector, consisting of 4 layers of single sided strip devices. In addition it features better μ coverage and improved trigger efficiency for single μ , e and dimuons. The results which have so far been presented or are likely in the near future include spectroscopy study, already started with the confirmation of the B_s discovery (through the decay $\bar{B}_S^0 \rightarrow \psi\phi$).¹⁰⁷ Evidence for new baryons like Λ_b (through the decay $\Lambda_b \rightarrow \Lambda\psi$) or even higher mass beauty mesons like the B_c may be found. The B_c meson appears of great theoretical interest as it is a system composed by two heavy quarks and can be a good laboratory to explore new dimensions of Heavy Quark Effective Theory (HQET).¹⁰⁸ Lifetime determination for different species (B^0 , B^- , etc.) is under way. Future results might include exploration of flavor tagging techniques which are of crucial importance for the prospect of measuring CP violation in B decays. The replacement of the present vertex detector with one with 3-D spatial information is likely to be quite helpful in achieving these goals.

The main advantage of the D0 detector relevant to B physics is the large μ coverage both in $p_\perp$ and η . The claim is that this feature will allow the study of b production cross section versus x_F and $p_\perp$, including the ability to separate gluon fusion from gluon splitting contribution. In addition, spectroscopy studies should be possible for states involving a ψ meson in the final state. It will be interesting to see how well the backgrounds for each of these physics goals will be controlled, given the absence of tracking information in this non magnetic detector. There is a proposal to upgrade D0 with the addition of a silicon vertex detector and magnetic field which may improve the beauty physics potential of this experiment.

5. B -factories

There is one physics goal which is not likely to be achieved with this genera-

Fig. 20 (a) The unitarity triangle, illustrating a relation among quark mixing matrix elements implied by unitarity. (b) The same triangle rescaled (by λV_{cb}) and plotted in the $\rho - \eta$ plane of the Wolfenstein representation of the CKM Matrix.¹⁰⁹ (c) Experimental constraints in the ρ and η plane (m_t assumed equal to $170 \text{ GeV}/c^2$).¹¹⁰

tion of experiments and represents the most ambitious and exciting perspective in beauty physics: the measurement of CP violation in B decays. Fig. 20 gives a graphic representation of the unitarity condition of the Cabibbo-Kobayashi-Maskawa (CKM) matrix which can be tested in B decays. Knowledge of the angles will require dedicated machines, the so called B -factories, or, possibly, dedicated experiments at existing or future hadron machines.

5.1 Phenomenology of CP Violation in B decays

The physics justification and a detailed analysis of the phenomenology of

CP violation in B decays is discussed in great detail by other authors.¹¹¹ Here only the concepts necessary to discuss the parameters affecting the luminosity required to probe the Standard Model parameters will be briefly summarized. CP violation in B decays can have in principle several manifestations:¹¹¹ (a) it can proceed through the mass matrix, in analogy with the K system, with CP eigenstates distinct from mass eigenstates, (b) alternatively, it can manifest itself directly in the decay amplitude, in processes where the rate $B \rightarrow f$ is different from $\bar{B} \rightarrow \bar{f}$, either as a function of time or integrated over all times. The latter case will occur when a decay can proceed through two different amplitudes with an interference term containing the CP violating phase. Examples are the interference in decays to flavor specific final states, i.e. states which uniquely identify the flavor of the decaying B , (e.g. $B^\pm \rightarrow K^\pm \pi^0$), or in neutral $\bar{B}^0$ decays to final states common to $\bar{B}^0$ and B^0 mesons, which can proceed via direct decay or via decay taking place after $B^0 - \bar{B}^0$ mixing, (e.g. $B^0(\bar{B}^0) \rightarrow \psi K_S$). This decay enjoys a unique place both from the theoretical and experimental standpoint. In this case, as in all the decays to CP eigenstates where there is a dominant decay diagram determining the transition, the experimental result can be translated into a measurement of the CP violating phase without the complications associated with strong interaction dynamics. This is not necessarily true in the case of $\pi^+\pi^-$, because of the possible interference between tree level diagram and penguin diagram which are likely to have comparable amplitudes. This additional complication is commonly referred to as “penguin pollution”,¹¹² but ways of circumventing this difficulty have been found.¹¹³

A brief description of the relationship between CP violating phase and experimental observables will be developed for a $B^0\bar{B}^0$ system, which is the case of interest for CP violation through mixing at threshold e^+e^- machines. This summary has the purpose of introducing the relevant parameter which govern the luminosity requirement of various machines. At higher energy e^+e^- machines and hadron machines a more complex set of initial states need to be considered.¹¹⁴ The decay rate for $\bar{B}^0 \rightarrow f$, where f is a CP eigenstate, at the proper time t (expressed in units of mean life) with the tagging B^0 decaying at proper time t' is given by:

$$\frac{d\Gamma[f(t), l^+(t')]}{dtdt'} \propto e^{-(t+t')} [1 - \sin x(t \pm t') \cdot \sin 2\phi], \quad (15)$$

and the rate for the C conjugate process is given by:

$$\frac{d\Gamma[f(t), l^-(t')]}{dtdt'} \propto e^{-(t+t')} [1 + \sin x(t \pm t') \cdot \sin 2\phi], \quad (16)$$

here the $+$ sign applies to C -even states and the $-$ sign to C -odd states, x is the mixing parameter $\Delta M/\Gamma$, measured to be 0.65 ± 0.08 ,¹¹⁵ and t and t' are measured

Fig. 21 $(t - t')$ distribution for $f(t)$ and $l^+(t')$. The curve is a fit to the spectrum.

in units of B lifetimes. The charge of the tag l determines the flavor of the B decaying into the CP eigenstate: l^+ identifies a $\bar{B}^0$ and l^- a B^0 . The CP violating phase ϕ is the only unknown parameter to be determined experimentally. At the $\Upsilon(4S)$ the $B\bar{B}$ pair is produced in a C -odd state, as it carries the quantum numbers of the virtual photon. We can integrate $d\Gamma/dt dt'$ over t or t' and obtain functions of $T = t - t'$:

$$R(T) \propto e^{-|T|}(1 - \sin x T \sin 2\phi) \quad (\text{for } f, l^+), \quad (17)$$

$$\bar{R}(T) \propto e^{-|T|}(1 + \sin x T \sin 2\phi) \quad (\text{for } f, l^-), \quad (18)$$

$$\bar{R}(T) = R(-T) \quad (19)$$

The time dependent spectrum is shown for (f, l^+) in Fig. 21 ; the spectrum for (f, l^-) is its mirror image. In this situation it is obvious that a time integrated measurement conveys no information: as the areas subtended by the spectra for (f, l^+) and (f, l^-) are equal, their difference is zero independent of the magnitude of the CP violating phase. The two spectra can be combined into a ‘time rectified distribution’ in order to increase the statistical power of the measurement by

adding to the (f, l^+) spectrum the (f, l^-) one after the time inversion $T \rightarrow -T$. In this case a counting measurement of the asymmetry can be performed via the quantity:

$$A_{C=-1}^{rect} = \frac{N_+ - N_-}{N_+ + N_-} \quad (20)$$

where N_+ is the number of events with positive times T in the rectified distribution and N_- is the corresponding number for negative T . The expression of A in terms of the relevant physical quantities related to mixing and CP violation can be obtained by integrating Eq. (17) over positive and negative T 's:

$$A_{C=-1}^{rect} = \frac{x}{1+x^2} \cdot \sin 2\phi = d(x) \cdot \sin 2\phi. \quad (21)$$

The dilution factor $d(x)$ is 0.46 for $x = 0.65$ for this time rectified measurement. If we integrate only starting from a minimum time difference $T > T_{min}$ the dilution factor improves up to ≈ 0.80 at $T_{min} \approx 2$ ps, with a sacrifice in the statistical accuracy of the measurement. A gain by 20% can be achieved by fitting the time rectified spectrum instead of performing a simple counting experiment. The dilution factor undergoes further degradation due to the time resolution of the measurement, which depends upon the spatial resolution achieved in the precision vertex detector and must be evaluated for each tagging strategy independently. In the case of C -even states, like $B\bar{B}$ produced from $\gamma^* \rightarrow B\bar{B}^*$, $B^* \rightarrow \gamma B$, the relative sign between proper times t and t' is positive and a time integrated measurement is possible. In this case, we can define a time integrated asymmetry:

$$A_{C=+1} = \frac{N_+ - N_-}{N_+ + N_-} \quad (22)$$

where N_+ are the events of the kind (f, l^+) and N_- are the events of the kind (f, l^-) .

Finally, at higher energy e^+e^- colliders or in hadron machines, the B pairs are not produced in a state of definite CP . The effective dilution factor depends upon the branching fraction for the species accompanying the neutral B meson. If we assume that the b flavored hadron population contains 10% of Λ_b baryons and that the B mesons are produced in the ratio $\bar{B}^0 : B^- : \bar{B}_s = 0.43 : 0.43 : 0.14$ there is a dilution factor $d(x, x_s) = 0.76$. No further dilution factor is involved, except from resolution effects, if a fit to the decay time distribution of the CP eigenstate is performed.

5.2 B -factory options

There are four main approaches which have been proposed to perform the measurement of CP asymmetry in B decays with a sensitivity sufficient to explore the full range of values allowed within the Standard Model. Each one has some distinct advantages and some challenging goals yet to be met in order to achieve the desired sensitivity.

1. e^+e^- colliders at $\sqrt{s}$ about 10 GeV.

This solution which has been extensively studied in laboratories in the United States (Cornell, SLAC)^{116,117} and Japan (KEK).⁸

In addition to the luminosity requirements which require some improvements with respect to present day e^+e^- colliders, there is an additional feature which must be implemented in these machines. The need to measure the proper time separation between the two B 's requires a novel way of operating the machine: the collider will be 'asymmetric', namely the e^+ beam will have an energy different from the e^- beam. This will produce a $\Upsilon(4S)$ 'boosted' along the beam axis by a factor:

$$\gamma\beta = \frac{(E_{high} - E_{low})}{M_{\Upsilon(4S)}}. \quad (23)$$

The product of the two beam energies is constrained by energy conservation to:

$$E_{high}E_{low} = \left(\frac{M_{\Upsilon(4S)}}{2}\right)^2. \quad (24)$$

These two equations determine the asymmetry ratio, or, equivalently, the energies of the two beams.

In this mode of operation the separation between the two B 's along the beam axis is related to the proper time separation through the relationship:

$$(z - z') = \frac{E_{high} - E_{low}}{M_{\Upsilon(4S)}}c(t - t'). \quad (25)$$

Without the boost one could in principle measure the sum of the decay lengths ($l + l'$) by reconstructing the decay vertices of the two B 's, but not the difference ($t - t'$). In fact, in the $\Upsilon(4S)$ rest frame the two B 's are moving back to back and there is no way to know the primary vertex to enough accuracy to extract the decay time difference $T = t - t'$ needed in the CP violation measurement, unless the beam collision point is known with accuracy comparable with the one of state of the art micro-vertex detectors. By increasing the asymmetry, the mean $\langle \Delta z \rangle = \langle z - z' \rangle$ increases, reducing the sensitivity to the spatial resolution of the vertex detector. However this increase poses a greater challenge to the

machine design, in particular the interaction region design is remarkably complex as two beams with different characteristics need to be focused on the same spot. The maximum difference between the negative and positive time distributions occurs when $T/\tau=0.88$, where τ is the B^0 lifetime. If we assume $\tau = 1.53$ ps,² this corresponds to $\Delta z = 170 \mu\text{m}$ for $\beta\gamma = 0.42$. A vertex resolution much better than this separation, achievable with a silicon detector system, does not introduce any appreciable dilution factor into the measured CP asymmetry.¹¹⁶ Another choice studied extensively is $\beta\gamma=0.5$.⁹

An alternative which was seriously considered for a while was a symmetric collider operating near the $\Upsilon(4S)$, namely in the energy region just above the $\Upsilon(4S)$ which is dominated by the $B\bar{B}^* + \bar{B}B^*$ channel. However the recent measurement²³ of the cross section for $B\bar{B}^* + \bar{B}B^*$ production performed by CLEO has substantially diminished the interest in this approach. In fact the peak of the $B\bar{B}^* + \bar{B}B^*$ cross section is (0.164 ± 0.032) nb, producing a luminosity requirement a factor of 7 higher than its asymmetric counterpart in order to perform the measurement with the same sensitivity. This result makes this option much less appealing.

2. e^+e^- colliders at $\sqrt{s} = M_{Z^0}$.

The most distinctive advantage of these machines is the high cross section for $b\bar{b}$ production (7 nb) and the high momentum of the decay products, which makes it easier to disentangle the vertex topologies. In addition, if polarized beams were available in high luminosity machines, flavor tagging would be achieved simply by the location in the forward/backward hemisphere. On the other hand, final states to be reconstructed are more complex and it is difficult to achieve a tagging and reconstruction efficiency competitive with the 10 GeV machines. Some exploratory studies have been performed at LEP.¹¹⁸ The luminosity requirement would be comparable to the one required by the 10 GeV machines, but this would imply an improvement by a factor of roughly 100 with respect to its present performance. In addition, precision vertexing may require a shrinking of the beam pipe radius at the interaction point which may not be very easy to accomplish. Even if there is an active program on B physics within all the experiments presently taking data at LEP, at the moment not much emphasis is put in achieving the capability of measuring CP violation.

3. Hadron machines.

The high cross section for $b\bar{b}$ production implies that present hadron machines, like the Tevatron, are already producing large amounts of B mesons, which would be probably sufficient to measure CP violation asymmetries if good efficiency for B reconstruction and flavor tagging could be achieved. Future higher energy facilities now in their planning stage, like LHC, appear even more promising. Even if it is difficult to predict $b\bar{b}$ production cross section at LHC energies, as at these energies extremely low x partons play a dominant role,⁸² the expected order of magnitude is 1 mb, whereas the total cross section does not increase

Table 2: Cross section and signal to background for $b\bar{b}$ events in fixed target and collider experiments operating in the next decade and beyond.

Accelerator	Mode†	$\sqrt{S}(\text{TeV})$	$\sigma_{b\bar{b}}(\mu\text{b})\ddagger$	$\sigma_{b\bar{b}}/\sigma_t$
HERAB	T	0.04	0.012	$1. \times 10^{-6}$
LHC	T	0.12	0.4 ± 0.2 *	$(8.0 \pm 4.0) \times 10^{-6}$
TEV	C	1.80	60 ± 25	$(8.0 \pm 3.5) \times 10^{-4}$
LHC	C	16.0	700 ± 200	$(7.3 \pm 2.0) \times 10^{-3}$

† T indicates fixed target operation and C indicate collider operation.

‡ The uncertainty in the cross section is the one given by the theoretical calculation by changing the values of the input parameters in some reasonable domain: the actual uncertainty may actually be much higher.

* The fixed target cross sections are given for hydrogen targets; using heavier targets increases the cross section by a factor $\approx A^{0.95}$, where A is the target atomic number.

appreciably with respect to the Tevatron energy.

Table 2 summarizes the beauty production cross section and the fraction of beauty events expected at the facilities expected to be operating in the next decade or so, either in collider mode or in fixed target mode.

The boost dilation factor $\gamma\beta$ is roughly between 5 and 10 times higher in fixed target mode than in collider mode and the average charged particle multiplicity in $b\bar{b}$ events ≈ 5 times smaller.¹¹⁹ On the other hand the boost focuses all the particles in a narrow cone, making precision vertexing and momentum reconstruction rather challenging tasks. In addition, there may be technical difficulties in producing the extracted beam without disrupting the beam quality for the collider. In this respect, the use of a jet target¹² may be an appealing alternative. This solution has the further advantage of determining very precisely the location of the primary vertex, without the need of tracking information. The $b\bar{b}$ cross section and the fraction of $b\bar{b}$ events are still quite low with respect to collider mode operation: $\sigma_{b\bar{b}}/\sigma_t$ can be increased by a factor $\approx A^{0.95-0.72}$, ≈ 4 using heavy targets.⁹²

There is still large uncertainty on the effective tagging efficiency which will be

reached in CP experiments taking place at present and future hadron machines. In addition, other inelastic interactions are likely to be part of the accepted sample, thus producing high trigger rates which may stretch the capabilities of state of the art data acquisition systems. It is conceivable that highly parallel architecture can handle event storage rates up to 1 KHz, which corresponds to an assumed data logging capability of 100 Mbytes/s and an event size of 100 Kbytes/s.¹⁰¹ However a better selectivity of beauty events would be desirable in order to prevent the off-line analysis task from being prohibitively long. In addition, if efficient tagging strategies are found, the B sample needed to achieve sufficient sensitivity may be smaller. It can be seen that the effort in this case is not in machine design but in the development of a data acquisition system capable of handling higher rates, trigger schemes with high selectivity for beauty events and efficient tagging strategies.

5.3 Luminosity requirements - General principles

It is easy to see that the asymmetry ratio A has a statistical error δA which, for small asymmetries, is roughly proportional to $1/\sqrt{N}$ where N is the number of flavor tagged events reconstructed in a specific CP eigenstate f . The statistical significance of the measurement is defined as:

$$s = A/\delta A. \quad (26)$$

The value of s chosen to define a measurement significant has some inherent arbitrariness: a rather prudent choice appears to be $s = 4$, which in turn implies:

$$N = s^2/A_{meas}. \quad (27)$$

The measured asymmetry A_{meas} differs from the theoretical A , which is given by $\sin 2\phi d(x)$, because of the presence of background events in the sample of reconstructed CP eigenstates and because of the dilution effect produced by wrong sign tags and is given by:

$$A_{meas} = r_{sig} \cdot (1 - 2w)d(x)\sin 2\phi, \quad (28)$$

where $r_{sig} = S/(S + B)$ is the ratio between the number of signal events and the total number of reconstructed events and w is the ratio between the number of wrong sing tags over the total number of tags.

The number of tagged events N is given by:

$$N = L\sigma(B/r_{sig})\epsilon_{rec}\epsilon_{tag}. \quad (29)$$

where L is the machine integrated luminosity, σ is the cross section for neutral B production, (B/r_{sig}) is the effective branching ratio for the decay mode

considered, ϵ_{rec} is the CP eigenstate reconstruction efficiency and includes trigger efficiency and detector acceptance, and ϵ_{tag} is the overall tagging efficiency, including wrong sign tags.

Equations 28 and 29 can be combined to give the integrated luminosity formula:

$$L = \frac{s^2}{\sigma d(x)^2 \sin^2 \phi \mathcal{B} \epsilon_{rec} \epsilon_{tag} r_{sig} (1 - 2w)^2} \quad (30).$$

The task of accelerator physicists to deliver adequate luminosity can be eased by devising an experiment capable of reconstructing efficiently several CP eigenstates and taking advantage of several tagging strategies.

5.4 Luminosity requirements - Rates

The first requirement to perform the measurement of CP violation in B decays is the capability of reconstructing exclusive final states. Even if the discussion of the physics principles underlying the measurement has been performed in terms of CP eigenstates, the class of final states which are useful is actually wider and includes all final states which are non-flavor specific, or, in other words, which are accessible both to B^0 and $\bar{B}^0$.¹²⁰ The modes which are actually interesting depend upon the approach taken in performing the measurement. A good product $\mathcal{B} \cdot \epsilon_{rec}$ and a good r_{sig} are the requirements to be met for a channel to be considered useful. For instance, the final state ψK_S is the ‘golden mode’ both at e^+e^- and hadronic machines, due to the unique signature provided by the ψ in the final state. On the other hand, charmless modes like $\pi^+\pi^-$ may have too much background in some experimental situations to be considered useful.

All modes can be classified into four main categories:

1. hidden charm final states ($\psi, \psi' \dots$),
2. double D final states,
3. modes containing a D^0 decaying to a CP eigenstate,
4. charmless final states.

Table 3 summarizes the results of several studies which have been performed at different laboratories for the benchmark decay channel ψK_S . The summary is just indicative of the widespread interest in the topic in the high energy physics community and some of the results listed will likely be refined in the near future. Additional decay modes can be used to measure ϕ_c . Some of them belong to a category of decays often referred to as “near CP eigenstates”, for instance ψK^{*0} . In principle, this decay can proceed via $l = 0, 1, 2$ partial waves. The even partial waves have opposite CP eigenvalue with respect to the odd one. It has been shown¹²⁰ that the analysis of the decay angular distributions can disentangle components of different CP . If a single partial wave dominates, “near CP eigenstates” are equivalent to CP eigenstates. However if an equal

Table 3: Measurements of Φ_c through the final state ψK_S .

Study	Mode	$\mathcal{B}$	$\epsilon_{rec}^\dagger$	$\mathcal{B} \times \epsilon_{rec}$
CESR-B ¹¹⁶	$\psi K_S^0, K_S \rightarrow \pi^+ \pi^-$	4×10^{-5}	0.38	1.4×10^{-5}
CESR-B	$\psi K_S^0, K_S \rightarrow \pi^0 \pi^0$	2×10^{-5}	0.18	2.2×10^{-6}
SLAC ¹¹⁷	$\psi K_S^0, K_S \rightarrow \pi^+ \pi^-$	4×10^{-5}	0.55	2.2×10^{-5}
SLAC	$\psi K_S^0, K_S \rightarrow \pi^0 \pi^0$	2×10^{-5}	0.54	1.1×10^{-5}
KEK ⁸	$\psi K_S^0, K_S \rightarrow \pi^+ \pi^-, \pi^0 \pi^0$	6×10^{-5}	0.65	3.9×10^{-5}
HERAB ¹⁵	$\psi K_S^0, K_S \rightarrow \pi^+ \pi^-$	4×10^{-5}	0.056	2.2×10^{-6}
LHC (Collider) ⁷⁵	$\psi K_S^0, K_S \rightarrow \pi^+ \pi^-$	4×10^{-5}	0.008	3.2×10^{-7}

† The ϵ_{rec} figures are taken from the different studies which have been performed with very different assumptions. There is a huge spread in their degree of reliability and a direct comparison between different approaches on the basis of these numbers would be very unwise.

Table 4: Modes useful for Measuring ϕ_u .

Study	Mode	$\mathcal{B}$	ϵ_{rec}	$\mathcal{B} \times \epsilon_{rec}$	$\frac{D_{deg}}{D_{deg}(\pi^+ \pi^-)}^\dagger$
CESR-B	$\pi^+ \pi^-$	2.0×10^{-5}	0.69	1.4×10^{-5}	1.0
SLAC	$\pi^+ \pi^-$	2.0×10^{-5}	0.20–0.43	$0.4\text{--}0.9 \times 10^{-5}$	1.0
CESR-B	$\rho^\pm \pi^\mp$	6.7×10^{-5}	0.40	2.7×10^{-5}	1/2
SLAC	$\rho^\pm \pi^\mp$	6.7×10^{-5}	0.215–0.585	$1.4\text{--}3.9 \times 10^{-5}$	1/2
CESR-B	$a_1^\pm \pi^\mp$	5.6×10^{-5}	0.25	1.1×10^{-5}	1/5
SLAC	$a_1^\pm \pi^\mp$	5.6×10^{-5}	0.095–0.3	$5.3\text{--}1.7 \times 10^{-5}$	1/5
CESR-B	$\rho^+ \rho^-$	2.2×10^{-5}	0.25	0.6×10^{-5}	1/9

† The factor $\frac{D_{deg}}{D_{deg}(\pi^+ \pi^-)}$ measures the degradation associated with a “near- CP eigenstate”.

mixture of the various partial waves is involved the number of events required to make an asymmetry measurement in decays involving two vector particles in the

Fig. 22 Reconstructed B candidate mass spectrum from CLEO for ψK^- based on 0.89 fb^{-1} of $\Upsilon(4S)$ data.

final state is increased by a factor of nine. Some of the modes involving ψ' or χ in the final state may be useful too.

Table 4 shows the corresponding results for the modes relevant to the measurement of ϕ_u . The major problem in the measurement of this angle is the level of background. Only upper limits exist for the branching ratios of all the decays mediated by the $b \rightarrow u$ transition. Therefore one has to rely on the validity of the WBS predictions. In this case the theoretical uncertainty is even bigger, as it involves the hadronization of a heavy meson into two light mesons, casting some doubts on several assumptions used in the calculations. The best upper limit⁴⁷ for $B \rightarrow \pi\pi$ is 2.9×10^{-5} at 90% C.L. If the WBS prediction is correct, it should soon be confirmed, as this upper limit is very close to the WBS prediction. The authors assign a factor of two uncertainty to their prediction¹²¹ but again some experimental input would be crucial to establish more firmly the expected rates. The modes which are considered in addition to $\pi^+\pi^-$ are all “near CP eigenstates”. In these channels, the two tree amplitudes which contribute to the decays of $B^0 \rightarrow f$ and $\bar{B}^0 \rightarrow \bar{f}$ are different. For instance, in the decay $\bar{B}^0 \rightarrow \pi^- \rho^+$ the virtual W^- hadronizes into a ρ^- , whereas in the CP conjugate decay the virtual W^+ materializes as a π^+ . Depending upon the magnitude of ratio between these two tree level amplitudes, $\rho \equiv M/M'$, there will be a degradation factor, D , in the statistics necessary to observe a CP asymmetry, given by $D \equiv 2\rho/(\rho^2 + 1)$. For $4 > \rho > 1/4$, $D > 0.5$.

The background estimates are very difficult to perform without the support of experimental data. An example on how the background can be evaluated through extrapolation from experimental data is the estimate for the case of ψK_S^0 can be performed using the CLEO $\psi K^\pm$ data shown in Fig. 22.⁴⁶ The ψK yield is 59 events and the background in the signal region is 1 event. This translates into a background fraction of 1.7%. On the other hand the $\psi K^\pm$ data sample contains a background component which is attributed to random combinations between ψ 's and charged particles of the right sign. In the momentum range characteristic of the K 's from $B \rightarrow \psi K$, π 's are at least equal 2/3 of the total sample of candidate K 's, while K_S^0 are identified by their decay. Therefore we can expect a background reduction factor of at least a factor of 3, corresponding to r_{sig} very close to 1, with a consequently negligible luminosity penalty. The backgrounds are large in the $D^+ D^-$ channel, whereas modes containing at least one D^* appear to be more useful. Some improvement may be expected by using vertex criteria in order to suppress the background. In addition, the value of r_{sig} is not only a function of the specific decay channel, but also of the tagging strategy. For instance, high momentum leptons provide a high purity tag, which enhances the B signal with respect to continuum background, whereas K tags do not provide any efficient background suppression.

The modes considered for the measurement of ϕ_u have also a substantial background associated with non-resonant $q\bar{q}$ production. This is illustrated by Fig. 23 which shows the results of a search for the decay $\bar{B}^0 \rightarrow \pi^+ \pi^-$ by the CLEO experiment.⁴⁷ These data can be used to estimate the value for r_{sig} for this channel, resulting in $r_{sig} = 0.7$. Again there is a sizable improvement for specific tags, most notably high momentum leptons, but these rare decay modes are the ones which benefit the most by being able to take advantage of many tagging strategies. Possible improvements of r_{sig} can be achieved by devising suitable vertex topology criteria¹²² which utilize the high precision vertex information needed to perform the measurement of the time separation between the decay times of the two B 's. It appears that a value of r_{sig} of 0.9 can be achieved with an ϵ_{rec} reduction to 63%. The background problem becomes worse in modes involving broad resonances, like ρ or a_1 : in this case the CLEO data show an increase of the background by a factor of 9 with respect to the $\pi^- \pi^+$ in the $a_1^\pm \pi^\mp$ channel and is estimated to be only slightly lower in the $\rho^\pm \pi^\mp$ channel. Consequently only clean tags are likely to be useful for these modes.

5.5 Luminosity requirements - Tagging efficiency

In order to measure the CP asymmetry it is necessary to determine the flavor of the reconstructed final state. The ability of using several tagging strategies is very important in reducing the luminosity requirements to achieve sufficient sensitivity to probe the Standard Model. Two factors determine the effectiveness

Fig. 23 B candidate mass spectra from CLEO for $\bar{B}^0 \rightarrow \pi^+\pi^-$ or $K^-\pi^+$ (a) using 1.37 fb^{-1} of $\Upsilon(4S)$ data, (b) 0.64 fb^{-1} of continuum data. The shaded histograms corresponds to events identified as $\pi^-\pi^+$.

of a tagging strategy: the tagging efficiency ϵ_{tag} and the fraction of wrong sign tags, $w_{tag} = N_{wrong}/(N_{wrong} + N_{right})$. The quantity which is relevant to the CP asymmetry measurement is the effective tagging efficiency, defined as $\epsilon_{tag}^{eff} = \epsilon_{tag} \times (1 - 2 \times w_{tag}^2)$.

The most widely studied tag is the lepton which comes from the decay chain $b \rightarrow X l \bar{\nu}$: this is a very simple tag as the charge of the lepton is directly related to the flavor of the parent quark. A negative lepton indicates that the parent is a $\bar{B}^0$ and a positive lepton indicates that the parent is a B^0 . However, this decay chain is only one component of the lepton spectrum from B decays as shown in Fig. 24. The additional component comes from the cascade decay $B \rightarrow DX$, $D \rightarrow Y l \bar{\nu}$ and accounts for roughly half the total rate. In the B rest frame the spectrum is dominated by the direct decay $b \rightarrow cl \bar{\nu}$ for lepton momenta above 1.4 GeV. Therefore high momentum leptons ($p_l^{CM} > 1.4$) GeV are among the highest purity tags, as ϵ_{tag} is very close to ϵ_{tag}^{eff} (with a tagging efficiency about 10% and an effective tagging efficiency of 8.3%).¹¹⁶ As the B 's are almost stationary in

Fig. 24 Lepton momentum spectrum from CLEO. The curves are fit to the primary $B \rightarrow X l \bar{\nu}$ component and the secondary $B \rightarrow D X$, $D \rightarrow Y l \bar{\nu}$ component.

the $\Upsilon(4S)$ rest frame, e^+e^- colliders can take advantage of a simple momentum cut to select leptons coming from $b \rightarrow cl\bar{\nu}$ decays. For hadronic machines the selection of the direct component is not so straightforward but alternative criteria may be used, like high $p_{\perp}$ or mapping of the vertex topologies. In general, lower efficiency and higher wrong sign fraction is expected in this case.

The CESR-B study has investigated the possibility of taking advantage of the whole spectrum, by noting that a lepton from D is an equally good tag, if its origin is unambiguous. Therefore very low momentum leptons ($p_l < 0.6$ GeV) are a relatively clean tag, as in this case cascade decays dominate. In the intermediate momentum region ($0.6 > p_l > 1.4$) one can discriminate between the two components through the correlation between lepton and ν momentum. In direct semileptonic decays the ν tends to have higher momentum

than in cascade semileptonic decays. As the other B is fully reconstructed and the detector considered in this study has good acceptance and resolution both for charged particles and photons, the “missing momentum” in the event provides a good measurement of the ν momentum. The criterion adopted is that the sum $|\text{missing momentum}| + |\text{lepton momentum}| > 2.0 \text{ GeV}/c$ corresponds to a lepton from the B , otherwise it is identified as coming from D semileptonic decay. These two additional lepton tags contribute an additional 6.8% to ϵ_{tag}^{eff} ,

thus almost equaling the contribution of high momentum leptons.

A tagging strategy which is very important for its high statistical power is the $K^\pm$ tag. Conceptually this tagging strategy is very similar to the high momentum lepton one: due to the decay chain $b \rightarrow c \rightarrow s$, K^- should come from $\bar{B}^0$ and K^+ only from B^0 . On the other hand, there is a further uncertainty in this case, because we do not detect quarks but hadrons. The observed $K^\pm$ can contain s quarks coming from $s\bar{s}$ popping in the hadronization phase or an s quark from $W \rightarrow \bar{c}s$. This is the reason why the wrong sign fraction is higher in this case and it is also more uncertain, as it depends on the reliability of the hadronization simulation in the event generator used. This uncertainty should be a great concern of groups working on Monte Carlo studies to evaluate the performance of experiments at future hadronic machines, where the complex hadronization process of the various partons involved has not yet been tuned to any experimental data. A tagging efficiency of the order of 33% is expected

for this strategy at e^+e^- B -factories, with a corresponding ϵ_{tag}^{eff} of the order of 20%.¹¹⁶

Another tagging strategy proposed by the CESR-B group which is very powerful in e^+e^- threshold machines is based on partially reconstructed B decays. As one B is fully reconstructed, it is not necessary to detect all the particles in the tagging B . In particular, if the missing particle is a D or a D^* , we can use kinematic fitting to identify the final state in an almost background free manner. In this case the charge of the D or the D^* identifies the parent B flavor. The overall efficiency obtained studying modes involving one, two or three $\pi^\pm$ and possibly one or two π^0 is 8.7%, with comparable ϵ_{tag} and tagging purity as the high momentum leptons.

A considerable effort is presently under way to identify new tagging strategies useful in experiments at hadron machines. For instance, techniques based on the evaluation of the total charge associated with detached vertices have been

proposed.¹²³ In addition the use of the charge of the π produced in the decay

$B^{**} \rightarrow \pi B$ as a flavor tag.¹²³ It is still quite unclear whether any substantial increase in tagging efficiency can be achieved with these methods.

6. Conclusions

The study of the decay properties of b -flavored hadrons has already provided extensive information through the effort of several experimental groups taking data either at e^+e^- colliders or at hadron machines. The bulk of our present knowledge on the properties of the lowest mass B mesons comes from e^+e^- machines at threshold, which in the near future will provide an extensive study of exclusive final channels, through the high statistics data sample which is collected by CLEO-II. In addition, LEP and Fermilab experiments are studying higher mass b -flavored mesons and baryons and measuring the individual lifetimes of different mesons.

Several groups are actively investigating the best strategy to measure CP violation in B decays with a high luminosity machine. The first of the new generation of detectors to turn on is the CLEO III detector, in conjunction with a high luminosity upgrade of the CESR e^+e^- collider at Cornell University, which has some chance of obtaining the first evidence for CP violation in charged B decays. Asymmetric e^+e^- B -factories are expected to turn on before the end of the century. In parallel, much progress should be made at hadron collider facilities in exploring beauty phenomenology and in developing improved experimental strategies to acquire high statistics b -flavored hadron samples. Therefore this decade will be crucial to the study of b decay phenomenology, and will lead to a significant improvement of our knowledge of the quark mixing matrix, thus providing a very sensitive probe of this sector of the Standard Model.

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